# Introduction to particle physics: Standard Model and beyond

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IFIC INSTITUT DE FÍSICA CORPUSCULAR

Lecture 4

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

ASTROPARTICLES Astroparticles and High Energy Physics Group

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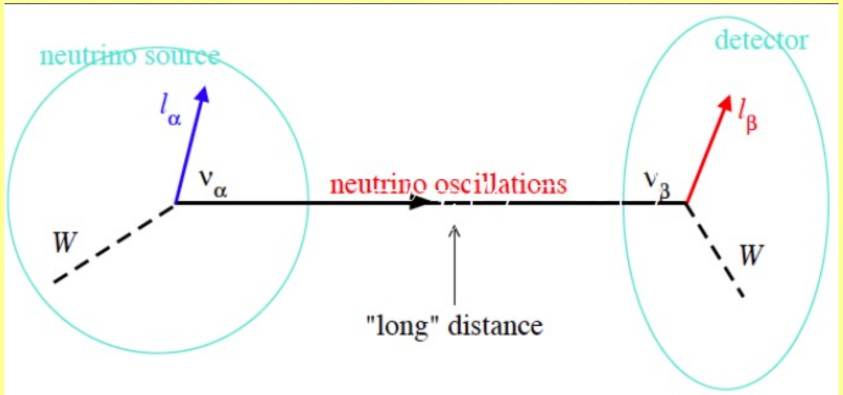
# Neutrino oscillations

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}}\bar{l}_\alpha \gamma^\mu P_L \nu_k U_{\alpha k} W_\mu^- - \frac{g}{\sqrt{2}}\bar{\nu}_k \gamma^\mu P_L l_\alpha \, U_{\alpha k}^* W_\mu^+ .$$

$$\nu_{\alpha L} = \sum_{i=1}^{3} U_{\alpha i}\nu_{iL}, \quad (\alpha = e, \mu, \tau),$$




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

| Production | Propagation | Detection |
| --- | --- | --- |
| $\lvert\nu_\alpha\rangle = \sum_j U_{\alpha j}^* \lvert\nu_j\rangle$ | $\nu_j : e^{-iE_j t}$ | $\langle\nu_\beta\rvert = \sum_j \langle\nu_j\rvert U_{\beta j}$ |
| coherent superposition of massive states | different propagation phases change $\nu_j$ composition | projection over flavour eigenstates |

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_j U_{\alpha j}^* \, U_{\beta j} e^{-i\frac{m_j^2}{2E}L} \right|^2$$

$$= \delta_{\alpha\beta} - 4\sum_{i>j} \mathfrak{Re}(U_{\alpha i}^* U_{\alpha j} U_{\beta i} U_{\beta j}^*) \sin^2\left(\frac{\Delta m_{ij}^2}{4E}L\right)$$

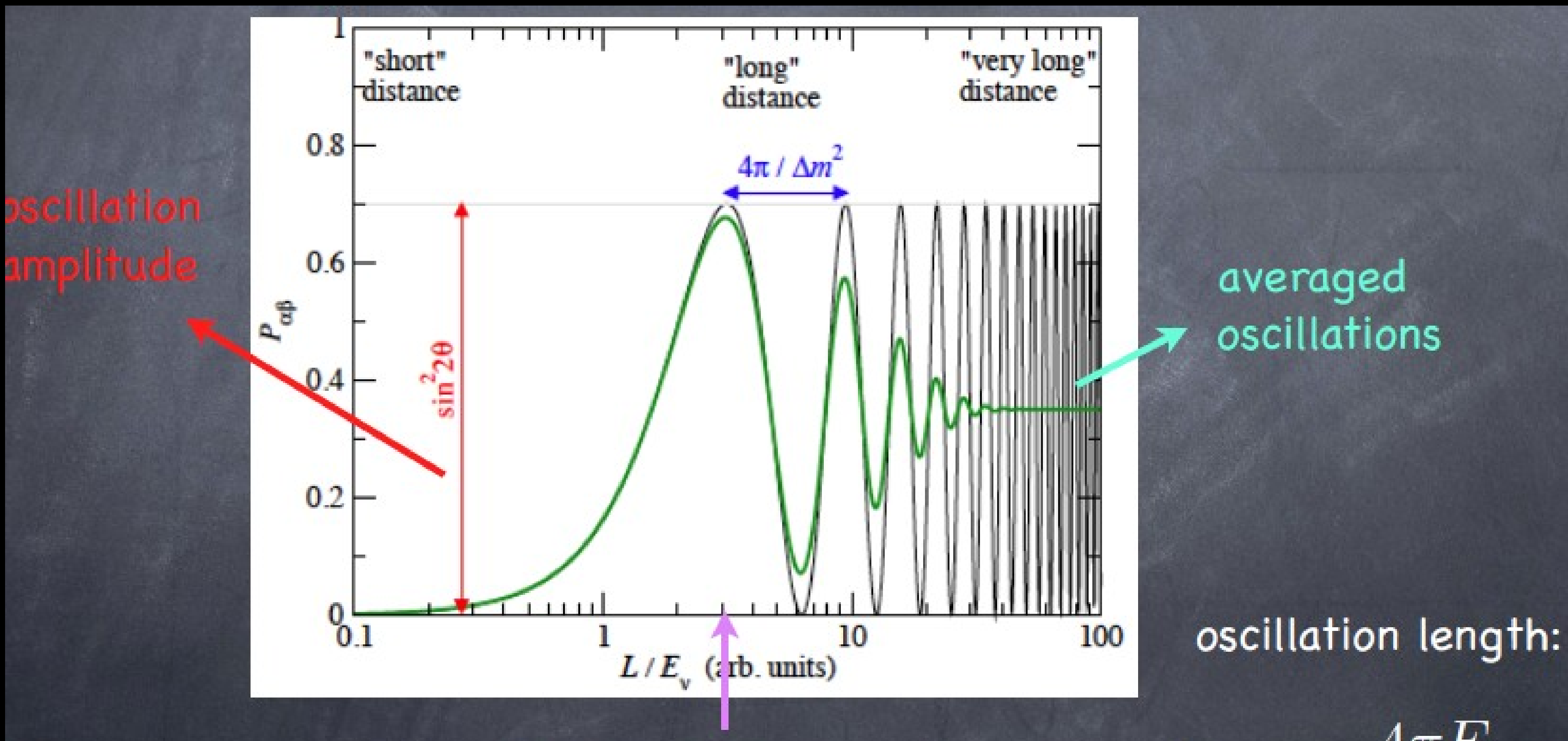
$$+2\sum_{i>j} \mathfrak{Im}(U_{\alpha i}^* U_{\alpha j} U_{\beta i} U_{\beta j}^*) \sin\left(\frac{\Delta m_{ij}^2}{2E}L\right)$$

where $E$ is the neutrino energy, $L$ is the distance traveled by neutrino, and $\Delta m_{ij} \equiv m_i^2 - m_j^2$ ($m_i$ being mass eigenvalues) are the mass squared differences. Here $\mathfrak{Re}$ and $\mathfrak{Im}$ denote real and imaginary parts.

## 2-neutrino oscilations

$$P_{\text{vacuum}}(\nu_e \to \nu_\mu) = \sin^2(2\theta)\ \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$\phi = \frac{\Delta m^2_{21} L}{4E} = 1.27 \frac{\Delta m^2_{21}[eV^2] L[km]}{E[GeV]}$$




first oscillation maximum:

oscillation length:

$$L_{osc} = \frac{4\pi E}{\Delta m^2}$$

| Experiment | | L (m) | E (MeV) | $\Delta m^2$ (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 | $10^5 - 10^6$ | $10^4$ | $10^{-2} - 10^{-3}$ |

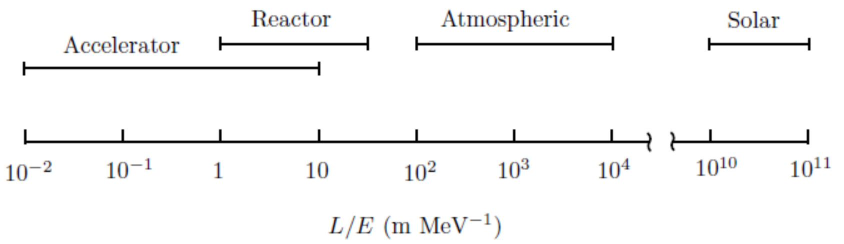
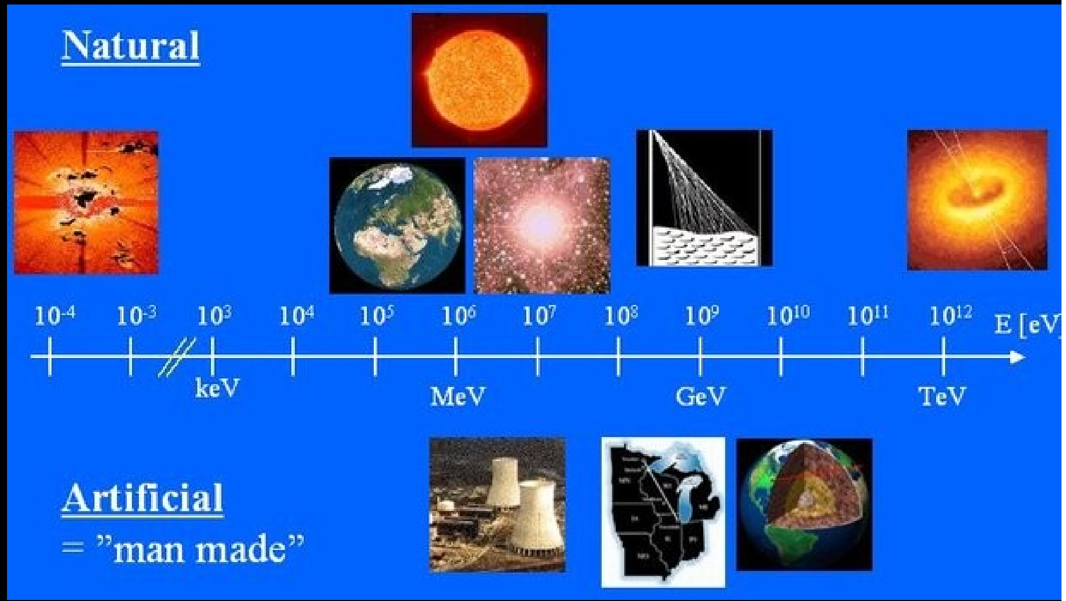
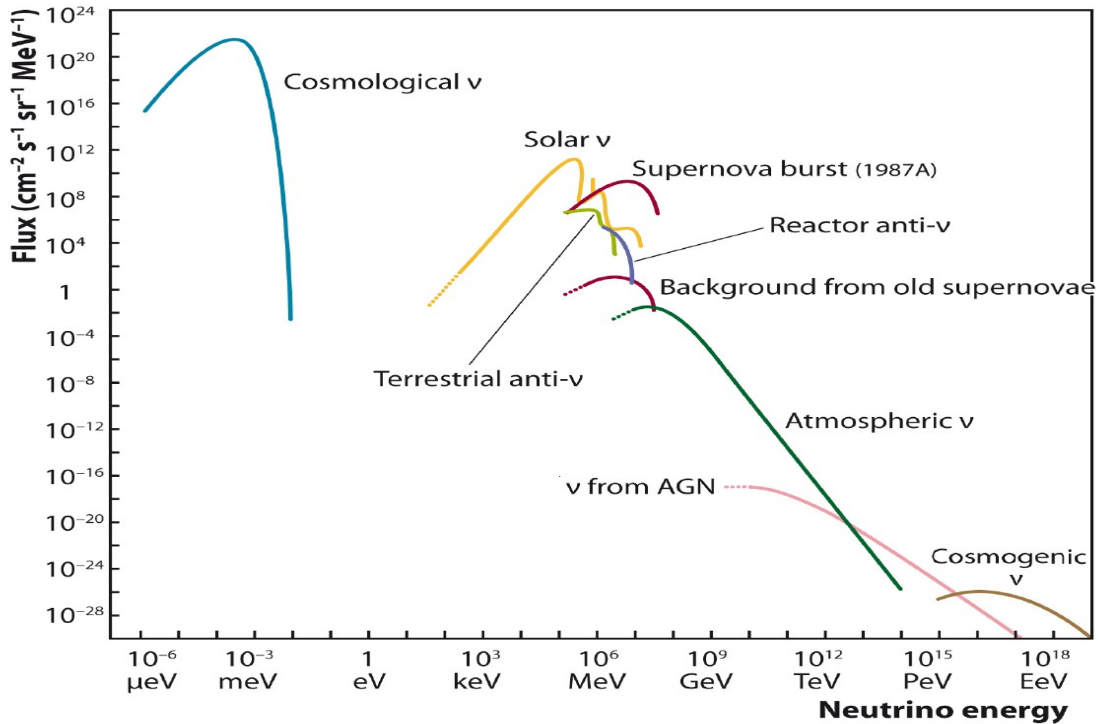
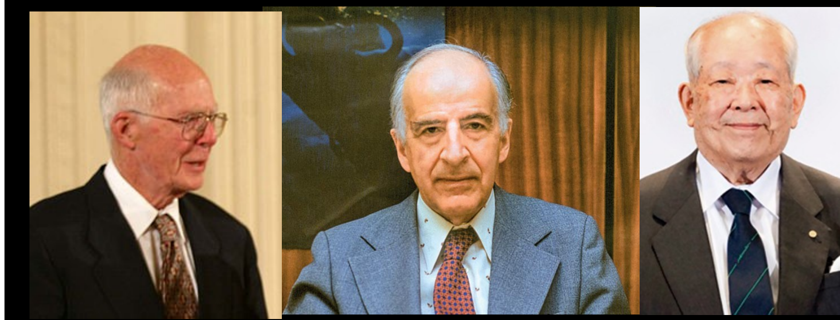



**Figure 4.3** Schematic illustration of the $L/E$ value characterizing various types of neutrino oscillation experiments.




# Let's turn to solar neutrinos



# OSCILLATIONS IN MATTER

$$V(x) = \sqrt{2} G_F N_e(x) \ ,$$

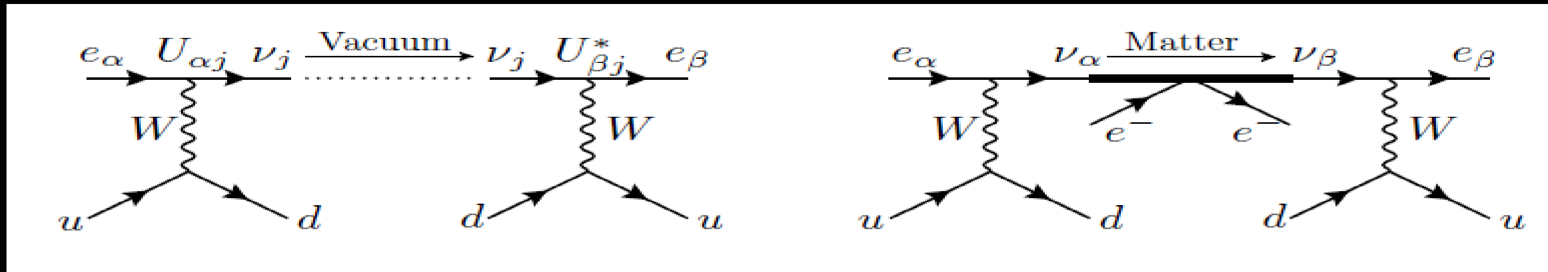
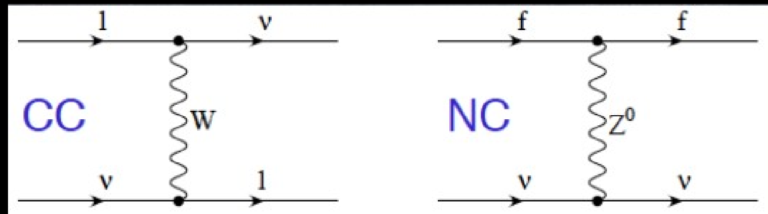
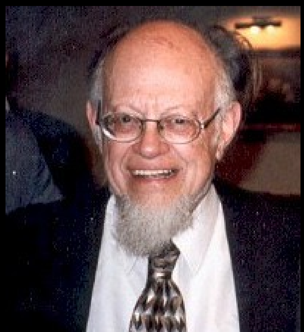



**Figure 4.1** Schematic illustration of neutrino oscillations in vacuo (left) and in matter (right).

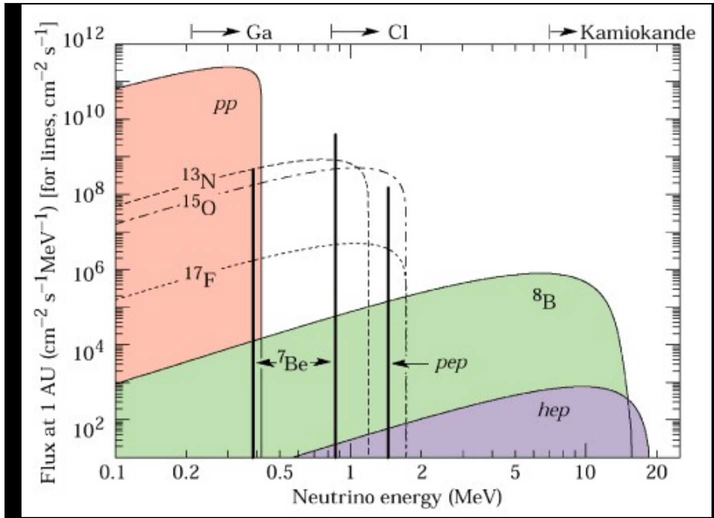



$$\cos 2\theta_m = \frac{\Delta m^2 \cos 2\theta - 2\sqrt{2}\, E G_F N_e}{\sqrt{\left(\Delta m^2 \cos 2\theta - 2\sqrt{2}\, E G_F\, N_e\right)^2 + \left(\Delta m^2 \sin 2\theta\right)^2}}$$

where $G_F$ is the Fermi constant, and $N_e(x)$ is the electron number density at $x$.



*MSW effect*



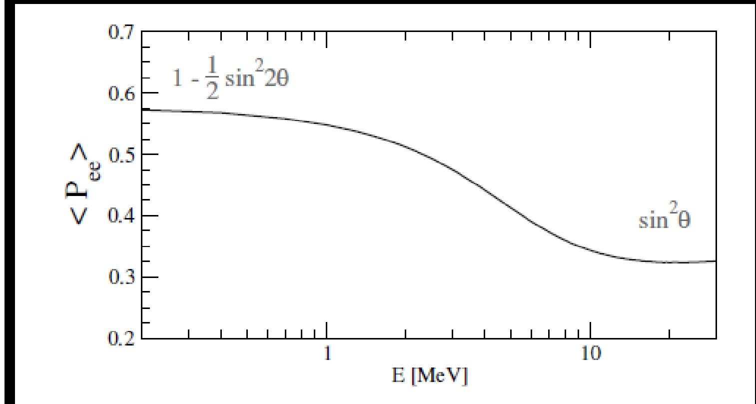




**Figure 4.5** Average $^8$B solar neutrino survival probability versus energy for best-fit oscillation parameters [83]. Matter effects are important for high-energy neutrinos, while low-energy neutrinos are suppressed as *in vacuo*. Courtesy of M. Tórtola.

**Homestake** ($E_\nu > 0.814$ MeV)

$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

**SAGE/GALLEX-GNO** ($E_\nu > 0.233$ MeV)

$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$

**Super-Kamiokade** ($E_e \gtrsim 5$ MeV)

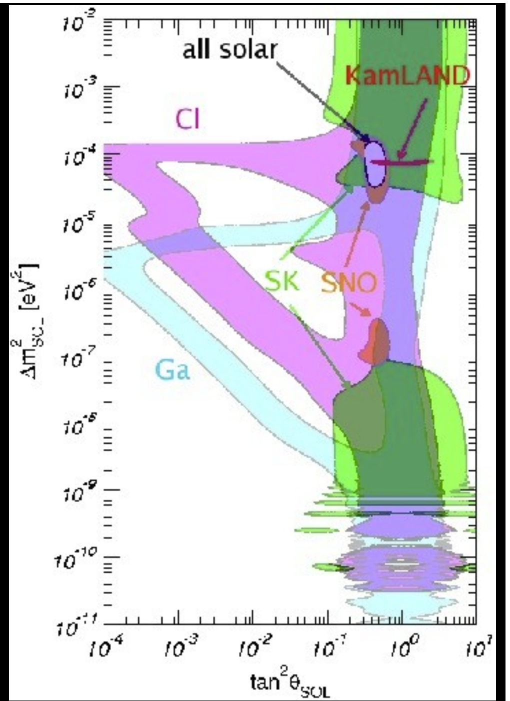
$\nu_x + e^- \rightarrow \nu_x + e^-$

**SNO** ($E_e \gtrsim 5$ MeV)

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

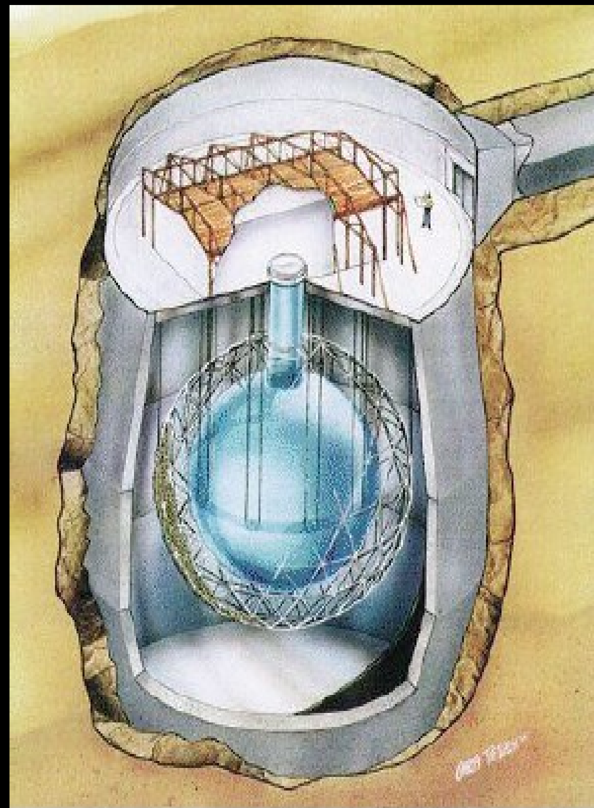
[NC] $\nu_x + d \rightarrow \nu_x + n + p$

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

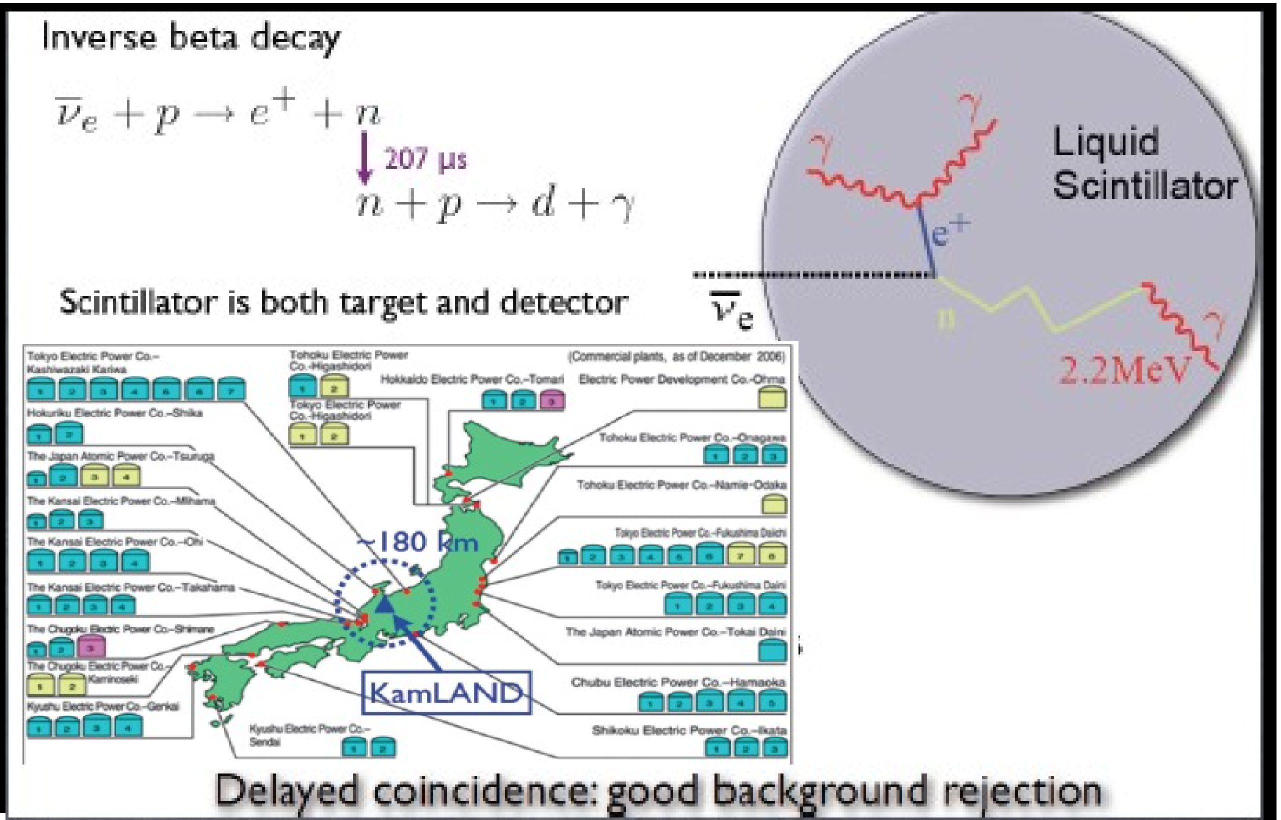



# SOLAR NEUTRINOS

| Experiment | Type | Method | Dates | Threshold (MeV) | Main Fluxes |
|---|---|---|---|---|---|
| Homestake Cl | radio | CC | 1968-2002 | 0.811 | $^8$B, $^7$Be |
| Kamiokande | active | ES | 1987-1995 | 7.0-9.0 | $^8$B |
| SAGE | radio | CC | 1990-now | 0.233 | pp, $^7$Be |
| GALLEX/GNO | radio | CC | 1991-2003 | 0.233 | pp, $^7$Be |
| Super-K | active | ES | 1996-now | 4.0-7.0 | $^8$B |
| SNO | active | ES/CC/NC | 1999-2006 | 4.0-7.25; 2.22(NC) | $^8$B |
| Borexino | active | ES | 2008-now | $\sim 0.8$ | $^7$Be, pep, $^8$B |



# REACTOR NEUTRINOS



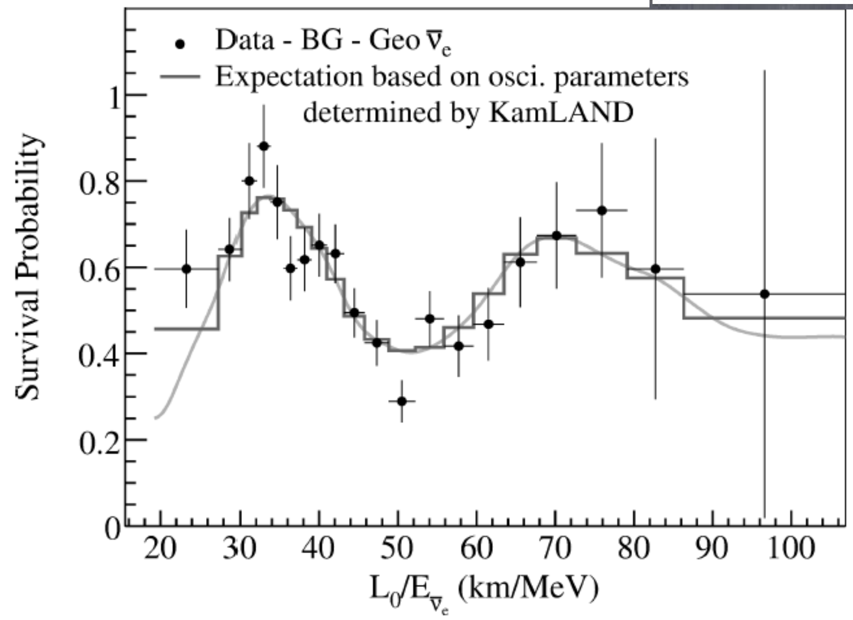
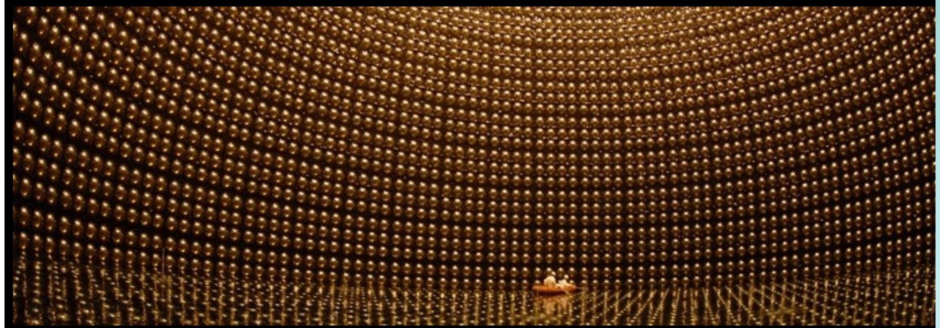
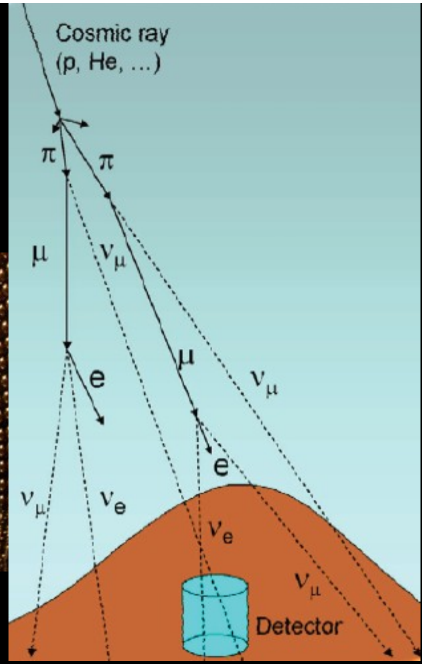
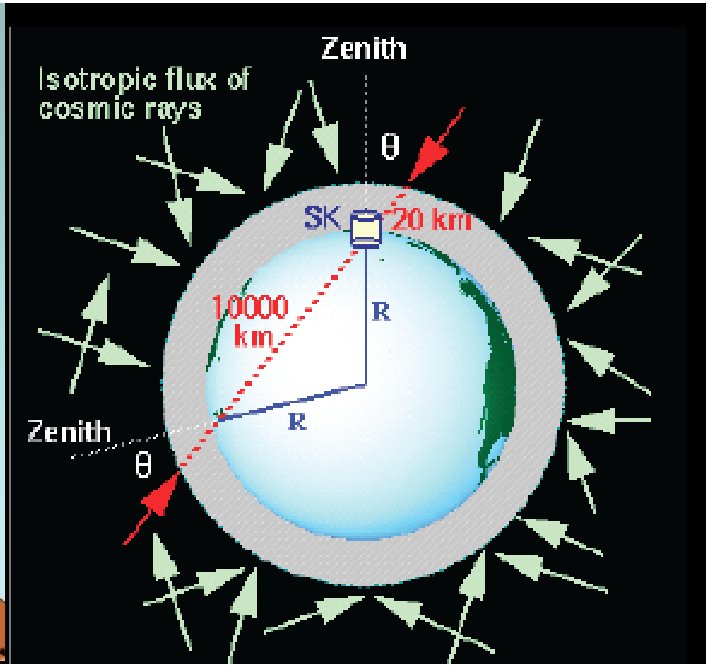



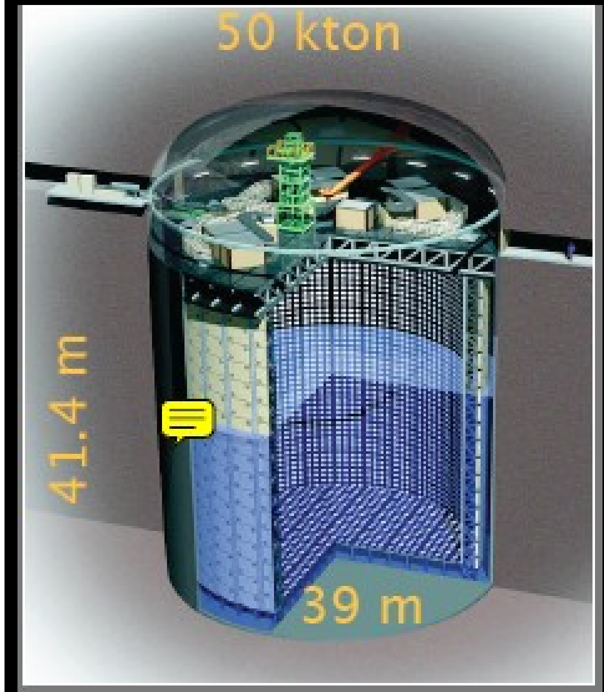

**Figure 4.8** Evidence for neutrino oscillation at the solar scale in the KamLAND reactor experiment, from Ref. [217].

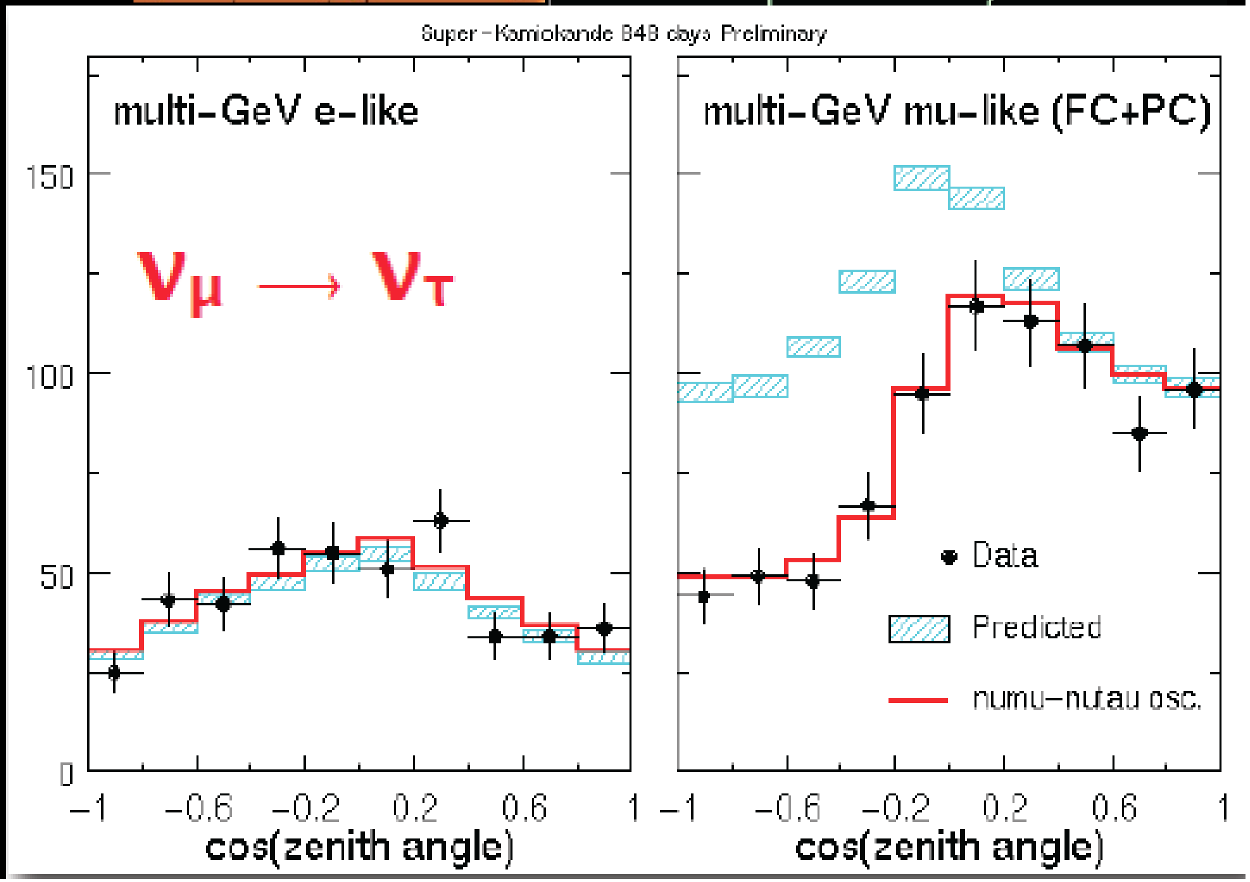
# *ATMOSPHERIC NEUTRINOS*

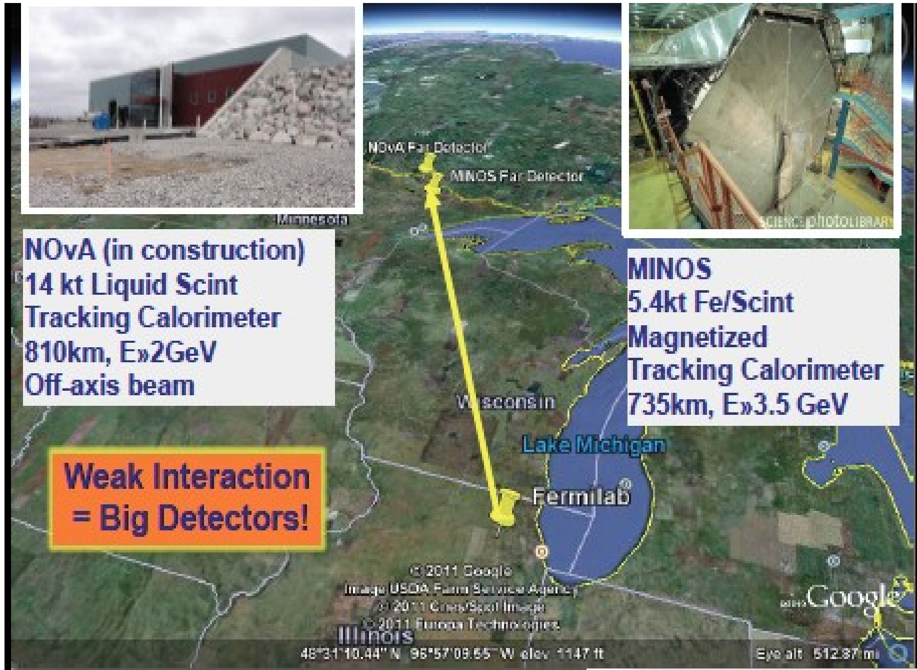


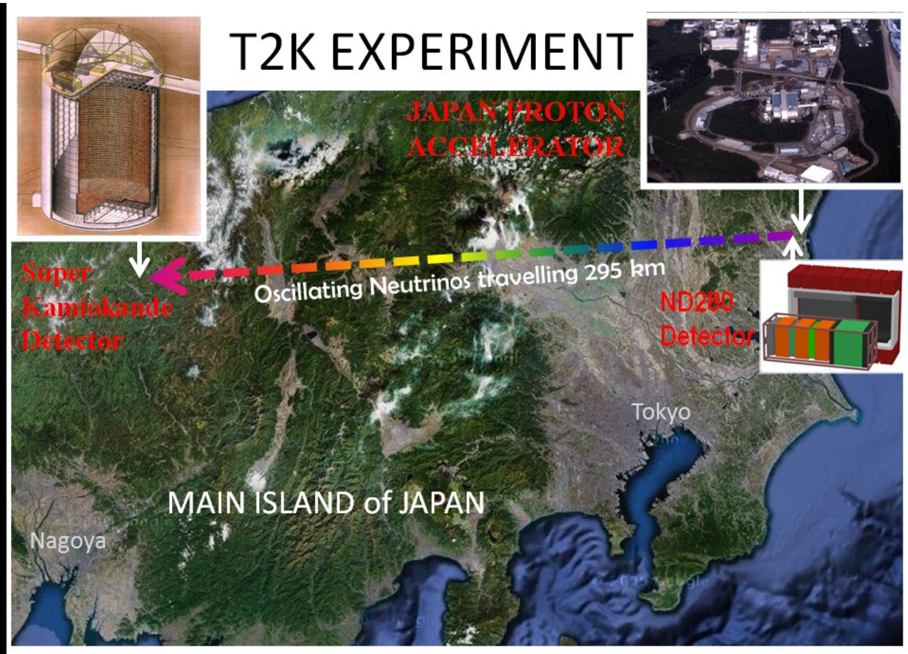





# *ACCELERATOR NEUTRINOS*

$$P(\nu_\mu \rightarrow \nu_\mu) = |\langle \nu_\mu | \nu_\mu(t) \rangle|^2 \simeq 1 - \sin^2(2\theta) \sin^2\left(1.27\,\Delta m^2_{32} \frac{L[\text{km}]}{E[\text{GeV}]}\right)$$

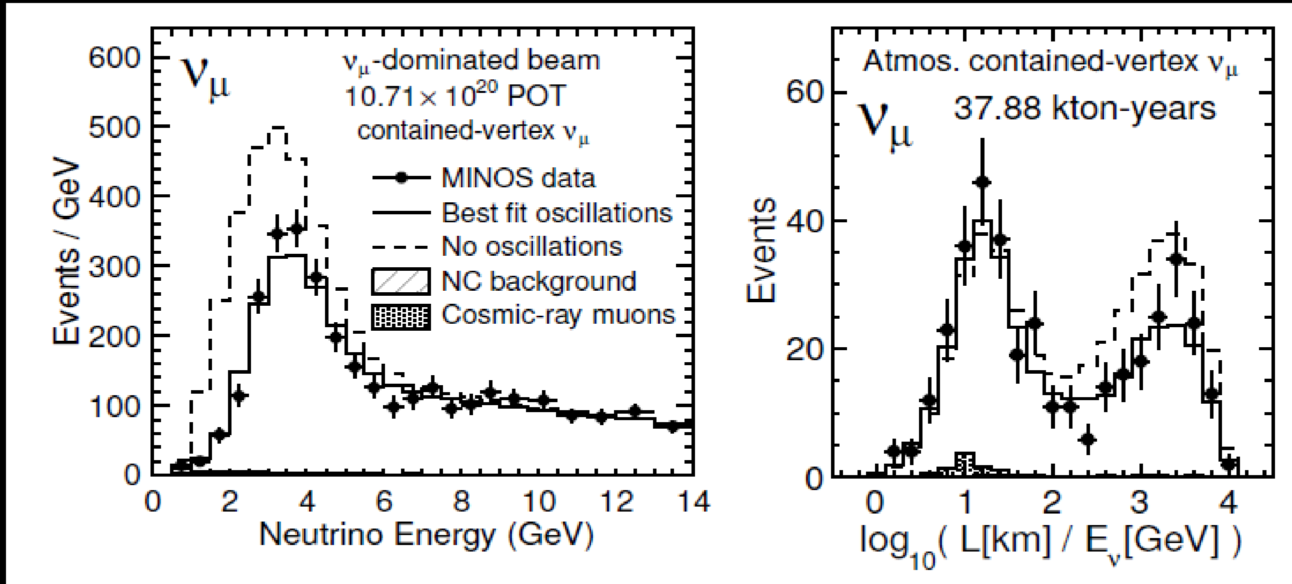
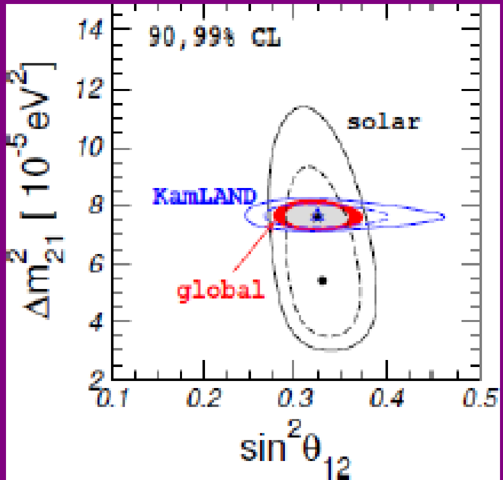
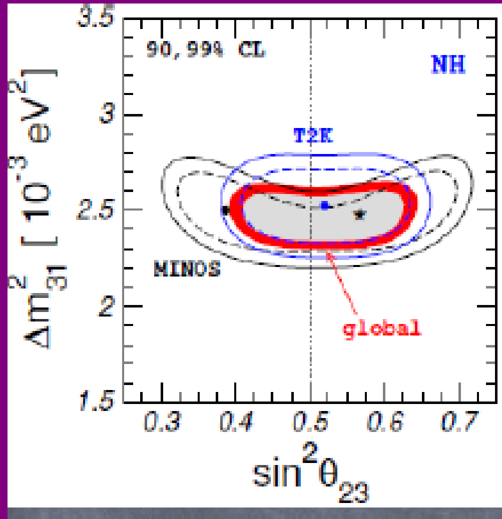


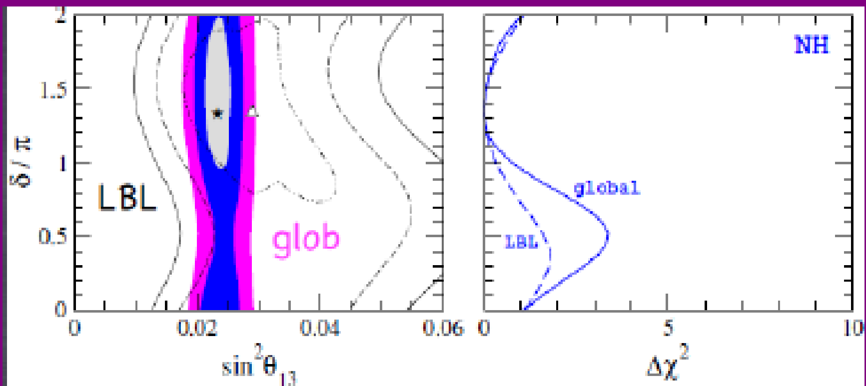

**Figure 4.10** Evidence for neutrino oscillation at the atmospheric scale in the MINOS accelerator experiment, from Ref. [233].

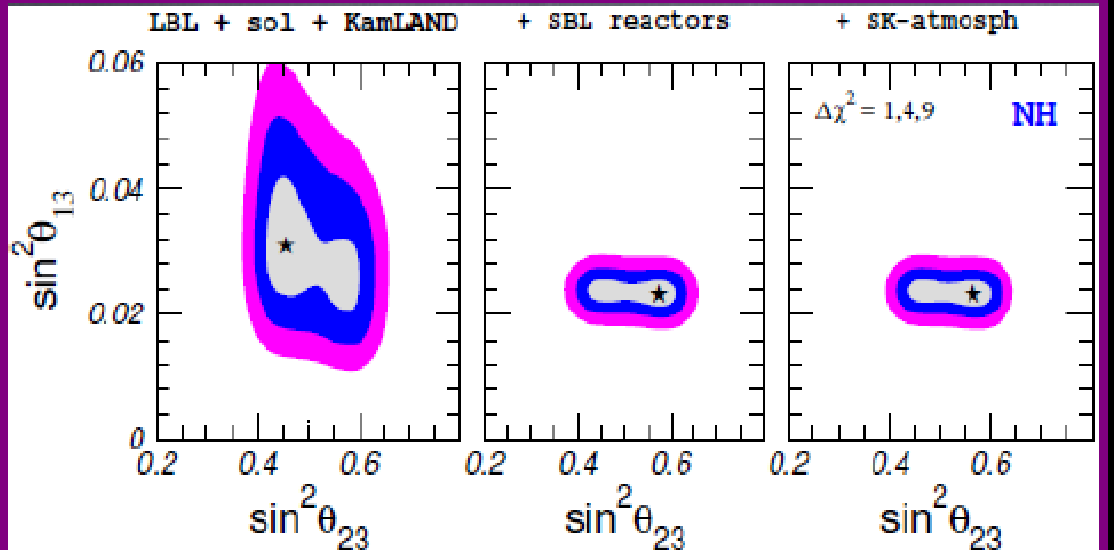
# Oscillations after nu2014

Forero, Tortola, JWFV arXiv:1405.7540



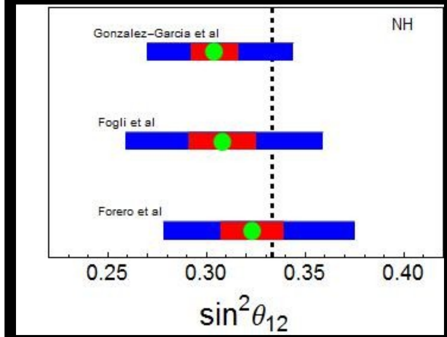



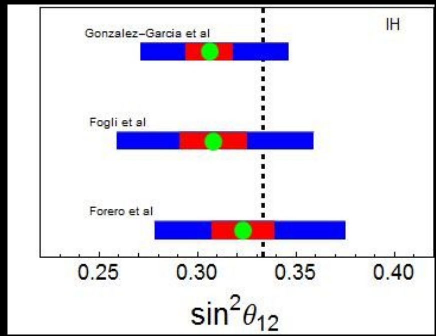

Double Chooz: 467.9 days [arXiv:1406.7763]

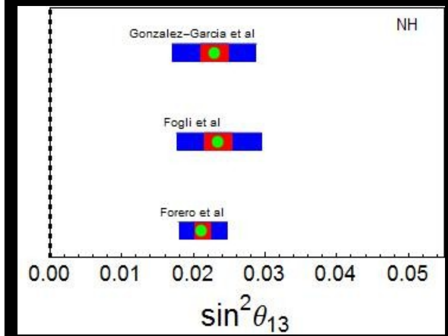
RENO: 800 days [talk by Seon-Hee Seo@ICHEP2014]

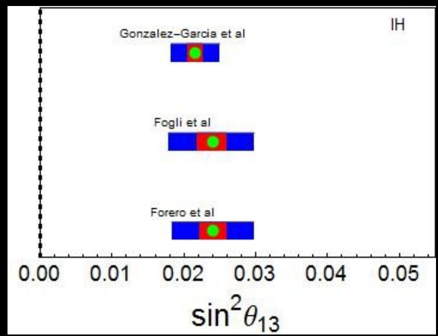
Daya Bay: 621 days of data (6AD + 8AD) [Talk by Chao Zhang@ICHEP2014]

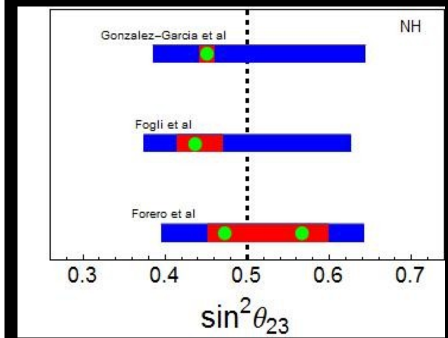
# NEUTRINO OSCILLATION PARAMETERS

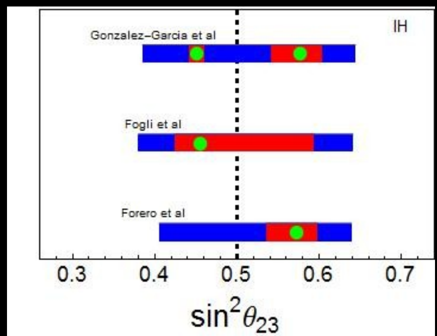


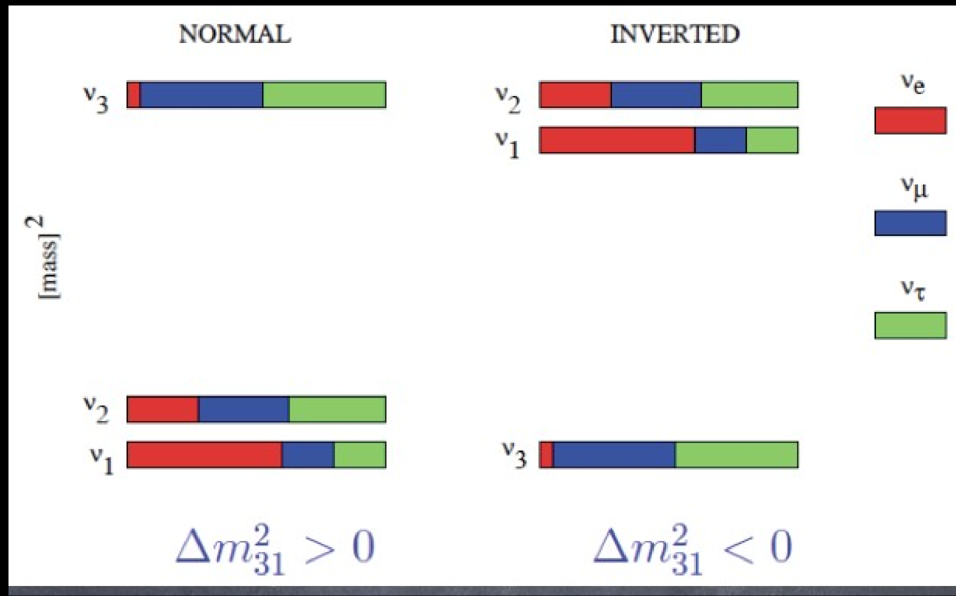



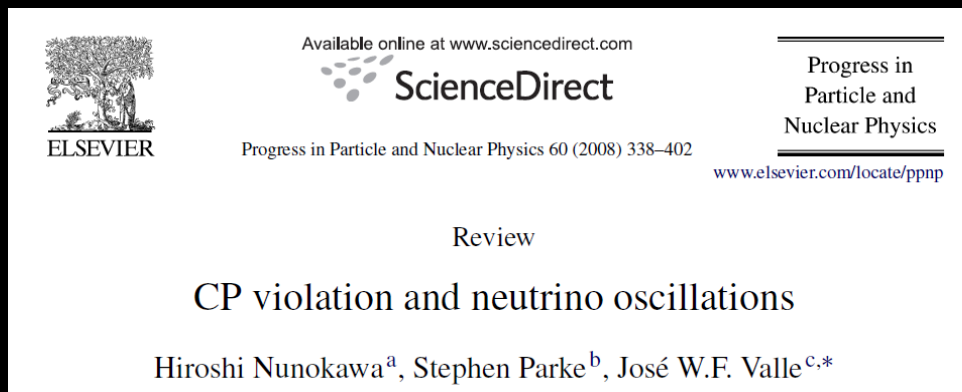




*Hint for max cp phase*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Progress in Particle and Nuclear Physics 60 (2008) 338–402

Progress in Particle and Nuclear Physics

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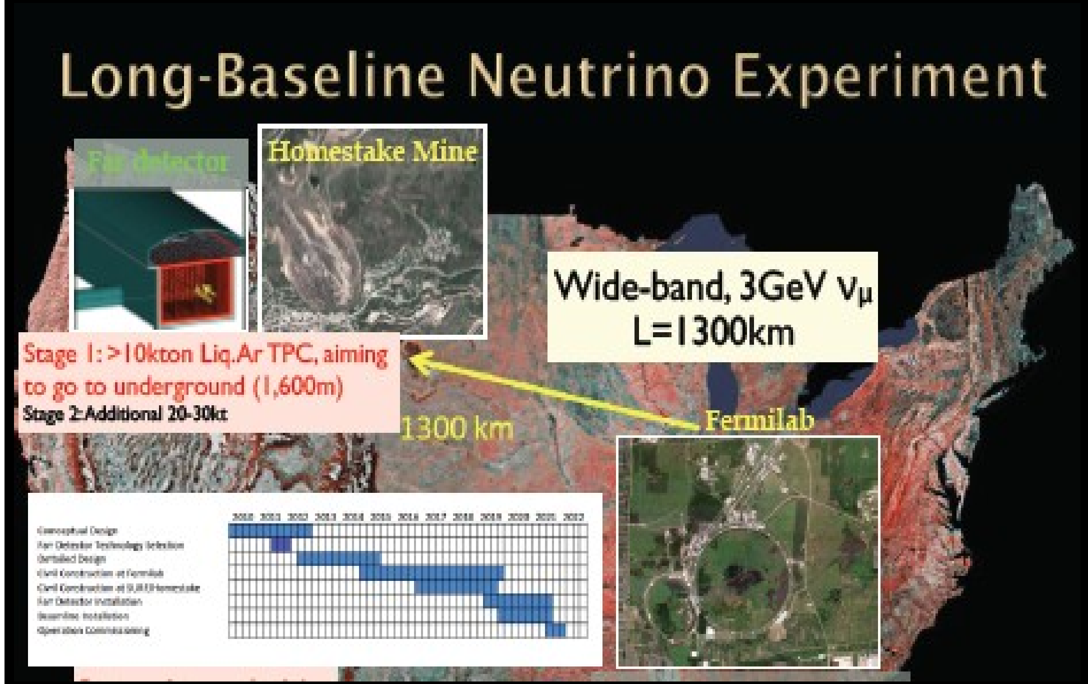
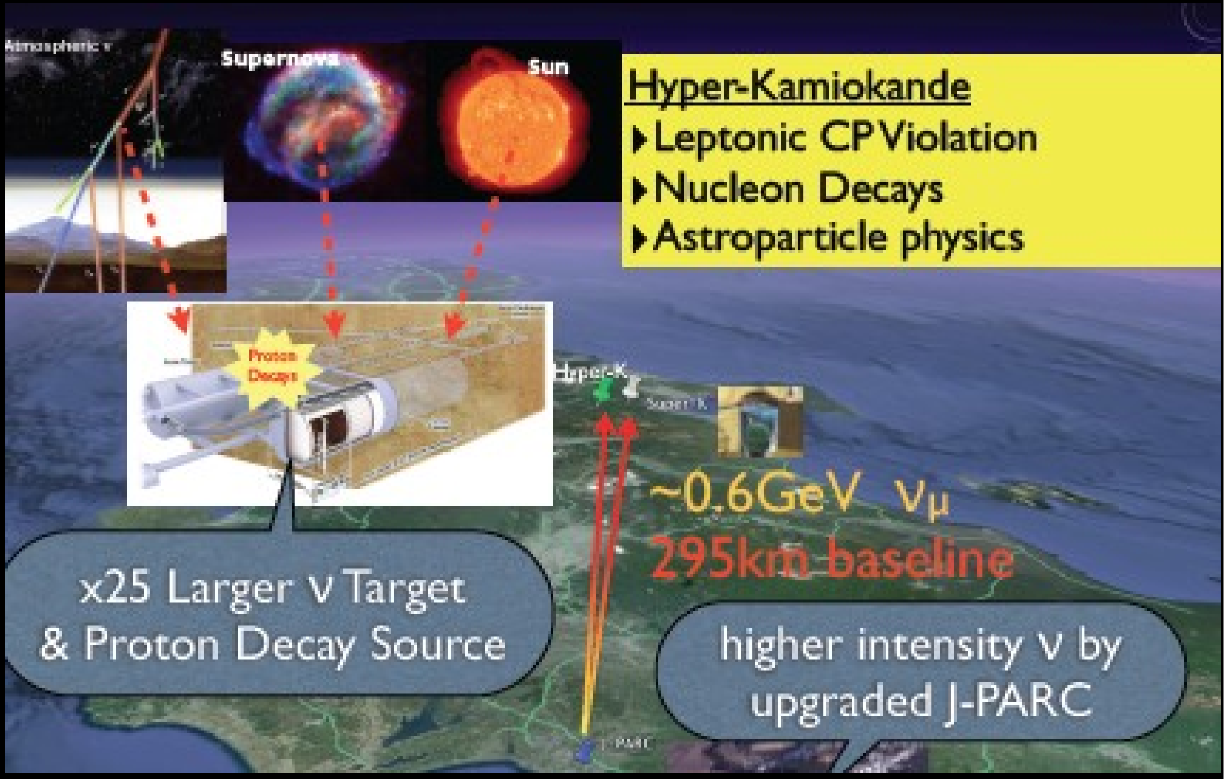
Review

CP violation and neutrino oscillations

Hiroshi Nunokawa[a], Stephen Parke[b], José W.F. Valle[c,*]

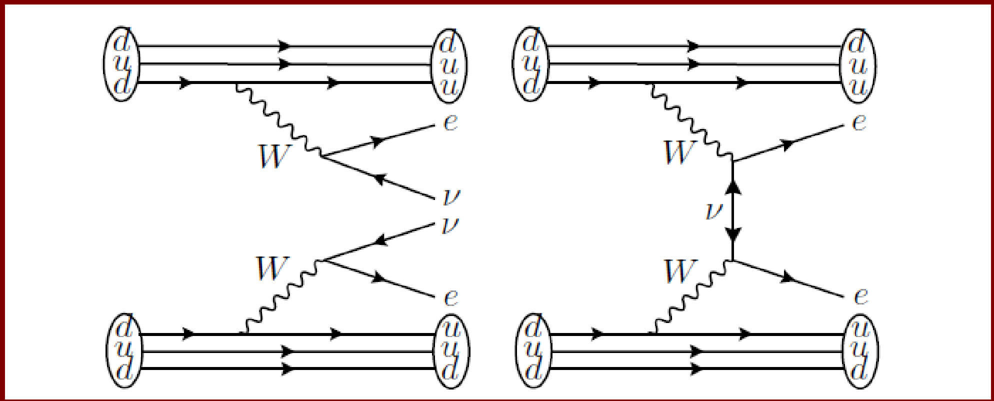
# TWO LBL PROPOSALS

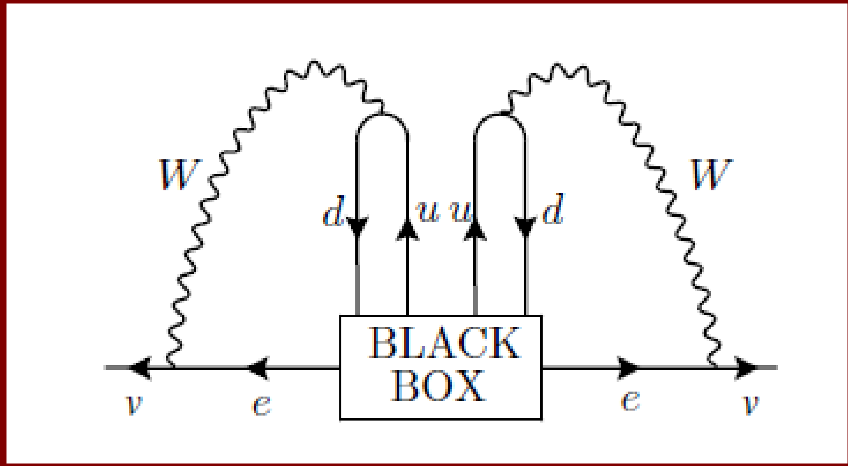


# Neutrinoless Double Beta Decay

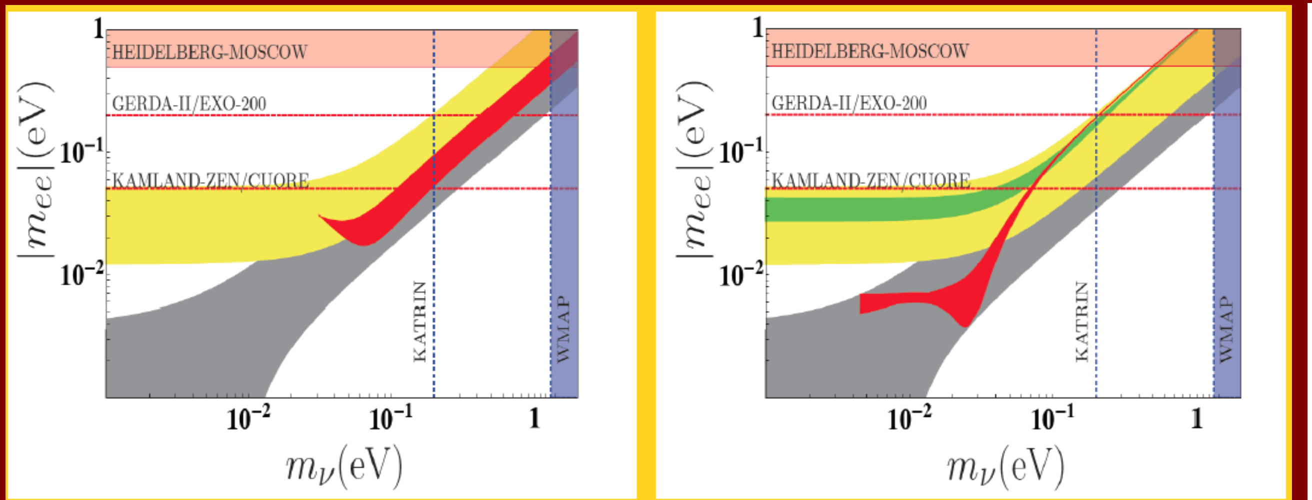
A.S. Barabash arXiv:1104.2714

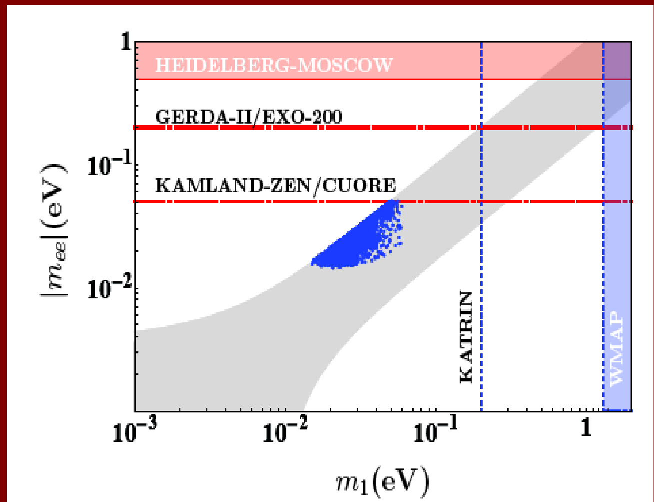



Schechter, JWFV 82
Lindner et al JHEP 1106 (2011) 091

Family symmetry dependent lower bound




Dorame et al
NPB861 (2012) 259-270

PhysRevD.86.056001

King et al Phys. Lett. B 724 (2013) 68

# OPEN ISSUES IN NEUTRINO PHYSICS

- What is the origin of neutrino mass? Why are neutrino masses so small ? Is it a remnant from unification ? Or does it follow from weak-scale physics ? Is this related to the origin of parity violation in the weak interaction ?

- Are neutrinos Dirac or Majorana particles? Does neutrinoless double beta decay take place?

- how to explain the pattern of neutrino mixing?

- Is CP violated in the lepton sector?

- Do lepton flavour violating processes, *e.g.*, $\mu \to e + \gamma$ , $\mu \to 3e$ , $\tau \to 3\mu$ *etc.* , occur and at what rates? $\mu \to e$ conversion oin nuclei, etc Does lepton flavour violation take place in the domain of high energy processes?