NEUTRINO EXPERIMENTS

- **Before discussing current experimental data, need to consider how neutrinos interact in matter (i.e. our detectors)**

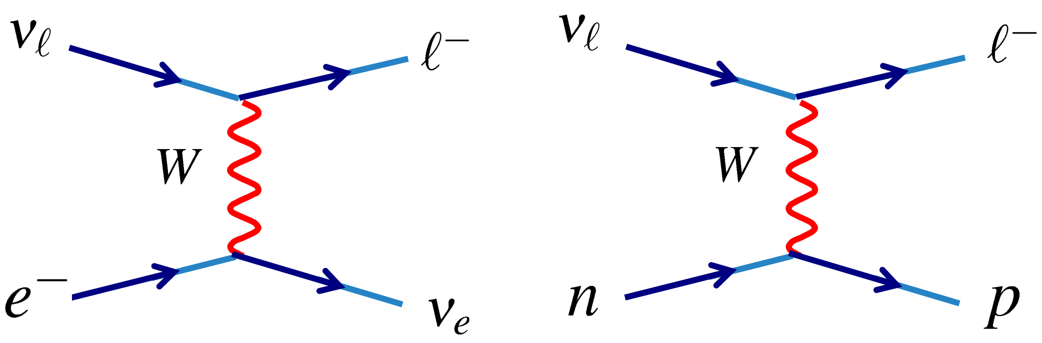
Two processes:

- Charged current (CC) interactions (via a W-boson) → charged lepton
- Neutral current (NC) interactions (via a Z-boson)

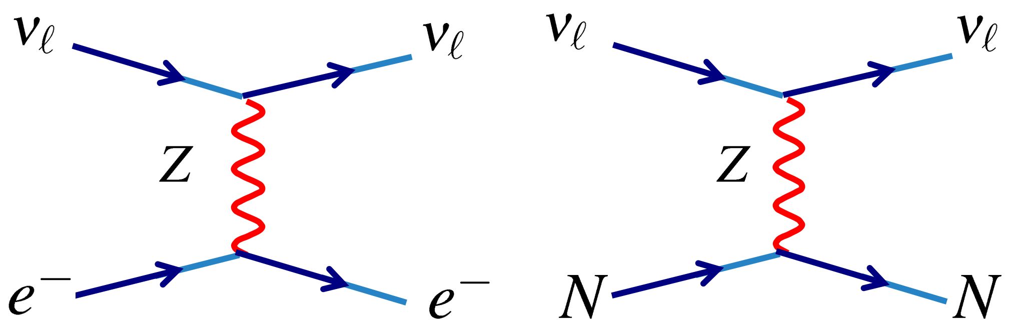
Two possible "targets": can have neutrino interactions with

- atomic electrons
- nucleons within the nucleus

CHARGED CURRENT



NEUTRAL CURRENT



NEUTRINO INTERACTION THRESHOLDS

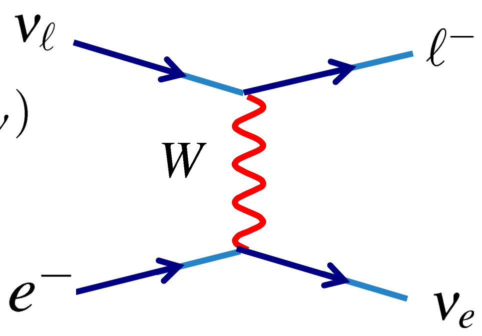
★ Neutrino detection method depends on the neutrino energy and (weak) flavour

- Neutrinos from the sun and nuclear reactions have $E_\nu \sim 1\,\mathrm{MeV}$
- Atmospheric neutrinos have $E_\nu \sim 1\,\mathrm{GeV}$

★ These energies are relatively low and not all interactions are kinematically allowed, **i.e.** there is a threshold energy before an interaction can occur. Require sufficient energy in the centre-of-mass frame to produce the final state particles

❶ **Charged current** interactions on atomic electrons (in laboratory frame)

$$p_\nu = (E_\nu, 0, 0, E_\nu)$$
$$p_e = (m_e, 0, 0, 0)$$



$$s = (p_\nu + p_e)^2 = (E_\nu + m_e)^2 - E_\nu^2$$

Require: $s > m_\ell^2$

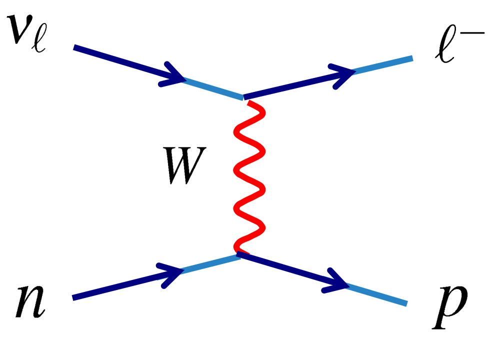
$$\boxed{E_\nu > \left[\left(\frac{m_\ell}{m_e}\right)^2 - 1\right]\frac{m_e}{2}}$$

- Putting in the numbers, for CC interactions with atomic electrons require

$$E_{\nu_e} > 0 \qquad \underbrace{E_{\nu_\mu} > 11\,\mathrm{GeV} \qquad E_{\nu_\tau} > 3090\,\mathrm{GeV}}$$

High energy thresholds compared to typical energies considered here

❷ charged current interactions on nucleons (in lab. frame)



$$s = (p_\nu + p_n)^2 = (E_\nu + m_n)^2 - E_\nu^2$$

Require: $s > (m_\ell + m_p)^2$

$$\Rightarrow \boxed{E_\nu > \frac{(m_p^2 - m_n^2) + m_\ell^2 + 2m_p m_\ell}{2m_n}}$$

- For CC interactions from neutrons require

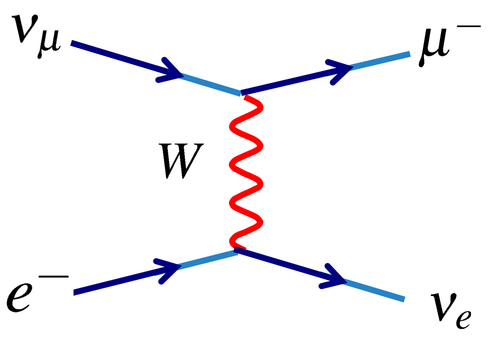
$$E_{\nu_e} > 0 \qquad E_{\nu_\mu} > 110\,\mathrm{MeV} \qquad E_{\nu_\tau} > 3.5\,\mathrm{GeV}$$

★ Electron neutrinos from the sun and nuclear reactors $E_\nu \sim 1\,\mathrm{MeV}$ which oscillate into muon or tau neutrinos cannot interact via charged current interactions – "they effectively disappear"

★ Atmospheric muon neutrinos $E_\nu \sim 1\,\mathrm{GeV}$ which oscillate into tau neutrinos cannot interact via charged current interactions – "disappear"

- To date, most experimental signatures for neutrino oscillation are a deficit of neutrino interactions (with the exception of SNO) because below threshold for produce lepton of different flavour from original neutrino

- In Handout 10 derived expressions for CC neutrino-quark cross sections in ultra-relativistic limit (neglecting masses of neutrinos/quarks)
- For **high energy muon** neutrinos can directly use the results from page 316



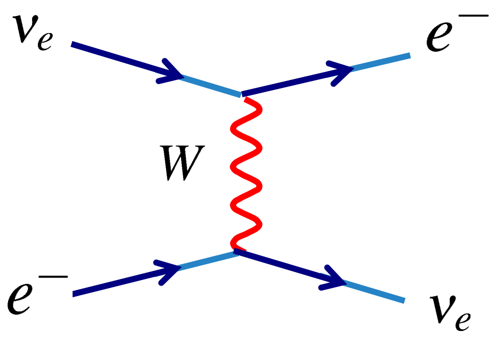
$$\sigma_{\nu_\mu e^-} = \frac{G_F^2 s}{\pi}$$

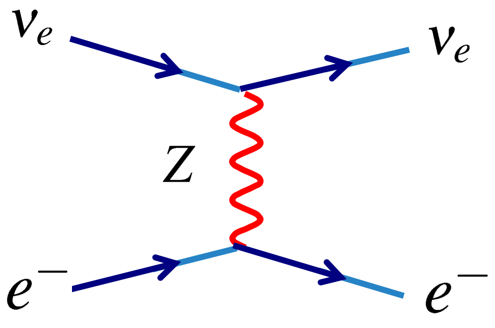
with $s = (E_\nu + m_e)^2 - E_\nu^2 \approx 2 m_e E_\nu$

$$\boxed{\sigma_{\nu_\mu e^-} = \frac{2 m_e G_F^2 E_\nu}{\pi}}$$

Cross section increases linearly with lab. frame neutrino energy

- For **electron** neutrinos there is another lowest order diagram with the same final state





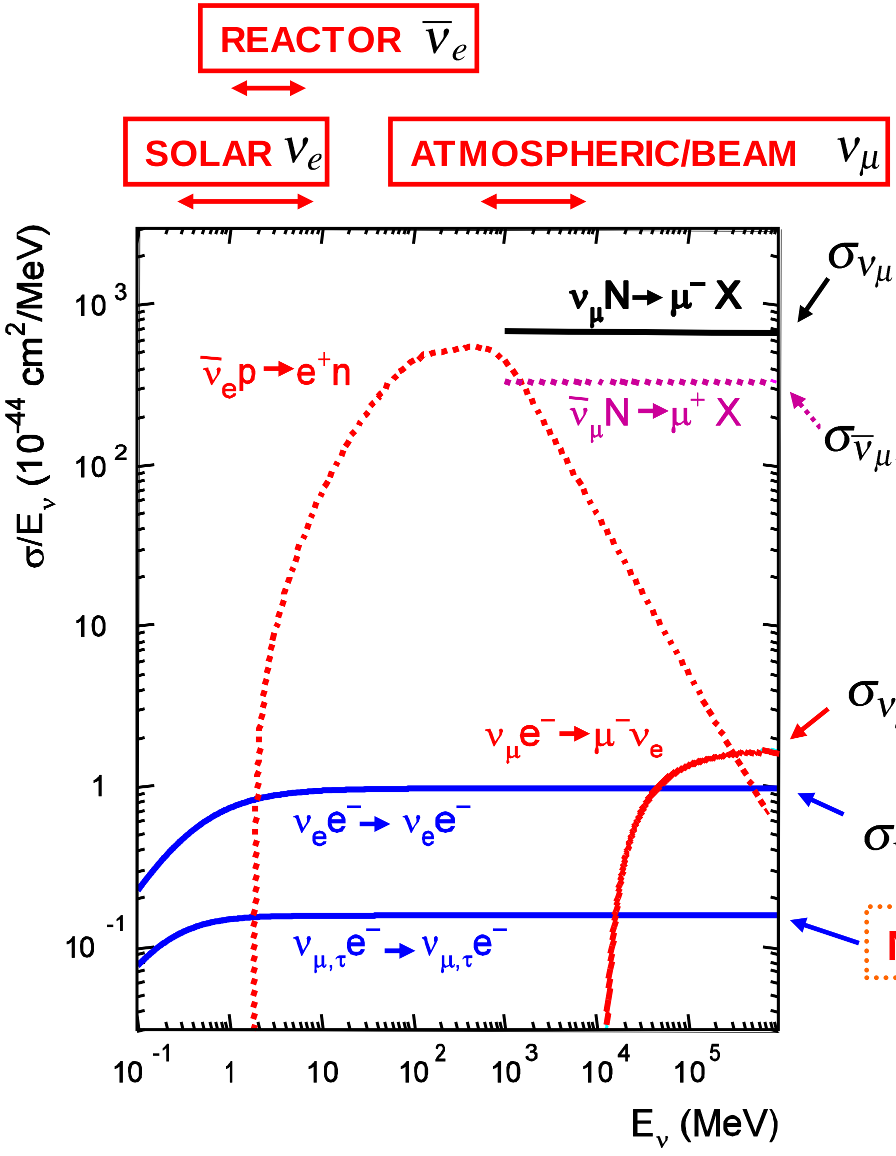
It turns out that the cross section is lower than the pure CC cross section due to negative interference when summing matrix elements $|M_{CC} + M_{NC}|^2 < |M_{CC}|^2$

$$\boxed{\sigma_{\nu_e e} \approx 0.6 \sigma_{\nu_e e}^{CC}}$$

- In the high energy limit the CC neutrino-nucleon cross sections are larger due to the higher centre-of-mass energy: $s = (E_\nu + m_n)^2 - E_\nu^2 \approx 2 m_n E_\nu$

NEUTRINO DETECTION

★ **The detector technology/interaction process depends on type of neutrino and energy**



$$\sigma_{\nu_\mu N} = 0.22 \frac{2 m_p G_F^2 E_\nu}{\pi}$$

$$\sigma_{\overline{\nu}_\mu N} = 0.33 \frac{2 m_p G_F^2 E_\nu}{3\pi}$$

Deep Inelastic Scattering (p. 332)

$$\sigma_{\nu_\mu e^-} = \frac{2 m_e G_F^2 E_\nu}{\pi}$$

CC only Threshold 11 GeV

$$\sigma_{\nu_e e^-} \approx 0.6 \frac{2 m_e G_F^2 E_\nu}{\pi}$$

NC + CC

NC only

Atmospheric/Beam Neutrinos

$$\nu_e, \nu_\mu, \overline{\nu}_e, \overline{\nu}_\mu : E_\nu > 1\,\mathrm{GeV}$$

➊ **Water Čerenkov:** e.g. Super Kamiokande

➋ **Iron Calorimeters:** e.g. MINOS, CDHS

- Produce high energy charged lepton – relatively easy to detect

Solar Neutrinos

$$\nu_e \;:\; E_\nu < 20\,\mathrm{MeV}$$

➊ **Water Čerenkov:** e.g. Super Kamiokande

- Detect Čerenkov light from electron produced in $\nu_e + e^- \rightarrow \nu_e + e^-$
- Because of background from natural radioactivity limited to $E_\nu > 5\,\mathrm{MeV}$
- Because Oxygen is a doubly magic nucleus don't get $\nu_e + n \rightarrow e^- + p$

➋ **Radio-Chemical:** e.g. Homestake, SAGE, GALLEX

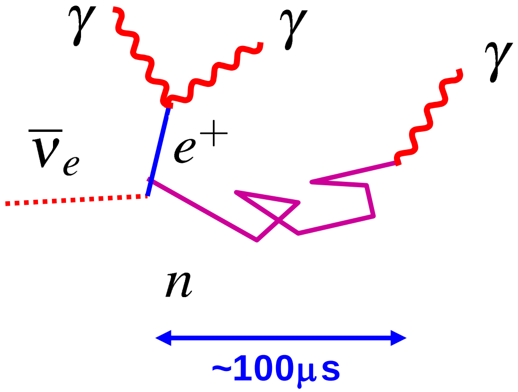
- Use inverse beta decay process, e.g. $\nu_e + {}^{71}\mathrm{Ga} \rightarrow e^- + {}^{71}\mathrm{Ge}$
- Chemically extract produced isotope and count decays (only gives a rate)

Reactor Neutrinos

$$\overline{\nu}_e \;:\; E_{\overline{\nu}} < 5\,\mathrm{MeV}$$

➊ **Liquid Scintillator:** e.g. KamLAND

- Low energies ➡ large radioactive background
- Dominant interaction: $\overline{\nu}_e + p \rightarrow e^+ + n$
- Prompt positron annihilation signal + delayed signal from *n* (space/time correlation reduces background)
- electrons produced by photons excite scintillator which produces light



1) LONG BASELINE NEUTRINO EXPERIMENTS

- **Initial studies of neutrino oscillations from atmospheric and solar neutrinos**
  - atmospheric neutrinos discussed in examinable appendix
- **Emphasis of neutrino research now on neutrino beam experiments**
- **Allows the physicist to take control – design experiment with specific goals**
- **In the last few years, long baseline neutrino oscillation experiments have started taking data: K2K, MINOS, CNGS, T2K**

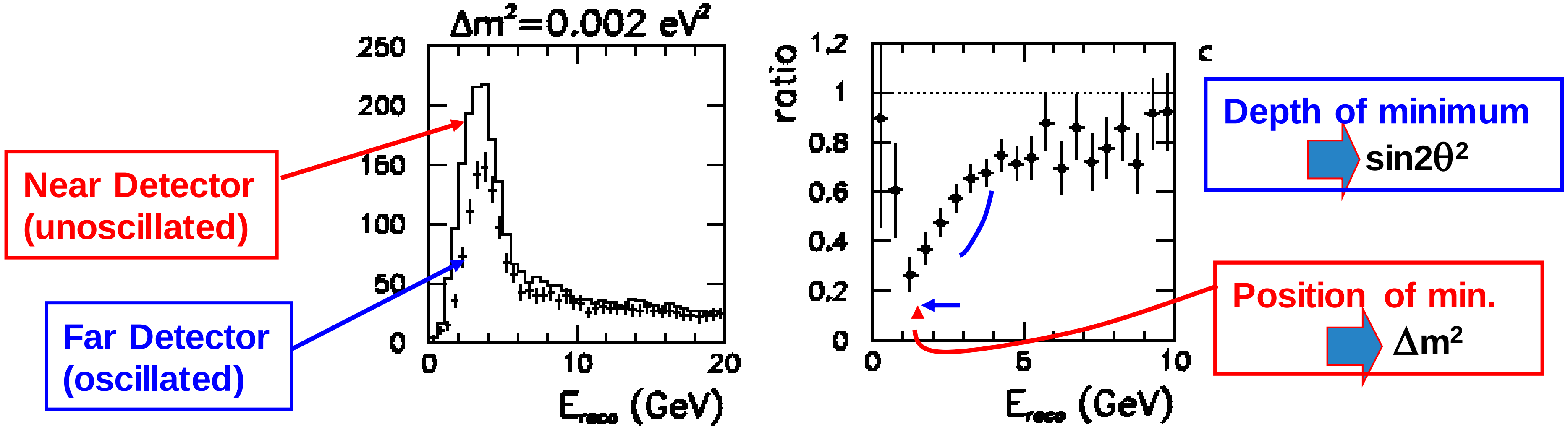
Basic Idea:

★ **Intense neutrino beam**

★ **Two detectors: one close to beam the other hundreds of km away**

★ **Measure ratio of the neutrino energy spectrum in far detector (oscillated) to that in the near detector (unoscillated)**

★ **Partial cancellation of systematic biases**



Near Detector (unoscillated)

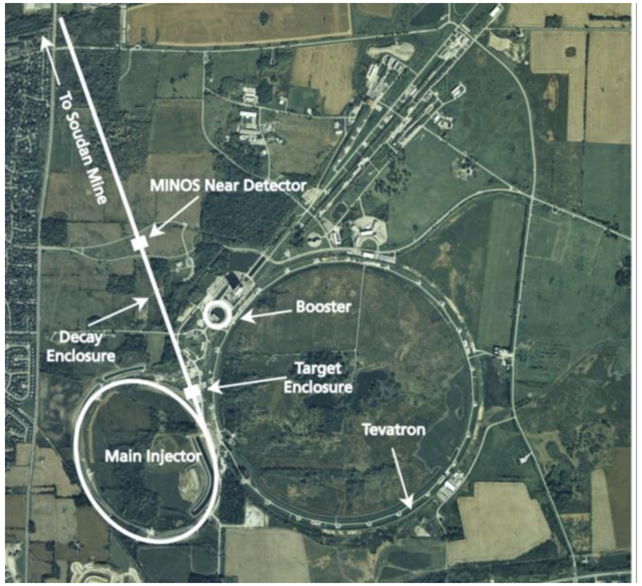
Far Detector (oscillated)

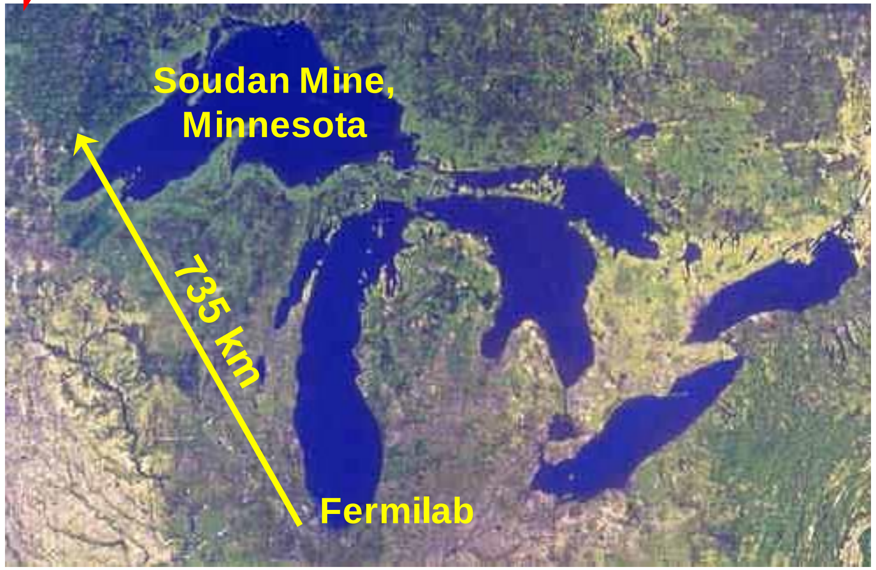
Depth of minimum ⇨ **$\sin 2\theta^2$**

Position of min. ⇨ **Δm^2**

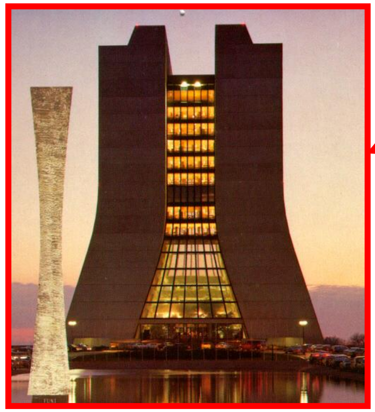
MINOS

- 120 GeV protons extracted from the MAIN INJECTOR at Fermilab (see p. 271)
- $2.5\text{x}10^{13}$ protons per pulse hit target → very intense beam - 0.3 MW on target





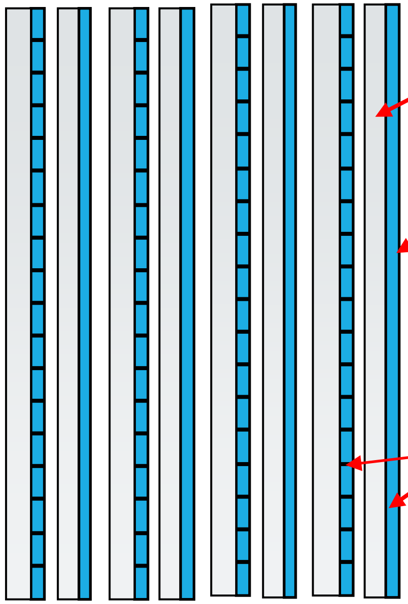
Two detectors:



- ★ 1000 ton, NEAR Detector at Fermilab : 1 km from beam
- ★ 5400 ton FAR Detector, 720m underground in Soudan mine, N. Minnesota: 735 km from beam

The MINOS Detectors:

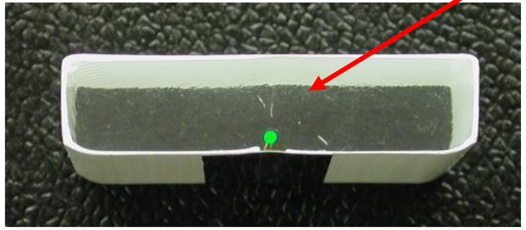
- Dealing with high energy neutrinos $E_\nu > 1\,\mathrm{GeV}$
- The muons produced by ν_μ interactions travel several metres
- Steel-Scintillator sampling calorimeter
- Each plane: 2.54 cm steel +1 cm scintillator
- A charged particle crossing the scintillator produces light – detect with PMTs

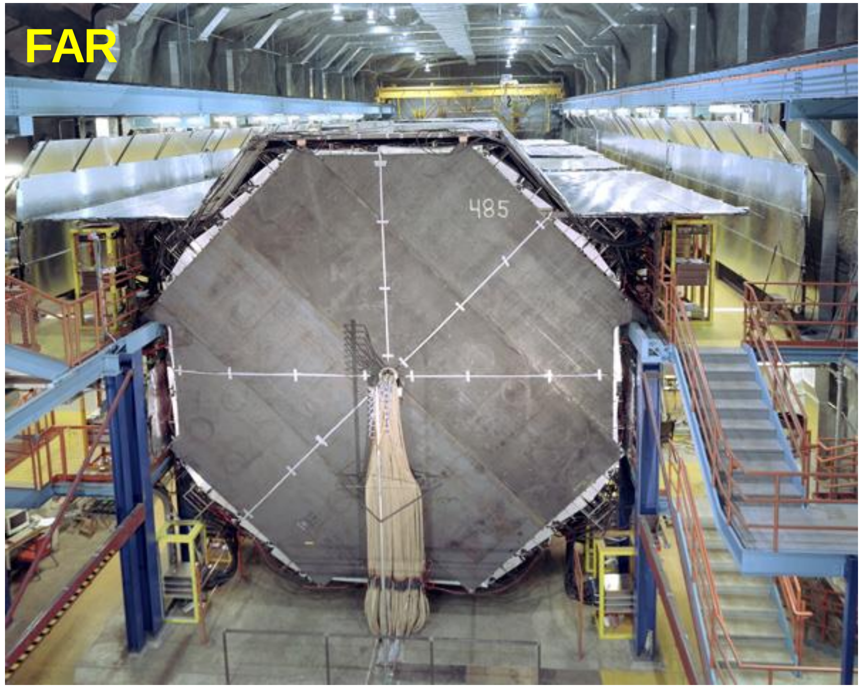


Steel

Plastic scintillator

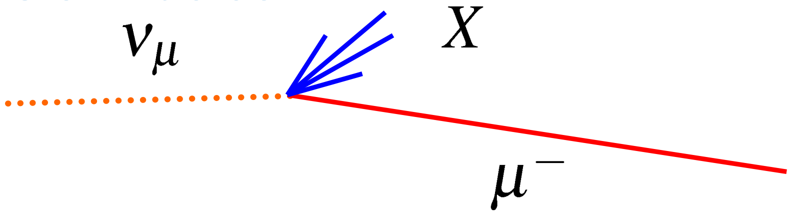
Alternate layers have strips in x/y directions



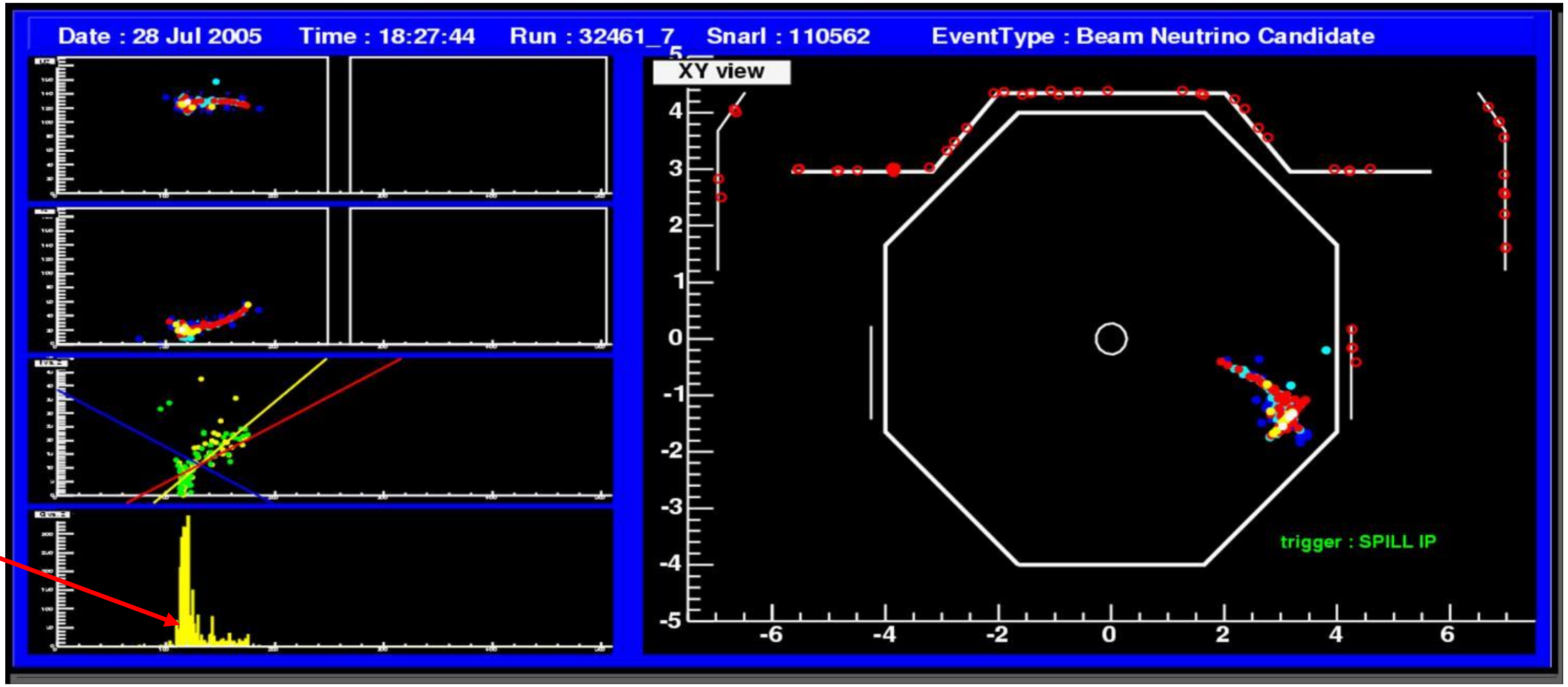


- Neutrino detection via CC interactions on nucleon

$$\nu_\mu + N \rightarrow \mu^- + X$$



Example event:



Signal from hadronic shower

- The main feature of the MINOS detector is the very good neutrino energy resolution

$$\boxed{E_\nu = E_\mu + E_X}$$

- Muon energy from range/curvature in B-field
- Hadronic energy from amount of light observed

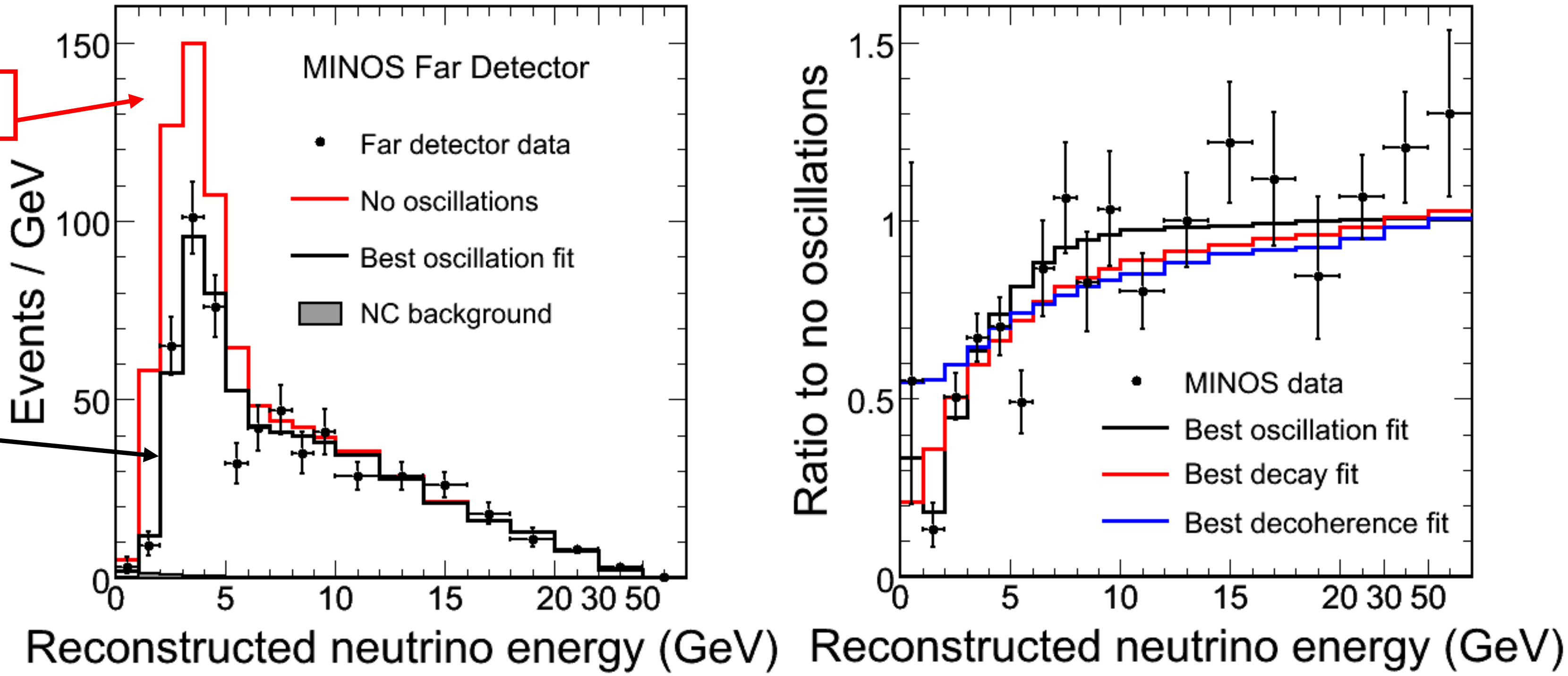
MINOS RESULTS

- For the MINOS experiment L is fixed and observe oscillations as function of E_ν
- For $|\Delta m^2_{32}| \sim 2.5 \times 10^{-3}\,\mathrm{eV}^2$ first oscillation minimum at $E_\nu = 1.5\,\mathrm{GeV}$
- To a very good approximation can use two flavour formula as oscillations corresponding to $|\Delta m^2_{21}| \sim 8 \times 10^{-5}\,\mathrm{eV}^2$ occur at $E_\nu = 50\,\mathrm{MeV}$, beam contains very few neutrinos at this energy + well below detection threshold

MINOS Collaboration, Phys. Rev. Lett. 101, 131802, 2008

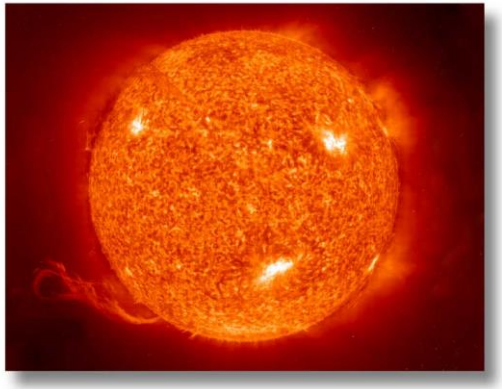
no oscillations

best fit osc



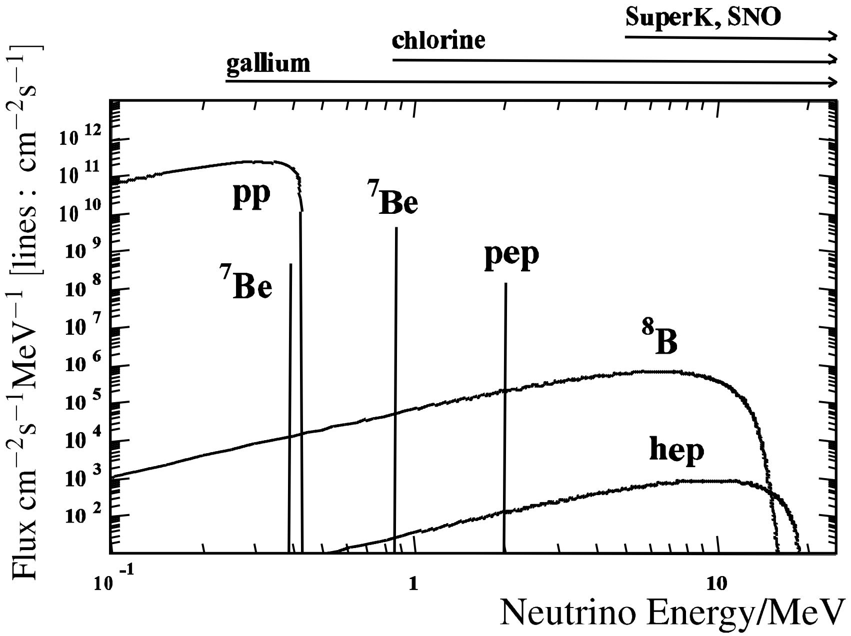
$$|\Delta m^2_{32}| = (2.43 \pm 0.12) \times 10^{-3}\,\mathrm{eV}^2$$

2) SOLAR NEUTRINOS



- The Sun is powered by the weak interaction – producing a very large flux of **electron neutrinos**

$$\boxed{2 \times 10^{38}\, \nu_e\, \mathrm{s}^{-1}}$$



- Several different nuclear reactions in the sun ⇨ complex neutrino energy spectrum

$$\boxed{p + p \rightarrow d + e^+ + \nu_e} \quad E_\nu < 0.5\,\mathrm{MeV}$$

$$\boxed{{}^8B \rightarrow {}^8Be^* + e^+ + \nu_e} \quad E_\nu \sim 5\mathrm{MeV}$$

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

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

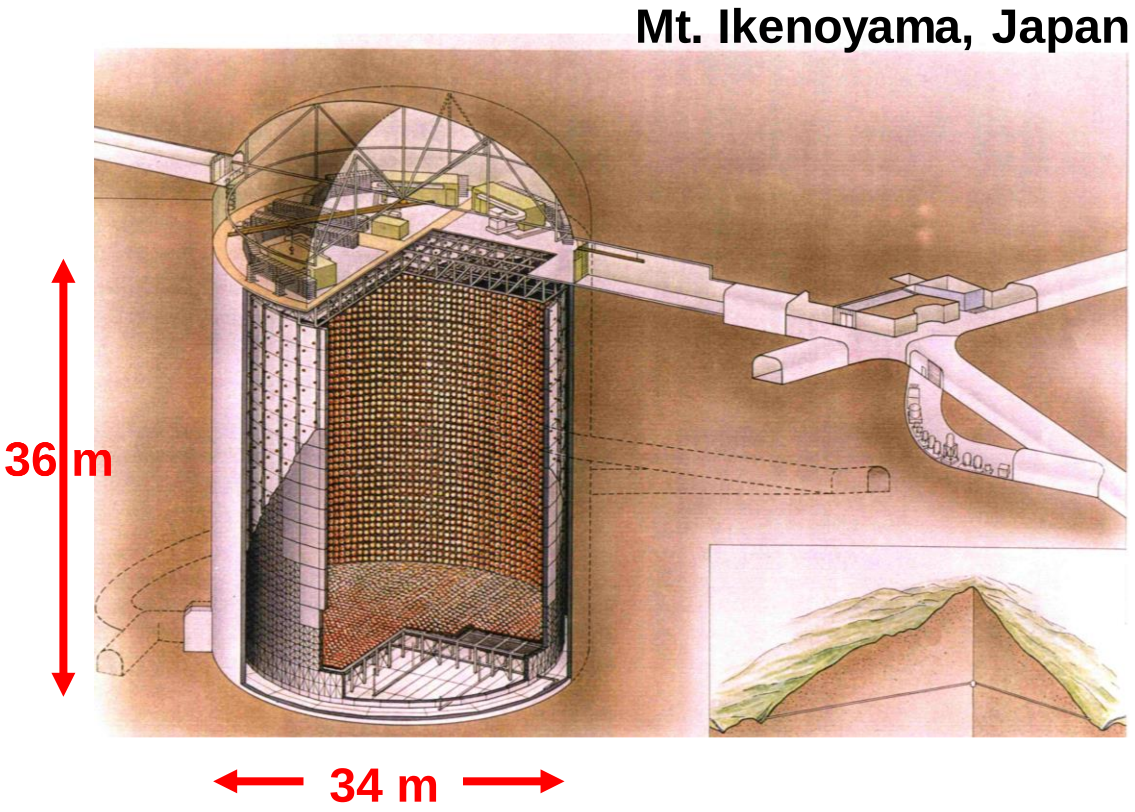
$${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$$

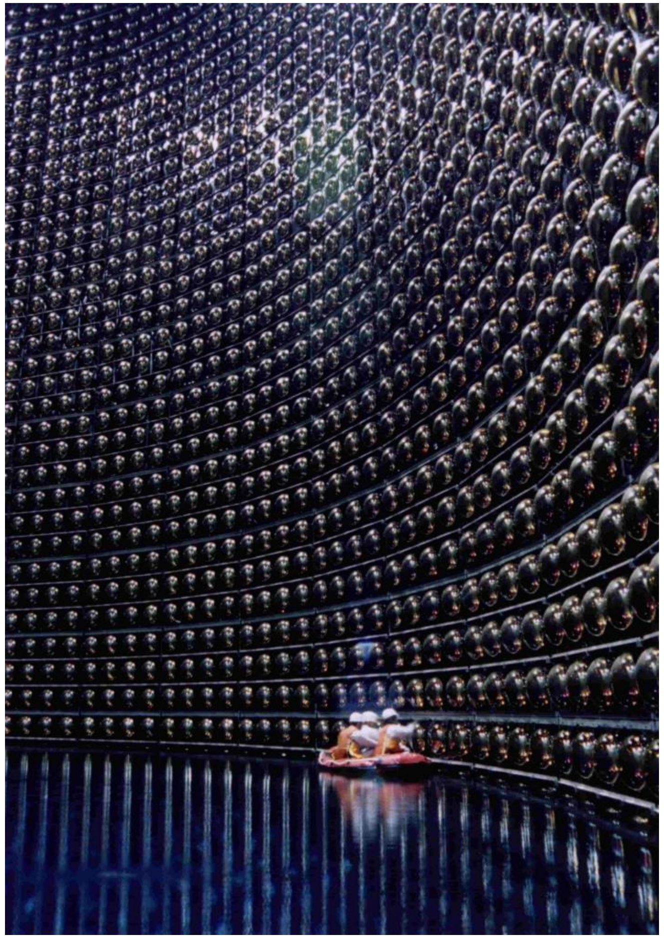
- All experiments saw a deficit of electron neutrinos compared to experimental prediction – the **SOLAR NEUTRINO PROBLEM**

- e.g. Super Kamiokande

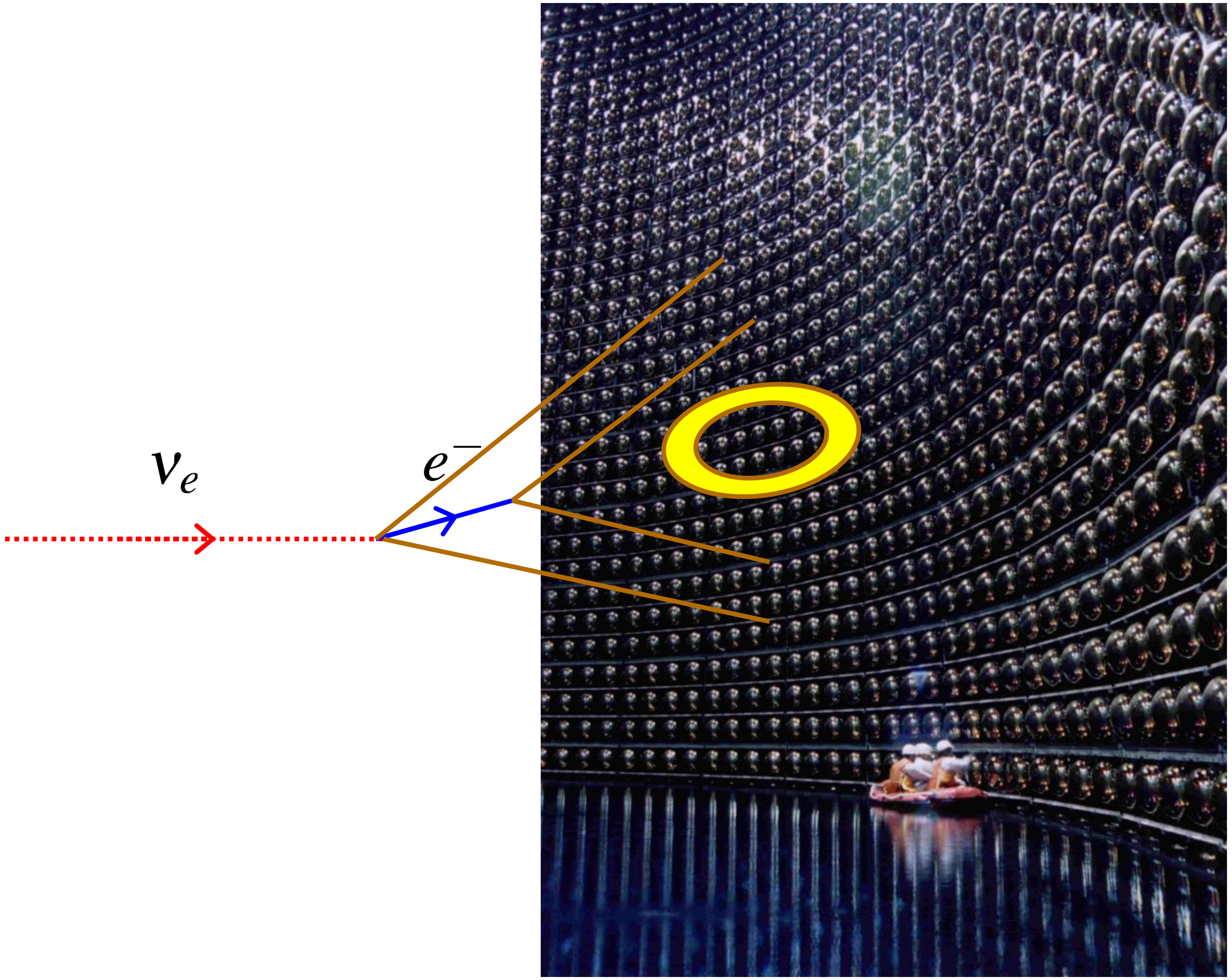
SOLAR NEUTRINOS I: SUPER KAMIOKANDE

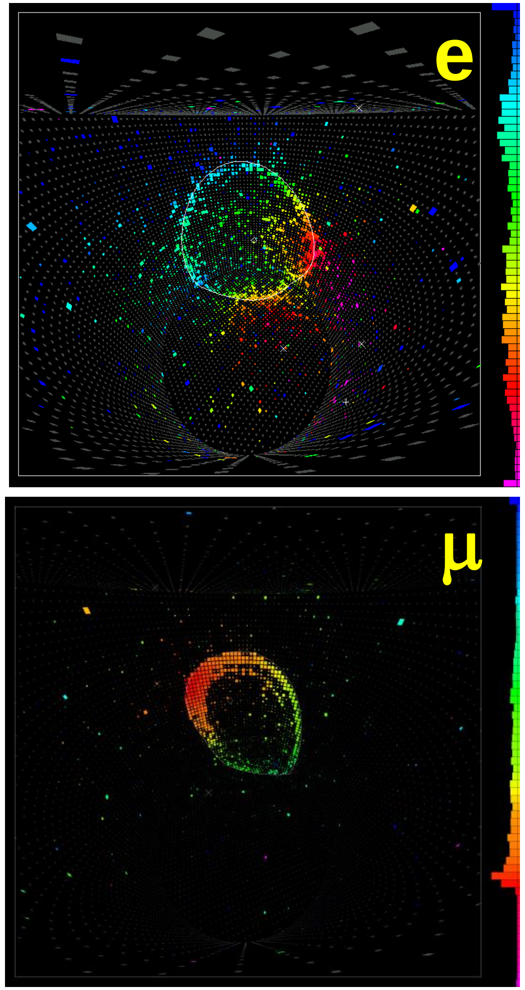
- 50000 ton water Čerenkov detector
- Water viewed by 11146 Photo-multiplier tubes
- Deep underground to filter out cosmic rays otherwise difficult to detect rare neutrino interactions





- Detect neutrinos by observing Čerenkov radiation from charged particles which travel faster than speed of light in water *c/n*



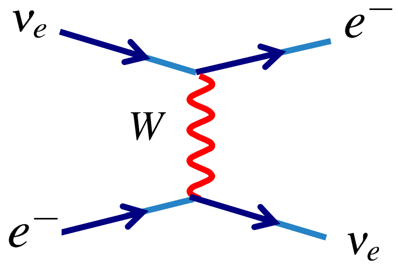


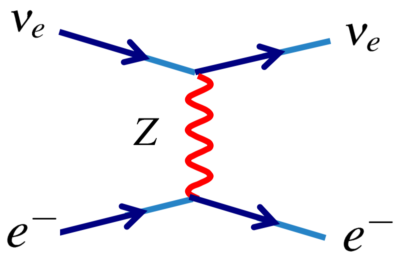
- Can distinguish electrons from muons from pattern of light – muons produce clean rings whereas electrons produce more diffuse “fuzzy” rings

- Sensitive to solar neutrinos with $E_\nu > 5\,\mathrm{MeV}$
- For lower energies too much background from natural radioactivity (β-decays)
- Hence detect mostly neutrinos from $^8B \rightarrow {}^8Be^* + e^+ + \nu_e$
- Detect electron Čerenkov rings from

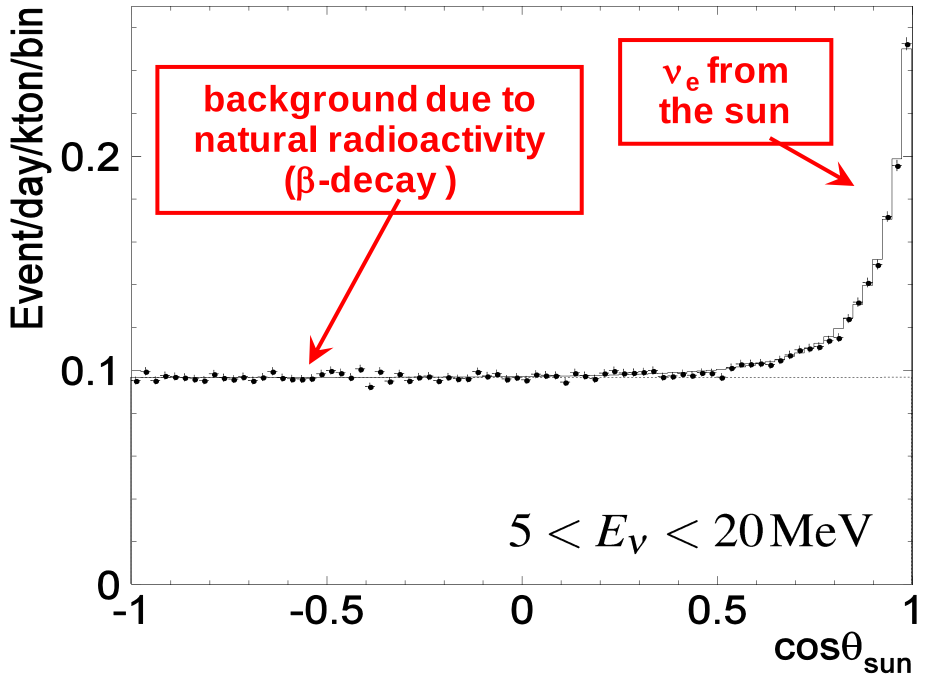
$$\nu_e + e^- \rightarrow \nu_e + e^-$$

- In LAB frame the electron is produced preferentially along the ν_e direction





S.Fukada et al., Phys. Rev. Lett. 86 5651-5655, 2001



Results:

- Clear signal of neutrinos from the sun
- However too few neutrinos

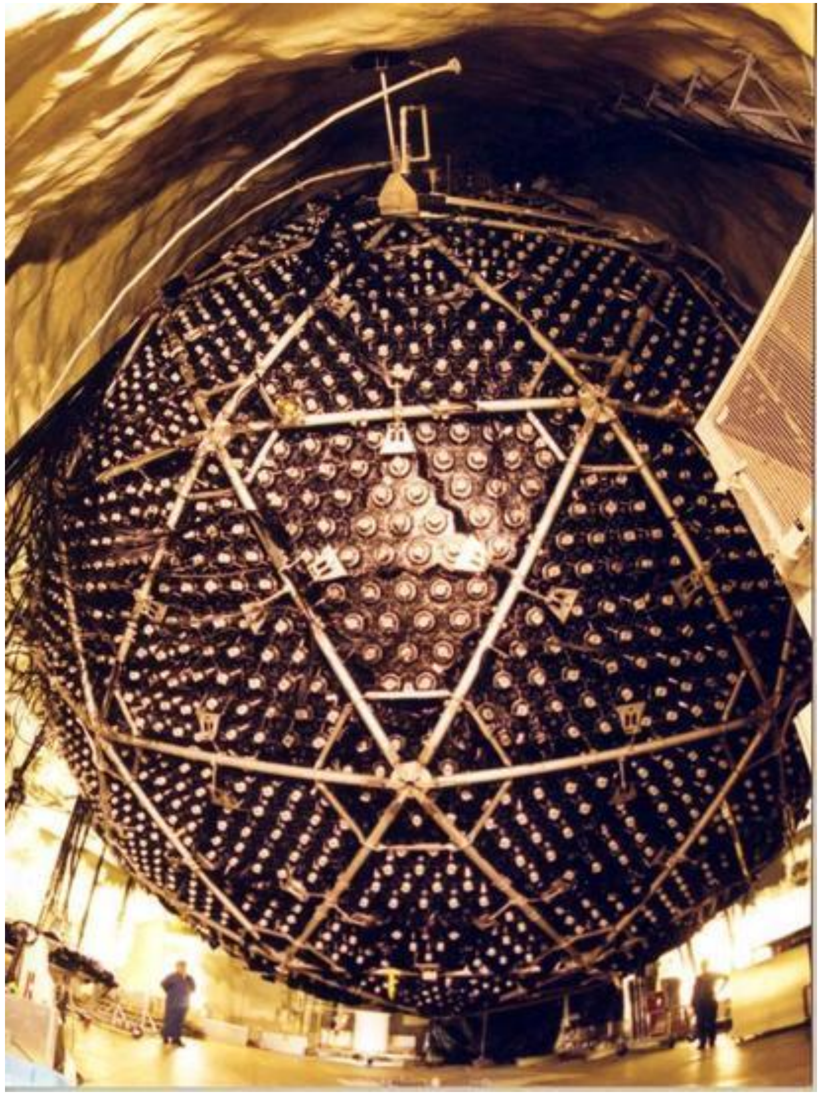
DATA/SSM = 0.45±0.02

SSM = “Standard Solar Model” Prediction

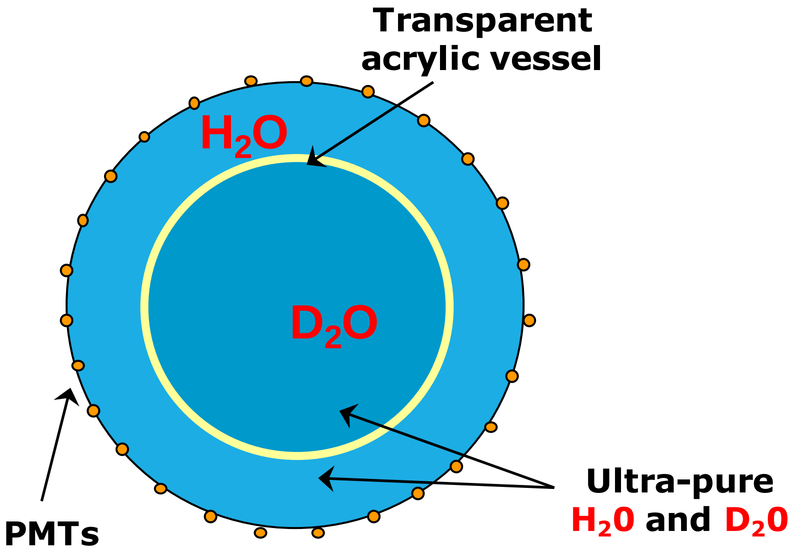
The Solar Neutrino “Problem”

SOLAR NEUTRINOS II: SNO

- Sudbury Neutrino Observatory located in a deep mine in Ontario, Canada



- 1000 ton heavy water (D_2O) Čerenkov detector
- D_2O inside a 12m diameter acrylic vessel
- Surrounded by 3000 tons of normal water
- Main experimental challenge is the need for very low background from radioactivity
- Ultra-pure H_2O and D_2O
- Surrounded by 9546 PMTs

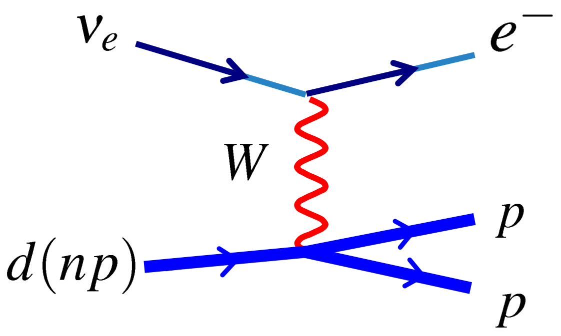


★ Detect Čerenkov light from three different reactions:

CHARGE CURRENT

- Detect Čerenkov light from electron
- Only sensitive to ν_e (thresholds)
- Gives a measure of ν_e flux

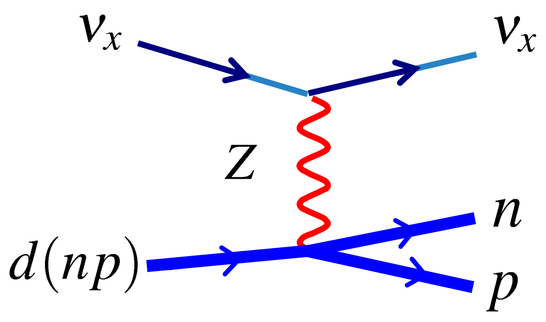
$$\boxed{\text{CC Rate} \propto \phi(\nu_e)}$$



NEUTRAL CURRENT

- Neutron capture on a deuteron gives **6.25 MeV**
- Detect Čerenkov light from electrons scattered by γ
- Measures total neutrino flux

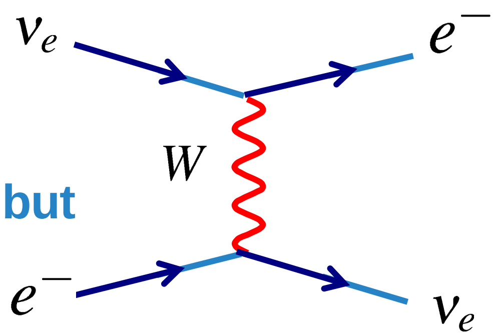
$$\boxed{\text{NC Rate} \propto \phi(\nu_e) + \phi(\nu_\mu) + \phi(\nu_\tau)}$$

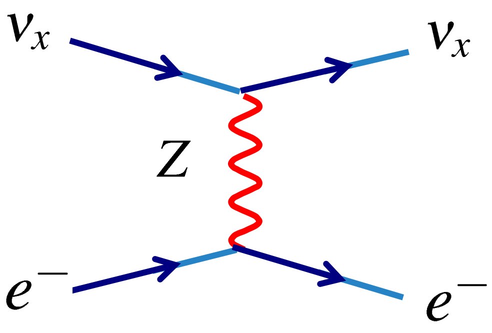


ELASTIC SCATTERING

- Detect Čerenkov light from electron
- Sensitive to all neutrinos (NC part) – but larger cross section for ν_e

$$\boxed{\text{ES Rate} \propto \phi(\nu_e) + 0.154(\phi(\nu_\mu) + \phi(\nu_\tau))}$$

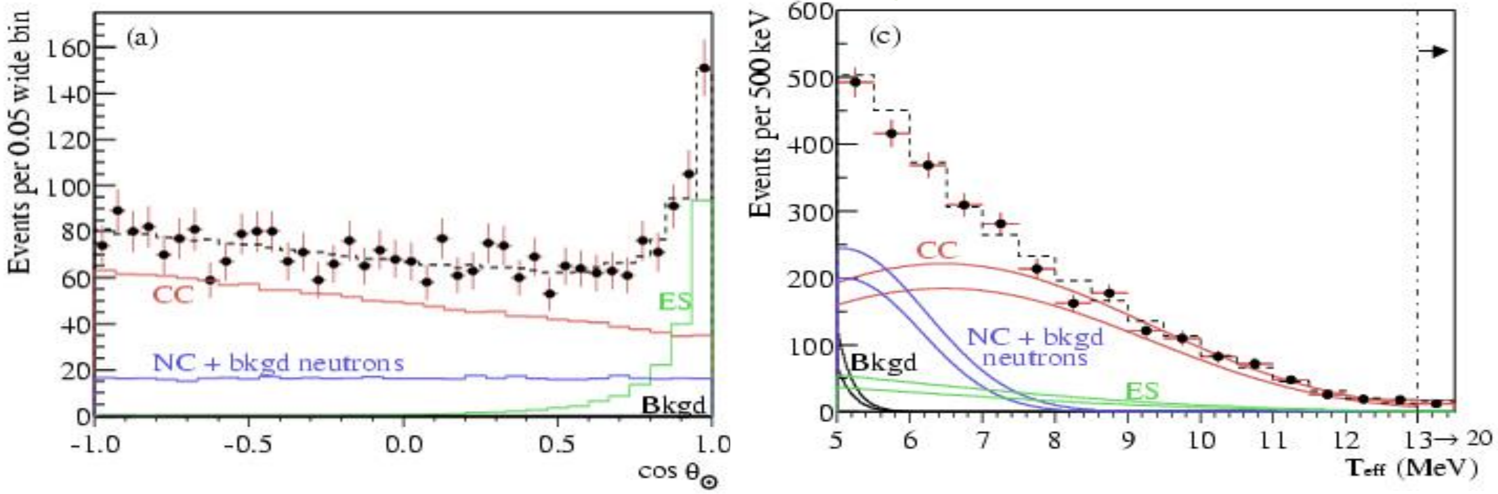




★ **Experimentally can determine rates for different interactions from:**

- angle with respect to sun: electrons from ES point back to sun
- energy: NC events have lower energy – 6.25 MeV photon from neutron capture
- radius from centre of detector: gives a measure of background from neutrons

SNO Collaboration, Q.R. Ahmad et al., Phys. Rev. Lett. 89:011301, 2002



★**Using different distributions obtain a measure of numbers of events of each type:**

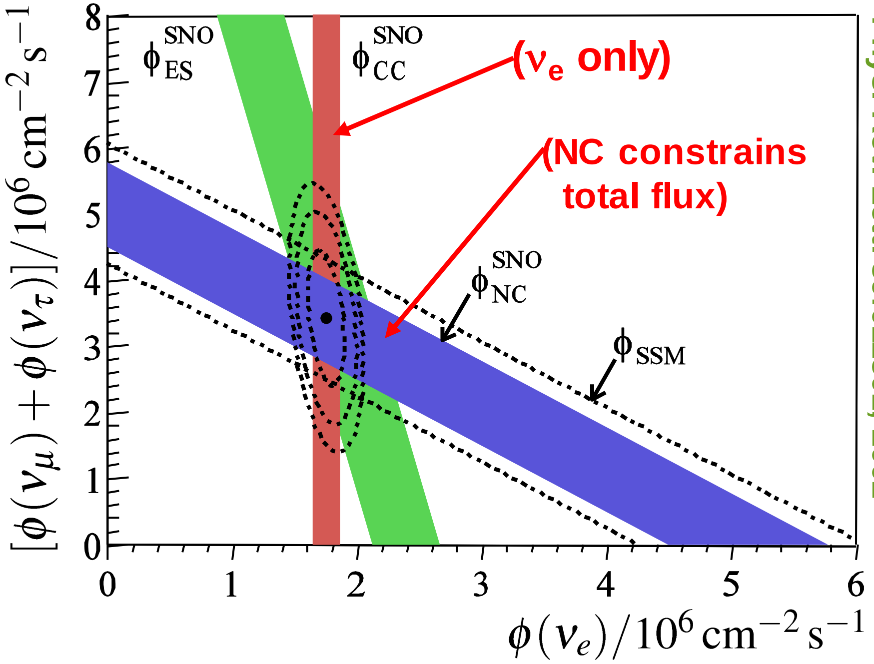
CC : 1968 ± 61 $\propto \phi(\nu_e)$

ES :   264 ± 26 $\propto \phi(\nu_e) + 0.154[\phi(\nu_\mu) + \phi(\nu_\tau)]$

NC :   576 ± 50 $\propto \phi(\nu_e) + \phi(\nu_\mu) + \phi(\nu_\tau)$

Measure of electron neutrino flux + total flux !

- ★Using known cross sections can convert observed numbers of events into fluxes
- ★The different processes impose different constraints
- ★ Where constraints meet gives separate measurements of ν_e and $\nu_\mu + \nu_\tau$ fluxes



(ν_e only)

(NC constrains total flux)

SNO Collaboration, Q.R. Ahmad et al., Phys. Rev. Lett. 89:011301, 2002

SNO Results:

$$\phi(\nu_e) = (1.8 \pm 0.1) \times 10^{-6}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

$$\phi(\nu_\mu) + \phi(\nu_\tau) = (3.4 \pm 0.6) \times 10^{-6}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

SSM Prediction:

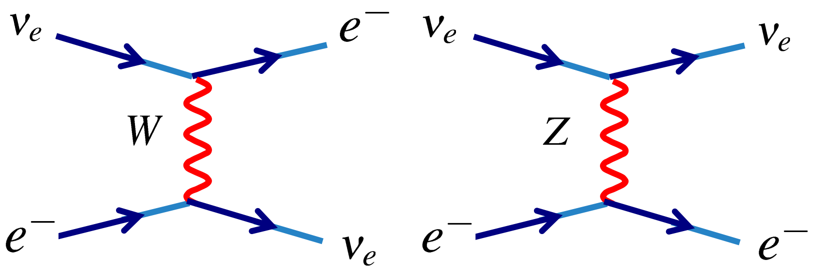
$$\phi(\nu_e) = 5.1 \times 10^{-6}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

- •Clear evidence for a flux of ν_μ and/or ν_τ from the sun
- •Total neutrino flux is consistent with expectation from SSM
- •Clear evidence of $\nu_e \rightarrow \nu_\mu$ and/or $\nu_e \rightarrow \nu_\tau$ neutrino transitions

Interpretation of Solar Neutrino Data

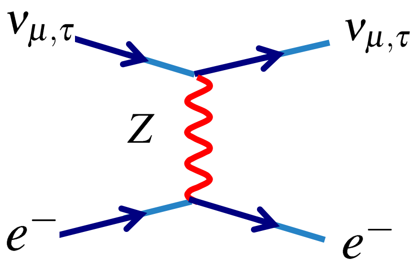
★ **The interpretation of the solar neutrino data is complicated by MATTER EFFECTS**

- The quantitative treatment is non-trivial and is not given here
- Basic idea is that as a neutrino leaves the sun it crosses a region of high electron density
- The coherent forward scattering process ($\nu_e \rightarrow \nu_e$ r an electron neutrino



CC + **NC**

is different to that for a muon or tau neutrino



NC

- **Can enhance oscillations – "MSW effect"**

★ **A combined analysis of all solar neutrino data gives:**

$$\Delta m^2_{\text{solar}} \approx 8 \times 10^{-5}\,\text{eV}^2,\ \sin^2 2\theta_{\text{solar}} \approx 0.85$$

3) REACTOR EXPERIMENTS

- To explain reactor neutrino experiments we need the full three neutrino expression for the electron neutrino survival probability (11) which depends on U_{e1}, U_{e2}, U_{e3}
- Substituting these PMNS matrix elements in Equation (11):

$$\begin{aligned} P(\nu_e \rightarrow \nu_e) &\approx 1 - 4U_{e1}^2 U_{e2}^2 \sin^2\Delta_{21} - 4(1-U_{e3}^2)U_{e3}^2 \sin^2\Delta_{32} \\ &= 1 - 4(c_{12}c_{13})^2(s_{12}c_{13})^2 \sin^2\Delta_{21} - 4(1-s_{13}^2)s_{13}^2 \sin^2\Delta_{32} \\ &= 1 - c_{13}^4(2s_{12}c_{12})^2 \sin^2\Delta_{21} - (2c_{13}s_{13})^2 \sin^2\Delta_{32} \\ &= 1 - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\Delta_{21} - \sin^2 2\theta_{13} \sin^2\Delta_{32} \end{aligned}$$

- Contributions with short wavelength (atmospheric) and long wavelength (solar)
- For a 1 MeV neutrino

$$\lambda_{\text{osc}}(\text{km}) = 2.47 \frac{E(\text{GeV})}{\Delta m^2(\text{eV}^2)}$$

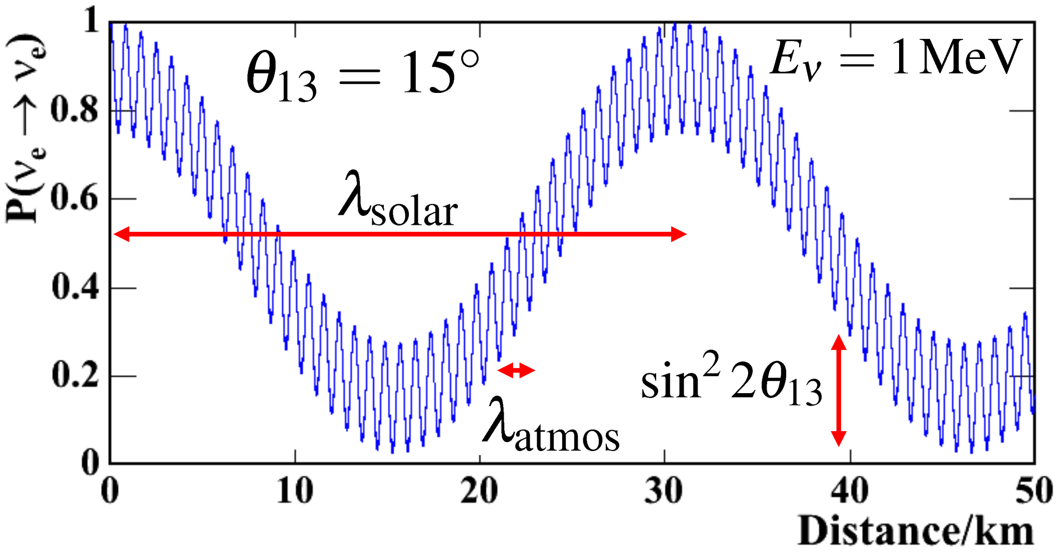
⇒

$$\lambda_{21} = 30.0\,\text{km}$$

$$\lambda_{32} = 0.8\,\text{km}$$

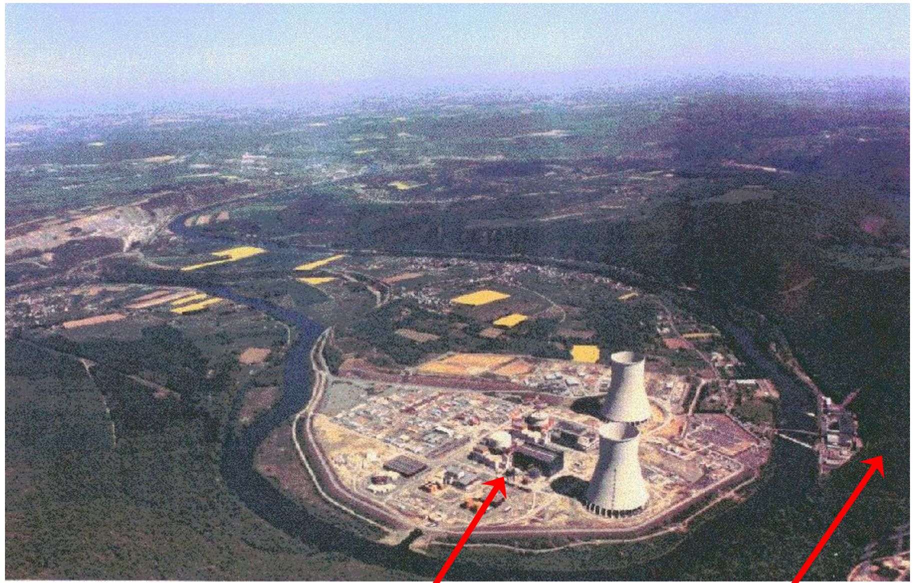
- Amplitude of short wavelength oscillations given by

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



REACTOR EXPERIMENTS I : CHOOZ

- Two nuclear reactors, each producing 4.2 GW
- Place detector 1km from reactor cores
- Reactors produce intense flux of $\overline{\nu}_e$

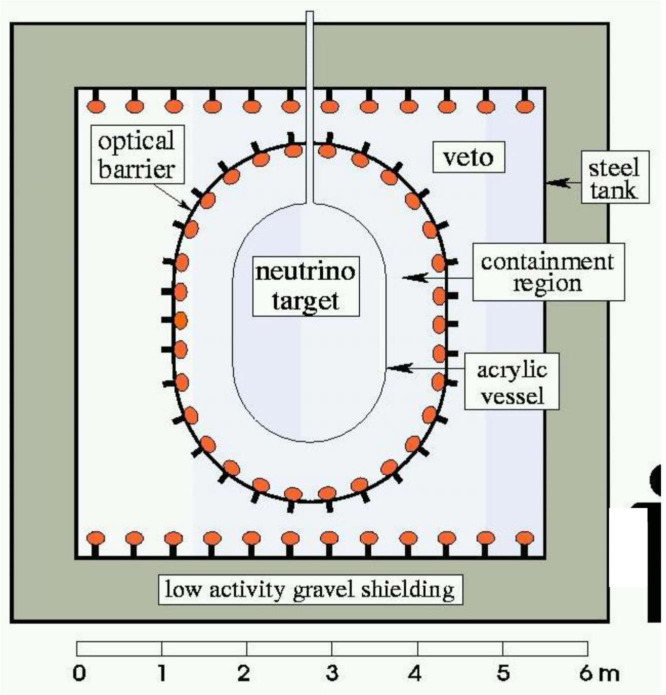


reactors

Detector
150m underground

France

Detector



- Anti-neutrinos interact via inverse beta decay $\overline{\nu}_e + p \to e^+ + n$
- Detector is liquid scintillator loaded with Gadolinium (large n capture cross section)
- Detect photons from positron annihilation and a delayed signal from photons from neutron capture on Gadolinium

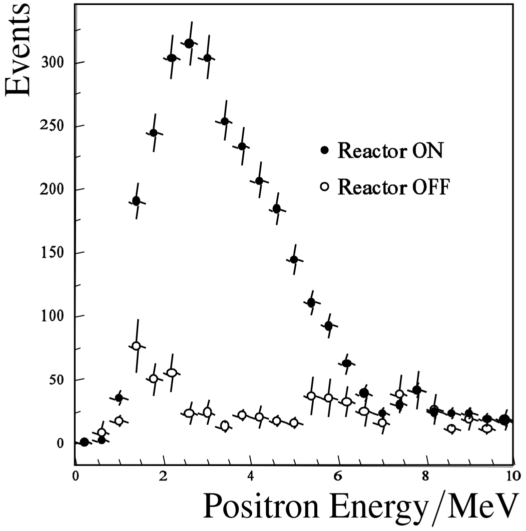
$$e^+ + e^- \to \gamma + \gamma$$

$$n + \mathrm{Gd} \to \mathrm{Gd}^* \to \mathrm{Gd} + \gamma + \gamma + \ldots$$

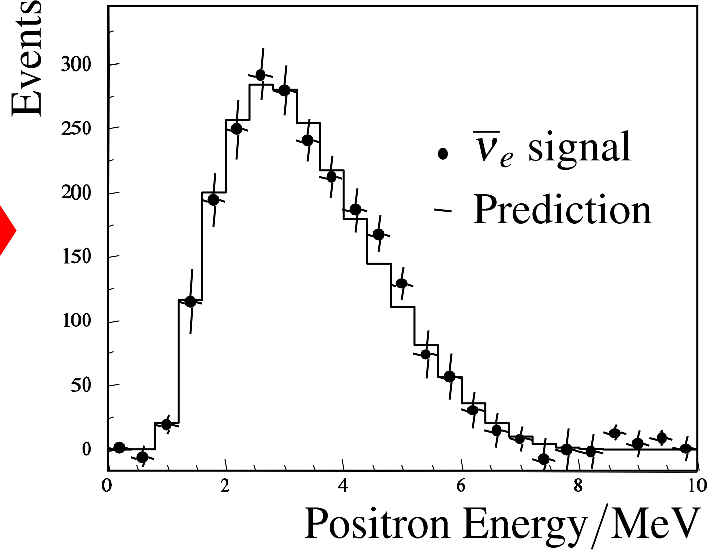
- At 1km and energies > 1 MeV, only the short wavelength component matters

$$P(\nu_e \to \nu_e) \quad = \quad 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\sin^2\Delta_{32} \approx 1 - \sin^2 2\theta_{13}\sin^2\Delta_{32}$$

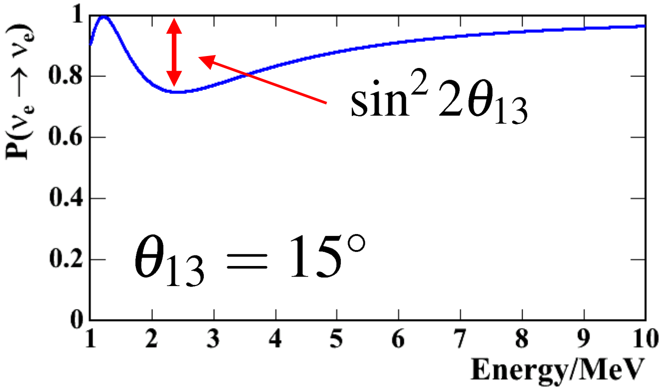
CHOOZ Raw Data



Background subtracted



Compare to effect of oscillations



★ Data agree with unoscillated prediction both in terms of rate and energy spectrum

$$\boxed{N_{\text{data}}/N_{\text{expect}} = 1.01 \pm 0.04}$$

CHOOZ Collaboration,
M.Apollonio et al.,
Phys. Lett. B420, 397-404, 1998

★ Hence $\sin^2 2\theta_{13}$ must be small !

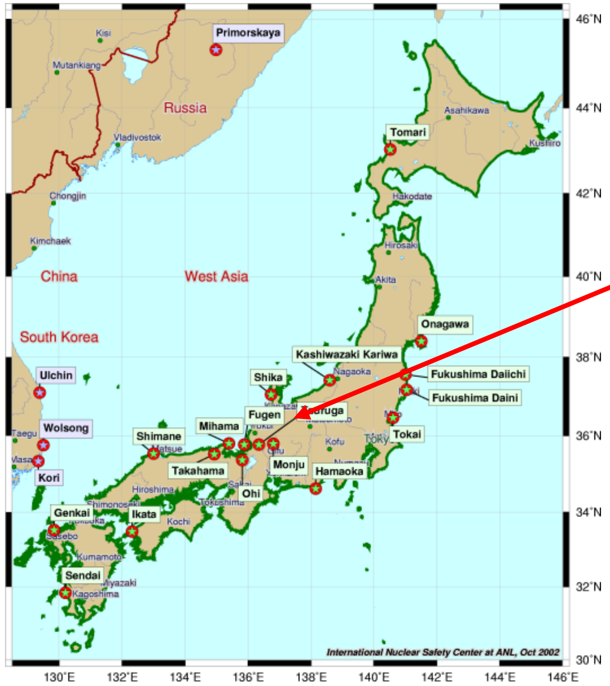
$$\boxed{\sin^2 2\theta_{13} < 0.12 - 0.2}$$

Exact limit depends on $|\Delta m^2_{32}|$

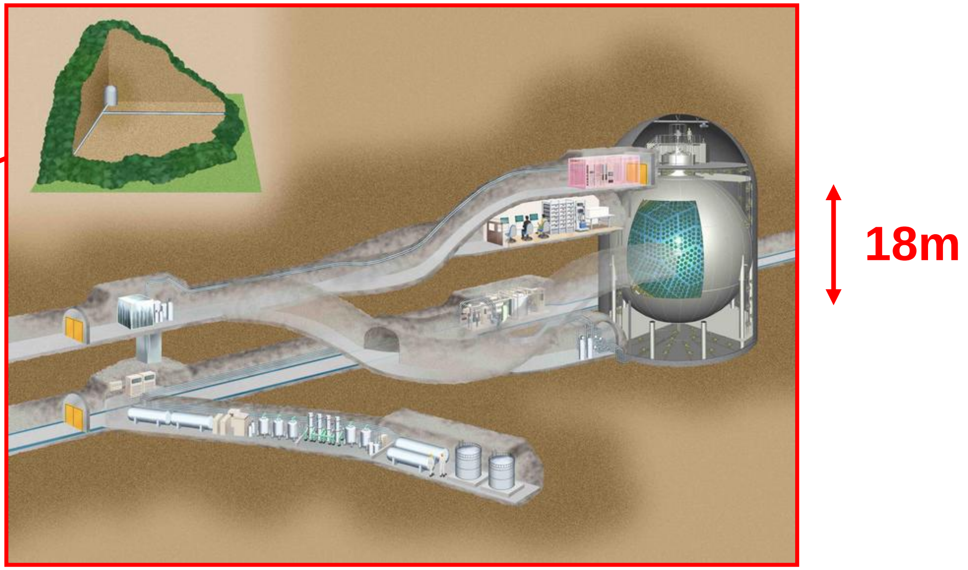
★ From atmospheric neutrinos (see appendix) can exclude $\theta_{13} \sim \frac{\pi}{2}$

- Hence the CHOOZ limit: $\sin^2 2\theta_{13} < 0.2$ can be interpreted as $\sin^2\theta_{13} < 0.05$

REACTOR EXPERIMENTS II : KAMLAND



- Detector located in same mine as Super Kamiokande



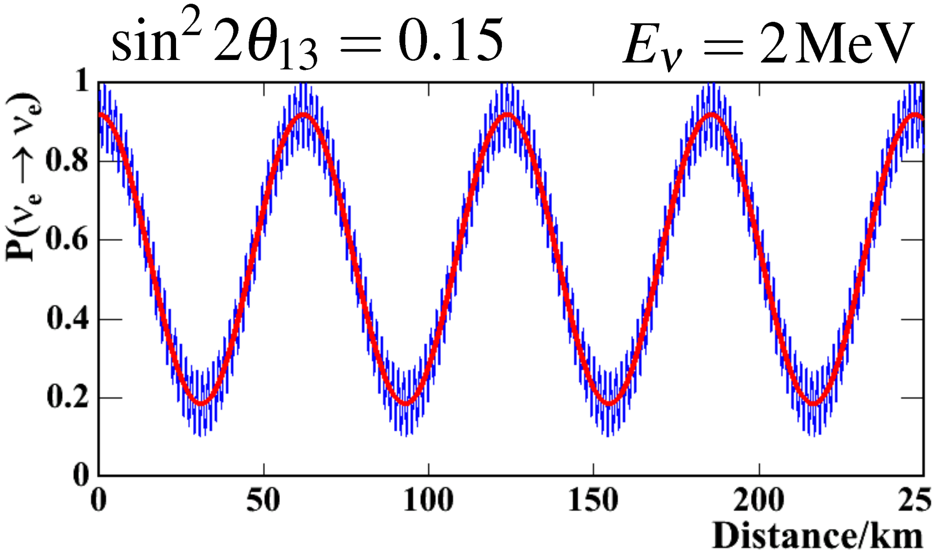
- 70 GW from nuclear power (7% of World total) from reactors within **130-240 km**
- Liquid scintillator detector, 1789 PMTs
- Detection via inverse beta decay: $\nu_e + p \rightarrow e^+ + n$

Followed by

$$e^+ + e^- \rightarrow \gamma + \gamma \qquad \textbf{prompt}$$

$$n + p \rightarrow d + \gamma(2.2\,\mathrm{MeV}) \qquad \textbf{delayed}$$

- For MeV neutrinos at a distance of 130-240 km oscillations due to Δm^2_{32} are very rapid
- Experimentally, only see average effect $\langle \sin^2 \Delta_{32} \rangle = 0.5$



★ **Here:**

$$\begin{aligned} P(\nu_e \to \nu_e) &= 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\sin^2\Delta_{32} \\ &\approx 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \frac{1}{2}\sin^2 2\theta_{13} \\ &= \cos^4\theta_{13} + \sin^4\theta_{13} - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ &\approx \cos^4\theta_{13}(1 - \sin^2 2\theta_{12}\sin^2\Delta_{21}) \end{aligned}$$

Averaging over rapid oscillations

neglect $\sin^4\theta_{13}$

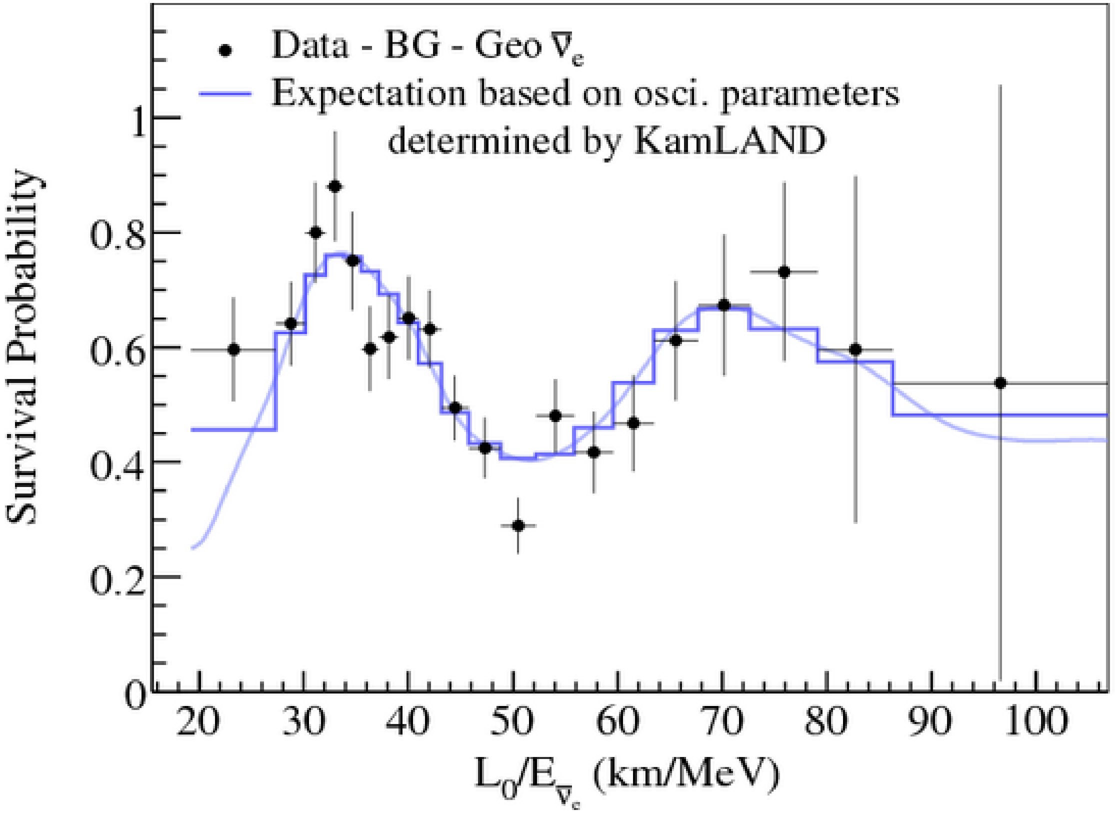
- Obtain two-flavour oscillation formula multiplied by $\cos^4\theta_{13}$
- From CHOOZ $\cos^4\theta_{13} > 0.9$

KamLAND RESULTS:

Observe: **1609** events

Expect: **2179±89** events (if no oscillations)

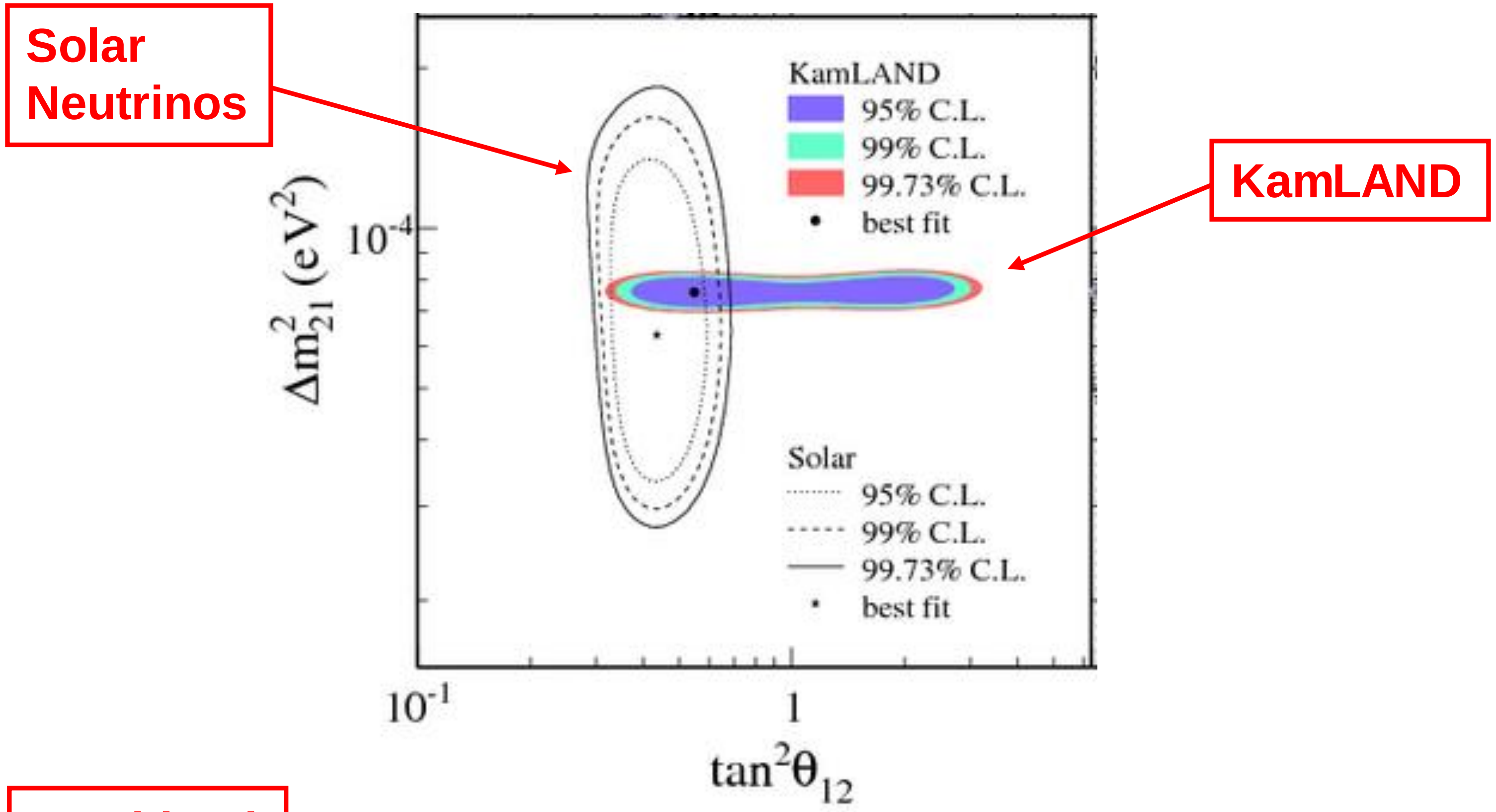
KamLAND Collaboration, Phys. Rev. Lett., 221803, 2008



- ★ Clear evidence of electron anti-neutrino oscillations consistent with the results from solar neutrinos
- ★ Oscillatory structure clearly visible
- ★ Compare data with expectations for different osc. parameters and perform χ^2 fit to extract measurment

COMBINED SOLAR NEUTRINO AND KAMLAND RESULTS

- ★ KamLAND data provides strong constraints on $|\Delta m^2_{21}|$
- ★Solar neutrino data (especially SNO) provides a strong constraint on θ_{12}



Combined

$$|\Delta m^2_{21}| = (7.59 \pm 0.21) \times 10^{-5}\,\mathrm{eV}^2$$

$$\tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$$

SUMMARY OF CURRENT KNOWLEDGE

SOLAR Neutrinos/KamLAND

KamLAND + Solar: $|\Delta m^2_{21}| \approx (7.6 \pm 0.2) \times 10^{-5}\,\mathrm{eV}^2$

SNO + KamLAND + Solar: $\tan^2\theta_{12} \approx 0.47 \pm 0.05$

$$\boxed{\sin\theta_{12} \approx 0.56; \qquad \cos\theta_{12} \approx 0.82}$$

Atmospheric Neutrinos/Long Baseline experiments

MINOS: $|\Delta m^2_{32}| \approx (2.4 \pm 0.1) \times 10^{-3}\,\mathrm{eV}^2$

Super Kamiokande: $\sin^2 2\theta_{23} > 0.92$

$$\boxed{\cos\theta_{23} \approx \sin\theta_{23} \approx \frac{1}{\sqrt{2}}}$$

CHOOZ + (atmospheric)

$$\boxed{\sin^2 2\theta_{13} < 0.15}$$

Daya Bay 2015

$$\boxed{\sin^2(2\,\theta_{13}) = 0.084 \pm 0.005}$$

- **For the approximate values of the mixing angles on the previous page obtain:**

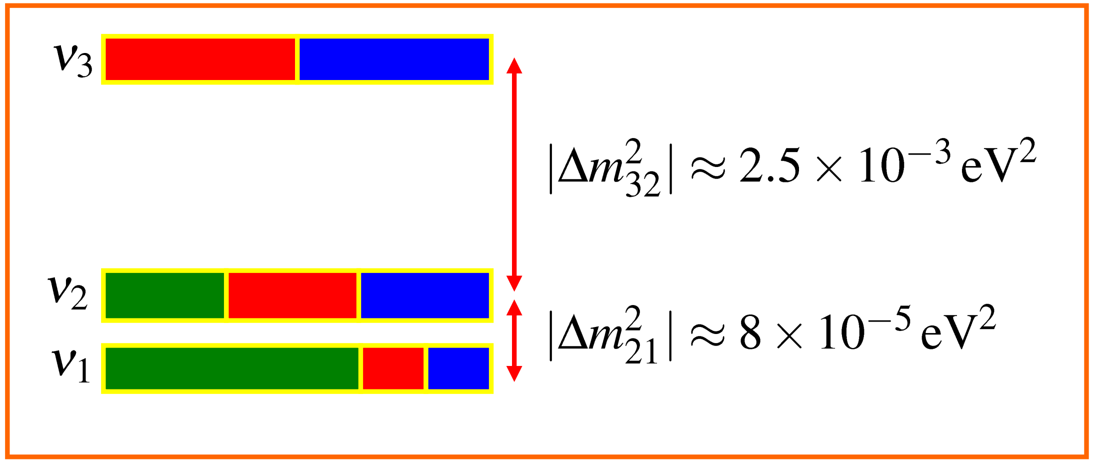
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \approx \begin{pmatrix} 0.85 & 0.53 & 0.1e^{i\delta}? \\ -0.37 & 0.60 & 0.71 \\ 0.37 & -0.60 & 0.71 \end{pmatrix}$$

★ **Have approximate expressions for mass eigenstates in terms of weak eigenstates:**

$$|\nu_3\rangle \approx \frac{1}{\sqrt{2}}(|\nu_\mu\rangle + |\nu_\tau\rangle)$$

$$|\nu_2\rangle \approx 0.53|\nu_e\rangle + 0.60(|\nu_\mu\rangle - |\nu_\tau\rangle)$$

$$|\nu_1\rangle \approx 0.85|\nu_e\rangle - 0.37(|\nu_\mu\rangle - |\nu_\tau\rangle)$$



Final Words: Neutrino Masses

- Neutrino oscillations require non-zero neutrino masses
- But only determine mass-squared differences – not the masses themselves
- No direct measure of neutrino mass – only mass limits:

$$m_\nu(e) < 2\,\mathrm{eV}; \quad m_\nu(\mu) < 0.17\,\mathrm{MeV}; \quad m_\nu(\tau) < 18.2\,\mathrm{MeV}$$

Note the e, μ, τ refer to charged lepton flavour in the experiment, e.g. $m_\nu(e) < 2\,\mathrm{eV}$ refers to the limit from tritium beta-decay

- Also from cosmological evolution infer that the sum

$$\boxed{\sum_i m_{\nu_i} < \text{few eV}}$$

★ 20 years ago – assumed massless neutrinos + hints that neutrinos might oscillate !
★ Now, know a great deal about massive neutrinos
★ But many unknowns: δ, mass hierarchy, absolute values of neutrino masses
★ Measurements of these SM parameters is the focus of the next generation of expts.