Neutrino physics using Nuclear Reactors

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Outline

- Theory:
  - Neutrino masses in the SM
  - Mixing Matrix
  - Neutrino Oscillations
- Experiment:
  - Present status
  - Summary of experimental results
  - Reactor experiments
  - Measurement of θ_{13}
  - 1rst generation experiments
  - 2nd generation experiments
- Conclusions

Theory: ν masses in the SM

- Masses for ν ’s in the SM are generated in the same way that for charged leptons and quarks (Dirac neutrinos):

$$\bar{\Psi}_i^L(x)\Phi(x)M_{ij}\psi_j^R(x)+\bar{\psi'}_i^R(x)\tilde{M}_{ij}\tilde{\Phi}^\dagger(x)\Psi_j^L(x)+c.c.$$

$$\Psi^L(x)=\left(\begin{array}{c}\nu_l\\ l\end{array}\right)_{L,i}$$

$$\Phi(x)=\left(\begin{array}{c}\phi^+\\ \phi^0\end{array}\right)$$

$$\psi^L(x)=\frac{1-\gamma_5}{2}\psi(x)$$

$$\begin{array}{rcl}\psi_i'^R(x)&=&\nu_i^R(x)\\ \psi_i^R(x)&=&l_i^R(x)\end{array}$$

$$\tilde{\Phi}(x)=\left(\begin{array}{c}\phi^0\\ \phi^-\end{array}\right)$$

$$\psi^R(x)=\frac{1+\gamma_5}{2}\psi(x)$$

- Once in the unitary gauge and after spontaneous symmetry breaking ($SU(2)_{ch} \times U(1)_Y \rightarrow U(1)_{em}$), the mass terms read

$$\bar{\psi}_i^L(x) M_{ij} \psi_j^R(x) + \bar{\psi}'^R_i(x) \tilde{M}_{ij} \psi'^L_j(x) + c.c.$$

$$\tilde{\Phi}(x) = \begin{pmatrix} \rho + \sigma(x) \\ 0 \end{pmatrix}$$

Unitary Gauge

- M and $\tilde{M}$ are arbitrary complex 3 X 3 matrices.

$$A_L \; M \; B_R^{-1} = M_D$$

Mass matrix for charged leptons

$$A_R \; \tilde{M} \; B_L^{-1} = \tilde{M}_D$$

Mass matrix for neutrinos

Diagonal mass matrices

Mixing Matrix

- Physical fields:

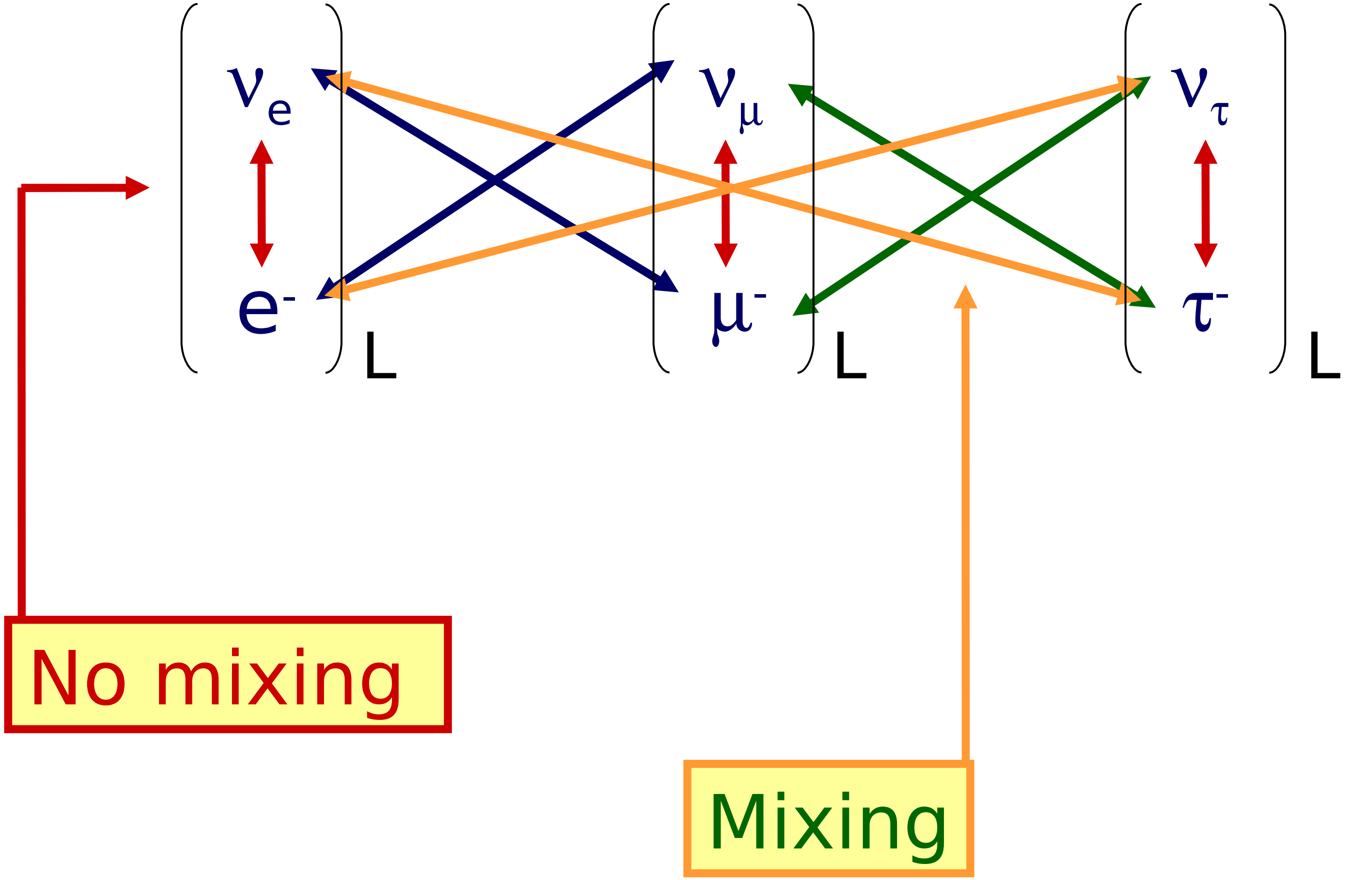
$$\begin{array}{rcl} l^{R}_{i}(x) & \rightarrow & B_R\, l^{R}_{i}(x) \\ \bar{l}^{L}_{i}(x) & \rightarrow & \bar{l}^{L}_{i}(x)\; A_L^{-1} \\ \nu^{R}_{i}(x) & \rightarrow & B_L\, \nu^{R}_{i}(x) \\ \bar{\nu}^{L}_{i}(x) & \rightarrow & \bar{\nu}^{l}_{i}(x)\; A_R^{-1} \end{array}$$

- Charged Currents:

$$J^{\mu}_{cc} \propto \bar{l}^{L}_{i}(x)\;\gamma^{\mu}\;\nu^{L}_{i}(x) \longrightarrow J^{\mu}_{cc} \propto \bar{l}^{L}_{i}(x)\;\gamma^{\mu}\;(A_L^{-1}A_R)_{i,j}\nu^{L}_{j}(x)$$

$$A_L^{-1}A_R = U_{PMNS}$$

Pontecorvo-Maki-Nakagawa-Sakata mixing matrix



$$\begin{pmatrix}\nu_e \\ e^-\end{pmatrix}_L \quad \begin{pmatrix}\nu_\mu \\ \mu^-\end{pmatrix}_L \quad \begin{pmatrix}\nu_\tau \\ \tau^-\end{pmatrix}_L$$

No mixing

Mixing

$U_{PMNS} \in SU(3)$

- **Three angles**
- **One phase**

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Effect of the mixing matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_1c_3 & c_1s_3 & s_1e^{-i\delta} \\ -c_2s_3 - s_1s_2c_3e^{i\delta} & c_2c_3 - s_1s_2s_3e^{i\delta} & c_1s_2 \\ s_2s_3 - s_1c_2c_3e^{i\delta} & -s_2c_3 - s_1c_2s_3e^{i\delta} & c_1c_2 \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{array}{ccc} \theta_1 = \theta_{13} & \theta_2 = \theta_{23} & \theta_3 = \theta_{12} \\ c_i = \cos\theta_i & s_i = \sin\theta_i & i = 1; 2; 3 \end{array}$$

Then the weak eigenstates $|\nu_l\rangle$ are a linear superposition of the mass eigenstates $|\nu_i\rangle$

ν oscillations

Weak eigenstates $|\nu_l\rangle$ are a linear superposition of mass eigenstates $|\nu_i\rangle$

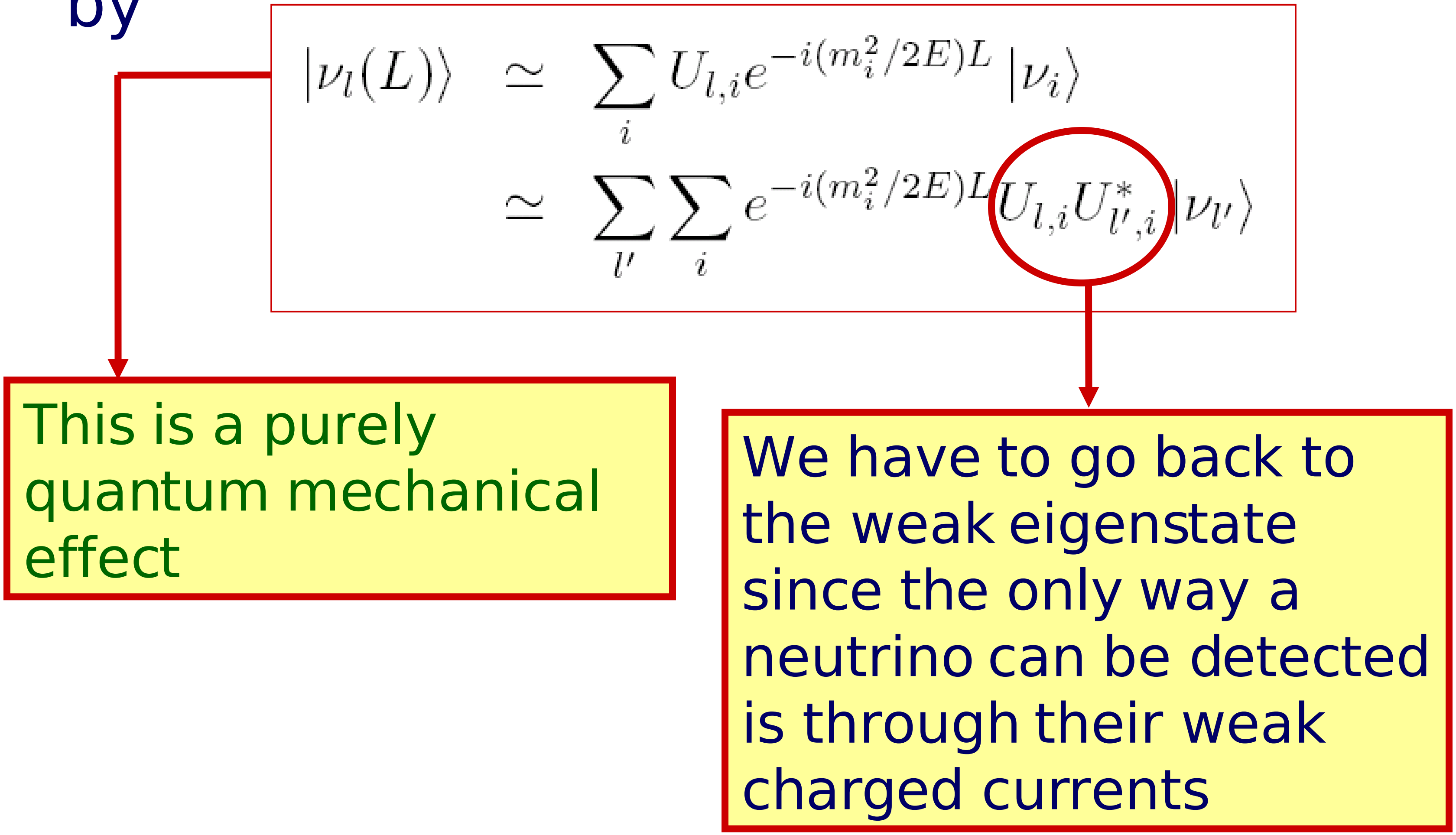
$$\boxed{|\nu_l\rangle = \sum_i U_{l,i}\,|\nu_i\rangle}$$

The mass eigenstate propagates according to

$$\boxed{|\nu_i(t)\rangle = e^{-i(E_i t - p_i L)}\,|\nu_i(0)\rangle \simeq e^{-i(m_i^2/2E)L}\,|\nu_i(0)\rangle}$$

where L=flight path and $m_i << p_i$, L

A neutrino that was created as at L=0 as a weak eigenstat $|\nu_l\rangle$, at L will be described by



$$\begin{aligned} |\nu_l(L)\rangle &\simeq \sum_i U_{l,i} e^{-i(m_i^2/2E)L} \, |\nu_i\rangle \\ &\simeq \sum_{l'} \sum_i e^{-i(m_i^2/2E)L} U_{l,i} U^*_{l',i} |\nu_{l'}\rangle \end{aligned}$$

This is a purely quantum mechanical effect

We have to go back to the weak eigenstate since the only way a neutrino can be detected is through their weak charged currents

The probability for the l → l’ transition is

$$\begin{aligned} P(\nu_l \rightarrow \nu_{l'}) \ &= \ \left|\sum_i e^{-i(m_i^2/2E)L} U_{l,i} U^*_{l',i}\right|^2 \\ & \sum_i \left|U_{l,i} U^*_{l',i}\right| + \mathcal{R} \sum_i \sum_{i \neq j} \\ & \times U_{l,i} U^*_{l',i} U^*_{l,j} U_{l',j} e^{i|m_i - m_j|^2 L/2p} \end{aligned}$$

$P(\nu_l \rightarrow \nu_{l'}) \neq 0$ if at least one of the $m_i \neq 0$ and at least one nondiagonal matrix element of the matrix U is $\neq 0$

$P(\nu_l \rightarrow \nu_{l'})$ is an oscillating function of the distance L

$|m_i - m_j|^2$ → Oscillation length

U → oscillation amplitude

CP violation ?

Yes if

$$P(\nu_l \rightarrow \nu_{l'}) \neq P(\bar{\nu}_l \rightarrow \bar{\nu}_{l'})$$

Magnitude of CP violation characterized by

$$\begin{aligned} & P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) - P(\nu_\mu \rightarrow \nu_e) \\ = \quad & -\left[P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau) - P(\nu_\mu \rightarrow \nu_\tau)\right] \\ = \quad & -\left[P(\bar{\nu}_e \rightarrow \bar{\nu}_\tau) - P(\nu_e \rightarrow \nu_\tau)\right] \\ = \quad & -4c_1^2 s_1 c_2 s_2 c_3 s_3 \sin\delta \left[\sin\Delta_{12} + \sin\Delta_{23} + \sin\Delta_{31}\right] \end{aligned}$$

$\Delta_{ij}=(m_i^2-m_j^2)\mathrm{x}L/2E$

CP violation is observable only if all three masses are different and all three angles are non-vanishing

Experiment: present status

- Atmospheric neutrino anomaly:
  - Cosmic rays impinging on H and O at the top of the earth's atmosphere produce mostly pions which decay through $\pi^- \to \mu^- \nu_\mu$; $\mu^- \to e^- \nu_e \nu_\mu$ (and c.c.).
  - After the full development of the decay chains, it is expected a **$\nu_\mu:\nu_e=2:1$ ratio**. This ratio is essentially independent of the neutrino production processes.
  - The **measured $\nu_\mu:\nu_e$ ratio is only about 60%** of the expected value (result confirmed by at least 4 detectors).

- Best explanation → Neutrino masses

- Preferred scenario: $\nu_\mu \to \nu_\tau$ oscillation

→ **Δm^2_{23}; $\sin^2(\theta_{23})$**

- However, it is not clear that $\nu_\mu \to \nu_e$ can be fully excluded…

- Missing solar neutrinos:
  - The Sun produces an intense flux of ν_e as a by-product of the fusion reactions that generate solar power.
  - Solar structure and fusion reactions inside the Sun are well understood → energy spectrum of neutrinos can be confidently predicted.
  - 7 experiments have been measuring solar ν flux → All of them reported a deficit !
  - The only viable explanation of the deficit appears to be ν oscillations (supported at the 3**σ** level).

- Best explanation → Neutrino masses

- **Δm^2_{12}; $\sin^2(\theta_{12})$** ($\nu_e \rightarrow \nu_\mu$ oscillation)

- Two solutions:

  Δm^2_{12} $\approx 10^{-5}$ eV^2 and

  ✓ SMA → $\sin^2(2\theta_{12}) \approx 10^{-2}$

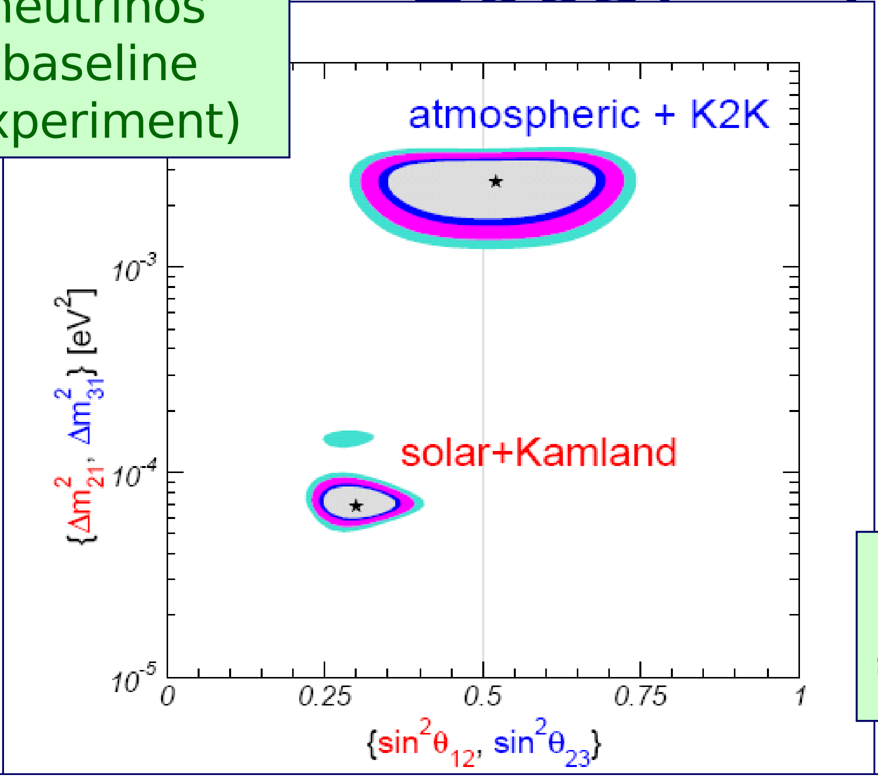
  ✓ LMA → $\sin^2(2\theta_{12}) \geq 0.5$

- Liquid Scintillator Neutrino Detector (LSND):
  - Appearance experiment: ν_μ coming from π and μ decays at rest, ν_μ coming from π decays in flight.
  - Evidence for $\nu_\mu \rightarrow \nu_e$ oscillations
  - Evidence for $\nu_\mu \rightarrow \nu_e$ oscillations (with limited statistics)
  - Claiming evidence for sterile neutrinos

Results not confirmed
by other experiments !

Summary of experimental results (~ 2005) - I

Atmospheric neutrinos + K2K (large baseline accelerator experiment)



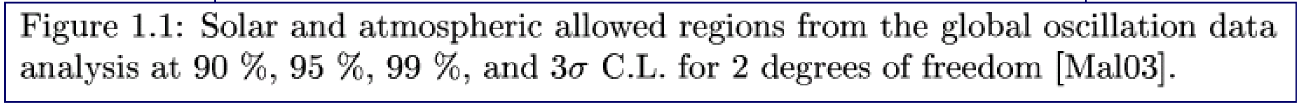


Figure 1.1: Solar and atmospheric allowed regions from the global oscillation data analysis at 90 %, 95 %, 99 %, and 3σ C.L. for 2 degrees of freedom [Mal03].

$|\Delta m^2_{32}| = (2\ ^{+1.0}_{-0.7}) \times 10^{-3}$ eV^2

$\sin^2(2\theta_{32}) = 1.0\ ^{+0.0}_{-0.2}$

Most solar data + KamLand reactor experiment

→

$\Delta m^2_{21} = (7\ ^{+2.0}_{-3.0}) \times 10^{-5}$ eV^2

$\sin^2(2\theta_{12}) = 0.8\ ^{+0.2}_{-0.2}$

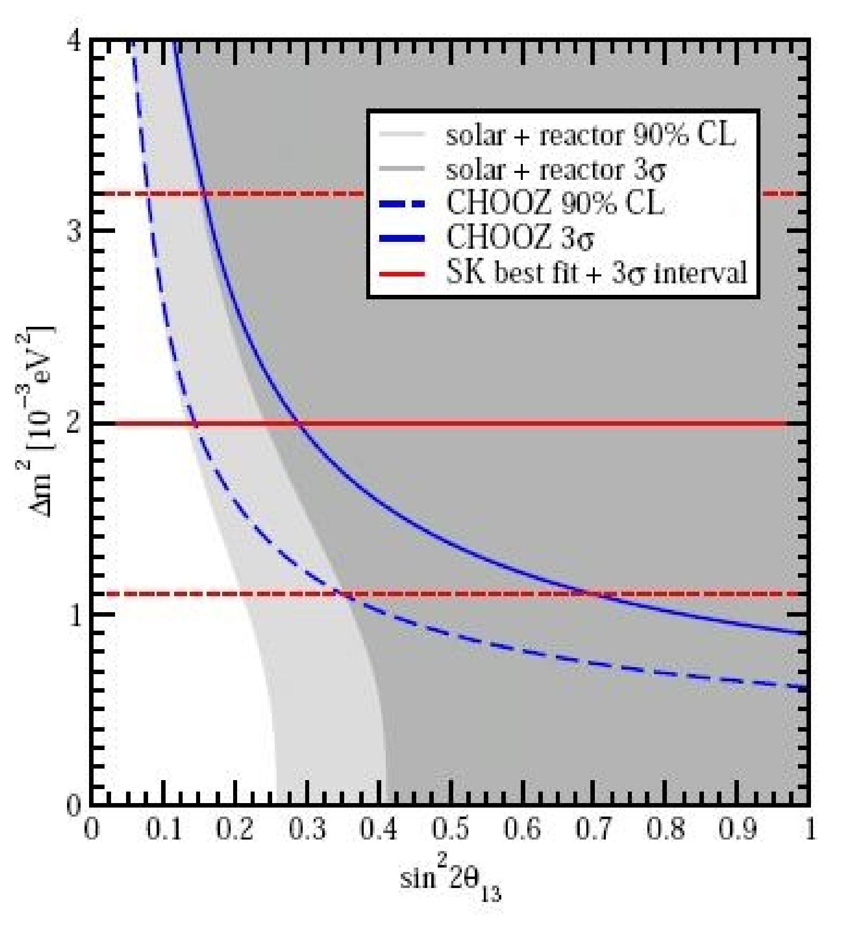
Summary of experimental results (~ 2005) - II

- Large mixing angle solution confirmed (LMA)

→ δ accessible if $\boldsymbol{\theta_{13}}$ not too small…

- LSND results not confirmed (almost excluded).

- $\sin^2(2\theta_{13}) < 0.16$ assuming $|\Delta m^2_{32}| = 2.0\text{x}10^{-3}\ \text{eV}^2$ (CHOOZ) (result strongly correlated with
- $|\Delta m^2_{32}|$). $\Delta m^2_{31} = 2.0\text{x}10^{-3}\ \text{eV}^2$.



Reactor experiments

- Nuclear reactors are an isotropic source of $\bar{\nu}_e$ coming from the fission products.
- The reactor $\bar{\nu}$ spectrum is well known (if the nuclear fuel composition is well known…)
- Very low cost as compared to accelerator neutrino experiments.
- The energy of the $\bar{\nu}_e$ is in the range of a few MeV 's, then they cannot produce μ's or τ's (which could subsequently produce ν_μ's or ν_τ's).

- Given the low energy of the $\bar{\nu}_e$, it is possible to measure the survival probability P($\bar{\nu}_e \rightarrow \bar{\nu}_e$)

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \, \sin^2(\Delta m^2_{31} L/4E)$$

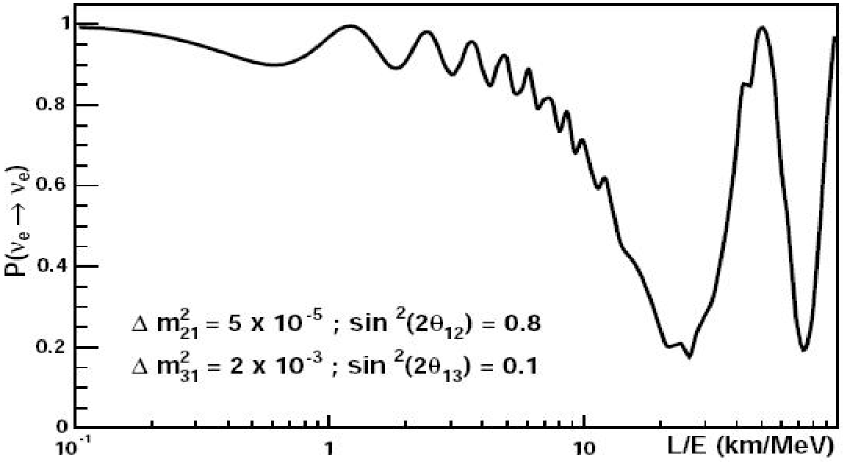


Figure 3: Probability of ν_e disappearance versus L/E for θ_{13} at its current upper limit

- Measurement free of ambiguities associated with matter effects and mass hierarchy and CP violating phase.

mass hierarchy

is $m_1 < m_2 < m_3$
or
$m_3 < m_1 < m_2$?

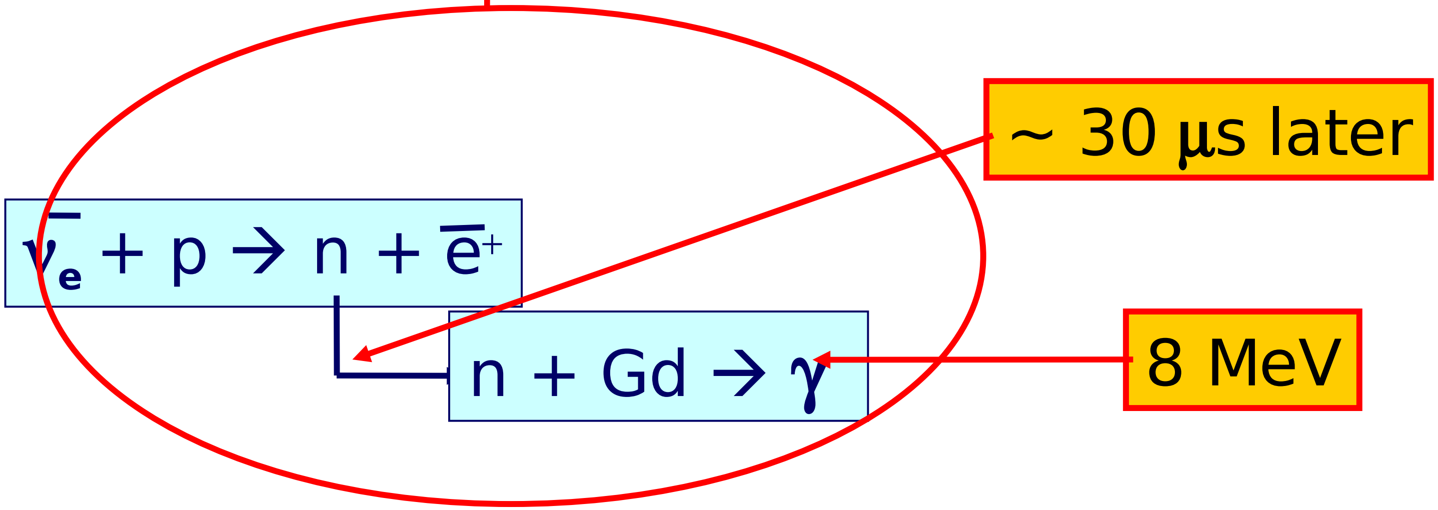
Measurement of θ_{13}

- A typical fission process liberates about 200 MeV of energy and produces about 6 $\bar{\nu}_e$, then for a typical commercial reactor (3 GW thermal energy)

$$3\ \text{GW} \sim 2\text{x}10^{21}\ \text{MeV/s} \rightarrow 6\text{x}10^{20}\ \bar{\nu}_e\text{/s}$$

Two prompt coincident signal

∀ $\bar{\nu}_e$ are observed through the reaction



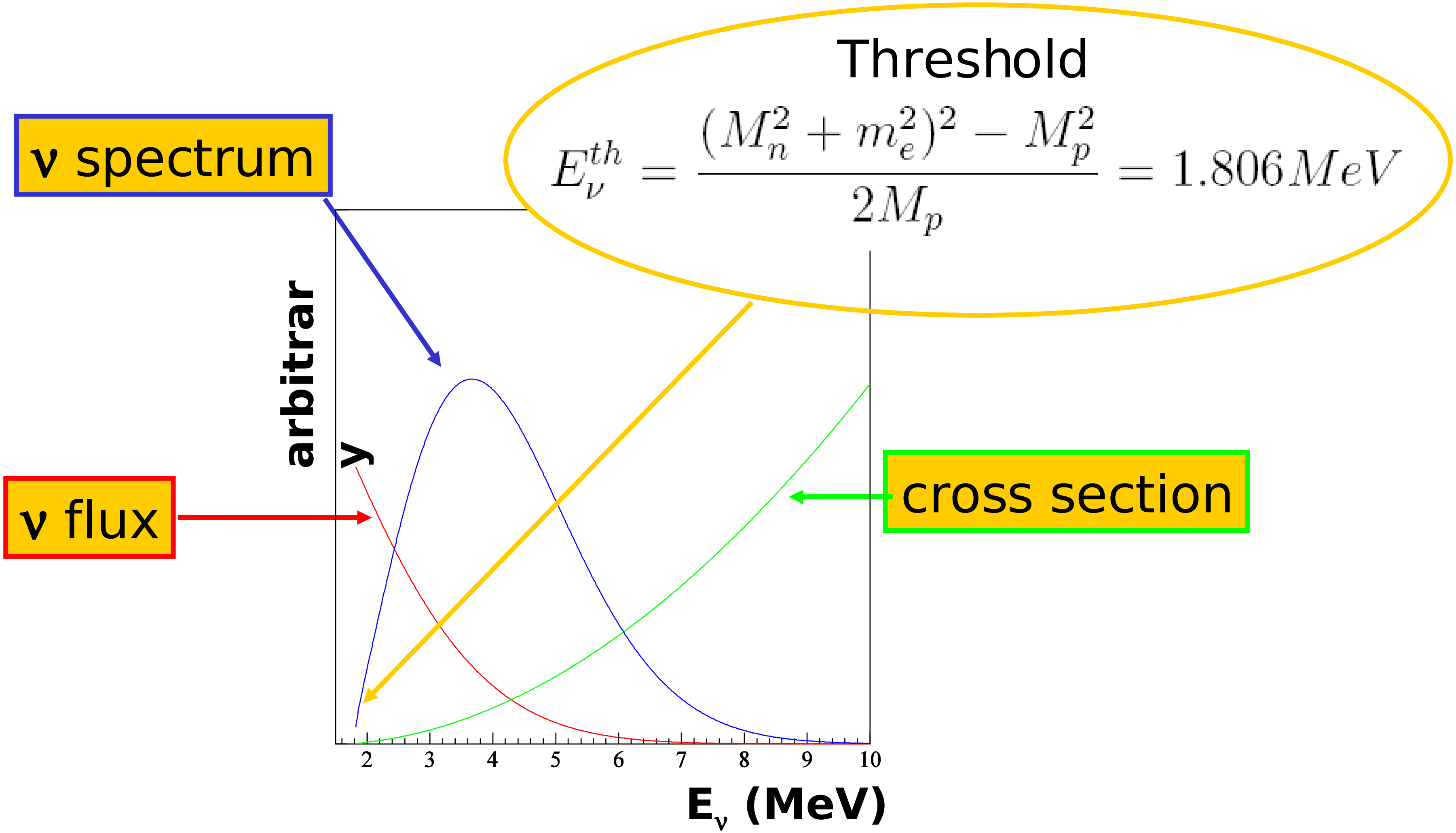
$\bar{\nu}_e + p \rightarrow n + e^+$

$n + Gd \rightarrow \gamma$

~ 30 μs later

8 MeV

- The observable neutrino spectrum is the product of the neutrino flux times the inverse **β**-decay cross section



Threshold

$$E_\nu^{th} = \frac{(M_n^2 + m_e^2)^2 - M_p^2}{2M_p} = 1.806\,MeV$$

ν spectrum

ν flux

cross section

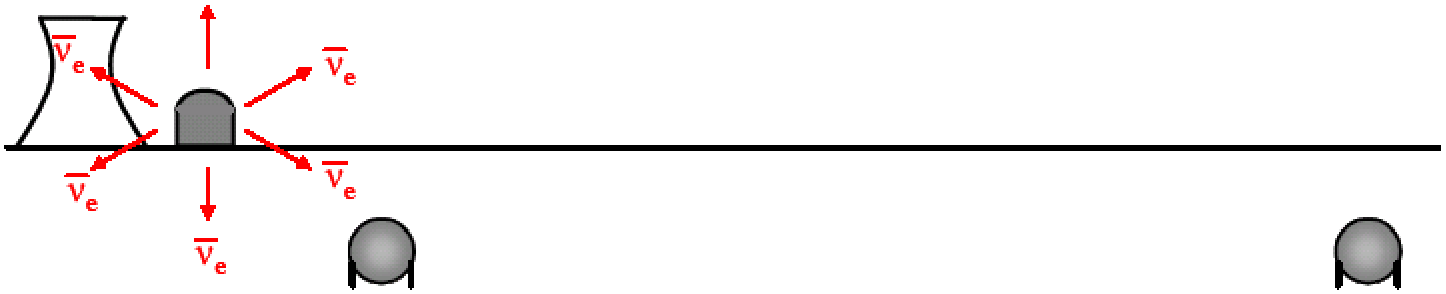
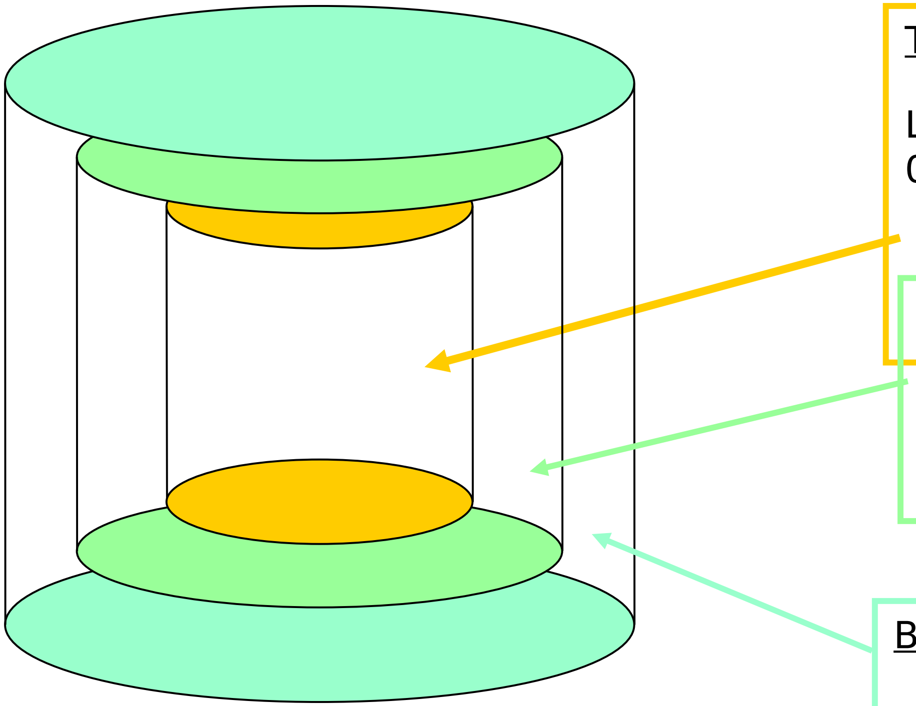


Figure 4: Schematic layout of a two detector reactor neutrino oscillation experiment.



Target:

Liquid scintillator + (0.05 – 0.1) % Gd

γ-catcher:

Liquid scintillator

Buffer:

Non-scintillating liquid

1^{rst} generation experiments

- Chooz (France)
  - Data taking completed (04/1997 - 07/1998).
  - Chooz detector in an underground cavity under ~100 m rock overburden (~ 300 m.w.e) for cosmic radiation shielding.
  - Detector with liquid scintillator loaded with 0.1% Gd
  - Two reactors with 8.5 GW_{th} total power.
  - Baseline of 1115 m and 998 m from each reactor.

FIG. 16. Aerial view of the CHOOZ power plant. The detector is located in a tunnel under the hills on the bottom right of the photograph.

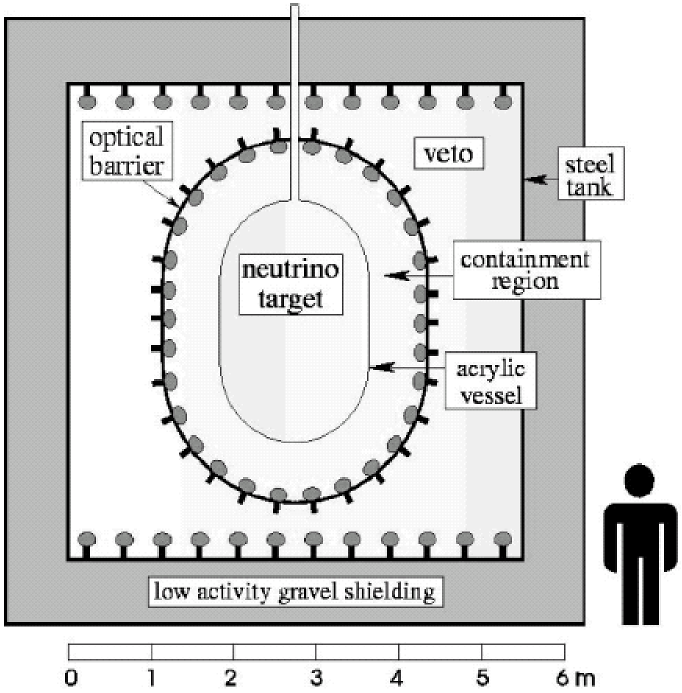


FIG. 17. Schematic drawing of the CHOOZ detector.

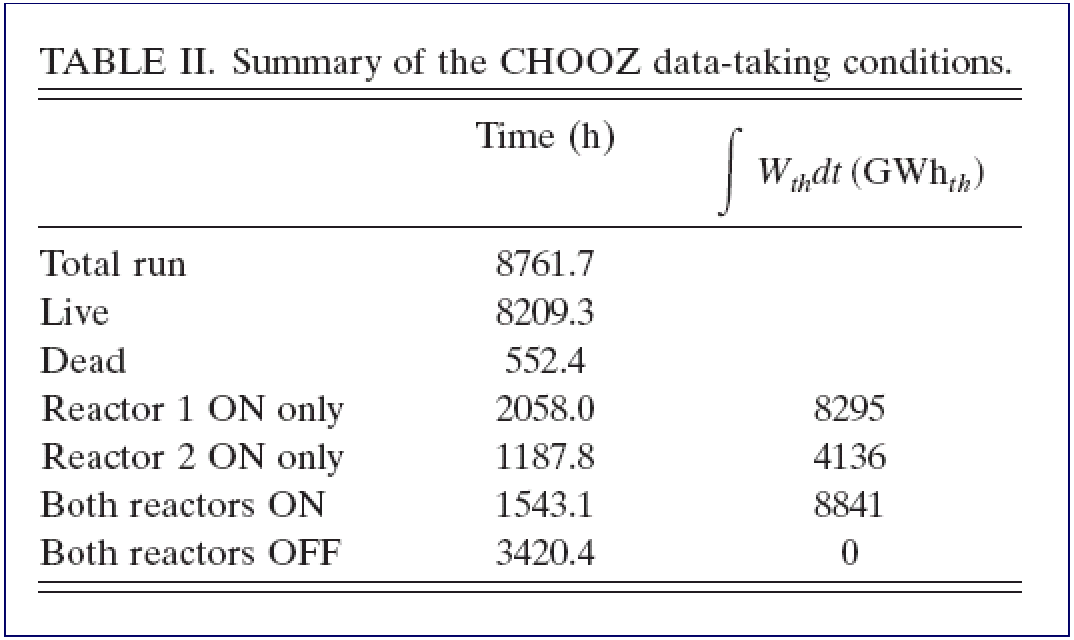


TABLE II. Summary of the CHOOZ data-taking conditions.

	Time (h)	$\int W_{th}dt$ (GWh$_{th}$)
Total run	8761.7	
Live	8209.3	
Dead	552.4	
Reactor 1 ON only	2058.0	8295
Reactor 2 ON only	1187.8	4136
Both reactors ON	1543.1	8841
Both reactors OFF	3420.4	0

- PaloVerde (USA – Arizona desert):
  - Data taking completed (10/1998 – 07/2000).
  - Segmented detector with liquid scintillator loaded with 0.1% Gd.
  - Three reactor with 11.6 GW_{th} total power.
  - Two reactors located at 890 m from the detector and the third at 750 m.
  - Total of 350.0 days of data taking.

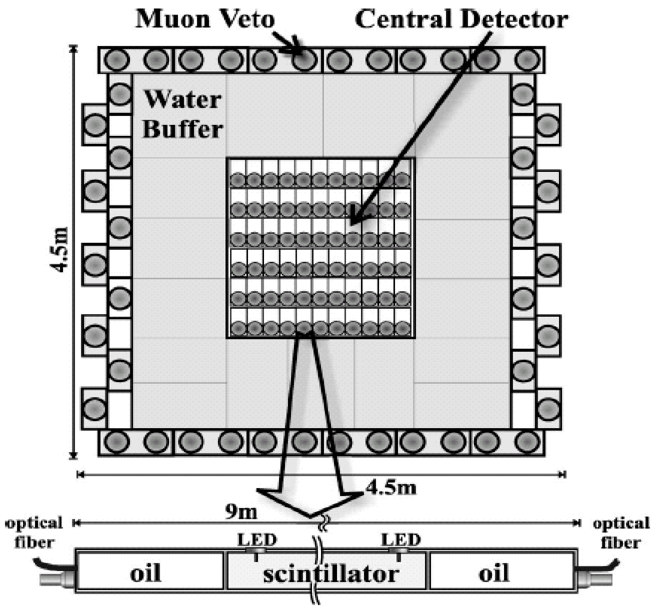


FIG. 20. Schematic view of the PALO VERDE neutrino detector.

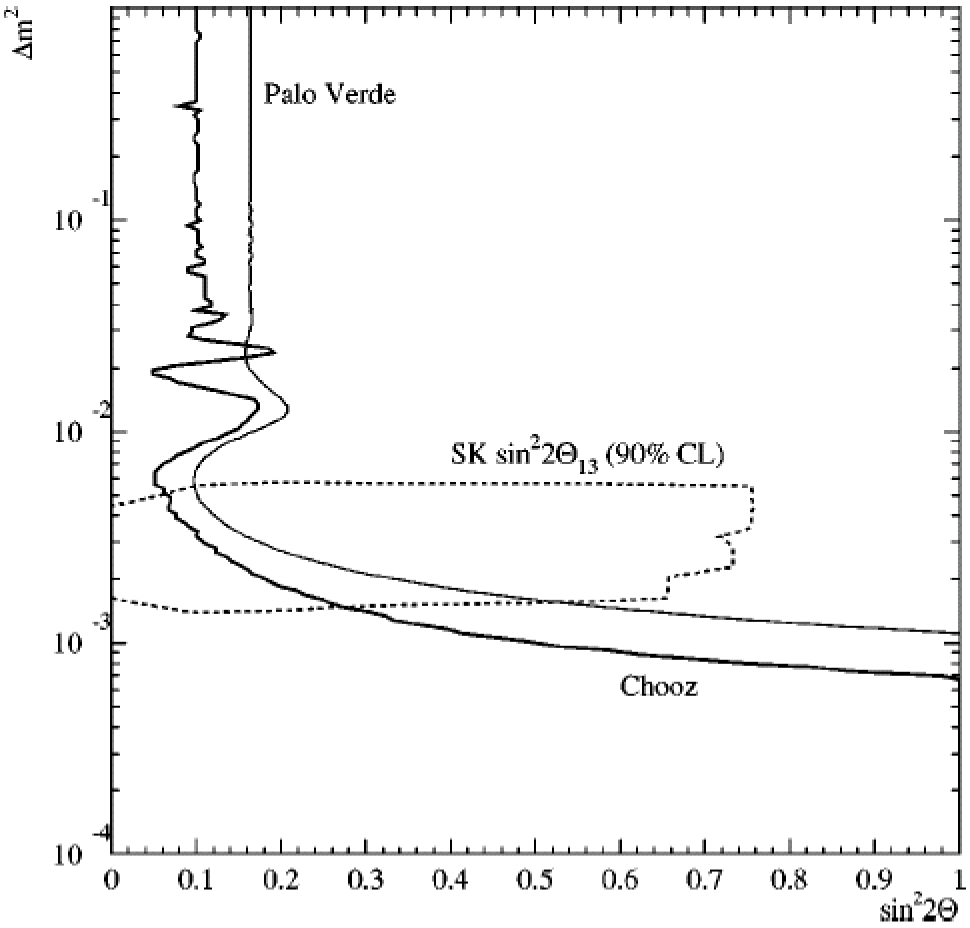


FIG. 29. Exclusion plot showing the allowed region of θ_{13} and Δm^2 based on the Super-Kamiokande preliminary analysis (the region inside the dotted curve). The regions excluded by the neutrino reactor experiments are to the right of the corresponding continuous curves.

2^{nd} generation experiments

- Double Chooz:
  - Two identical detectors with 12.7 m^3 of liquid scintillator loaded with 1% Gd.
  - Far – near configuration of the detectors
  - Far detector → 1.05 Km from reactors, 300 m.w.e shielding
  - Near detector → 100 to 200 m away from the reactors, underground cavity with 50 to 80 m.w.e. shielding.
  - Typical three volume detectors.
  - Data taking starting in 2008 - 2009.

Two detectors in the far-near configuration:

- cancelation of systematic errors coming from the lack of detailed knowledge of the ν flux and spectrum.
- reduction of systematic errors related to the detector and to the event selection procedure

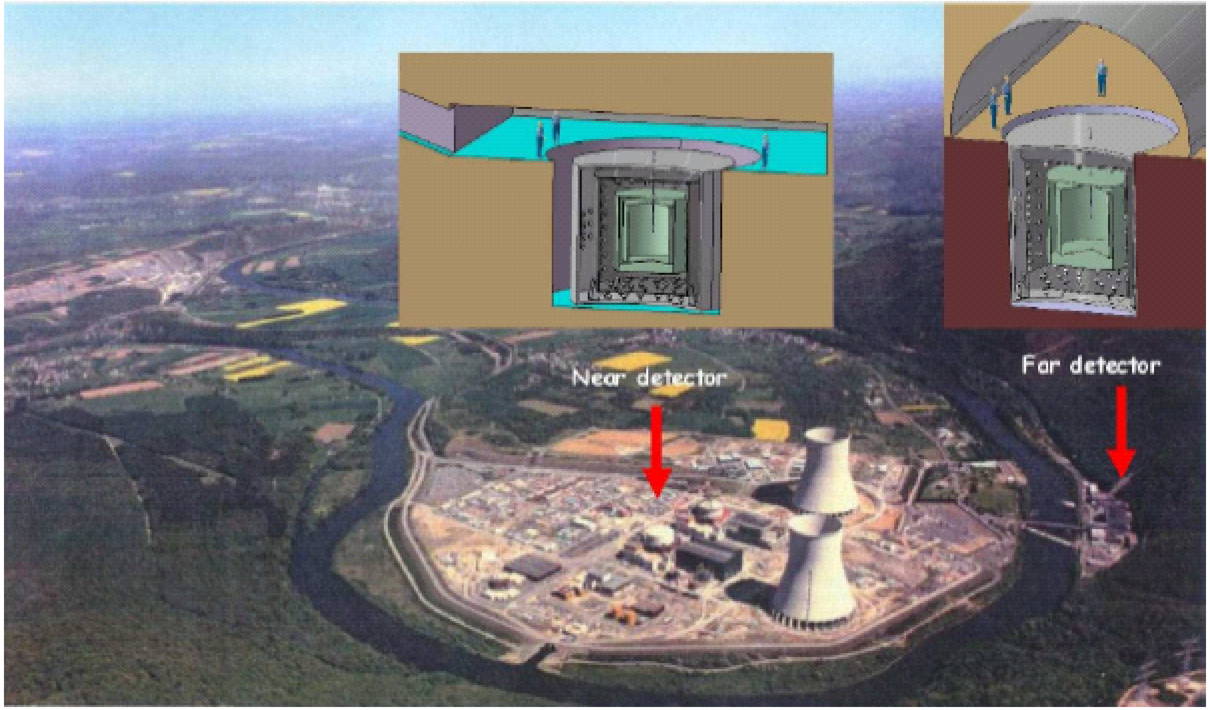
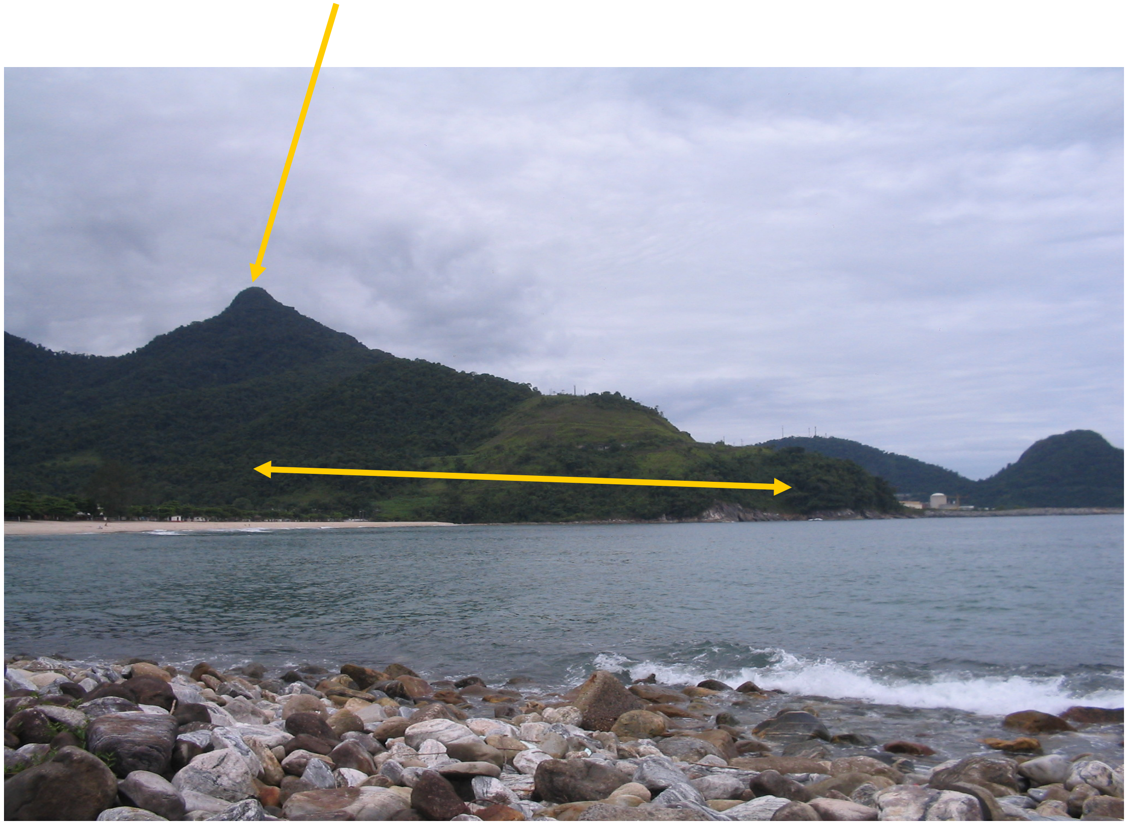


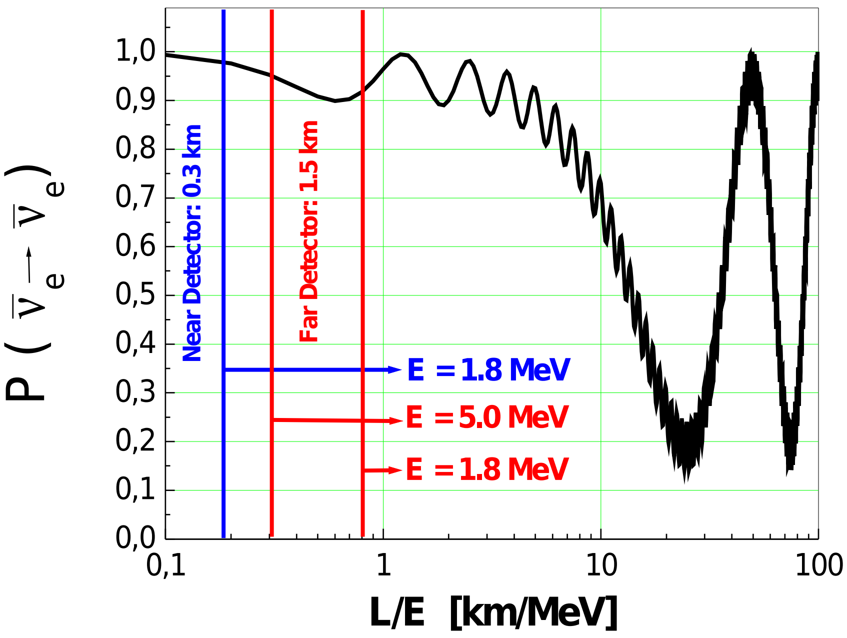
Figure 3.1: Overview of the experiment site.

- Angra dos Reis (Brazil):
  - Two detectors in the far-near configuration.
  - Far detector:
    - 2000 m.w.e. overburden
    - 500 ton of liquid scintillator doped with Gd
    - 12.5 m diameter
    - 1500 m away from the reactors
  - Near detector:
    - 250 m.w.e. overburden
    - 50 ton liquid scintillator doped with Gd
    - 7.2 m diameter
    - 300 m away from reactors
  - 3 volume standard detectors.
  - Two reactors with 4 GW_{th} total power
  - Sensitivity up to $\sin^2(2\theta_{13}) \sim 0.006$

“Morro do Frade”



	Very Near	Near	Far
Signal (events/day)	1800 (50m)	2500 (300m)	1000 (1500m)
Muon rate (Hz)	150	~ 30	0.3
Correlated background (^{9}Li) (events/day)	44	< 20	~ 2



- Extra: Neutrino applied physics
  - Very near detector for a safeguard program
    - 1ton three volume detector
    - L < 50 m from the reactor cores
    - ~ 3 m diameter
  - Useful also to:
    - study background
    - study of systematic errors
    - test of detector elements and performance (electronics, PMT’s, geometry, liquid scintillator, etc.)
- Angra experiment
  - Full detector array → ~2010-2011 (?)
  - Very near detector → ~ 2008 (?)

Conclusions

- Measurement of PMNS matrix parameters is in the beginning
- Reactor experiments able to measure θ_{13} with a good precision
- If $\theta_{13} \neq 0$ then it is possible to measure the CP violating phase δ
- Other measurements are possible with reactor neutrino's experiments: $\sin^2\theta_w$, fuel monitoring (safeguards), neutrino magnetic moment, etc.