Daya Bay II and Future Reactor Experiments

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Neutrino Oscillation Workshop 2012

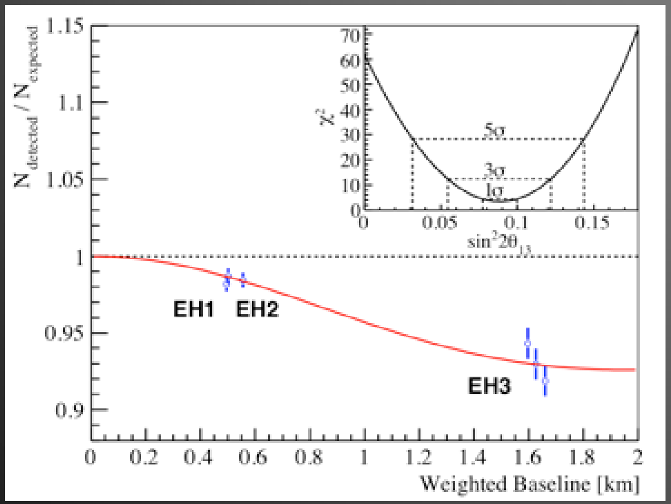
Conca Specchiulla (Otranto, Lecce, Italy)

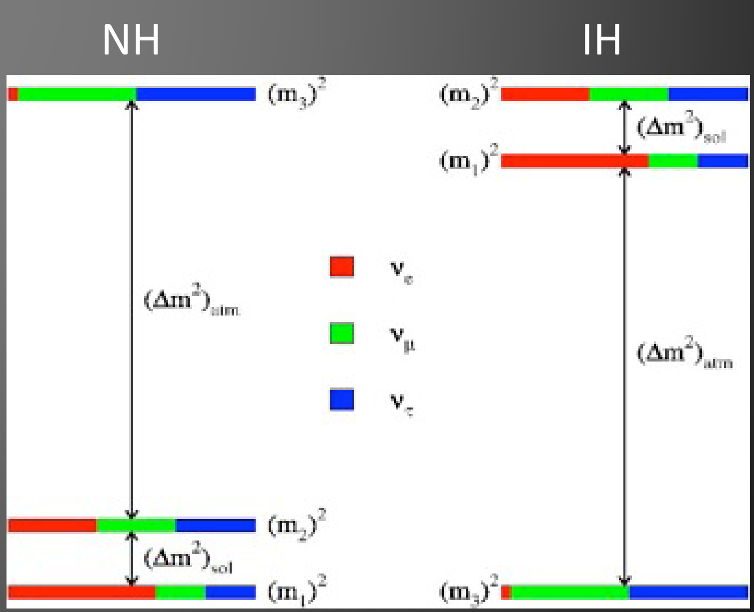
September 9-16, 2012

The large θ_{13} era

- Non-zero and large θ_{13} observed by Daya Bay and the $\sin^2 2\theta_{13}$ precision can reach to 5% in three years.
- Mass hierarchy and CP phase are the main focus of next generation neutrino experiments.
- A medium baseline reactor neutrino experiment can measure mass hierarchy independent of CP phase.

Daya Bay, Dec 24, 2011 - May 11, 2012
$\sin^2 2\theta_{13}$ = 0.089 ± 0.010(stat) ± 0.005(sys)





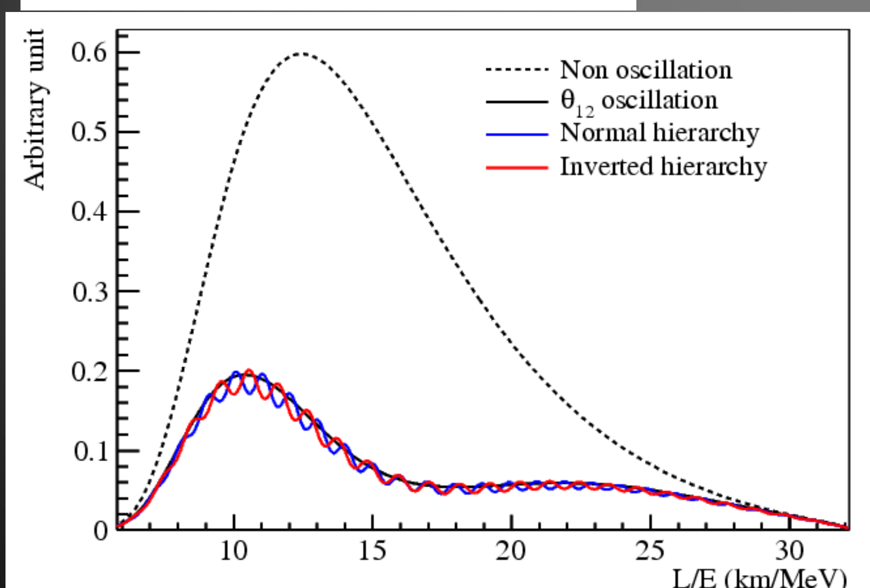
Reactor neutrino to determine MH

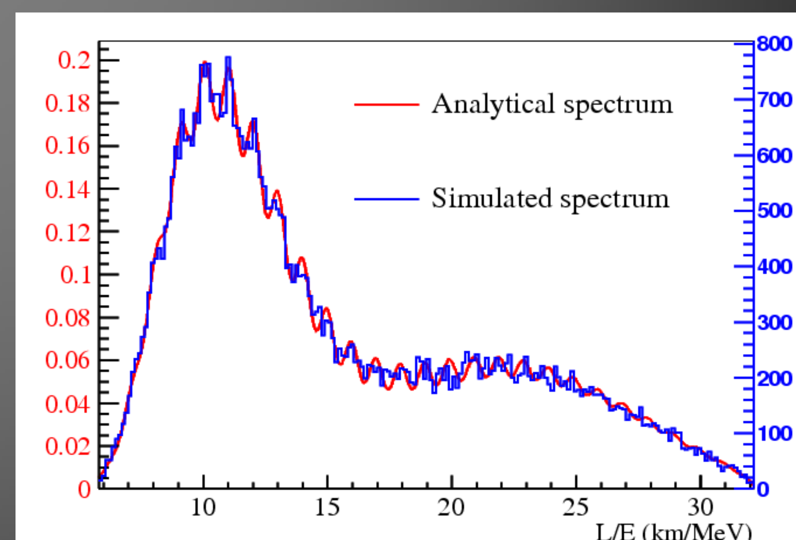
$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

$$
\begin{aligned}
\Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\
\mathrm{NH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\
\mathrm{IH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}|
\end{aligned}
$$

S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., hep-ex/0612022 L.

Zhan, Y. Wang, J. Cao, L. Wen,
PRD78:111103, 2008
PRD79:073007, 2009





50000 events

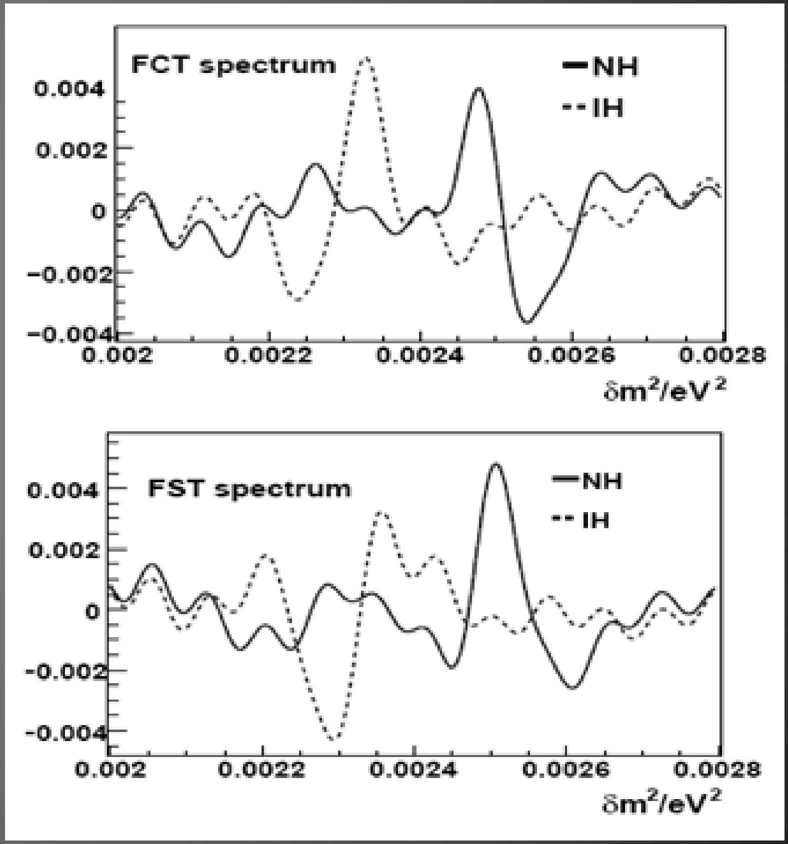
Fourier transform to L/E spectrum

- L/E spectrum⇔δm^2 spectrum (oscillation frequency)

$$F(L/E) = \phi(E)\sigma(E)P_{ee}(L/E)$$

$$FST(\omega) = \int_{t_{min}}^{t_{max}} F(t)\sin(\omega t)\mathrm{d}t$$

$$FCT(\omega) = \int_{t_{min}}^{t_{max}} F(t)\cos(\omega t)\mathrm{d}t$$



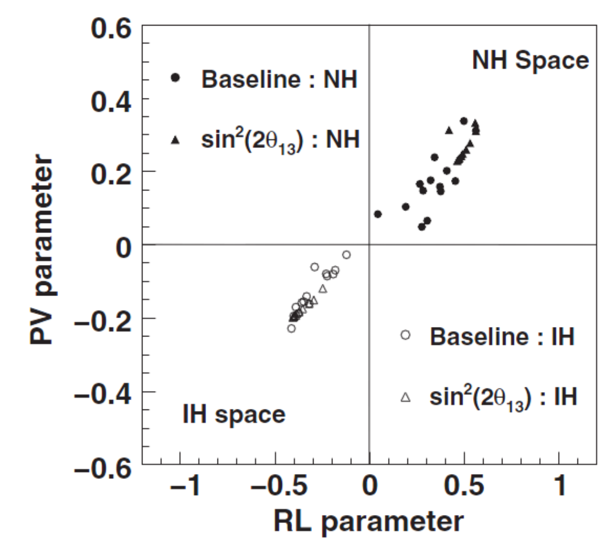
- Clear distinctive features:
  - FCT:
    - NH: valley at the left side
    - IH: valley at the right side
  - FST:
    - NH: prominent peak
    - IH: prominent valley
- **No pre-condition of Δm^2_{32} : features depends on shape but not absolute peak position.**

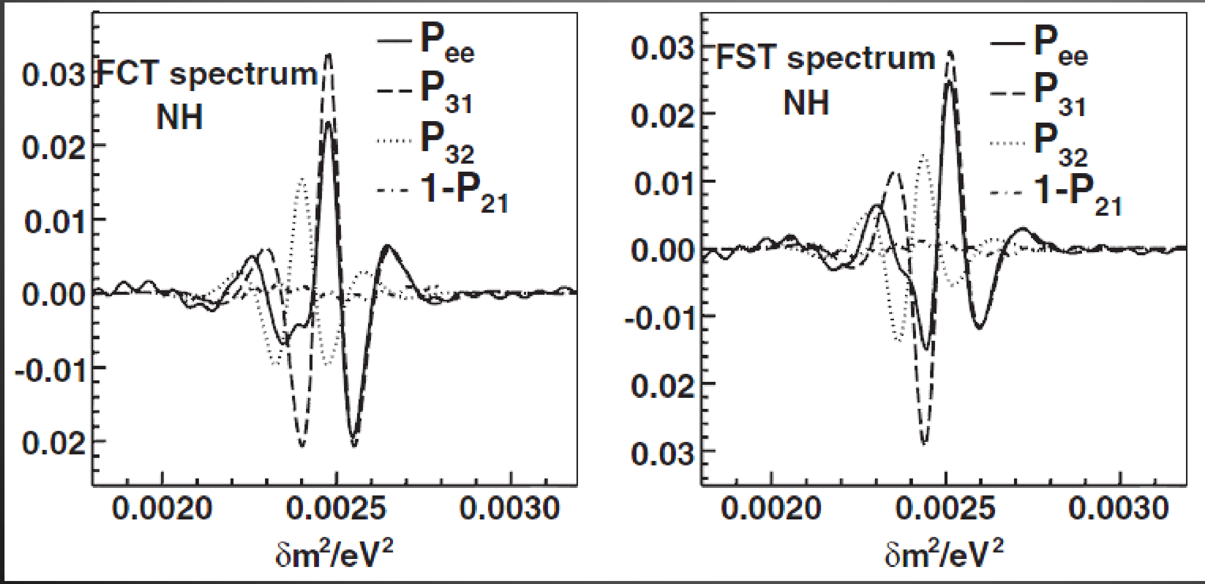
Quantify features of FCT and FST

- Define quantities

$$RL = \frac{RV - LV}{RV + LV}, \ PV = \frac{P - V}{P + V}$$

  – RV/LV: amplitude of the right/left valley in FCT
  – P/V: amplitude of the peak/valley in FST
- NH: PV > 0 and RL >0, IH: PV <0 and RL <0
- Combined to one quantity: PV+RL





L. Zhan et al., PRD78:111103,2008

Considering experimental conditions

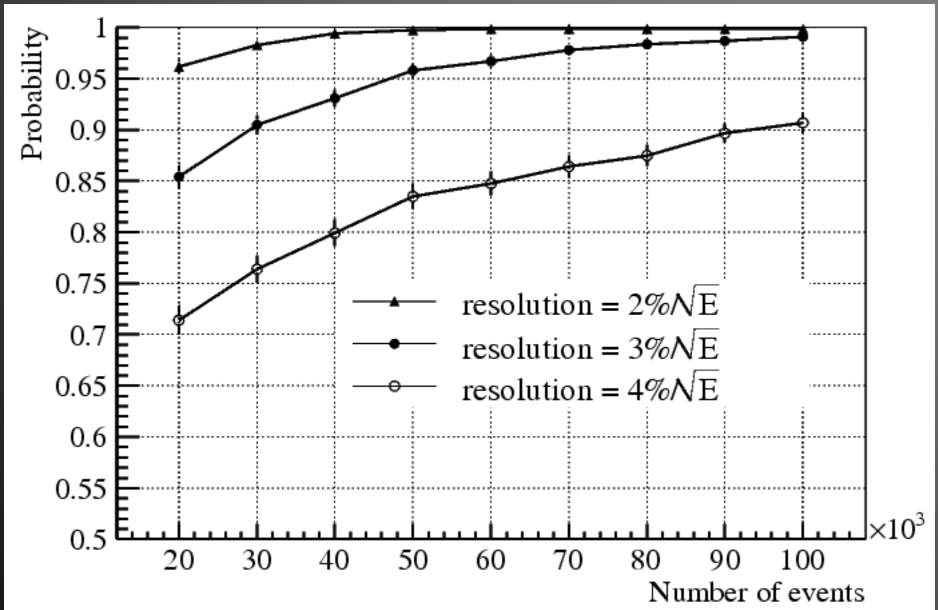
- Un-binned Fourier transform of N detected events

$$FST(\omega) = \sum_{i=1}^{N} \sin(\omega L/E_i'), \quad FCT(\omega) = \sum_{i=1}^{N} \cos(\omega L/E_i'),$$

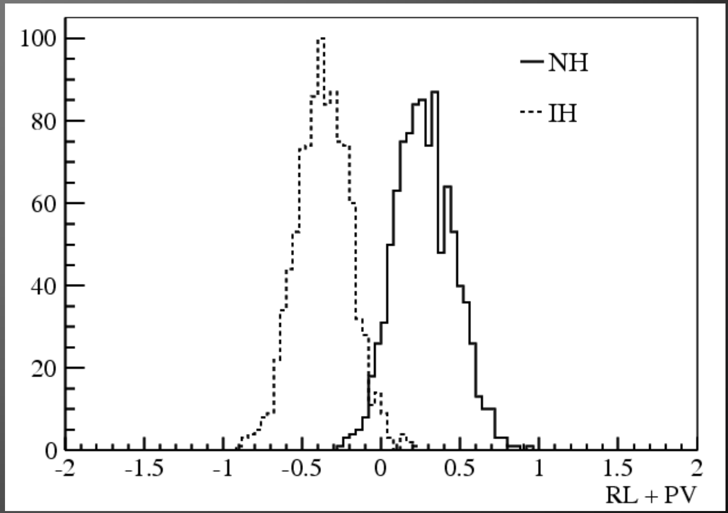
- Energy resolution is very important for Δm^2_{32} and Δm^2_{31} oscillation measurement.

Energy resolution	3%/sqrt(E)
Baseline	58 km
Thermal Power	35 GW

50 k events = 20 kt x 3-years



96% discrimination power ($\sin^2 2\theta_{13}$ = 0.089)



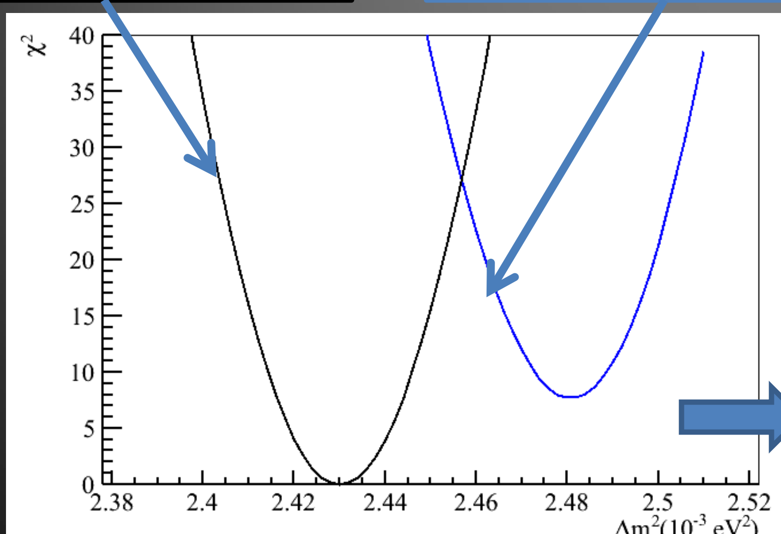
Alternative method to FT: χ^2 fit

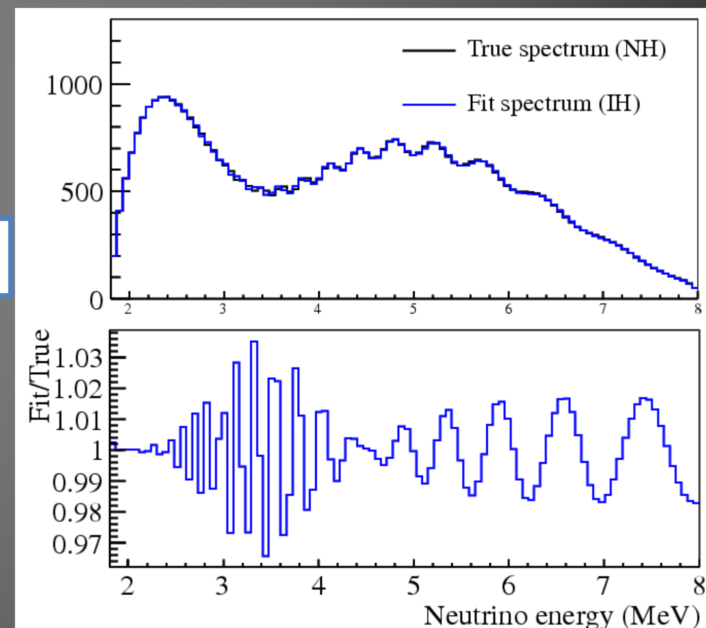
- Assume the truth is NH/IH, and calculate the truth spectrum.
- Calculate the spectra for NH and IH case and fit them to the truth spectrum respectively.
- Energy resolution is taking into account.

$$\chi^2 = \sum_i \frac{(F_i(\Delta m^2) - T_i(1+\varepsilon+\varepsilon_i))^2}{T_i} + \left(\frac{\varepsilon}{\sigma}\right)^2 + \left(\frac{\varepsilon_i}{\sigma_i}\right)^2$$

NH spectrum fits to NH

IH spectrum fits to NH

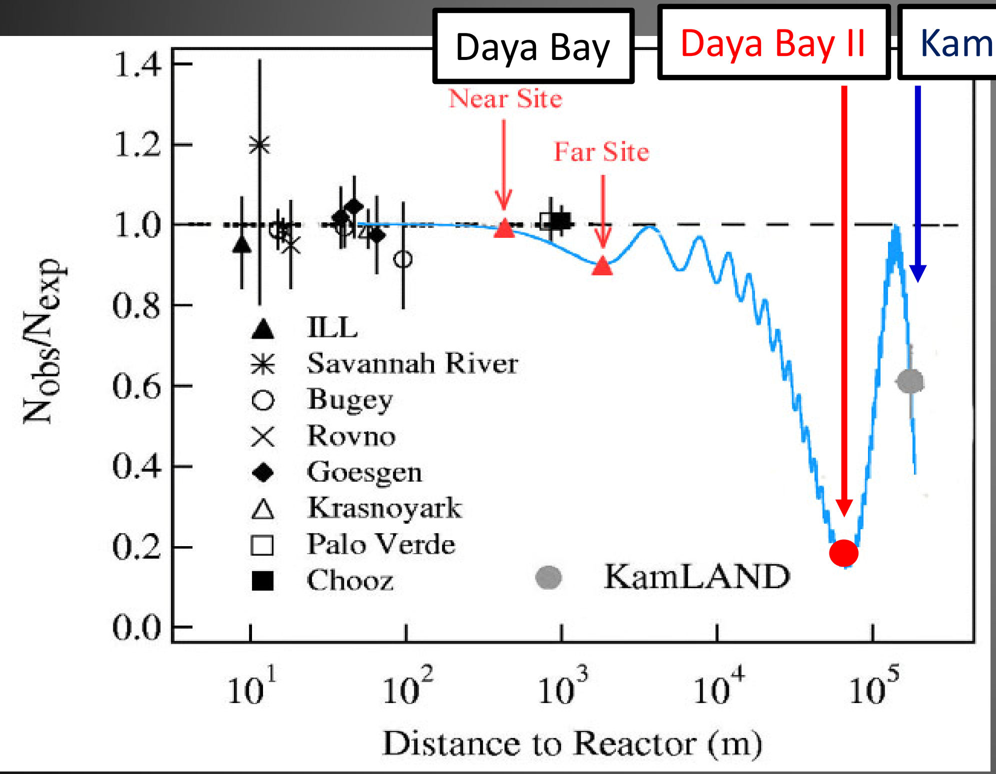




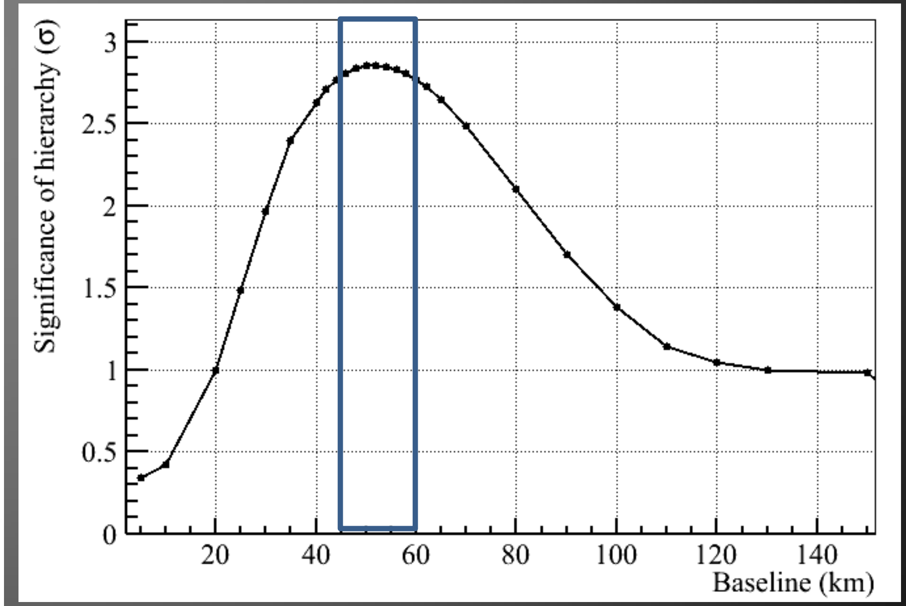
If truth is NH, NH spectrum may fit it better. Δm^2 is fitted without constrain.

Optimal baseline

- Proper baseline: 45-60 km, around θ_{12} oscillation maximum.



20 kt detector and 3 years

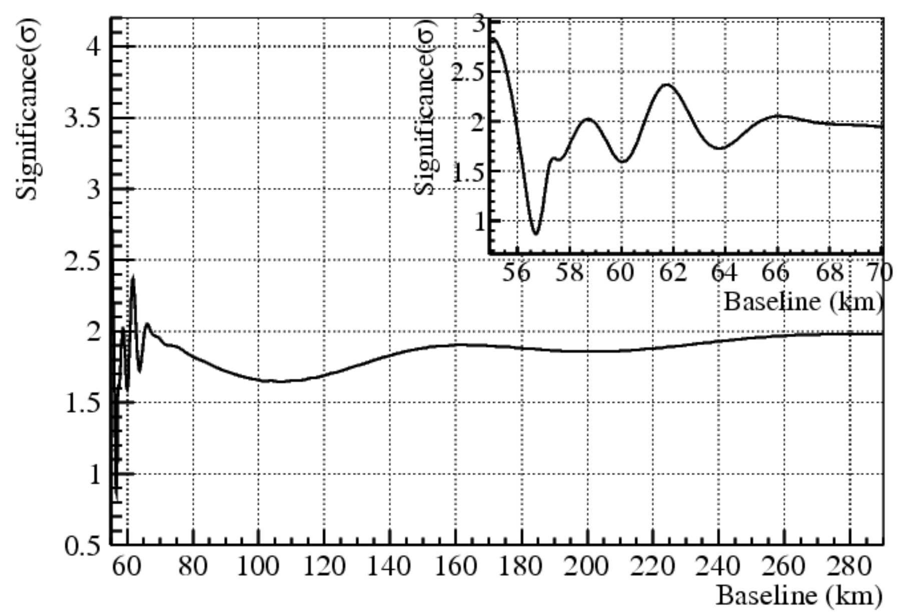


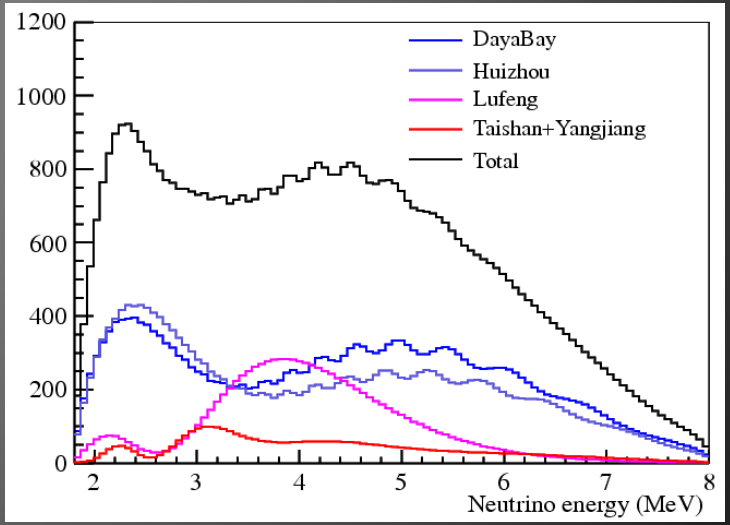
The reactors and possible sites

	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW

Complex interference between reactors

- Adding one reactor (more statistics) is not always helpful.
- Example:
  - One reactor (6X2.9 GW) at 55 km, the significance is 2σ.
  - Add another reactor
    - Statistics doubles with equal baseline.
    - Helpful, if the baseline difference < 1 km.
    - Harmful as background, if the baseline difference > 1 km.
    - The worst baseline difference is 2 km due to θ_{13} oscillation cancellation.





Example of peak and valley cancellation

Scientific Goals

1. Neutrino Mass hierarchy
2. Precision measurement of mixing parameters: θ_{12}, ΔM^2_{12}, ΔM^2_{31} ➔ test the unitarity of the mixing matrix
3. Supernova neutrinos
4. Geo-neutrinos
5. Exotics searches
    1. Sterile neutrinos
    2. Monopoles, fractional charged particles, ….
6. Target for neutrino beams
7. Atmospheric neutrinos
8. Solar neutrinos
9. High energy cosmic-rays & neutrinos
    1. Point source: GRB, AGN, BH, …
    2. Diffused neutrinos
    3. Dark matter

Precision measurement of mixing parameters

- Fundamental to the Standard Model and beyond
- Probing the unitarity of U_{PMNS} to ~1% level !

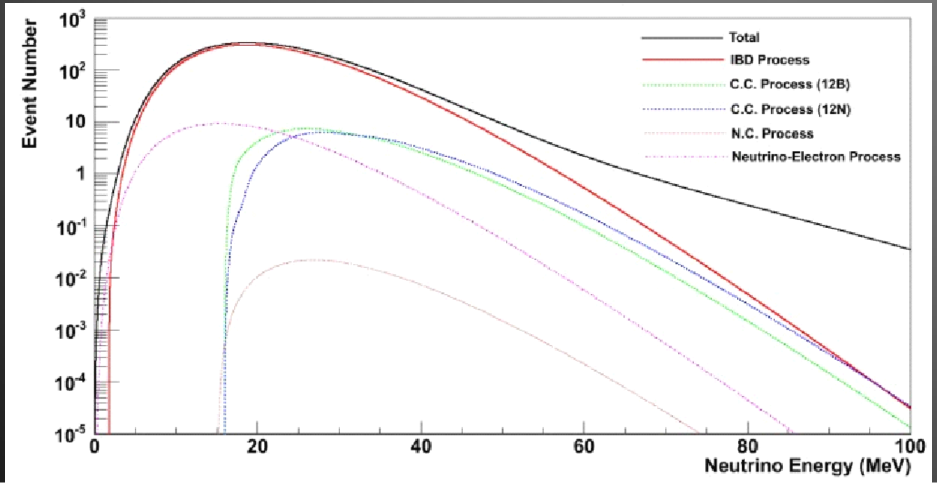
	Current	Daya Bay II
Δm^2_{12}	3%	< 1%
Δm^2_{31}	5%	< 1%
$\sin^2\theta_{12}$	6%	< 1%
$\sin^2\theta_{23}$	20%	-
$\sin^2\theta_{13}$	14% ➔ 5% (Daya Bay in 3 years)	-

To be elaborated, may need near detectors < 1 km.

Supernova neutrinos

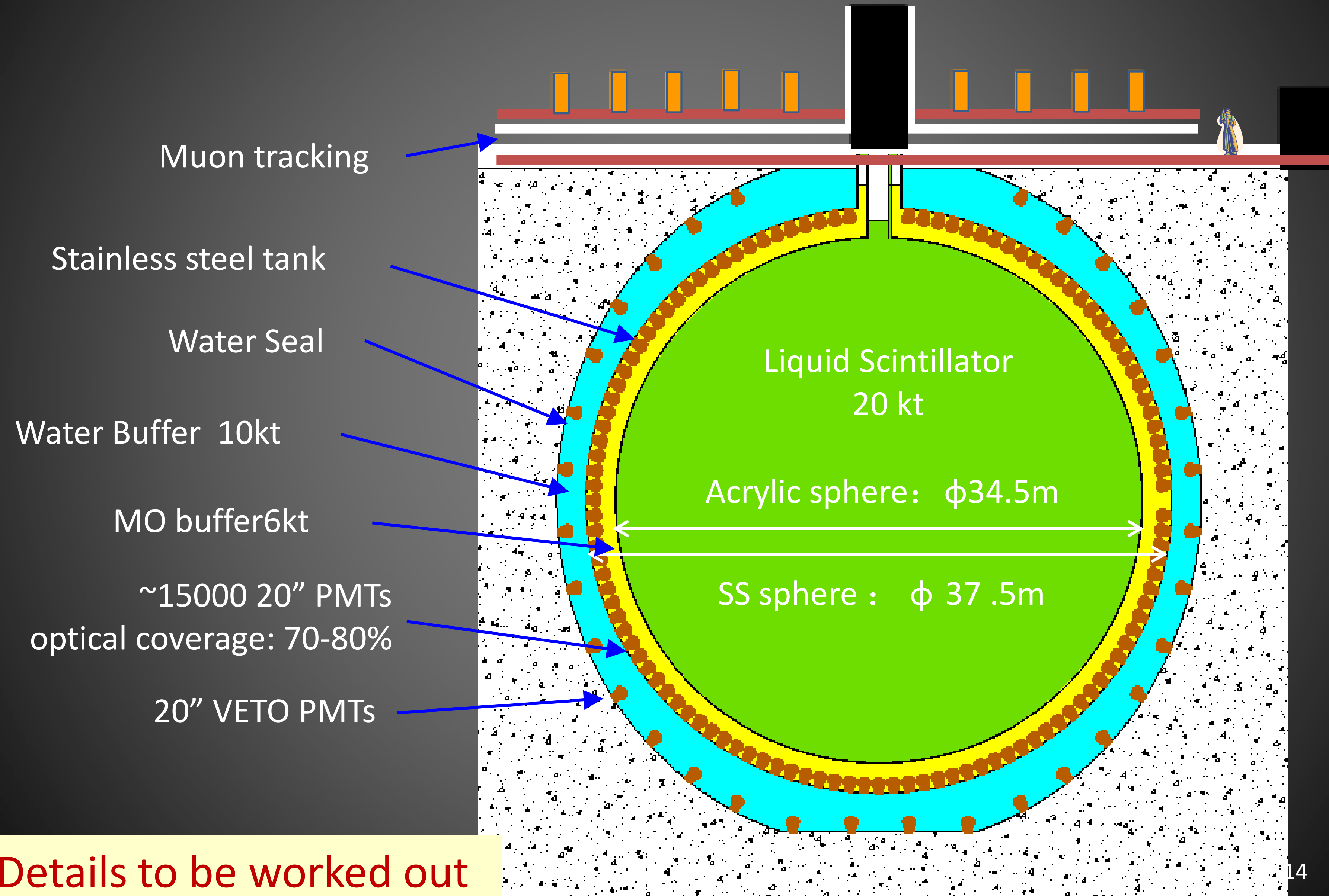
- Less than 20 events observed so far
- Assumptions:
  - Distance: 10 kpc (our Galaxy center)
  - Luminosity: 3×10^{53} erg
  - Detector: 20 kt scintillator
- Many types of events:
  - $\bar{\nu}_e + p \rightarrow n + e^+$, ~ 3000 correlated events
  - $\bar{\nu}_e + {}^{12}C \rightarrow {}^{12}B^* + e^+$, ~ 10-100 correlated events
  - $\nu_e + {}^{12}C \rightarrow {}^{12}N^* + e^-$, ~ 10-100 correlated events
  - $\nu_x + {}^{12}C \rightarrow \nu_x + {}^{12}C^*$, ~ 600 correlated events
  - $\nu_x + p \rightarrow \nu_x + p$, single events
  - $\nu_e + e^- \rightarrow \nu_e + e^-$, single events
  - $\nu_x + e^- \rightarrow \nu_x + e^-$, single events

Water Cerenkov detectors can not see these correlated events



Energy spectra & fluxes of all types of neutrinos

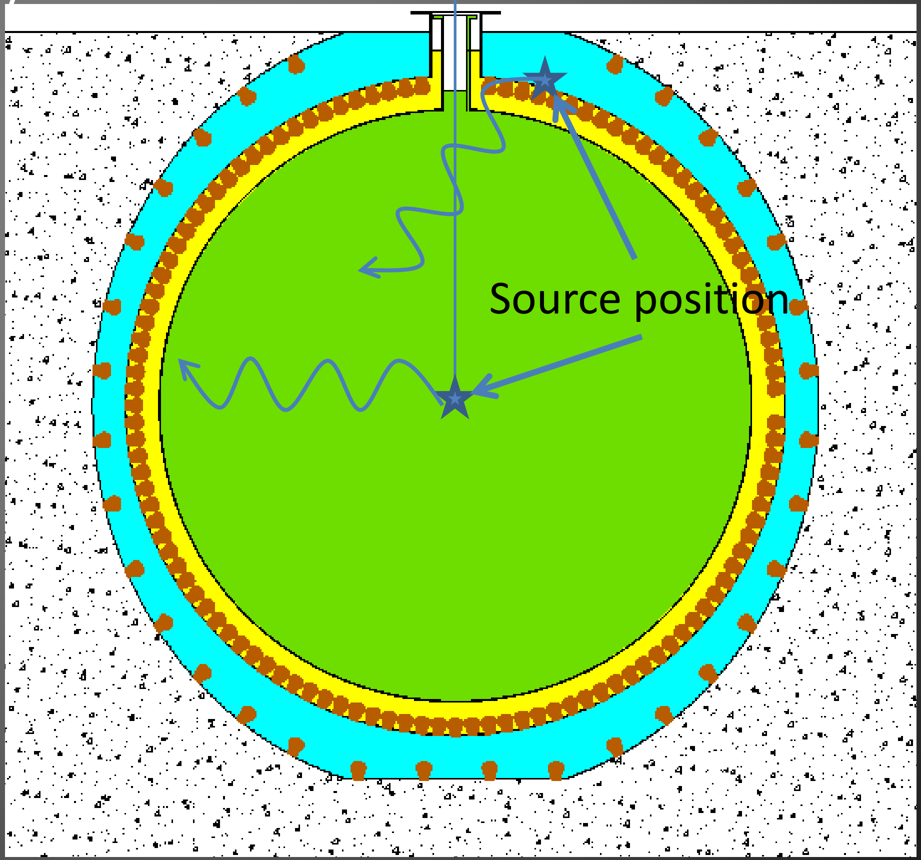
Detector Concept



Details to be worked out

Sterile neutrino

- Put radioactive source in detector (L = 0-17 m, larger acceptance) or outside of detector (L = 2- 34 m, smaller acceptance)
- Vertex reconstruction to determine baseline L.
- Measure the oscillation vs. L/E.



Isotopes produced by reactor with E_ν > 1.8 MeV and $T_{1/2}$ > 10 h

M	$T_{1/2}$	E_0/MeV	D	$T_{1/2}$	E_0/MeV
^{90}Sr	28.78a	0.546	Y	64.1h	2.282
^{91}Sr	9.63h	2.699	Y	58.51d	1.544
^{93}Y	10.18h	2.874	Zr	1.53e6a	0.091
^{97}Zr	16.9h	2.658	Nb	72.1m	1.934
^{106}Ru	373.6d	0.039	Rh	29.8s	3.541
^{112}Pd	21.03h	0.288	Ag	3.13h	3.956
^{125}Sn	9.64d	2.364	Sb	2.758a	0.767
^{131m}Te	30h	0.182	Te	25m	2.233
^{132}Te	3.204d	0.493	I	2.295h	3.577
^{159}Sm	9.4h	0.722	Eu	15.19d	2.451
^{140}Ba	12.75d	1.047	La	1.678d	3.762
^{144}Ce	284.9d	0.319	Pr	17.28m	2.997

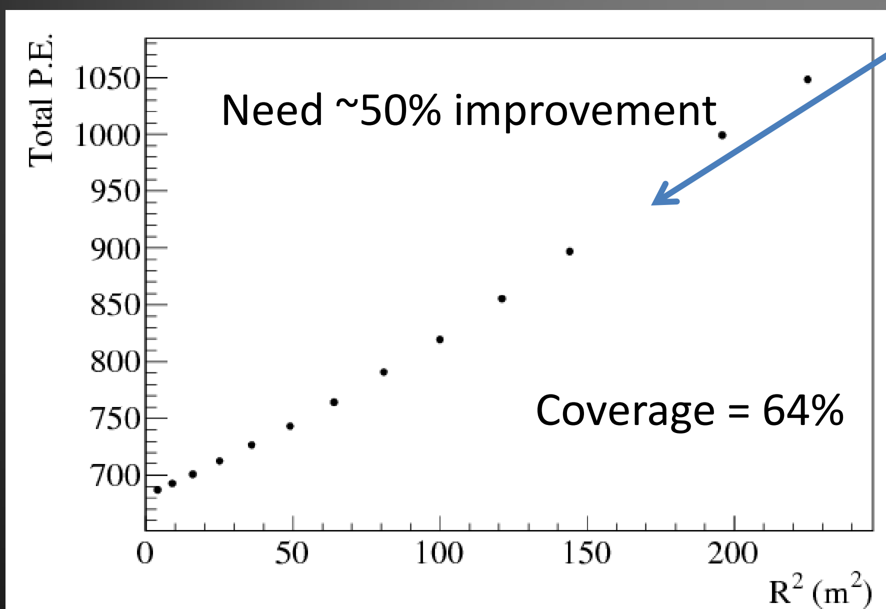
Technical challenges

- Requirements:
  - Large detector: 20 kt LS
  - Energy resolution: 3%/√E ➔ 1200 p.e./MeV
- Ongoing R&D:
  - Low cost, high QE "PMT"
    - New type of PMT
  - Highly transparent LS: 15m ➔ >20m
    - Understand better the scintillation mechanism
    - Find out traces which absorb light, remove it from the production

Energy resolution

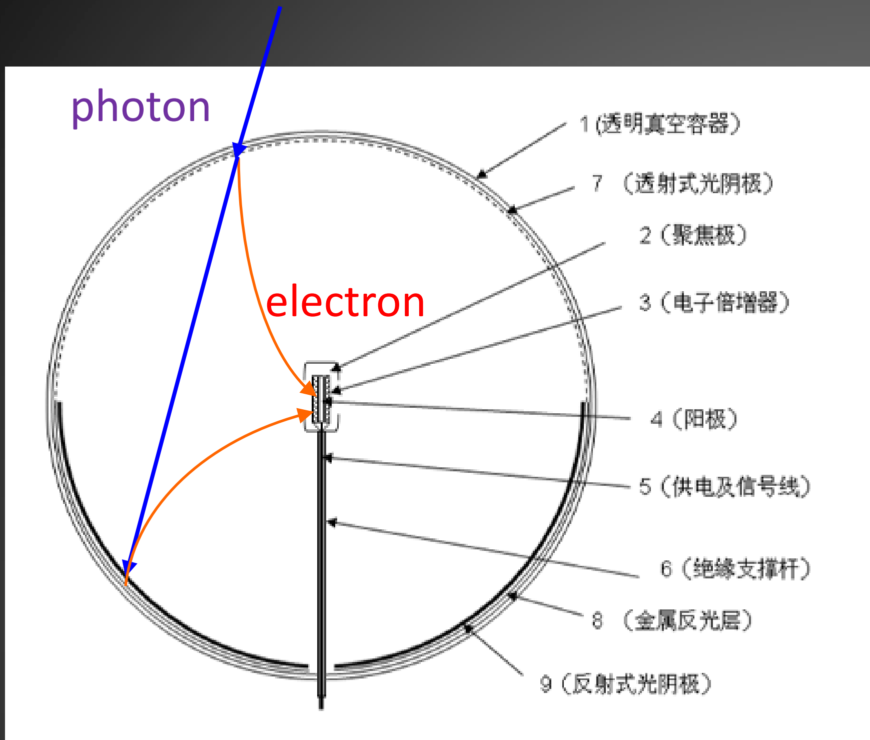
	KamLAND	Daya Bay II
Detector	~1 kt Liquid Scintillator	20 kt Liquid Scintillator
Energy Resolution	6%/√E	3%/√E
Light yield	250 p.e./MeV	1200 p.e./MeV

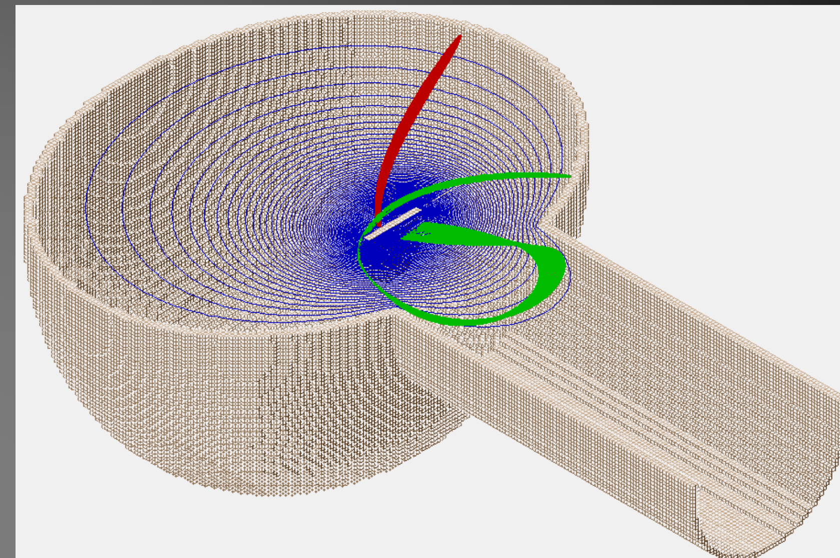
How?



- Daya BayII preliminary simulation
  - Use Daya Bay's PMT and LS.
  - Use Daya Bay's result 161 P.E./MeV as normalization.
  - Modify geometry
- Possible improvements > 50%
  - High PMT QE (SBA) or new PMT (MCP-PMT), 20% → 30%
  - Other options
    - Coverage: 64%→75%
    - More transparent LS
    - Low temperature scintillator

A new type of PMT: high photon detection eff.

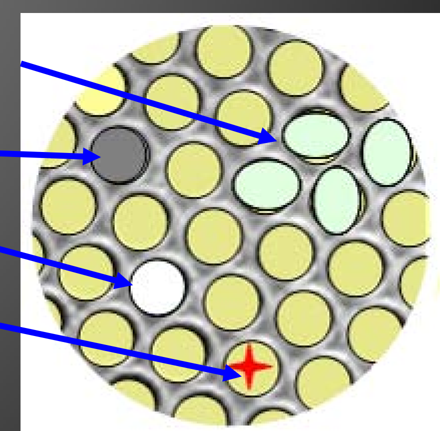




- Top: transmitted photocathode
- Bottom: reflective photocathode
  additional QE: ~ 80%*40%
- MCP (Microchannel Plate) to replace Dynodes → no blocking of photons

Low cost MCP by accepting the followings for SPE detection.

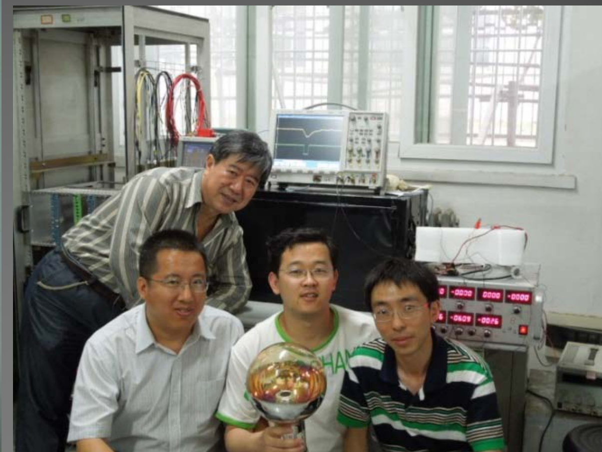
1. Asymmetric surface;
2. Blind channels;
3. Non-uniform gains
4. Flashing channels



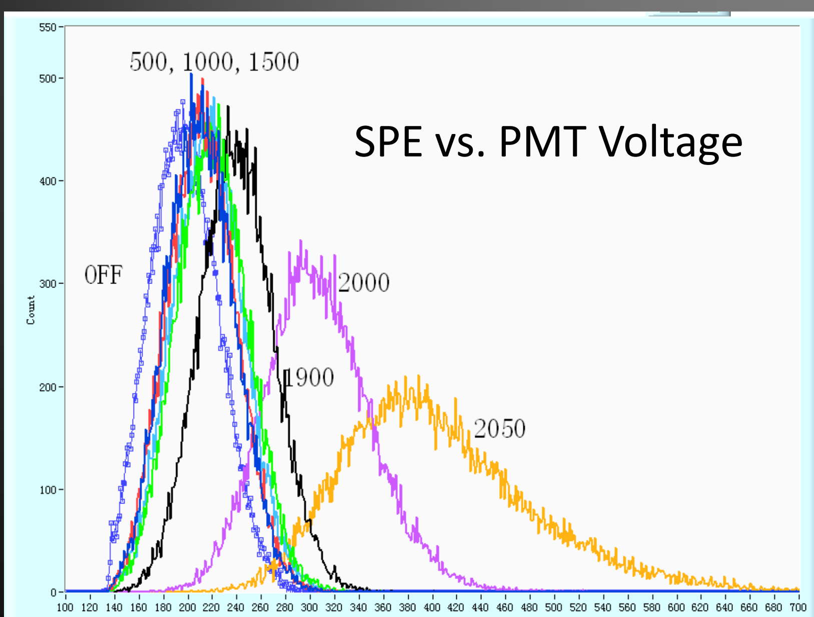
MCP surface

Prototypes

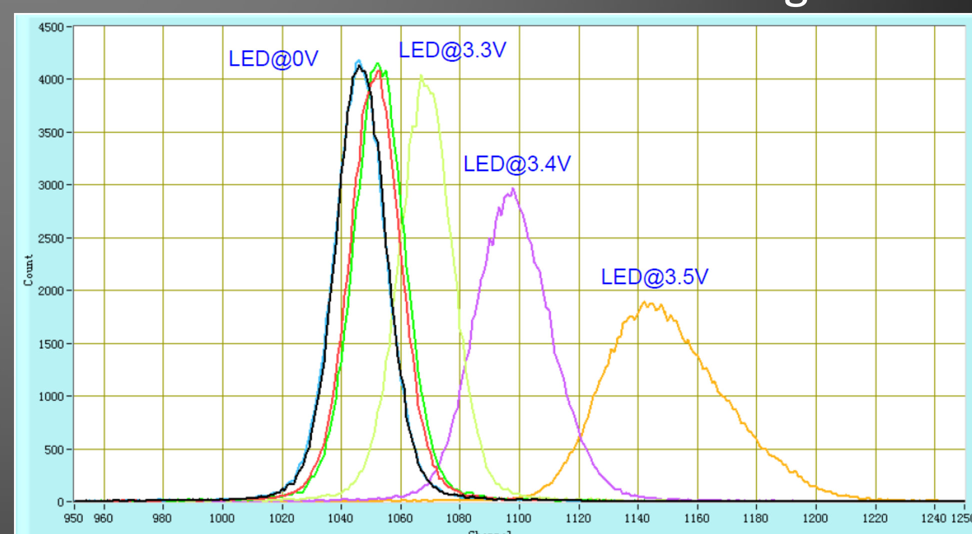
5” MCP-PMT



8” MCP-PMT



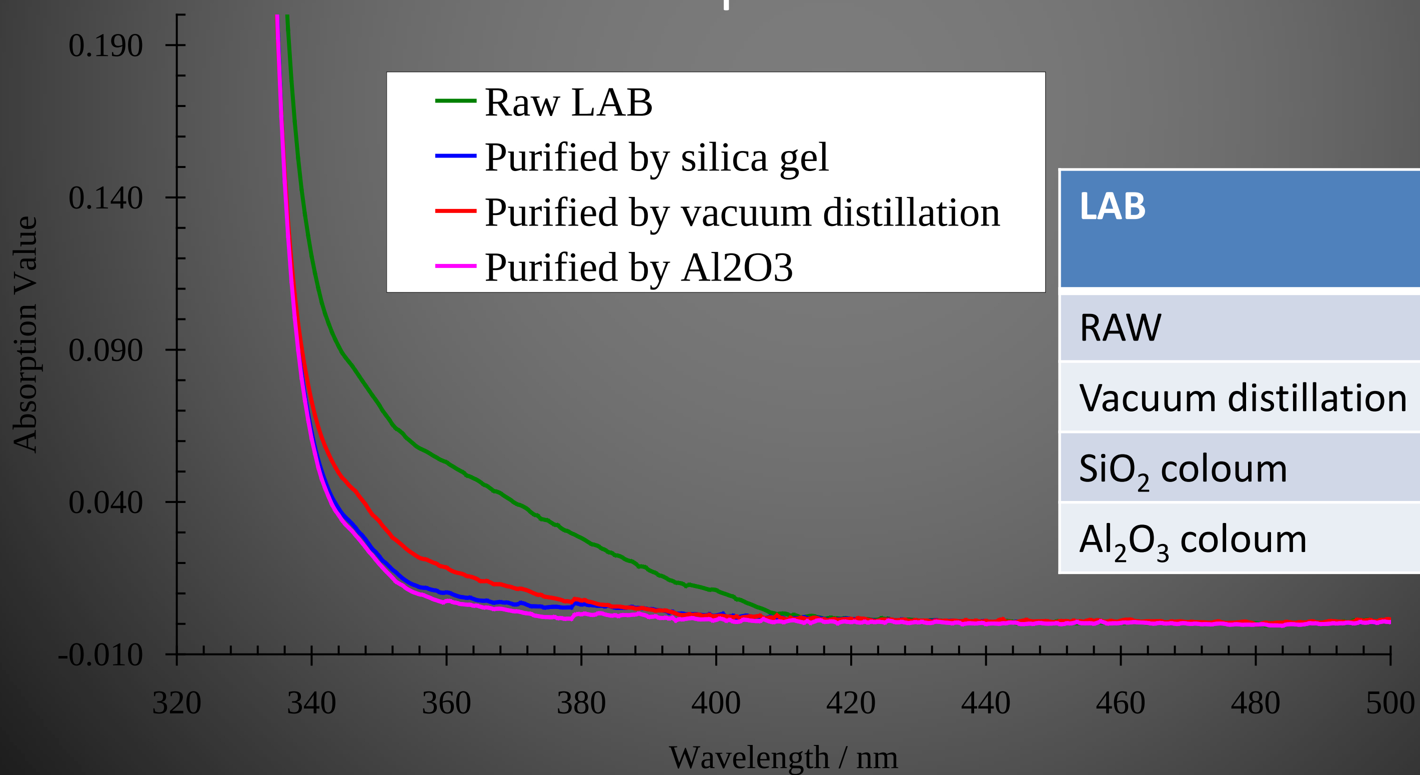
MPE vs the luminance of the LED light



LAB based liquid scintillator

- To enhance the attenuation length
  - Improve raw materials (using Dodecane instead of MO）
  - Improve the production process for large volume
  - Purification

Test on purification



LAB	Atte. Length @ 430 nm
RAW	14.2 m
Vacuum distillation	19.5 m
SiO_2 coloum	18.6 m
Al_2O_3 coloum	22.3 m

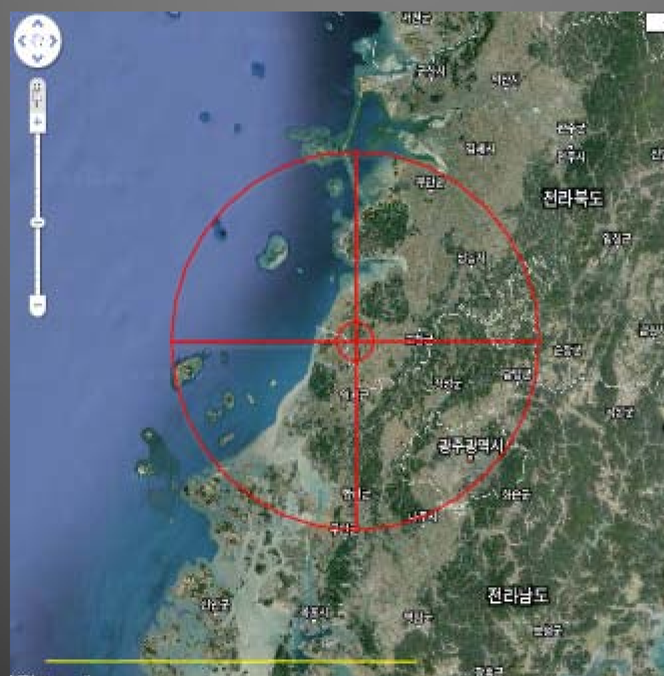
Other future reactor experiments

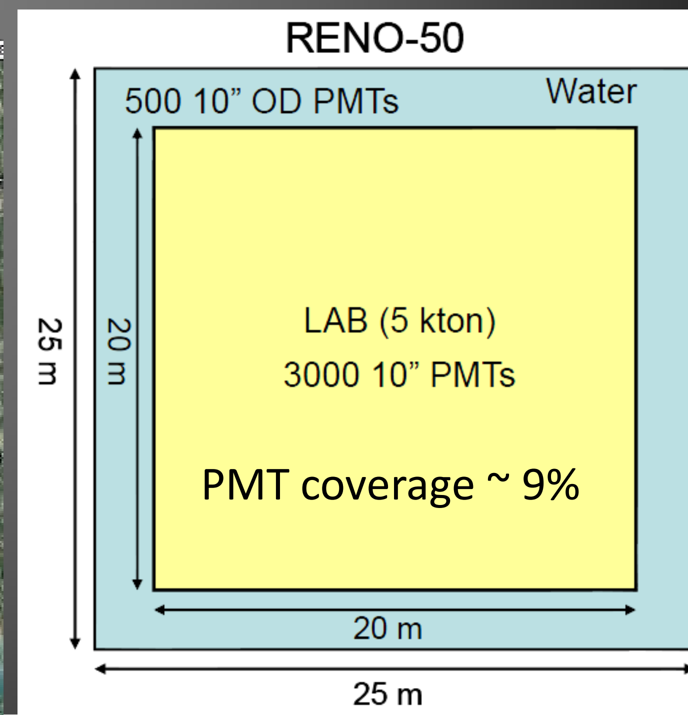
- RENO-50: 5000 tons ultra-low-radioactivity Liquid Scintillation Detector at L = 50 km.

$$\frac{\delta \sin^2\theta_{12}}{\sin^2\theta_{12}} \sim 1.0\%(1\sigma) \quad \text{in a year}$$

S.B. Kim, talk at Neutrino 2012

- Mass Hierarchy
- Solar neutrino
- Geoneutrino
- Supernovae
- T2K beam
- Exotic





Summary

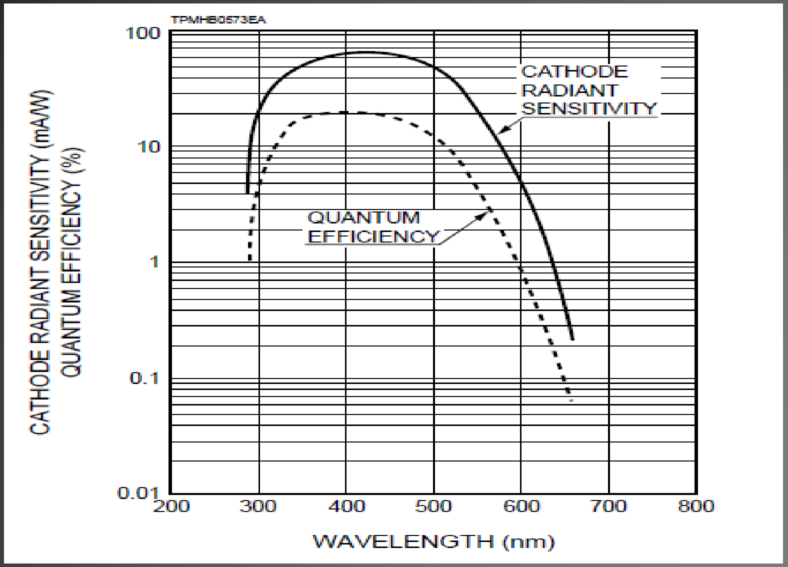
- The large θ_{13} discovery accelerates the experiments on mass hierarchy and CP phase.
- Daya Bay II proposed in 2008-2009, now boosted by the large θ_{13}
  - Science case is strong with significant technical challenges
  - Funding are promising
  - Possible time schedule:
    - Proposal to government: 2015
    - Construction: 2016-2020

Thanks colleagues for providing slides and materials

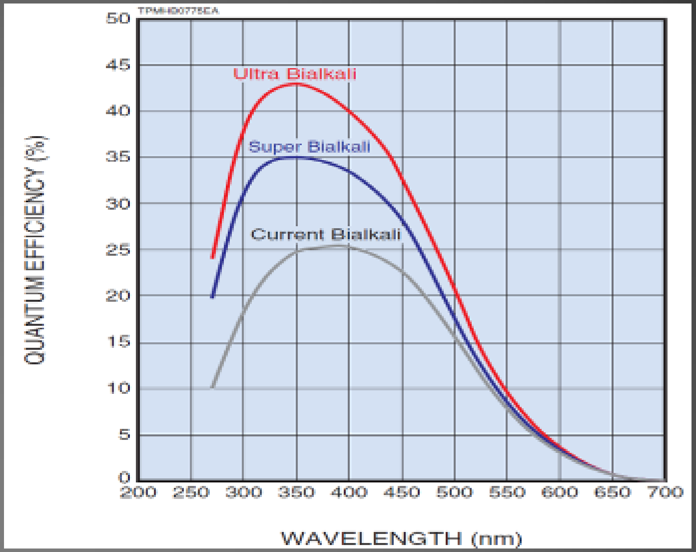
backup

The Quantum Efficiency of PMT

The QE of 20“ PMT-R3600



The QE of SBA/UBA



High QE PMTs: SBA (35%) and UBA (43%)

are only available in small format (< 5" diameter ?)

➢Can we improve the Quantum Efficiency of Photocathode or

Photon Detection Efficiency for the large area 20” PMT ?

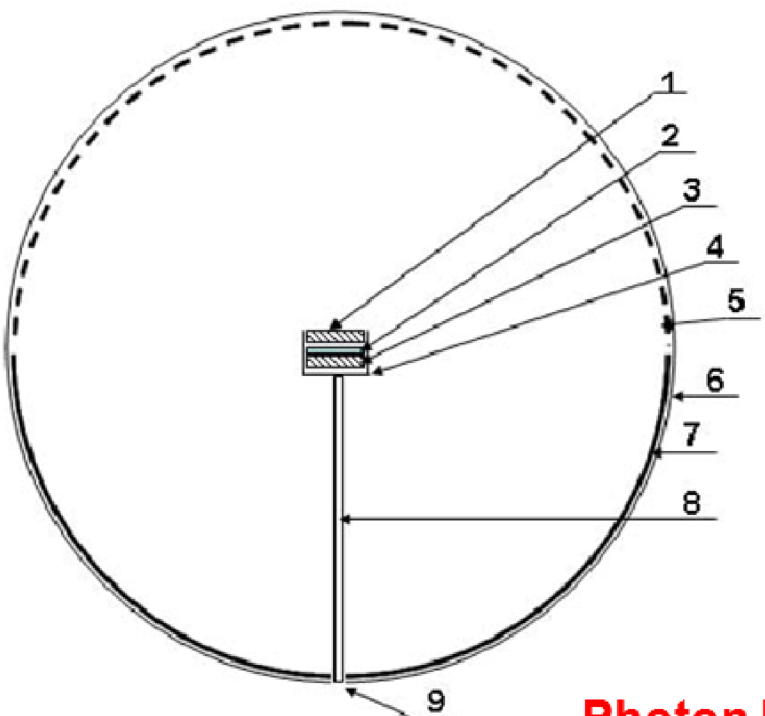
QE: 20%→30%

The new design of a large area PMT

High photon detection efficiency + Single photoelectron Detection + Low cost

1) **Using transmission photocathode (front hemisphere) and reflective photocathode (back hemisphere)** ⇨ **~ 4π viewing angle!!**

2) **Using two sets of Microchannel plates (MCPs) to replace the dynode chain**



1. up MCP
2. anode
3. down MCP
4. insulated trestle table
5. transmission photocathode
6. glass shell
7. reflection photocathode
8. bracket of the cables
9. glass joint

- **Quantum Efficiency:**

  Transmission photocathode: 30%

  Reflection photocathode: 35%

- **MCP Collection Efficiency:** 70%

Photon detection efficiency:

30% * 70% = 21%

40% * 35% * 70% = 9.8%

- **Total Photon Detection Efficiency:** ~ 30.8%

Photon Detection Efficiency: 15.4% → 30.8% × **~2 at least**