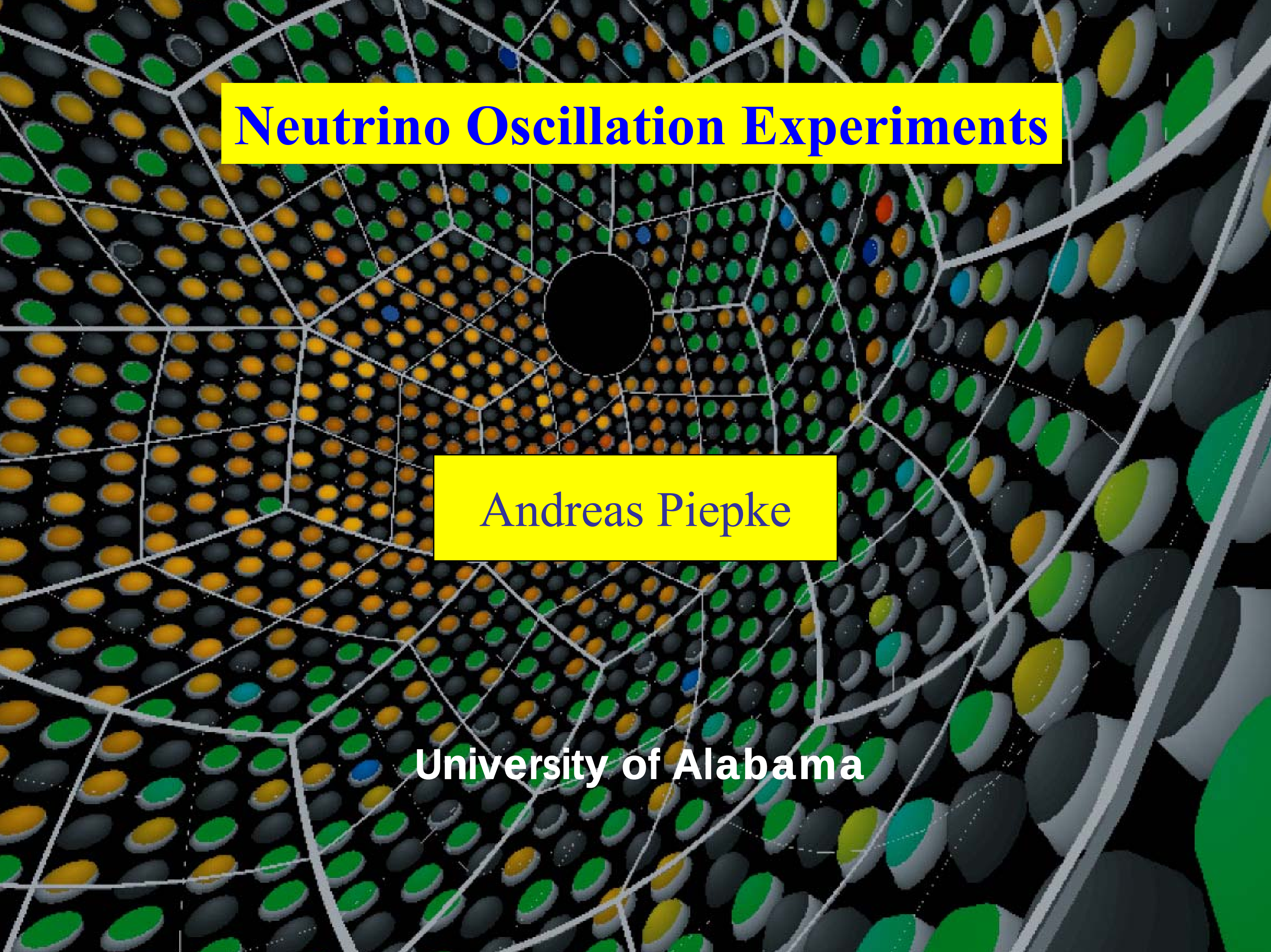


Neutrino Oscillation Experiments

Andreas Piepke

University of Alabama

Particle physics:

Neutrino masses are zero in the minimal Standard Model.

Extensions of the SM naturally give $m_\nu \neq 0$. → probe new physics.

Astrophysics and cosmology:

Neutrinos are the only probes allowing us to "look" inside Sun and Supernovae.

Universe contains 330 ν/cm^3, from Big Bang. m_ν necessary ingredient for Dark Matter problem. Important?

$\Omega_\nu / \Omega_B < 0.3$ (WMAP) $\Omega_\nu / \Omega_B < 3.0$ (Tritium decay)

$\Omega_B = 0.047 \pm 0.006$, $\Omega_M = 0.29 \pm 0.07$ and $\Omega_{Tot} = 1.02 \pm 0.02$

Laboratory neutrino mass measurements consistency check that can be done.

Neutrino Oscillations and Flavor Mixing

Mass (objects with definitive mass plain wave) and flavor states (objects that participate in weak interaction) are not identical.

$$\left|\nu_\ell(L,t)\right\rangle = \sum_i U_{\ell i} e^{-i(m_i^2/2E)L} \left|\nu_i(0)\right\rangle$$

Mixing matrix called Maki-Nakagawa-Sakata (MNS)

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

Unitary matrix, usually given in terms of a three dimensional rotation.
Oscillation experiments measure the corresponding “mixing” angles.

For massive neutrinos two ways of flavor conversion:

Vacuum or medium with constant parameters	Dense Matter, non-uniform medium MSW
During propagation phase difference increase between eigenstates gives rise to vacuum oscillations.	Different scattering CC+NC for ν_e only NC for ν_μ and ν_τ Gives rise to neutrino potential $\Delta V = \sqrt{2}\, G_F n_e$ Adiabatic flavor conversion: change of mixing in medium change of flavor of eigenstates

Vacuum oscillations: transition probability P. It is an oscillatory function of the flight path L.

$$P \ldots {}_{\alpha j} U^*_{\beta j} e^{-i(m_j^2/2E)L} \Big|^2$$

From energy distribution info on $\Delta m^2_{ij} = m^2_i - m^2_j$ Oscillatory function in L/E

From amplitude combination of mixing matrix elements

$$P(\nu_\alpha \to \nu_\beta, L) = \delta_{\alpha\beta} - 4\sum_{j>i} \Re\left[U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}\right] \sin^2\left(\frac{1.27 \cdot \Delta m^2_{ij} \cdot L}{E_\nu}\right)$$

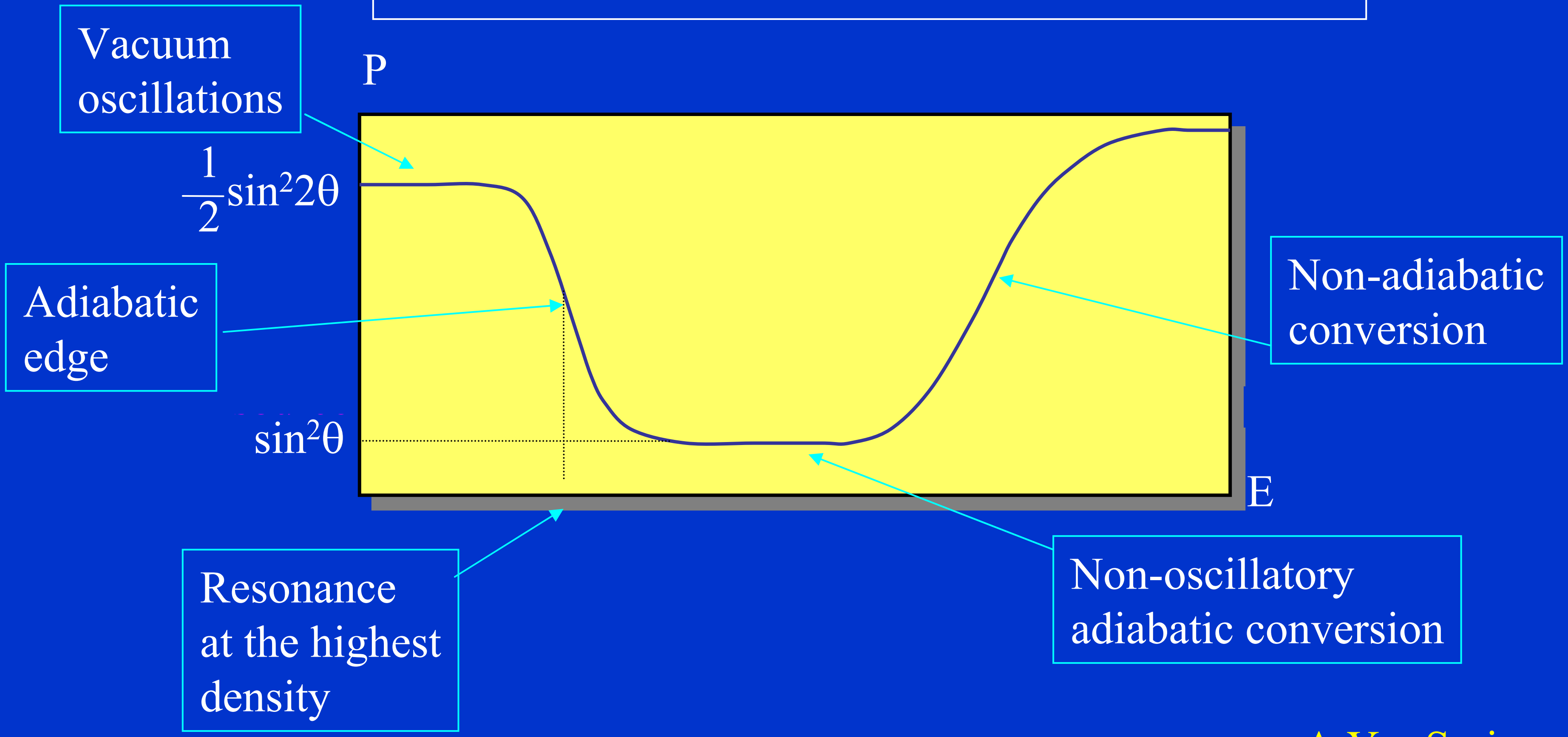
$$\pm 2\sum_{j>i} \Im\left[U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}\right] \sin^2\left(\frac{2.54 \cdot \Delta m^2_{ij} \cdot L}{E_\nu}\right)$$

Zero for CP conservation

In matter:

Mixing angle depends on E_ν and n_e (electron density of medium)

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\cos 2\theta - 2V E/\Delta m^2)^2 + \sin^2 2\theta}$$



A.Yu. Smirnov

Vacuum oscillations and matter induced conversion are quite different mechanisms.
However, if our understanding of neutrino mass and mixing is correct both should yield a consistent set of parameters!

Solar neutrinos:

Measurements of solar neutrinos observed a flux of only 50 to 65% of that expected based on Standard Solar Model. E_ν=0.3 – 12 MeV, L=1.5 $\cdot 10^8$ km. Solar neutrino problem $\Delta m^2_{sol} = 8 \cdot 10^{-5}$ eV^2

Atmospheric neutrinos:

For neutrinos generated in pion and muon decays in atmosphere ν_e flux found to agree with model predictions only 65% of expected ν_μ flux was observed. $E_\nu \sim$ GeV, L=30 – 10000 km. Atmospheric neutrino problem $\Delta m^2_{atm} = 2 \cdot 10^{-3}$ eV^2

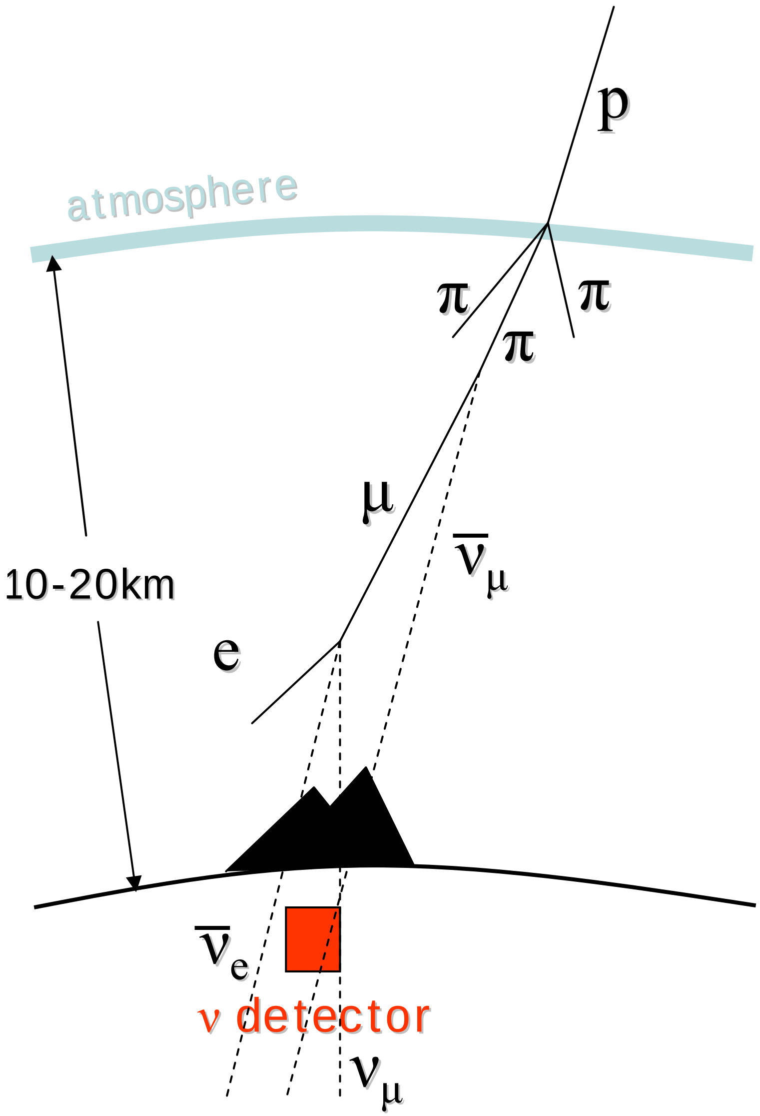
LSND:

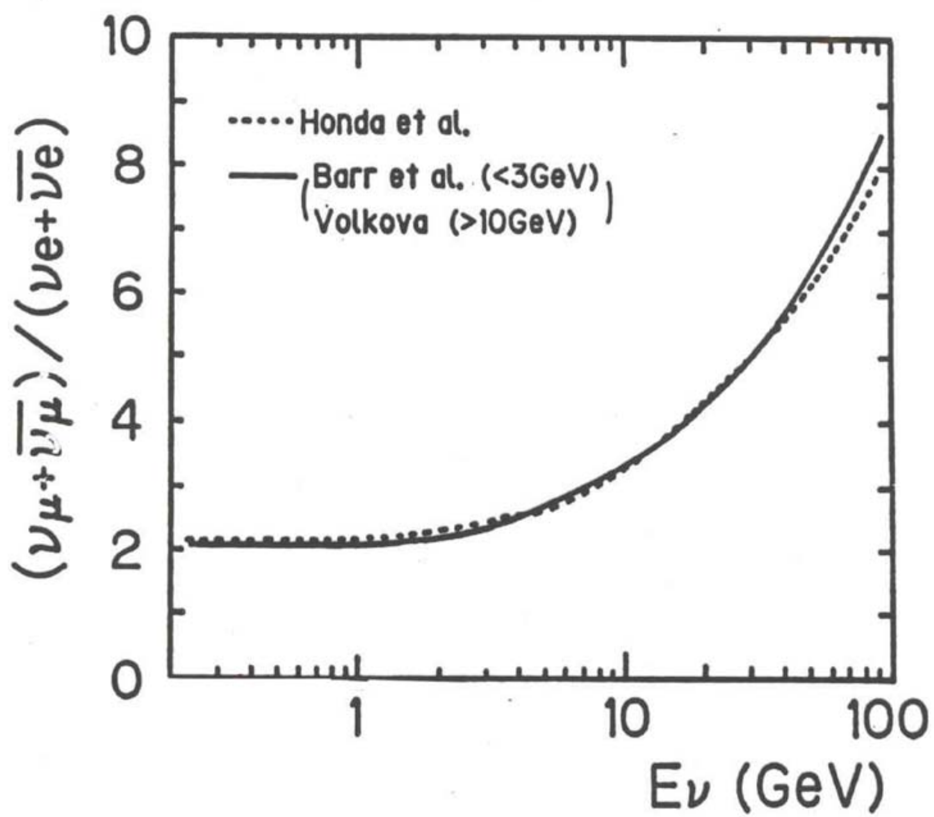
Experiment at beam dump of LAMPF looking at neutrinos from muon decay found appearance of unexpected flavor $\overline{\nu}_e$. $E_\nu \sim 100$ MeV. L=30 m. Not yet independently confirmed! $\Delta m^2_{LSND} = 1$ eV^2

All of these observations can be explained by neutrino oscillations.

Atmospheric neutrinos

Atmospheric Neutrino Production

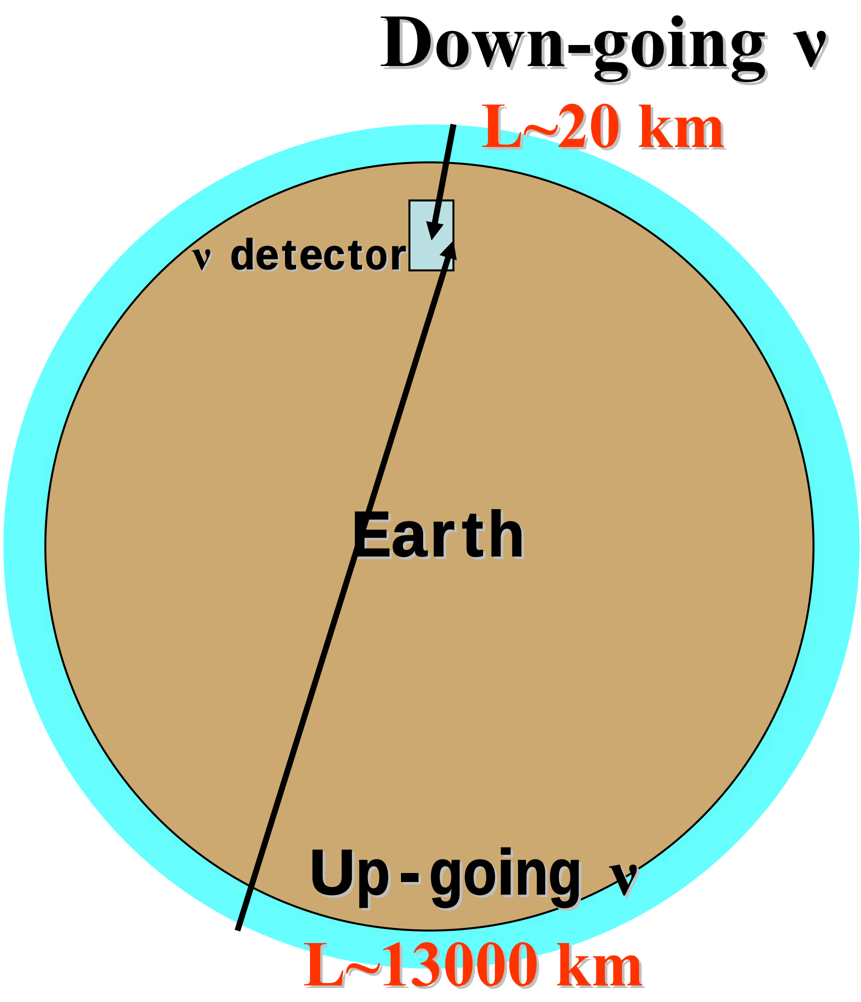




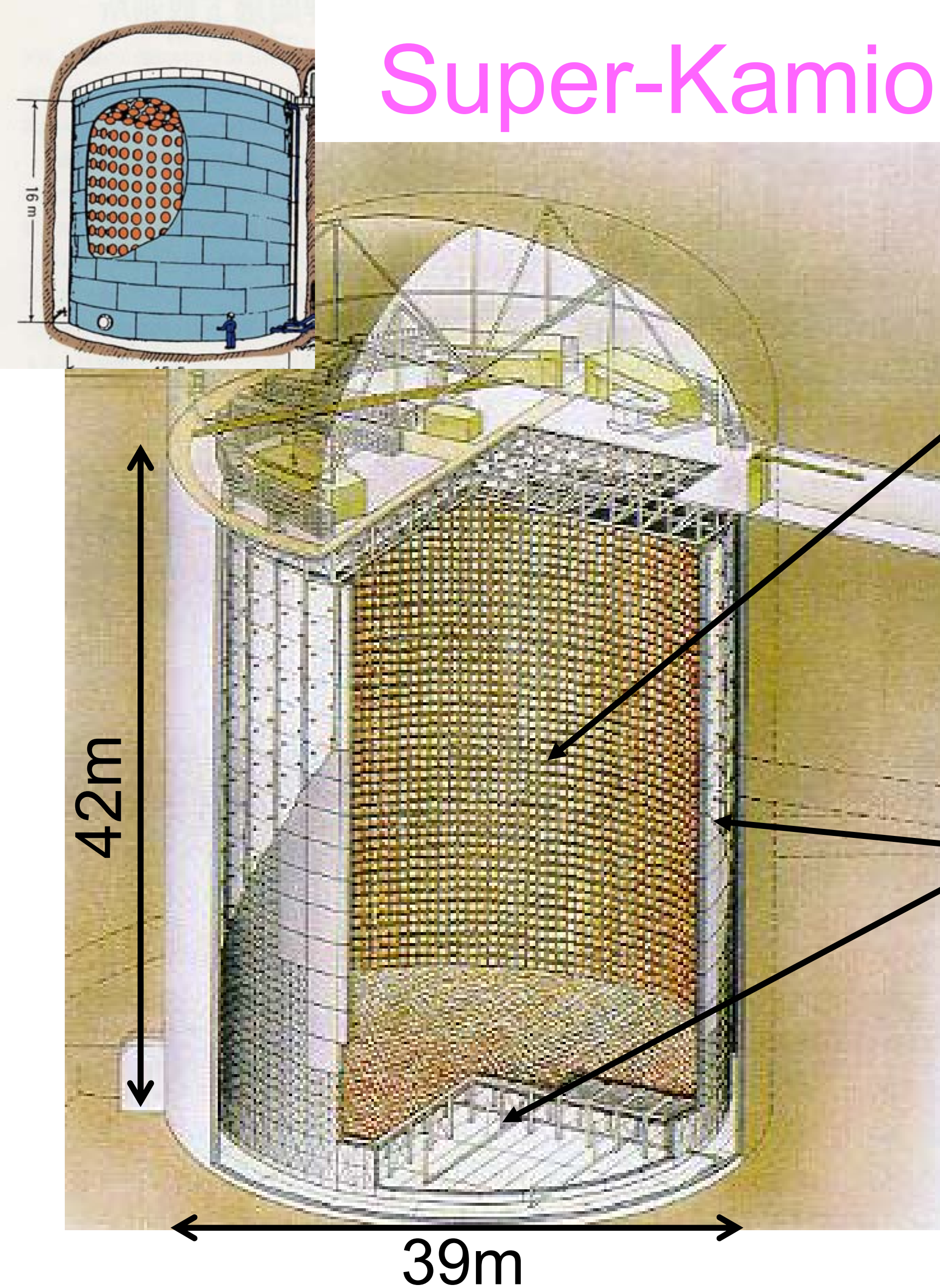
At low energy (~GeV) expect

$$N_{\nu_\mu} \simeq 2N_{\nu_e}$$

For multiple GeV neutrinos good directional correlation with outgoing charged lepton: measure L



Super-Kamiokande (1996-)



50,000 ton water Cherenkov detector

(Fid. Mass is 22,500 tons)

11,146 × (50cm ϕ PMT) : Inner detector

40% photo-cathode coverage

Number of observed Ch photons ~ 6 /MeV (excluding scattered or reflected photons)

1,885 × (20cm ϕ PMT) : Outer detector

2m active detector region + 0.6m layer (no photon detection)

⇒ muon veto

⇒ γ (and neutron) shield

SK collaboration: Japan, USA, Korea, Poland

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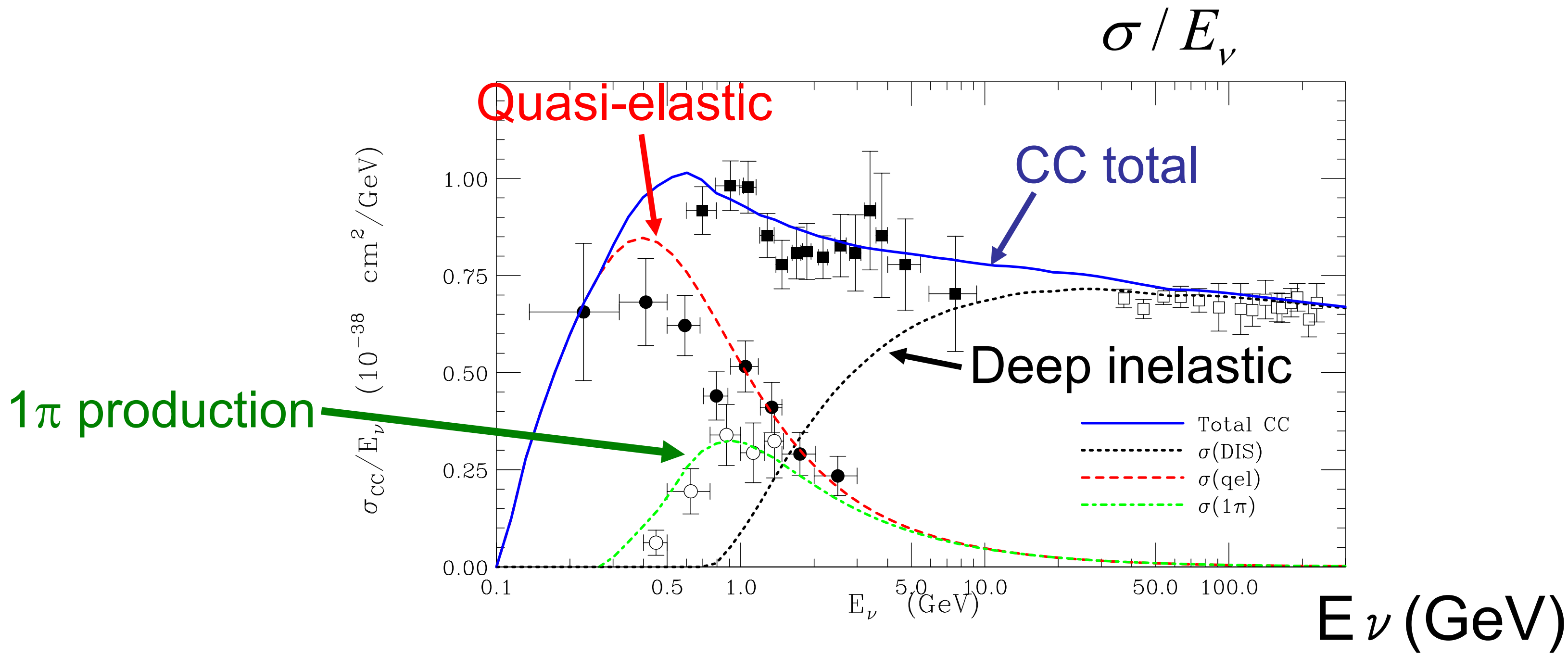
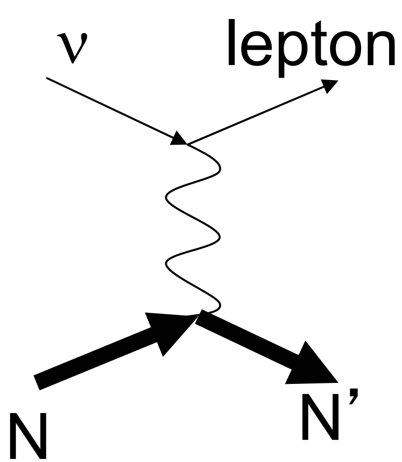
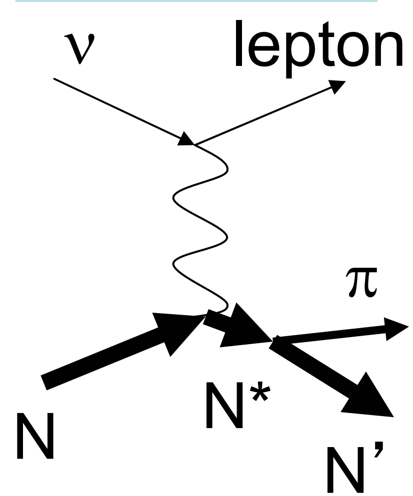
Neutrino interactions



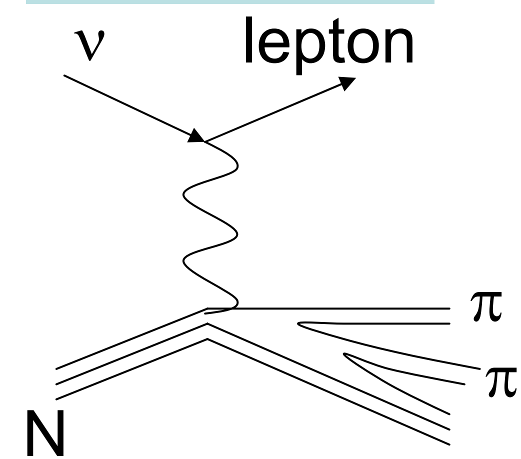
Quasi-elastic



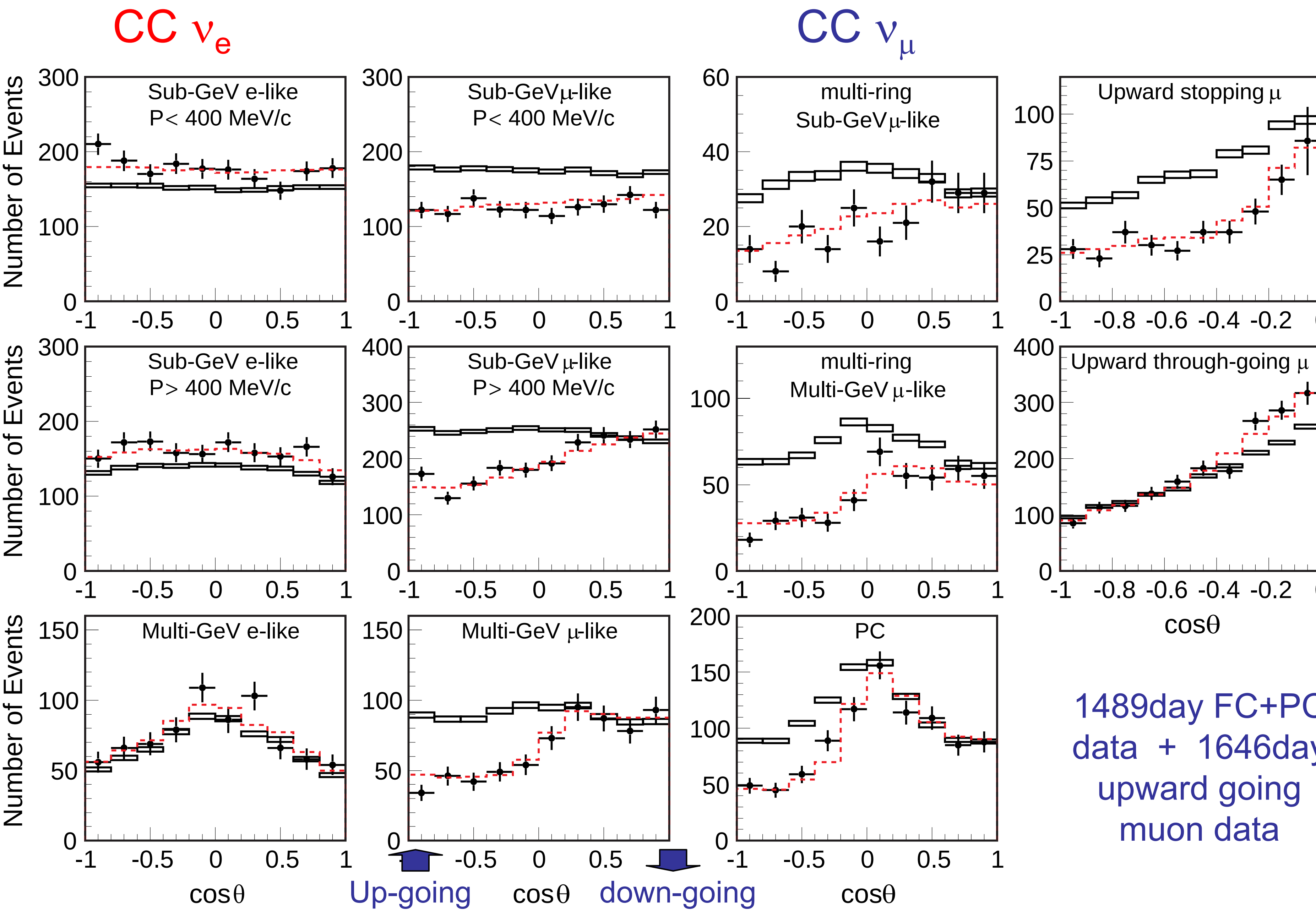
1π production



Deep inelastic



Super-K atmospheric neutrino data



1489day FC+PC data + 1646day upward going muon data

Consistent with $\nu_\mu \rightarrow \nu_\tau$ oscillations due to lack of ν_e appearance.

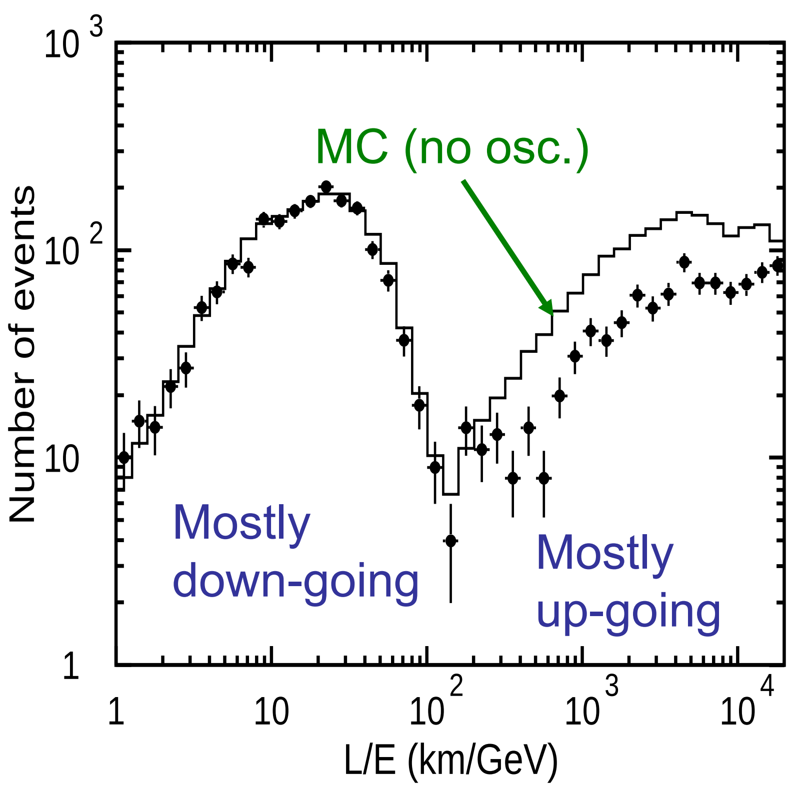
Independently confirmed at nuclear reactors where $\nu_e \rightarrow \nu_x$ could not be observed at Δm^2_{atm}.
Most stringent bound from Chooz and Palo Verde experiments.

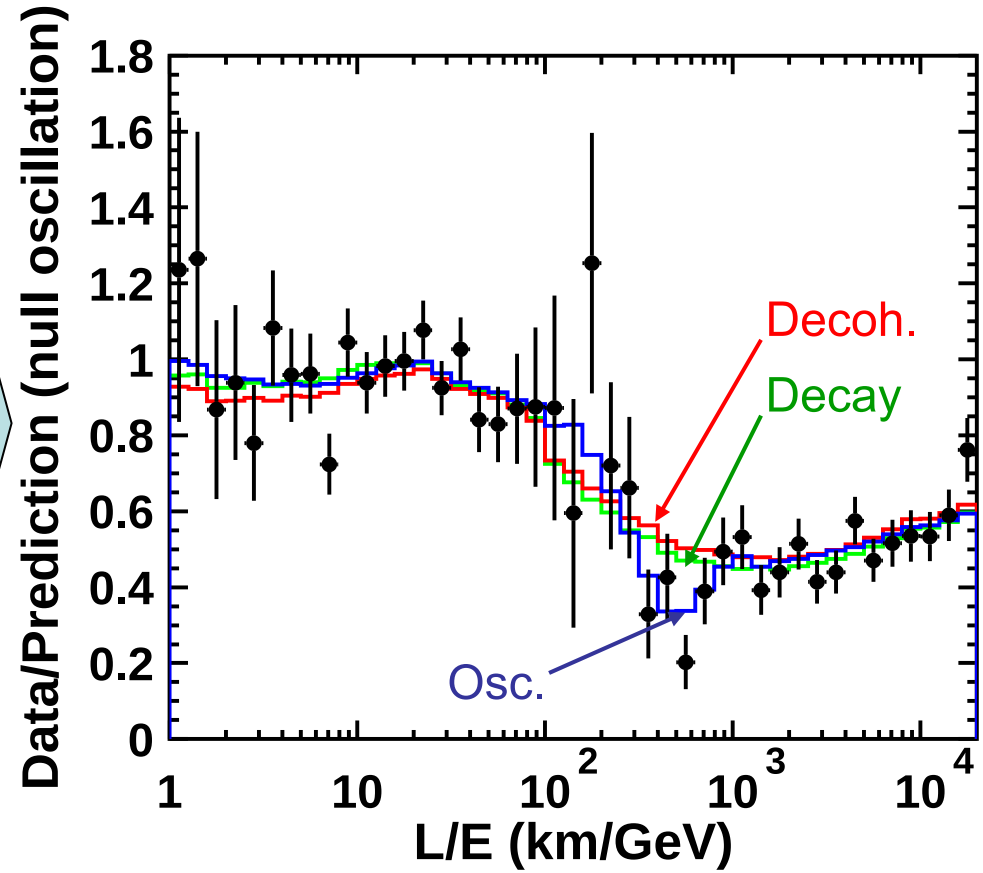
Anomoulus flux ratio observed by:
IMB (water Cherenkov)
Kamiokande (water Cherenkov)
Soudan II (iron tracking calorimeter)
Macro (liquid scintillator)

SK collab.
hep-ex/0404034

L/E distribution

1489 days FC+PC





➔Evidence for oscillatory signature

Decay and decoherence disfavored at 3.4 and 3.8σ levels, respectively.

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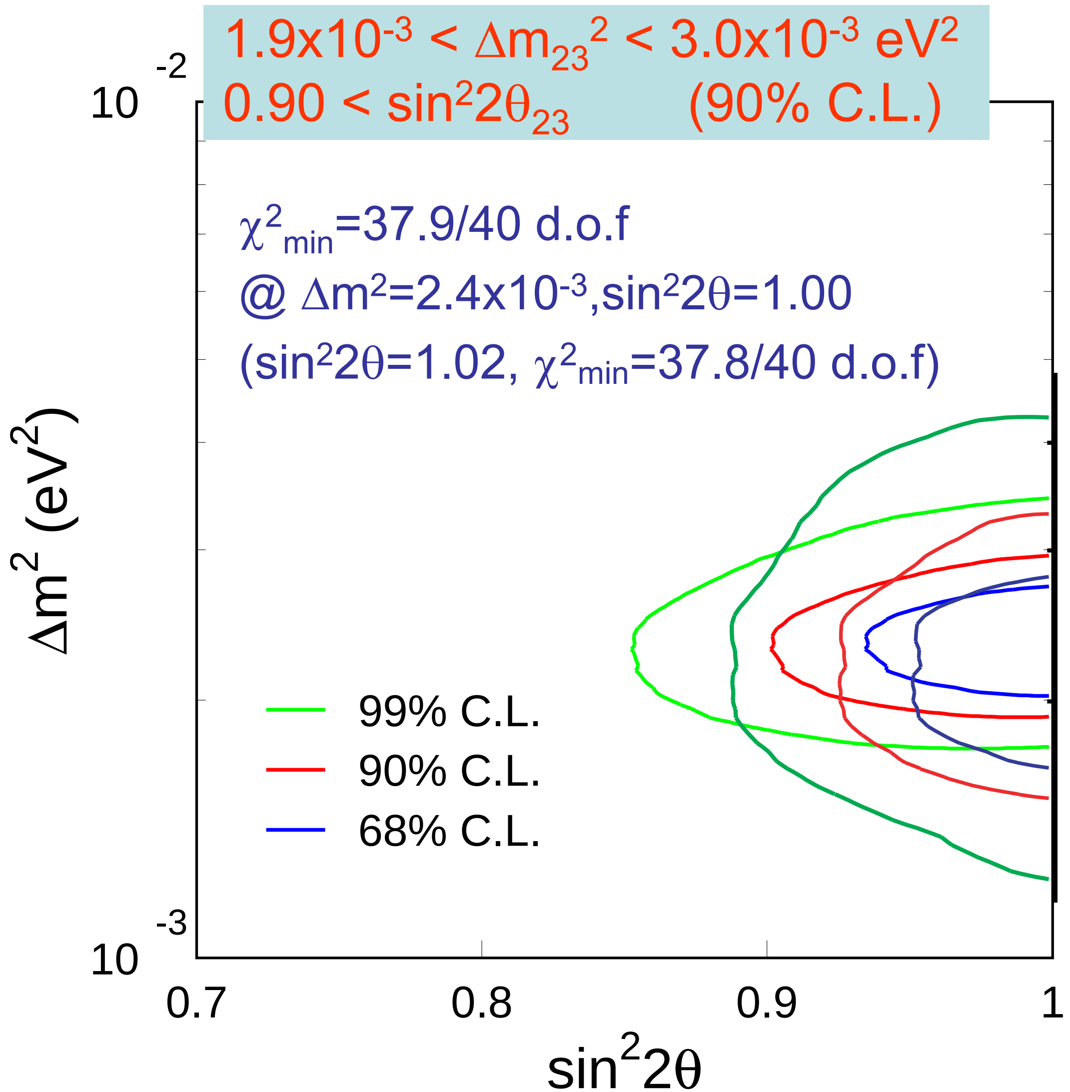
Allowed neutrino oscillation parameters



- ➔ Stronger constraint on Δm^2
- ➔ Consistent with that of the standard zenith angle analysis

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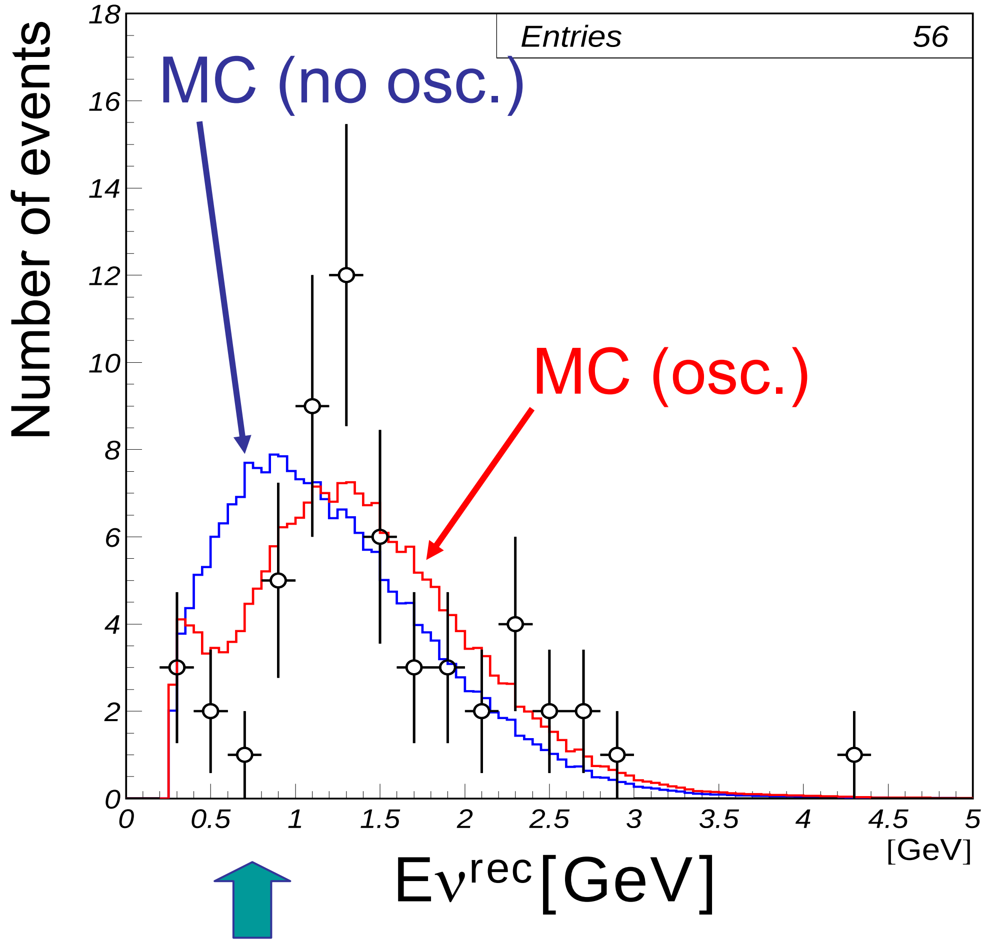
K2K experiment

K2K Collaboration

JAPAN, KOREA, U.S.A., POLAND, CANADA, ITALY, FRANCE, SPAIN, SWITZERLAND, RUSSIA

Use KEK 12 GeV proton beam on Al target. $\langle E_\nu \rangle = 1.3$ GeV
ν_μ from π^+ decay in flight, π^- suppressed by focusing horns.

K2K energy spectrum (based on single-ring μ-like events)



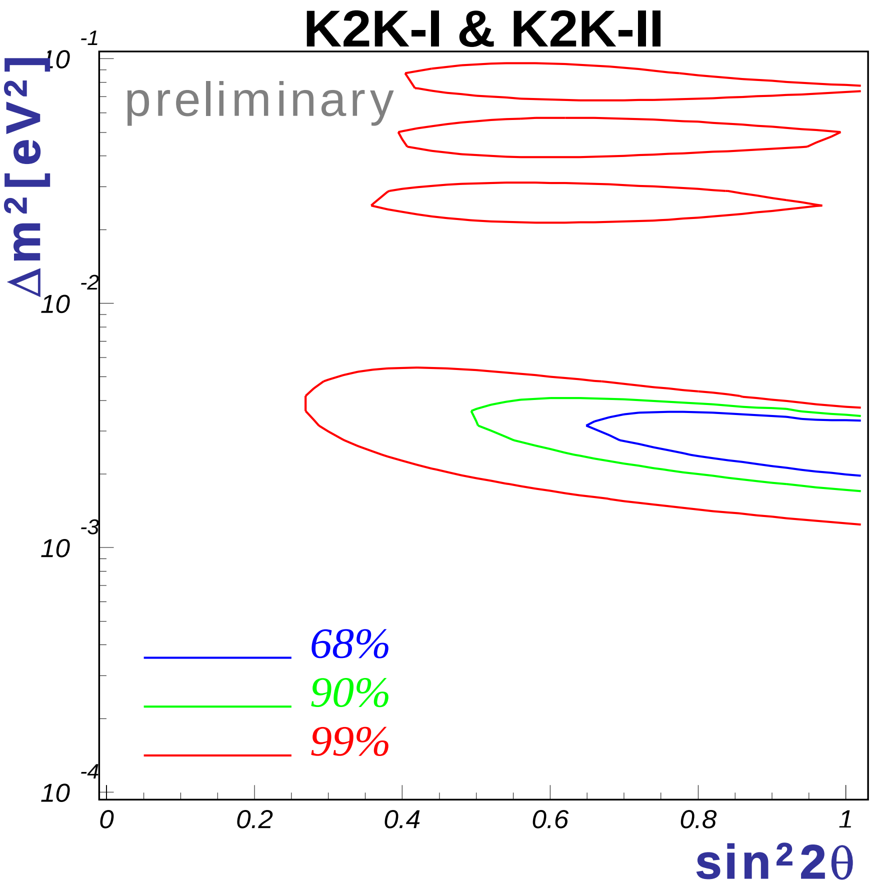
Deficit of events

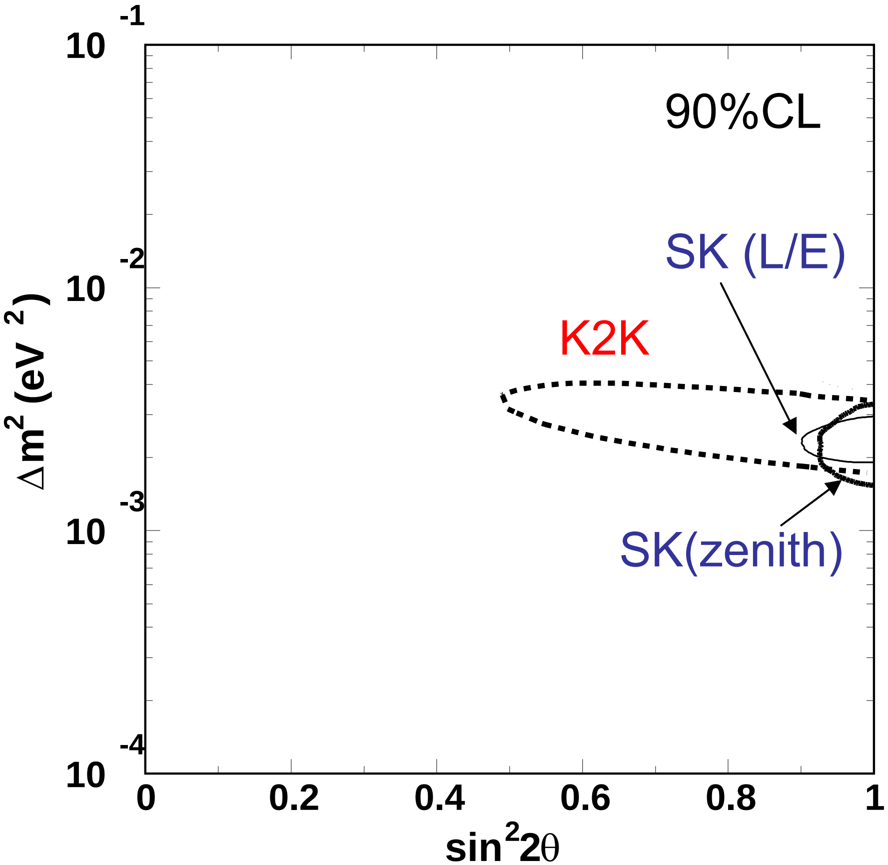
MC normalization: number of events

108 events obs'd

150.9±11 events expected

Allowed parameter region





Best fit values

$\sin^2 2\theta = 1.00$

$\Delta m^2 = 2.7\times10^{-3} ev^2$

$\Delta m^2 = (1.7 \sim 3.5)\times 10^{-3}\ eV^2$

(90% C.L.) @ $\sin^2 2\theta = 1.0$

Very strong evidence for $\nu_\mu \rightarrow \nu_\tau$ oscillations with:

$\Delta m^2_{atm} = (2.2 \pm 0.7) \cdot 10^{-3}\ eV^2$ Maltoni et al. hep-ph/0405172

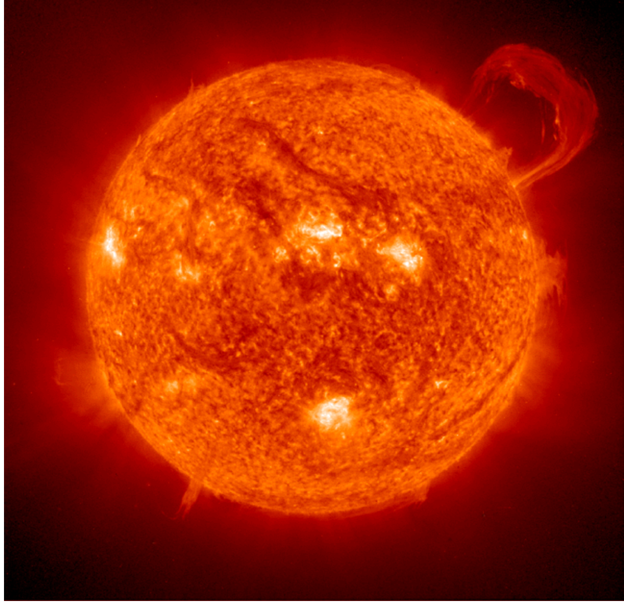
$\sin^2\theta_{23} = 0.5 \pm 0.14$ Maximal mixing!

Zenith angle dependent atmospheric neutrino flux tell-tale sign of oscillations.
Consistent with reactor experiments.
Confirmed at particle accelerator.

There is a solid case for oscillations.

Solar neutrinos

ν_e are abundant by-products of nuclear fusion in the sun



$$p + p \rightarrow {}^2H + e^+ + \nu_e + 0.42 MeV$$

"pp" 99.75%

$$p + e^- + p \rightarrow {}^2H + \nu_e + 1.44 MeV$$

"pep" 0.25%

$${}^2H + p \rightarrow {}^3He + \gamma + 5.49\ MeV$$

86%

$${}^3He + {}^3He \rightarrow \alpha + 2p + 12.86 MeV$$

14%

$${}^3He + \alpha \rightarrow {}^7Be + \gamma + 1.59 MeV$$

"hep" 2.4*10^{-5}

$${}^3He + p \rightarrow \alpha + e^+ + \nu_e$$

"^{7}Be" 99.89%

$${}^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e + 0.8617 MeV$$

$${}^7Li + p \rightarrow \alpha + \alpha + 17.35 MeV$$

0.11%

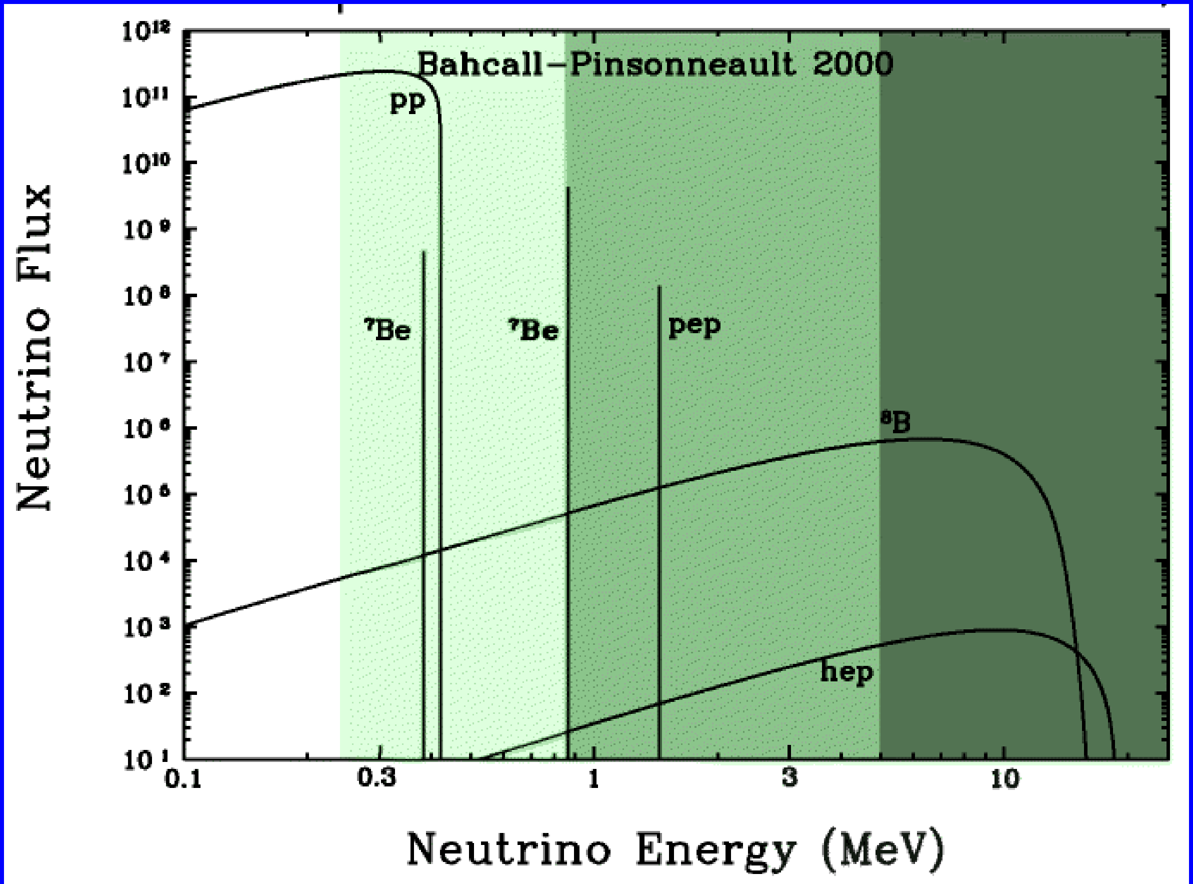
$${}^7Be + p \rightarrow {}^8B + \gamma + 0.14 MeV$$

"^{8}B" 0.11%

$${}^8B \rightarrow {}^8Be + e^+ + \nu_e + 14.6 MeV$$

$${}^8Be \rightarrow \alpha + \alpha + 3 MeV$$

Quantitative solar model gives absolute flux model (Standard Solar Model by Bahcall et al.)



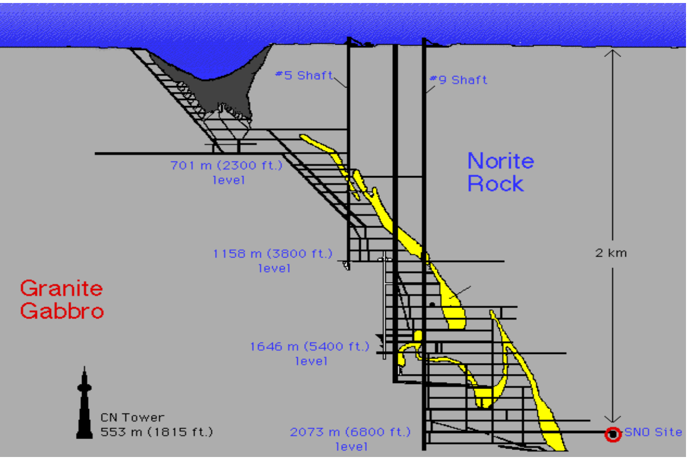
Measurements of solar neutrinos proved that nuclear fusion is powering the sun.

The solar neutrino problem

Experiment	Year	Detection Reaction	Ratio Exp/BP2000
Chlorine (127 t)	1970-1995	$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$	0.34 ± 0.03
Kamiokande (680t)	1986-1995	$\nu_x + e^- \rightarrow \nu_x + e^-$	0.54 ± 0.08
SAGE (23 t)	1990-	$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$	0.55 ± 0.05
Gallex + GNO (12 t)	1991-	$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$	0.57 ± 0.05
SuperK (22kt)	1996-	$\nu_x + e^- \rightarrow \nu_x + e^-$	$0.451^{+0.017}_{-0.015}$

The solution of the problem: SNO and KamLAND

The Sudbury Neutrino Observatory



1000 tonnes D_2O

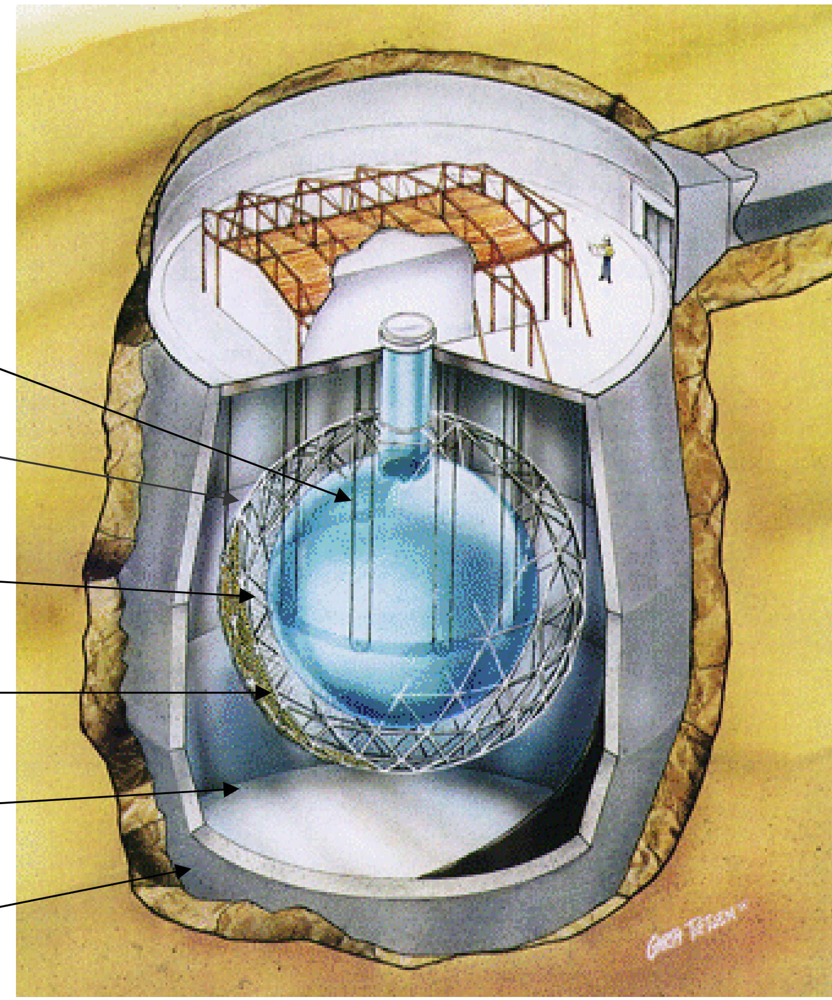
Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

Urylon Liner and Radon Seal



J.Wilkerson

The SNO Collaboration

SNO Solar ν Physics

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

- Gives ν_e energy spectrum well
- Weak direction sensitivity ∝ 1-1/
- ν_e only.

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

- Measure total ^8B ν flux from the
- Equal cross section for all ν type

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

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

Key physics signatures

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

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

$$\Phi_{^8Bx} = \Phi_{nc}$$

$$\Phi_{^8Bx} = \Phi_{cc} + (\Phi_{es} - \Phi_{cc})/.015$$

Φ_{day} vs Φ_{night}

Φ_{CC} E spectrum

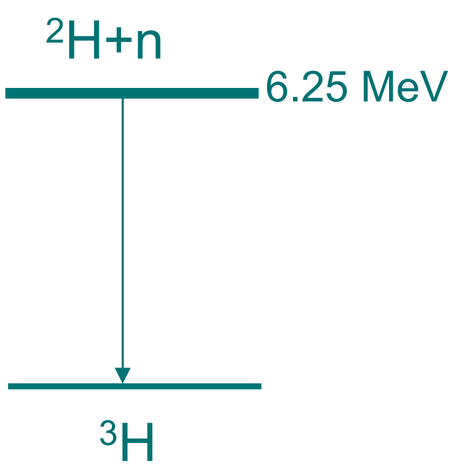
J.Wilkerson

SNO - 3 neutron detection methods

Phase I (D_2O)

Nov. 99 - May 01

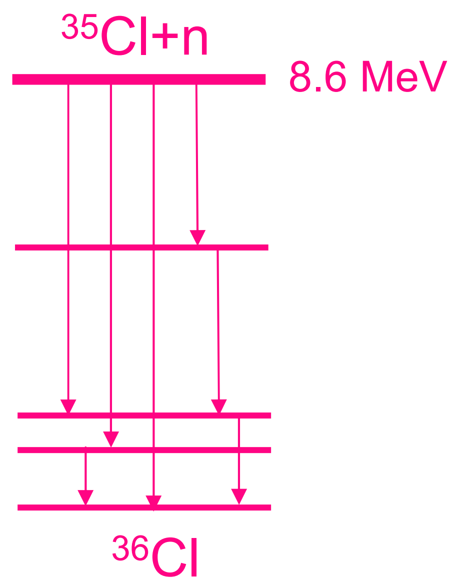
n captures on
$^{2}H(n, \gamma)^{3}H$
σ = 0.0005 b
Observe 6.25 MeV γ
PMT array readout
Good CC



Phase II (salt)

July 01 - Sep. 03

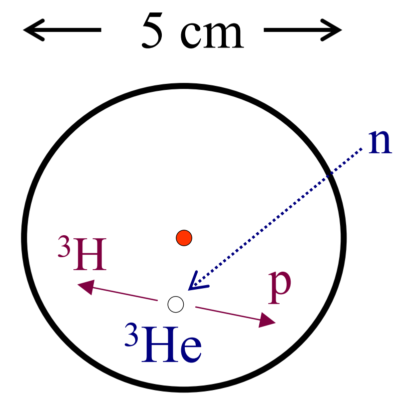
2 t NaCl. n captures on
$^{35}Cl(n, \gamma)^{36}Cl$
σ = 44 b
Observe multiple γ's
PMT array readout
Enhanced NC



Phase III (^{3}He)

Summer 04 - Dec. 06

40 proportional counters
$^{3}He(n, p)^{3}H$
σ = 5330 b
Observe p and ^{3}H
PC independent readout
Event by Event Det.



$$n + {}^{3}He \rightarrow p + {}^{3}H$$

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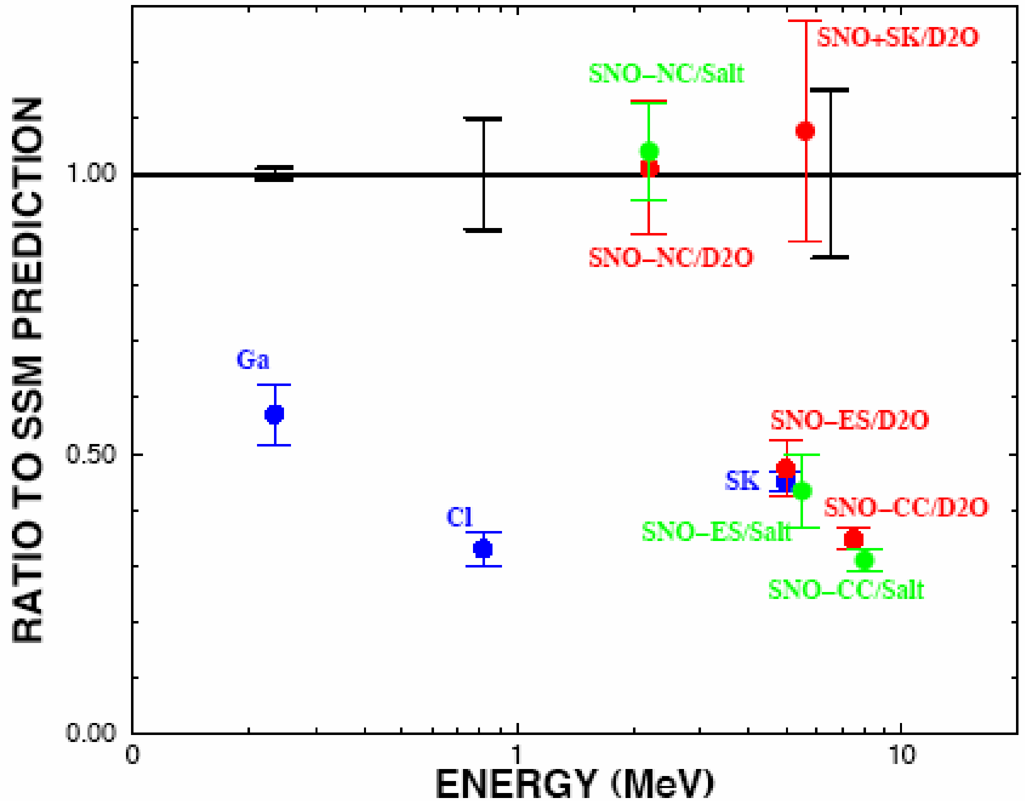
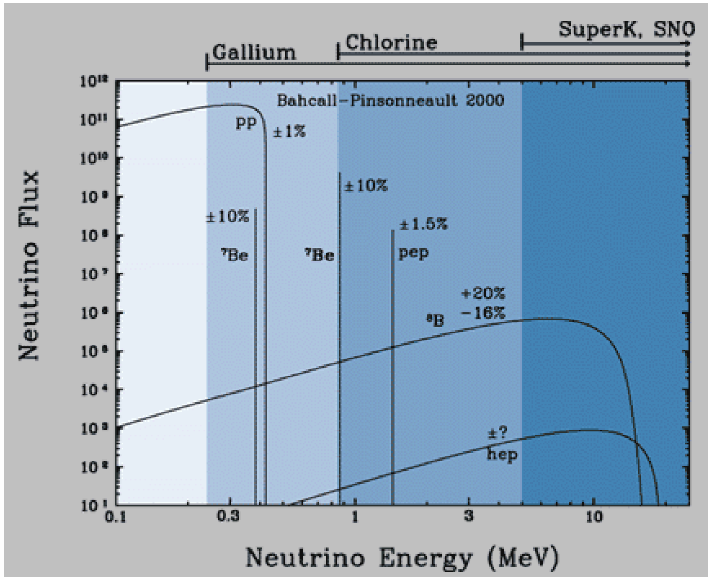
Solar ν Results from SNO





Solar ν deficit is due conversion of electron type neutrinos into muon or tau neutrinos, as shown by NC measurement.
→ solar matter induced flavor conversion.

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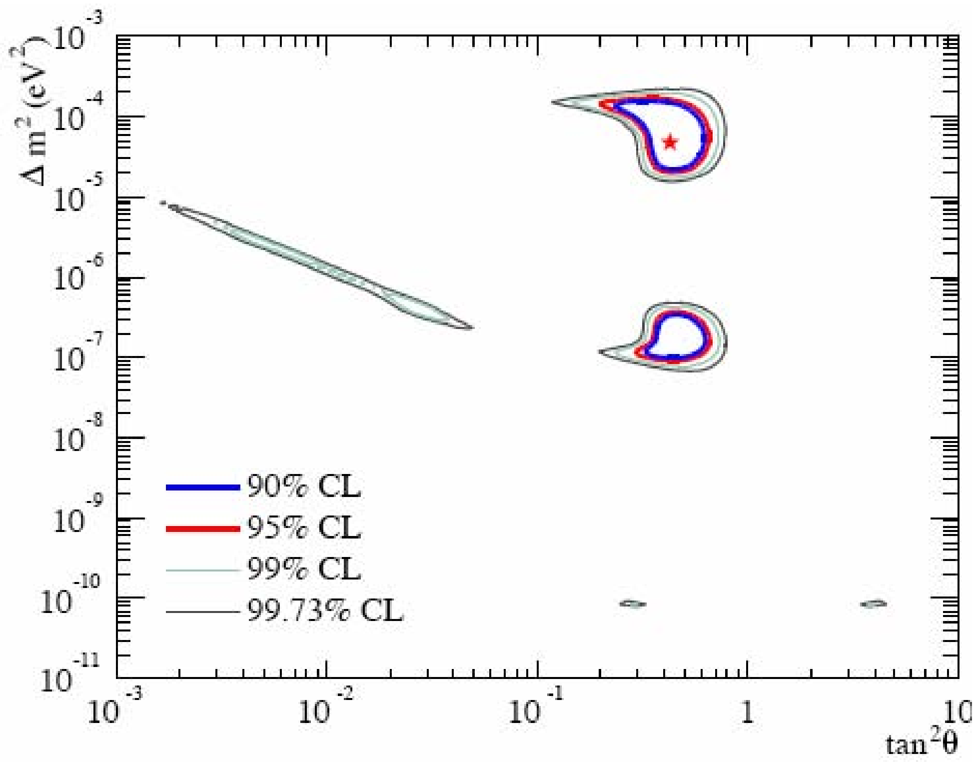
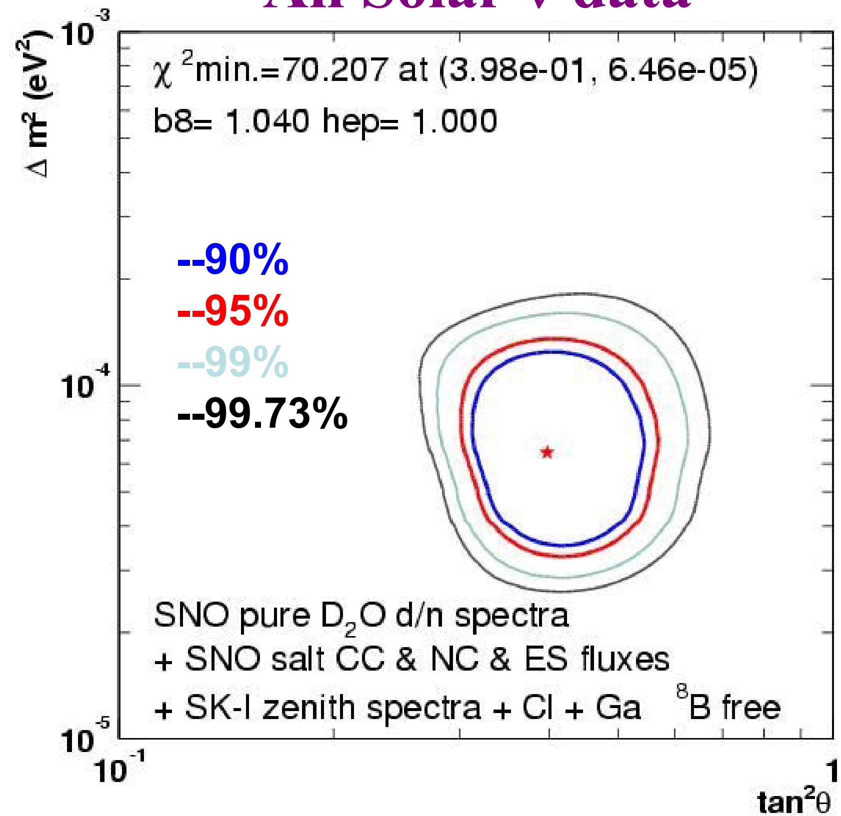
SNO First Salt Result (PRL 92, 181301, 2004)

Salt Phase

SNO only



All Solar ν data



Disfavors maximal mixing at a level equivalent to 5.4 σ.

Demonstrate at nuclear reactor by means of vacuum oscillations: KamLAND

•Demonstrate neutrino oscillations in Δm^2_{sol}-range using reactor anti-neutrinos.

•Precision measurement of θ_{sol} and Δm^2_{sol}

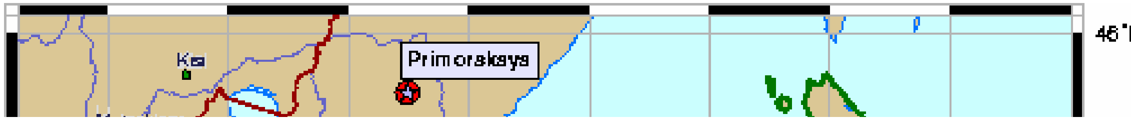
Solar experiments	KamLAND
Neutrinos	Anti-neutrinos
$1.5 \cdot 10^8$ km	200 km
ν's travel through dense matter	Very little matter
Strong magn. field (10^3-10^4 G)	Weak magn. field
Solar model	Reactor model

→ Orthogonal approach

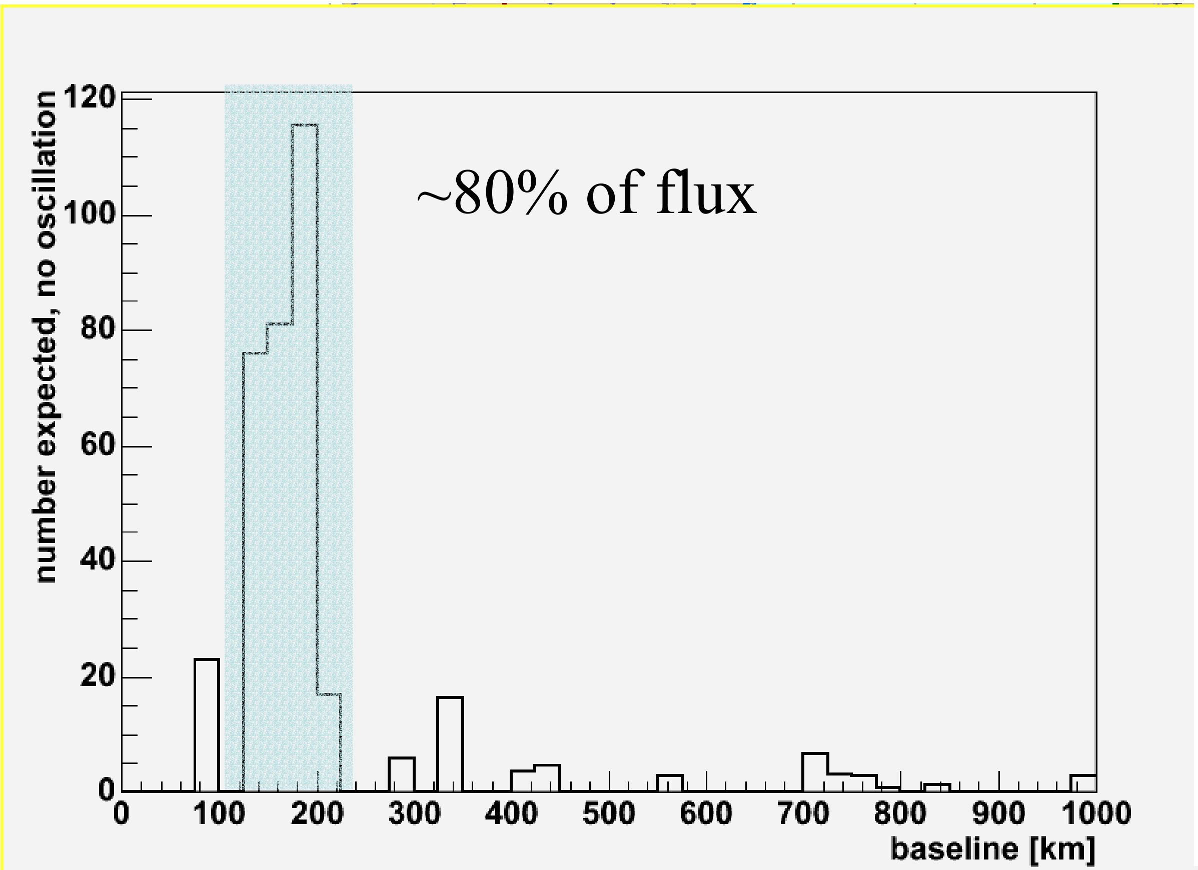
The KamLAND Collaboration

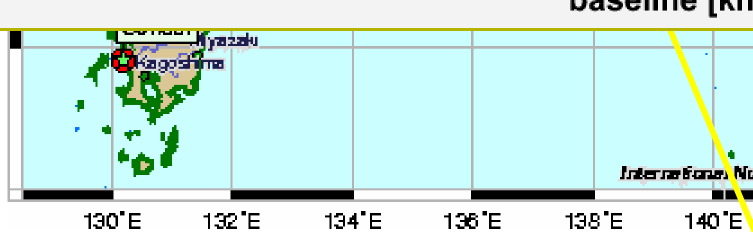
T. Araki,[1] K. Eguchi,[1] S. Enomoto,[1] K. Furuno,[1] K. Ichimura,[1] H. Ikeda,[1] K. Inoue,[1] K. Ishihara,[1,*] T. Iwamoto,[1,*] T. Kawashima,[1] Y. Kishimoto,[1] M. Koga,[1] Y. Koseki,[1] T. Maeda,[1] T. Mitsui,[1] M. Motoki,[1] K. Nakajima,[1] H. Ogawa,[1] K. Owada,[1] J.-S. Ricol,[1] I. Shimizu,[1] J. Shirai,[1] F. Suekane,[1] A. Suzuki,[1] K. Tada,[1] O. Tajima,[1] K. Tamae,[1] Y. Tsuda,[1] H. Watanabe,[1] J. Busenitz,[2] T. Classen,[2] Z. Djurcic,[2] G. Keefer,[2] K. McKinny,[2] D.-M. Mei,[2,†] A. Piepke,[2] E. Yakushev,[2] B.E. Berger,[3] Y.D. Chan,[3] M.P. Decowski,[3] D.A. Dwyer,[3] S.J. Freedman,[3] Y. Fu,[3] B.K. Fujikawa,[3] J. Goldman,[3] F. Gray,[3] K.M. Heeger,[3] K.T. Lesko,[3] K.-B. Luk,[3] H. Murayama,[3] A.W.P. Poon,[3] H.M. Steiner,[3] L.A. Winslow,[3] G.A. Horton-Smith,[4] C. Mauger,[4] R.D. McKeown,[4] P. Vogel,[4] C.E. Lane,[5] T. Miletic,[5] P.W. Gorham,[6] G. Guillian,[6] J.G. Learned,[6] J. Maricic,[6] S. Matsuno,[6] S. Pakvasa,[6] S. Dazeley,[7] S. Hatakeyama,[7] A. Rojas,[7] R. Svoboda,[7] B.D. Dieterle,[8] J. Detwiler,[9] G. Gratta,[9] K. Ishii,[9] N. Tolich,[9] Y. Uchida,[9,‡] M. Batygov,[10] W. Bugg,[10] Y. Efremenko,[10] Y. Kamyshkov,[10] A. Kozlov,[10] Y. Nakamura,[10] C.R. Gould,[11] H.J. Karwowski,[11] D.M. Markoff,[11] J.A. Messimore,[11] K. Nakamura,[11]

Is there a definite Oscillation Baseline L?



The Baseline has a rather well defined range:



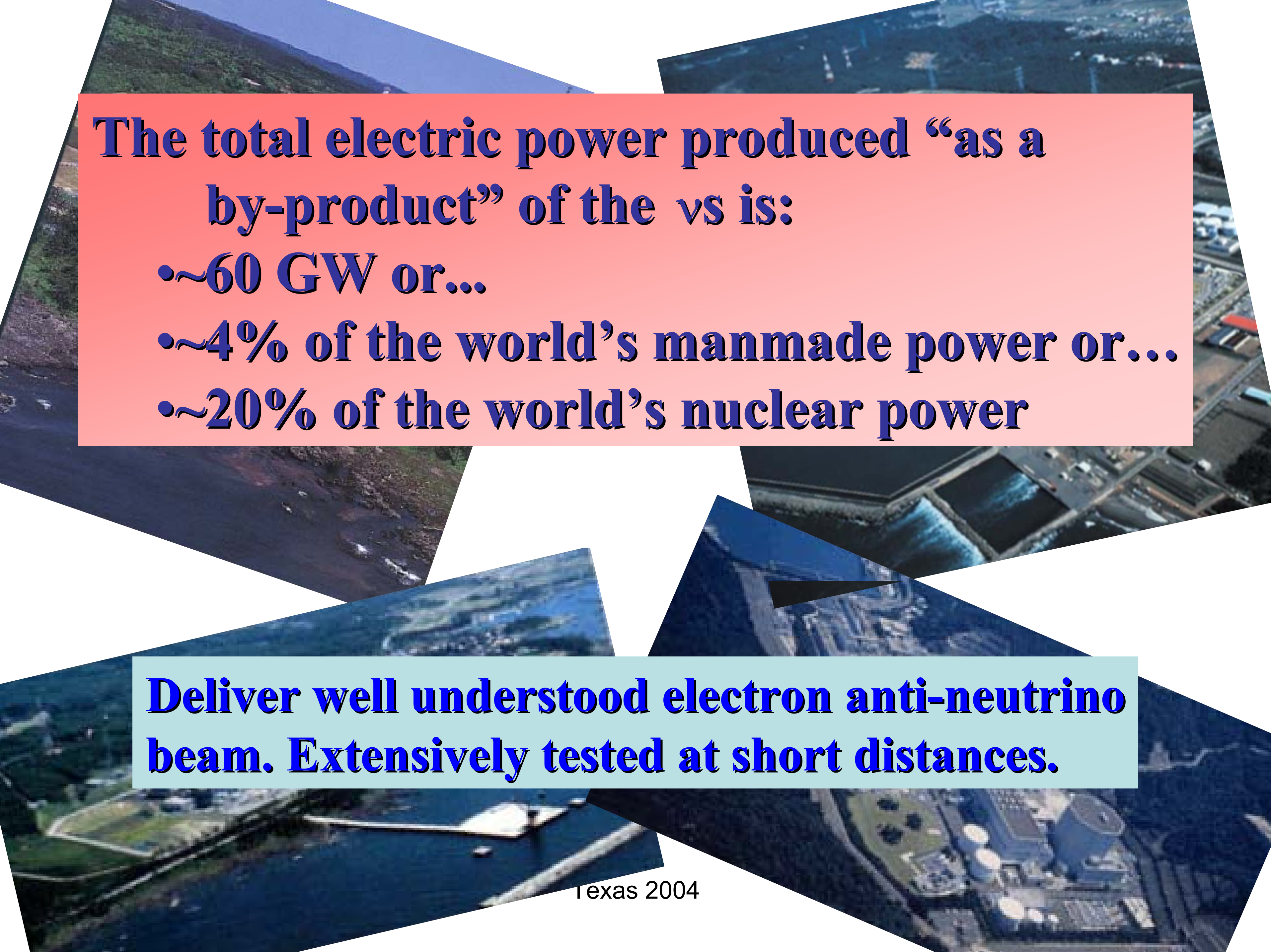


Over the data period

Korean reactors 3.4±0.3%

Rest of the world +JP research reactors 1.1±0.5%

Japanese spent fuel 0.04±0.02%

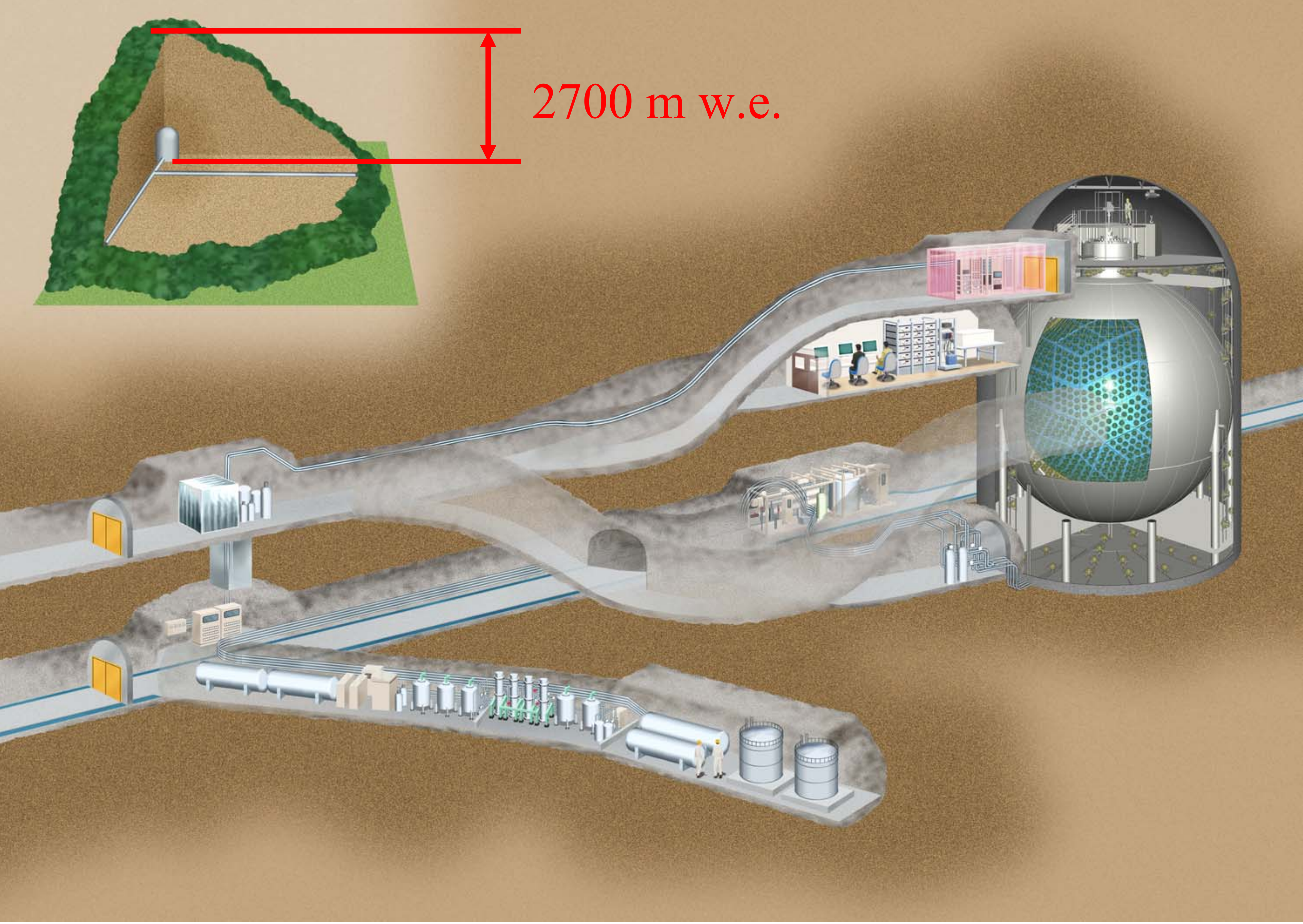


The total electric power produced "as a by-product" of the νs is:

- **~60 GW or...**
- **~4% of the world's manmade power or…**
- **~20% of the world's nuclear power**

Deliver well understood electron anti-neutrino beam. Extensively tested at short distances.

The KamLAND Detector


2700 m w.e.

ν det. at low energy is tricky: beware of backgrounds !

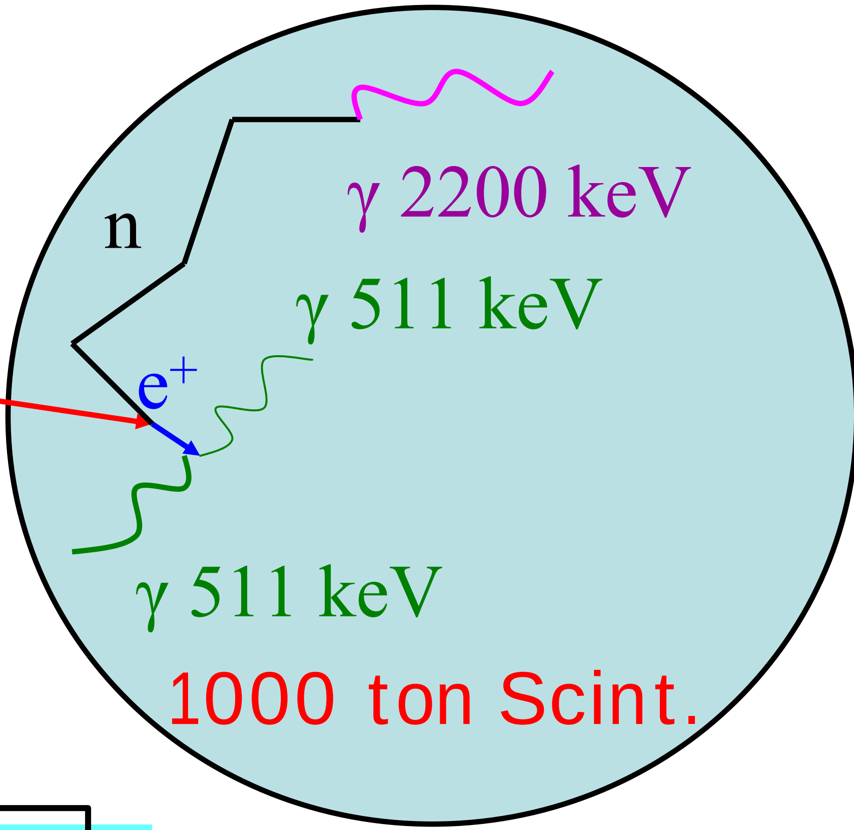
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

$\tau \approx 200\ \mu s$

$$p + n \rightarrow d + \gamma(2.2\ MeV)$$

Event tagging by delayed coincidence in energy, time and space

$\overline{\nu}_e$



10-40 keV

800 MeV

$$E_{\overline{\nu}} \cong E_{e^+} + E_n + (M_n - M_p) + m_{e^+}$$

→ E_ν measurement

○ **Detector site : Old Kamiokande site (2700 m.w.e.)**

○ **1,000 ton Liquid Scintillator**

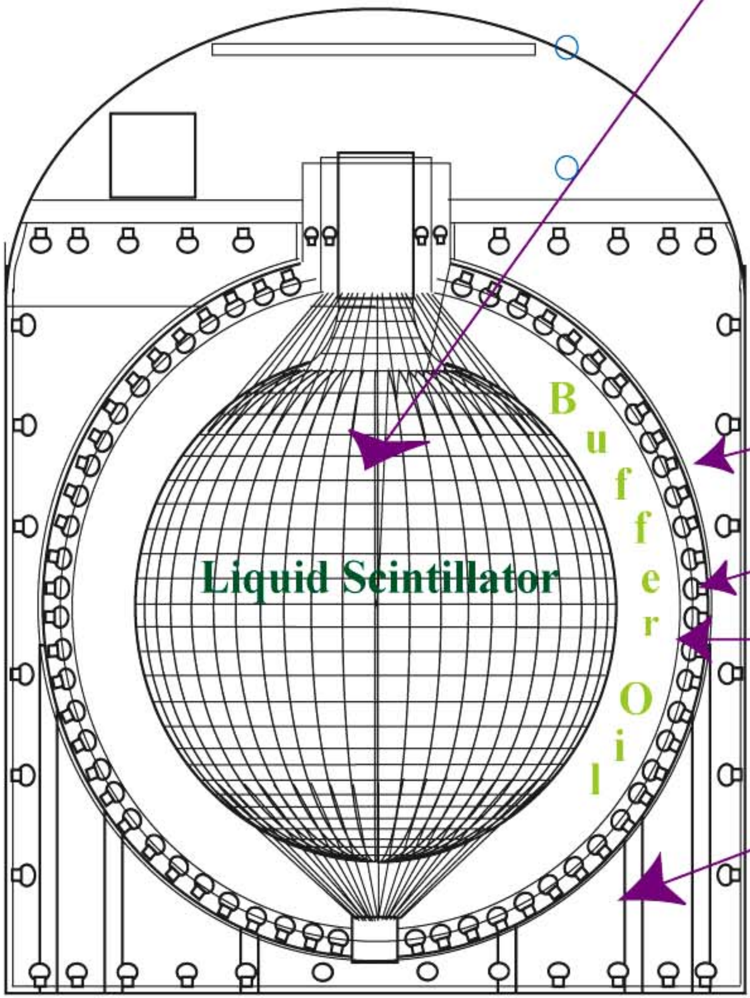
80%: dodecane, 20%: pseudocumene, 1.5 g/liter: PPO

(= 0.78)

housed in spherical balloon (13m diameter)

of transparenet nylon/EVOH composite film (135 m)

supported by cargo net structure



○ **3,000 m^3 Scintillation Light Detector**

○ 18m diameter stainless steel tank filled with paraffin oil (= 0.04%, lighter than LS)

○ 1,325 17-inch+554 20-inch PMT's photosensitive coverage ~ 34 %

○ 3mm thick acrylic wall (120 plates) : Rn barrier

○ **Water Cherenkov Outer Detector**

225 Kamiokande 20-inch PMT's

The Data

Number of Observed & Expected Events

	1st result	2nd result (515.1 d)
	162.2 ton•yr	766.3 ton•yr
Observed ev.	54	258
Expected ev.	86.8 ± 5.6	365.2 ± 23.7
Background ev.	0.95 ± 0.99	17.8 ± 7.3
accidental	0.0086 ± 0.0005	2.69 ± 0.02
$^{9}Li/^{8}He$ (β, n)	0.94 ± 0.85	4.8 ± 0.9
fast neutron	0 ± 0.5	< 0.89
$\alpha(^{13}C,n)^{16}O$	1.9±1.3	10.3±7.1

disappearance

On average 2 days per hit! For a 540 ton detector.

Evidence for Reactor $\bar{\nu}_e$ Disappearance

$$\frac{N_{obs} - N_{BG}}{N_{expected}}$$

=

1st

0.611 ± 0.085 (stat)

± 0.041 (syst)

99.95 % CL

2nd

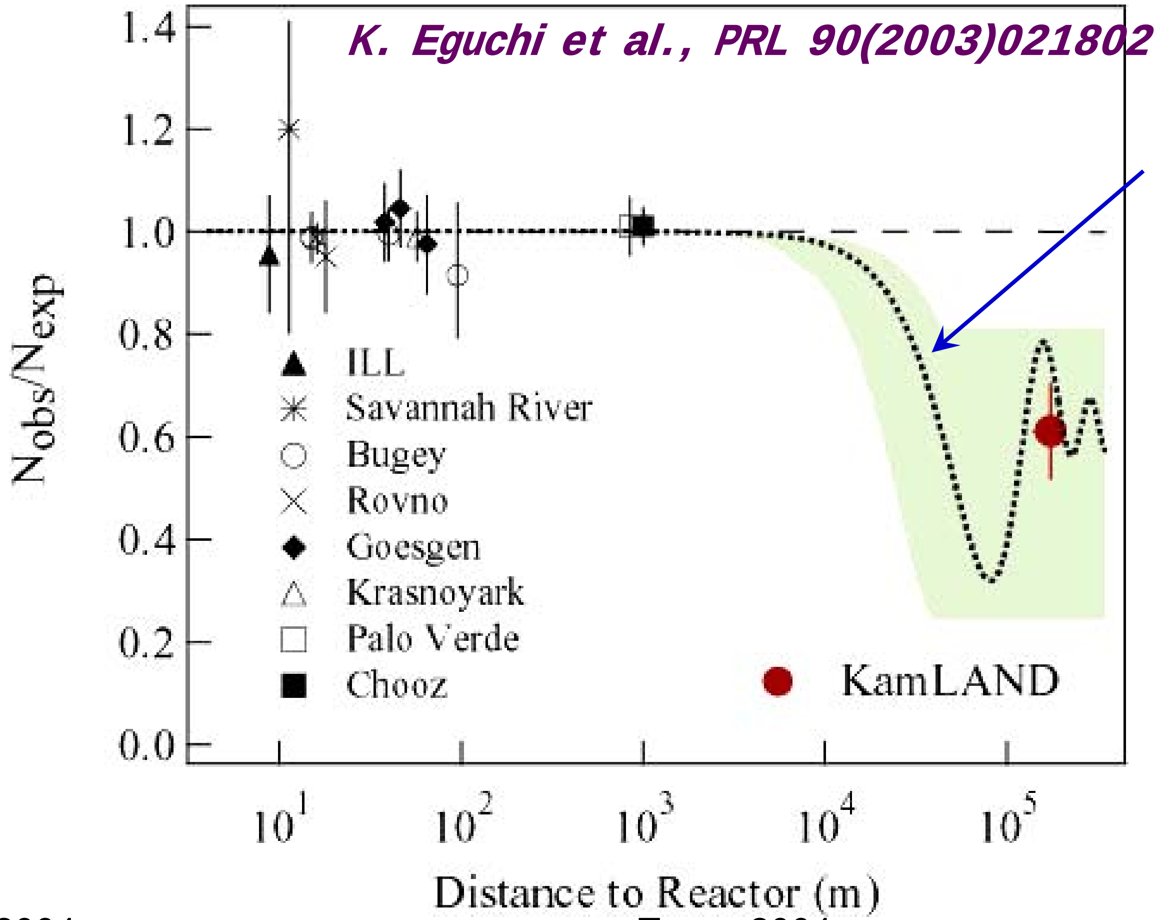
$= 0.658 \pm 0.044$ (stat)

± 0.047 (syst)

99.998 % CL

Analysis Results

1st result : Evidence for Reactor Antineutrino Disappearance

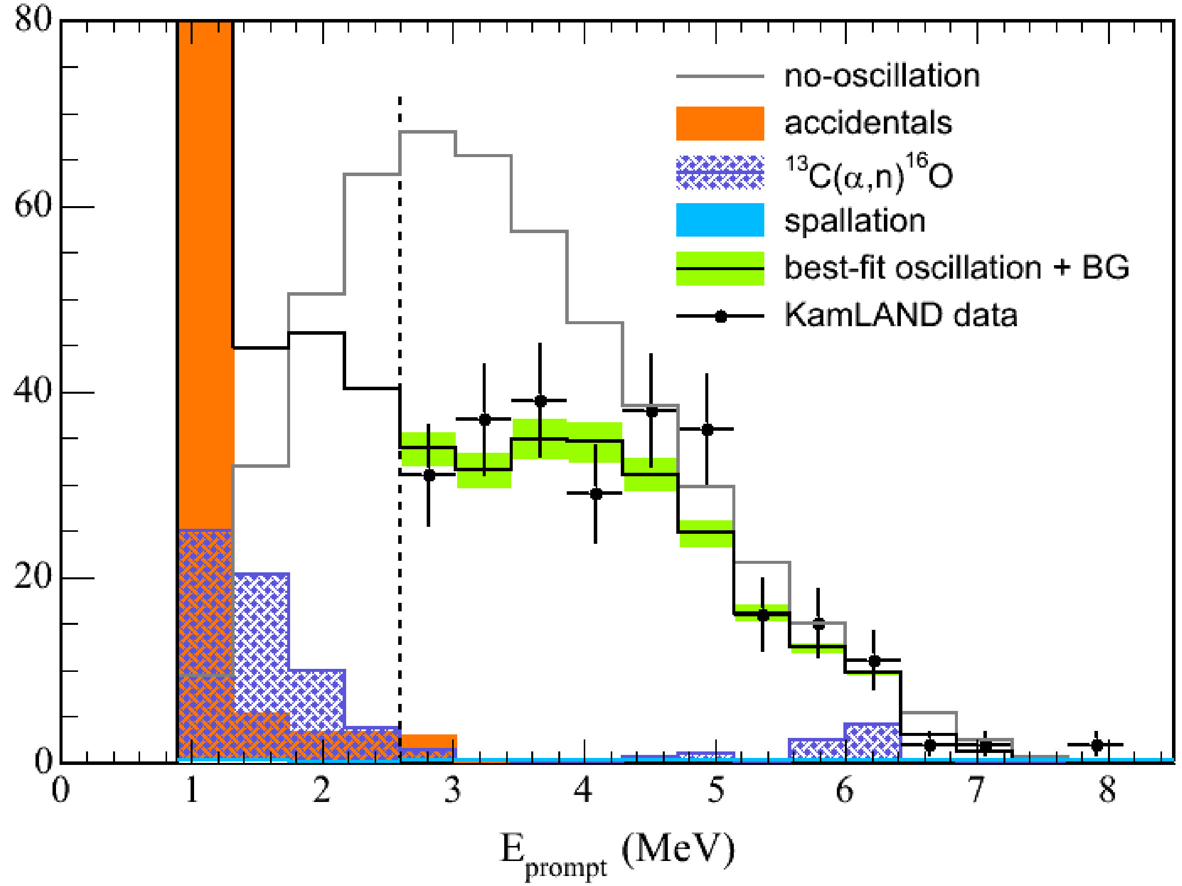


LMA:
$\Delta m^2 = 5.5\times10^{-5}\ eV^2$
$\sin^2 2\Theta = 0.833$

What else do we know?

Energy spectrum adds substantial information

Best fit to oscillations gives a Pearson $\chi^2/ndf=24.2/17$ *(goodness of fit 11%)*



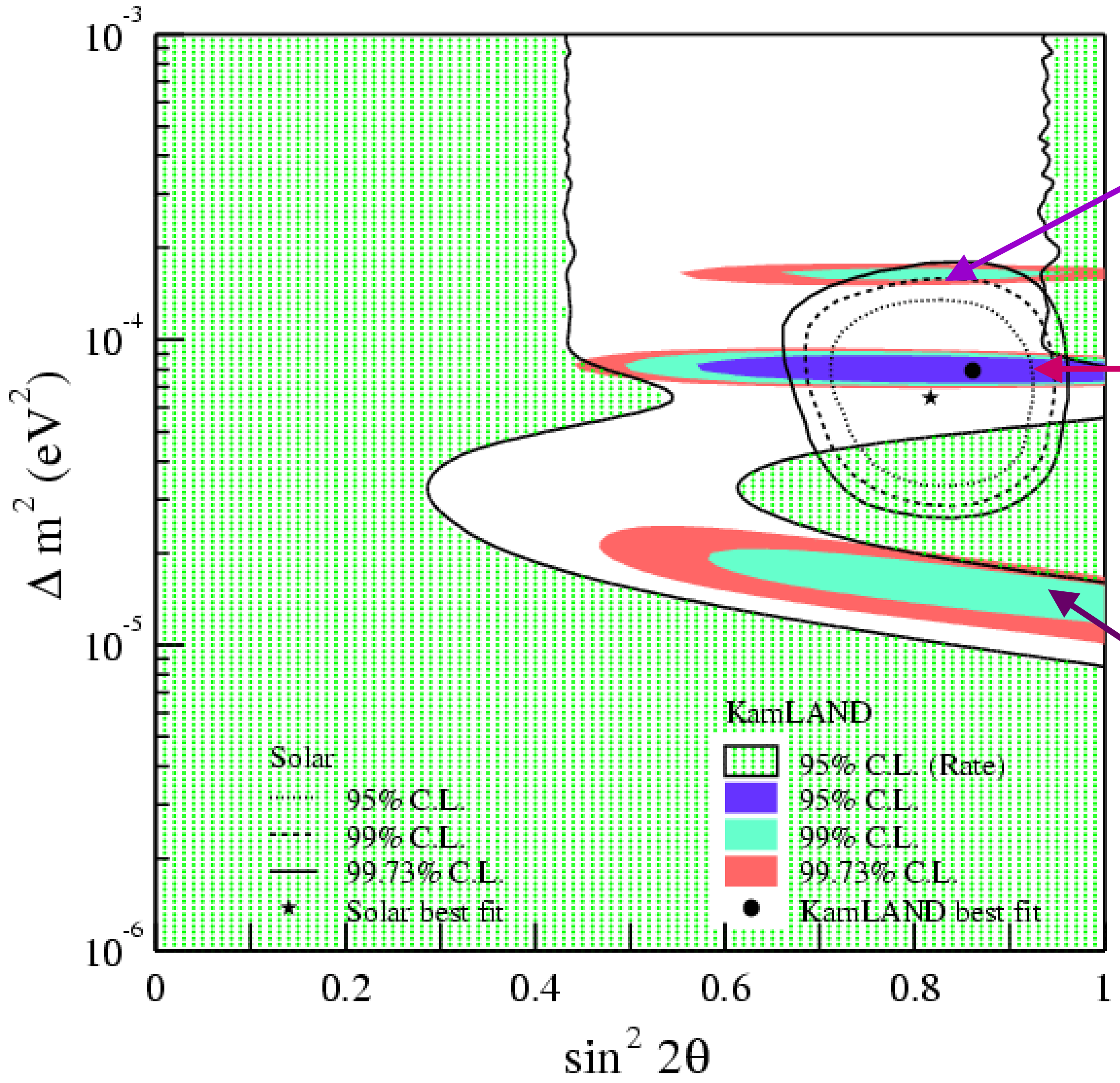
Below E_{prompt}=2.6MeV there is also "background" from geo-neutrinos (not shown here)

Fit to a rescaled reactor spectrum is much worse ($\chi^2/ndf=37.3/18$, goodness 0.4%)

So the evidence for oscillations does not simply rely on the knowledge of reactor power

Un-binned likelihood fit to 2-flavor oscillations

Rate and shape analysis

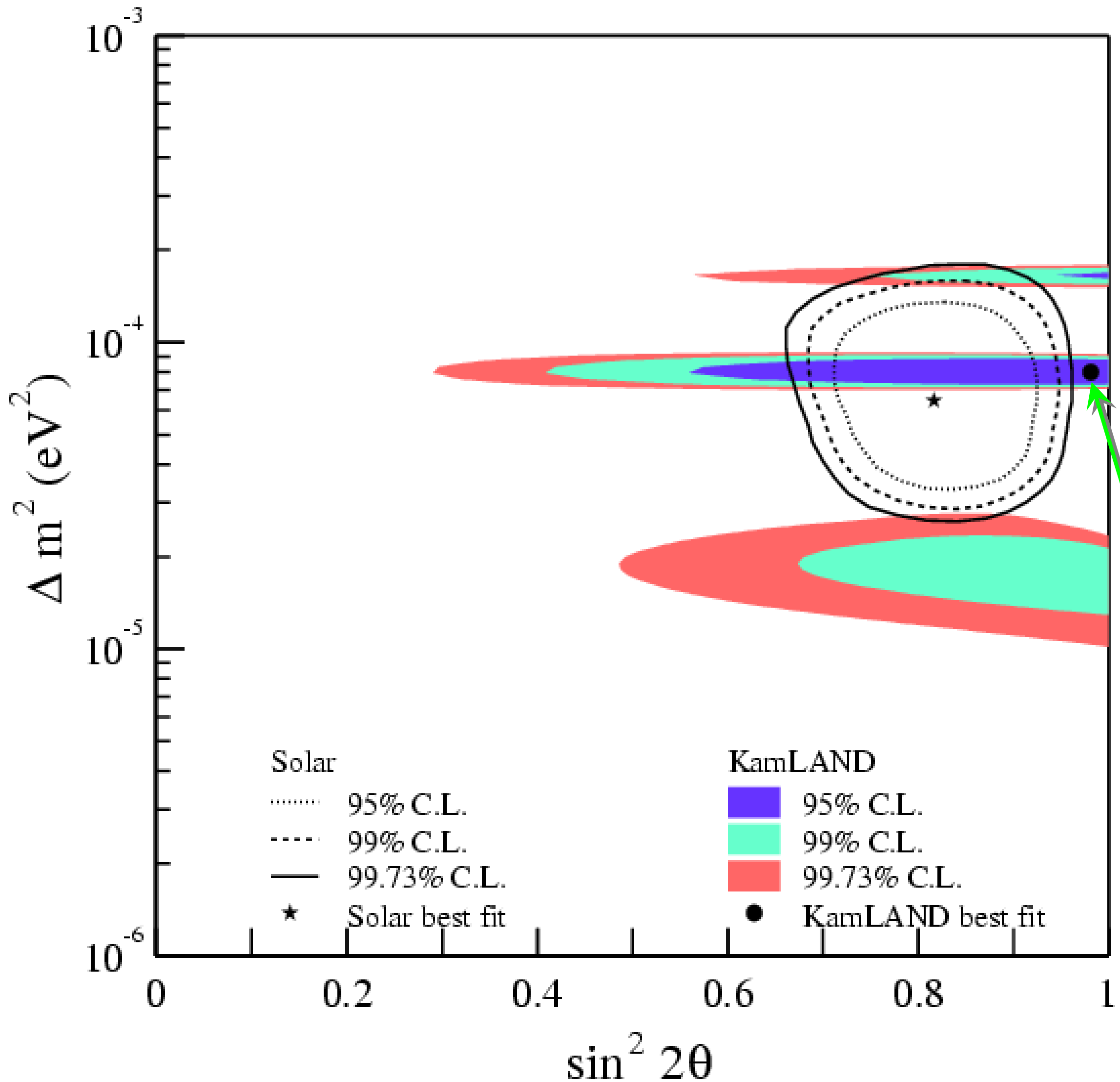


LMA2 : disfavored at 98.0% CL

LMA1 : best fit
$\Delta m^2 = 7.9 \times 10^{-5}\ eV^2$
$\sin^2 2\theta = 0.86$

LMA0 : disfavored at 97.5% CL

Allowed Parameter Regions (spectrum only fit)



Δm^2 & $\sin^2 2\theta$

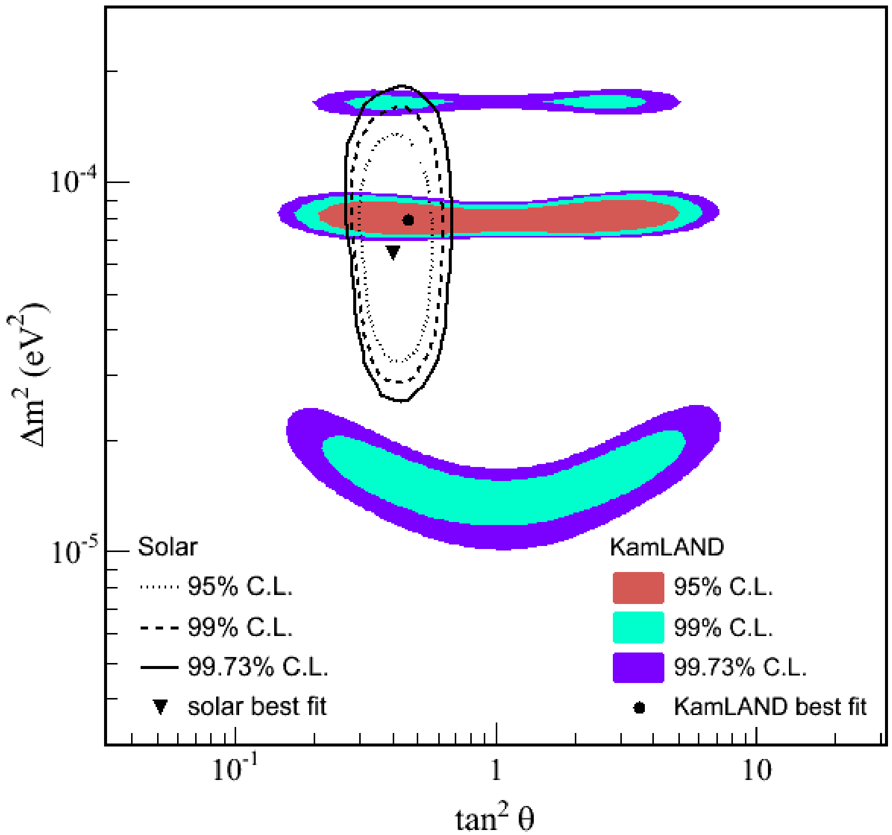
are determined mostly by spectrum distortion

strongly suggest

reactor neutrino anomaly
← neutrino oscillations

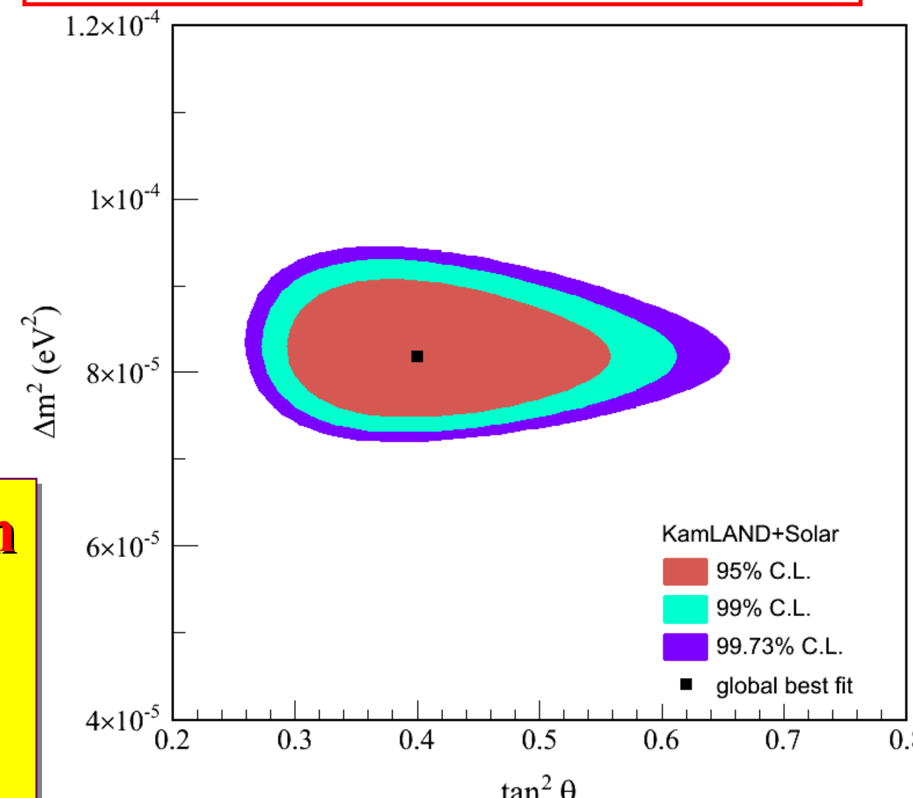
spectrum distortion favors maximal mixing

Combined solar ν – KamLAND 2-flavor analysis



$$\Delta m_{12}^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5} eV^2$$

$$\tan^2\theta_{12} = 0.40^{+0.10}_{-0.07}$$



Assume CPT invariance

The most precise determination of Δm^2 to date.
Δm^2 dominated by KamLAND
tan2θ dominated by solar exp.

SNO shows deficit in ν_e flux but the correct $\nu_e + \nu_\mu + \nu_\tau$ flux → evidence for particle physics solution of solar ν problem. Solar model is basically correct.

$\overline{\nu}_e$ disappearance observed in KamLAND at 99.998% c.l.

KamLAND data shows significant spectral modification → direct evidence for neutrino oscillations.

Solar neutrino deficit explained through MSW effect. Terretrial measurement observes same mixing parameters using anti-particles and vacuum oscillations.

Take SNO and KamLAND together: the solar neutrino problem has been resolved.

Combined analysis with solar experiments yields:

$$\Delta m_{12}^2 = 7.9 {}^{+0.6}_{-0.5} \times 10^{-5}\, eV^2; \tan^2\theta_{12} = 0.40 {}^{+0.10}_{-0.07}$$ precision data!

There is now direct and independently confirmed evidence for ν oscillations in both the atmospheric and solar parameter ranges.

Neutrinos are massive particles!

$$\Delta m_{31}^2 = \left(2.2^{+0.7}_{-0.5}\right)\cdot 10^{-3}\ \mathrm{eV}^2 \qquad \sin^2\theta_{23} = 0.5^{+0.14}_{-0.12}$$

$$\Delta m_{21}^2 = \left(7.9^{+0.6}_{-0.5}\right)\cdot 10^{-5}\ \mathrm{eV}^2 \qquad \sin^2\theta_{12} = 0.3^{+0.04}_{-0.05}$$

$$\sin^2\theta_{13} < 0.028$$

Absolute mass still unknown. If degenerate (<2.2 eV) could be important DM component.

To be determined by new generation of β–decay and ββ–decay experiments.