Liquid Scintillator Detector Technology for Mass Hierarchy Determination with Reactor Neutrinos

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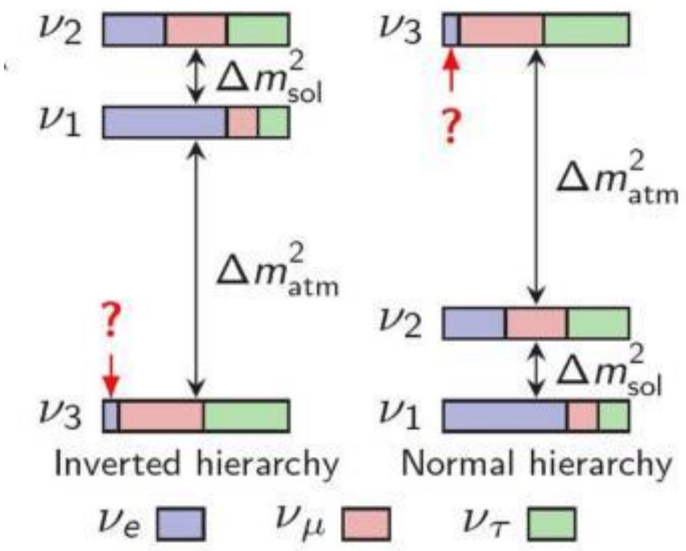
Institute of High Energy Physics

NNN13, Kavli IPMU, Kashiwa, Nov. 12, 2013

Neutrino Oscillation

In a 3-ν framework

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

θ_{23} ~ 45°
Atmospheric
Accelerator

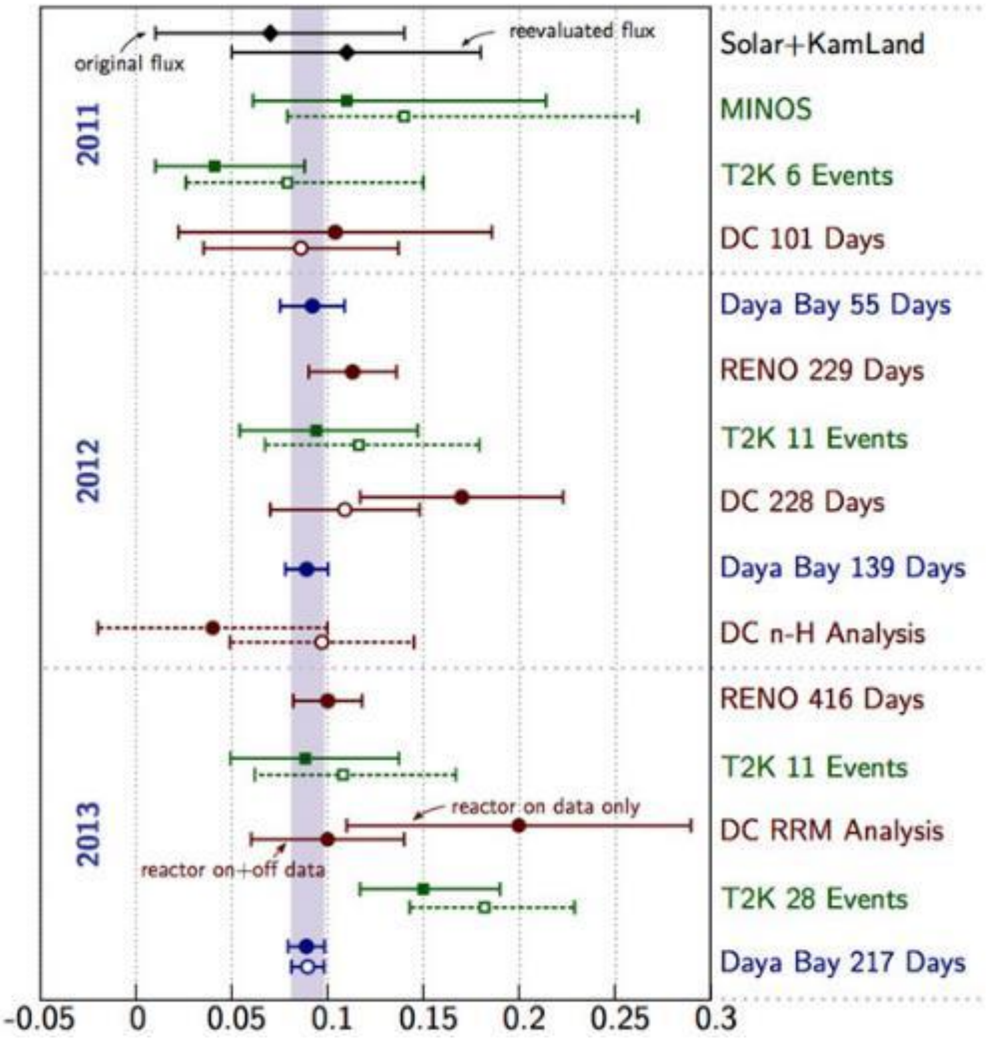
θ_{13} ~ 9°
Reactor
Accelerator

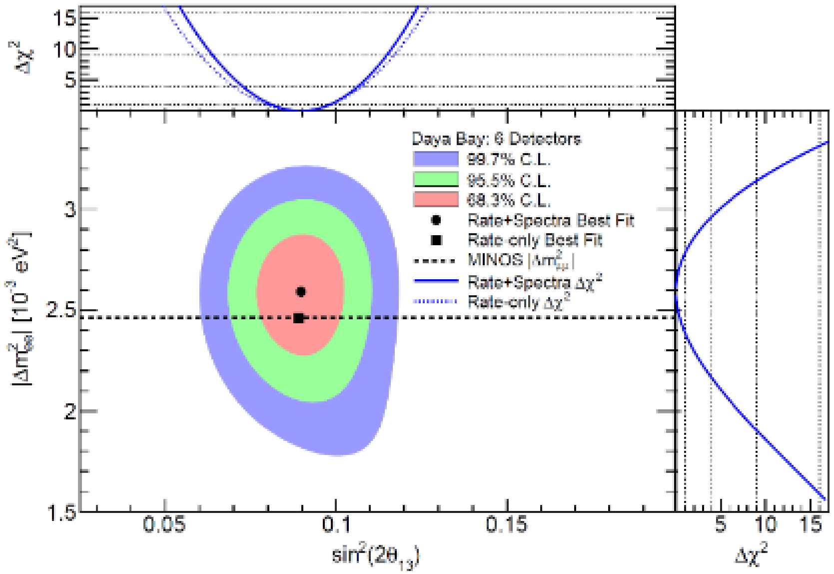
θ_{12} ~ 34°
Solar
Reactor

Unknowns:

- **δ_{CP}**
- **Mass Hierarchy**
- **θ_{23} octant**

Latest Results from Daya Bay





rate+shape analysis, arXiv: 1310.6732

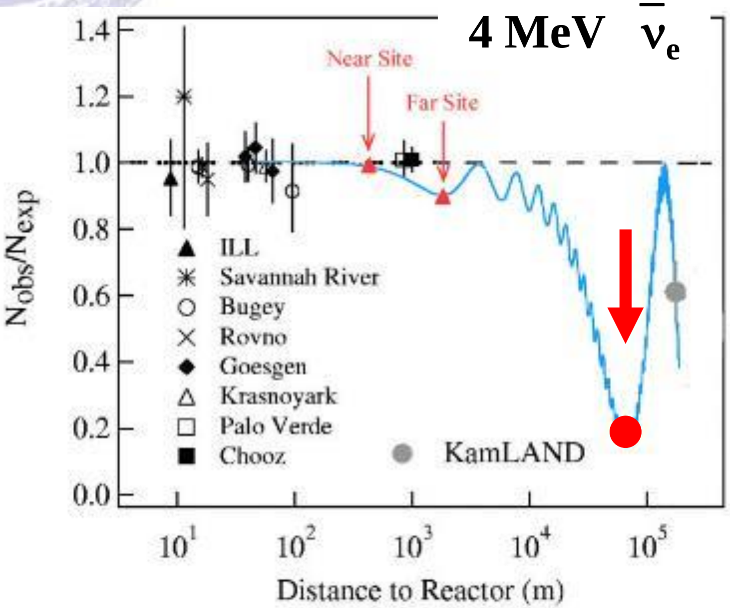
$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

$$\left|\Delta m^2_{ee}\right| = 2.59^{+0.19}_{-0.20} \times 10^{-3}\ \mathrm{eV}^2$$

$$\Delta m^2_{ee} \sim 0.7\Delta m^2_{31} + 0.3\Delta m^2_{32}$$

$$\Delta m^2_{\mu\mu} \sim 0.3\Delta m^2_{31} + 0.7\Delta m^2_{32} + CP$$

Determine MH with Reactors



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

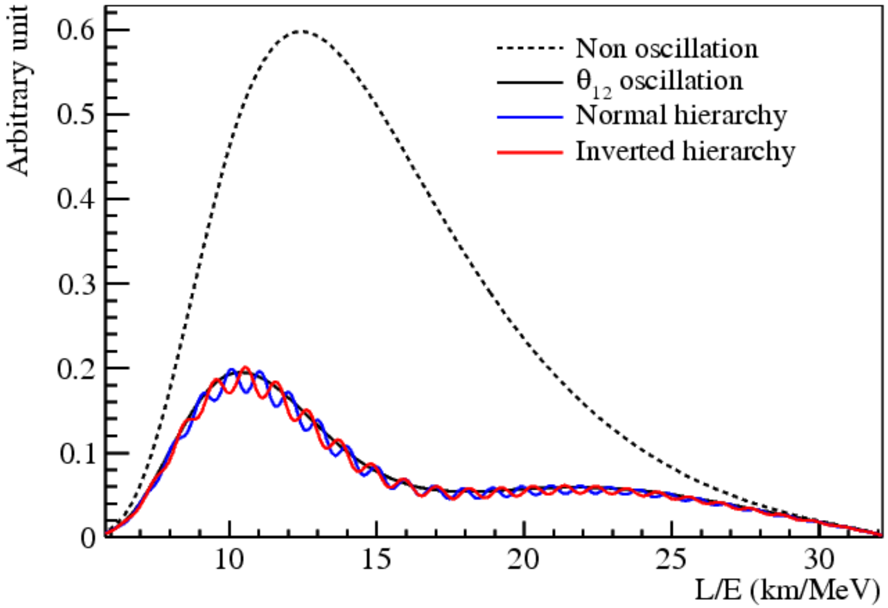
→ Relative measurement

Further improvement with $\Delta m^2_{\mu\mu}$ measurement from accelerator exp.

→ Absolute measurement

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

S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., PRDD78 (2008) 071302
L. Zhan, Y. Wang, J. Cao, L. Wen,
PRD78:111103, 2008, PRD79:073007, 2009

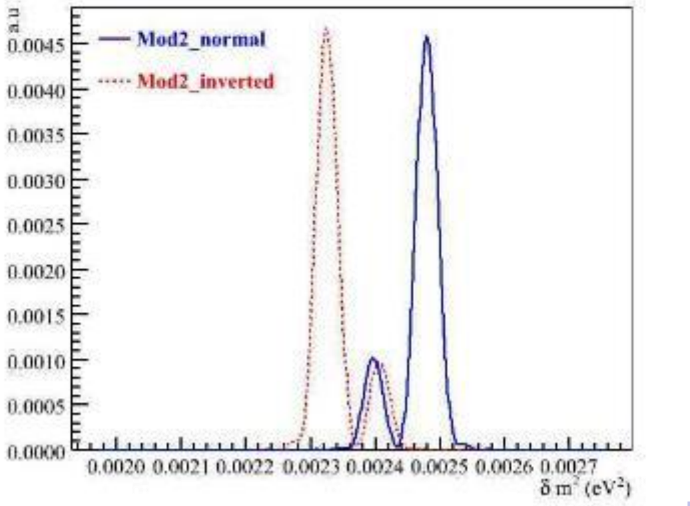


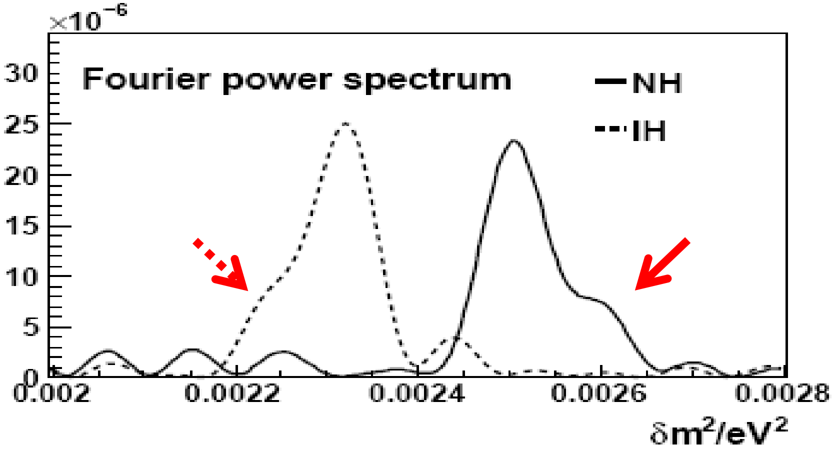
Interference: Relative Measurement

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

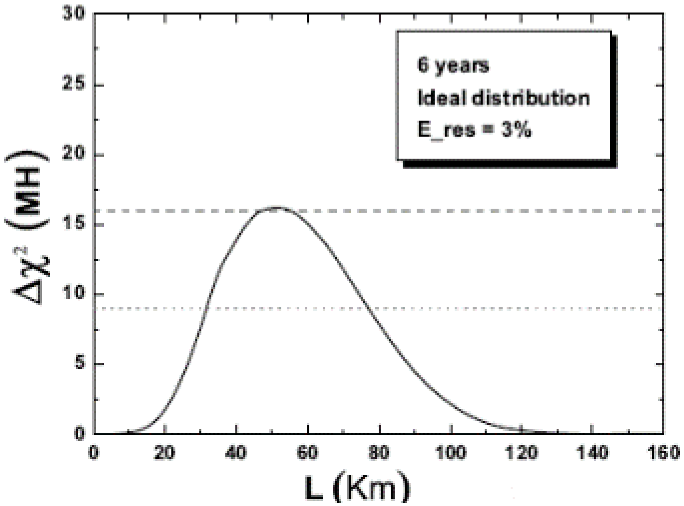
$$\begin{aligned} P_{21} &= 0.81\ \sin^2\Delta_{21} \\ P_{31} &= 0.7 \times \sin^2 2\theta_{13} \times \sin^2\Delta_{31} \\ P_{32} &= 0.3 \times \sin^2 2\theta_{13} \times \sin^2\Delta_{32} \end{aligned}$$

- The relative larger (0.7) oscillation and smaller (0.3) oscillation, which one is slightly (1/30) faster?
- Take Δm^2_{32} as reference, after a Fourier transformation
  - 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}

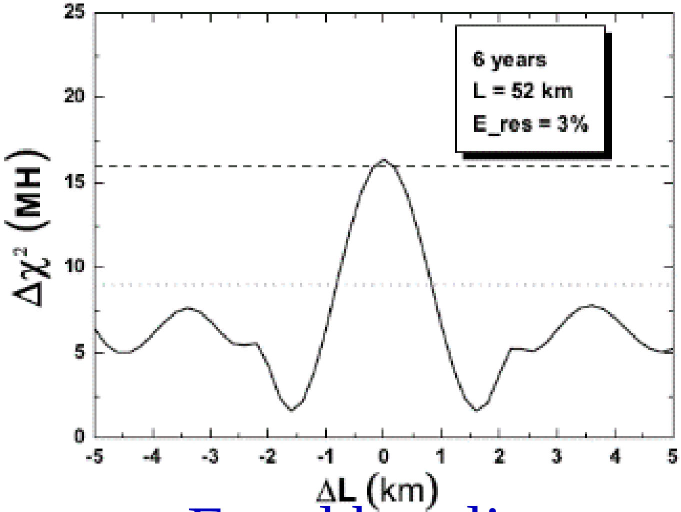




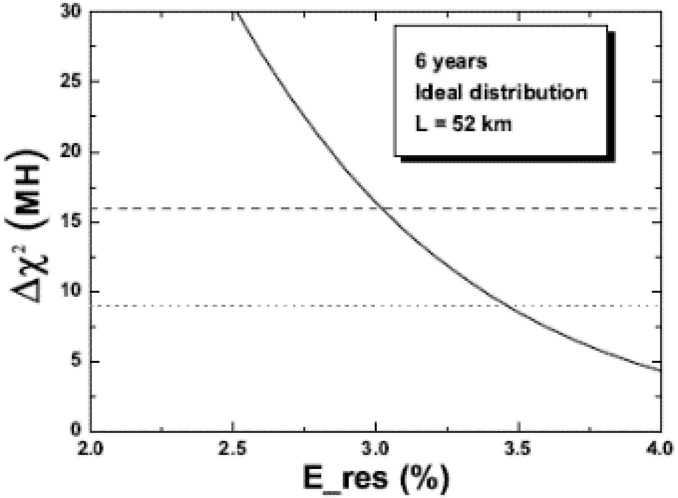
Requirements



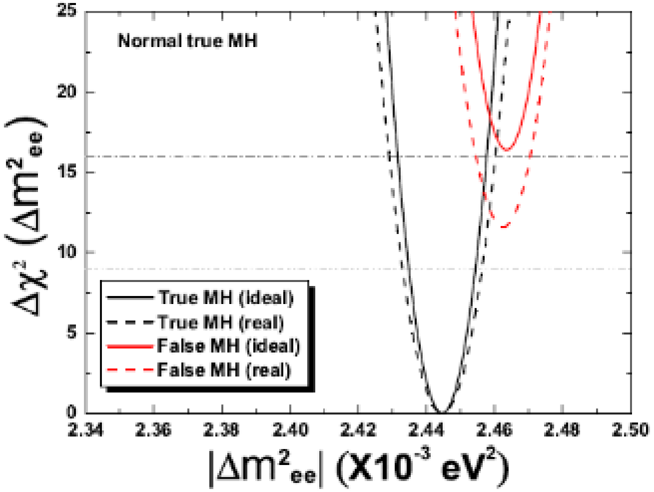
Proper baseline: 45-60 km



Equal baselines



3% Energy resolution



100k events=20 kton×35 GW×6 year

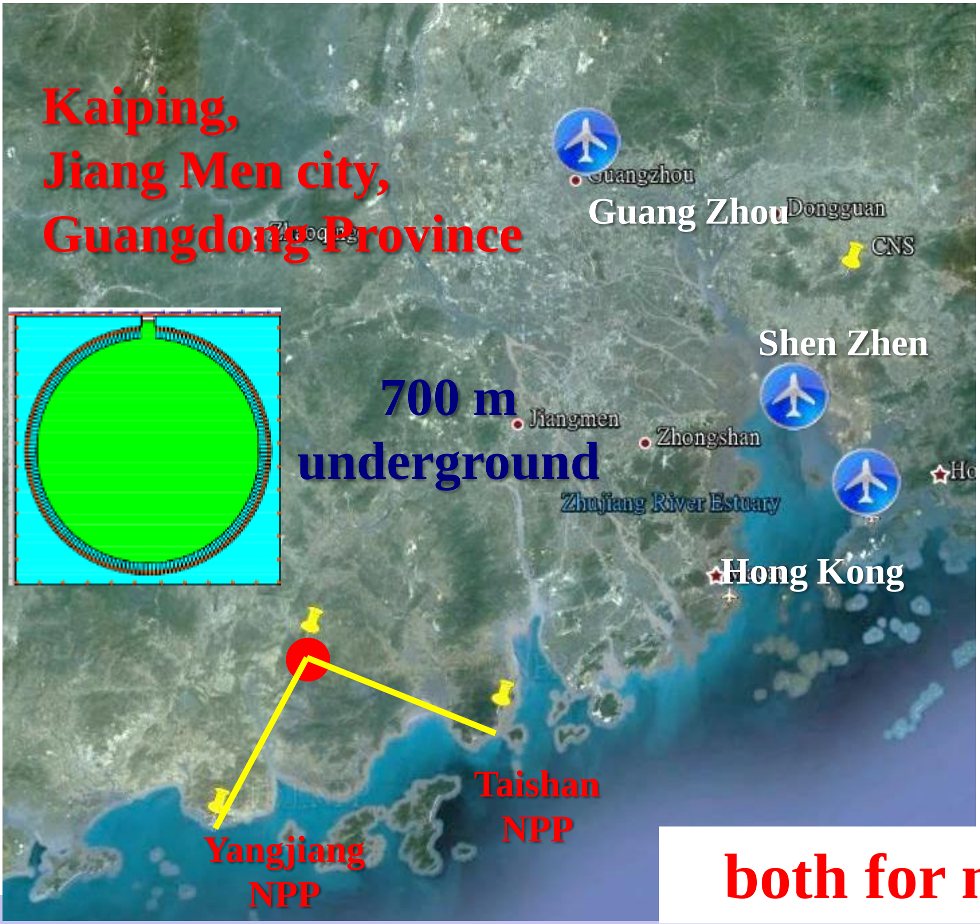
Experiments

JUNO (was Daya Bay-II)

- ⇨ Idea in 2008 (PRD78:111103, 2008; PRD79:073007, 2009)
- ⇨ Approved in Feb. 2013

RENO-50

- ⇨ From RENO-50 workshop, Jun.13-14, 2013

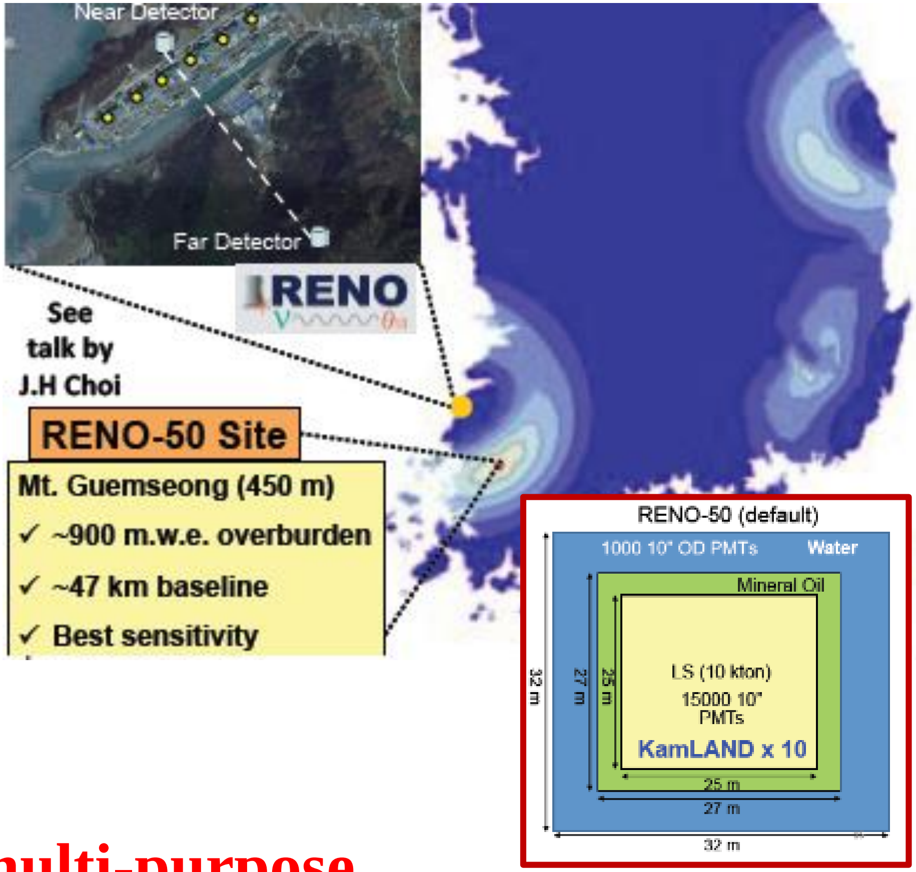


Kaiping,
Jiang Men city,
Guangdong Province

700 m underground

Taishan NPP

Yangjiang NPP



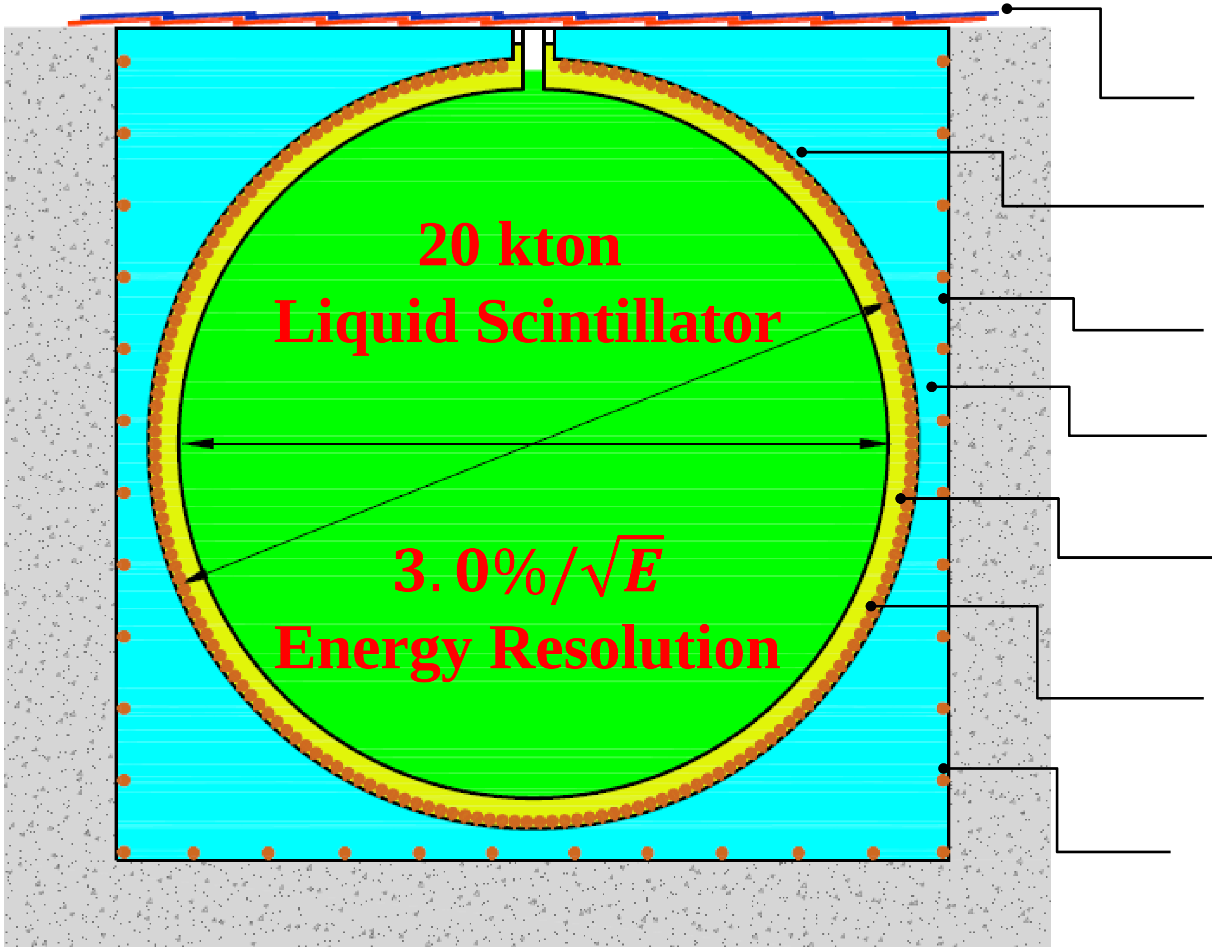
See talk by J.H Choi

RENO-50 Site

Mt. Guemseong (450 m)
- ✓ ~900 m.w.e. overburden
- ✓ ~47 km baseline
- ✓ Best sensitivity

both for multi-purpose

JUNO Detector



20 kton
Liquid Scintillator

$3.0\%/\sqrt{E}$
Energy Resolution

Muon Tracker

Stainless Steel Tank

Water Seal

20kton Water

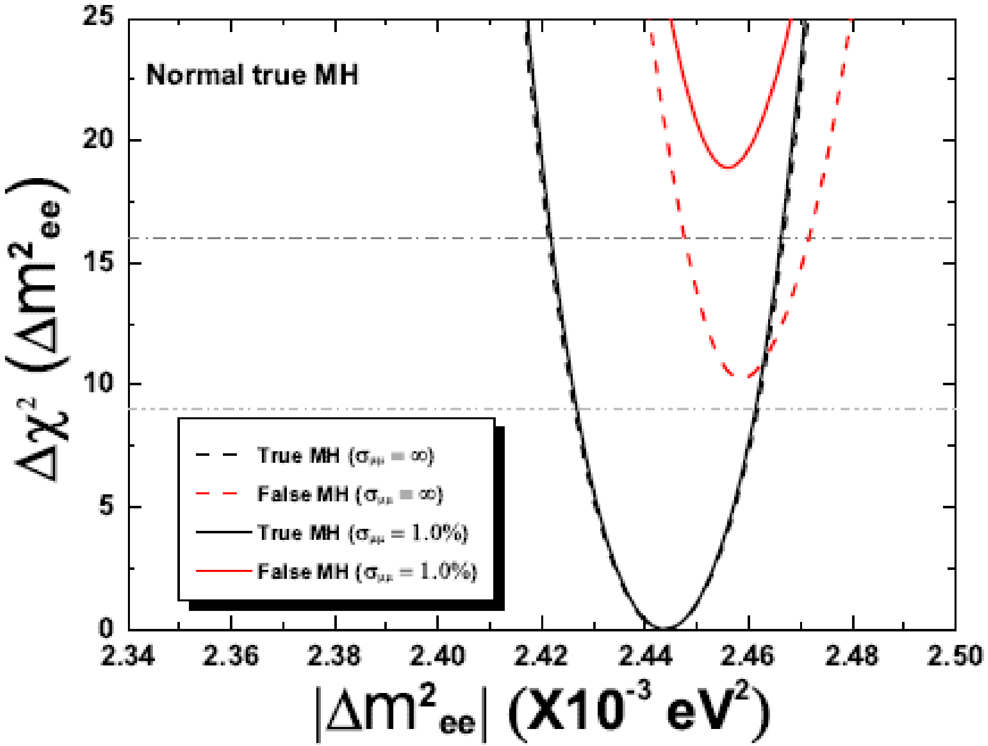
6kton Mineral Oil

~15000 20” PMTs
Coverage ~80%

1500 20” Veto PMTs

The mechanics of the ~40 m diameter detector is challenging. Many options are under consideration.

JUNO Sensitivity on MH

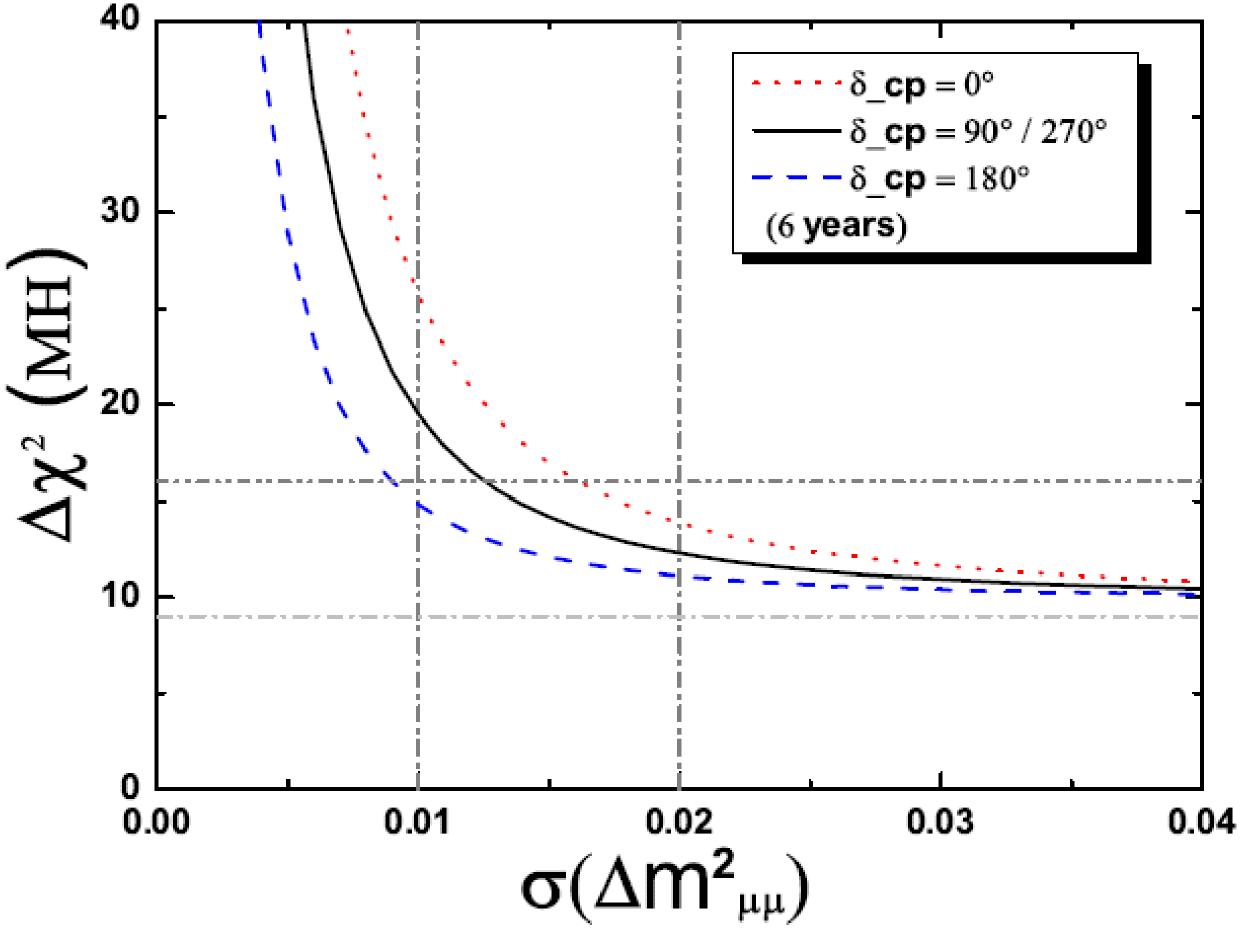


MH sensitivity with 6 years' data of JUNO (Y.F. Li et al, PRD 88, 013008 (2013)):

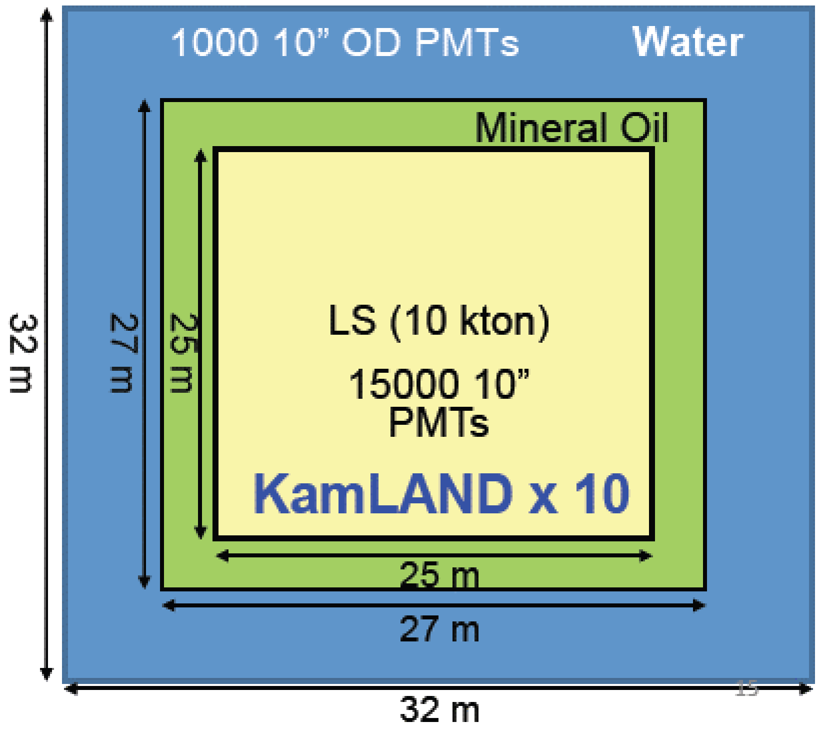
- Statistics only: 4σ for relative measurement, 5σ with absolute measurement
- Taking into account the spread of reactor cores, uncertainties from energy non-linearity, backgrounds, etc. 3σ for relative measurement, 4σ with absolute measurement.

Absolute Measurement on MH

- Effective Δm^2 for two-neutrino oscillations ($\text{reactor: } \Delta m^2_{ee}$, $\text{accelerator: } \Delta m^2_{\mu\mu}$)



RENO-50 Detector


RENO-50 (default)

- Need increase the default photoelectron yield by 5 times to reach $3\%/\sqrt{E}$ if taking Mass Hierarchy as a major goal.

Default RENO-50 detector:

--PMT coverage: 24 % (15,000 PMTs)
--Atten. Length: 12.45 m
--PMT QE: 24 %

$$\frac{6.8\%}{\sqrt{E/MeV}}$$

Other Experiments/Proposals for MH

Exp.	Type
T2K	Accelerator
Hyper-K	Accelerator & Atmospheric
NOvA	Accelerator
LBNE	Accelerator
PINGU	Atmospheric
~~LBNO~~	~~Accelerator~~
INO	Atmospheric
RENO-50	Reactor

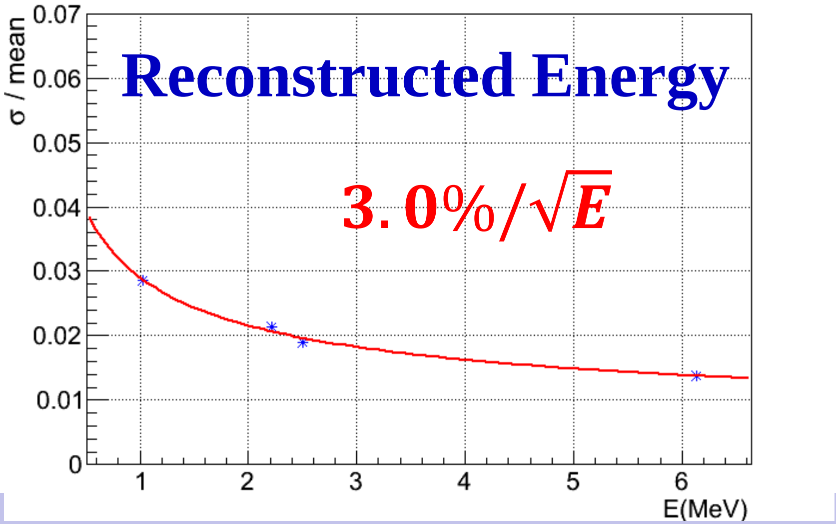
JUNO: Competitive in schedule and Complementary in physics

- Have chance to be the first to determine MH
- Independent of the yet-unknown CP phase (Acc. and Atm. do)
- Combining with other experiments can significantly improve the sensitivity
- Well established liquid scintillator detector technology

Energy Resolution

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

Red denote the R&D requirements to reach 3% energy resolution

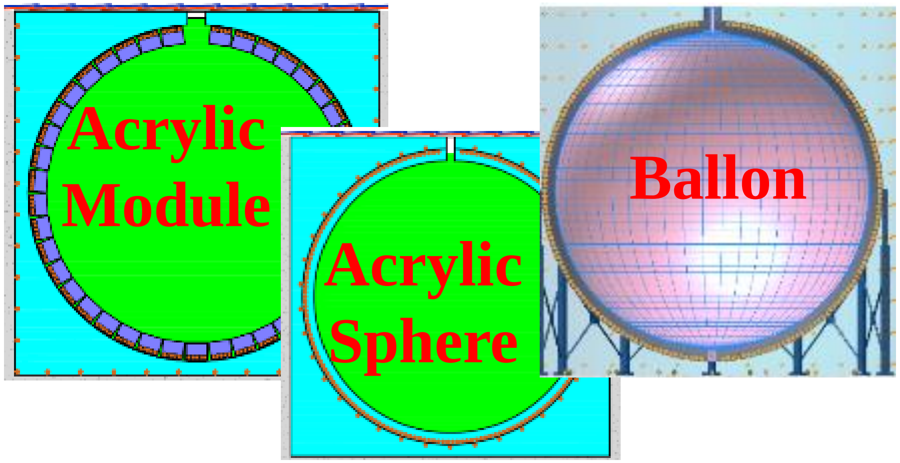


Reconstructed Energy

$3.0\%/\sqrt{E}$

Detector Challenges

- **Three major challenges**
  - ⇨ High transparency liquid scintillator (purification R&D)
  - ⇨ High efficiency PMT (new type PMT R&D led by IHEP)
  - ⇨ Huge detector (mechanic options)



IBD Signal

Estimated IBD rate: ~40/day

- Signal:

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

$$n + p \rightarrow d \quad + \gamma\ (2.2\ \text{MeV})$$

$\tau \sim 200\ \mu s$

- LS without Gd-loading for
  - Better attenuation length ➔ E resolution
  - Lower irreducible accidental backgrounds from LS, important for a larger detector:
    - With Gd: ~ 10^{-12} g/g
    - Without Gd: ~ 10^{-16} g/g
  - Less risk
- Recipe: LAB + 3g/L PPO + 15mg/L bis-MSB

Daya Bay experience: safe, very good transparency

Linear Alky Benzene

- Improve production quality + Precise distillation in factory, followed by purification onsite.
- Specially produced LAB by the factory: Attn = 20.5 m
- After purification → 24 m

- **Further purification of special Nanjing LAB**
  - Al_2O_3 column (SiO_2, activated carbon)
  - Vacuum distillation
  - Molecular distillation

Molecular distillation

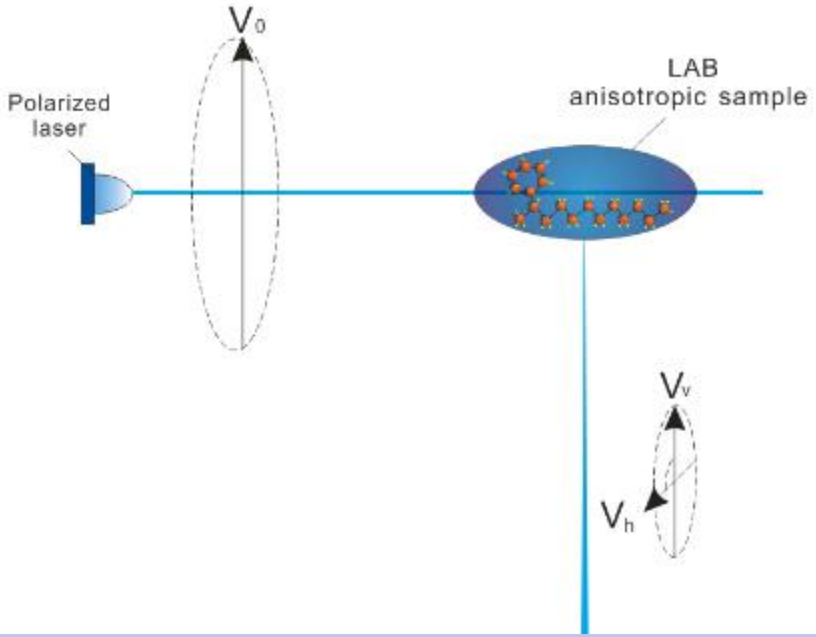
Vacuum distillation

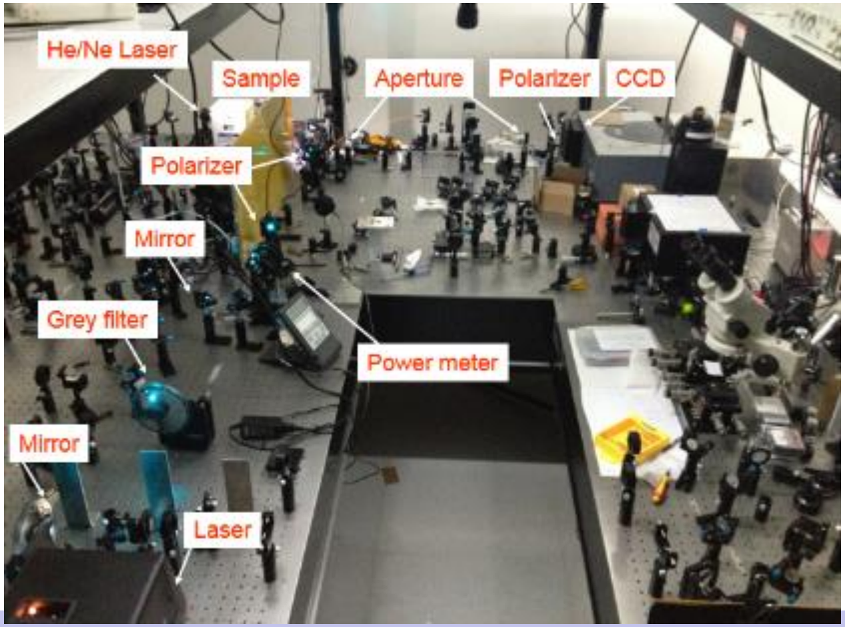
Al_2O_3 column

Rayleigh Scattering

$$\frac{1}{l_{atten}} = \frac{1}{l_{absorb}} + \frac{1}{l_{ray}} + \ldots$$

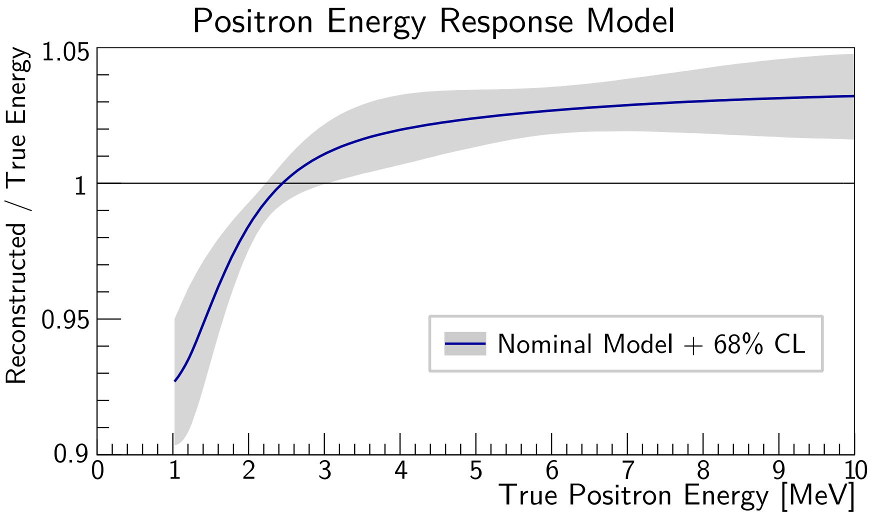
- **M. Wurm et al: 40±5 m** (Rev.Sci.Instrum. 81 (2012) 053301)
- **JUNO team: 27±1.2 m @430nm** (to be verified, and test on purified sample)



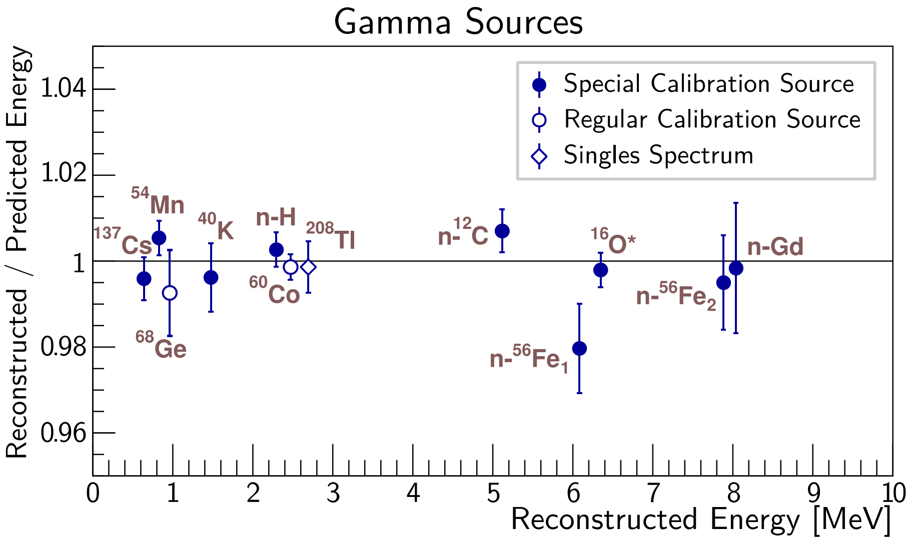


Energy Non-linearity

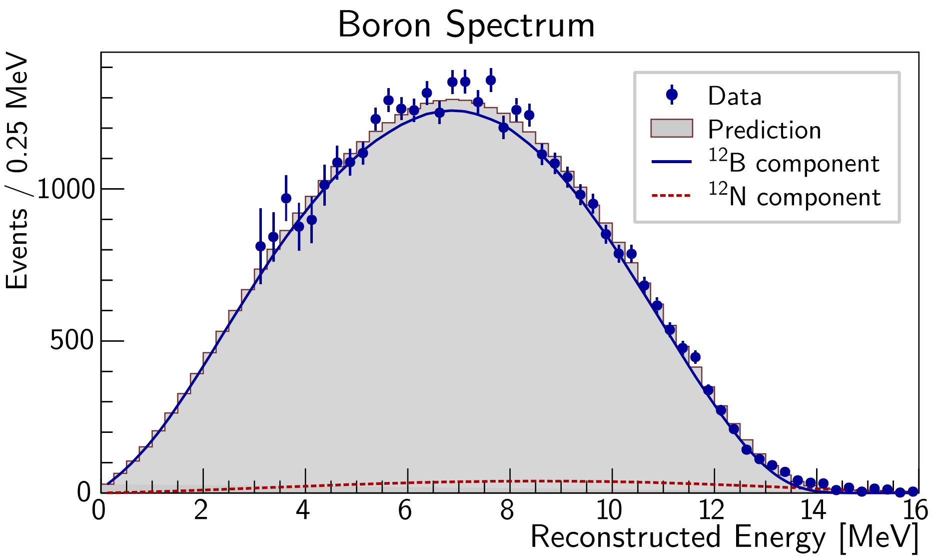
- LS detector is non-linear
- Daya Bay: LS non-linearity and electronics non-linearity
  - Using FADC
  - How to better calibrate?



Positron Energy Response Model



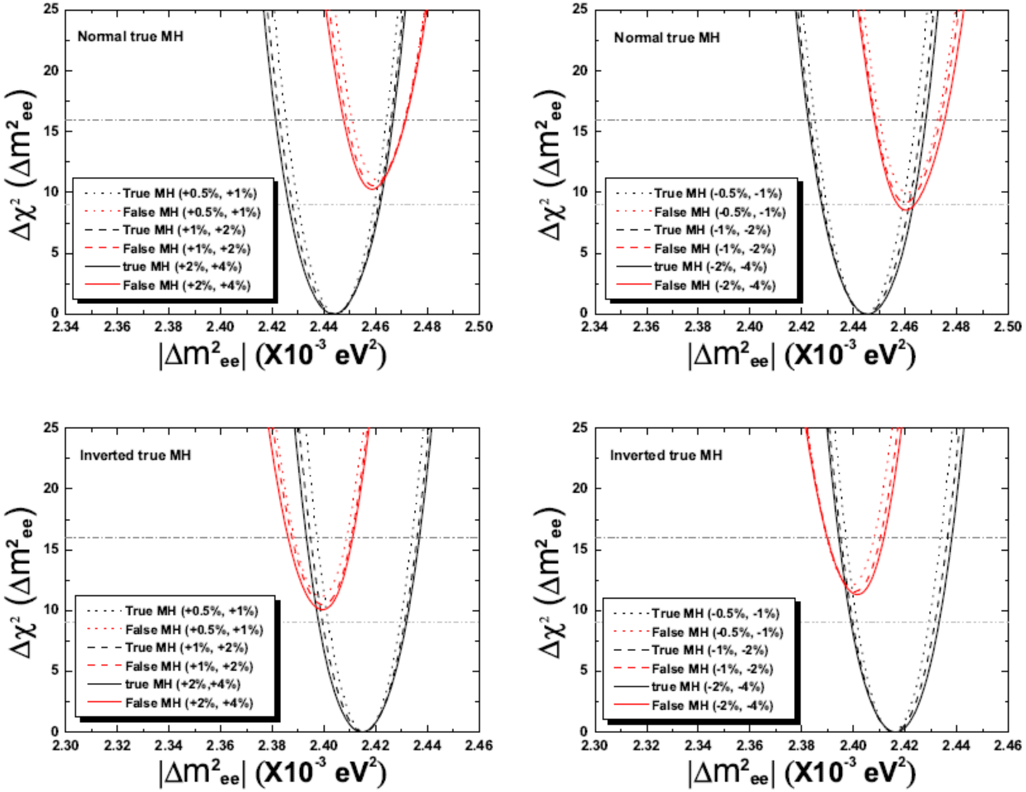
Gamma Sources

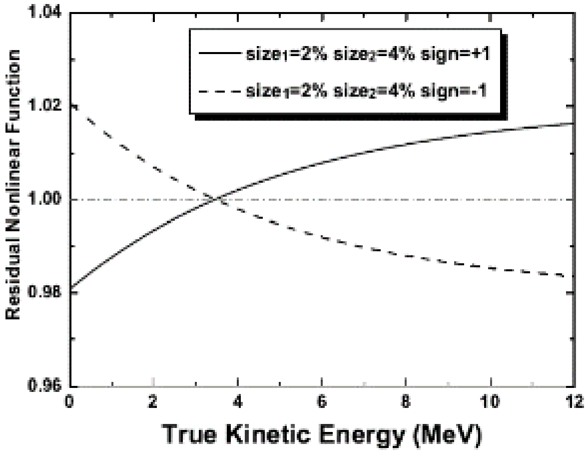


Boron Spectrum

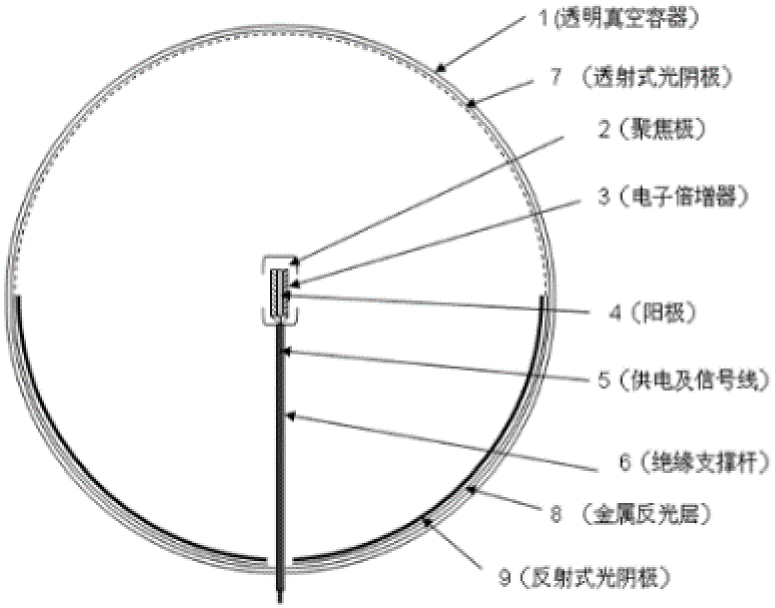
Impact of non-linearity

- Repetitive small oscillation structure of the measure spectrum can self-calibrate non-linearity (PRD 88, 013008 (2013))
- Assuming an unknown 2% residual non-linearity, the impact to MH is under control.

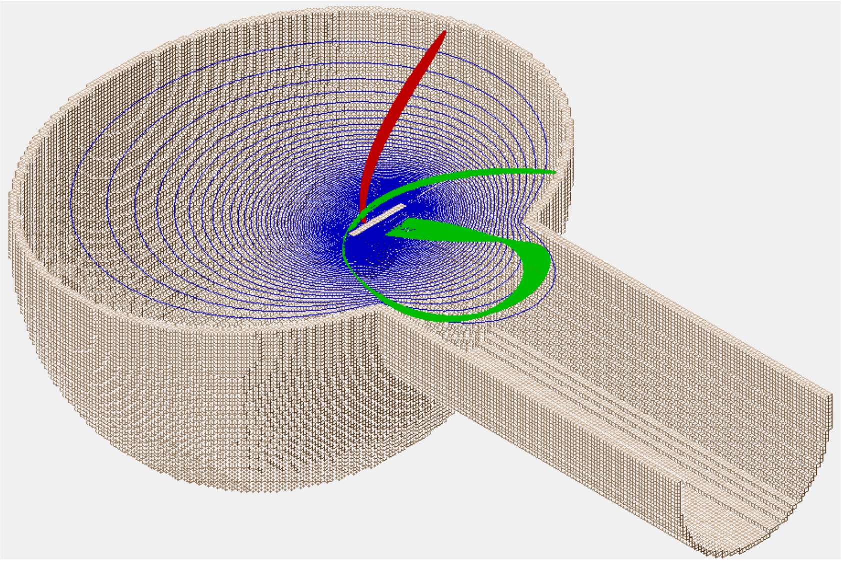




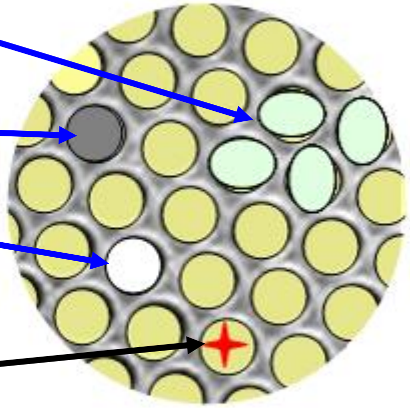
A new type of PMT: higher photon detection eff.



- ➢ **Top: transmitted photocathode**
- ➢ **Bottom: reflective photocathode**
- ➢ **MCP to replace Dynodes ➔ no blocking of photons**



Low cost MCP by accepting the following:



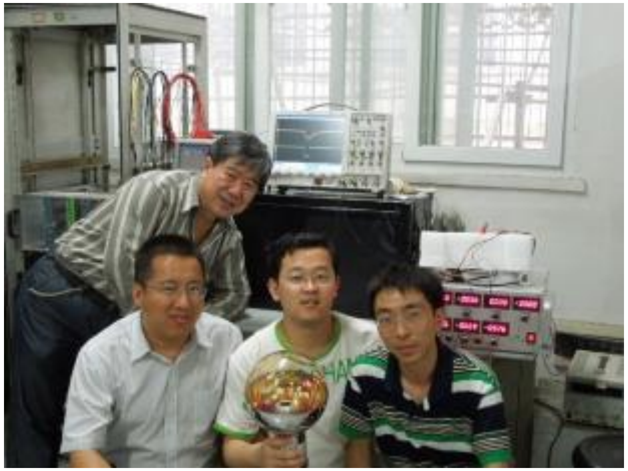
1. asymmetri

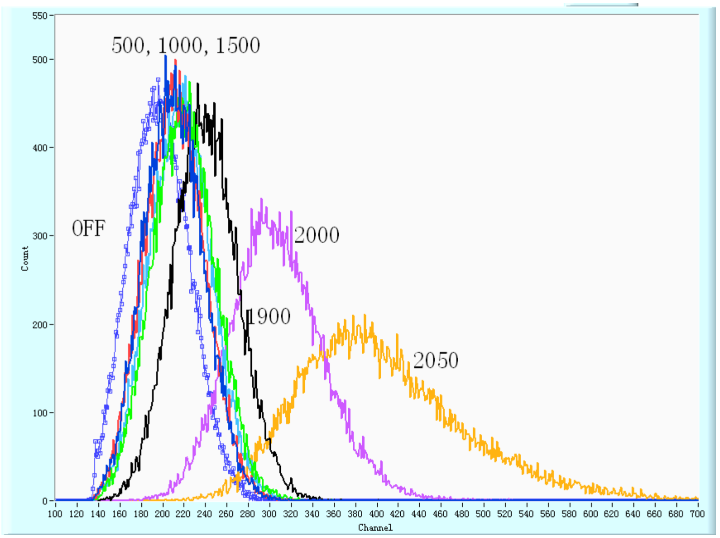
2. Blind ch

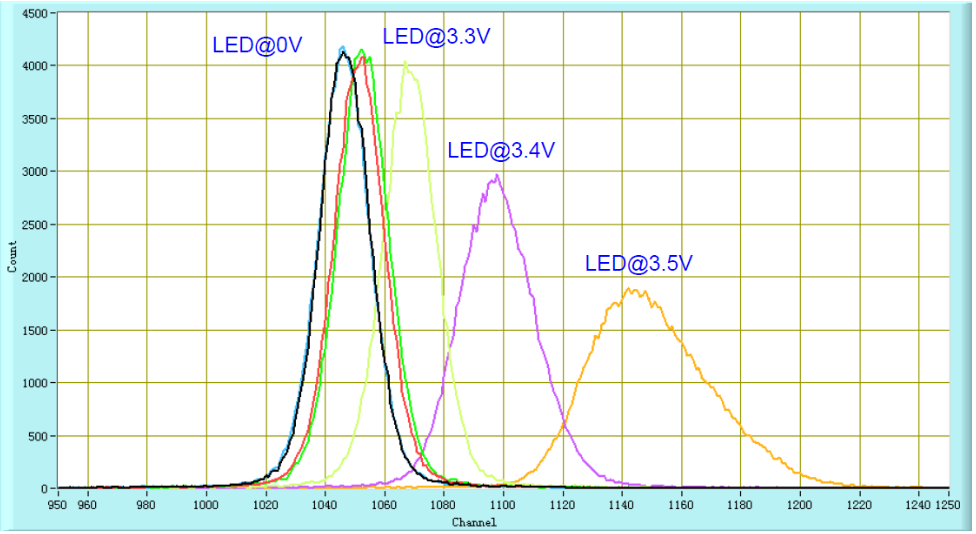
3. Non-unifo

4. Flashing channels

Prototypes







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HZC PHOTONICS

中核（北京）核仪器厂
CNNC Beijing Nuclear Instrument Factory

Background

Assumptions:

- **Overburden is 700m**
  - **E_m ~ 211 GeV, R_m ~ 3.8 Hz**
- **Single rates from LS and PMT are 5Hz, respectively**
- **Good muon tracking and vertex reconstruction**
- **Similar muon efficiency as DYB**

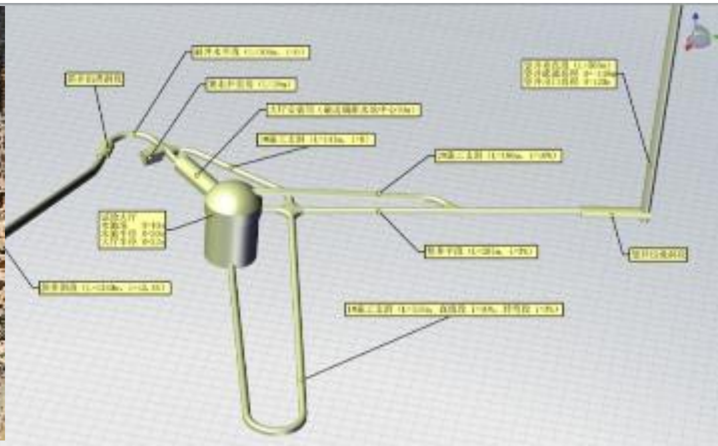
	Daya Bay	Daya Bay II
Mass (ton)	20	20,000
E_m (GeV)	~57	~211
L_m (m)	~1.3	~ 23
R_m (Hz)	~21	~3.8
$R_{singles}$ (Hz)	~50	~10

	B/S @ DYB EH1	B/S @ DYB II	Techniques needed for DYB II detector
Accidentals	~1.4%	~10%	Low PMT radioactivity; LS purification; prompt-delayed distance cut
Fast neutron	~0.1%	~0.4%	High muon detection efficiency (similar as DYB)
^{9}Li/^{8}He	~0.4%	~0.8%	Muon tracking; If good track, distance to muon track cut (<5m) and veto 2s; If shower muon, full volume veto 2s

JUNO: Brief schedule

- Civil preparation：2013-2014
  - Current status: site survey completed. Civil design on-going.
- 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

600m bore hole




Entrance

Kaiping Watch Towers

- **An UNESCO World Heritage Site**

Thanks!