



*IUPAP Young Scientist Award*

# Exploring neutrino puzzles

$\theta_{13}$ ,  $\Delta m_{31} > 0?$ ,  $\nu = \bar{\nu}?$

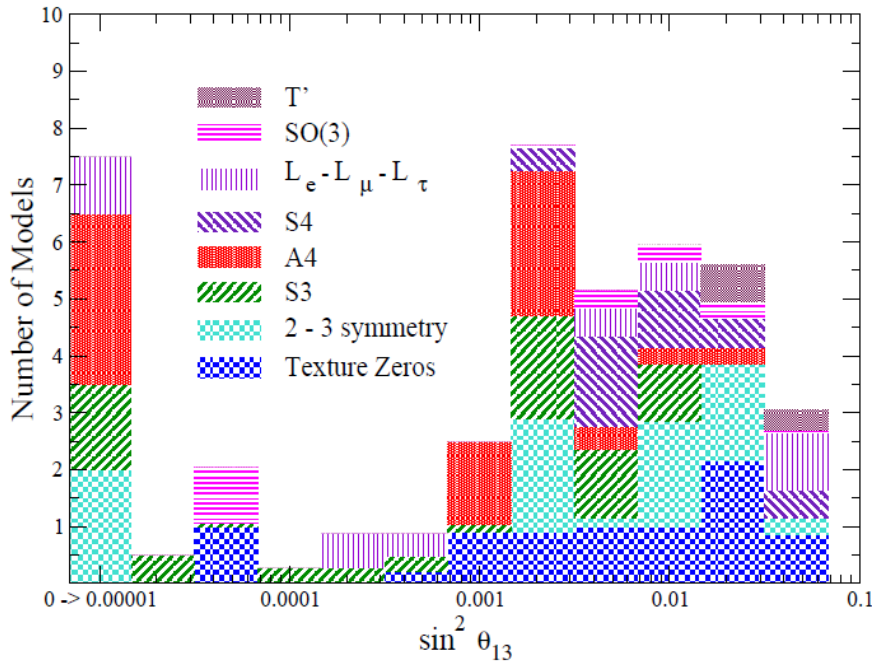
Liangjian Wen



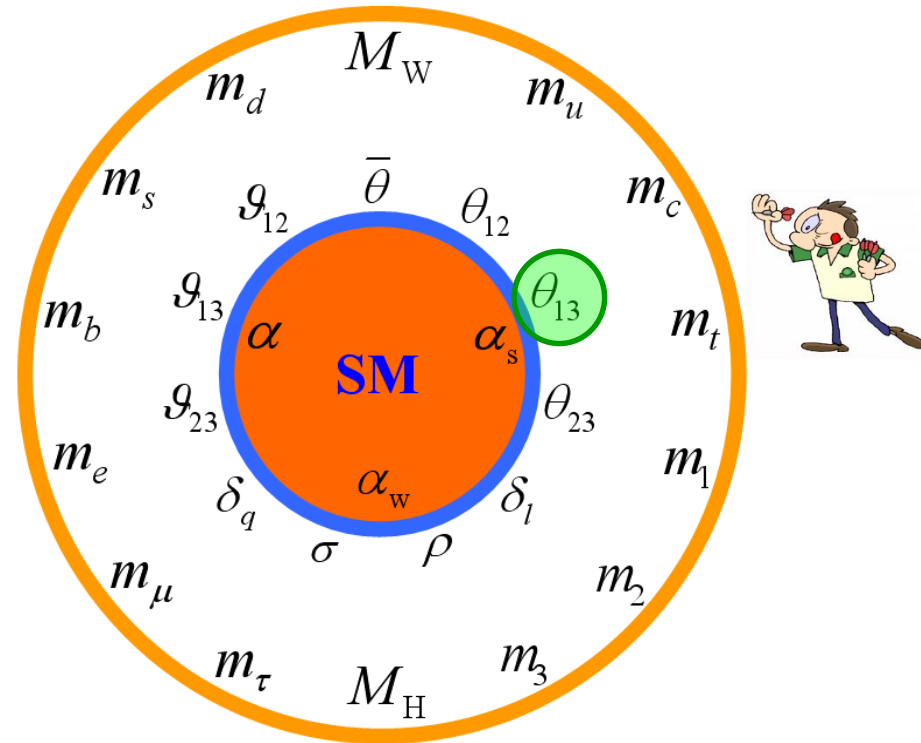
中国科学院高能物理研究所  
Institute of High Energy Physics Chinese Academy of Sciences

# $\theta_{13}$

- A fundamental parameter of lepton flavor physics
- Gateway to measure leptonic CP violation
- Very sensitive model/theory discriminator

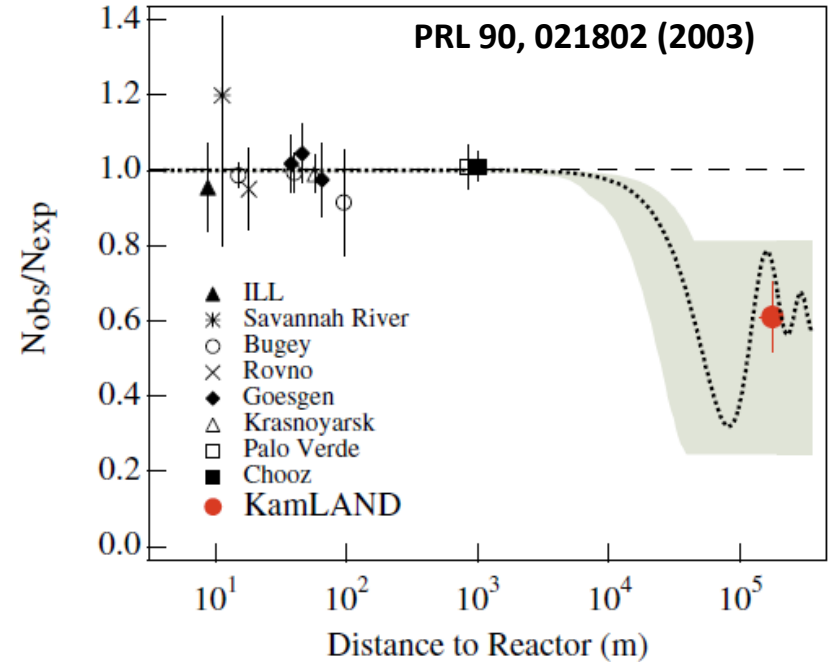
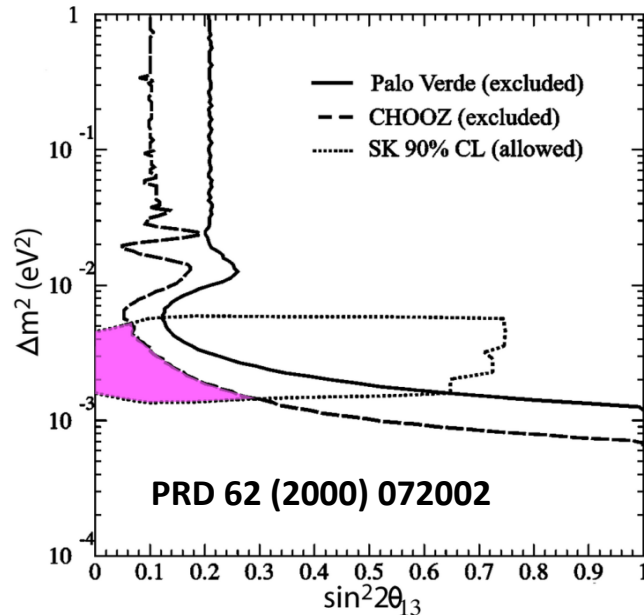


C.H. Albright: arXiv:0911.2437



Fritzsch-Xing Plot

# A little history of $\bar{\nu}_e$ disappearance ...



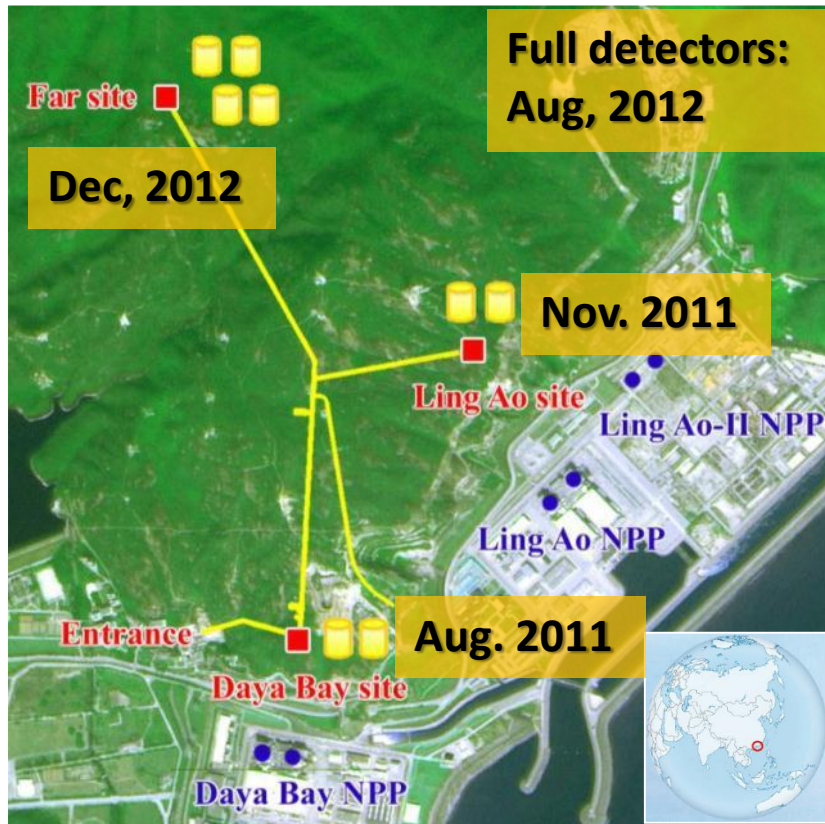
## Precision of early Reactor experiments (3-6%):

- Reactor power:  $\sim 1\%$
- $\nu$  spectrum:  $\sim 0.3\%$
- Fission rate:  $\sim 2\%$
- Target mass:  $\sim 1-2\%$
- Backgrounds:  $\sim 1-3\%$
- Efficiency:  $\sim 2-3\%$

**Near-far relative measurement was proposed** (Mikaelyan and Sinev, hep-ex/9908047) to reduce the uncertainties from reactor and detector

# Observation of $\bar{\nu}_e$ disappearance at Daya Bay

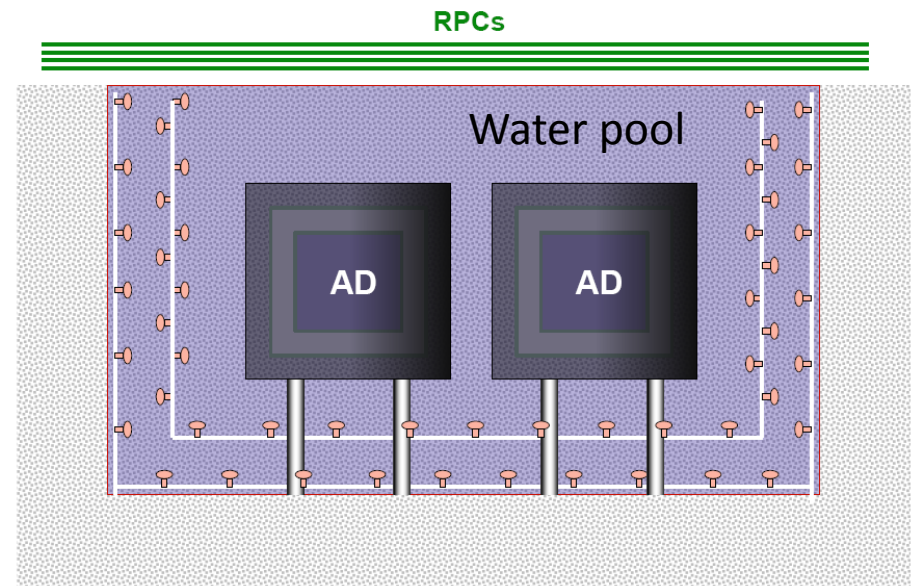
# Daya Bay Experiment



Design sens. :  $\sin^2 2\theta_{13} \sim 0.01$  (90% CL)

→ rapid obs. of  $\bar{\nu}_e$  disappearance

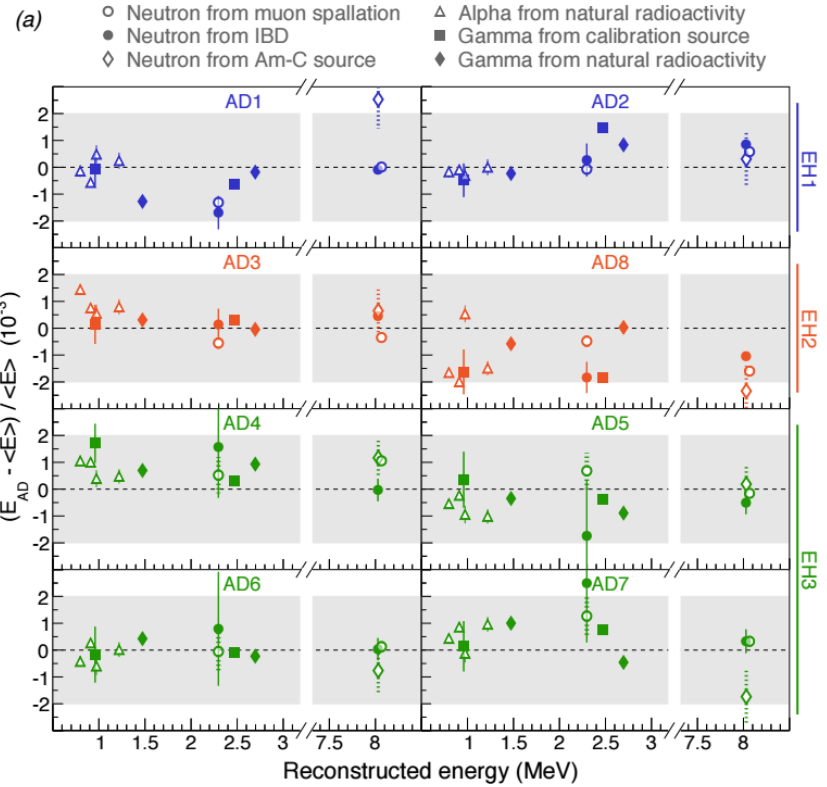
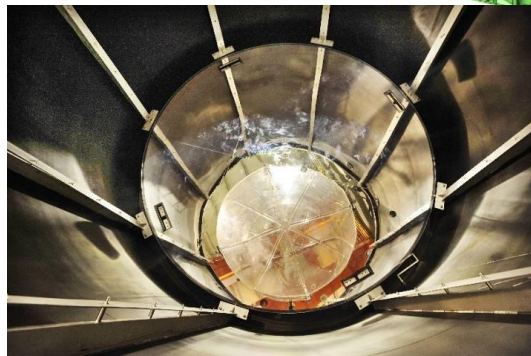
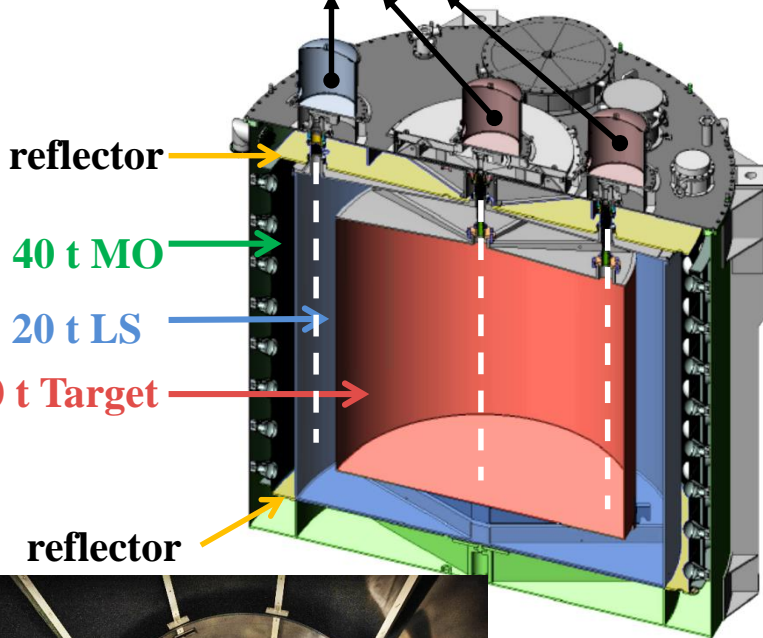
→ precision measurements of  $\theta_{13}$



- Luminosity : 1400 ton·GW (5-20 times of DC and RENO)
- Close to mountains → enough shielding
- Featured design → side-by-side calibration (2-4 ADs at each site) → actual relative detector error:  $0.2\%/\sqrt{N}$  (design value: 0.38%)

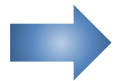
# Energy Calibration

## Automated Calibration Units (ACU)



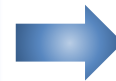
**The relative energy scale uncertainty < 0.2%**

**PMT gain calibration**  
(dark noise, LED)



**Energy Rec.**

- calibration Sources
- spallation neutrons



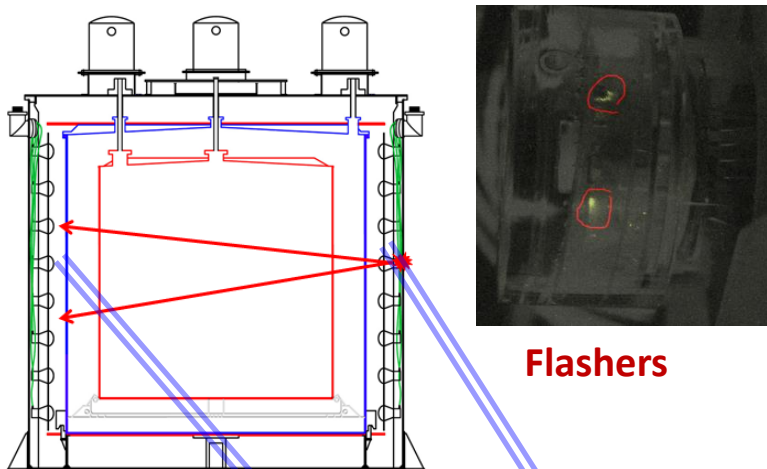
**Relative Energy Scale**

- $^{68}\text{Ge}$ ,  $^{60}\text{Co}$ ,  $^{241}\text{Am}$ - $^{13}\text{C}$
- **Neutrons (IBD, spallation)**
- Special sources
- Natural radioactivity

# Instrumental background: PMT Flasher

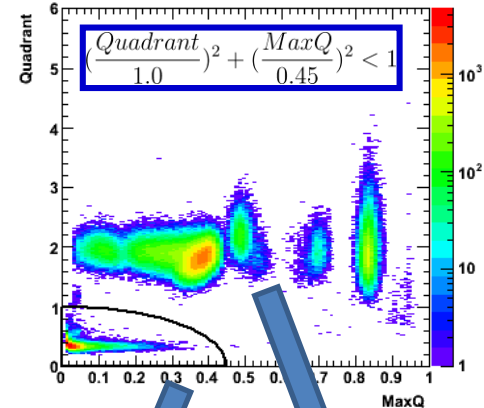
Common phenomena in the past large neutrino experiments (KamLAND, Super-K, Borexino, SNO), caused by discharge on dynodes or bases. **Not easy to efficiently reject at that time** → Turn off the problematic PMT

**A highly-efficient flasher cut developed for DYB: ~100% eff., 0.01% error**

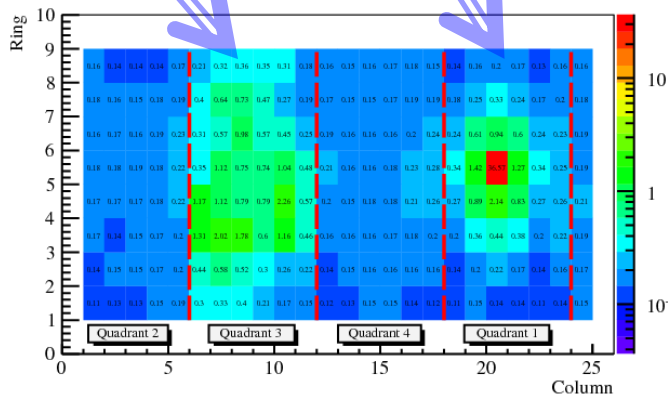
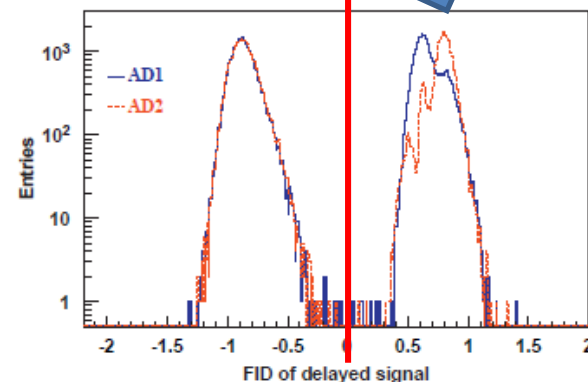


Flashers

(5MeV, 12MeV) region



Signal Flasher



# $^8\text{He}/^9\text{Li}$ background

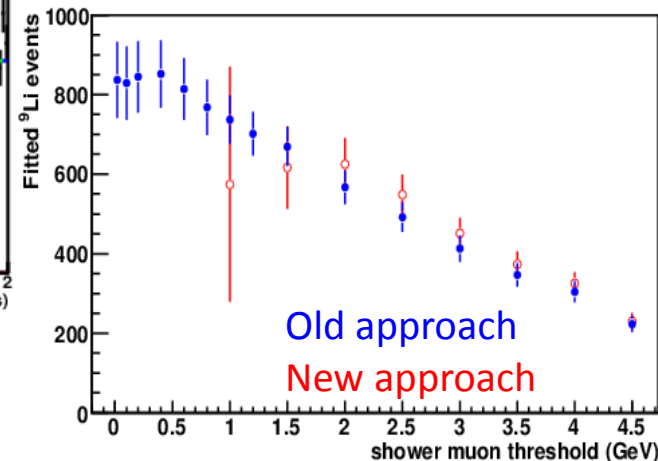
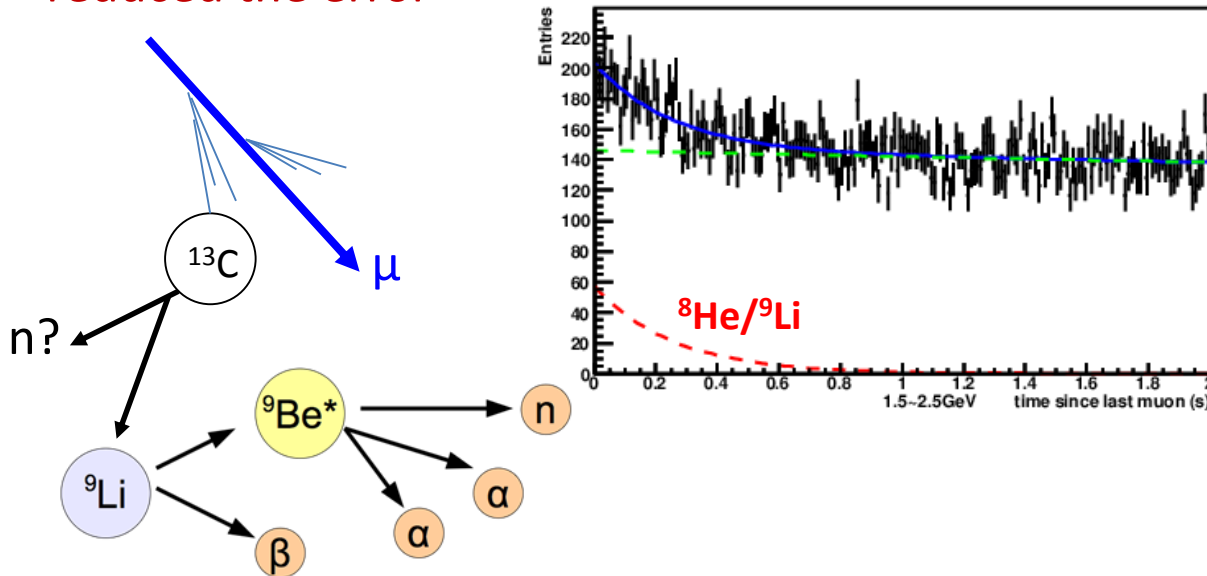
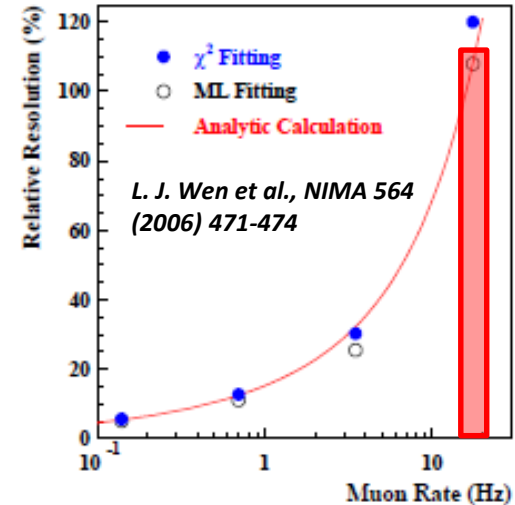
**$^8\text{He}/^9\text{Li}$  dominates the background uncertainty**

**Classical method:** time-since-last-muon fit

**Difficulty:** large error when muon rate is high, impossible to estimate the Li9 production yield for muons that have low energy deposition

**My Guess:**  $^8\text{He}/^9\text{Li}$  production accompanied with neutron  
 → reduce the rate of muon sample

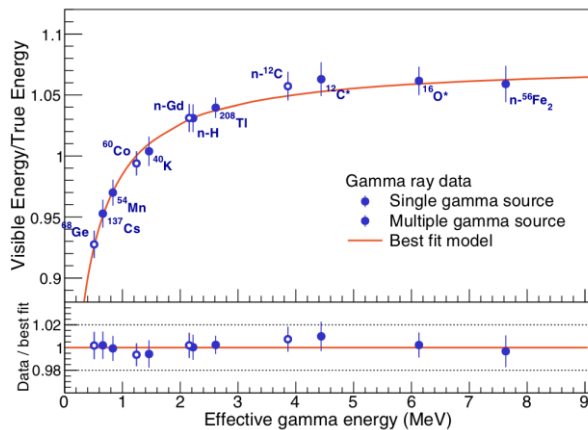
**Result:** successful data-driven test and significantly reduced the error



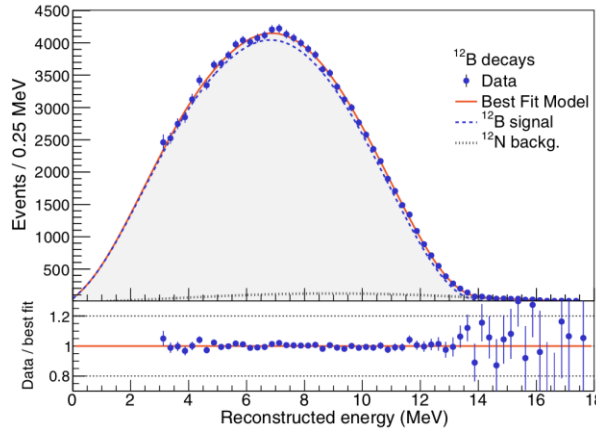
**$\beta$ -n emitter: muon spallation on Carbon nuclei**

# Detector energy response model

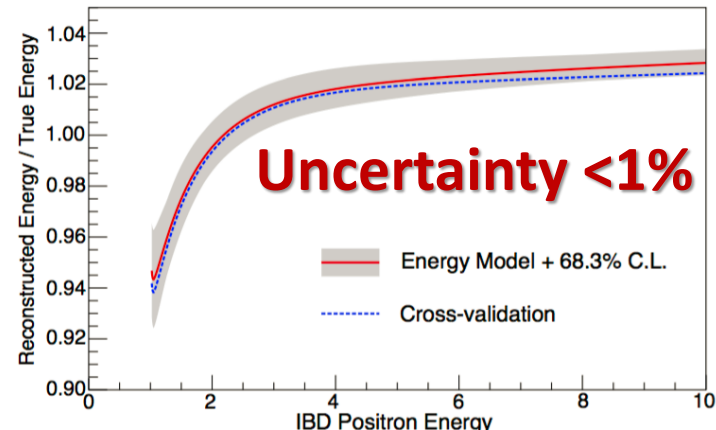
- Non-linear energy response in Liquid scintillator
  - Quenching (known as Birks' law) and Cerenkov (particle-, E- dep.)
  - Electronics (E- dep, modeled based on MC and single channel FADC measurement)
- Energy model: fit to various gamma lines and  $^{12}\text{B}$  beta-decay spectrum
- Validated with
  - $^{208}\text{Th}$ ,  $^{212}\text{Bi}$ ,  $^{214}\text{Bi}$  beta-decay spectrum; Michel electron
  - Bench tests of Compton scattering electrons in LS



gamma



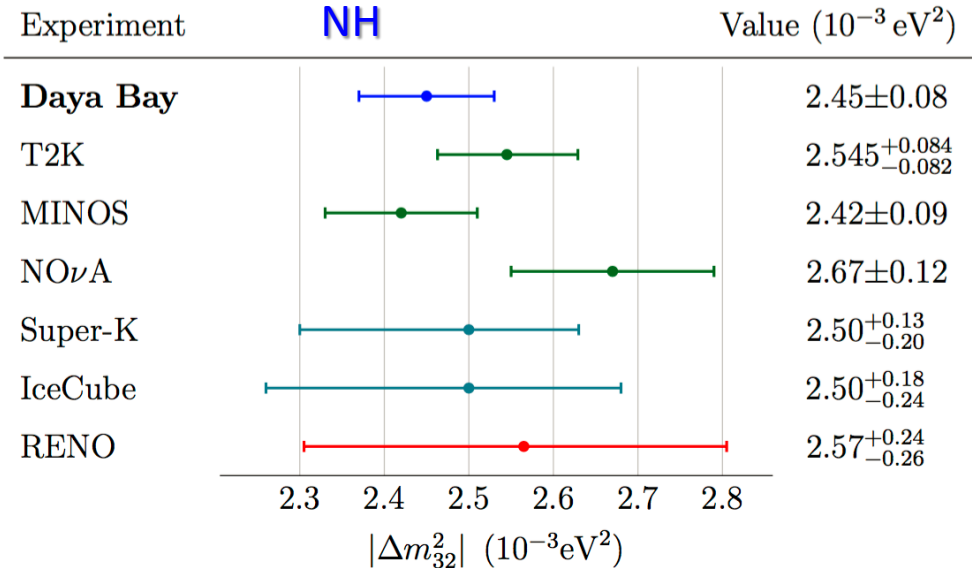
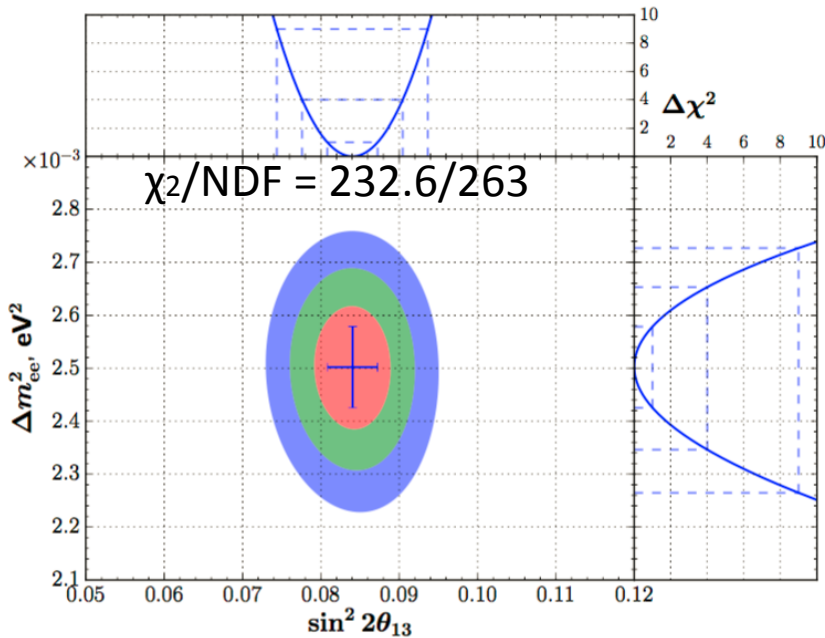
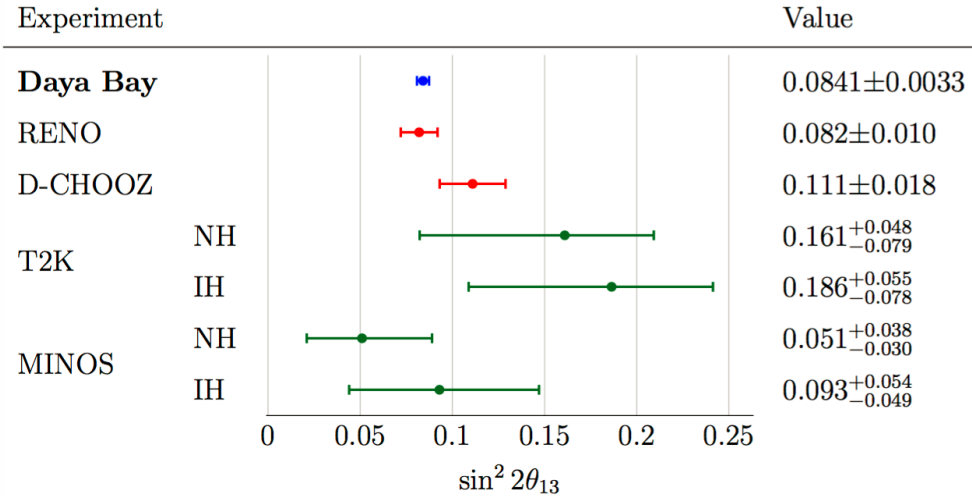
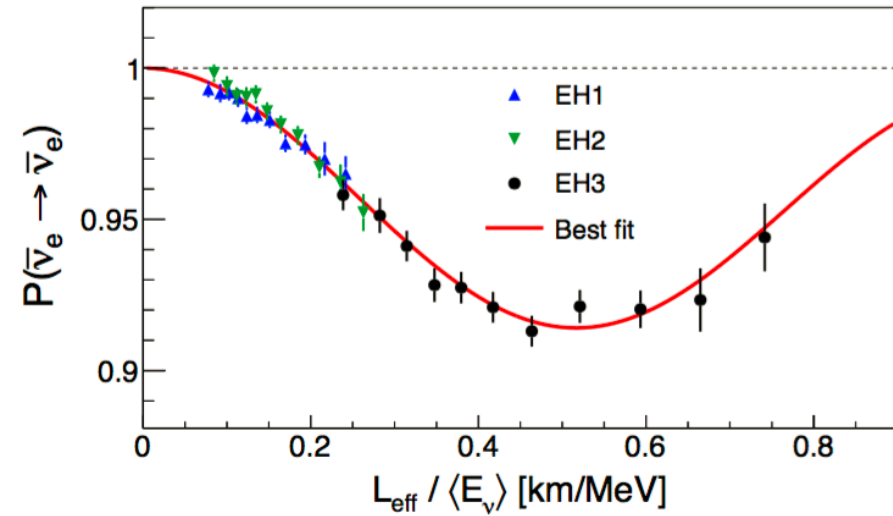
electron



positron

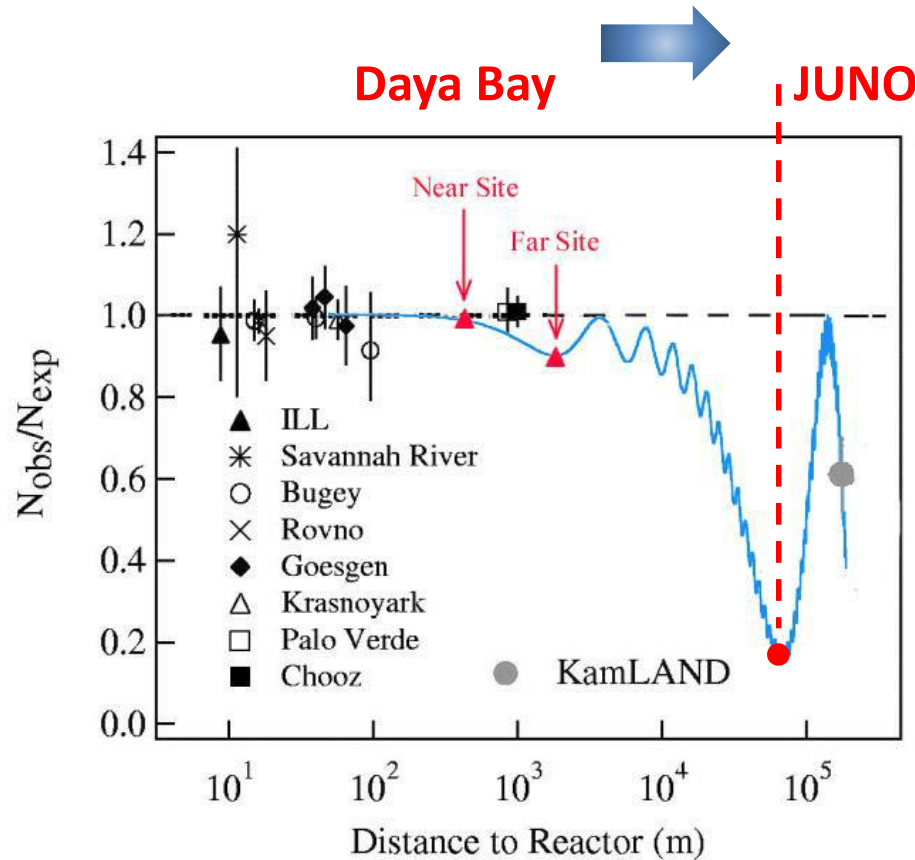
Experience on DYB energy model is valuable to JUNO (similar LS).

# From discovery to precision measurement



See talk by Jiajie Ling, and DYB posters

# Exploring $\nu$ mass ordering (NMO)



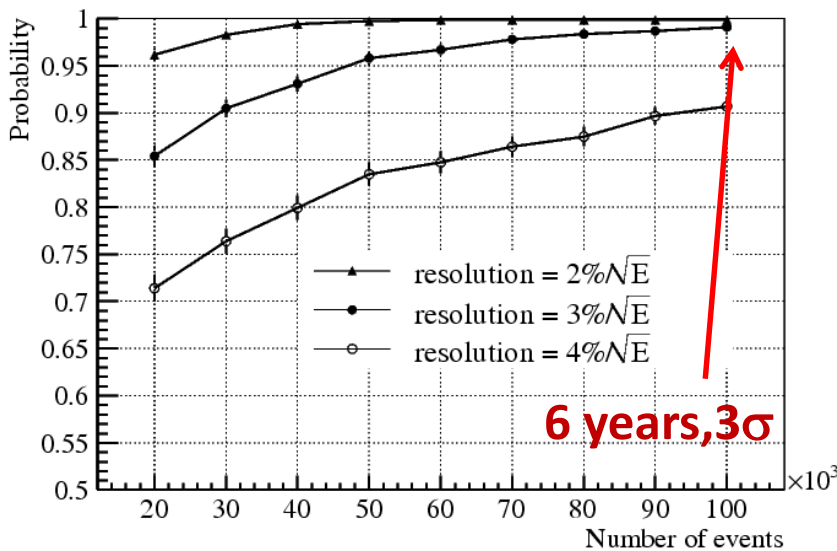
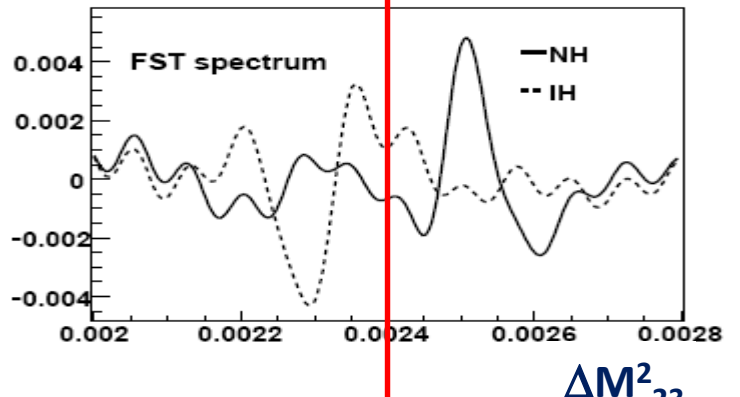
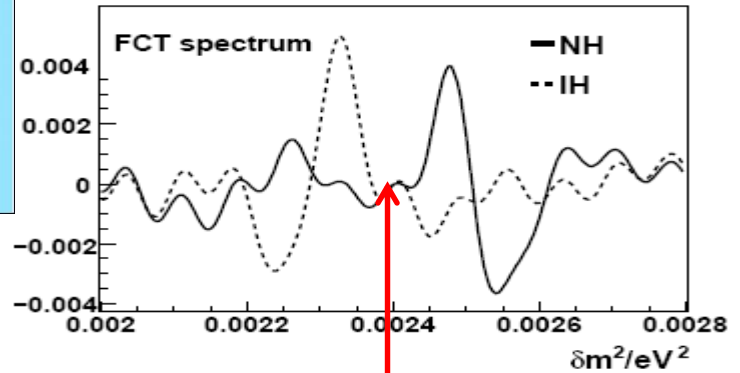
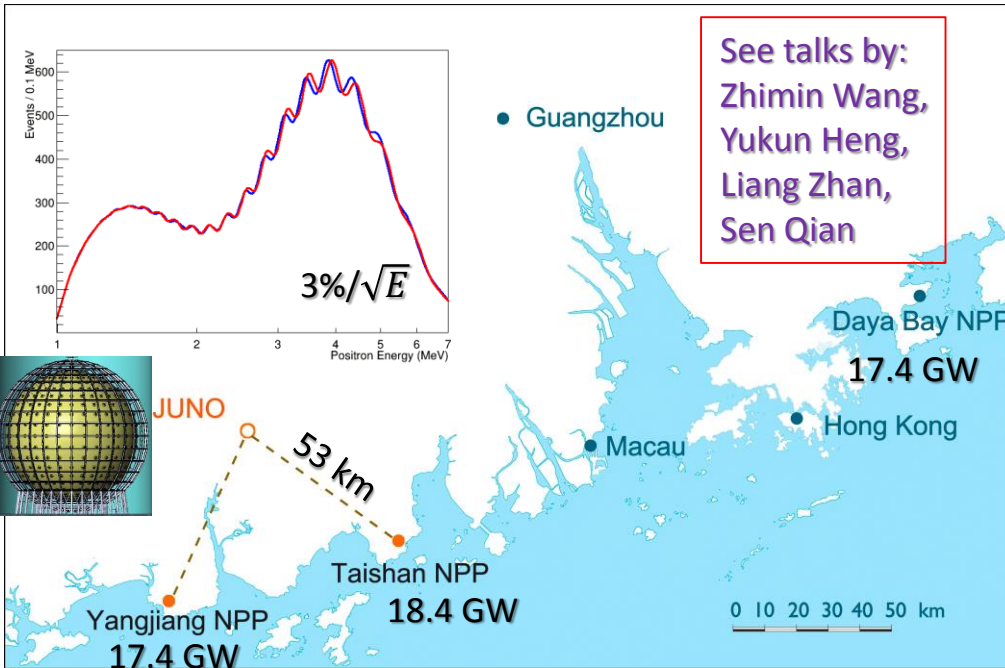
**Continue catching  
reactor neutrinos ...**

# Determine NMO at JUNO



L. Zhan, Y. Wang, J. Cao, L. Wen,  
PRD78:111103, 2008, PRD79:073007, 2009

Detector size: 20kt  
Energy resolution:  $3\%/\sqrt{E}$   
Thermal power: 36 GW  
Baseline 58 km



# JUNO Experiment

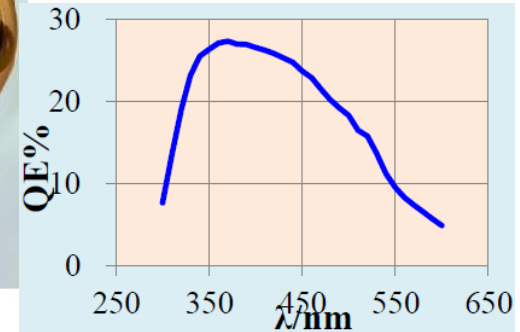
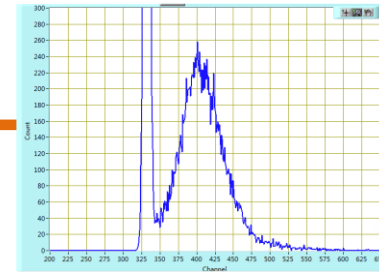
## Rich physics topics:

- neutrino mass ordering
- precision measurement
- Supernova  $\nu$
- Geo  $\nu$
- Solar  $\nu$
- Sterile  $\nu$
- Atmospheric  $\nu$
- Exotics

J. Phys. G 43: 030401 (2016) [arXiv:1507.05613]

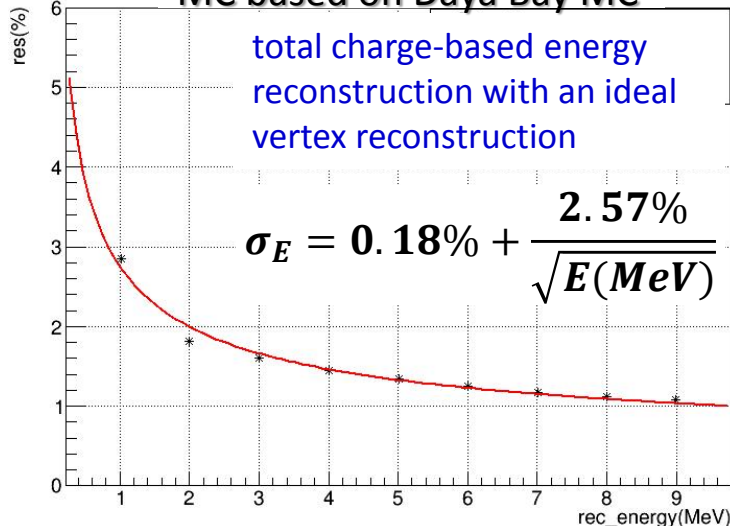


MCP 20" (NNVT)



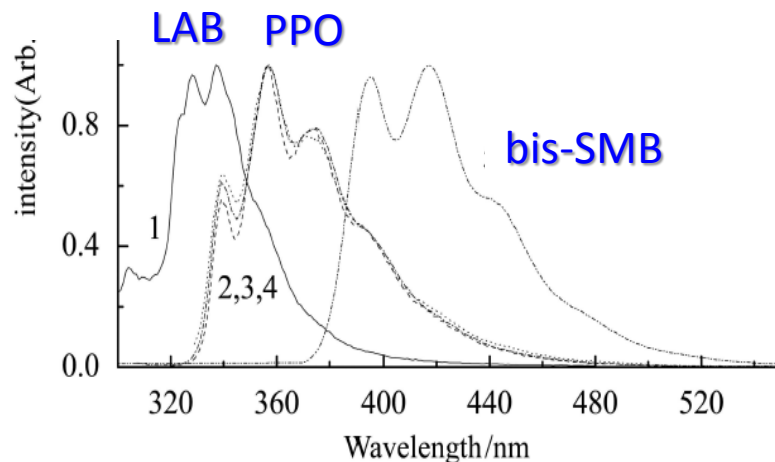
Type	8"	20"
	Typ.	Typ.
Photocathode characteristics		
Spectral Range(nm)	300-650	300-650
Maximum sensitivity at (nm)	380	380
Sensitivity		
Luminous( $\mu\text{A}/\text{lm}$ )	70	60
<b>OE at 420nm(%)</b>	<b>26</b>	<b>26</b>
Supply Voltage(V)	-1700	-1600
Gain	$1 \times 10^7$	$1 \times 10^7$
Anode Dark Current(nA)	100	150
Background Noise(cps)	5 K	30 K
Single Electron Spectrum		
Energy Resolution(%)	60	40
Peak to Valley Ratio	2.5	3.5
Anode Pulse		
Rise Time(ns)	1.7	1.7
Duration at half height(ns)	8.8	8.8

## MC based on Daya Bay MC



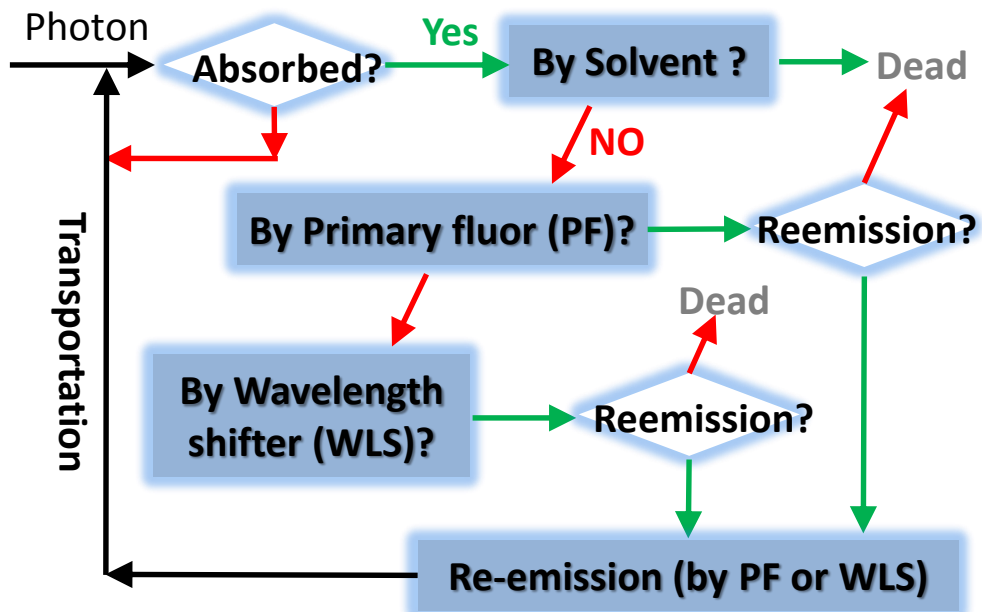
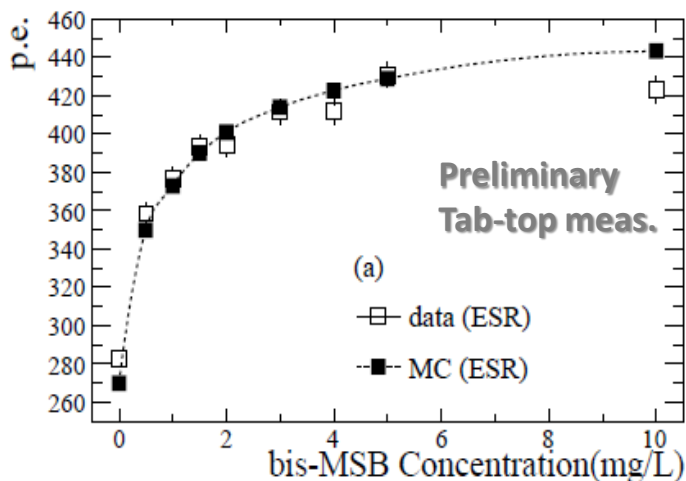
# Optical Model for large LS detectors

- **What's the best LS recipe?**
  - **Detector size dependent, cannot rely on lab experiment**
- **Predict the detector non-uniformity**
- **Understand non-linearity from Cerenkov**



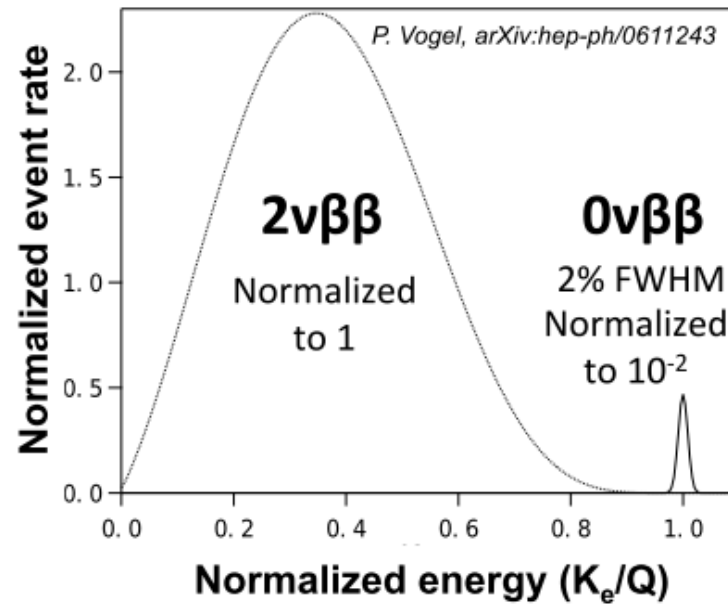
Developed a new optical model to address those issues. Key optical parameters:

- Molar attn. coefficient of each composition
- Quantum yield of each fluor



L.J Wen, Ph.D thesis  
 X.F. Ding, L.J. Wen, et al, CPC 39 (12) (2015) 126001.  
 X.Y. Li, L.J. Wen, et al, paper in preparation

# Exploring nature of $\nu$ 's mass



# EXO-200 and nEXO

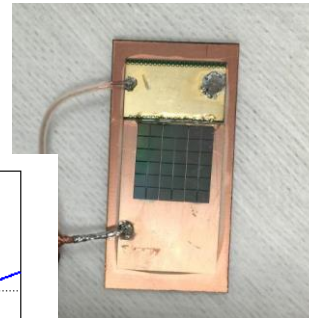
Expt.	Exposure (ton yr)	$T_{1/2}^{0\nu\beta\beta}$ ( $10^{27}$ yr)	Reference
EXO-200	0.1	0.019	Nature 510 (2014) 229
nEXO	4.7*5	6.6	Talk by C. Licciardi



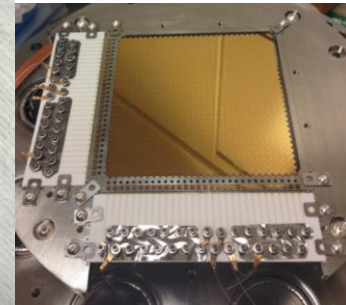
ICP-MS Laboratory

- ~ 5 tonne LXe TPC, 4.7 tonnes of active  $^{enr}\text{Xe}$  (90% or higher)
- < 1.0% ( $\sigma/E$ ) energy resolution
- Various R&D's going on at IHEP

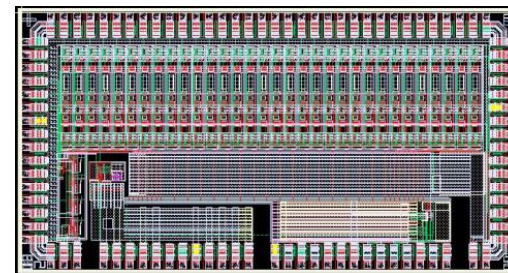
Liquid Xenon Setup



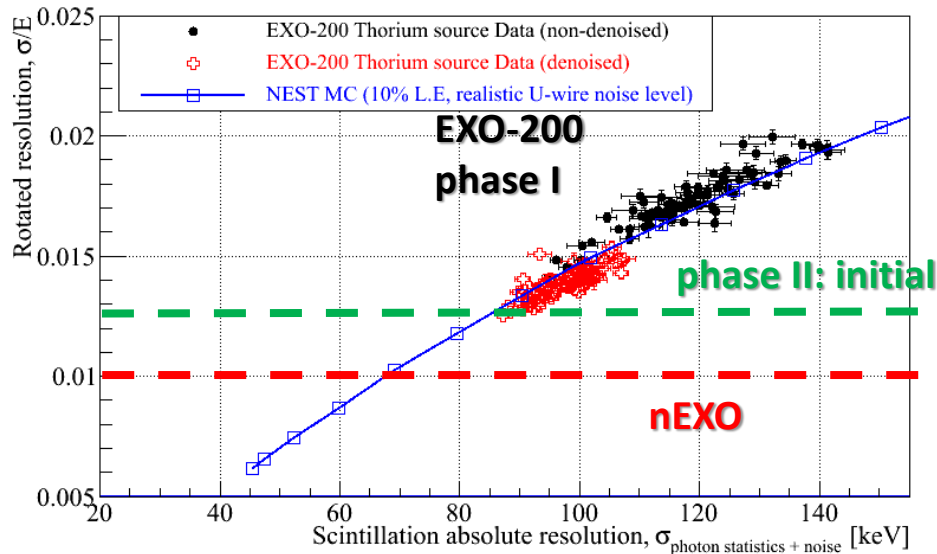
SiPM tests



Charge readout tile



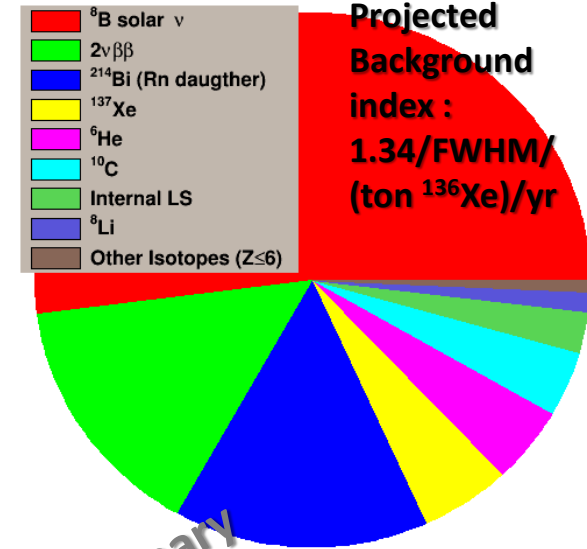
Code charge readout  
ASIC electronics



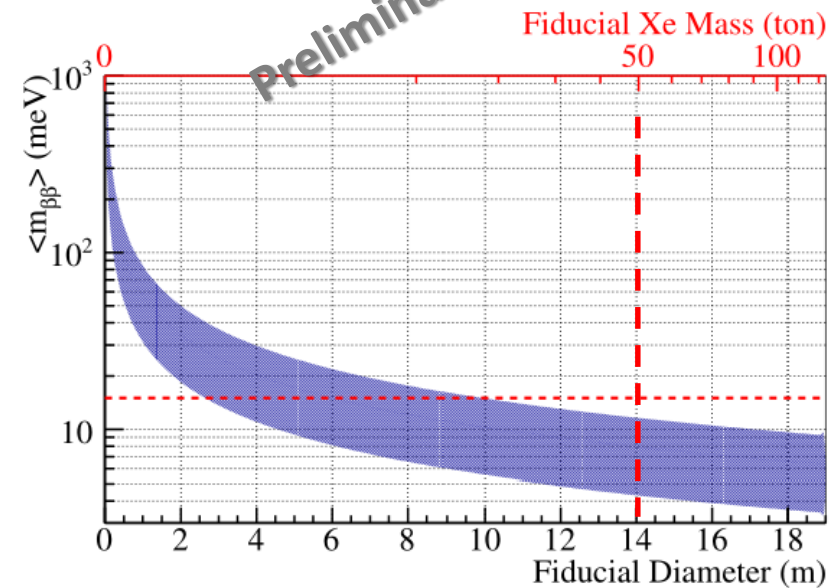
# Ultimate $0\nu\beta\beta$ search at JUNO

The JUNO LS detector has good potential for DBD search

- $3\%/\sqrt{E}$  energy resolution
- 35.4 m diameter of LS
- Clean balloon hold  $^{enr}\text{Xe}$  gas (>80%  $^{136}\text{Xe}$ ) dissolved LS
- LS purity:  $10^{-15}$  g/g (U/Th)  $\rightarrow$   $10^{-17}$  g/g (U/Th)
- Excellent muon track rec.  $\rightarrow$  reject cosmogenic isotopes



Future Experiment	Target Mass ton·yr	Sensitivity $T_{1/2}$ , yr (90% C.L.)	Sensitivity $m_{\beta\beta}$ , meV (90% C.L.)
EXO-200 upgrade [32]	0.16 · 3	$5.7 \times 10^{25}$	110 - 260
nEXO [33]	5 · 5	$6.6 \times 10^{27}$	15 - 25
KamLAND-Zen 800 [11]	~0.8 · ?	-	50
KamLAND2-Zen [34]	~1 ton	-	20
SNO+ Phase I [7]	0.8 · 5	$9 \times 10^{25}$	55 - 133
SNO+ Phase II [7]	8 · 5	$7 \times 10^{26}$	19 - 46
CUORE [31]	0.75 · ?	$9.5 \times 10^{25}$	50 - 130
GERDA-II [35]	0.038 ton · ? yr	$1.4 \times 10^{26}$	110 - 190
JUNO Xe-LS	50 · 5	$21.3 \times 10^{27}$	4 - 15



---

**Many puzzles to be studied in neutrinos.  
Keep working hard ...**

**Thanks!**