Daya Bay II: Jiangmen Underground Neutrino Observatory (JUNO)

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Windows on the Universe

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Outline

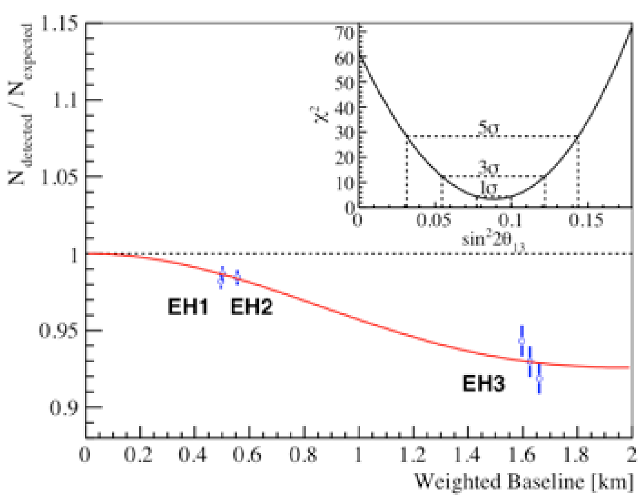
- Physics
- Challenges
- Detector concepts
- Site optimization and civil
- Project status and plan
- Summary

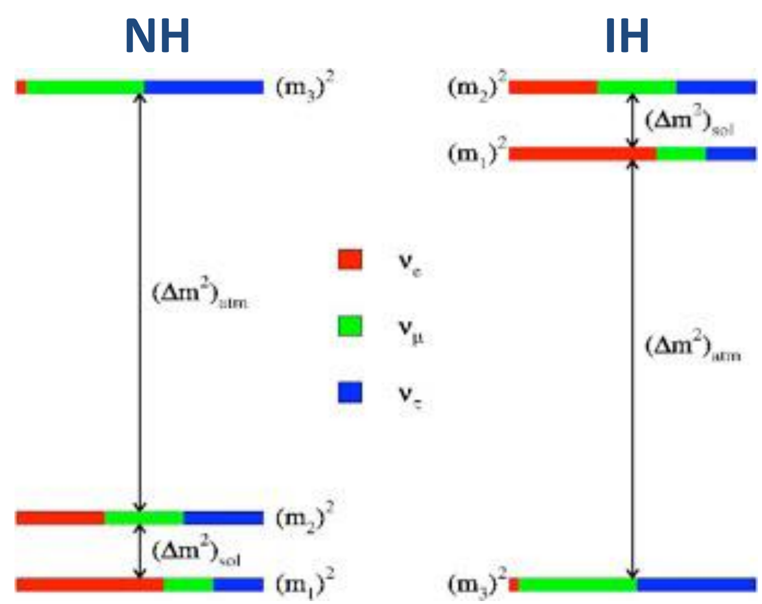
The large θ_{13} era

- 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

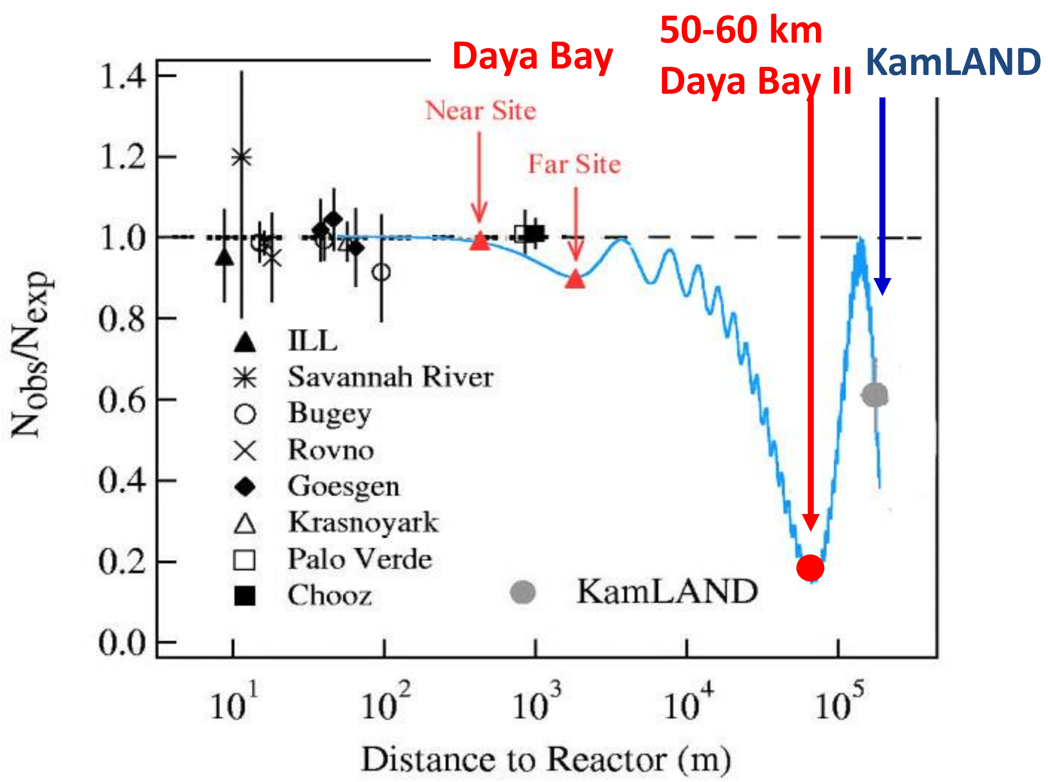
$\sin^2 2\theta_{13} = 0.089 \pm 0.010(\text{stat}) \pm 0.005(\text{sys})$





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



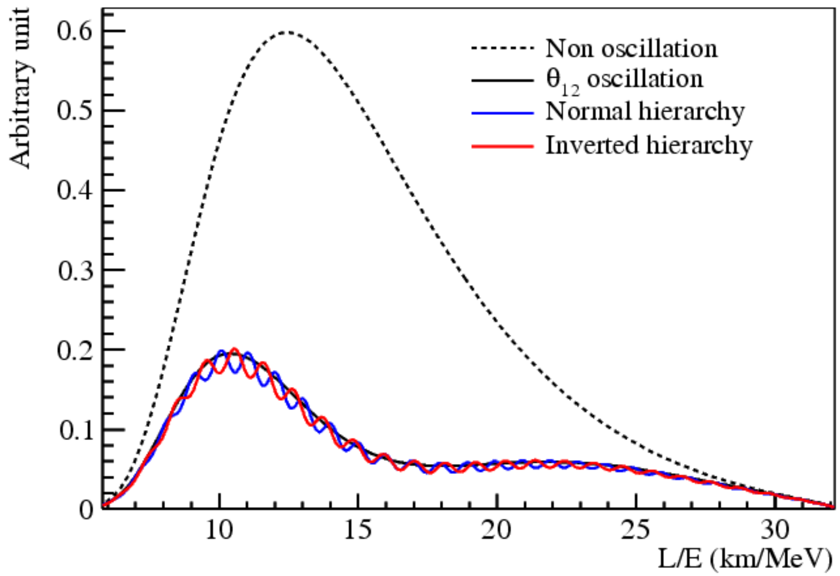
Reactor antineutrino to determine MH

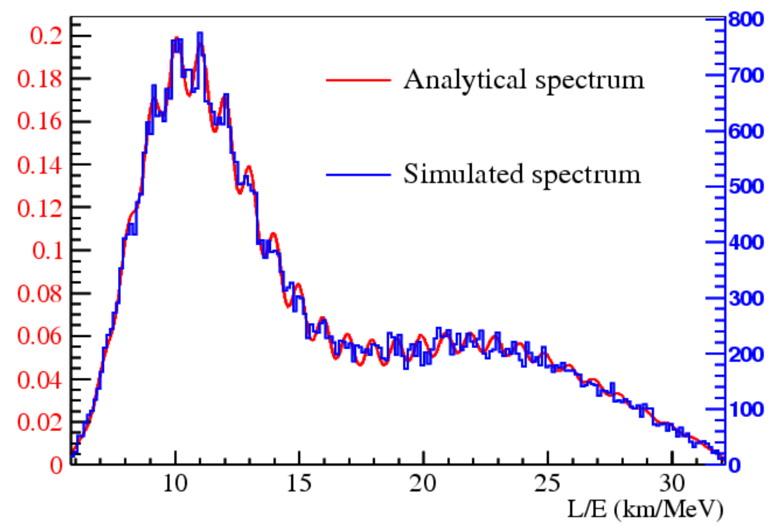
$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

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

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

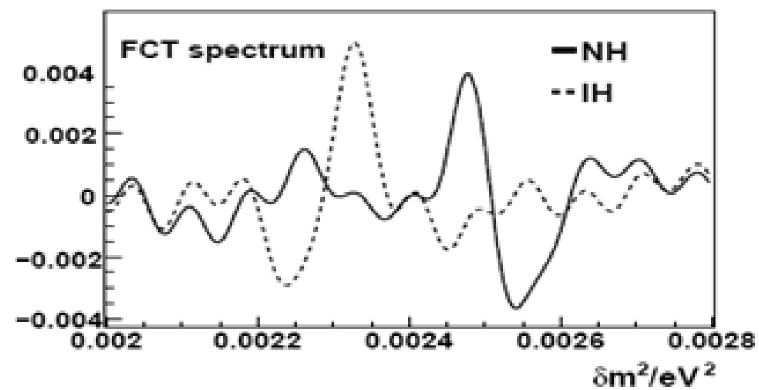
Fourier transform to L/E spectrum

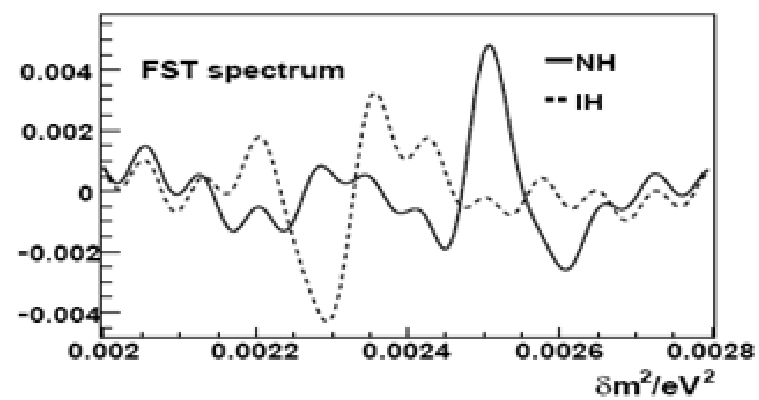
- **L/E spectrum⇔δm² spectrum (oscillation frequency), enhance the visiable features in in ΔM² regime**

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

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

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





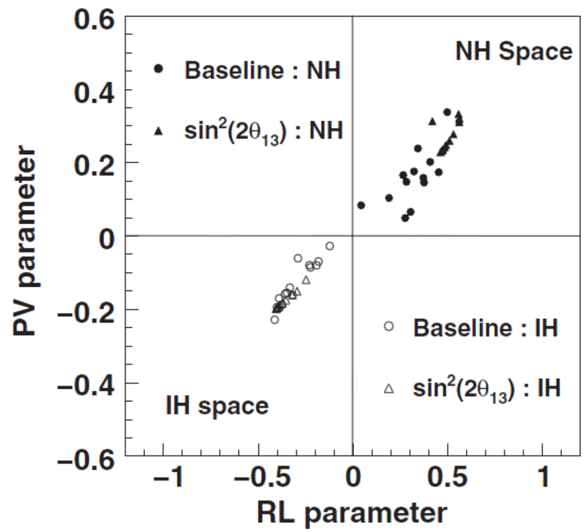
- **Clear distinctive features:**
  - **FCT:**
    - **NH: valley at the left side**
    - **IH: valley at the right side**
  - **FST:**
    - **NH: prominent peak**
    - **IH: prominent valley**
- **No pre-condition of Δm^2_{32} : features depends on shape but not absolute peak position.**

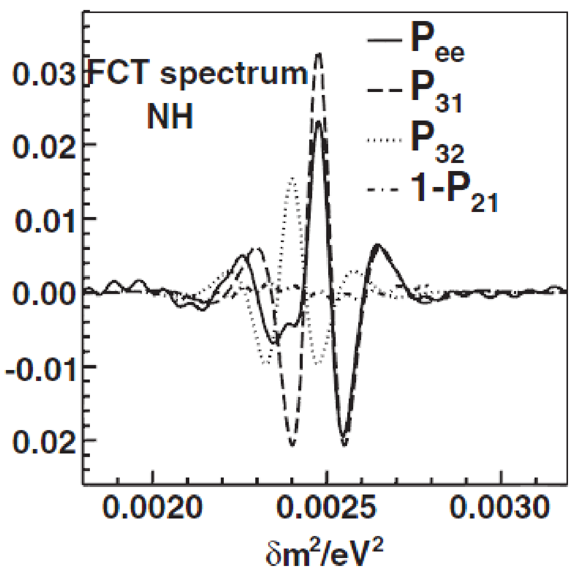
Quantify features of FCT and FST

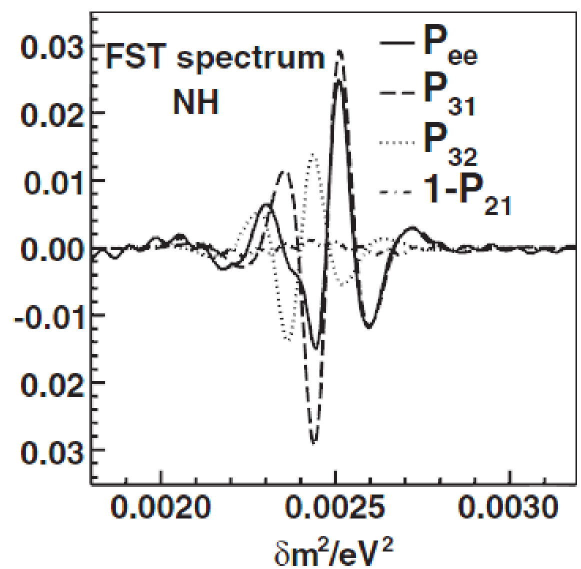
- **Define quantities**

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

  – **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}

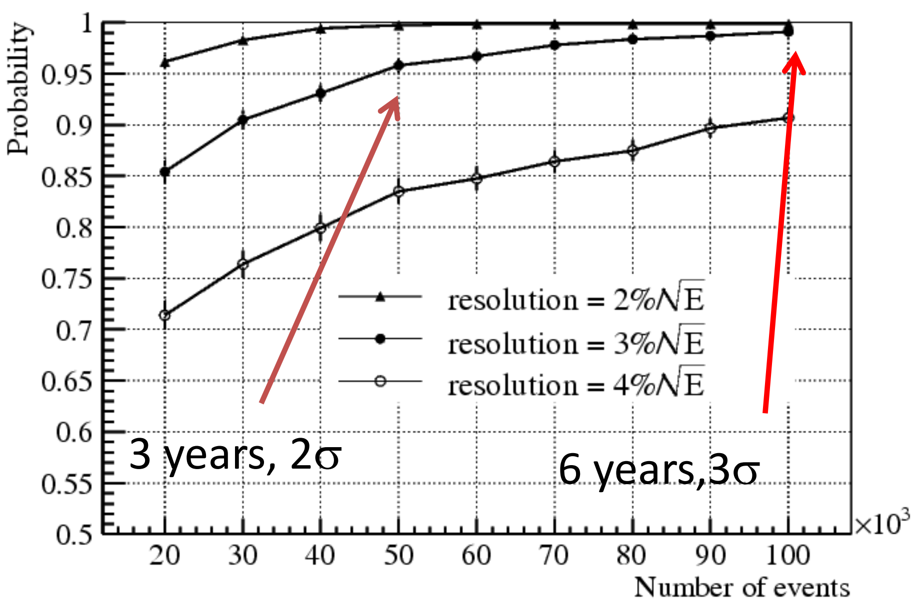
L. Zhan et al., PRD78:111103,2008

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

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 !**

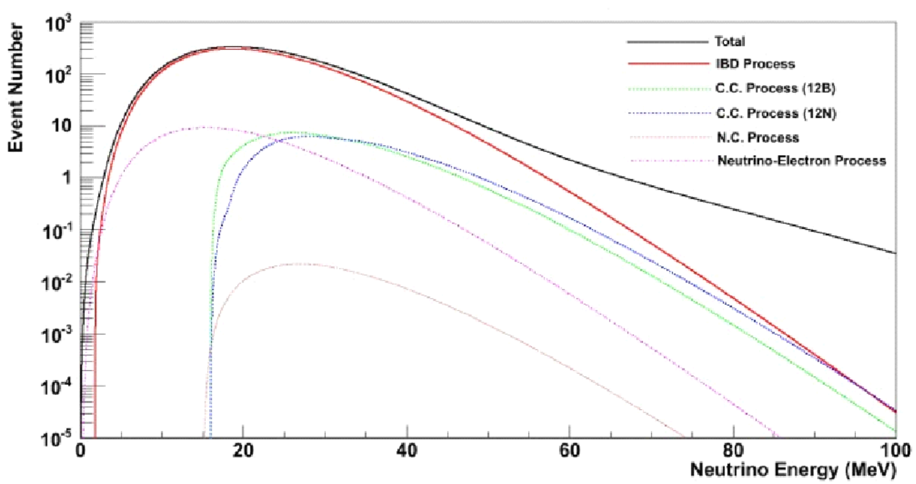
	Current	Daya Bay II
Δm^2_{21}	3%	0.6%
Δm^2_{31}	5%	0.6%
$\sin^2\theta_{12}$	6%	0.7%
$\sin^2\theta_{23}$	20%	-
$\sin^2\theta_{13}$	14% → 5% (Daya Bay in 3 years)	15%

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

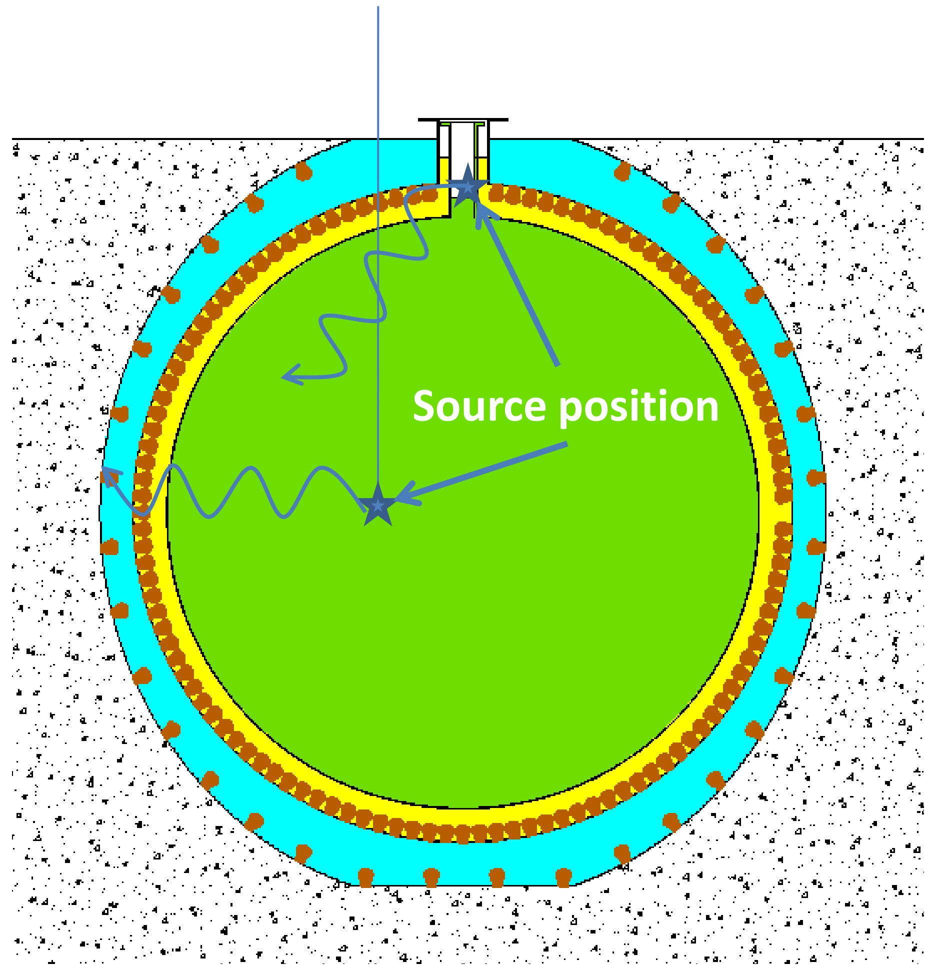
Water Cerenkov detectors can not see these correlated events



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 and Engineering challenges

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

Energy resolution Approach

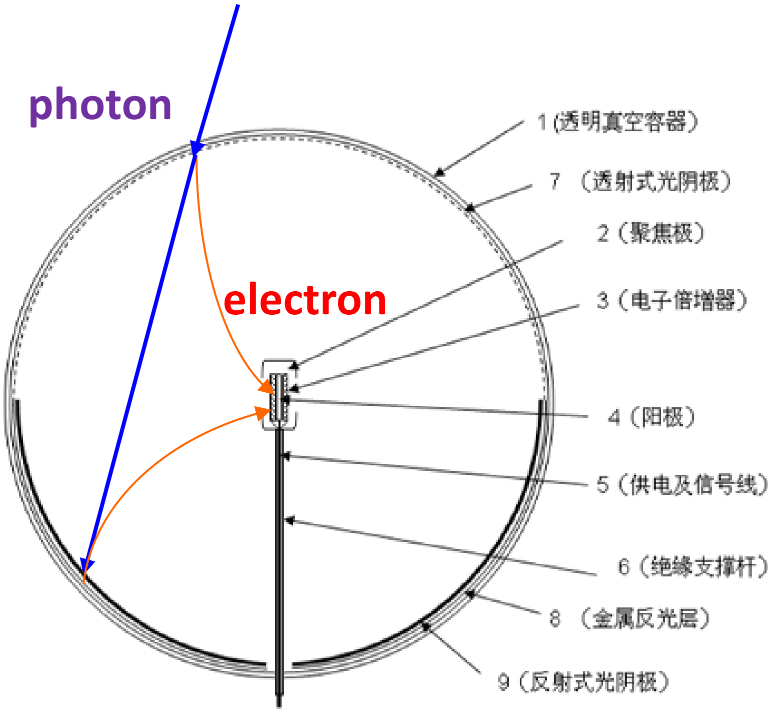
	KamLAND	JUNO
Detector	~1 kt Liquid Scintillator	20 kt Liquid Scintillator
Energy Resolution	6%/√E	3%/√E
Light yield	250 p.e./MeV	1200 p.e./MeV

How?

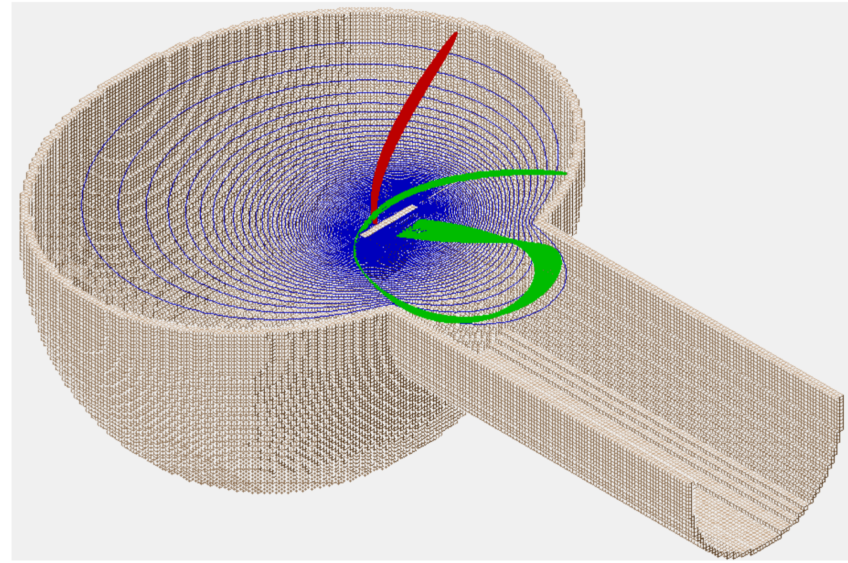
- Highly transparent LS
  - Attenuation length/D: 15m/16m → 30m/34m X 0.9
- High light yield LS:
  - KamLAND: 1.5g/l PPO → 5g/l PPO
    Light Yield: 30% → 45% X 1.5
- Photocathode coverage:
  - KamLAND: 34% → ~80% X 2.3
- High QE "PMT":
  - 20" SBA PMT QE: 25% → 35% X 1.4
    or New PMT QE: 25% → 40% 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

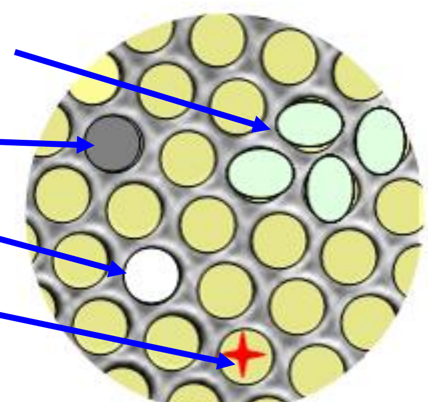


- Top: transmitted photocathode
- Bottom: reflective photocathode
  additional QE: ~ 80%*40%
- MCP (Microchannel Plate) to replace Dynodes ➔ no blocking of photons



Low cost MCP by accepting the followings for SPE detection.

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



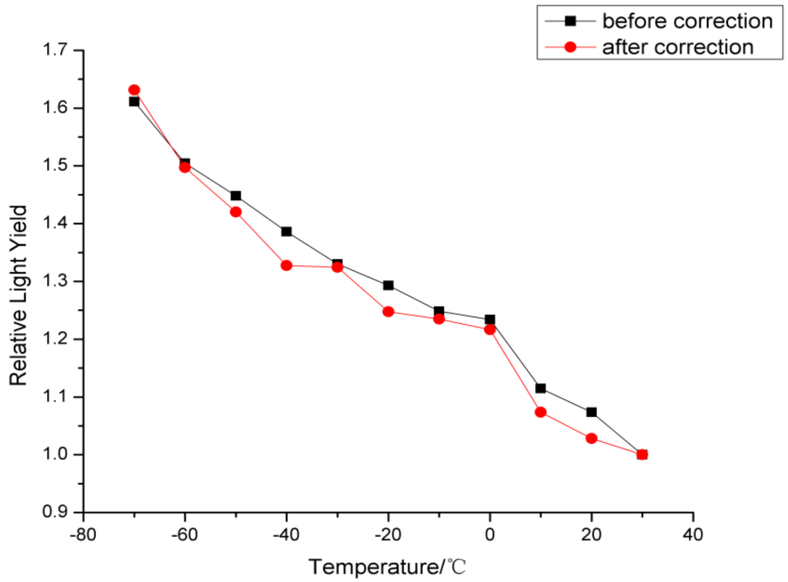
MCP surface

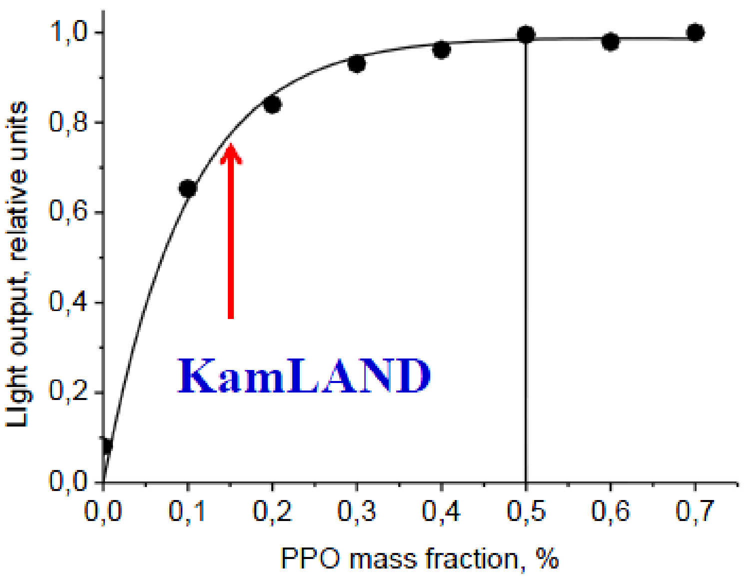
LAB based liquid scintillator

- 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

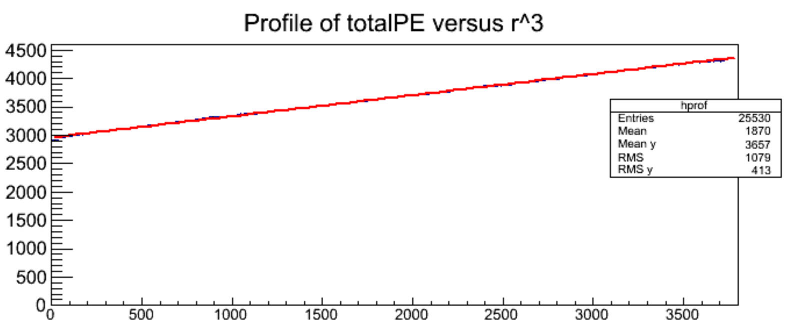
LAB	Atte. Length @ 430 nm
RAW	14.2 m
Vacuum distillation	19.5 m
SiO_2 coloum	18.6 m
Al_2O_3 coloum	22.3 m

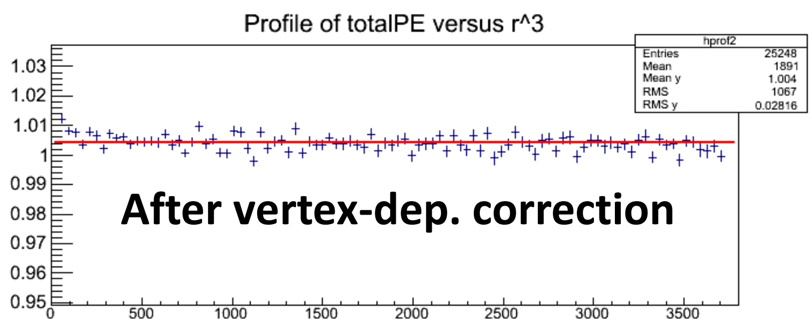


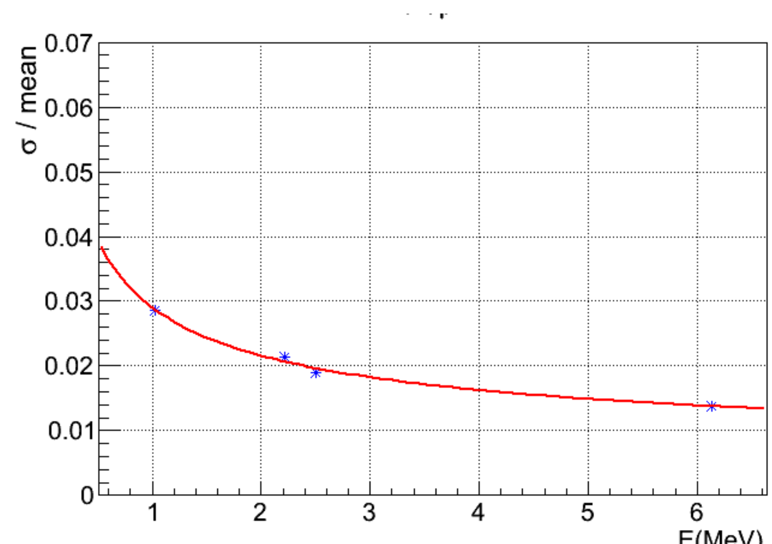


Energy Resolution

- **DYBII MC, based on DYB MC (tuned to data), except**
  - **DYBII Geometry and 80% photocathode coverage**
  - **SBA 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**



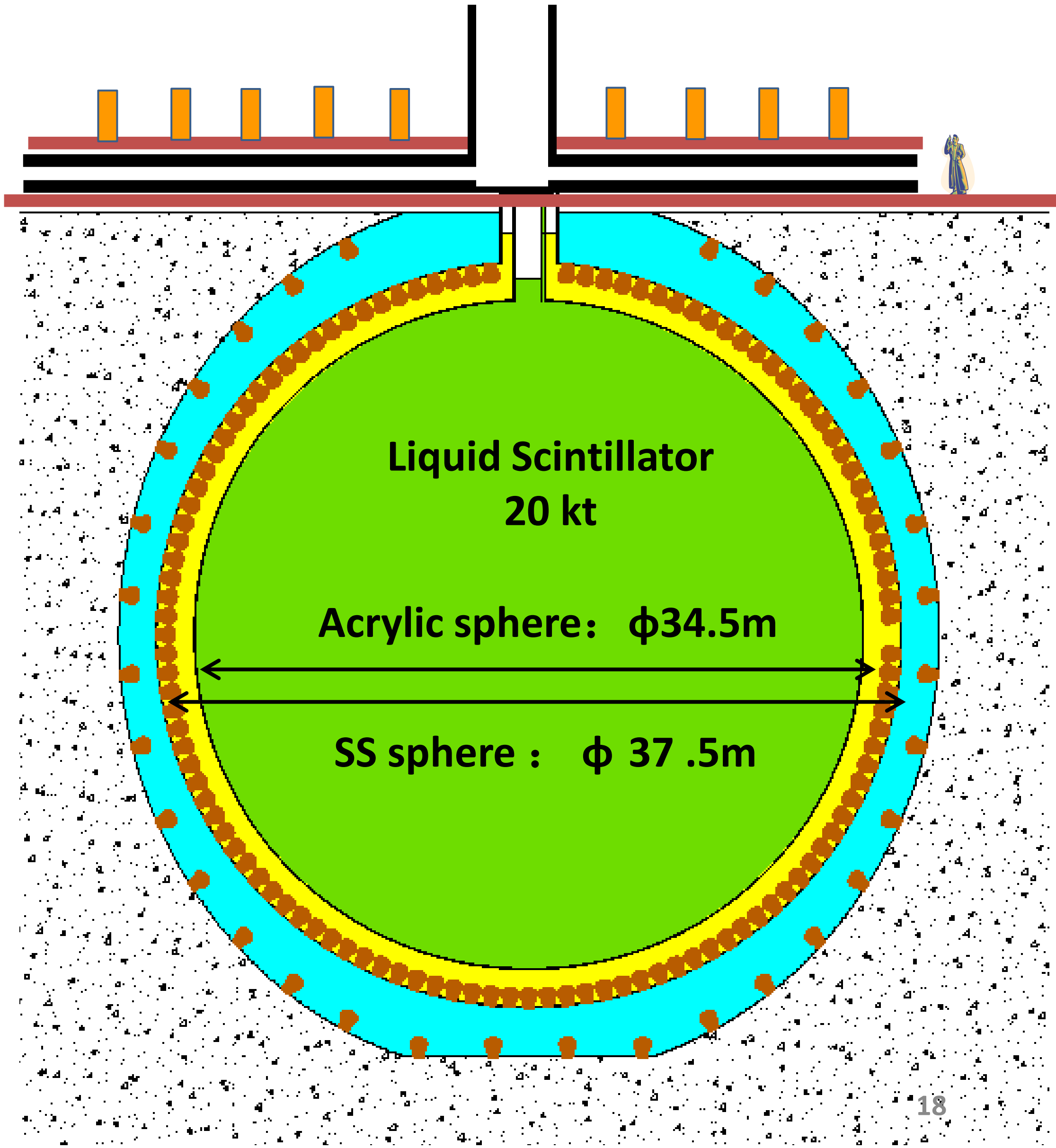




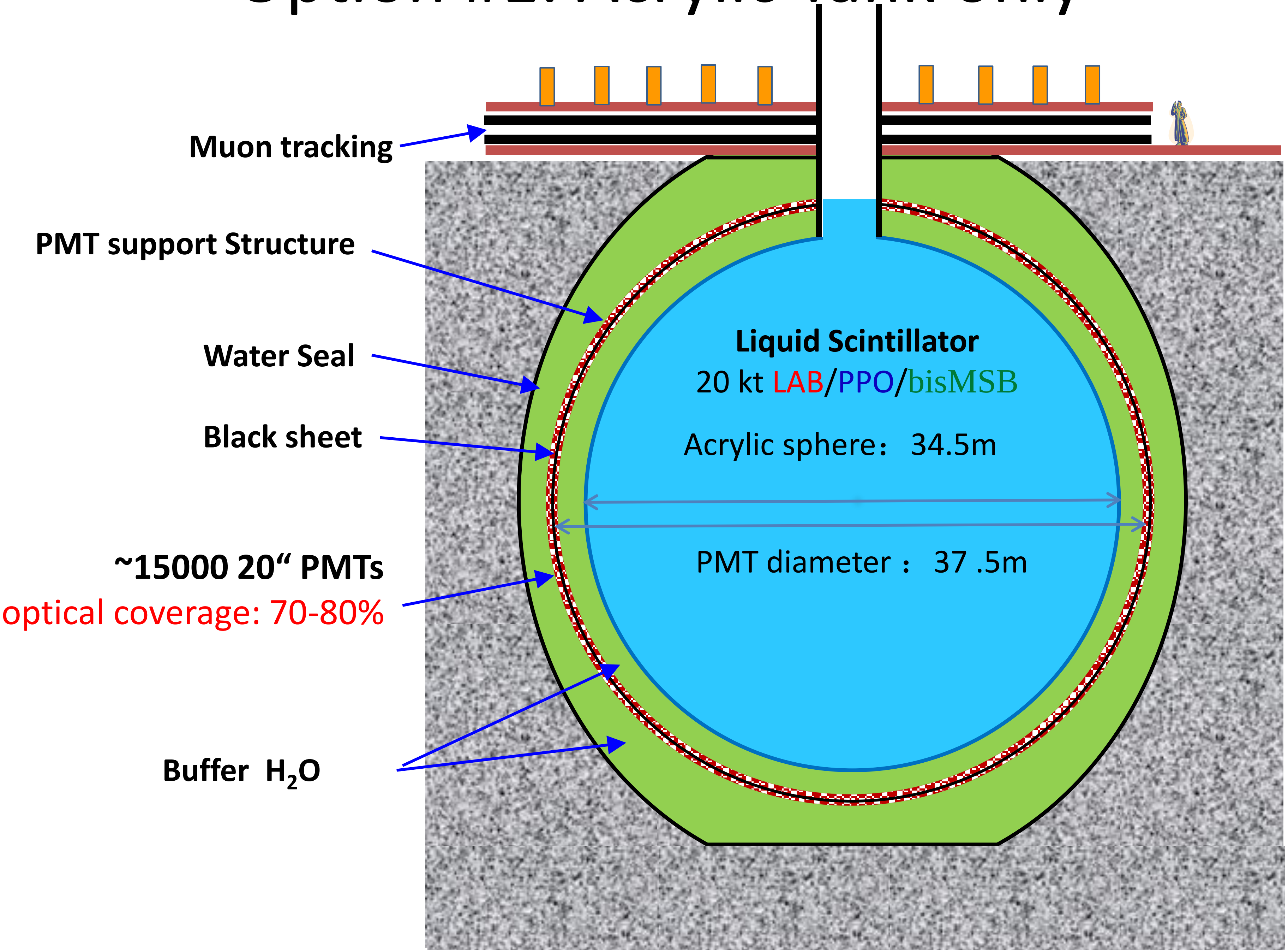
$$3\%/\sqrt{E} \quad or \quad (2.6/\sqrt{E}+0.3)\%$$

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

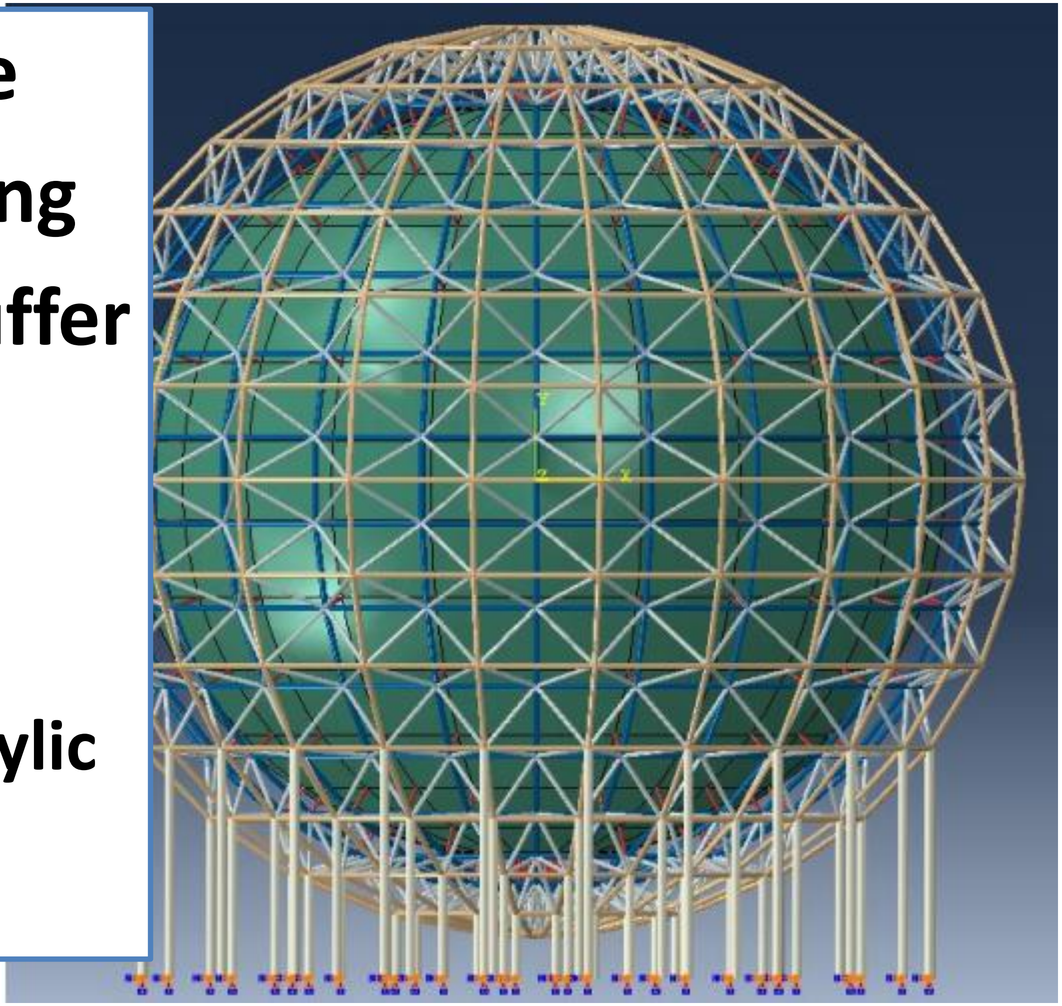


Option #1: Acrylic Tank only



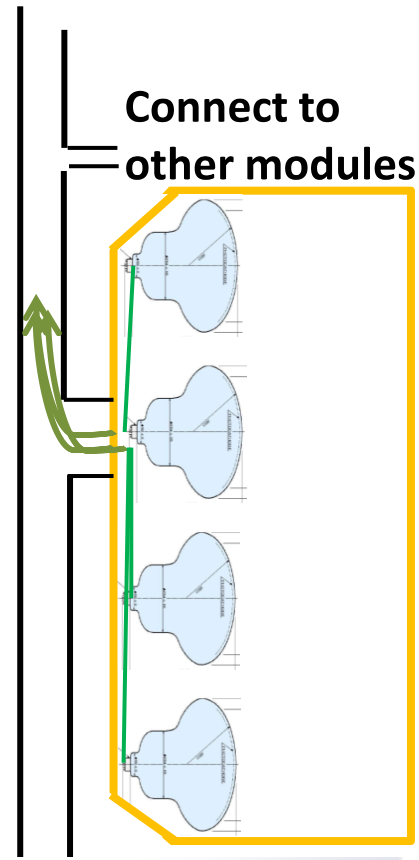
Option 1: Acrylic + SS Struct

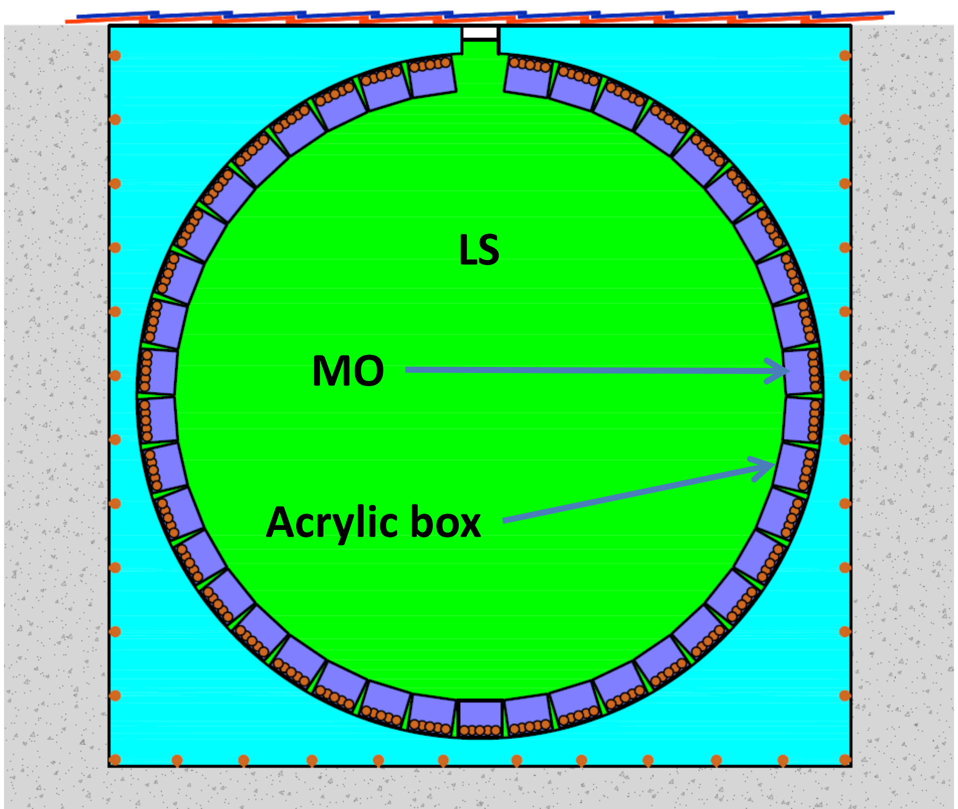
- No more interference
- “Easy” for PMT holding
- Water replaces oil buffer ➔cheap
- Difficulties:
  - Larger pressure difference for the acrylic tank.

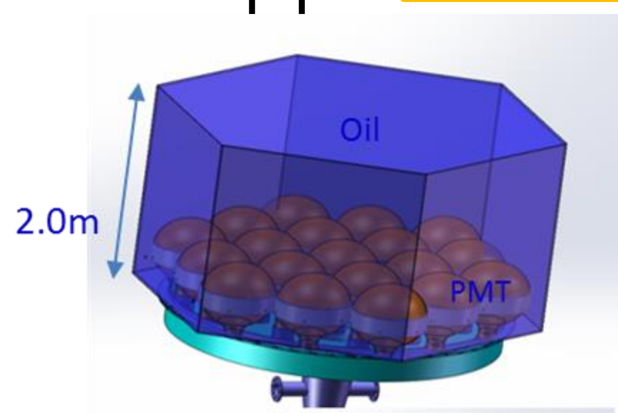


Option 2: acrylic box

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

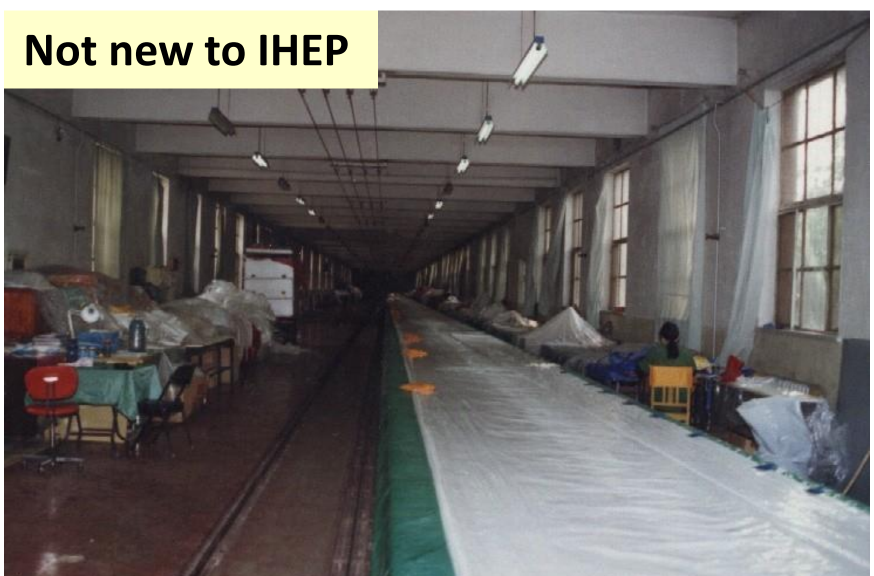


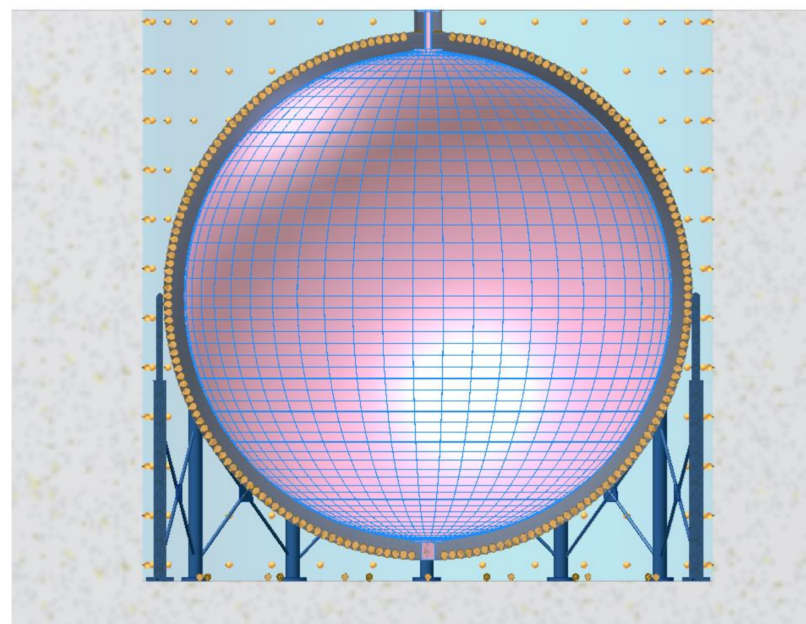




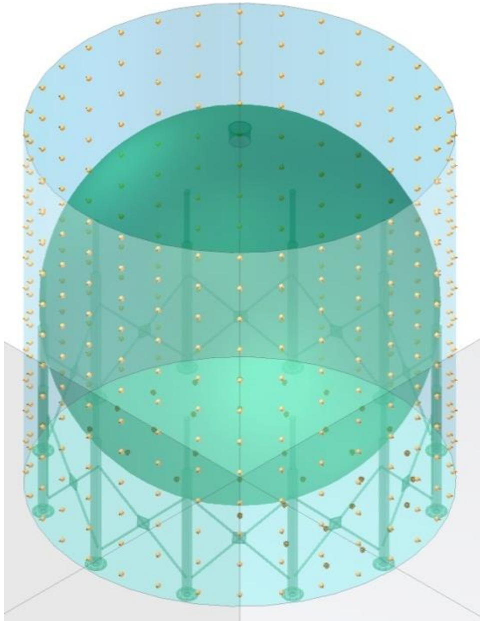
Option 3: balloon

- "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, …





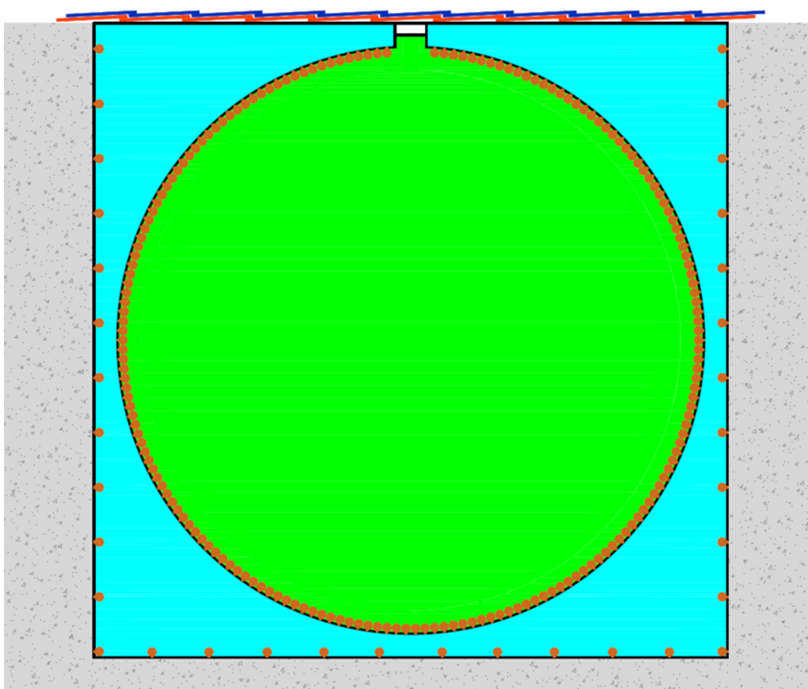
Option 4: Steel tank only



- No problem for construction
- Backup plan for the failure balloon option
- But
  - PMT protection
  - high backgrounds
  - Resolution affected by backgrounds

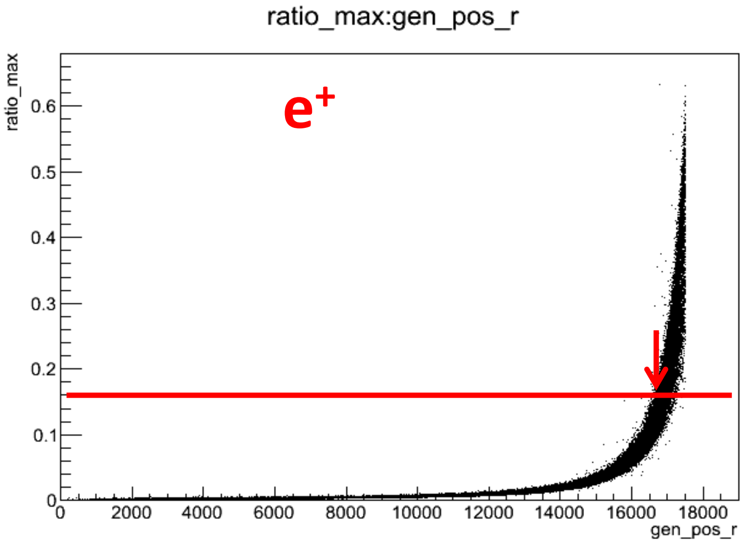
If the PMT glass is the same as Daya Bay, radioactivity will be 44 Bq/PMT, or 3.3 MHz in total

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**



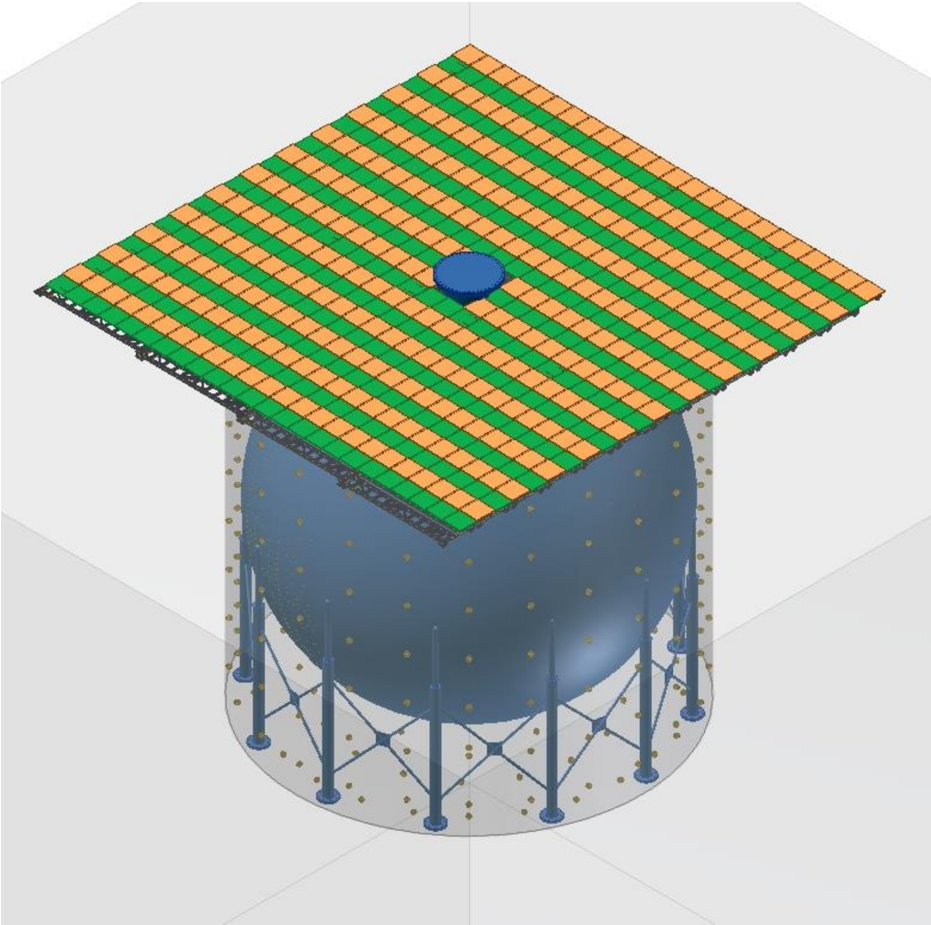
Equivalent to fiducial volume cut.

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

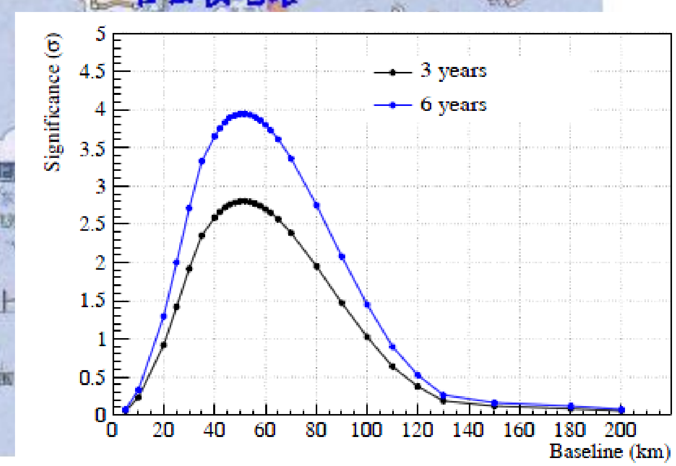


The site: Kaiping county, Jiangmen City

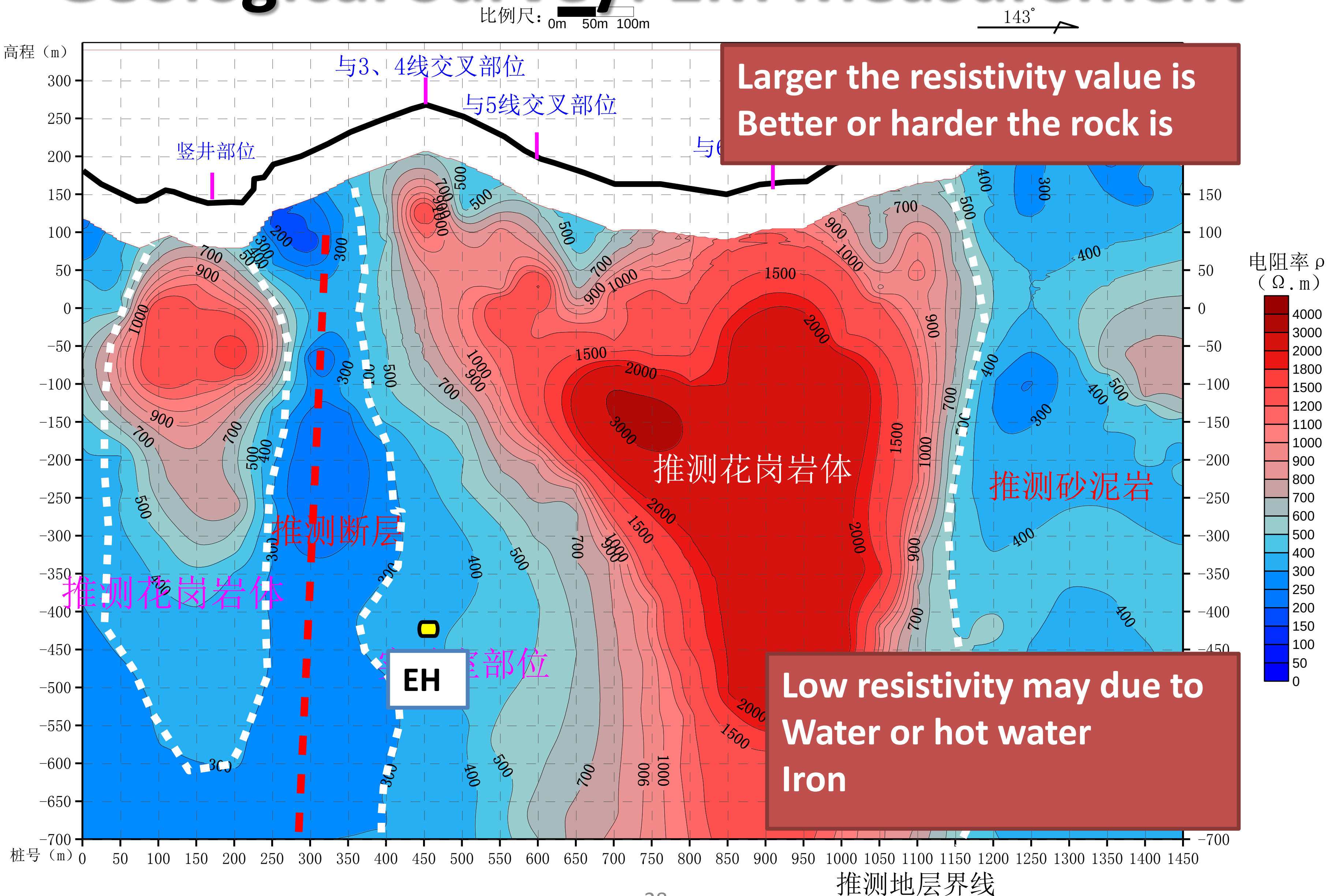
	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	**17.4 GW**	**18.4 GW**

Site: Kaiping county, Jiangmen City in Guangdong province

- Baseline:50~60km to nuclear power complex
- Same distance away to both Yanjiang and Taishan Nuclear Power complex
- The interference from other power plant (>200km) is neglectable



Geological Survey: EM Measurement

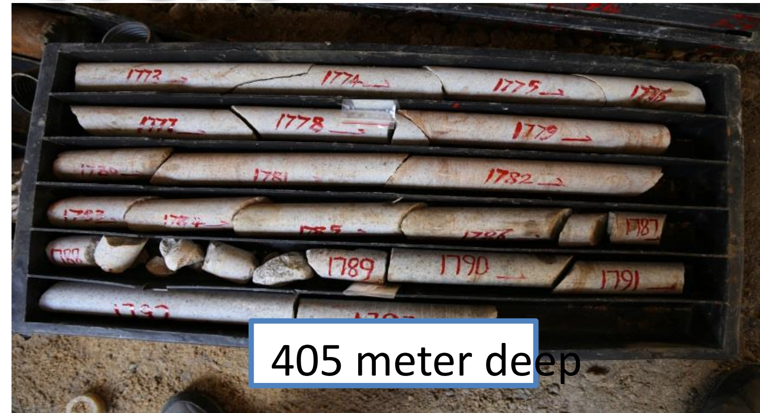


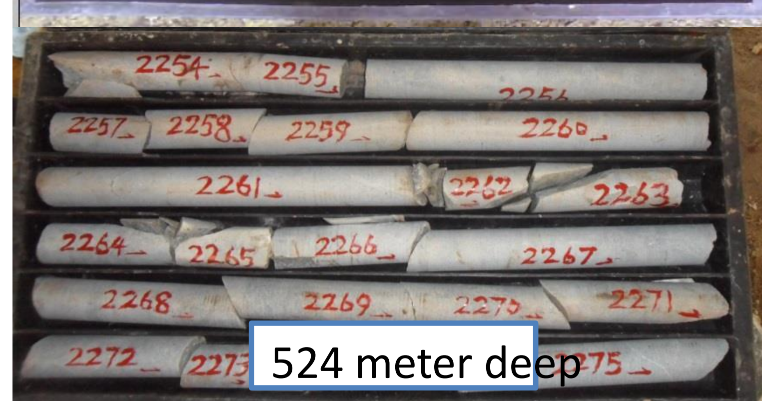
Larger the resistivity value is
Better or harder the rock is

Low resistivity may due to
Water or hot water
Iron

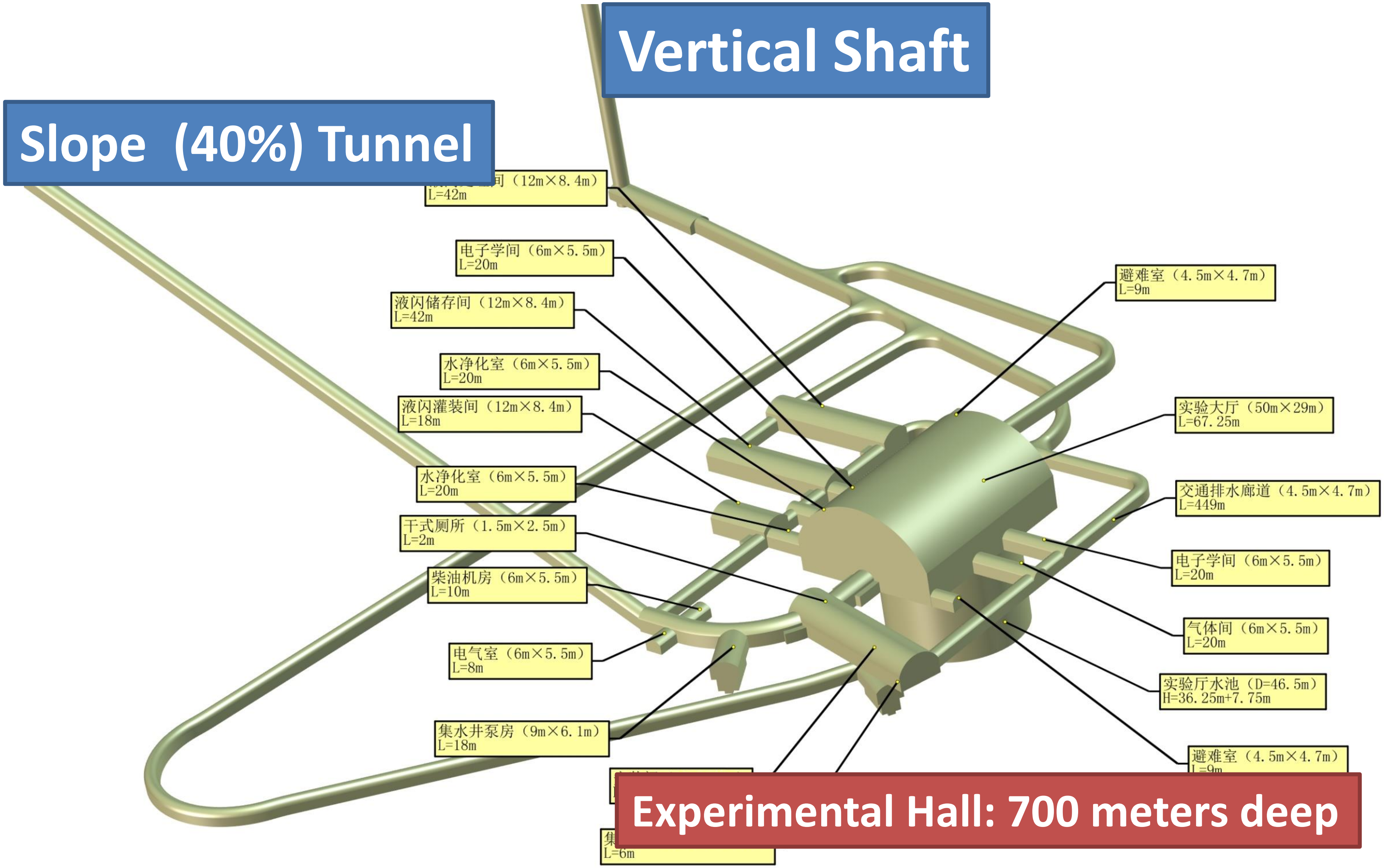
Exploratory Wells

We are lucky that the experimental hall is underneath granite as well as vertical shaft

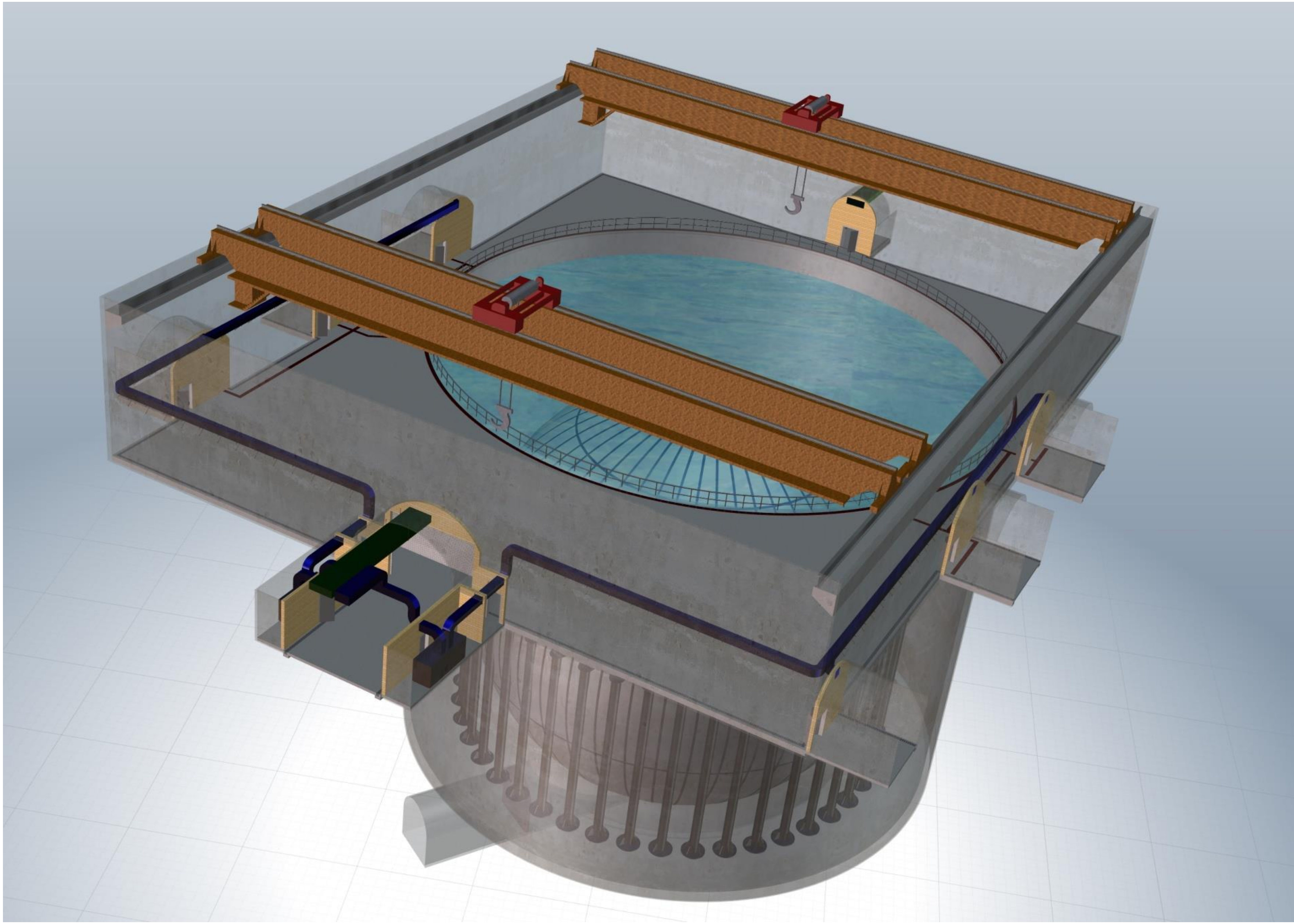




Underground Facility



Experimental Hall



Status and Plan

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

- **Geological Survey will be finished in two months**
- **Civil Feasibility report (~CD2) submitted this month**
- **Civil Engineering Design will be finished this year.**
- **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**

Summary

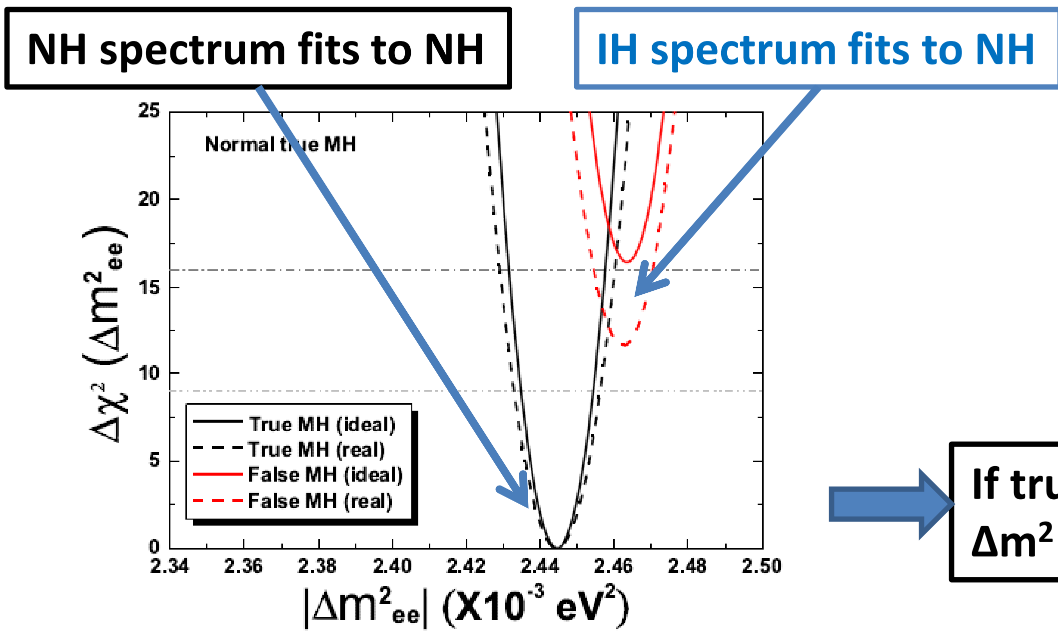
- Daya Bay II project is now boosted by the large θ_{13}
- Rich potential neutrino physics
- Although a lot of technical and engineering challenging, preliminary study shows it is not impossible.
- A few key R&D efforts has been started, more will come.
- Detector design and civil design is undergoing
- Strong supports from the Chinese government and the Chinese funding agencies.

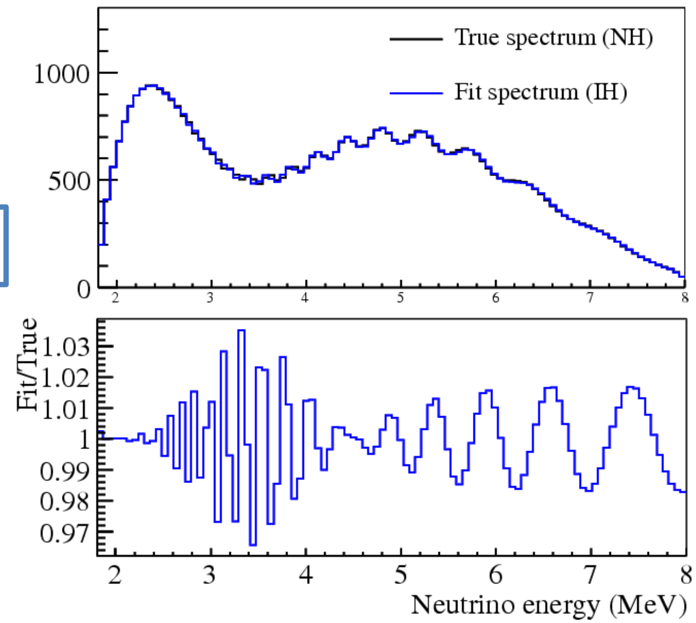
backup

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.

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



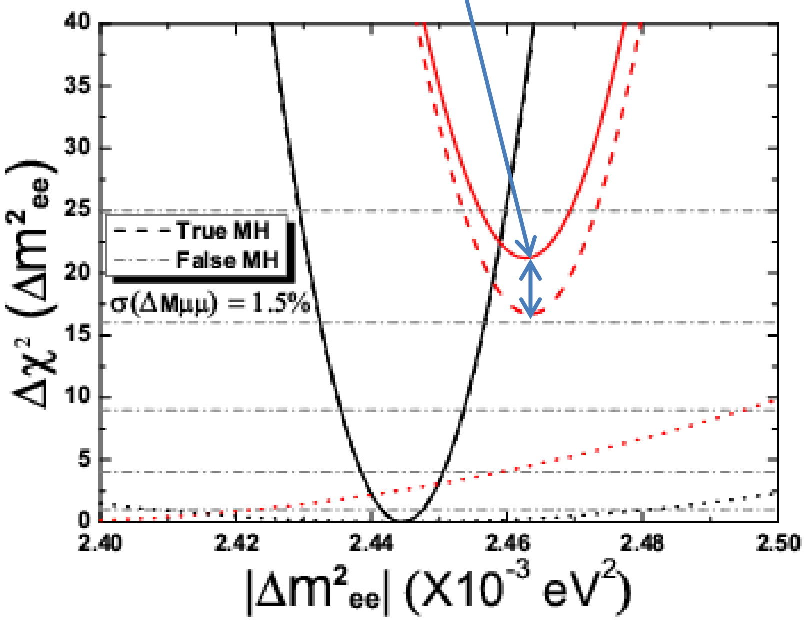


If truth is NH, NH spectrum may fit it better.
Δm^2 is fitted without constraint.

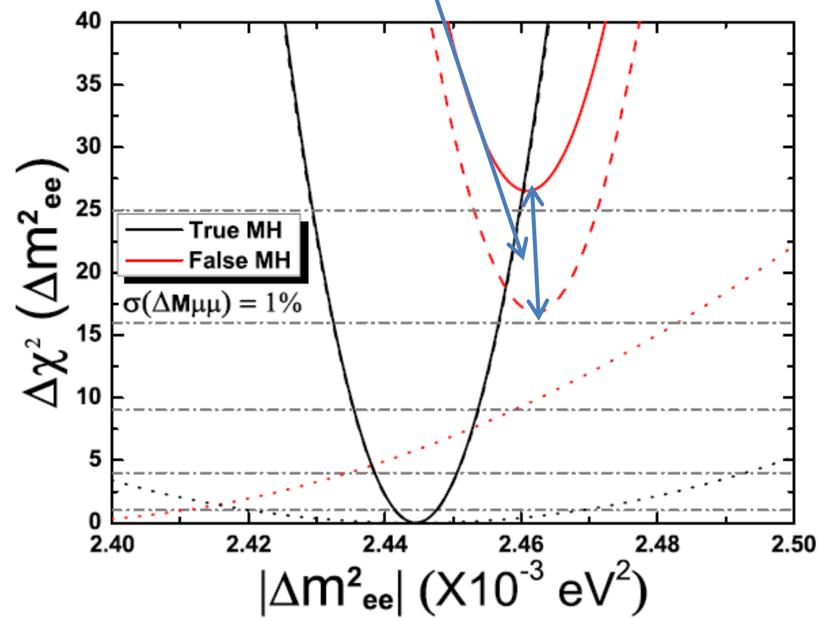
Taking into account Δm^2_{32}

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

Improved by 1.5% precision



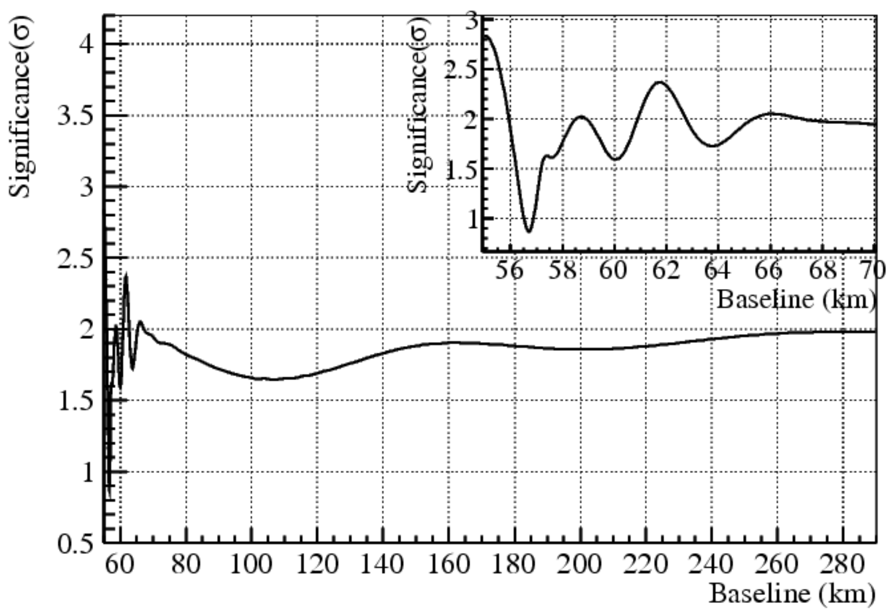
Improved by 1% precision

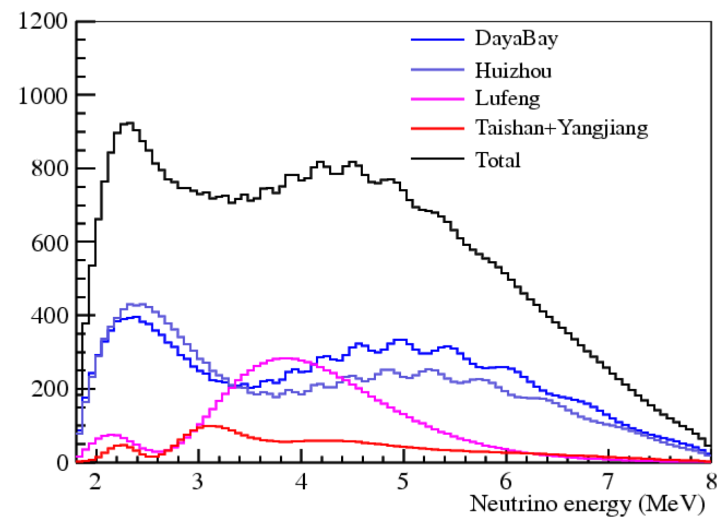


Yu-Feng Li, Jun Cao, Yifang Wang, Liang Zhan, arXiv:1303.6733

Complex interference between reactors

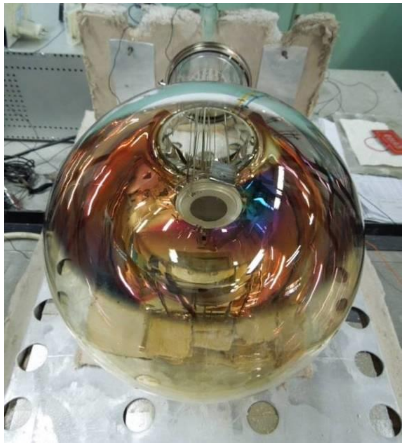
- Adding one reactor (more statistics) is not always helpful.
- Example:
  - One reactor (6X2.9 GW) at 55 km, the significance is 2σ.
  - Add another reactor
    - Statistics doubles with equal baseline.
    - Helpful, if the baseline difference < 1 km.
    - Harmful as background, if the baseline difference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

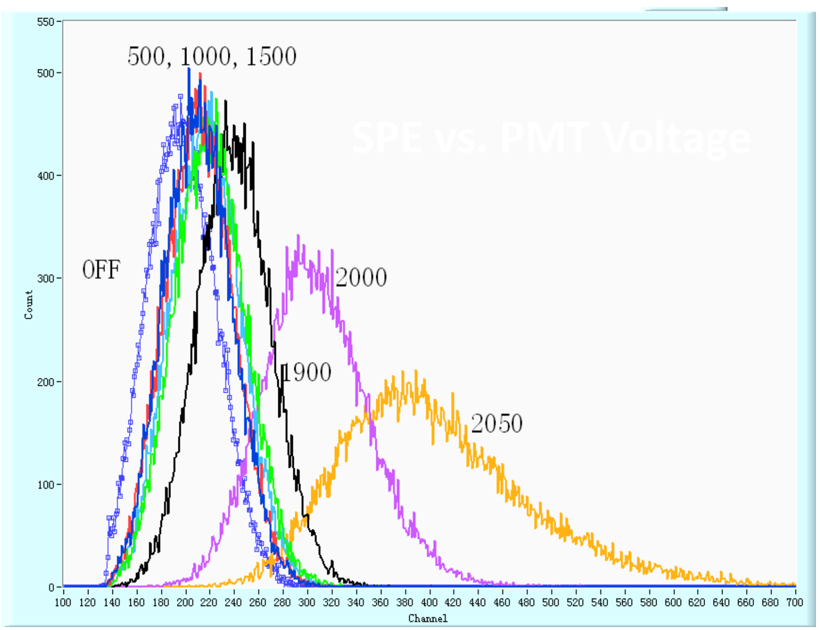




Example of peak and valley cancellation

Prototypes





MPE vs the luminance of the LED light