RENO and Related Physics

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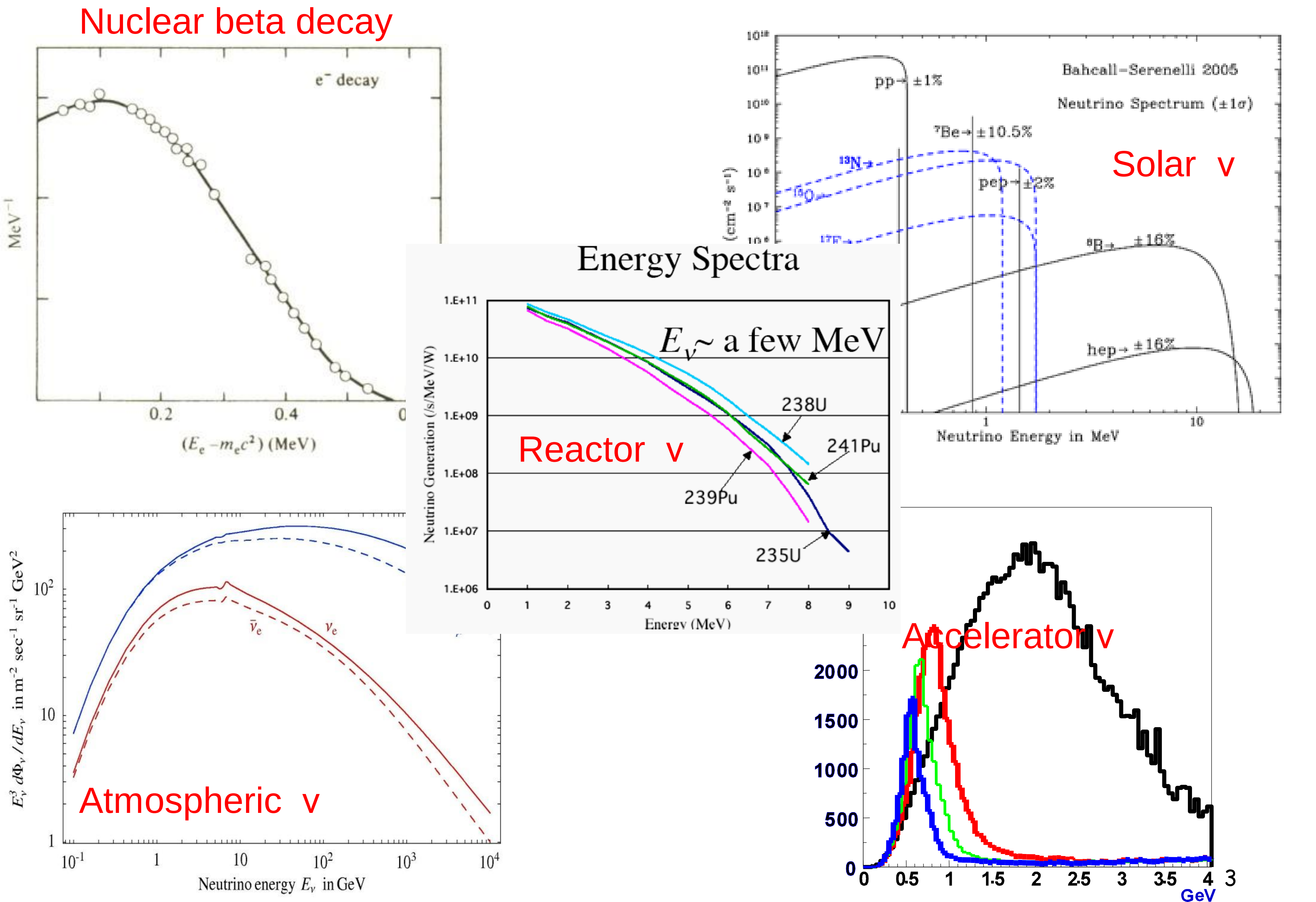
Outline

- Neutrino sources.
- Reactor neutrinos.
- Θ_{13}
- Asian reactor neutrino exp.
- Future reactor experiment.

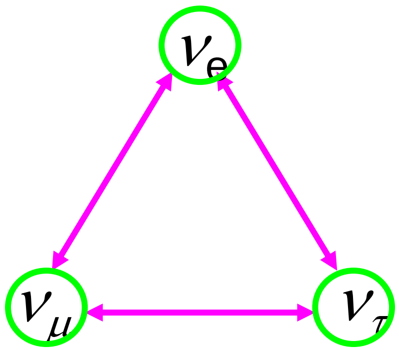
Neutrinos



Nuclear beta decay
e⁻ decay
MeV⁻¹
0.2
0.4
$(E_e - m_e c^2)$ (MeV)
Solar ν
Bahcall–Serenelli 2005
Neutrino Spectrum (±1σ)
pp→ ±1%
⁷Be→ ±10.5%
pep→ ±2%
⁸B→ ±16%
hep→ ±16%
Neutrino Energy in MeV
Energy Spectra
$E_\nu \sim$ a few MeV
Reactor ν
Neutrino Generation (/s/MeV/W)
238U
241Pu
239Pu
235U
Energy (MeV)
Atmospheric ν
$E_\nu^3\, d\Phi_\nu / dE_\nu$ in m⁻² sec⁻¹ sr⁻¹ GeV²
Neutrino energy E_ν in GeV
Accelerator ν
GeV

3

Neutrino Mixing



$$s_{ij} = \sin\theta_{ij}$$

$$c_{ij} = \cos\theta_{ij}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

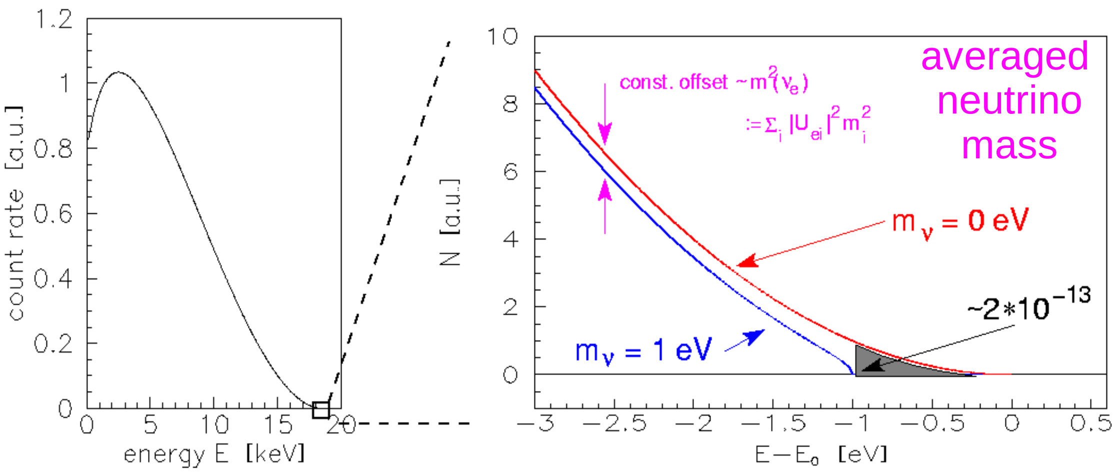
Atmospheric ($\nu_\mu \to \nu_x$)	Not measured	Solar ($\nu_e \to \nu_x$)
$\Delta m^2_{31} = 2.4(1^{+0.21}_{-0.26}) \times 10^{-3}\, eV^2$		$\Delta m^2_{21} = 7.92(1 \pm 0.09) \times 10^{-5}\, eV^2$
$\sin^2\theta_{23} = 0.44(1^{+0.41}_{-0.22})$	$\sin^2 2\theta_{13} < 0.16$	$\sin^2\theta_{12} = 0.314(1^{+0.18}_{-0.15})$

Probability of flavor oscillation depends on mixing angle & mass difference square, neutrino energy, baseline.

$$P\left(\nu_\alpha \to \nu_\beta\right) = \sin^2 2\theta \ \sin^2 \Delta_{\alpha\beta}$$

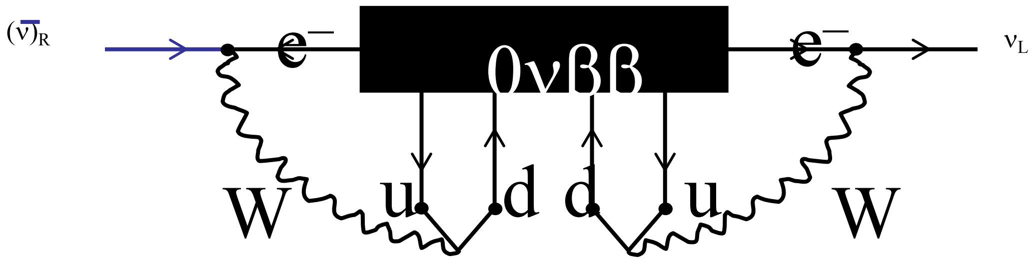
$$\Delta_{ij} \equiv \frac{\Delta m_{ij}{}^2 L}{4E_\nu} = 1.27\frac{\Delta m^2(eV^2)L(km)}{E_\nu(GeV)}$$

Neutrino mass



(1) Single Beta Decay end point is sensitive to neutrino mass ; m_β

$$m_\beta = \sqrt{c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2}$$



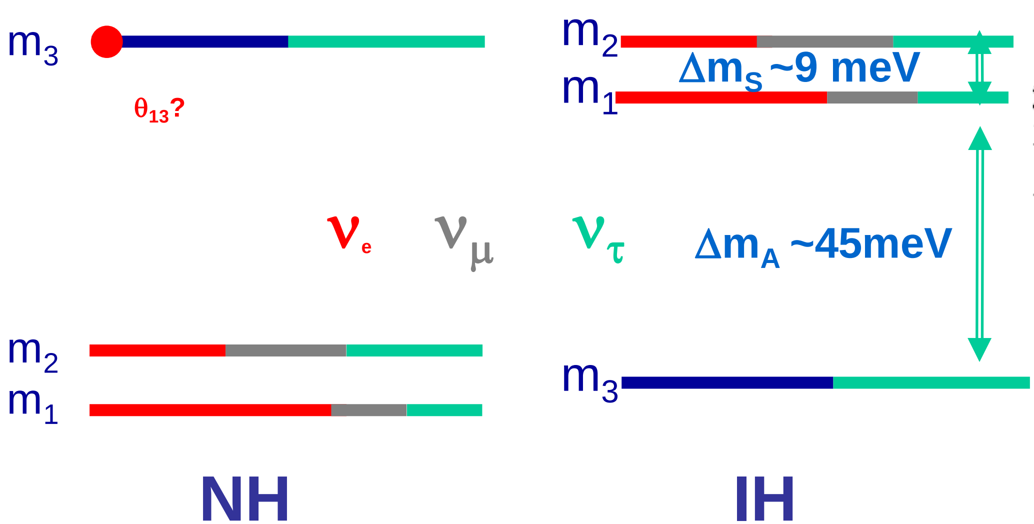
(2) Double Beta Decay experiment is sensitivie to neutrino mass ; $m_{\beta\beta}$

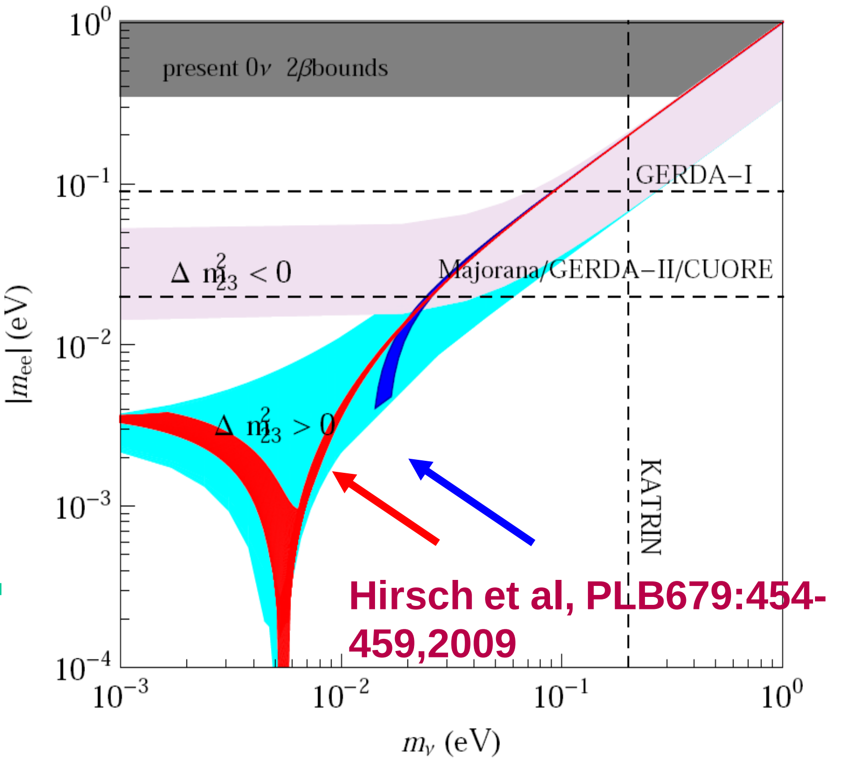
$$m_{\beta\beta} = c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 e^{2i\lambda_2} m_2 + s_{13}^2 e^{2i(\lambda_3 - \delta_{13})} m_3$$

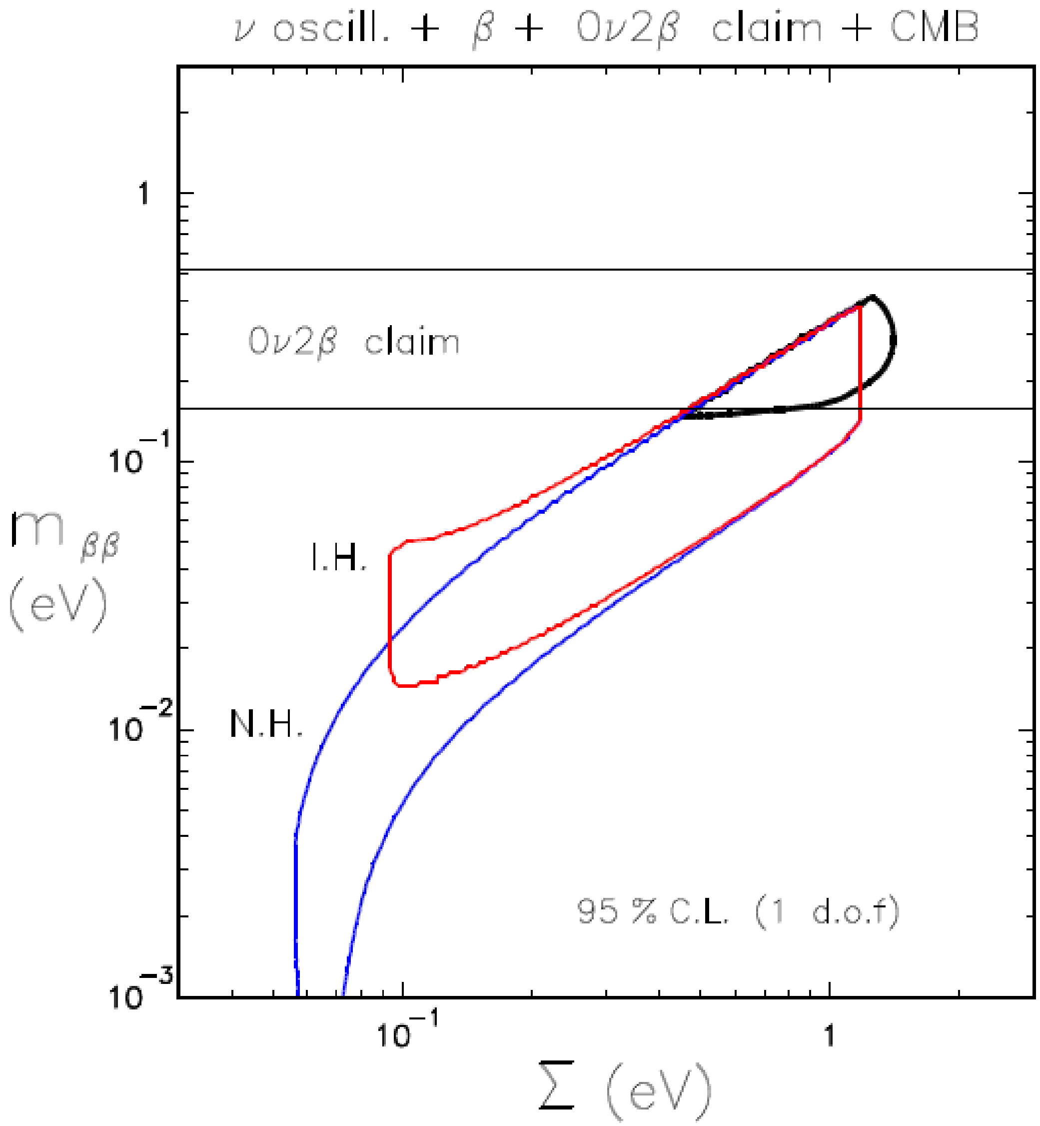
$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu} \left|M_{0\nu}\right|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Still we don't know about ν in

1. Majorana or Dirac – Double beta decay(DBD) exp.
2. Absolute mass – DBD or Beta
3. Mass ordering(Hierarchy) – LBL or Reactor
4. **Θ_{13} – Reactor or LBL**
5. CP Phase - LBL







ν oscill. + β + 0ν2β claim + CMB
1
10^{-1}
10^{-2}
10^{-3}
$m_{\beta\beta}$ (eV)
0ν2β claim
I.H.
N.H.
95 % C.L. (1 d.o.f)
10^{-1}
1
Σ (eV)

Possibilities for θ_{13} measurement

- **Reactor $\bar{\nu}_e$ disappearance** while traveling L ~ 1.5 km.
  - look for small ν_e disappearance from large isotropic flux

    $P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2(2\theta_{13})\sin^2(1.27\Delta m^2_{atm} L/E)$

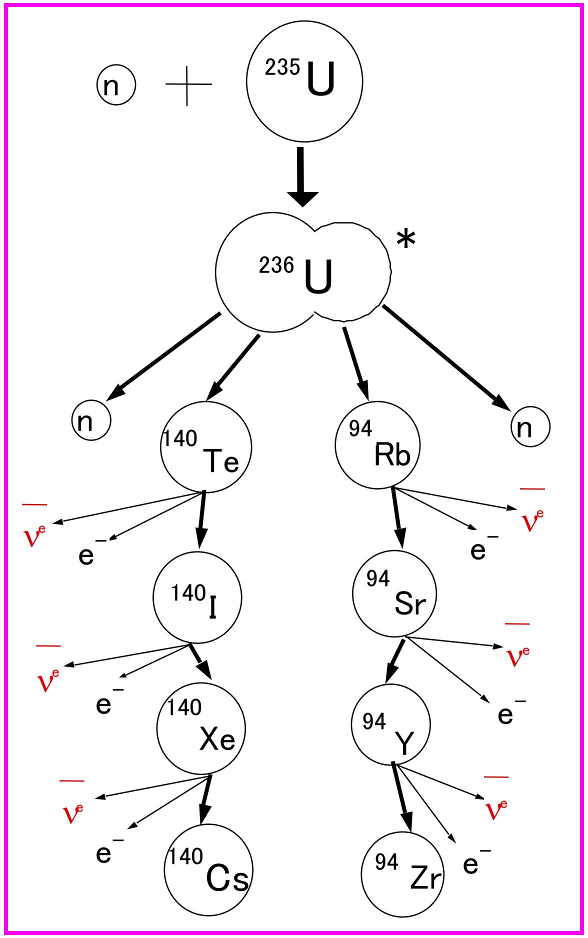
L/E ~ 500km/GeV. This process depends on θ_{13} alone. A relatively modest-scale reactor experiment can cleanly determine whether **$\sin^2 2\theta_{13} > 0.01$**

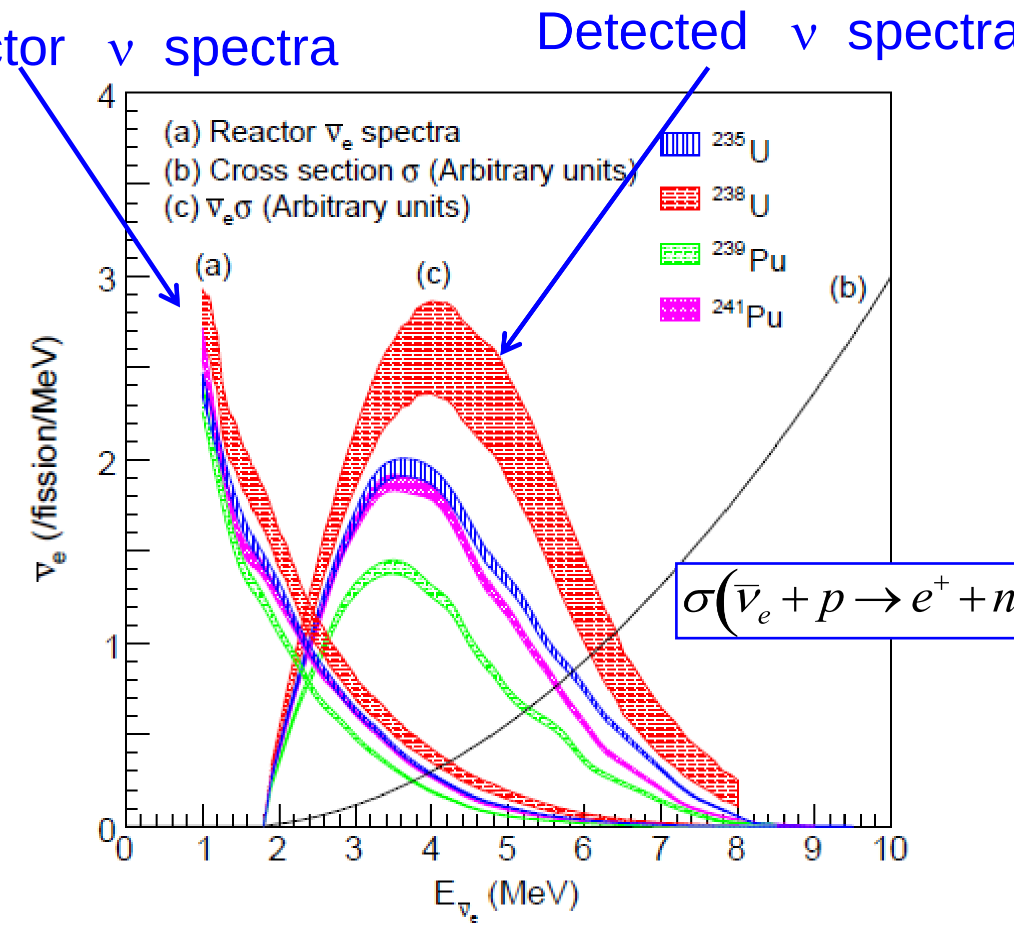
- **Accelerator $\nu_\mu \to \nu_e$** while traveling L > several hundred km.
  - look for small ν_e appearance in ν_μ beam

    $P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2(1.27\Delta m^2_{atm} L/E)$

L/E ~ 400 km/GeV. This process depends on θ_{13}, θ_{23}, the CP phase δ, and on whether the spectrum is normal or inverted. (T2K experiment)

Neutrino Production in Reactor





$\sigma\left(\overline{\nu}_e + p \rightarrow e^+ + n\right)$

ν are produced in
β-decays of fission products.

$$7 \times 10^{20} \overline{\nu}_e / \sec / 3GW$$

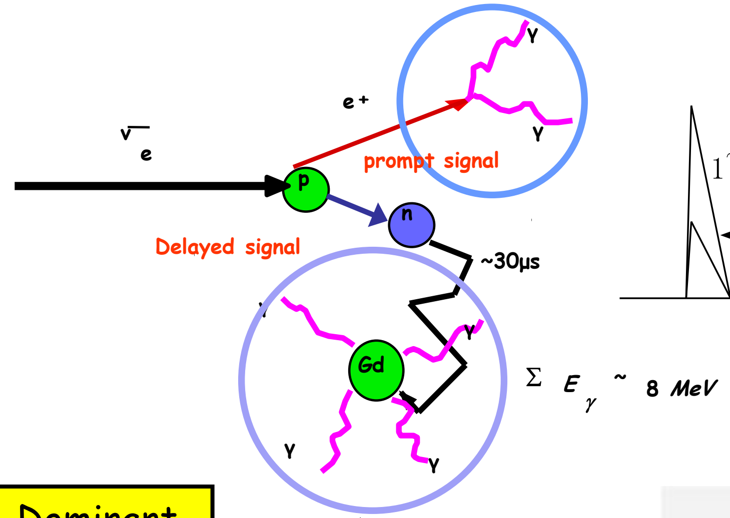
Nakajima et al., NIM A569, 837(2006)

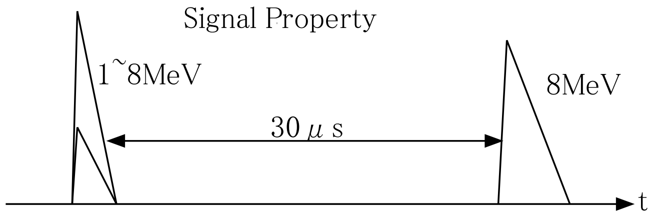
4 isotopes contributes more than 99.9%

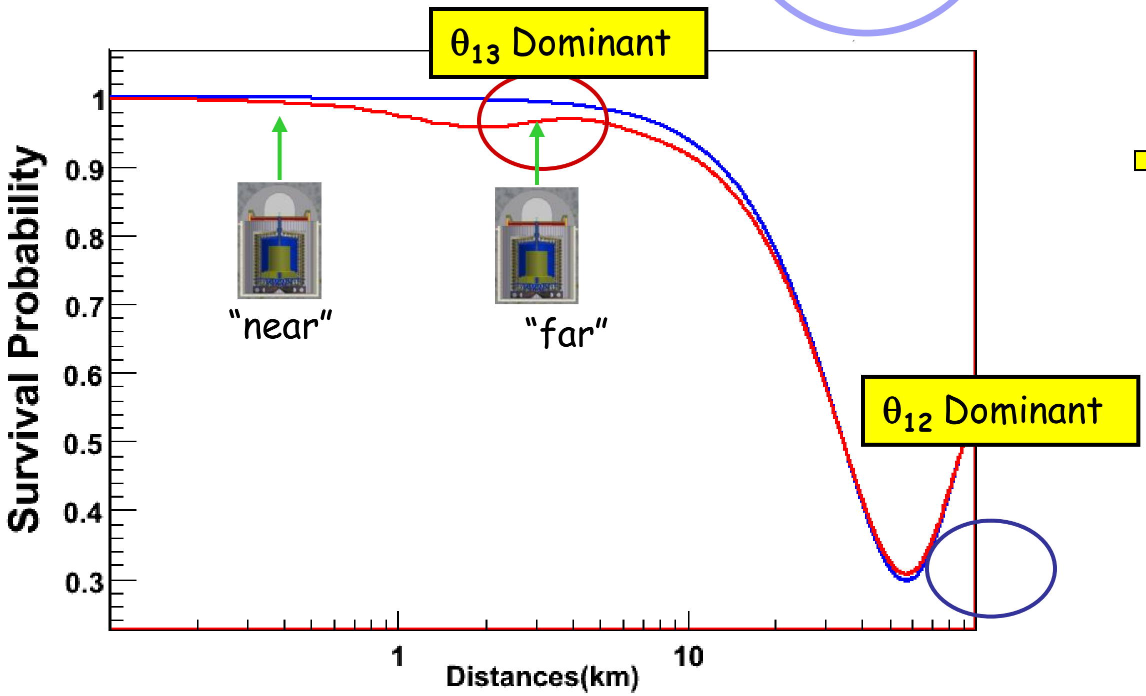
Reactor Neutrino Experiment at a Glance

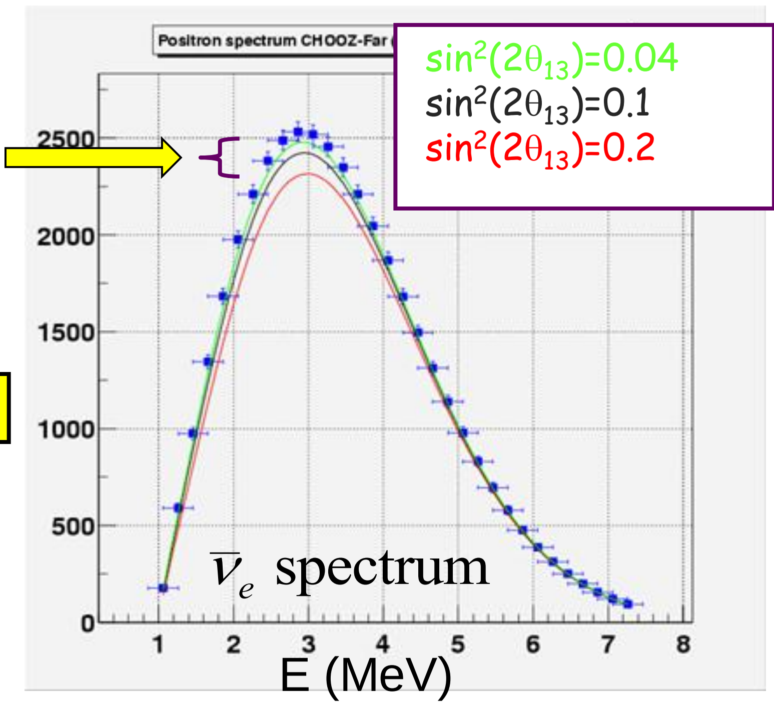
Inverse Beta Decay

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









$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2(2\theta_{13})\sin^2\Delta_{31} - \cos^4\theta_{13}\sin^2(2\theta_{12})\sin^2\Delta_{21}$$

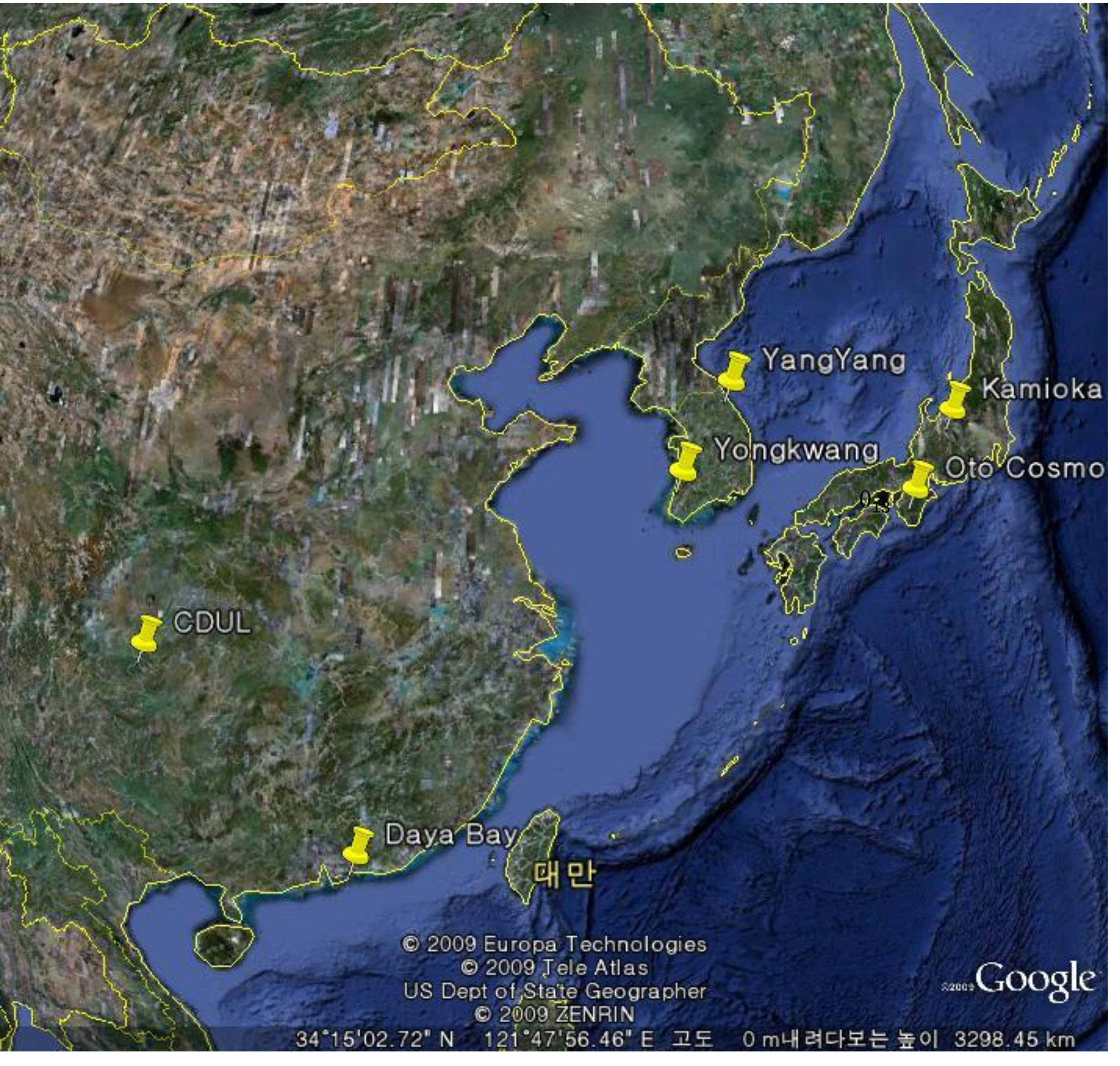
Comparison of Reactor Neutrino Experiments

Experiments	Location	Thermal Power (GW)	Distances Near/Far (m)	Depth Near/Far (mwe)	Target Mass (tons)
Double-CHOOZ	France	8.7	280/1050	60/300	10/10
RENO	Korea	17.3	290/1380	120/450	16/16
Daya Bay	China	11.6	360(500)/1985(1613)	260/910	$40\times2/80$

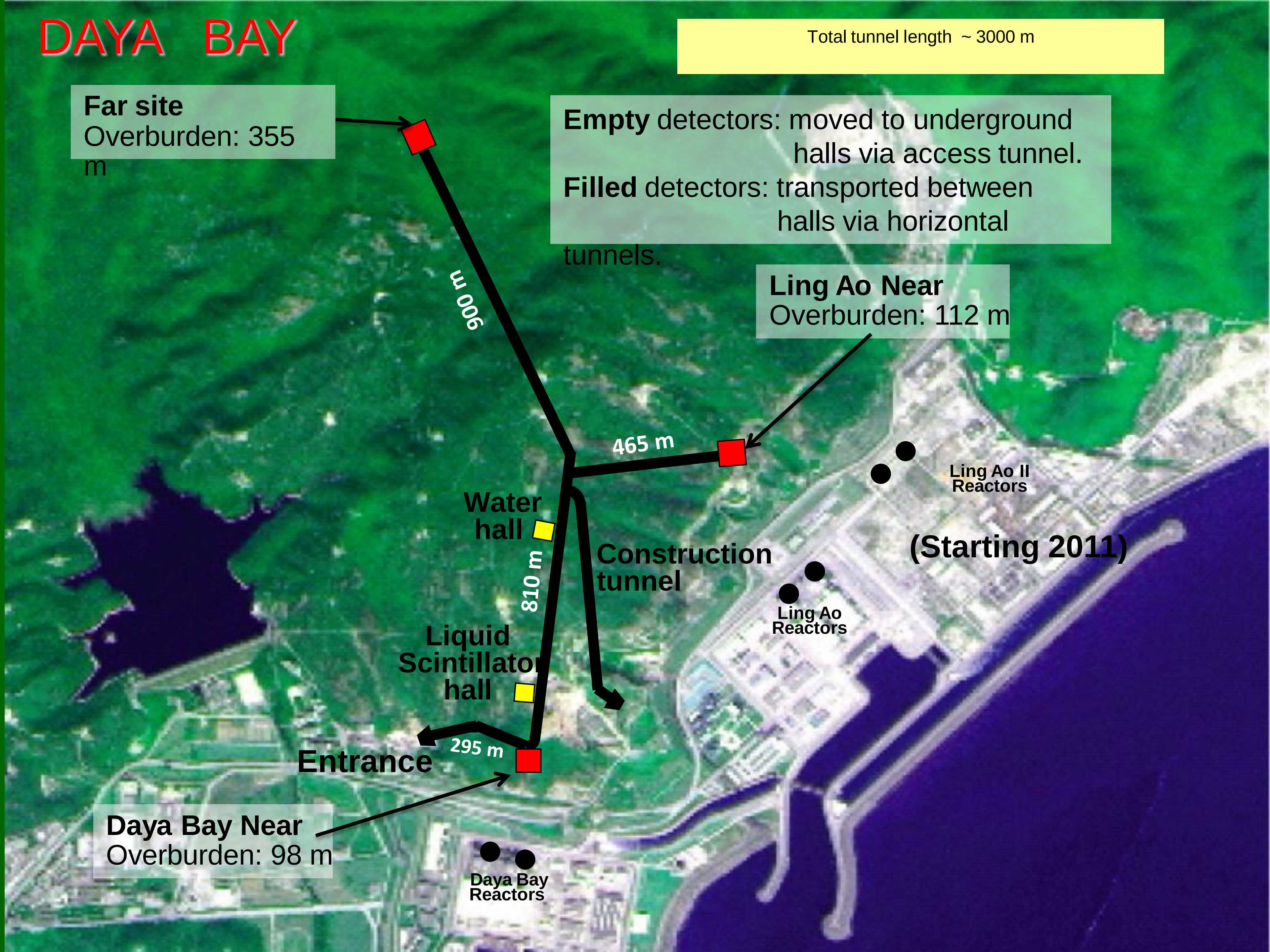
Critical points for $\sin^2(2\theta_{13})$

- **Low background:**
  - 3 main sources : cosmogenic(^{9}Li), fast neutron, accidental coincidence
  - Deep underground for reducing cosmogenic background
  - Purer materials for low background at E<10 MeV to reduce accidentals
- **Reduce systematic uncertainties:**
  - Reactor-related:
    - near and far detectors configuration canceling reactor uncertainties
    - Ramaining uncertainties due to multiple reactors
  - Detector-related:
    - Identical detectors should be confirmed by precise calibration
    - Long-term stability of detectors should be confirmed.

Neutrino Laboratories in Asia



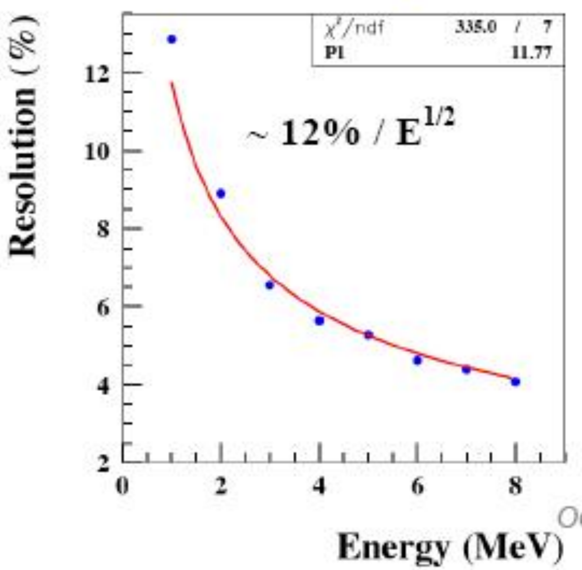
SK
Θ_{13} exp
  RENO
  DAYA BAY
Double Beta
  CANDLES(^{48}Ca)
  CaMoO4 (^{100}Mo)
CDUL : New Lab.

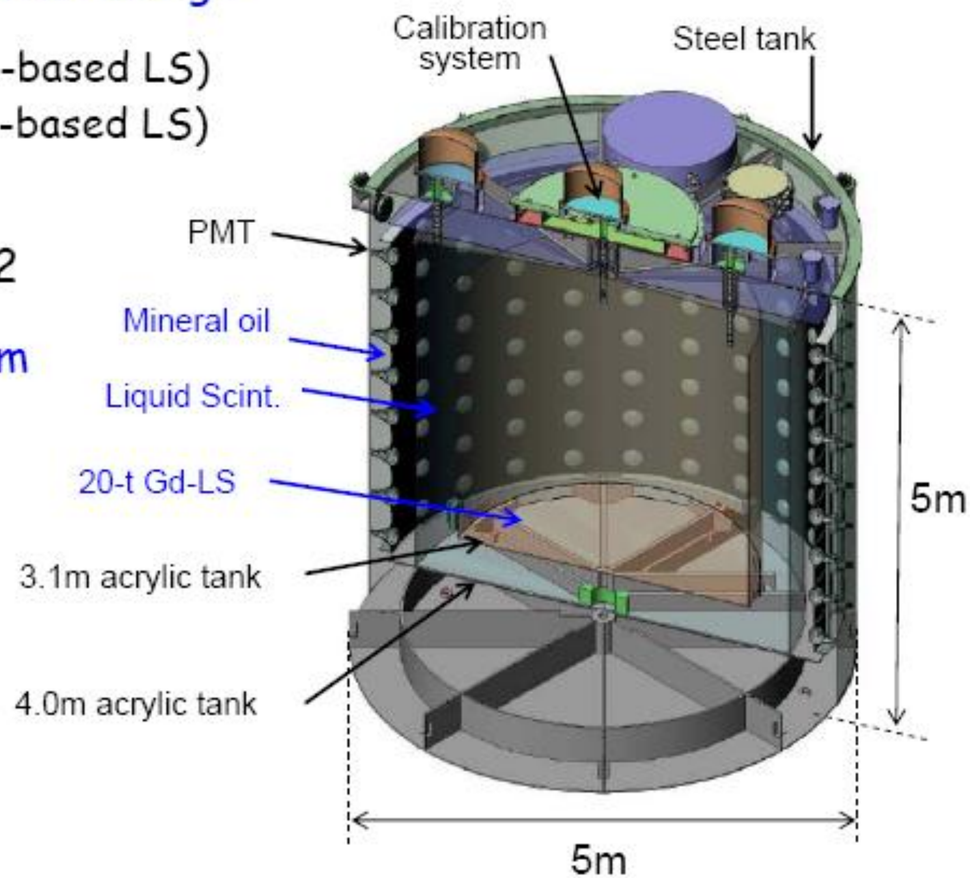

DAYA BAY
Total tunnel length ~ 3000 m
Far site
Overburden: 355 m
Empty detectors: moved to underground halls via access tunnel.
Filled detectors: transported between halls via horizontal tunnels.
Ling Ao Near
Overburden: 112 m
900 m
465 m
Ling Ao II
Reactors
(Starting 2011)
Water
hall
810 m
Construction
tunnel
Ling Ao
Reactors
Liquid
Scintillator
hall
295 m
Entrance
Daya Bay Near
Overburden: 98 m
Daya Bay
Reactors

DAYA BAY

Antineutrino Detectors

- Three-zone cylindrical detector design
  - Target: 20 t (0.1% Gd LAB-based LS)
  - Gamma catcher: 20 t (LAB-based LS)
  - Buffer : 40 t (mineral oil)
- Low-background 8" PMT: 192
- Reflectors at top and bottom





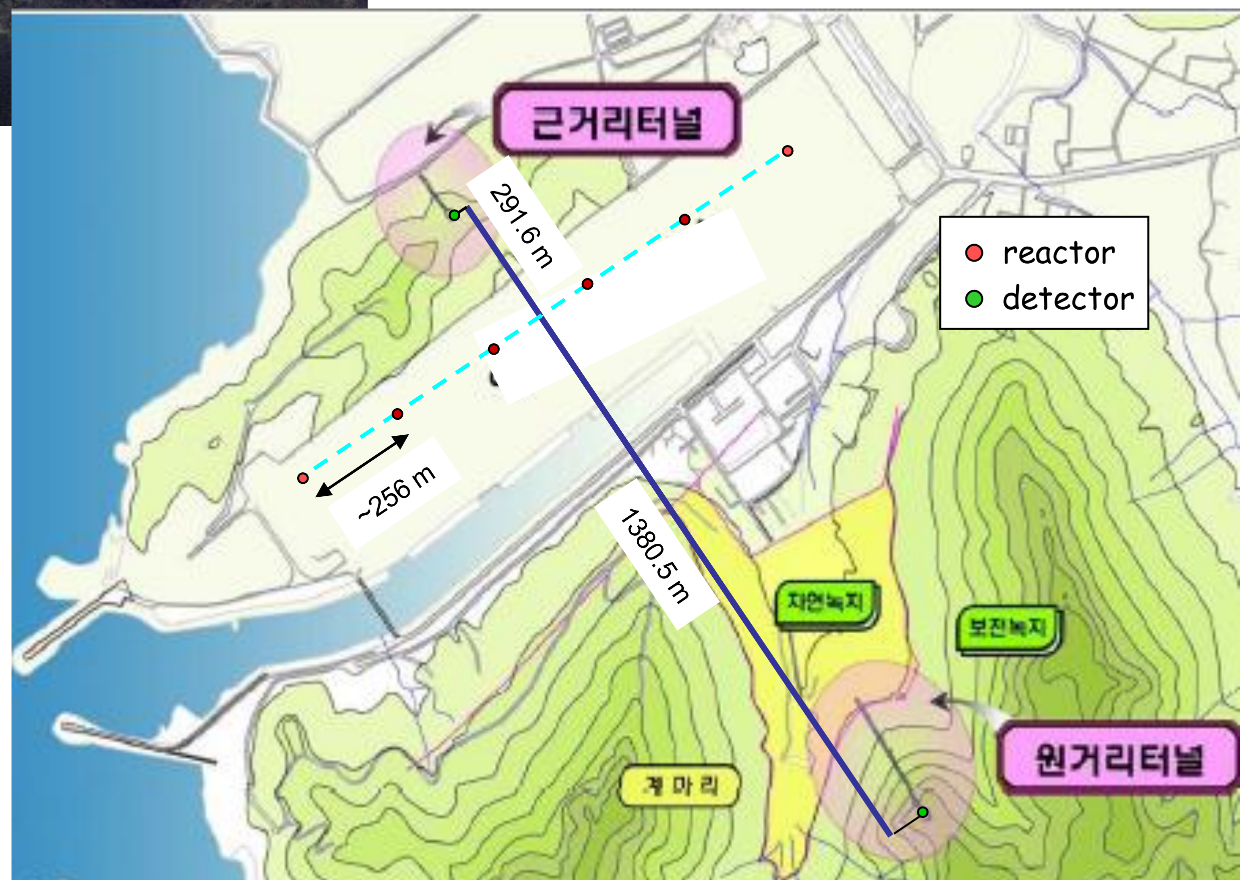
Status: Experimental Components

Link, Neutrino Champagne 2009

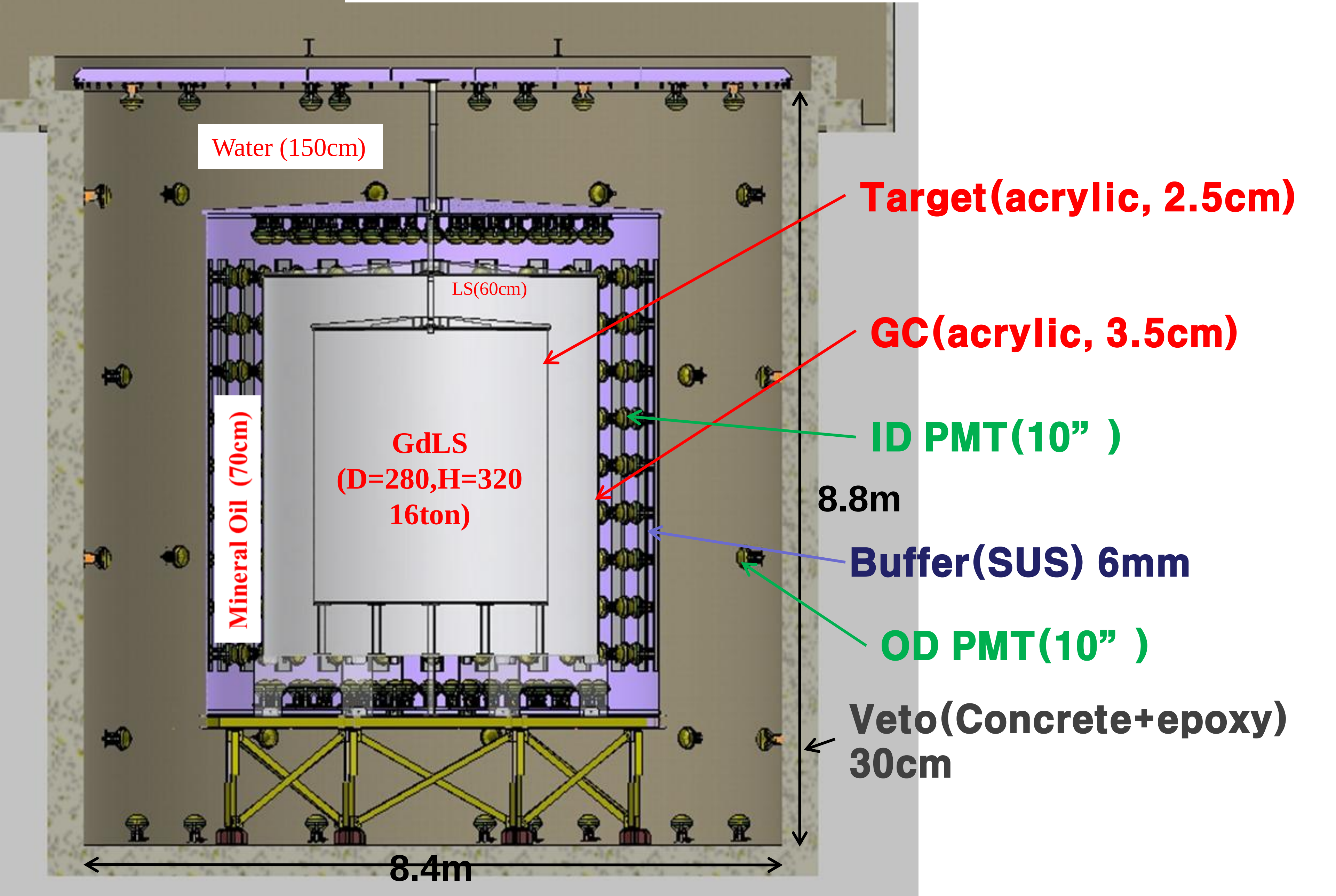
RENO

Yonggwang Nuclear Power Plant

- Six ~ 1 GW_e class PWRs
- Total average thermal power of 16.4 GW (max 17.3 GW)
- Started operation in 1986~2002.
- Operational factor > 90%



RENO Detector Structure (near & far)

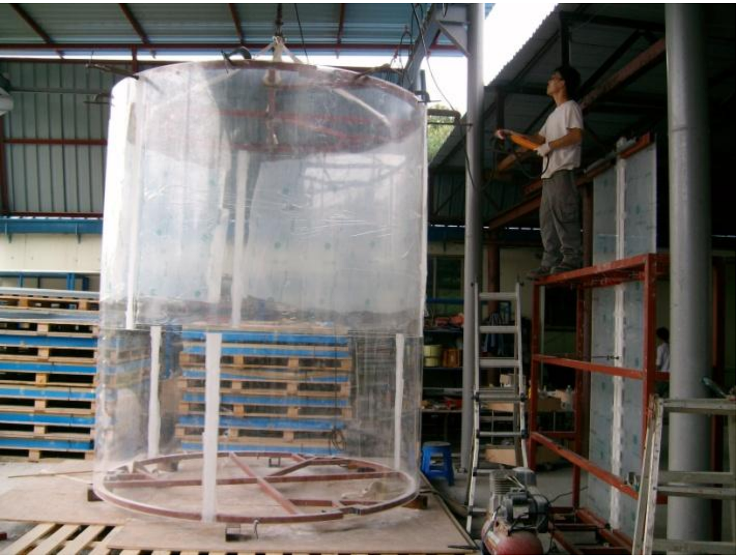


Near & far tunnels are completed

(2008.6~2009.3)

by Daewoo Eng. Co. Korea

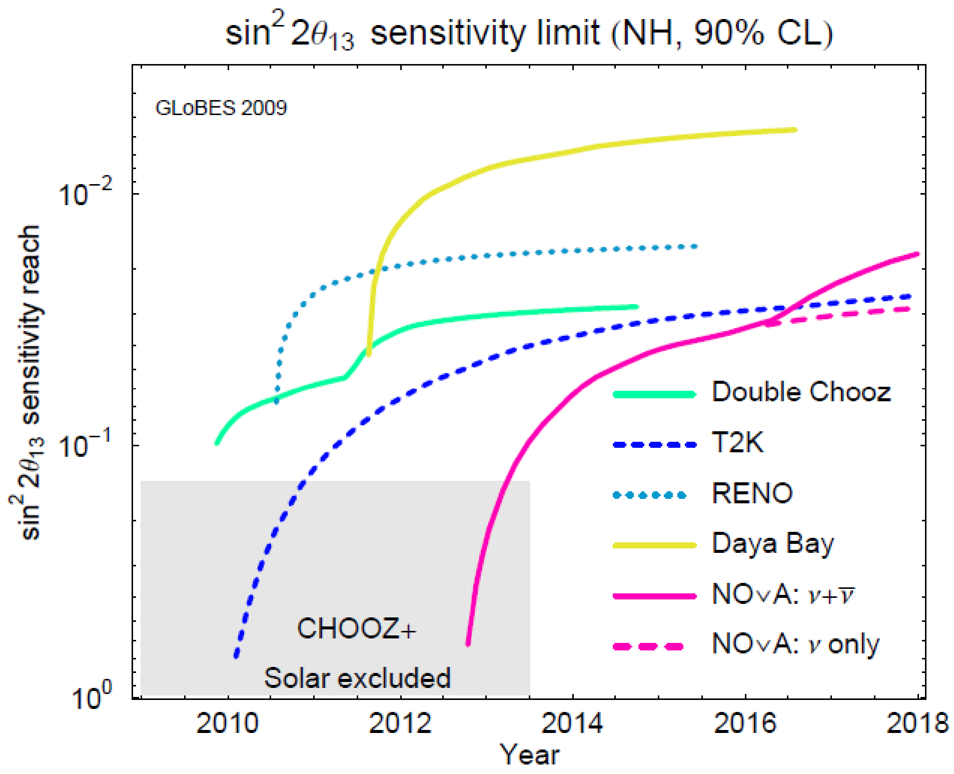
Acrylic vessels will be ready in Nov. 2009

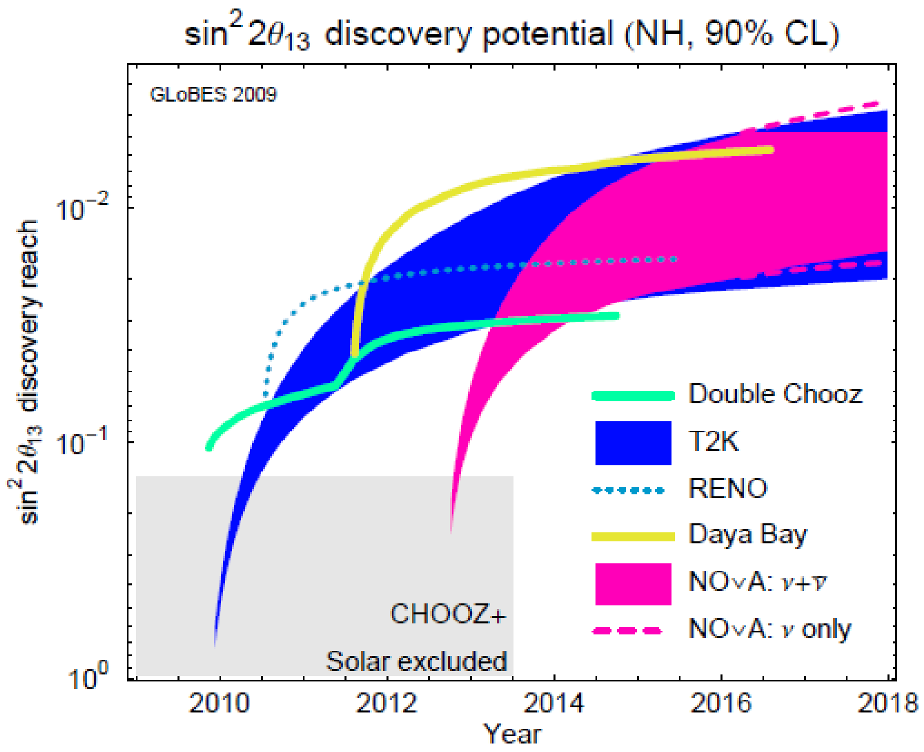


A half of target

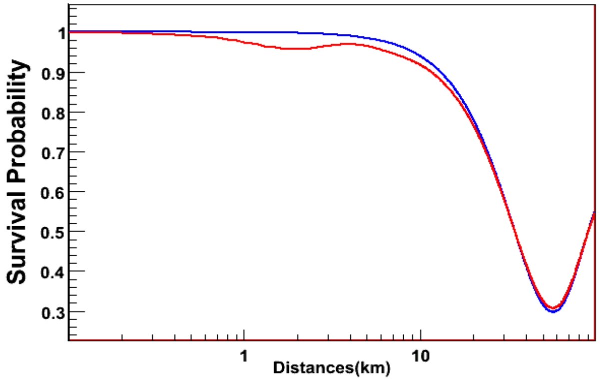
Sensitivities & discovery potential

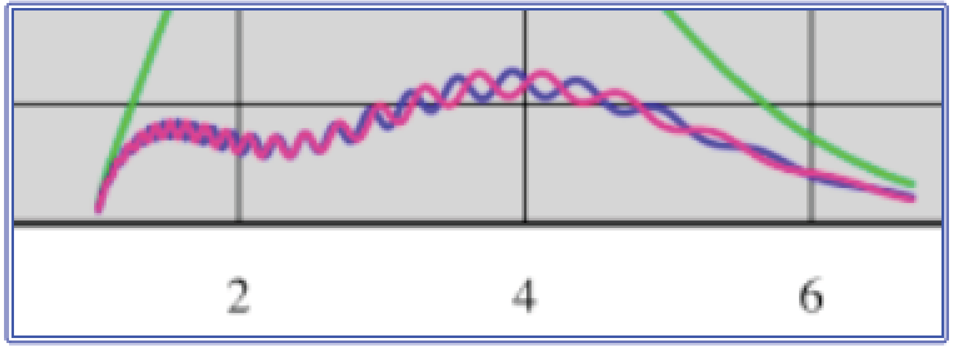
Huber et al., hep-ph/0907.1896





Determination of Mass Hierarchy@50km



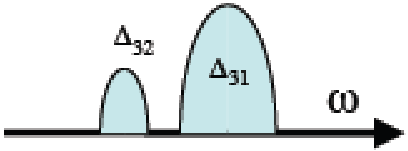


$$\text{Ripple} \propto \sin^2 2\theta_{13}\left(\sin^2\Delta_{31} + \tan^2\theta_{12}\sin^2\Delta_{32}\right)$$

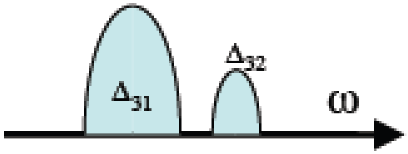
It is essential that θ_{12} is not maximum ($\tan^2\theta_{12}$~0.4)

Fourier Analysis => Power Spectrum Peaks at $\omega = \left|\Delta m^2_{31}\right|, \quad \left|\Delta m^2_{32}\right|$

The smaller peak is $\left|\Delta m^2_{32}\right|$ and larger peak is $\left|\Delta m^2_{31}\right|$,



$\Rightarrow \left|\Delta m^2_{31}\right| > \left|\Delta m^2_{32}\right|$: Normal Hierarchy



$\Rightarrow \left|\Delta m^2_{31}\right| < \left|\Delta m^2_{32}\right|$: Inverted Hierarchy

Summary

- Neutrino mixing parameter θ_{13} is important for lepton sector CP violation, neutrino mass .
- 0 nu Double beta decay depends neutrino mass hierarchy.
- $\sin^2(2\theta_{13})$ = 0.01 – 0.02 sensitivity can be reached with 3 year data of Double Chooz, RENO, DAYA BAY
- Mass hierarchy may be accessible with kTon detector @ 50km base line.