ISAPP

Valencia, 2008

Neutrino Oscillation Phenomenology - I

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Outline

Lecture 1:

- Neutrino oscillations
  oscillations in vacuum and matter
- Present neutrino oscillation experiments
  solar, atmospheric, reactor, accelerator

Lecture 2:

- Global three flavour analysis
  discussion of three flavour effects
  summary of present status and open questions
- the LSND puzzle and recent MiniBooNE results

The Standard Model

Flavours:	1	2	3
Quarks:	u d	c s	t b
Leptons:	ν_e e	ν_μ μ	ν_τ τ

The Fermions in the Standard Model come in three generations (“Flavours”)

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	e	μ	τ

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Neutrinos are the “partners” of the charged leptons
(precisely: form a doublet under the SU(2) gauge symmetry)

Flavour neutrinos

A neutrino of flavour α is defined by the charged current interaction with the corresponding charged lepton:

$$\mathcal{L}_{\rm CC} = -\frac{g}{\sqrt{2}} W^\rho \sum_{\alpha=e,\mu,\tau} \bar{\nu}_{\alpha L} \gamma_\rho \ell_{\alpha L} + \text{h.c.}$$

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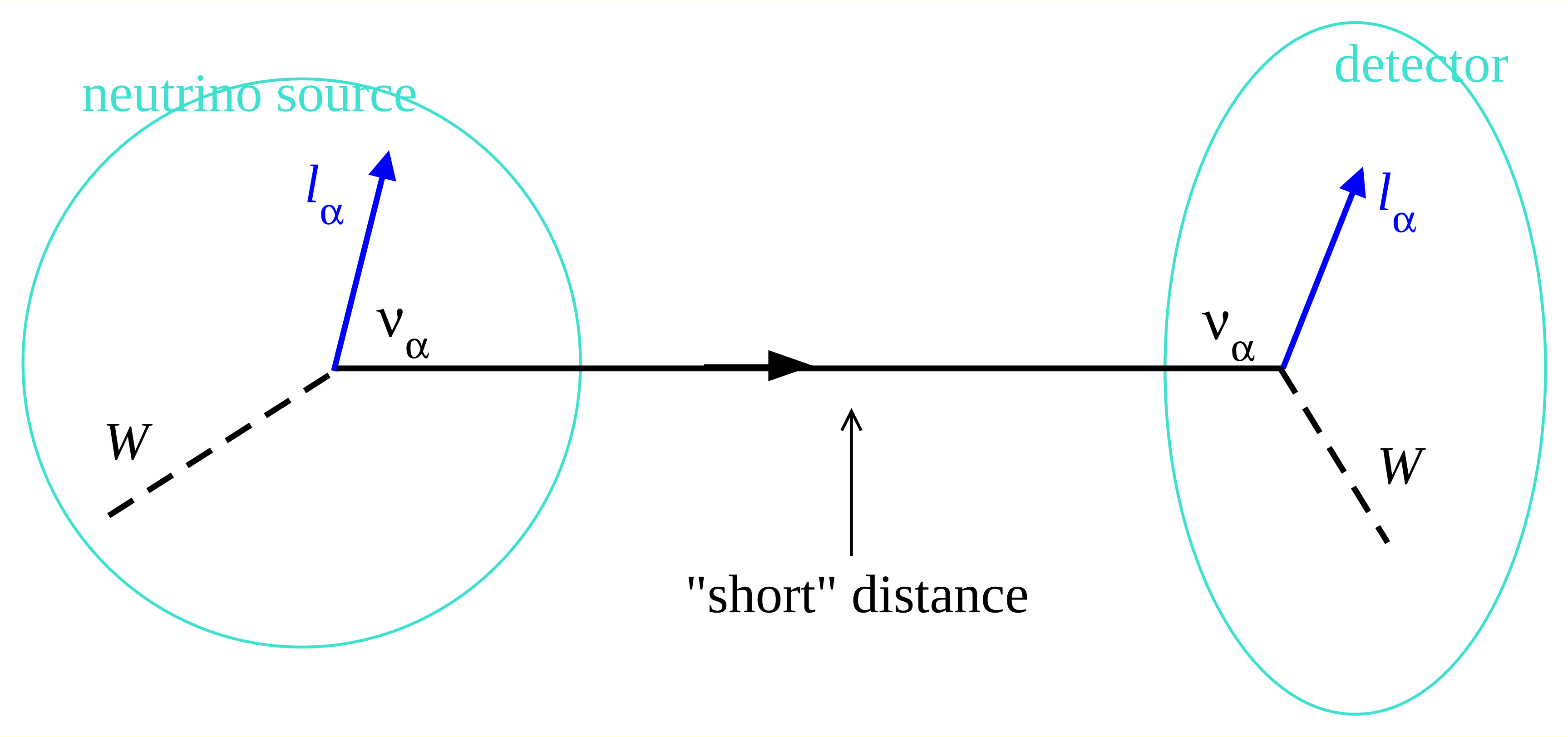
for example

$$\pi^+ \to \mu^+ \nu_\mu$$

the muon neutrino ν_μ comes together with the charged muon μ^+

Flavour neutrinos



Let's give mass to the neutrinos

Majorana mass term:

$$\mathcal{L}_{\mathrm{M}} = -\frac{1}{2} \sum_{\alpha,\beta=e,\mu,\tau} \nu_{\alpha L}^{T} C^{-1} \mathcal{M}_{\alpha\beta} \nu_{\beta L} + \mathrm{h.c.}$$

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any complex symmetrix matrix $\mathcal{M}$ can be diagonalised by a unitary matrix as

$$U_\nu^T \mathcal{M} U_\nu = m \,, \qquad m: \text{ diagonal}, \; m_i \geq 0$$

Lepton mixing

$$\mathcal{L}_{\rm CC} = -\frac{g}{\sqrt{2}} W^\rho \sum_{\alpha=e,\mu,\tau} \sum_{i=1}^{3} \bar{\nu}_{iL} U^*_{\alpha i} \gamma_\rho \ell_{\alpha L} + \text{h.c.}$$

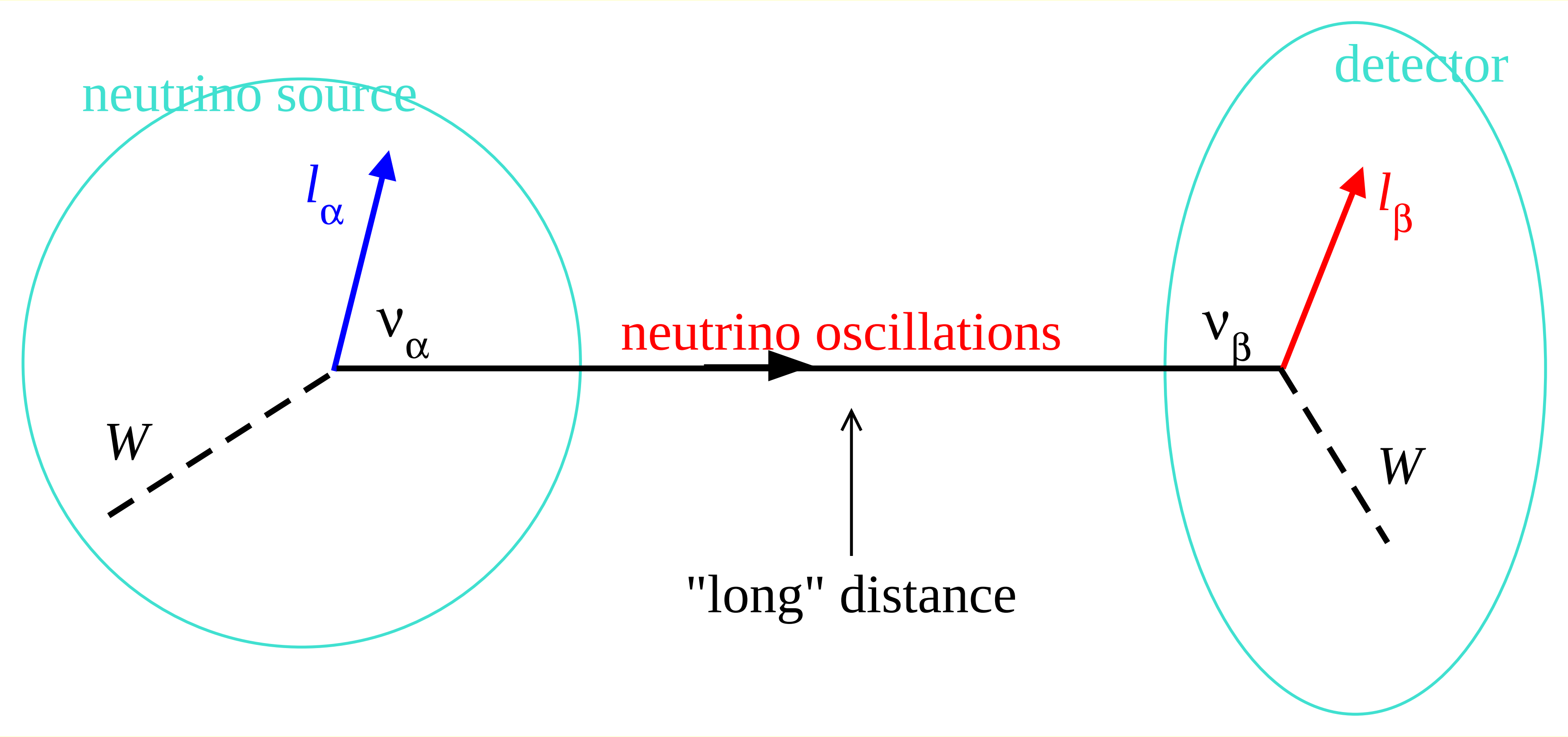
$$\mathcal{L}_{\rm M} = -\frac{1}{2} \sum_{i=1}^{3} \nu_{iL}^T C^{-1} \nu_{iL} m_i^\nu - \sum_{\alpha=e,\mu,\tau} \bar{\ell}_{\alpha R} \ell_{\alpha L} m_\alpha^\ell + \text{h.c.}$$

The unitary lepton mixing matrix:

$$(U_{\alpha i}) \equiv U_{\rm PMNS} = V^{\rm Dirac} \, D^{\rm Maj}$$

$$D^{\rm Maj} = \text{diag}(e^{i\alpha_i/2})$$

Neutrino oscillations



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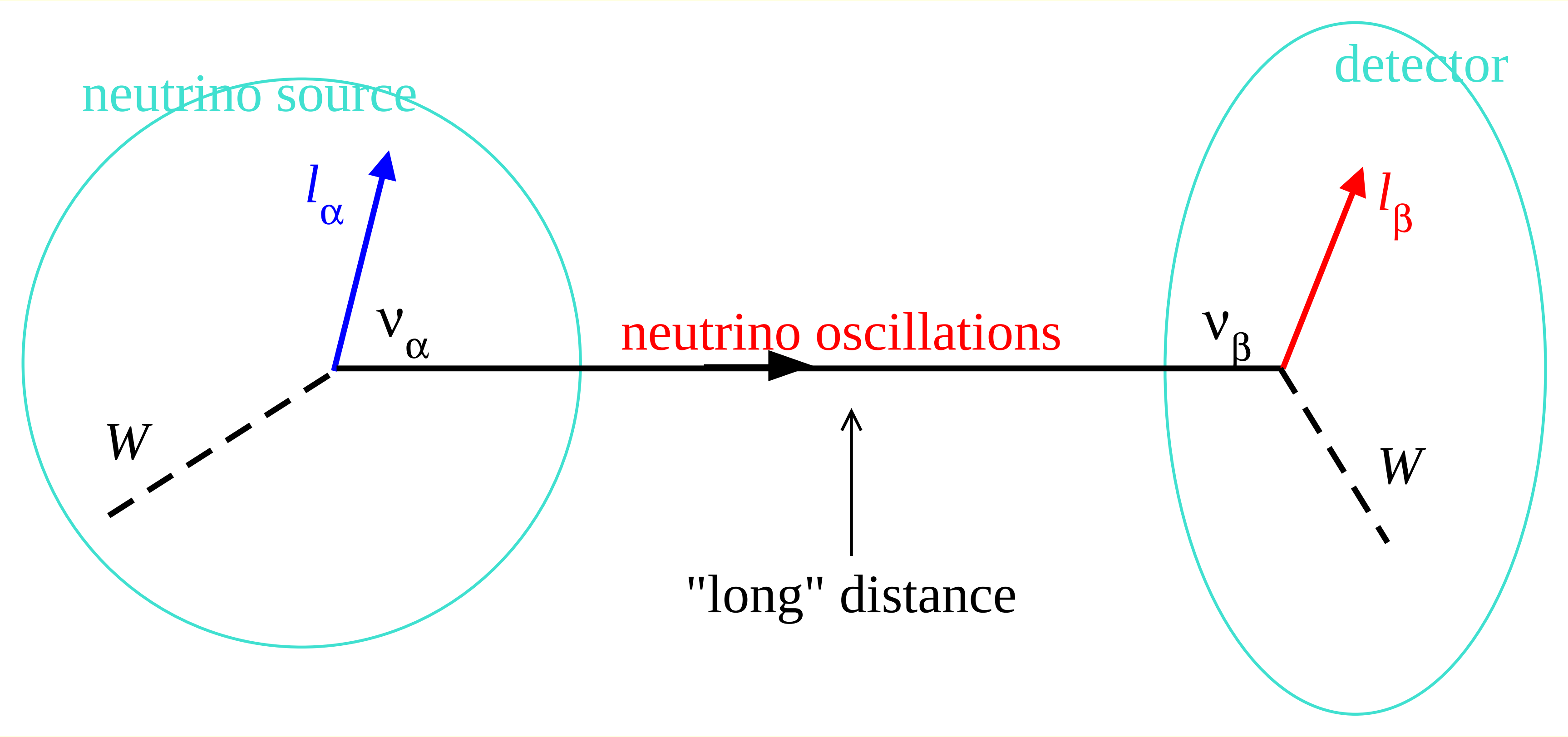

$$|\nu_\alpha\rangle = U^*_{\alpha i}|\nu_i\rangle \qquad e^{-i(Et-p_i x)} \qquad |\nu_\beta\rangle = U^*_{\beta i}|\nu_i\rangle$$

propagating states are states with definite mass

Neutrino oscillations (in vacuum)

oscillation amplitude:

$$\mathcal{A}_{\nu_\alpha \to \nu_\beta} = \langle \nu_\beta | \quad \text{propagation} \quad | \nu_\alpha \rangle$$

$$= \sum_{i,j} \langle \nu_j | U_{\beta j} \quad e^{-i(Et - p_i x)} \quad U^*_{\alpha i} | \nu_i \rangle$$

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$$Et - p_i x = Et - \sqrt{E^2 - m_i^2}\, x \approx Et - Ex + \frac{m_i^2 x}{2E}$$

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oscillation probability:

$$P_{\nu_\alpha \to \nu_\beta} = \left| \mathcal{A}_{\nu_\alpha \to \nu_\beta} \right|^2$$

The oscillation probability in vacuum

$$P_{\nu_\alpha \to \nu_\beta}(L) = \sum_{jk} U_{\alpha j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k} \exp\left[-i \frac{\Delta m^2_{kj} L}{2\, E_\nu}\right]$$

$\Delta m^2_{kj} \equiv m^2_k - m^2_j$: oscillations are sensitive only to mass-squared differences (not to absolute mass!)

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to observe oscillations one needs

- non-trivial mixing $U_{\alpha i}$
- non-zero mass-squared differences Δm^2_{kj}
- a suitable value for L/E_ν

The oscillation phase

$$\phi = \frac{\Delta m^2 L}{4E_\nu} = 1.27 \frac{\Delta m^2[\mathrm{eV}^2]\, L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}$$

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- "short" distance: $\phi \ll 1$: no oscillations can develop and $P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta}$ because of $\sum_j U_{\alpha j} U^*_{\beta j} = \delta_{\alpha\beta}$.
- "long" distance: $\phi \gtrsim \pi/2$: oscillations are observable
- "very long" distance: $\phi \gg 2\pi$: oscillations are averaged out (indep. of L and E_ν):

$$P_{\nu_\alpha \to \nu_\beta} = \sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2$$

2-neutrino oscillations

Two-flavour limit:

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}, \qquad P = \sin^2 2\theta \, \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$

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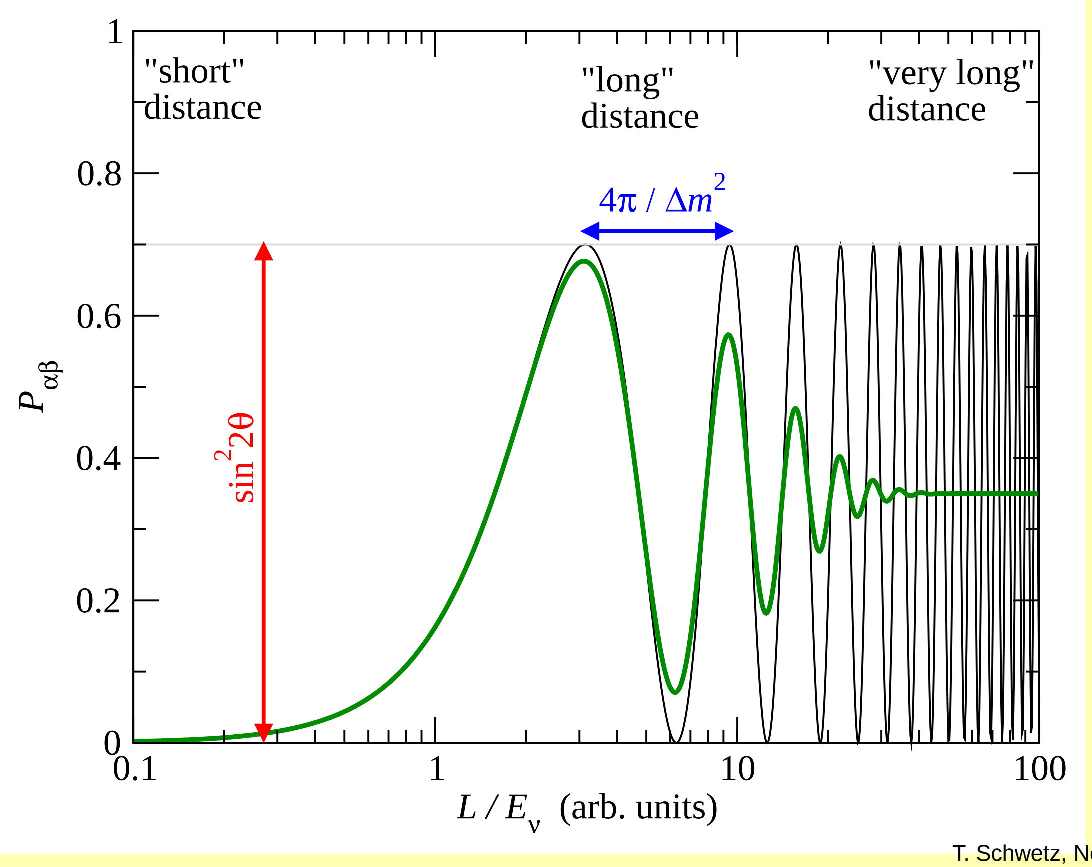

Appearance vs. disappearance

- appearance experiments:

$$P_{\nu_\alpha \to \nu_\beta}\,, \qquad \alpha \neq \beta$$

"appearance" of a neutrino of a new flavour $\beta \neq \alpha$ in a beam of ν_α

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- disappearance experiments:

$$P_{\nu_\alpha \to \nu_\alpha}$$

measurement of the "survival" probability of a neutrino of given flavour

General properties of vacuum oscillations

$$P_{\nu_\alpha \to \nu_\beta} = \sum_{jk} U_{\alpha j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k} \exp\left[-i \frac{\Delta m^2_{kj} L}{2\, E_\nu}\right]$$

- Unitarity: $\sum_\beta P_{\nu_\alpha \to \nu_\beta} = 1$

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- Phases in U induce CP violation: $P_{\nu_\alpha \to \nu_\beta} \neq P_{\bar\nu_\alpha \to \bar\nu_\beta}$
- there is no CP violation in disappearance experiments:

$$P_{\nu_\alpha \to \nu_\alpha} = P_{\bar\nu_\alpha \to \bar\nu_\alpha} = \sum_{k,j} |U_{\alpha k}|^2 |U_{\alpha j}|^2 e^{-i \Delta m^2_{kj} L / 2E}$$

(but $P_{\alpha\alpha}$ may still depend on $\cos\delta, \sin^2\delta, ...$)

Eff. Schrödinger equation

The evolution of the flavour state can be described by an effective Schrödinger equation:

$$i\frac{d}{dt}\begin{pmatrix} a_e \\ a_\mu \\ a_\tau \end{pmatrix} = H_{\rm vac}\begin{pmatrix} a_e \\ a_\mu \\ a_\tau \end{pmatrix}$$

where

$$\begin{aligned} H_{\rm vac}^{\nu} &= U \text{diag}\left(0, \frac{\Delta m^2_{21}}{2E_\nu}, \frac{\Delta m^2_{31}}{2E_\nu}\right) U^\dagger \\ H_{\rm vac}^{\bar\nu} &= U^* \text{diag}\left(0, \frac{\Delta m^2_{21}}{2E_\nu}, \frac{\Delta m^2_{31}}{2E_\nu}\right) U^T \end{aligned}$$

Neutrino oscillations in matter

The matter effect

When neutrinos pass through matter the interactions with the particles in the background induce an effective potential for the neutrinos

The coherent forward scattering amplitude leads to an index of refraction for neutrinos

L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978); *ibid.* D **20**, 2634 (1979)

Effective Hamiltonian in matter

$$H^{\nu}_{\rm mat} = U \text{diag}\left(0, \frac{\Delta m^2_{21}}{2E_\nu}, \frac{\Delta m^2_{31}}{2E_\nu}\right) U^\dagger + \text{diag}(\sqrt{2}G_F N_e, 0, 0)$$

$$H^{\bar\nu}_{\rm mat} = \underbrace{U^* \text{diag}\left(0, \frac{\Delta m^2_{21}}{2E_\nu}, \frac{\Delta m^2_{31}}{2E_\nu}\right) U^T}_{H_{\rm vac}} - \underbrace{\text{diag}(\sqrt{2}G_F N_e, 0, 0)}_{V_{\rm mat}}$$

$N_e(x)$: electron density along the neutrino path

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$N_e(x)$: electron density along the neutrino path

for non-constant matter the Hamiltonian depends on time:

$$i \frac{d}{dt} a = H_{\rm mat}(t) a$$

Effective Hamiltonian in matter

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$N_e(x)$: electron density along the neutrino path

Remember: $U = V^{\rm Dirac} D^{\rm Maj}$

$\Rightarrow$ Majorana phases do not show up in oscillations

Effective matter potential - 1

Effective 4-point interaction Hamiltonian in the SM

$$H_{\text{int}}^{\nu_\alpha} = \frac{G_F}{\sqrt{2}}\,\bar{\nu}_\alpha \gamma_\mu (1-\gamma_5)\nu_\alpha \underbrace{\sum_f \bar{f}\gamma^\mu (g_V^{\alpha,f} - g_A^{\alpha,f}\gamma_5) f}_{J^\mu_{\text{mat}}}$$

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ordinary matter: e^-, p, n

non-relativistic, unpolarised, neutral

$$\langle \bar{f} \gamma^\mu f \rangle = \frac{1}{2} N_f \delta_{\mu 0} \,, \quad \langle \bar{f} \gamma_5 \gamma^\mu f \rangle = 0 \,, \quad N_e = N_p$$

Effective matter potential - 2

$$
\begin{aligned}
J^\mu_{\text{mat}} &= \frac{1}{2}\delta_{\mu 0} \sum_{f=e,p,n} N_f \, g_V^{\alpha,f} \\
&= \frac{1}{2}\delta_{\mu 0} \left[N_e \left(g_V^{\alpha,e} + g_V^{\alpha,p} \right) + N_n g_V^{\alpha,n} \right]
\end{aligned}
$$

Effective matter potential - 2

$$J^{\mu}_{\rm mat} = \frac{1}{2}\delta_{\mu 0} \sum_{f=e,p,n} N_f \, g_V^{\alpha,f}$$

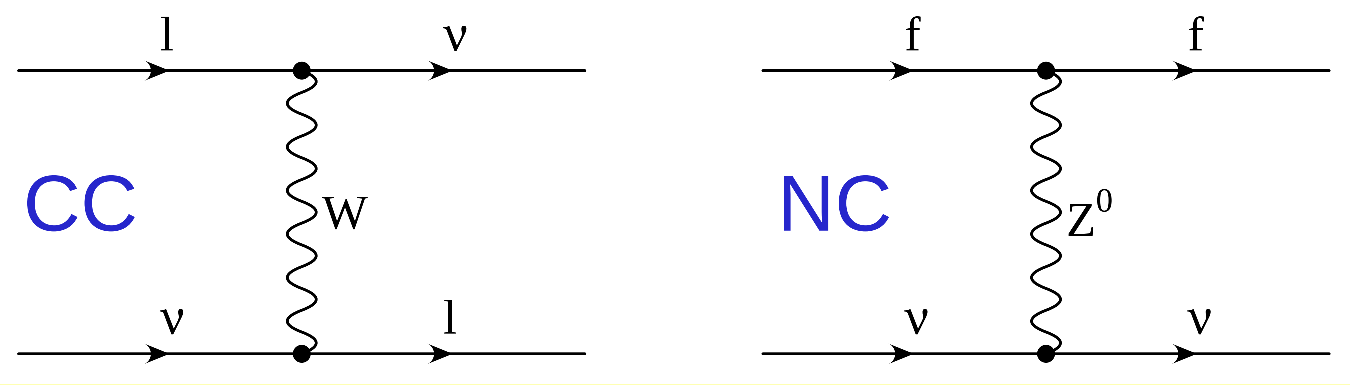
$$= \frac{1}{2}\delta_{\mu 0} \left[N_e \left(g_V^{\alpha,e} + g_V^{\alpha,p}\right) + N_n g_V^{\alpha,n}\right]$$

g_V	e^-	p	n
ν_e	$2\sin^2\Theta_W + \frac{1}{2}$	$-2\sin^2\Theta_W + \frac{1}{2}$	$-\frac{1}{2}$
$\nu_{\mu,\tau}$	$2\sin^2\Theta_W - \frac{1}{2}$	$-2\sin^2\Theta_W + \frac{1}{2}$	$-\frac{1}{2}$

$$\Rightarrow \quad V_{\rm mat} \propto \left(N_e - \frac{1}{2}N_n, -\frac{1}{2}N_n, -\frac{1}{2}N_n\right)$$

Effective matter potential - 3

$$V_{\mathrm{mat}} = \sqrt{2} G_F \mathrm{diag}\left(N_e - N_n/2, -N_n/2, -N_n/2\right)$$



- only ν_e fell CC (there are no μ, τ in normal matter)
- NC is the same for all flavours $\Rightarrow$ potential proportional to identiy has no effect on the evolution
- NC has no effect for 3-flavour active neutrinos, but is important in the presence of sterile neutrinos

Neutrino oscillations in constant matter

diagonalize the Hamiltonian in matter:

$$H^{\nu}_{\rm mat} = U \text{diag}\left(0, \frac{\Delta m^2_{21}}{2E_\nu}, \frac{\Delta m^2_{31}}{2E_\nu}\right) U^\dagger + \text{diag}(\sqrt{2} G_F N_e, 0, 0)$$

$$= U_m \text{diag}\,(\lambda_1, \lambda_2, \lambda_3)\, U_m^\dagger$$

Same expression for oscillation probability, but replace "vacuum" parameters by "matter" parameters

2-neutrino oscillations in constant matter

Two-flavour case:

$$P_{\rm mat} = \sin^2 2\theta_{\rm mat} \, \sin^2 \frac{\Delta m^2_{\rm mat} L}{4E}$$

with

$$\sin^2 2\theta_{\rm mat} = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - A)^2}$$

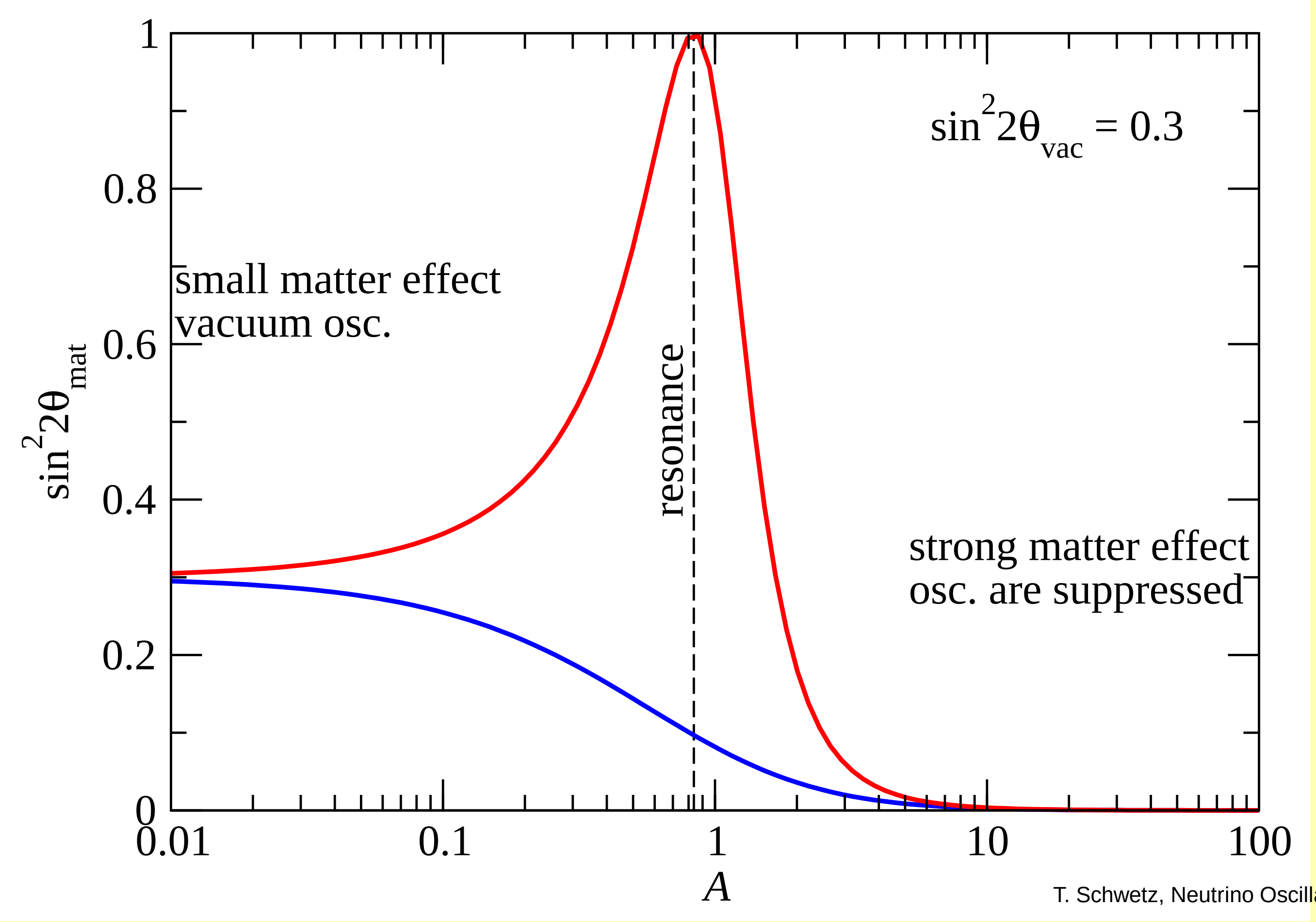
$$\Delta m^2_{\rm mat} = \Delta m^2 \sqrt{\sin^2 2\theta + (\cos 2\theta - A)^2}$$

$$A \equiv \frac{2EV}{\Delta m^2}$$

2-neutrino oscillations in constant matter

$$\sin^2 2\theta_{\rm mat} = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - A)^2} \qquad A \equiv \frac{2EV}{\Delta m^2}$$

resonance for $\cos 2\theta = A$: "MSW resonance"



Evidences for neutrino oscillations

Neutrino oscillation experiments

natural neutrino sources:

- solar neutrinos
  Homestake, SAGE+GNO, Super-K, SNO, Borexino

- atmospheric neutrinos
  Super-Kamiokande

artificial neutrino sources:

- reactor neutrinos
  Chooz (1 km), KamLAND (180 km)

- long-baseline accelerator experiments
  K2K (250 km), MINOS (735 km)

3-flavour oscillation parameters

Δm^2_{31} Δm^2_{21}

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

atmospheric+LBL Chooz solar+KamLAND

3-flavour oscillation parameters

$$\Delta m^2_{31} \qquad\qquad\qquad\qquad \Delta m^2_{21}$$

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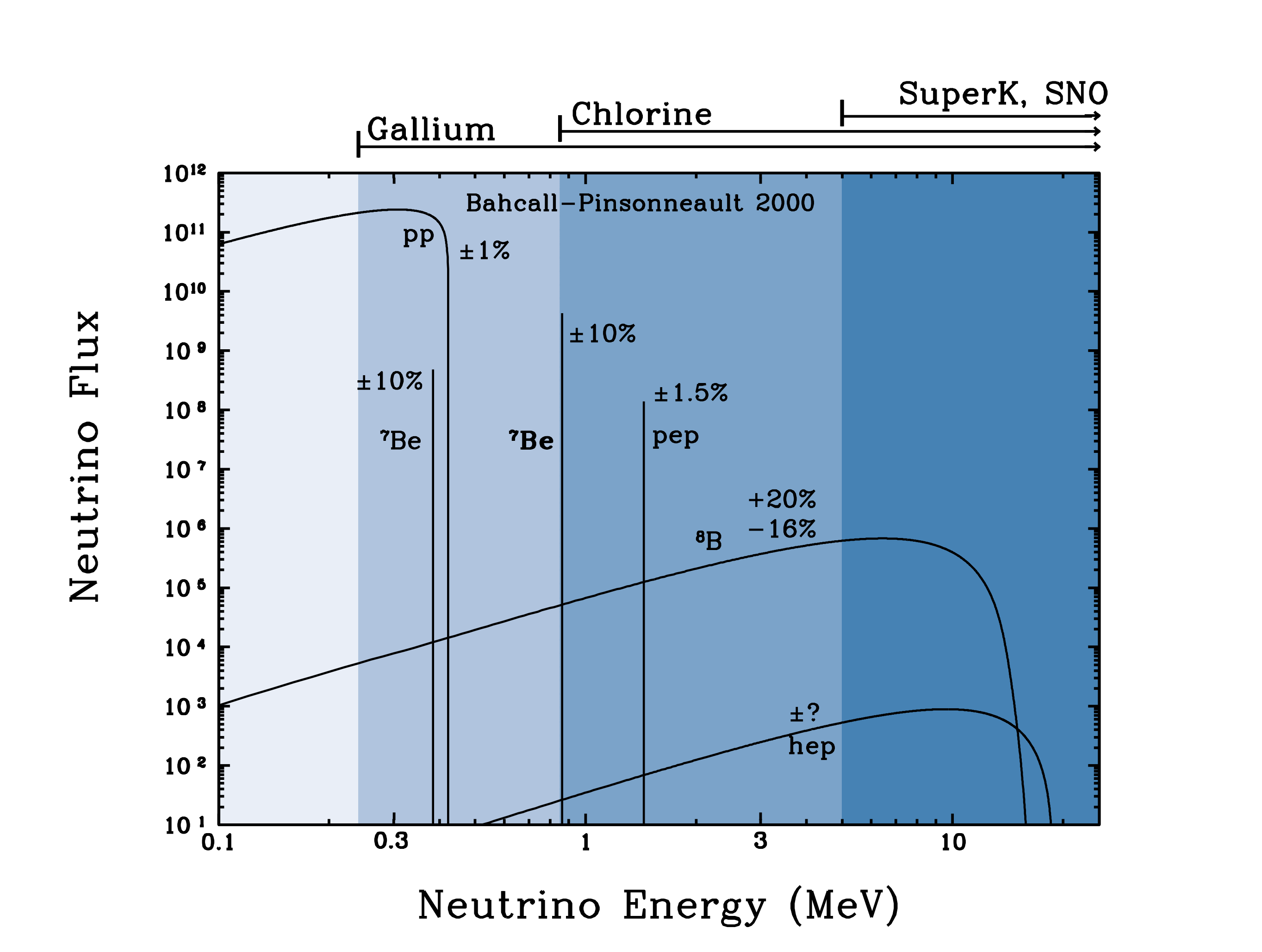
atmospheric+LBL — Chooz — solar+KamLAND

3-flavour effects are suppressed because
$\theta_{13} \ll 1$ und $\Delta m^2_{21} \ll \Delta m^2_{31}$

$\Rightarrow$ dominant oscillations are well described by effective two-flavour oscillations

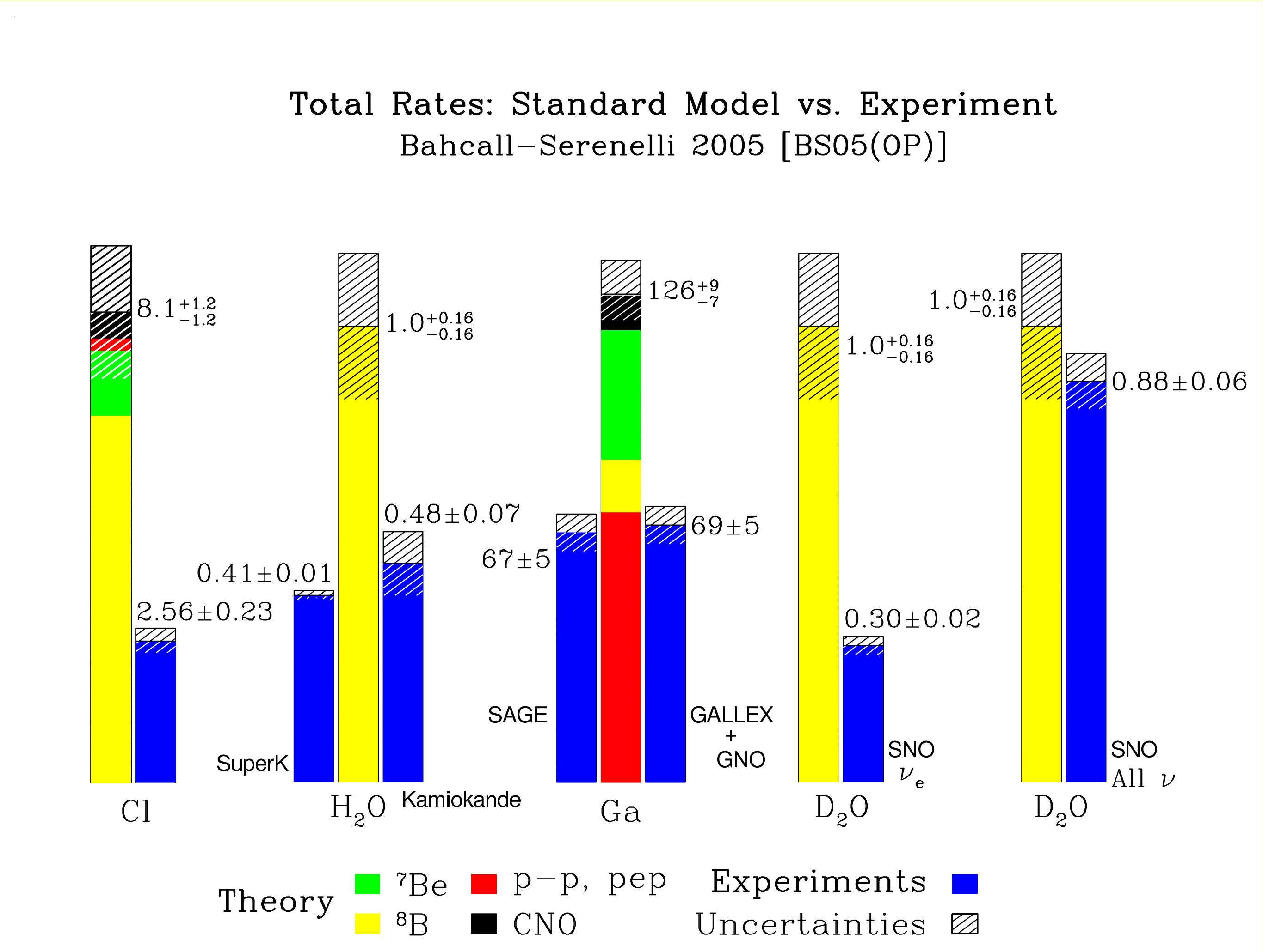
Solar neutrinos and the parameters Δm^2_{21}, θ_{12}

The solar neutrino flux



Solar neutrino experiments

summary of solar neutrino experiments



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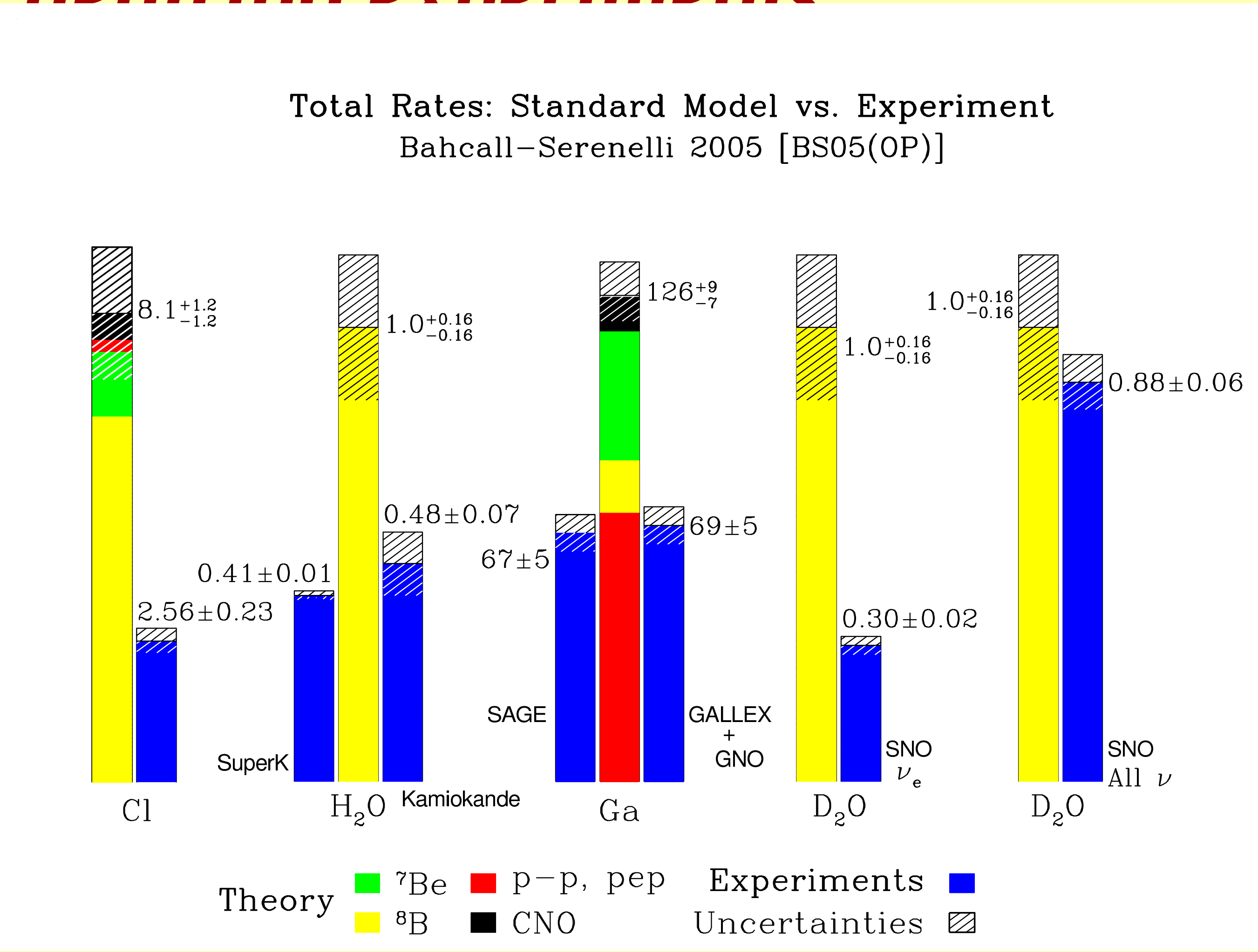


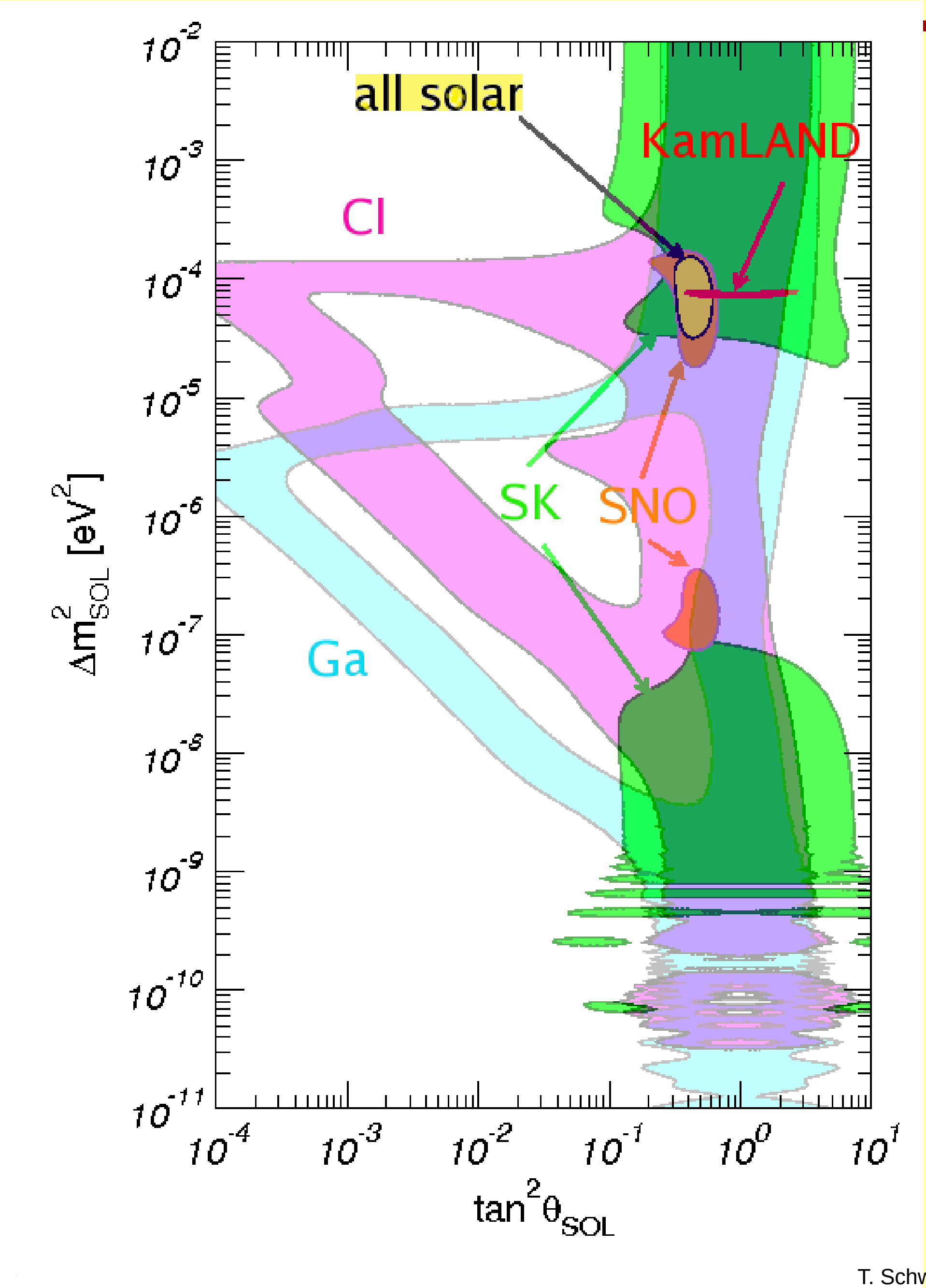
SNO:

$$\nu_e + d \to p + p + e^-$$
$$\nu_x + d \to p + n + \nu_x$$

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.301 \pm 0.033$$

7σ evidence for a non-zero $\nu_{\mu,\tau}$ flux from the sun

’Solar’ parameters



Probing solar properties with neutrinos

Neutrinos as messengers from the center of the sun:

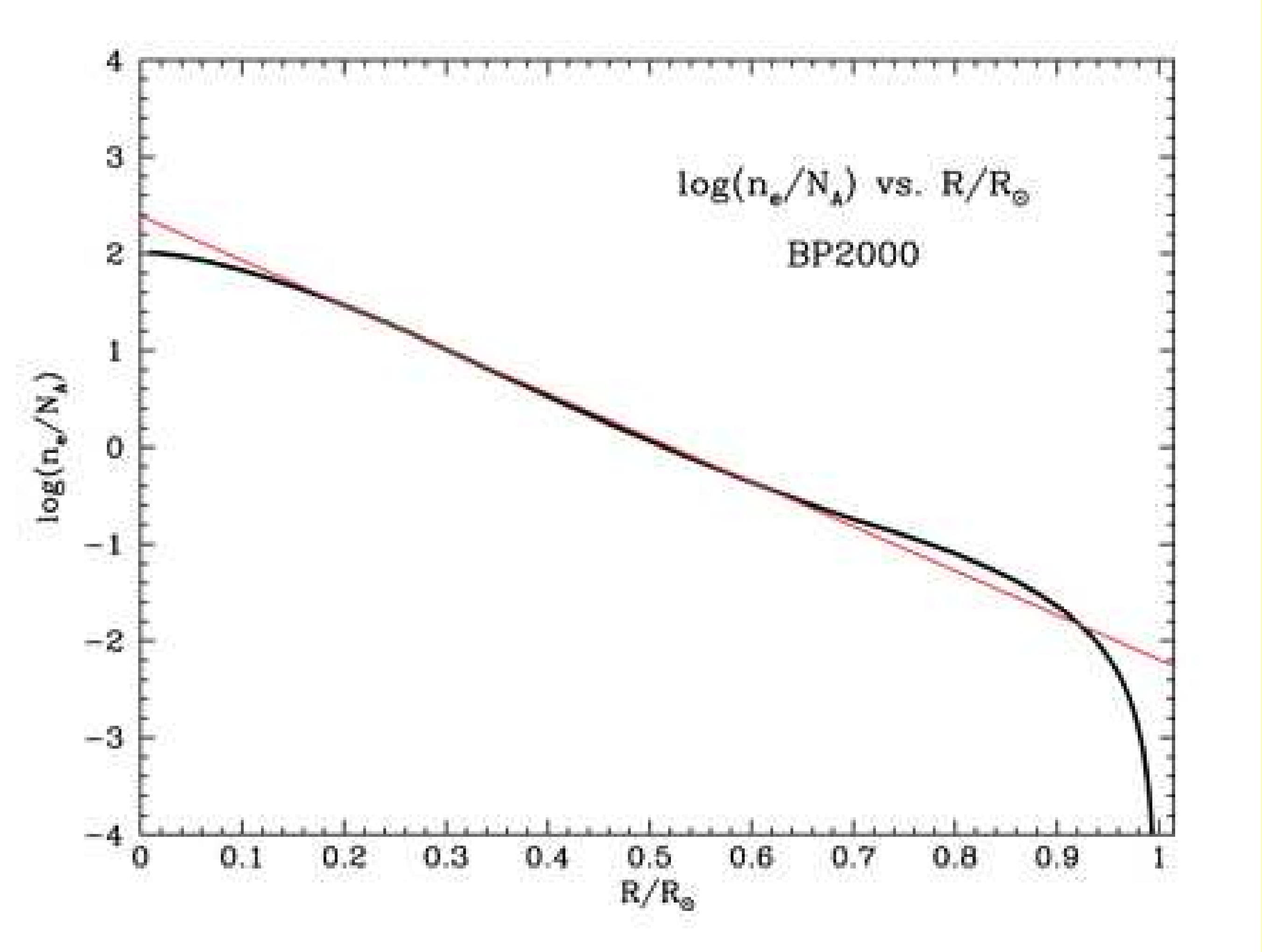
boron-8 neutrino flux $\Phi \propto T^{20}$

where T is the temperature at the center of the sun

the measurement of the solar neutrino flux allows a determination of T with an accuracy of 1%:

$$T = 15.7(1 \pm 0.01) \times 10^6\,\mathrm{K}$$

The electron density in the sun



The LMA-MSW mechanism

evolution is adiabatic if $\left(\frac{1}{\theta_m}\frac{d\theta_m}{dx}\right)^{-1} \gg L_{\rm osc}$

using $\Delta m^2 = 8 \times 10^{-5}$ eV^2 the oscillation length is

$$L_{\rm osc} = \frac{4\pi E}{\Delta m^2} \simeq 30\,{\rm km}\left(\frac{E}{\rm MeV}\right)$$

for large mixing angles ($\sin^2\theta_{12} \simeq 0.3$):

$$\left(\frac{1}{\theta_m}\frac{d\theta_m}{dx}\right)^{-1} \sim \left(\frac{1}{V}\frac{dV}{dx}\right)^{-1} \sim \text{size of sun} \gg 30\,{\rm km}$$

$\Rightarrow$ **adiabatic evolution**

The LMA-MSW mechanism

the electron neutrino is born at the center of the sun as

$$|\nu_e\rangle = \cos\theta_m |\nu_1\rangle + \sin\theta_m |\nu_2\rangle$$

then $|\nu_1\rangle$ and $|\nu_2\rangle$ evolve adiabatically to the Earth

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$$|\nu_e\rangle = \cos\theta_m|\nu_1\rangle + \sin\theta_m|\nu_2\rangle$$

then $|\nu_1\rangle$ and $|\nu_2\rangle$ evolve adiabatically to the Earth

$$P_{ee} = P_{e1}^{\rm prod} P_{1e}^{\rm det} + P_{e2}^{\rm prod} P_{2e}^{\rm det}$$

$P_{e3}^{\rm prod} \approx \sin^2\theta_{13} \approx 0$, interference term averages out

$$P_{e1}^{\rm prod} = \cos^2\theta_m\,, \quad P_{1e}^{\rm det} = \cos^2\theta$$
$$P_{e2}^{\rm prod} = \sin^2\theta_m\,, \quad P_{2e}^{\rm det} = \sin^2\theta$$

$$\Rightarrow \qquad P_{ee} = \cos^2\theta_m\cos^2\theta + \sin^2\theta_m\sin^2\theta$$

The LMA-MSW mechanism

in the center of the sun we have

$$A \equiv \frac{2EV}{\Delta m^2} \simeq 0.2 \left(\frac{E_\nu}{\mathrm{MeV}} \right) \left(\frac{8 \times 10^{-5}\,\mathrm{eV}^2}{\Delta m^2} \right)$$

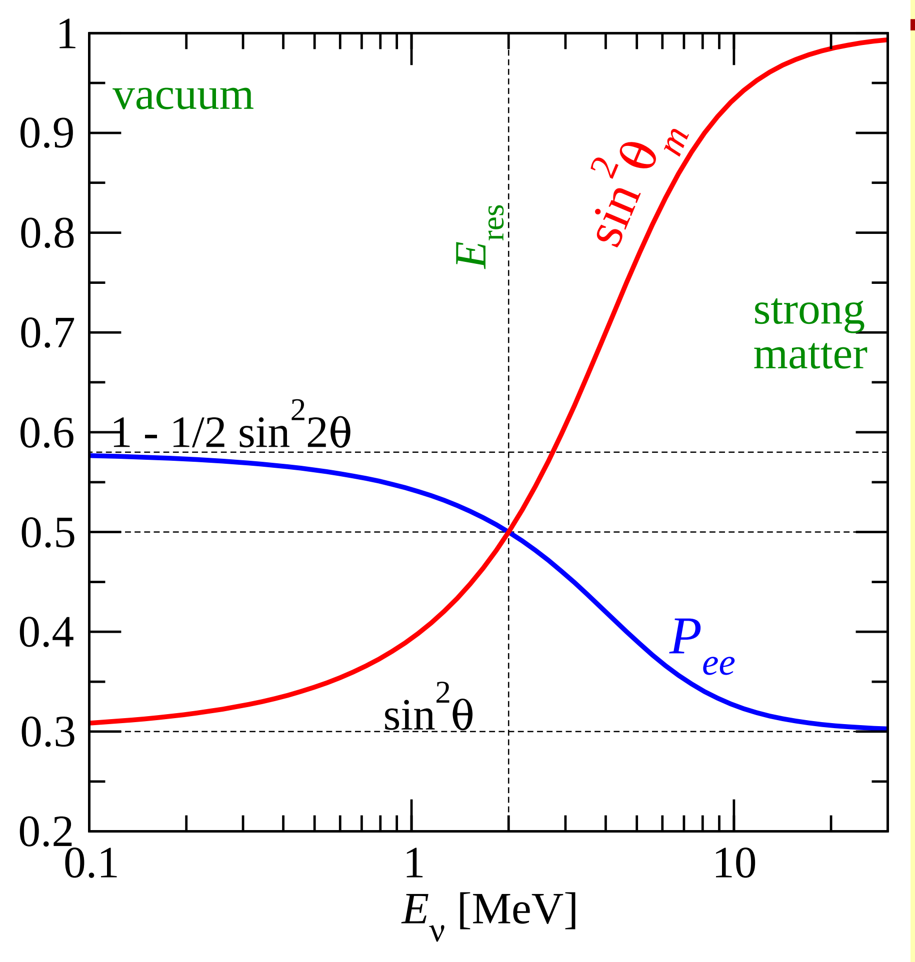
resonance occurs for

$$A = \cos 2\theta = 0.4$$

$$\Rightarrow \qquad E_{\mathrm{res}} \simeq 2\,\mathrm{MeV}$$

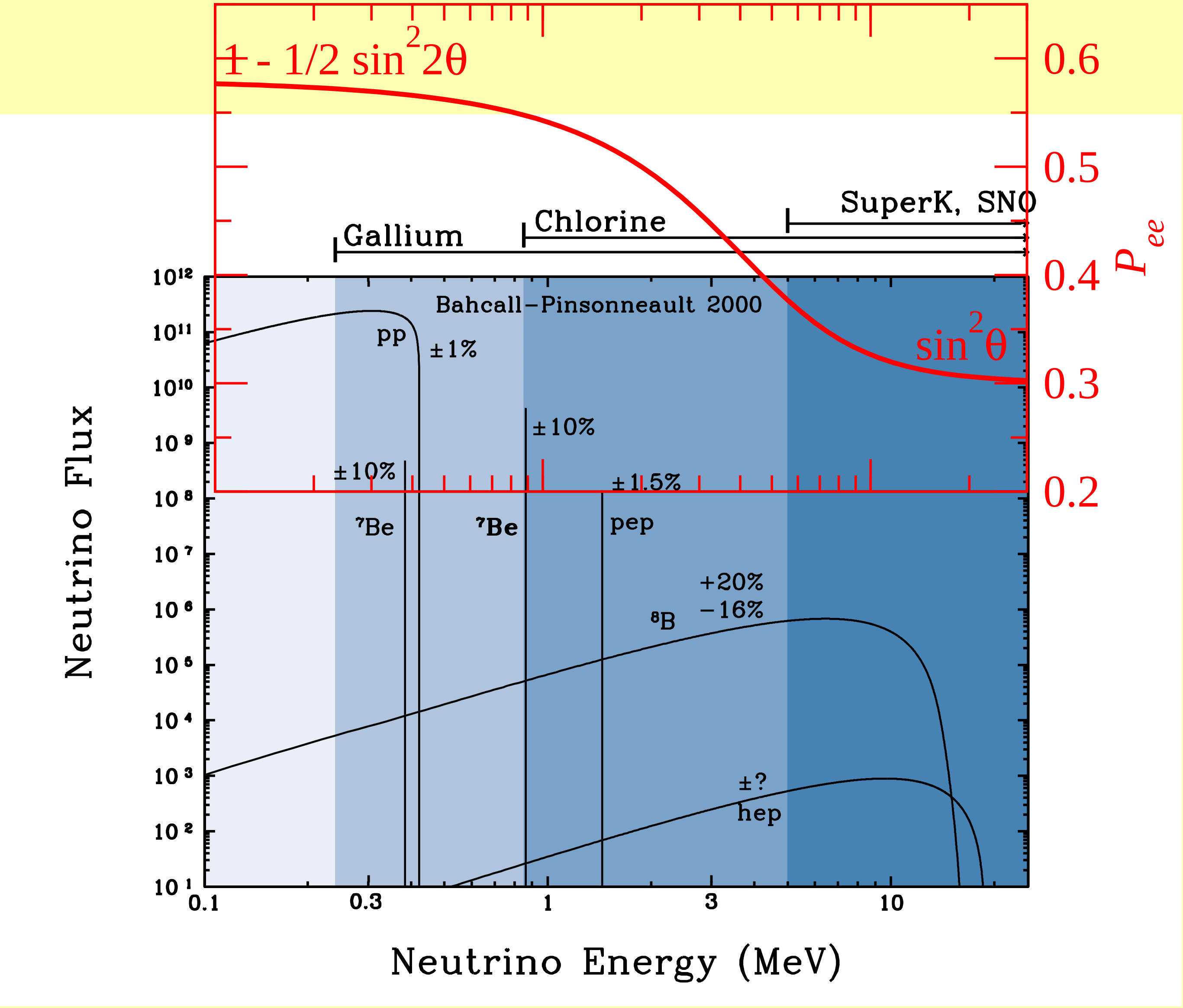
The LMA-MSW mechanism

$$P_{ee} = \cos^2\theta_m \cos^2\theta + \sin^2\theta_m \sin^2\theta$$



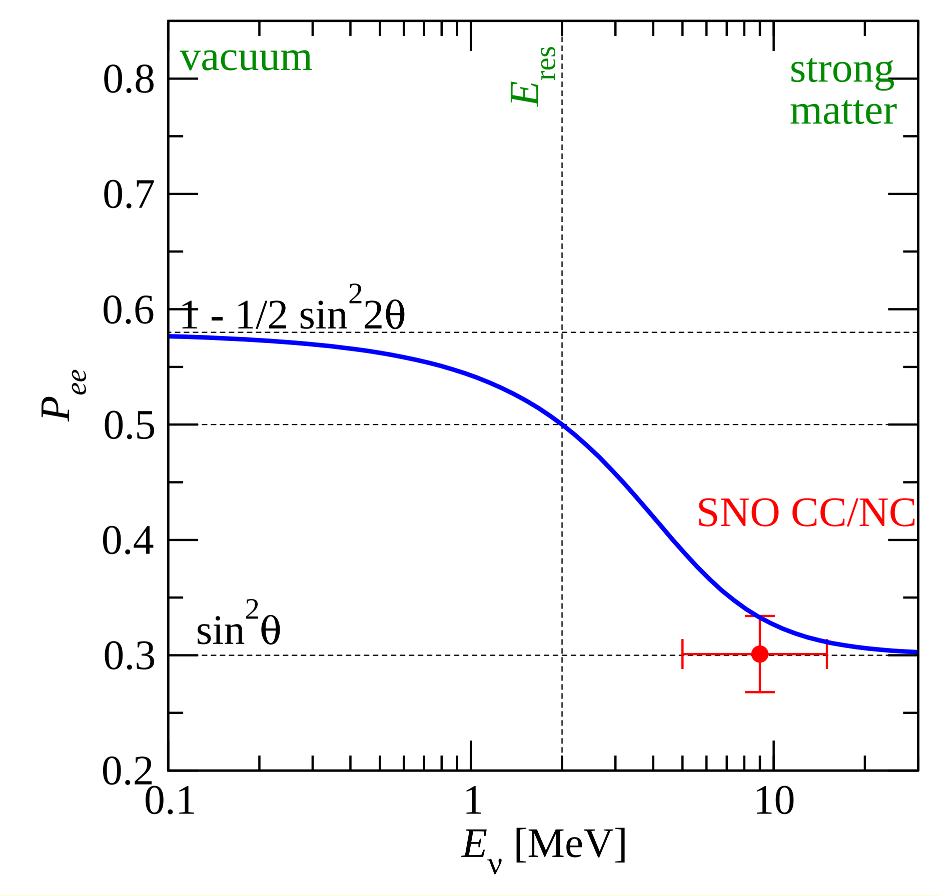
$$P_{ee} = \begin{cases} c^4 + s^4 = 1 - \frac{1}{2}\sin^2 2\theta & \text{vacuum} \quad (\theta_m = \theta) \\ \sin^2\theta & \text{strong matter} \quad (\theta_m = \pi/2) \end{cases}$$

The LMA-MSW mechanism



SNO evidence for the MSW effect

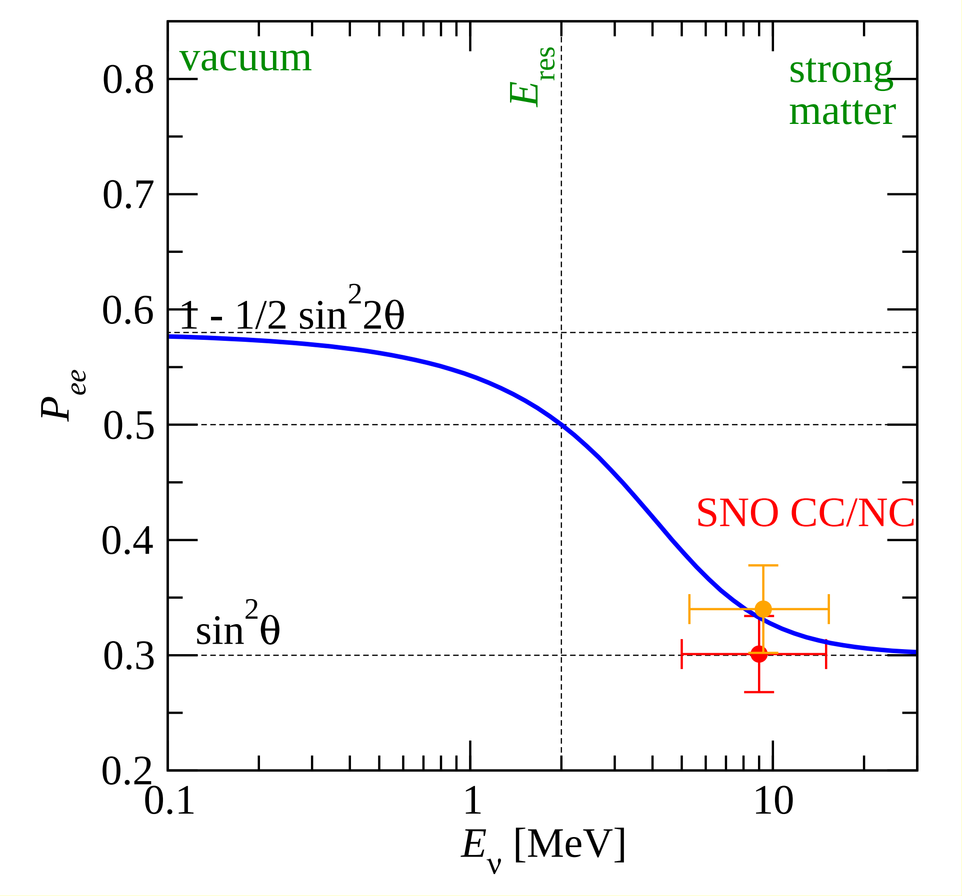
CC/NC measurment of SNO:



- constrains $\sin^2\theta_{12}$: $\phi_{\rm CC}/\phi_{\rm NC} \approx P_{ee}^{\rm SNO} \approx \sin^2\theta_{12}$
- $\phi_{\rm CC}/\phi_{\rm NC} < 1/2$: evidence for matter eff. and MSW reson.

new CC/CN from SNO NCD phase

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.340 \pm 0.038 \rightarrow 0.301 \pm 0.033$$



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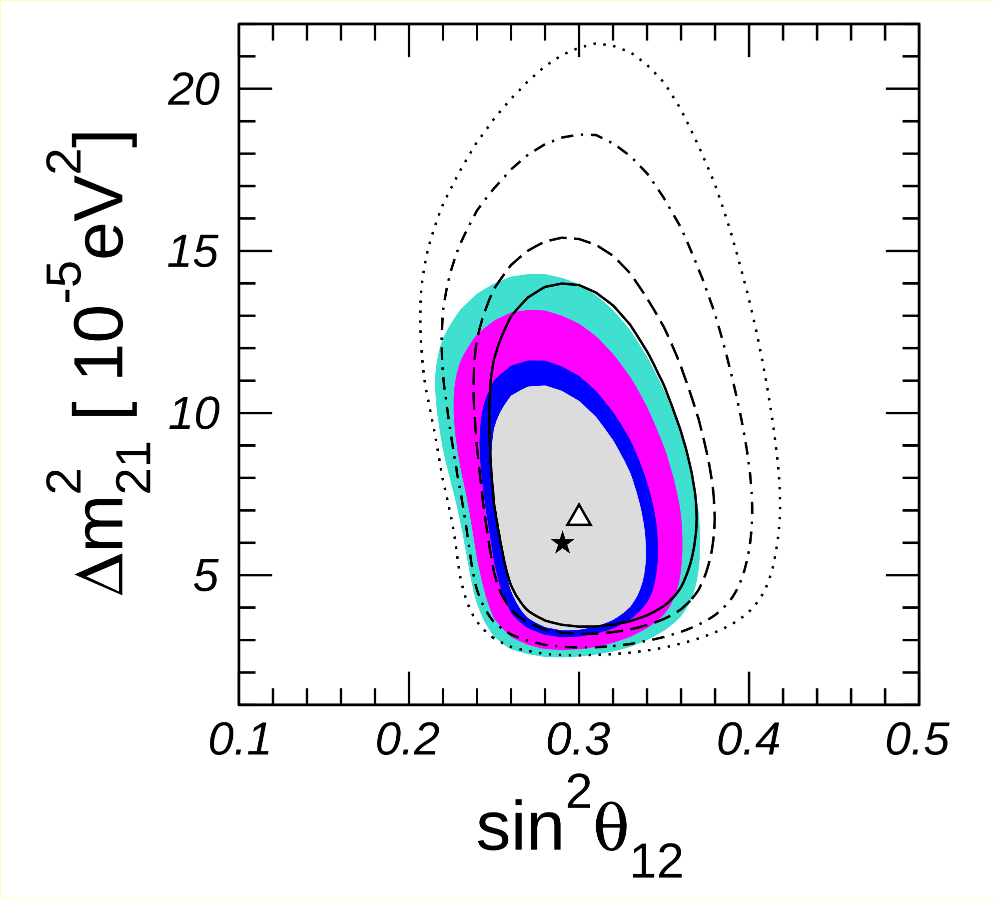
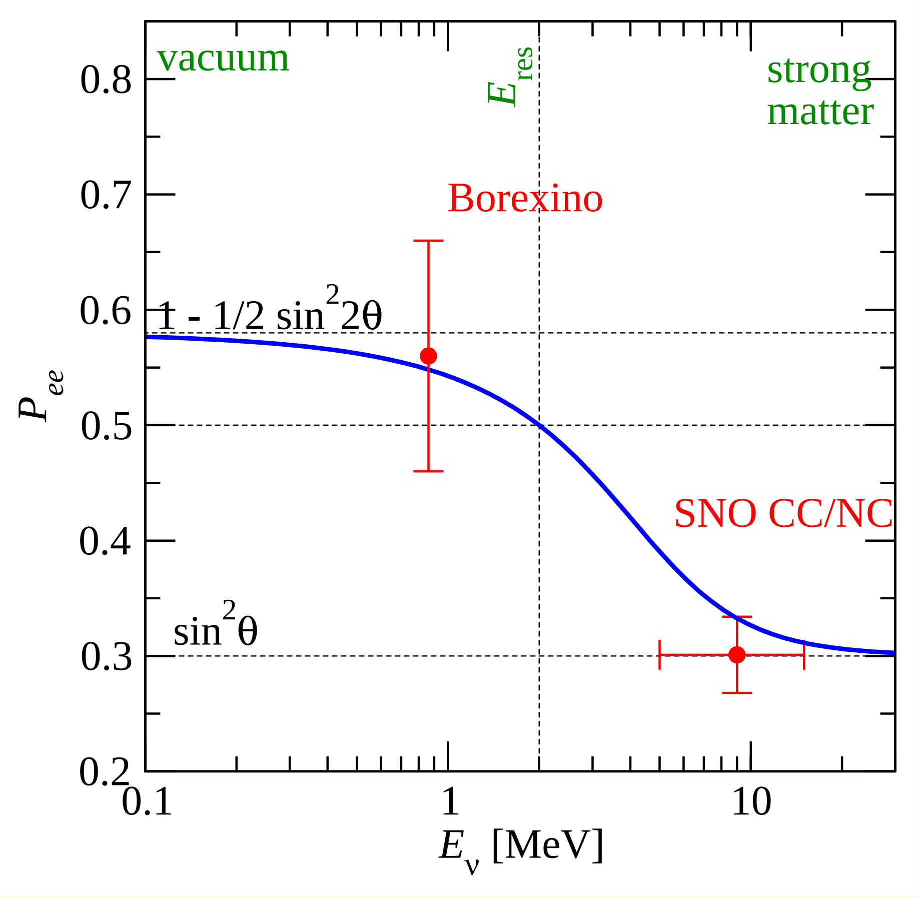


Testing the transition region

BOREXINO: measurment of the Be7 neutrino line at 0.862 MeV by $e\nu \to e\nu$ scattering $(\Rightarrow)$



Reactor neutrino experiments

Reactor experiments

... have played always an important role in neutrino physics

Starting from the discovery of the neutrino in the

Reines-Cowan experiment C.L. Cowan et al., Science 124 (1956) 103

there have been many important experiments, e.g.:

Gösgen G. Zacek et al., Phys. Rev. D34 (1986) 2621
Bugey Y. Declais et al., Nucl. Phys. B434 (1995) 503
CHOOZ M. Apollonio et al., Phys. Lett. B466 (1999) 415
Palo Verde F. Boehm et al., Phys. Rev. D64 (2001) 112001
KamLAND Eguchi et al., Phys. Rev. Lett. 90 (2003) 021802
. . .

Reactor experiments

- Nuclear power reactors are an intense source of $\bar{\nu}_e$
- Inverse β-decay offers a detection process with a clear experimental signature:

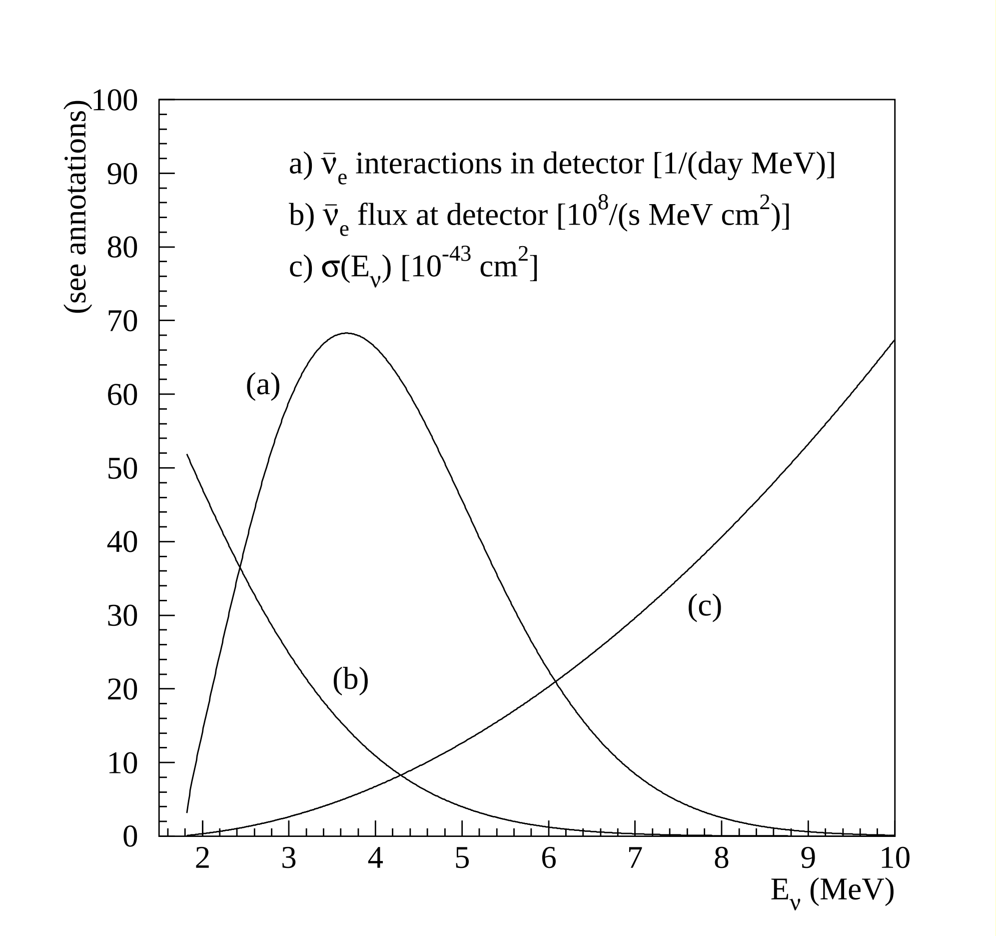
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

prompt positron + delayed neutron capture.

Energy threshold: $E_\nu \geq m_e + m_n - m_p \approx 1.8$ MeV

Reactor experiments

Bemporad, Gratta, Vogel, Rev.Mod.Phys.74(2002)297 [hep-ph/0107277]



$$\langle E_\nu \rangle \approx 3 - 4\,\mathrm{MeV}$$

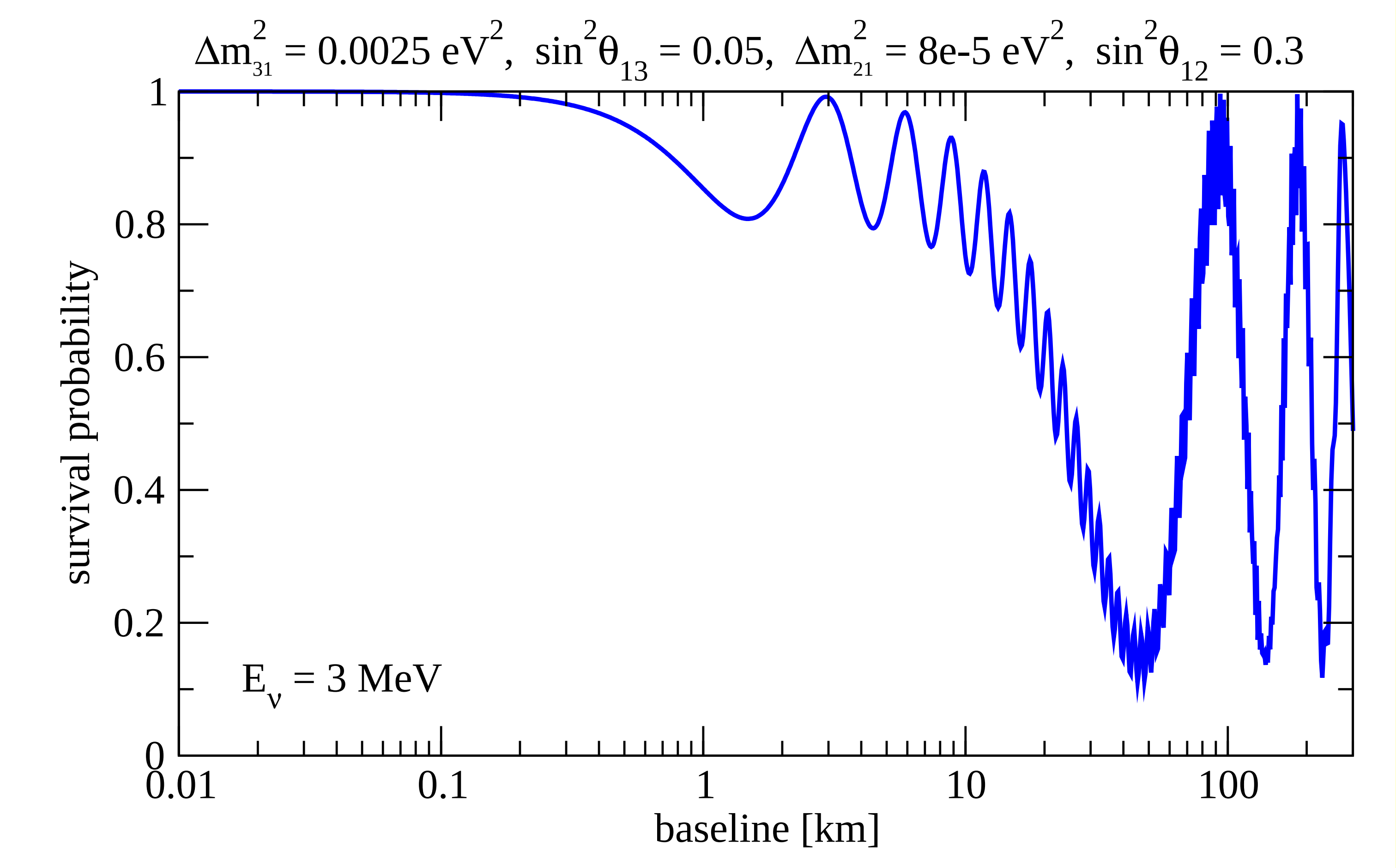
Reactor experiments

A reactor neutrino experiment can only be a
$\bar{\nu}_e$ disappearance experiment,

since for $E_\nu \sim 4$ MeV neither μ nor τ can be produced in the detector

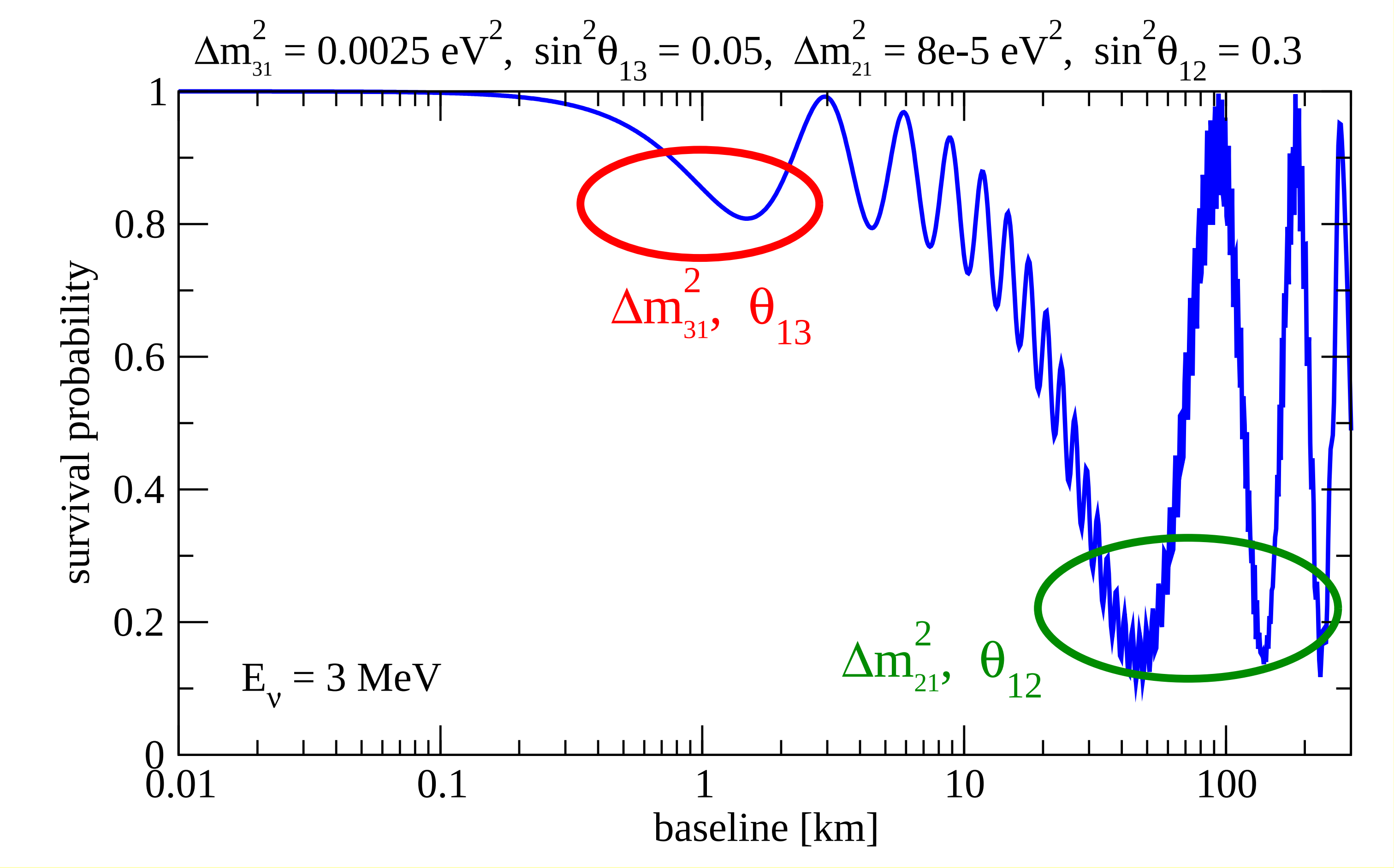
P_{ee} *at reactors*

The 3-flavour $\bar{\nu}_e \to \bar{\nu}_e$ survival probability:



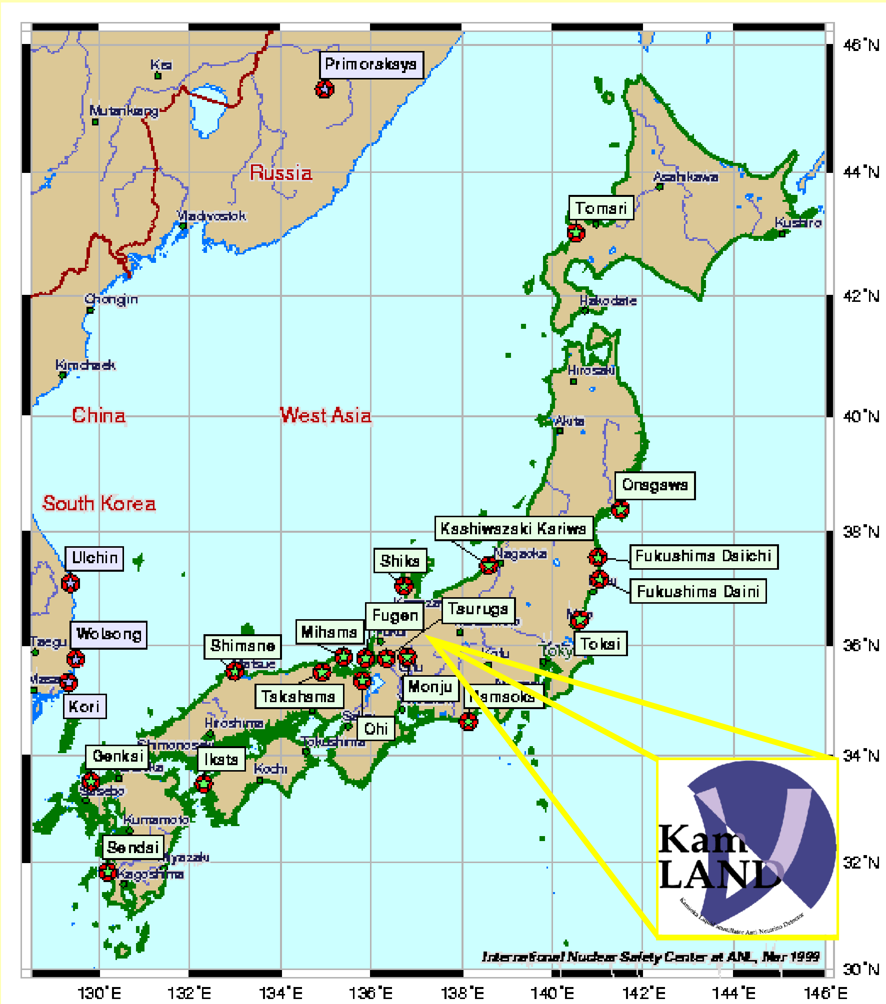
P_{ee} *at reactors*

The 3-flavour $\bar{\nu}_e \to \bar{\nu}_e$ survival probability:



The KamLAND reactor neutrino experiment

Kamioka Liquid scinitillator Anti-Neutrino Detector



detection of $\bar{\nu}_e$ produced in surrounding nuclear power plants

70 GW of nuclear power (7% of world total) is generated at a distance 175 ± 30 km from Kamioka

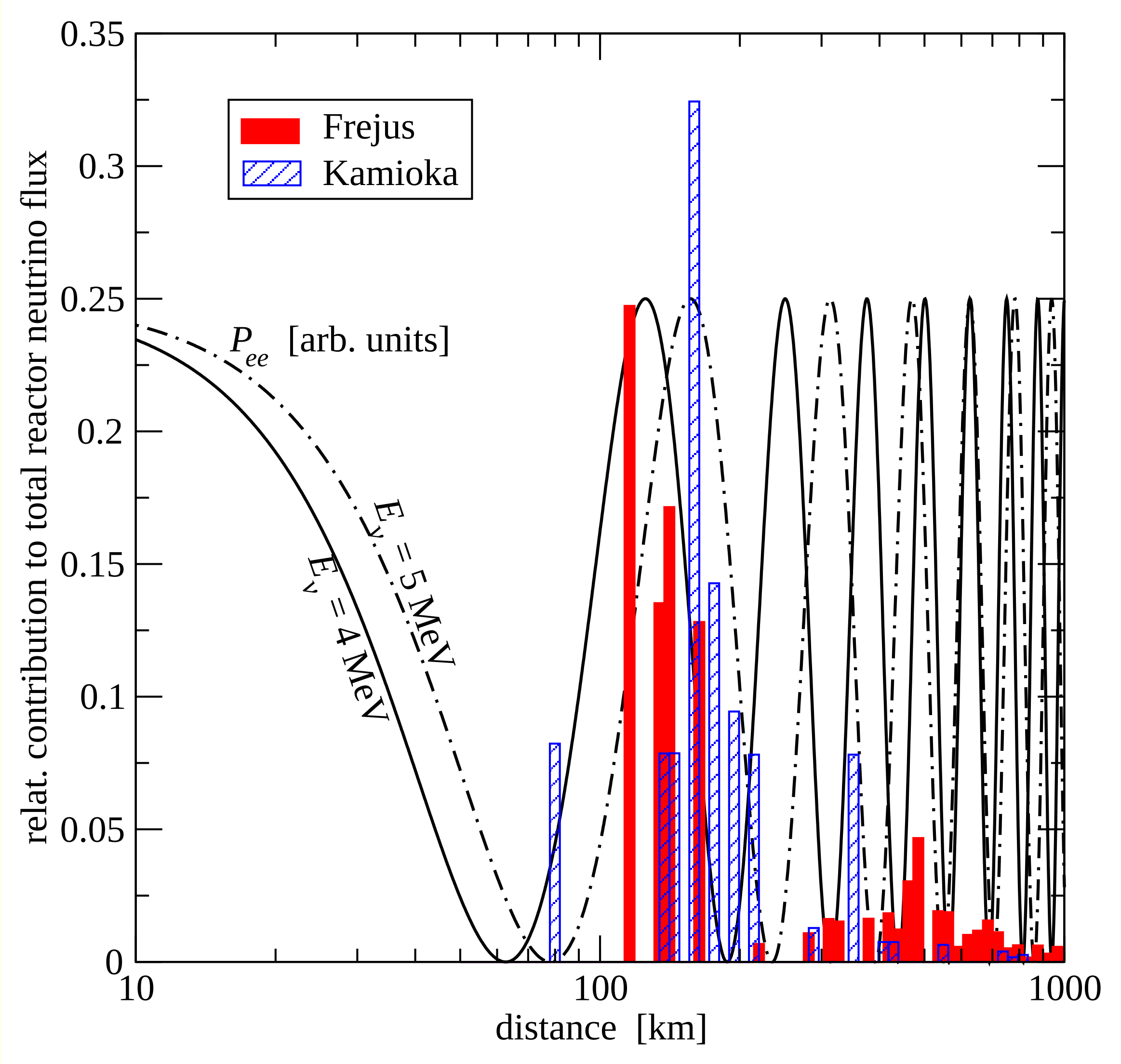
The KamLAND reactor neutrino experiment - 2

neutrino energy from nuclear reactors: $E_\nu \simeq 4\,\mathrm{MeV}$

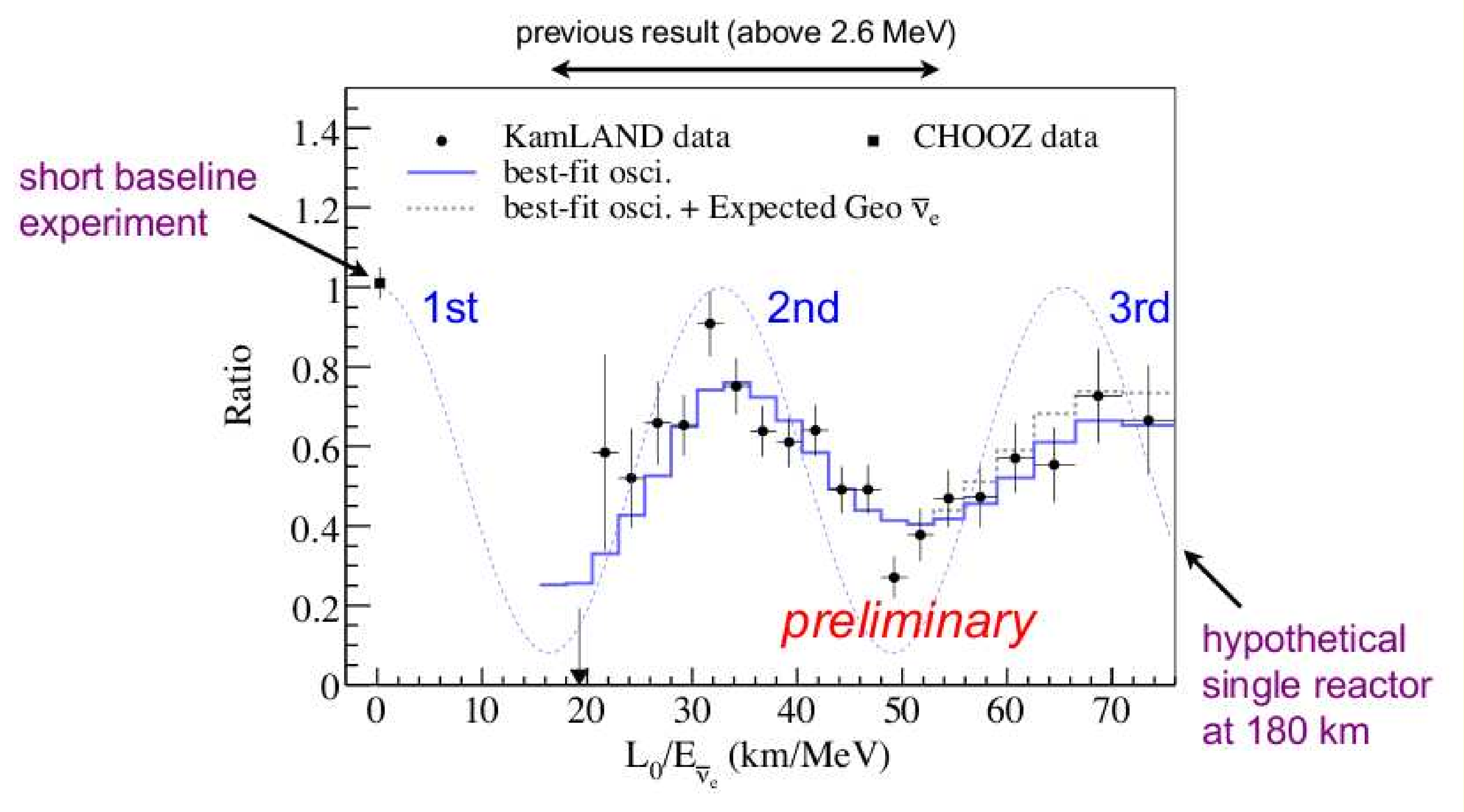
$$\Rightarrow \qquad \frac{E_\nu}{L} \sim \frac{4\,\mathrm{MeV}}{175\,\mathrm{km}} \sim 2 \times 10^{-5}\mathrm{eV}^2$$

just the correct order of magnitude to test the LMA-MSW solution for the solar neutrino problem

Reactor distribution in KamLAND



The KamLAND energy spectrum

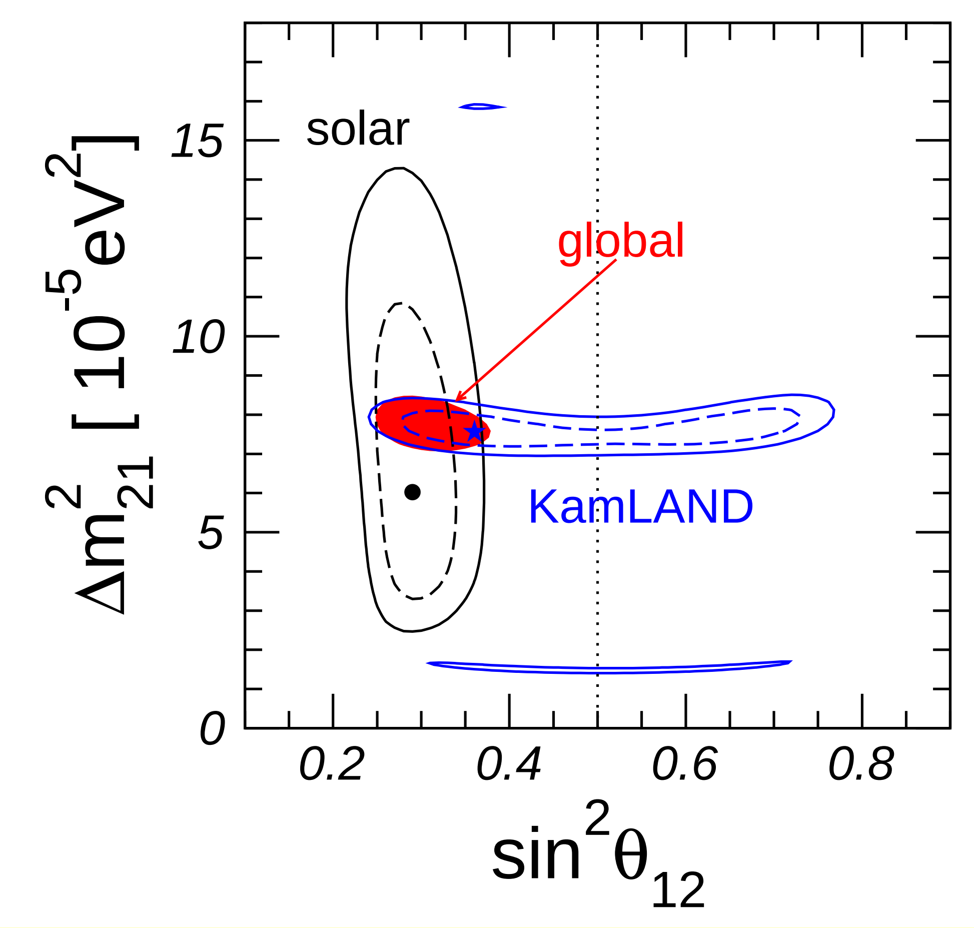


evidence for flux suppression and oscillations in $1/E_\nu$

$\Rightarrow$

KamLAND vs solar data

90% and 99.73% CL contours



Δm^2_{21}:
measured by KamLAND

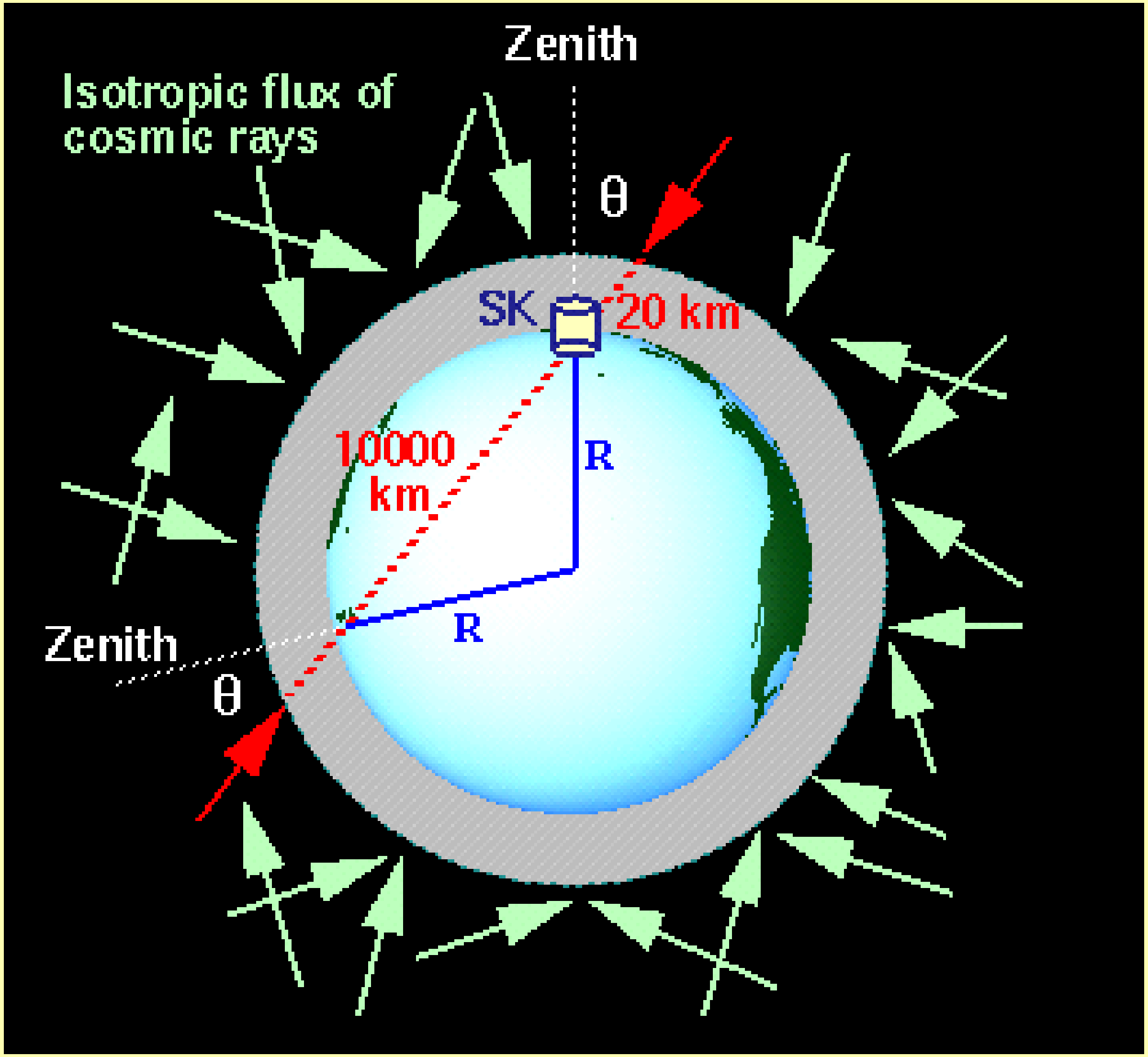
$\sin^2\theta_{12}$:
measured by SNO

$$\Delta m^2_{21} = 7.6 \pm 0.2 \times 10^{-5}\,\mathrm{eV}^2,\ \sin^2\theta_{12} = 0.31^{+0.016}_{-0.023}$$

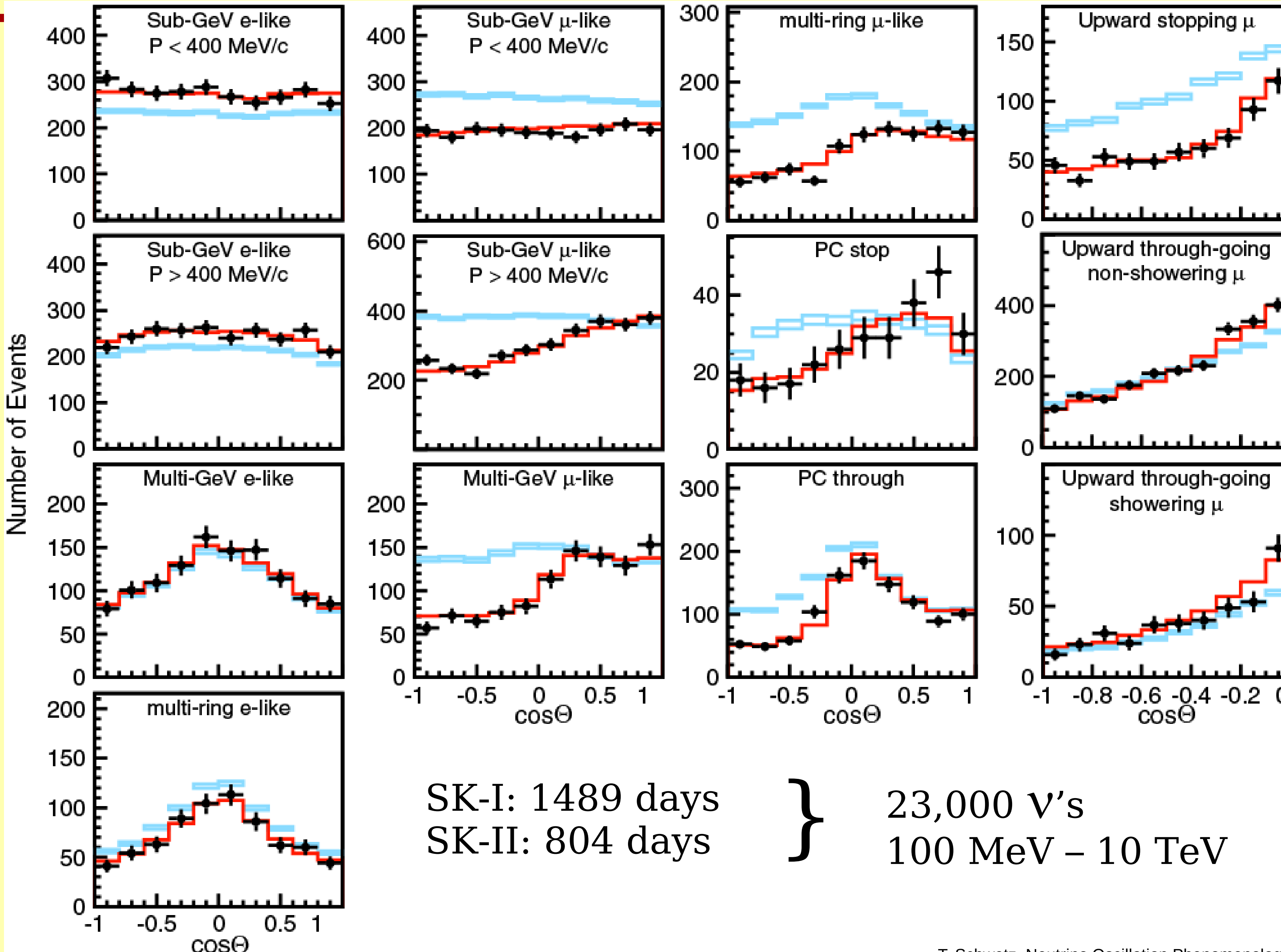
The “atmospheric” parameters Δm^2_{31}, θ_{23}

Atmospheric neutrinos

Atmospheric neutrinos



Super-K atmospheric neutrino data



SK-I: 1489 days
SK-II: 804 days

} 23,000 ν's
100 MeV – 10 TeV

Oscillations of atmospheric neutrinos

$$P_{ee}^{\mathrm{atm}} \approx 1 - \mathcal{O}(\theta_{13}, \Delta m^2_{12})$$

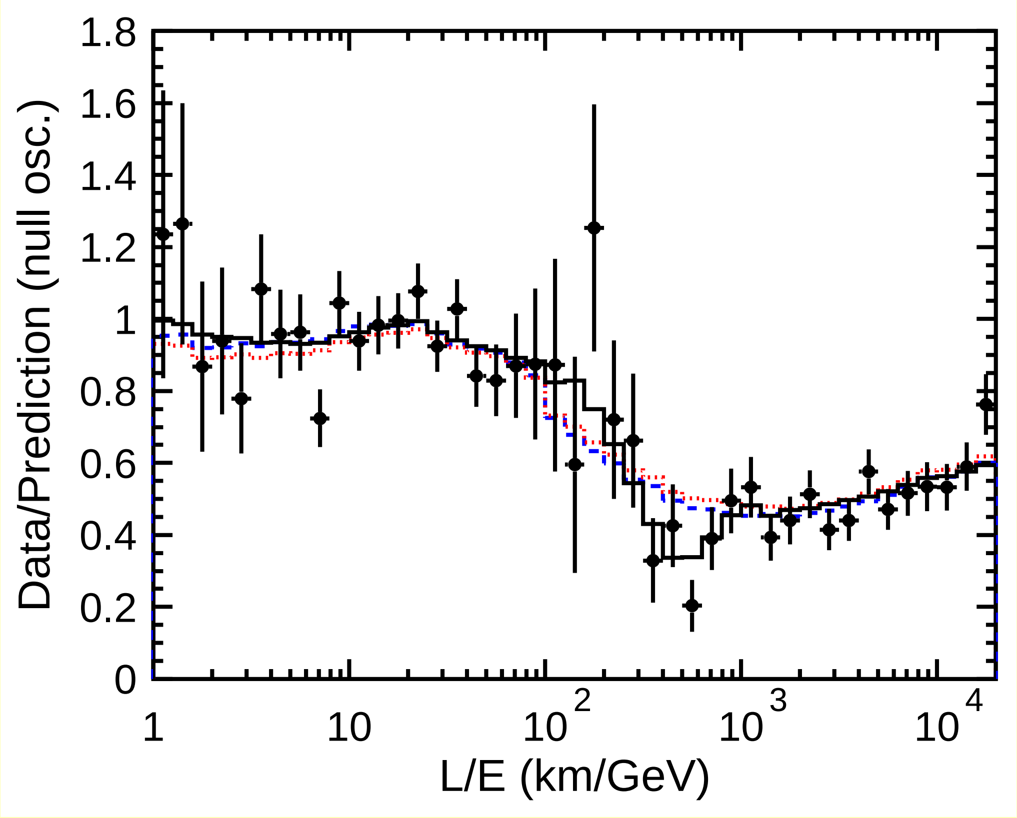
$$P_{\mu\mu}^{\mathrm{atm}} \approx 1 - P_{\mu\tau}^{\mathrm{atm}} \approx 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu}$$

with

$$\sin^2 2\theta_{23} \approx 1\,, \qquad |\Delta m^2_{31}| \simeq 0.0024\,\mathrm{eV}^2$$

Oscillatory signal in atmospheric neutrinos

Super-K Coll., Phys. Rev. Lett. **93** (2004) 101801 $\Rightarrow$

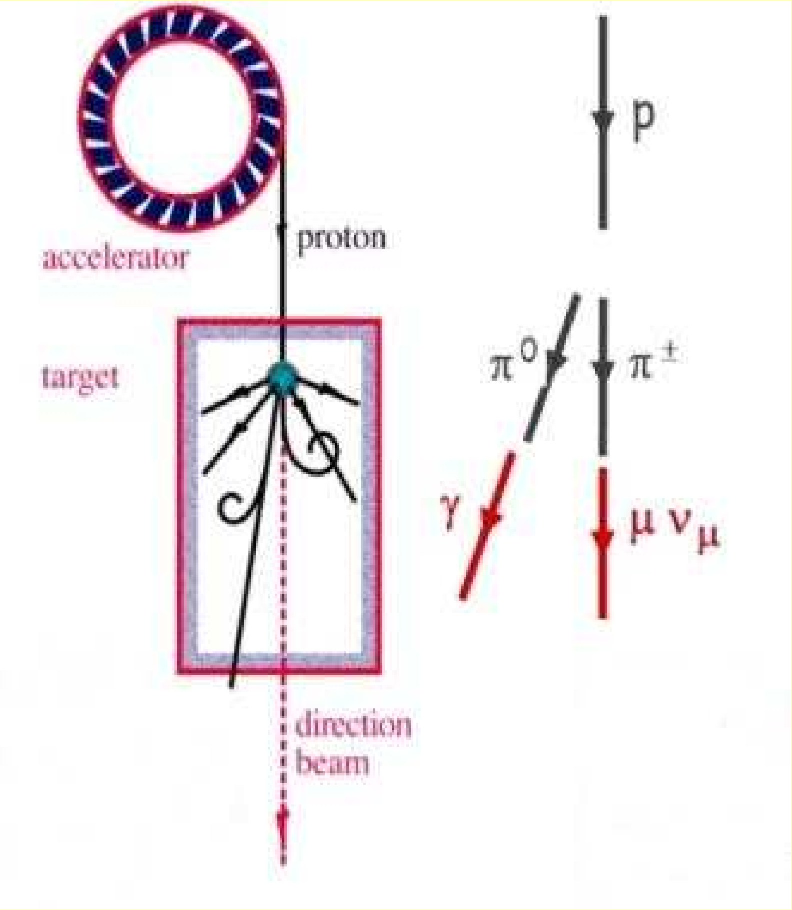


$$P_{2\nu} = 1 - \sin^2 2\theta \, \sin^2 \left(\frac{\Delta m^2}{4} \frac{L}{E_\nu} \right)$$

Long-baseline experiments

first generation of LBL experiments
(ν_μ-disappearance)

The neutrino source

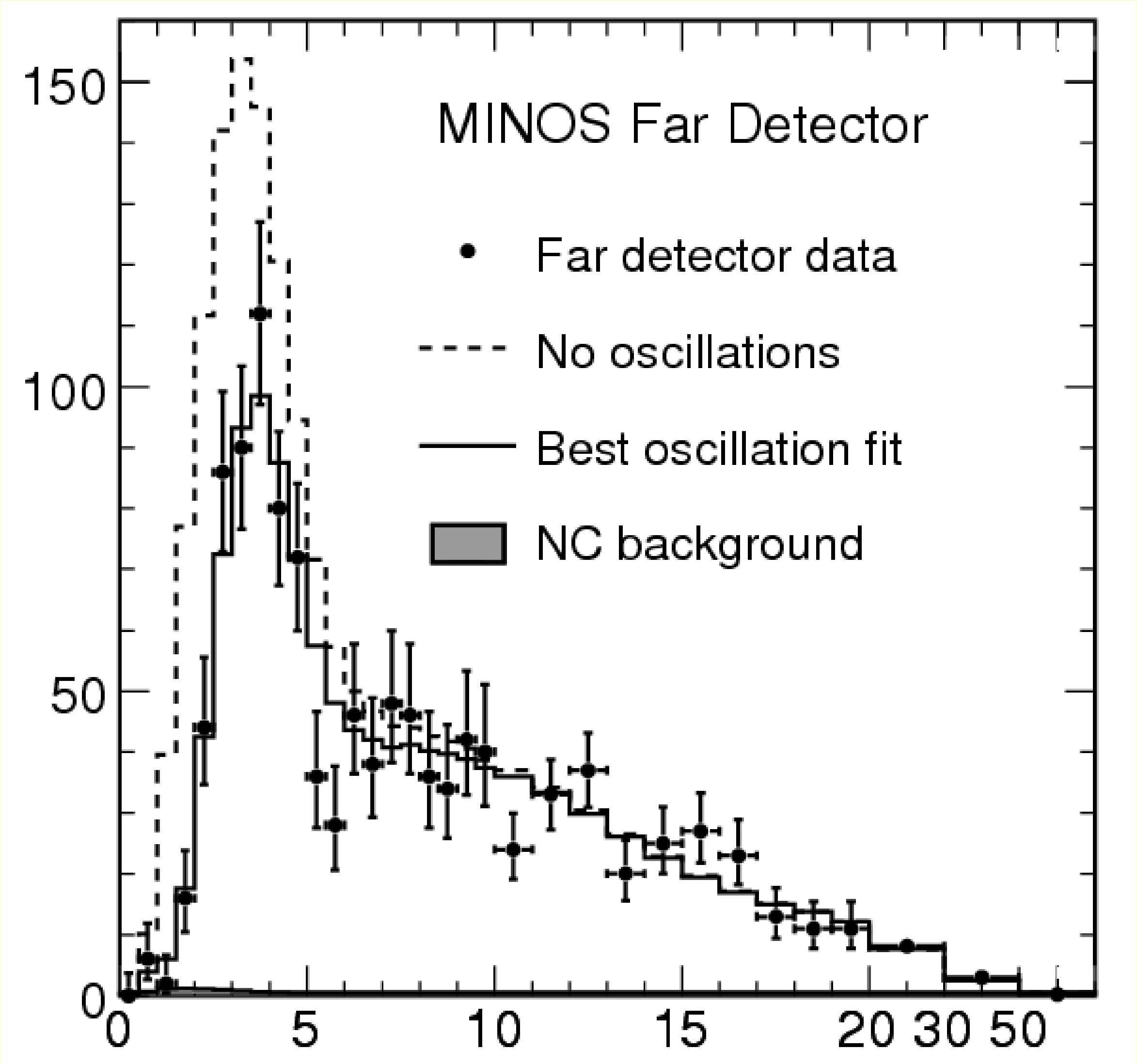


neutrino production via pion decay $\Rightarrow \nu_\mu$ beam

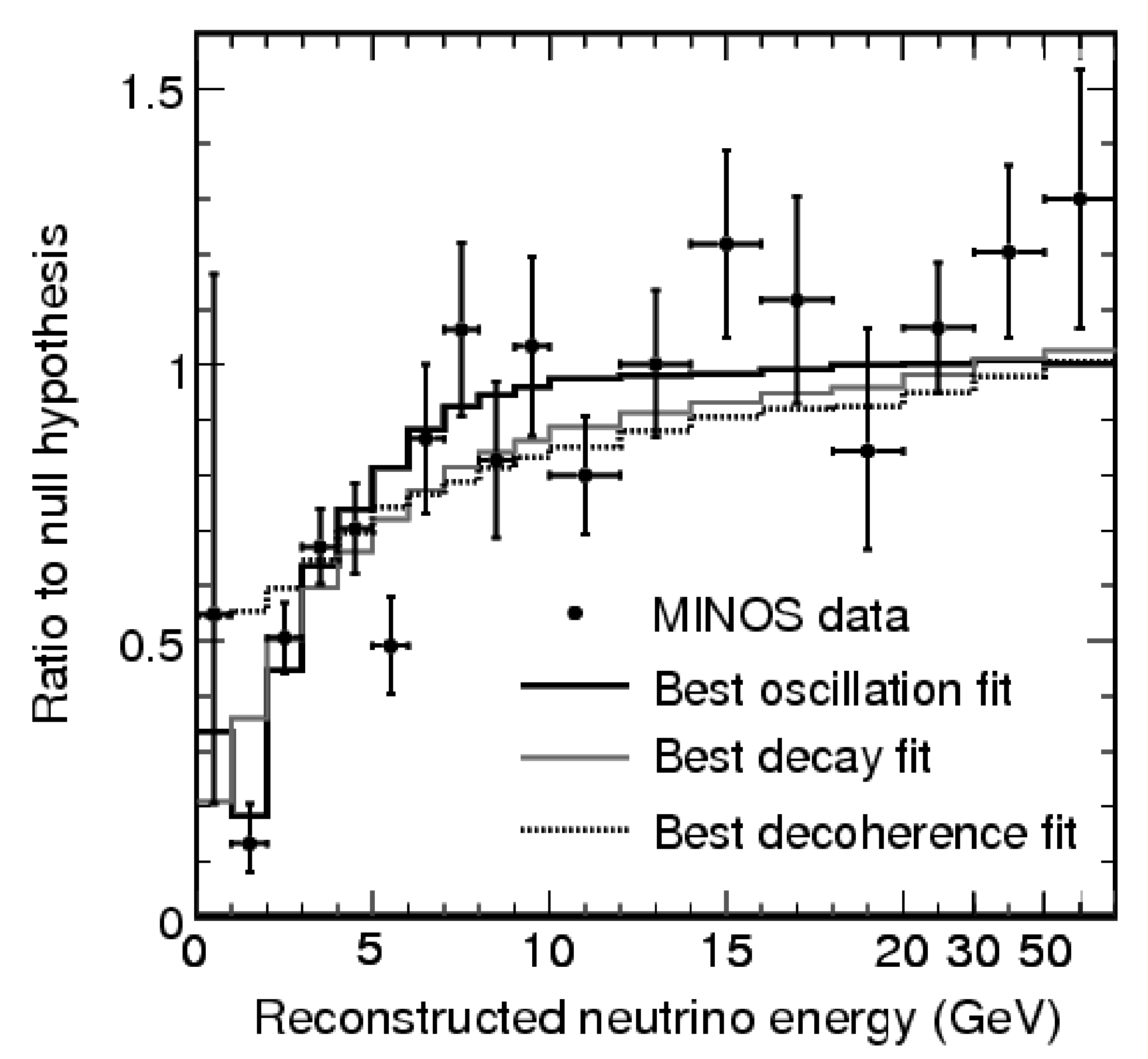
K2K vs MINOS

	K2K	MINOS
source	KEK	Fermilab
detector	Super-K	Soudan
baseline	250 km	735 km
neutrino energy	1.3 GeV	3 GeV
E_ν/L [eV^2]	5.2×10^{-3}	4.1×10^{-3}
channel	$\nu_\mu \to \nu_\mu$	$\nu_\mu \to \nu_\mu$
obs. events	112	848
expect. w/o osc.	$158.1^{+9.2}_{-8.6}$	1065 ± 60

MINOS energy spectrum

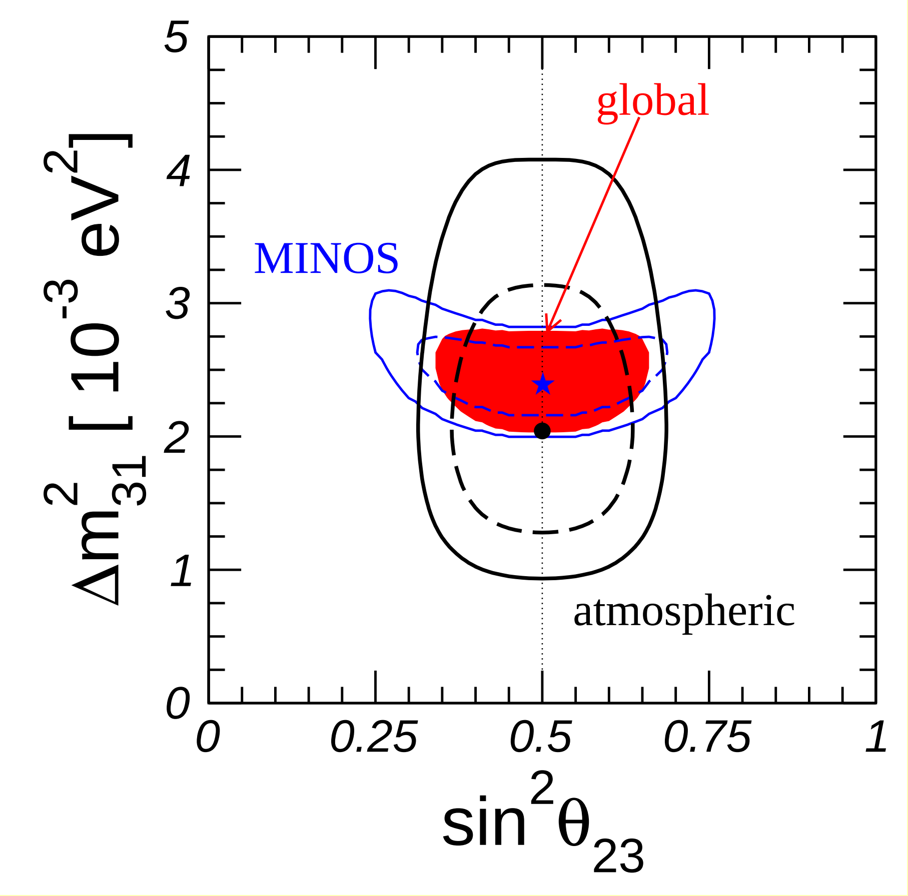


MINOS survival probability



Super-K + K2K + MINOS

90%, 99.73% CL regions



$$\Delta m^2_{31} = 2.4 \pm 0.15 \times 10^{-3}\,\mathrm{eV}^2,\ \sin^2\theta_{23} = 0.50 \pm 0.063$$