Daya Bay II: A multi-purpose reactor neutrino experiment

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Outline

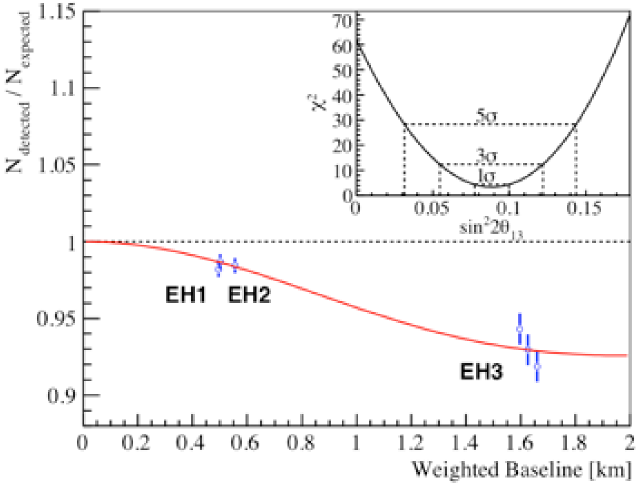
- Physics
- Challenges
- Detector concepts
- Site optimization and civil
- Schedule
- Summary

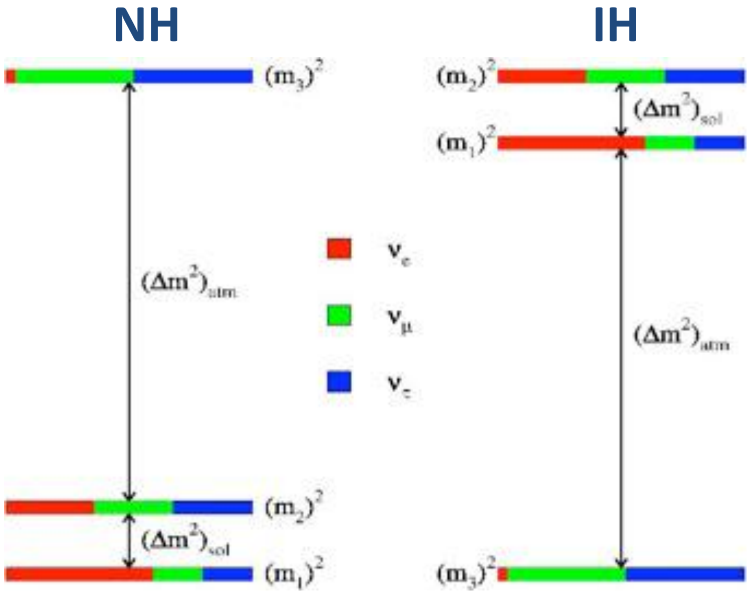
The large θ_{13} era

- The non-zero and large θ_{13} has been observed by Daya Bay, Double Chooz, Reno, and accelerator experiments
- Daya Bay will measure $\sin^2 2\theta_{13}$ to 4-5% precision 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

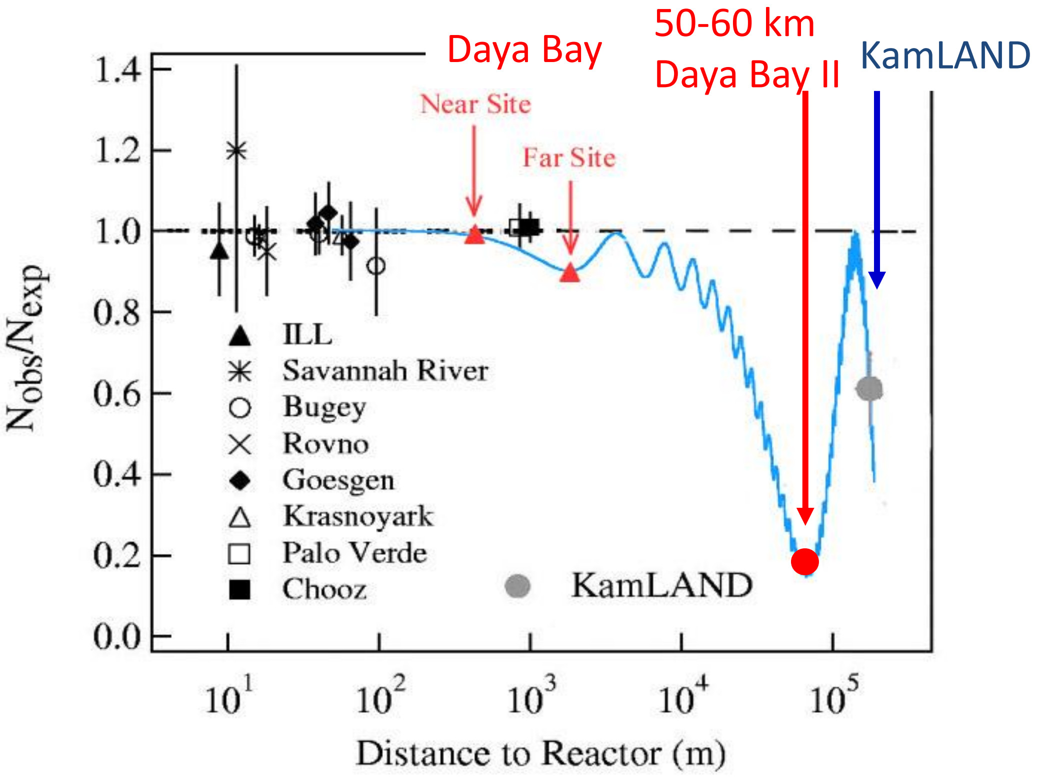
$\sin^2 2\theta_{13} = 0.089 \pm 0.010\text{(stat)} \pm 0.005\text{(sys)}$





Daya Bay II Experiment

- 20 kton LS detector
- 2-3 % energy resolution
- Rich physics possibilities
  - **Mass hierarchy**
  - Precision measurement of 3 mixing parameters
  - Supernova neutrino
  - Geoneutrino
  - Sterile neutrino
  - Atmospheric neutrinos
  - Exotic searches



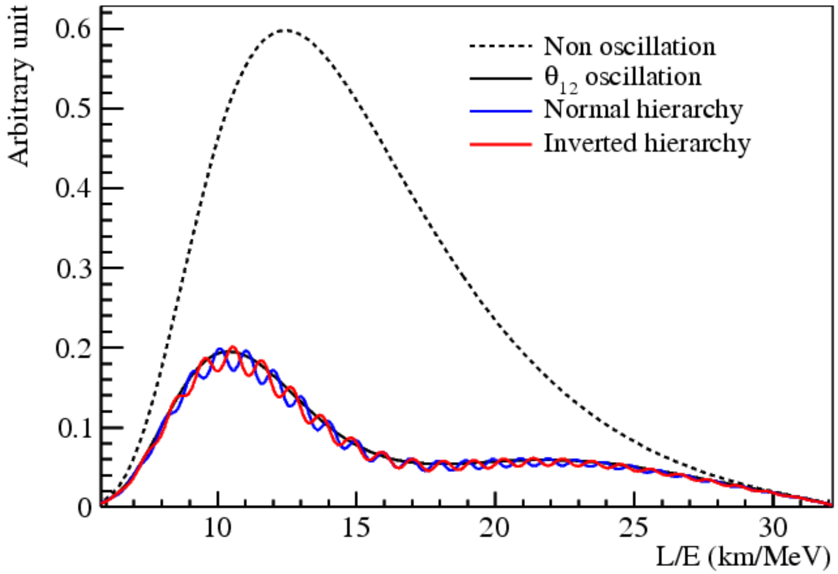
Reactor antineutrino to determine MH

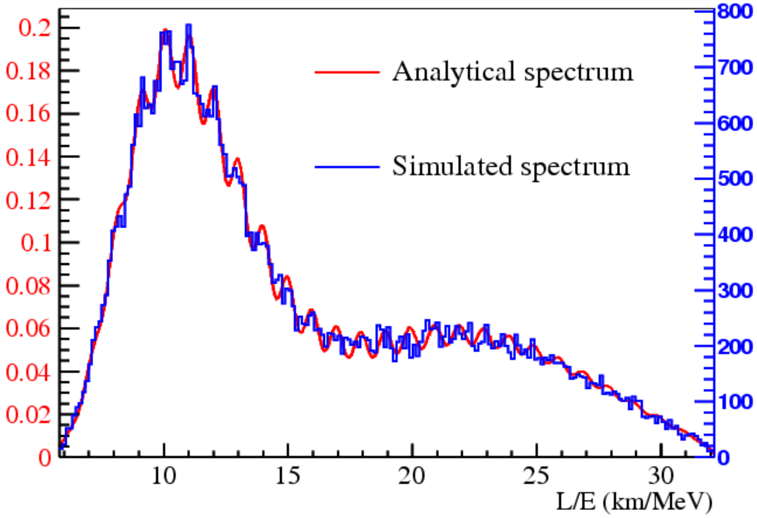
$$\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}$$

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

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

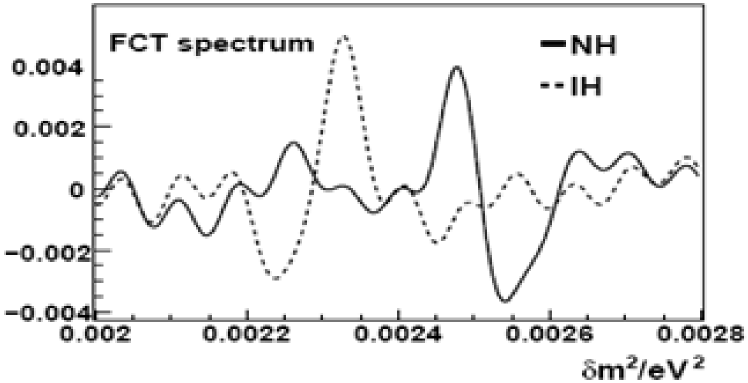
Fourier transform to L/E spectrum

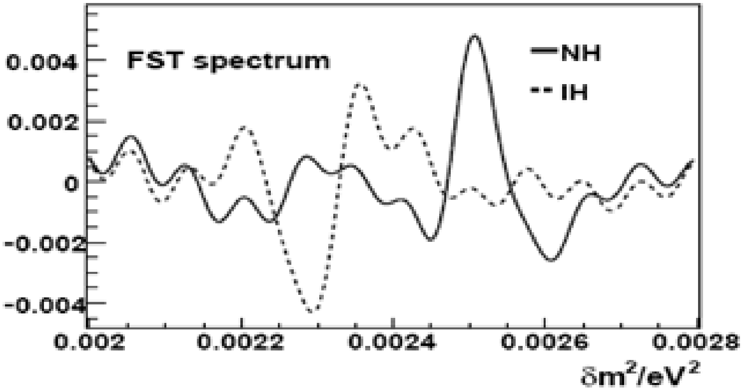
- L/E spectrum⬄δm^2 spectrum (oscillation frequency)

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

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

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





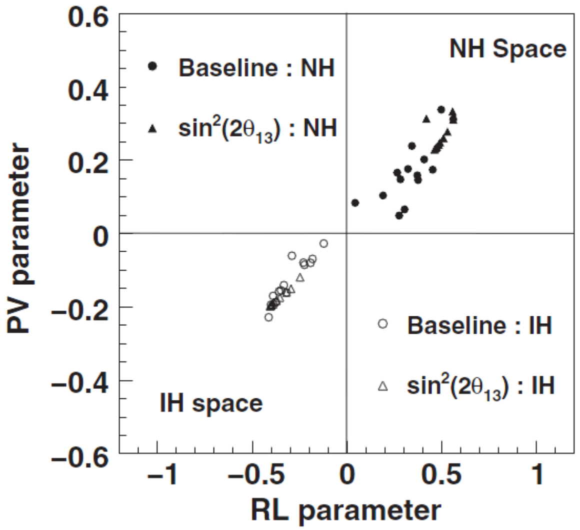
- Clear distinctive features:
  - FCT:
    - NH: valley at the left side
    - IH: valley at the right side
  - FST:
    - NH: prominent peak
    - IH: prominent valley
- **No pre-condition of Δm^2_{32} : features depends on shape but not absolute peak position.**

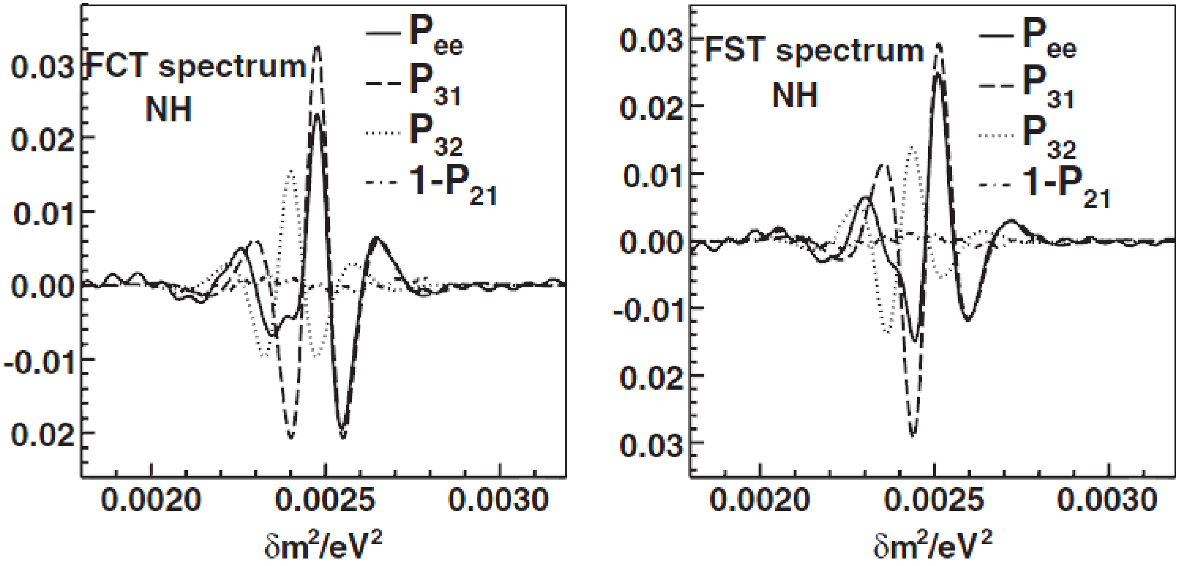
Quantify features of FCT and FST

- 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





Interference of two oscillation components of P_{31} and P_{32}

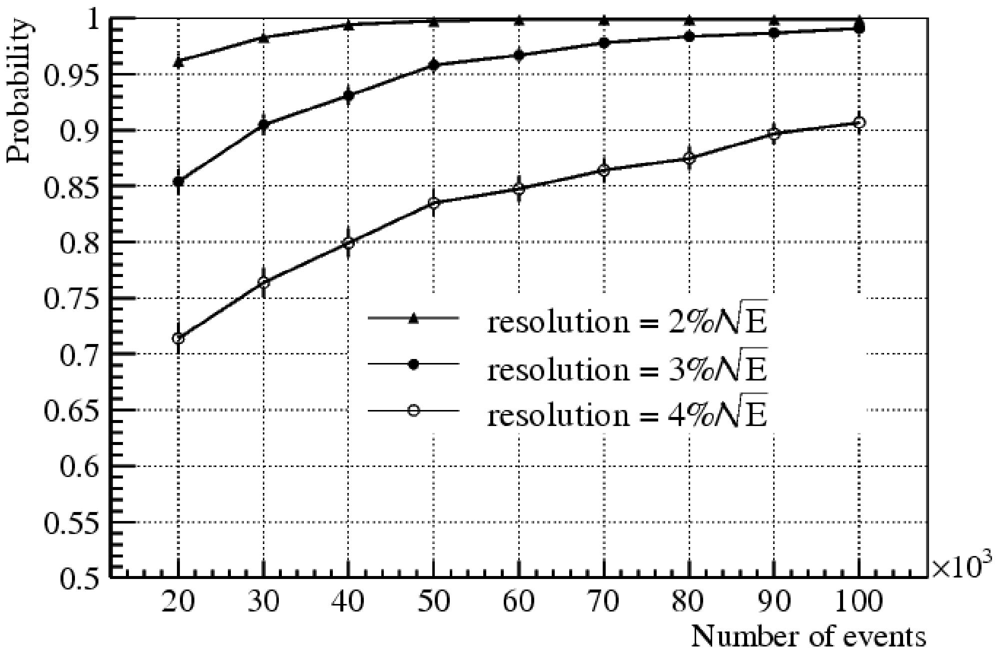
L. Zhan et al., PRD78:111103,2008

Experimental requirements

- Un-binned Fourier transform of N detected events

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

- 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

20kt LS detector
3 years ~ 2 sigma
6 years ~ 3 sigma

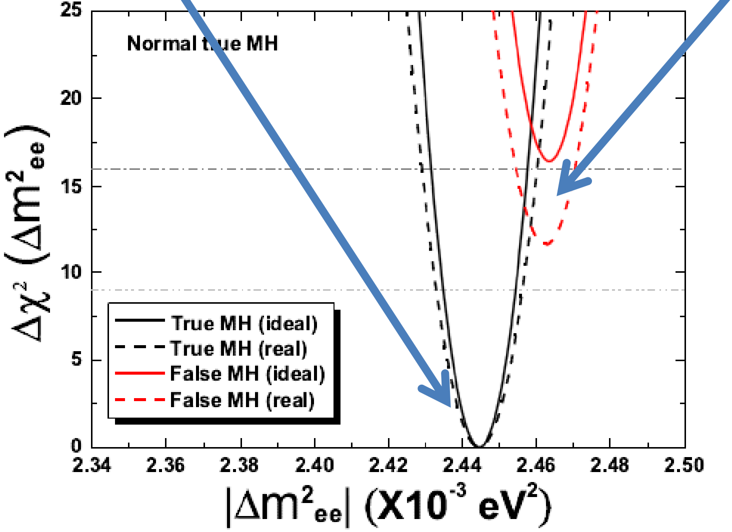
Alternative method: χ^2 fit

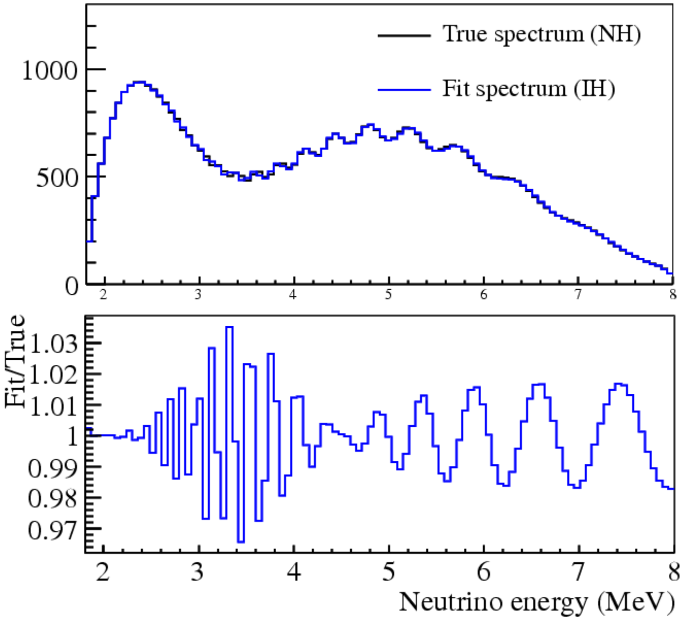
- Assume the truth is NH/IH, and calculate the truth spectrum.
- Calculate the spectra for NH and IH case and fit them to the truth spectrum respectively.
- Energy resolution is taken into account.

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

NH spectrum fits to NH

IH spectrum fits to NH



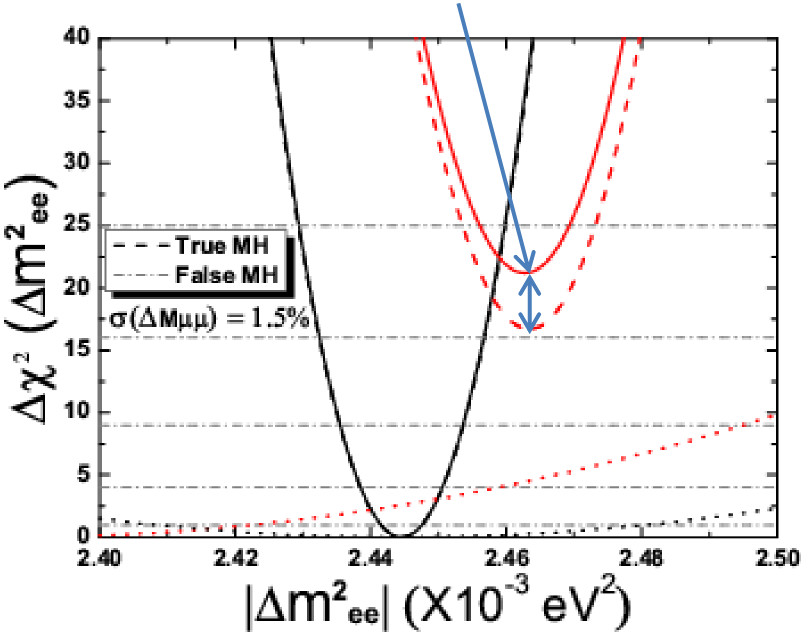


If truth is NH, NH spectrum may fit it better.
Δm^2 is fitted without constraint.

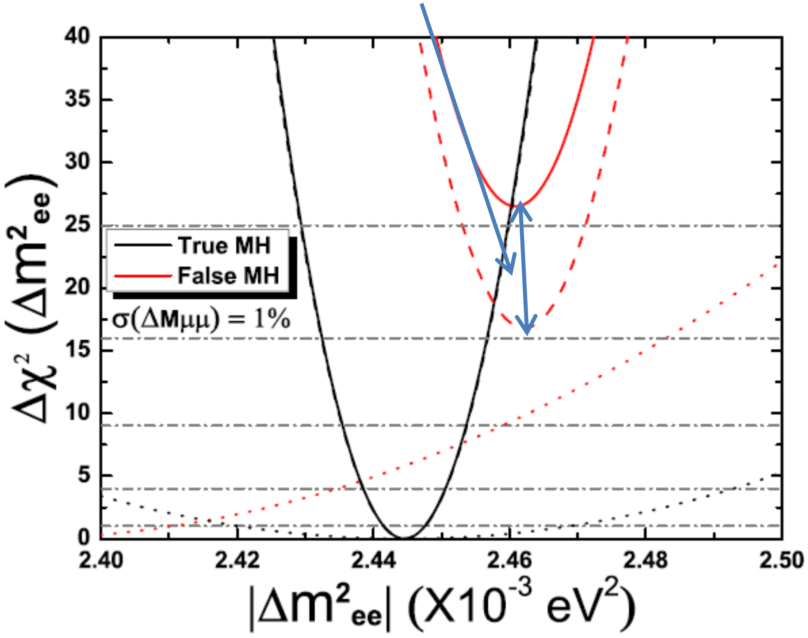
Taking into account Δm^2_{32}

- MH sensitivity improved by taking into account the Δm^2_{32} from T2K and Nova in the future

Improved by 1.5% precision



Improved by 1% precision



Yu-Feng Li, Jun Cao, Yifang Wang, Liang Zhan, arXiv:1303.6733

Other physics reach

1. Precision measurement of mixing parameters: θ_{12}, ΔM^2_{12}, ΔM^2_{31} ➔ test the unitarity of the mixing matrix
2. Supernova neutrinos
3. Geo-neutrinos
4. Sterile neutrinos
5. Target for neutrino beams
6. Atmospheric neutrinos
7. Solar neutrinos
8. 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 !

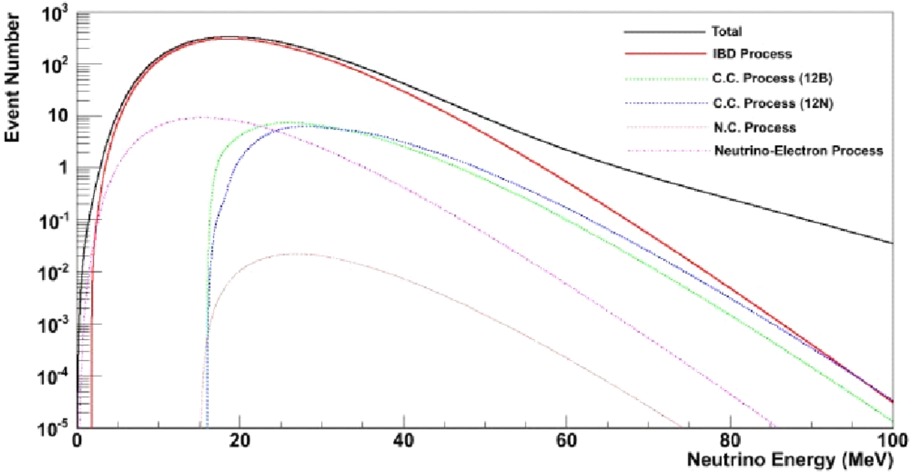
	Current	Daya Bay II
Δm^2_{21}	3%	0.6%
Δm^2_{31}	5%	0.6%
$\sin^2\theta_{12}$	6%	0.7%
$\sin^2\theta_{23}$	20%	-
$\sin^2\theta_{13}$	14% ➔ 5% (Daya Bay in 3 years)	15%

Will be more precise than CKM matrix elements.

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

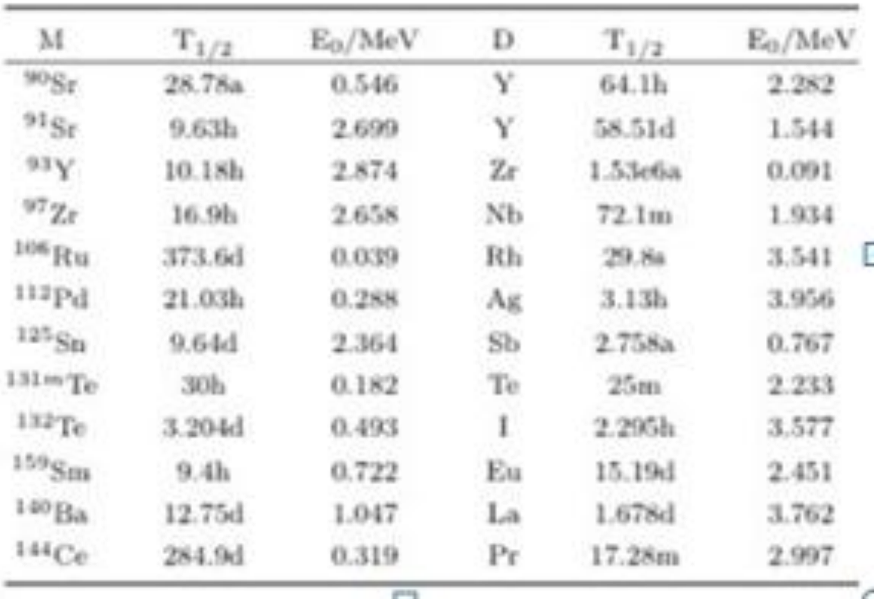


Energy spectra & fluxes of all types of neutrinos

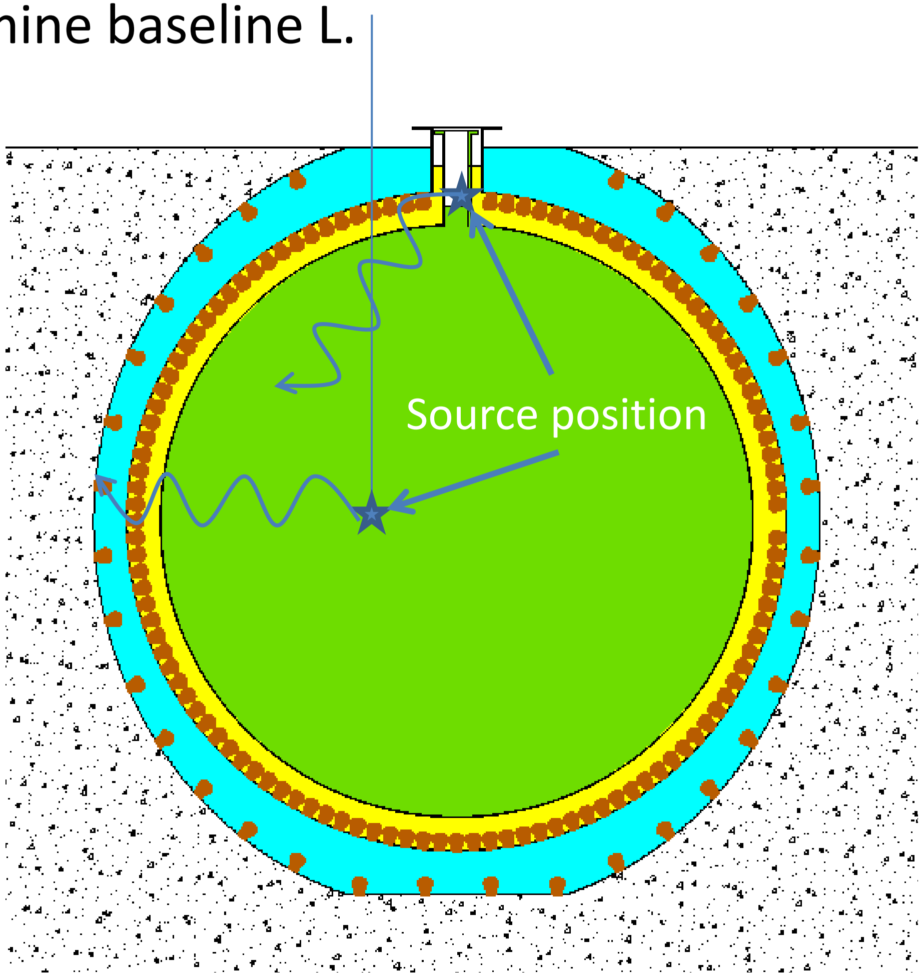
Sterile neutrino

- Put radioactive source in detector center (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?

- Highly transparent LS
  - Attenuation length/D: 15m/16m → 30m/34m X 0.9
- High light yield LS:
  - KamLAND: 1.5g/l PPO → 5g/l PPO

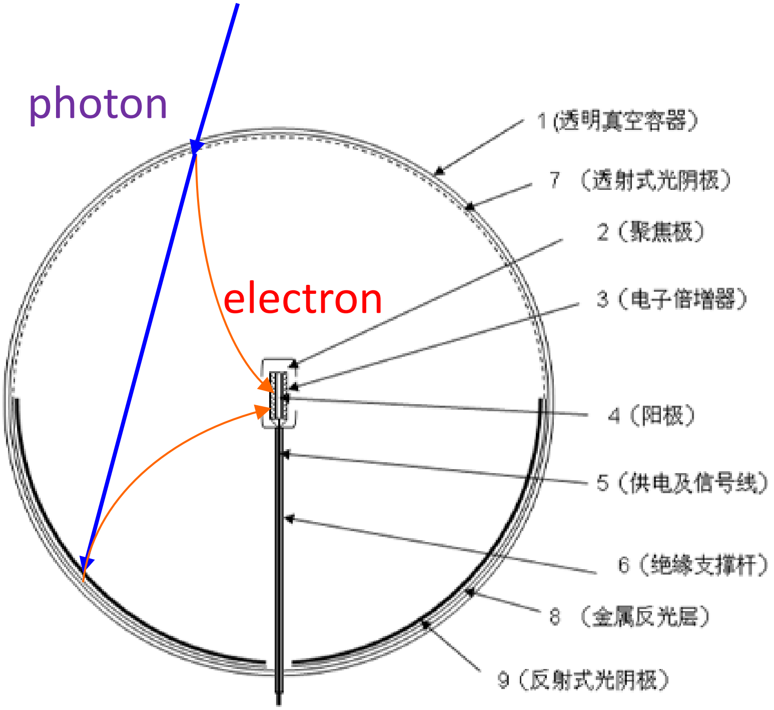
    Light Yield: 30% → 45% X 1.5
- Photocathode coverage:
  - KamLAND: 34% → ~80% X 2.3
- High QE "PMT":
  - 20'' SBA PMT QE: 25% → 35% X 1.4

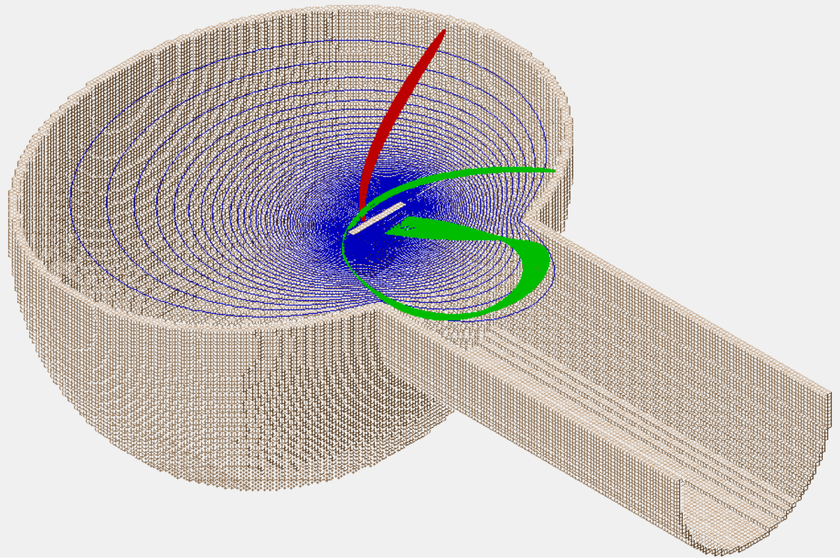
    or New PMT QE: 25% → 40% X 1.6

    Both: 25% → 50% X 2.0

X 4.3-5.0 → (3.0-2.5)%/√E

A new type of PMT: MCP-PMT

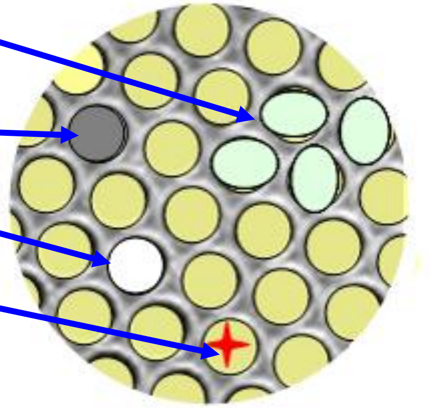




- Top: transmitted photocathode
- Bottom: reflective photocathode
  additional QE: ~ 80%*40%
- MCP (Microchannel Plate) to replace Dynodes ➔ no blocking of photons

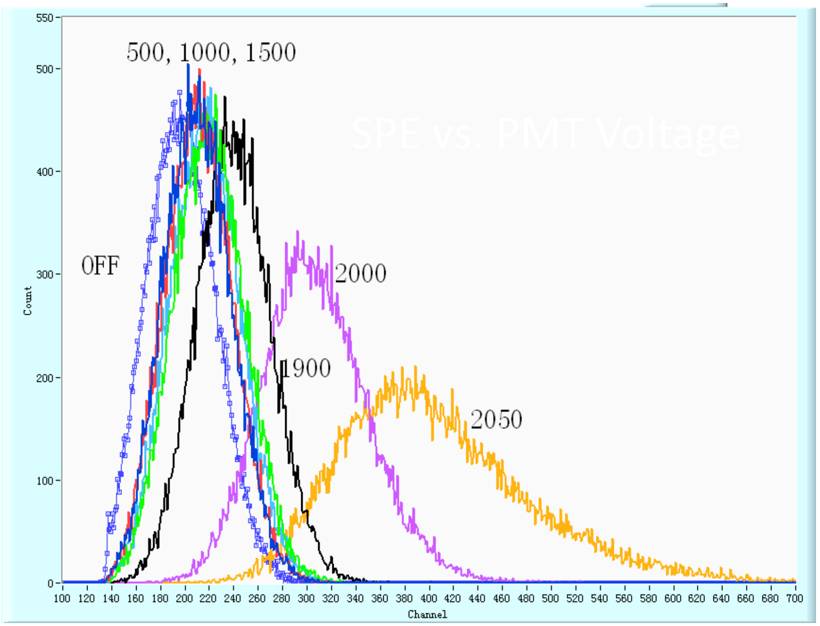
Low cost MCP by accepting the followings for SPE detection.

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

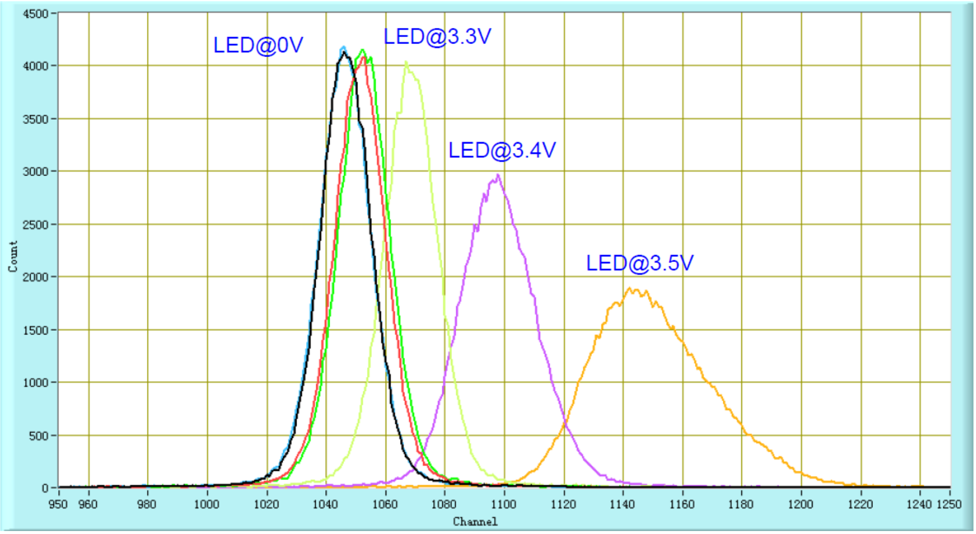


MCP surface

Prototypes



MPE vs the luminance of the LED light

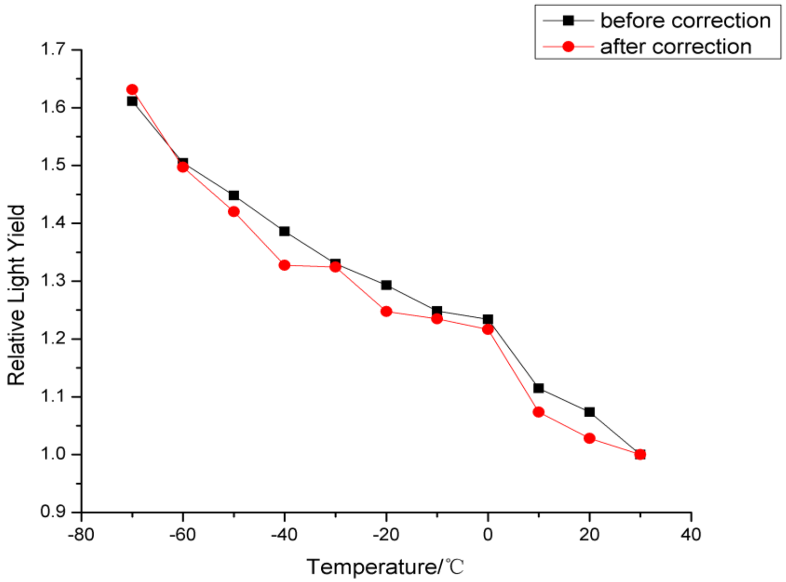


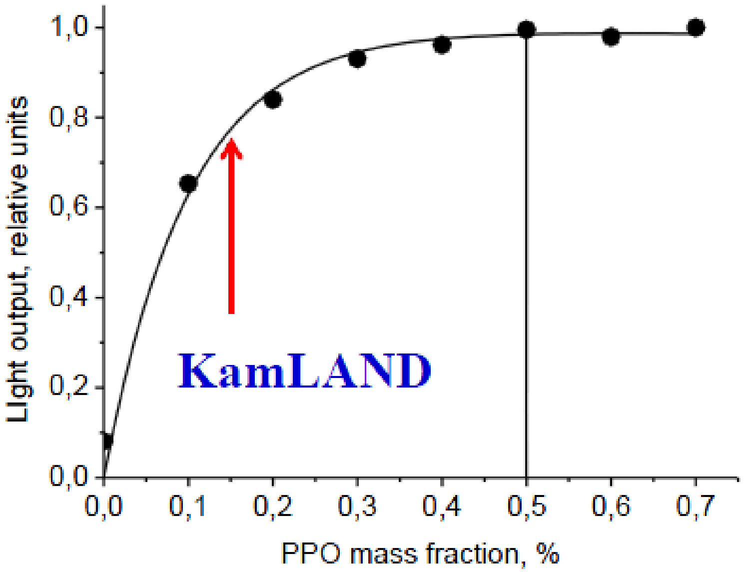
LAB based liquid scintillator

- To enhance the attenuation length
  - Improve raw materials (using Dodecane instead of MO）
  - Improve the production process for large volume
  - Purification
- High light yield
  - Lower temperature
  - Fluor concentration optimization

Test on purification

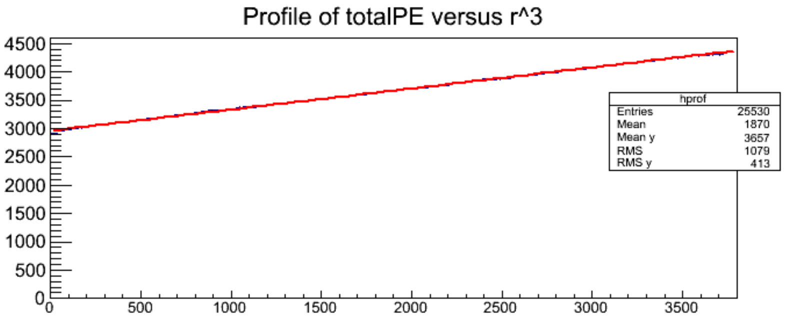
LAB	**Atte. Length @ 430 nm**
RAW	14.2 m
Vacuum distillation	19.5 m
SiO_2 coloum	18.6 m
Al_2O_3 coloum	22.3 m



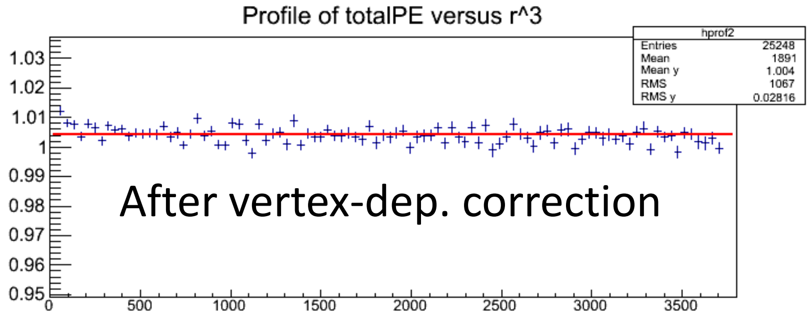


MC example

- DYBII MC, based on DYB MC (tuned to data), except
  - DYBII Geometry and 80% photocathode coverage
  - SAB PMT: maxQE from 25%➔35%
  - Lower detector temperature to 4 degree (+13% light)
  - LS attenuation length (1m-tube measurement@430nm)
    - From 15m = absorption 24 m + Raylay scattering 40 m
    - To 20 m = absorption 40 m + raylay scattering 40 m

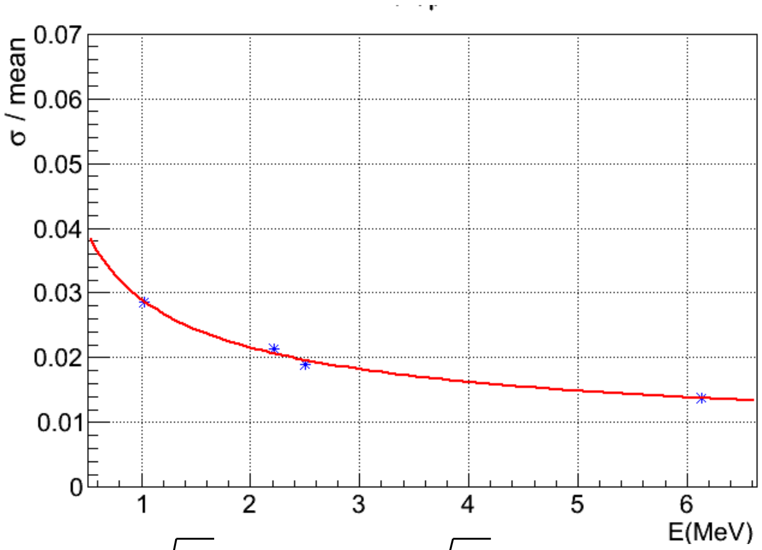


Profile of totalPE versus r^3



Profile of totalPE versus r^3

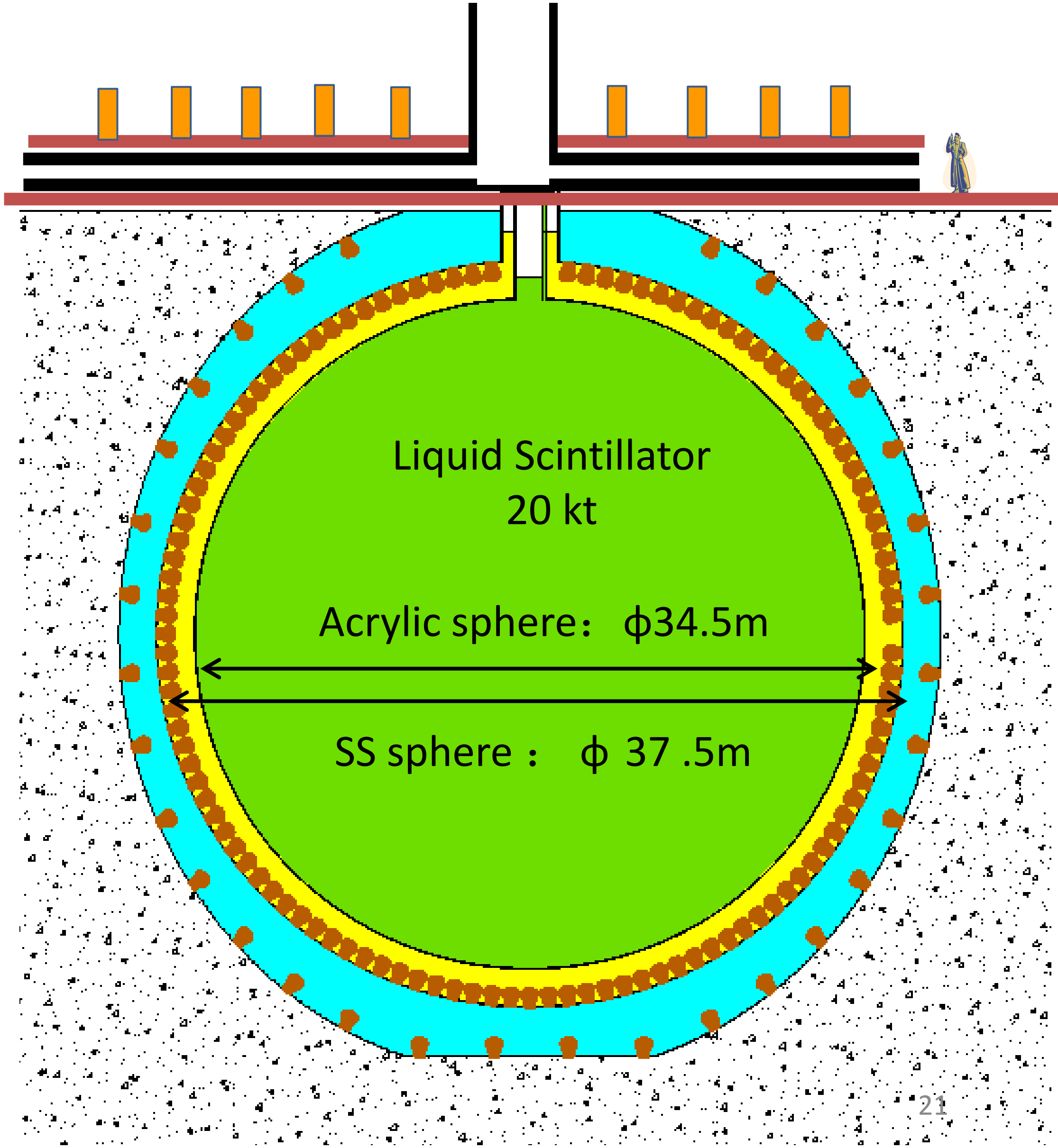
After vertex-dep. correction



$3\%/\sqrt{E}$ *or* $(2.6/\sqrt{E}+0.3)\%$

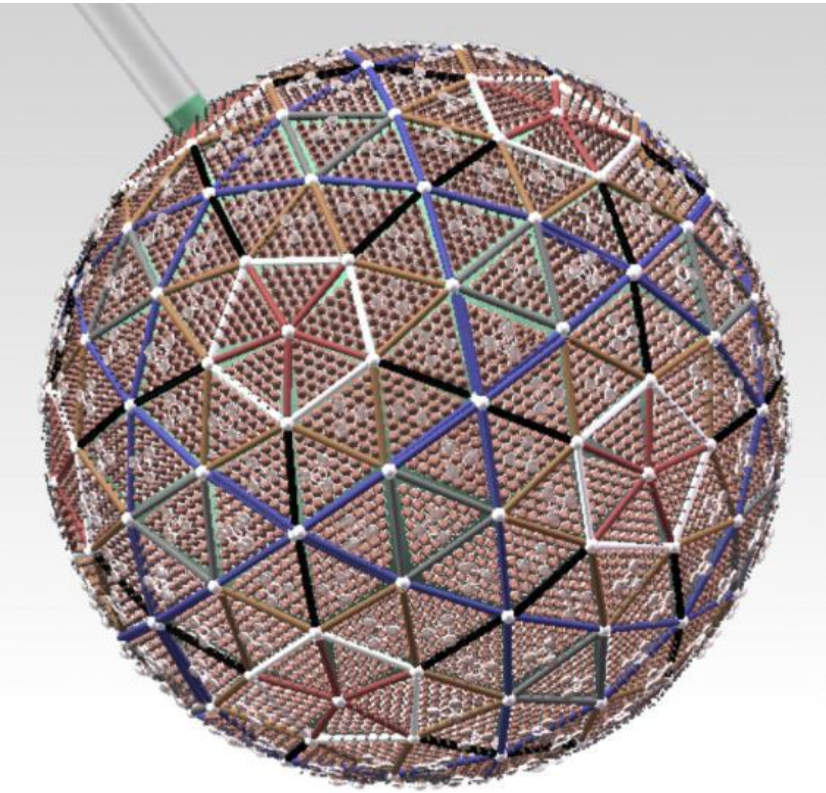
Detector Concept

- Extremely difficult to build both the stainless steel tank and the acrylic tank
- Options:
  - No steel tank, only acrylic tank
  - Steel tank +
    - Acrylic box/wall
    - Balloon
    - nothing



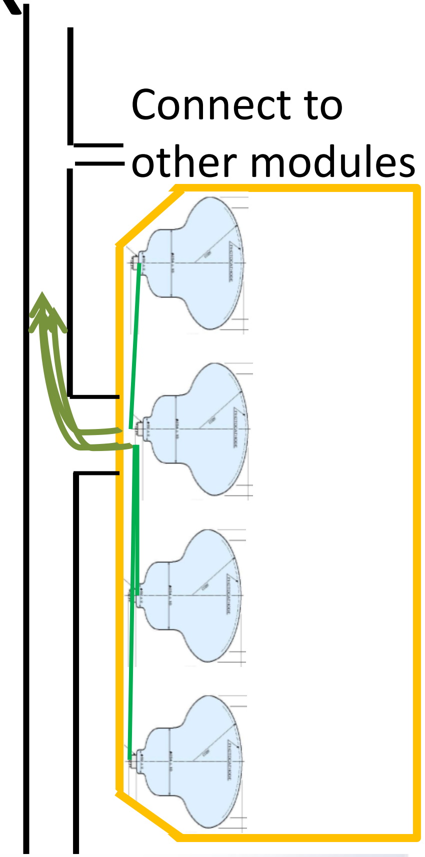
Option 1: no steel tank

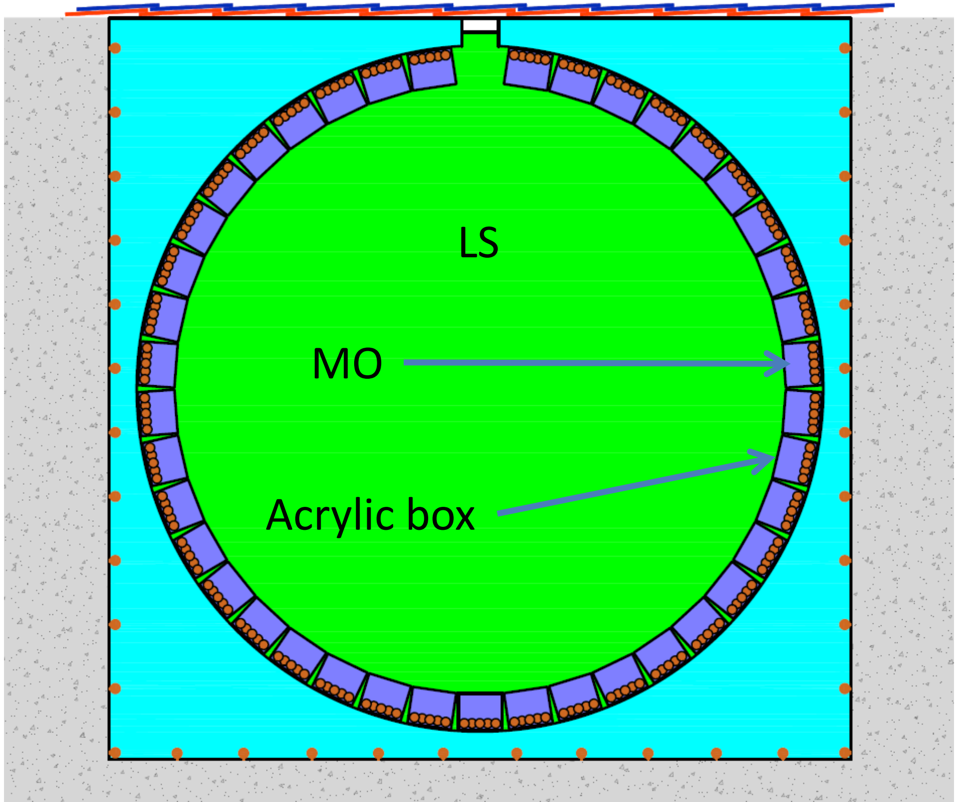
- No more interference
- “Easy” for PMT holding
- Water replaces oil buffer ➔cheap
- Difficulties:
  - Larger pressure difference for the acrylic tank.

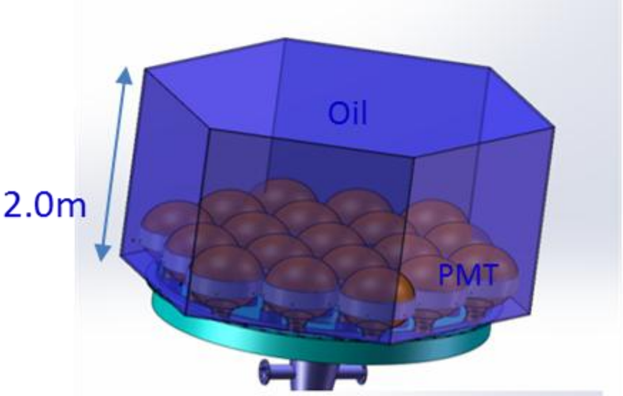


Option 2: acrylic box

- Mineral oil in the optical modules
- Pipe for filling MO and cabling
- Concerns: leakage through cables



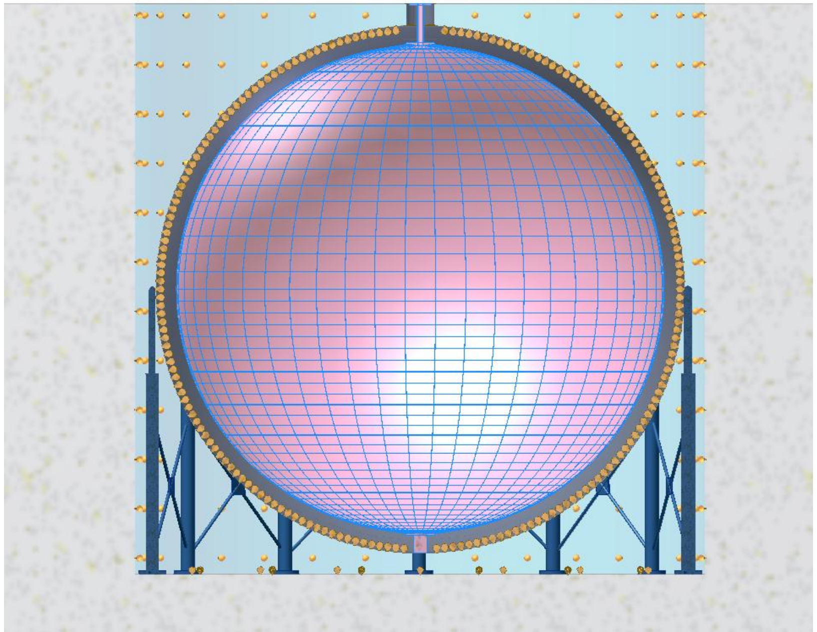




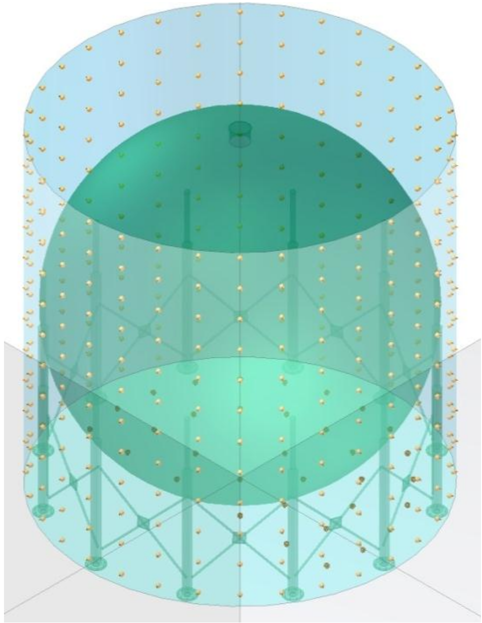
Option 3: balloon

- “Cheap” for construction & quick for installation
- Experience from Borexino (0.5kt) & KamLAND (1kt)
- Need to consider film materials(mechanics, transparency, compatibility, welding technique, radon permeability, …) , cleanness, leak check, deployment, backup plan if fails, …

Not new to IHEP



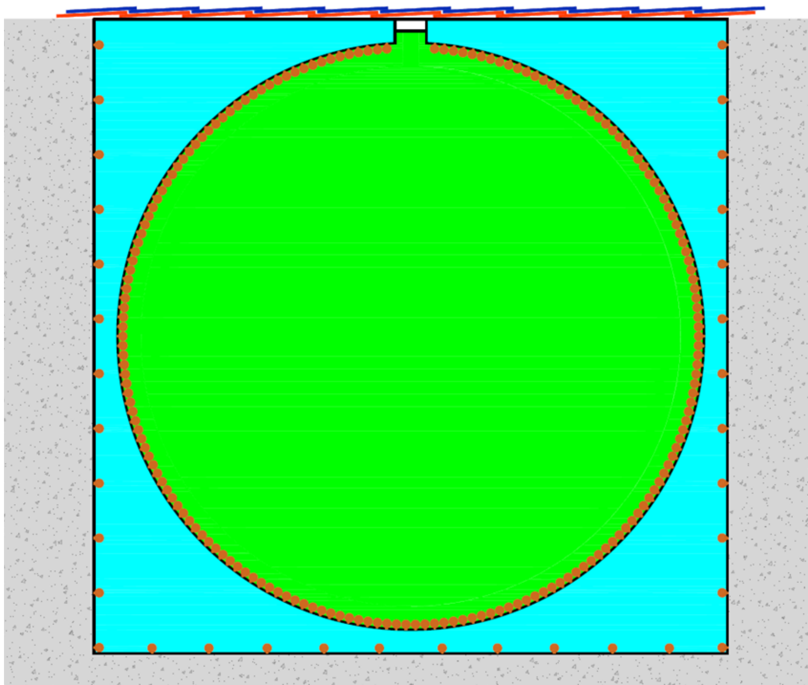
Option 4: Steel tank only



- No problem for construction
- A fall back plan of the balloon option
- But
  - PMT protection
  - Trigger rate by backgrounds
  - Resolution affected by backgrounds

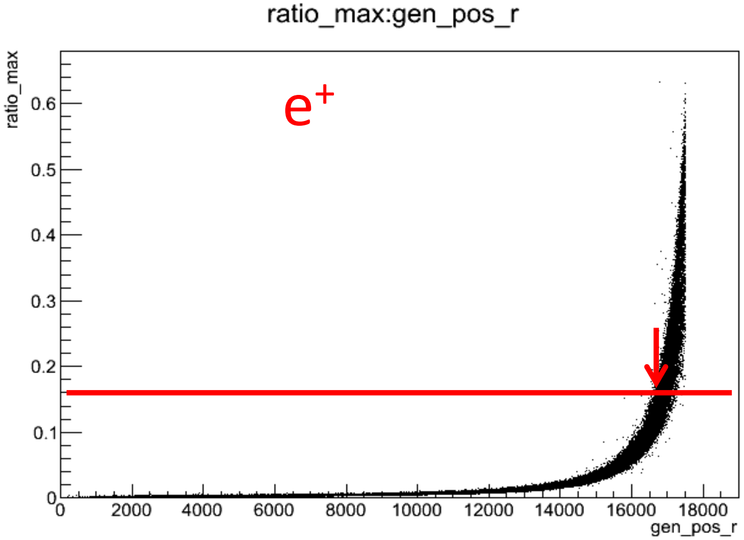
If the PMT glass is the same as Daya Bay, radioactivity will be 44 Bq/PMT, or 3.3 MHz in total

If better glass is used, it may be reduced to 1 MHz



Online background suppression

- Divide PMTs to 1476 regions
- Look at the charge ratio Q_i/Q_{total} (i: the region ID)
  - Cut charge ratio < 0.16
  - Cut also $N_{p.e.}$ <500(~0.4 MeV)
- Event rates is reduced to 0.6kHz



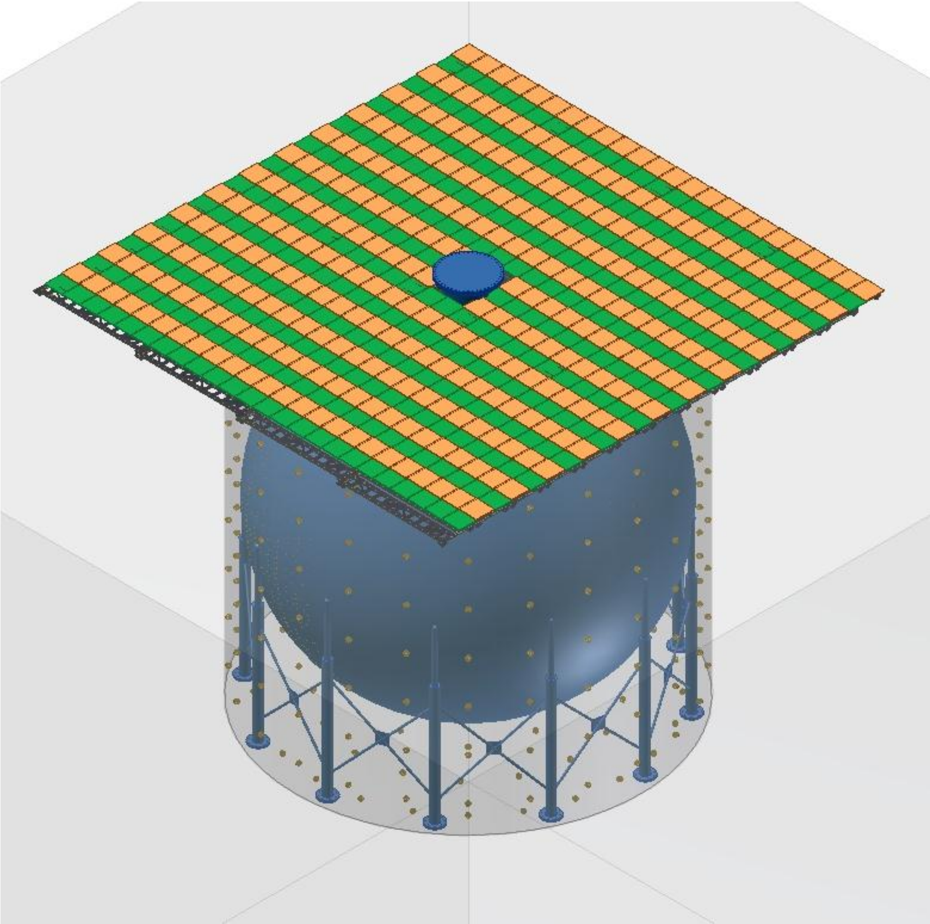
Equivalent to fiducial volume cut.

Resolution is affected:

	No Background (vertex corrected)		Mix Background(1MHz, 500ns) (vertex corrected)	
Energy(MeV)	sigma	mean	sigma	mean
2*0.511	0.030	1	0.035	0.94
2.22	0.024	1	0.027	0.97
1.173+1.333	0.021	1	0.024	0.97
6.13	0.016	1	0.017	0.99

VETO

- Water
  - A MC simulation show that ~ 2m water, 1500 20” PMT is good enough
- Top VETO Options:
  - RPC
  - Plastic scintillator
  - Liquid scintillator
  - Two layers?
    - precise muon tracking

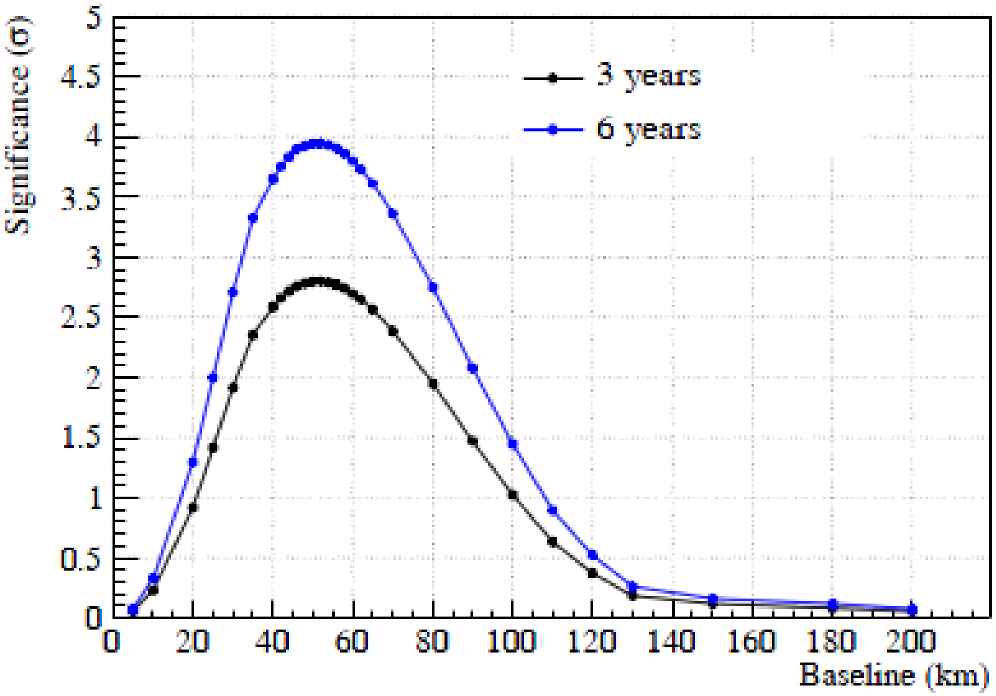


The site: Kaiping county, Jiangmen City

	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**

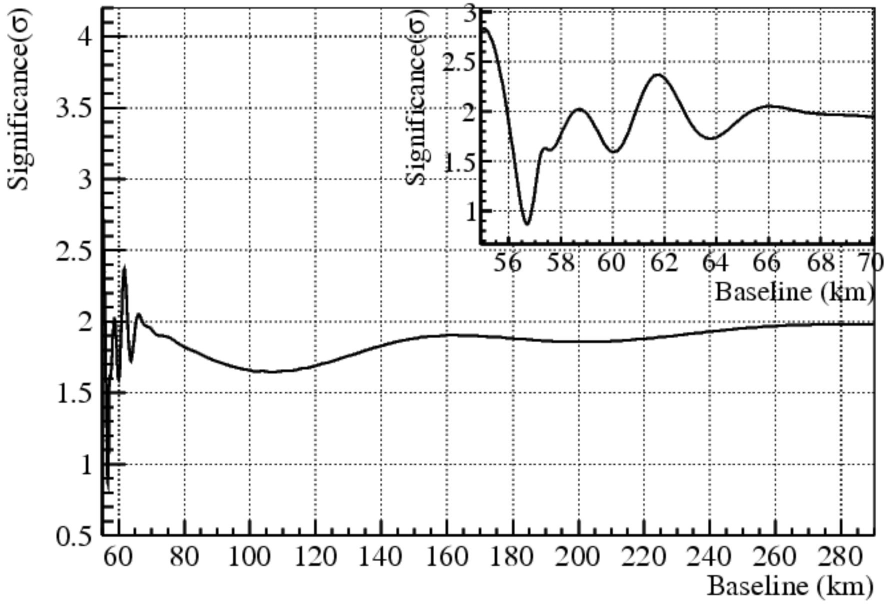
Optimal baseline

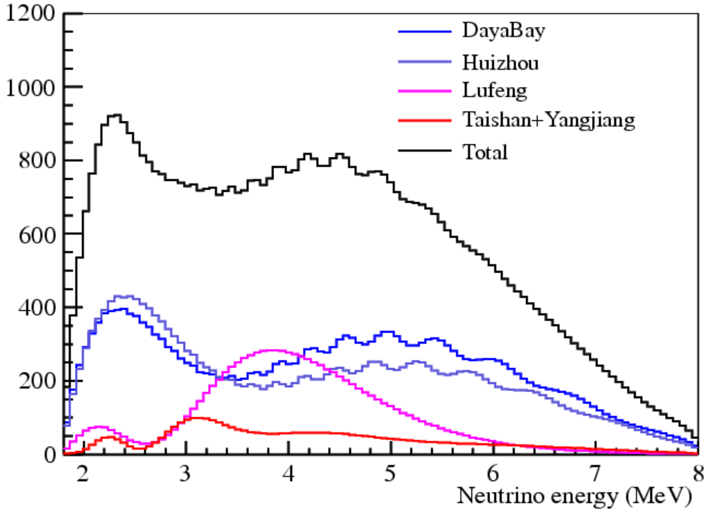
- Proper baseline: ~50 km, around θ_{12} oscillation maximum.



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.



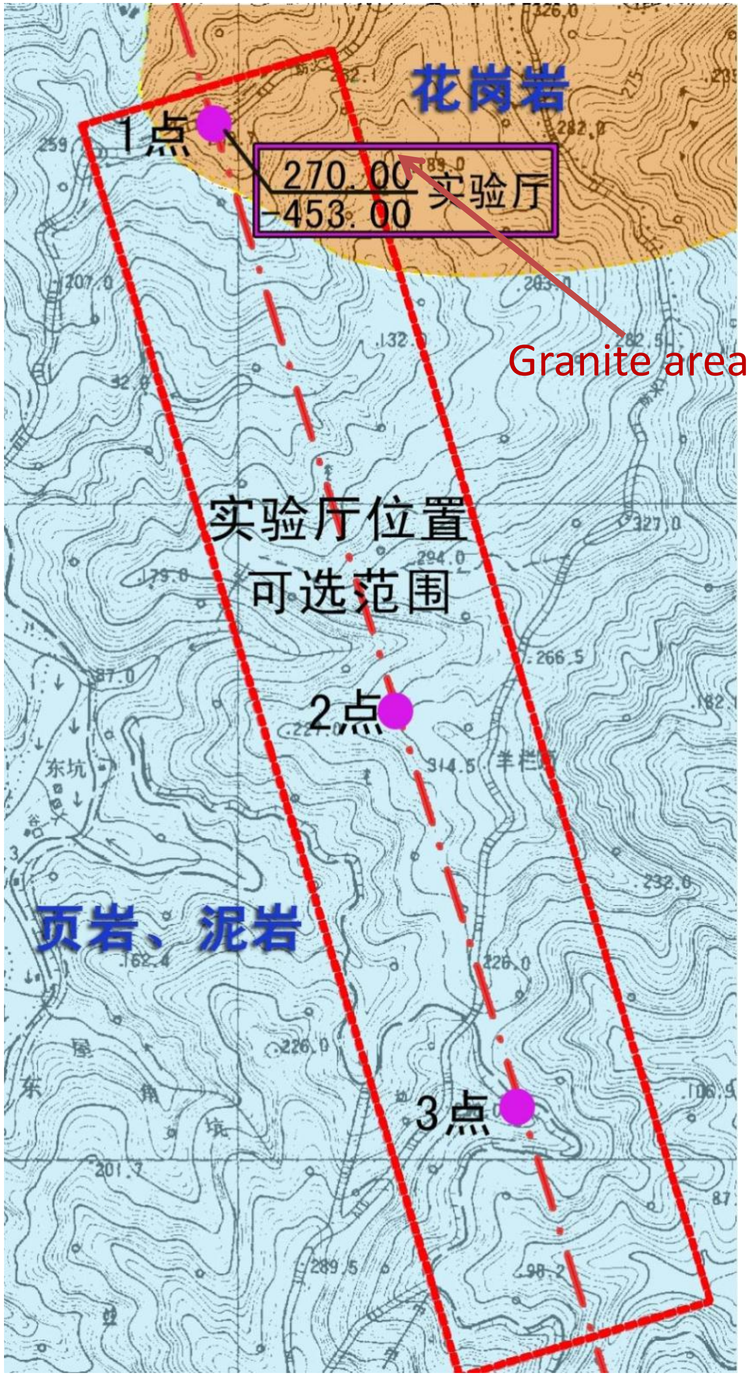


Example of peak and valley cancellation

Kaiping county, Jiangmen City in Guangdong province

Site survey

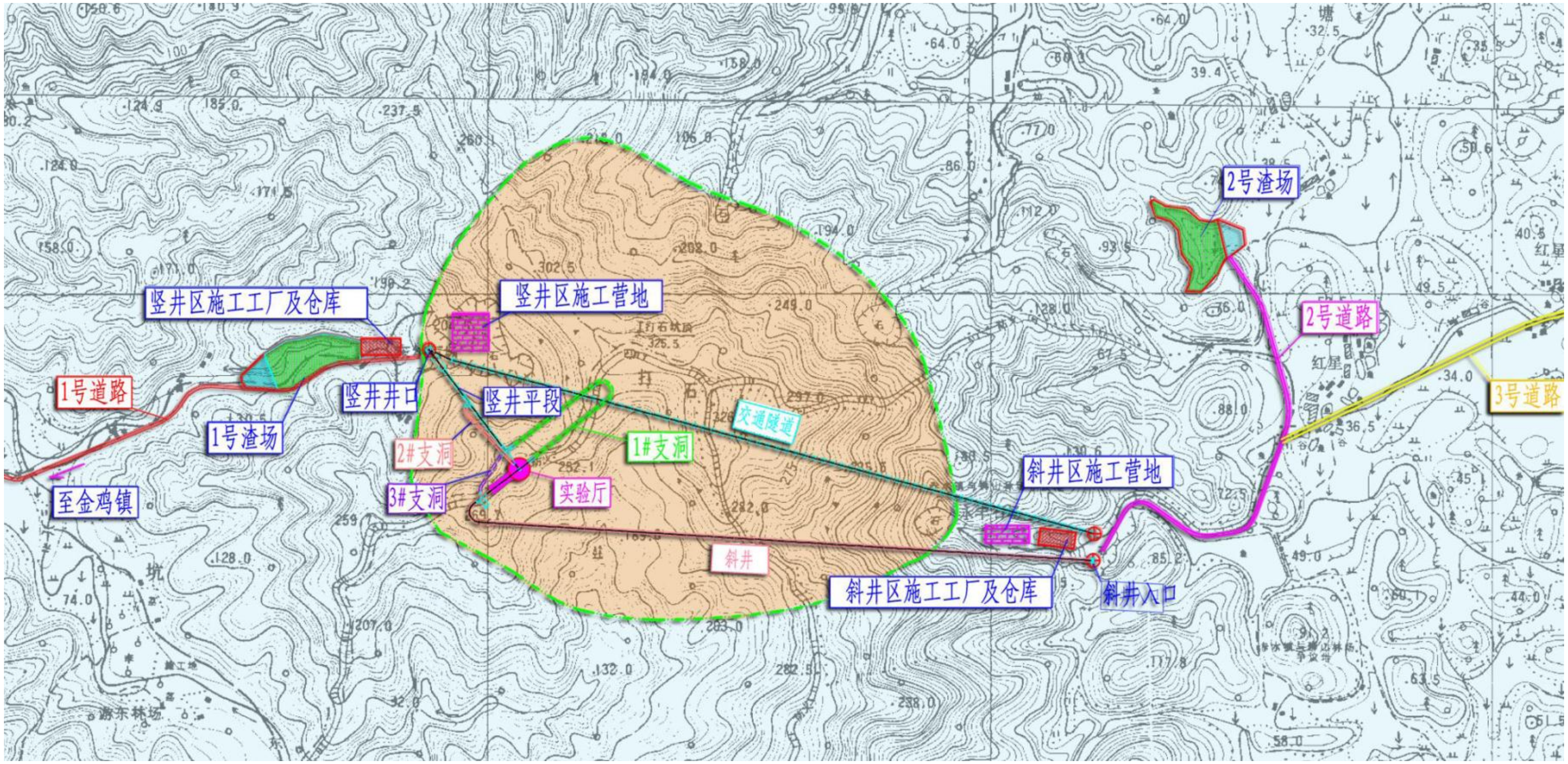
- Experimental hall selected
- Preliminary geological survey:
  - Review held on Dec. 17, 2012
  - No show-stoppers
- Detailed geological survey has been going on smoothly



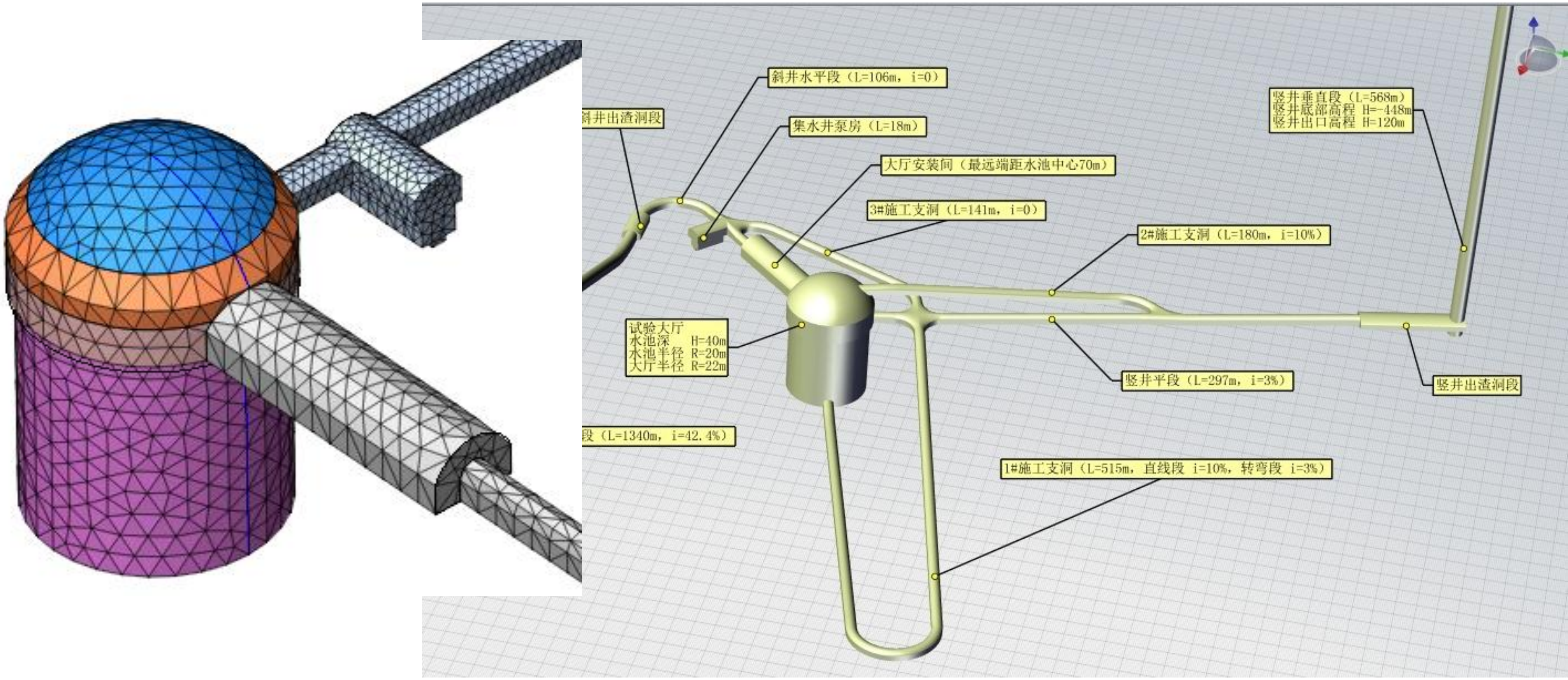
Granite area

Construction plan

- Two options considered
  - Rails(40%, 1100m) + vertical shaft (600m)
  - Rails(40%, 1100m) + horizontal tunnel (6600m)
- Conceptual design completed. Review held on Dec.17, 2012.
  - Rails + vertical shaft is chosen for cost and schedule reasons
  - No show-stoppers



Experimental hall



- Preliminary study shows that:
  - Stability of the hall is not a problem
  - Total time needed for construction is 3 years

Brief schedule

- Civil preparation: 2013-2014
- Civil construction: 2014-2017
- Detector R&D: 2013-2016
- Detector component production: 2016-2017
- PMT production: 2016-2019
- Detector assembly & installation: 2018-2019
- Filling & data taking: 2020

After a number of reviews, we are approved by the CAS(~ CD1)

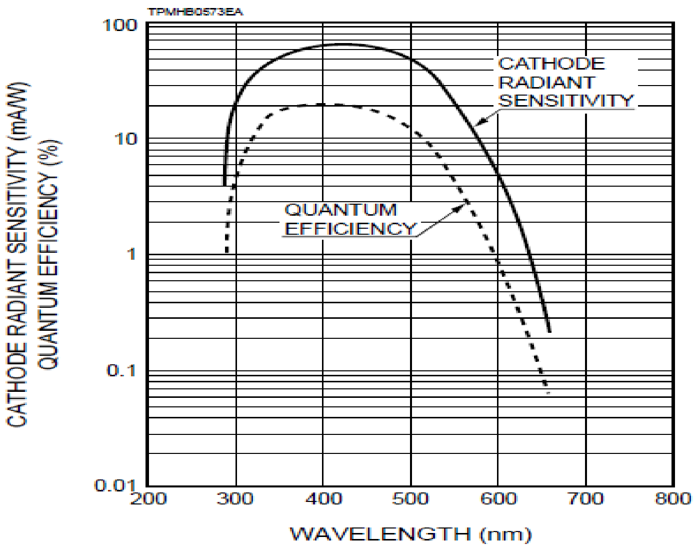
Summary

- Daya Bay II proposed in 2008-2009, now boosted by the large θ_{13}
- Rich physics potential
- Although challenging, preliminary study shows it is not impossible.
- A few R&D efforts has been started, more will come.
- Detector design and civil design have been started.
- Good support from the local government and the Chinese funding agencies.

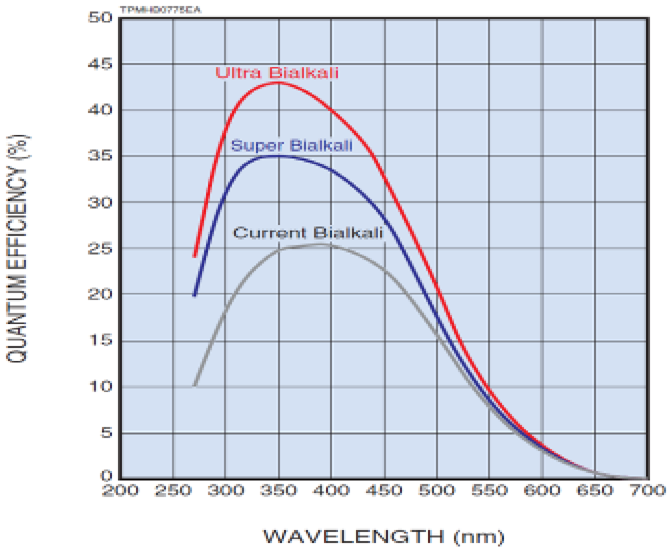
backup

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 ?

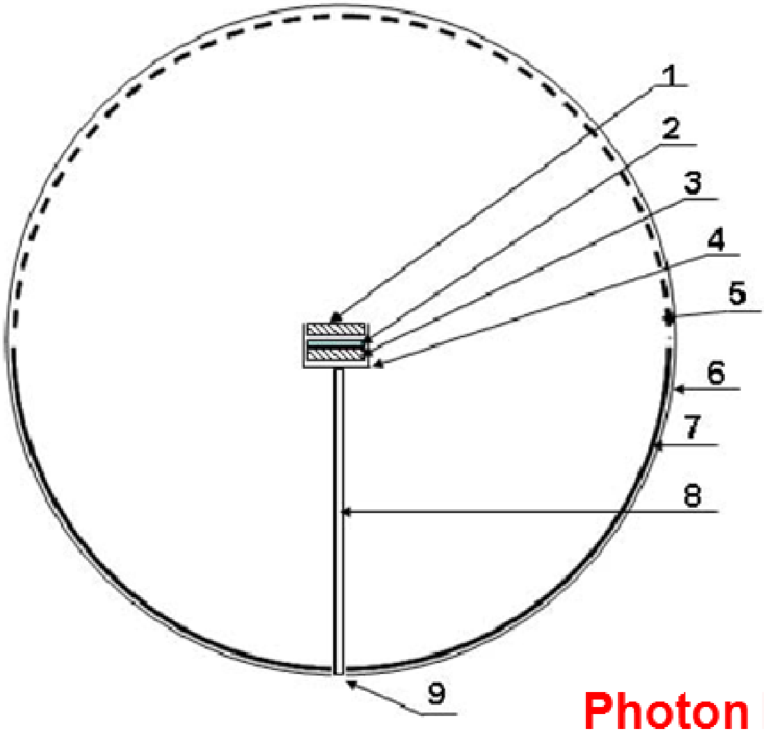
QE: 20%→30%

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**