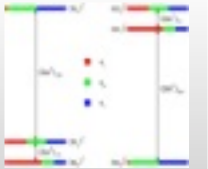
Resolving Neutrino Mass Hierarchy using Nuclear Reactor(s)

Wei Wang, College of William and Mary

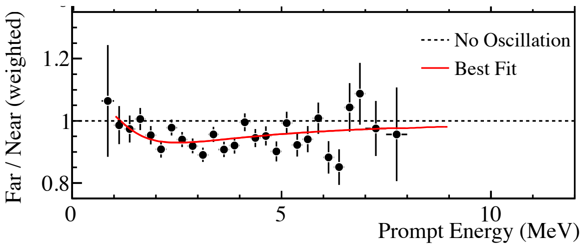
Invisibles'13, Lumley Castle, July 16, 2013

- *A review of MH via reactors and key challenges*
- *Sensitivity studies using JUNO as an example*
- *Subtleties in statistics*
- *Status of the field*
- *Summary*

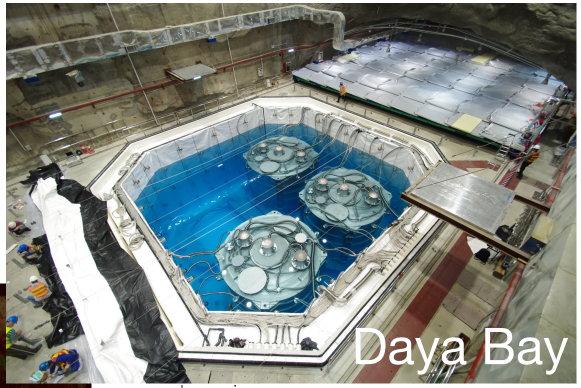
Nuclear Reactors and Neutrinos



courtesy: Karsten Heeger

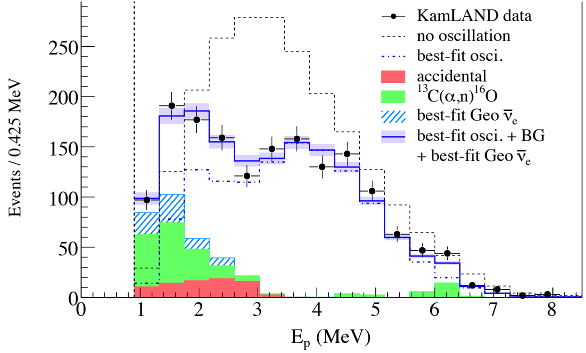


2012 - Observation of short baseline reactor electron neutrino disappearance



2008 - Precision measurement of Δm_{12}^2 . Evidence for oscillation

2003 - First observation of reactor antineutrino disappearance



1995 - Nobel Prize to Fred Reines at UC Irvine

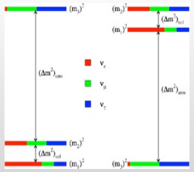
1980s & 1990s - Reactor neutrino flux measurements in U.S. and Europe

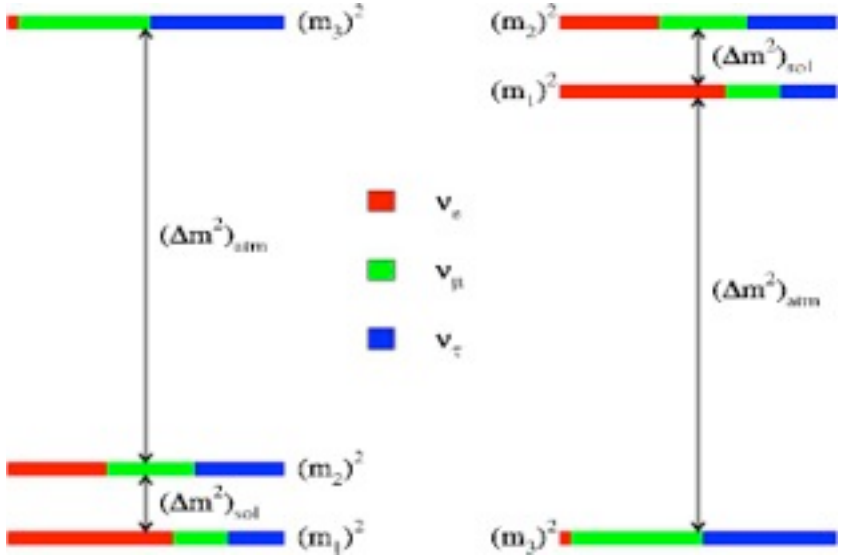
1956 - First observation of (anti)neutrinos

Past Reactor Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France

KamLAND, Japan
Double Chooz, France
Reno, Korea
Daya Bay, China

The Gate to Mass Hierarchy is Open





- How to resolve neutrino mass hierarchy using reactor neutrinos
  - KamLAND (long-baseline) measures the solar sector parameters
  - Short-baseline reactor neutrino experiments designed to utilize the oscillation of atmospheric scale
  - ✓ Both scales can be probed by observing the spectrum of reactor neutrino flux

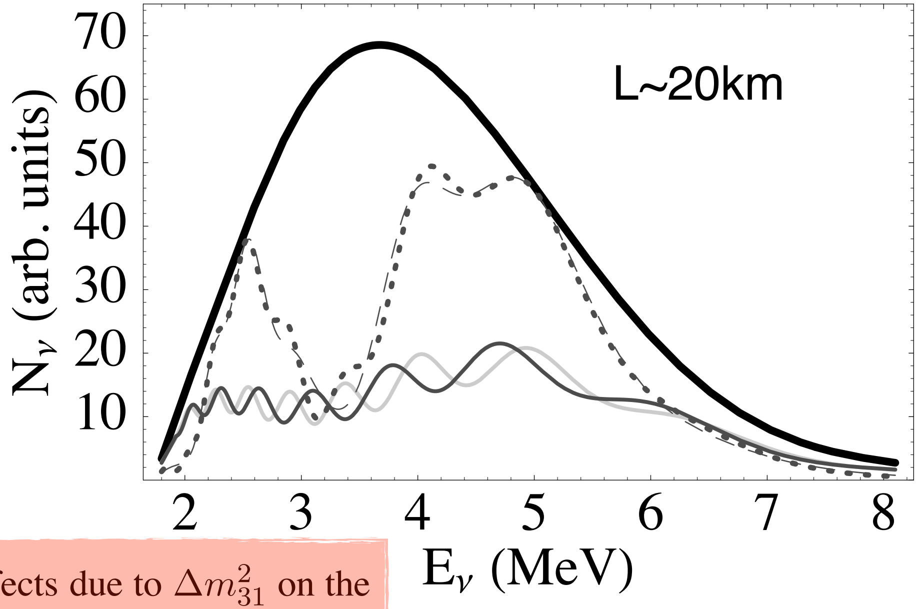
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \boxed{\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}}$$

$$-\boxed{\sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})}$$

✓The mass hierarchy is contained in the spectrum

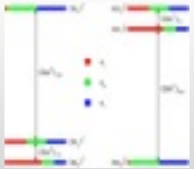
✓Independent of the unknown CP phase

Petcov&Piai, arXiv:0112074



- the value of $\sin^2\theta$, which controls the magnitude of the sub-leading effects due to Δm^2_{31} on the $\Delta m^2_{\odot}-$driven oscillations: the effect of interest vanishes in the decoupling limit of $\sin^2\theta \to 0$;

Fourier Transformation to Extract Mass Hierarchy

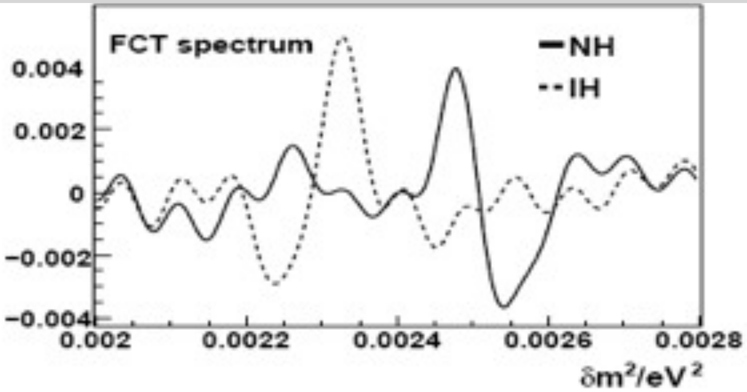


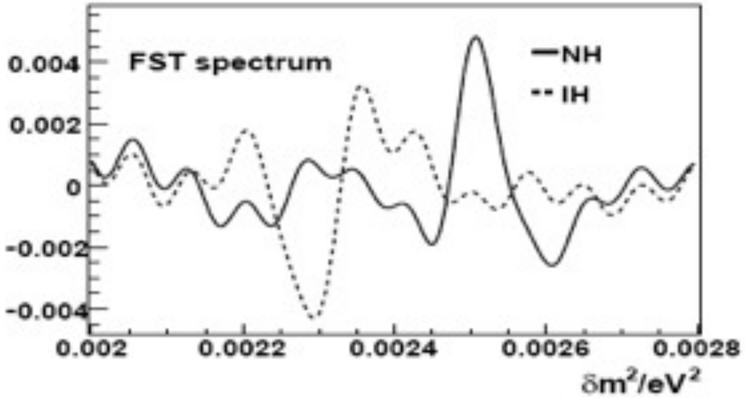
- Treating L/E as the time domain, the frequency domain simply corresponds to Δm^2

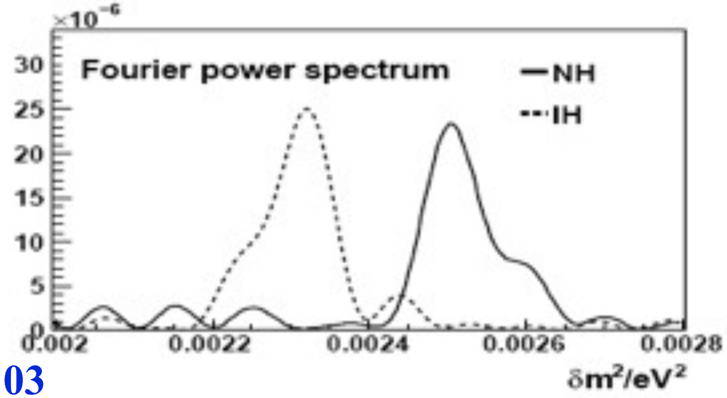
$$FST(\omega) = \int_{t_{min}}^{t_{max}} F(t)\sin(\omega t)dt$$

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

- In the Δm^2 domain, take Δm^2_{32} as the reference point,
  - NH: take "+" sign, the effective Δm^2 peaks on the right of Δm^2_{32}, then a valley
  - IH: take "-" sign, the effective Δm^2 peaks on the left of Δm^2_{32}, right to a valley
- Δm^2 spectra have very distinctive features for different hierarchies
- In principle, no need for the absolute value of Δm^2_{32}



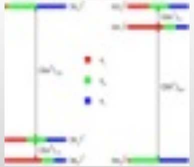




L. Zhan et al., PRD78(2008)111103

J. Learned et al proposed the FT method 2006

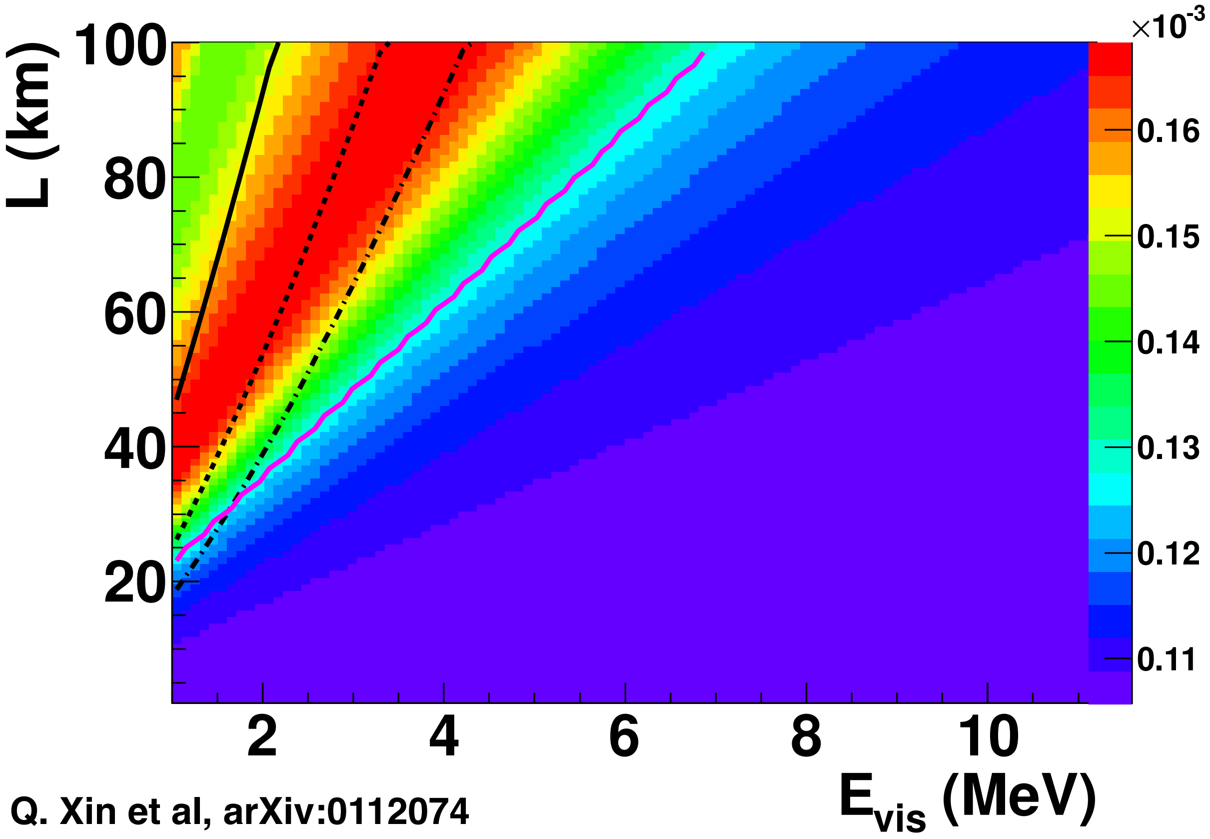
Reading the Signal in Another Way



$$P_{\bar{\nu}_e\rightarrow\bar{\nu}_e} = 1 - 2s^2_{13}c^2_{13} - 4c^4_{13}s^2_{12}c^2_{12}\sin^2\Delta_{21}$$

$$+2s^2_{13}c^2_{13}\sqrt{1-4s^2_{12}c^2_{12}\sin^2\Delta_{21}}\cos(2\Delta_{32}\pm\phi)$$

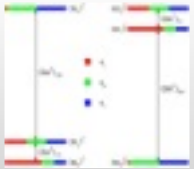
$$\tan\phi = \frac{c^2_{12}\sin 2\Delta_{21}}{c^2_{12}\cos 2\Delta_{21} + s^2_{12}} \quad \Rightarrow \quad \Delta m^2_\phi(L,E) = \frac{\phi}{1.27}\cdot\frac{E}{L}$$

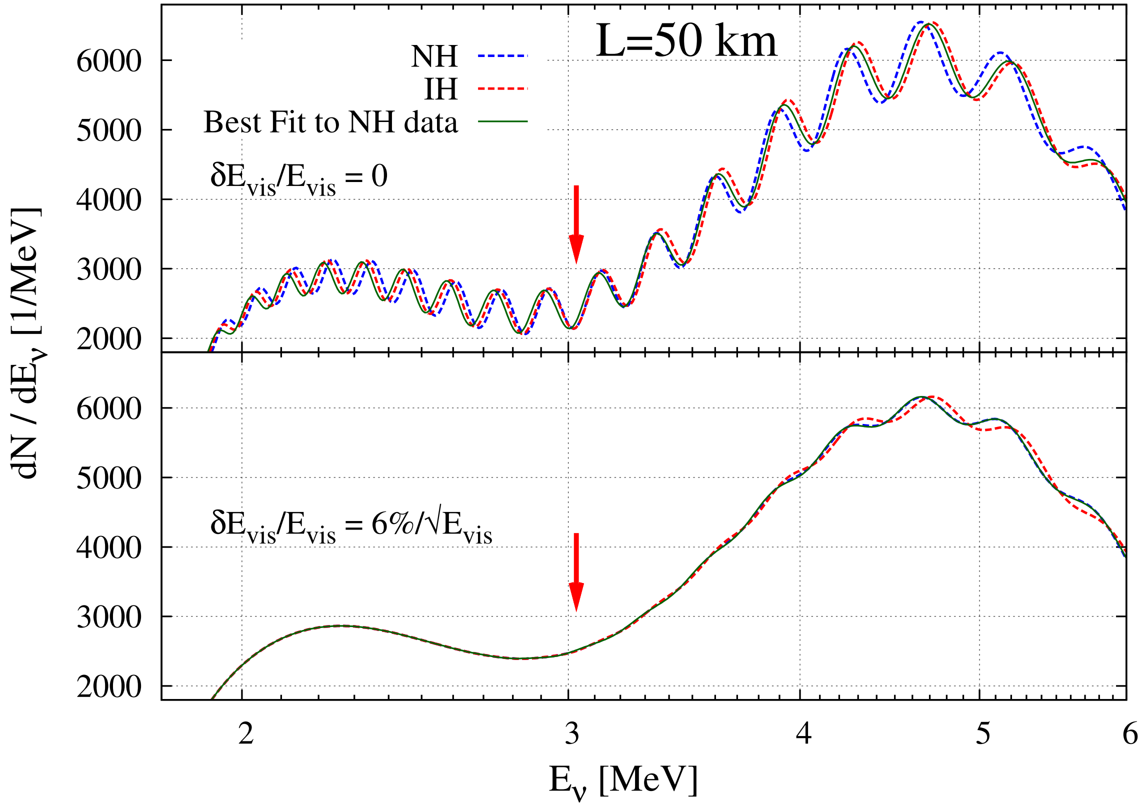


Q. Xin et al, arXiv:0112074

- Reading it from a different perspective gives us, the experimentalists, a few obvious catches
  - Δm^2_{32} uncertainty is too big for the small differences caused by different mass hierarchies. The shift can be easily absorbed by the uncertainty
  - Energy resolution squeeze the "useful" part from the left

The Energy Resolution Requirement





S.F. Ge et al, arXiv:1210.8141

- In order to see the atmospheric scale oscillations in the survival spectrum, to the first order, the energy resolution should be at least the ratio between solar mass-squared difference and the atmospheric one is ~3%

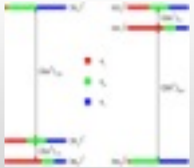
$$\frac{\Delta E}{E} = \sqrt{a^2 + \frac{b^2}{E} + \frac{c^2}{E^2}}$$

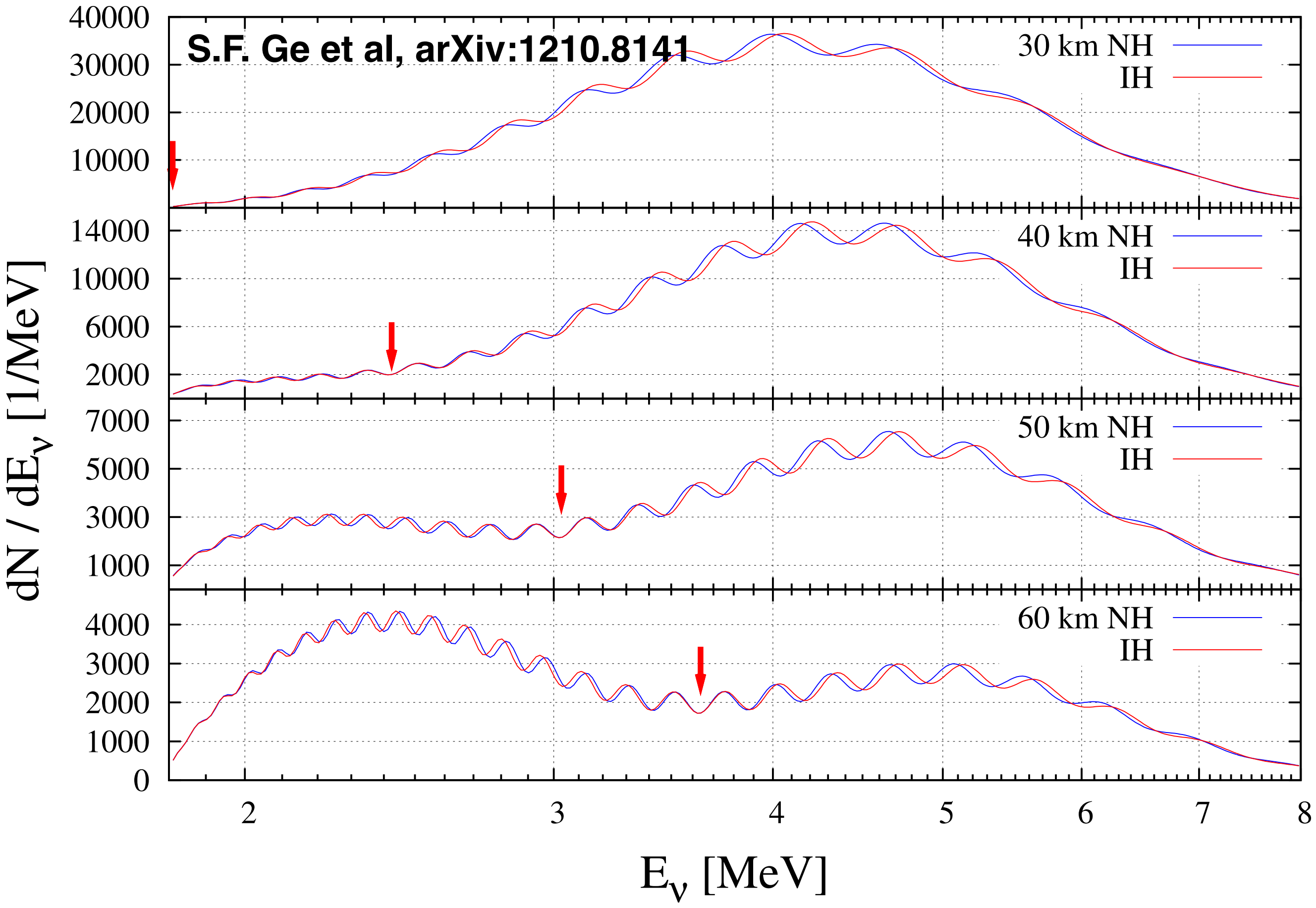
leakage & non-uniformity

Photon statistics (dominant). Needs <3%

Noise

Give The MH Signal a Closer Look

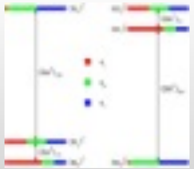




- It is obvious that the baseline is better beyond 30km
- Practically speaking (for real experiments), the power lies in the contrast between the lower part and the higher part of the inverse beta decay spectrum

- At the energy where the effective mass-squared difference shift disappears, NH and IH spectra are identical. Below and above this energy, the phase difference between NH and IH shift in different direction.

Energy Scale Places Another Challenge



S.J. Parke et al, arXiv:0812.1879

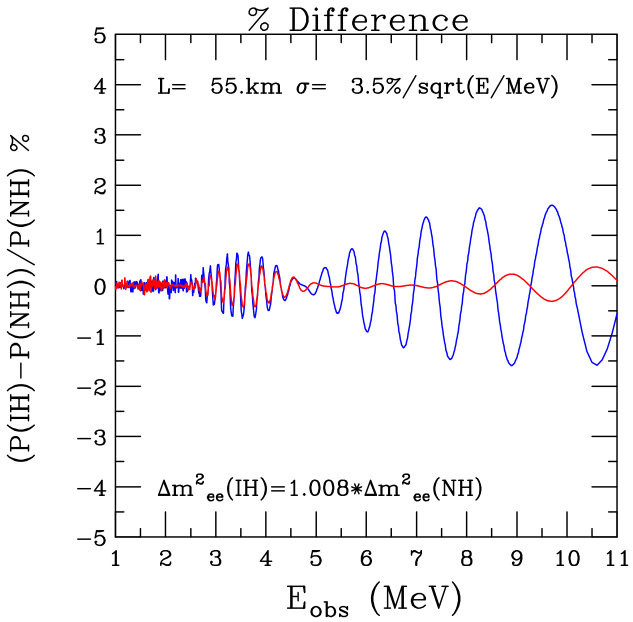
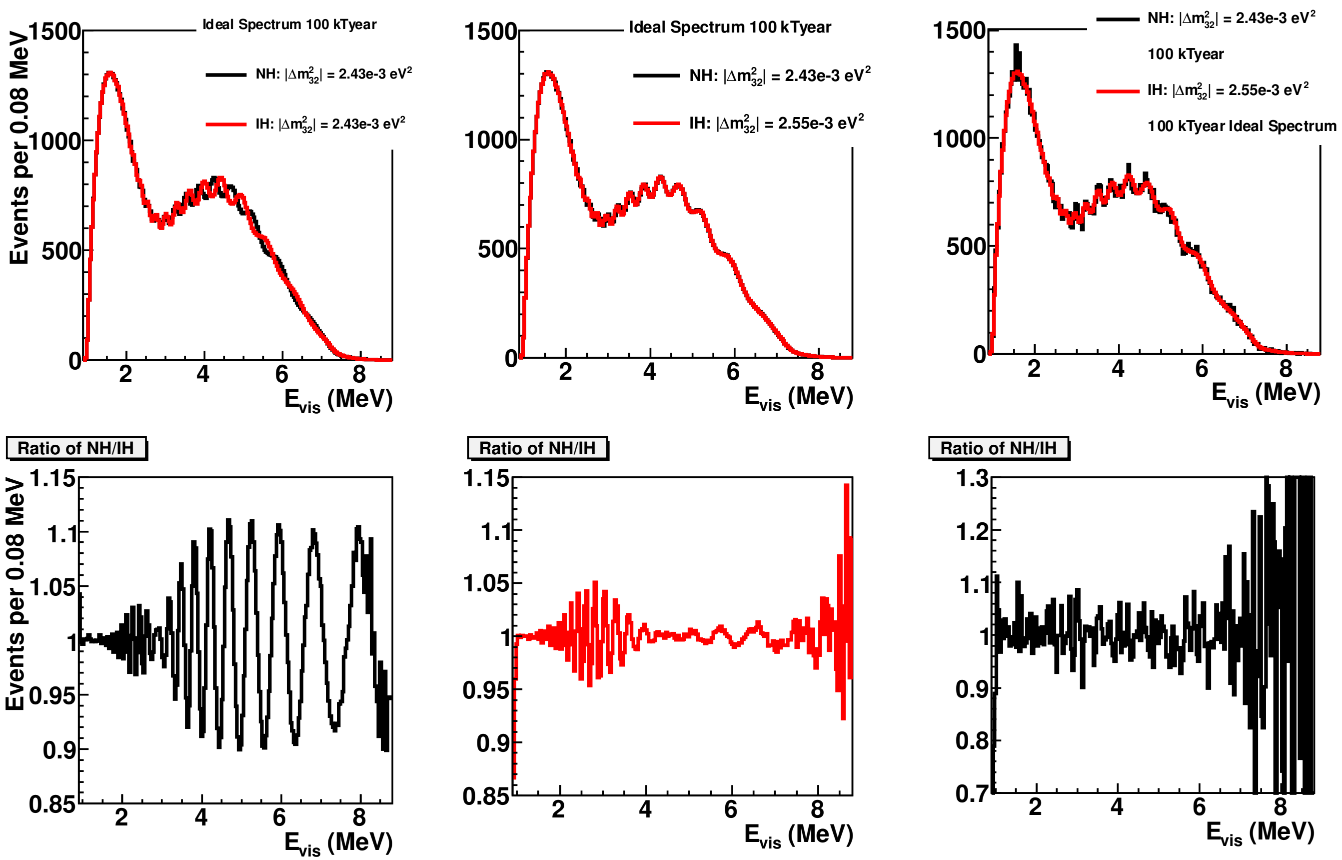


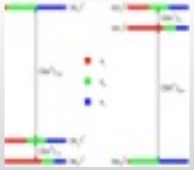
Figure 4. The percentage difference between the inverted hierarchy and the normal hierarchy. The blue curve is assuming $E_{obs} = E_{true}$ and maximum difference is less than 2%. Whereas for the red curve we have assumed that $E_{obs} = 1.015 E_{true} - 0.07$ MeV for the IH, so as to represent a relative calibration uncertainty in the neutrino energy. Here the maximum percentage difference is less than 0.5%.

Q. Xin et al, arXiv:1208.1551



- Oscillation is governed by ~$\Delta m^2_{32}/E$, thus they have the same role
- Uncertainty in Δm^2_{32} causes nearly degenerated spectra between NH and IH

Degenerated Spectrum

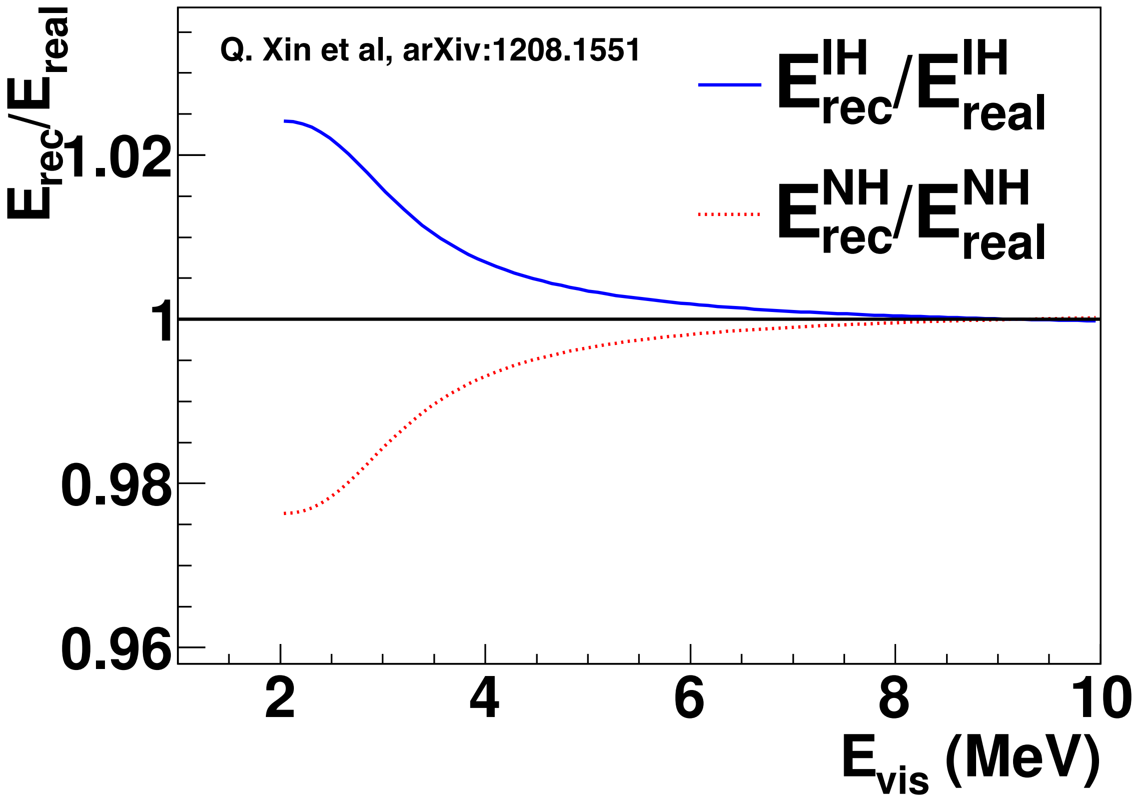


- Recall the survival probability

$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - 2s_{13}^2c_{13}^2 - 4c_{13}^4s_{12}^2c_{12}^2\sin^2\Delta_{21} + 2s_{13}^2c_{13}^2\sqrt{1-4s_{12}^2c_{12}^2\sin^2\Delta_{21}}\,\boxed{\cos(2\Delta_{32}\pm\phi)}$$

⇨

$$E_{rec} = \frac{2|\Delta' m_{32}^2| + \Delta m_{\phi}^2(E_{\bar{\nu}_e}, L)}{2|\Delta m_{32}^2| - \Delta m_{\phi}^2(E_{\bar{\nu}_e}, L)}E_{real}$$



Could there be identical oscillation patterns?

- The current uncertainty in atmospheric mass-squared difference, combined with a non-linear energy response, would create the same survival spectrum for both mass hierarchies.
- No way to resolve MH if the non-linear energy response allows such curves

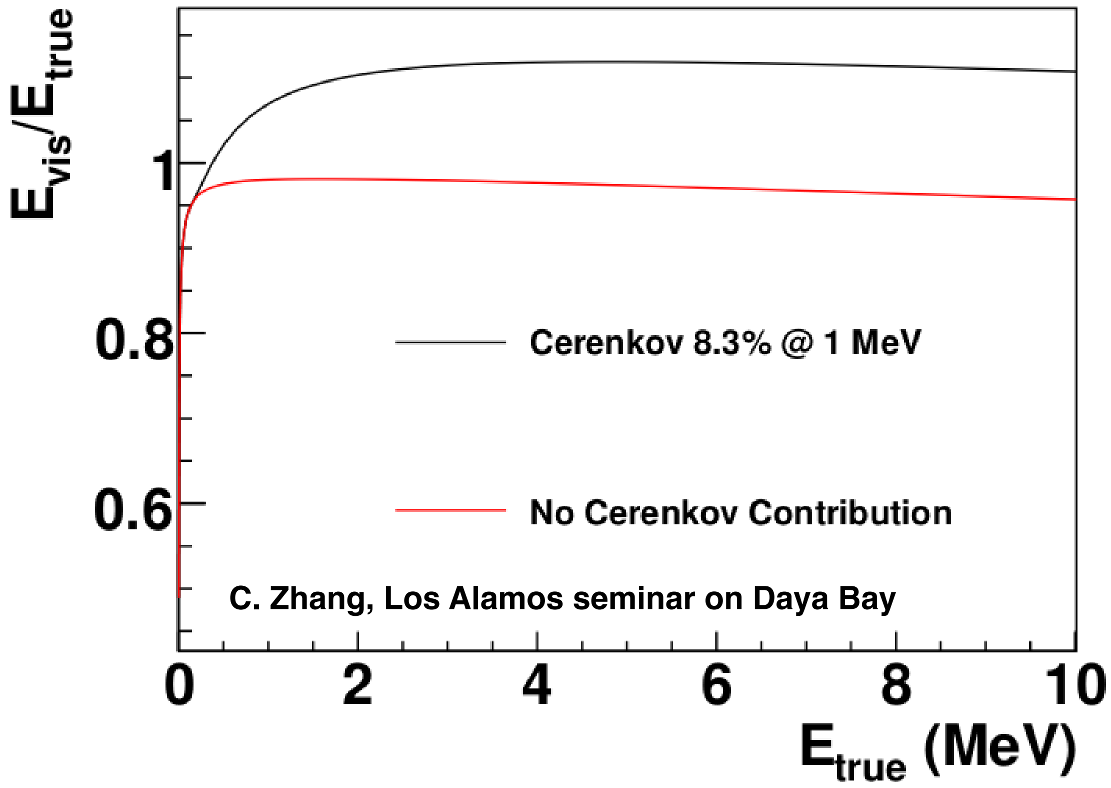
Practical Energy Scale Issues Related to Reactor MH Experiments

Inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$

- We need "free" protons and we need photons, the more the better

➡ Liquid scintillator detector seems the ideal choice: protons (H), many photons, and cheap. It turned out to be this is the choice of all current proposals.

➡ But liquid scintillator has a notorious feature: energy non-linearity due to quenching and Cherenkov lights



C. Zhang, Los Alamos seminar on Daya Bay

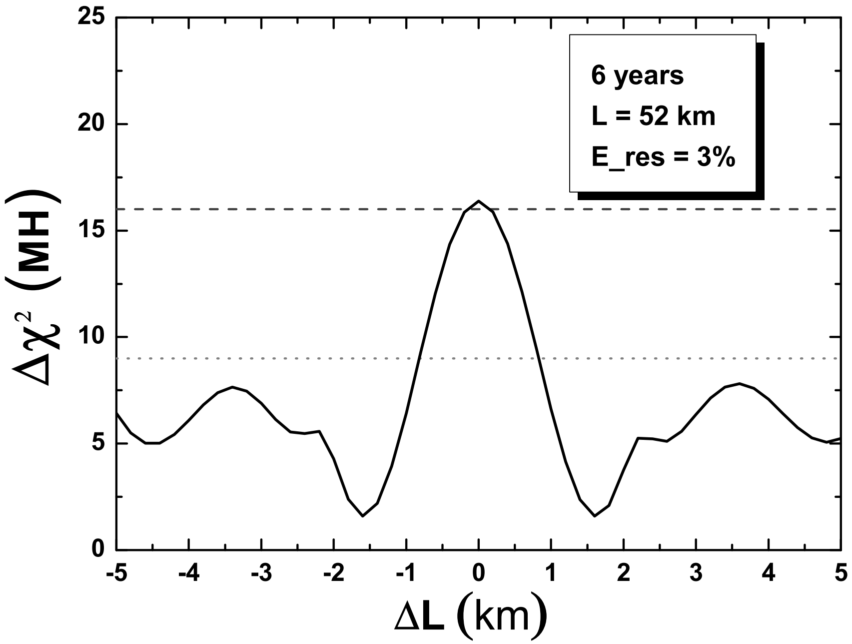
➡ Based on past/current understanding, the "convenient" non-linearity curve which could cause degeneracy follows a similar shape to the liquid scintillator energy response.

➡ There could be difficulties in resolving MH due to the non-linearity feature of LS

Challenges in Resolving MH using Reactor Flux

- Energy resolution
- Energy non-linearity
- Statistics
- Reactor distribution
  - The mass hierarchy information is in the multiple atmospheric oscillation cycles in the survival spectrum. For the valuable part of the spectrum ~3.5MeV, the oscillation length is ~3.5km.
  - Thus, if two reactor cores with equal or close powers differ by half oscillation length, the mass hierarchy signal will get cancelled.

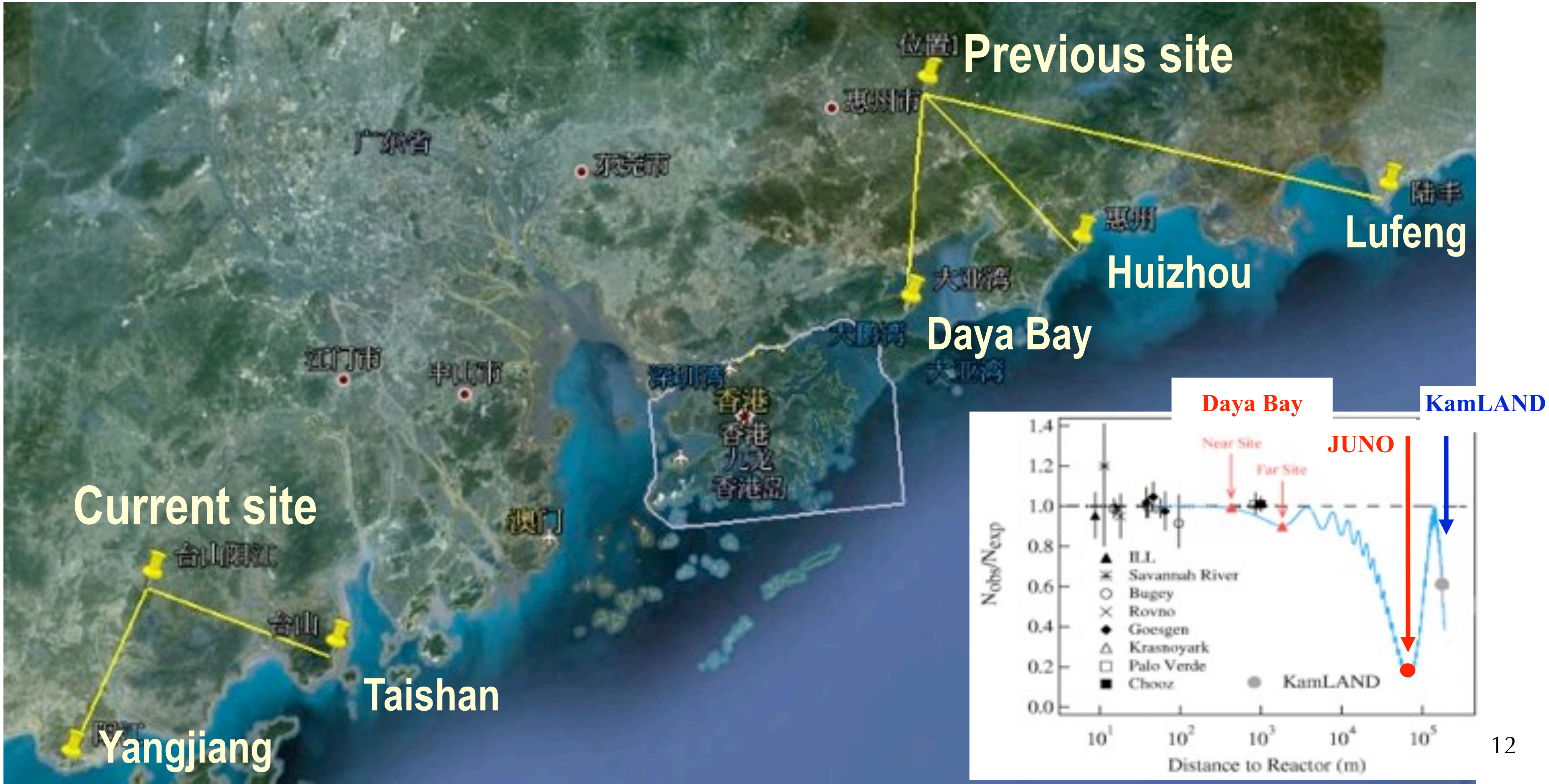
Y.F. Li et al, arXiv:1303.6733



- What is the status of the field?
  - JUNO (Jiangmen Underground Neutrino Observatory, previously dubbed as Daya Bay II) in China. Stealing slides from Yifang Wang et al from IHEP
  - RENO-50 in South Korea. Stealing slides from RENO-50 collaborators

JUNO：Kaiping county, Jiangmen city

	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	**running**	**planned**	**approved**	**Construction**	**construction**
power/GW	**17.4**	**17.4**	**17.4**	**17.4**	**18.4**

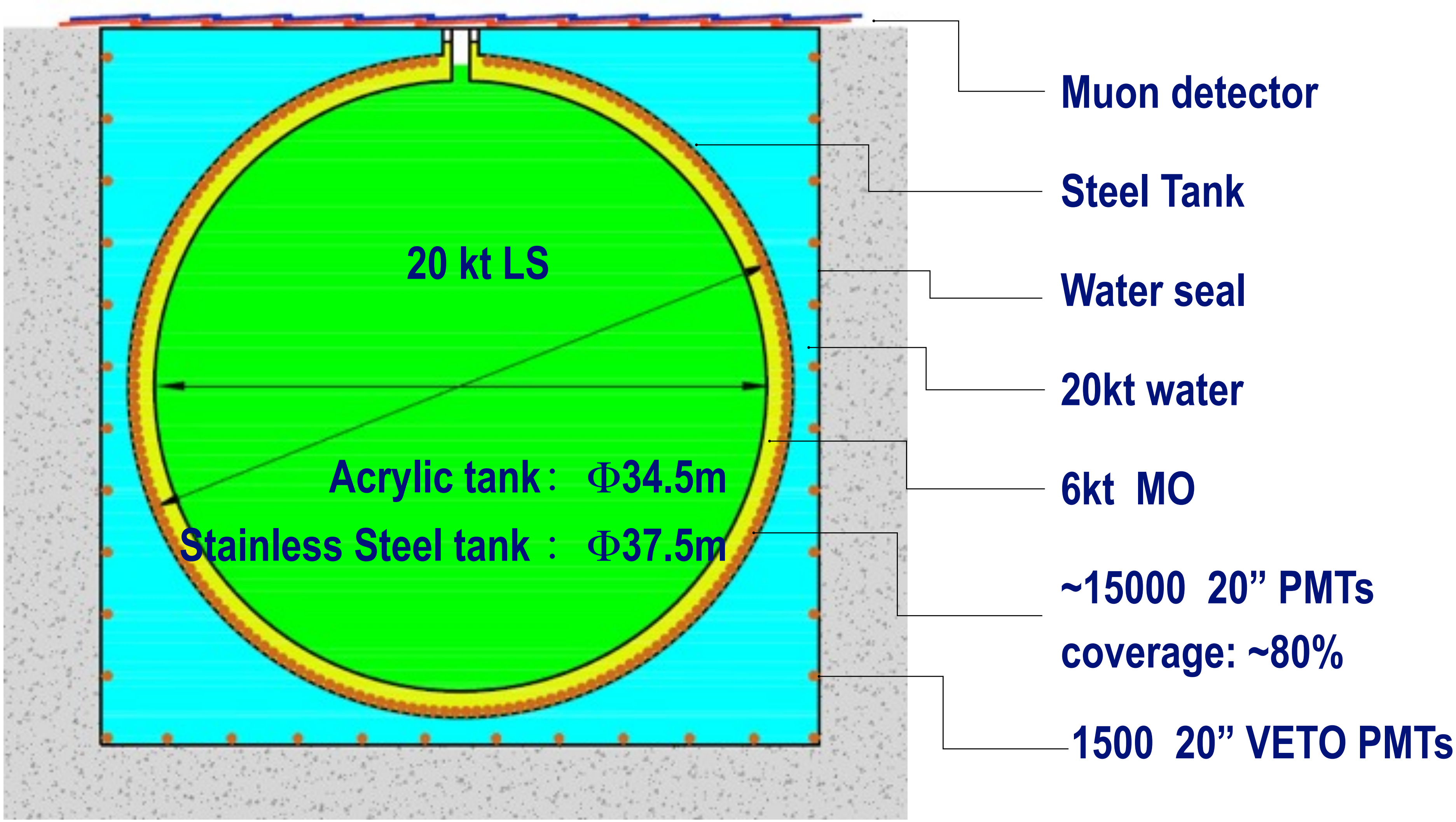


Site selection

- **Allowed region determined**
- **Experimental hall selected:**
  - **In granite**
  - **Mountain height: 270 m**
- **Preliminary geological survey completed:**
  - **Review held on Dec. 17, 2012**
  - **No show-stoppers**
- **Detailed geological survey started and first round data are available now**
- **Contacts with local government established, good support**

JUNO: a large LS detector

- LS volume: × 20➔ for more mass & statistics
- light(PE) × 5➔ for resolution



Challenges of a 20kt LS Detector

- **Large detector: >10 kt LS**
- **Energy resolution: < 3%/√E → 1200 p.e./MeV**

	Daya Bay	BOREXINO	KamLAND	JUNO
LS mass	**20t**	**~300t (100t F.V.)**	**~1 kt**	**20kt**
Photocathode Coverage	**~12%**	**~34%**	**~34%**	**?**
Energy Resolution	**~7.5%/√E**	**~5%/√E**	**~6%/√E**	**3%/√E**
Light yield	**~160 p.e./MeV**	**~500 p.e/MeV**	**~250 p.e./MeV**	**1200 p.e./MeV**

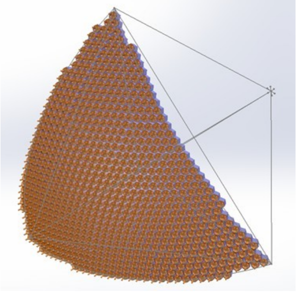
More photons, how and how many ?

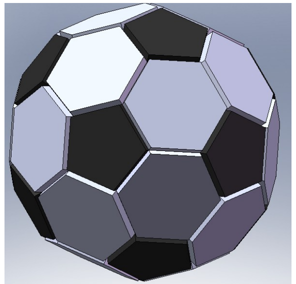
- **Highly transparent LS:**
  - ⇨ Attenuation length/D: 15m/16m → 30m/34m ×0.9
- **High light yield LS:**
  - ⇨ KamLAND: 1.5g/l PPO → 5g/l PPO
    Light Yield: 30%→ 45%; × 1.5
- **Photocathode coverage :**
  - ⇨ KamLAND: 34% → ~ 80% × 2.3
- **High QE "PMT":**
  - ⇨ 20" SBA PMT QE: 25% → 35% × 1.4
    or New PMT QE: 25% → 40% × 1.6
    Both: 25% → 50% × 2.0

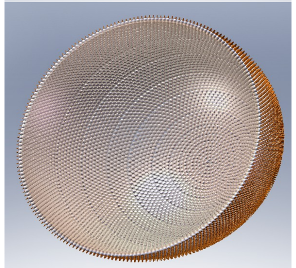
4.3 – 5.0 → (3.0 – 2.5)% $/\sqrt{E}$

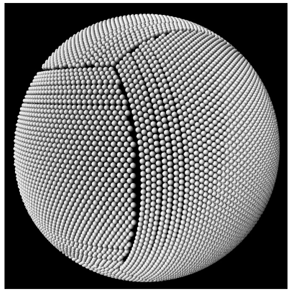
Other contributions:

0.5% constant term & 0.5% neutron recoil uncertainty


Triangle modules, ~14,300 PMTs ~72%

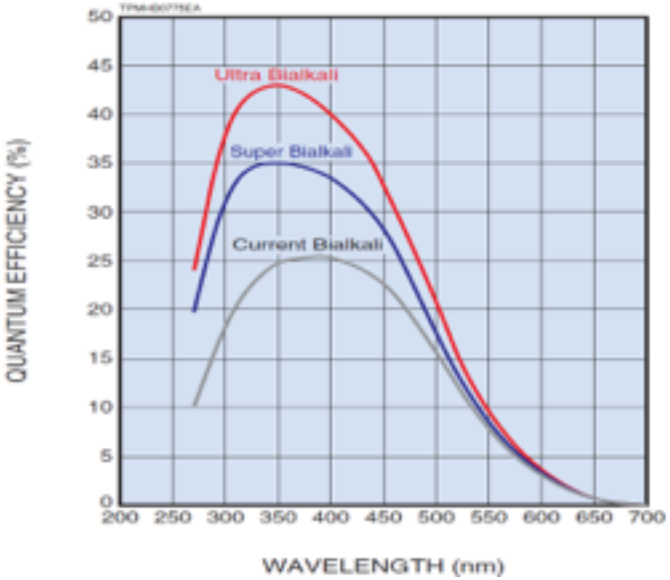

~14,000 PMTs, ~74%. Can be improved to ~83% if fill 2,600 PMTs at gaps


Latitude/longitude design, ~15,000 PMTs, ~77%

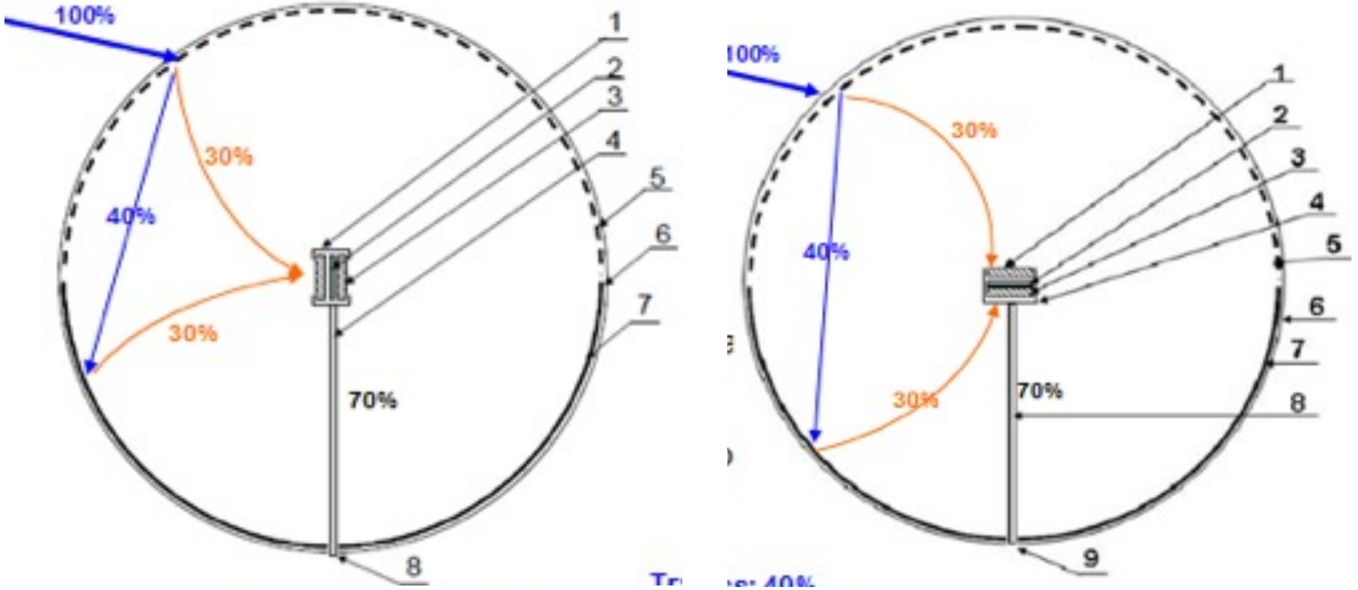

Volleyball, ~15,000 PMTs, ~78%

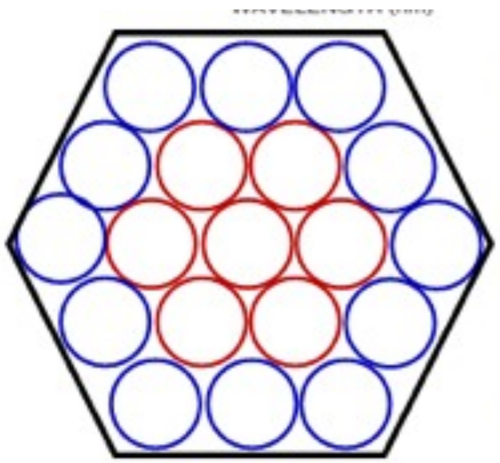
More Photoelectrons-- PMT

SBA photocatode



New type of PMT: MCP-PMT



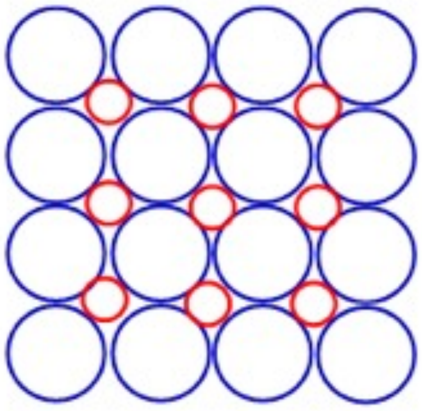


No clearance:

coverage 86.5%

1cm clearance:

coverage: 83%

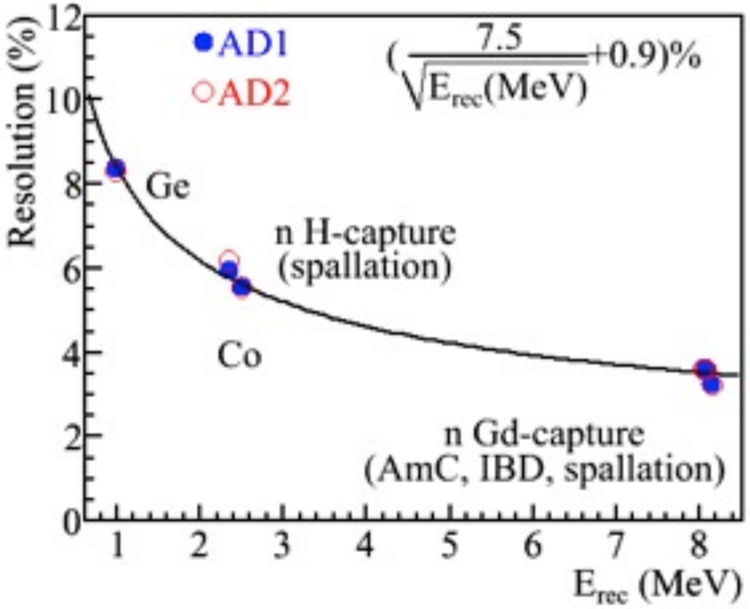


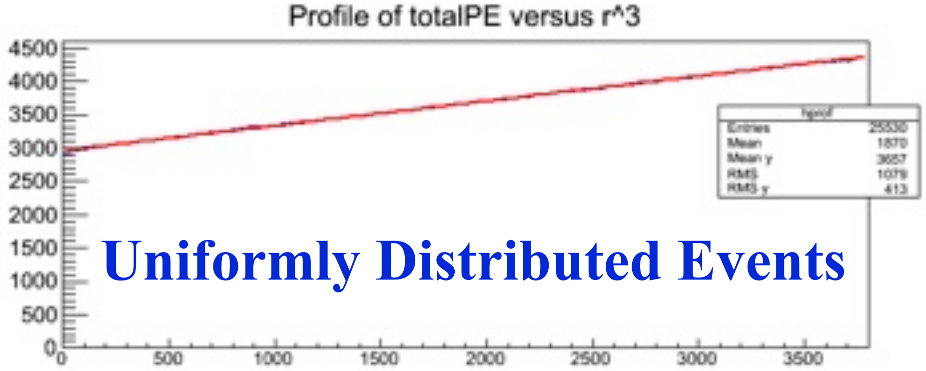
20" + 8" PMT

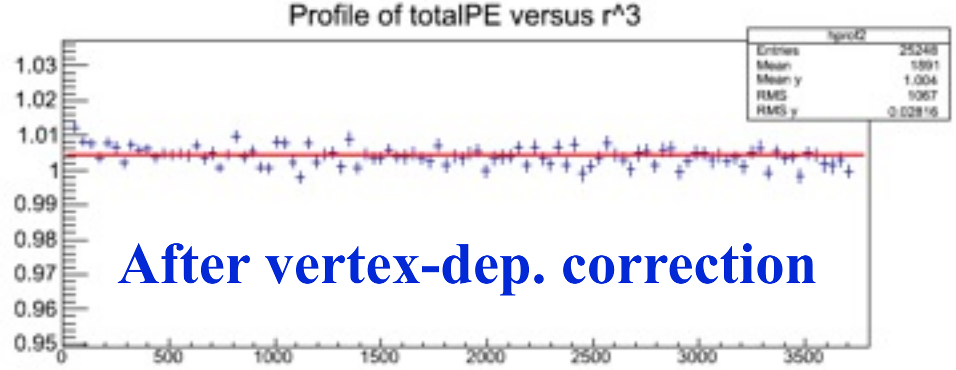
8" PMT for better timing(vertex)

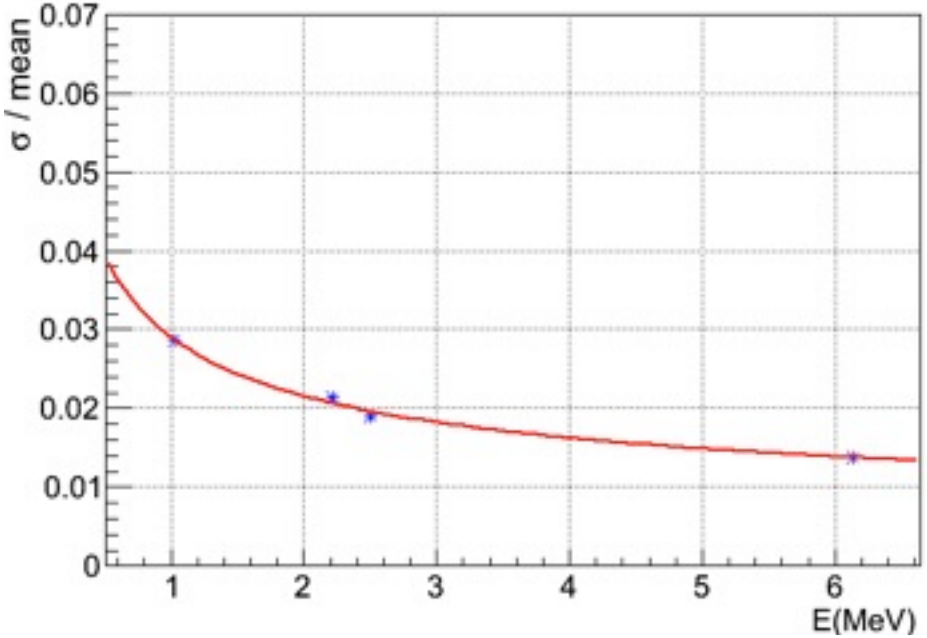
MC example：Energy Resolution

- **JUNO MC, based on DYB MC (tuned to data), except**
  - ⇨ JUNO 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 24m + Raleigh scattering 40 m
    - ✓ to 20 m = absorption 40 m + Raleigh scattering 40m



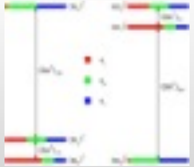






$3.0\%/\sqrt{E}$, or $(2.6/\sqrt{E}+0.3)\%$

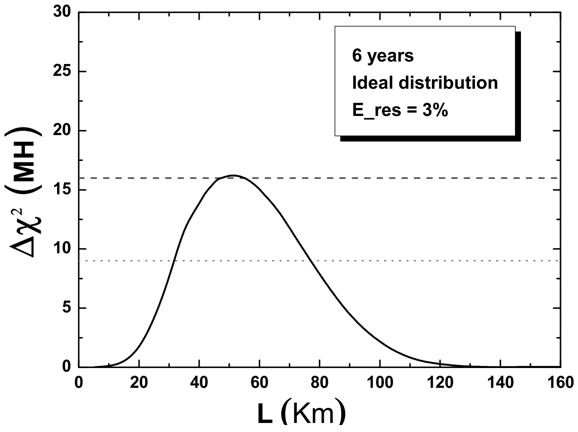
Sensitivity Prediction of JUNO

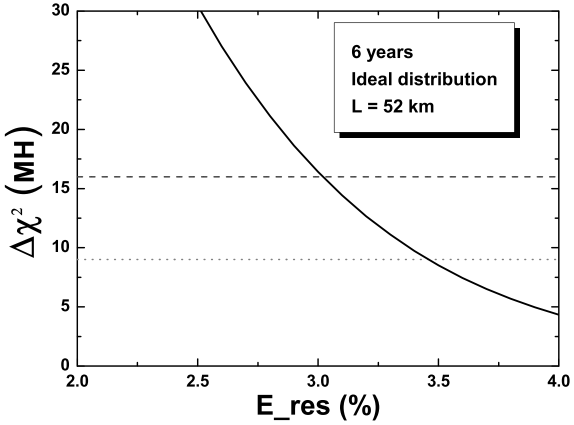


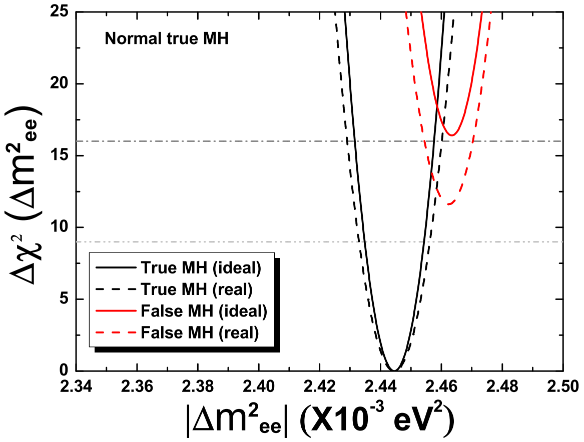
Chi-square analysis to fit the Asimov data generated assuming true MH

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

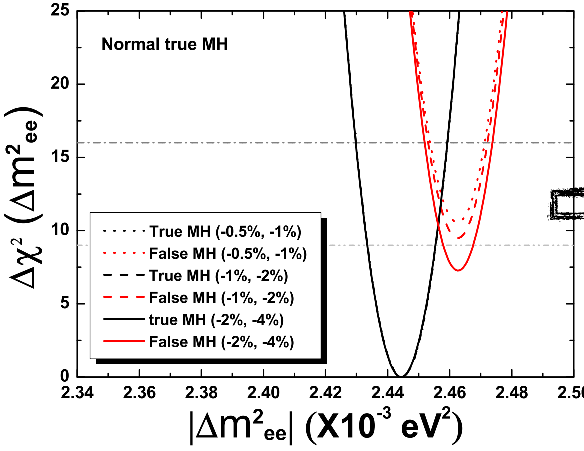
$$\Delta\chi^2_{\rm MH} = |\chi^2_{\rm min}({\rm N}) - \chi^2_{\rm min}({\rm I})|$$



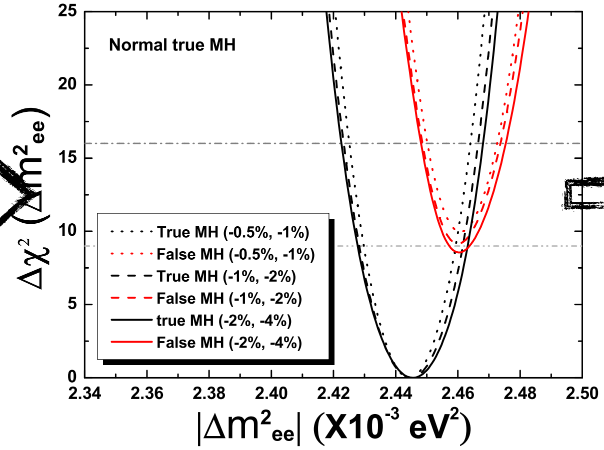




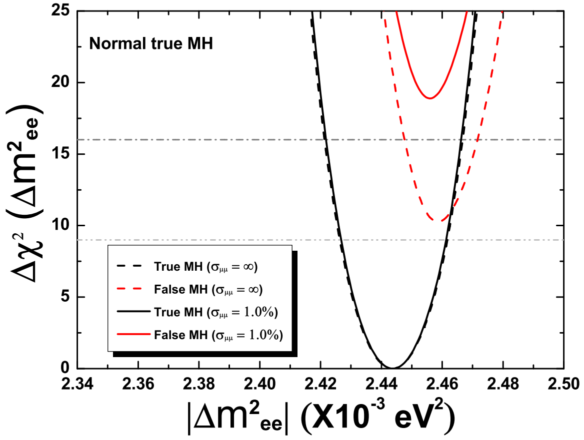
With non-linearity residual



With energy self-correction

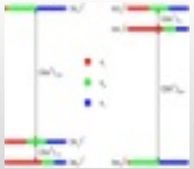


With 1% $\Delta m^2_{\mu\mu}$ *prior*

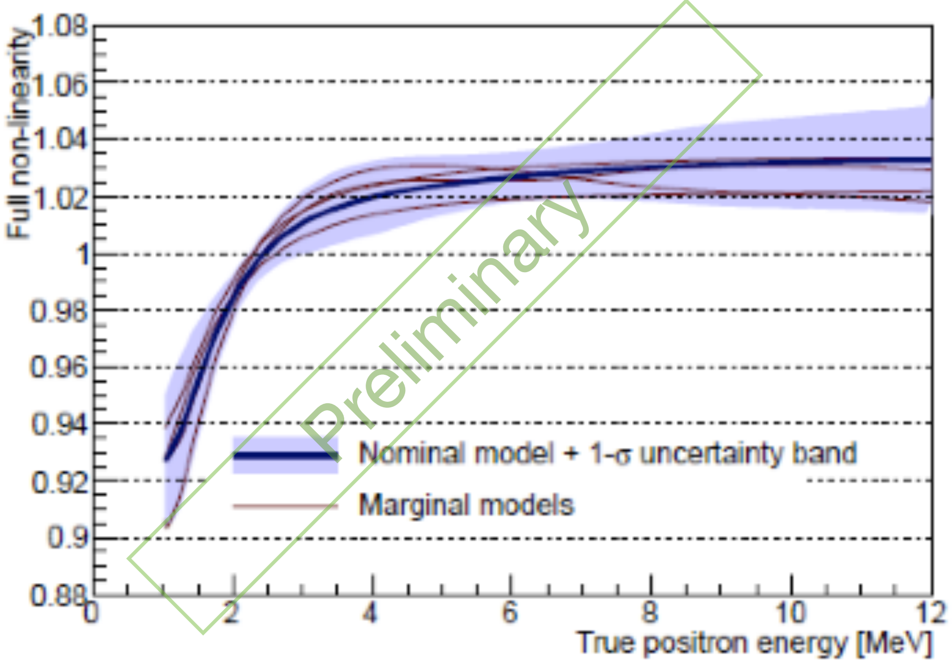


Y.F. Li et al, arXiv:1303.6733

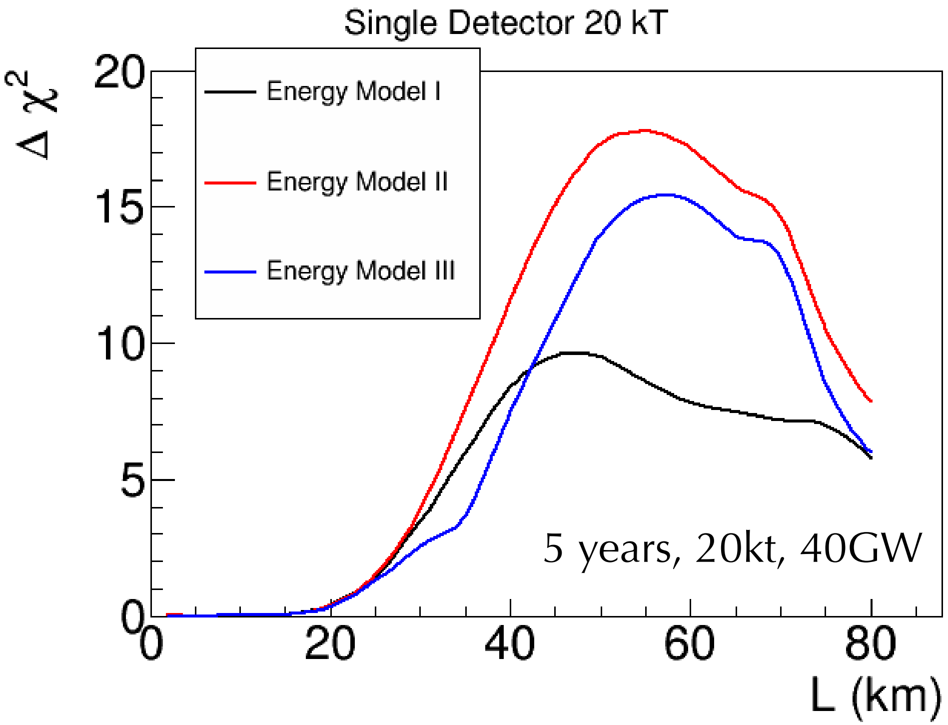
Cross Check using Daya Bay Energy Model



Cross checks by X. Qian

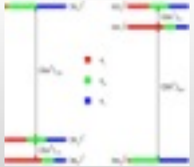


- Daya Bay has released a preliminary energy model by weighting multiple models
  - The functional format has certain degrees of flexibility
  - The overall uncertainty is conservative
- Also includes backgrounds and reactor spectrum energy correlations

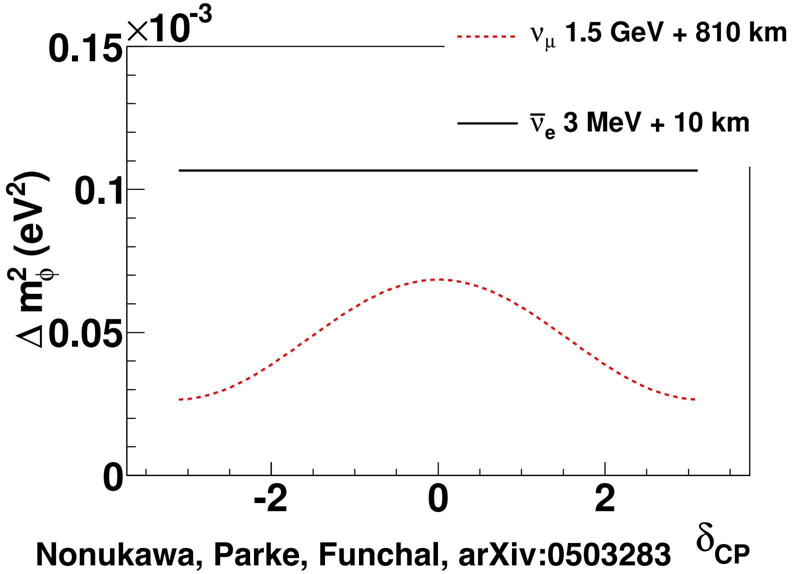


- Model I: degeneracy model
- Model II: linear energy model
- Model III: the Daya Bay model

What Can Further Improve the Sensitivity?



- We see that if future $\Delta m^2_{\mu\mu}$ measurement could be improved to ~1%, the sensitivity can be improved significantly. (NOvA? PINGU?)
- Reactor flux uncertainty improvements can also improve the uncertainty (FRM-4? Daya Bay?)
- Dual detector can improve the sensitivity if assume fully correlation energy model (Money?)
- Energy scale improvements are always effective (smart/thorough calibration systems)



Nonukawa, Parke, Funchal, arXiv:0503283
Q. Xin et al, arXiv:1208.1551

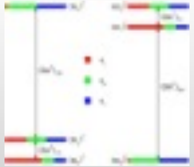
2nd detector and energy scale

2nd Detector	$\Delta\chi^2$	$\Delta\chi^2$ ($\sigma_{scale}/4$)
20kt at 53km	4.2	14.3
0.1kt at 2km	4.9	11.5
5kt at 30km	10.3	13.6

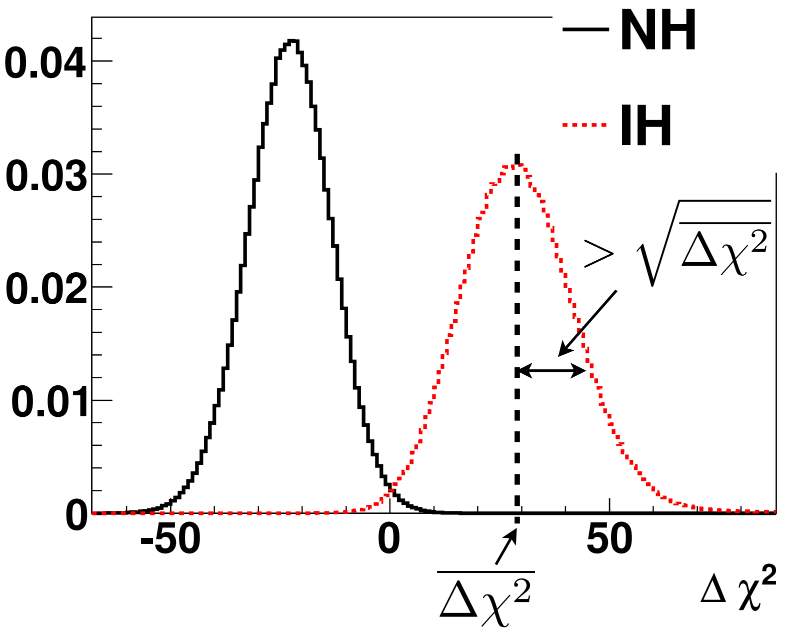
Improving Reactor Flux Uncertainty

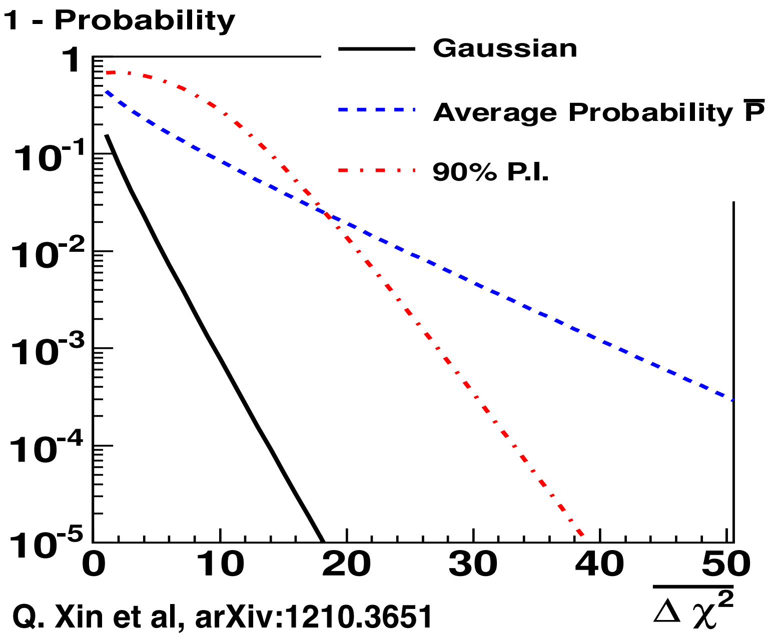
Uncertainty improvement	$\Delta\chi^2$ (Model I)	$\Delta\chi^2$ (Model II)	$\Delta\chi^2$ (Model III)
Current ~3%	9.5	17.3	13.9
Factor 2	11.5	21.7	18.4
Factor 3	12.1	23.2	19.9
Factor 4	12.4	23.8	20.5
Factor 5	12.6	24.1	20.9

Sensitivity of MH Experiments



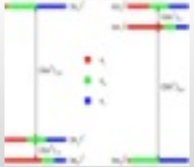
- A common practice to show the quality of proposed/designed experiments is to use the delta chi-square method using the so-called Asimov data set.
  - It is meant to evaluate the performance of the most probable or the median experimental results without any statistical fluctuation.
  - We quote the squared root of the delta chi-square as the confidence interval in unit of sigma, which is based on Wilks' Theorem.
  - Not proper for the mass hierarchy case due to its discrete nature. The median sensitivity (Asimov dataset) is reduced by half if counted in unit of sigma's for the reactor MH sensitive. (Other types of experiments, if signal has no large amount of statistics should check with MC)





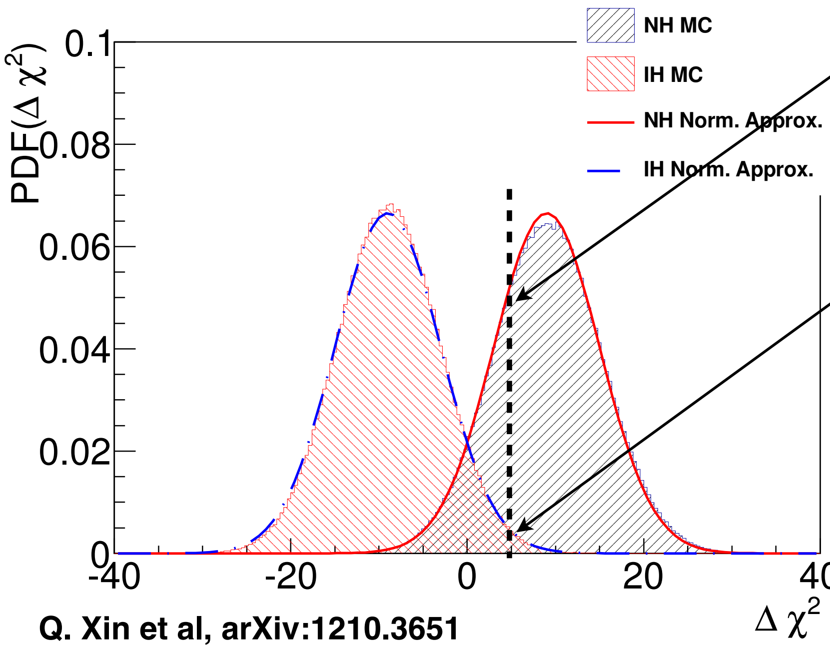
Q. Xin et al, arXiv:1210.3651

Confidence Interval using Discriminator PDFs



- The neutrino mass hierarchy measurement is basically a model comparison case, or hypothesis test.
- Not complete if evaluating sensitivity only based on the sign of delta chi-square from Asimov dataset.
- We suggest a confidence interval setting method using discriminator PDFs. (This method has been effectively used in **L. Zhan et al., PRD79(2009)073007** based on Monte Carlo)

$$P(NH|\Delta\chi^2) = \frac{P(\Delta\chi^2|NH)\cdot P(NH)}{P(\Delta\chi^2)} = \frac{P(\Delta\chi^2|NH)}{P(\Delta\chi^2|NH)+P(\Delta\chi^2|IH)} = \frac{1}{1+e^{-\Delta\chi^2/2}}$$



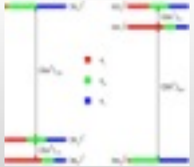
Q. Xin et al, arXiv:1210.3651

NOTE:

- The left example here is a 2-value binomial case, close to the reactor mass hierarchy resolution, sufficient to illustrate key points
  - Sensitivity, now confidence level, is between the square root value and the >0 probability value.
- To be accurate, one should do complete MC to obtain PDFs like in **L. Zhan et al., PRD79(2009)073007.**

See also: G. Cowen et al arXiv:1007.1727

RENO-50 (Based on RENO-50 Workshop)

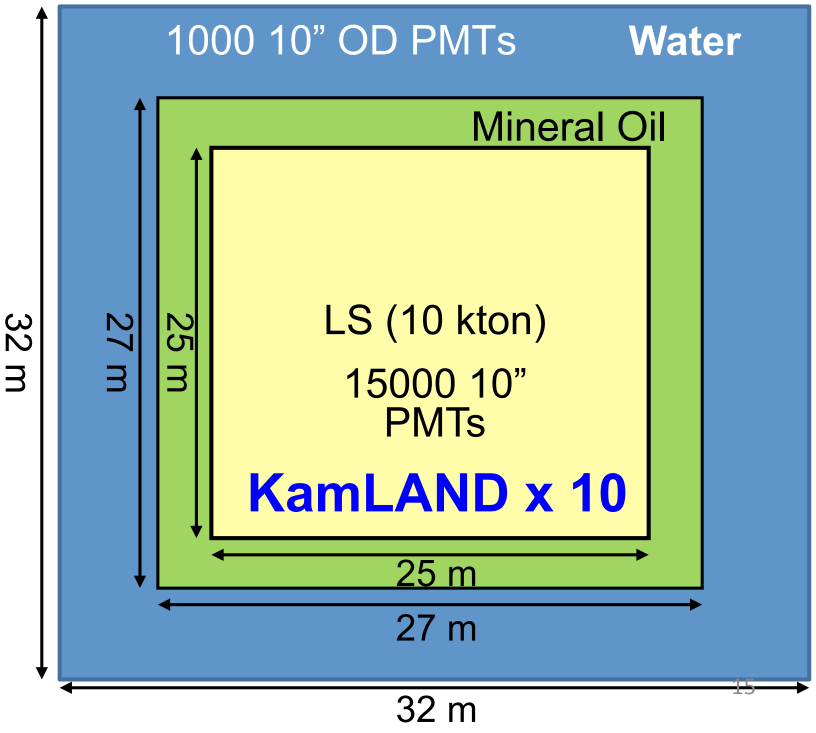


- Utilizing the current 6 RENO reactors
- Baseline ~47km
- Target mass 10kt
- Cylinder-shaped detector

➡ Simulation resolution is ~6% at 1MeV

➡ Need to improve photoelectrons

RENO-50 (default)



1000 10” OD PMTs

Water

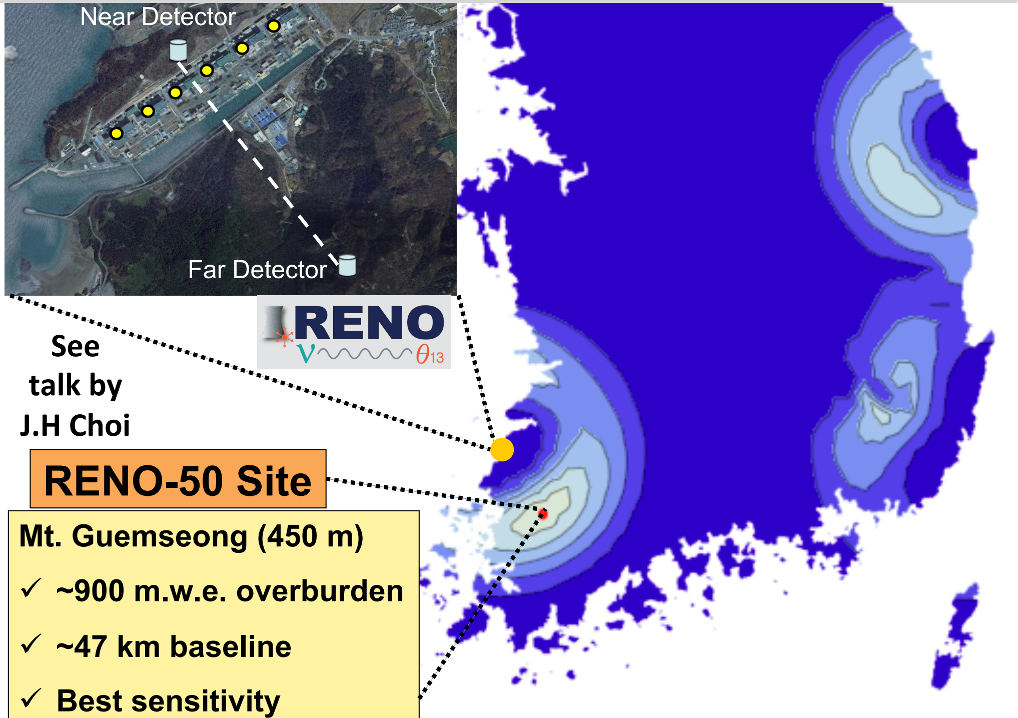
Mineral Oil

LS (10 kton)

15000 10” PMTs

KamLAND x 10

RENO-50 Workshop

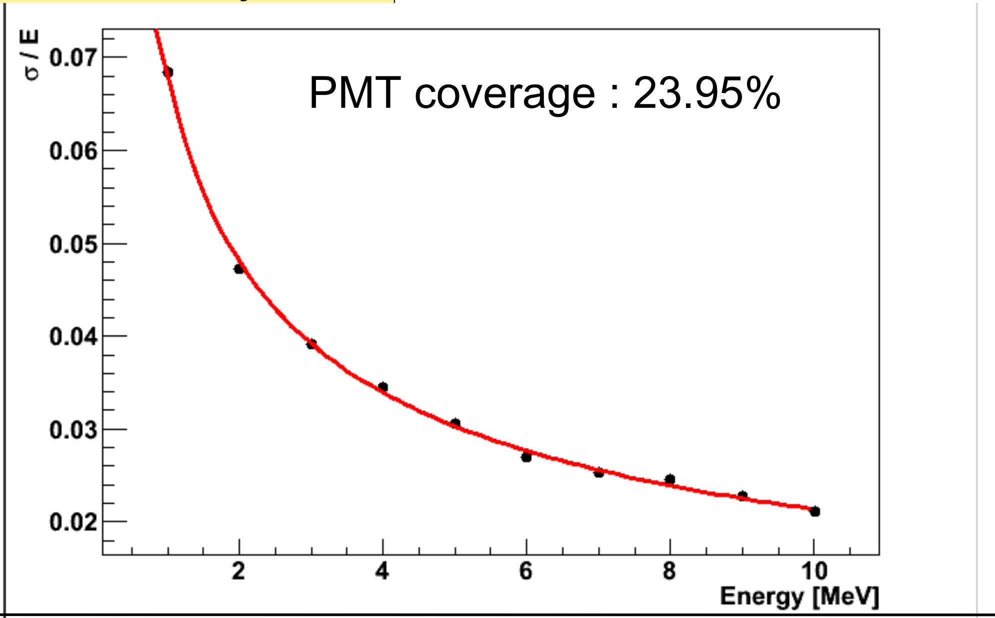


See talk by J.H Choi

RENO-50 Site

Mt. Guemseong (450 m)

- ✓ **~900 m.w.e. overburden**
- ✓ **~47 km baseline**
- ✓ **Best sensitivity**



Improve the optical properties

1. Increase the attenuation length of Liquid Scintillator.
   - 1.5 times current value : 18.7m @ 430 nm
   - 2.0 times current value : 24.9m @ 430 nm

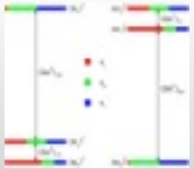
2. Increase the PMT Quantum Efficiencies.
   - 1.25 times current value : 30.0% @ 427 nm
   - 1.5 times current value : 36.0% @ 427 nm

3. Increase the PMT coverage.
   - 25000 PMTs : 40.86 % coverage

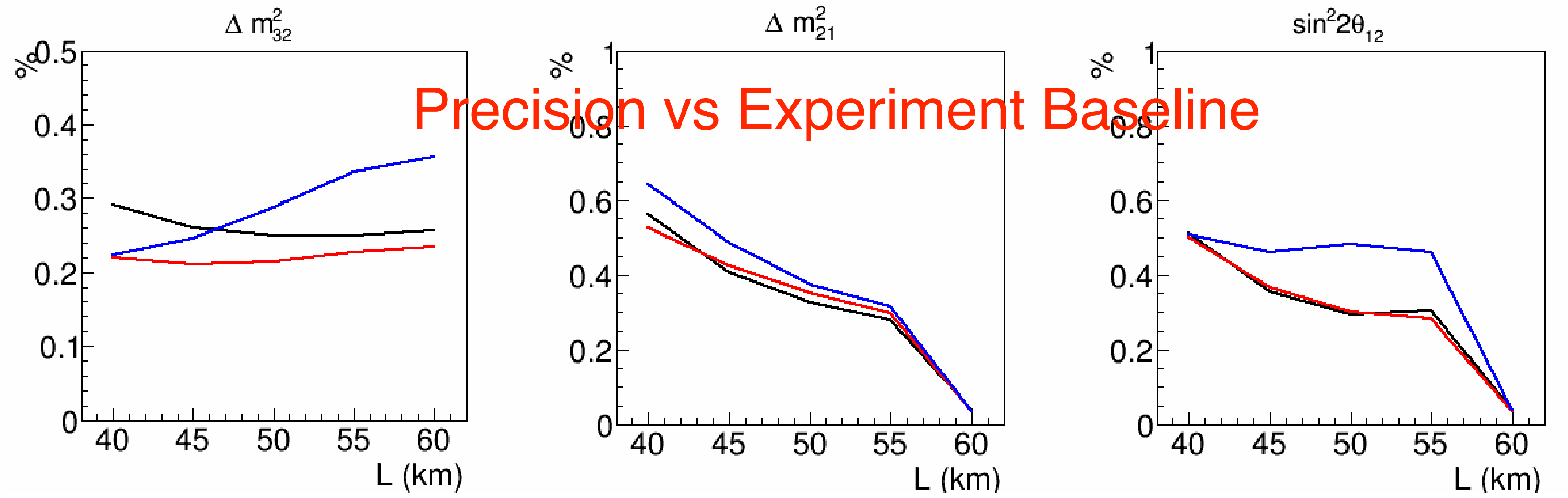
Cf) Default value
- 24% PMT coverage
- Att.length of LS is 12.4m @ 430 nm
- PMT QE is 24% @ 427 nm

Jungsic Park, RENO-50 Workshop

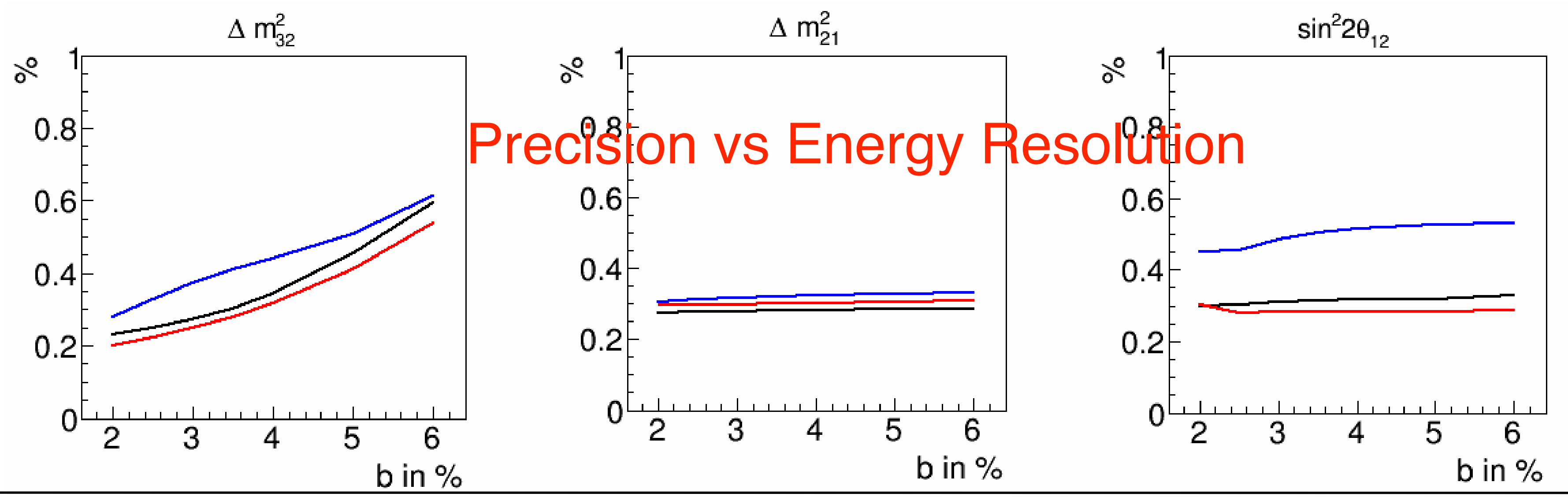
Precision Measurements Warranted



- If the JUNO detector performance could reach designed goals, our cross check shows the sub-percent level precision measurements are less sensitive to the energy scale uncertainty and warranted --> enable a future ~1% level PMNS unitarity test



Precision vs Experiment Baseline



Precision vs Energy Resolution

Overall Schedule of JUNO

2013

Complete conceptual design, complete civil design, & bidding

2014

Start civil construction, complete prototyping (PMT & detector)

2015

PMT production line manufacturing

2016

Start PMT production, start detector production or bidding

2017

Complete civil construction, start detector construction & assembly

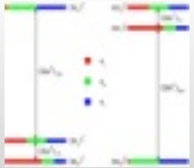
2018

Start LS production

2019

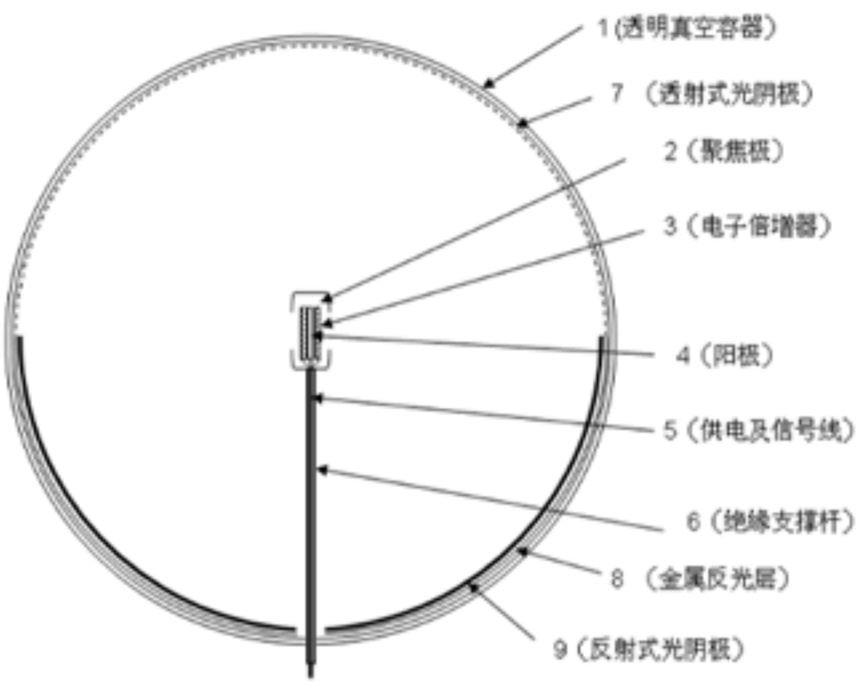
Complete detector assembly & installation, & LS filling

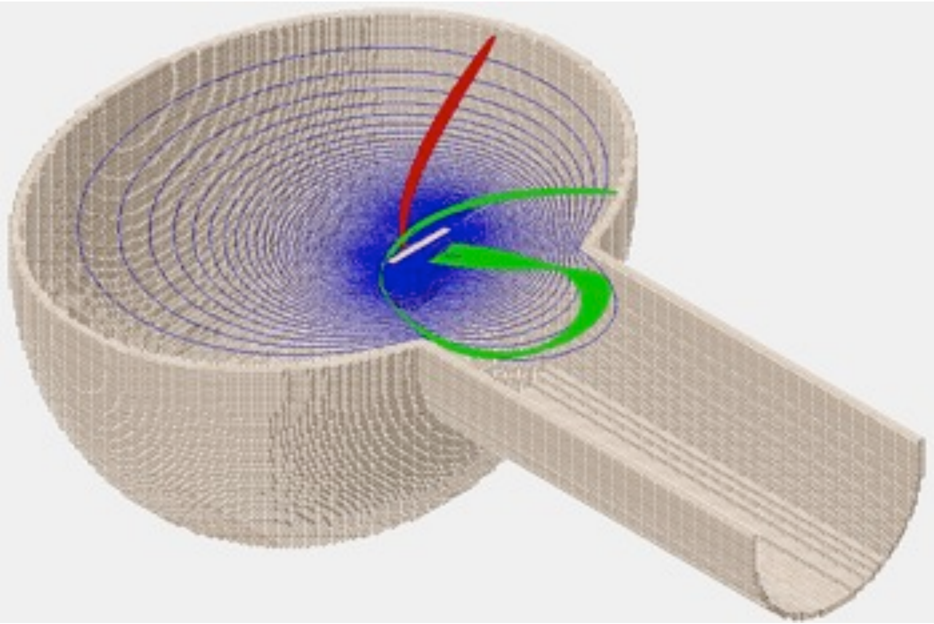
Summary and Conclusion



- The mass hierarchy information is definitely in the survival spectrum of reactor antineutrinos (optimized baseline: ~60km)
- To resolve the mass hierarchy, medium-baseline reactor experiments face unprecedented challenges
  - Energy resolution <3%/√E
  - Energy scale uncertainty needs to be controlled <1%
  - No "sabotage" reactors
  - Statistics
- The statistical case of determining mass hierarchy is different from quantities whose measurements can be approximated by normal distributions.
  - Subtleties in the sensitivity evaluation using chi-square difference approach.
- There are other valuable physics topics: sub-percent precision measurements and PMNS matrix unitarity test are the leading ones; proton decay is competitive for Kaon channel if time response is good
- **A case definitely worth pursuing!**

A new type of PMT: higher photon detection eff.





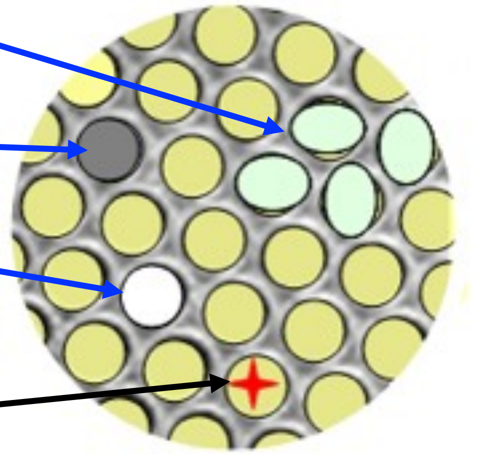
- Top: transmitted photocathode
- Bottom: reflective photocathode

  additional QE: ~80%*40%
- MCP to replace Dynodes ➔ no blocking of photons

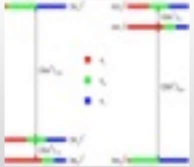
~ ×2 improvement

Low cost MCP by accepting the following:

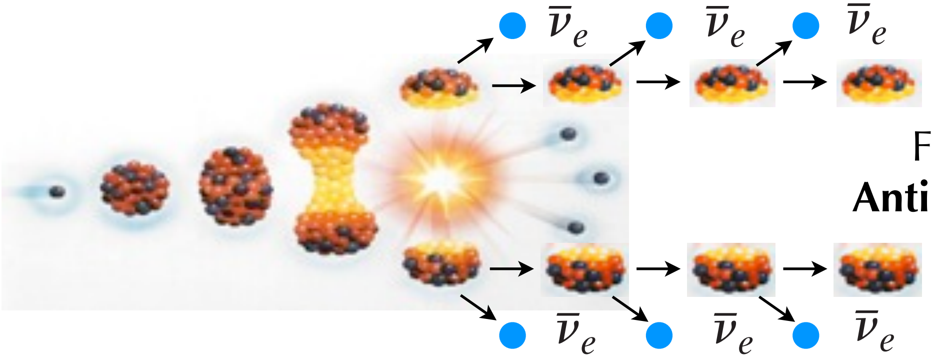
1. asymmetric surface;
2. Blind channels;
3. Non-uniform gains
4. Flashing channels



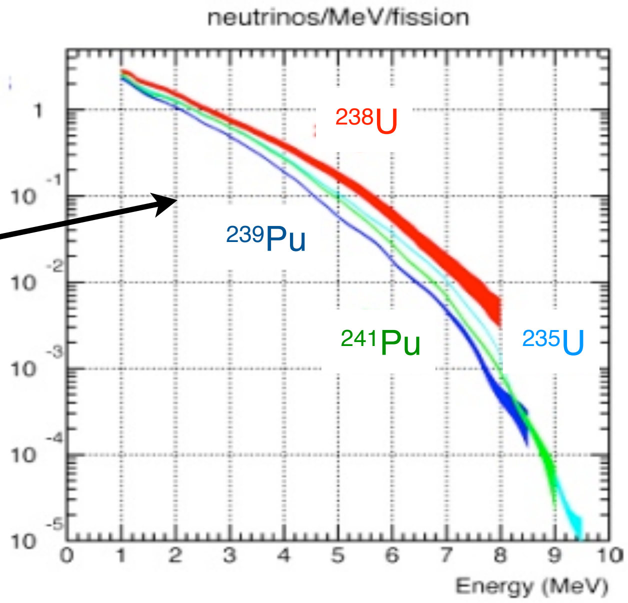
Nuclear Reactors as Antineutrino Sources



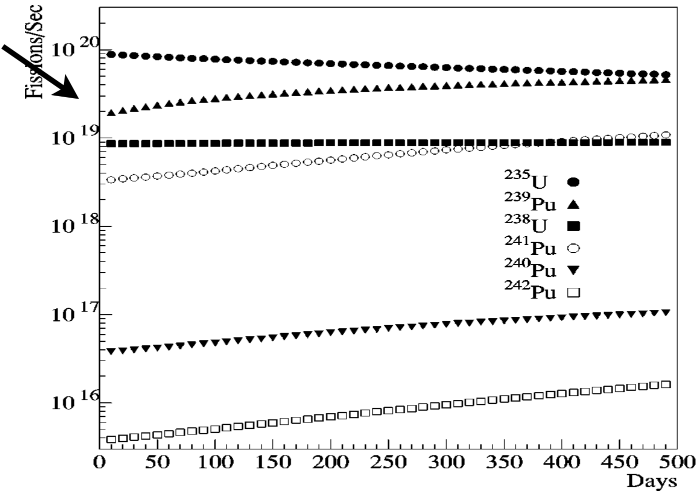
Fission fragments beta decay release antineutrinos



Fission Isotope
Antineutrino Spectra



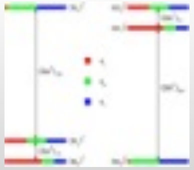
Fission Fractions

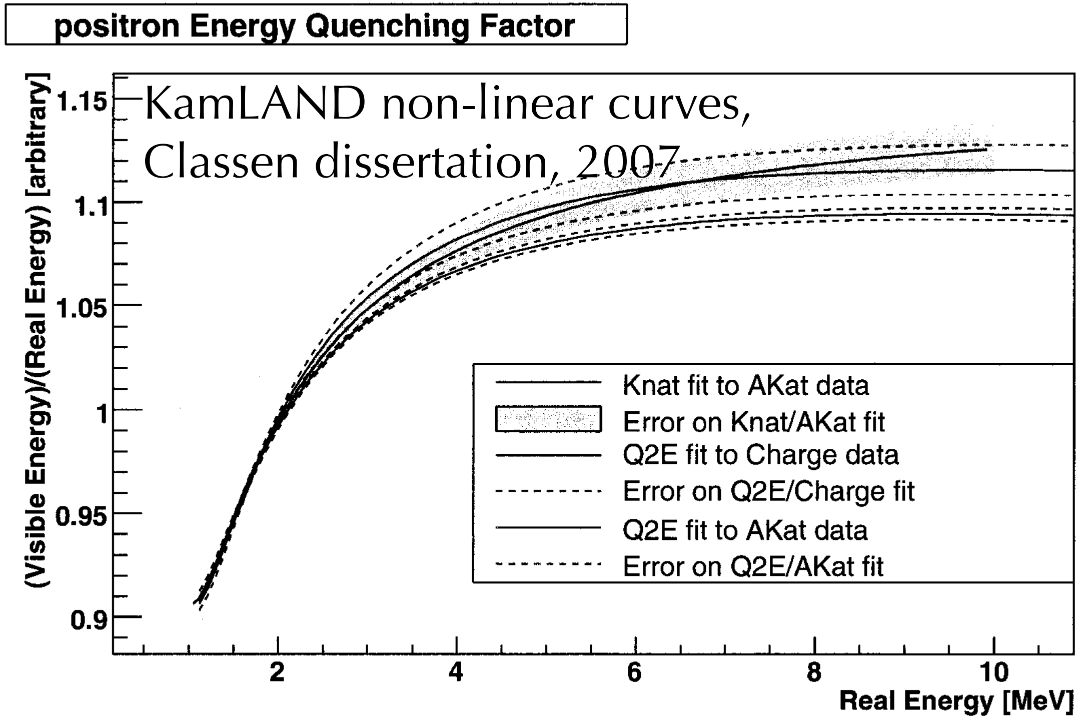


- ~6 antineutrinos released per fission
- ~200 MeV **Energy Released per Fission, e_i**
- 4 dominant fission isotopes: ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu, >99.9%
  - **Fission Fractions, f_i/F**, of each isotope evolves as the reactor “burns”. Fractions are simulated using both commercial and open source reactor core simulation programs.
  - **Antineutrino Spectra, S_i**, are converted based on the electron spectra of ^{235}U, ^{239}Pu, ^{241}Pu measured at Grenoble in 80’s by Feilitzsch et al. ^{238}U antineutrino spectrum is calculated by Vogel et al.
- **Thermal Power, W_{th}**, through reactor monitoring

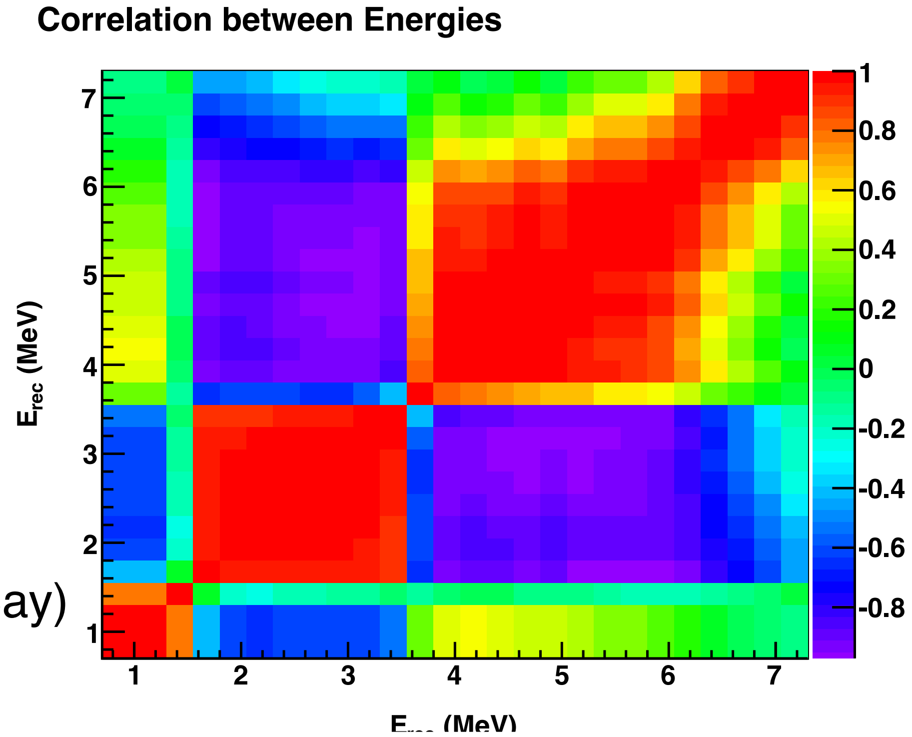
$$S(E_\nu) = \frac{W_{th}}{\sum_i (f_i/F) e_i} \sum_i^{istopes} (f_i/F) S_i(E_\nu)$$

Useful Energy Scale References



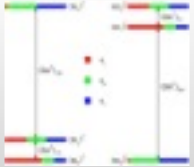


KamLAND non-linear curves,
Classen dissertation, 2007



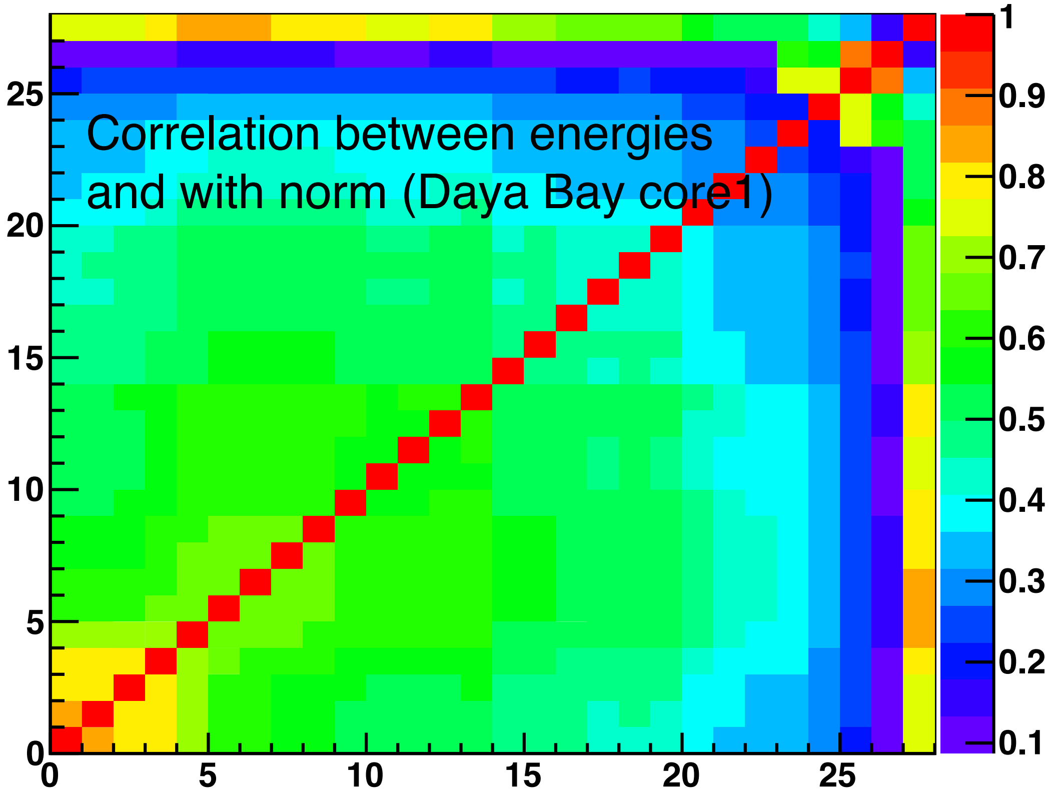
Correlation between energies
caused by energy model (Daya Bay)

Reactors and Reactor Flux References

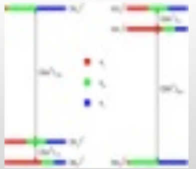


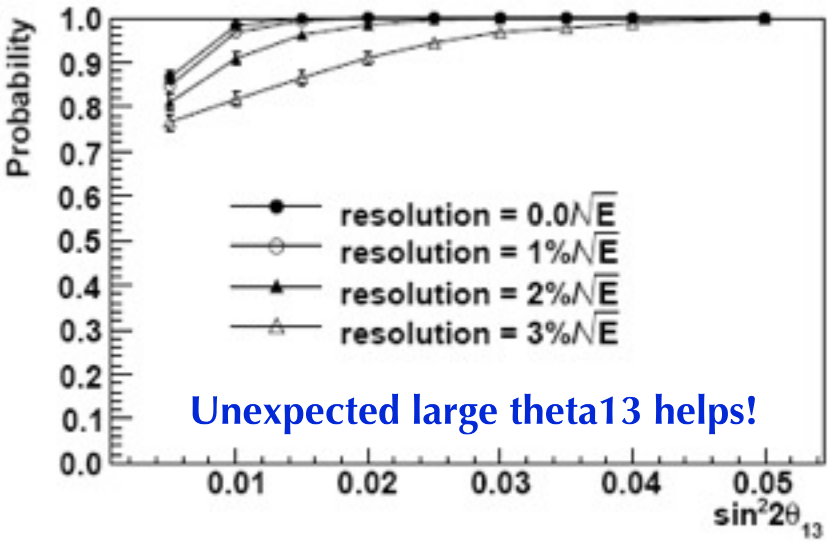
Y.F. Li et al, arXiv:1303.6733 (JUNO core baselines)

Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline(km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline(km)	52.76	52.63	52.32	52.20	215	265

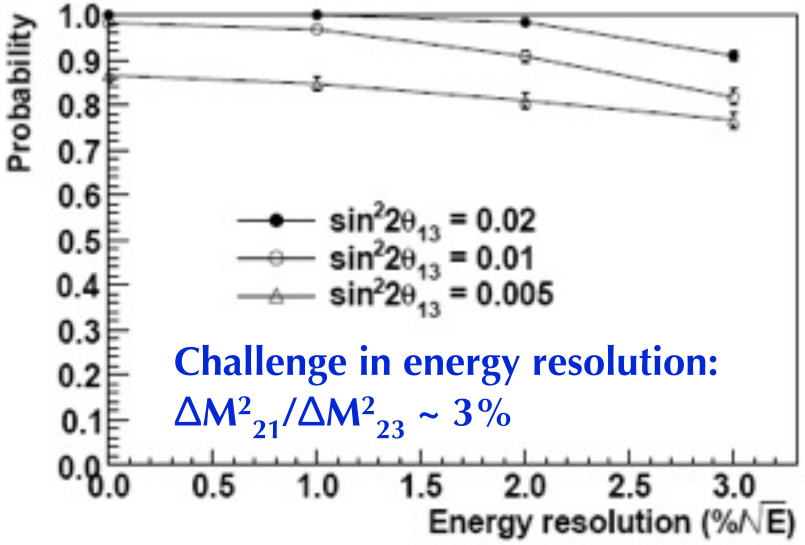


Expected Sensitivities and Challenges



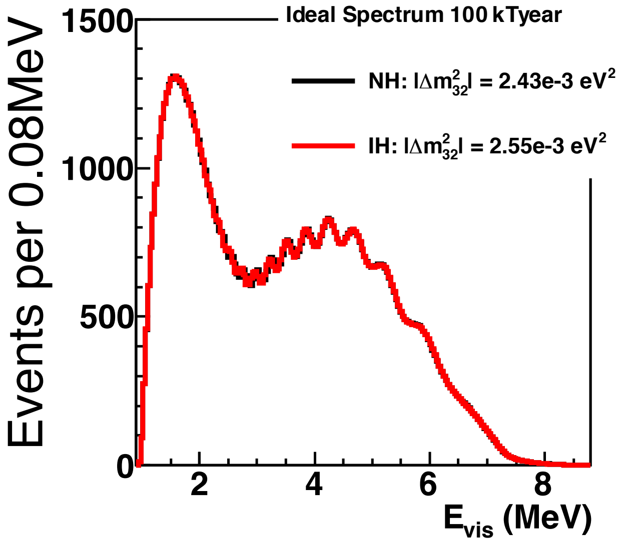


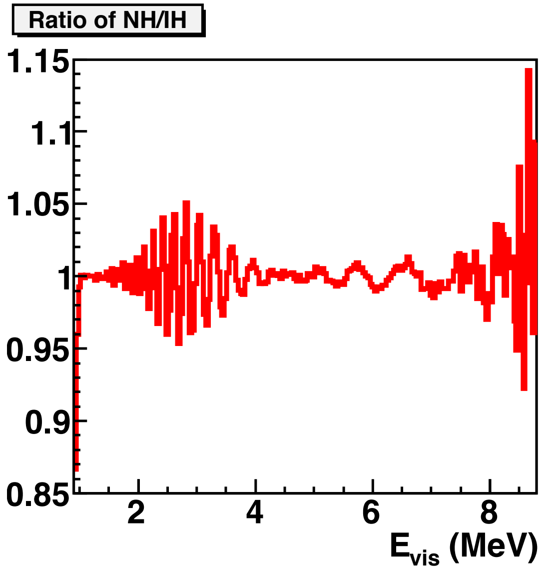
Unexpected large theta13 helps!



Challenge in energy resolution: $\Delta M^2_{21}/\Delta M^2_{23} \sim 3\%$

L. Zhan, et al, Phys.Rev.D79:073007, 2009





X. Qian et al, arXiv:1208.1551

- Energy resolution is a challenge due to the ratio of $\Delta M^2_{21}/\Delta M^2_{23}$, ~3%.
- The current uncertainty in ΔM^2_{23} leads to challenges in energy scale. The oscillation is driven by,

$$\cos\left(\frac{\Delta m^2_{32}L}{2E} \pm \phi(\theta_{12}, \Delta m^2_{21}, L, E)\right)$$

Uncertainties in energy scale must be small enough so the normal and inverted hierarchies have different spectra, ~1-2% based on arXiv: 1208.1551