Status of neutrino oscillations

NEUTRINO ν
2002 MUNICH

G.Fiorillo (Univ.Napoli)
G. Mangano (INFN Napoli)

ISSUES

- Solar neutrinos
- Atmospheric neutrinos
- Accelerator neutrinos
- Future longbaseline experiments
- Neutrino properties: mass, Majorana vs. Dirac, magnetic moments
- neutrino in astrophysics and cosmology
- Dark matter and WIMPS
- Cosmic Rays and Neutrino telescopes

Solar Neutrinos

Solar Neutrinos   Experimental Results

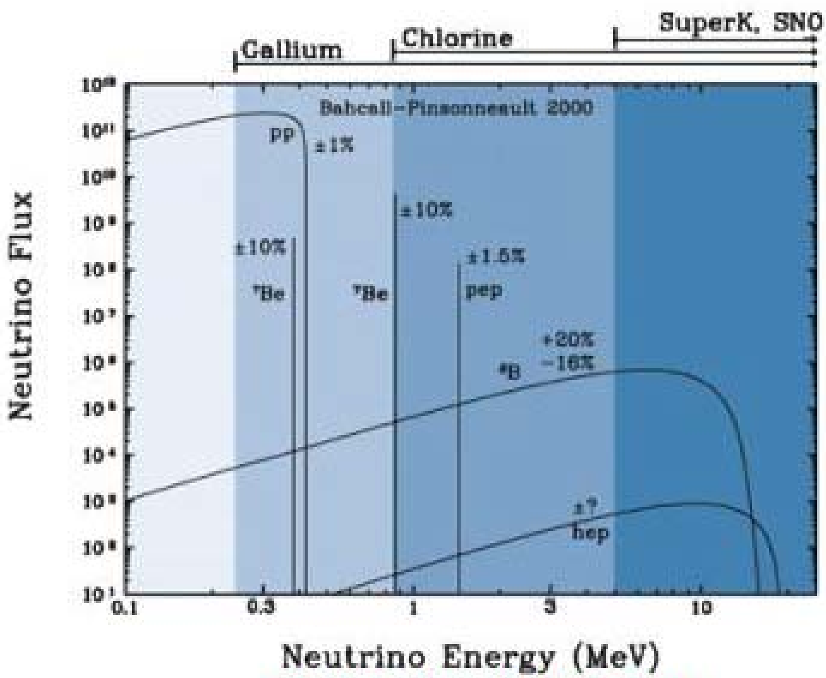

Figure by J. Bahcall

SAGE+GALLEX/GNO

$\nu_e + ^{71}Ga \rightarrow ^{71}Ge + e^-$

Flux = 0.58 SSM

Homestake

$\nu_e + ^{37}Cl \rightarrow ^{37}Ar + e^-$

Flux = 0.33 SSM

Kamiokande + Superkamiokande

$\nu_x + e^- \rightarrow \nu_x + e^- \quad \sigma_{\mu\tau} = \frac{1}{6} \times \sigma_e$

Flux = 0.46 SSM

Neutrino Flavor Change ?

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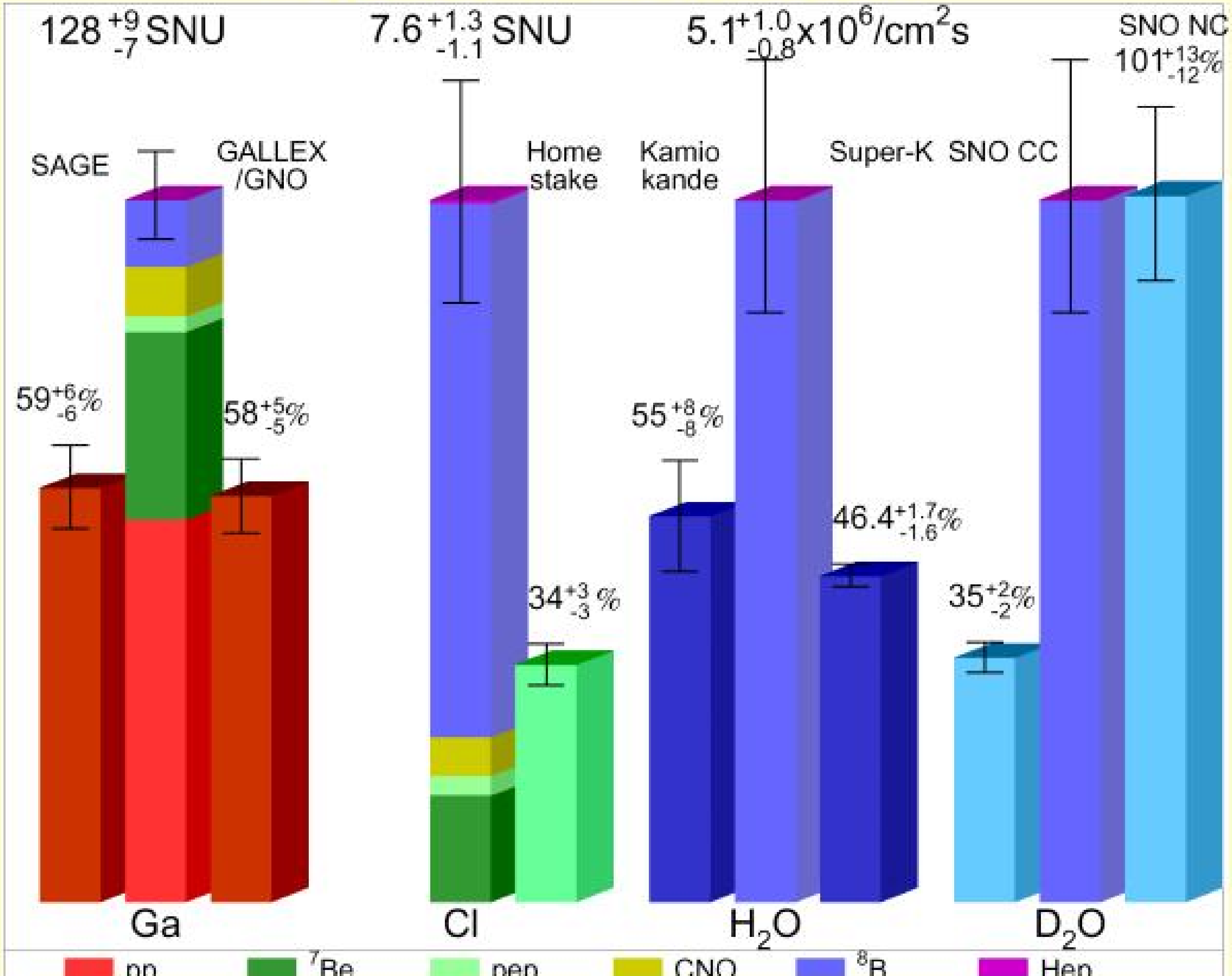
Solar ν Problem



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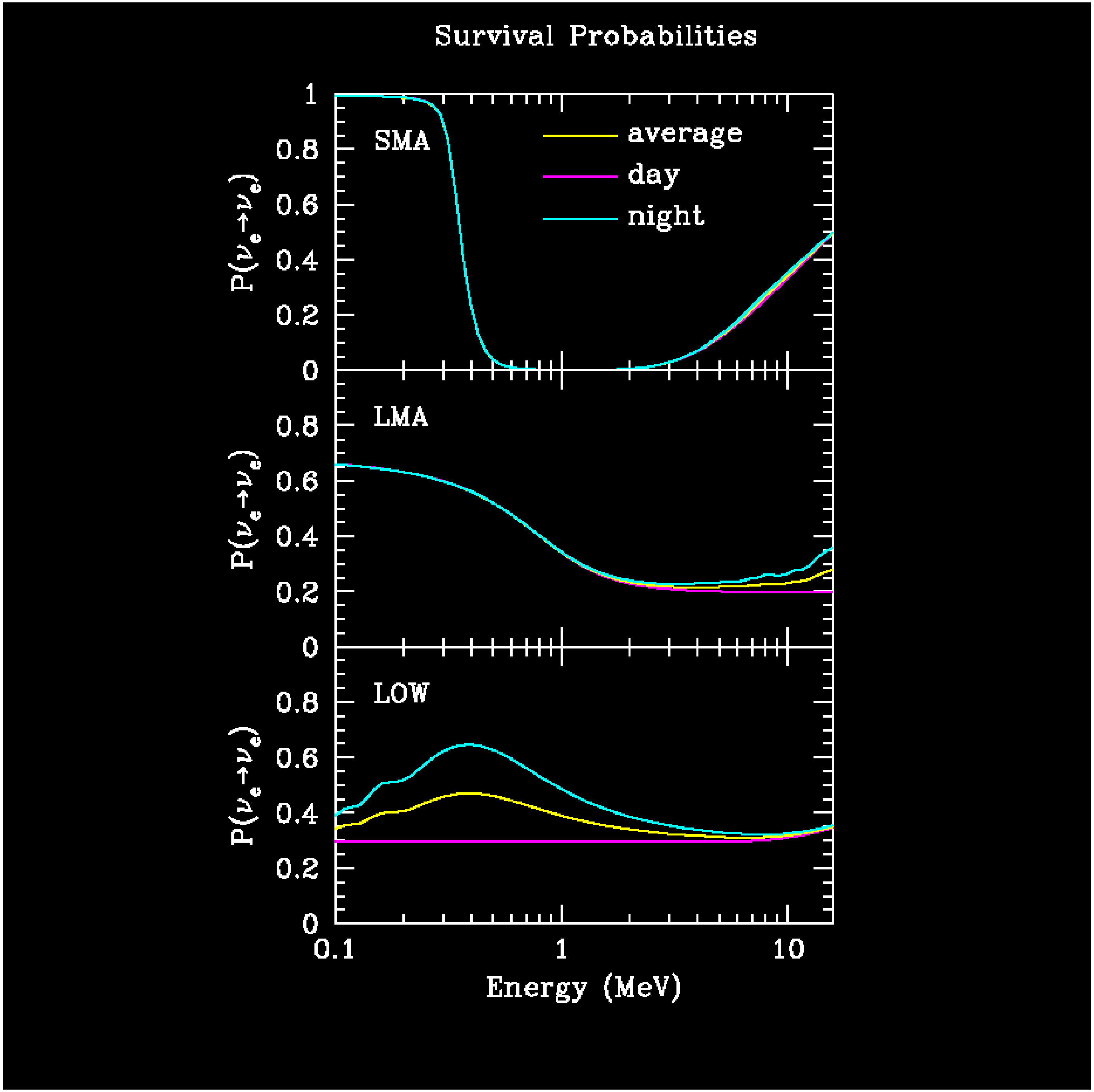
REACTION	TERM. (%)	ν ENERGY (MeV)
$p + p \rightarrow {}^2H + e^+ + \nu_e$	(99.96)	≤ 0.423
or		
$p + e^- + p \rightarrow {}^2H + \nu_e$	(0.44)	1.445
${}^2H + p \rightarrow {}^3He + \gamma$	(100)	
${}^3He + {}^3He \rightarrow \alpha + 2p$	(85)	
or		
${}^3He + {}^4He \rightarrow {}^7Be + \gamma$	(15)	
${}^7Be + e^- \rightarrow {}^7Li + \nu_e$	(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 model


Survival Probabilities
SMA
LMA
LOW
average
day
night
P(νe→νe)
Energy (MeV)
0.1
1
10
0
0.2
0.4
0.6
0.8
1

Highlights: 1988-1995

- **1988: helioseismology + ν's: 0.5%**

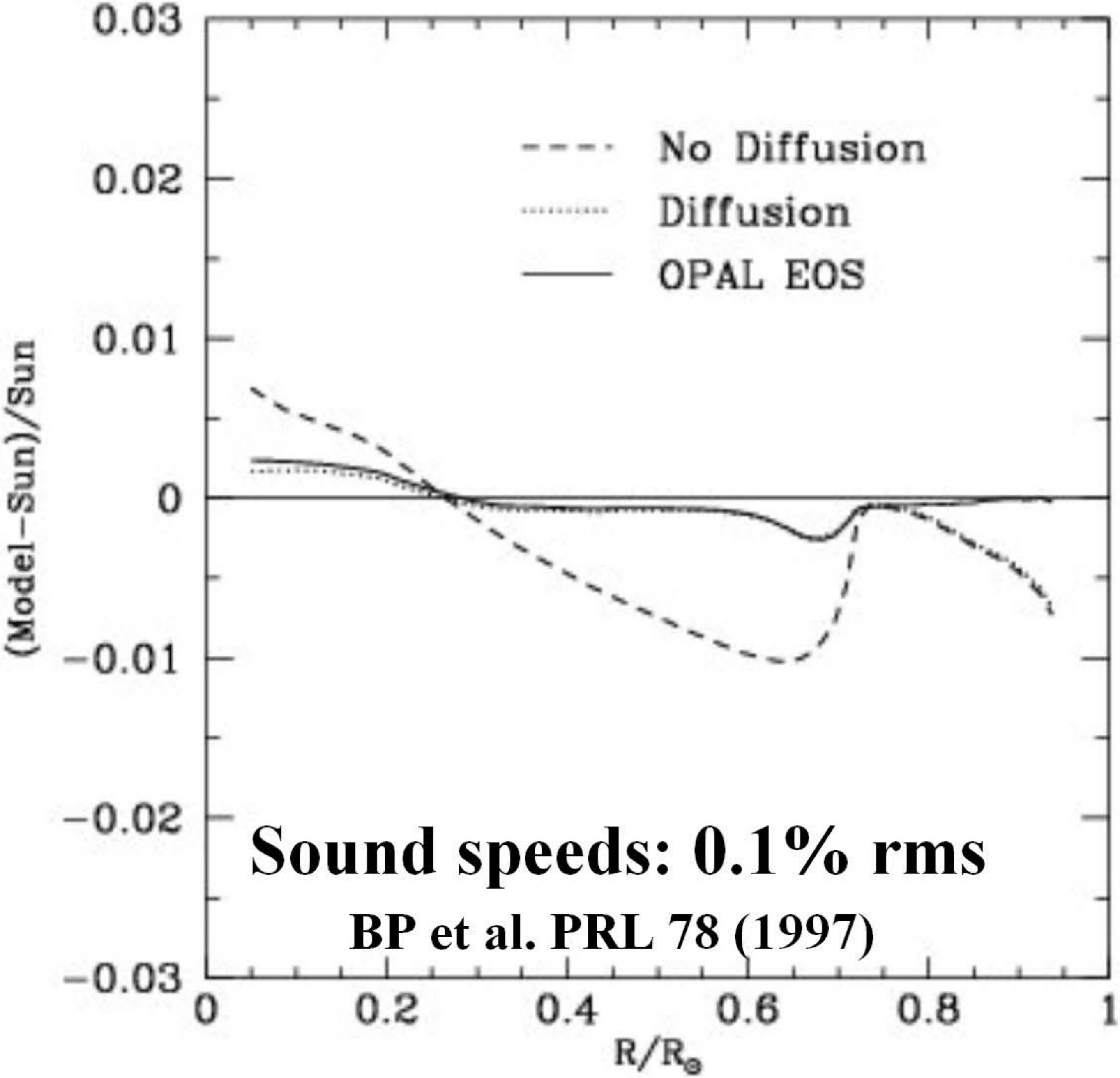
- 1990-1994:Radiative opacity, E.O.S.

- 1990-1995: Element Diffusion

^{8}B flux: + 35% [RMP 67 (1995)]

J. Bahcall

J. Bahcall



Sound speeds: 0.1% rms

BP et al. PRL 78 (1997)

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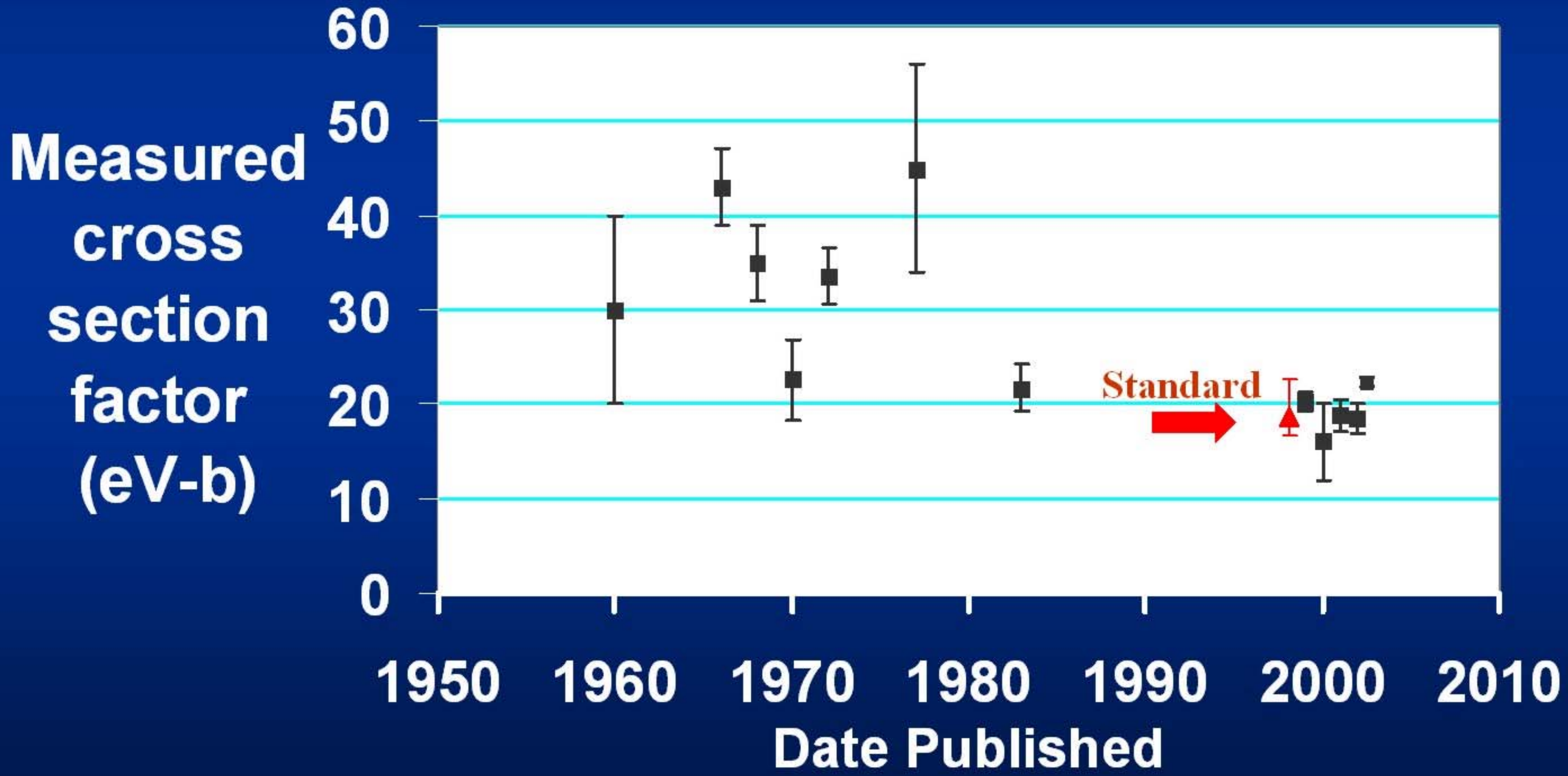
BP00 %Uncertainties

Source	^{8}B	^{7}Be
p-p	0.04	0.02
$^{3}He + ^{3}He$	0.02	0.02
$^{3}He + ^{4}He$	0.08	0.08
$p + ^{7}Be$	$^{+0.14}_{-0.07}$	0.00
Composition	0.08	0.03
Opacity	0.05	0.03
Diffusion	0.04	0.02
Luminosity	0.03	0.01

Cross section: $^{7}Be(p,\gamma)^{8}B$

$\varphi(^{8}B) \propto$ Cross Section Factor



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Super-K Solar Neutrinos

- 1496 Live Days between May 31st, 1996 and July 15th, 2001
- High Statistics
- Measures ^{8}B, limits *hep* flux
- ^{8}B flux time variations
- Studies energy spectrum
- Some sensitivity to other than *e*-type neutrinos

Oscillation Signatures

- Suppression of ^{8}B flux
- Appearance of other active flavors (with SNO)
- Spectral Distortion
- Daily variations of ^{8}B flux
- Anomalous yearly variations of ^{8}B flux

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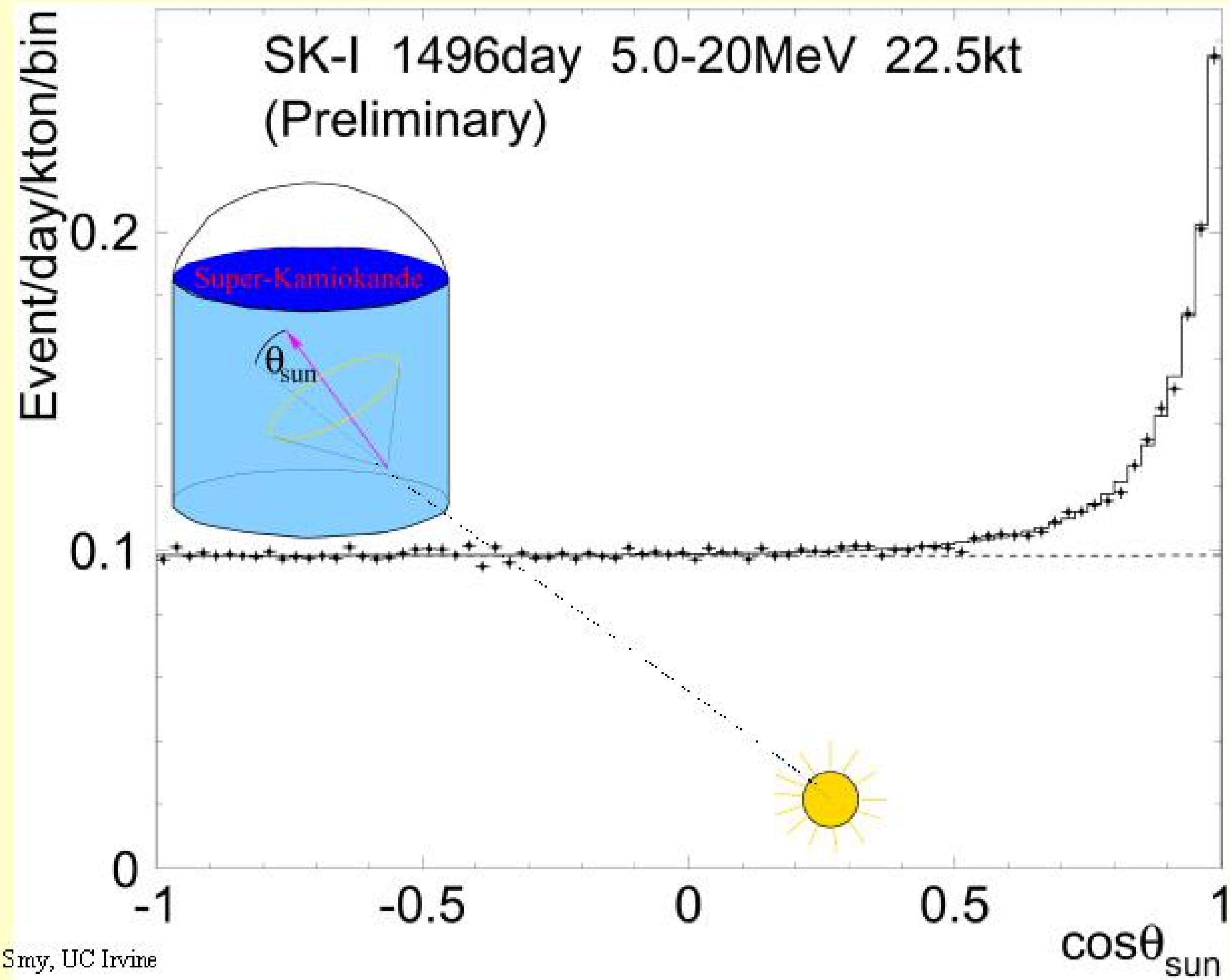
Solar Peak above 5 MeV



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Super-K Solar Neutrino Rate

1496 Day Final Sample:

flux is
$2.35 \pm 0.02(\textbf{stat.}) \pm 0.08(\textbf{sys.}) \times 10^6/\textbf{cm}^2 \cdot \textbf{s}$
or $0.465 \pm 0.005(\textbf{stat.})^{+0.016}_{-0.015}(\textbf{sys.}) \times \textbf{SSM}$

- 22,400 solar neutrino events
- 18-21 MeV: 4.9±2.7 events
- Expect ~1 *hep* neutrino (SSM)
- Expect ~2 *hep* neutrinos (oscillation best fit: ~4x SSM)
- 90% C.L. upper limit of *hep* flux: $73 \times 10^3/cm^2s$ (7.9xSSM)

Expect:

- 48,200 solar neutrinos (from SSM)
- 16,700 *e*-type solar neutrinos (from SNO)
- About 5,700 μ/τ-type solar neutrinos

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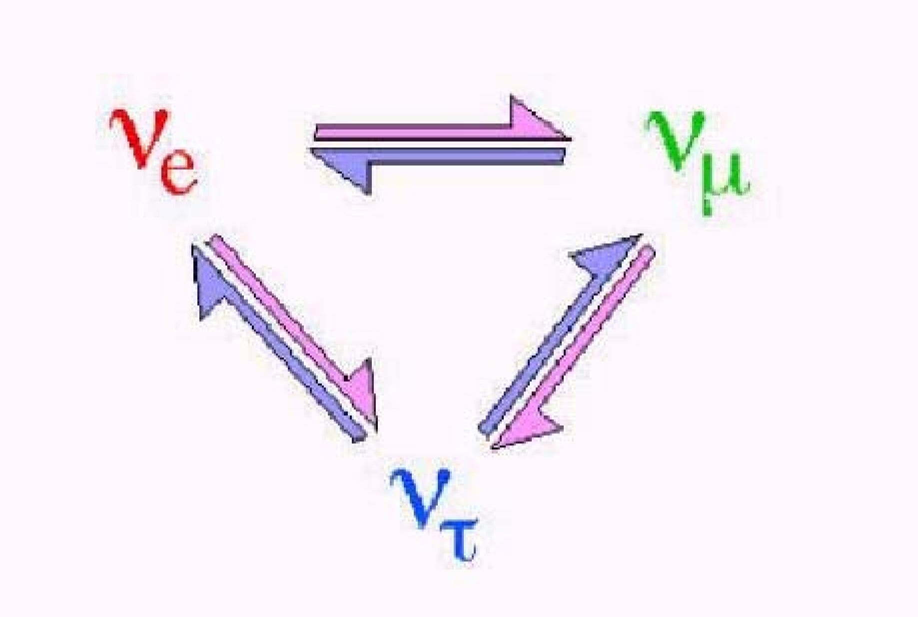
ν Oscillations



The Large Mixing Angle MNS matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = R_{23} R_{13} R_{12} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

solar LMA MSW

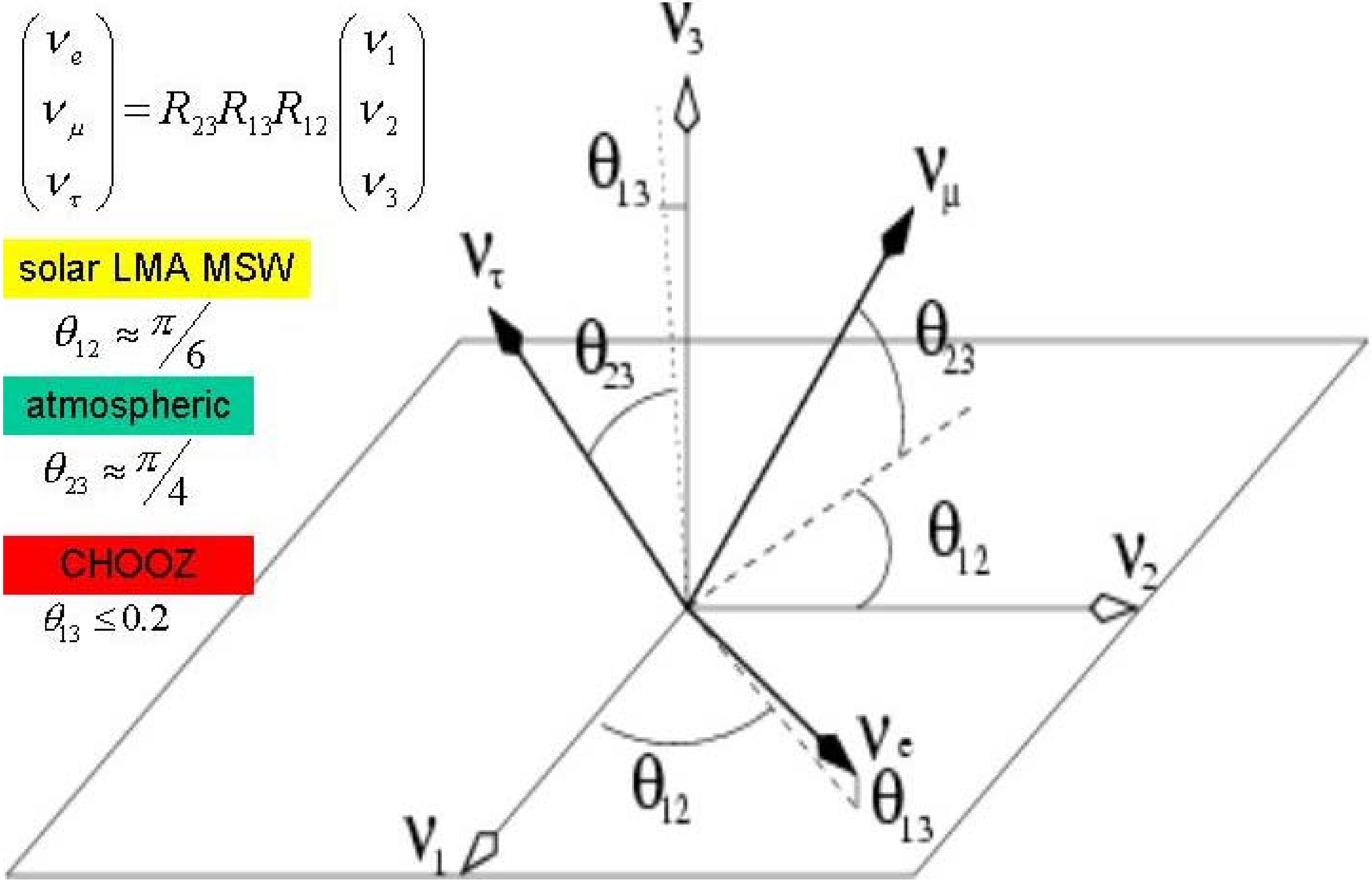
$\theta_{12} \approx \pi/6$

atmospheric

$\theta_{23} \approx \pi/4$

CHOOZ

$\theta_{13} \leq 0.2$



The Maki-Nakagawa-Sakata matrix

$$V^{E_L} m^E_{LR} V^{E_R\dagger} = \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix}$$

Majorana matrix

$$V^{\nu_L} m^\nu_{LL} V^{\nu_L T} = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}$$

Constructing ⇒ $U_{MNS} = V^{E_L} V^{\nu_L \dagger}$

Three physical phases give CP violation

Parametrising ⇒ $U_{MNS} = R_{23} R_{13} P_1 R_{12} P_2$

$$R_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \quad R_{13} = \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \quad R_{13} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Lepton mixing and neutrino oscillations in vacuum

$$\nu_a = U_{ai}\,\nu_i$$

ν_a – flavour eigenstates, ν_i – mass eigenstates

Transition probability:

$$P(\nu_a \to \nu_b; t) = \left|\sum_i U_{bi}\, e^{-iE_i t}\, U_{ai}^*\right|^2$$

Can be obtained from the evolution equation

$$i\frac{d}{dt}\begin{pmatrix}\nu_a\\ \nu_b\\ .\\ .\\ .\end{pmatrix} = U \begin{pmatrix}E_1 & & & & \\ & E_2 & & & \\ & & . & & \\ & & & . & \\ & & & & .\end{pmatrix} U^\dagger \begin{pmatrix}\nu_a\\ \nu_b\\ .\\ .\\ .\end{pmatrix}$$

2-flavour case:

$$U = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}$$

$$P(\nu_a \to \nu_b; t) = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m_{ij}^2}{4E}\,L\right)$$

Neutrino oscillations in matter (3f)

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[U\begin{pmatrix}E_1 & 0 & 0\\ 0 & E_2 & 0\\ 0 & 0 & E_3\end{pmatrix}U^\dagger + \begin{pmatrix}V(t) & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

$$E_i = \sqrt{p^2+m_i^2} \simeq p + \frac{m_i^2}{2p}; \qquad t \simeq r$$

$$U = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_1}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_1} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

$$V(t) = [V(\nu_e)]_{CC} = \sqrt{2}G_F N_e(t)$$

$[V(\nu_e)]_{NC} = [V(\nu_\mu)]_{NC} = [V(\nu_\tau)]_{NC}$ – do not contribute

3f effects in oscillations of solar neutrinos

- What do the solar ν_e oscillate to?

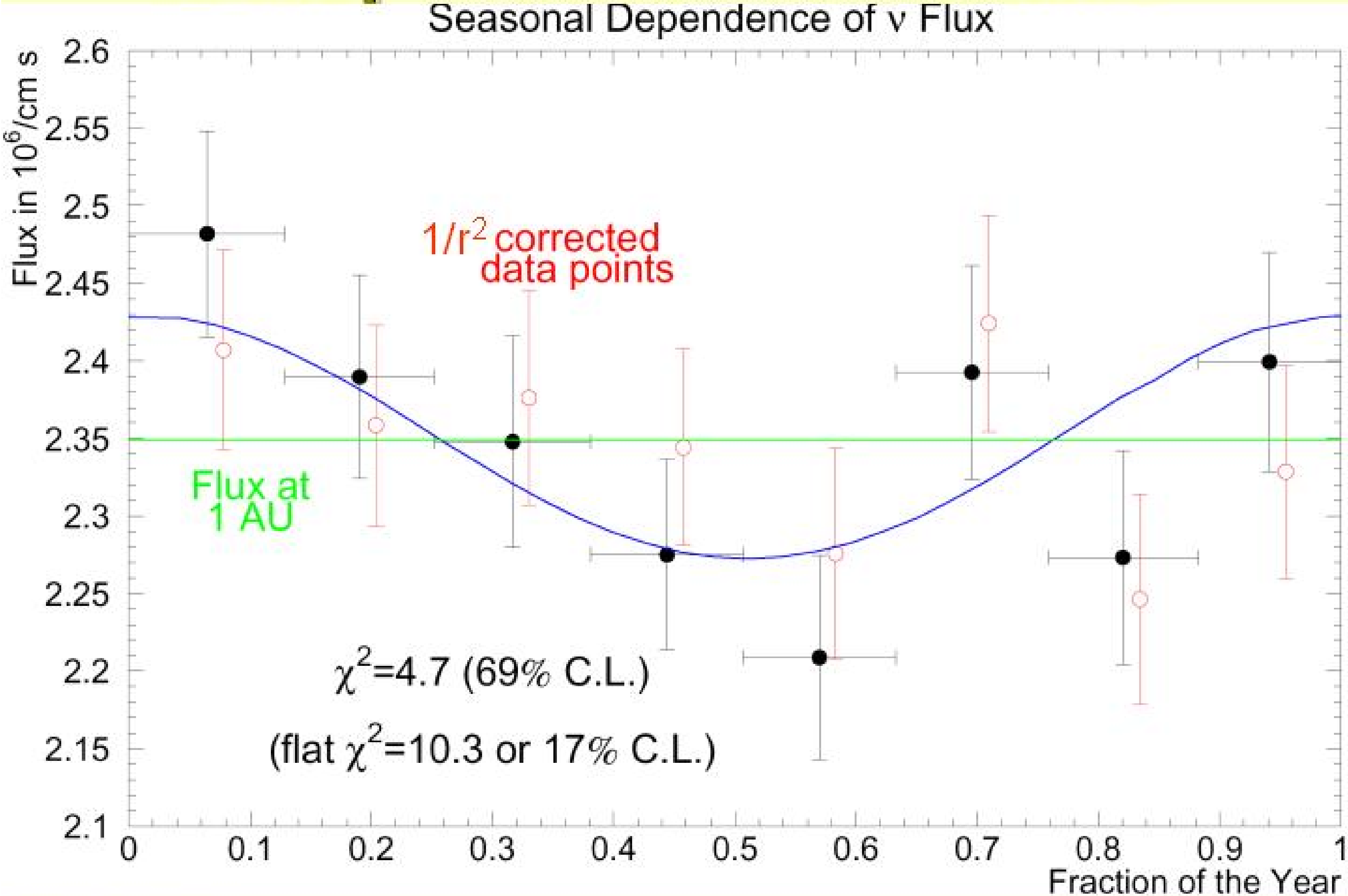
From $|U_{e3}| \ll 1$: $\quad \nu_3 \simeq s_{23}\,\nu_\mu + c_{23}\,\nu_\tau$

$\Rightarrow$ From unitarity of U: Solar ν oscillations between

ν_e and $\nu' = c_{23}\,\nu_\mu - s_{23}\,\nu_\tau$

$\Rightarrow$ Solar ν_e oscillate into a superposition of ν_μ and ν_τ with almost equal weights

Yearly Variation of SK Rate



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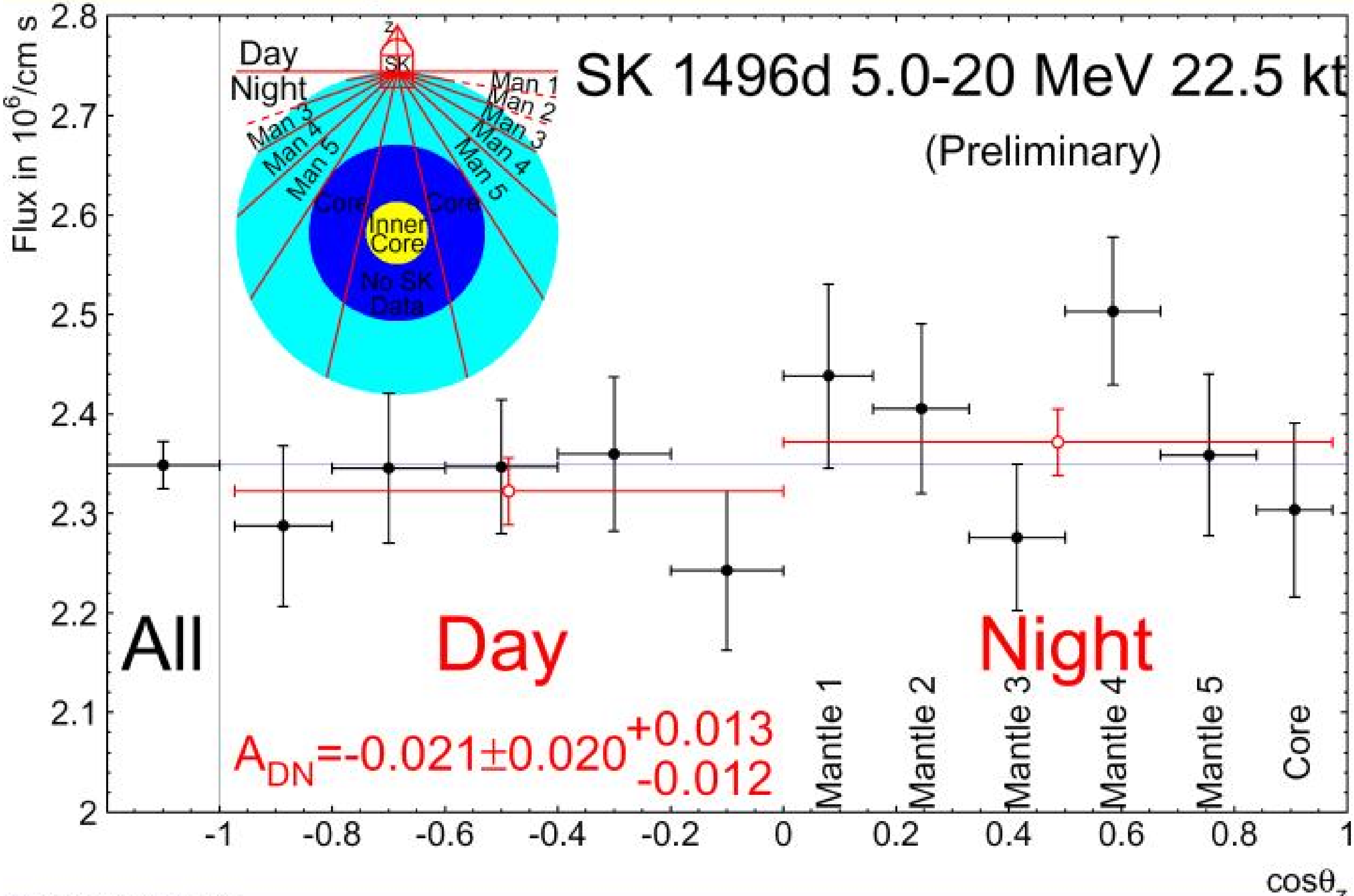
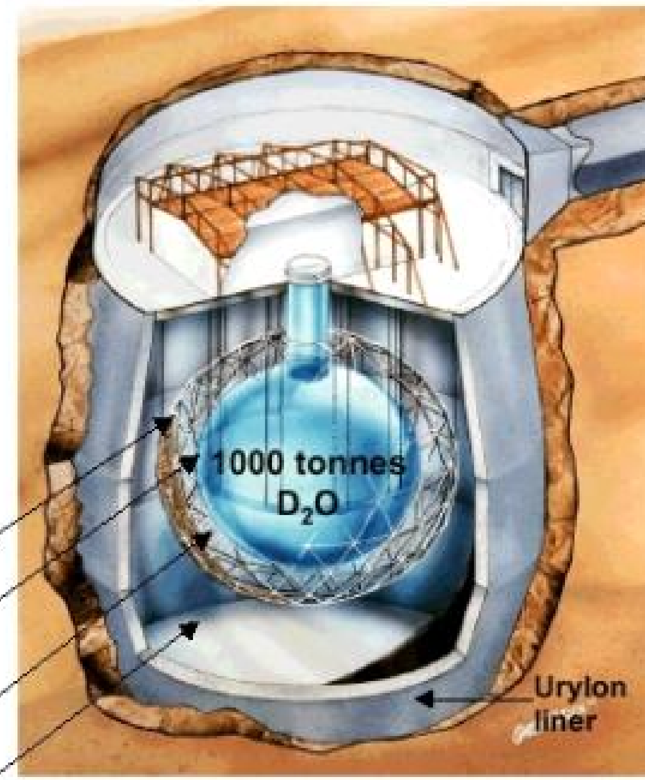
Daily Variation of SK Rate



The SNO Detector



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)

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ν Reactions in SNO

CC $\nu_e + d \Rightarrow p + p + e^-$

- -Good measurement of ν_e energy spectrum
- -Weak directional sensitivity $\propto$ 1-1/3cos(θ)
- - ν_e only.

NC $\nu_x + d \Rightarrow p + n + \nu_x$

- - Equal cross section for all ν types
- - Measure total ^8B ν flux from the sun.

ES $\nu_x + e^- \Rightarrow \nu_x + e^-$

- -Low Statistics
- -Mainly sensitive to ν_e,, some sensitivity to ν_μ and ν_τ
- -Strong directional sensitivity

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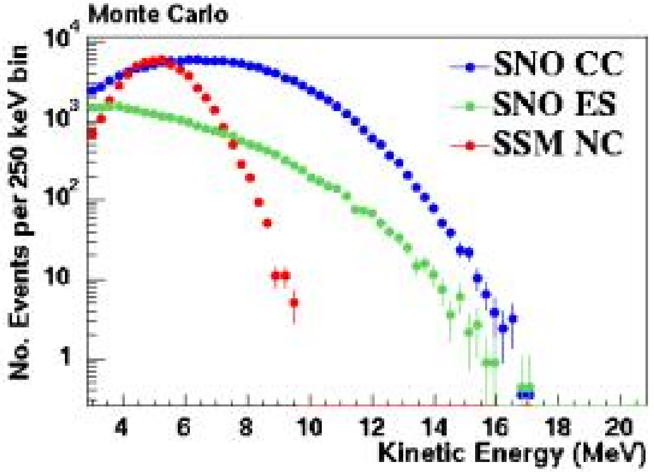
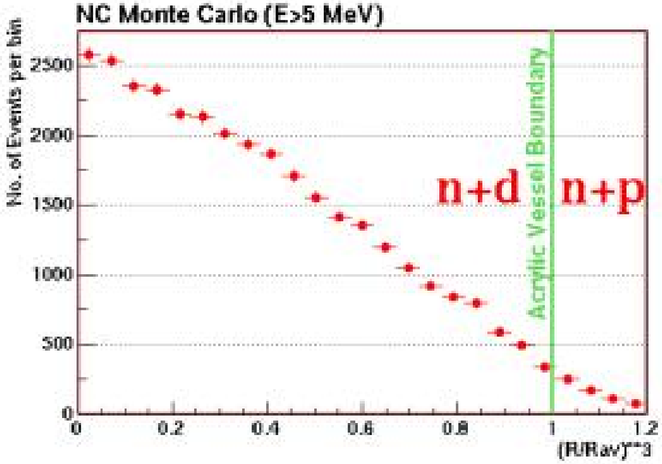
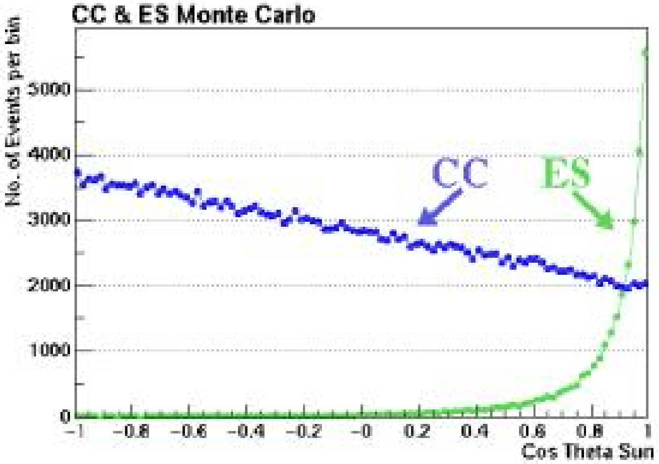
Signal Information

- Hits and Energy
- Direction from Sun
- Radial Response



$n + d \rightarrow t + \gamma \ldots \rightarrow e^-$ (E_γ = 6.25 MeV)





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Neutrino Physics From SNO

June 2001

$$\frac{\Phi_{cc}}{\Phi_{es}} = \frac{\nu_e}{\nu_e + 0.154(\nu_\mu + \nu_\tau)} = 1 \, ?$$

$$\frac{\Phi_{cc}}{\Phi_{nc}} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau} = 1 \, ?$$

Perform a Hypothesis Test for Flavor Change by assuming pure ^{8}B Spectral shape and testing if flux ratios equal 1.

$$\Phi_{day} = \Phi_{night} \quad ?$$

Test if interaction with electrons in the Earth changes Mu and Tau neutrinos back to Electron neutrinos

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Solar Neutrino Flux From SNO Data

Total ^{8}B Solar Neutrino Flux Originating in the Sun

June 2001 $\Phi_x = \Phi_{cc} + (\Phi_{es} - \Phi_{cc}) \times (1/\varepsilon)$

April 2002 $\Phi_x = \Phi_{nc}$

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The Pure D_2O Phase Dataset

- Livetime: 306.4 days (November 2, 1999 ➡ May 27, 2001)
  Day: 128.5 days Night: 177.9 days
- Energy Threshold: 5 MeV Kinetic
- Fiducial Volume Cut: 550 cm
- Total Number of Events after cuts: 2928
  Neutron Bkg 78^{+12}_{-12} Cherenkov Bkg 45^{+18}_{-12}

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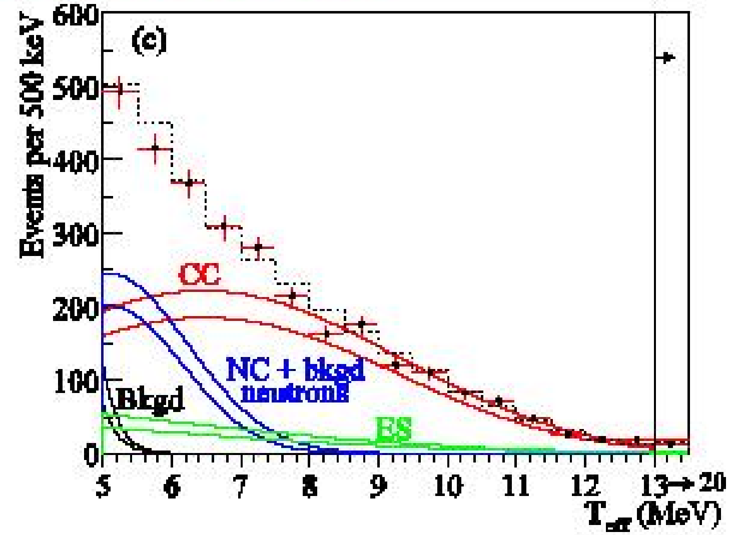
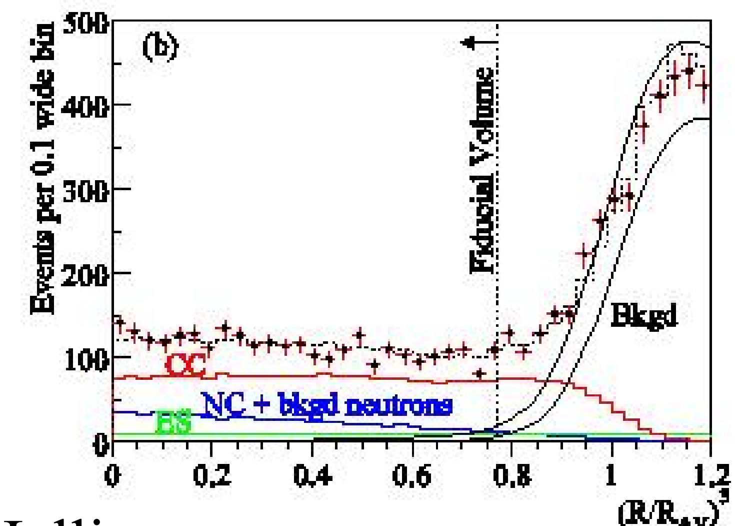
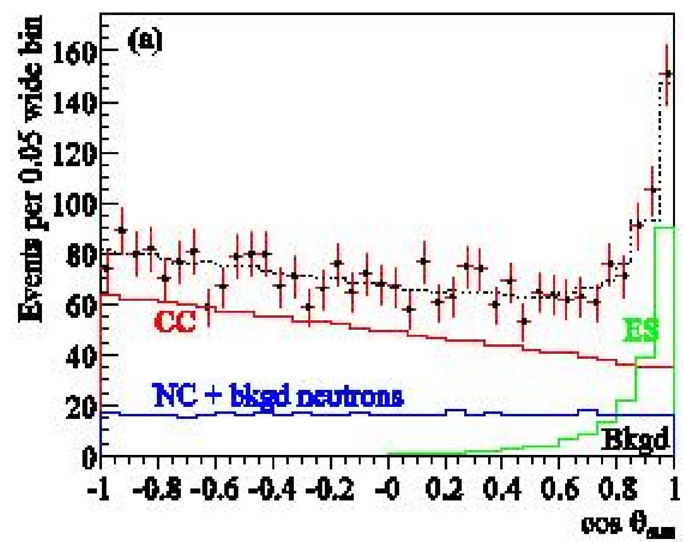
Shape Constrained Signal Extraction Results

#EVENTS

CC	$1967.7^{+61.9}_{+60.9}$
ES	$263.6^{+26.4}_{+25.6}$
NC	$576.5^{+49.5}_{+48.9}$







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Shape Constrained Neutrino Fluxes

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

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

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

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

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

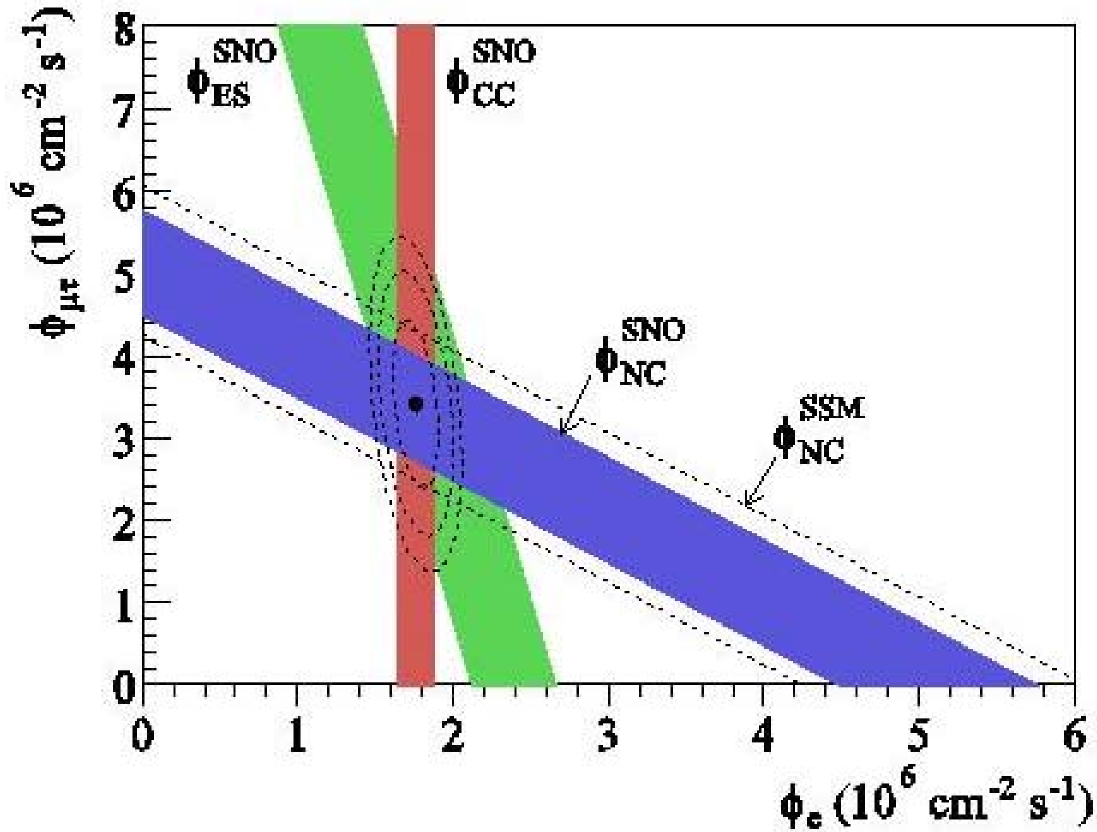
$$\Phi_{e} = 1.76^{+0.05}_{-0.05}\,(\text{stat.})\,^{+0.09}_{-0.09}\,(\text{syst.})\times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

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

High threshold results agrees with first publication.

Physics Implication Flavor Content

$\Phi_{ssm} = 5.05^{+1.01}_{-0.81} \quad \Phi_{sno} = 5.09^{+0.44}_{-0.43}{}^{+0.46}_{-0.43}$



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Strong evidence of flavor change

A_e versus A_{total}

Signal Extraction in Φ_{CC}, Φ_{NC}, Φ_{ES}.

$A_{cc} = 14.0 \pm 6.3^{+1.5}_{-1.4}$

$A_{nc} = 20.4 \pm 16.9^{+2.4}_{-2.5}$

Signal Extraction in Φ_e, Φ_{total}.

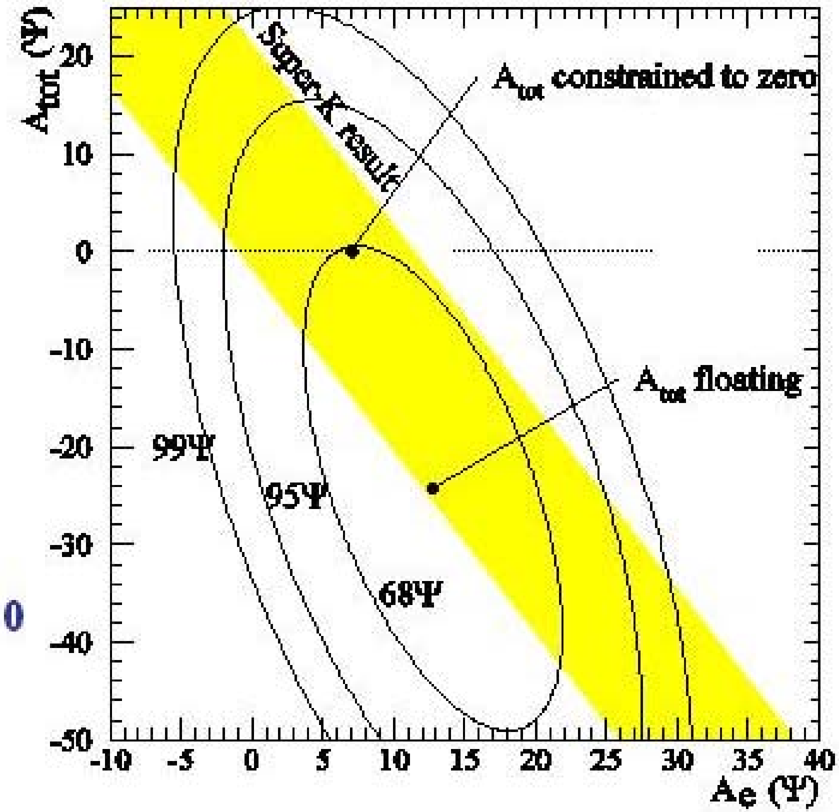
$A_e = 12.8 \pm 6.2^{+1.5}_{-1.4}$

$A_{tot} = -24.2 \pm 16.1^{+2.4}_{-2.5}$

Signal Extraction in Φ_e, Φ_{total}, + $A_{total} = 0$

$A_e = 7.0 \pm 4.9^{+1.3}_{-1.2}$

$A_e^{sk} = 5.3 \pm 3.7^{+2.0}_{-1.7}$



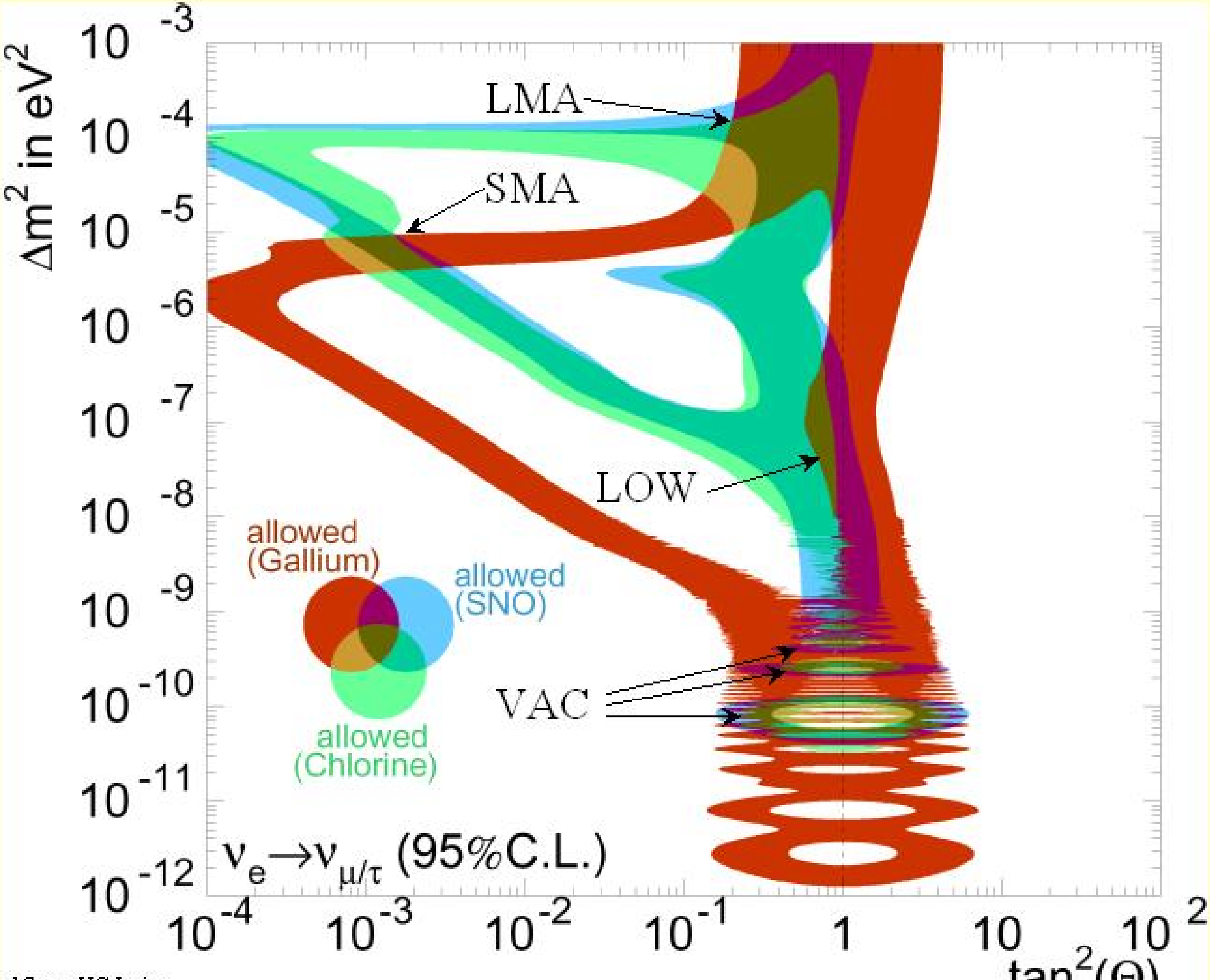
Global fit

LMA: large mixing angle

SMA: small mixing angle

LOW: small squared mass difference

VAC: vacuum oscillations



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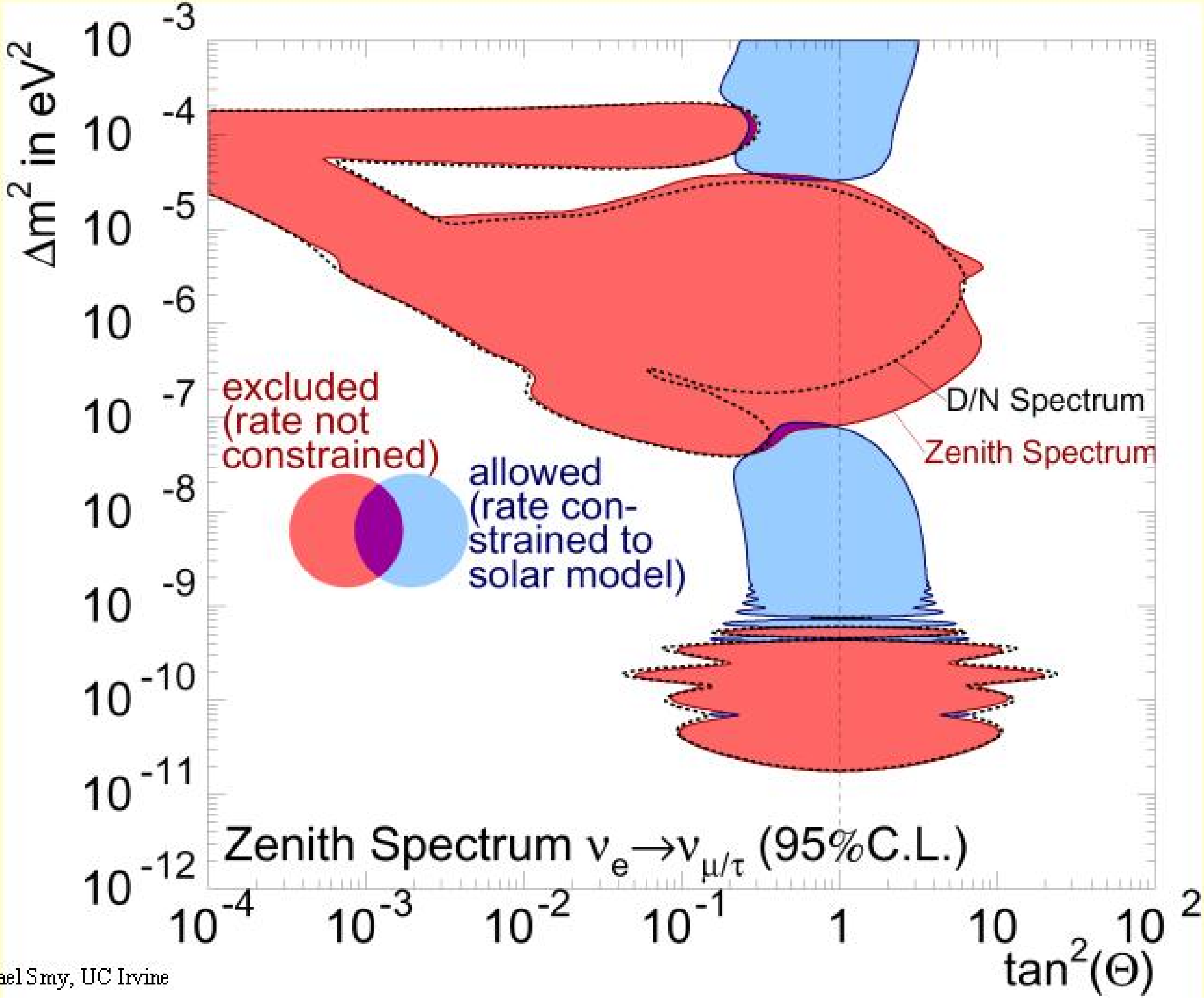

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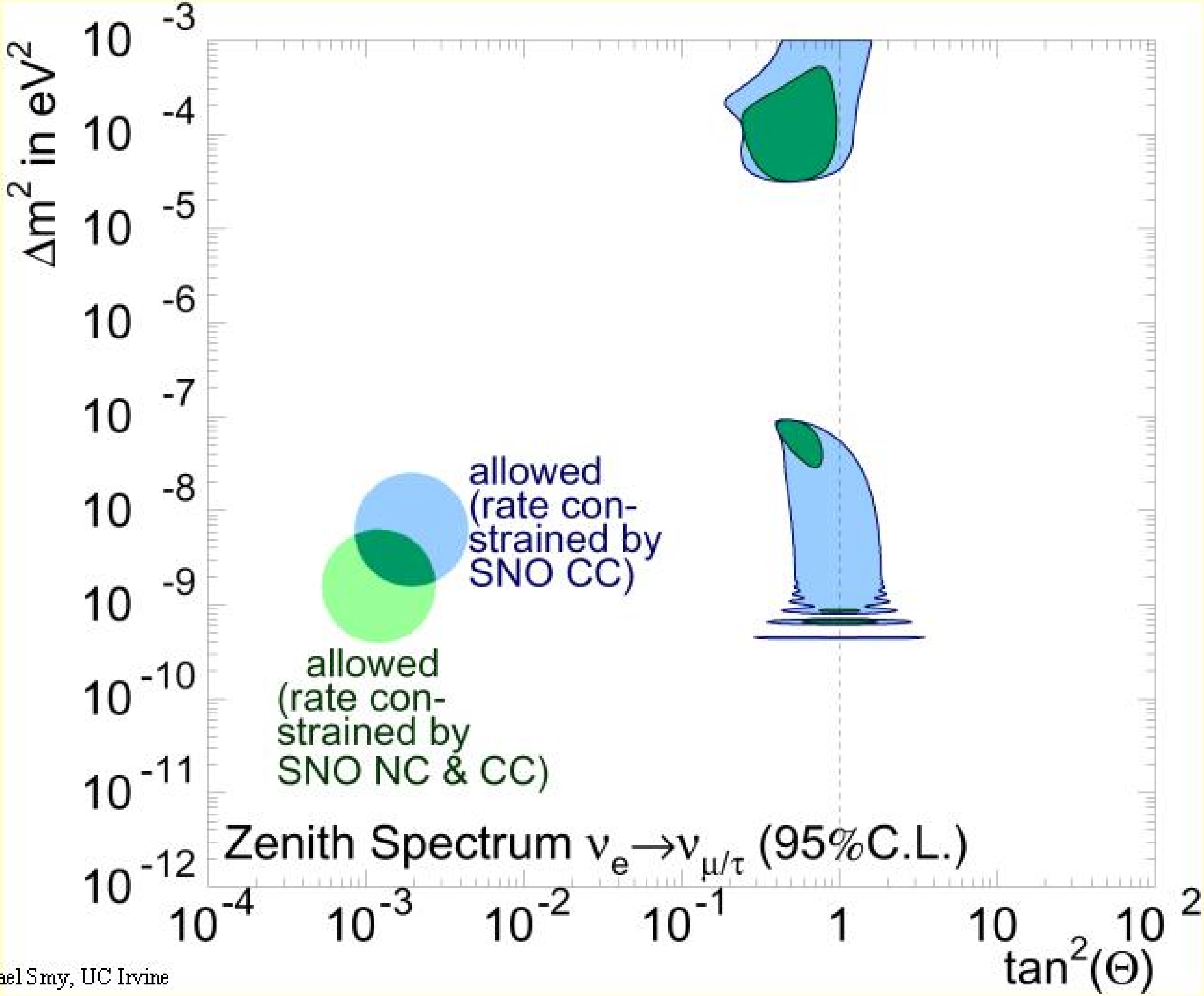

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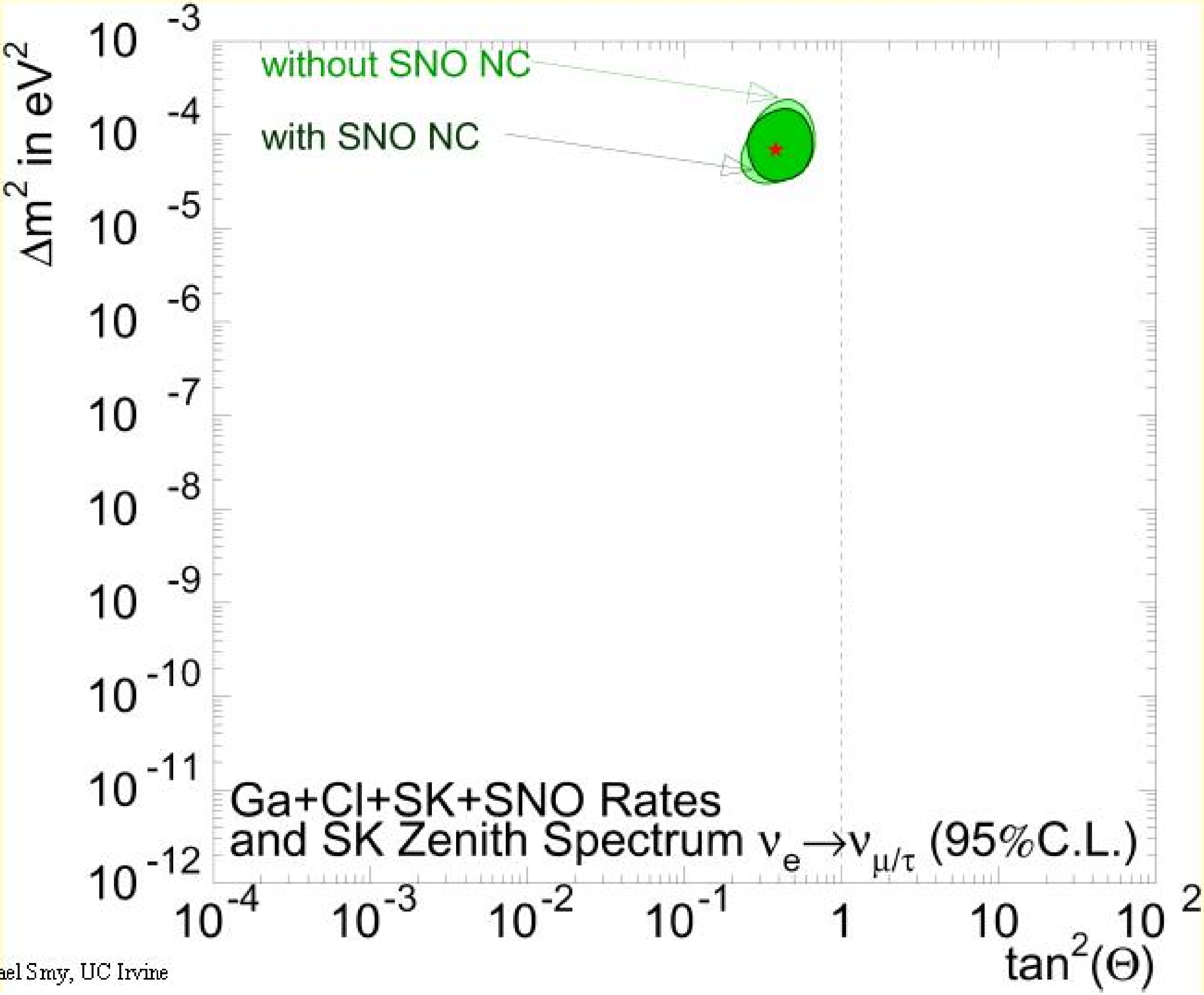

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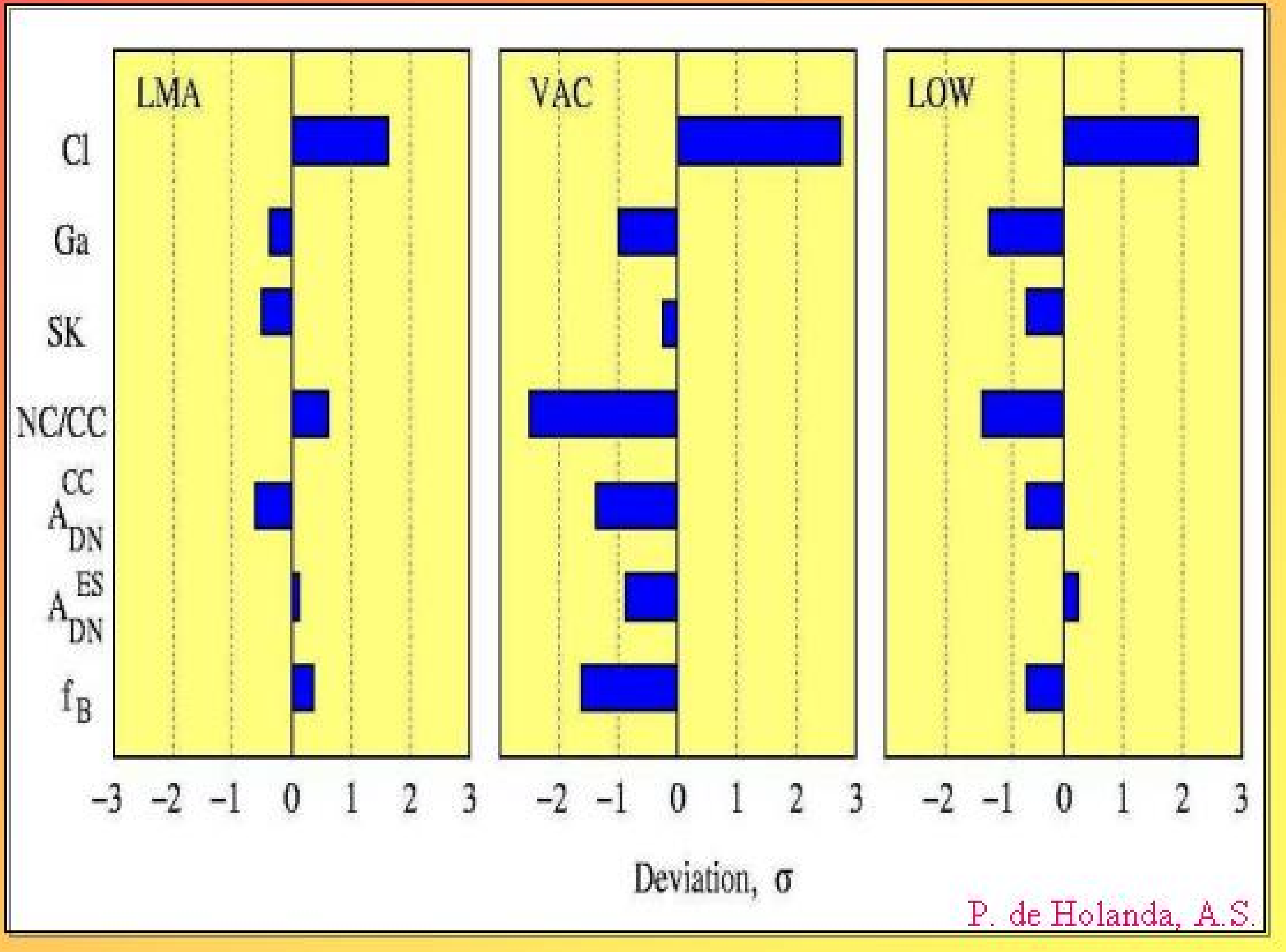
Pull-off diagrams



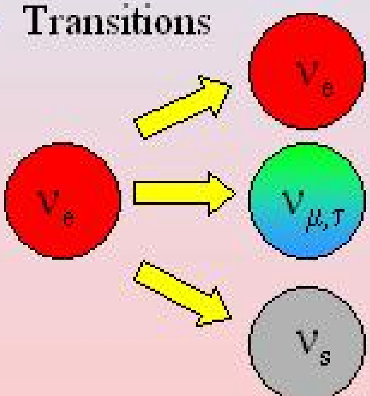
Nu_s and solar neutrinos

- Pure oscillations $\nu_e - \nu_s$ are excluded at about 5σ level

- Oscillations $\nu_e - \nu_x$ where

$$\nu_x = \cos\eta\ \nu_{\mu,\tau} + \sin\eta\ \nu_s$$

- Transitions



P_{ee}

$(1 - P_{ee}) \cos^2\eta$

$(1 - P_{ee}) \sin^2\eta$

- Matter potential is modified:

$$V = \sqrt{2}\, G_F \left(n_e - \sin^2\eta\ \frac{n_n}{2}\right)$$

- Fluxes detected by different reactions

charged currents:

$$\Phi_{CC} = f_B\ P_{ee}$$

neutral currents:

$$\Phi_{NC} = f_B\,[1 - (1 - P_{ee}) \sin^2\eta]$$

neutrino-electron scattering

$$\Phi_{ES} = f_B\,[P_{ee} - r\,(1 - P_{ee}) \cos^2\eta]$$

where f_B is the boron neutrino flux

$$r = \sigma(\nu_\mu e) / \sigma(\nu_e e)$$

Degeneracy of parameters:

two combinations $f_B P_{ee}$ $\quad f_B (1 - P_{ee})\cos^2\eta$

Barger et al,

A Yu Smirnov

Bound on sterile

Global fit of the solar neutrino data

J.N.Bahcall, M.C. Gonzalez-Garcia, C Pena-Garay

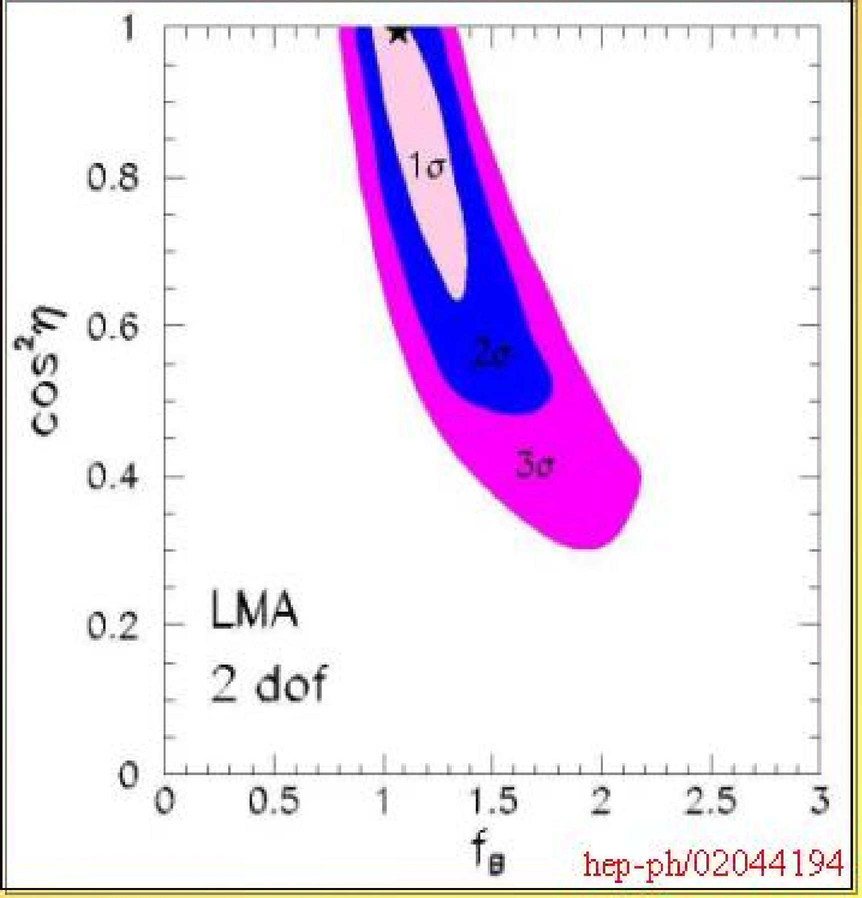
For each pair of values of
$\cos^2\eta$ and f_B
χ^2 is minimized with respect to
Δm^2, $\tan^2\theta$

$\Rightarrow$ $\chi^2(\cos^2\eta, f_B)$

χ^2_{min}

$\sin^2\eta = 0, \quad f_B = 1.07$

$\sin^2\eta < \begin{cases} 0.35, & 1\sigma \\ 0.70, & 3\sigma \end{cases}$



hep-ph/02044194

Start of KamLAND

Kamioka Liquid Scintillator Anti-Neutrino Detector

Junpei Shirai
Research Center for Neutrino Science, Tohoku University
for KamLAND Collaboration

Neutrino2002, May25-30, Munich, Germany

1. KamLAND Overview
2. Reactor $\overline{\nu}$ experiment by KamLAND
3. Detector Performance
   Energy, Vertex, Background
4. Summary

Reactor $\overline{\nu}_e$ experiment

- Pure $\overline{\nu}_e$ flux
- Flux is well known (~1%)

→ Front detector is not necessary.

- Low energy (<several MeV) → Disappearance exp., Large L/E

$$N_{ev} = \sum_i^{\text{reactors}} \frac{1}{4\pi L_i^2} \phi_i \left(1 - \sin^2 2\theta \, \sin^2 \frac{\Delta M^2 L_i}{4E_\nu}\right) \sigma(\bar{\nu} p \to e^+ n) \, N_p$$

KamLAND

Powerful (70GW) reactors → $1.3\times 10^6 \, \overline{\nu}_e$/s/cm^2 (≥1.8MeV)

@L ~ 175±35km → $\Delta M^2 = \sim 6\times 10^{-6}$ eV^2 (@$\sin^2\theta \sim 1$)

1000ton LS (CH_2) → 10^{32} free protons

→ 550 /yr (No oscill., Fid. vol. 600 ton, Reactor eff. 80%)

Covers LMA !!

$\bar{\nu}_e$ Detection

$\bar{\nu}_e\, p \rightarrow e^+ n$ ($E_\nu > 1.8$MeV)

$e^+ e^- \rightarrow 2\gamma$ (0.51MeV) "Prompt" ($=E_\nu - 0.77$MeV)

180μs

$np \rightarrow d\gamma$(2.2MeV) "Delayed"

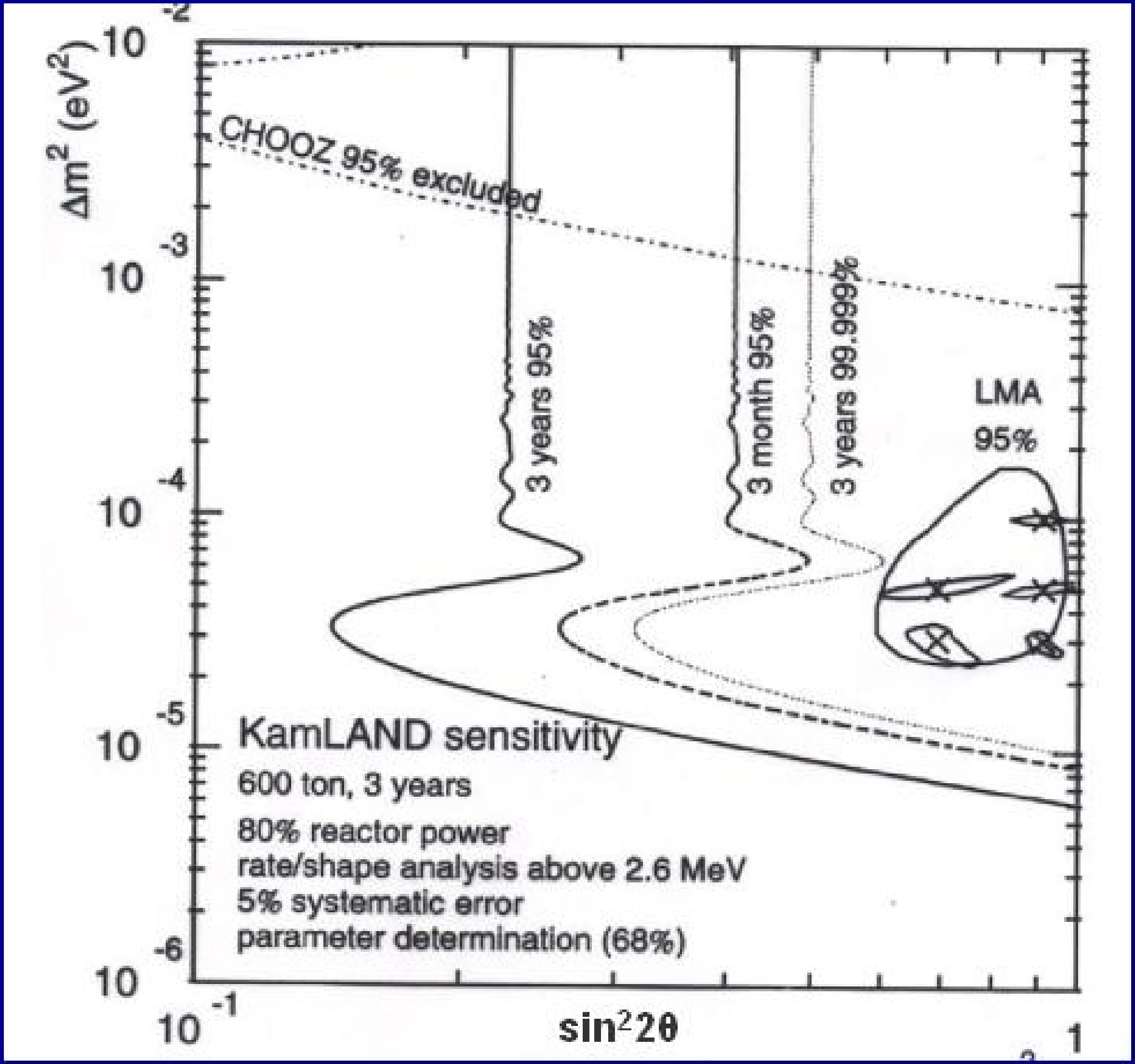
- $\bar{\nu}_e$ only (CC)
- Reject BG (delayed signal← timing, distance, energy)
- σ is large (~$100\sigma(\nu e \rightarrow \nu e)$) and well known.
- E_ν is measured by prompt energy.

- KamLAND Liquid Scintillator

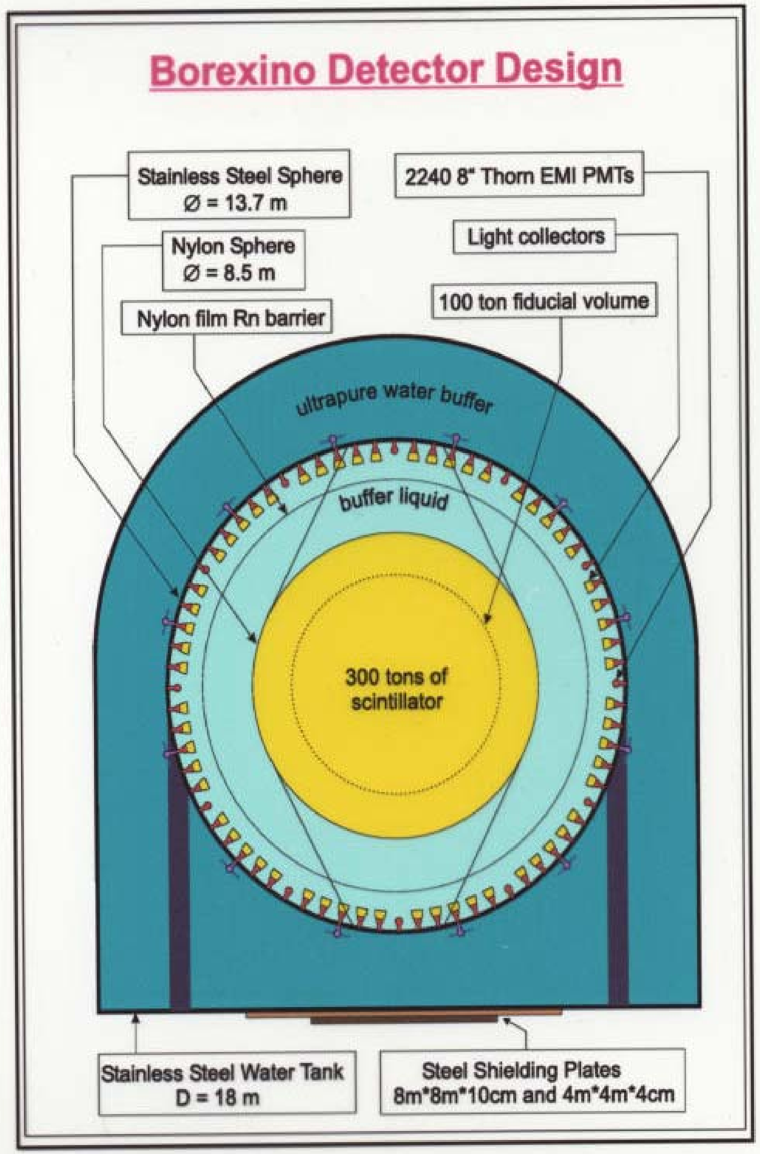
  Large light yield, High purity, Pulse shape discrimination (n/γ, α/γ)

  Fast response, cheap, safe

KamLAND sensitivity



Blind analysis desirable!



1

^{7}Be neutrinos line at 863 keV

Figure 1. Schematic view of BOREXINO. The ultrapure scintillator (300t) inside a nylon vessel is shielded differentially by means of a liquid buffer (1040t), a steel sphere on which the tubes are mounted, and the outer water buffer which is contained in an external steel tank with dimensions of about 18m. A

The "Borexino" program

Main interaction:

$\nu_x + e \rightarrow \nu_x + e$

Measurement of the ν from ^7Be

250-800 KeV

- Rates expected (ev/day):

	S.S.M. (B.P.)	MSW-SMA	MSW-LMA ±3 σ	MSW-LOW ±3 σ	VO ±3 σ
With SK total rates	55	$12^{+16}_{-0.5}$	32^{+7}_{-8}	26	38^{+15}_{-10}
Before SNO			36^{+5}_{-4}	32^{+7}_{-3}	32^{+9}_{-4}
After SNO			35^{+5}_{-3}	32±3	32^{+5}_{-4}

Expected background: ~15 ev/day

Atmospheric neutrinos

Evidence for muon neutrino disappearance

(SK, MACRO, SOUDAN2)

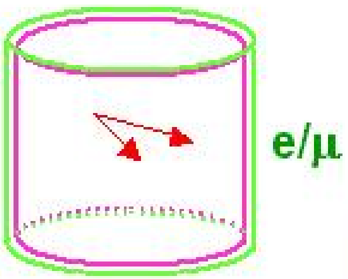
M. Shiozawa

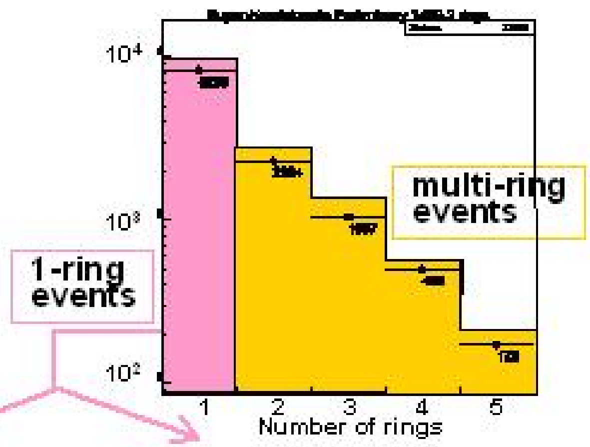
1489 days of contained event data

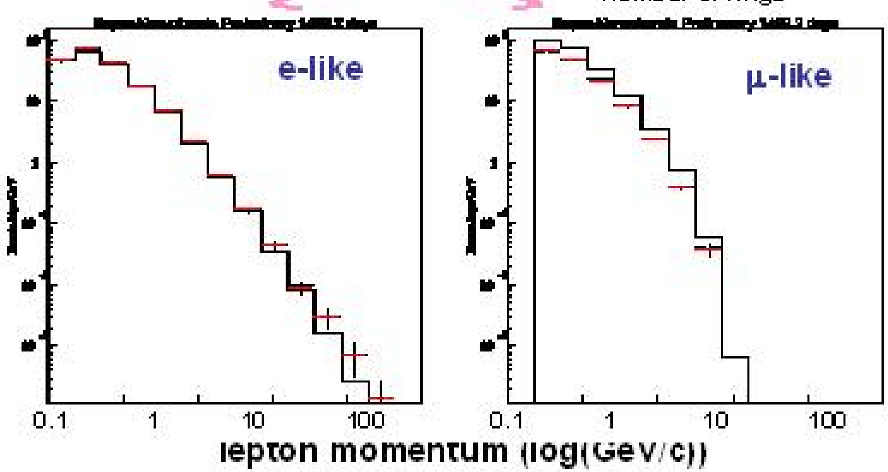
Contained event

(sub-GeV, multi-GeV sample)

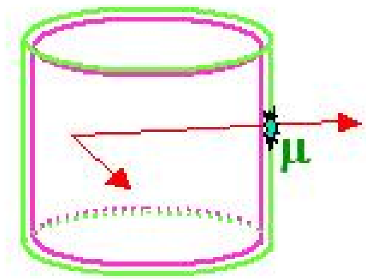
Fully Contained (FC)







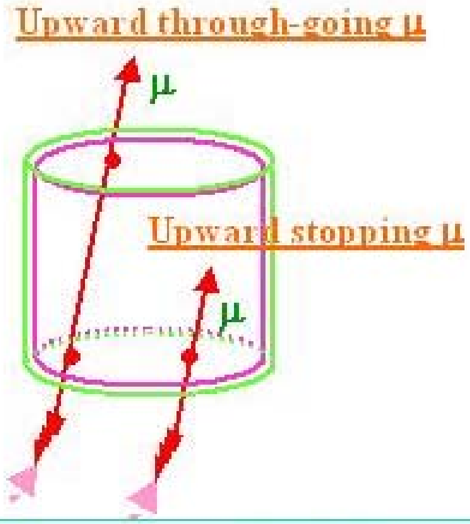
Partially Contained (PC)

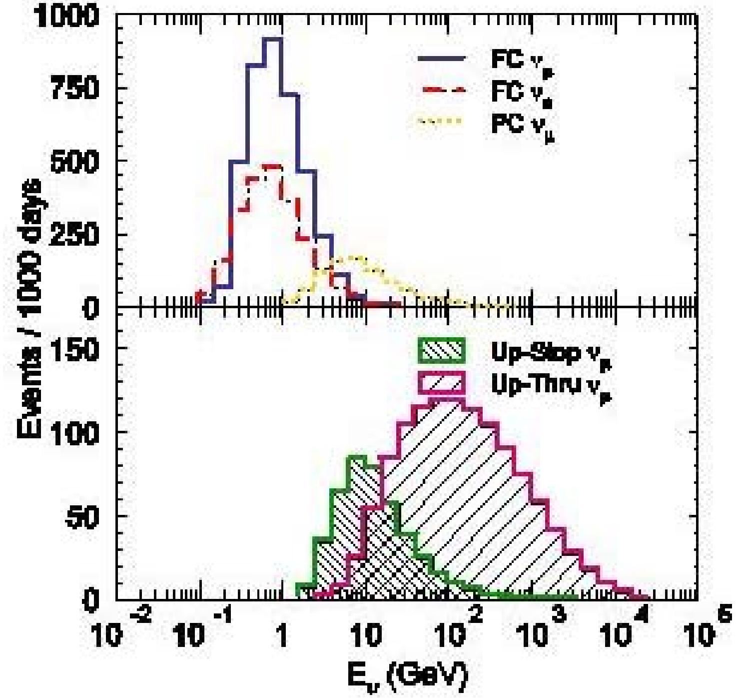


All are assumed to be μ–like

M. Shiozawa

Another technique of atmospheric ν observation



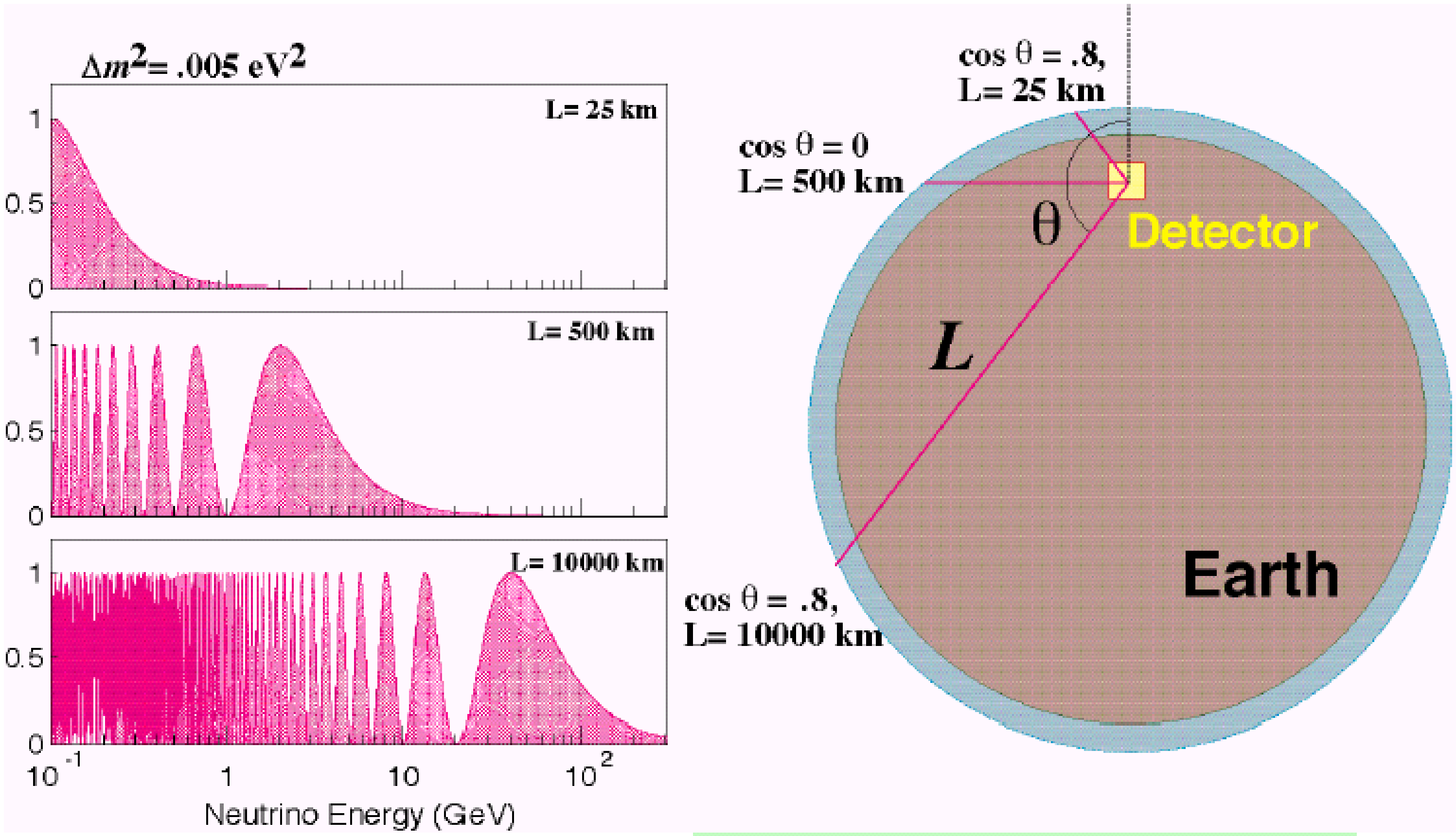


- different energy scale
- different detection technique

Up through-going μ, 1678days, Obs. 1.7 +- 0.04 +- 0.02 ($\times 10^{-13} cm^{-2} s^{-1} sr^{-1}$)
Exp. 1.97+-0.44

Up stopping μ, 1657days, Obs. 0.41+-0.02+-0.02 ($\times 10^{-13} cm^{-2} s^{-1} sr^{-1}$)
Exp. 0.73+-0.16

Zenith angle distribution



$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

M. Shiozawa

Zenith angle distributions (FC+PC+up-μ)

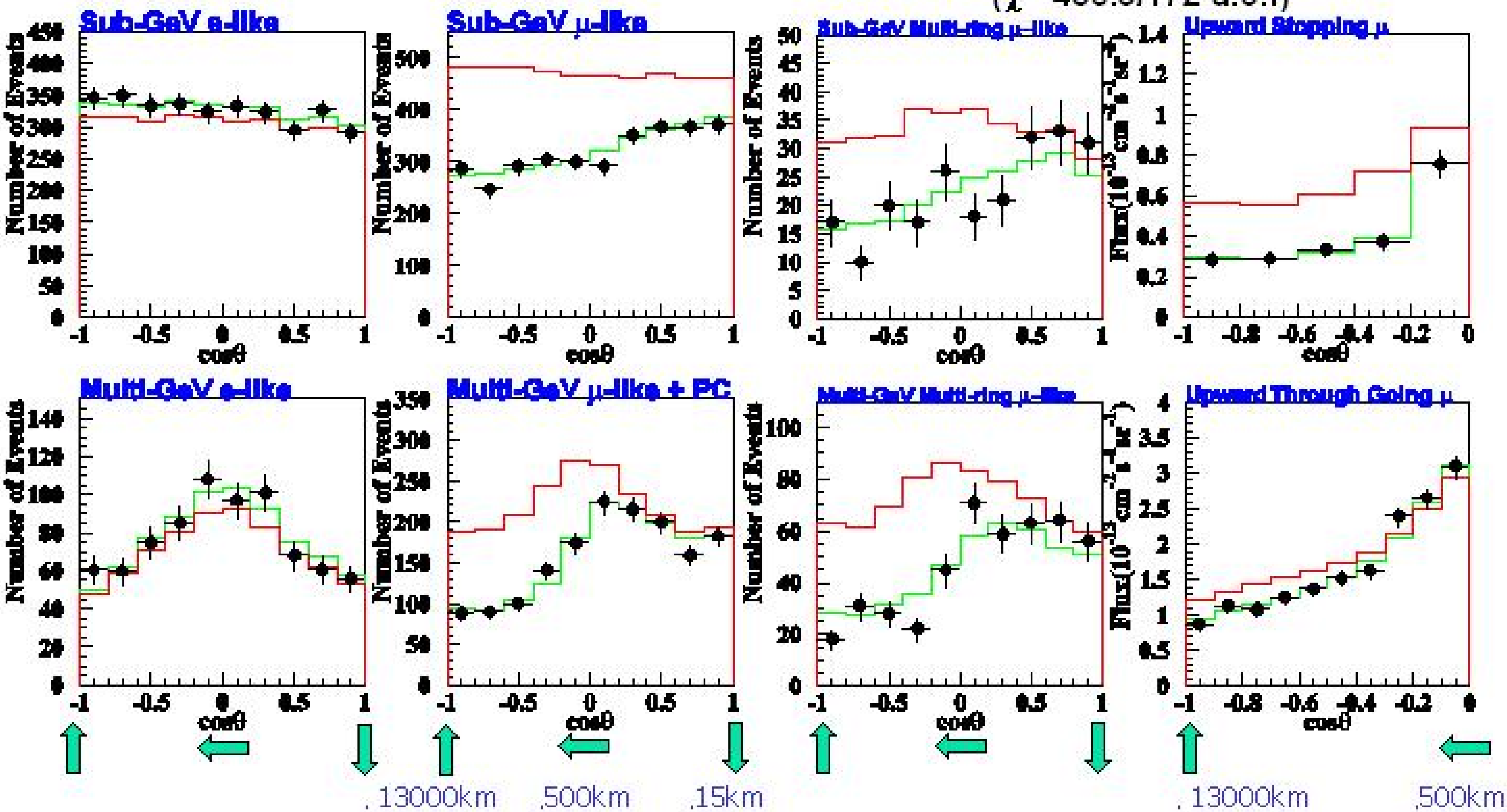
May-2002 Neutrino2002 @ Munich

$\nu_\mu \leftrightarrow \nu_\tau$

2-flavor oscillations

Best fit (Δm^2=2.5x10^{-3}eV^2, $\sin^2 2\theta$=1.0
χ^2_{min}=163.2/170 d.o.f)

Null oscillation
(χ^2=456.5/172 d.o.f)



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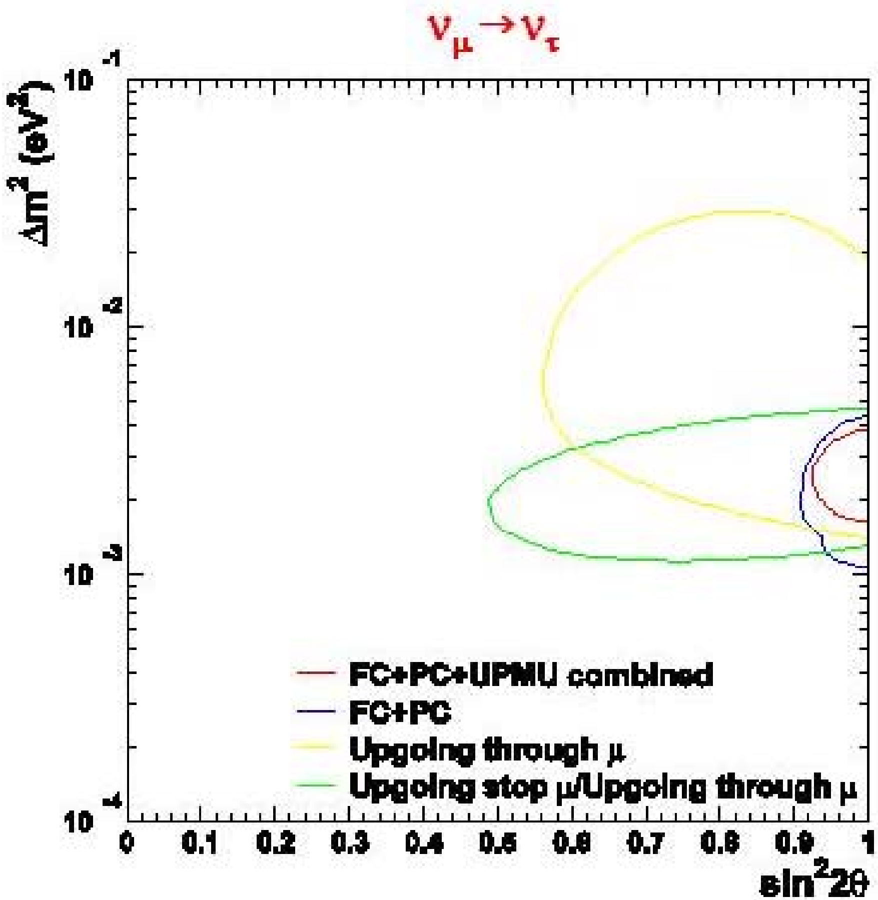
Combined allowed regions



$\nu_\mu \leftrightarrow \nu_\tau$ oscillations

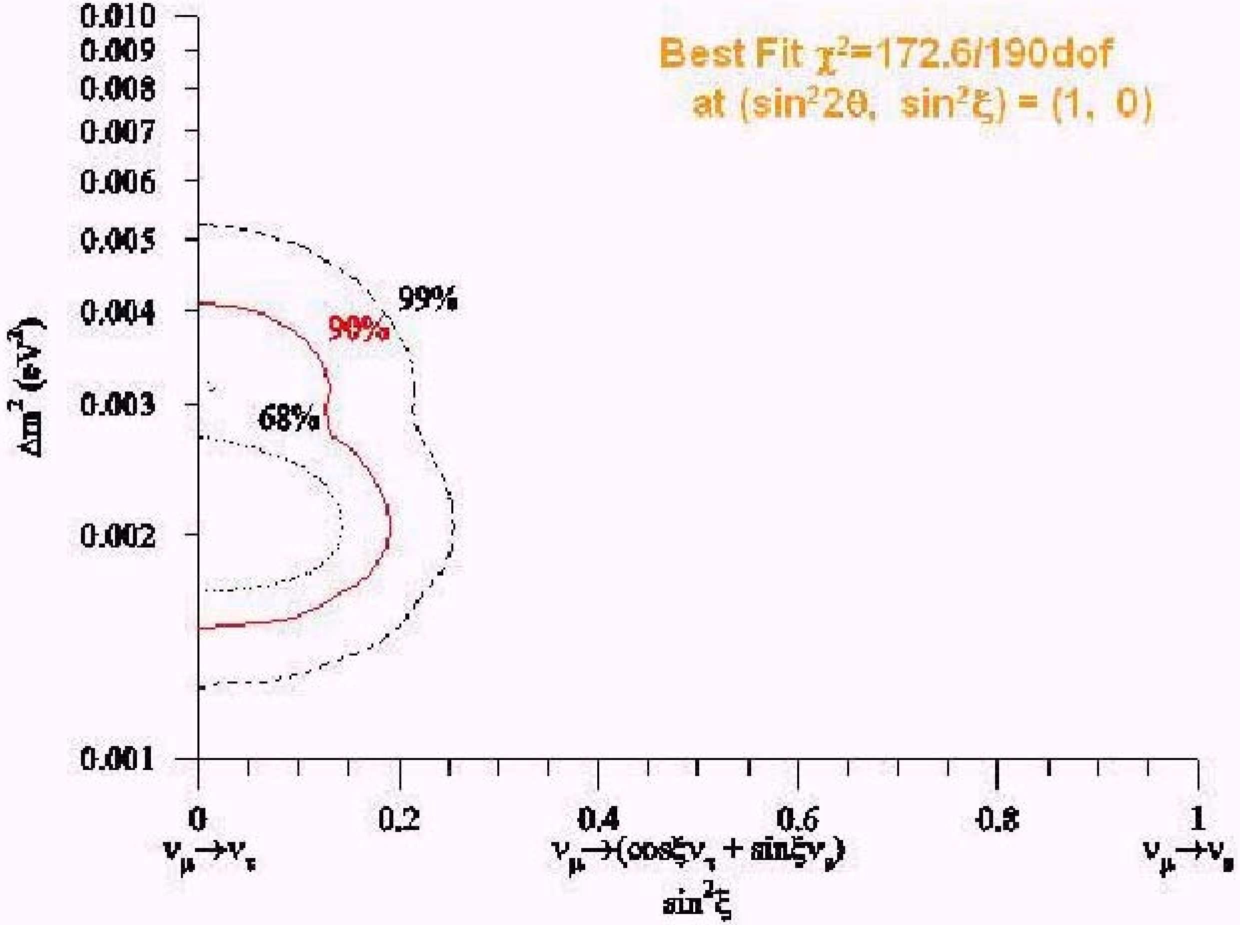
Best fit($\Delta m^2=2.5\times10^{-3}, \sin^2 2\theta=1.0$
χ^2_{min}=163.2/170 d.o.f)

No oscillation
(χ^2 =456.5/172 d.o.f)

$\Delta m^2 = (1.6 \sim 3.9)\times10^{-3} eV^2$

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

limit on $\nu_\mu \leftrightarrow \nu_s$ admixture



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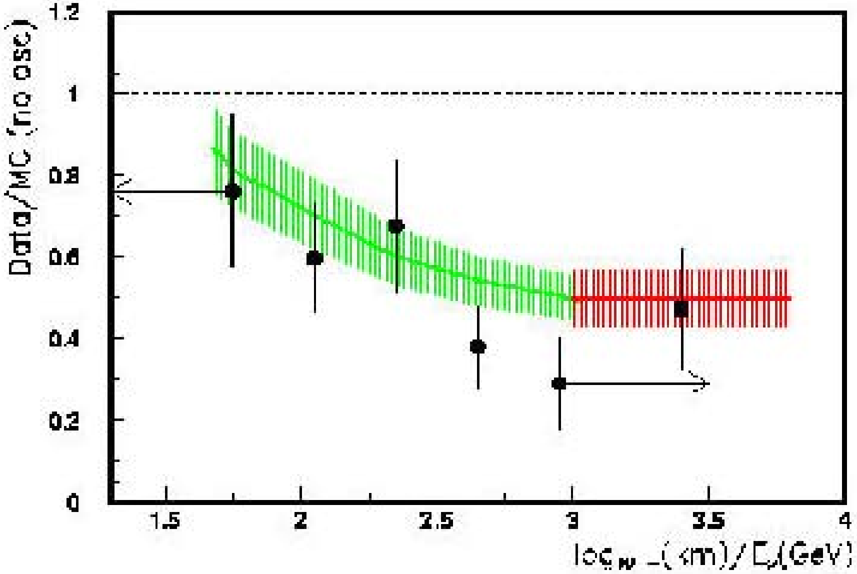
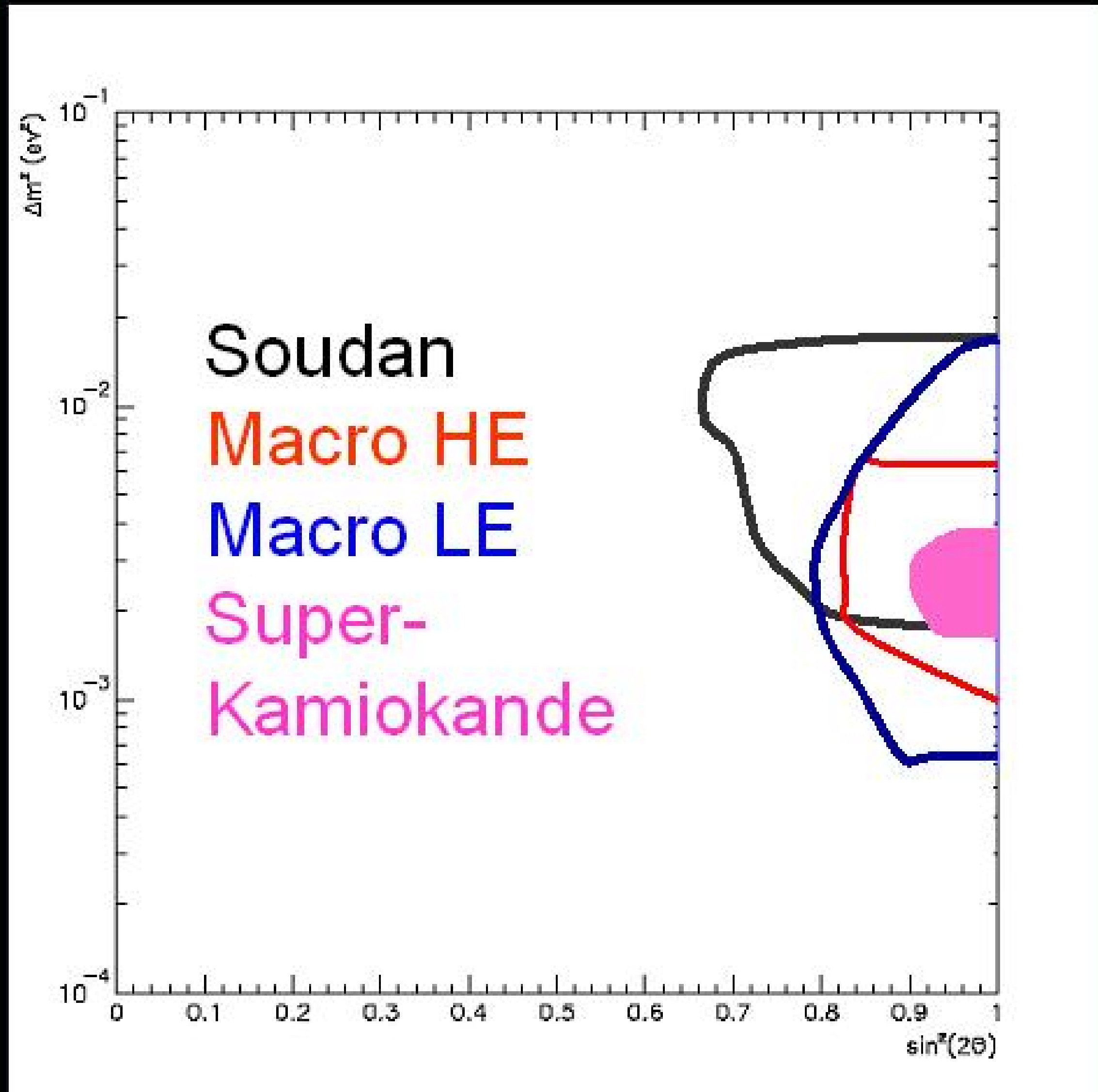
MACRO L/E using multiple scattering

$$\sigma_{MCS} \simeq \frac{X}{\sqrt{3}} \frac{13.6 \cdot 10^{-3} GeV}{p\beta c} \sqrt{X/X^0} \cdot (1 + 0.038 \ln(X/X^0))$$

- E estimate from Multiple Scattering
- 3 E bins (streamer tubes in digital mode)
- 4 E bins (streamer tubes in drift mode + Neural Net)



Δm^2, $\sin^2(2\theta)$ Comparison

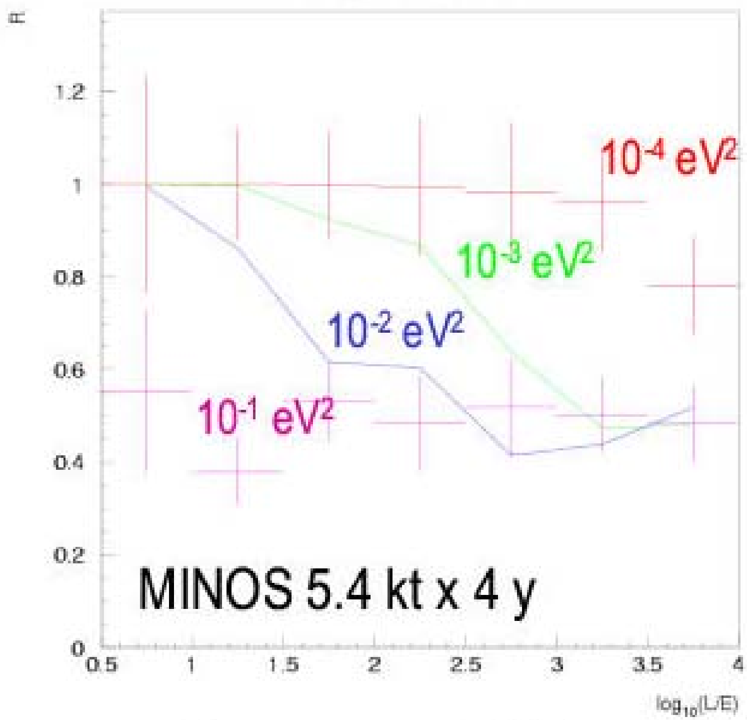


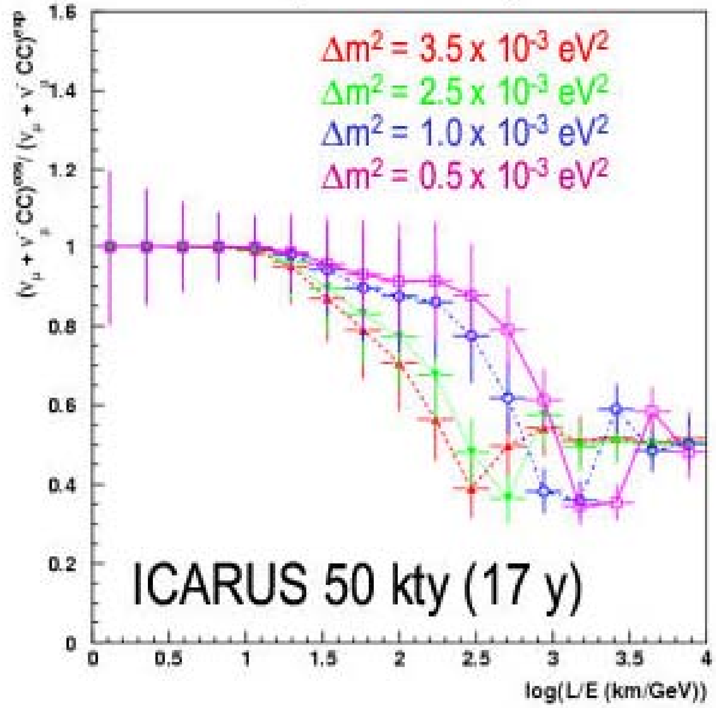
T. Tabarelli de Fatis

Forthcoming experiments

Neutrino 2002 Munich

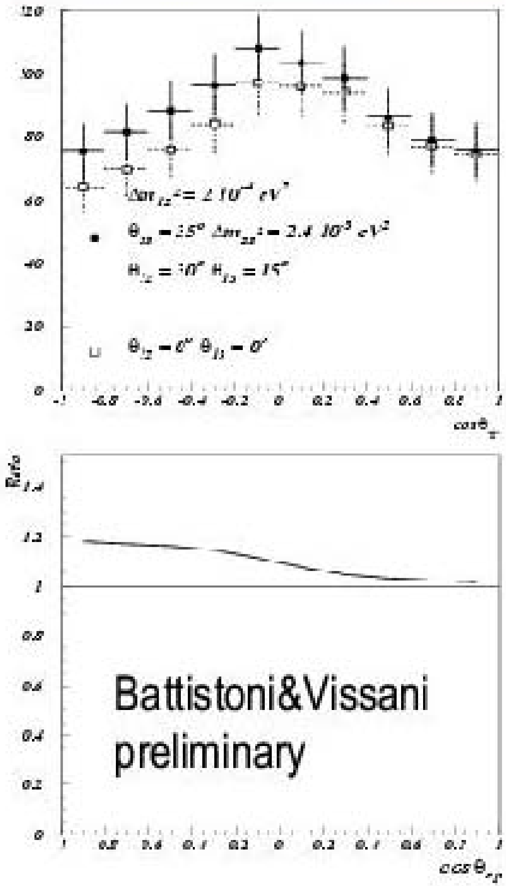
- Check of Super-K
- Not for precision measurements *(with atmospheric ν's!)*





- Low mass and limited acceptance at high energies

ICARUS (20 kty)



- Improved reconstruction of the neutrino direction at low energies
  - (resolution limited by Fermi motion and nuclear effects)
- With some luck a zenith angle dependence might be detectable

  (Some model dependence in the correction for the up/down asymmetry of low energy neutrino events)
- Key to Θ_{13} or non maximal Θ_{23}, if LMA parameters fixed elsewhere
- Precision measurement in SuperICARUS?

Accelerator experiments

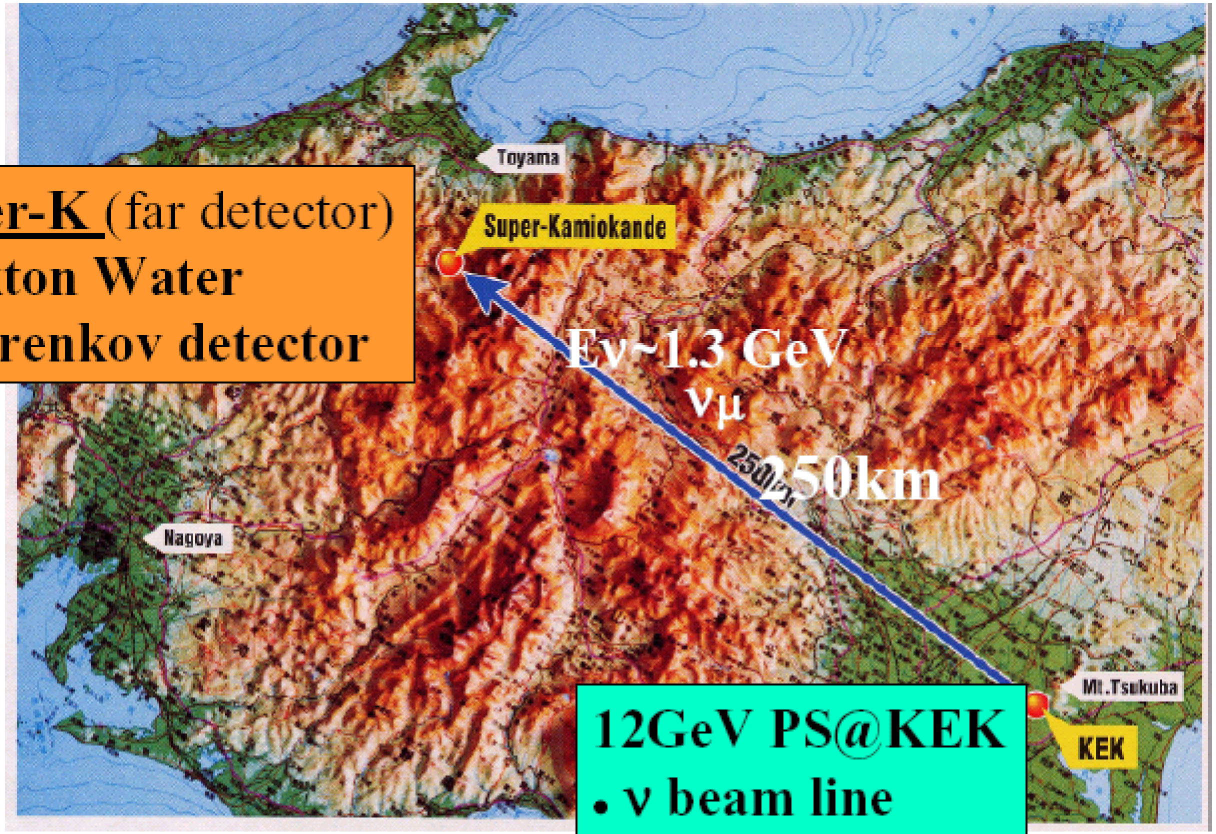
Laboratory tests of ν_μ disappearance

(K2K, MINOS)

K. Nishikawa

KEK to Kamioka Neutrino Oscillation Experiment

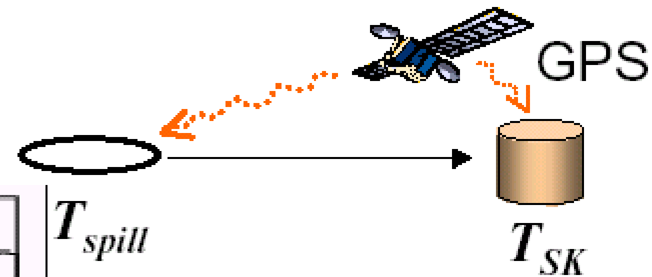
Super-K (far detector)
50 kton Water Cherenkov detector



12GeV PS@KEK
- **ν beam line**
- **Beam monitor**
- **Near detectors**

Super-K Event selection

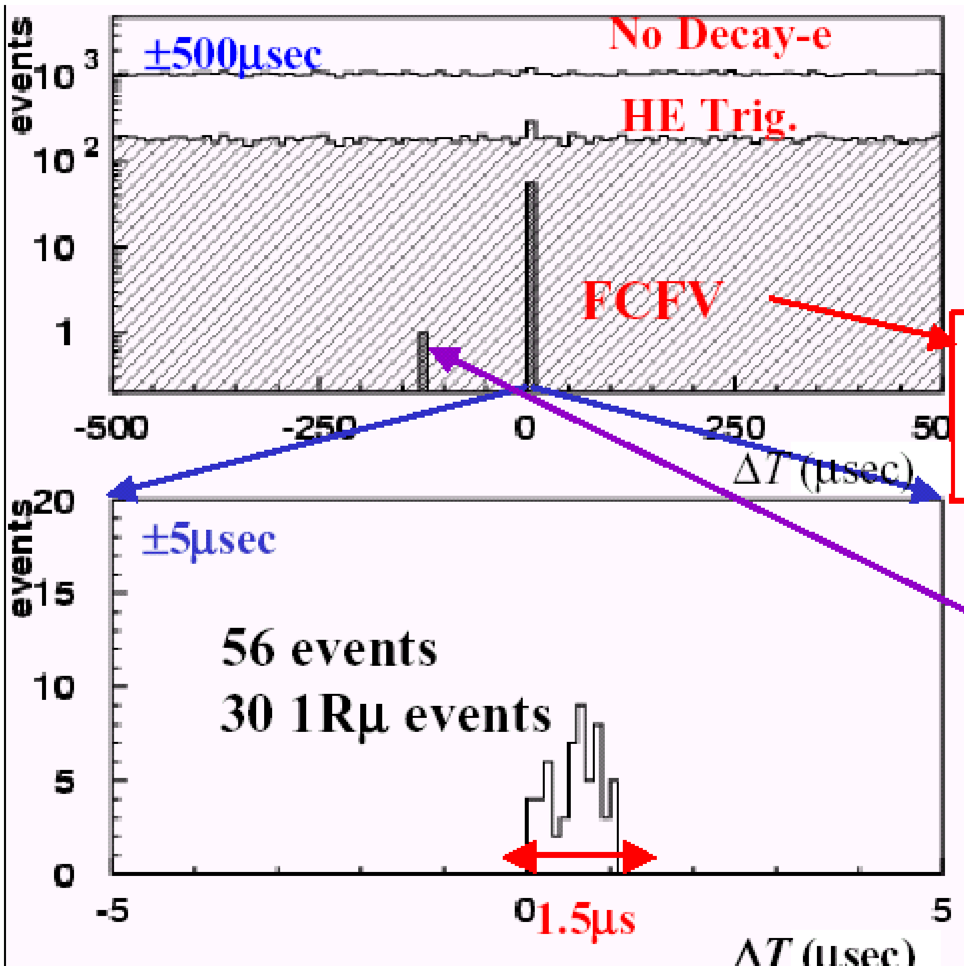
$$-0.2 \le \Delta T \equiv T_{SK} - T_{Spill} - \mathrm{TOF} \le 1.3\mu\,\mathrm{sec}$$



T_{Spill}: Abs. time of spill start

T_{SK}: Abs. time of SK event

TOF: 0.83ms (KEK to Kamioka)

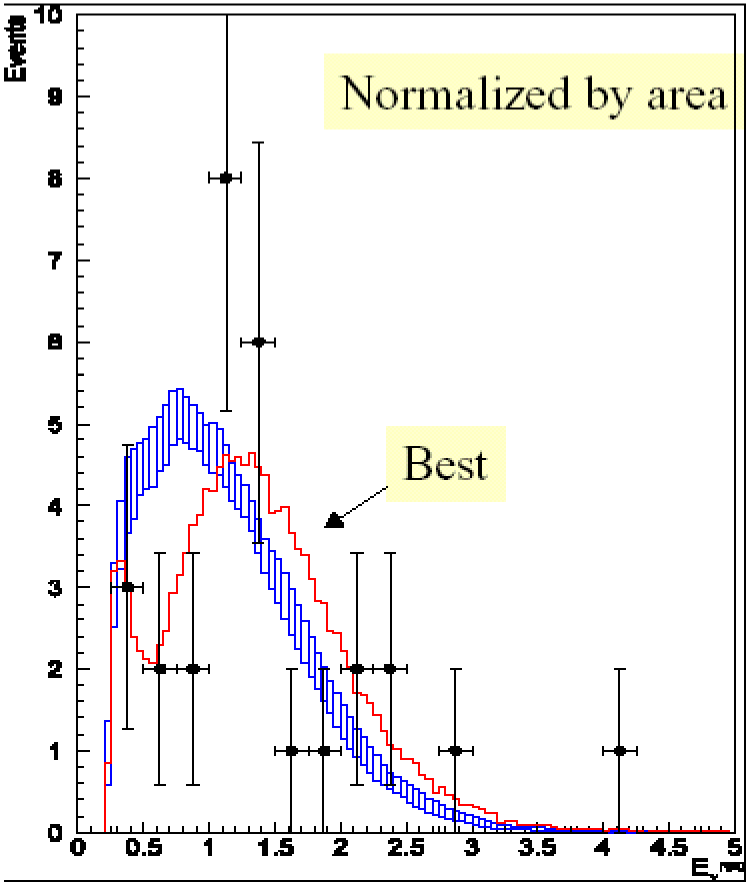


FC: fully contained
(No activity in Outer Detector)
FV: 22.5kt Fiducial Volume

Expected Atm. ν BG
$<10^{-3}$ within 1.5μs.

K. Nishikawa

Is best fit point also for 1Rμ shape & Nsk ?



Best fit point ($\sin^2 2\theta$, Δm^2)

method 1

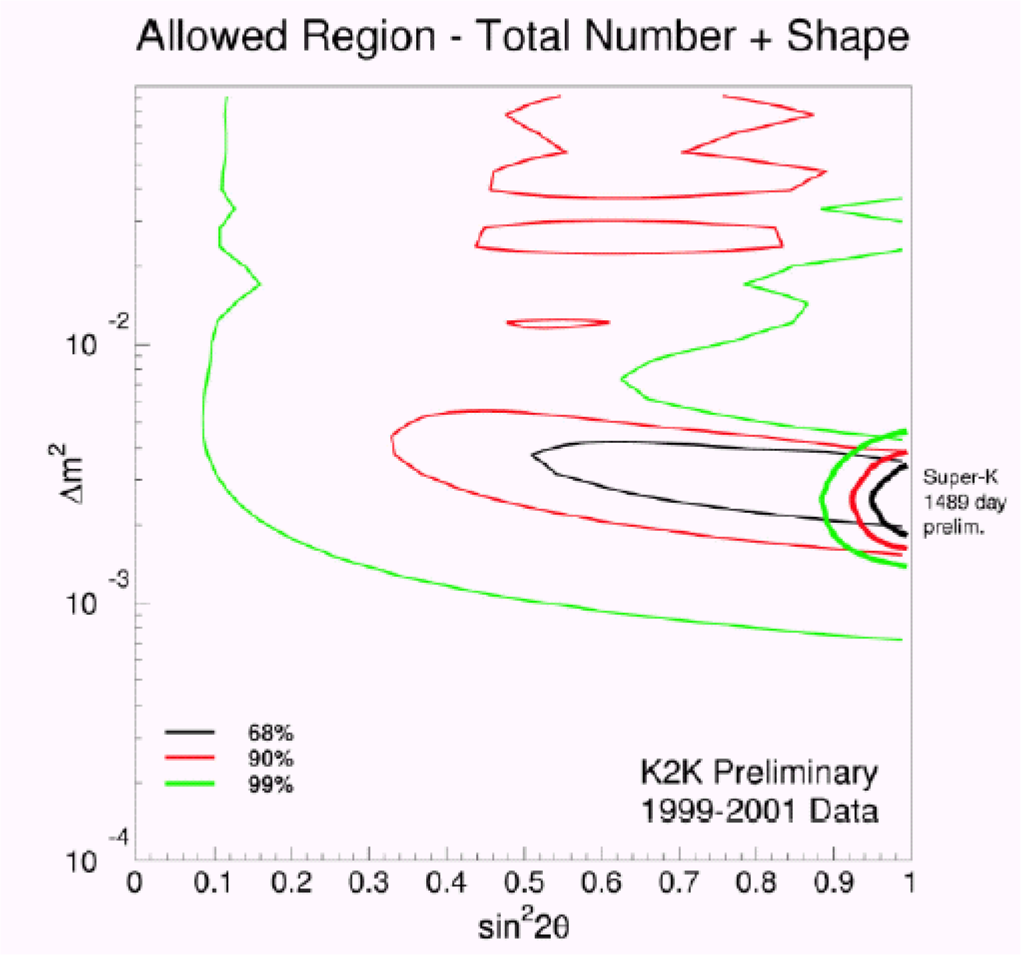
KS test prob.(shape)= 79%

N_{SK} prediction =54 (obs 56)

method 2 KS-test

N_{SK}	82%
shape	93%
N_{SK}+shape	50%

Comparison with SK atm ν observation



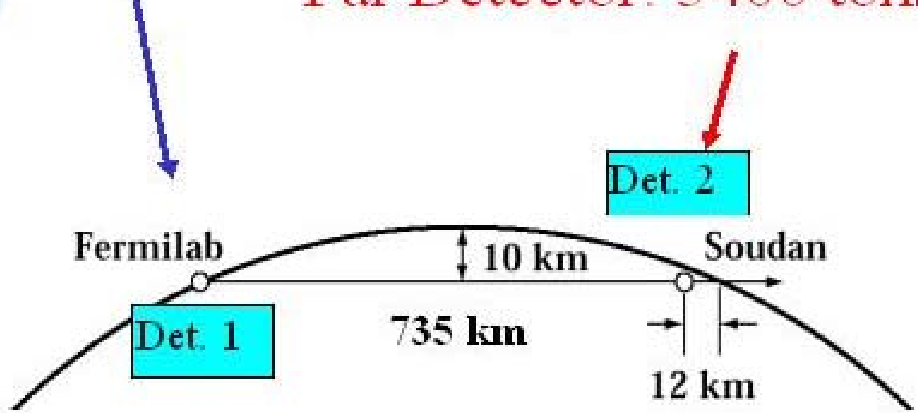
D. Michael

The MINOS Experiment

- Precision measurements of:
  - Energy distribution of oscillations
  - Measurement of oscillation parameters
  - Participation of neutrino flavors
- Direct measurement of ν vs $\overline{\nu}$ oscillation
  - Magnetized far detector: atm. ν's.
  - Likely eventual measurement with beam

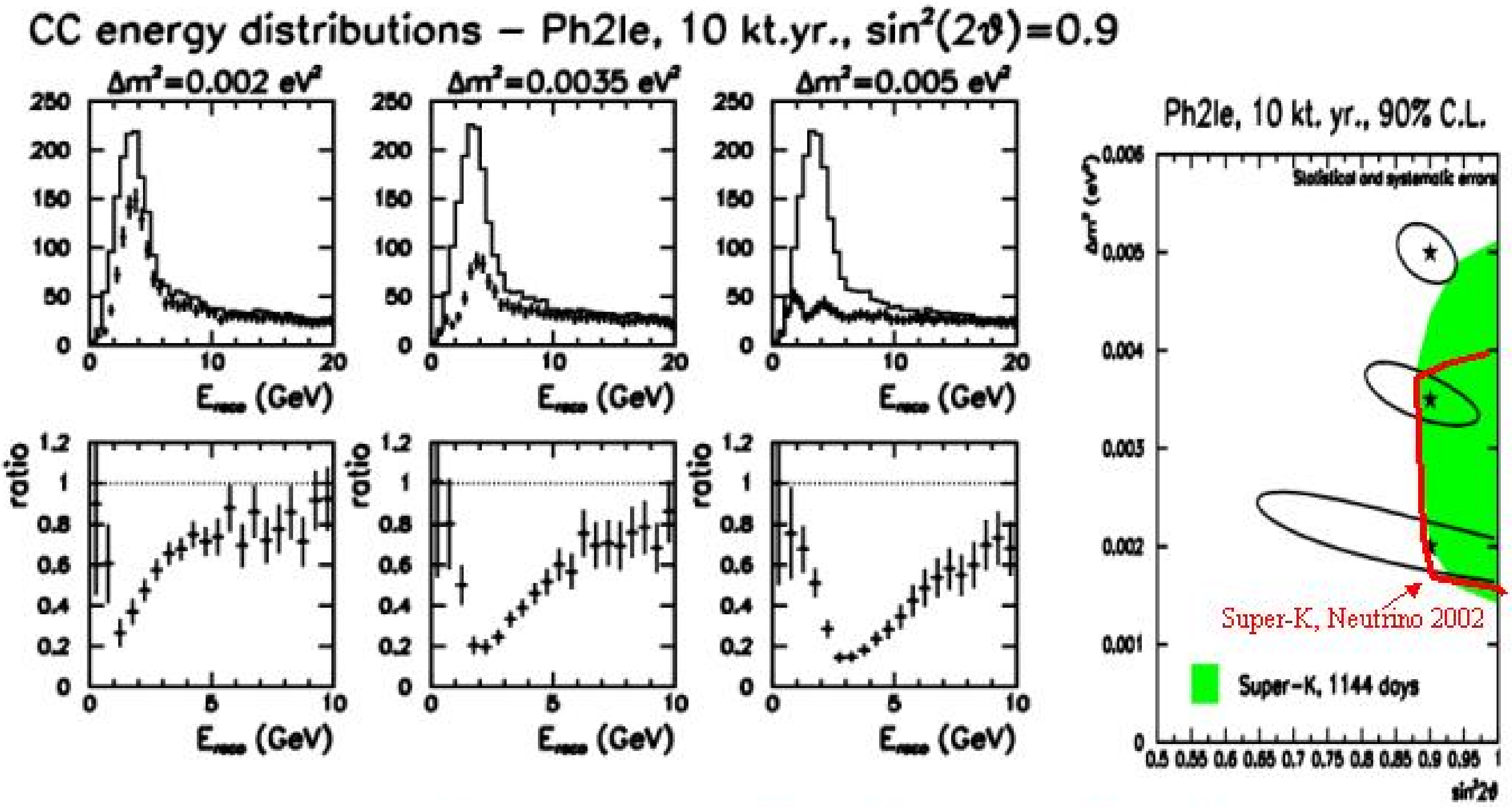
Near Detector: 980 tons

Far Detector: 5400 tons



D. Michael

Measurement of Oscillations in MINOS



Note: MINOS beam results are presented for only 2 years of running! Longer-term running is certainly possible, even probable. Results are statistics limited.

Searches for tau neutrino appearance

with atmospheric (SK)

and accelerator experiments (CNGS)

M. Shiozawa

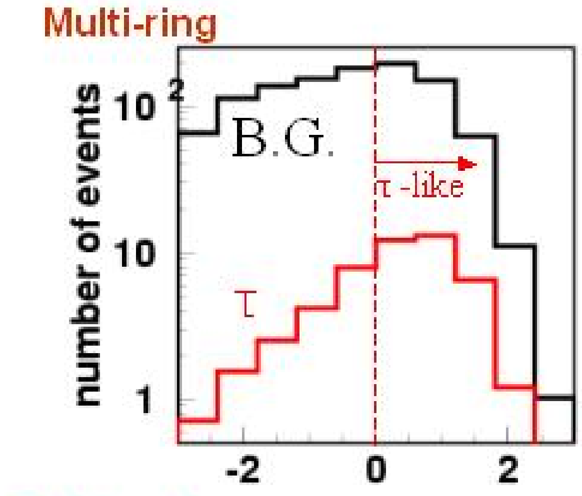
□ τ detection in atmospheric ν

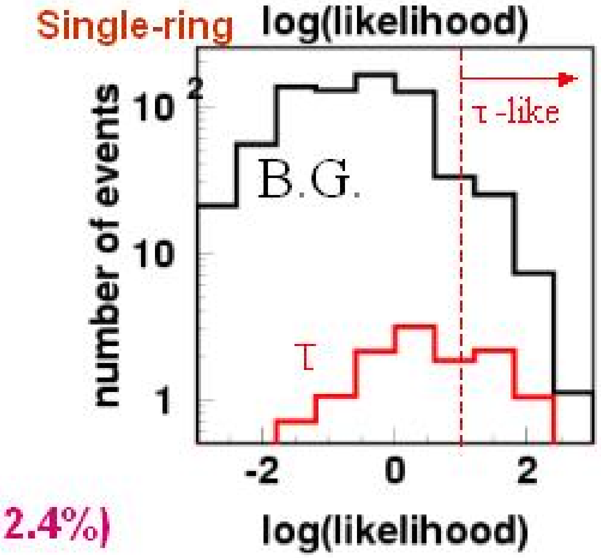
Selection Criteria
- multi-GeV, multi-ring
- most energetic ring is e-like
- log(likelihood) > 1 (single-ring)
  > 0 (multi-ring)

<u>τ likelihood is defined using:</u>
- total energy
- number of rings
- number of decay electrons
- max(Ei)/ΣEi
- distance between ν interaction point and decay-e point
- max(P_μ)
- Pt/Evis$^{3/4}$
- PID likelihood of most energetic ring

τ–like selection: effτ=44%, S/N=8%

observed τ–like events: 506
MC expectation: CC ν_τ 37 events,
BG 461 events (CCν_e 43.1%, CCν_μ 24.5%, NC 32.4%)

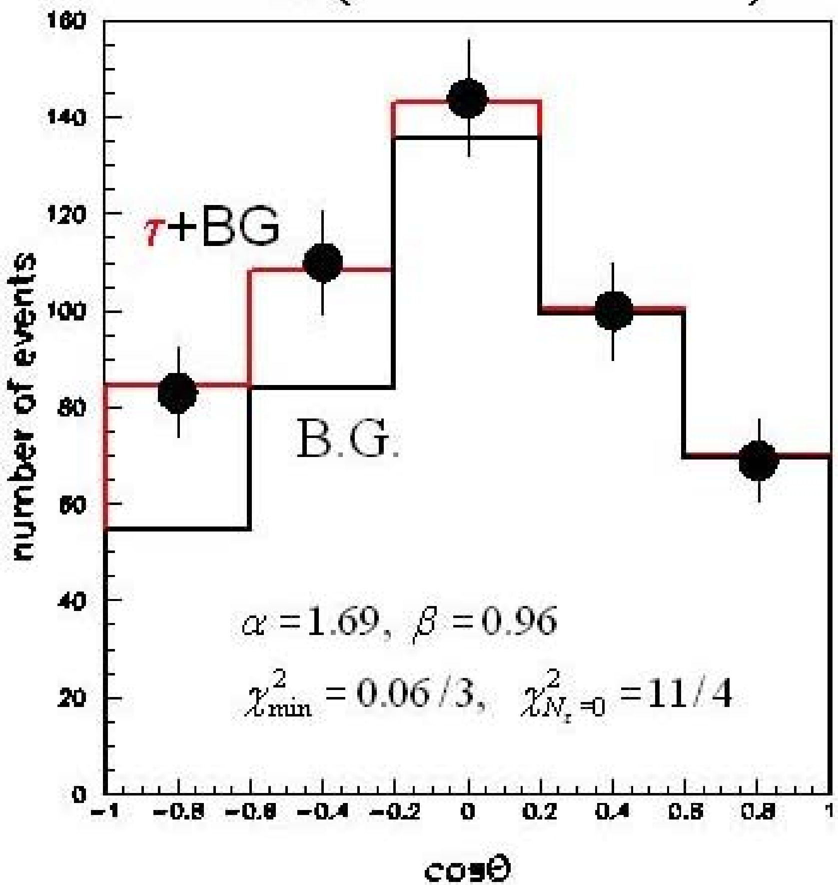




M. Shiozawa

zenith angle dist. of τ-like events

$$\chi^2 = \sum_{\cos\theta}^{5} \left(\frac{N_{data} - \left(\alpha N_{MC}^{\tau} + \beta N_{MC}^{BG} \right)}{\sigma} \right)^2$$



- $N^{FC}_{\tau} = \alpha N^{\tau}_{MC}$/(eff.=0.44)
  =145+-44(stat.)
  +11/-16(sys.)
  N_{exp}=86
- consistent with $\nu_\mu \leftrightarrow \nu_\tau$
- another analysis gives similar results:
  *analysis-2(neural network)
  N^{FC}_{τ}=99+-39(stat.)
  +-13(Δm^2)
  +0/-16(3-flavor)

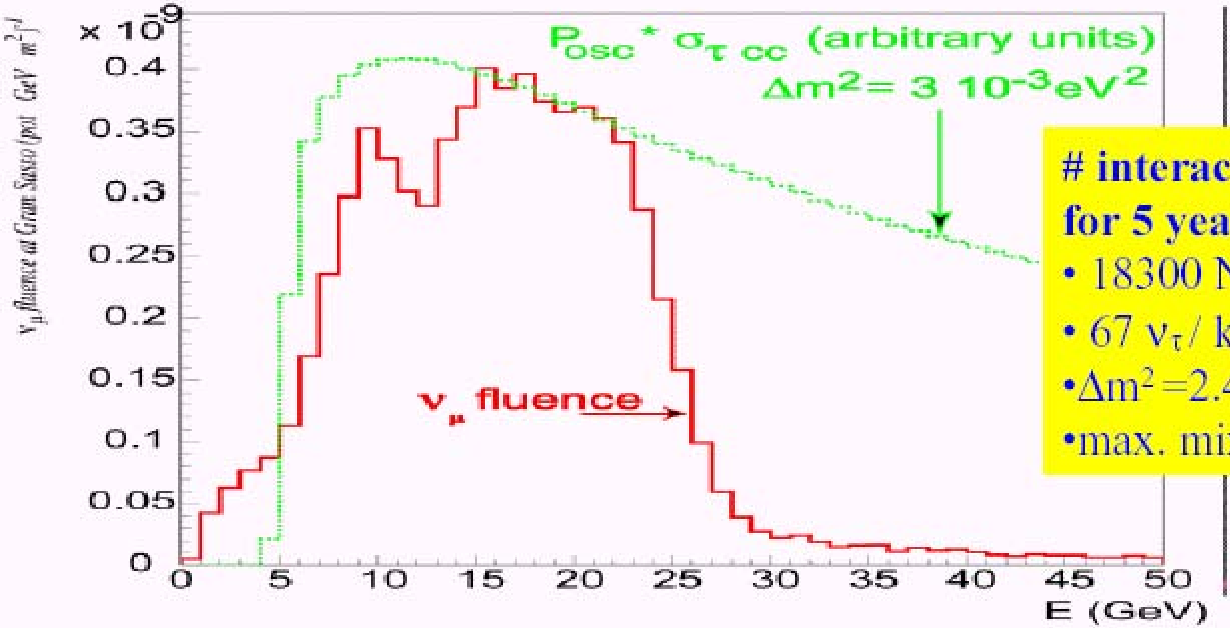
CNGS beam optimized for appearance

Shared SPS operation

200 days/year

4.5×10^{19} pot / year

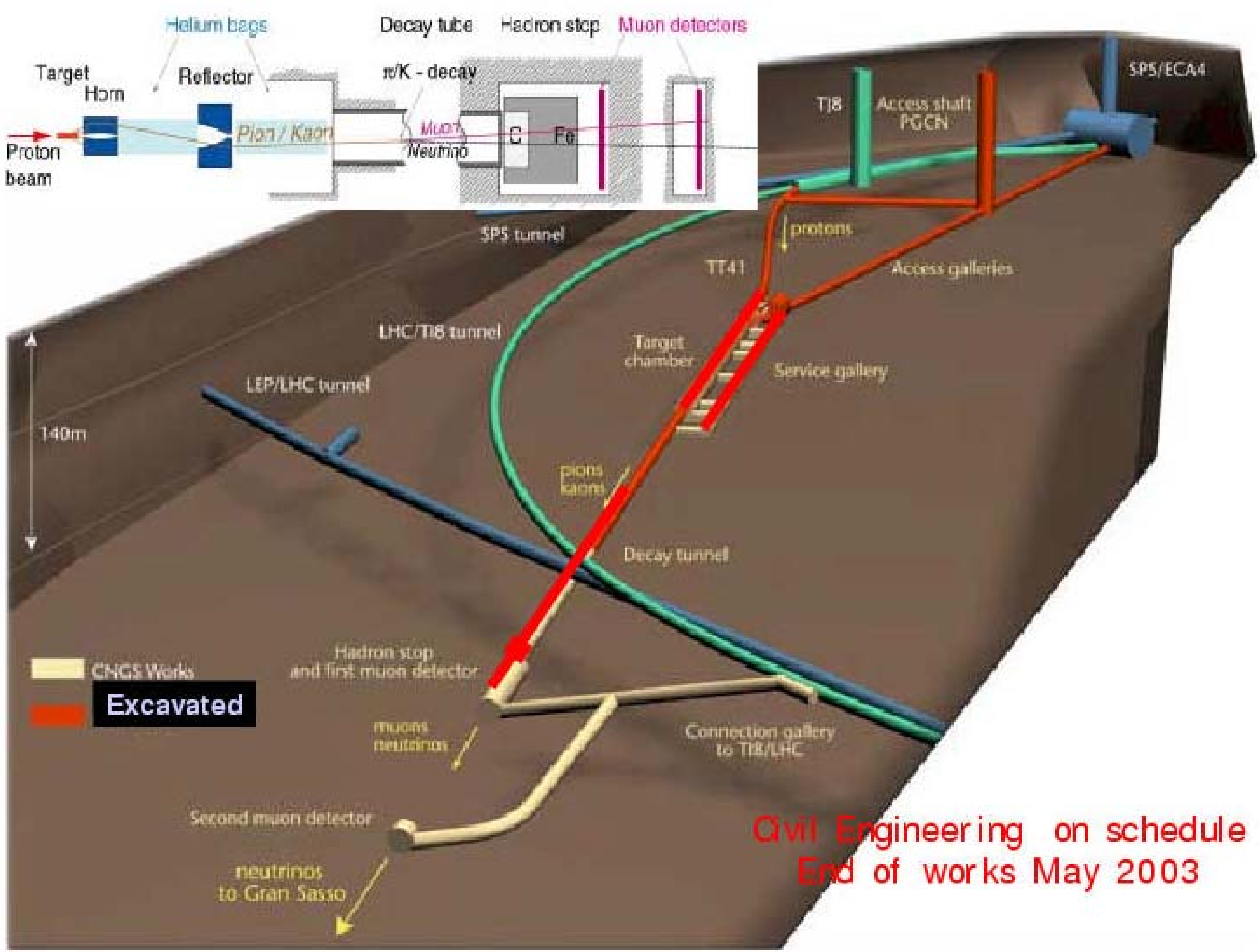
$< E >_\nu$ (GeV)	17
$(\nu_e + \bar{\nu}_e) / \nu_\mu$	0.87 %
$\bar{\nu}_\mu / \nu_\mu$	2.1 %
ν_τ prompt	negligible



 # interactions ν for 5 years :

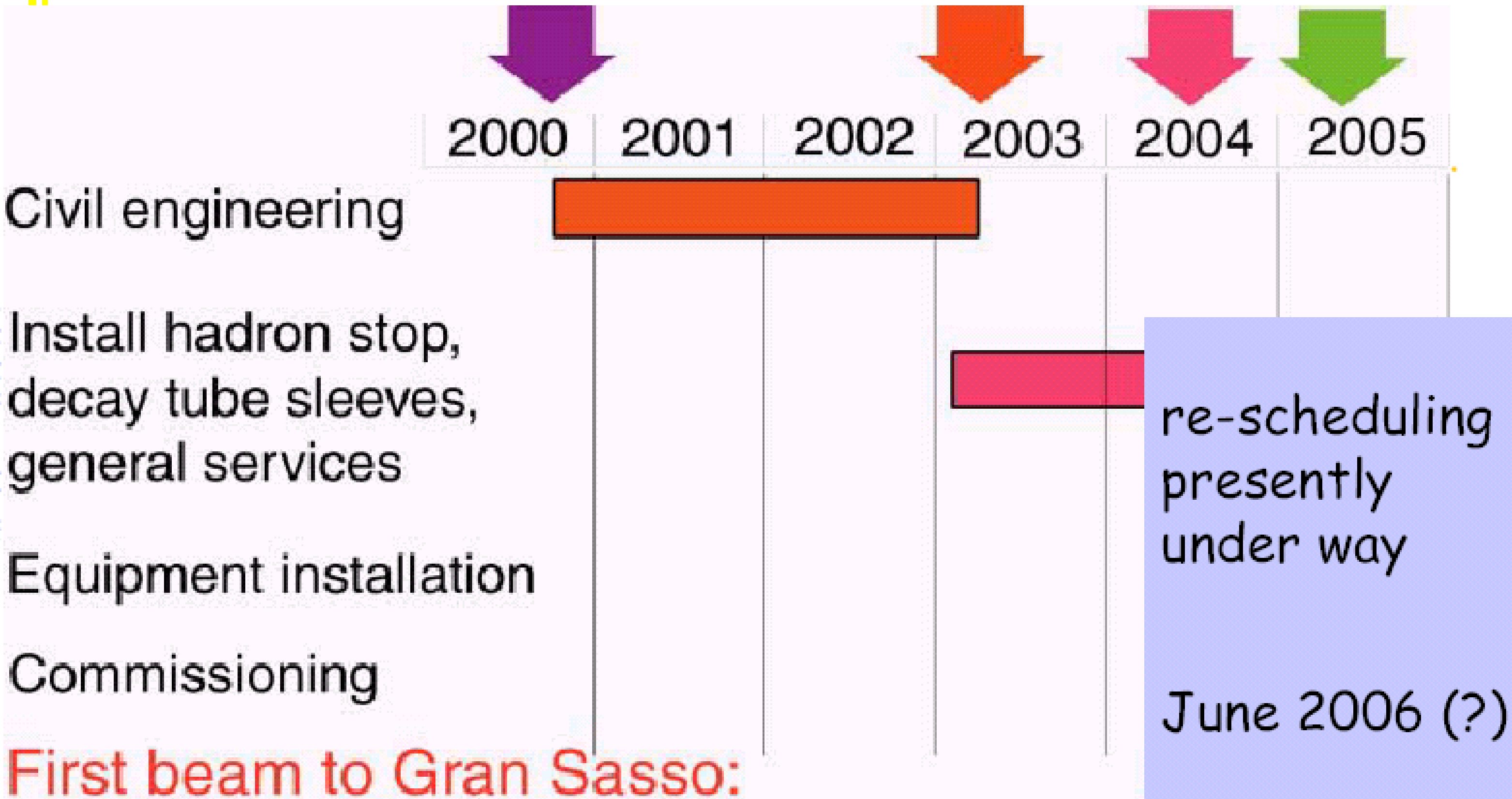
- 18300 NC+CC / kt
- 67 ν_τ / kt
- $\Delta m^2 = 2.4\times10^{-3}$ eV^2
- max. mixing

S. Katsanevas



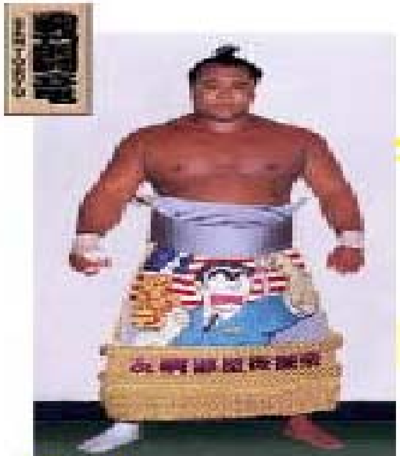
Civil Engineering on schedule
End of works May 2003

CNGS : schedule



Reevalution: Cost 71 -> 77.6 MCHF
Manpower 60-> 80 manyears

S. Katsanevas



2 ways of detecting τ appearance

ν_μ ..... $\nu_\tau \rightarrow \tau^- + X$

oscillation — CC interaction

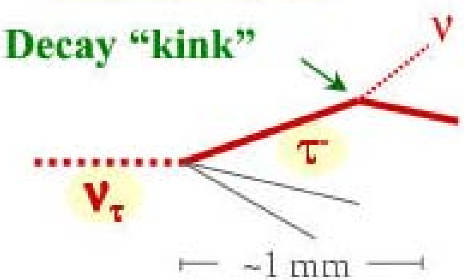
$\mu^- \; \nu_\tau \; \bar{\nu}_\mu$	BR 18 %
$h^- \; \nu_\tau \; n\pi^0$	50 %
$e^- \; \nu_\tau \; \bar{\nu}_e$	18 %
$\pi^+ \pi \pi \; \nu_\tau \; n\pi^0$	14%

OPERA: Observation of the decay topology of τ *(à la CHORUS)*

In photographic emulsion

(~ µm granularity)

A digital Cloud chamber



ICARUS: detailed TPC image in liquid argon and kinematic criteria *(à la NOMAD)*

(~ mm granularity)

A digital Bubble chamber

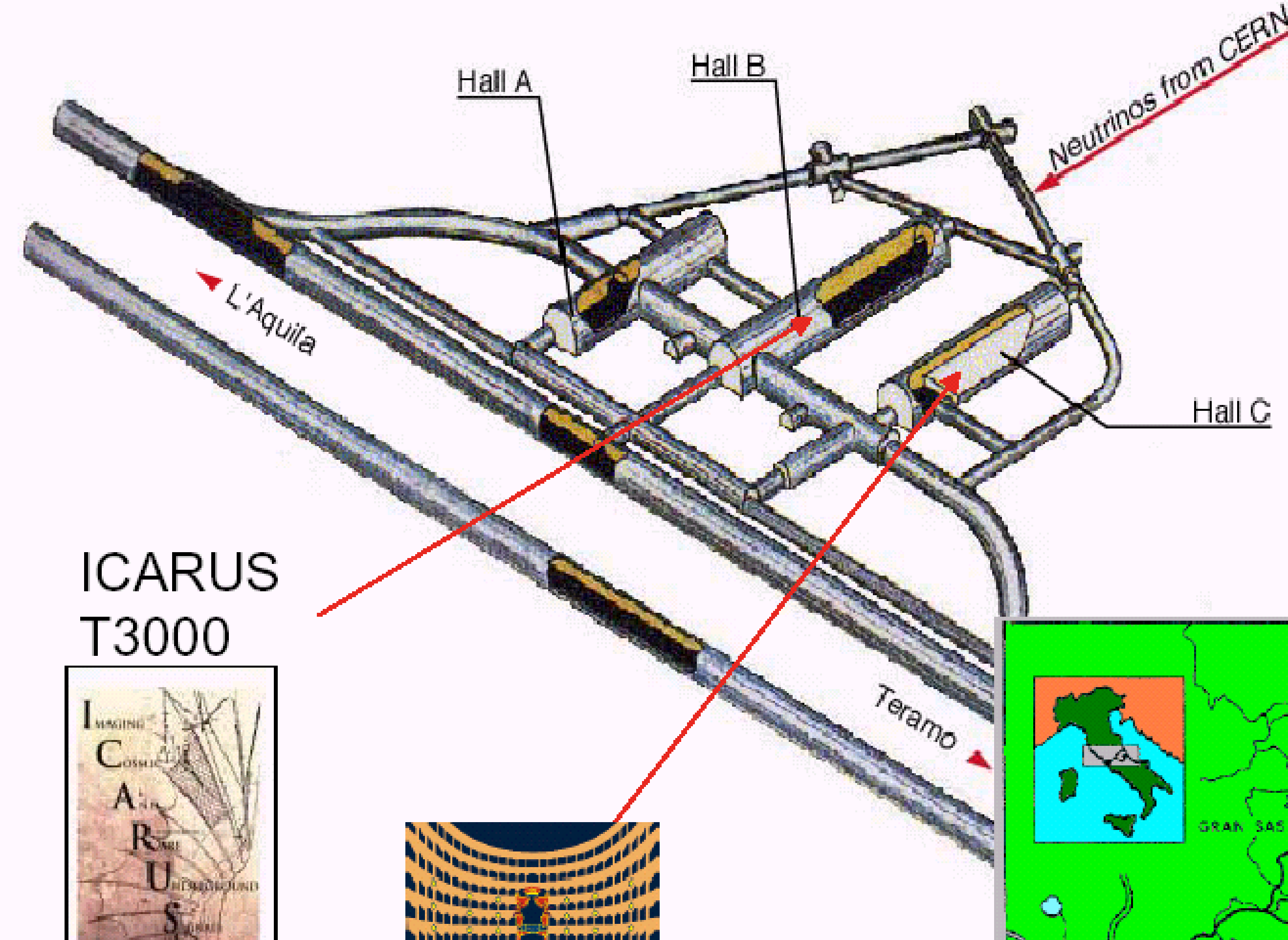
But also: ν_μ ... $\nu_e \rightarrow e^- + X$

CNGS Program Status and Physics Pot

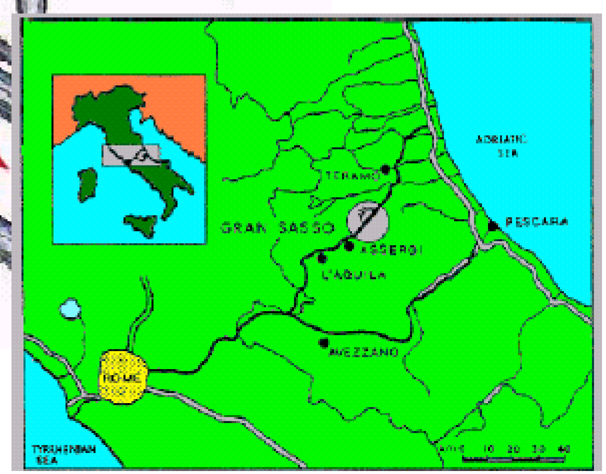
Nu2002 Munchen

S. Katsanevas

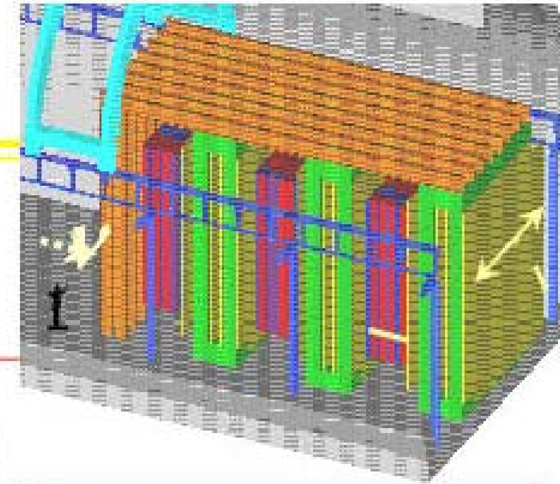
LNGS Laboratory and the 2 detectors

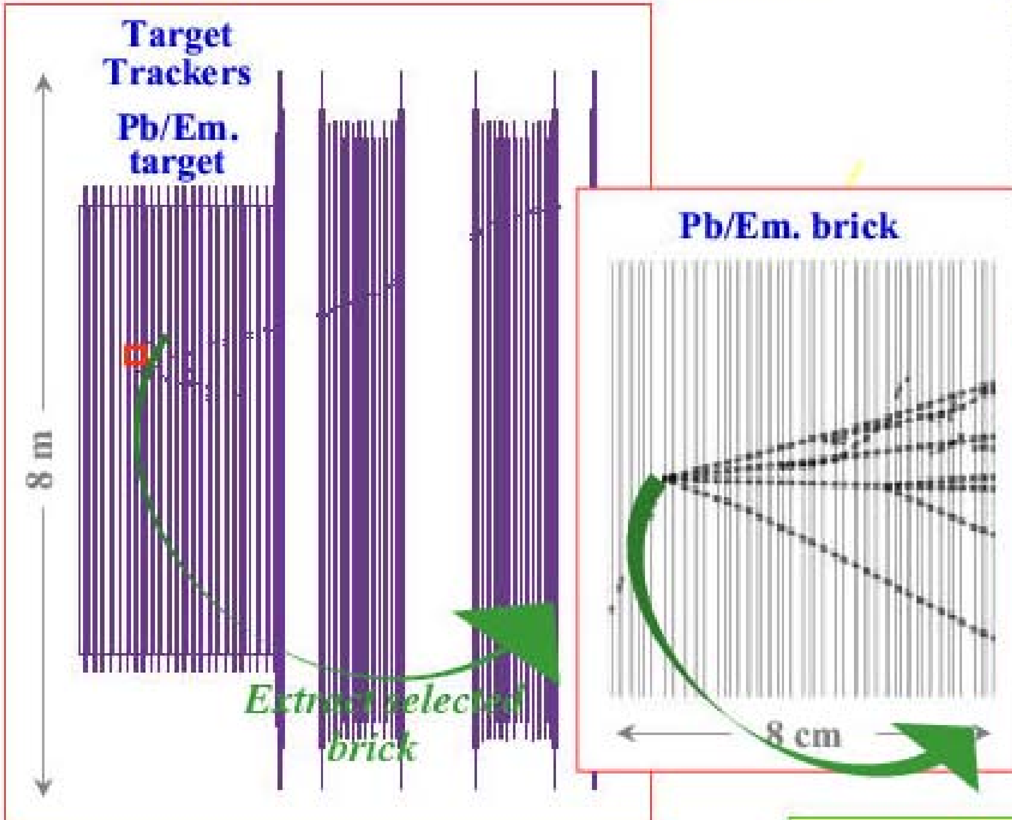


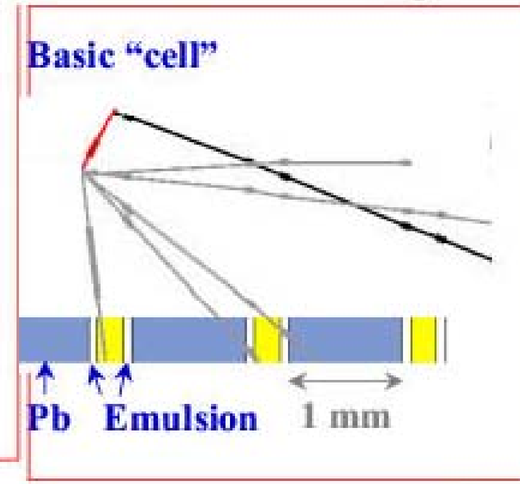
OPERA



CNGS1: OPERA a hybrid detector







Electronic detector

→ finds the brique of ν interaction

→ μ ID, charge et p

Emulsion analysis

→ vertex

→ decay kink

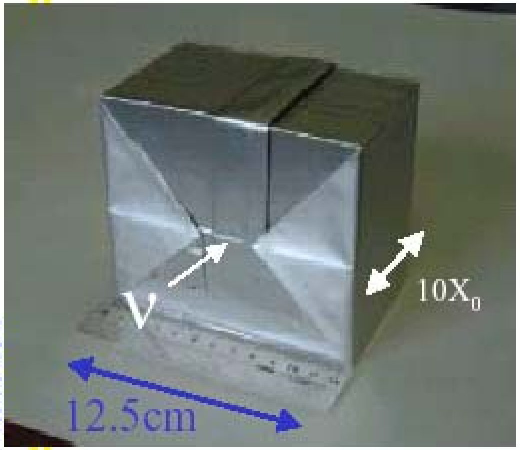
→ e/γ ID,

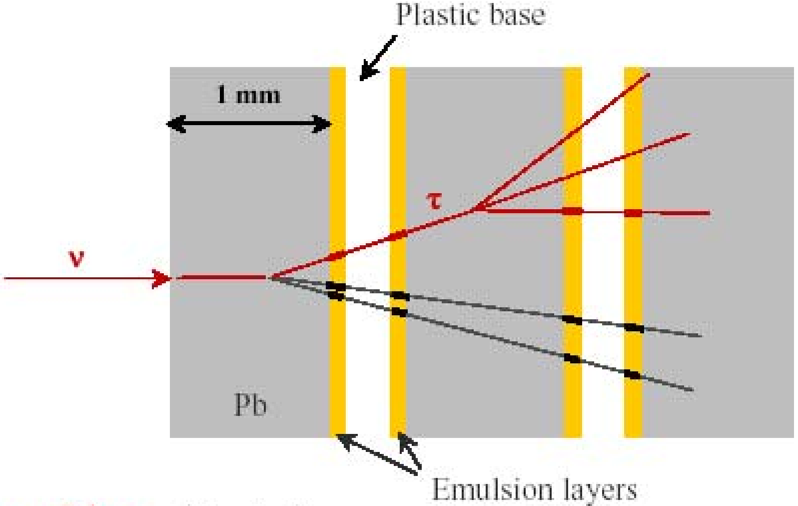
multiple scattering, kinématics

CNGS Program Status and Physics Potential
Nu2002 Munchen

S. Katsanevas

The smallest OPERA element





56 emulsion films / brick

- To the full detector:
  2 supermodules
  31 walls / supermodule
  52 x 64 bricks /wall
  200 000 bricks

S. Katsanevas

Sensitivity $\nu_\mu \rightarrow \nu_\tau$

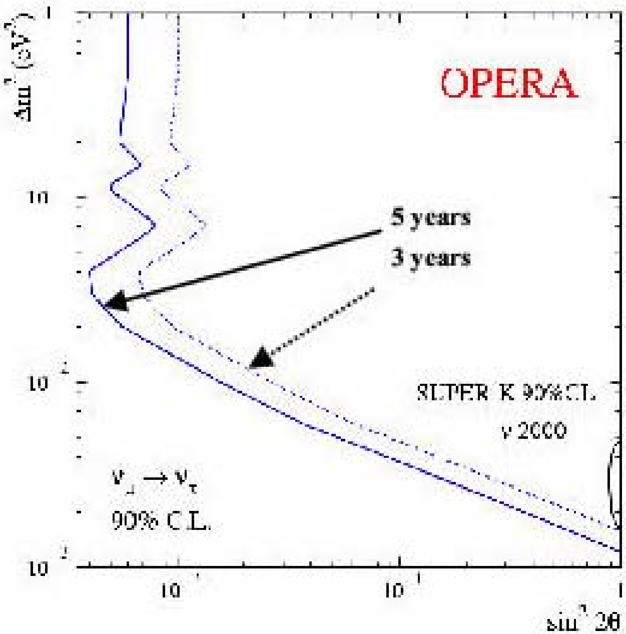
S. Katsanevas

5x1.8=9 Kt years

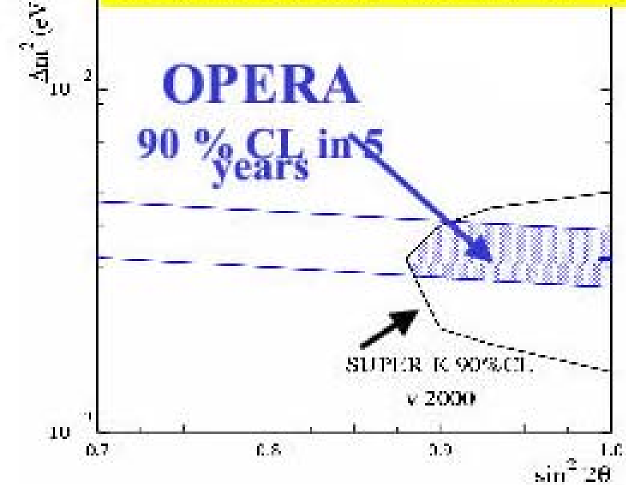
2.25 10^{20} p.o.t.

- Prob of 3σ significance for $\Delta m^2 = 2.5\ 10^{-3}\ eV^2$: ~ 99%

Decay mode	Signal 1.2*10–3	Signal 2.4*10-3	Signal 5.4*10-3	Bkgnd.
$\tau \rightarrow e$ long	0.8	3.1	15.4	0.15
$\tau \rightarrow \mu$ long	0.7	2.9	14.5	0.29
$\tau \rightarrow h$ long	0.9	3.4	16.8	0.24
$\tau \rightarrow e$ short	0.2	0.9	4.5	0.03
$\tau \rightarrow \mu$ short	0.1	0.5	2.3	0.04
Total	2.7	10.8	53.5	0.75



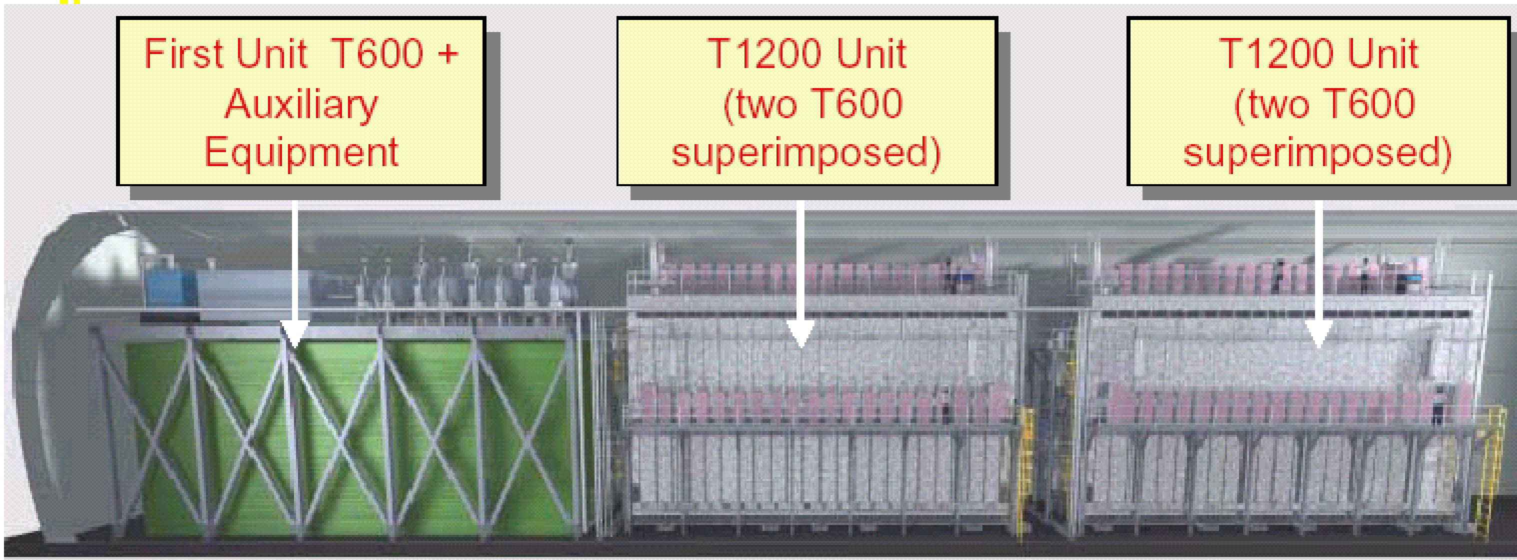
90 % CL for $\Delta m^2 \sim 2.5\ 10^{-3}\ eV^2$ ~19%



Uncertainties on background (±33%) and on efficiencies (±15%) accounted for

ICARUS T3000 (proposed)

T3000 Detector in Hall B of LNGS (cloning of T600)



Improved statistics for:

≈ 70 Metres

Future extension to additional modules

1. **Solar neutrinos**
2. **Atmospheric neutrinos**
3. **Supernova neutrinos**
4. **CERN-NGS neutrinos**
5. **Proton decay**

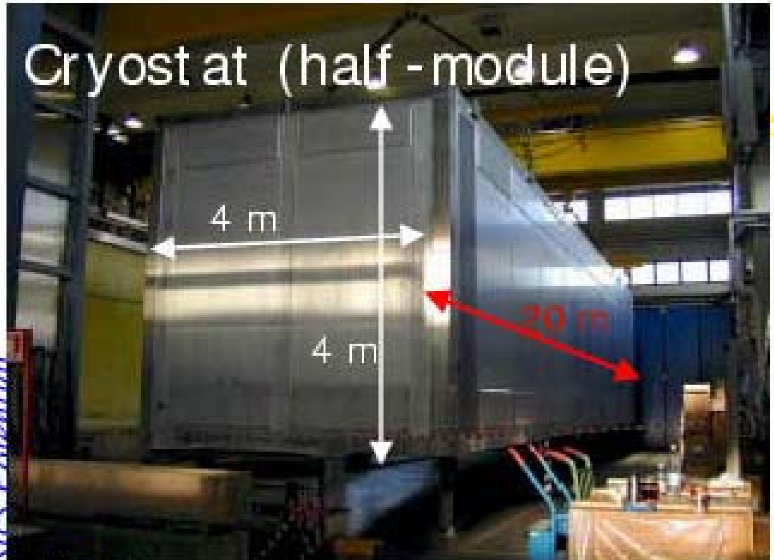
T600: installed in LNGS in 2003

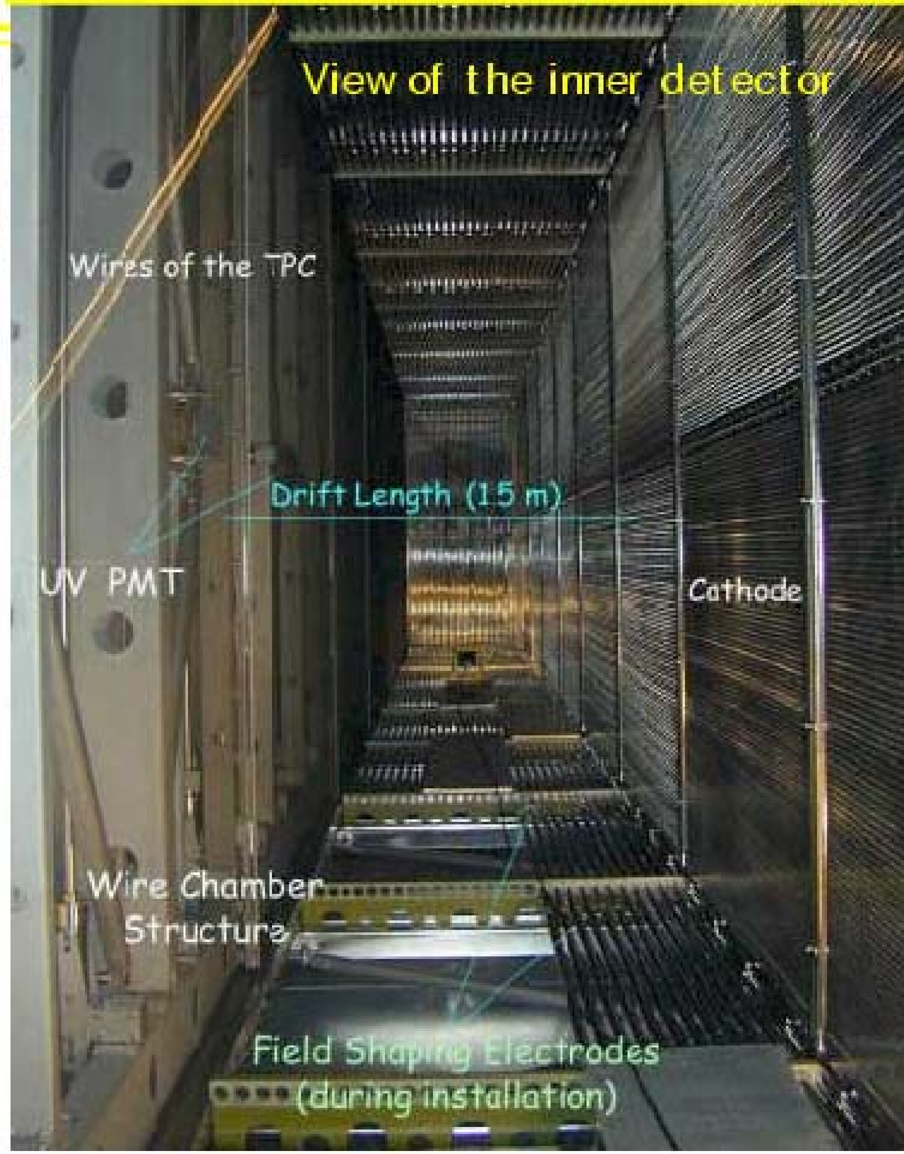
T3000: operational by summer 2006

Program Status and Physics Potential

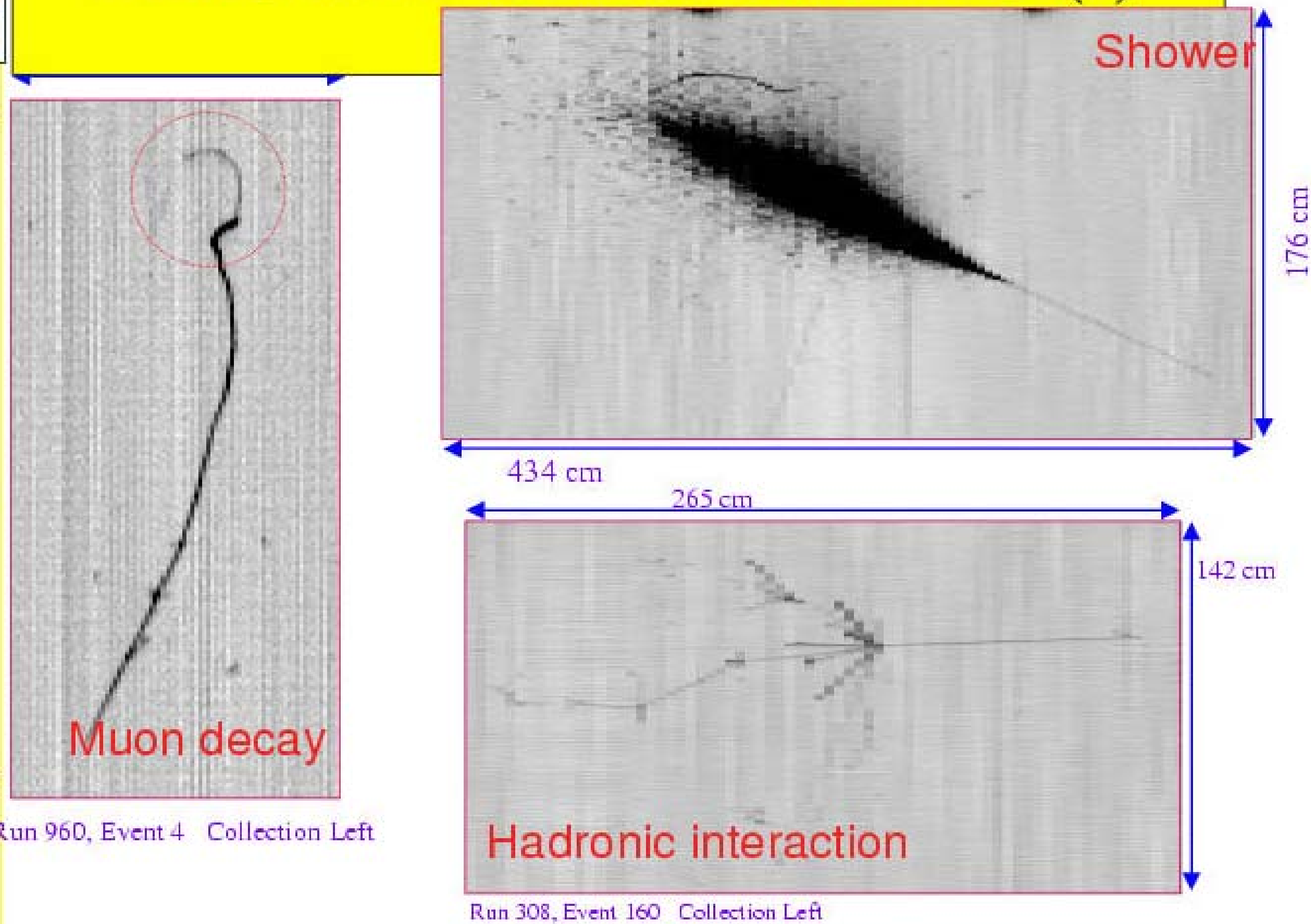
S. Katsanevas

ICARUS T300 prototype



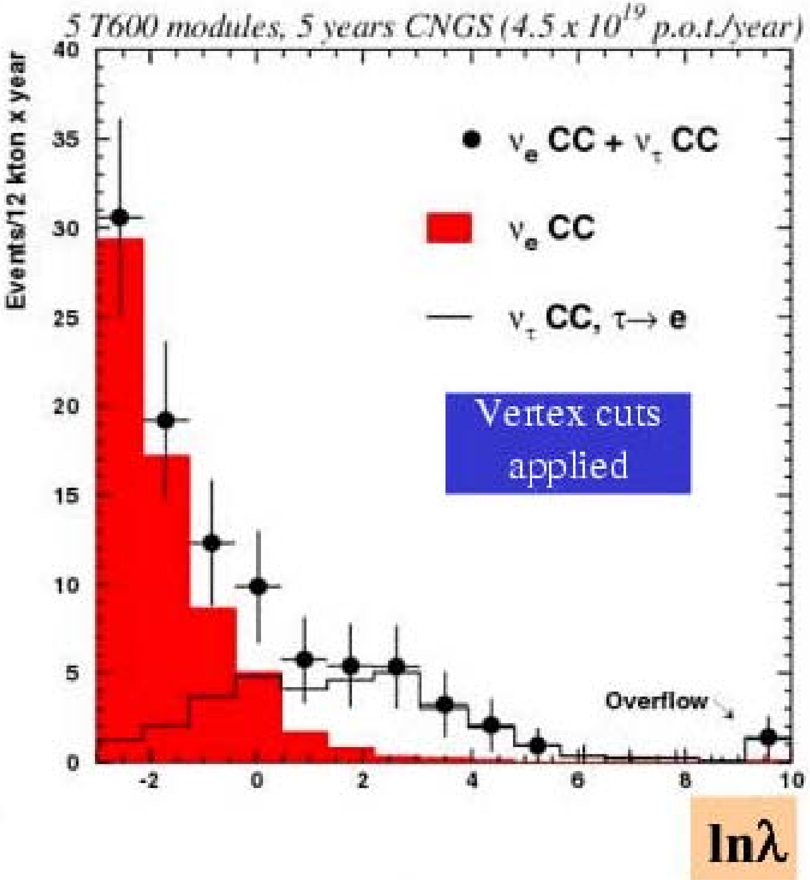


Electronic bubble chamber (I)



τ→e search: 3D likelihood

- Analysis based on 3 dimensional likelihood
  - $E_{visible}$,
  - P_T^{miss},
    $\rho_l \equiv P_T^{lep}/(P_T^{lep}+P_T^{had}+P_T^{miss})$
  - **Exploit correlation between variables**
  - Two functions built:
    - L_S ([Evisible, P_T^{miss}, ρ_l]) (signal)
    - L_B ([Evisible, P_T^{miss}, ρ_l]) (ν_e CC background)
  - Discrimination given by



$$\ln\lambda \equiv L([Evisible, P_T^{miss}, \rho_l]) = L_S / L_B$$

S. Katsanevas

$\nu_\mu \rightarrow \nu_\tau$ appearance search summary

ICARUS T3000 detector

(2.35 kton active LAr)

5 year CNGS "shared" running

(2.25 x 10^{20} p.o.t.)

τ decay mode	Signal $\Delta m^2 =$ 1.6×10^{-3} eV^2	Signal $\Delta m^2 =$ 2.5×10^{-3} eV^2	Signal $\Delta m^2 =$ 3.0×10^{-3} eV^2	Signal $\Delta m^2 =$ 4.0×10^{-3} eV^2	BG
$\tau \rightarrow e$	3.7	9	13	23	0.7
$\tau \rightarrow \rho$ DIS	0.6	1.5	2.2	3.9	< 0.1
$\tau \rightarrow \rho$ QE	0.6	1.4	2.0	3.6	< 0.1
Total	4.9	11.9	17.2	30.5	0.7

Super-Kamiokande: $1.6 < \Delta m^2 < 4.0$ at 90% C.L.

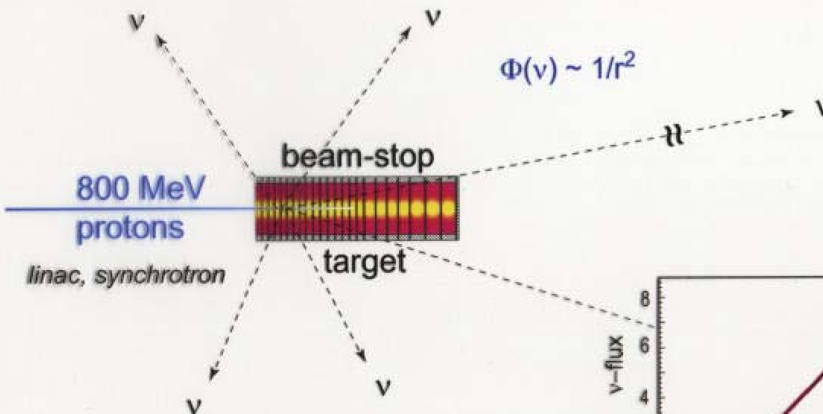
SAME SENSITIVITY AS OPERA

S. Katsanevas

Electron neutrino appearance

(LSND & KARMEN, MINIBOONE)

$\bar{\nu}_\mu$ - $\bar{\nu}_e$ Oscillation Searches at Beam Stop Sources



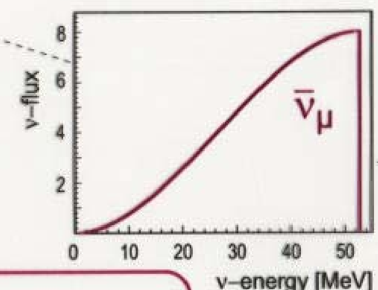
short baseline geometry

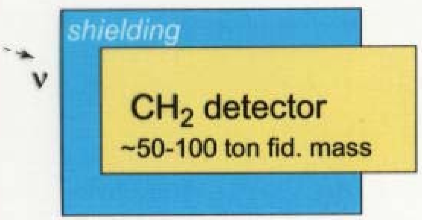
$\langle L_\nu \rangle$ = 15-30 m from target

$\langle E_\nu \rangle$ = 35 MeV

$\langle L_\nu / E_\nu \rangle \sim$ 1 m / MeV

Δm^2 scale ~ 1 eV^2





~10^{30} free protons

decay at rest (DAR)

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

analytical ν-spectra 0-53 MeV

$\xrightarrow{\text{flavour oscillation}}$ $\bar{\nu}_e + p \rightarrow e^+ + n$

inverse ß-decay off free protons: delayed coincidence signature

π^- and μ^- captured by nuclei

→ small intrinsic $\bar{\nu}_e$ contamination (few x 10^{-4})

G. Drexlin

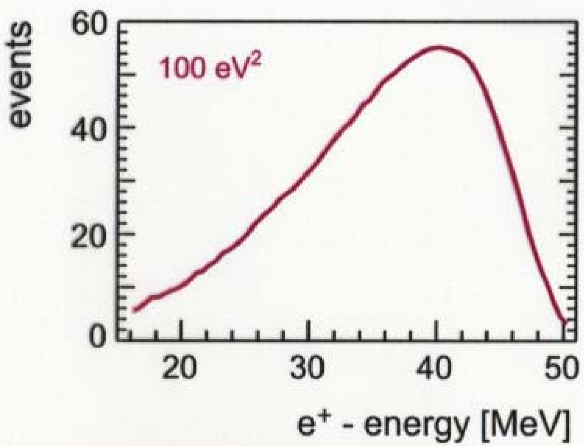
$\bar{\nu}_e$ - Appearance Searches

Oscillation Signal

$\bar{\nu}_e + p \rightarrow n + e^+$

Q = -1.8 MeV

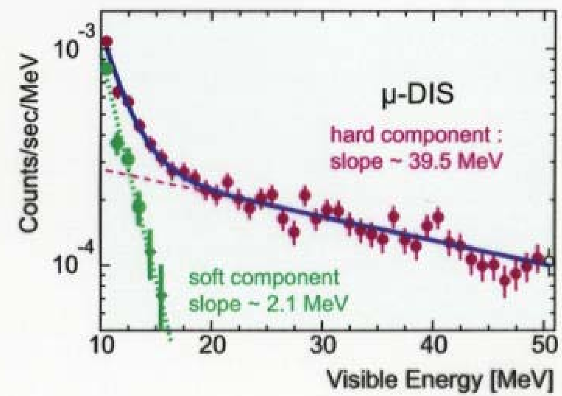
therm. & capt. → p(n,γ) 2.2 MeV, Gd(n,γ) 7.8 MeV



clear signature (del. coincidence)
point-like ν-target: excl. L/E resolution
s ~10^{-41}cm^2: expect small signal (<100evts)
extr. small contamination, small ν-bg

CR Background Source

μ-induced deep inelastic scattering
in Fe-shielding of experiment
HE- neutrons : recoil proton & n-capture γ

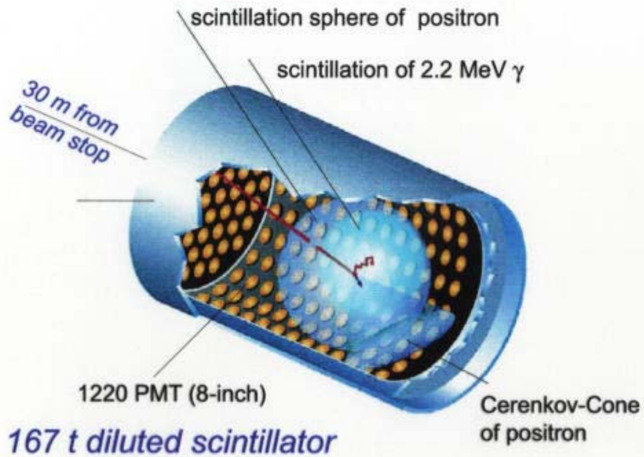


LSND:	KARMEN2:
PID for e^+ and proton	active veto of μ-DIS duty cycle

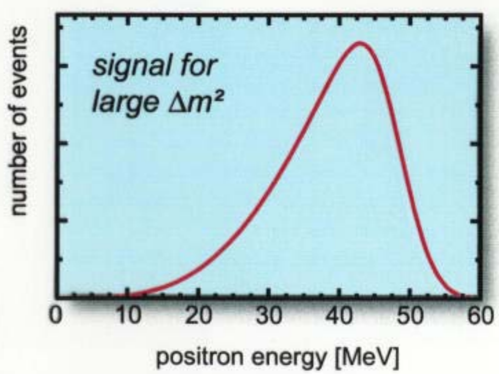
G. Drexlin

G. Drexlin

LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance search



167 t diluted scintillator



$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e + p \rightarrow e^+ + n$$

$\downarrow$ τ = 186 μs

$p(n,\gamma)d$ (2.2 MeV)

e^+ identification:

a) check veto activity
discriminate cosmic rays
b) PID: relativistic particle (Cerenk.+scint.)
discriminate neutrons, muons
c) positron energy 20(36)-60 MeV
discriminate ν-nucleus interactions

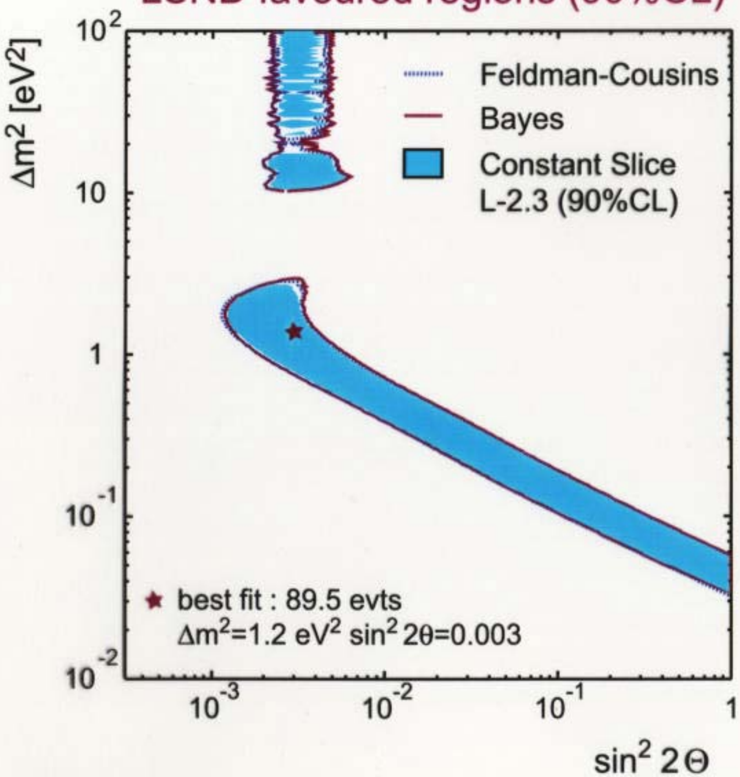
γ identification:

a) low detector threshold 1 ms after e^+
b) R-parameter distribution
Likelihood Ratio correlated/uncorrelated
use : energy / time / position correl.
discriminate accidentals

LSND event based maximum likelihood analysis

A. Aguilar et al. (LSND Collab.), Phys. Rev. **D64** (2001) 112007

LSND favoured regions (90%CL)



5697 candidate events
with 4 fit variables (3600 bins) :

- electron energy E_e
- scattering angle cos $\Theta\nu$
- distance along axis z
- likelihood ratio $R\gamma$

'combined' LSND likelihood contour for DAR *and* DIF data

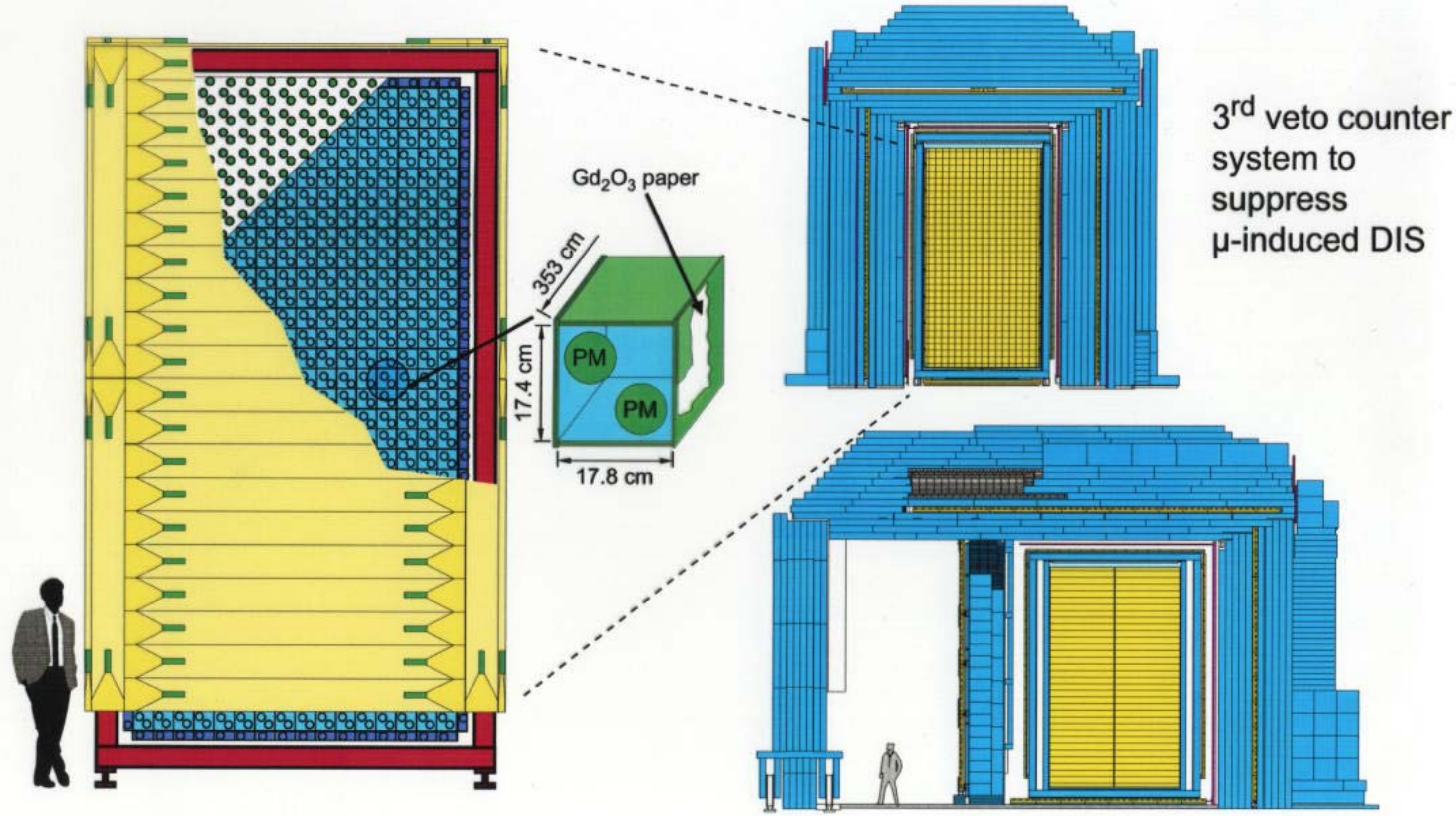
electron energy range : 20-200 MeV

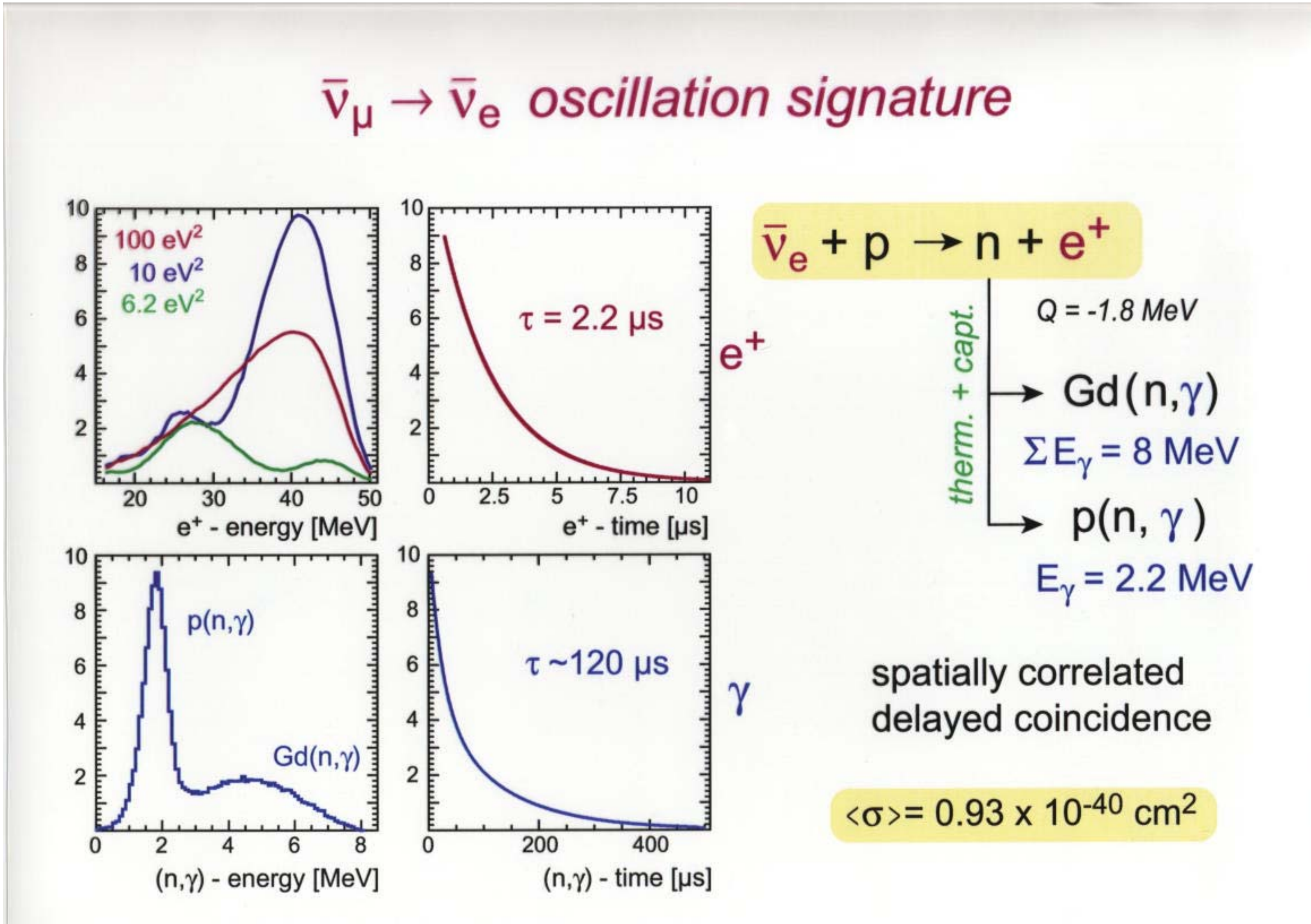
global $\bar{\nu}_\mu$ - $\bar{\nu}_e$ *and* ν_μ - ν_e analysis

G. Drexlin

KARMEN liquid scintillation calorimeter

56 to. scintillator $(5.6 \times 3.2 \times 3.5)\,m^3$ $\Delta E/E = 11.5\%/\sqrt{E(MeV)}$





$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation signature
100 eV²
10 eV²
6.2 eV²
e⁺ - energy [MeV]
τ = 2.2 μs
e⁺ - time [μs]
e⁺
p(n,γ)
Gd(n,γ)
(n,γ) - energy [MeV]
τ ~120 μs
(n,γ) - time [μs]
γ
$\bar{\nu}_e + p \rightarrow n + e^+$
Q = -1.8 MeV
therm. + capt.
Gd(n,γ)
ΣEγ = 8 MeV
p(n, γ)
Eγ = 2.2 MeV
spatially correlated
delayed coincidence
<σ>= 0.93 x 10⁻⁴⁰ cm²

G. Drexlin

Comparison of LSND and KARMEN2

	LSND (93-98)	KARMEN2 (97-01)
proton charge	28.896 C	9.425 C
beam current / pulse	1 mA / 600 μs	200 μA / 0.5 μs
neutrino flux	$1.2 \times 10^{22}\ \bar{\nu}_\mu$	$2.71 \times 10^{21}\ \bar{\nu}_\mu$
intrinsic $\bar{\nu}_e$ contam.	$\sim 8 \times 10^{-4}$	6.4×10^{-4}
detector distance	30 m	17.6 m
fid. detector mass	85 to.	50 to.
bg-suppression	PID (R_γ -likelihood)	duty cycle, veto μ-DIS
osc. detect. efficiency	0.42 ± 0.03	0.192 ± 0.015
max. mixing signal	16.650 evts	2.913 evts
bg-expectation	5.474 evts	15.8 evts
beam-on signal	5.697 evts	15 evts

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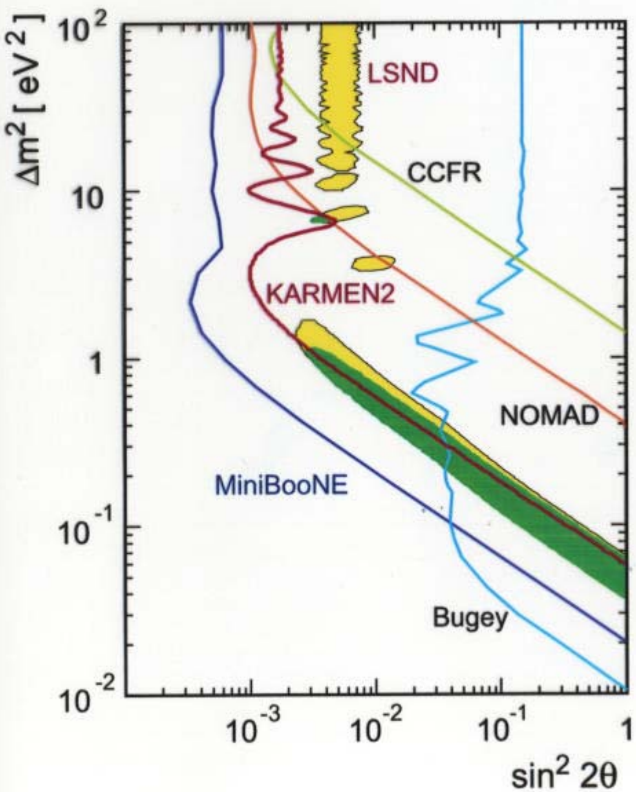
Conclusions

final oscillation results from LSND and KARMEN2 published
and compatibility analysis submitted for publication



LSND (1993-98)

combined DAR & DIF analysis (new reconstr.)
$87.9 \pm 22.4 \pm 6.0$ *beam excess* events
$P = (0.264 \pm 0.067 \pm 0.045)\%$

KARMEN2 (1997-01)

final DAR oscillation analysis 4y of data
15 evts. ↔ (15.8 ± 0.5) bg expect. *no excess*
$\sin^2 2\theta < 1.7 \times 10^{-3}$, most stringent limit so far

LSND & KARMEN2

detailed statistical analysis using full inform.
incompatibility at individual 60% Confid. Levels
areas of stat. compatibility only at $\Delta m^2 < 1$ eV^2
LF-number violating μ-decays excluded

LSND vs. KARMEN (waiting for MiniBooNE)

4f neutrino oscillations

If LSND is right $\Rightarrow$ 3 different Δm^2 necessary:

$$\Delta m^2_{\odot}, \quad \Delta m^2_{\mathrm{atm}}, \quad \Delta m^2_{\mathrm{LSND}}$$

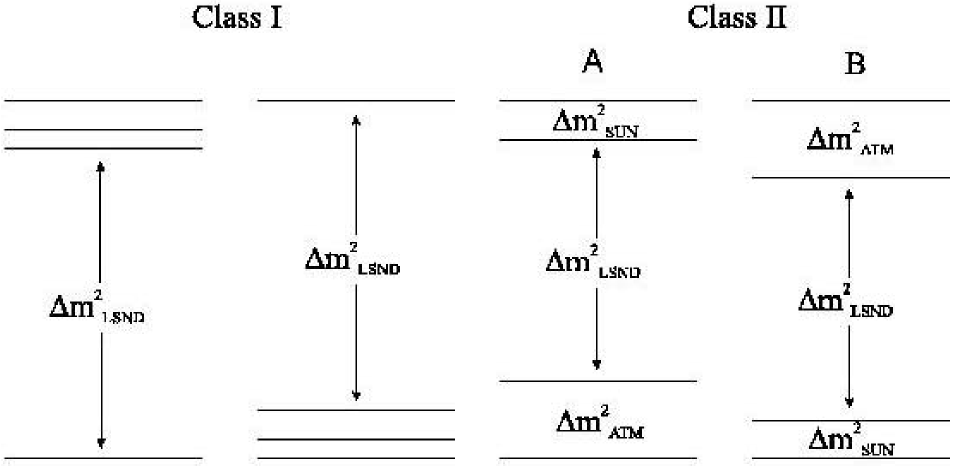
$\Rightarrow$ 4 light neutrino species: $\nu_e, \ \nu_\mu, \ \nu_\tau, \ \nu_s$

(An alternative: strong CPT violation in neutrino sector, $(\Delta m^2)_{\nu\nu} \neq (\Delta m^2)_{\overline{\nu}\overline{\nu}}$ – Murayama & Yanagida, 2000; Barenboim, Borissov, Lykken & Smirnov, 2001; Barenboim, Beacom, Borissov & Kayser, 2002)

4 flavours $\Rightarrow$ 6 mixing angles θ_{ij}, 3 Dirac-type $\not{CP}$ phases

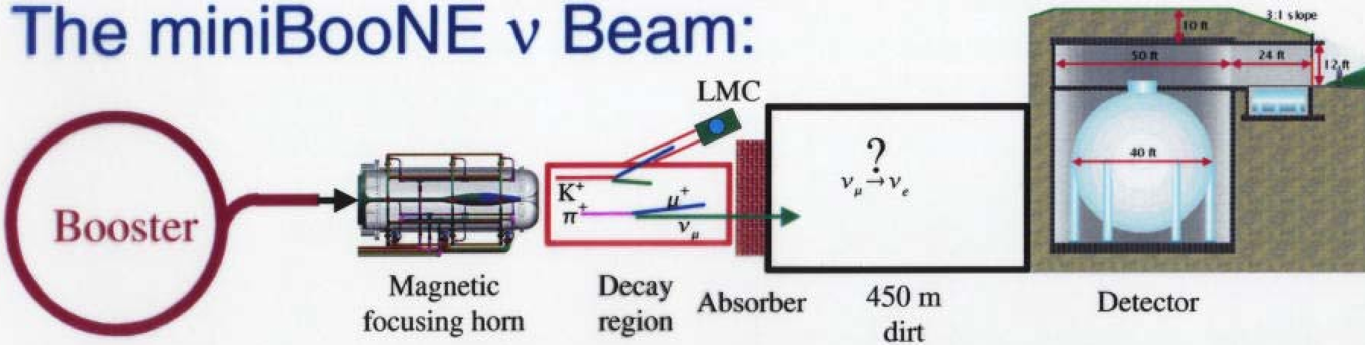
A simplification: Only 2 classes of 4f schemes can fit the data,

(3+1) and (2+2)



– E. Akhmedov ν2002 –

The miniBooNE ν Beam:

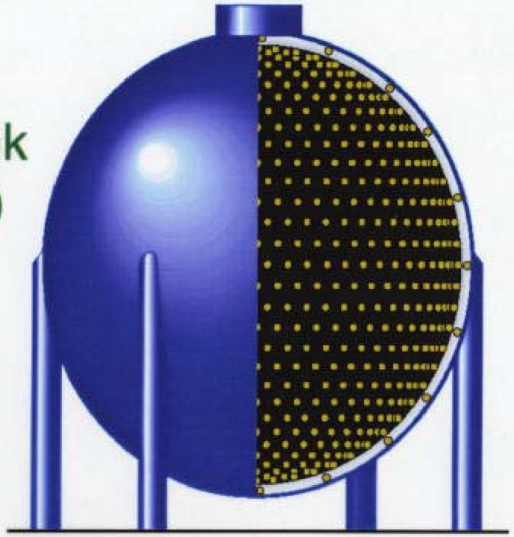


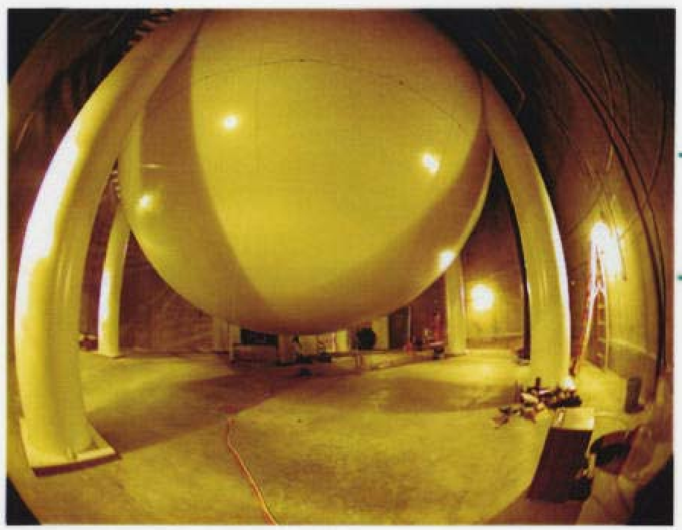
- 8 GeV protons from the FNAL booster...
- on a Be target, produce π^+ ...
- π^+ are focused via the neutrino "horn"...
- π^+ decay ($\pi^+ \rightarrow \mu\nu_\mu$) in 50m pipe...
- yielding intense source of ν_μ

R. Tayloe

The miniBooNE ν Detector:

- 12 meter (40') diameter spherical tank
- 807 tons (250kgal, 445 tons fiducial) of mineral oil
- Optically isolated inner region lined with 1280 8" PMTs (10% coverage)





- Veto region with 240 PMTs
- Extensive calibration system: laser flasks, muon tracker, stopping muon cubes

R. Tayloe

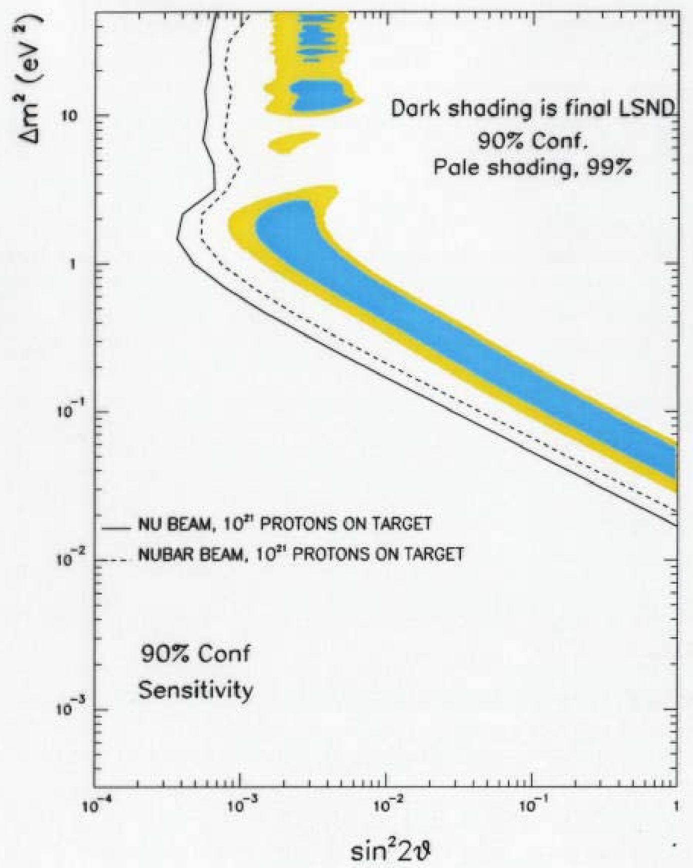
miniBooNE Expected Signal:

In 2 years
(10^{21} protons on target):

- miniBooNE will confirm or refute the LSND signal

and then...
-Antineutrino running...

and then if a signal is confirmed..
-2nd detector



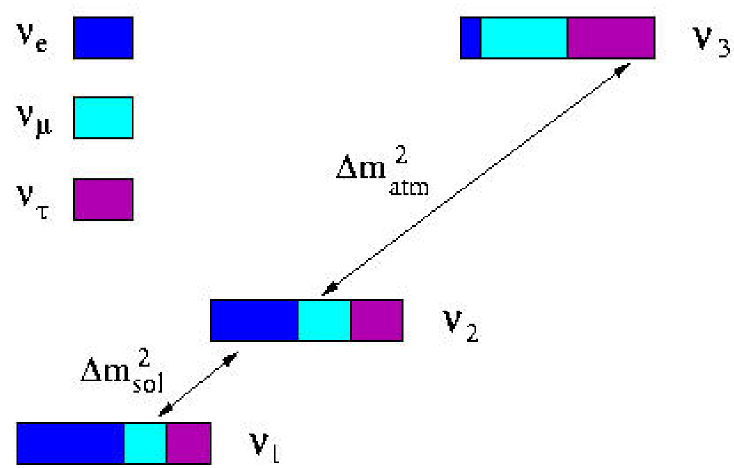
R. Tayloe

Searches for subleading electron neutrino appearance

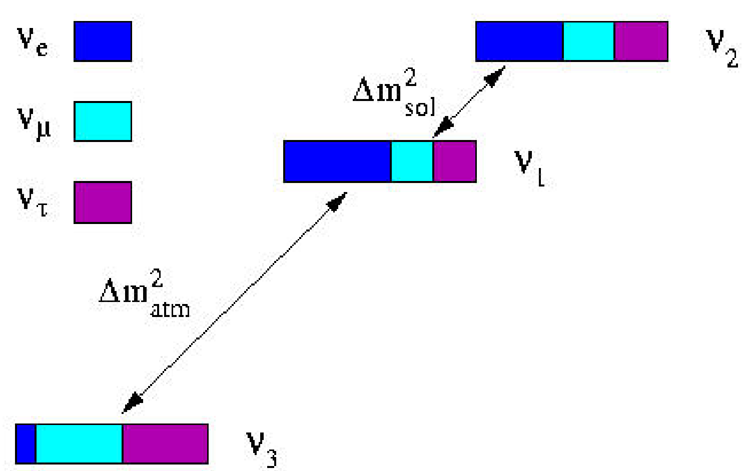
Precision measurements of

3ν-oscillations

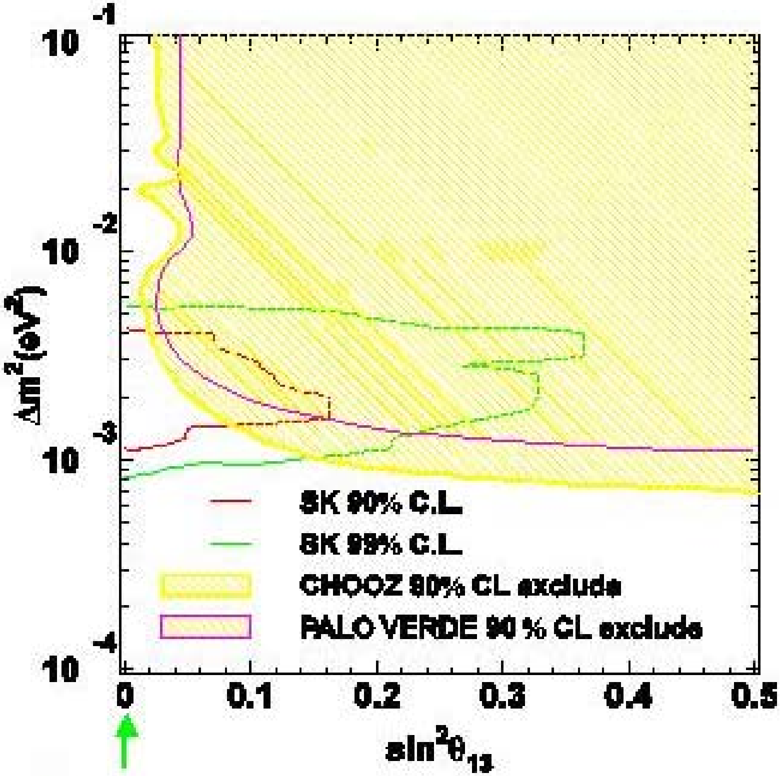
Normal hierarchy:



Inverted hierarchy:

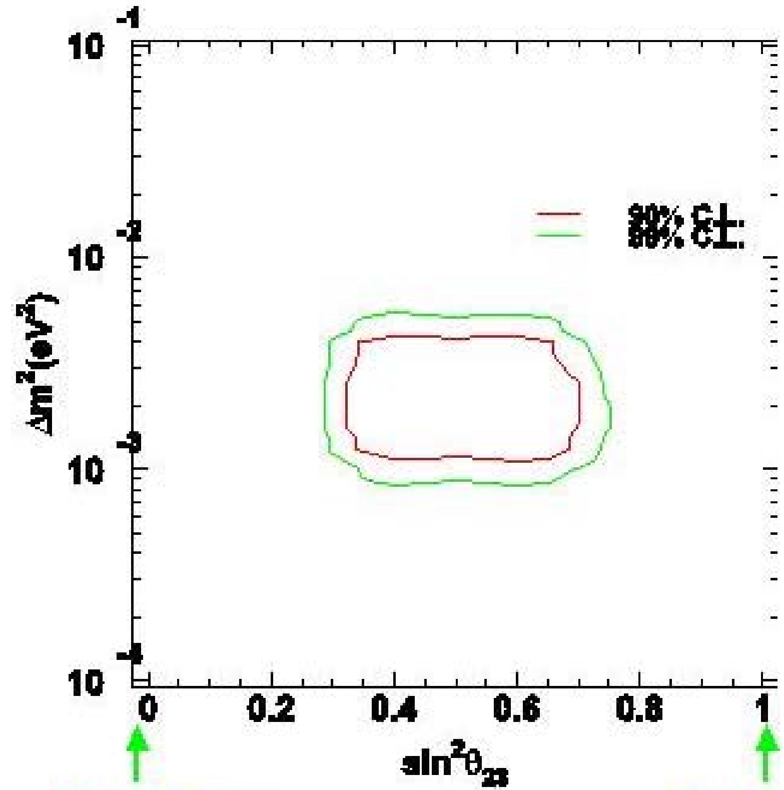


Allowed region for active 3-flavor oscillations



Pure $\nu_\mu \leftrightarrow \nu_\tau$

getting close to CHOOZ's limit on θ_{13}



Pure $\nu_e \leftrightarrow \nu_\tau$

Pure $\nu_e \leftrightarrow \nu_\mu$

consistent with CHOOZ's excluded region

3f effects in atmospheric neutrino oscillations

(1) Dominant channel $\nu_\mu \leftrightarrow \nu_\tau$

In 2f case – no matter effects (neglecting tiny $V_{\mu\tau}$ caused by rad. corrections). Independent from the sign of Δm^2_{31} (direct vs inverted hierarchy). In 3f case – weak sensitivity to matter effects, sign of Δm^2_{31}

(2) Subdominant channels $\nu_e \leftrightarrow \nu_{\mu,\tau}$

Contribution to μ – like events: subleading, difficult to observe
In 2f limits – suppression of oscillation effects on e-like events:

- $\Delta m^2_{21} \to 0$ (E.A., Dighe, Lipari & Smirnov, 1998) :

$$\frac{F_e - F_e^0}{F_e^0} = \tilde{P}_2(\Delta m^2_{31},\, \theta_{13}, V_{\rm CC}) \cdot (r\, s^2_{23} - 1)$$

- $s_{13} \to 0$ (Peres & Smirnov, 1999):

$$\frac{F_e - F_e^0}{F_e^0} = \tilde{P}_2(\Delta m^2_{21},\, \theta_{12}, V_{\rm CC}) \cdot (r\, c^2_{23} - 1)$$

At low energies $r \equiv F^0_\mu / F^0_e \simeq 2$; also $s^2_{23} \simeq c^2_{23} \simeq 1/2$ – a conspiracy to hide oscillation effects on e-like events! Results from a peculiar flavour composition of the atmospheric ν flux.

The Importance of θ_{13}

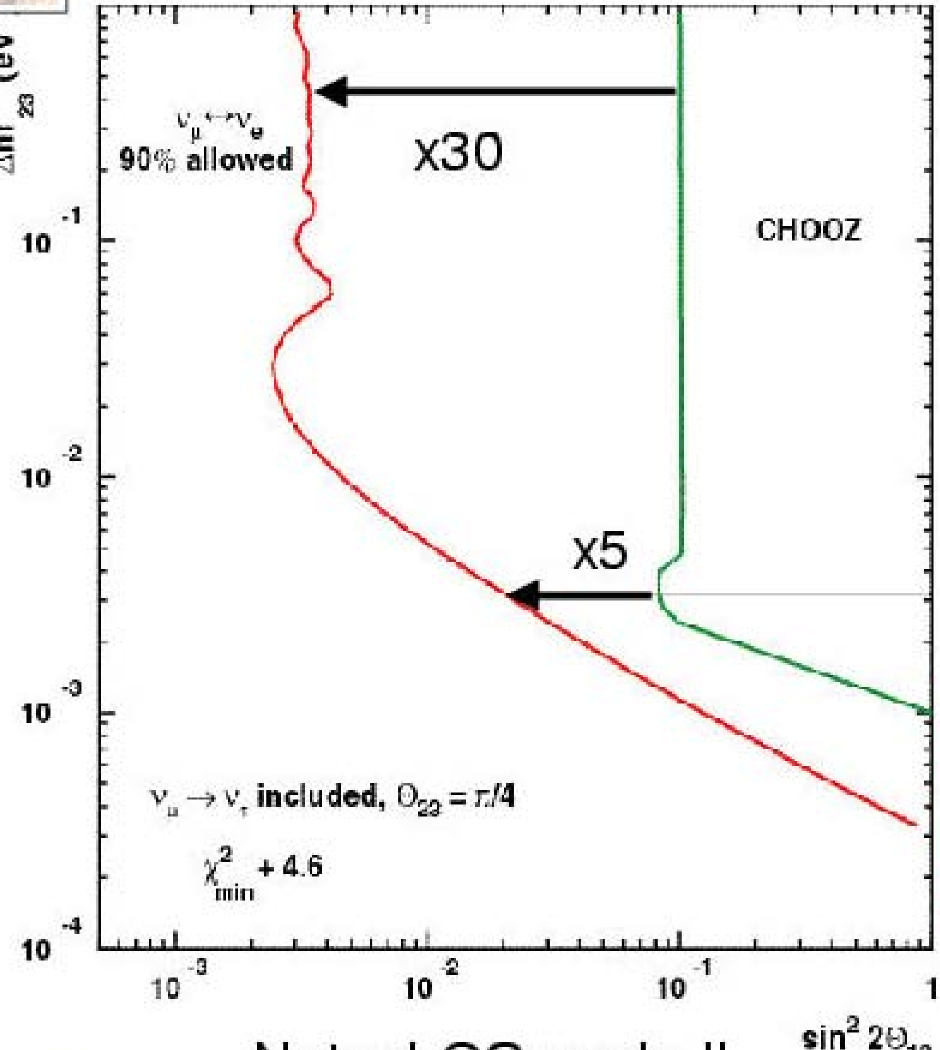
CHOOZ $\Rightarrow$ θ_{13} is small: $\sin^2 2\theta_{13} < 0.1$

All effects in the $\nu_e \to \nu_\mu$-transition depend crucially on θ_{13} :

- the total transition rate
- matter effects
- the effects due to the sign of Δm^2_{31}
- CP violating effects

The size of θ_{13} determines if these effects can be studied

Expected sensitivity to θ_{13}



Note: LOG-scale !!

ICARUS
5 years dedicated SPS
2.35 kton fid. mass

Sensitivity assuming both $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_e$ at the same Δm^2 (three family mixing)

$$\sin^2 2\theta_{13} > 2 \times 10^{-2}$$
$$for\ \ \Delta m^2_{32} = 3 \times 10^{-3} eV^2$$

Θ_{13} limit from 9 to 5^0

$N \geq 2$ with CP and Matter Effects

Precision: $N = 2$ description insufficient $\Rightarrow$ modifications

- $2 \to 3$ neutrino framework $\Rightarrow$ more parameters & CP effects
- MSW: parameter mapping in matter

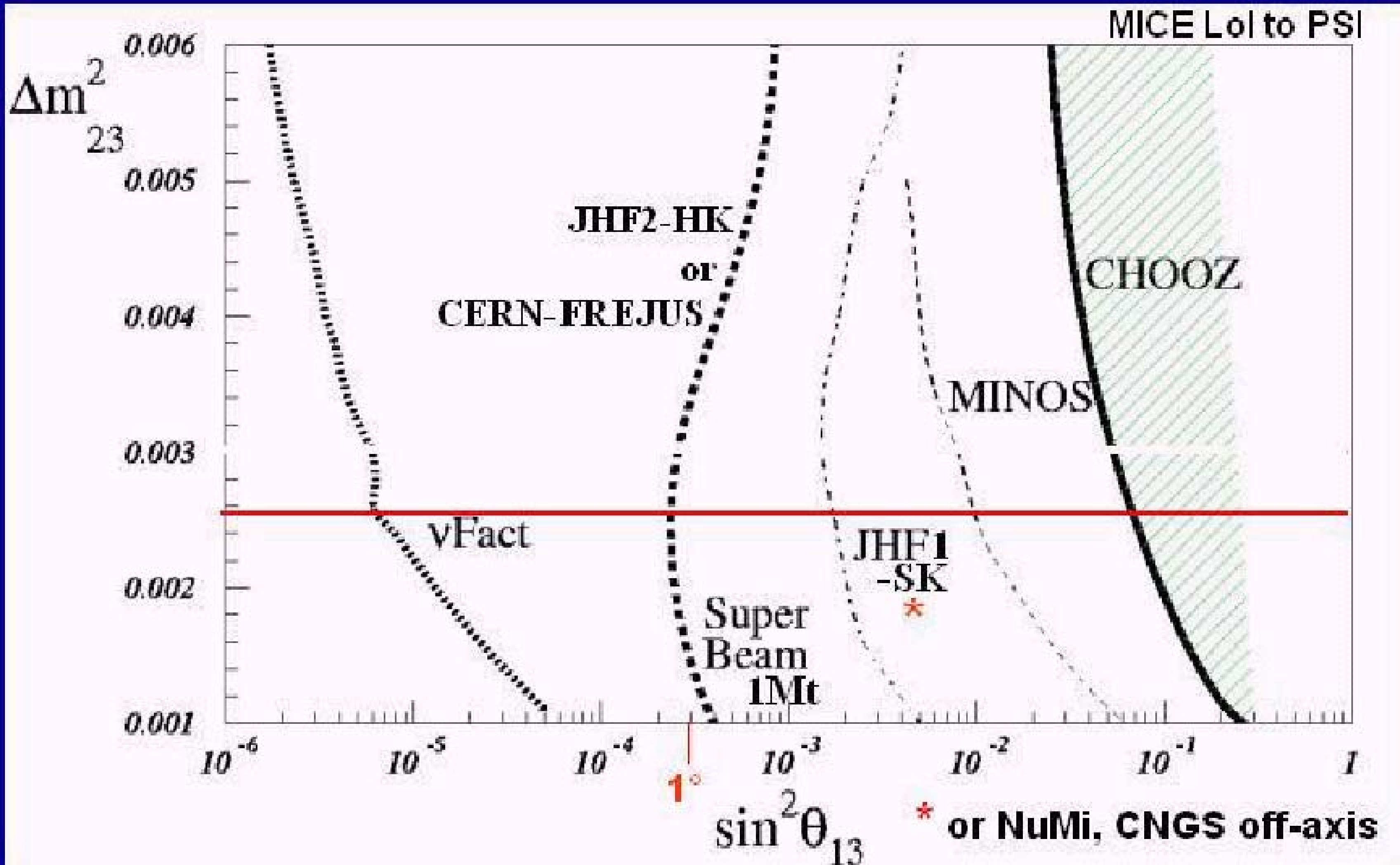
$$\Rightarrow \quad P(\nu_{e_l} \to \nu_{e_m}) = \underbrace{\delta_{lm} - 4 \sum_{i>j} \mathrm{Re} J_{ij}^{e_l e_m} \sin^2 \Delta_{ij}}_{P_{CP}} \underbrace{-2 \sum_{i>j} \mathrm{Im} J_{ij}^{e_l e_m} \sin 2\Delta_{ij}}_{P_{\not{CP}}}$$

Shorthands: $J_{ij}^{e_l e_m} := U_{li} U_{lj}^* U_{mi}^* U_{mj} \qquad \Delta_{ij} := \frac{\Delta m_{ij}^2 L}{4E}$

Neutrinos: $P(\nu_{e_l} \to \nu_{e_m}) = P_{CP} + P_{\not{CP}}$

Antineutrinos: $P(\overline{\nu}_{e_l} \to \overline{\nu}_{e_m}) = P_{CP} - P_{\not{CP}}$

$\Rightarrow$ **e.g. CP Asymmetries:** $\mathrm{a}^{\mathrm{CP}} := \frac{\mathrm{P}(\nu_{e_l} \to \nu_{e_m}) - \mathrm{P}(\overline{\nu}_{e_l} \to \overline{\nu}_{e_m})}{\mathrm{P}(\nu_{e_l} \to \nu_{e_m}) + \mathrm{P}(\overline{\nu}_{e_l} \to \overline{\nu}_{e_m})} = \frac{P_{\not{CP}}}{P_{CP}}$



year: 2020 2015 2009 2007

G€: 2 1.0 0.2

ν Oscillations: a personal view

- Neutrinos bring NEW physics:
  evidences for neutrino masses and mixing
- Broad experimental programme planned to
  - cross-check the results
  - measure the oscillation parameters
- Very promising future for LBL experiments
  - precise masses and mixings
  - CP violation
  - NSI, FCNC, CPT, ...

Neutrino masses

See-saw mechanism

Gell-Mann, Ramond, Slansky and Yanagida ; Mohapatra and Senjanovic, Schechter and Valle,…

Diracmatrix

$$\begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_{LR} \\ m_{LR}^T & M_{RR} \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

Heavy Majorana matrix

Light Majorana matrix

Diagonalise $\rightarrow m_{LL} \overline{\nu}_L \nu_L^c$

$$m_{LL} = m_{LR} M_{RR}^{-1} m_{LR}^T$$

L is violated by right-handed Majorana mass. L may be global or a part of gauged B-L which is spontaneously broken.

The goal is to reproduce a successful light Majorana matrix

Successful leading order Majorana matrices

Barbieri,Hall,Smith,Strumia,Weiner;Altarelli,Feruglio;many others…

	Type A (zero in 11)	Type B (non-zero 11)
Hierarchy $m_1^2; m_2^2$ ü m_3^2	$m_{LL}^{HI} \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix} \frac{m}{2}$	Large neutrinoless double beta decay
Inverted hierarchy m_1^2 ù m_2^2 ý m_3^2	$m_{LL}^{IH(A)} \approx \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \frac{m}{\sqrt{2}}$	$m_{LL}^{IH(B)} \approx \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/2 & 1/2 \\ 0 & 1/2 & 1/2 \end{pmatrix} m$
Degenerate m_1^2 ù m_2^2 ù m_3^2	$m_{LL}^{DEG(A)} \approx \begin{pmatrix} 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{2} & \frac{1}{2} \end{pmatrix} m$	$m_{LL}^{DEG(B1)} \approx \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} m$ $m_{LL}^{DEG(B2)} \approx \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} m$

Pseudo-Dirac

Which Majorana matrix do we shoot for?

Ultimately an experimental question:

- Neutrinoless double beta decay resolves type A from B.
- Neutrino factory can resolve "normal" from "inverted".
- Galaxy structure can constrain "degenerate" mass scale.

In the meantime we have two guiding theoretical principles:

I. Naturalness – want to avoid fine-tuning and produce a light Majorana matrix that is stable under quantum corrections

II. Symmetry - SUSY, GUTs and Family Symmetry are elements of realistic models of quark and lepton masses and mixing angles

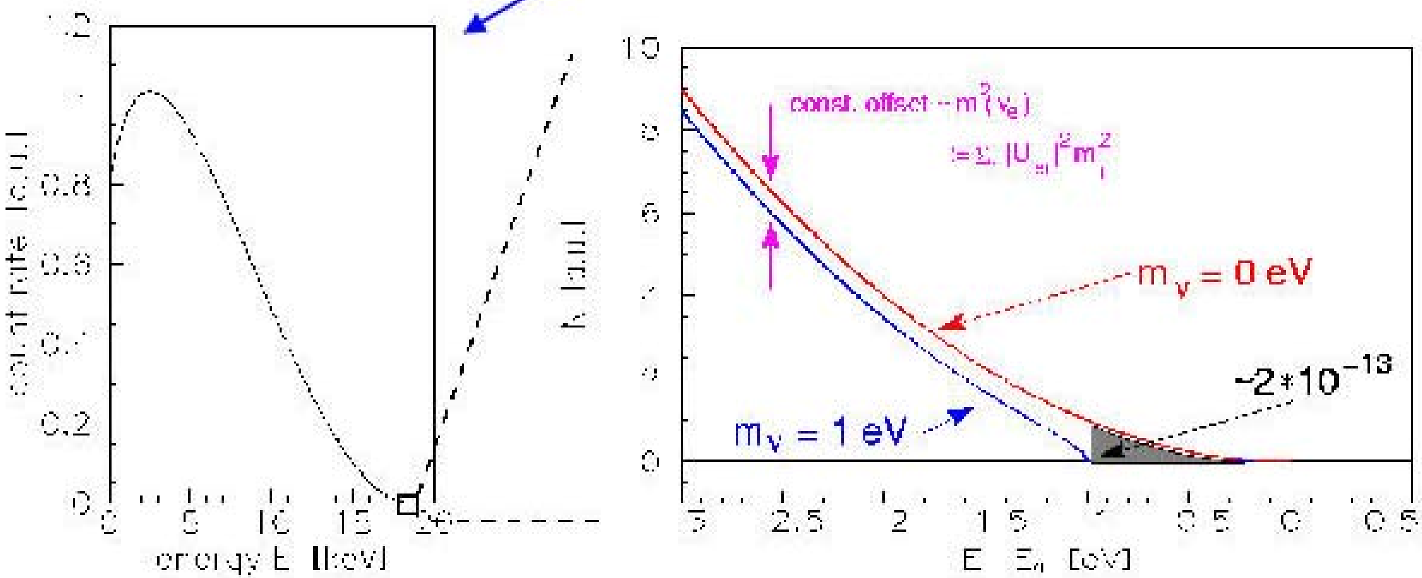
Direct measurement of $m(\nu_e)$

Tritium β decay: $^3H \rightarrow {}^3He^+ + e^- + \bar{\nu}_e$

super–allowed

$E_0 = 18.6$ keV

$t_{1/2} = 12.3$ a

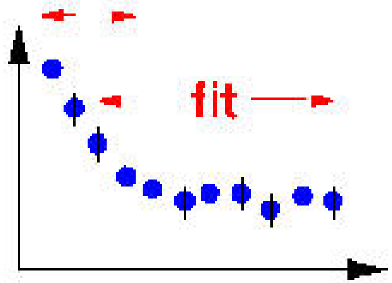


Need very high energy resolution &
very high signal rate &
very low background

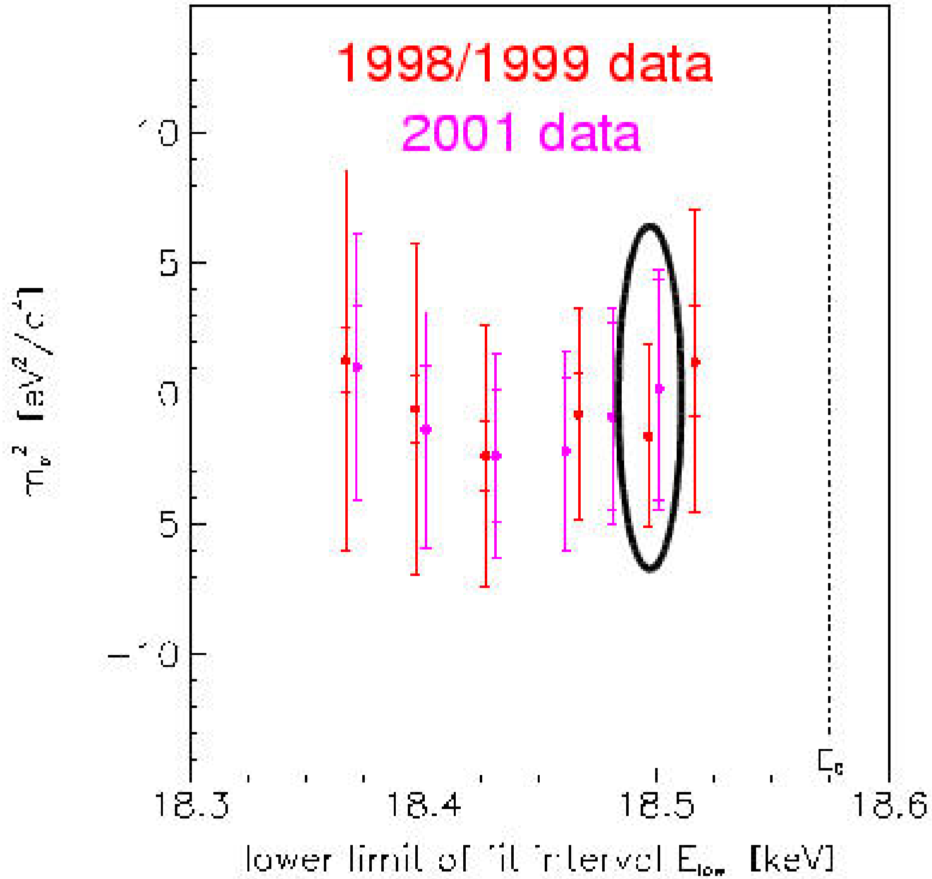
C. Weinheimer

C. Weinheimer

Results of 1998/1999, 2001 data



(see poster E2)



1998/1999:	$m^2(\nu) = -1.6 \pm 2.5 \pm 2.1$ eV^2	$\Rightarrow$	$m(\nu) < 2.2$ eV (95% C.L.)
2001:	$m^2(\nu) = +0.1 \pm 4.2 \pm 2.0$ eV^2		
1998/1999/2001:	$m^2(\nu) = -1.2 \pm 2.2 \pm 2.1$ eV^2	$\Rightarrow$	$m(\nu) < 2.2$ eV (95% C.L.)

$\Rightarrow$ **Mainz sensitivity limit reached, final analysis of all Mainz data soon**

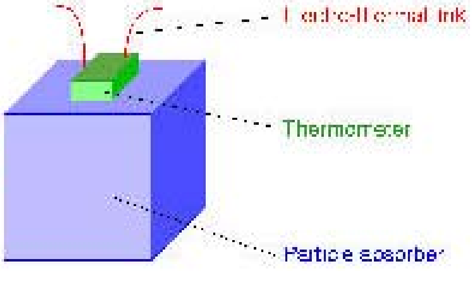
Cryogenic Bolometer Rhenium Experiments

Multi–purpose, scalable new detector technology

Basic idea: β emitting crystal = cryodetector

⇒ single final state: excitation by excited electronic states and inelastic scattering is collected

free choice of β emitter: ^{187}Re: E_0 = 2.5keV ($t_{1/2} = 5\ 10^{10}$y)



Current experiments:

MANU2 (F. Gatti et al., Genova)

– Re metallic crystal (1.5 mg)

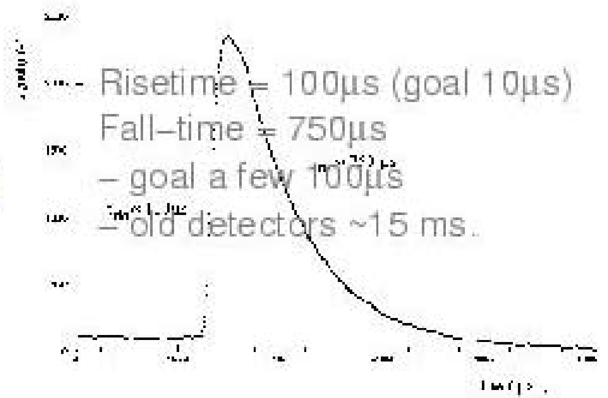
– BEFS measured (F.Gatti et al., Nature 397 (1999) 137)

– Sensitivity:

current: m(ν) < 26 eV

near future: sensitivity of 10 eV expected

future: eV resolution by s.c. sensors



Risetime = 100µs (goal 10µs)

Fall–time = 750µs

– goal a few 100µs

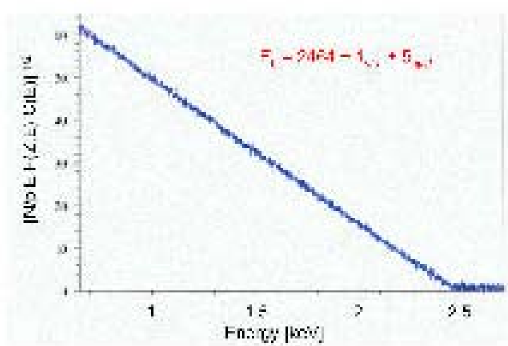
– old detectors ~15 ms

MiBeta (E. Fiorini et al., Milano,Como)

– $AgReO_4$ (250 –350 µg)

– Sensitivity: similar to MANU2

(see poster E4)



C. Weinheimer

Which way to sub–eV neutrino masses?

Neutrinos of galactic supernova (s. talk by J. Beacom)

- galactic SN only every 40 years
- not sensitive below 1eV (uncertainty in time spectrum of neutrino emission)

Large scale structure (s. talk by S. Hannestad)

- model depedent
- neutrino mass from lab can serve as input for astrophysics

complementary

Search for $0\nu\beta\beta$ (s. talk by O. Cremonesi)

Direct neutrino mass determination

- **^{187}Re β decay with cryogenic bolometers**
- **Tritium β decay with electrostatic deflector (UTA–exp.)**
- **Tritium β decay with MAC–E–Filter**
  - first MAC–E–Filters (Mainz/Troitsk) are very successful
  - no material in beam line, no tails of resolution function
  - quasi „single final state“ experiment
  - also: not–integrating MAC–E–TOF mode

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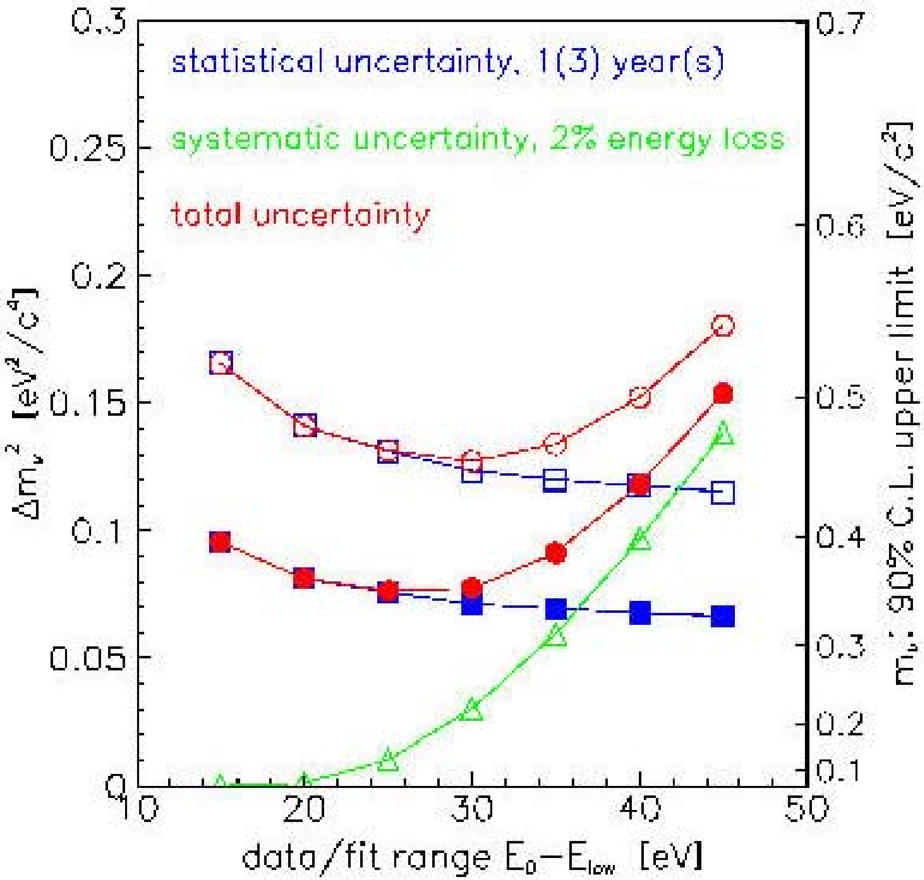
Estimation of sensitivity



energy resolution: 1eV
source area: 29 cm²
gaseous source column density: 5 10¹⁷/cm²
max accepted starting angle: 51°
background rate: 11 mHz

First simulations with conservative assumptions

C. Weinheimer

⇒ Sensitivity on $m(\nu_e)$ $\approx 0.35 eV/c^2$

Double Beta Decay

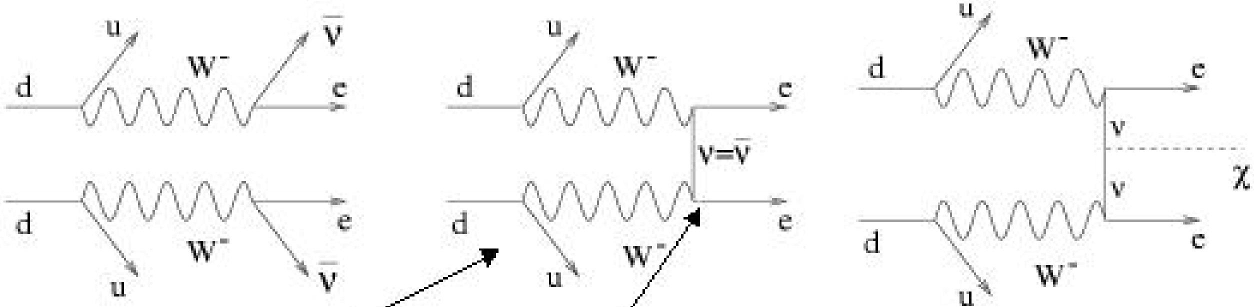
Three main decay modes

a) DBD2ν: $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e$

b) DBD0ν : $(A,Z) \rightarrow (A,Z+2) + 2e^-$

c) DBDχ: $(A,Z) \rightarrow (A,Z+2) + 2e^- + n\chi$

SM allowed →



New neutrino properties:

$\nu = (\nu)^c$

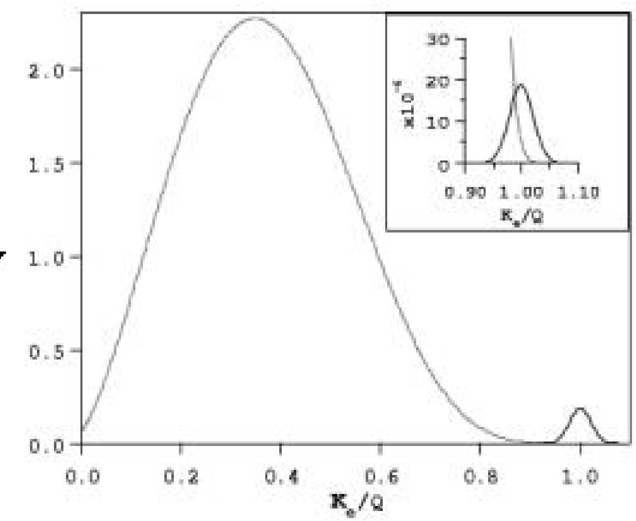
$m_\nu \neq 0$

Helicity matching

2 electrons sum energy spectra:

Main experimental signature ...

(single electron E and angular distributions)



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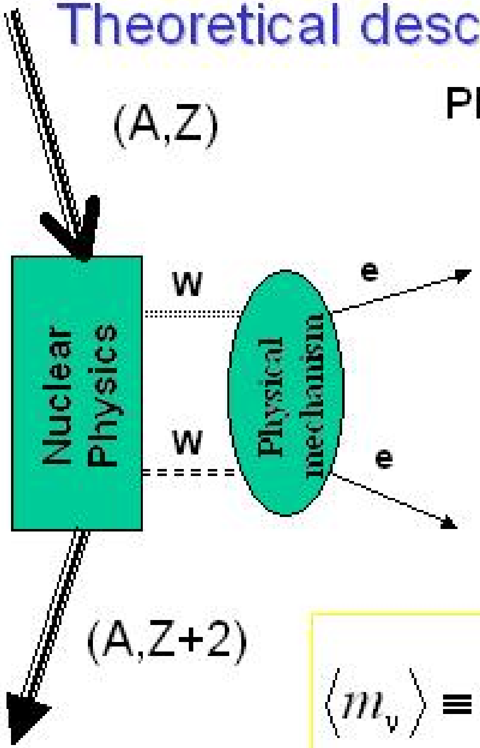
DBD & Neutrino Properties

Theoretical description ...



Phase space: high Q

Nuclear matrix element:
Relevant uncertainty source (h)

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \sum_k G_k(Q,Z) M_k^2 \, \omega_k^2$$

Physical mechanism

$$G(Q,Z) M^2 \langle m_\nu \rangle^2$$

Neutrino mass

±1 if CP conserved

$$\langle m_\nu \rangle \equiv m_{ee} = \left| \sum_k U_{ek}^2 m_k \right| = \left| \sum_k |U_{ek}|^2 e^{i\alpha_{ek}} m_k \right|$$

Pontecorvo-Maki-Nakagawa-Sakata
mixing matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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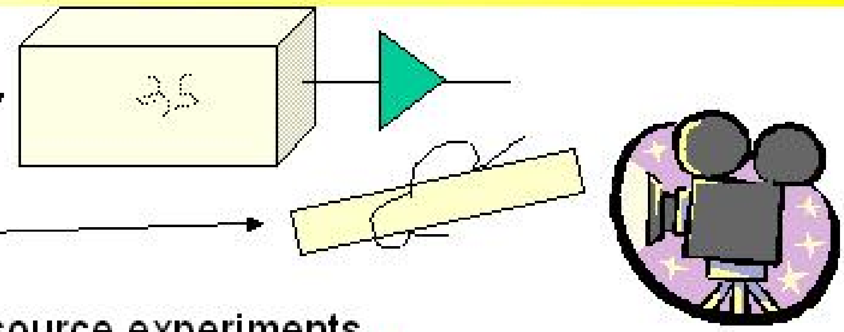
$0\nu2\beta$ Experimental Situation

2 main experimental approaches:

- Active Source
- Passive Source



Best $0\nu2\beta$ results involve active source experiments

Experiment	Isotope	$T_{1/2}^{0\nu}$ (y)	$<m_\nu>$ (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

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Evidence for 0ν2β: KDHK

Klapdor-Kleingrothaus HV et al. hep-ph/0201231
Klapdor-Kleingrothaus HV and Sarkar U. hep-ph/0201224

EVIDENCE FOR NEUTRINOLESS DOUBLE BETA DECAY

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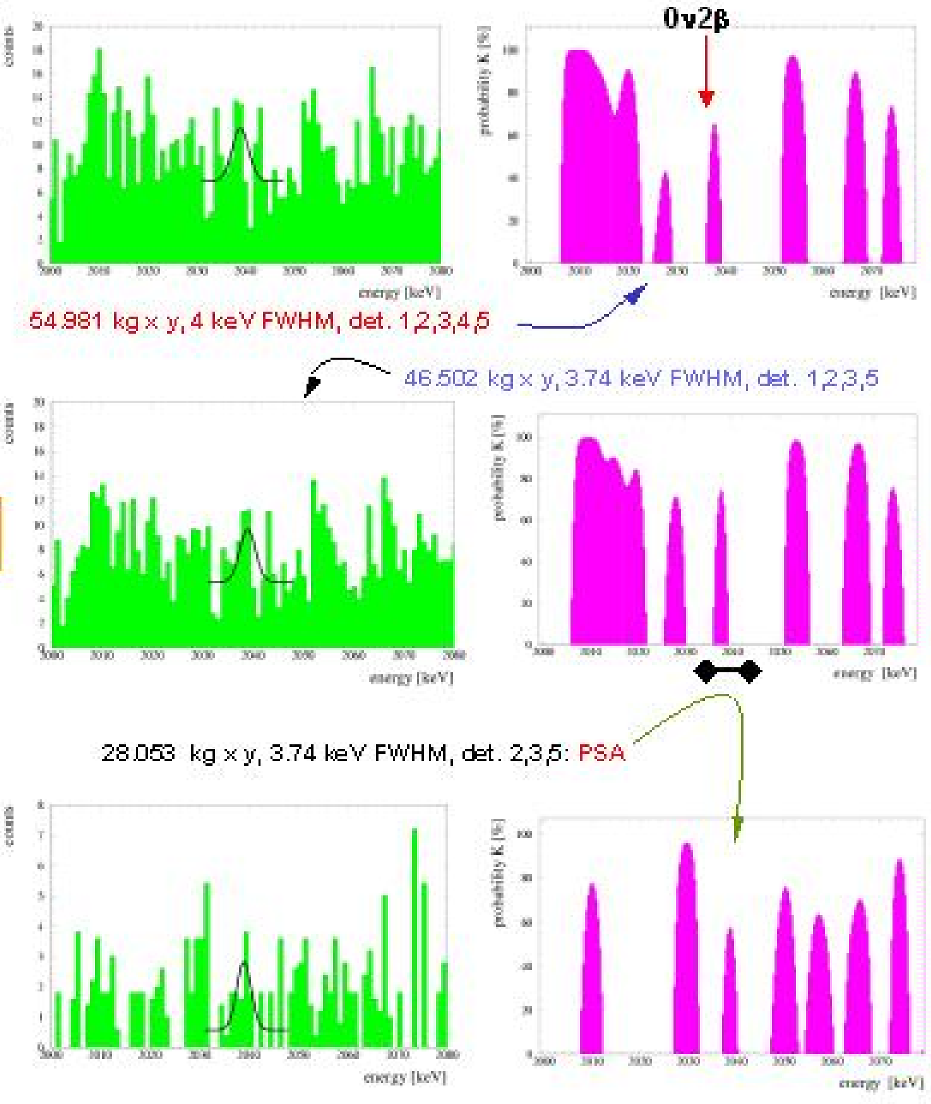
2.2 - 3.1 σ effect

The data of the HEIDELBERG-MOSCOW double beta decay experiment for the measuring period August 1990 - May 2000 (54.9813kg y or 723.44molyears), published recently, are analyzed using the potential of the Bayesian method for low counting rates. First evidence for neutrinoless double beta decay is observed giving first evidence for lepton number violation. The evidence for this decay mode is 97% (2.2σ) with the Bayesian method, and 99.8% c.l. (3.1σ) with the method recommended by the Particle Data Group. The half-life of the process is found with the Bayesian method to be $T^{0\nu}_{1/2} = (0.8 - 18.3) \times 10^{25}$ y (95% c.l.) with a best value of 1.5×10^{25} y. The deduced value of the effective neutrino mass is, with the nuclear matrix elements from [], $\langle m \rangle = (0.11 - 0.56)$ eV (95% c.l.), with a best value of 0.39 eV. Uncertainties in the nuclear matrix elements may widen the range given for the effective neutrino mass by at most a factor 2. Our observation which at the same time means evidence that the neutrino is a Majorana particle, will be of fundamental importance for neutrino physics.
PACS. 14.69.Pq Neutrino mass and mixing - 23.40.Bw Weak-interaction and lepton (including neutrino) aspects - 23.40.-s Beta decay; double beta decay; electron and muon capture.



Reanalysis of the 1990-2000 Heidelberg-Moscow data

- Peak Detection Procedure
- Bayesian approach

Natural radioactivity lines recognized!
Select a small Energy interval around E_0

O. Cremonesi

Future projects

Experiment	Author	Isotope	Detector description	$T^{5y}_{1/2}$(y)	$<m_\nu>$*
COBRA	Zuber 2001	^{130}Te	10 kg CdTe semiconductors	1×10^{24}	0.71
CUORICINO	Arnaboldi et al 2001	^{130}Te	40 kg of TeO_2 bolometers	1.5×10^{25}	0.19
NEMO3	Sarazin et al 2000	^{100}Mo	10 kg of bb(0n) isotopes (7 kg Mo) with tracking	4×10^{24}	0.56
CUORE	Arnaboldi et al. 2001	^{130}Te	760 kg of TeO_2 bolometers	7×10^{26}	0.027
EXO	Danevich et al 2000	^{136}Xe	1 t enriched Xe TPC	8×10^{26}	0.052
GEM	Zdesenko et al 2001	^{76}Ge	1 t enriched Ge diodes in liquid nitrogen + water shield	7×10^{27}	0.018
GENIUS	Klapdor-Kleingrothaus et al 2001	^{76}Ge	1 t enriched Ge diodes in liquid nitrogen	1×10^{28}	0.015
MAJORANA	Aalseth et al 2002	^{76}Ge	0.5 t enriched Ge segmented diodes	4×10^{27}	0.025
DCBA	Ishihara et al 2000	^{150}Nd	20 kg enriched Nd layers with tracking	2×10^{25}	0.035
CAMEO	Bellini et al 2001	^{116}Cd	1 t $CdWO_4$ crystals in liquid scintillator	$> 10^{26}$	0.069
CANDLES	Kishimoto et al	^{48}Ca	several tons of CaF_2 crystal in liquid scintillator	1×10^{26}	
GSO	Danevich 2001	^{160}Gd	2 t Gd_2SiO_5:Ce cristal scintillator in liquid scintillator	2×10^{26}	0.065
MOON	Ejiri et al 2000	^{100}Mo	34 t natural Mo sheets between plastic scintillator	1×10^{27}	0.036
Xe	Caccianiga et al 2001	^{136}Xe	1.56 t of enriched Xe in liquid scintillator	5×10^{26}	0.066
XMASS	Moriyama et al 2001	^{136}Xe	10 t of liquid Xe	3×10^{26}	0.086

* Staudt, Muto, Klapdor-Kleingrothaus Europh. Lett 13 (1990) 31