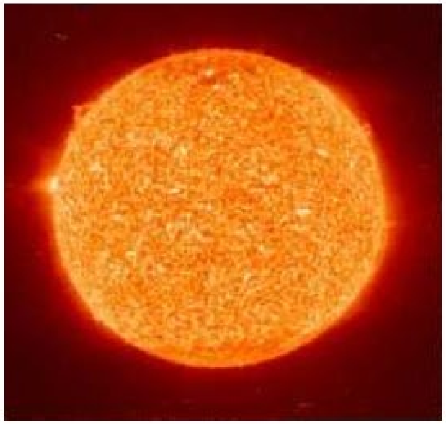
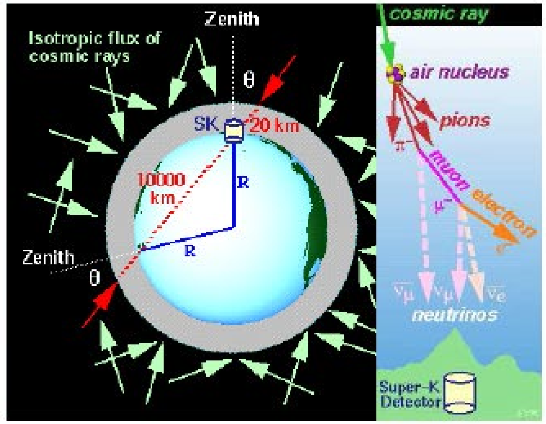
5.3 Neutrino oscillation experiments

Neutrino sources





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Experiment		L (m)	E (MeV)	$\lvert\Delta m^2\rvert$ (eV^2)
Solar		10^{10}	1	10^{-10}
Atmospheric		$10^4 - 10^7$	10^2–10^5	$10^{-1} - 10^{-4}$
Reactor	SBL	$10^2 - 10^3$	1	$10^{-2} - 10^{-3}$
	LBL	$10^4 - 10^5$		$10^{-4} - 10^{-5}$
Accelerator	SBL	10^2	10^3–10^4	> 0.1
	LBL	$10^5 - 10^6$	$10^3 - 10^4$	$10^{-2} - 10^{-3}$

Short
Long
baseline

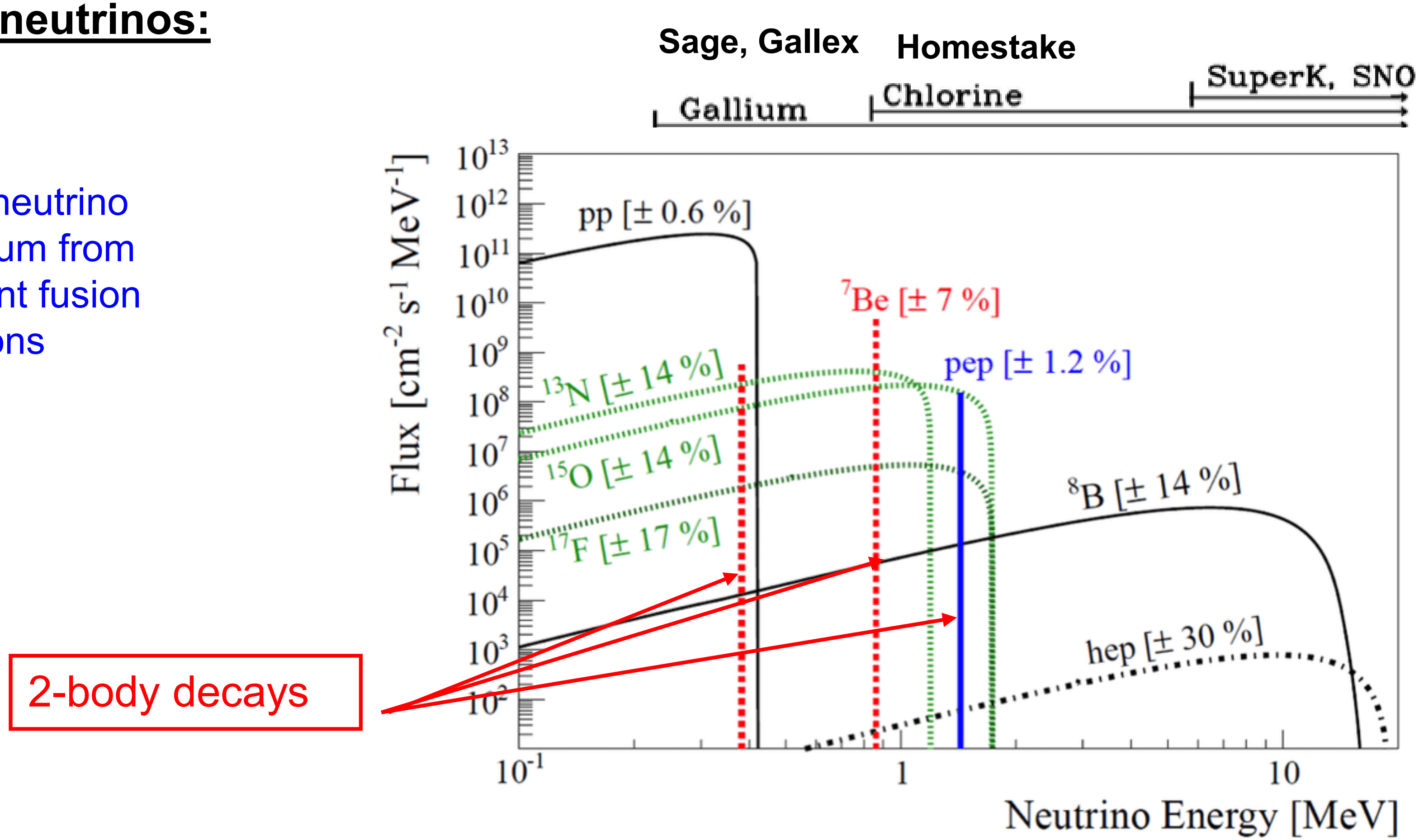
Studied neutrino sources can be well described by a “2-neutrino mixing model”:

e. g. For solar neutrinos:

$$\mathcal{P}\left(\nu_e \to \nu_x\right) = \sin^2\left(2\theta\right)\sin^2\left(\frac{\Delta m^2}{4E}L\right)$$

Solar neutrinos:

Solar neutrino spectrum from different fusion reactions



Reaction for neutrino detection on earth:

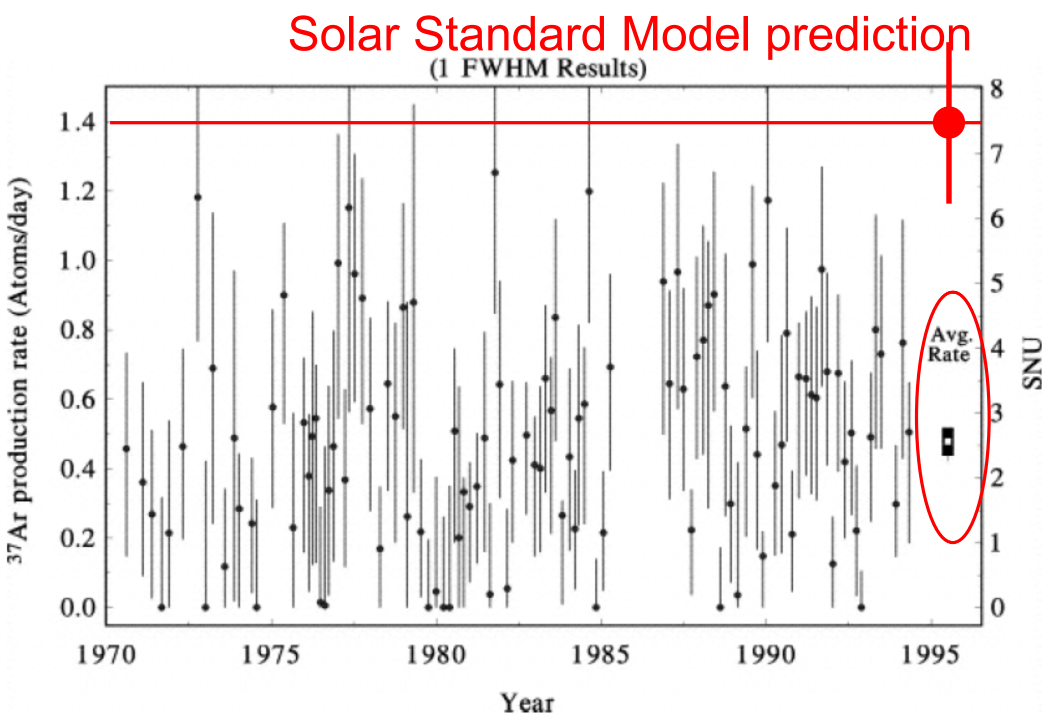
Cl_2 detectors	$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e$, ${}^{37}Ar \rightarrow {}^{37}Cl$ (EC)	$E_\nu > 0.8$ MeV
Ga detectors	$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e$	$E_\nu > 0.2$ MeV
H_2O detectors	Elastic scattering: $\nu_e + e \rightarrow \nu_e + e$	$E_\nu > 5$ MeV (detection)

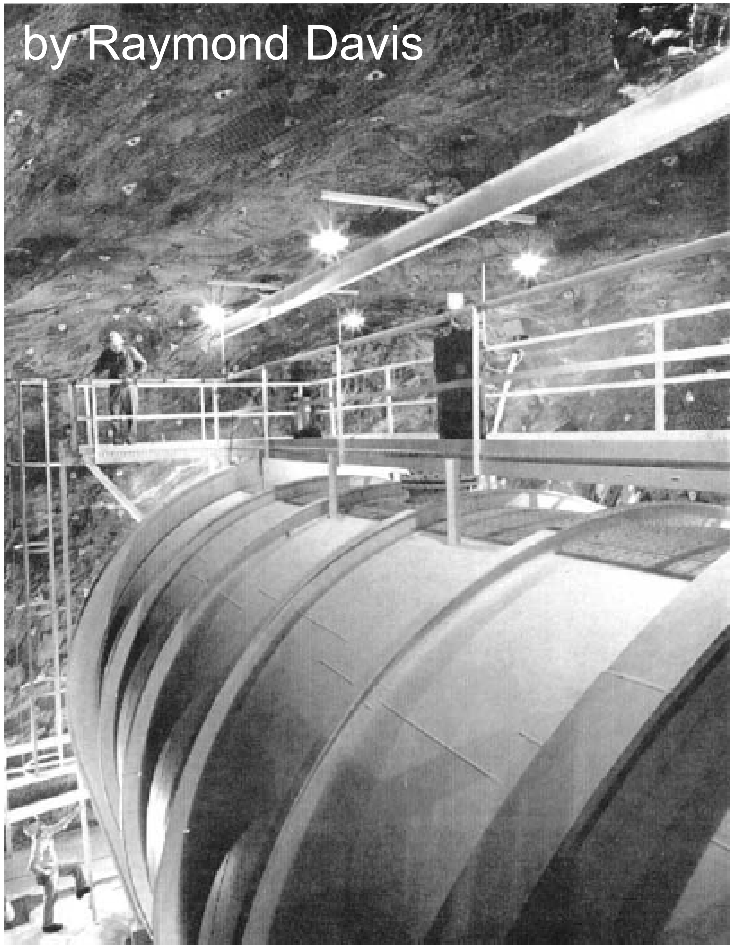
Radio-chemical experiments – the pioneer: Homestake

$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e$, ${}^{37}Ar \rightarrow {}^{37}Cl$ (EC)

- Homestake mine, 1400 m underground
- 615 t of C_2Cl_4 (perchloroethilene) = 2.2×10^{30} atoms of ${}^{37}Cl$
- Use ${}^{36}Ar$ and ${}^{38}Ar$ to carry-out the few atoms of ${}^{37}Ar$ (~ 1 atom/day)
- Count radioactive ${}^{37}Ar$ decays

Homestake Cl_2 experiment

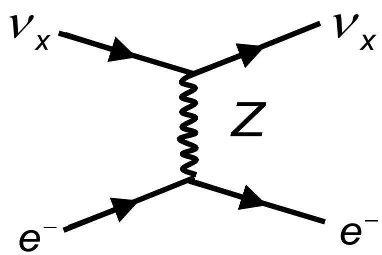


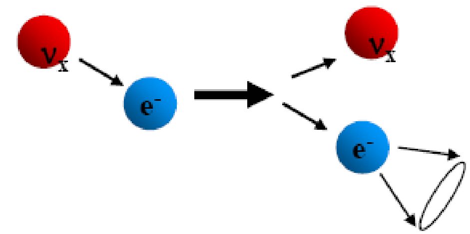


Neutrino detection with water detectors [E_ν~O(GeV)]

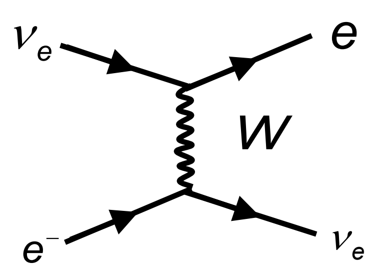
Water = "active target" (Cherenkov effect)

Elastic scattering ES

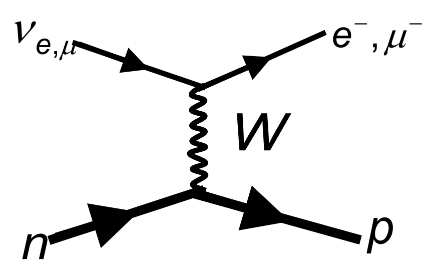




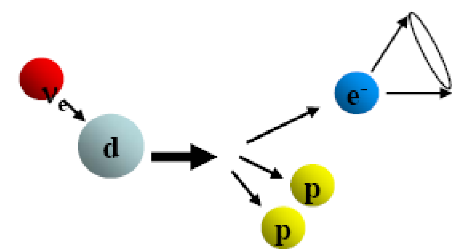
Cherenkov light from electron



Charged current CC



Kinematical limit for ν_μ: $E_\nu > m_\mu$

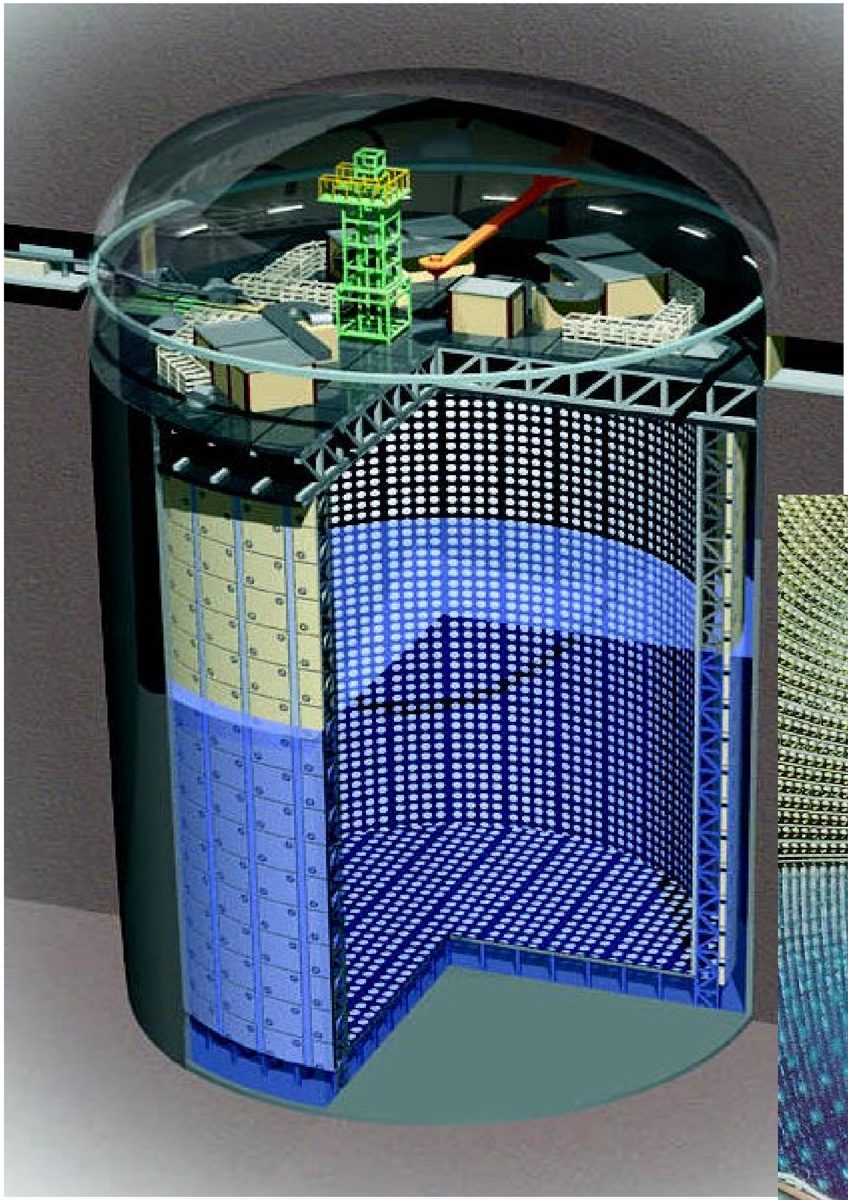


Detection of Cherenkov photons: Photo multiplier

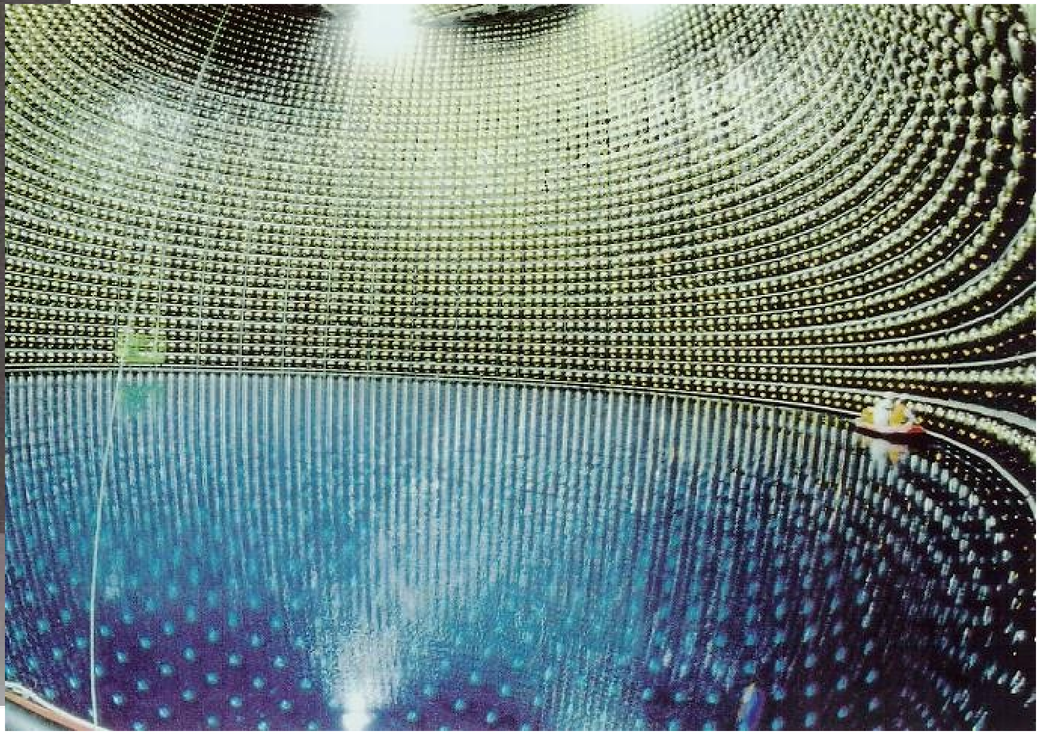
Experiments:

(Super)-Kamiokande

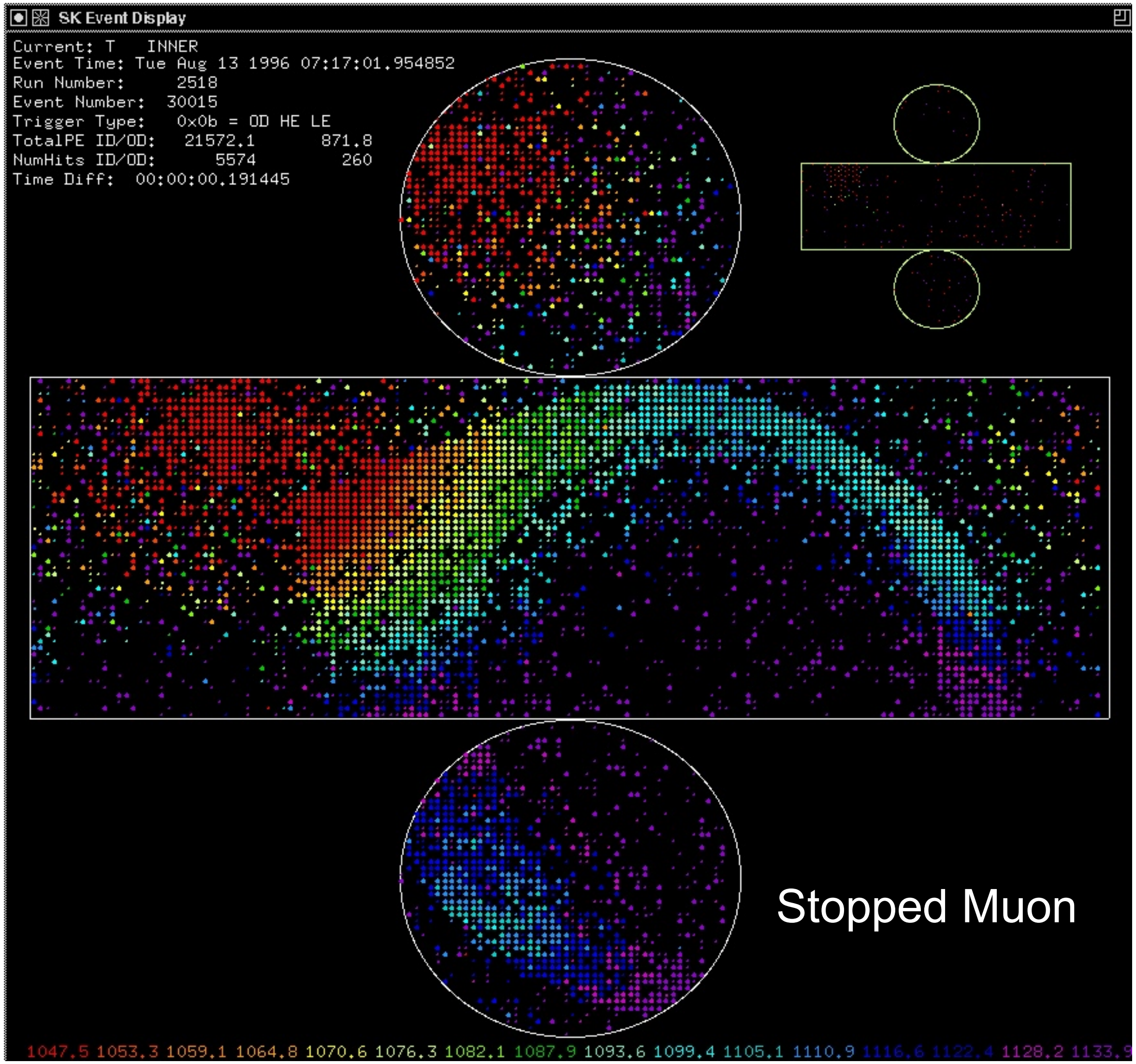
Super-Kamiokande

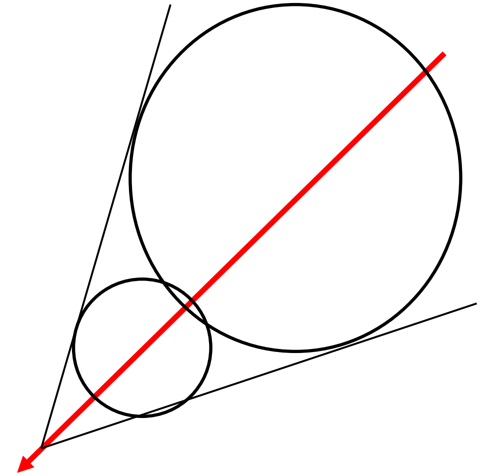


- Largest artificial water detector (50 kt)
- 11000 PMTs (50 cm tubes!): 40% of surface covered with photo-cathode



$\nu_\mu \rightarrow \mu$ stopped





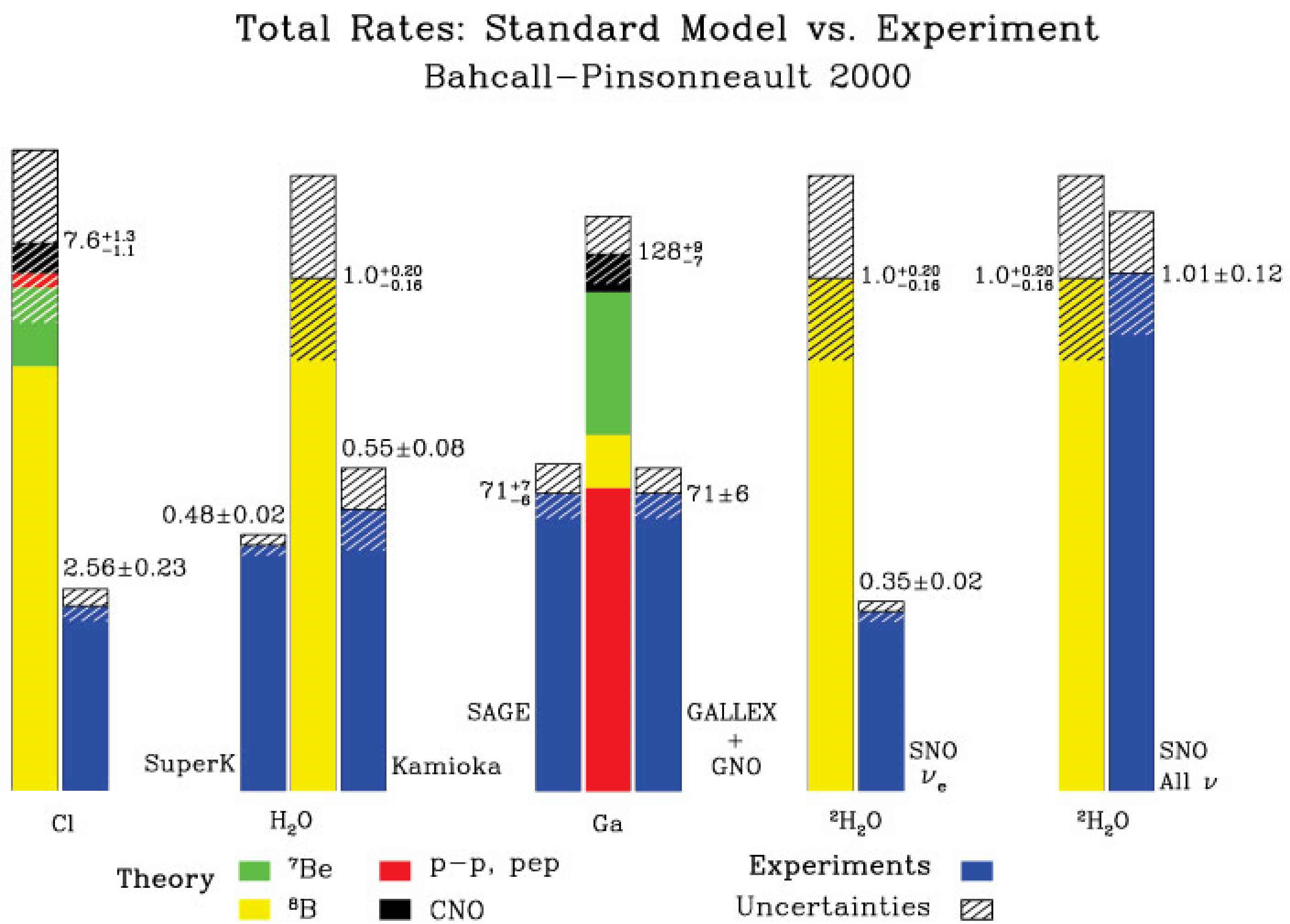
Cherenkov cone:

$$\cos\theta = \frac{1}{\beta n}$$

$$\Leftrightarrow \theta = 42^o \; (\beta = 1)$$

Experiment can distinguish electron and muon events, can measure energy

Solar Neutrino Problem

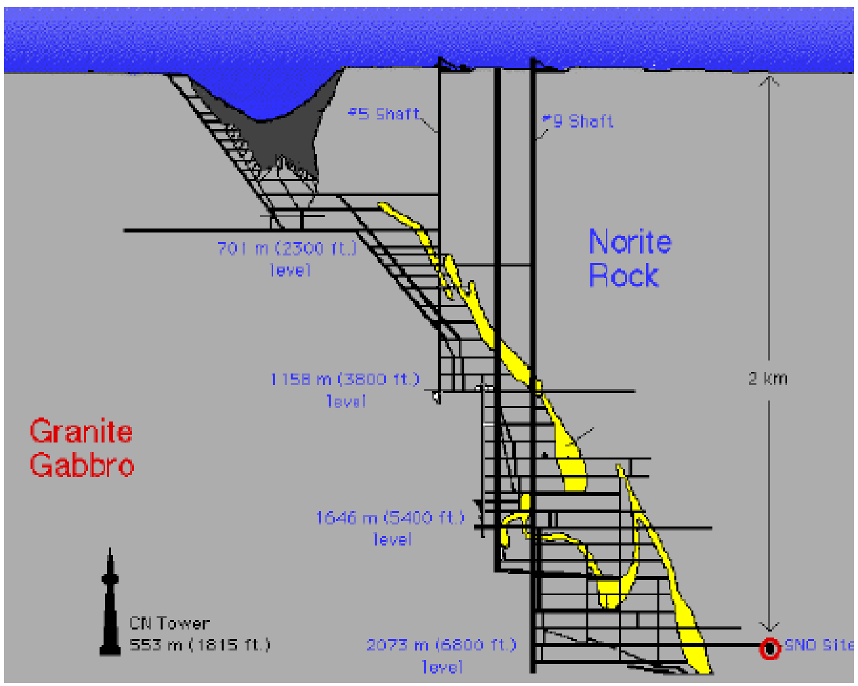


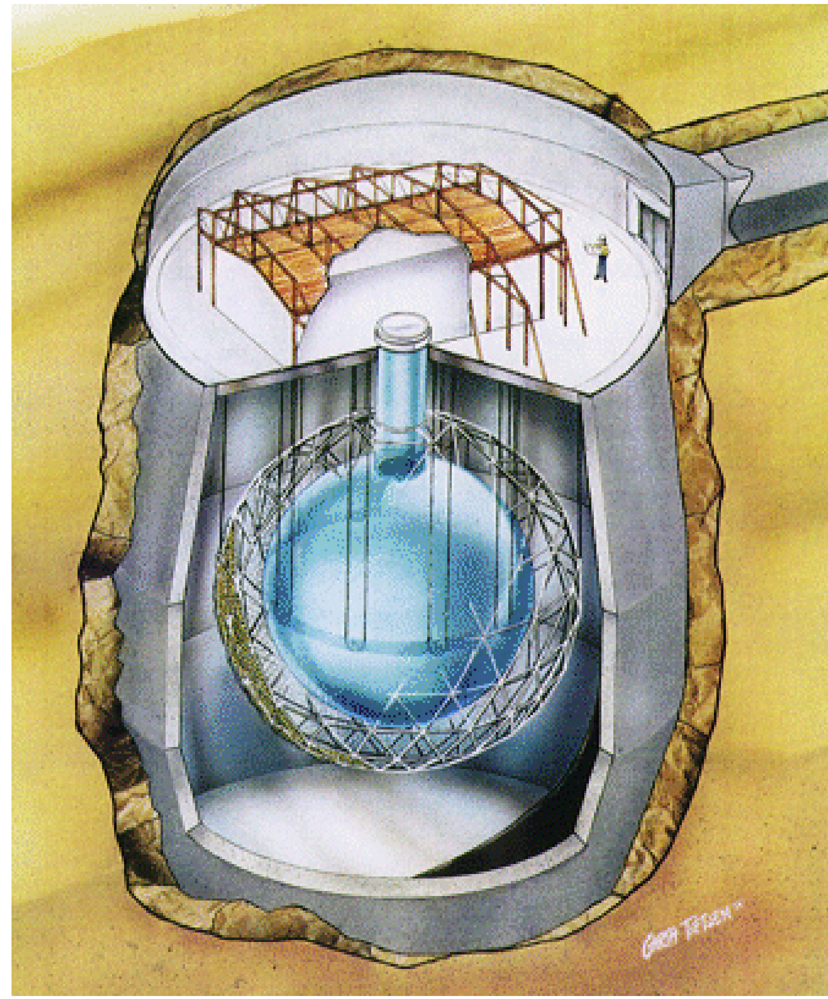
Depending on the neutrino energy between 70% and 35% of the expected neutrino flux from the sun is seen. Solution: $\nu_e \rightarrow \nu_{\mu}, \nu_{\tau}$

Sudbury Neutrino Observatory

Try to measure the "oscillated" neutrinos of different flavors

- 6 m radius transparent acrylic vessel
- 1000 t of heavy water (D_2O)
- 9456 inward looking photo multipliers
- Add 2 t of NaCl to detect neutrons





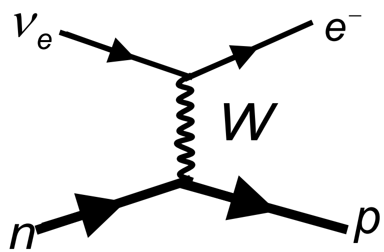
Solar Neutrino (^8B) detection with SNO

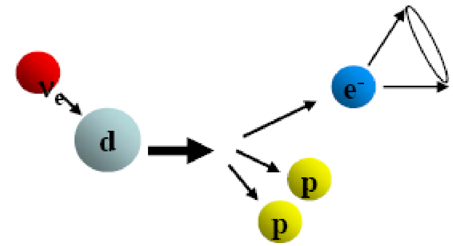
Charged current

$$\sigma(\nu_\mu) = \sigma(\nu_\tau) = 0$$

(kinematics)

$$\phi_{CC} = \phi_{\nu_e}$$



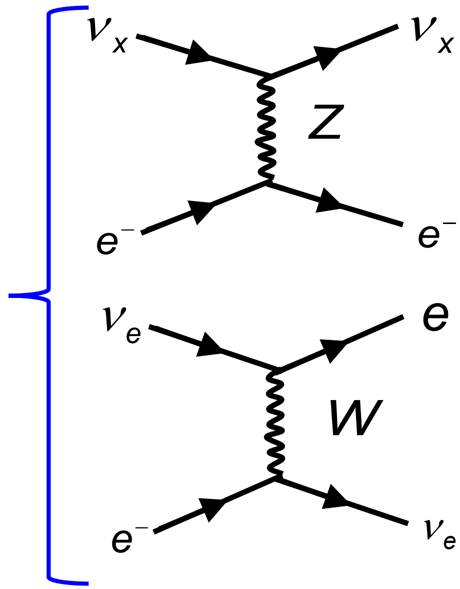


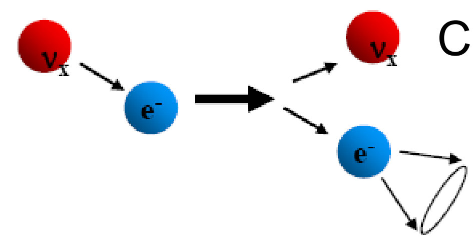
Cherenkov Light

Elastic scattering

$$0.154 \cdot \sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$$

$$\phi_{ES} = \phi_{\nu_e} + (\phi_{\nu_\mu} + \phi_{\nu_\tau})/6$$



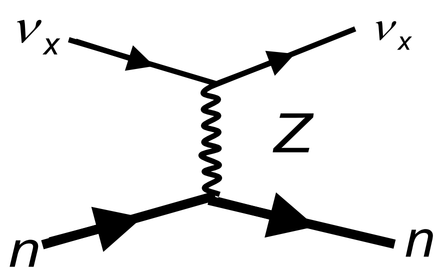


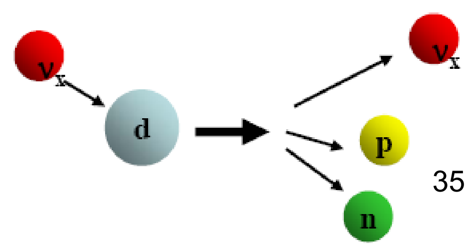
Cherenkov Light

Neutral current

$$\sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$$

$$\phi_{NC} = \phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}$$





Neutron

$^{35}Cl\,(n,\gamma)^{36}Cl$

SNO Evidence for Neutrino Oscillation

Phys. Lett. B539, 179 (2002),

$$\phi_{CC}^{SNO} = 1.76^{+0.06}_{-0.05}(\text{stat})^{+0.09}_{-0.09}(\text{syst}),$$
$$\phi_{ES}^{SNO} = 2.39^{+0.24}_{-0.23}(\text{stat})^{+0.12}_{-0.12}(\text{syst}),$$
$$\phi_{NC}^{SNO} = 5.09^{+0.44}_{-0.43}(\text{stat})^{+0.46}_{-0.43}(\text{syst}).$$

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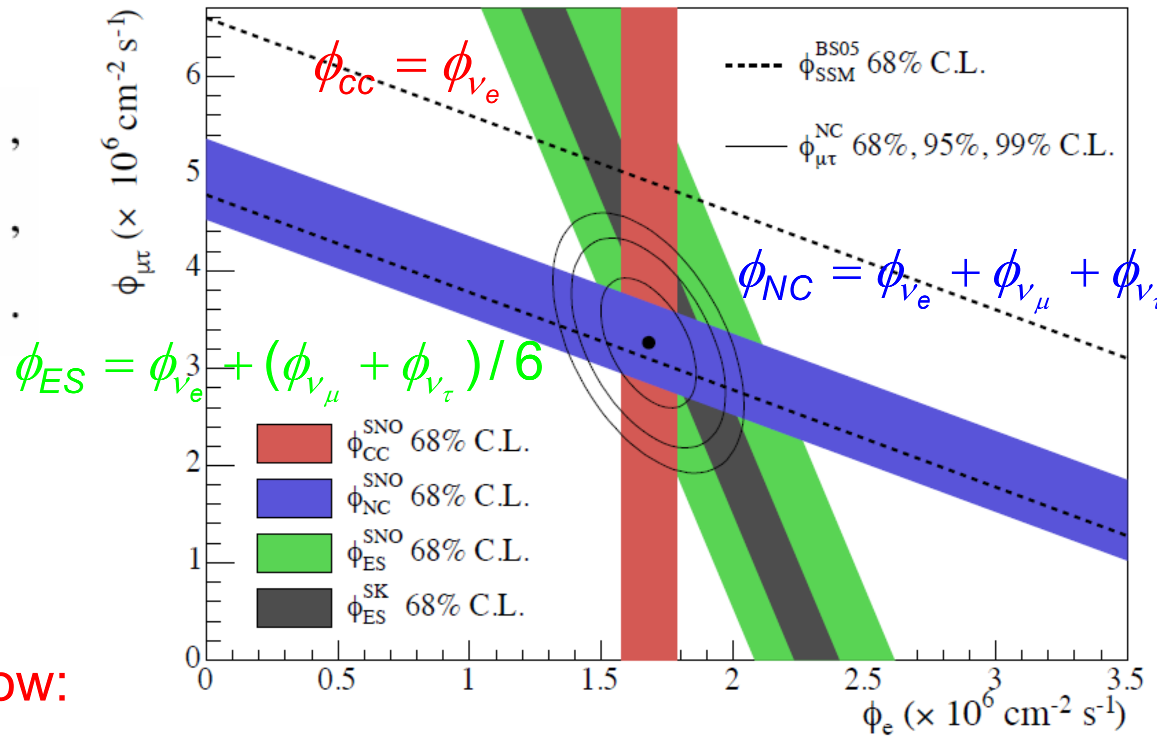


Electron neutrino flux is too low:

$$P_{\nu_e\nu_e} = (35 \pm 2)\%$$

Total flux of neutrinos is correct!!

Interpreted as $\nu_e \leftrightarrow \nu_\mu$ or ν_τ oscillation

But in case of simple "vacuum oszillation": $P_{\nu_e\nu_e} \geq 1 - \frac{1}{2}\sin^2 2\theta \geq 50\%$

Vacuum oscillation effect is enhanced by matter inside the sun.
Reminder: the neutrino leaves the sun in a fixed mass state.

W. Rohdejohan

Fits to data: $\sin^2\theta_{12} \approx 0.33$

$\Delta m^2_{21} \equiv \Delta m^2_{sol} \approx 7\times 10^{-5}\,\mathrm{eV}^2$

Only works with "resonance" matter effect in sun:

$$\cos 2\theta_{12} - x > 0$$

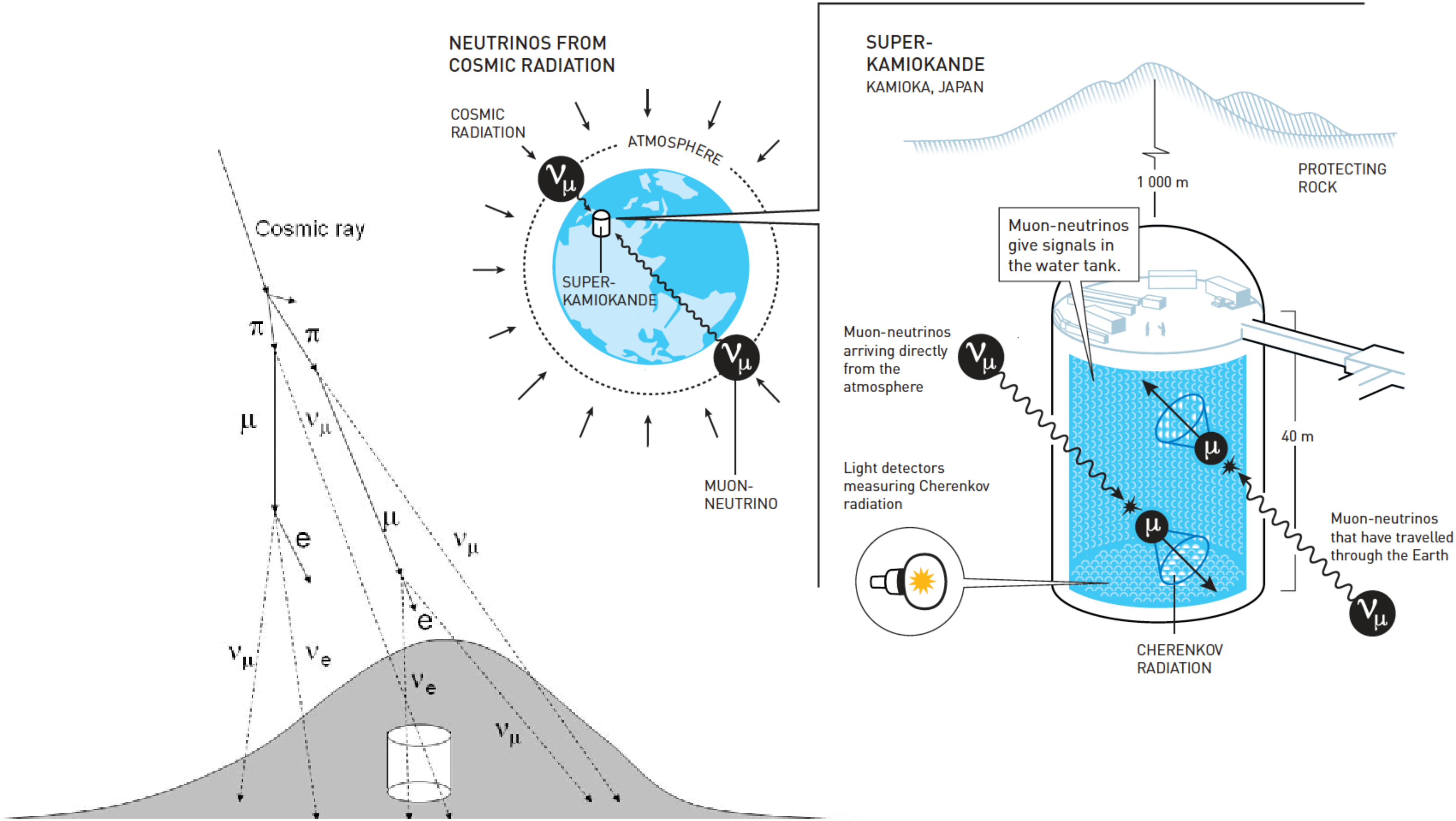
$$\cos 2\theta_{12} - \frac{A}{\Delta m^2_{sol}} > 0 \quad \Rightarrow \quad \Delta m^2_{sol} \cos 2\theta_{12} > A > 0$$

Choosing $\cos 2\theta_{12} > 0$ fixes $\Delta m^2_{sol} = m_2^2 - m_1^2 > 0$

$$\Rightarrow \quad \Delta m^2_{21} = m_2^2 - m_1^2 > 0$$

i.e. matter effect inside sun fixes $m_2 > m_1$

Atmospheric neutrinos (produce by cosmic rays in the atmosphere)



Muon neutrino : electron neutrino = 2 :1

Super-Kamiokande:

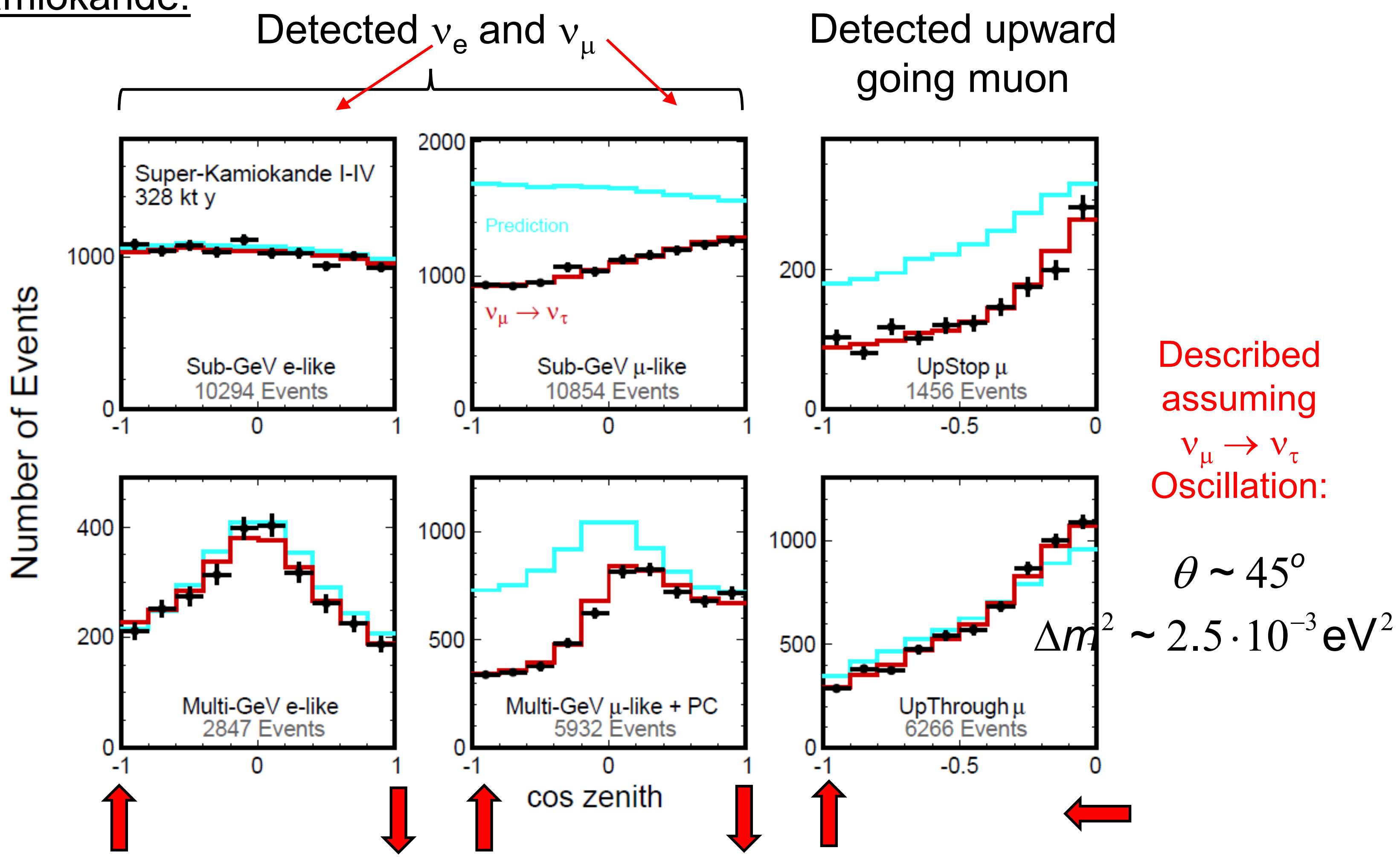


Figure 14.4: The zenith angle distributions of Super-Kamiokande atmospheric neutrino events. Fully contained 1-ring e-like and μ-like events with visible energy < 1.33 GeV (sub-GeV) and > 1.33 GeV (multi-GeV), as well as upward stopping and upward stopping μ samples are shown. Partially contained (PC) events are combined with multi-GeV μ-like events. The blue histograms show the non-oscillated Monte Carlo events, and the red histograms show the best-fit expectations for ν_μ-ν_τ oscillations. (This figure is provided by the Super-Kamiokande Collaboration) *PDG 2020*

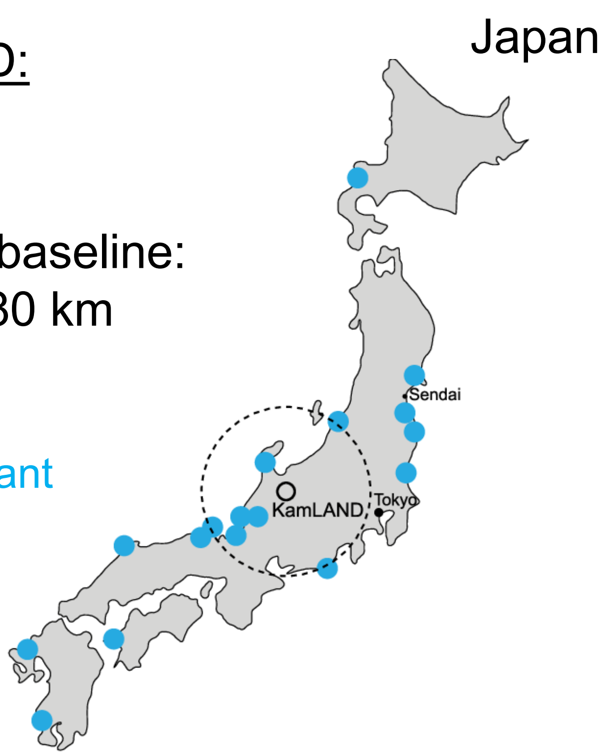
Reactor anti-neutrinos (from neutron β-decays):

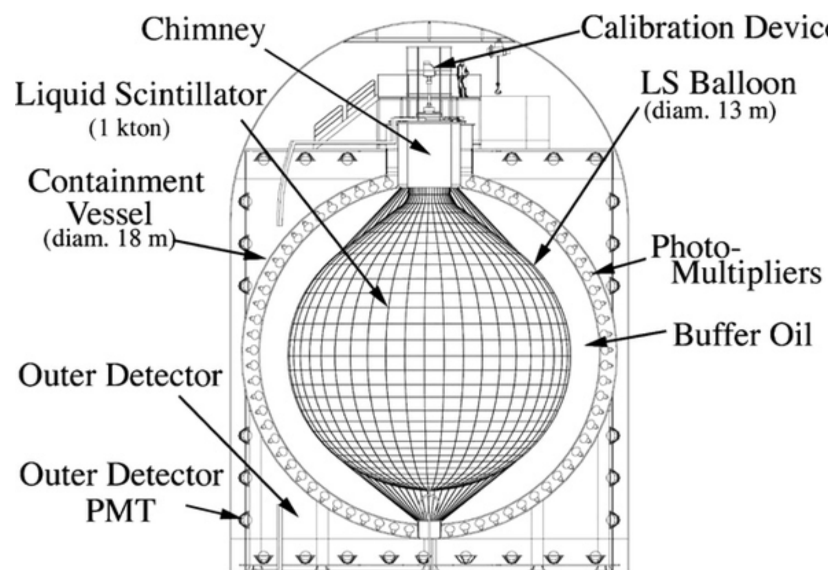
Name	Reactor power (GW_{th})	Baseline (km)	Detector mass (t)	Year
KamLAND	various	180 (ave.)	1,000	2001–
Double Chooz	4.25×2	1.05	8.3	2011–2018
Daya Bay	2.9×6	1.65	20×4	2011–
RENO	2.8×6	1.38	16	2011–
JUNO	26.6 (total)	53	20,000	

KamLAND:

Average baseline:
L = 180 km

● Nuclear power plant





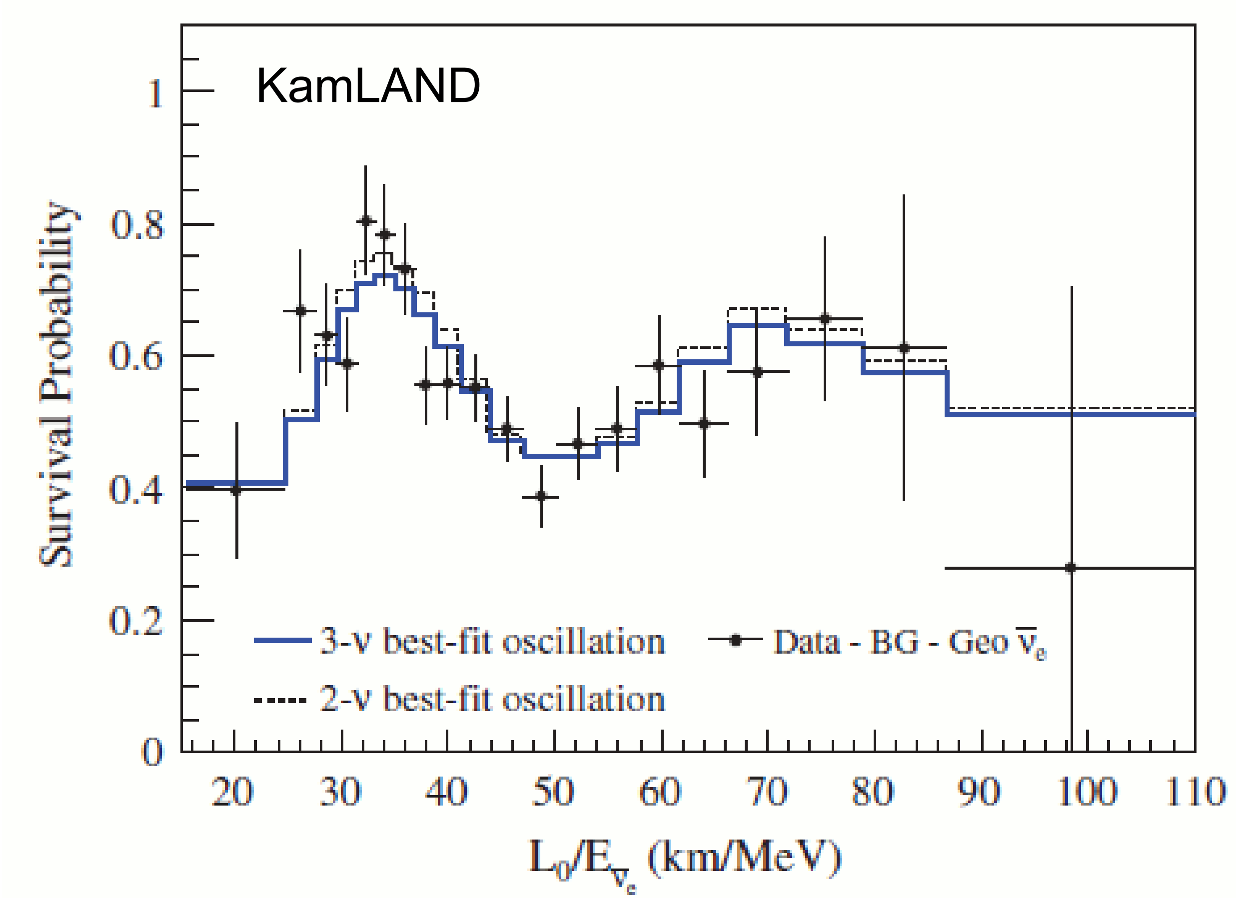
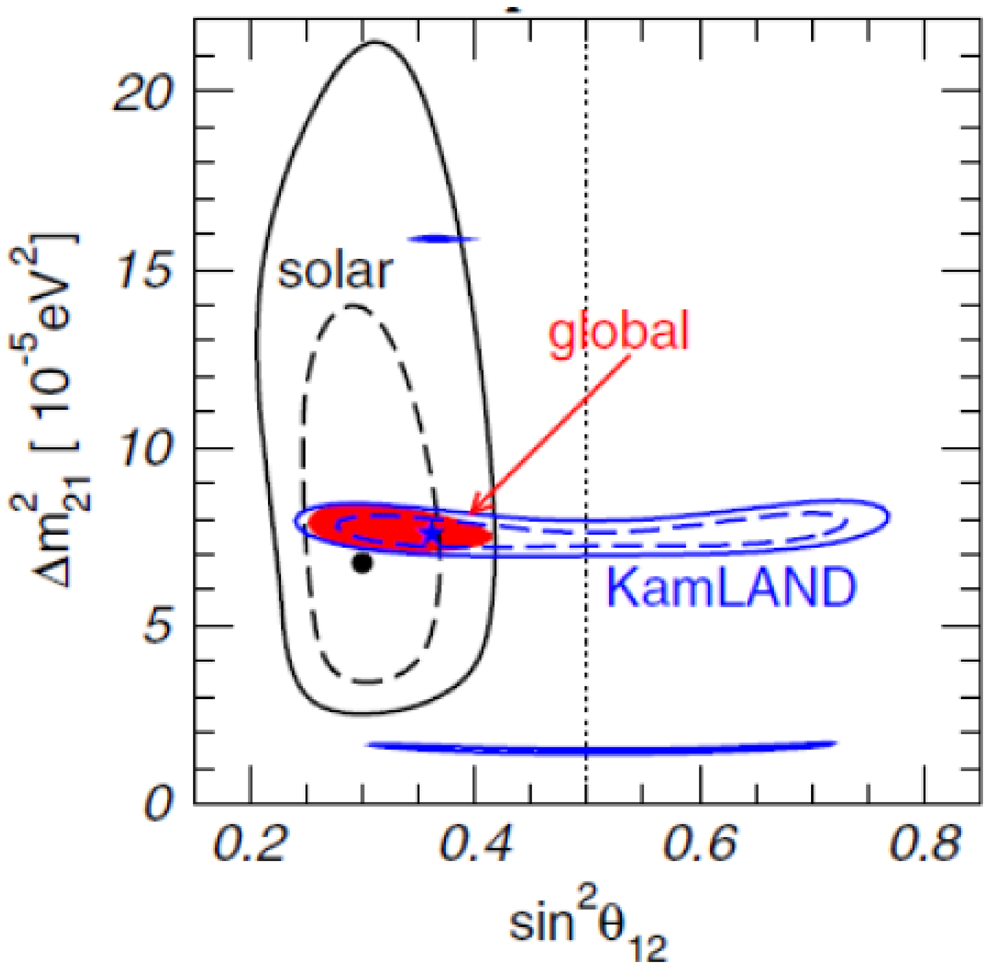


Figure 14.7: Ratio of the observed $\bar{\nu}_e$ spectrum to the expectation for no-oscillation versus L_0/E for the KamLAND data. $L_0 = 180$ km is the flux-weighted average reactor baseline. The 3-ν histogram is the best-fit survival probability curve from the three-flavour unbinned maximum-likelihood analysis using only the KamLAND data. This figure is taken from [150]. *PDG 2020*

$\nu_e \rightarrow \nu_e$ at distances of L_0 =180km very well described by the 2 neutrinos model

⇨ KamLAND confirms solar neutrinos results: large mixing angle and $\Delta m^2 \approx 7\times10^{-5}$ eV^2



T. Schwetz-Mangold

Measurement of θ_{13}

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric neutrino mixing}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & & c_{13} \end{pmatrix}}_{\text{reactor neutrinos; accelerator neutrinos}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar neutrino mixing; KamLAND}}$$

Atmospheric neutrino mixing: $\Delta m^2_{atm} \sim 2.5 \cdot 10^{-3}\,\text{eV}^2$, $\theta_{23} \sim 45^o$

reactor neutrinos; accelerator neutrinos: $\theta_{13} > ??$

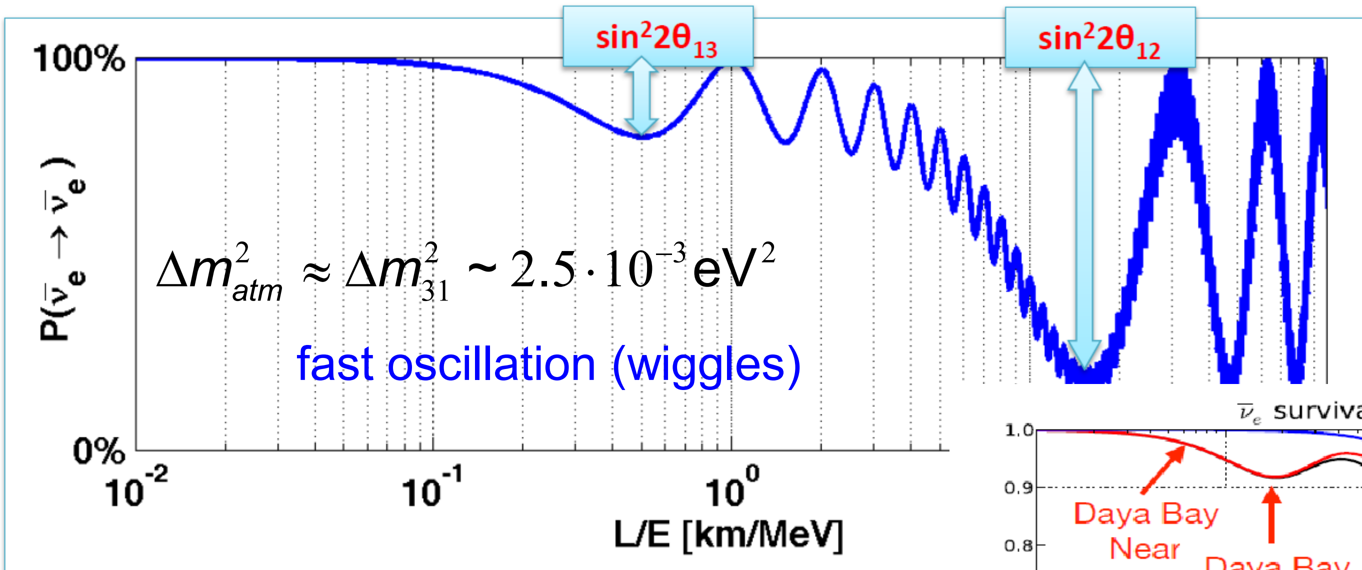
Solar neutrino mixing; KamLAND: $\Delta m^2_{sol} \sim 7 \cdot 10^{-5}\,\text{eV}^2$, $\theta_{12} \sim 33^o$

To observe CP violation in neutrino mixing a finite value of $\sin^2\theta_{13}$ is necessary.

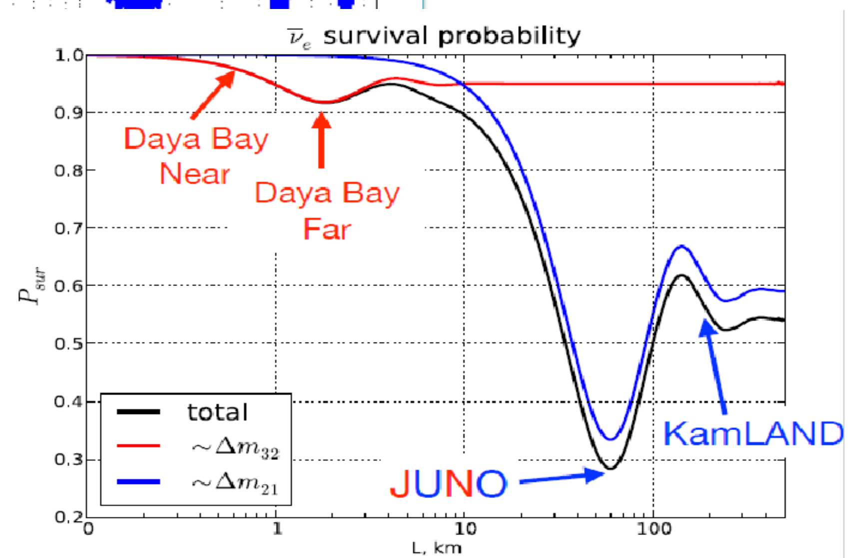
θ_{13} with reactor neutrinos:

Survival probability for 3-neutrino mixing:

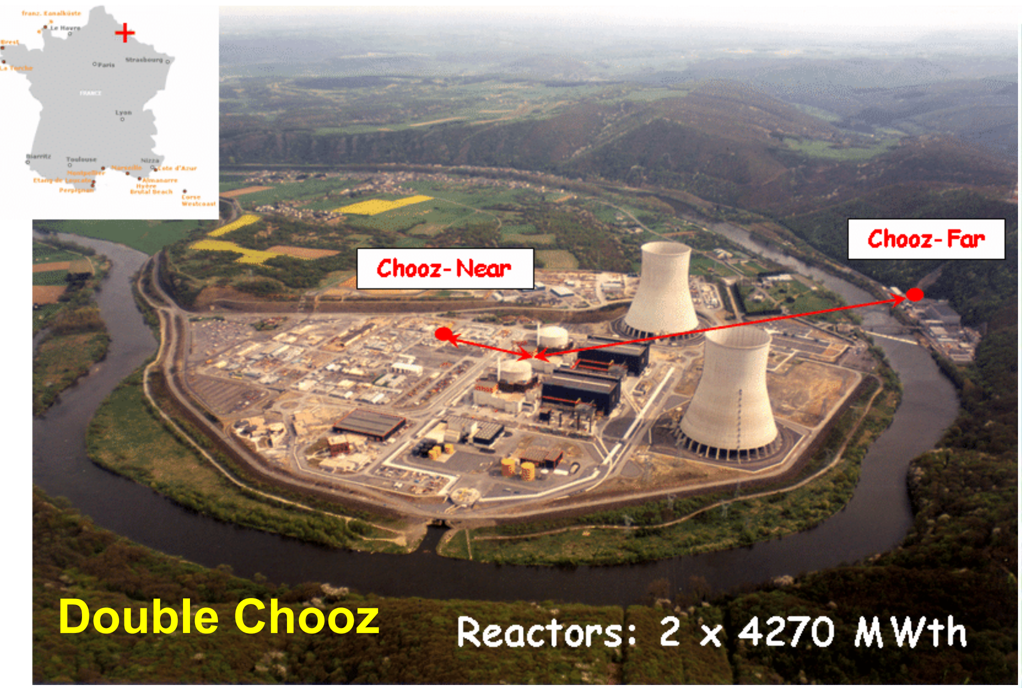
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

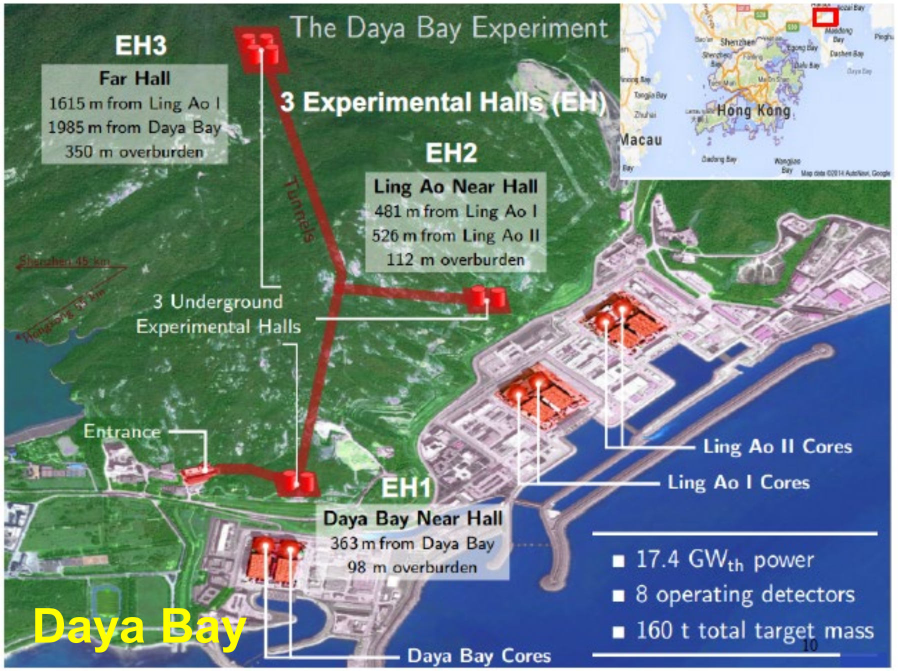


$$\Delta m^2_{sol} \approx \Delta m^2_{21}$$
$$\sim 7\cdot 10^{-5}\,\mathrm{eV}^2$$

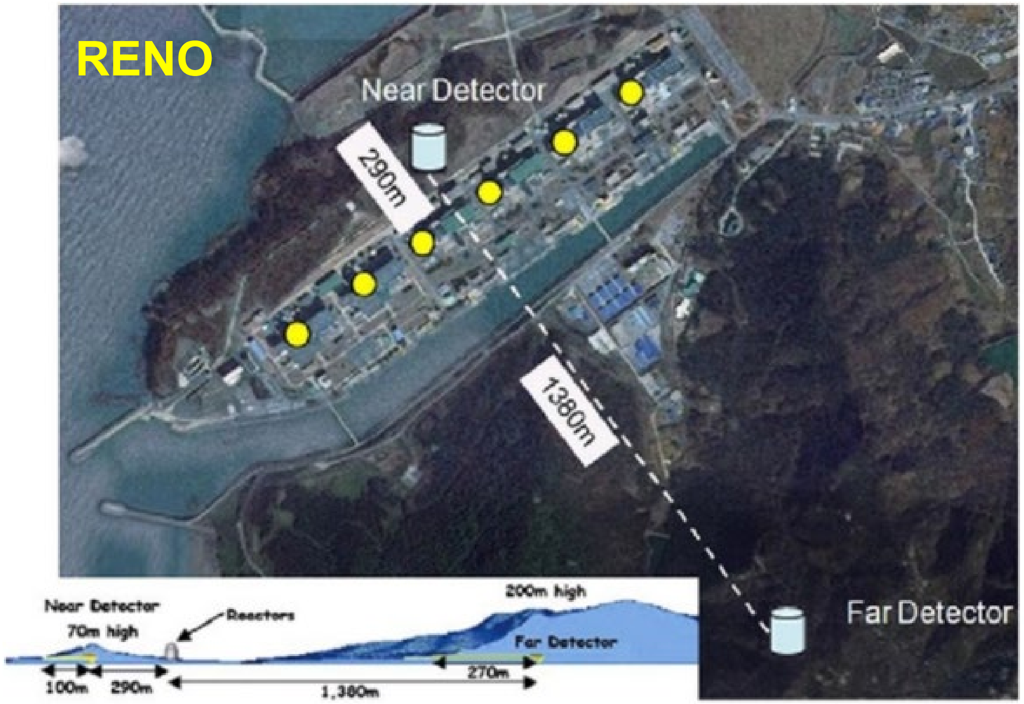


The $\overline{\nu}_e$ survival probability as a function of the distance from the nuclear power plant (NPP).





(China)

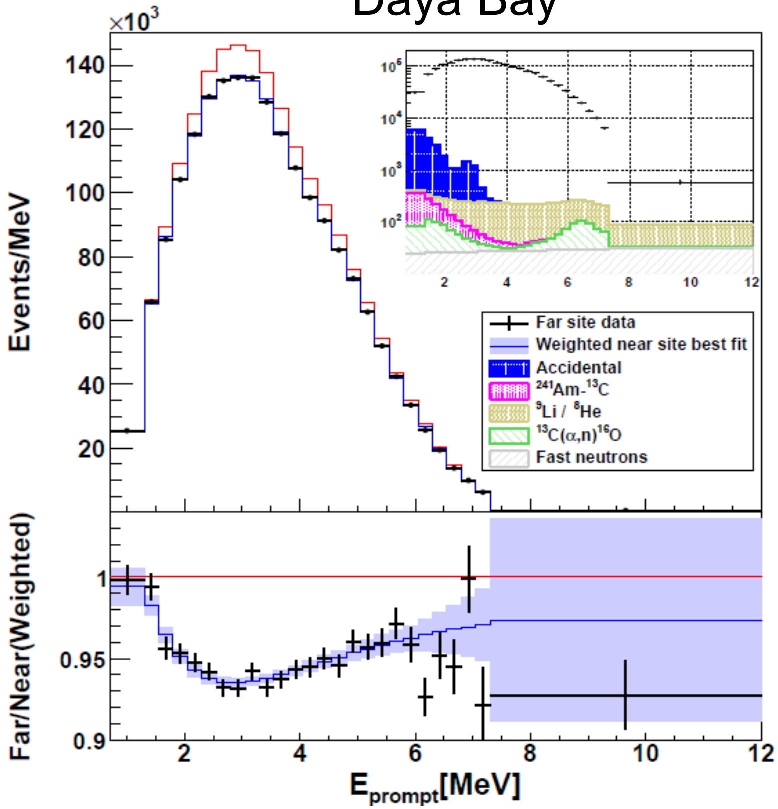


All experiments have a “near” detector to monitor the neutrino flux and a “far” (typ. Distance 1.5 km) to measure the deficit.

(South Korea)

The 3 reactor neutrino experiments published first results in 2012: Double Chooz reported an indication of electron antineutrino disappearance with the ratio of observed to expected events of R= 0.944±0.016 ±0.04 ruling out the no-oscillation hypothesis at 94.6% CL. Daya Bay observed of R= 0.940±0.011 ±0.004 corresponding to 5.2σ of a non-zero value of θ_{13}. RENO reported R= 0.920±0.000 ±0.014 indicating a non-zero value of θ_{13} with a significance of 4.9σ.

Daya Bay



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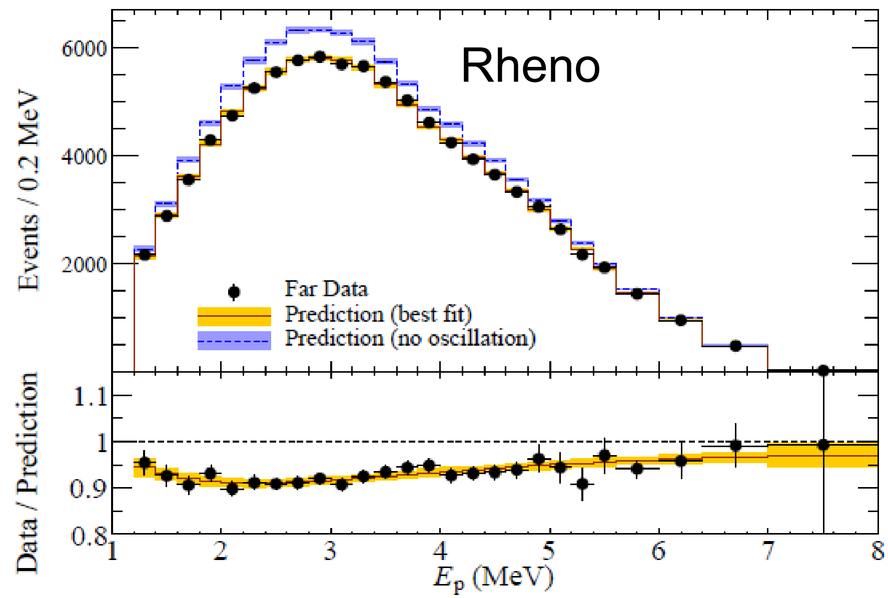
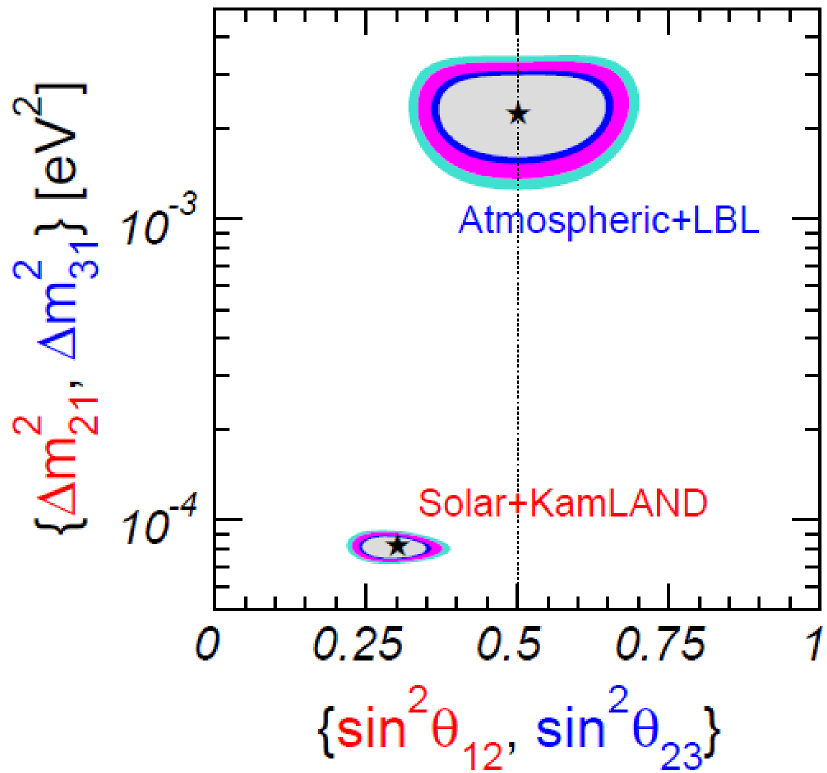


Summary: Neutrino Mixing



$\Longrightarrow$

$$\left[\begin{array}{l} \theta_{12} \sim 33^o \\ \theta_{23} \sim 45^o \\ \theta_{13} \sim 9^o \end{array}\right.$$

T..Schwetz-Mangold

$$|U_{PMNS}| \approx \begin{pmatrix} 0.82 & 0.58 & >0 \\ 0.64 & 0.58 & 0.71 \\ 0.64 & 0.58 & 0.71 \end{pmatrix}$$

Summary: Neutrino masses

Normal $\Delta m^2_{13} > 0$

Inverted $\Delta m^2_{13} < 0$