Lucio Ludovici
INFN Roma

Siena
11th October 2001

Recent Results in Neutrino Physics

Seventh Topical Seminar on The Legacy of Lep and SLC
Siena 8-11 October 2001

Mass Direct Measurements

Direct kinematic limits on $m_{\nu x}^2 = S \, |U_{xi}|^2 m_i^2$

m_{ne} < 2.2 eV (1) — Mainz Tritium endpoint (eventually m_{ν}^2>0!) Troitsk experiment 2.5 eV (+ seasonal anomaly ?!) ® ~0.5 eV reachable in future. Criogenic Microcalorimetry (^{187}Re), now <26 eV (® 10 eV) (Genova, Milano).

m_{nm} < 190 keV (1) — p ®mn at rest. Limited by the uncertainty on the pion mass (Dm/m=2.6·10^{-6}). Clever idea to reach ~10 keV sensitivity using decay in flight at the BNL (g-2) ring.

m_{nt} < 15.5 MeV (1) — Exploit kinematic correlation Mh,Eh in t®np(p°)n_t (Aleph,Cleo,Opal). ® ~3 MeV, Babar, Belle (systematics ?!).

(1) 95% CL

Double Beta Decay

SM 2nbb observed with radiochemical inclusive methods.
Direct counting experiment search the non-SM 0nbb (DL=2)
Physics beyond SM or limit on $t_{1/2}^{0nbb}$ ® limit on $<m_\nu>= S\ U_{ei}^2 m_i$

		90%CL limit $<m_\nu>$ (eV)
Heid.-Moscow	^{76}Ge	0.40
IGEX	^{76}Ge	0.44
UCI	^{82}Se	5.4
ELEGANT	^{100}Mo	2.7
Kiev-Firenze	^{116}Cd	3.3
Missouri	^{128}Te	1.5
Milano	^{130}Te	2.6
Cal.UN.PSI	^{136}Xe	3.5
UCI	^{150}Nd	7.1

$<m_\nu>$ limited (~1 eV) by the uncertainty on the nuclear matrix element calculations

Cancellations possible

In models with neutrino mass degeneration ® constraint on the mixing angles combination $S\ U_{ei}^2$

Source "Breaking News"

now, <2005, >=2005, sometime/maybe

Sun — SNO 2001

SNO, GNO, Super-K, Borexino

Atmosphere — Super-K 1998

Super-K, Soudan2, Monolith, UNO

Reactors — Chooz 1999

MUNU, Kamland

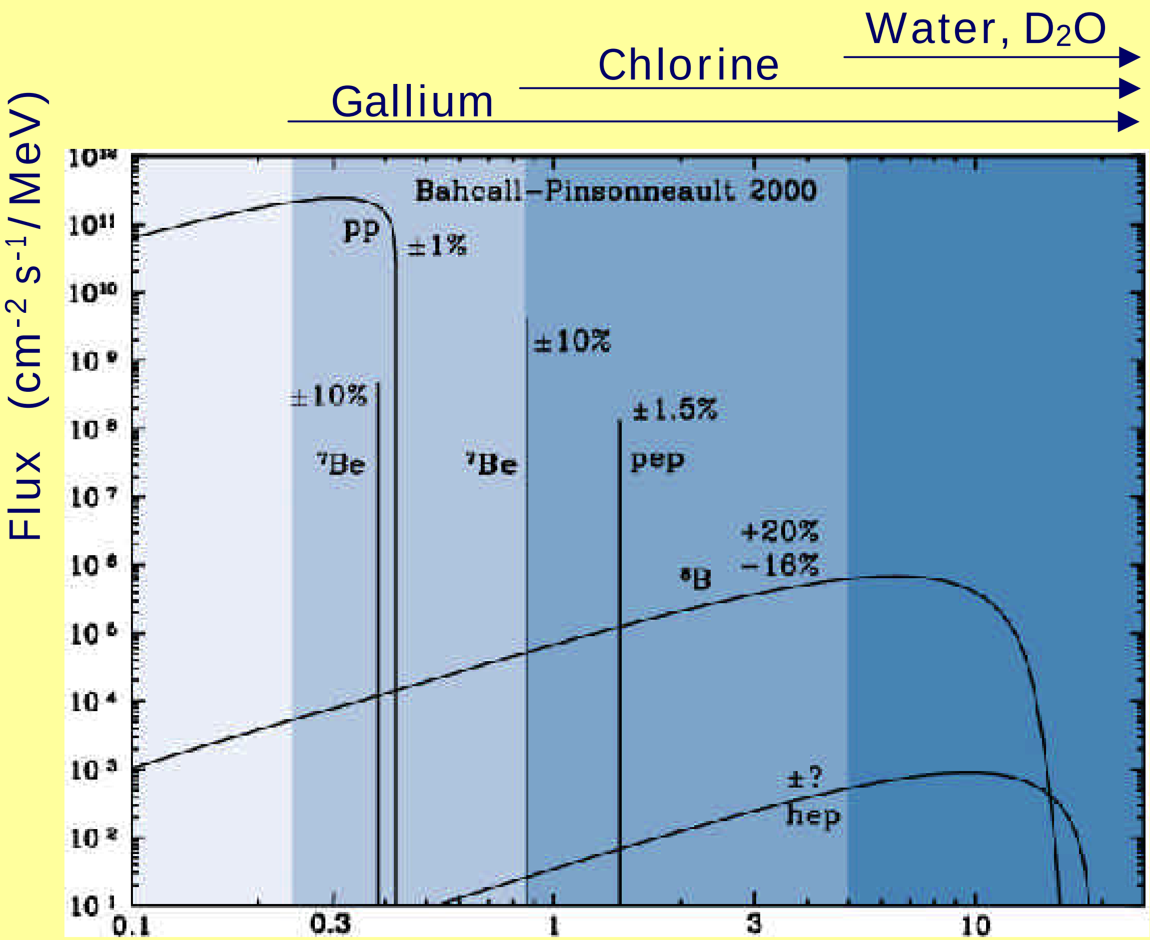
Accelerators — K2K 2000

K2K (JHF), MiniBoone, Minos, Opera, Icarus, NuFact

Astrophysics — Amanda 2000

Baikal, Amanda, Antares, ICECUBE, Km^3

Neutrino from the SUN



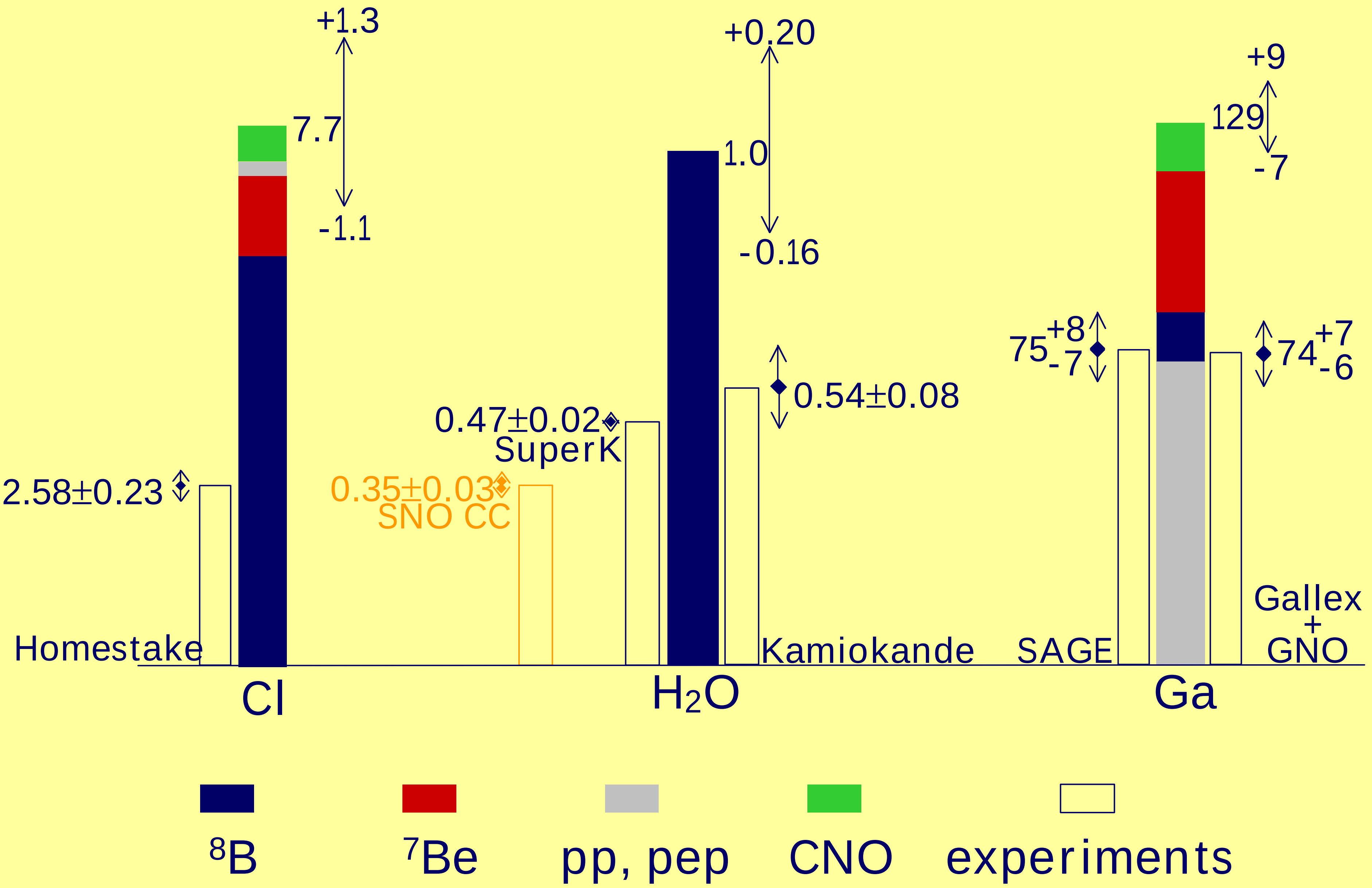
Chlorine
Homestake
$n_e + {}^{37}Cl$ ® ${}^{37}Ar + e^-$

Gallium
SAGE, Gallex,GNO
$n_e + {}^{71}Ga$ ® ${}^{71}Ge + e^-$

Water
Kamioka, SuperK
$n_x + e^-$ ® $n_x + e^-$ (ES)

D_2O
SNO
$n_x + e^-$ ® $n_x + e^-$ (ES)
$n_e + d$ ® $p + p + e^-$ (CC)
$n_x + d$ ® $n + p + n_x$ (NC)

The Problem...


+1.3
7.7
-1.1
+0.20
1.0
-0.16
+9
129
-7
75 +8 -7
74 +7 -6
0.54±0.08
0.47±0.02
SuperK
2.58±0.23
0.35±0.03
SNO CC
Homestake
Kamiokande
SAGE
Gallex
+
GNO
Cl
H2O
Ga
8B
7Be
pp, pep
CNO
experiments

SNO

NC (1:1), ES (1:6.5) :
Sensitivity to $n_{m,t}$

CC vs NC (CC vs ES) :
$n_e \rightarrow$active is a smoking gun (appearance, flux independent)

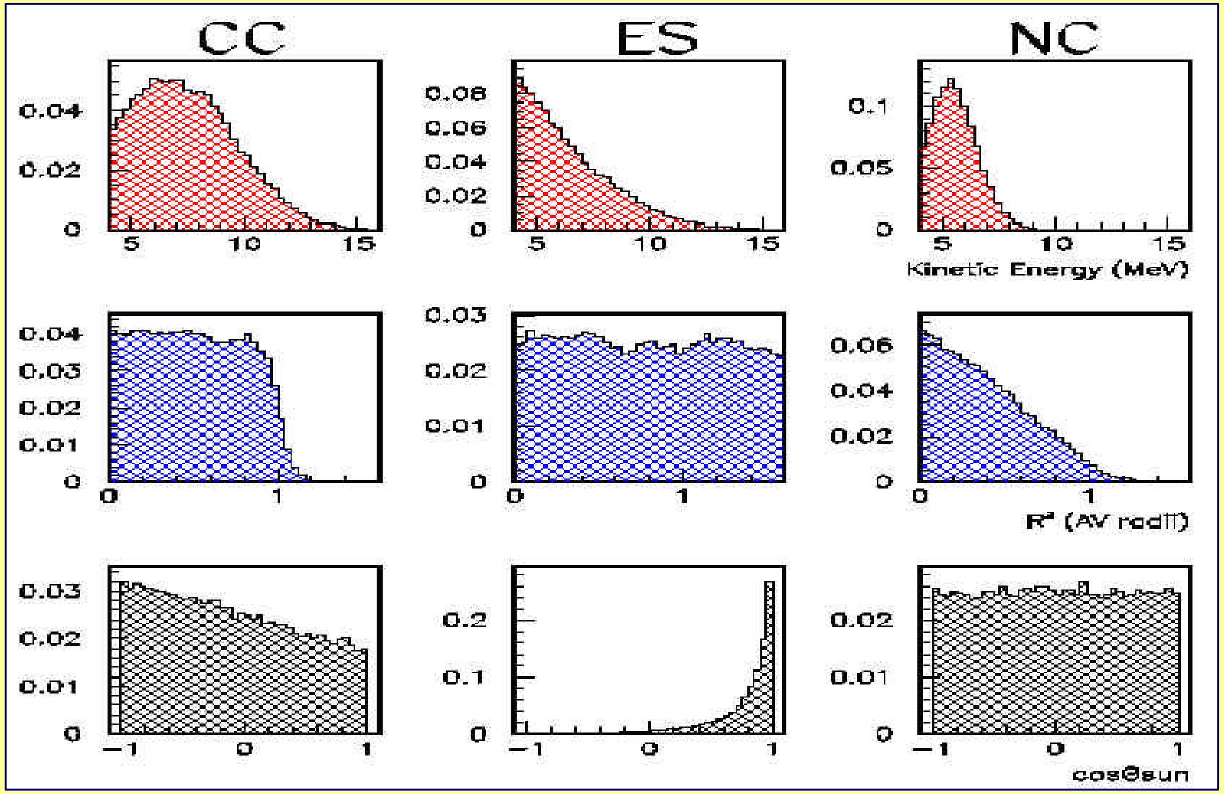
NC :
Total n flux from ^{8}B

CC (ΔE/E»20%) :
MSW spectral distortion, Day/Night effect, seasonal

CC+ES+NC, SNO I, II, III
Large potential to explore the parameter space (SMA, LMA, LOW, Vacuum)

energy direction flavour

$n_e + d \rightarrow p + p + e^-$ $n_x + e^- \rightarrow n_x + e^-$ $n_x + d \rightarrow n + p + n_x$



Appearance of Active Neutrino in te ^{8}B Flux

(units: 10^6 cm^{-2}s^{-1})

$$F^{CC}_{SNO}(^8B) = 1.75 \pm 0.07 \, (\text{stat}) \, ^{+0.12}_{-0.11} \, (\text{sist}) \pm 0.05 \, (\text{teor})$$ SNO

$$F^{ES}_{SNO}(^8B) = 2.39 \pm 0.34 \, (\text{stat}) \, ^{+0.16}_{-0.14} \, (\text{sist})$$ SNO

$$F^{ES}_{SNO} - F^{CC}_{SNO} = 0.64 \pm 0.40$$ 1.6s SNO

$$\Phi^{ES}_{SK}(^8B) = 2.32 \pm 0.03 \, (\text{stat}) \, ^{+0.08}_{-0.07} \, (\text{sist})$$ SuperK

$$F^{ES}_{SK} - F^{CC}_{SNO} = 0.57 \pm 0.17$$ 3.3s SNO+SuperK

Appearance in the solar flux of active neutrino $\neq n_e$

Pure $n_e \to n_{sterile}$ oscillation excluded at more than 3s

^{8}B and ^{7}Be Flux in Chlorine

$F^{ES}_{SK}(^{8}B)$ - $F^{CC}_{SNO}(^{8}B) \Rightarrow$ $F^{\nu_\mu+\nu_\tau}(^{8}B) = 0.57 \pm 0.17 \cdot 10^{6}\ cm^{-2}\ s^{-1}$

$F^{CC}_{SNO}(^{8}B) \Rightarrow$ $F^{\nu_e}(^{8}B) = 1.75 \pm 0.15 \cdot 10^{6}\ cm^{-2}\ s^{-1}$

$\Phi^{37Cl}(^{8}B) = 2.00 \pm 0.19$ SNU (BP: 5.9 SNU)

Homestake: $\Phi^{37Cl} = 2.56 \pm 0.23$ SNU

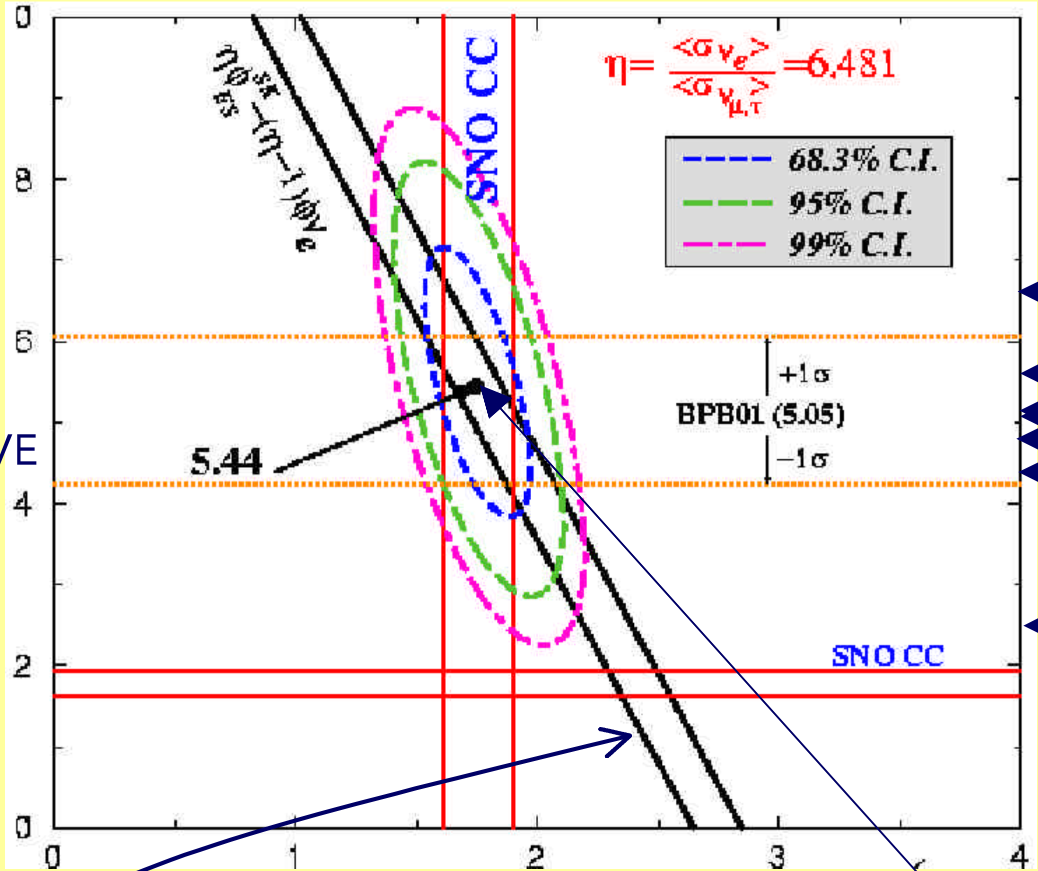
$\Phi^{37Cl}(^{7}Be+pep+CNO) = 0.56 \pm 0.30$ SNU (BP: 1.8 SNU)

^{7}Be (+CNO+pep) suppression (31±17%) is consistent with the ^{8}B suppression (35±3%). The ^{7}Be puzzle is solved.

The Bahcall's Glory

$(10^6/cm^2/s)$

F^{ACTIVE}



BP95B
B82
BPB98C BPB01
Filippone, Schramm 82
Turck-Chieze, Lopez 93
Dar 96

F^{n_e} $(10^6/cm^2/s)$

$F^{ES} = F^{n_e} + 1/h \cdot (F^{ACTIVE} - F^{n_e})$

Total ^{8}B neutrino flux:
$5.44 \pm 0.99 \cdot 10^6\ cm^{-2}s^{-1}$

Solar: Present and Future

Oscillation

Evidence for inclusive appearance of n_m, n_t in the n_e produced in the sun's thermonuclear reaction

⇒SNO II, SNO III

Standard Solar Model

Direct measurement of the active neutrino flux from ^8B confirms calculations (most cited: BPB2001). Other components are expected less model dependent, but ...

⇒GNO (pp), Borexino (pin down ^7Be line)

Distorsioni spettrali

No evidence. Chlorine and water reconciled

⇒SNO, Super-K(>6MeV), Borexino (1-5MeV)

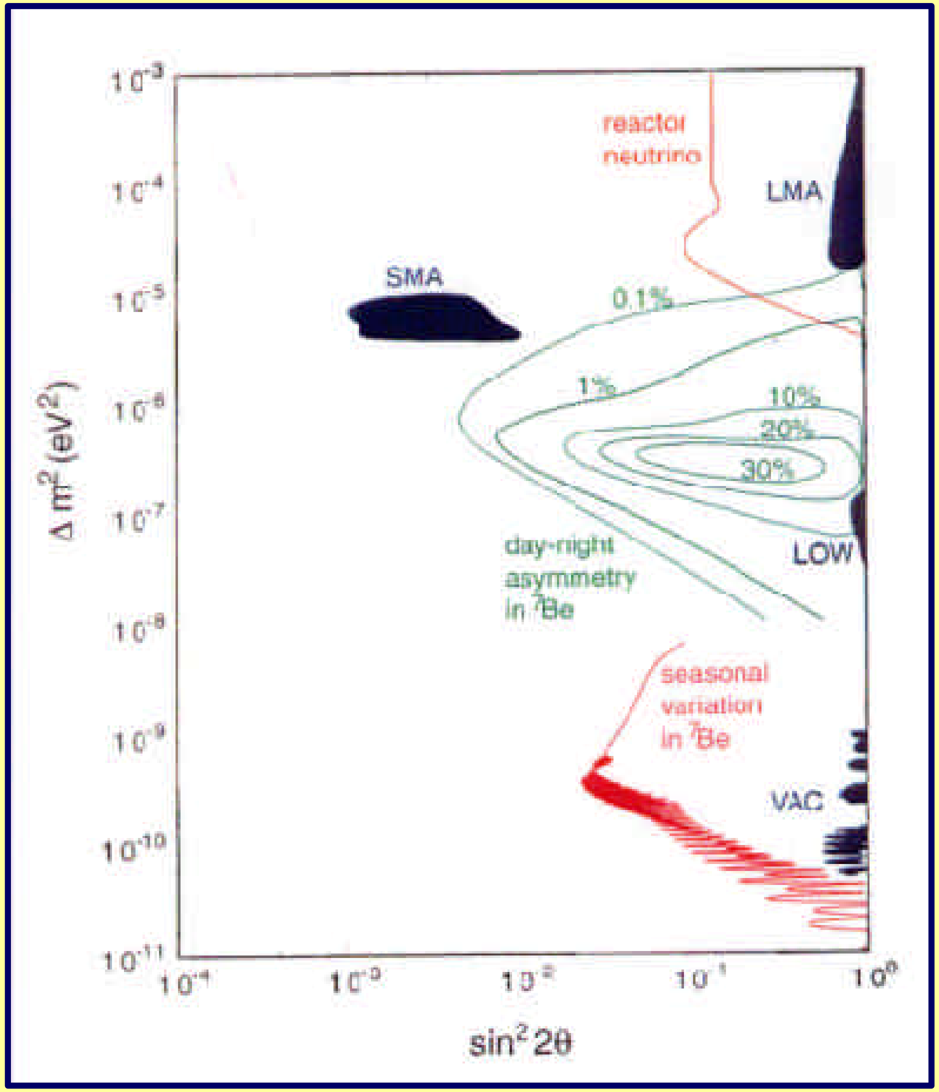
Day/Night, seasonal variations

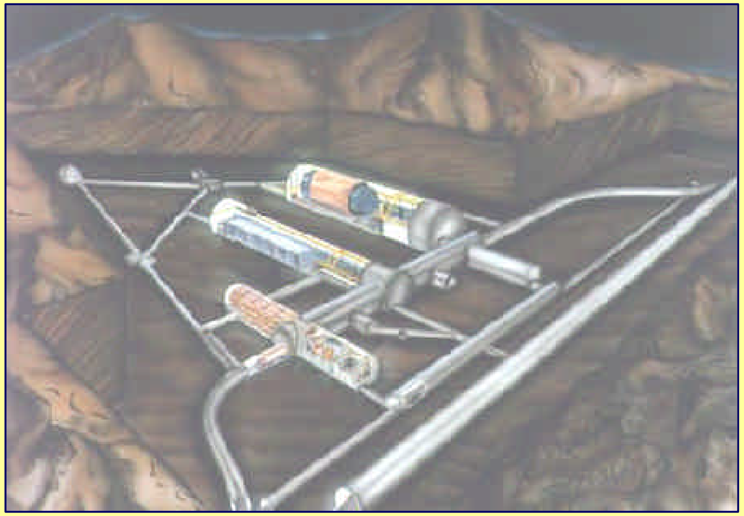
No evidence. ⇒GNO, SNO, Borexino

Kamland

Reactor neutrino could (if LMA) provide the final clue to the long standing solar neutrino problem

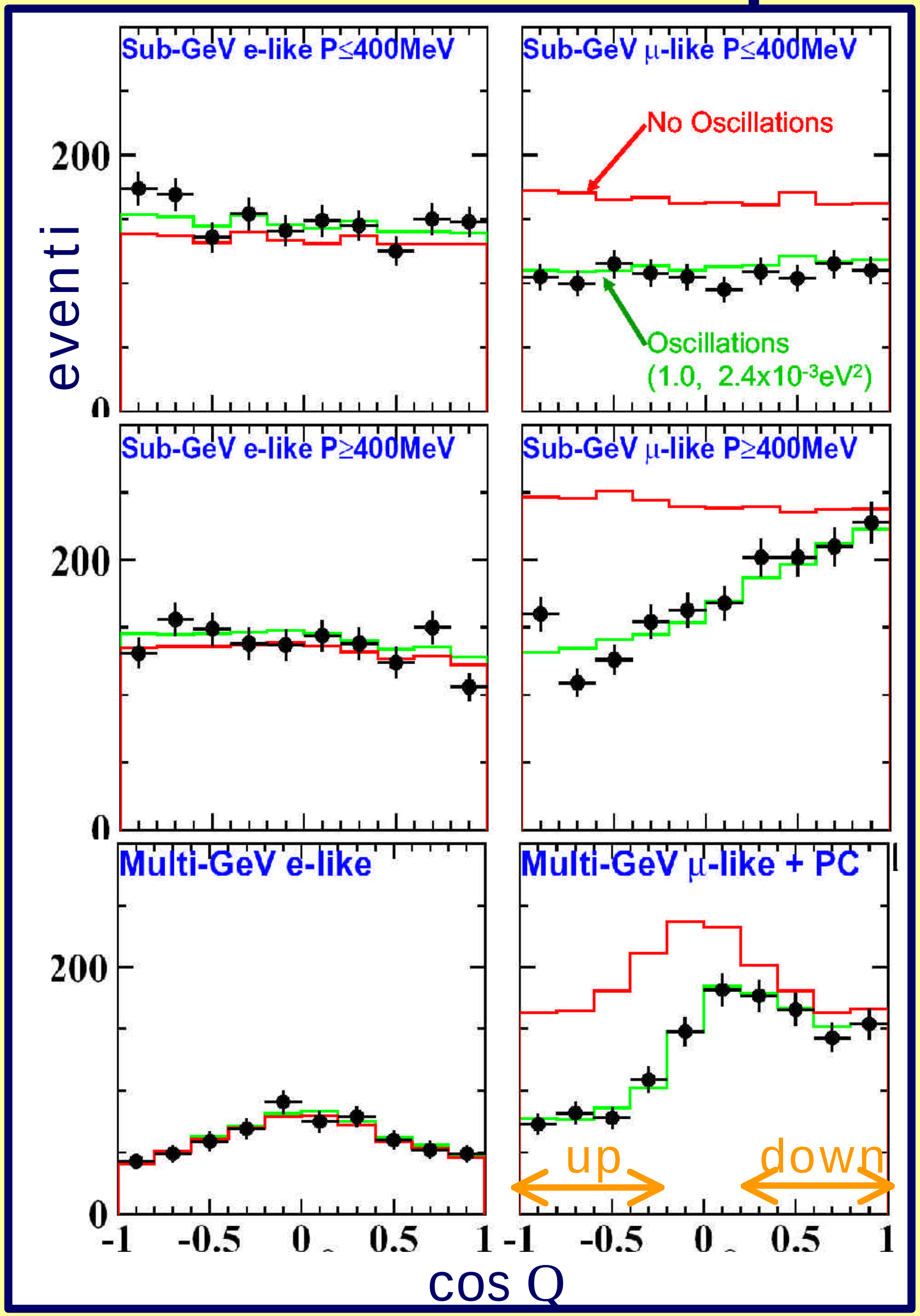
KamLAND@Kamioka





Borexino@LNGS

Atmospheric: zenith



Calculations: DF_{atm} / F_{atm} = 20%

SuperK statistic 79.5 kt·yr

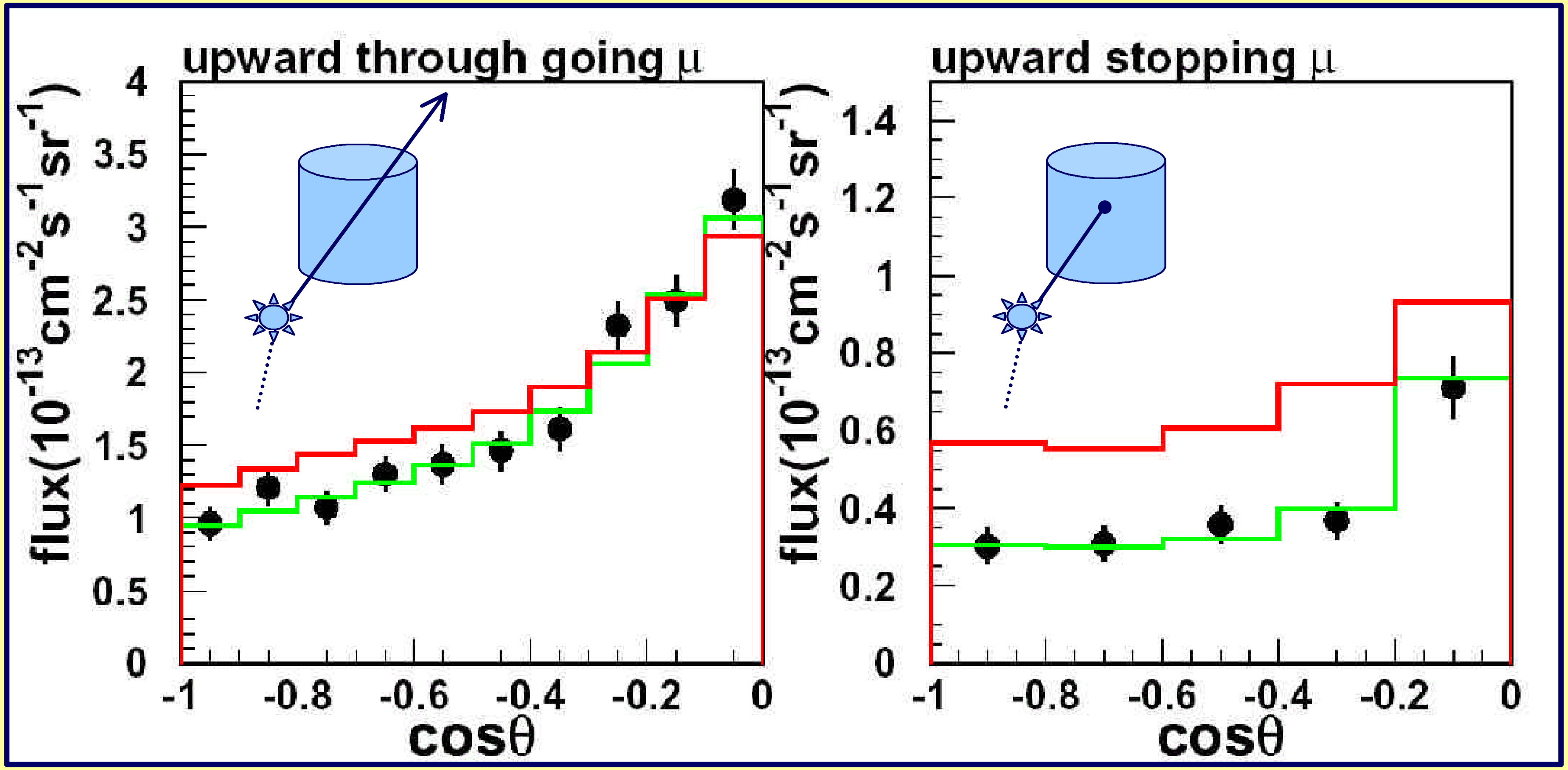
Evidence for oscillation:

- 50% deficit of n_m flux
- n_e flux as expected
- $F_{up} \sim ½ F_{down}$!

Up/Down = 0.54±0.04±0.01

c^2_{min} = 132.4/137 dof
for $n_m \rightarrow n_t$ with
$\sin^2 2q = 1$, $Dm^2 = 2.4 \cdot 10^{-3}$ eV^2

Atmospheric: up-ward muons

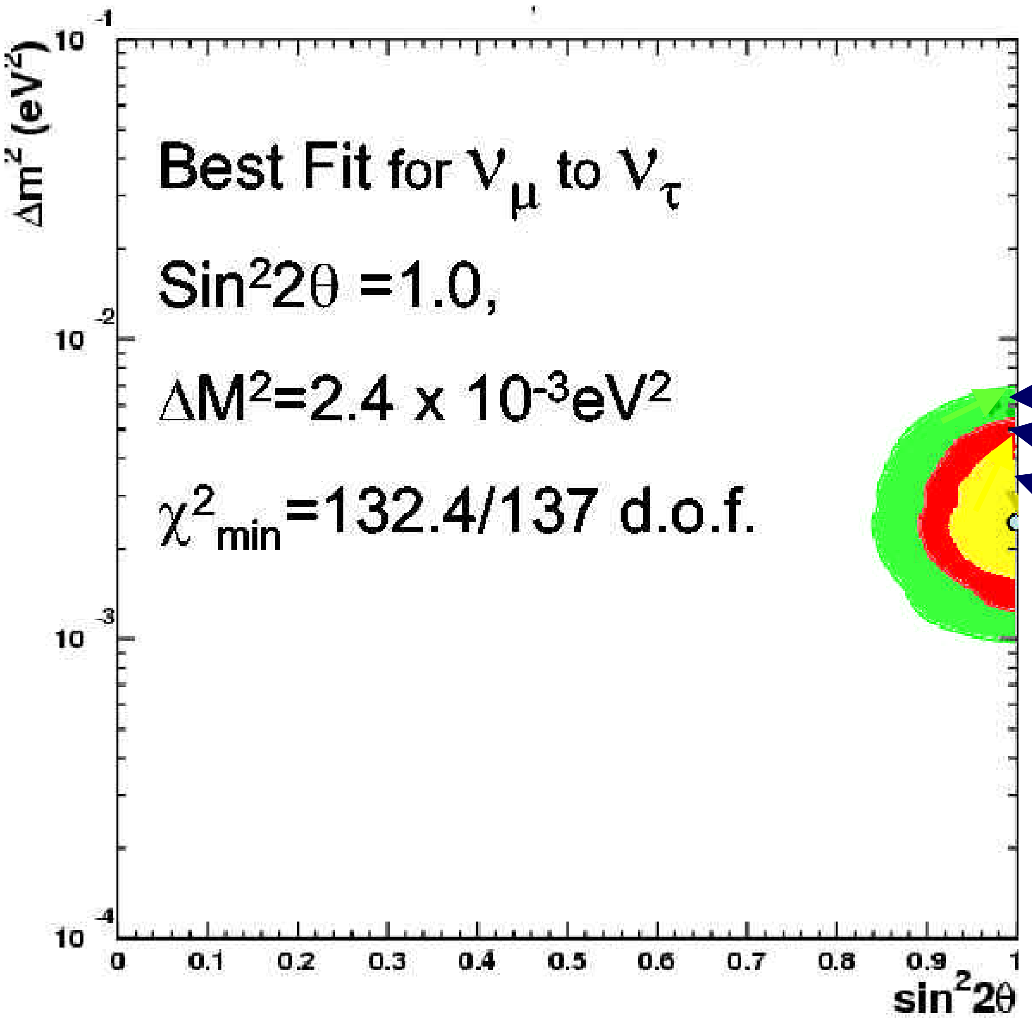


$\langle E_\nu \rangle \sim 100$ GeV

$\langle E_\nu \rangle \sim \langle E \rangle$ PC events

Stopping/Passing through → normalisation

Oscillation Parameters



99% CL

90% CL

68% CL

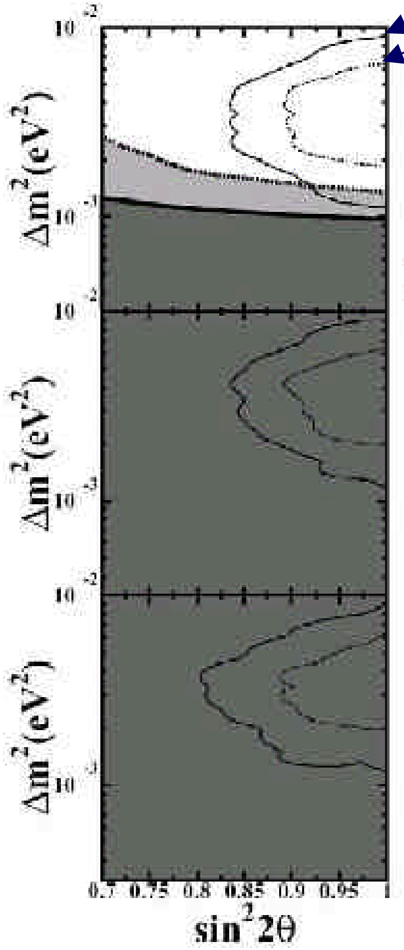
Dm^2 = (1.3-5) · 10^{-3} eV^2
sin^{2}2q>0.88, 90% CL

This is consistent with Soudan2 e Macro (tough it is almost inconsistent with previous, old Kamiokande results....)

t or sterile Neutrino ?

SuperK

Allowed regions
1-ring FC events
(99%, 90% CL)



nm→nt

nm→ns
Dm²>0

nm→ns
Dm²<0

Excluded regions
multi-ring, PC, up-m
90% CL 99% CL

Sterile neutrino signature:

- NC disappearance
- Different matter effects

P = sin 2q, L

$$P \rightarrow P_{matt} = \frac{P}{\sqrt{(z-\cos 2q)^2+\sin^2 2q}}$$

$z = 2VE_\nu / Dm^2$,

Combined analysis of:

1) NC enriched multi-ring
2) PC with E_{vis}>5GeV
3) Upward muons

Direct tau appearance:
Multiring excess, p^o (K2K)
Present significance ~2s

Sterile Neutrino ? No, Thanks?

Solar

Purely sterile oscillation excluded at 95%CL by absence of Day/Night effect in SuperK. SNO(+SuperK) evidence for n_e oscillation into active neutrino.

Atmospheric

Maximal mixing $n_m \to n_t$ favoured. Pure $n_m \to n_s$ excluded at 99% CL. Subdominant active component: $\sin^2 q_{e3} < 0.1$ (Chooz).

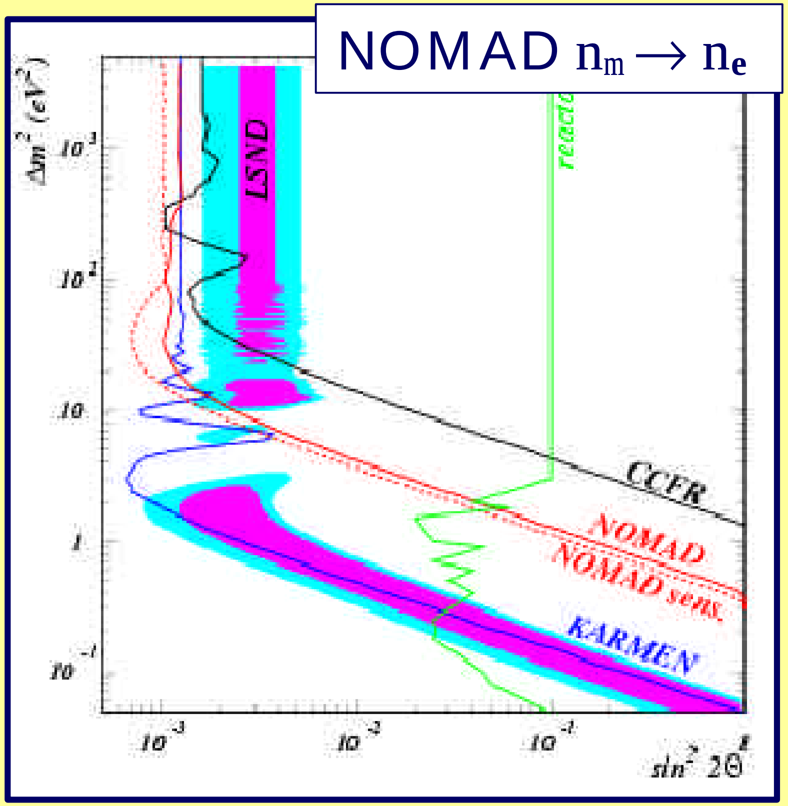
Three neutrinos : 3x3 matrix (3angles+1phase) + 2 Dm^2

Relatively large mixing with a sterile neutrino are not excluded by present atmospheric and solar data. Models with 3 active + 1 sterile neutrino (3+1, 2+2) fit present data.

Sterile Neutrino ? May be

Final LSND analysis (167t mineral oil: Cherenkov+ scintill.)
Appearance of $\bar{n}_e$ p→e$^+$n (→np→dg(2.2MeV)) in a source of 20-60 MeV $\bar{n}_m$ from m$^+$ decay at rest. Consistent n_e excess seen in 20-200 MeV n_m produced in p$^+$ decay in flight. Signal 83.3±21.2 events.

Combined fit: P($n_m \rightarrow n_e$) = (0.26 ±0.06±0.04)%



Karmen II at ISIS: no signal seen. 4 events expected. Karmen-LSND combined analysis inconclusive.

Nomad $n_m \rightarrow n_e$ escluded Dm^2>~10 eV^2

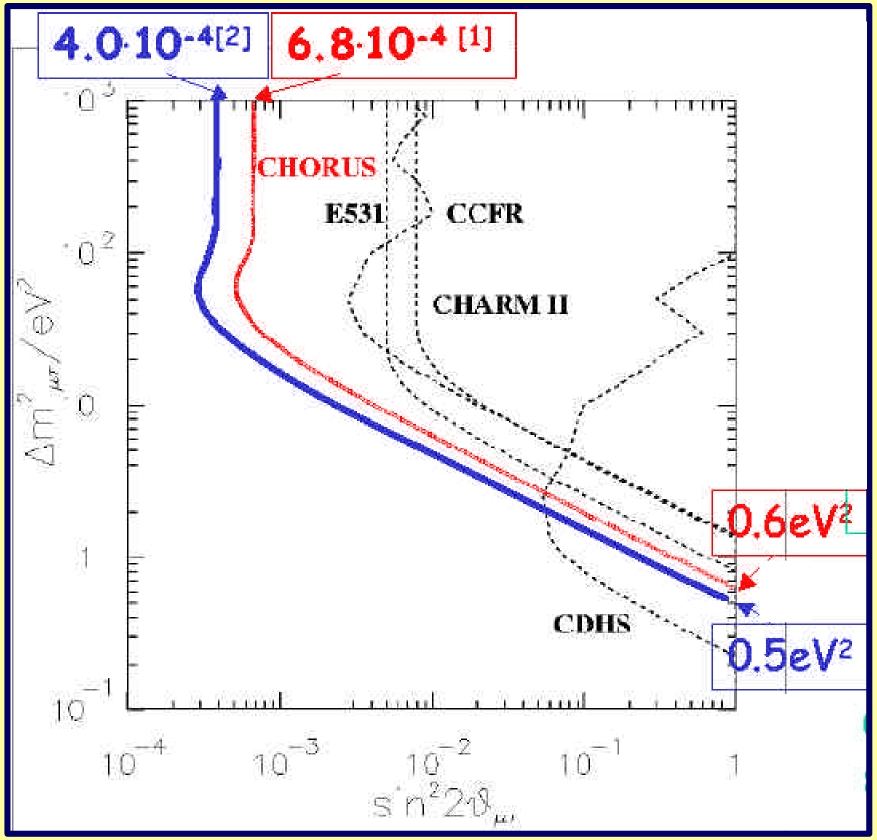
Miniboone at the Fermilab Booster is called to clarify this issue.

Chorus and Nomad

Search for t produced in n_t charged current interactions in a n_m beam. t lepton signature:

CHORUS: nuclear emulsion target → direct detection of the t and its decay

NOMAD: drift chamber target → observation through precise kinematic reconstruction (missing Pt, isolation,...)



No surprises!

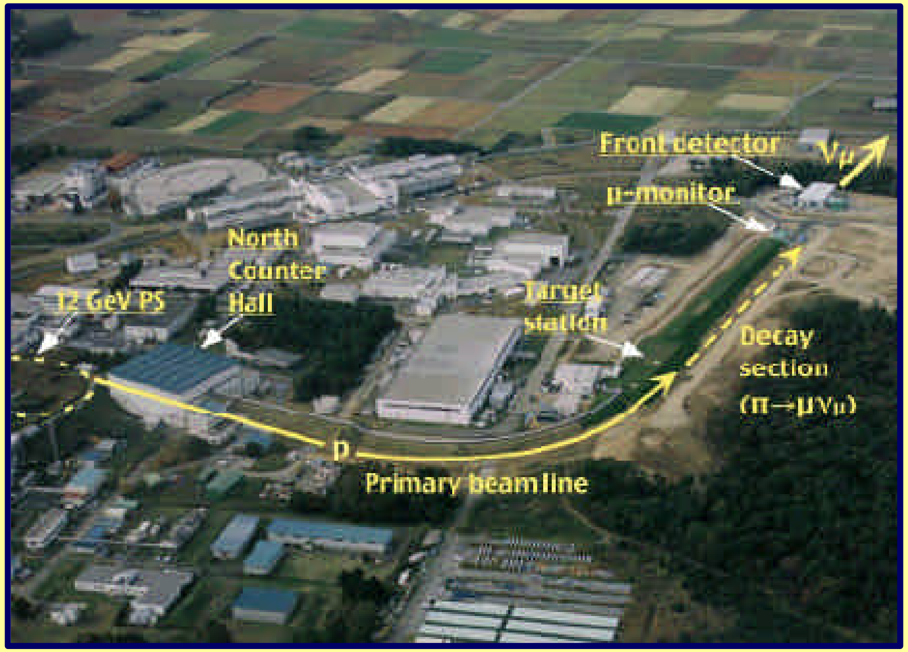
Nomad final analysis
Chorus → P = 10^{-4}

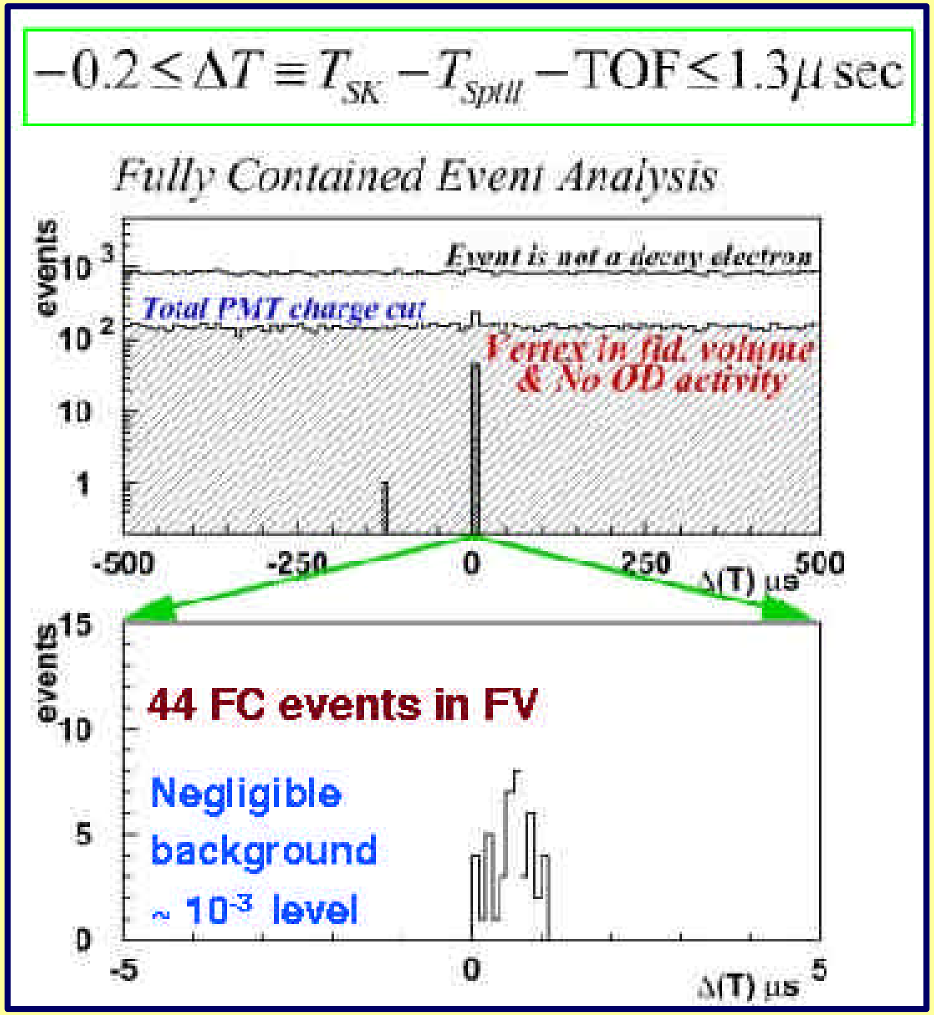
Small mixing and large Dm^2, motivated by once-upon-a- time popular arguments like solar+hierarchy, cosmology.

Training ground for future LBL experiments

K2K: First Generation LBL

KEK 12 GeV Proto-syncrotron
$6 \cdot 10^{12}$ protons/cycle (1.1 ms/2.2 s)
Horn focussed WBB $\langle E_\nu \rangle \sim 1.3$GeV
Close detector at 300m: miniSK+SciFi
Far detector at 250 Km: SuperK
$3.9 \cdot 10^{19}$ PoT (10^{20} within 2004)





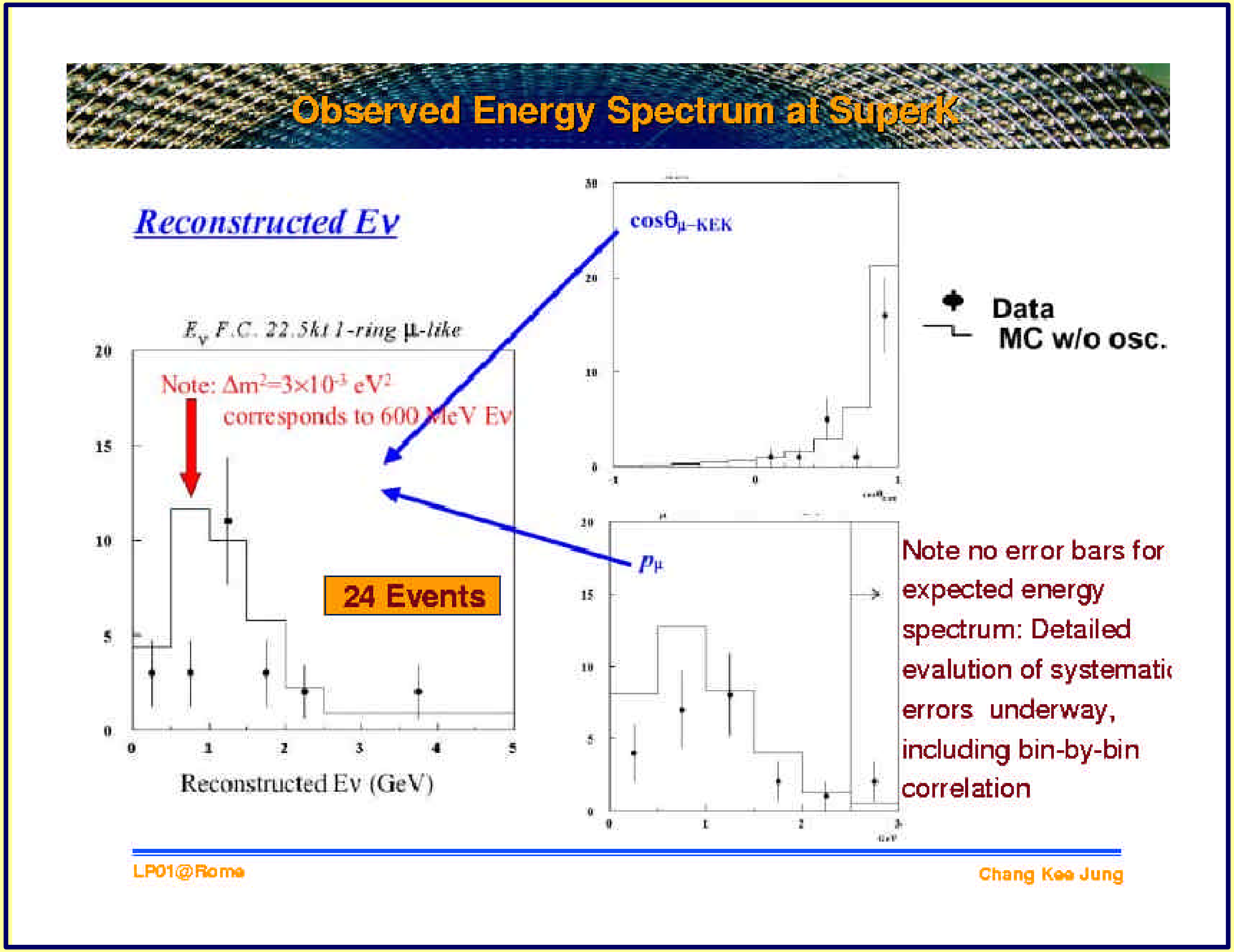
K2K: Data vs MC(no osc.)

	Observed	No Oscill.	Dm^2 $3 \cdot 10^{-3}$ eV^2	Dm^2 $5 \cdot 10^{-3}$ eV^2	Dm^2 $7 \cdot 10^{-3}$ eV^2
FC 22.5 kt	44	$63.9^{+6.1}_{-6.6}$	41.5	27.4	23.1
1-ring	26	38.4 ± 5.5	22.3	14.1	13.1
m-like	24	34.9 ± 5.5	19.3	11.6	10.7
e-like	2	3.5 ± 1.4	2.9	2.5	2.4
multi-ring	18	25.5 ± 4.3	19.3	13.3	10.0

Main sistematics: Fiducial volume cuts in the close detector
Close to Far extrapolation

Probability of no oscillation is < 3%

First Energy Spectrum



Neutrino Astrophysics

Gamma Ray Bursts emitted neutrino:

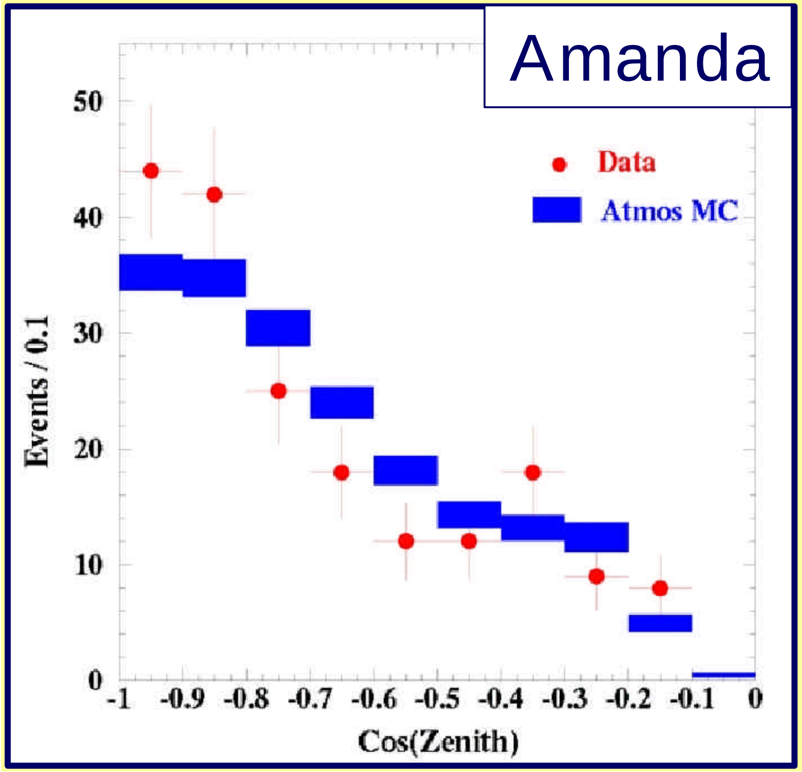
$E^2 dN/dE < 4 \cdot 10^{-4} \cdot \min(1, E/E_{break})$ TeV cm^{-2} (Amanda)

Pointlike continuous sources:

Different limits for spectral indexes E^{-2}-E^{-3}

High energy diffused flux

$E^2 dN/dE < 10^{-6}$ s^{-1} sr^{-1} GeV^{-1} (Amanda)



Hot issues (acceleration mechanism of UHECR, GRB origin, AGN, supernova bursts)

A Km^3 detector mandatory. Worth one per emisphere: Antarctic, Mediterranean sea?

Quest for larger effective mass to study ultra-PeV neutrinos . AUGER: 10 Gt and EUSO: 10 Tt effective mass. Acustic and radio detection under study.

A Daydream Roadmap

Kamland shows next year that solar is LMA and in a few years measures Dm^2_{12} at 2% and $\sin^2 2q_{12}$ at 4%.

MiniBoone confirms in a few years the ansatz that a 3x3 matrix is enough.

Before the end of this decade, next generation atmospheric and LBL experiments see oscillation patterns (modulation cycle, tau appearance, NC appearance) and measure oscillation parameters at Dm^2_{23} at 10% and $\sin^2 2q_{23}$ at 4%.

A large mass atmospheric detector with charge capability measures the sign of Dm^2_{23} comparing the resonant matter effects of neutrino and anti-neutrinos.

In the year 201? JHF to SuperK and/or a SuperBeam from a high power proton driver, measure the small q_{13}.

In the year 201? a NuFactory is build to feed detectors at different baselines. The era of leptonic CP violation begin. The phase d is determined and q_{13} is precisely determined. (Almost) all transition are measure, including n_e ® n_t.

Conclusive Notes

It seems the solar neutrino problem has a SNOking gun

The Standard Solar Model acquitted of charge

KamLMAnd chance to pin down oscillation parameters

Borexino LMA vs LOW vs VAC (^{7}Be, day/night, seasonal)

q_{13}? q_{13}? q_{13}? q_{13}? q_{13}? Beyond Chooz? ~~CP~~ effects only if q_{13}>~0.1^{o}

Sterile neutrinos ? LSND $\rightarrow$ MiniBoone

Atmospheric: exotic interpretation ? Oscillation pattern !

DM^2 are small : direct measurements $\rightarrow$ n mass scale $\rightarrow$ Ω_{ν}

K2K deficit 30% : 2s$\rightarrow$3s (systematics?). Energy spectrum

Astronomy: Km^3 needed. New detection methods for UHEn

NuFact: fundamental questions about neutrino masses, stopping muons physics, tagged charm factory, step toward a muon collider.