KamLAND $\rightarrow \Delta m^2_{21}$

- Reactor antineutrino experiment @ Kamika mine (Japan)
- liquid-scintillator detector:
  - 1kt target mass (20% PC + 80% paraffin)
  - design like Borexino, but less clean (radioactivity)
- Disappearance search: $P_{\bar{e}\bar{e}} \simeq 1 - \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$

Neutrino source:

- combined $\bar{\nu}_e$ flux from all Japanese nuclear power plants
- in 2002: $\sum P_{th} = 68\,GW$
  baselines between 140 to 210km

$\rightarrow$ sensitivity range for Δm^2_{21}: $\sim 10^{-5} - 10^{-4}\,eV^2$

Neutrino detection:

Prompt signal

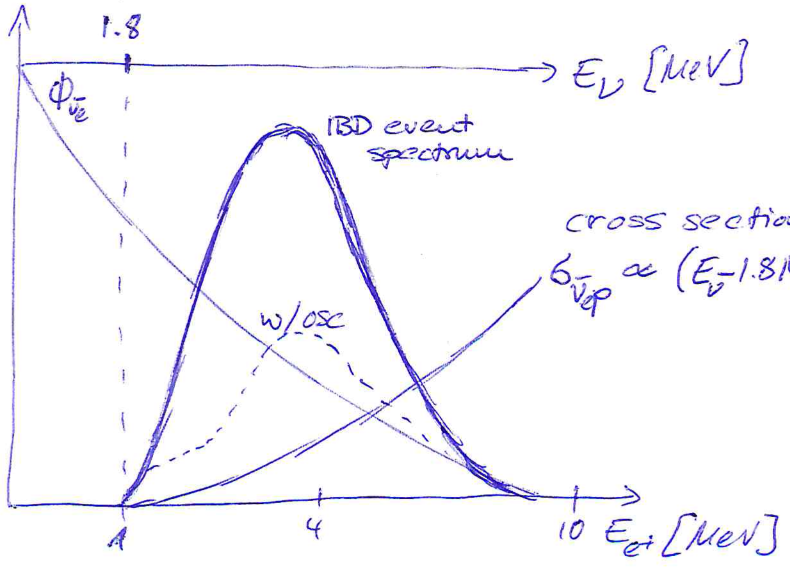
$\hookrightarrow e^+ + e^- \rightarrow \gamma\gamma + E_{kin} \Rightarrow$ neutrino energy

- Inverse beta decay on H: $\bar{\nu}_e + p \rightarrow e^+ + n$

$\hookrightarrow n + H \rightarrow d + \gamma$ [2.2 MeV]

delayed signal

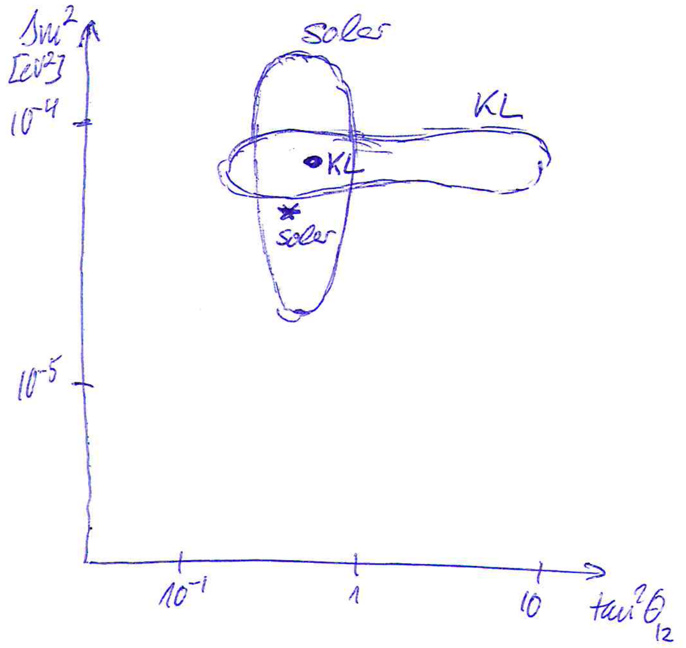
- coincidence signal ($\tau_{nH} \sim 200\mu s$) $\rightarrow$ background discrimination
- threshold: $1.8\,MeV = m_n + m_e - m_p = E_{thr}$
- expected prompt event spectrum



Result (2002):

- deficit observed: 258 ev. vs. 365 ev. expected
  18 background events
- using known baselines and reactor powers:
  → fit to observed oscillation pattern: $\Delta m^2_{21} = (7.9 \pm 0.6) \cdot 10^{-5}\,eV^2$

Combined solar + KL result for solar mixing:



- solar for θ_{12}, KL for Δm^2_{21}
- combination provides some sensitivity to $\sin^2\theta_{13}$

solar ^8B

↪ $P_{ee} = \sin^2\theta_{12}$

KamLAND

baseline ~180 km

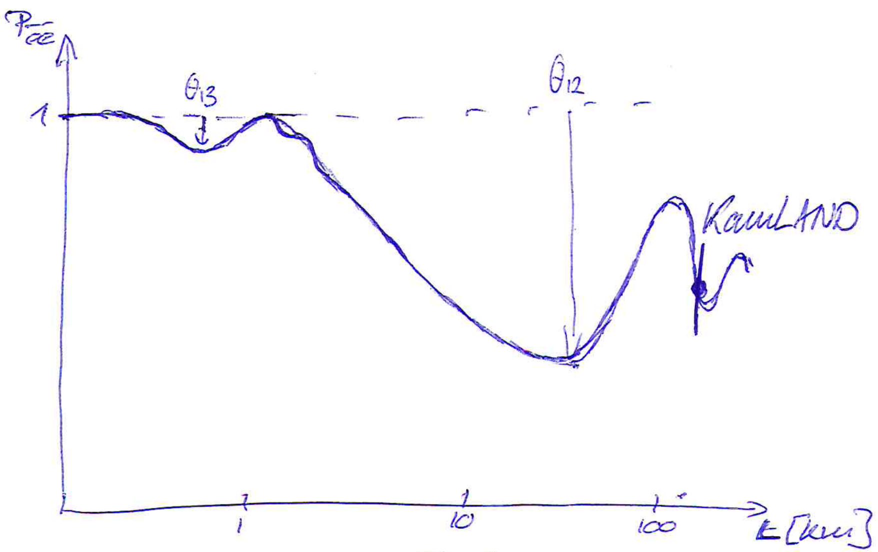
→ averaging over Δm^2_{13} provides:

$$P_{ee} = \underbrace{\cos^4\theta_{13}}_{0.95 \text{ for } \theta_{13} \sim 10^\circ}\left(1 - \sin^2 2\theta_{12} \sin^2\Delta_{12}\right) + \underbrace{\sin^4\theta_{13}}_{\sim 6 \cdot 10^{-4}}$$

→ $\cos^4\theta_{13}$ term leads to further reduction of P_{ee}

→ KL finds larger value for θ_{12} in two-flavor picture

→ ≈2σ evidence for $\theta_{13} > 0$



c) Reactor mixing

- $|\Delta m^2_{31}| \approx |\Delta m^2_{32}| \pm \Delta m^2_{21} \approx |\Delta m^2_{32}|$
  → right magnitude / baseline established!
- old CHOOZ experiment: upper limit $\sin^2 2\theta_{13} \lesssim 0.10$
  → θ_{13} known to be small

Two types of experiments:

A) ≥2-detector reactor antineutrino experiments

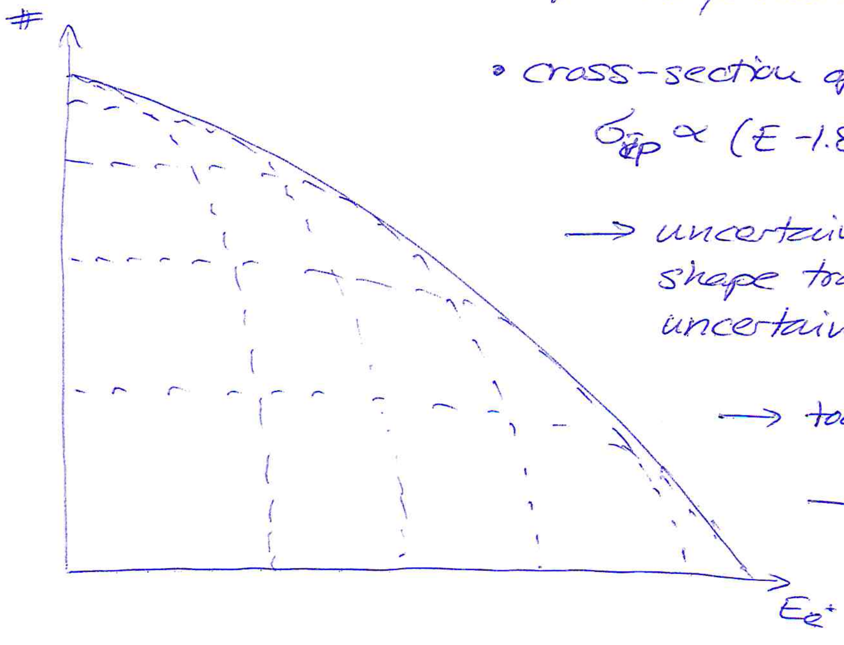
Disappearance search: $P_{\bar{e}\bar{e}} = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$

↳ Optimum baseline: 1-2 km for $E_{\bar{\nu}} \sim 2-4$ MeV

Main challenge:

Uncertainty on reactor spectrum

- $\bar{\nu}_e$ produced in β^--decays of many different n-rich fission products
- for individual decays:
  inversion of known β^--spectrum to obtain $\bar{\nu}_e$ spectrum
- for complete spectra of ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu products:
  β^- spectra measured at BILL spectrometer @ ILL Grenoble
  → inversion based on 30 effective β branches



- cross-section of IBD:
  $\sigma_{\bar{\nu}p} \propto (E - 1.8\,\text{MeV})^2$

→ uncertainty on spectral shape translate to rate uncertainties in detectors

→ today: $\frac{\Delta R}{R} \gtrsim 2\%$

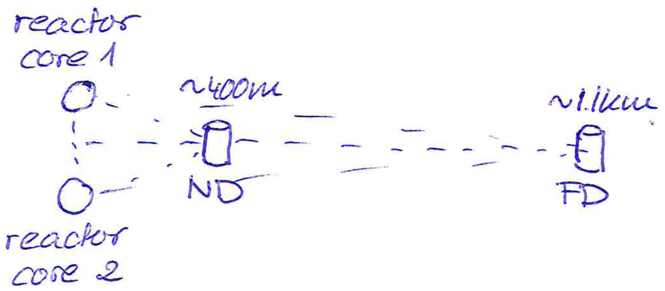
→ potentially same order as oscillation signal

→ Near Detector + Far Detector concept

↓ rate + spectrum normalization

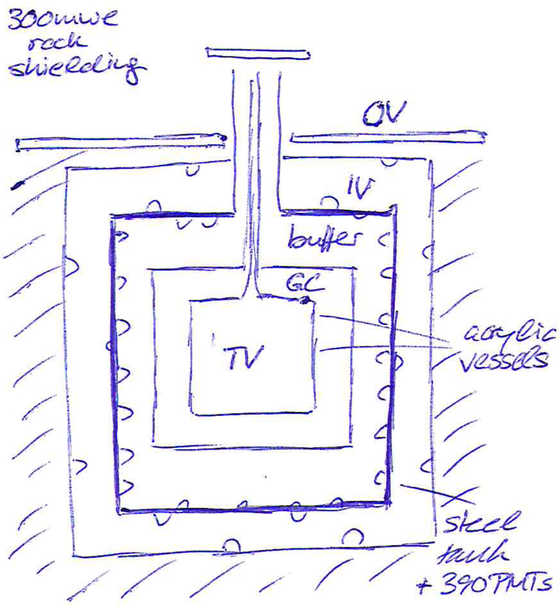
↓ oscillation search

Example: Double-Chooz experiment



→ two functionally identical detectors

Detector layout



- Target volume (TV)
  - 8t of liquid scintillator doped with Gd

$$\bar{\nu}_e + p \to e^+ + n \quad \hookrightarrow_{30\mu s} n + Gd \to Gd^* \quad \hookrightarrow 3\gamma\ [\Sigma E \sim 8\,\mathrm{MeV}]$$

→ coincidence signature
  - faster
  - at higher energy

Rate: ~50 d^{-1}

  - target mass determined to ~0.1% accuracy

- Gamma Catcher (GC): LS w/o Gd

  mean free path Gd-γ's: several 10 cm

  → increased γ detection eficiency

- Buffer: inactive liquid, shielding from external γ's

- Inner Veto & Outer Veto (IV/OV):

  coincidence veto and track reco for cosmic muons

  → cosmogenic background suppression,

$$\text{e.g. } {}^9Li \to {}^9Be^* + \textcircled{e^-} + \bar{\nu}_e$$

↳ prompt, $E_\beta < 10\,\mathrm{MeV}$

$${}^9Be^* \to \alpha\alpha\, \textcircled{n}$$

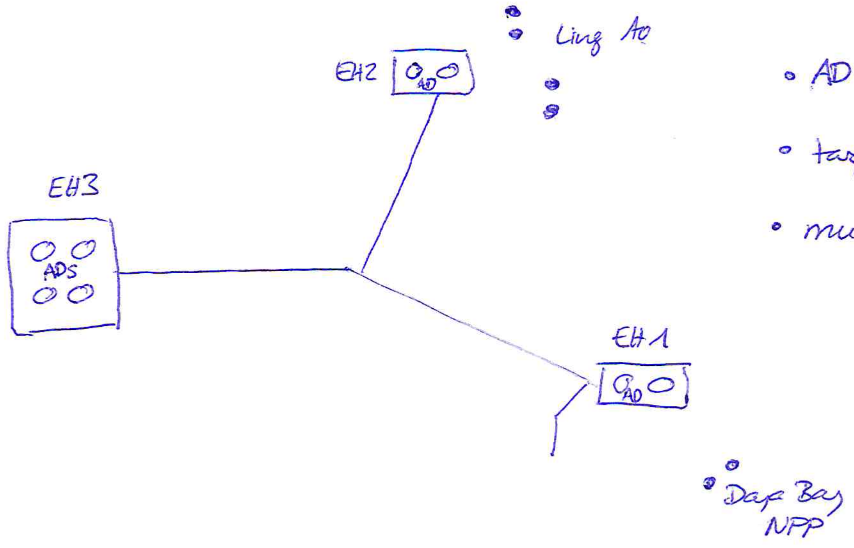
↳ delayed, capture on Gd

Rate: ~2 d^{-1}

↳ comperable to oscillation effect!

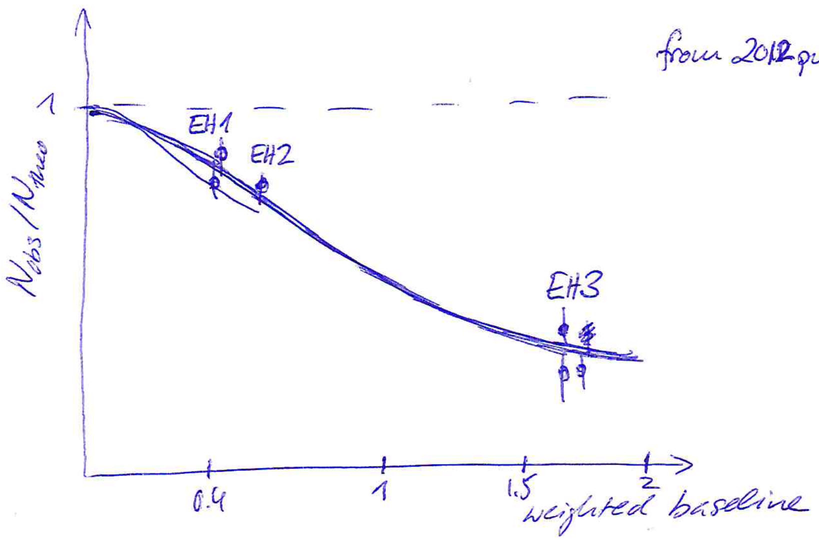
Other reactor experiments

- RENO (South Korea): 6 reactor cores, 2 detectors
- Daya Bay (Southern China):
  6 reactors, 8 detectors:



- AD design similar to DC
- target mass: ~20t (x8)
- much larger reactor power

→ best result so far: $\sin^2 2\Theta_{13} = 0.084 \pm 0.005$ (2015)



from 2012 publication

B) "Short" long-baseline beam experiment

Appearance experiment: $\nu_\mu \rightarrow \nu_e$

→ complementary systematics to reactor experiments

Oscillation probability for short baselines:

$$P_{\mu e(\bar{\mu}\bar{e})} = \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\left(\frac{B_\pm L}{2}\right) \qquad [1]$$

$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2\sin^2\left(\frac{AL}{2}\right) \qquad [2]$$

$$+ J\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{B_\pm}\sin\left(\frac{AL}{2}\right)\sin\left(\frac{B_\pm L}{2}\right)\cos\left(\mp\delta - \frac{\Delta_{13}L}{2}\right) \qquad [3]$$

with $J = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$

$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E}\,;\quad B_\pm = |A \pm \Delta_{13}|\,;\quad \underbrace{A = \sqrt{2}\,G_F N_e}_{\text{matter potential}}$$

- Matter effects: scale with

$$\frac{\Delta_{13}}{B_\pm} = \frac{\Delta_{13}}{|A\pm\Delta_{13}|} \approx \frac{1}{\left|\frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{31}} \pm 1\right|} \longrightarrow 1 \quad \text{for } E_\nu \ll \frac{\Delta m^2_{31}}{2\sqrt{2}G_F N_e}$$

→ negligible for $E_\nu \lesssim 2\,\text{GeV}$ or $L \lesssim 1000\,\text{km}$ (1^{st} osc. maximum)

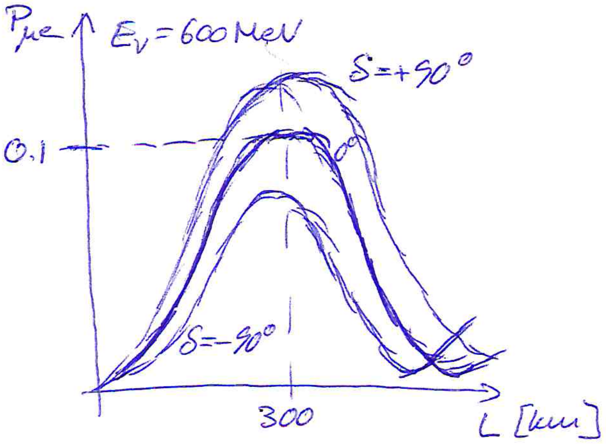
- term [2]: negligible for short baselines (scales with $(\Delta_{12}L)^2$)

$$\Rightarrow P_{\mu e(\bar{\mu}\bar{e})} = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta_{13}L}{2}\right) \qquad [1]$$

$$+ J\sin\left(\frac{\Delta_{12}L}{2}\right)\sin\left(\frac{\Delta_{13}L}{2}\right)\cos\left(\mp\delta - \frac{\Delta_{13}L}{2}\right) \qquad [3]$$

- term [1]: sensitivity to θ_{13}
- term [3]: sensitivity to δ_{CP} from difference $P_{\mu e}$ vs. $P_{\bar{\mu}\bar{e}}$

■ T2K experiment : Tokai → Kamioka (295km)

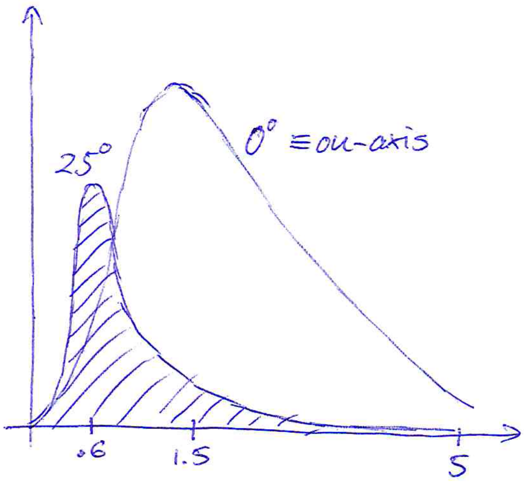


→ influence of δ changes both amplitude and distance to the 1st oscillation maximum!

Neutrino source: $\overset{(-)}{\nu}_\mu$ beam (cf. MINOS)

- protons on fixed target ↕
- beam power: $P = 700$ kW
- wide-band beam: $E_{max} = 1.5$ GeV
- off-axis beam:

  aimed 2.5° away from far detector



- π decay kinematics

  → beam maximum shifted to lower energies + increased flux

Near detector: ND280

- composite detector: scintillator strip + gas TPC modules
- magnetized
- contribution : → unoscillated spectrum & flux

  → intrinsic beam contamination with ν_e (~1%)

  → cross sections for CC/NC interactions, especially NC-π^0 production

Far detector: Super-Kamiokande

- detection / energy reco of CC ν_e and ν_μ events

  ν_e – appearance ($\nu_\mu \to \nu_e$)

  ν_μ – disappearance ($\nu_\mu \to \nu_x$)

Event identification & backgrounds

- $CC\nu_e$ vs. $CC\nu_\mu$: ring fuzziness
- $CC\nu_e$ vs. $NC\pi^0$:

$$\nu_\mu + N \xrightarrow{NC} X + \pi^0 + \nu_\mu$$

$$\pi^0 \to \gamma\gamma \to 2\times \text{em. showers}$$

→ two fuzzy rings, difficult to seperate for small decay angles

  - ☐ single-ring vs. multi-ring
    → handled well by most recent reco algorithms

- $CC\nu_e$ from osc. vs. beam contamination
  → irreducible

Result of 2013:

- based on 6×10^{20} p.o.t. (protons on target)
- 28 ν_e-events observed at $E_\nu < 1.2$ GeV
- Expected background: 4.6 ± 0.5 (mostly ν_e contamination)

→ clear excess (significance: 5.5σ)

→ in combination with reactor measurement of θ_{13}: some preference for $\delta_{CP} \approx -90°$