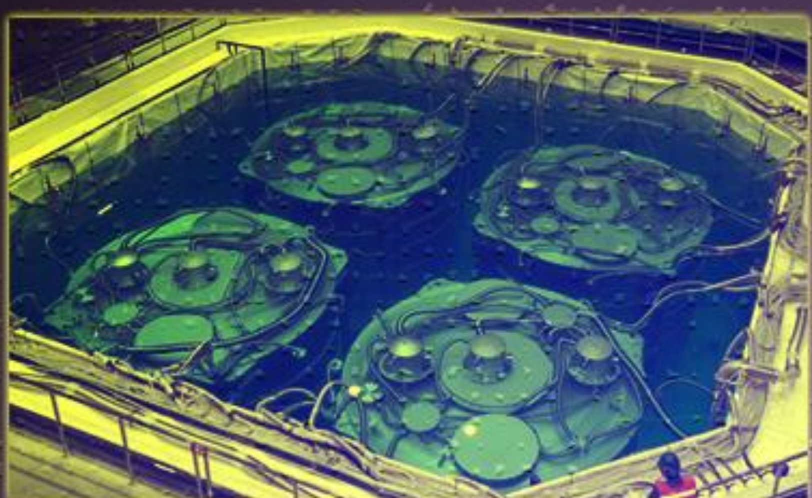
Future Reactor Experiments

Miao HE

Institute of High Energy Physics, Beijing



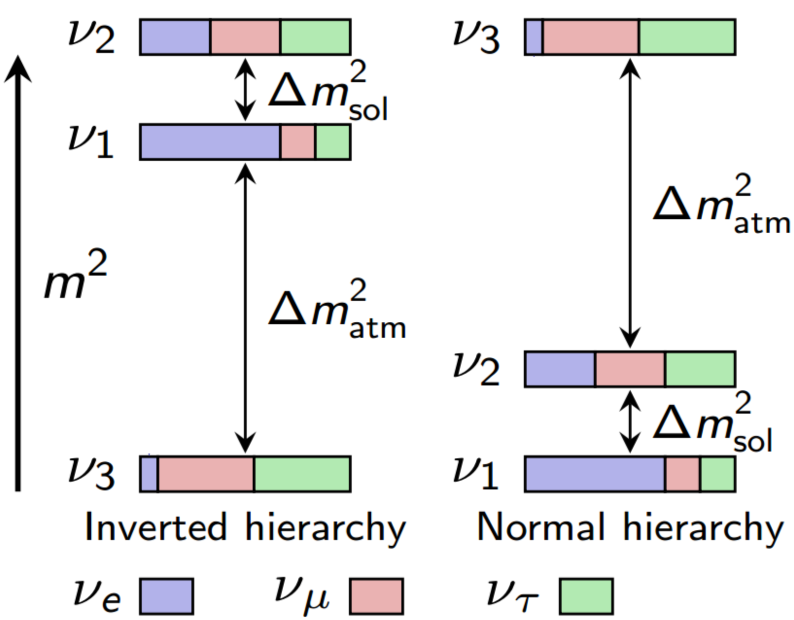
International Workshop on Neutrino Factories, Super Beams and Beta Beams

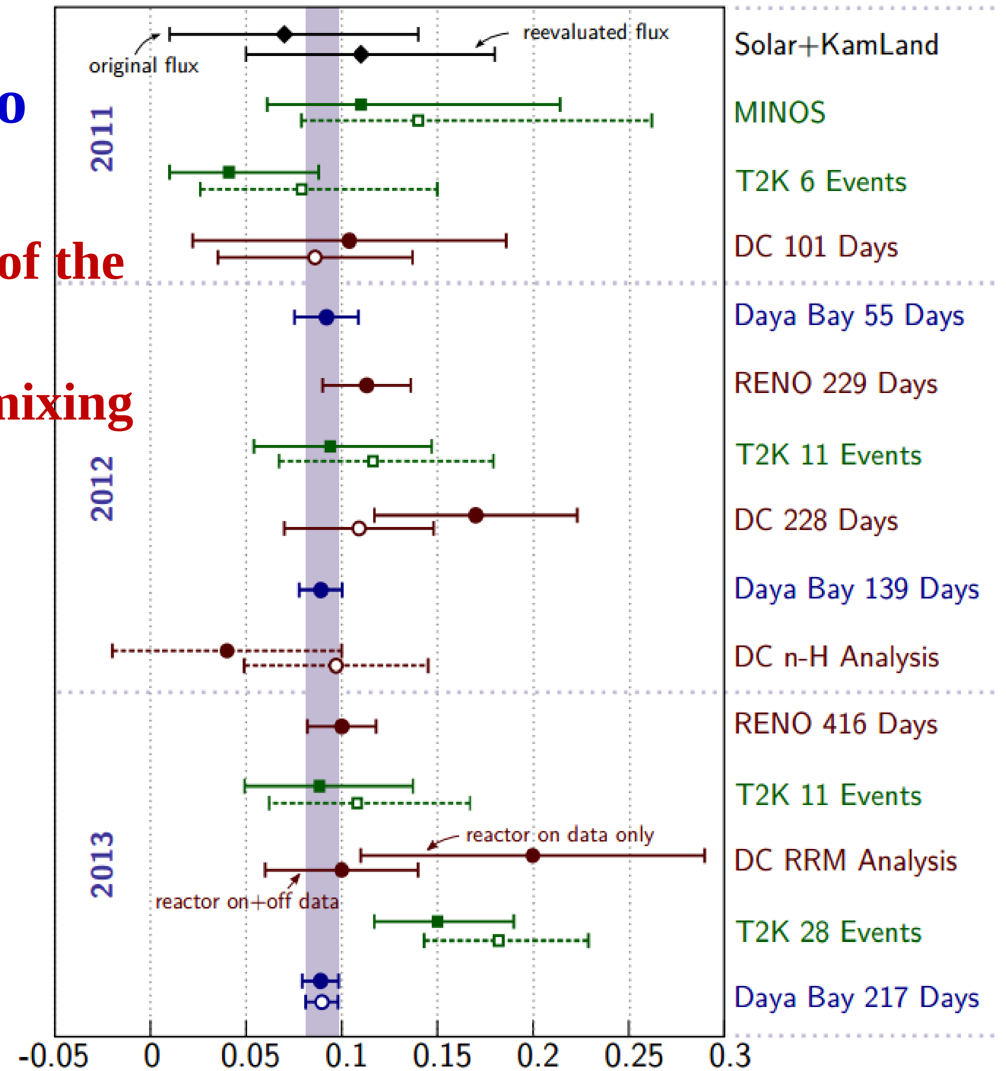
NUFACT 2013

August 19-24,2013,IHEP,Beijing,China

New era of neutrino experiments

- **Main focus: Mass hierarchy and CP phase**
- **What role a reactor neutrino experiment can play ?**
  - ⇨ **Mass hierarchy independent of the CP phase**
  - ⇨ **Precision measurement of 4 mixing parameters**





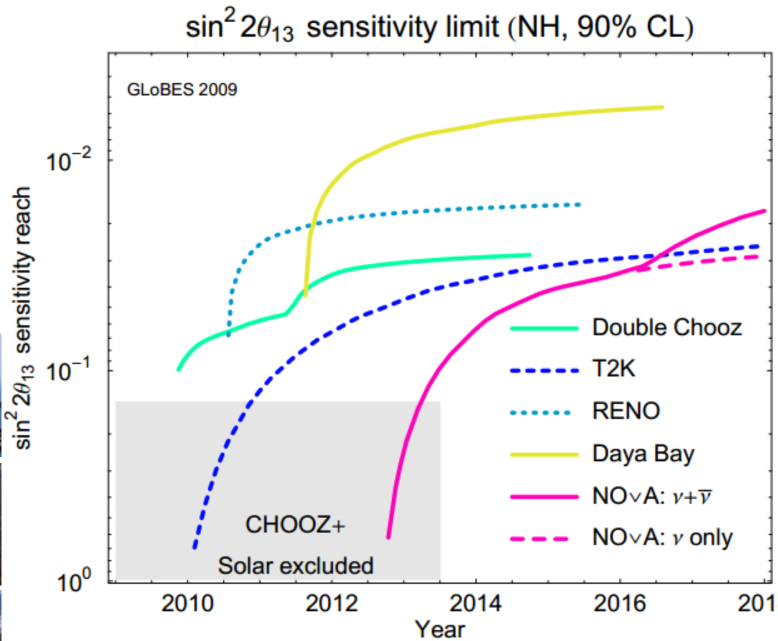
S. Jetter

Outline

- Future sensitivity of ongoing reactor experiments
- Mass Hierarchy by reactor neutrinos
- The Jiangmen Underground Neutrino Observatory (JUNO)
- RENO-50
- Summary

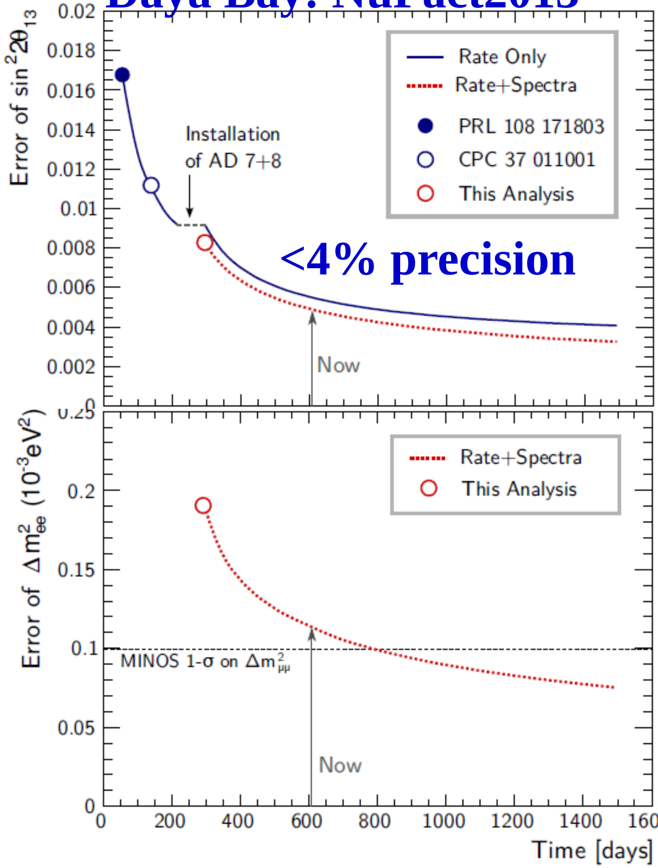
Future sensitivity of ongoing reactor experiments

Experiments	Sensitivity (3y, 90% C.L.)
Daya Bay	~0.008
Double Chooz	~0.03
RENO	~0.02

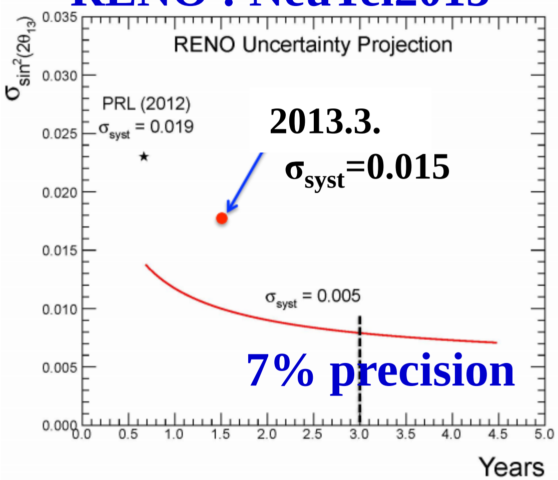


Huber et al. JHEP 0911:044, 2009

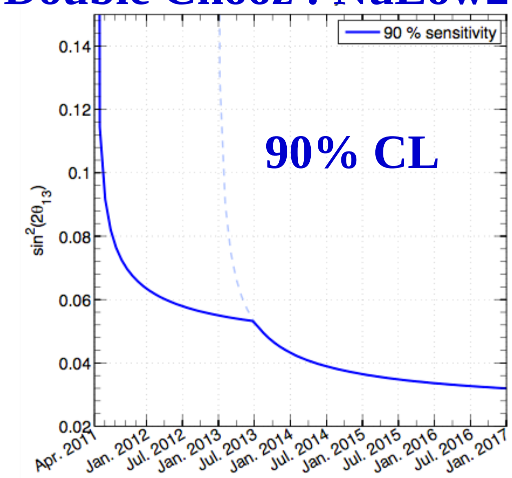
Daya Bay: NuFact2013



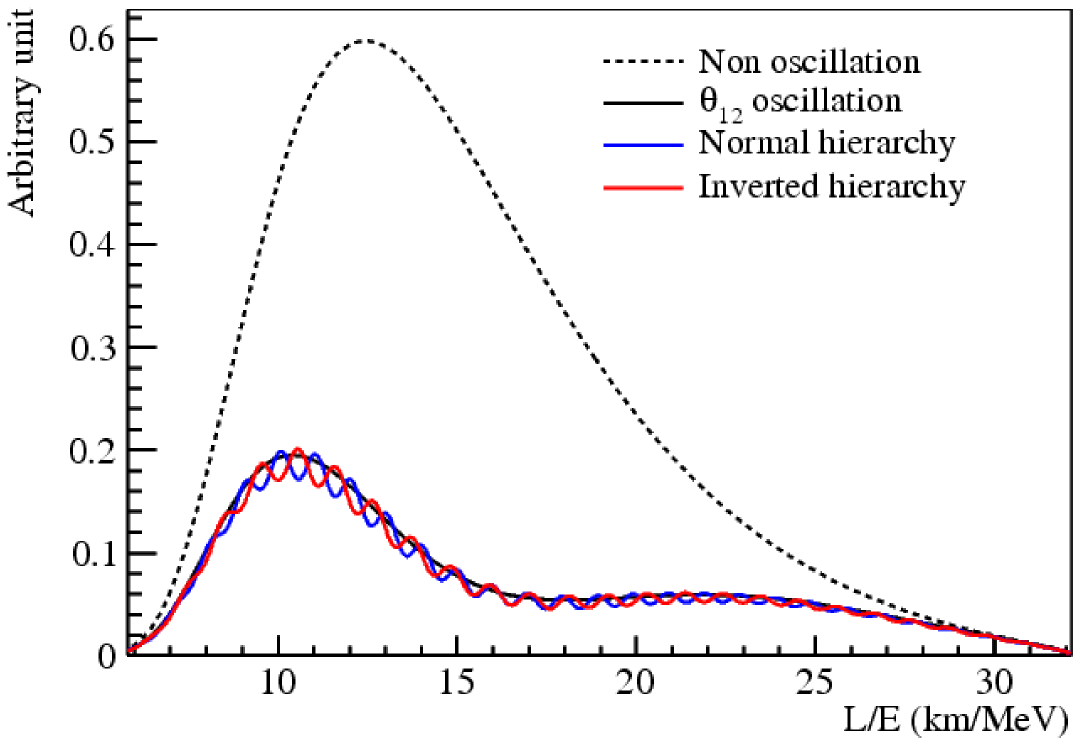
RENO : NeuTel2013



Double Chooz : NuLow2011



Mass Hierarchy by Reactor neutrinos



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

$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$

$$P_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$$

$$P_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31})$$

$$P_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})$$

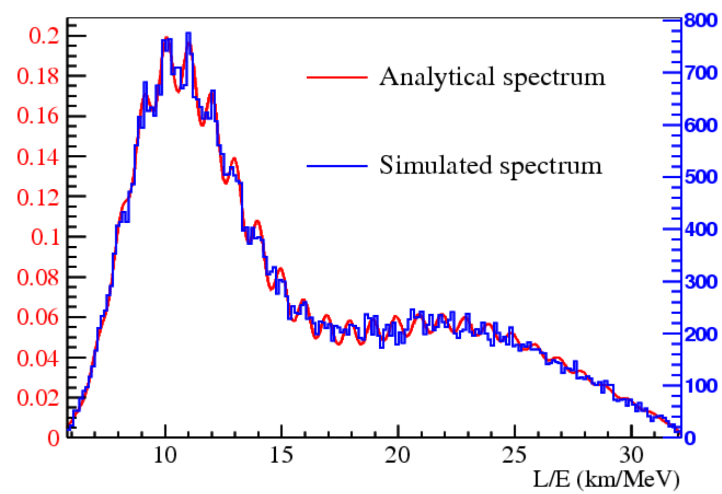
$$\Delta_{21} << \Delta_{31} \approx \Delta_{32}$$

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

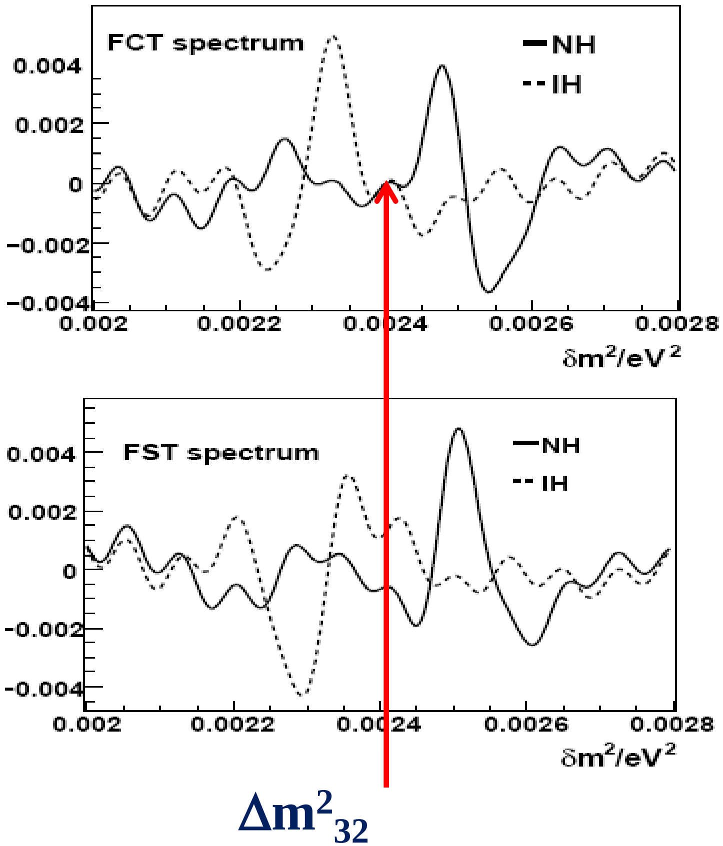
Precision energy spectrum measurement: Looking for interference between P_{31} and P_{32}

➔ relative measurement



Mass hierarchy: sensitivity

- **Thanks to a large θ_{13}**

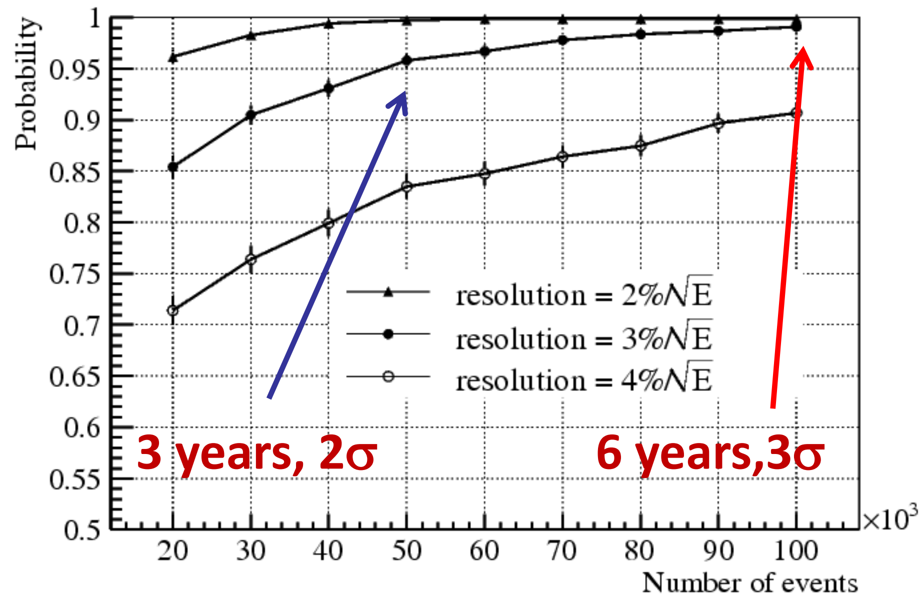


$$\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$$

$$\mathrm{NH}: \ |\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$$

$$\mathrm{IH}: \ |\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$$

Fourier transformation:



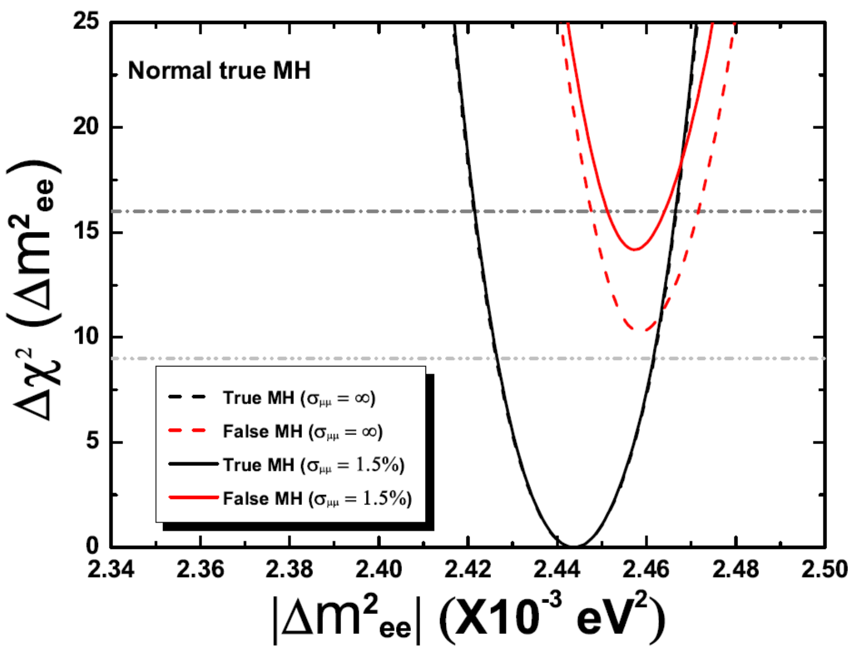
Detector size: 20kt
Energy resolution: 3%/√E
Thermal power: 36 GW
Baseline 58 km

L. Zhan, Y.F. Wang, et al., PRD78:111103,2008; PRD79:073007,2009

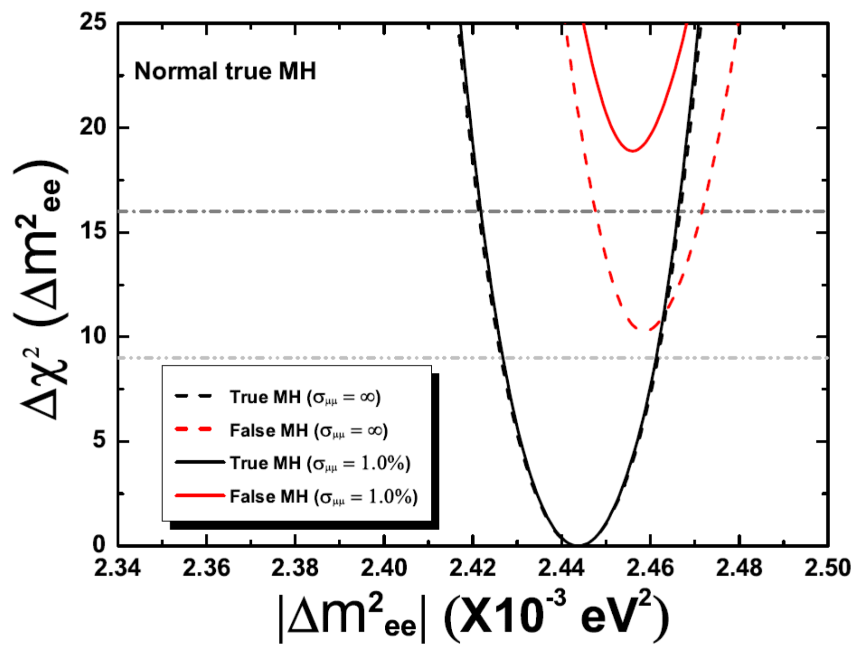
Taking into account $\Delta m^2_{\mu\mu}$

- **MH sensitivity improved by taking into account the $\Delta m^2_{\mu\mu}$ from T2K and Nova in the future**

Improved by precision 1.5%



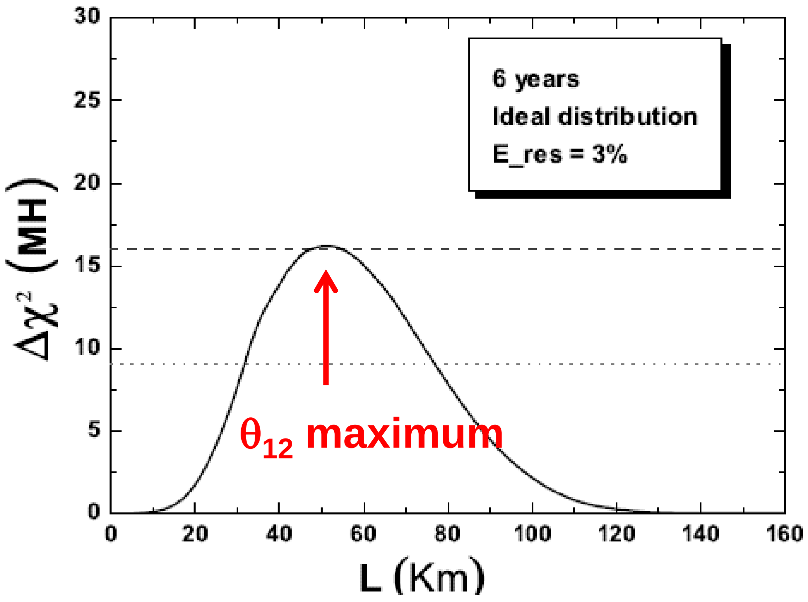
Improved by precision 1%

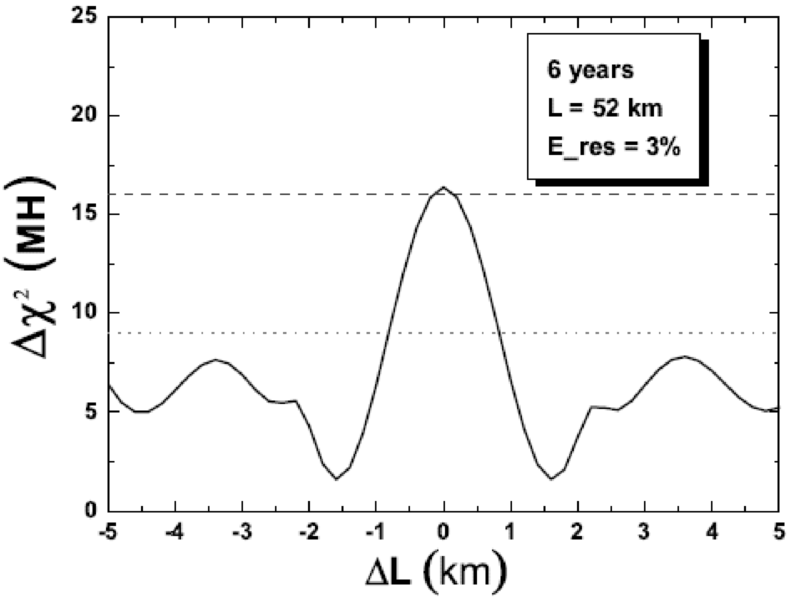


Yu-Feng Li, Jun Cao, Yifang Wang, Liang Zhan, arXiv:1303.6733

Optimum baseline

- **Optimum at the oscillation maximum of θ_{12}**
- **Multiple reactors may cancel the oscillation structure**
  - ⇨ Baseline difference cannot be more than 500 m





Energy scale can be self-calibrated

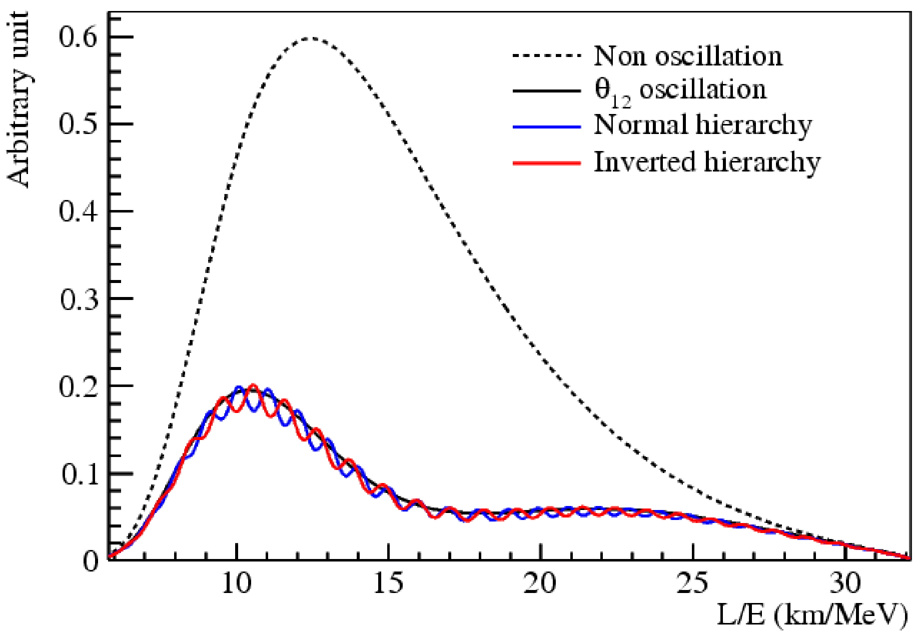
If we have a residual non-linearity in data, and add a quadratic non-linear function in the fitting process:

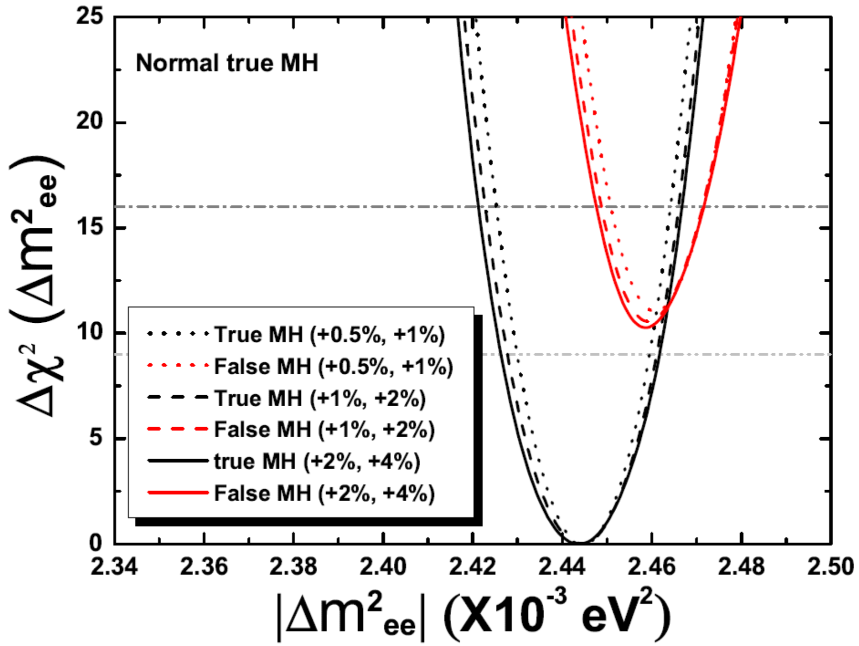
$$\frac{E_{\rm rec}}{E_{\rm true}} \simeq 1 + q_0 + q_1 E_{\rm true} + q_2 E^2_{\rm true}$$

by introduce a self-calibration(based on Δm^2_{ee} peaks):

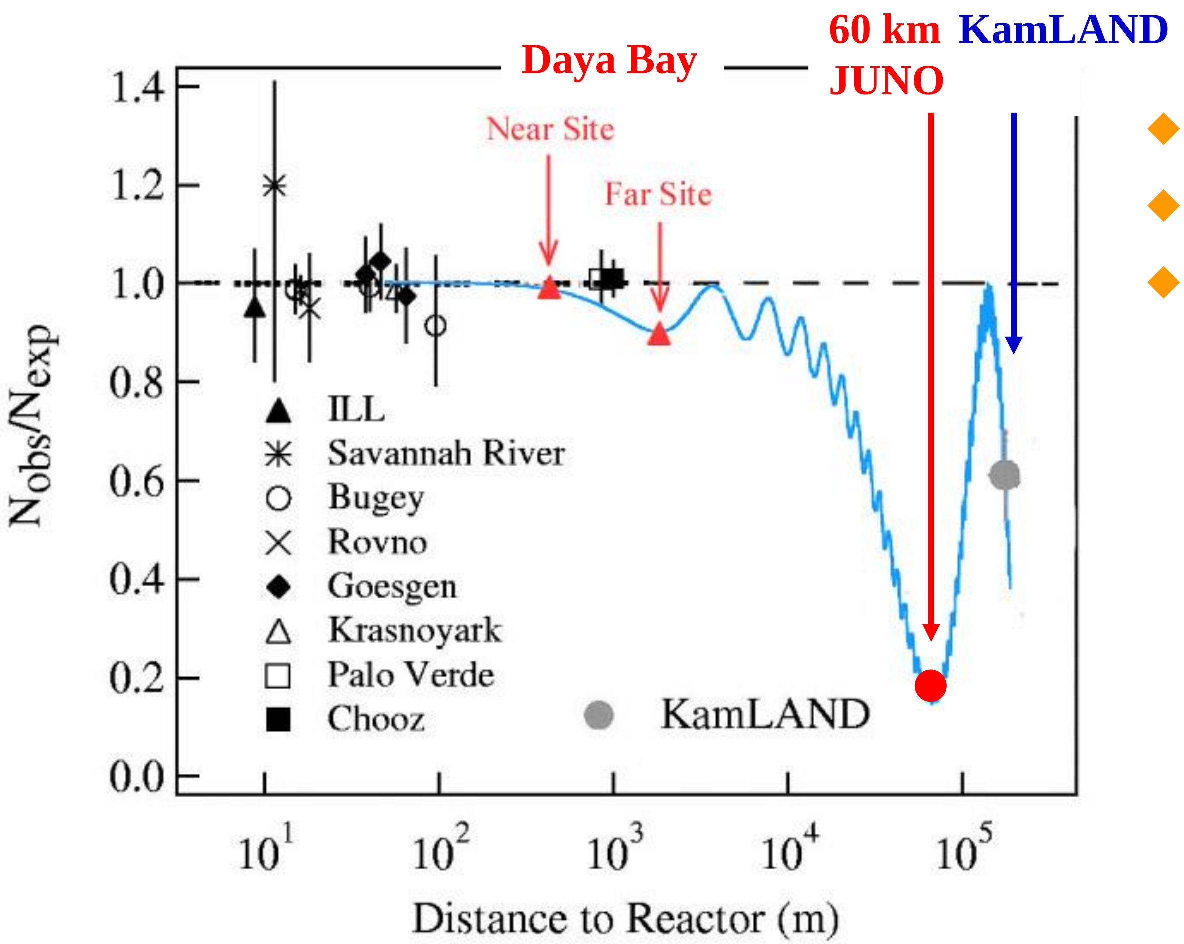
$$\chi^2_{\rm NL} = \sum_{i=0}^{2} q_i^2/(\delta q_i)^2$$

effects can be corrected and sensitivity is un-affected





The Jiangmen Underground Neutrino Observatory
(JUNO, known as Daya Bay II)

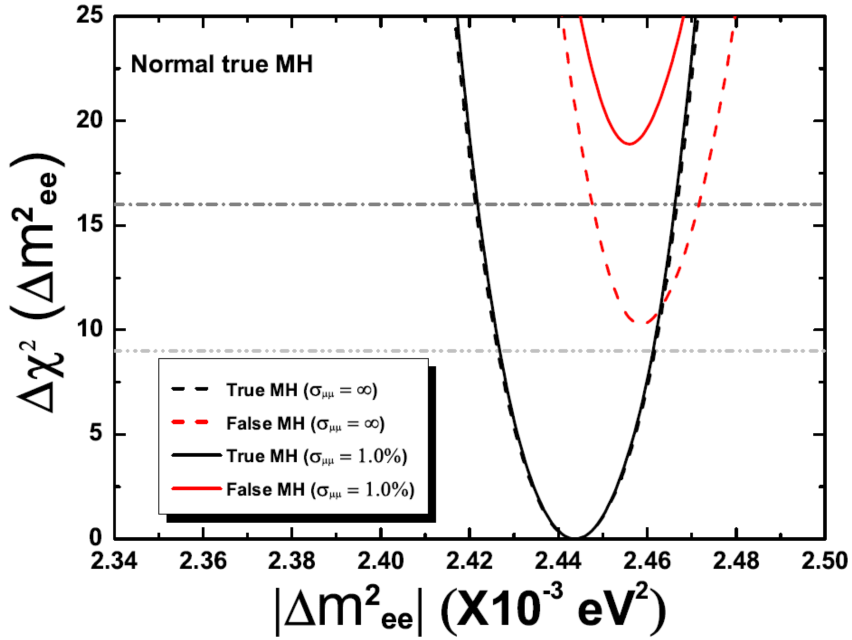


- **20 kton LS detector**
- **3% energy resolution**
- Rich physics possibilities
  - ⇨ **Mass hierarchy**
  - ⇨ **Precision measurement of 4 mixing parameters**
  - ⇨ **Supernovae neutrino**
  - ⇨ **Geoneutrino**
  - ⇨ **Sterile neutrino**
  - ⇨ **Atmospheric neutrinos**
  - ⇨ **Exotic searches**

Talk by Y.F. Wang at ICFA seminar 2008, Neutel 2011; by J. Cao at Nutel 2009, NuTurn 2012 ;
Paper by L. Zhan, Y.F. Wang, J. Cao, L.J. Wen, PRD78:111103,2008; PRD79:073007,2009

Physics prospective of JUNO

Y.F Li *et al*, arXiv:1303.6733



Probing the unitarity of U_{PMNS} to ~1%

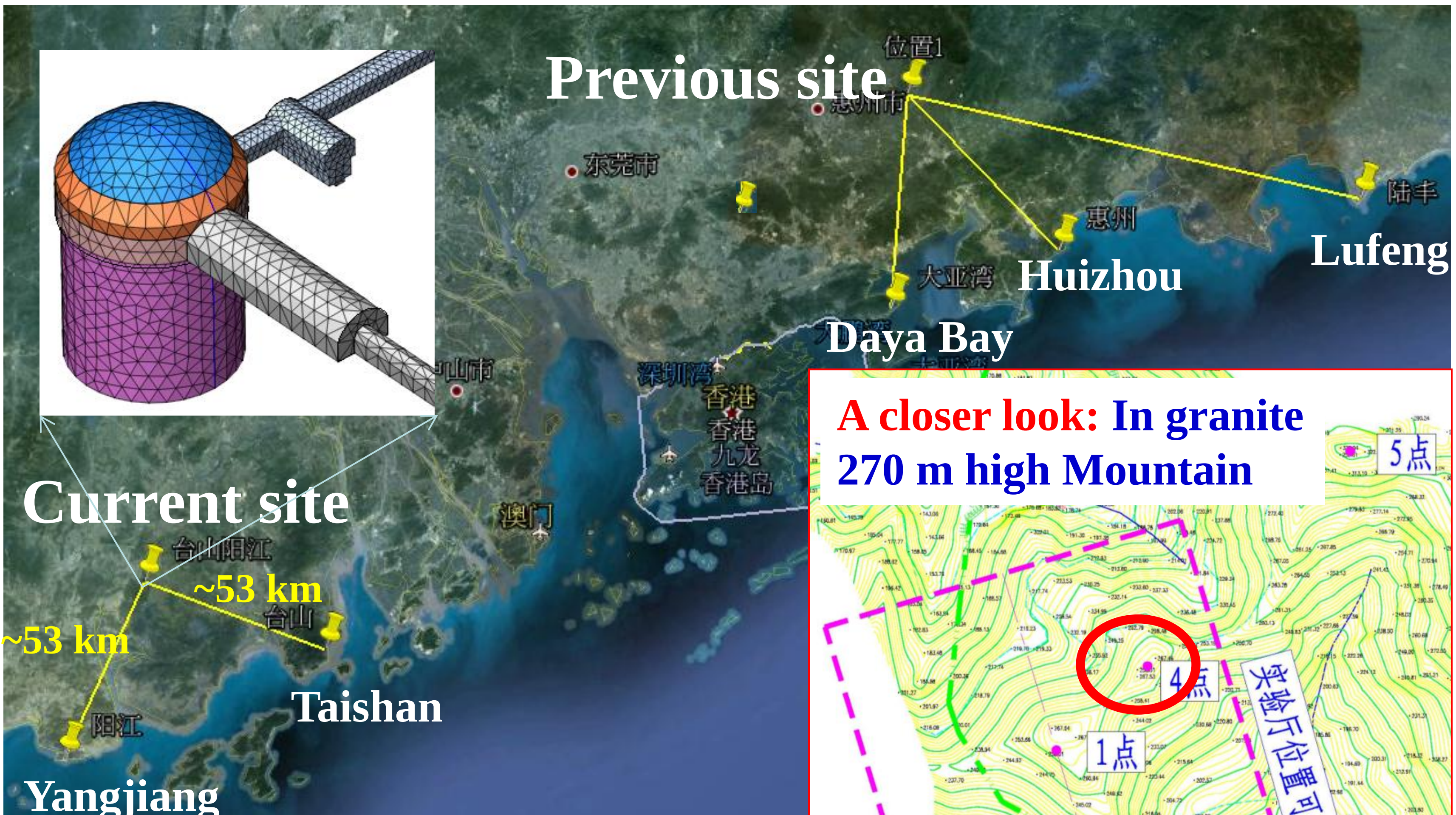
	Current	JUNO
Δm^2_{12}	~3%	~0.6%
Δm^2_{23}	~5%	~0.6%
$\sin^2\theta_{12}$	~6%	~0.7%
$\sin^2\theta_{23}$	~20%	N/A
$\sin^2\theta_{13}$	~14% → ~4%	~ 15%

MH sensitivity with 6 years' data of JUNO (*arXiv:1303.6733*):

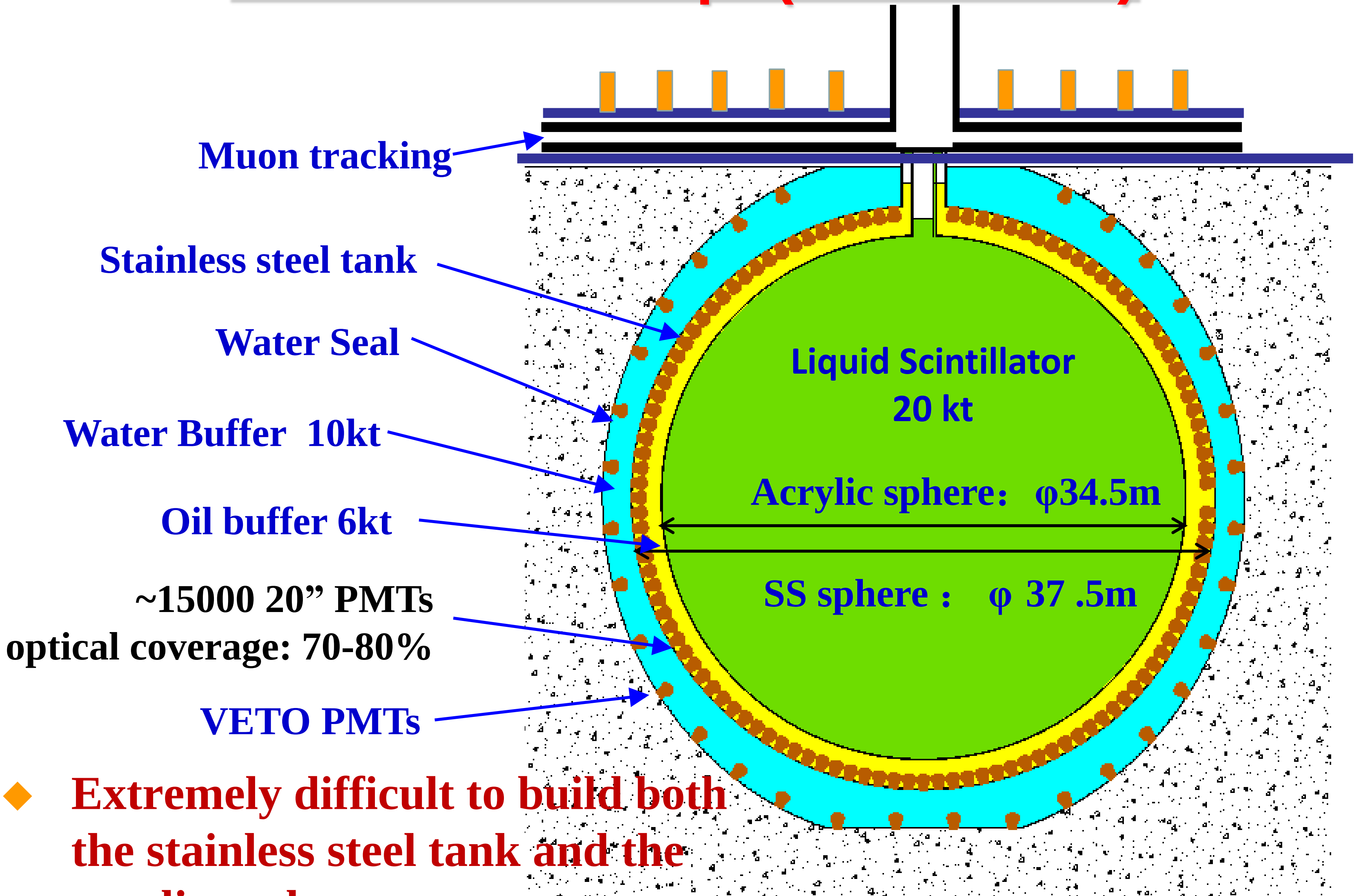
- Ideal case: $\Delta\chi^2$>16 with relative measurement, $\Delta\chi^2$>25 with absolute Δm^2 measurement (if accelerator experiments, e.g NOvA, T2K, can measure $\Delta m^2_{\mu\mu}$ to ~1% level)
- **Taking into account the spread of reactor cores, uncertainties from energy non-linearity, etc.** $\Delta\chi^2$>9 with relative measurement, $\Delta\chi^2$>16 with absolute Δm^2 measurement

Experiment site: Kaiping county, Jiangmen city

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



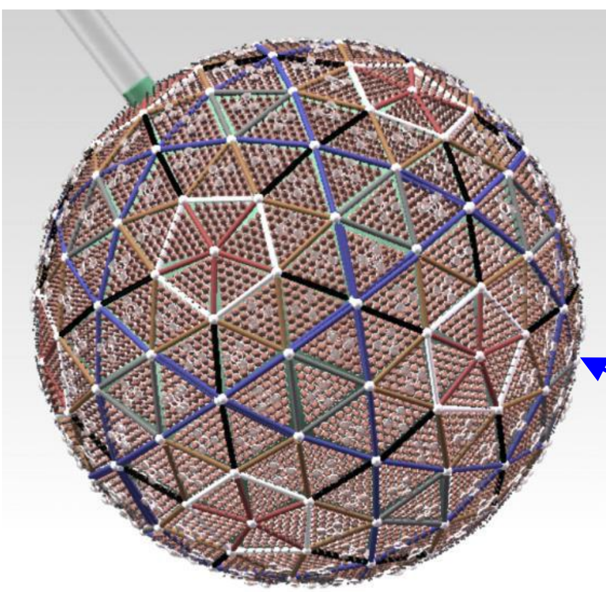
Detector Concept (Traditional)

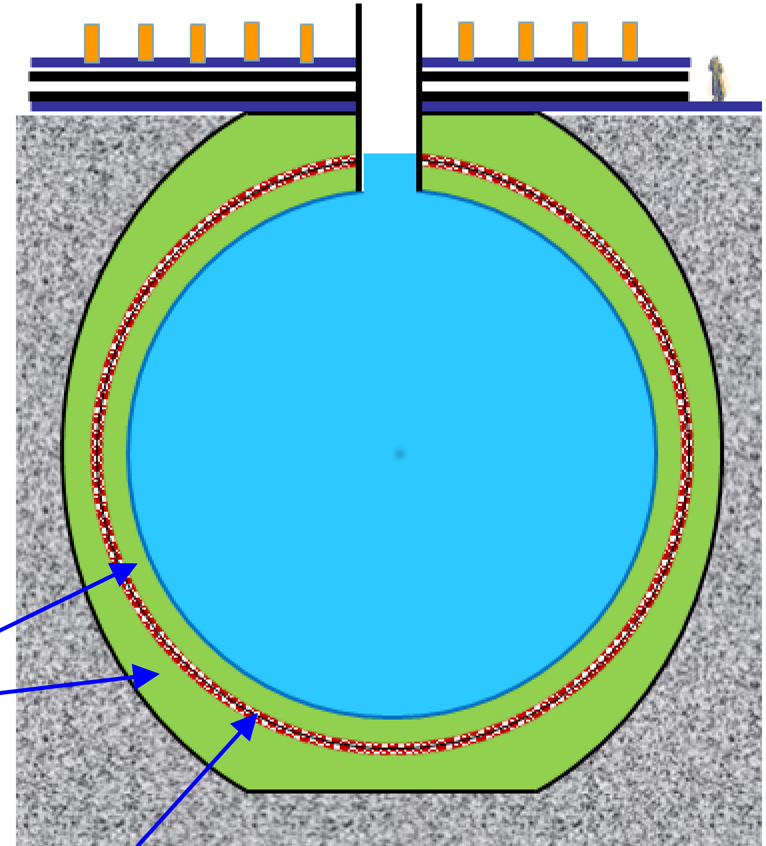


- Extremely difficult to build both the stainless steel tank and the acrylic tank

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.



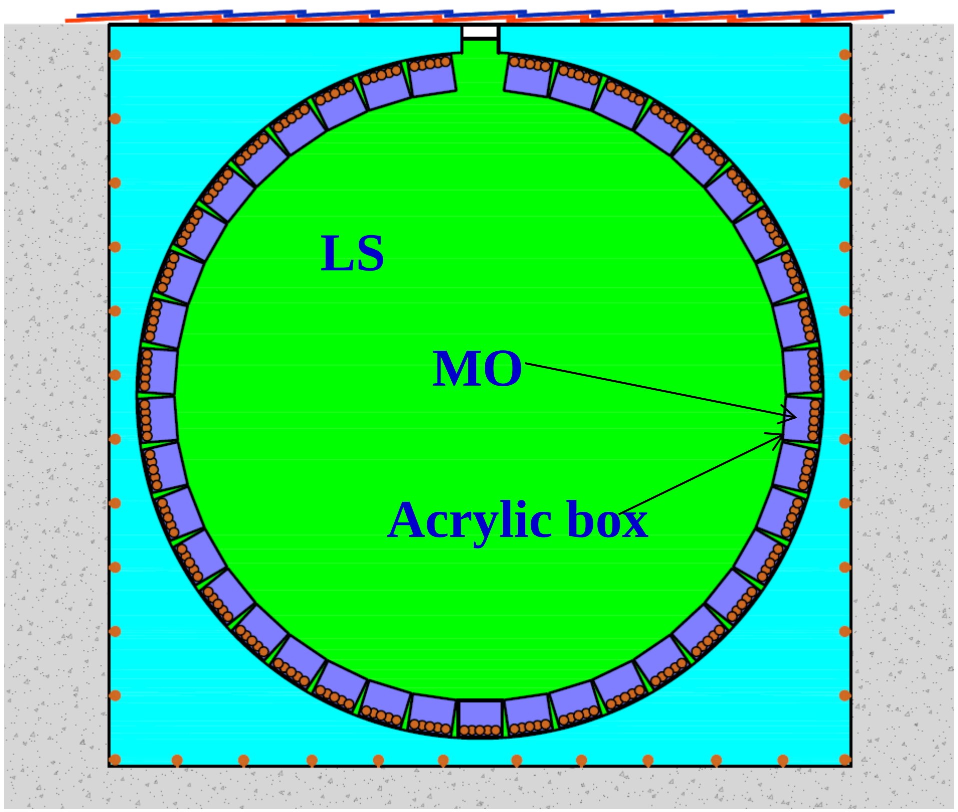


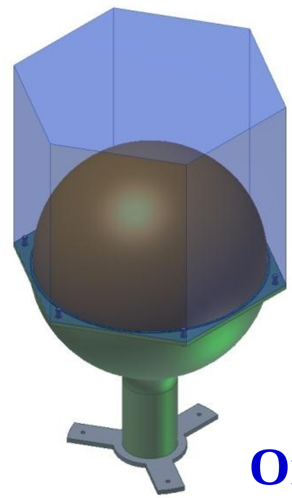
Buffer H_2O

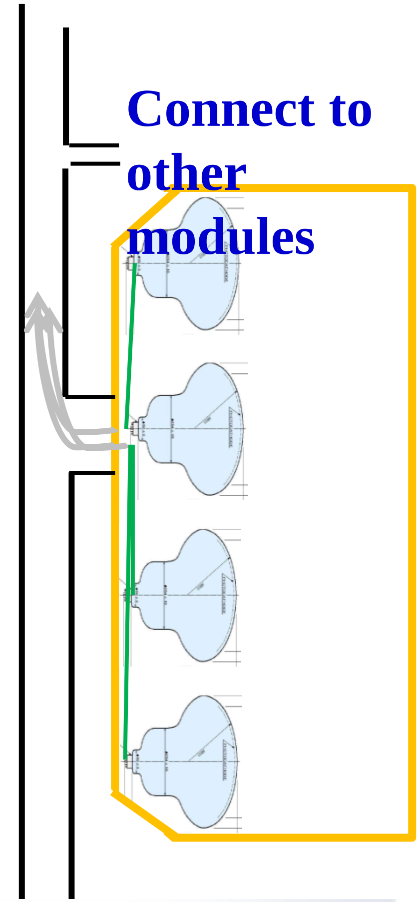
PMT support Structure

Option 2: acrylic box

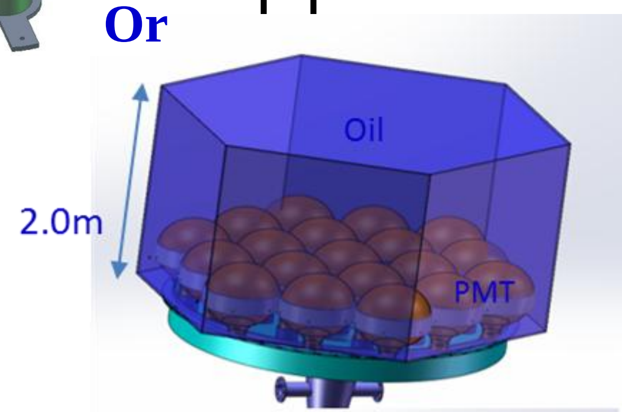
- Mineral oil in the optical modules
- Pipe for filling MO and cabling
- Concerns: leakage through cables





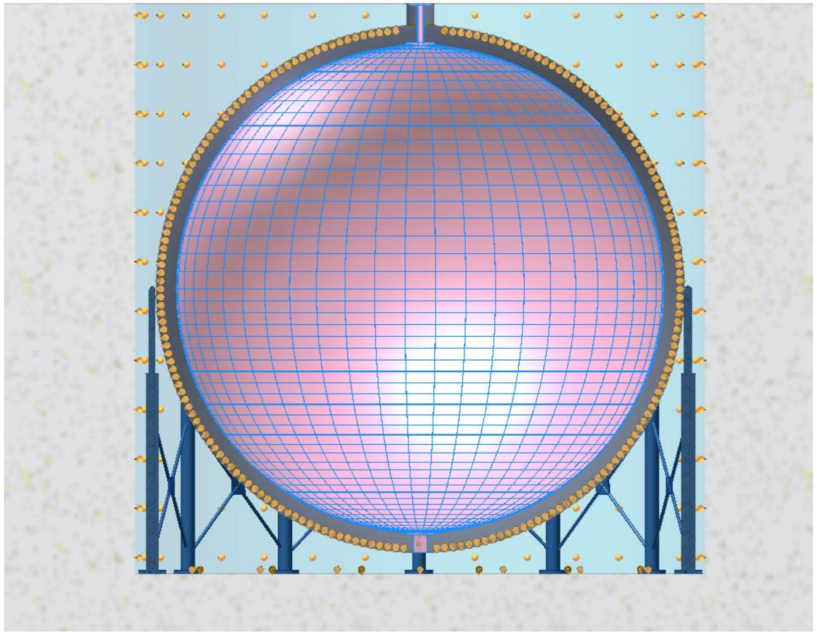


Or



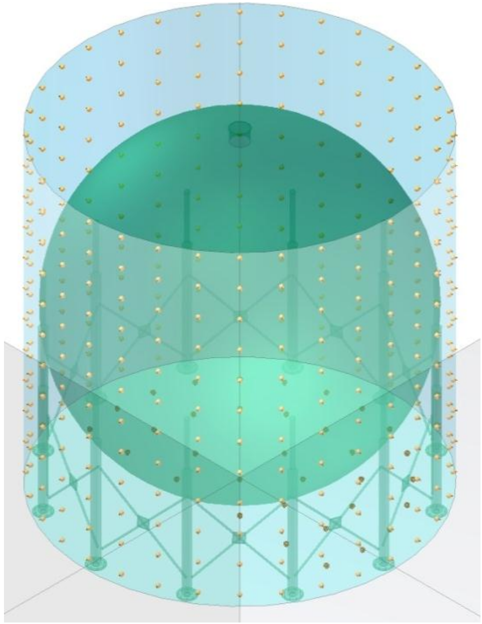
Option 3: balloon

- "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, …



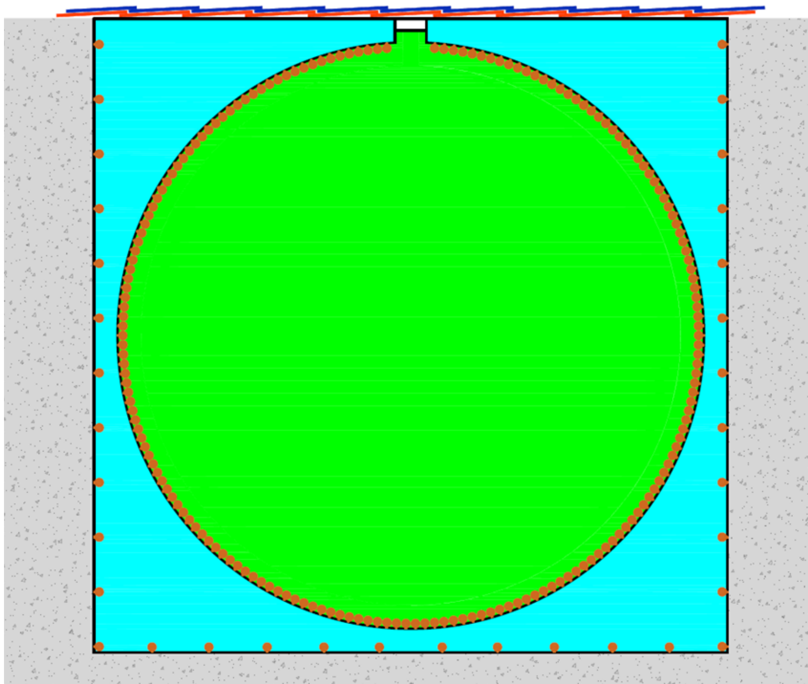
Option 4: steel tank only

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



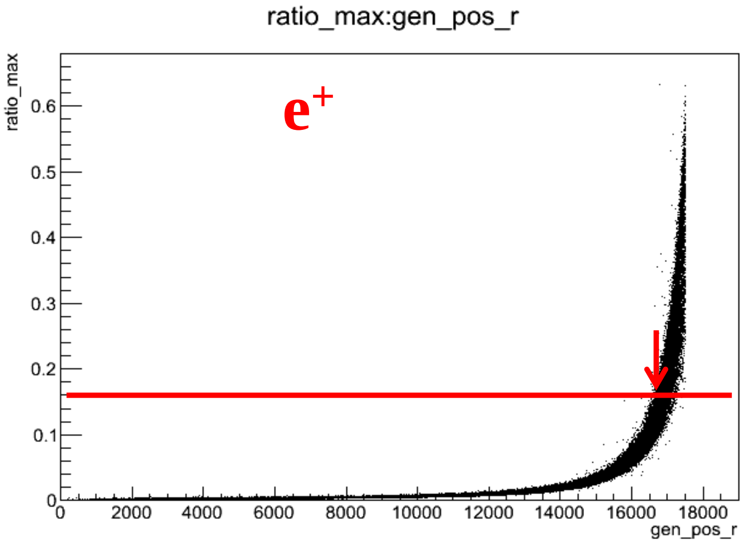
If the PMT glass is the same as Daya Bay, radioactivity will be 44 Bq/PMT, or 3.3 MHz in total

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**

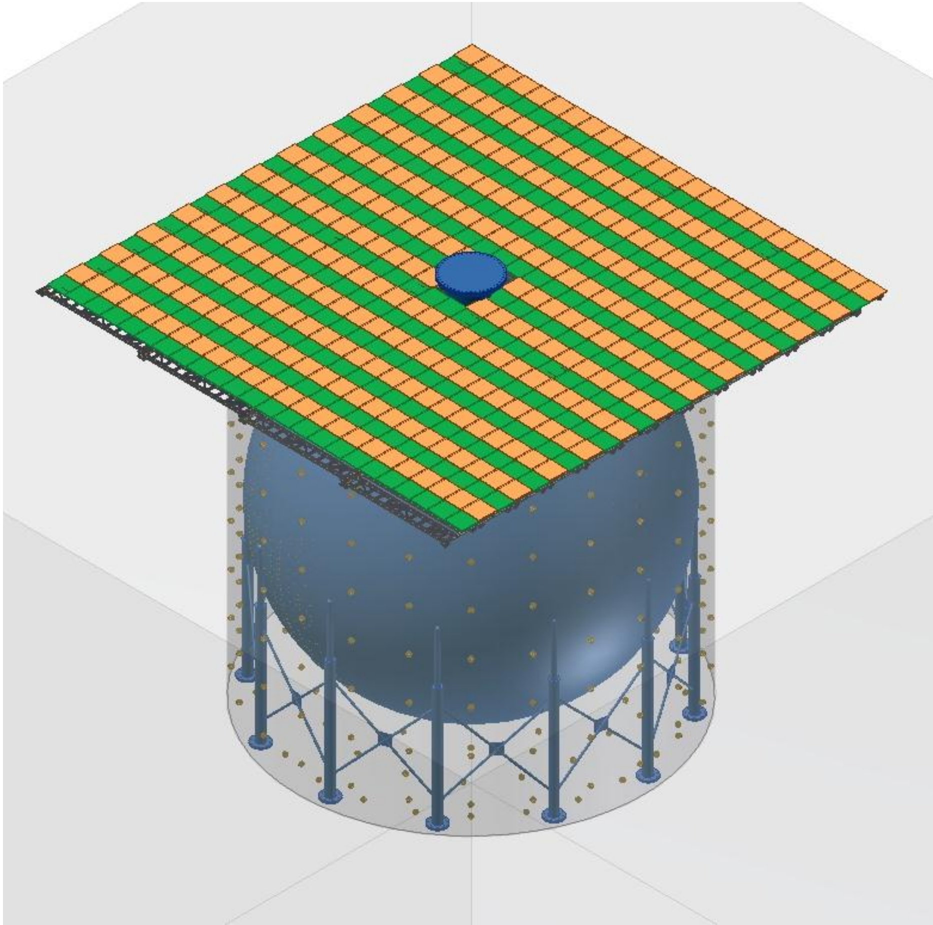


Resolution is affected:

	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

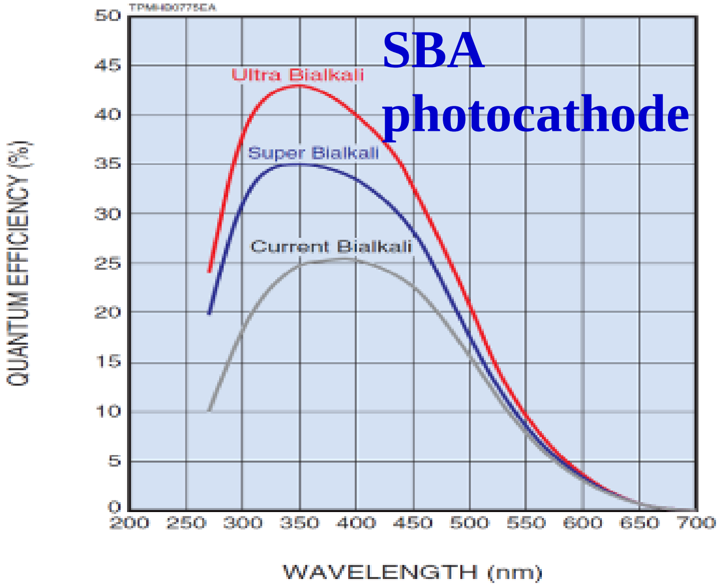


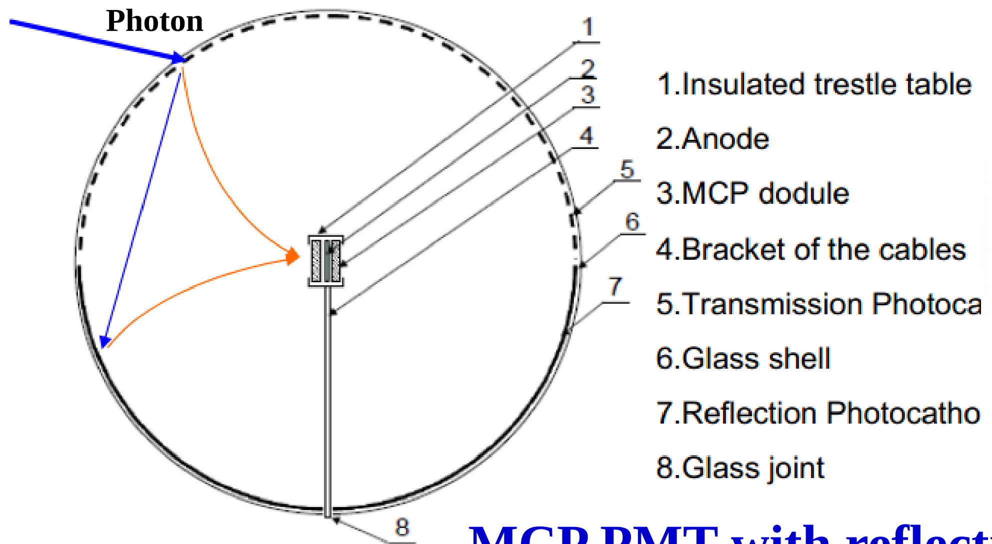
Technical Challenges

- **Requirements:**
  - ⇨ **Large detector: 20 kt LS**
  - ⇨ **Energy resolution: 3%/√E ➔ 1200 p.e./MeV**
- **Ongoing R&D:**
  - ⇨ **Low cost, high QE "PMT"**
  - ⇨ **Highly transparent LS: 15m ➔ 30m**

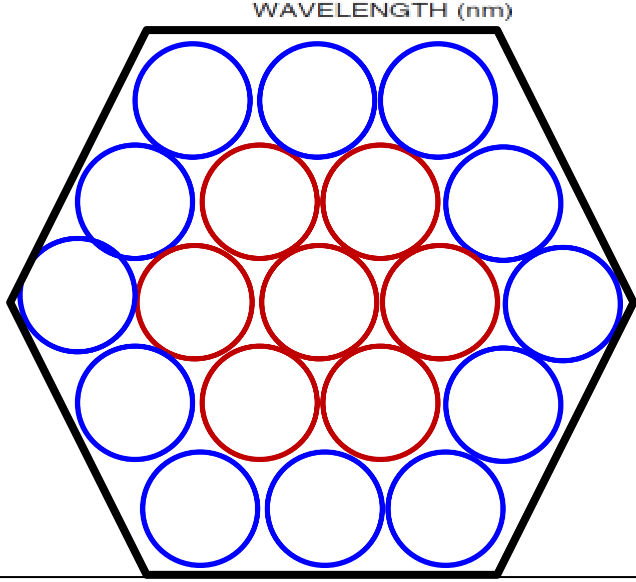
	KamLAND	JUNO
LS mass	**~1 kt**	**20 kt**
Energy Resolution	**6%/√E**	**3%/√E**
Light yield	**250 p.e./MeV**	**1200 p.e./MeV**

More Photoelectrons -- PMT





MCP PMT with reflection photocathode at bottom

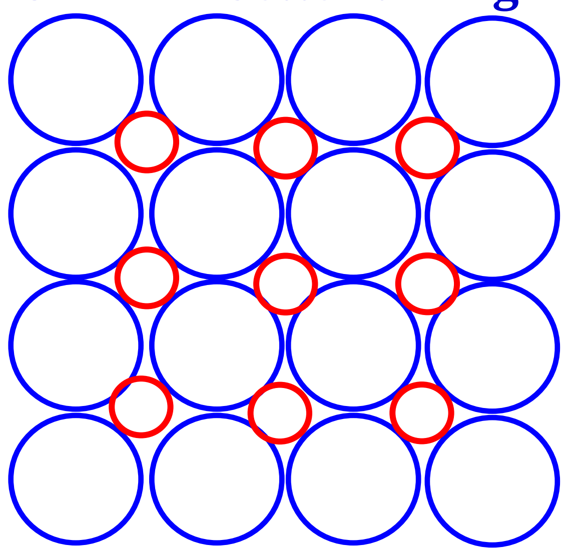


No clearance: coverage 86.5%

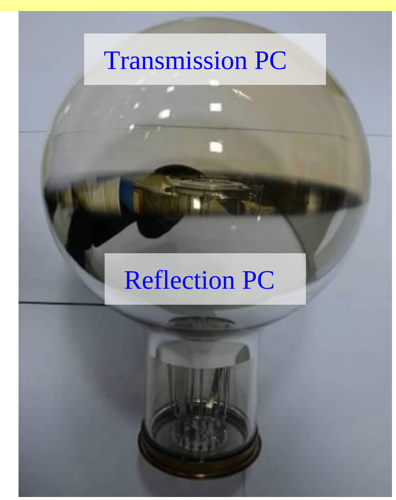
1cm clearance: coverage: 83%

20" + 8" PMT

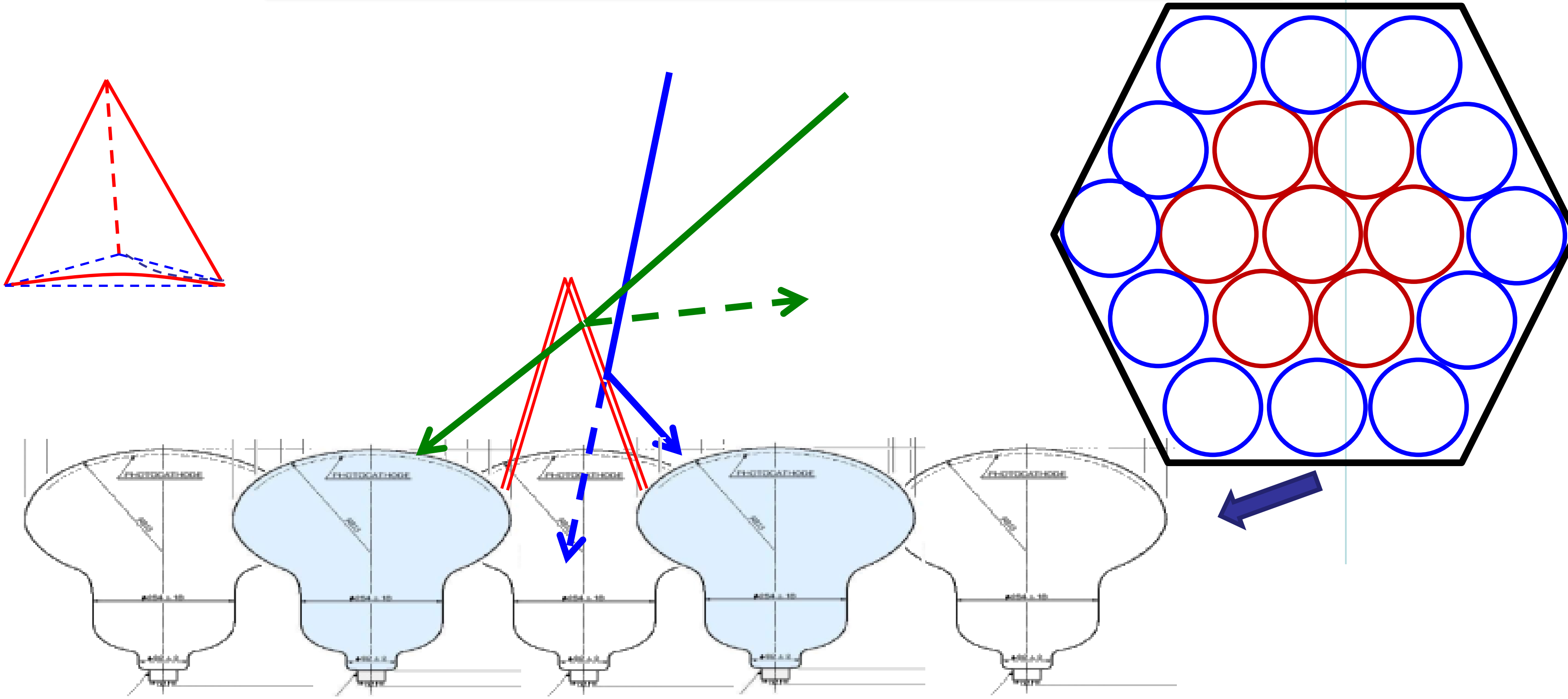
8" PMT better timing



MCP-PMT prototype



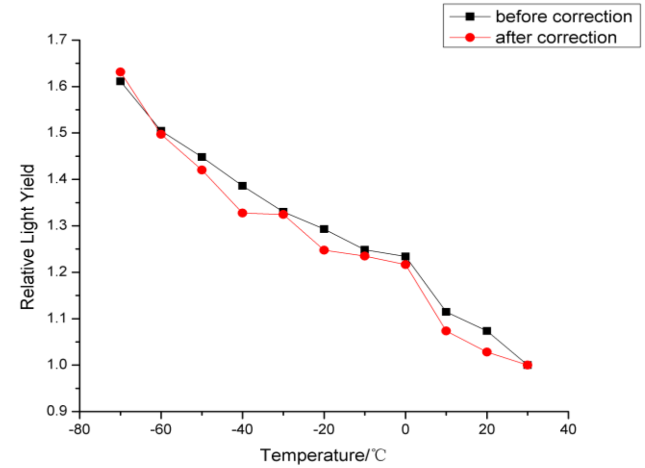
More Photoelectrons -- reflection



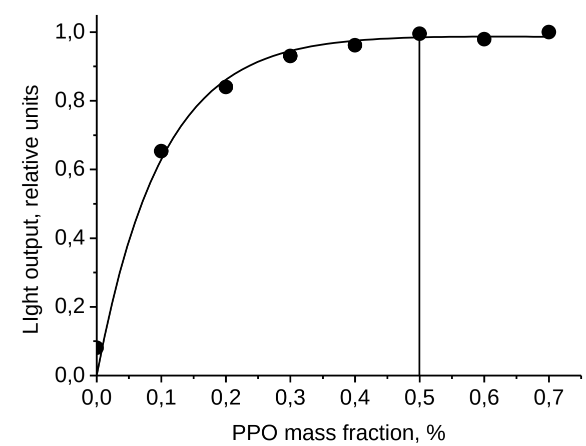
- Two thin acrylic panels with air gap – Total internal reflection
- For uniformly distributed events, MC simulation shows ~6% increase on p.e. in average.
- Reflecting to local PMTs won't impact on vertex reconstruction

More Photoelectrons-- LS

- **Attenuation length.**
- **Low temperature (4 degree)**
- **Fluor concentration optimization (especially at low temperature)**



100L LAB sample from Nanjing LAB factory. Attenuation length: 20.5m @430nm



Molecular distillation

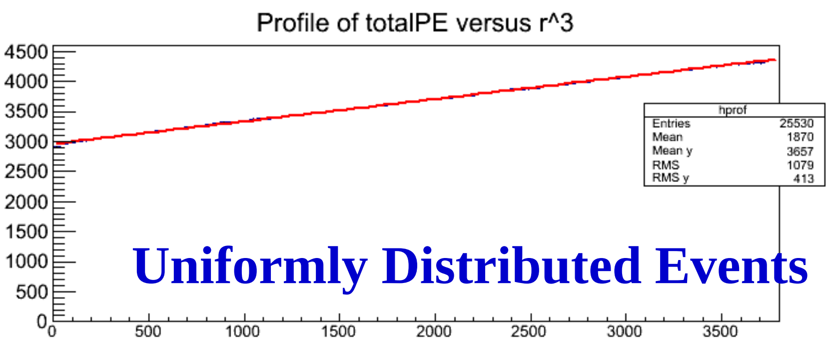
Vacuum distillation

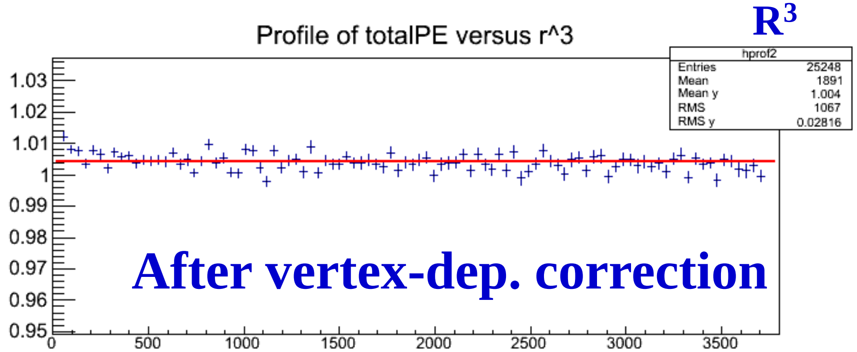
Al_2O_3 column

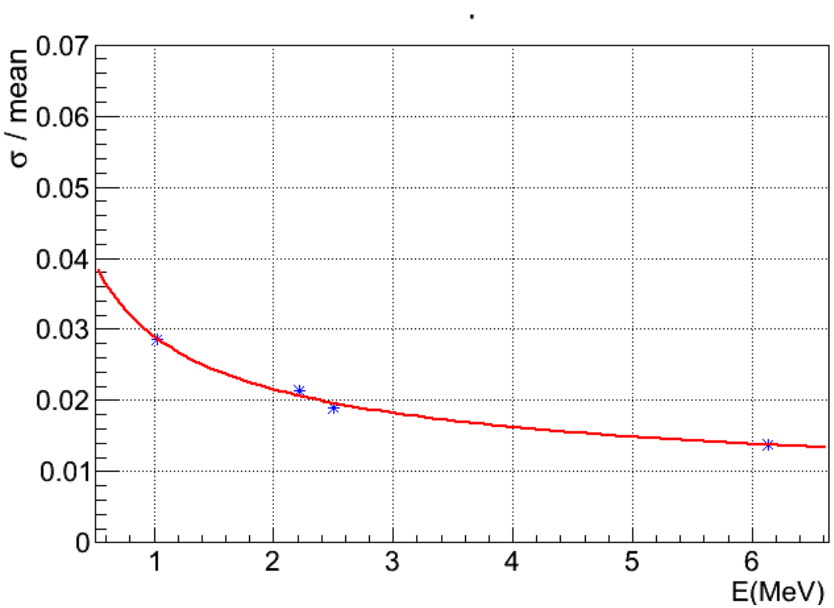
Al_2O_3 → **24m @430nm**

Energy Resolution from MC

- **JUNO MC, based on DYB MC (p.e. tuned to data), except**
  - JUNO Geometry and 80% photocathode coverage
  - High QE Bialkali. QE: from 25% -> 35%
  - Increase the LS light yield by 13%
  - LS attenuation length (1m-tube measurement@430nm)
    - ✓ from 15m = absorption 24m + Raylay scattering 40 m
    - ✓ to 20 m = absorption 40 m + Raylay scattering 40m







$3.0\%/\sqrt{E}$, or $(2.6/\sqrt{E} + 0.3)\%$

Signal and Backgrounds

- **Signal**

$$\bar{\nu}_e + p \rightarrow e^{+} + n \quad \textbf{(IBD)}$$

$$n + p \rightarrow d + \gamma \quad \textbf{(2.2MeV, ~200μs)}$$

  - ⇨ Estimated IBD rate: ~40/day

- **Assumptions for backgrounds calculation**
  - ⇨ Overburden is 700m
    - ✓ E_μ ~ 211 GeV, R_μ ~ 3.8 Hz
  - ⇨ Single rates from LS and PMT are 5Hz, respectively
  - ⇨ Good muon tracking and vertex reconstruction
  - ⇨ Similar muon efficiency as DYB

	Daya Bay	JUNO
Mass (ton)	20	20,000
E_μ (GeV)	~57	~211
L_μ (m)	~1.3	~ 23
R_μ (Hz)	~21	~3.8
$R_{singles}$ (Hz)	~50	~10

	B/S @ DYB EH1	B/S @ JUNO
Accidentals	~1.4%	~10%
Fast neutron	~0.1%	~0.4%
$^9Li/^8He$	~0.4%	~0.8%

Project status

- **Funding**
  - Great support from CAS: “special fund for advancement”
  - Approved on Feb.1, 2013
- **Brief schedule**
  - Construction: 2013-2019
  - Filling & data taking： 2020
- **Collaboration**
  - Two get-together meetings in Jan. and Jul. 2013
  - Next meeting in Jiangmen (experimental site), Jan. 2014.
  - Welcome collaborators

Proposal for RENO-50

Soo-Bong Kim (KNRC, Seoul National University)

"International Workshop on RENO-50, June 13-14, 2013"

KNRC
Korea Neutrino Research Center

Overview of RENO-50

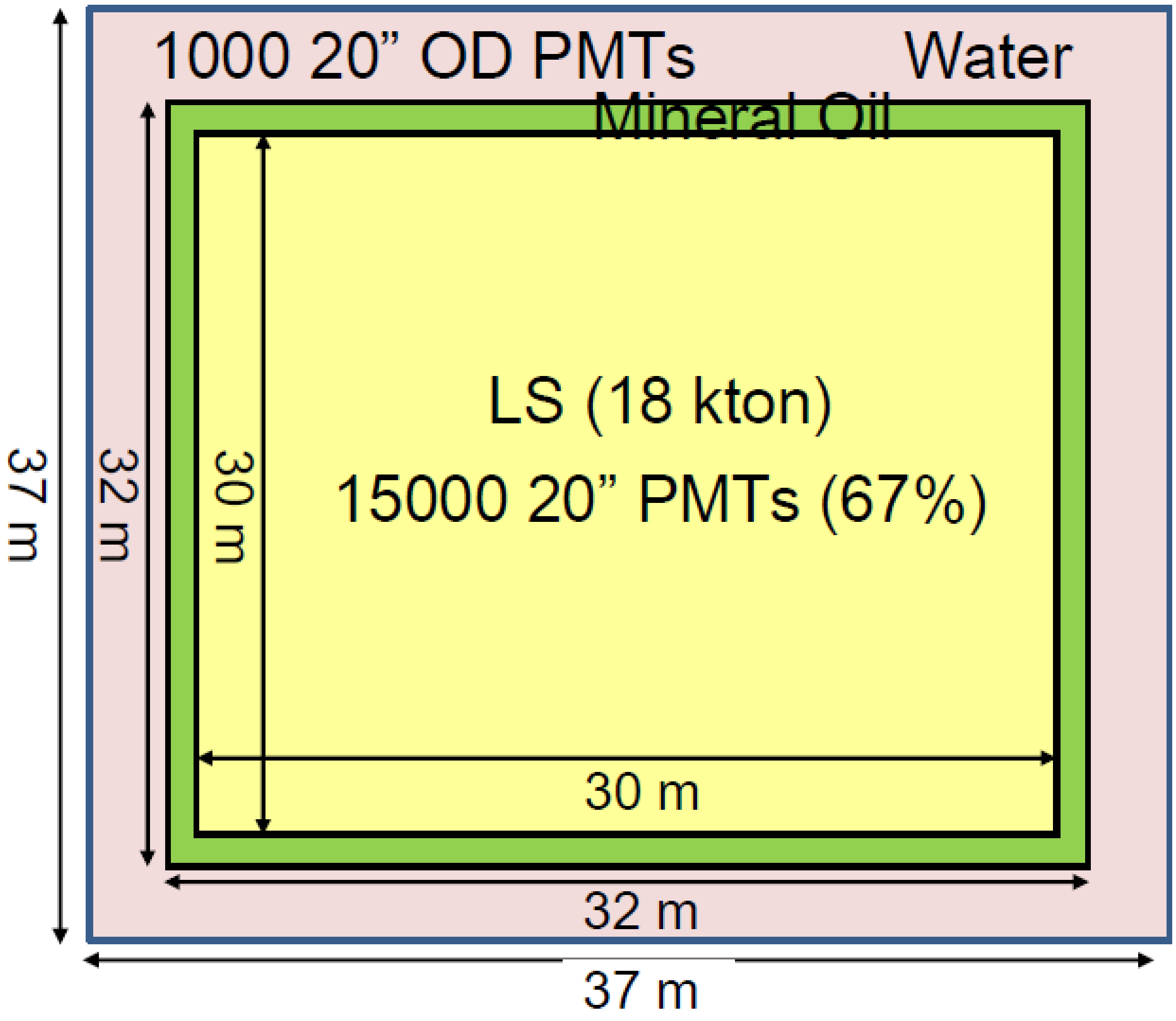
- **RENO-50** : An underground detector consisting of 18 kton ultra-low-radioactivity liquid scintillator & 15,000 20" PMTs, at 50 km away from the Hanbit(Yonggwang) nuclear power plant

- **Goals** : - High-precision measurement of θ_{12} and Δm^2_{21}
  - Determination of neutrino mass hierarchy
  - Study neutrinos from reactors, (the Sun), the Earth, Supernova, and any possible stellar objects

- **Budget** : $ 100M for 6 year construction
  (Civil engineering: $ 15M, Detector: $ 85M)

- **Schedule** : 2013 ~ 2018 : Facility and detector construction
  2019 ~ : Operation and experiment

Conceptual Design of RENO-50



Summary

- **Ongoing reactor experiments can measure $\sin^2 2\theta_{13}$ to <4% precision**
- **Next generation reactor neutrino experiments focus on mass hierarchy determination and precision measurement of mixing parameters. Science case is strong with significant technical challenges.**
- **JUNO was proposed a few years ago, now boosted by the large θ_{13}. Funding is approved from CAS.**
- **A similar proposal from RENO-50**
- **Start data taking: around 2020**

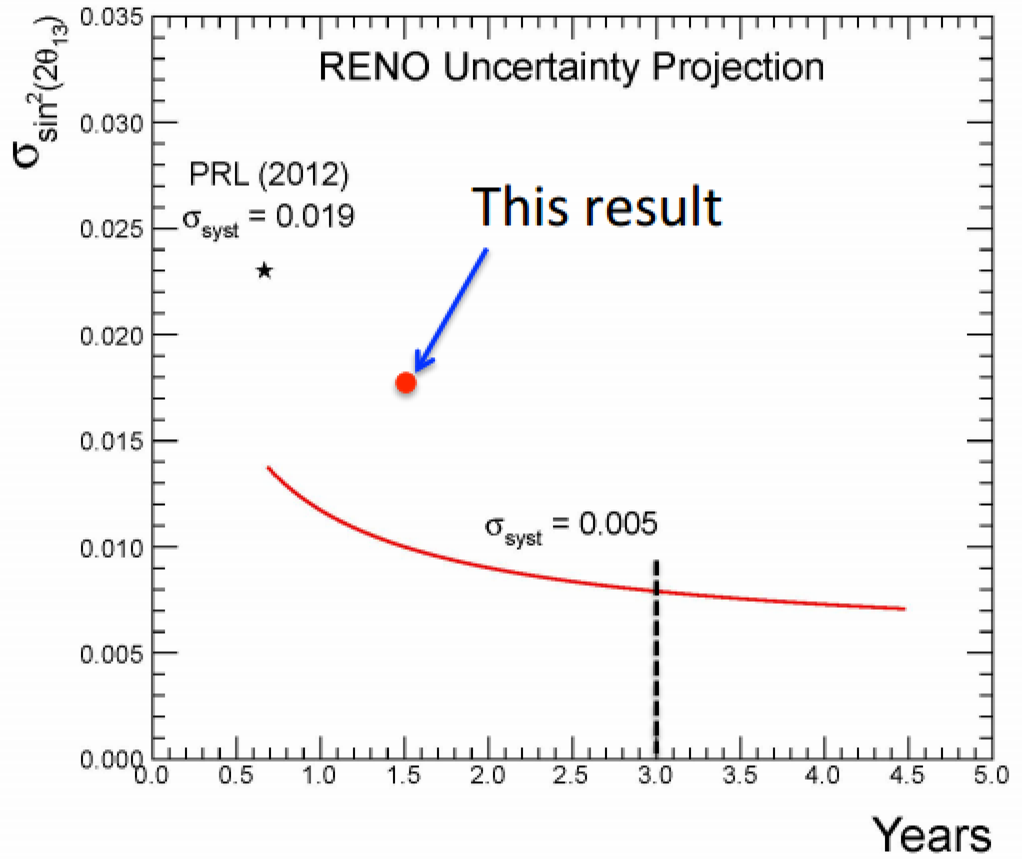
backup

Future Plan for Precision Measurement of θ_{13}

RENO

$$\sin^2 2\theta_{13} = 0.100 \pm 0.010(stat.) \pm 0.015(syst.)$$

(402 days) 0.100 ± 0.018 (5.6 σ) → ± 0.01 (10 σ) (3 years)



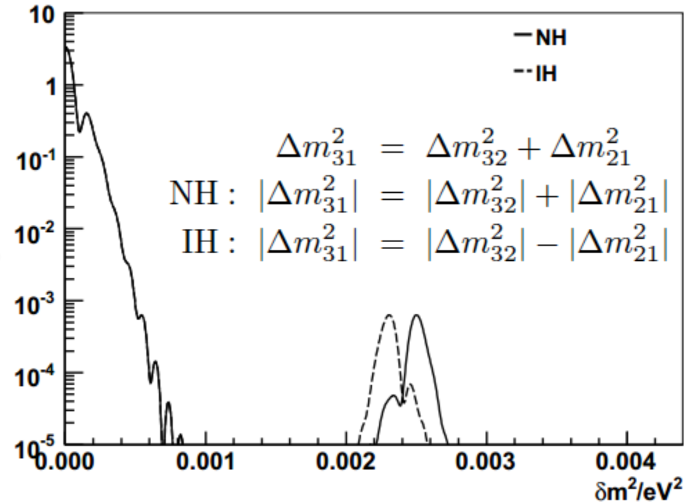
w/ 3 years of data:

Stat. error: 0.006
Sys. error: < 0.010

Tot. error: < 0.011

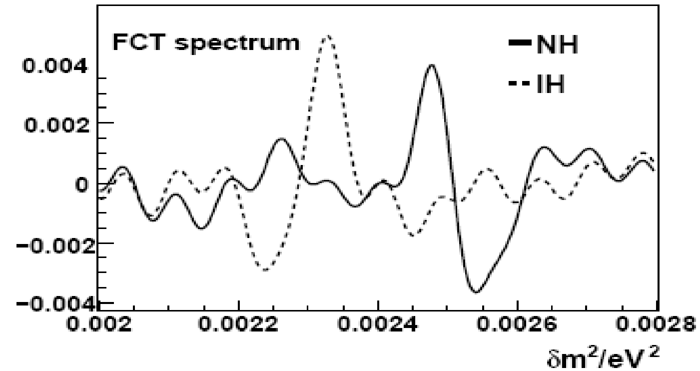
Fourier transformation of L/E spectrum

- L/E spectrum ⇔ δm^2 spectrum (δm^2 ~oscillation frequency)
- Take Δm^2_{32} as reference
  - NH: $\Delta m^2_{31} > \Delta m^2_{32}$, Δm^2_{31} peak at the right of Δm^2_{32}
  - IH: $\Delta m^2_{31} < \Delta m^2_{32}$, Δm^2_{31} peak at the left of Δm^2_{32}

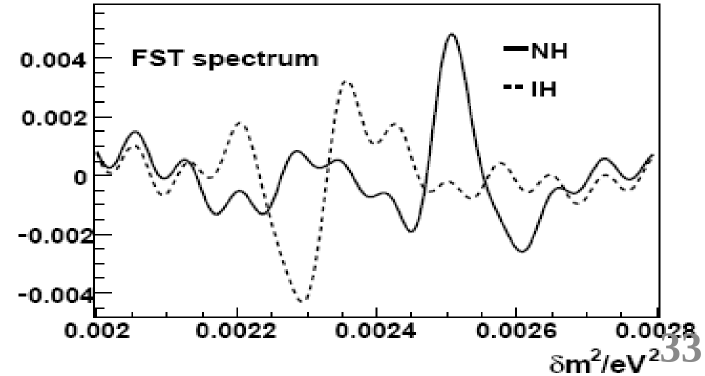


- The Fourier formalism:

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



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



- Distinctive features
- No pre-condition of Δm^2_{32}

Quantitative Features of FCT and FST

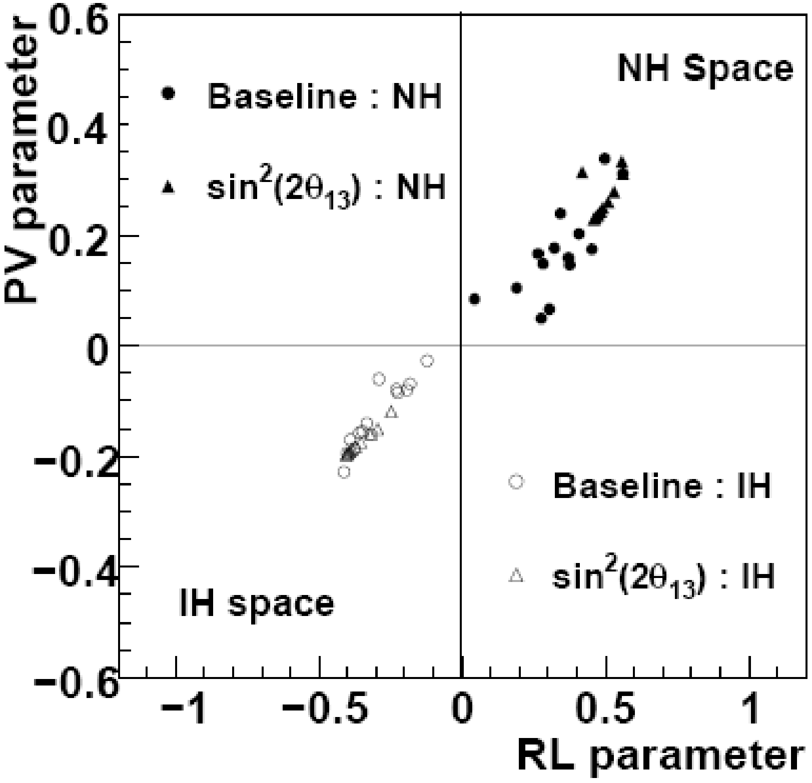
- **To quantify the symmetry breaking, we define:**

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

RV/LV: amplitude of the right/left valley in FCT

P/V: amplitude of the peak/valley in FST

- **For asymmetric P_{ee}**
  - ⇨ **NH: RL>0 and PV>0**
  - ⇨ **IH: RL<0 and PV<0**



Two clusters of RL and PV values show the sensitivity of mass hierarchy determination

Baseline: 46-72 km

$\sin^2(2\theta_{13})$: 0.005-0.05

Others from global fit

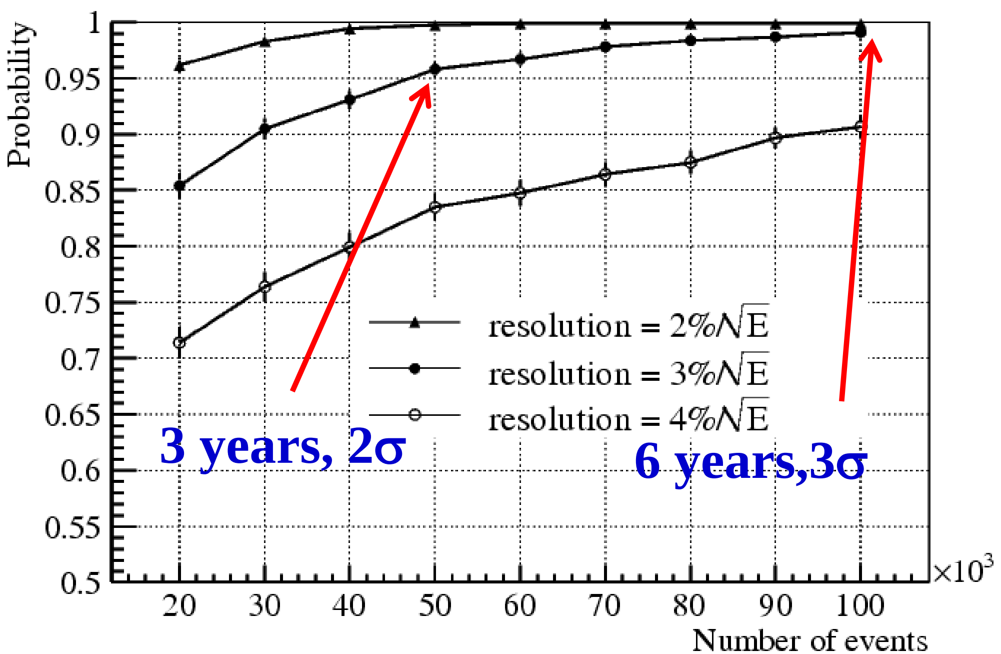
L. Zhan et al., PRD78:111103,2008

Experimental requirements based on the latest θ_{13} measurement

- **Un-binned Fourier transform of N detected events**

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

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



- **New default parameters:**
  - Detector size: 20kt
  - Energy resolution: 3%
  - Thermal power: 36 GW
  - Baseline 58 km

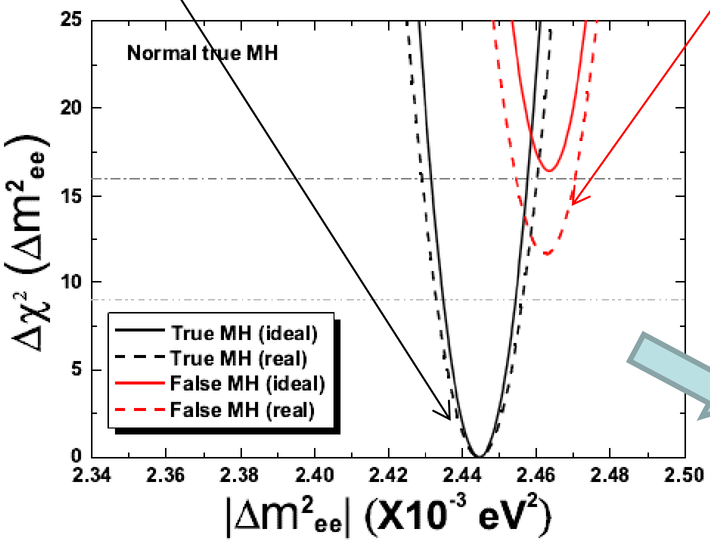
Alternative method: χ^2 fit

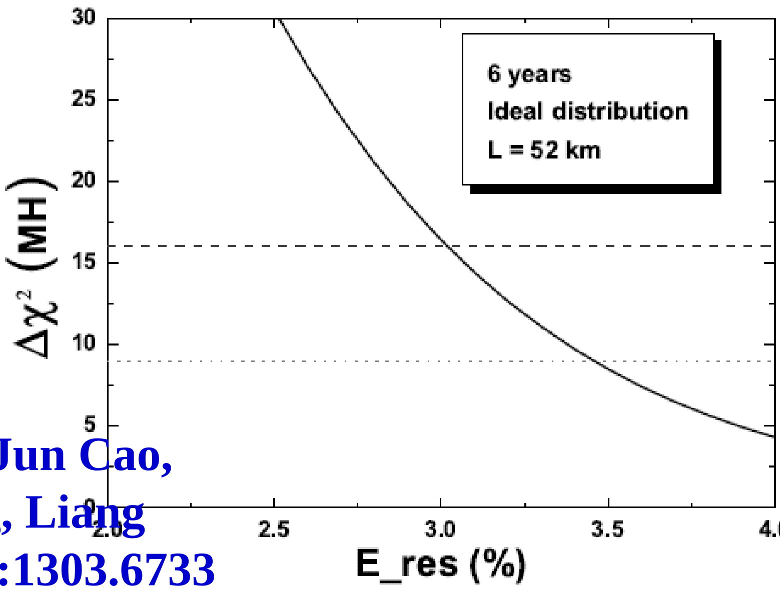
- Assume the truth is NH/IH, and calculate the truth spectrum.
- Calculate the spectra for NH and IH case and fit them to the truth spectrum respectively.
- Energy resolution is taking into account.

$$\chi^2_{\rm REA} = \sum_{i=1}^{N_{\rm bin}} \frac{[M_i - T_i(1+\sum_k \alpha_{ik}\epsilon_k)]^2}{M_i} + \sum_k \frac{\epsilon_k^2}{\sigma_k^2}$$

NH spectrum fits to NH

IH spectrum fits to NH





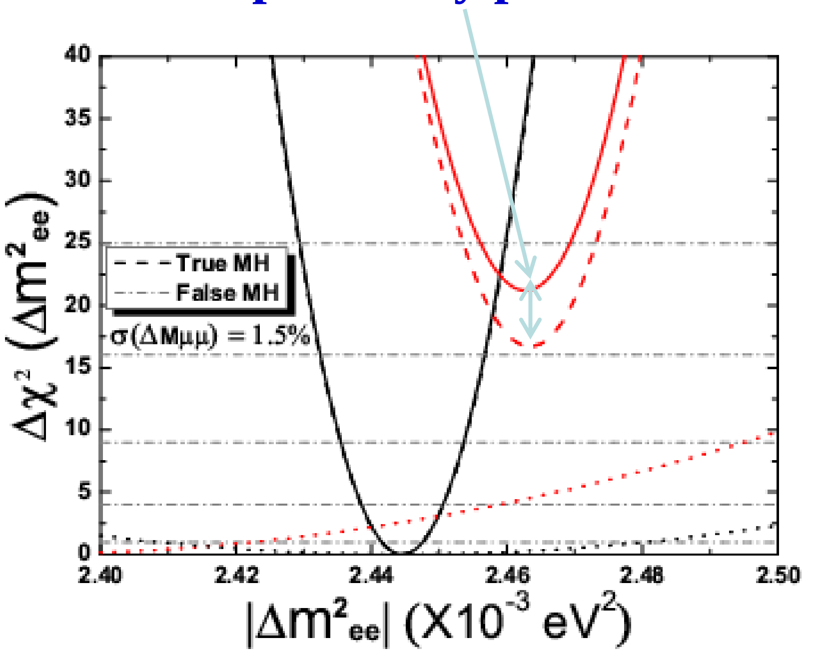
Yu-Feng Li, Jun Cao, Yifang Wang, Liang Zhan, arXiv:1303.6733

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

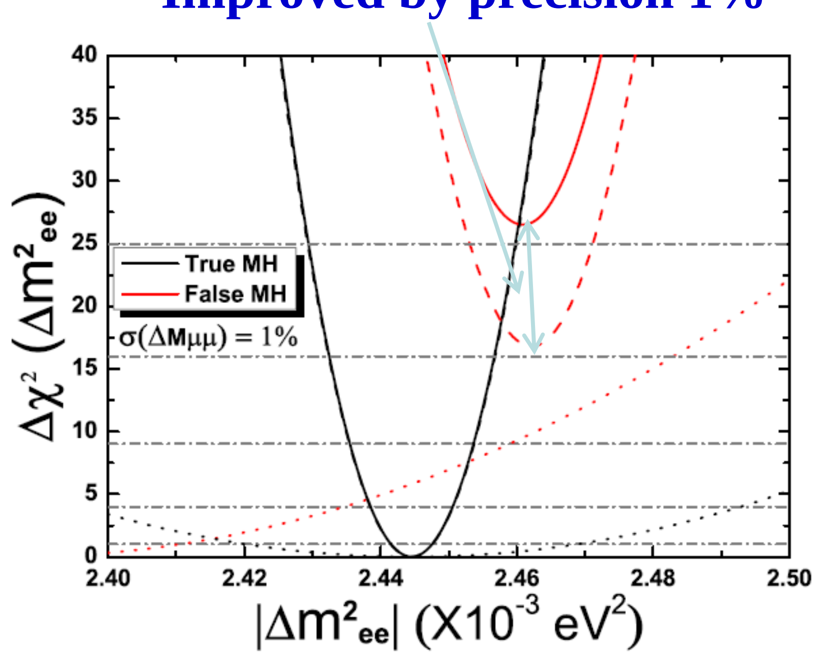
Taking into account Δm^2_{32}

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

Improved by precision 1.5%



Improved by precision 1%



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

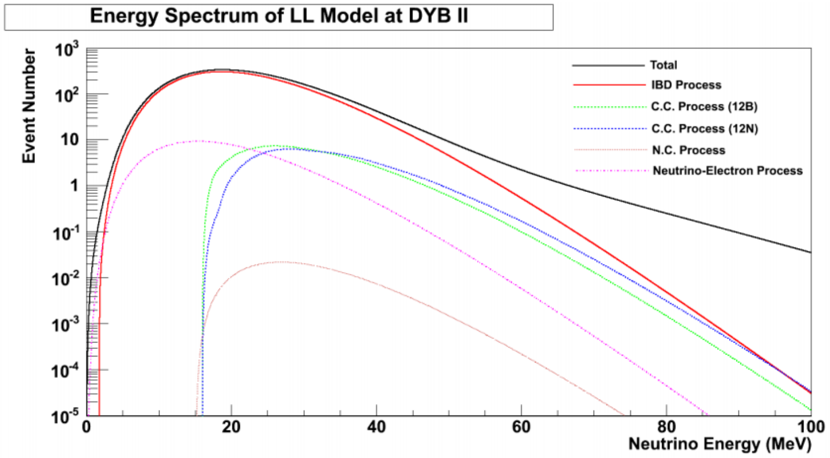
Supernova neutrinos

- Less than 20 events observed so far
- Assumptions:
  - Distance: 10 kpc (our Galaxy center)
  - Energy: 3×10^{53} erg
  - Ln the same for all types
  - Tem. & energy

$T(\nu_e) = 3.5$ MeV, $<E(\nu_e)> = 11$ MeV

$T(\bar{\nu}_e) = 5$ MeV, $<E(\bar{\nu}_e)> = 16$ MeV

$T(\nu_x) = 8$ MeV, $<E(\nu_x)> = 25$ MeV

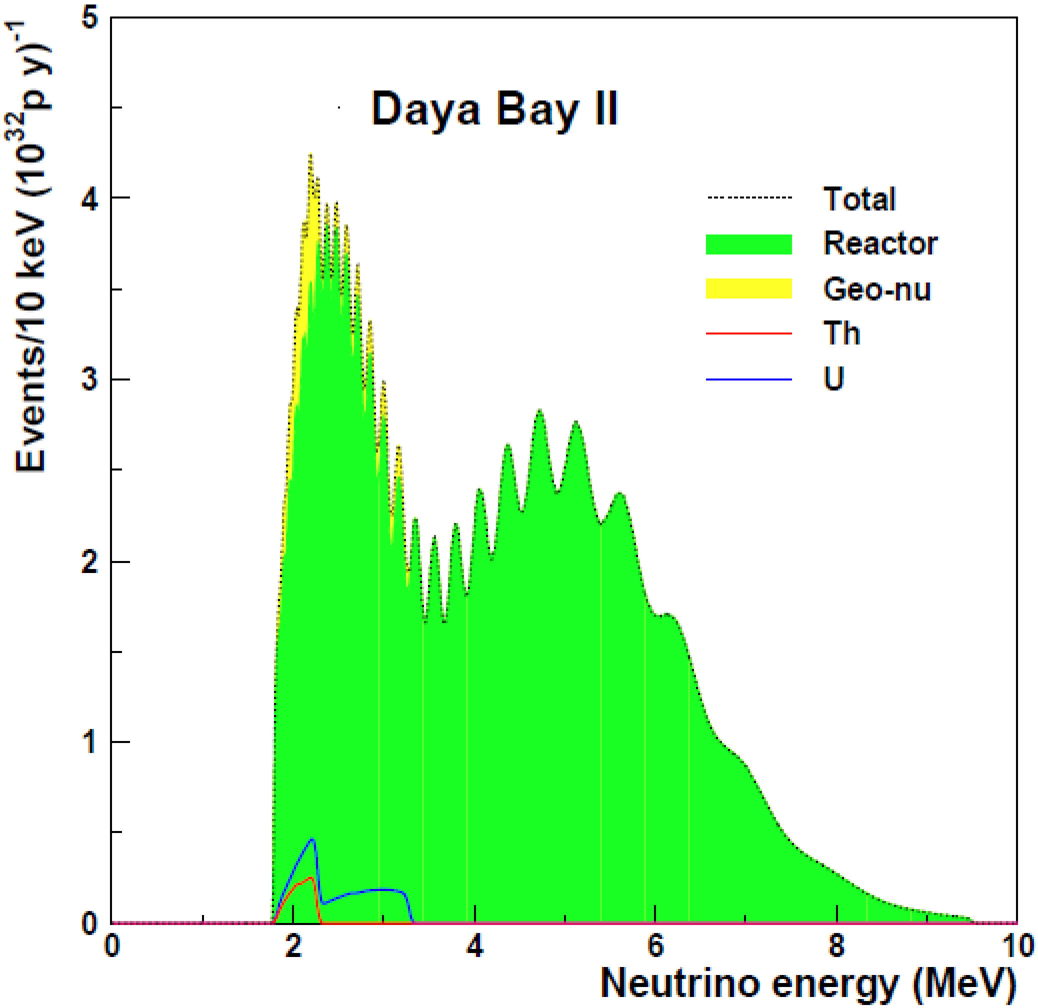


- Many types of events:
  - $\bar{\nu}_e + p \rightarrow n + e^+$, ~ 3000 correlated events
  - $\bar{\nu}_e + {}^{12}C \rightarrow {}^{12}B + e^+$, ~ 10-100 correlated events
  - $\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$, ~ 10-100 correlated events
  - $\nu_x + {}^{12}C \rightarrow \nu_x + {}^{12}C^*$, single 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

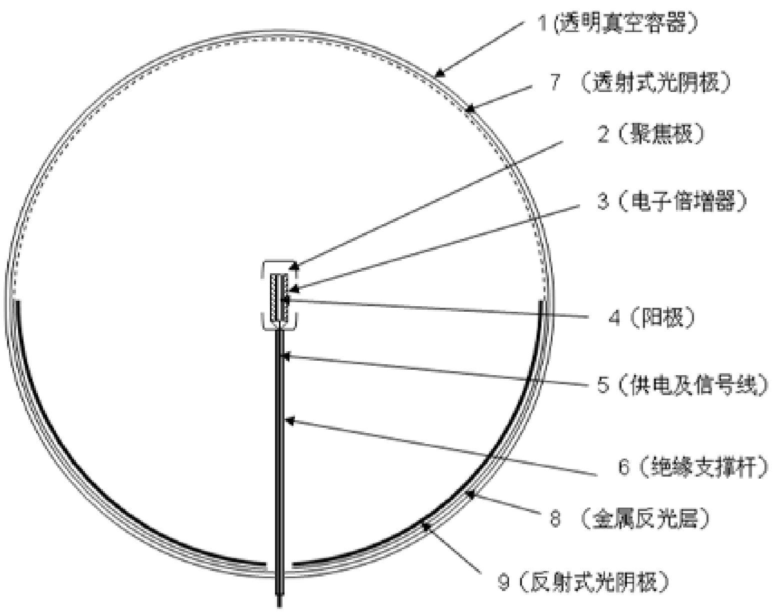
Geoneutrinos

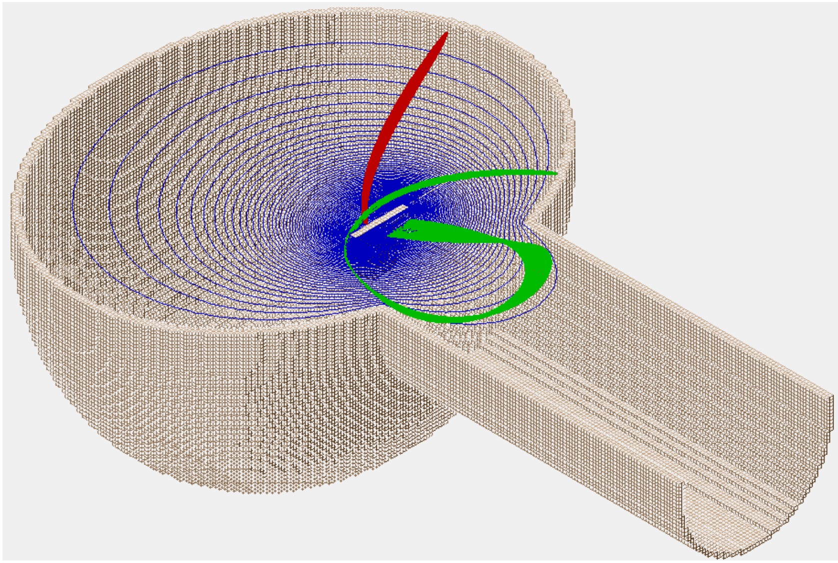
- **Current results:**
  - ⇨ **KamLAND:** **40.0±10.5±11.5 TNU**
  - ⇨ **Borexino:** **64±25±2 TNU**
- **Desire to reach an error of 3 TNU: statistically dominant**
- **JUNO: >×10 statistics, but difficult on systematics**
- **Background to reactor neutrinos**



Stephen Dye

A new type of PMT: higher photon detection eff.





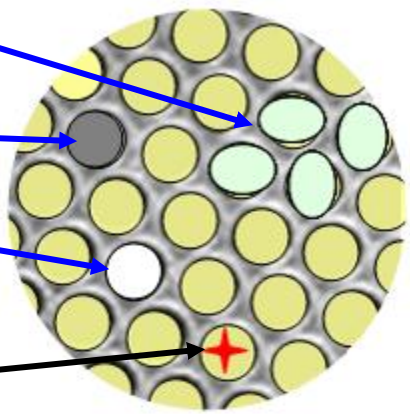
- **Top: transmitted photocathode**
- **Bottom: reflective photocathode**

  additional QE: ~ 70%*25%
- **MCP to replace Dynodes ➔ no blocking of photons**

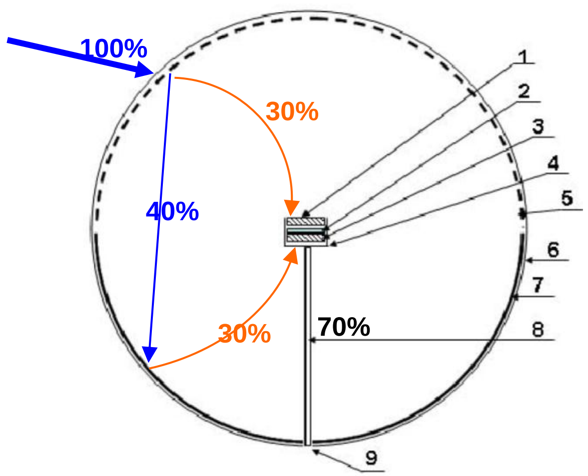
~ ×2 improvement

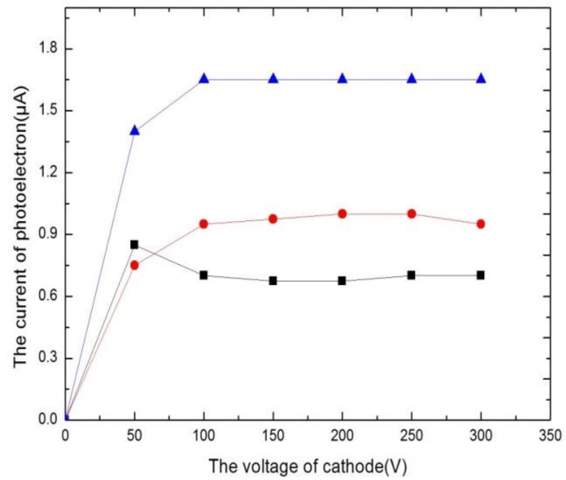
Low cost MCP by accepting the following:

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



Two main achievements

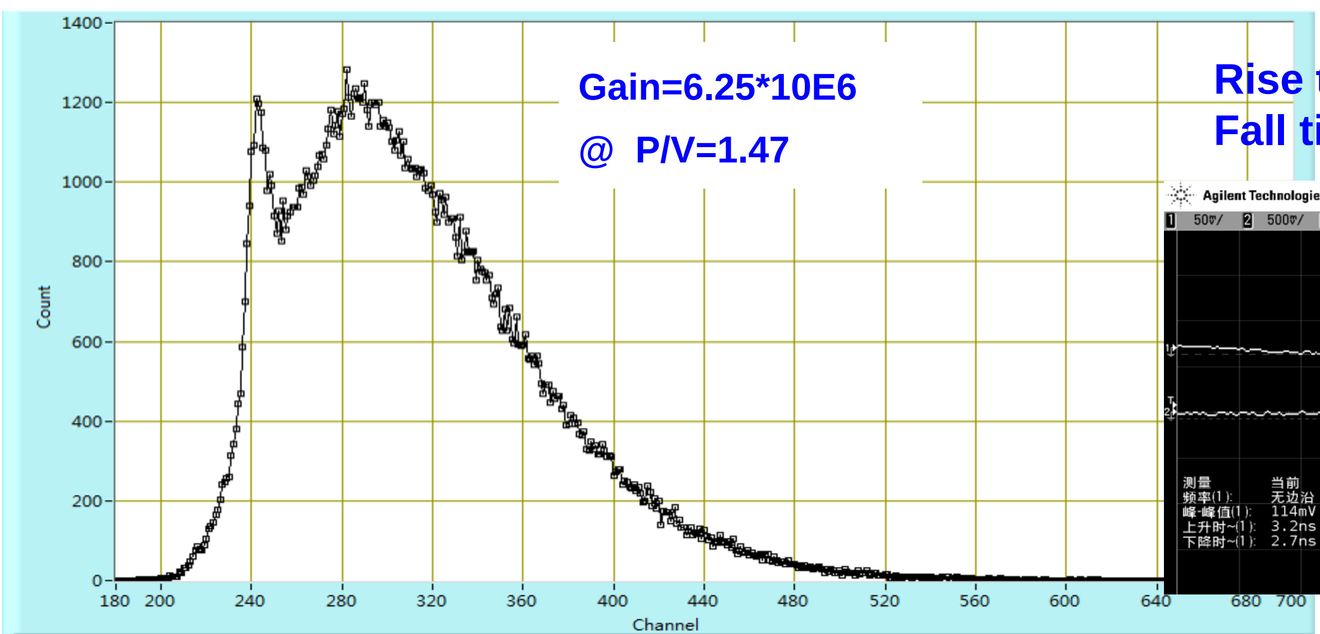




Sum

Reflective photocathode

Transmitted photocathode



Rise time： 2.7ns；

Fall time： 3.2ns