Neutrino Physics and Astrophysics

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Neutrino mixing

- EW CC: $j_\alpha^W = 2 \sum_{l=e,\mu,\tau} \bar{\nu}_{lL} \gamma_\alpha l_L + 2 \sum_{q=u,c,t q'=d',s',b'} \bar{q}_L \gamma_\alpha q'_L$

where ν_{lL}, l_L,q_L are left-handed neutrino, lepton and quark fields and $q'_L = \sum_{q=d,s,b} U_{q'q} q_L$

- In analogy to quark mixing in the lepton sector: $\nu_{lL} = \sum_k U_{lk} \nu_{kL}$ where U is unitary, ν_k is the ν field with mass m_k.
- Since Q_ν=0 neutrinos can be Dirac or Majorana particles...

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Dirac mass term

$$L^D = -\sum_{l',l} \bar{\nu}_{l'R} M_{l'l} \nu_{lL} + h.c = -\bar{\nu}'_R M \nu'_L + h.c.$$

$$\nu'_L = \begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} \qquad \nu'_R = \begin{pmatrix} \nu_{eR} \\ \nu_{\mu R} \\ \nu_{\tau R} \end{pmatrix}$$

- Diagonalisation M=VmU$^+$ $\Longrightarrow \mathcal{L}$ in terms of mass eigenstates :

$$L^D = -\bar{\nu}_R m \nu_L - \bar{\nu}_L m \nu_R = -\bar{\nu} m \nu = -\sum_{k=1}^{3} m_k \bar{\nu}_k \nu_k$$

$$\nu_R = V^+ \nu'_R \qquad \nu = \nu_R + \nu_L = \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\nu_L = U^+ \nu'_L$$

Majorana mass term

- Using ν_{lL} and $(\nu_{lL})^c = C\bar{\nu}_{lL}{}^T$ (Charge conjugation matrix)
- $L^M = -\frac{1}{2}\sum_{l',l}(\bar{\nu}_{l'L})^c M_{l'l}\nu_{lL} + h.c = -\frac{1}{2}(\bar{\nu}'_L)^c M\nu'_L + h.c.$
- M is symmetric $M = (U^+)^T m U^+$

Violates L

$$L^M = \frac{1}{2}(\nu'_L)^T C^{-1}(U^+)^T m U^+ \nu'_L + h.c. = -\bar{\chi} m \chi = \frac{1}{2}\sum_{k=1}^{3} m_k \bar{\chi}_k \chi_k$$

$$\chi = U^+\nu'_L + (U^+\nu'_L)^c = \begin{pmatrix} \chi_1 \\ \chi_2 \\ \chi_3 \end{pmatrix}$$

Field with majorana mass m_k

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General term

- Dirac +Majorana mass terms with L&R-handed fields

$$L^{D-M} = -\frac{1}{2}\left[(\bar{\nu'}_L)^c M_L \nu'_L + (\bar{\nu}'_R M_R (\nu'_R)^c + \bar{\nu_R}' M_D \nu'_L + (\bar{\nu_L}')^c M_D^T (\nu'_R)^c\right] + h.c.$$

$$L^{D-M} = -\frac{1}{2}(\bar{n_L})^c M n_L + h.c.$$

$$n_L = \begin{pmatrix} \bar{\nu'}_L \\ (\nu'_R)^c \end{pmatrix}$$

$$M = \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix}$$

- Diagonalising M we get :

$$L^{D-M} = -\frac{1}{2}\bar{\chi} m \chi = -\frac{1}{2}\sum_{k=1}^{6} m_k \bar{\chi}_k \chi_k$$

$$\underset{\substack{\uparrow \\ \text{Majorana type}}}{\chi} = U^{+} n_L + (U^{+} n_L)^c = \begin{pmatrix} \chi_1 \\ \vdots \\ \chi_6 \end{pmatrix}$$

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More on the general mass term

$$n_L = U\chi_L \qquad \nu_{lL} = \sum_{k=1}^{6} U_{lk}\chi_{kL} \qquad (\nu_{lR})^c = \sum_{k=1}^{6} U_{\bar{l}k}\chi_{kL}$$

1st 3 rows

Last 3 rows

Right handed neutrinos (sterile)

- $\nu_l \longrightarrow \nu_{l'}$ flavour transitions are possible
- Active to sterile neutrinos are also possible !

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For one family

- M=Om'O^T (no CP violation) $O = \begin{pmatrix} sin\theta & -cos\theta \\ cos\theta & sin\theta \end{pmatrix}$

$$\nu_L = sin\theta\chi_{1L} - cos\theta\chi_{2L}$$
$$(\nu_R)^c = cos\theta\chi_{1L} + sin\theta\chi_{2L}$$

$$m_L = sin^2\theta m'_1 + cos^2\theta m'_2$$
$$m_R = cos^2\theta m'_1 + sin^2\theta m'_2$$

$$2m_D = sin2\theta(m'_1 - m'_2)$$

- M eigenvalues :

$$m'_{1,2} = \frac{1}{2}(m_L + m_R \pm \sqrt{(m_L - m_R)^2 + 4m_D^2})$$

$$sin2\theta = \frac{2m_D}{\sqrt{(m_L - m_R)^2 + 4m_D^2}}$$

Seesaw Mechanism

- Limiting case $m_L \approx 0$, $m_R >> m_D$

$m_1 \approx m_R$, $m_2 \approx m_D{}^2/m_R$

$$m'_{1,2} = \frac{1}{2}(m_L + m_R \pm \sqrt{(m_L - m_R)^2 + 4m_D^2})$$

$$sin2\theta = \frac{2m_D}{\sqrt{(m_L - m_R)^2 + 4m_D^2}}$$

$\theta \approx m_D/m_R$

$\nu_L \approx -\chi_{2L}$ $(\nu_R)^c \approx \chi_{1L}$

If $m_D \approx m_{l,q}$ then $m_\nu \approx m_q{}^2/m_R$ or $m_l{}^2/m_R$

m_R is assumed GUT scale ~10^{14}GeV

The heavy right-handed Majorana mass generates the small active neutrino mass

Oscillations in vacuum

$|\nu_l\rangle = \Sigma_k U^*_{lk} |\nu_k\rangle$ $|\nu_k(t)\rangle = e^{-iE_k t} |\nu_k(0)\rangle$

$|\nu_l(t)\rangle = \Sigma_{l'} \Sigma_k U_{l'k} e^{-iE_k t} U^*_{lk} |\nu_{l'}\rangle$

Transition amplitude: $A_{ll'}(t) = \langle \nu_{l'} | \nu_l(t)\rangle = \Sigma_k U_{l'k} U^*_{lk} e^{-iE_k t}$

$P(\nu_l \longrightarrow \nu_{l'}) = |A_{ll'}(t)|^2 = \Sigma_{kj} U^*_{lk} U_{l'k} U_{lj} U^*_{l'j} e^{-i(E_k - E_j)t}$

relativistic ν: $m \ll E$: $E_k - E_j \approx \Delta m_{kj}^2/2E$

$P(\nu_l \longrightarrow \nu_{l'}) = |A_{ll'}(t)|^2 = \Sigma_{kj} U^*_{lk} U_{l'k} U_{lj} U^*_{l'j} e^{-i(\Delta m^2_{kj}\ L/2E)}$

Oscillations cont'd

- Measuring oscillations will give us information on the mass differences
- Measurement of symmetry conservation:
  - CP violated : $P(\nu_\alpha \longrightarrow \nu_\beta) \neq P(\overline{\nu}_\alpha \longrightarrow \overline{\nu}_\beta)$
  - T violated :$P(\nu_\alpha \longrightarrow \nu_\beta) \neq P(\nu_\beta \longrightarrow \nu_\alpha)$
  - CPT conserved :$P(\nu_\alpha \longrightarrow \nu_\beta) = P(\overline{\nu}_\beta \longrightarrow \overline{\nu}_\alpha)$

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Mixing in two families

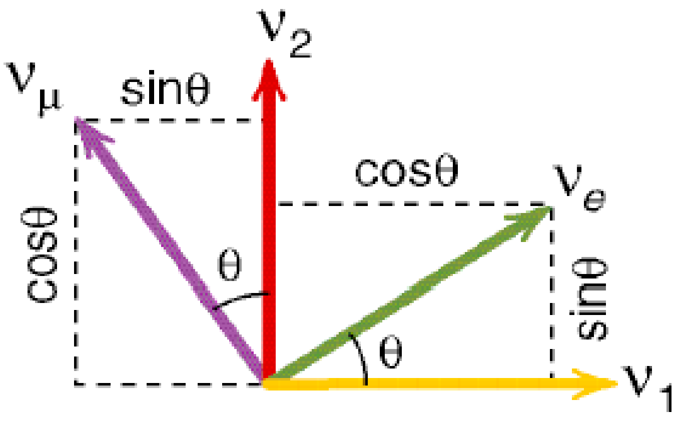
- Then mass and weak states are connected by means of an unitary transformation, the PMNS mixing matrix, which depends of a single parameter, the mixing angle θ

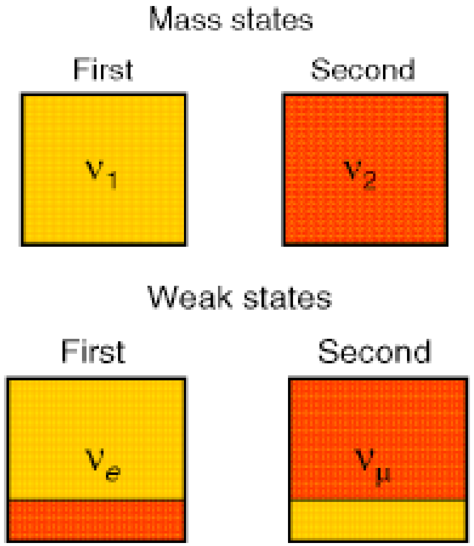
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{aligned} \nu_l &= \cos\theta \nu_1 - \sin\theta \nu_2 \\ \nu_{l'} &= \sin\theta \nu_1 + \cos\theta \nu_2 \end{aligned}$$

$$P_{\nu_1 \rightarrow \ \nu_2} = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$

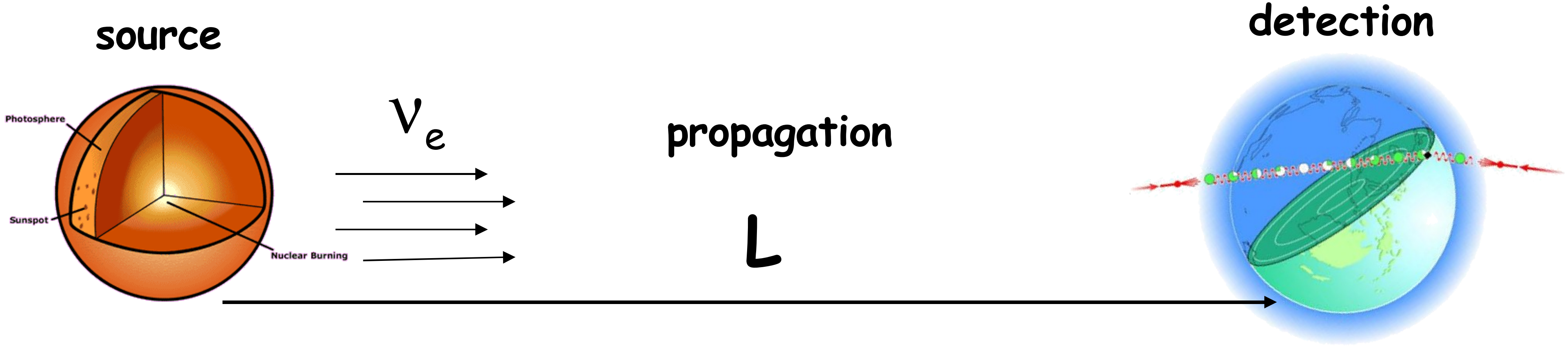
$$L_v = \frac{4\pi E}{\Delta m^2} \approx 2.47 \frac{E(GeV)}{\Delta m^2(eV^2)} \ km$$





PMNS: Pontecorvo-Maki-Nakagawa-. Sakata

Neutrino oscillations



The weak interaction produces neutrinos of a given flavour

$$|\nu(x_0)>=|\nu_e>$$
$$= c|\nu_1> +s|\nu_2>$$

The mass eigenstates Propagate at different velocities

$$|\nu(x)>= c|\nu_1> e^{i(Et-\vec{k}_1\vec{x})}$$
$$+s|\nu_2> e^{i(Et-\vec{k}_2\vec{x})}$$

Detection again via weak interaction

$$\nu_e + n \rightarrow e^- + p$$

$$P(\nu_e \rightarrow \nu_\mu) = |<\nu_\mu|\nu(x)>|^2$$

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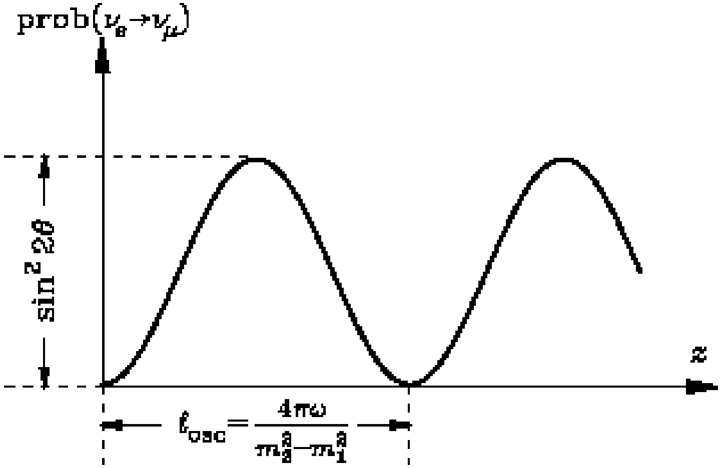
Oscillation Probability

$$P_{(\nu_e \to \nu_\mu)}(L) = sin^2(2\theta) sin^2 \left(1.27 \frac{\Delta m^2(eV^2)}{E(GeV)} L(km) \right)$$

$$P_{\nu_e \to \nu_e}(L) = 1 - P_{\nu_e \to \nu_\mu}(L)$$



$$L_v = \frac{4\pi E}{\Delta m^2} \approx 2.47 \frac{E(GeV)}{\Delta m^2(eV^2)}\ km$$

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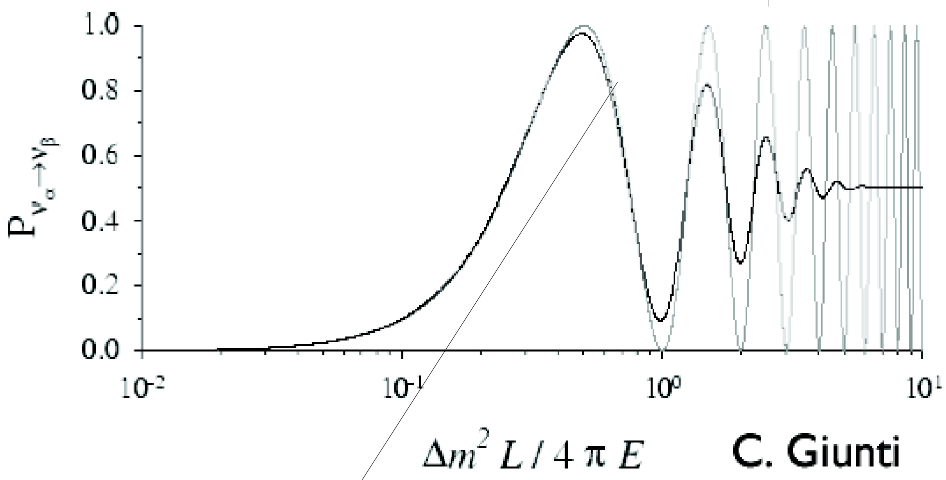
Sensitivity to oscillations

- Disappearance experiments measure survival probability
- Appearance look for a different flavour
- No signal for $\frac{\Delta m^2 L}{2E} \ll 1$
- Averaged out if $\frac{\Delta m^2 L}{2E} \gg 1$



C. Giunti

single energy value

Gaussian E spectrum

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Do oscillations solve the solar neutrino problem ?

- So far experiments did not measure NC
- If SSM is right NC will reproduce SSM fluxes

- Pontecorvo proposed neutrino oscillations in 1969

$$P_{\nu_e \to \nu_e}(E, L(t)) = 1 - \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L(t)}{4E} \right)$$

- With the sun excentricity one should observe seasonal variation n neutrino fluxes

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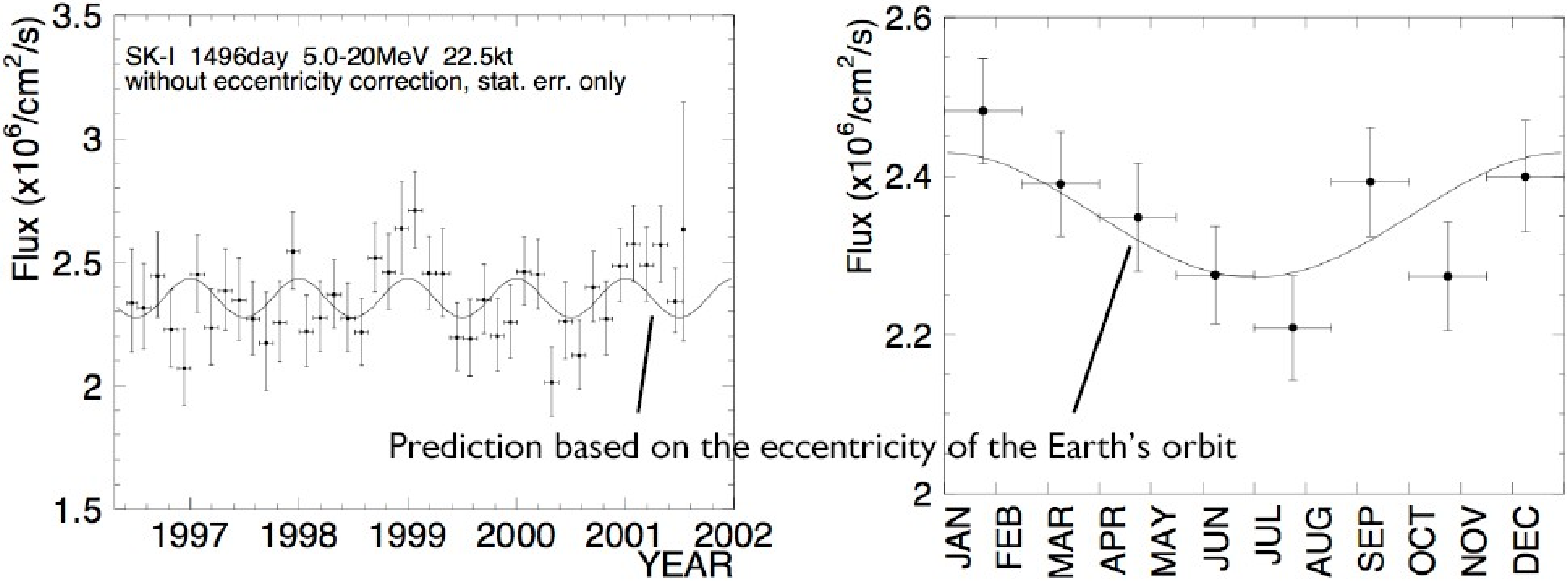
Seasonal variations ?

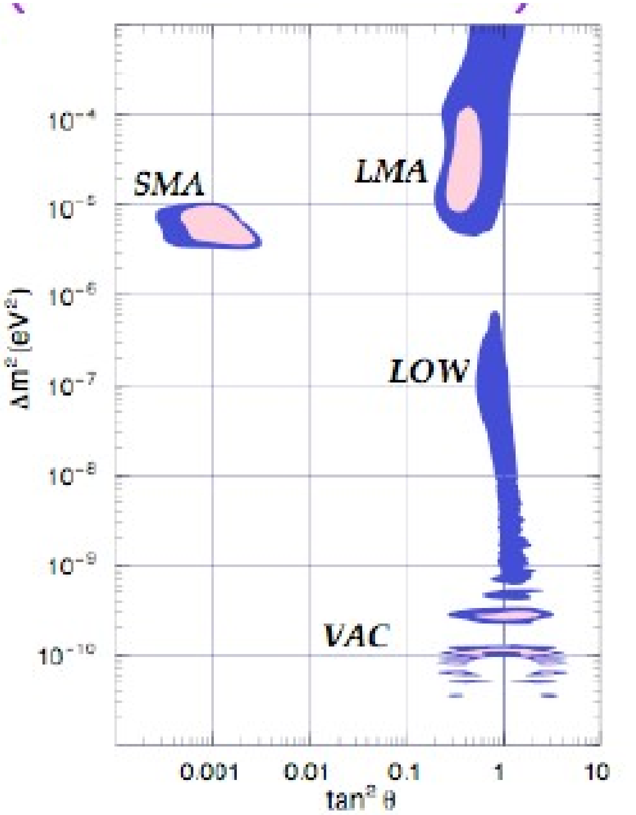


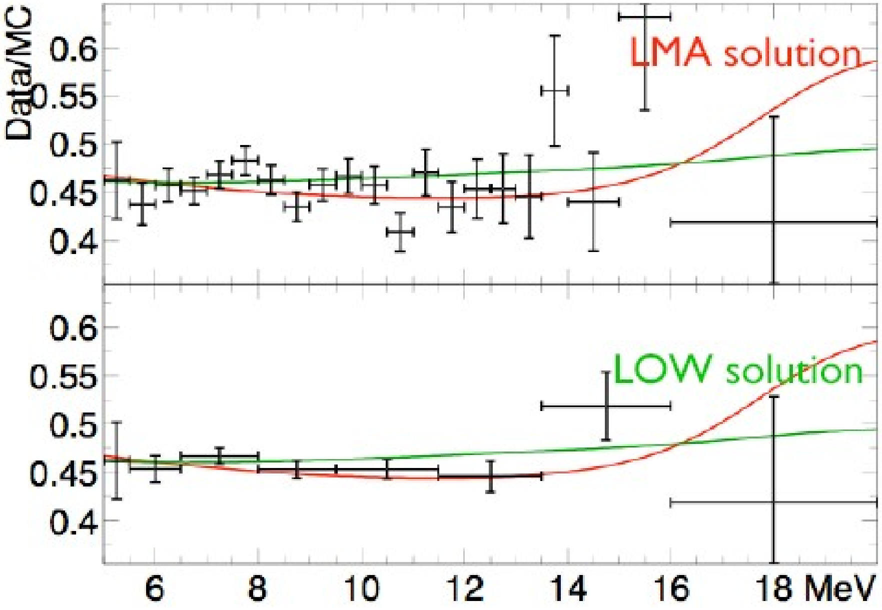
Prediction based on the eccentricity of the Earth's orbit

- The observed variations are compatible with the modulation due to the distance variation
- <u>No extra variation</u> that could be attributed to oscillations

And the E spectrum distortion?

- No distortion of the ^{8}B spectrum is observed in the recoil electron energy in SK…





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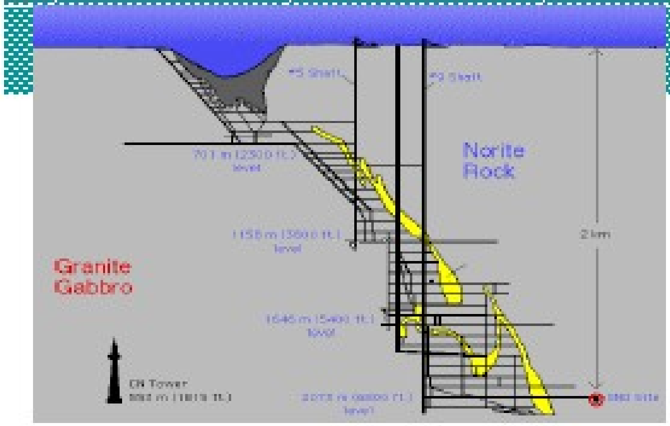
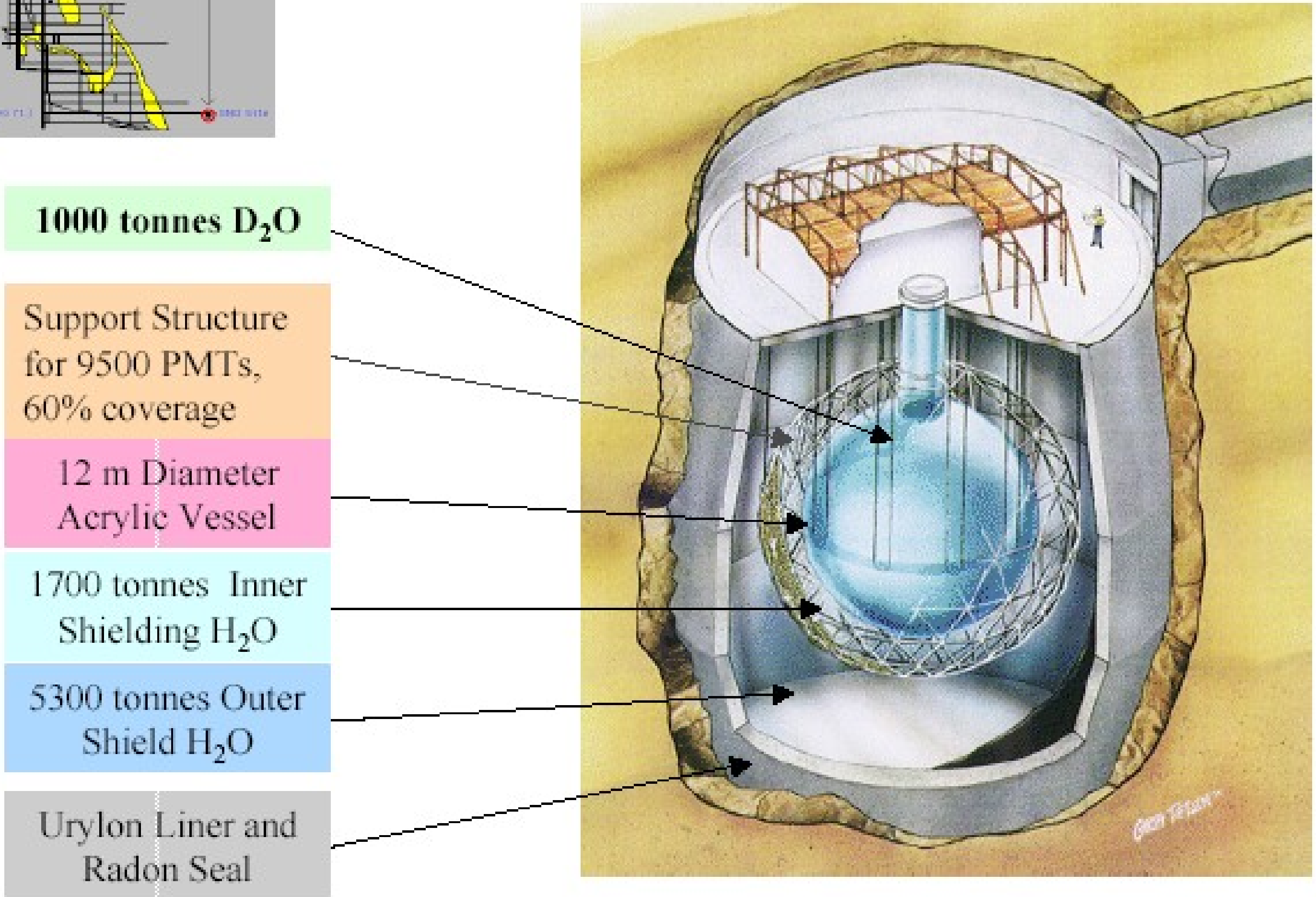
What about neutral currents ?

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

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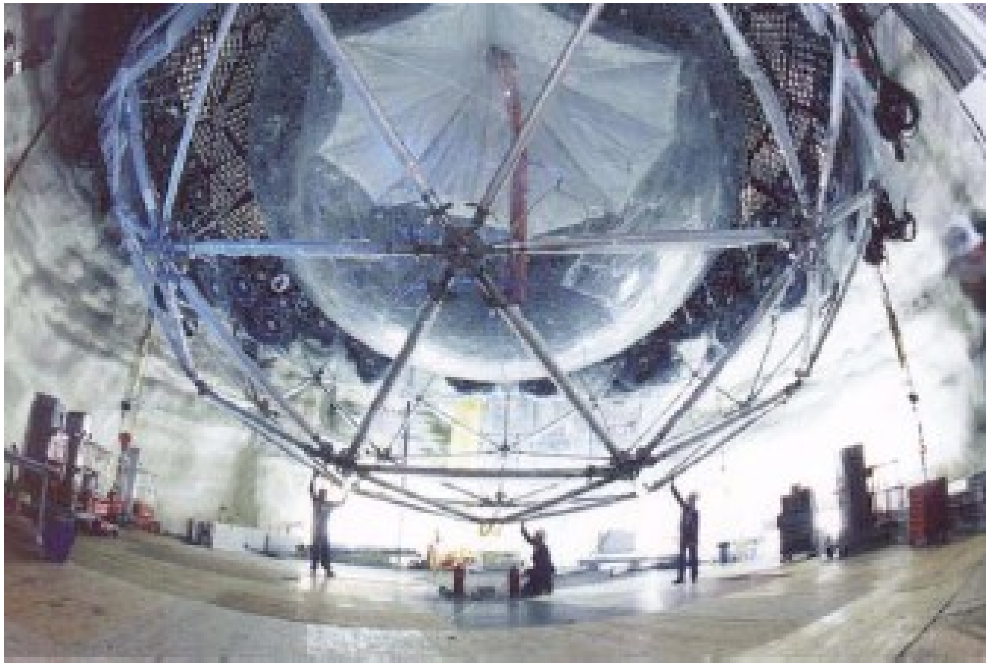
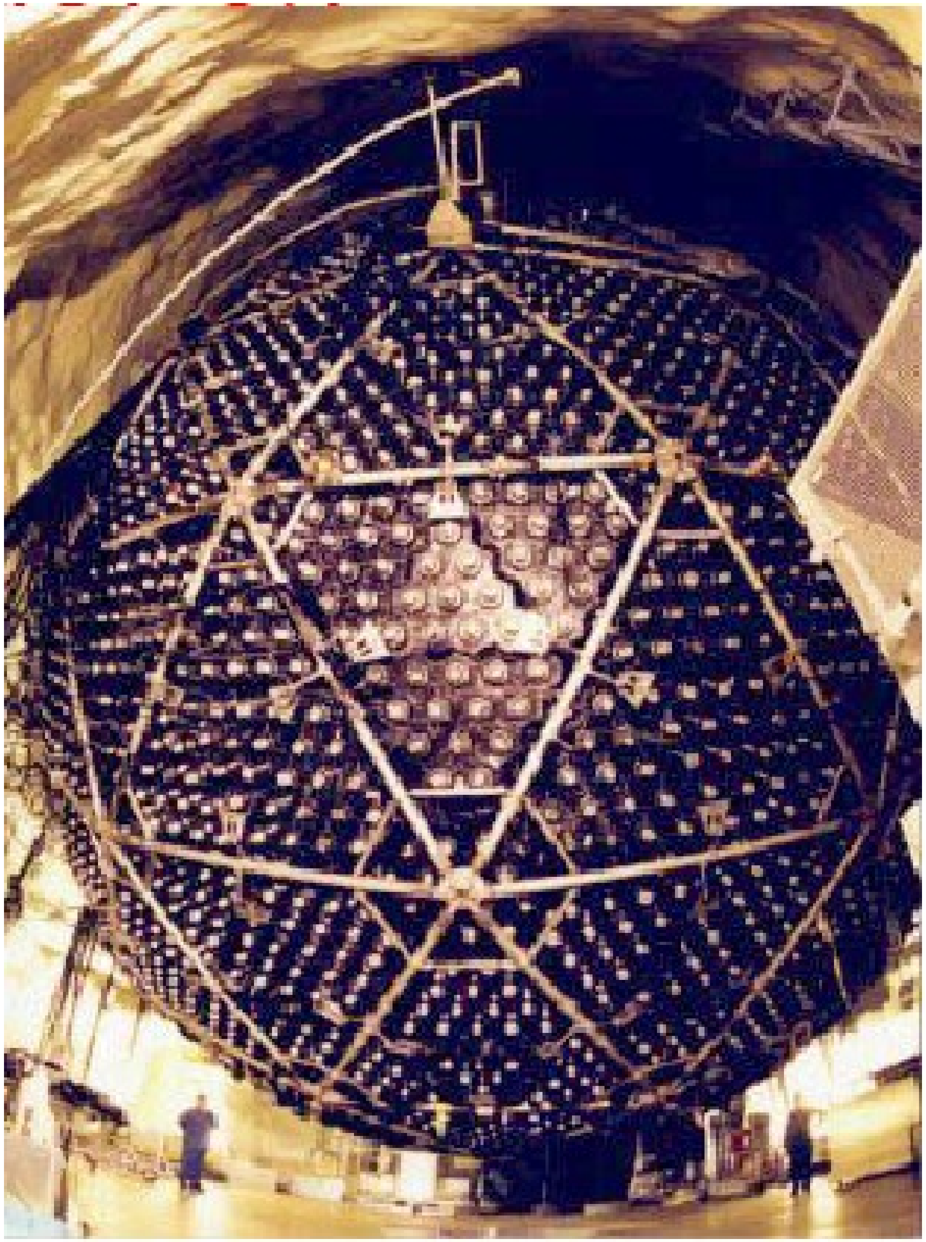
SNO detector

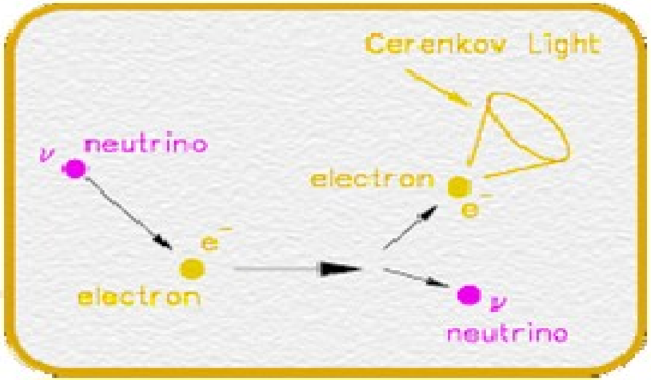




Signals in SNO

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

Strong directional sensitivity

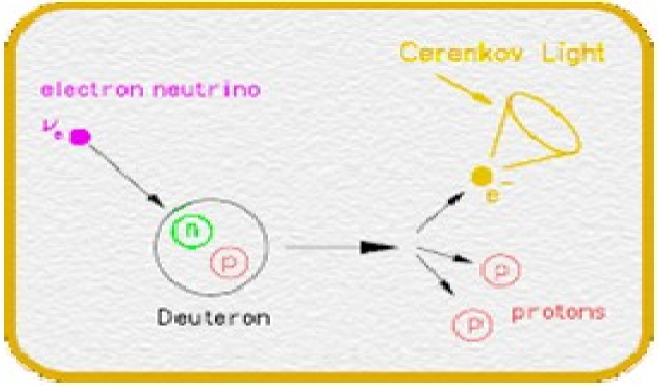


CC $\nu_e + d \rightarrow p + p + e^-$

Good measurement of ν_e spectrum

Weak directional sensitivity

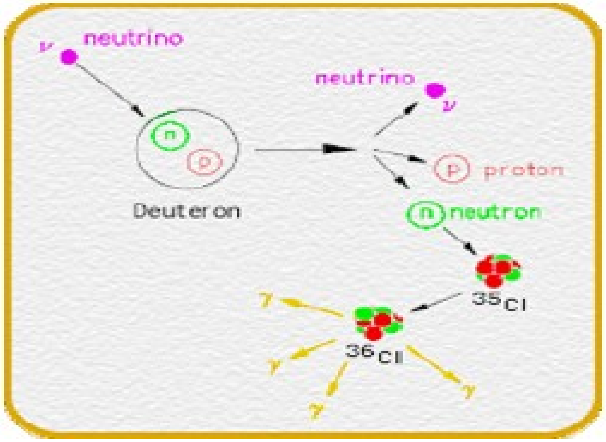
ν_e only



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

Measure total ^{8}B flux from the sun

Equal cross section for all types

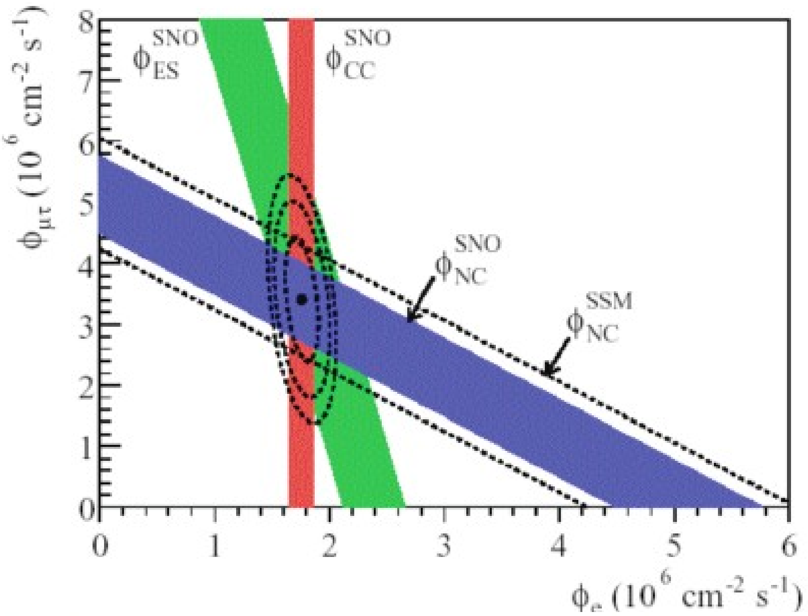


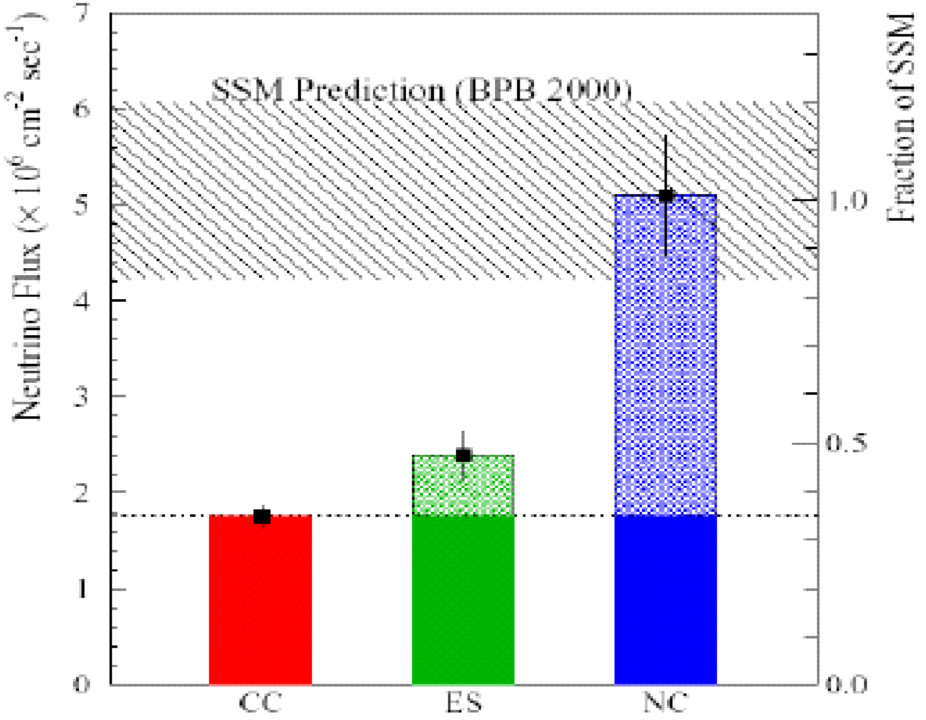
SNO observations

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

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

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

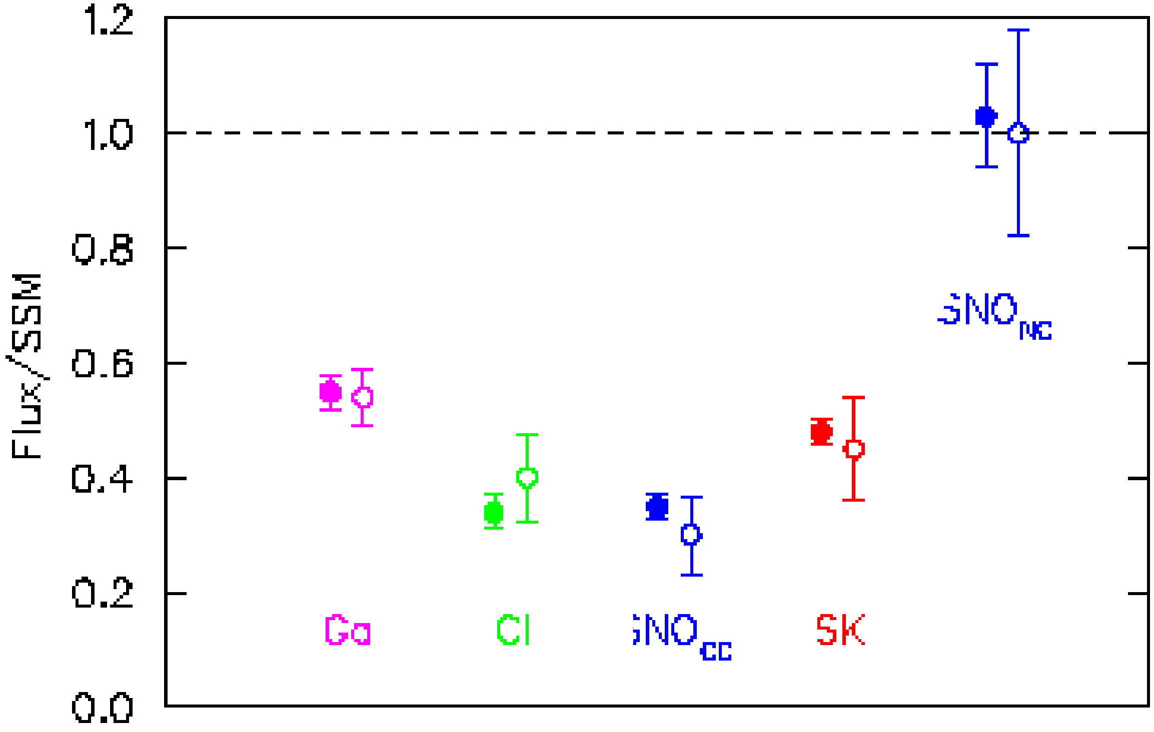




$$\Phi_{CC}^{SNO} = (1.68 \pm 0.06^{+0.06}_{-0.09}) \quad \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$$
$$\Phi_{NC}^{SNO} = (4.94 \pm 0.21^{+0.38}_{-0.34}) \quad \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$$
$$\Phi_{ES}^{SNO} = (2.35 \pm 0.22 \pm 0.15) \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

$$\frac{\Phi_{CC}^{SNO}}{\Phi_{NC}^{SNO}} = 0.340 \pm 0.023^{+0.029}_{-0.031}$$

The solar neutrino problem



So the sun is shining the expected number of neutrinos but many of them are ν_μ and/or ν_τ! Not only Davis, but also Bahcall was right!

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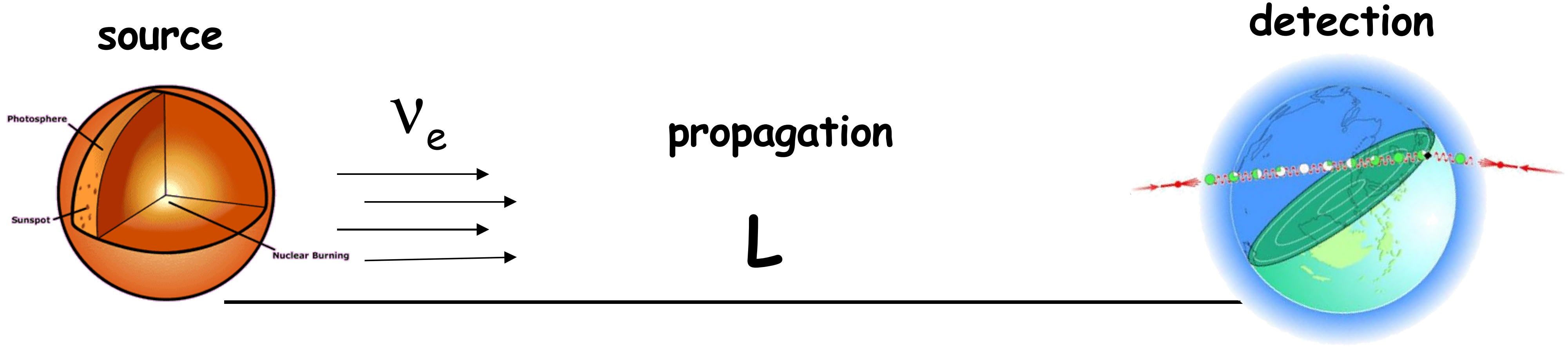
Fine-tuning oscillations ?



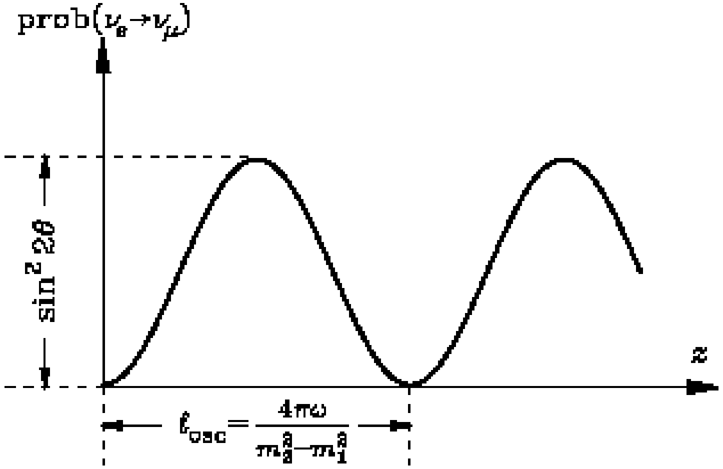
source

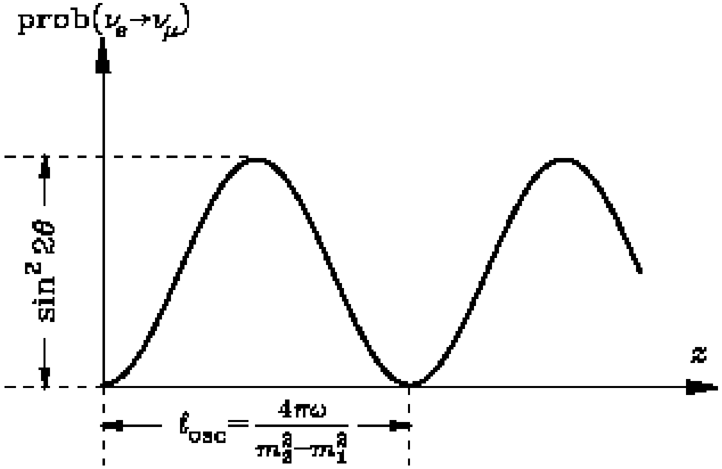
ν_e

propagation

L

detection





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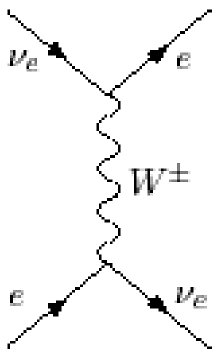
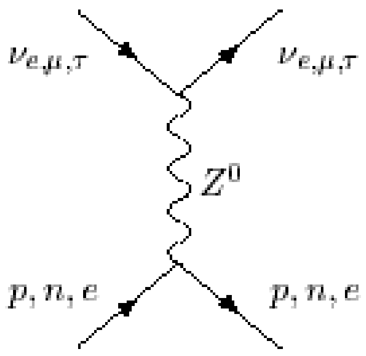
Neutrino oscillations in Matter

ν_e,ν_μ, ν_τ interact with e, p and n of matter via NC interactions (Z). Only ν_e interact via (CC) with the electrons of the medium


Only ν_e


All

- Neutrinos are subject to a potential linked due to their interaction with the medium

$$V_{CC} = \sqrt{2} G_F N_e \qquad V_{NC} = -\frac{1}{2}\sqrt{2} G_F N_n$$

- $V_e = V_{CC} + V_{NC}$
- $V_\mu = V_\tau = V_{NC}$

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Hamiltonian in matter

$$H_m = \begin{pmatrix} E_1\cos^2\theta + E_2\sin^2\theta + C + \sqrt{2}G_F\rho_e & -(E_2-E_1)\sin\theta\cos\theta \\ -(E_2-E_1)\sin\theta\cos\theta & E_2\cos^2\theta + E_1\sin^2\theta + C \end{pmatrix}$$

$$H_m = (E_1\cos^2\theta + E_2\sin^2\theta + C)\cdot\mathbf{I} + \begin{pmatrix} \sqrt{2}G_F\rho_e & -\frac{1}{2}(E_2-E_1)\sin 2\theta \\ -\frac{1}{2}(E_2-E_1)\sin 2\theta & (E_2-E_1)\cos 2\theta \end{pmatrix}$$

To diagonalize H_m one needs θ_m such that

$$\tan 2\theta_m = \frac{-(E_2-E_1)\sin 2\theta}{\sqrt{2}G_F\rho_e - (E_2-E_1)\cos 2\theta}$$

Maximal for $\theta_m = \pi/4$

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{1 - 2\cdot\frac{2\sqrt{2}\rho_e G_F E}{\Delta m^2}\cos 2\theta + (\frac{2\sqrt{2}\rho_e G_F E}{\Delta m^2})^2}$$

$$\begin{aligned} |\nu_e > &= \cos\theta_m|\nu_1>_m - \sin\theta_m|\nu_2>_m \\ |\nu_\mu > &= \sin\theta_m|\nu_1>_m + \cos\theta_m|\nu_2>_m \end{aligned}$$

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Oscillations in matter

- Oscillation probability change in matter. There can be a resonant enhancement of the oscillation probability. The Mikheyev-Smirnov-Wolfenstein (MSW) effect.

$$\rho_e = \rho_R = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F E}$$

Only for $\Delta m^2>0$ and neutrinos or $\Delta m^2<0$ and anti-neutrinos !!

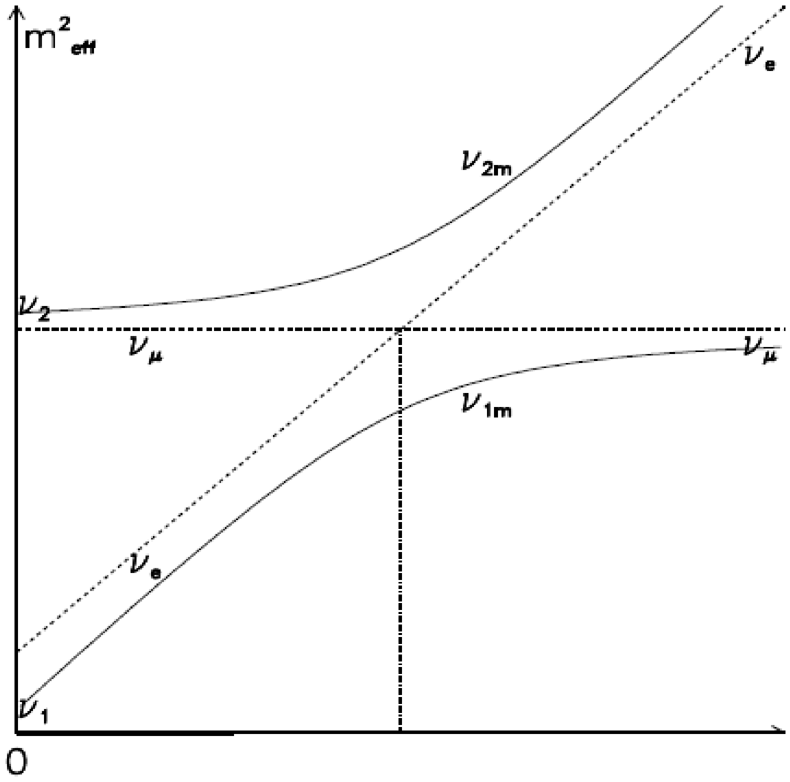
P_{osc}^{matter} can be large (≈1) even if mixing angle in vacuum is small.

- In practice this implies that (if MSW is at work) ν_e can oscillate to ν_μ, ν_τ BEFORE exiting the sun

$$\mathrm{L}_0 = \frac{2\pi}{\sqrt{2}\rho_e G_F} \qquad \sin^2 2\theta_m = \frac{\sin^2 2\theta}{1 - 2 \cdot \frac{L_v}{L_0} \cos 2\theta + (\frac{L_v}{L_0})^2}$$

Oscillation length in matter: $$L_m = \frac{L_v}{\sqrt{1 - 2\frac{L_v}{L_0} \cos 2\theta + (\frac{L_v}{L_0})^2}}$$

Adiabatic condition

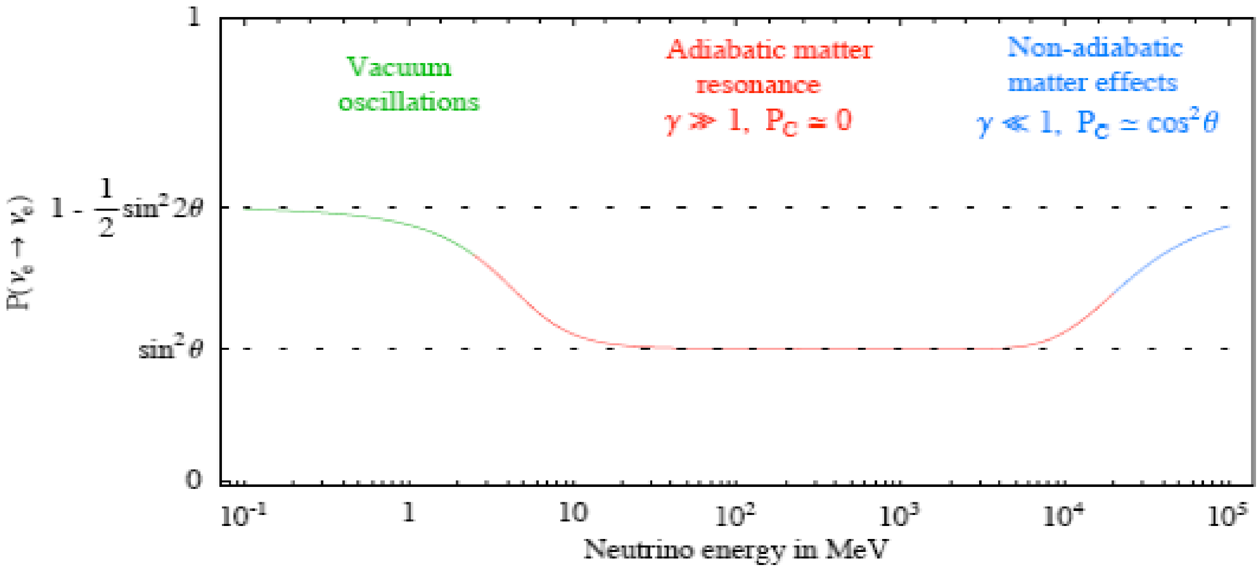


Fulfilled if the density layer corresponding to the resonance is thicker than an oscillation length

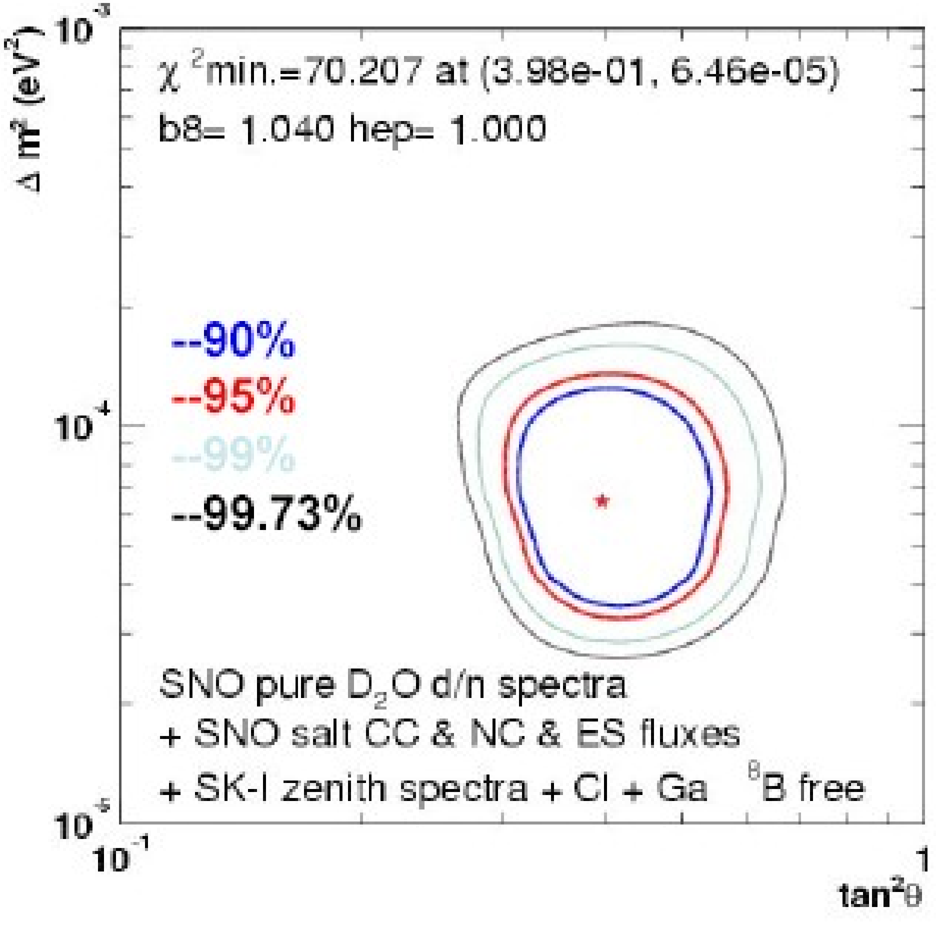
$$\Delta\rho_R = \rho_R \tan 2\theta$$

$$(\frac{d\rho}{dr})^{-1}\Delta\rho_R > L_m$$

$$\frac{d\rho}{dr} < \frac{(\Delta m^2)^2 \sin^2 2\theta}{8\pi\sqrt{2}G_F E^2}$$



Solar oscillations



Neutrinos produced at the sun (ν_e) oscillate to other neutrinos via matter-enhanced MSW.

$\Delta m^2 = 8 \times 10^{-5}$ eV^2

$\theta \approx 30^0$

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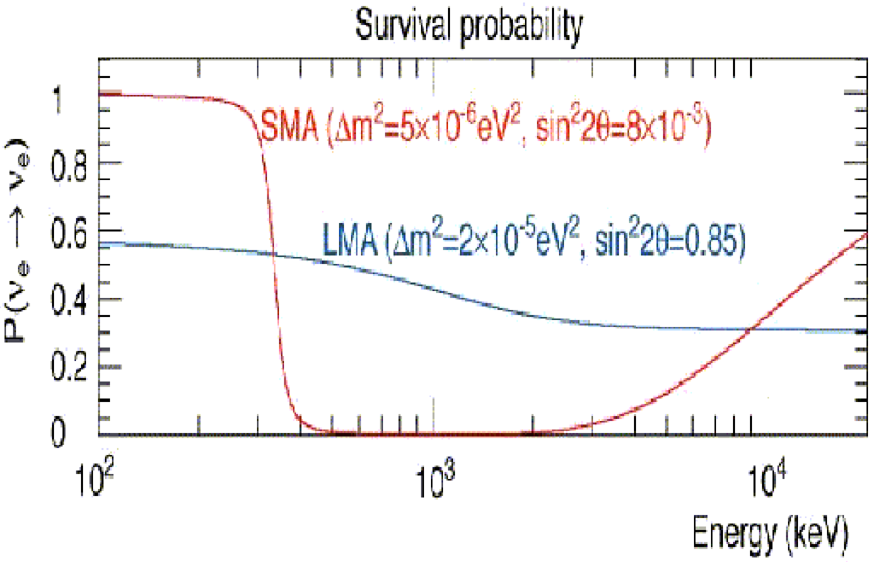
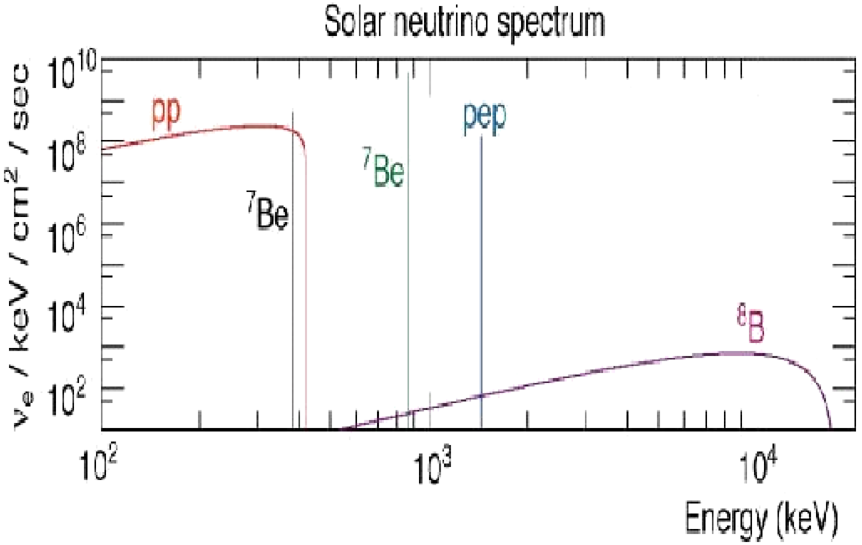
Solar neutrino oscillations

Matter effect on ν_e from Sun to Earth



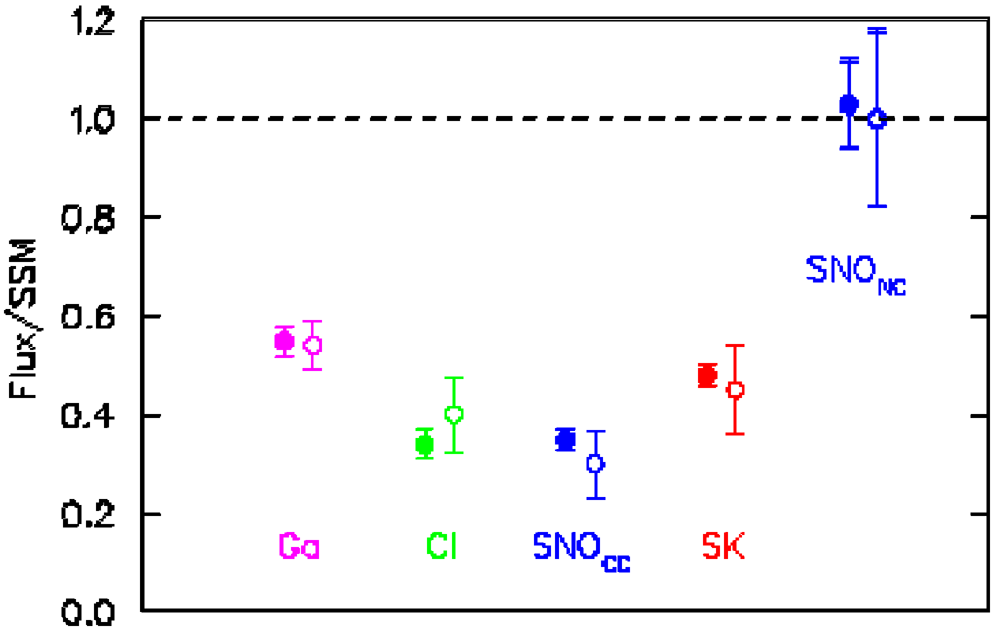


The LMA solar solution

+

matter effects

explain beautifully
all solar neutrino experiments



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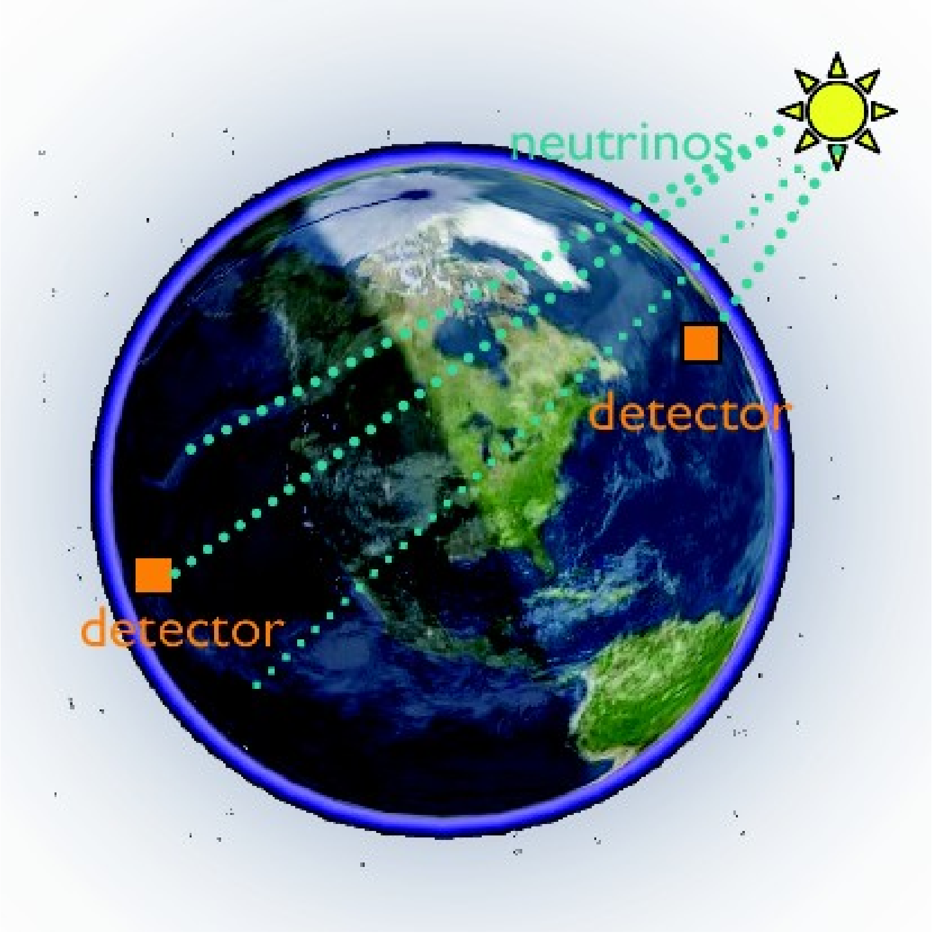
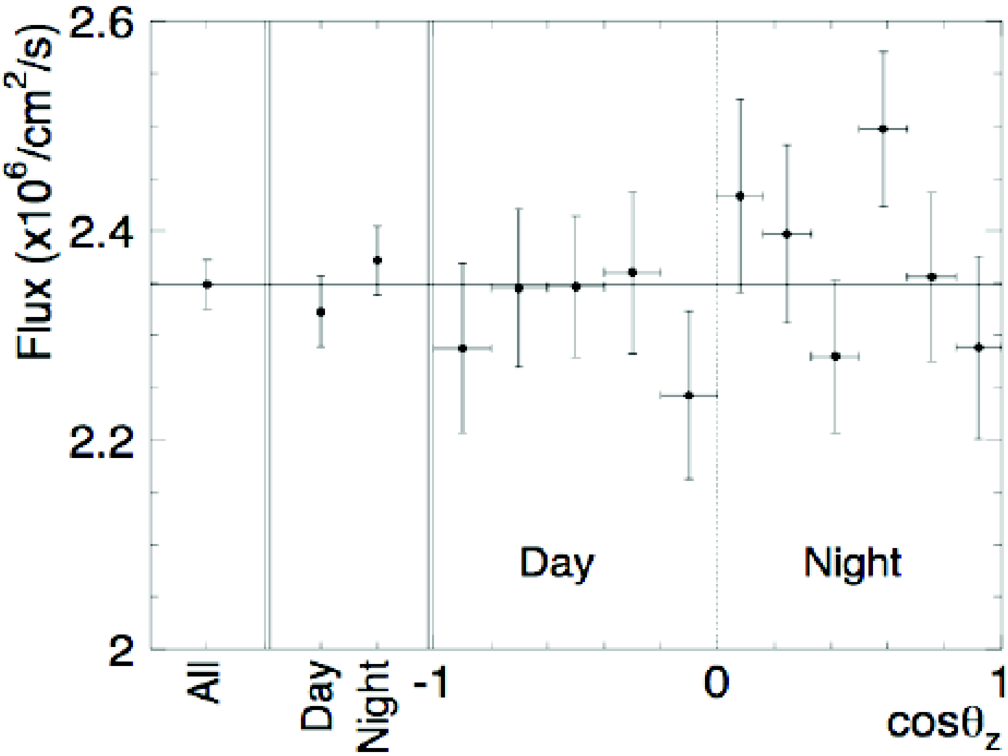
Neutrino regeneration in the Earth ?





- SK sees no significant day-night effect

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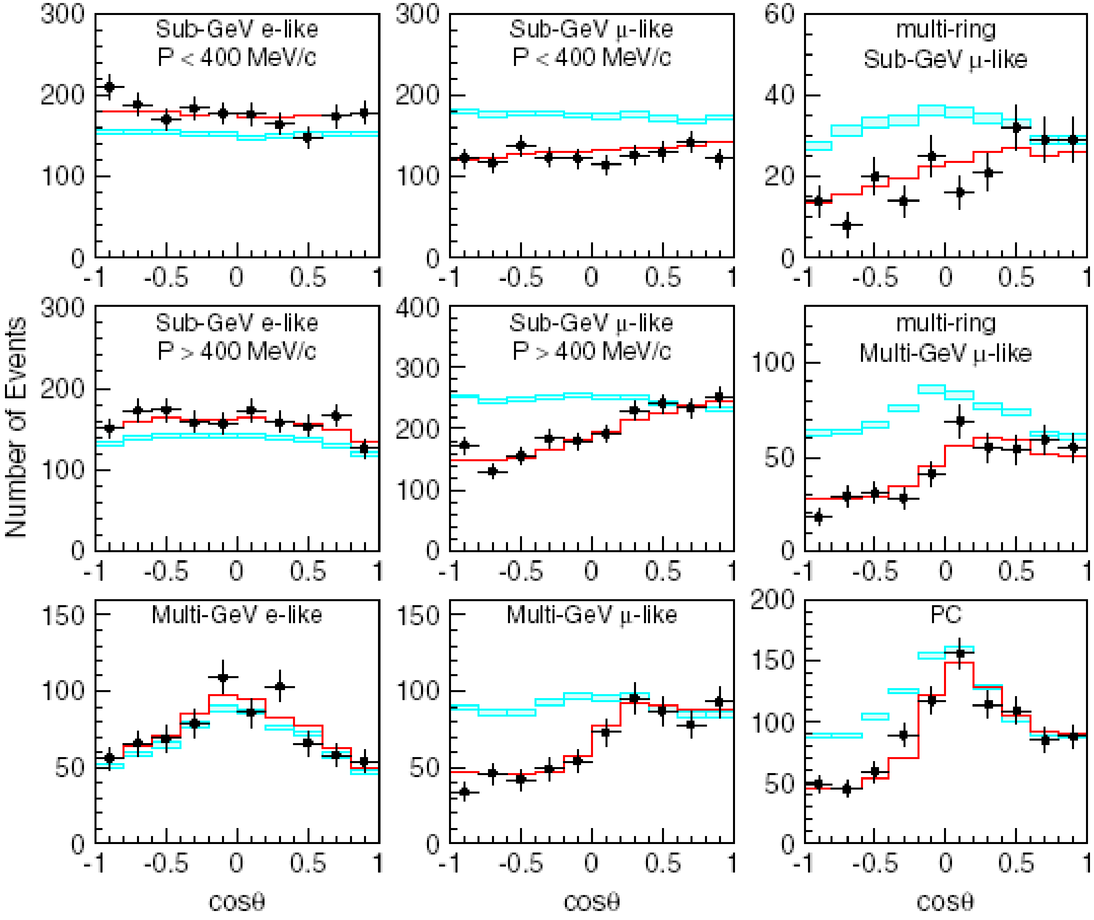
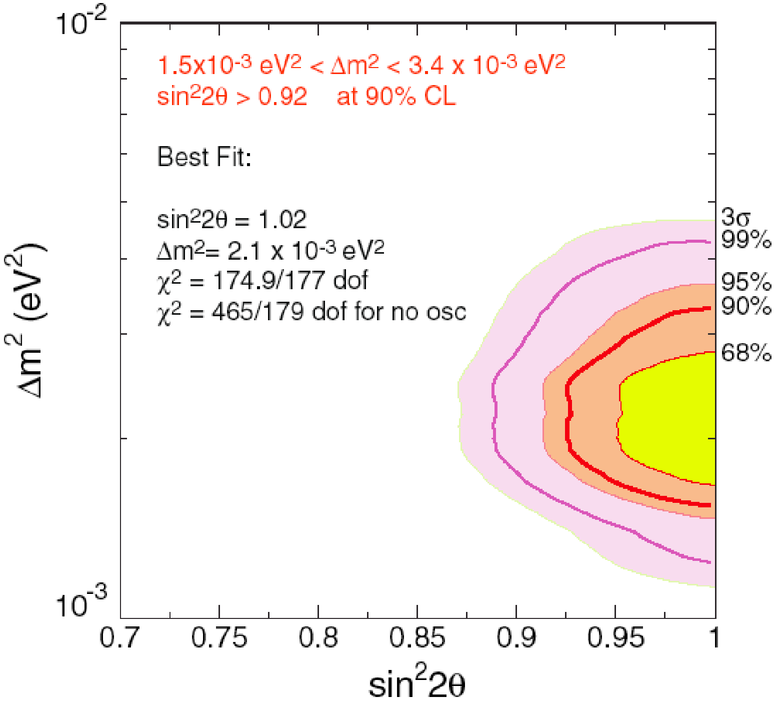
Atmospheric ν oscillations



ν_e **ν_μ** **ν_μ**



1.5×10^{-3} eV^2 < Δm^2 < 3.4×10^{-3} eV^2
$\sin^2 2\theta > 0.92$ at 90% CL

Best Fit:

$\sin^2 2\theta = 1.02$
$\Delta m^2 = 2.1 \times 10^{-3}$ eV^2
$\chi^2 = 174.9/177$ dof
$\chi^2 = 465/179$ dof for no osc

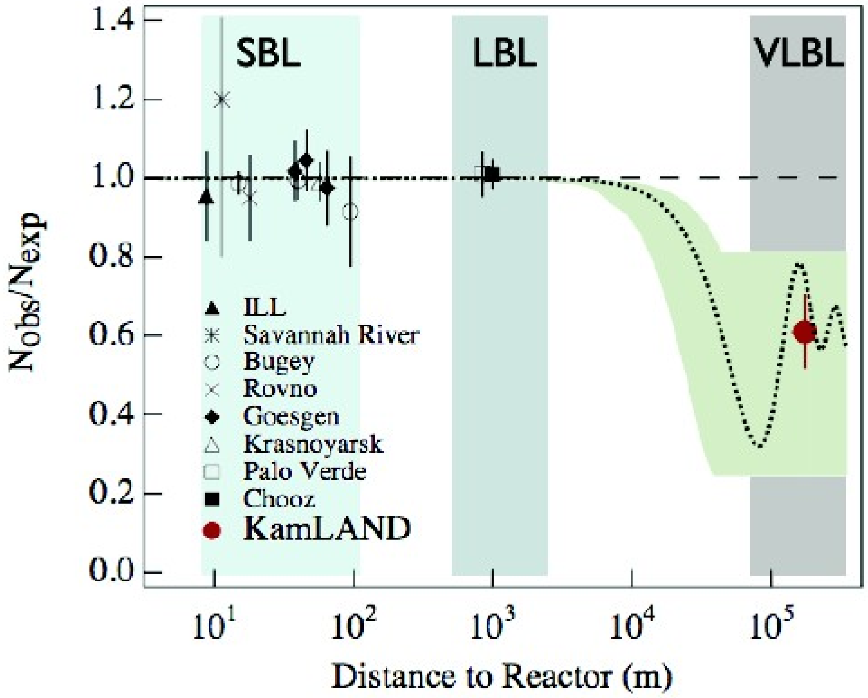
$$\nu_\mu \rightarrow \nu_\tau oscillations$$

$$\Delta m^2 = 2.1 \cdot 10^{-3} eV^2$$

$$sin^2 2\theta \approx 1$$

Reactor experiments

- SBL 10-100m from the reactor : exclusion regions
- LBL ~1 km CHOOZ, sensitive to Atmospheric neutrino parameter space
- VLBL 100km KamLAND evidence for disappearance



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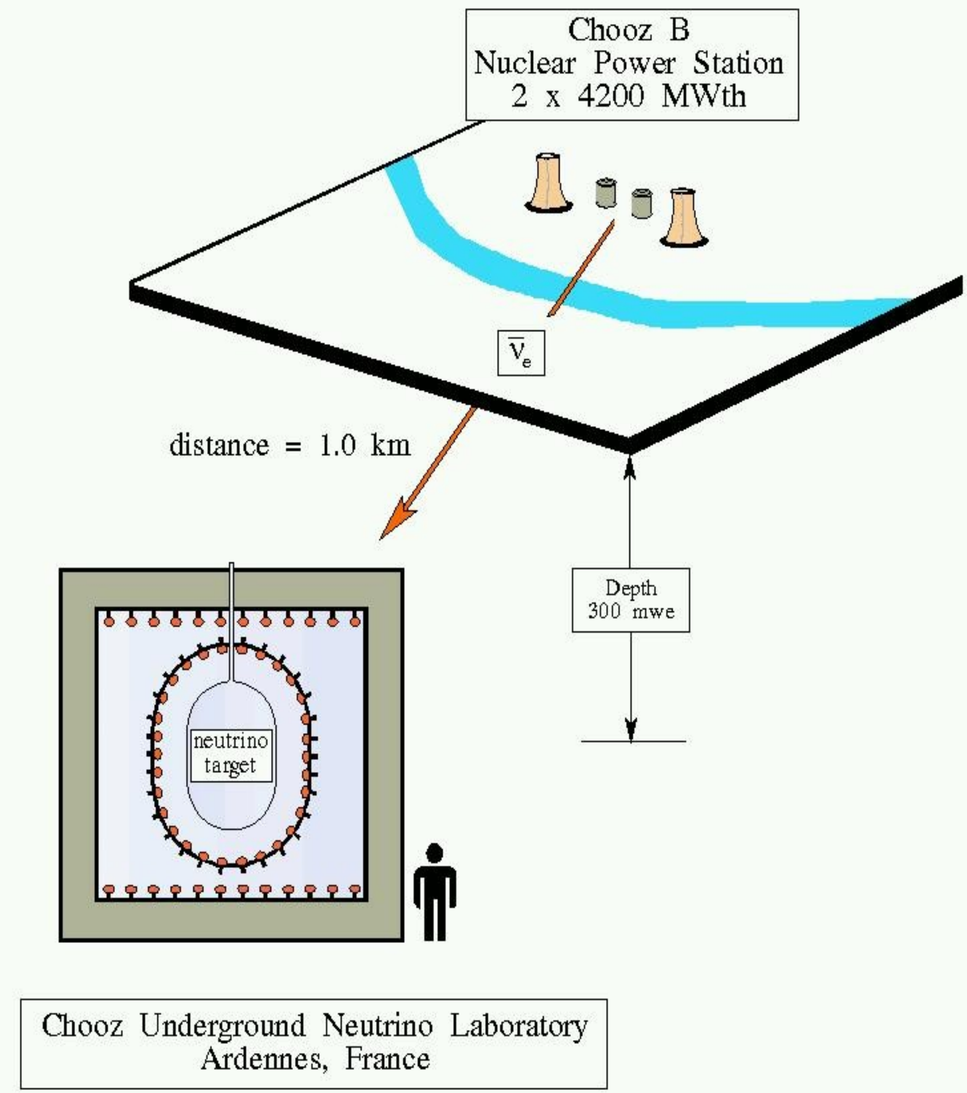
LBL experiments

- Liquid scintillator +Gd
- Coincidence from e^+ capture and n-capture (8MeV gamma)



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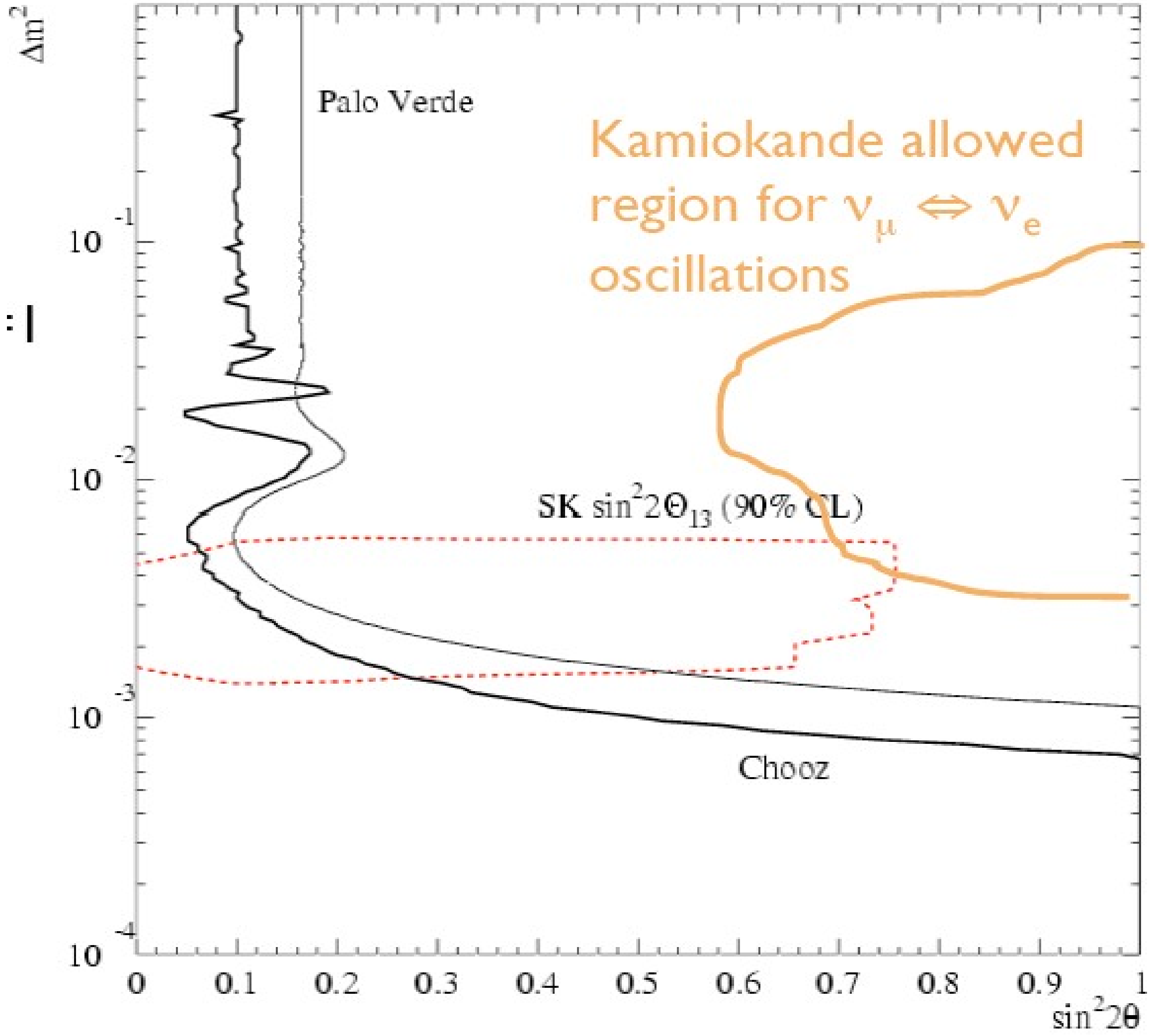
Chooz and Palo Verde

- No disappearance observed
- Excludes the region allowed by SK atmospheric neutrino anomaly



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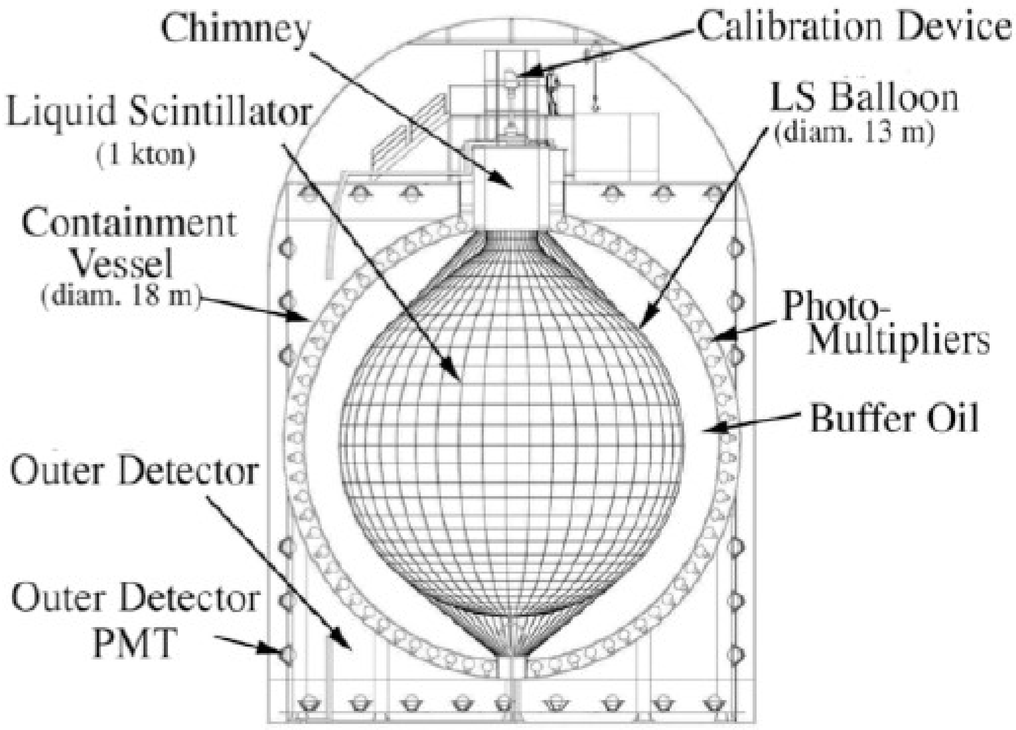
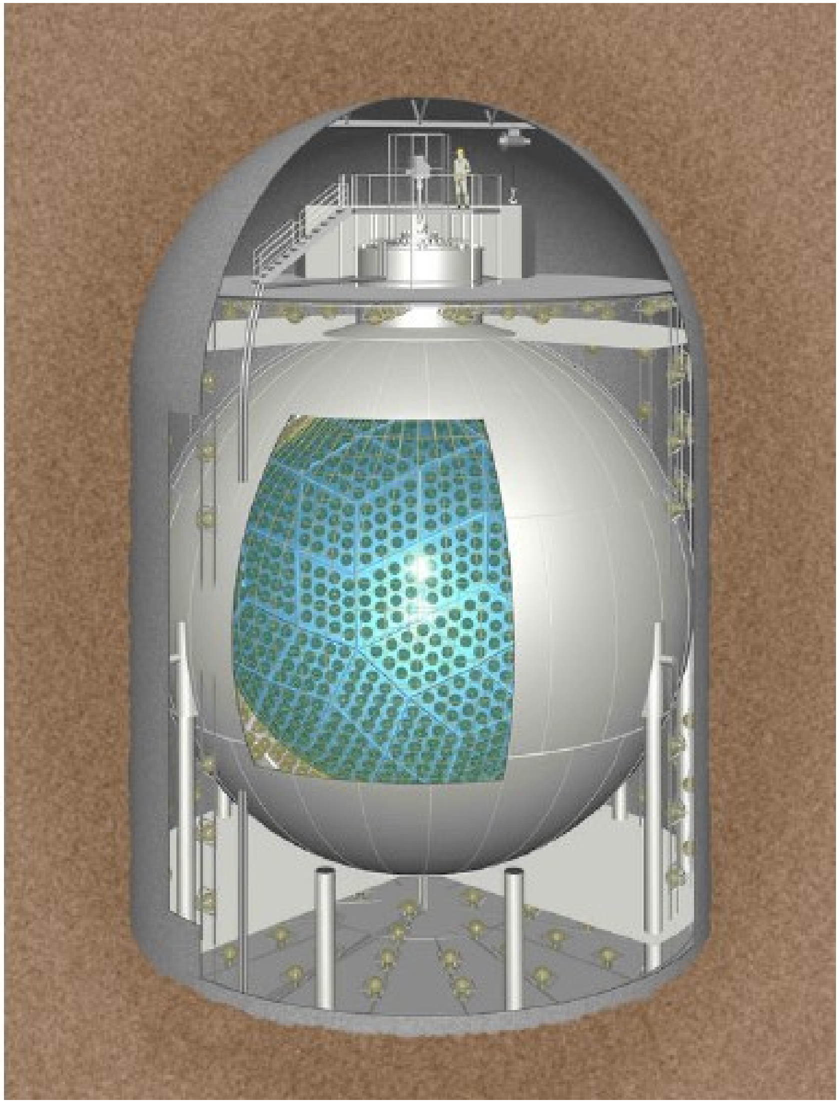
KamLAND

- Measuring $\bar{\nu}_e$ from several reactors in Japan
- 1200m^3 of scintillator





Kamland location & flux

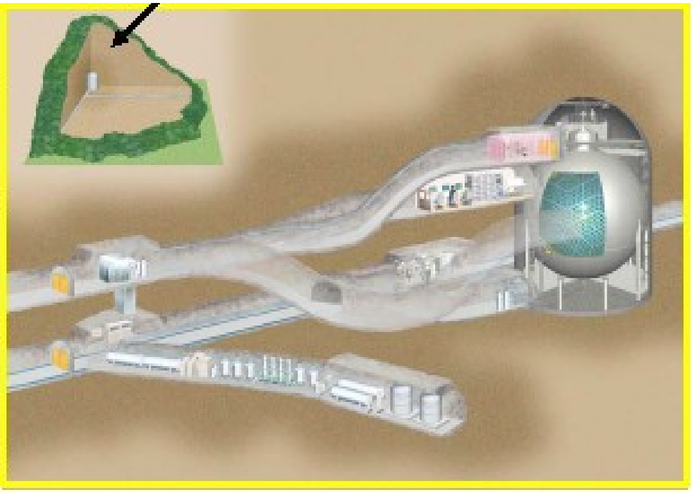
Many reactors contribute to the antineutrino flux at KamLAN

	Site	Dist (km)	Cores (#)	P_{therm} (GW)	Flux ($cm^{-2}\ s^{-1}$)	Rate noosc* ($yr^{-1}\ kt^{-1}$)
Japan	Kashiwazaki	160	7	24.3	$4.1 \cdot 10^5$	254.0
	Ohi	179	4	13.7	$1.9 \cdot 10^5$	114.3
	Takahama	191	4	10.2	$1.2 \cdot 10^5$	74.3
	Tsuruga	138	2	4.5	$1.0 \cdot 10^5$	62.5
	Hamaoka	214	4	10.6	$1.0 \cdot 10^5$	62.0
	Mihama	146	3	4.9	$1.0 \cdot 10^5$	62.0
	Sika	88	1	1.6	$9.0 \cdot 10^4$	55.2
	Fukushima1	349	6	14.2	$5.1 \cdot 10^4$	31.1
	Fukushima2	345	4	13.2	$4.8 \cdot 10^4$	29.5
	Tokai2	295	1	3.3	$1.6 \cdot 10^4$	10.1
	Onagawa	431	3	6.5	$1.5 \cdot 10^4$	9.3
	Simane	401	2	3.8	$1.0 \cdot 10^4$	6.3
	Ikata	561	3	6.0	$8.3 \cdot 10^3$	5.1
	Genkai	755	4	10.1	$7.8 \cdot 10^3$	4.8
	Sendai	830	2	5.3	$3.4 \cdot 10^3$	2.1
	Tomari	783	2	3.3	$2.3 \cdot 10^3$	1.4
South Korea	Ulchin	712	4	11.5	$9.9 \cdot 10^3$	6.1
	Yonggwang	986	6	17.4	$7.8 \cdot 10^3$	4.8
	Kori	735	4	9.2	$7.5 \cdot 10^3$	4.6
	Wolsong	709	4	8.2	$7.1 \cdot 10^3$	4.3
Total Nominal		-	70	181.7	$1.3 \cdot 10^6$	803.8

*E_ν>3.4MeV (E_{prompt}>2.6MeV)

Detailed power and fuel Composition calculation used

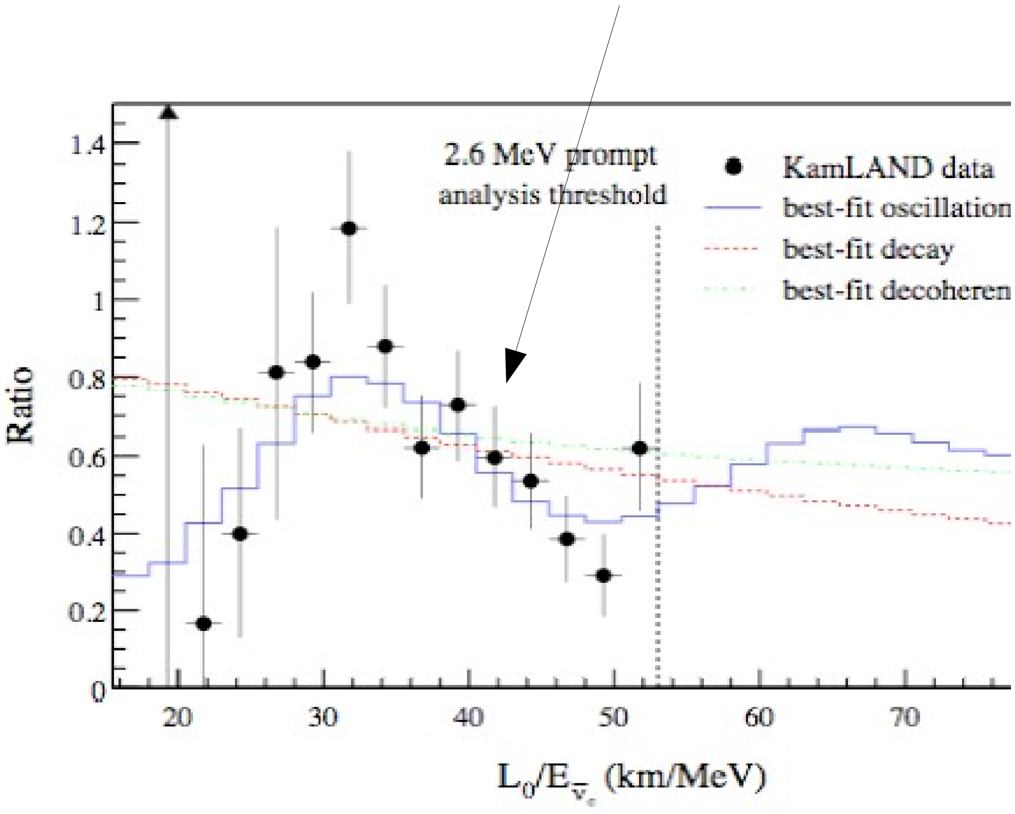
From electrical power Japanese average fuel used



KamLAND results

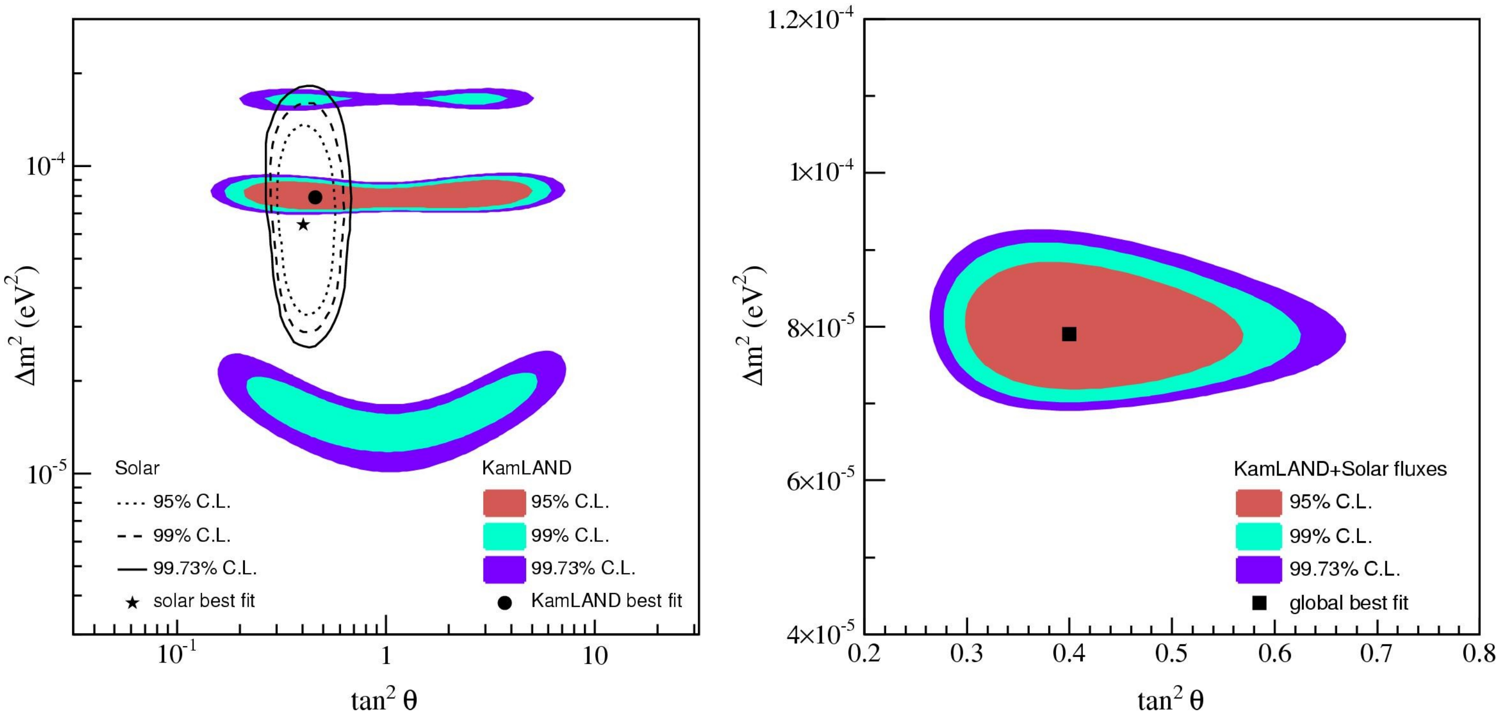
- Disappearance of $\bar{\nu}_e$ observed
- Designed to check the Large Mixing Angle solar neutrino solution
- R=0.658±0.044±0.047

L/E dependance !!



KamLAND confirms solar oscillations

- LMA solution confirmed !



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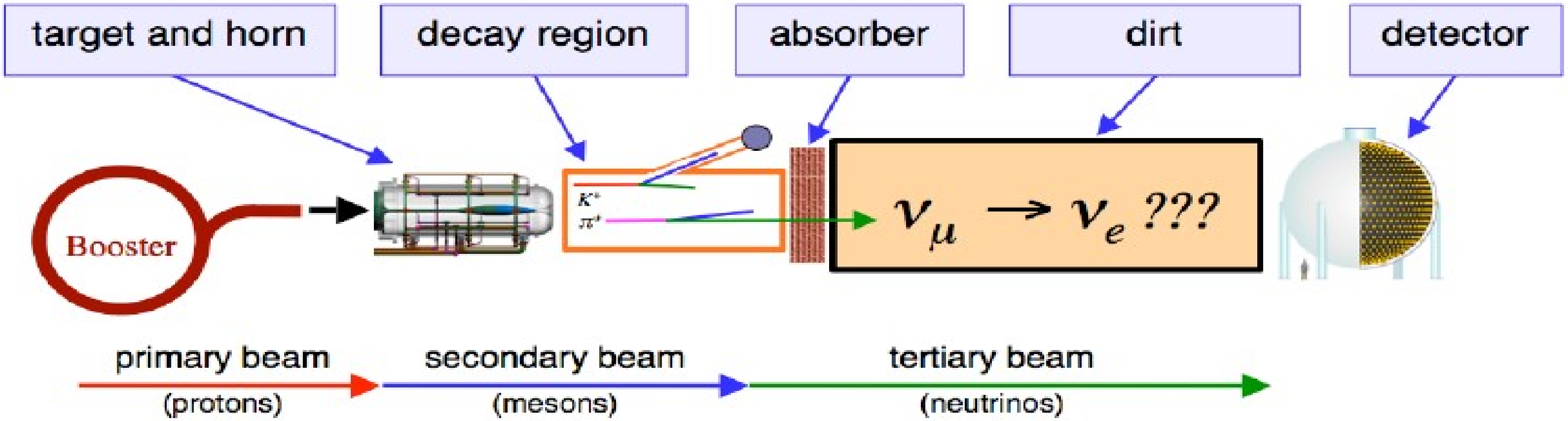
Accelerator experiments



- Neutrinos produced by the decay of pions, kaons and muons from a proton beam onto a target
  - Pion decay in flight: mostly muon neutrinos (OR anti-neutrinos) with energies ~ GeV or more; e.g. SBL: CHORUS, NOMAD, CHARM, LSND; LBL: MINOS, OPERA, ICARUS, T2K
  - Muon decay at rest: muon anti-neutrinos of low energy from muondecay, with energy ~ tens MeV; e.g. KARMEN, LSND
  - Beam dump: protons of very high energy are completely stopped by a target; muon and electron neutrinos with energy ~ 100 GeV

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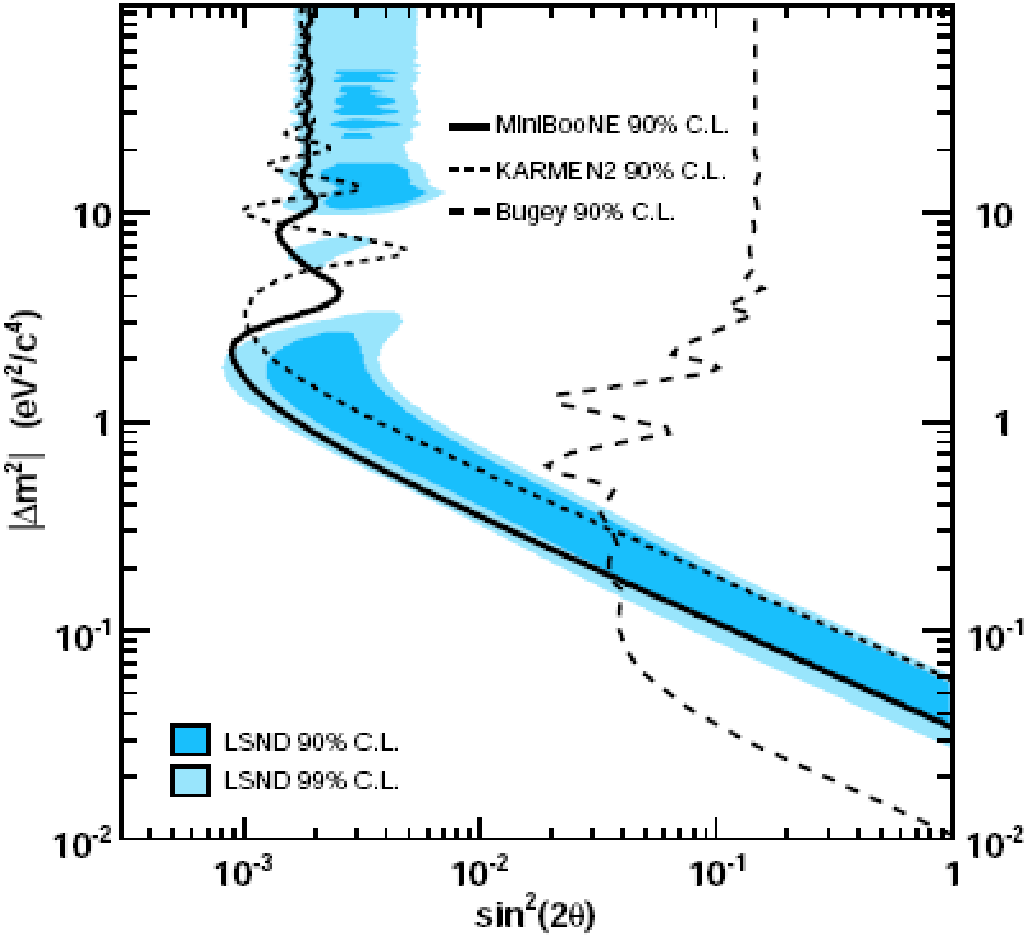
$\nu_\mu \longleftrightarrow \nu_e$ SBL

- Only LSND claims a signal in $\bar{\nu}_\mu \to \bar{\nu}_e$ and weaker in $\nu_\mu \to \nu_e$
- L=30m E~30MeV
- Not confirmed by other experiments



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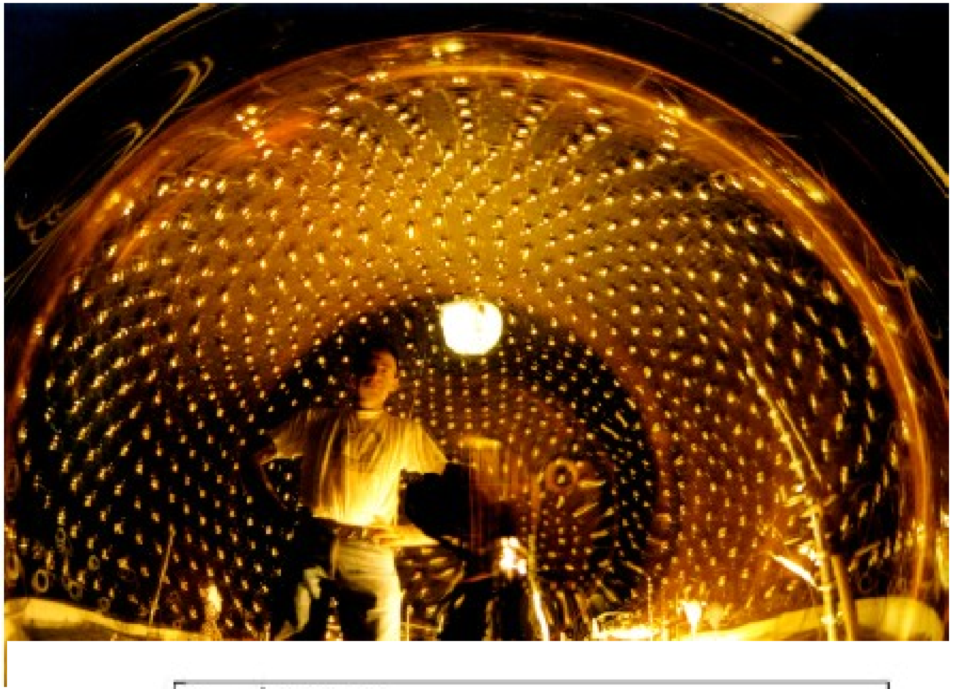
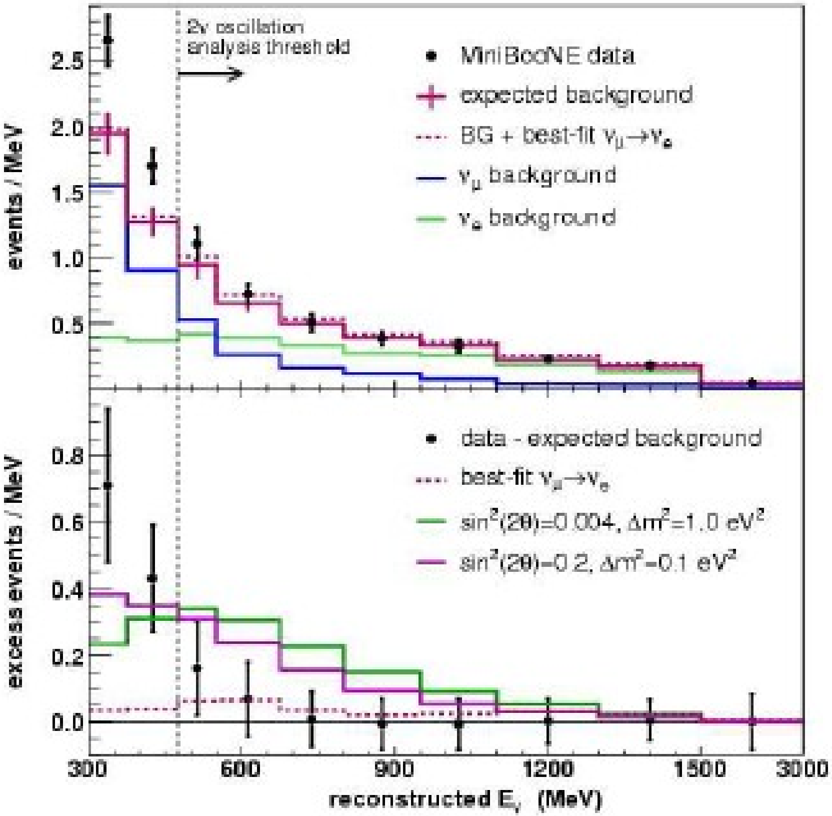


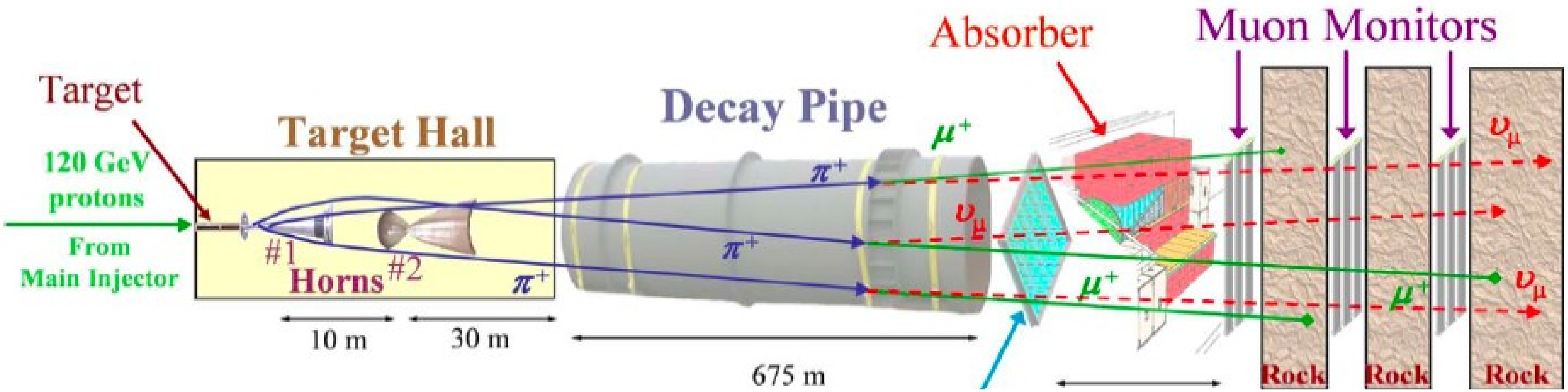
MiniBoone

- Concept of sterile neutrino:
  - non-interacting light particle
  - Singlet in the SU(2)xU(1) group
  - mixed with active neutrinos

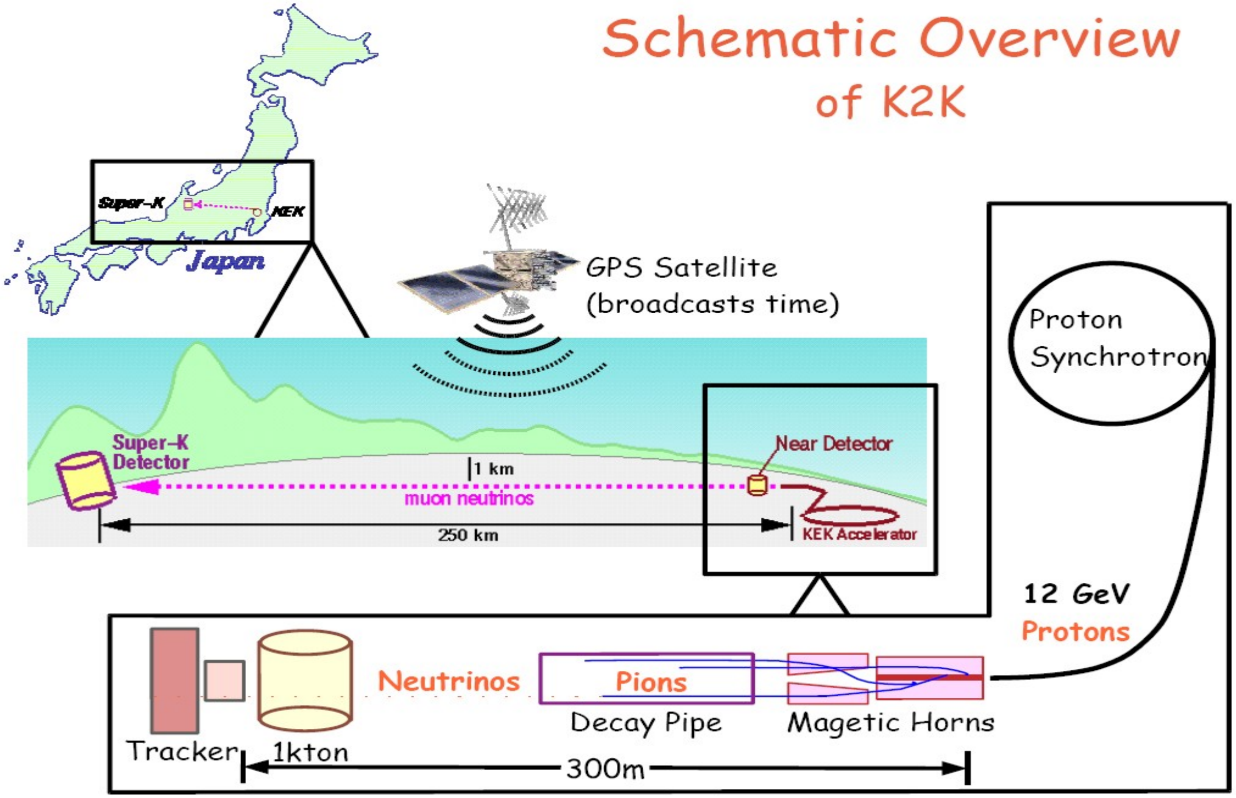


L=500m E=500MeV

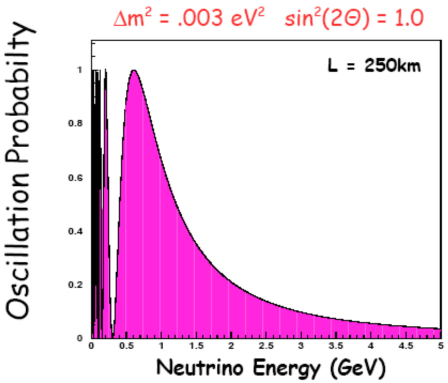
Now running anti-nu mode

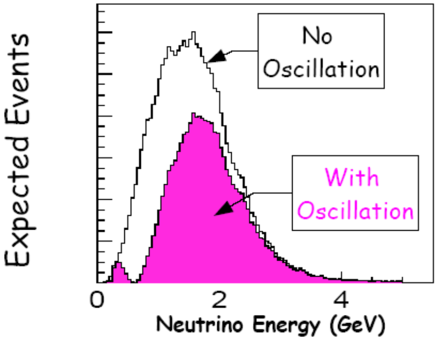

Target
120 GeV protons
From Main Injector
Target Hall
#1
Horns
#2
π^+
π^+
π^+
Decay Pipe
μ^+
υ_μ
Absorber
Muon Monitors
υ_μ
μ^+
υ_μ
μ^+
Rock
Rock
Rock
10 m
30 m
675 m

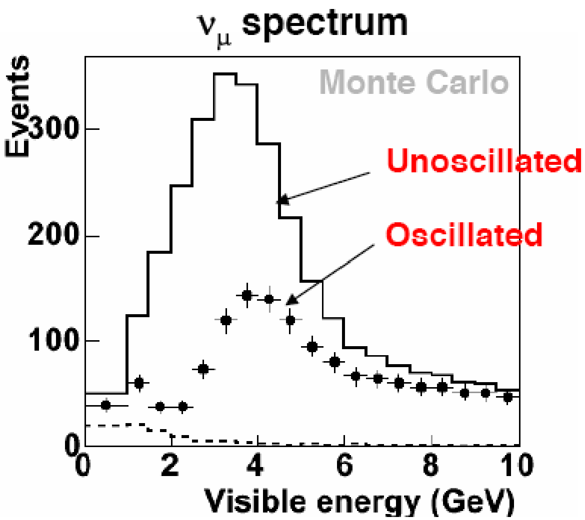
Minos & K2K:


Schematic Overview
of K2K
Super-K
KEK
Japan
GPS Satellite
(broadcasts time)
Proton
Synchrotron
Super-K
Detector
1 km
muon neutrinos
250 km
Near Detector
KEK Accelerator
12 GeV
Protons
Neutrinos
Pions
Decay Pipe
Magetic Horns
Tracker
1kton
300m

K2K/Minos: confirm atmospheric oscillation with a controled beam





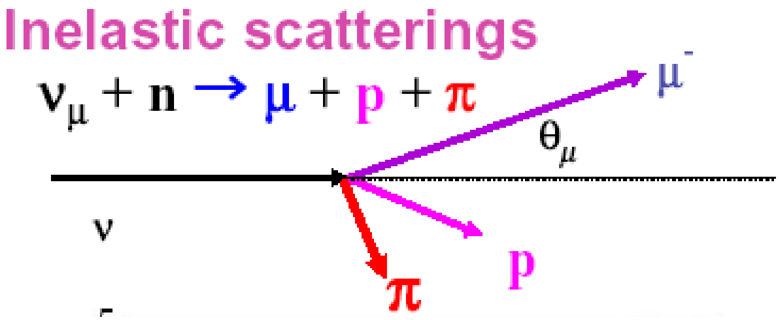


E_{K2K} ~1GeV=> L~250 Km

E_{Numi} ~3GeV => L~750 Km

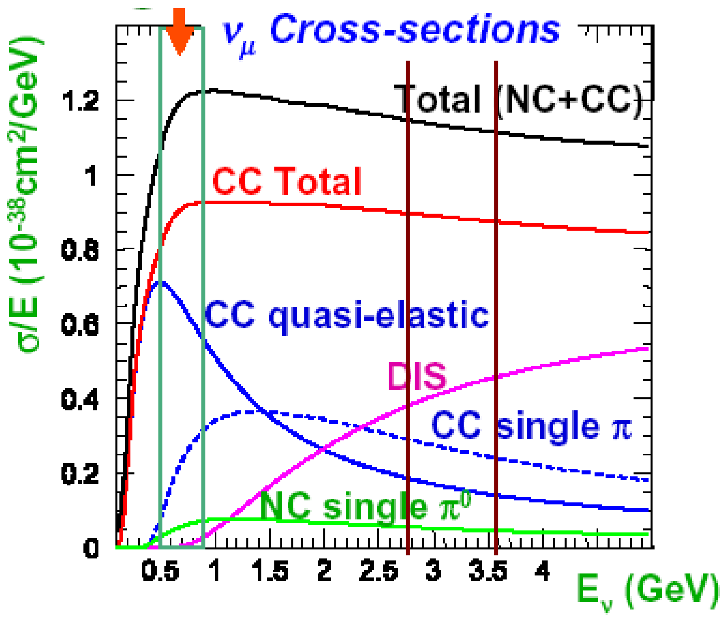
Cross sections and energy reconstruction

Numi/MINOS


Inelastic scatterings

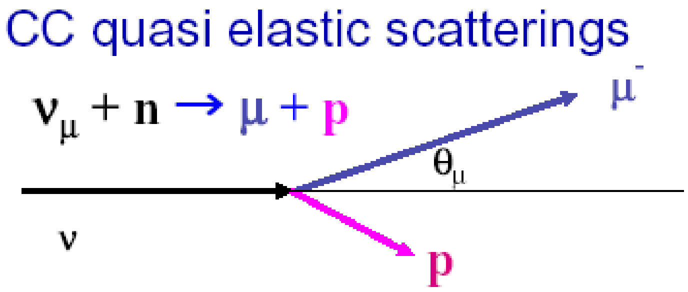
$\nu_\mu + n \rightarrow \mu + p + \pi$

Beam E~120GeV



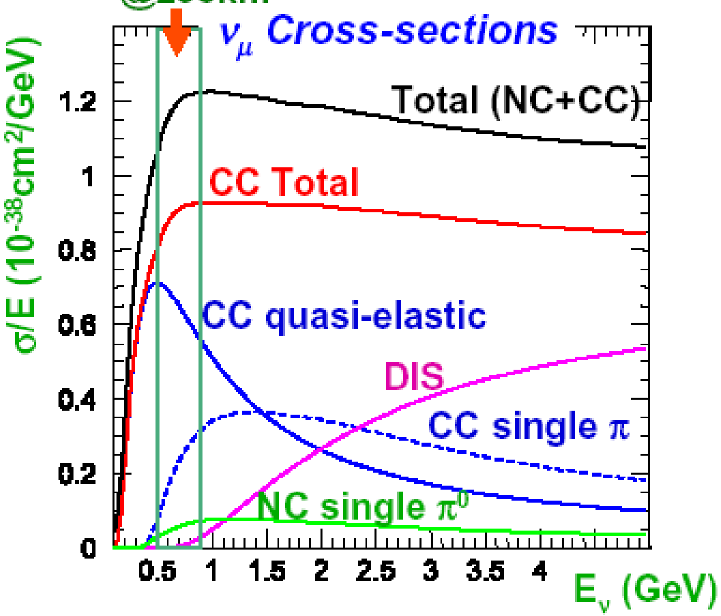
Oscillation maximum@750 km

K2K


CC quasi elastic scatterings

$\nu_\mu + n \rightarrow \mu + p$

Oscillation maximum @295km



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Detectors

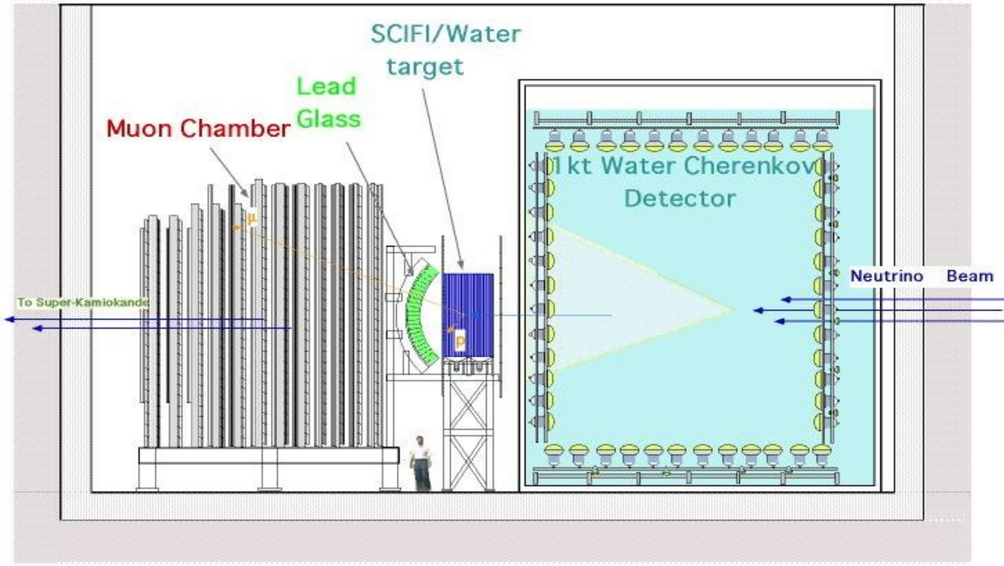
Far Detector

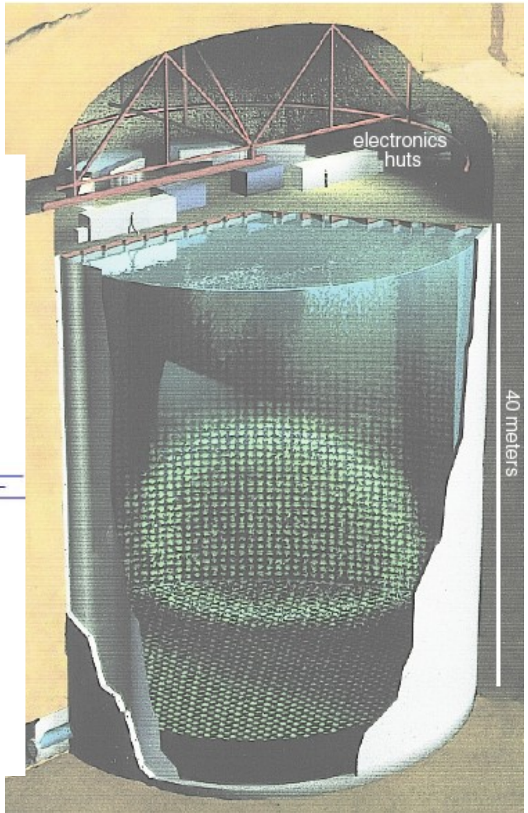
Data taking since ~ September 2001
Installation fully completed in July 2003.

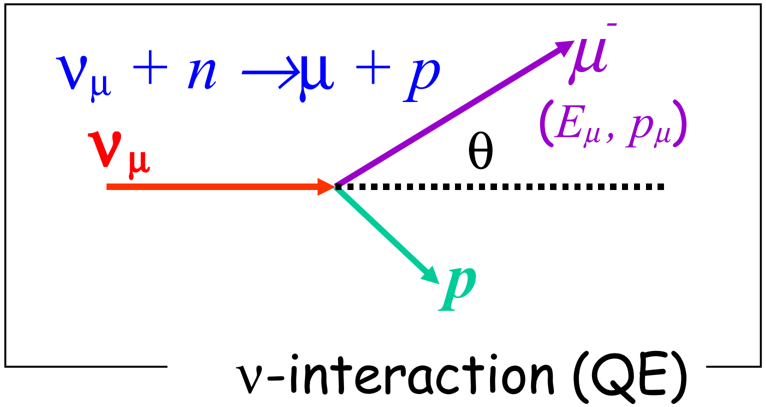
Near Detector

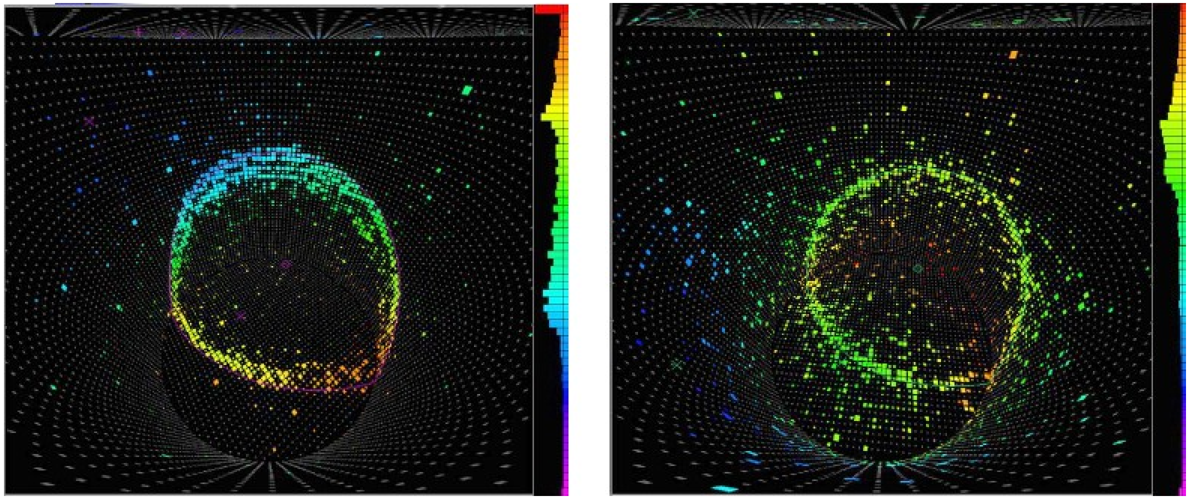

Plane installation fully completed on Aug 11, 2004

Two different technologies:
Water & Iron



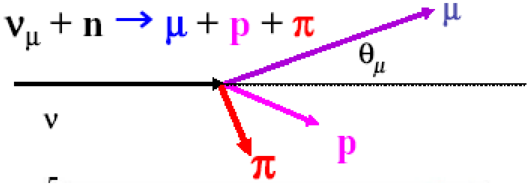



$\nu_\mu + n \to \mu + p$

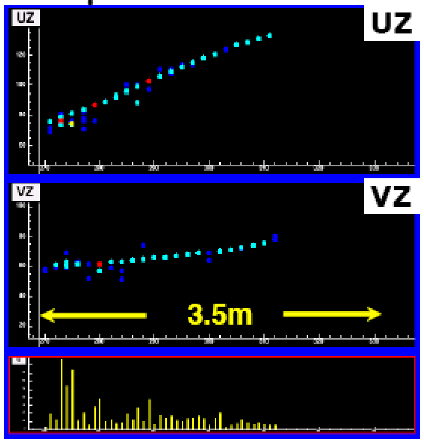


Neutrinos in water & iron

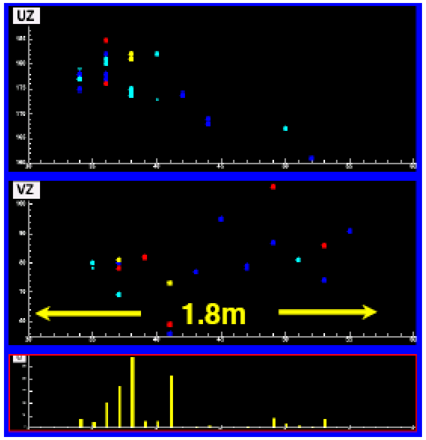
Inelastic scatterings


$\nu_\mu + n \to \mu + p + \pi$

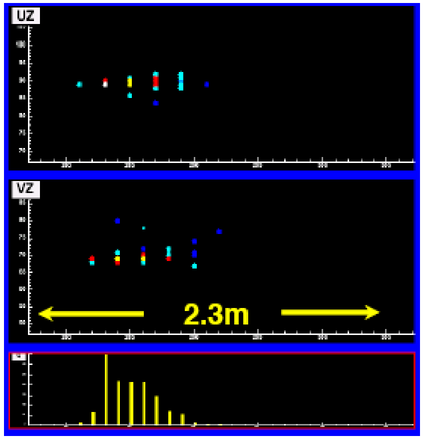
ν_μ CC Event



NC Event



ν_e CC Event



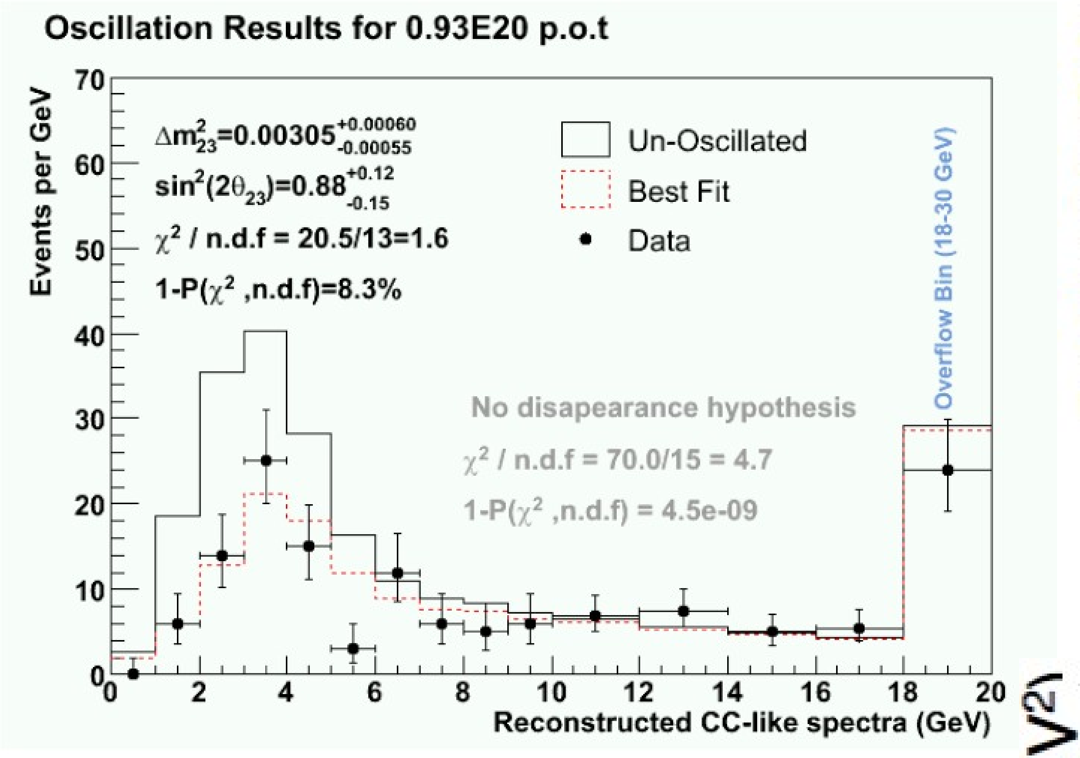
- long μ track+ hadronic activity at vertex

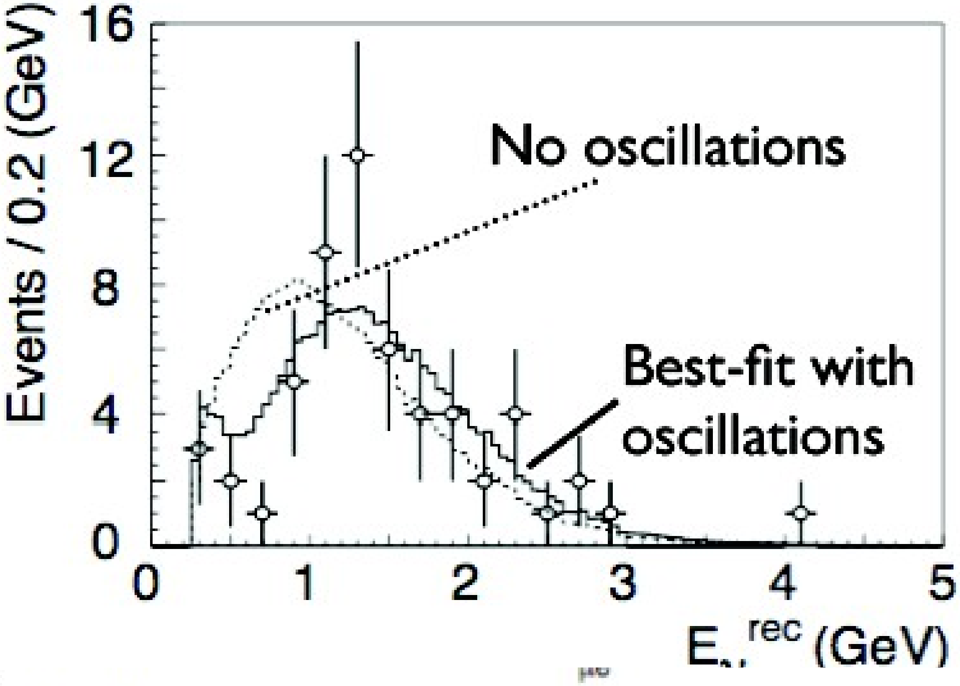
- short event, often diffuse

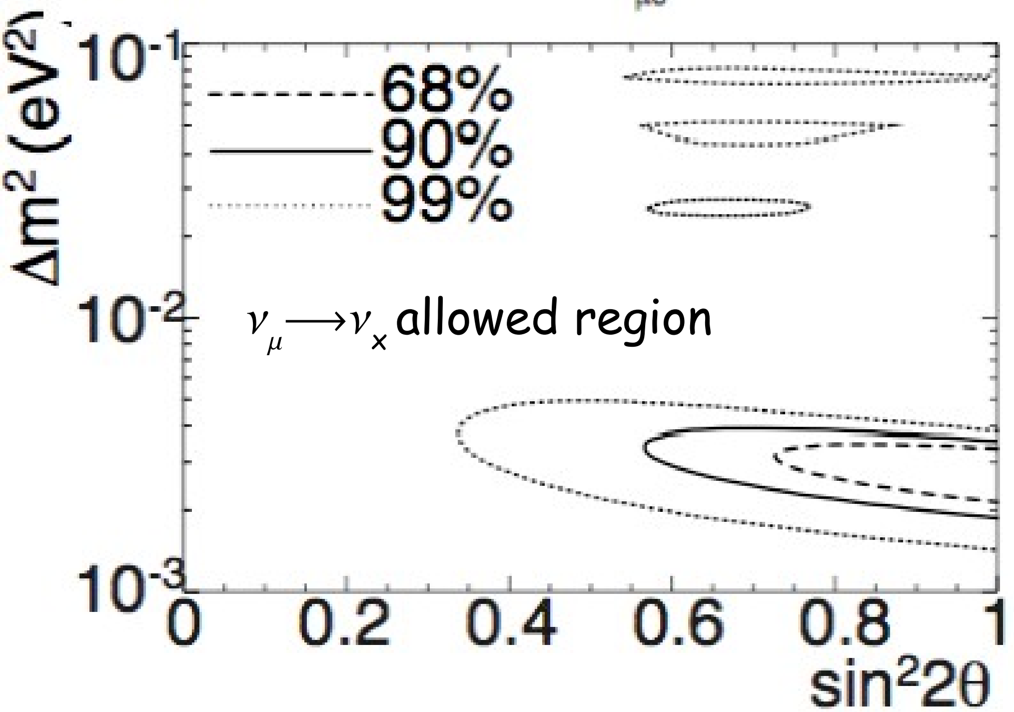
- short, with typical EM shower profile

$$E_\nu = \underset{\substack{\uparrow\\ 55\%/\sqrt{E}}}{E_{shower}} + \underset{\substack{\uparrow\\ 6\%\text{ range, }10\%\text{ curvature}}}{P_\mu}$$

Minos/K2K results

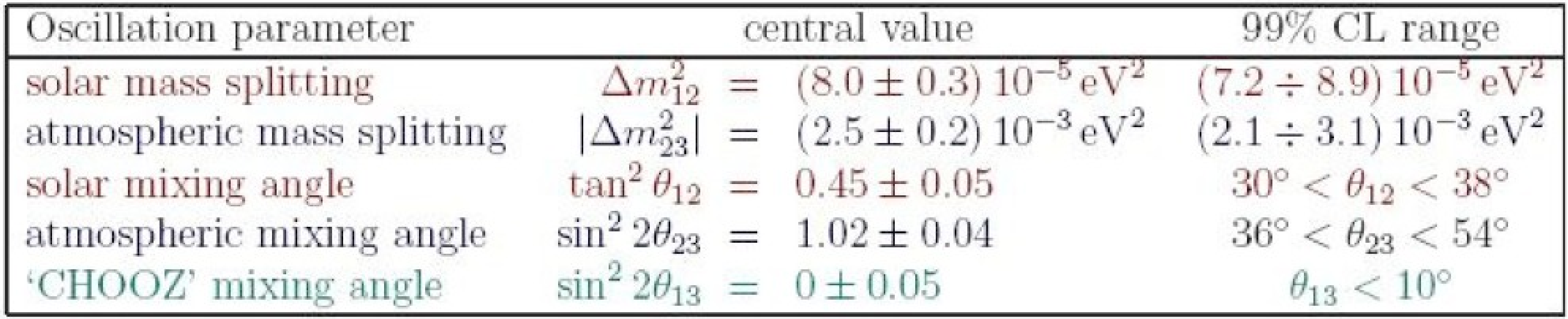




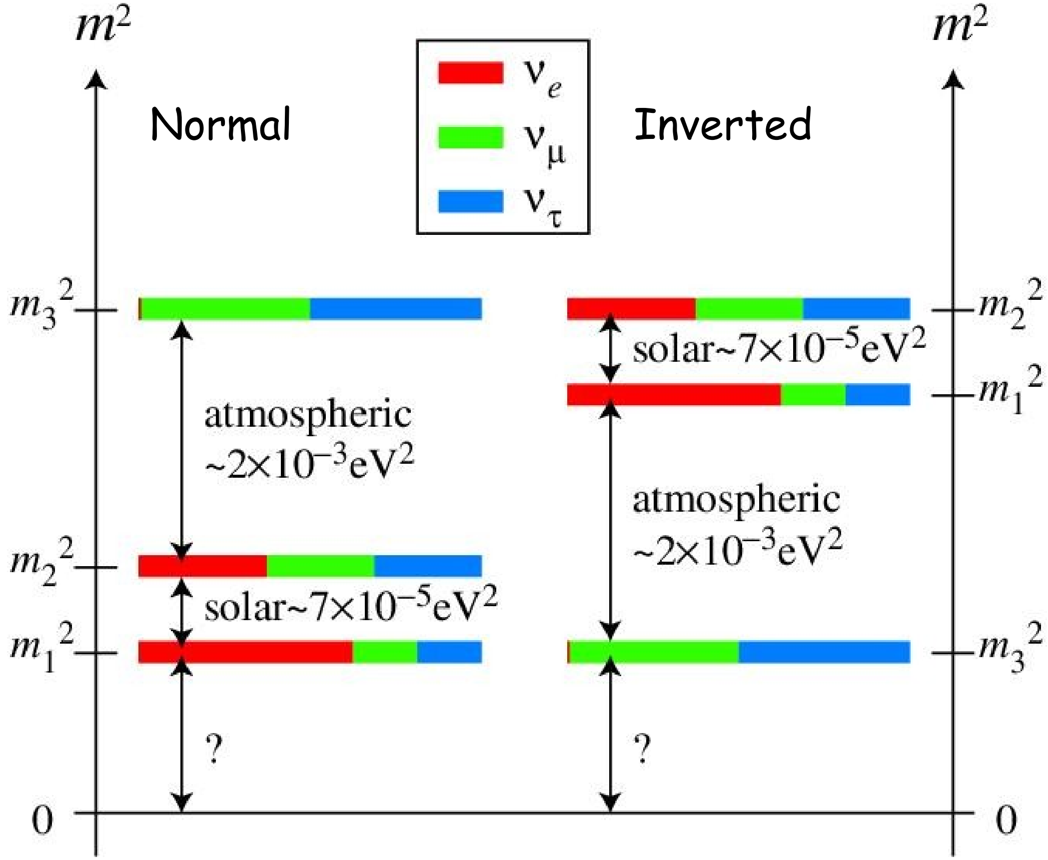


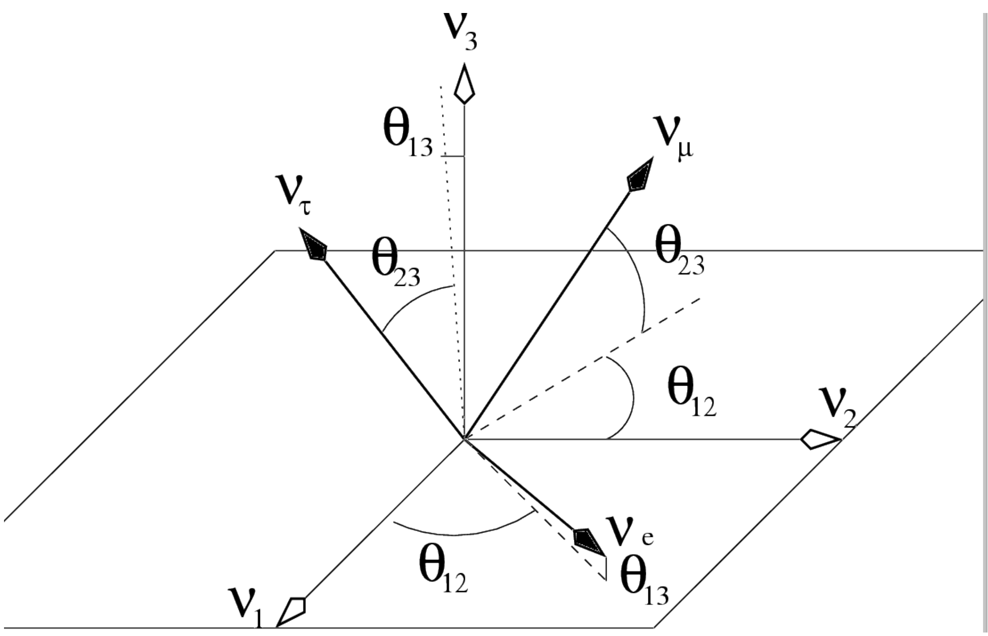
ATMOSPHERIC
OSCILLATION
CONFIRMED!

Oscillations revisited



Oscillation parameter	central value	99% CL range
solar mass splitting	$\Delta m^2_{12} = (8.0 \pm 0.3)\, 10^{-5}\, \mathrm{eV}^2$	$(7.2 \div 8.9)\, 10^{-5}\, \mathrm{eV}^2$
atmospheric mass splitting	$\|\Delta m^2_{23}\| = (2.5 \pm 0.2)\, 10^{-3}\, \mathrm{eV}^2$	$(2.1 \div 3.1)\, 10^{-3}\, \mathrm{eV}^2$
solar mixing angle	$\tan^2 \theta_{12} = 0.45 \pm 0.05$	$30° < \theta_{12} < 38°$
atmospheric mixing angle	$\sin^2 2\theta_{23} = 1.02 \pm 0.04$	$36° < \theta_{23} < 54°$
'CHOOZ' mixing angle	$\sin^2 2\theta_{13} = 0 \pm 0.05$	$\theta_{13} < 10°$





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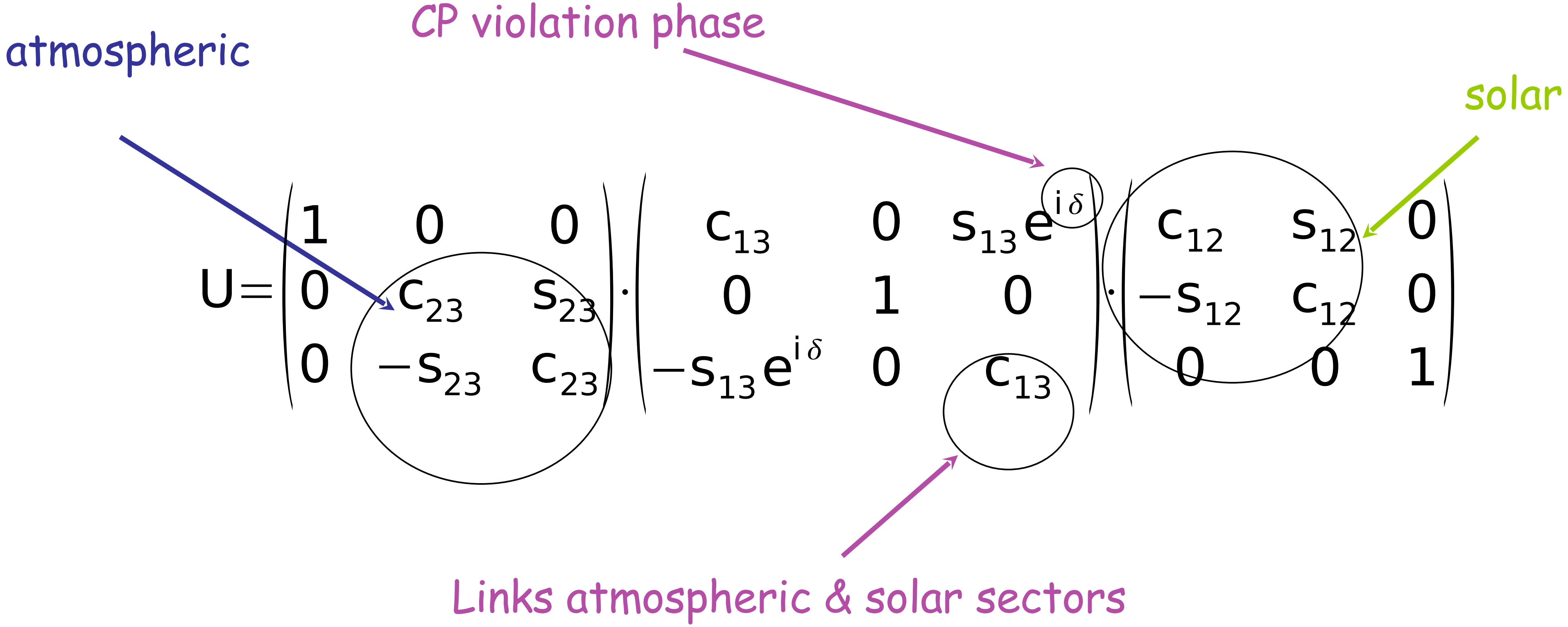
The neutrino mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

If $\delta \neq 0, \pi, 2\pi\ldots$ then weak interactions violate CP symmetry in the lepton sector (as in the quark sector)



atmospheric

CP violation phase

solar

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

Links atmospheric & solar sectors

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