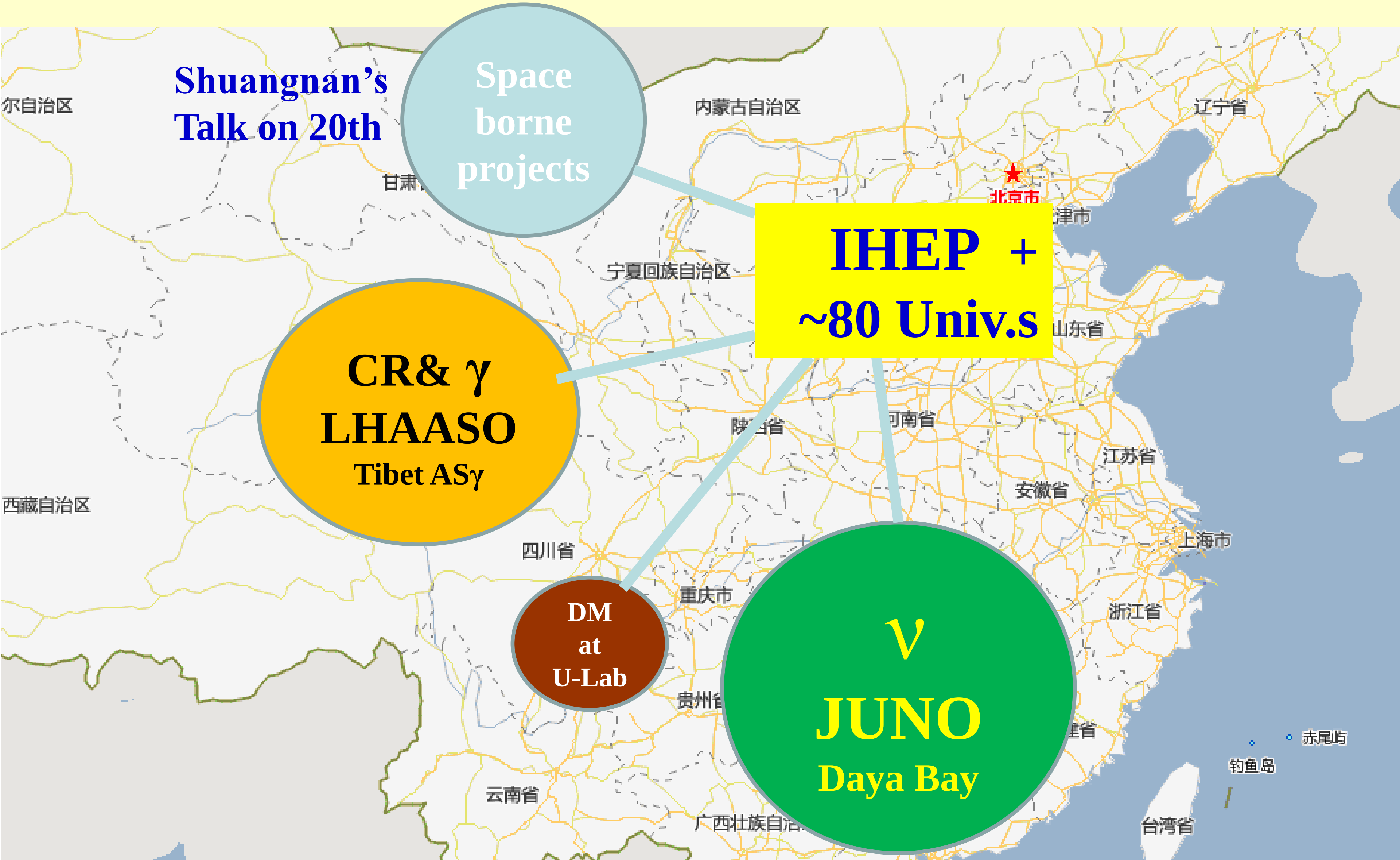
Astroparticle Physics in China



Daya Bay Experiment and the Neutrino Physics in China

Yifang Wang
Institute of High Energy Physics
Vulcano, May, 2014

Neutrino Oscillation

- **If the neutrino mass eigenstate is different from that of the weak interaction, neutrinos can oscillate: from one type to another during the flight:**

$\nu_e \longrightarrow \nu_\mu \longrightarrow \nu_e \longrightarrow \nu_\mu \longrightarrow$

Oscillation probability: $P(\nu_e \to \nu_\mu) = \sin^2(2\theta)\,\sin^2(1.27\Delta m^2 L/E)$

Oscillation amplitude ($\sin^2(2\theta)$)

Oscillation frequency (Δm^2)

Oscillation matrix for 3 generations:

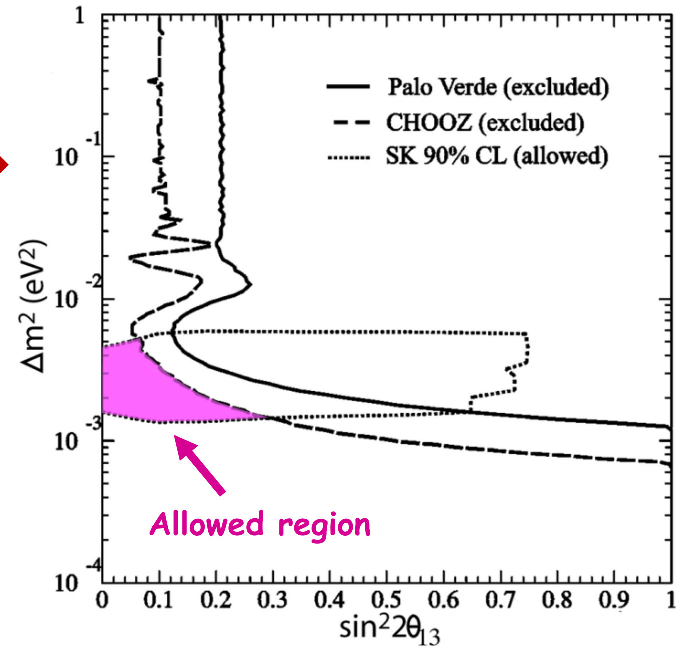
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- **Known parameters:** θ_{23}, θ_{12}, $|\Delta M^2_{23}|$, ΔM^2_{12},
- **Recent progress:** θ_{13}
- **Unknown parameters:** **mass hierarchy(ΔM^2_{23}), CP phase δ**

Direct Searches in the Past

- **Palo Verde & Chooz: no signal**

$Sin^2 2\theta_{13} < 0.15$ @ 90%C.L.
if $\Delta M^2_{23} = 0.0024\ eV^2$



- **T2K: 2.5 σ over bkg（2011）**

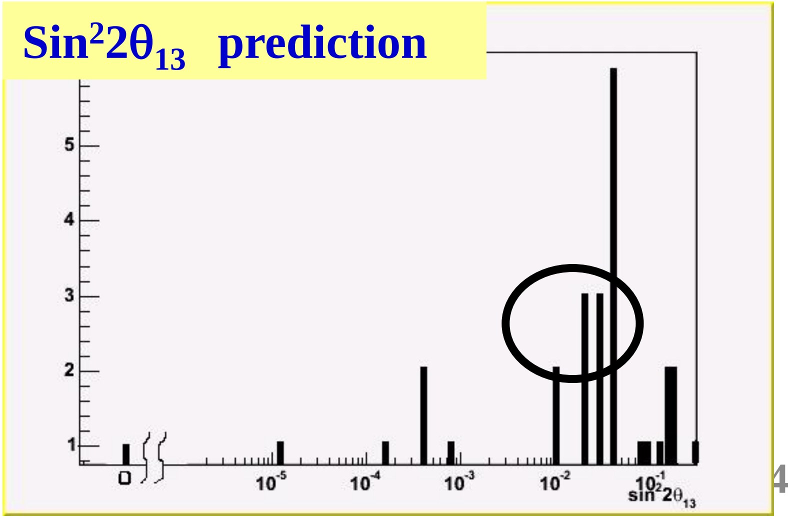
$0.03 < Sin^2 2\theta_{13} < 0.28$ @ 90%C.L. for NH
$0.04 < Sin^2 2\theta_{13} < 0.34$ @ 90%C.L. for IH

- **Minos: 1.7 σ over bkg（2011）**

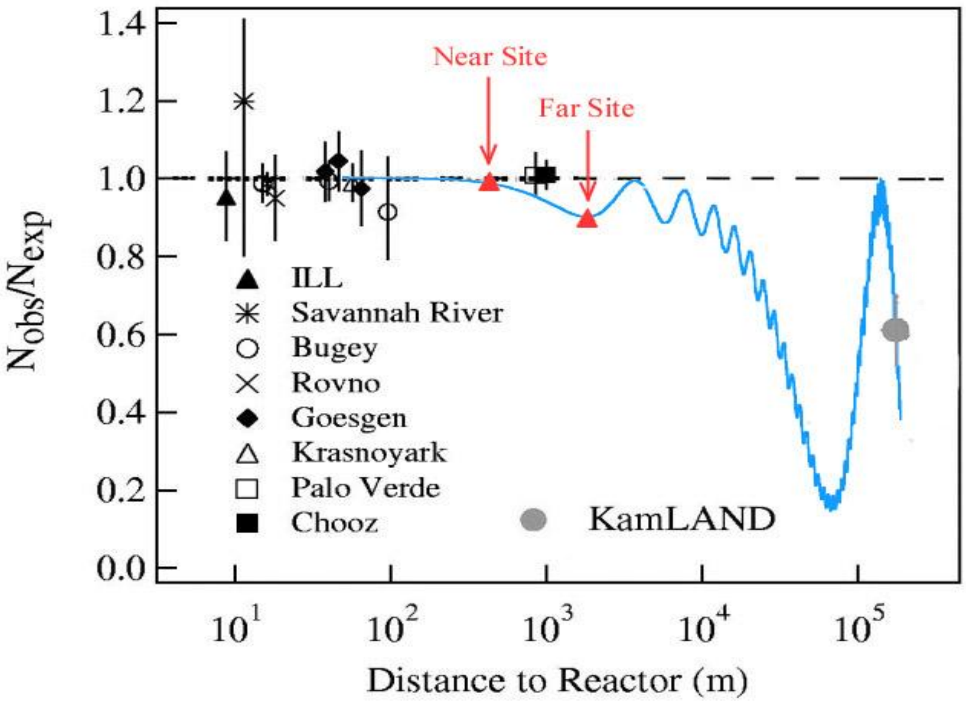
$0 < Sin^2 2\theta_{13} < 0.12$ @ 90%C.L. NH
$0 < Sin^2 2\theta_{13} < 0.19$ @ 90%C.L. IH

- **Double Chooz: 1.7 σ（2011）**

$sin^2 2\theta_{13} = 0.086 \pm 0.041(stat) \pm 0.030(sys)$



Reactor Experiments: comparing observed/expected neutrinos



$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{13} L/E) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12} L/E)$$

Precision of past experiments, typically 3-6%

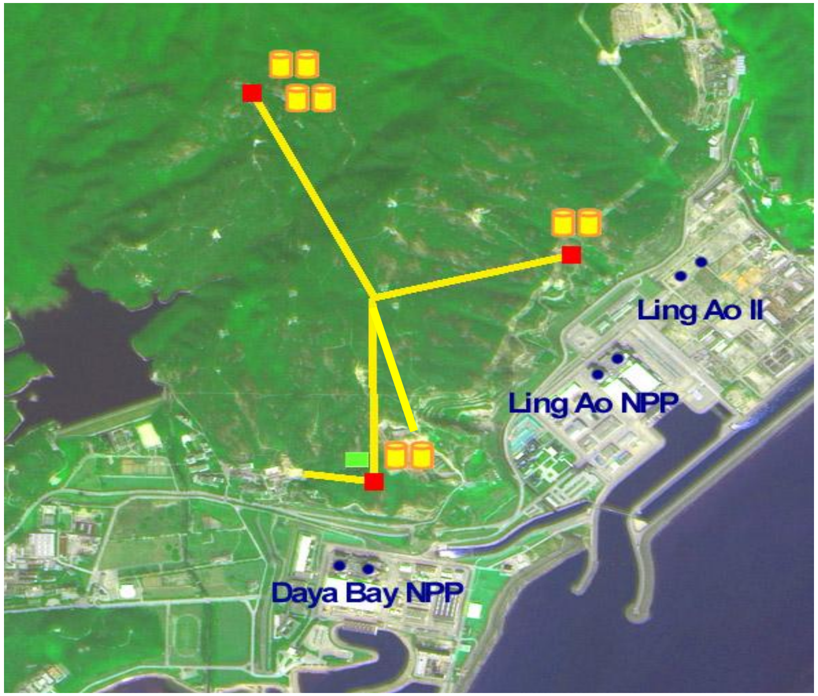
- **Reactor power: ~ 1%**
- **Spectrum: ~ 0.3%**
- **Fission rate: 2%**

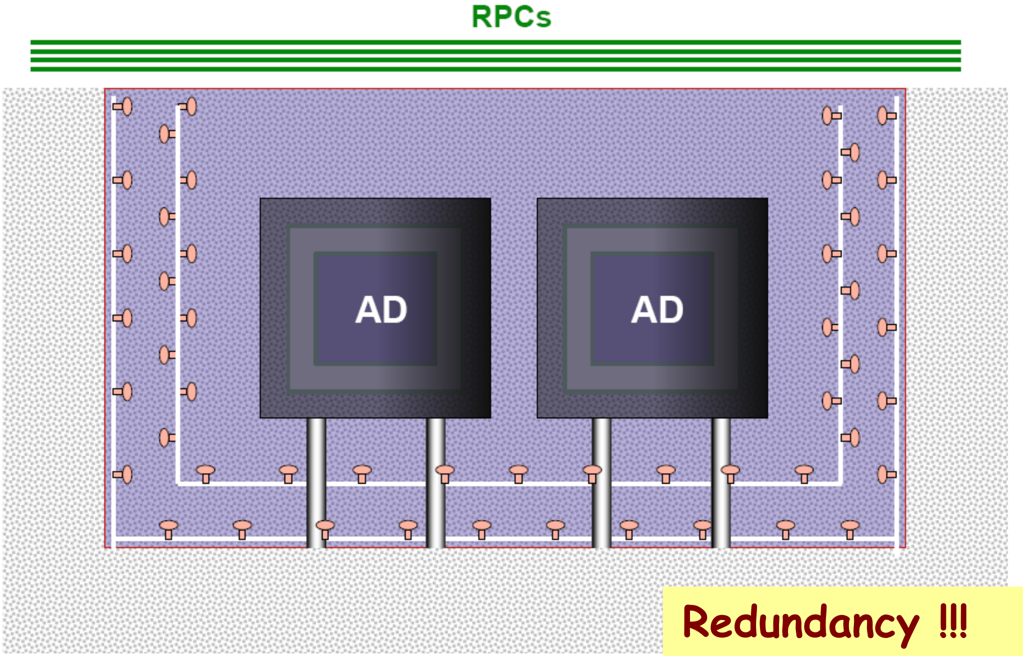
- **Backgrounds: ~1-3%**

- **Target mass: ~1-2%**
- **Efficiency: ~ 2-3%**

Our design goal: a precision of ~ 0.4%

Daya Bay Experiment: Layout





Redundancy !!!

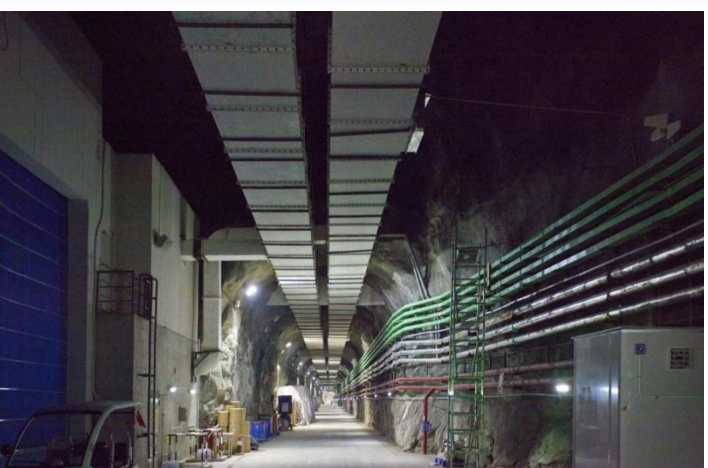
- Relative measurement to cancel Corr. Syst. Err.
  - 2 near sites, 1 far site
- Multiple AD modules at each site to reduce Uncorr. Syst. Err.
  - Far: 4 modules， near: 2 modules

Cross check; Reduce errors by $1/\sqrt{N}$

- Multiple muon detectors to reduce veto eff. uncertainties
  - Water Cherenkov： 2 layers
  - RPC： 4 layers at the top + telescopes

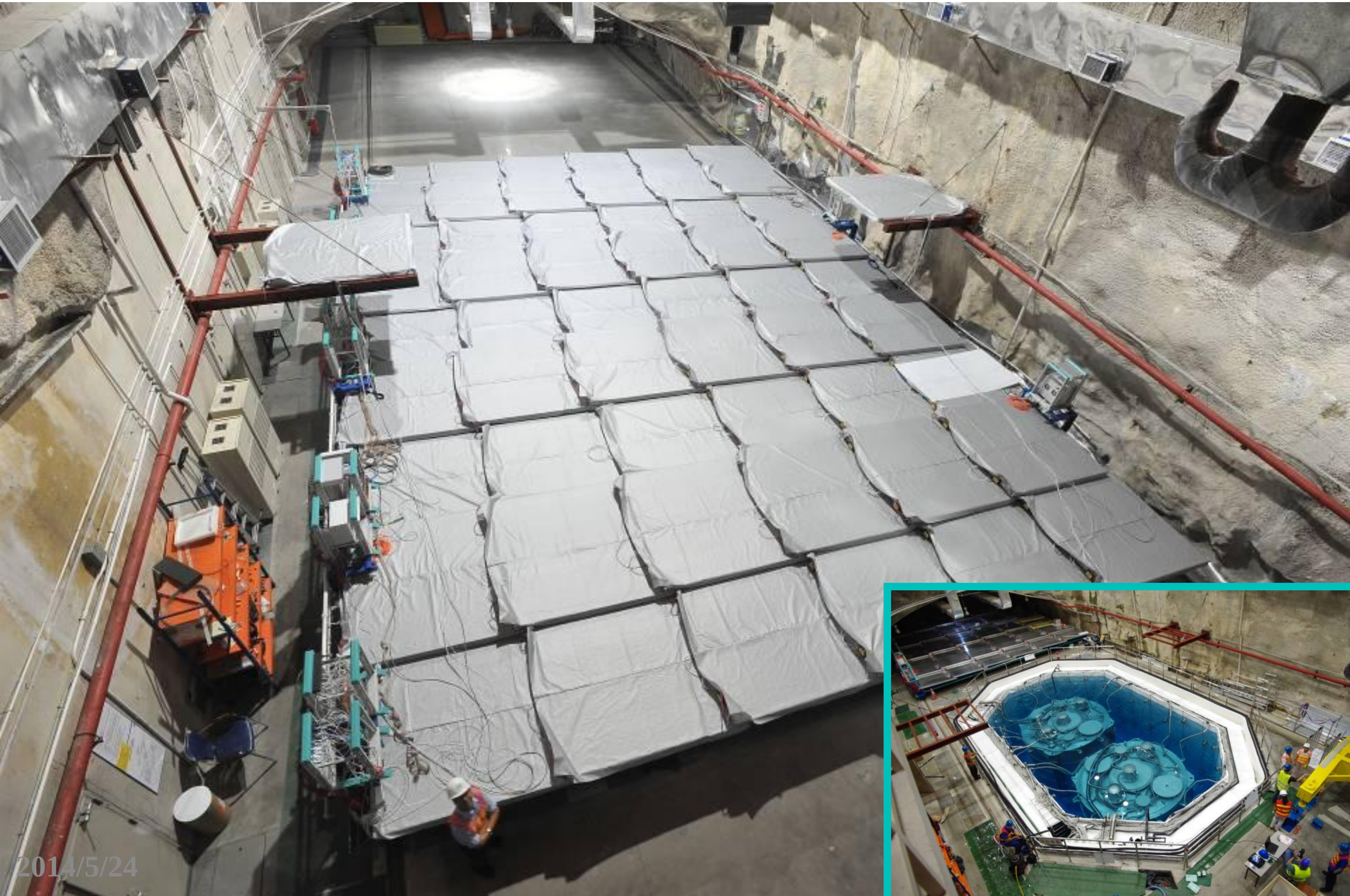
Tunnel and Underground Lab

- Tunnel: ~ 3100m
- 3 Exp. hall
- 1 hall for LS
- 1 hall for water



A total of ~ 3000 blasting right next reactors. No one exceeds safety limit set by National Nuclear Safety Agency（0.007g）

Experimental Hall in Operation



Daya Bay: Data taking & analysis status

Two detector comparison [1202.6181]

- 90 days of data, Daya Bay near only
- NIM A **685** (2012), 78-97

First oscillation analysis [1203:1669]

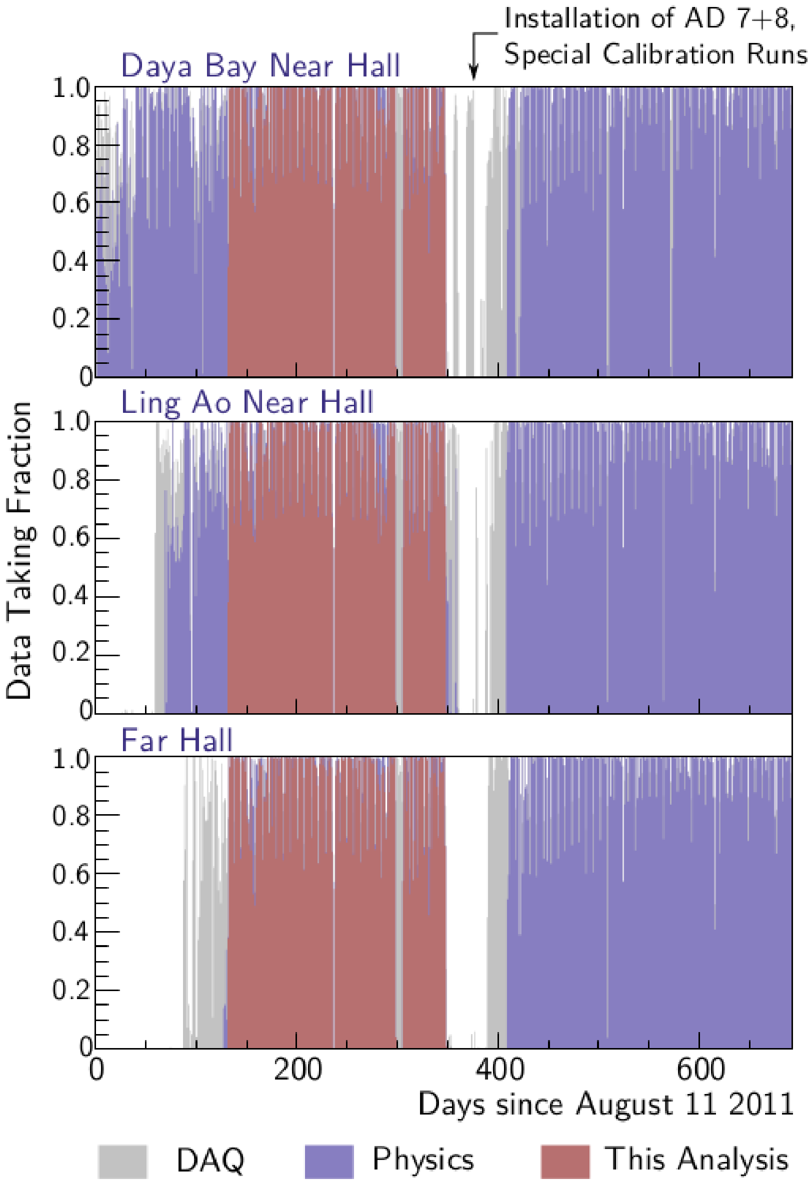
- 55 days of data, 6 ADs near+far
- PRL **108** (2012), 171803

Improved oscillation analysis [1210.6327]

- 139 days of data, 6 ADs near+far
- CP C **37** (2013), 011001

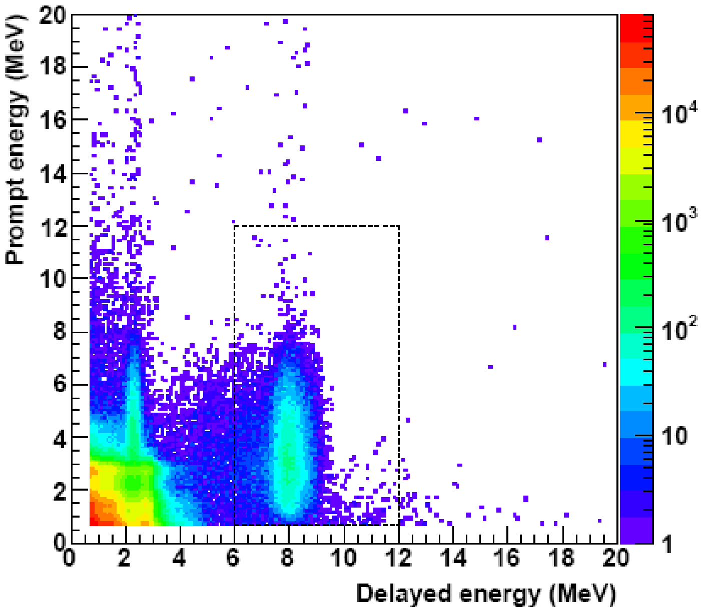
Spectral Analysis arXiv:1310.6732

- 217 days complete 6 AD period
- 55% more statistics than CPC result
- Reported at NuFACT'2013, paper submitted



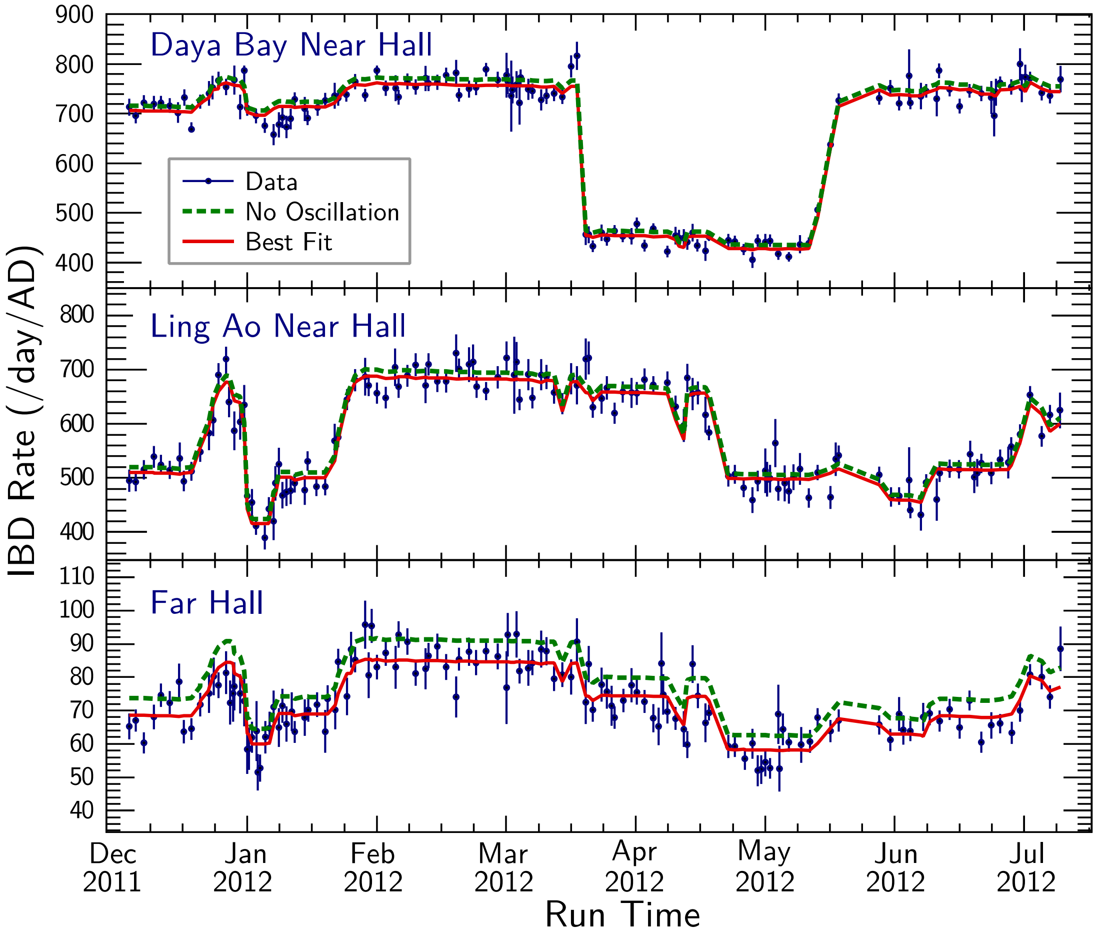
Neutrino Event Selection

- **Pre-selection**
  - **Reject Flashers**
  - **Reject Triggers within (-2 μs, 200 μs) to a tagged water pool muon**
- **Neutrino event selection**
  - **Multiplicity cut**
    - ✓ Prompt-delayed pairs within a time interval of 200 μs
    - ✓ No triggers($E > 0.7$MeV) before the prompt signal and after the delayed signal by 200 μs
  - **Muon veto**
    - ✓ *1s* after an AD shower muon
    - ✓ *1ms* after an AD muon
    - ✓ *0.6ms* after an WP muon
  - **$0.7\text{MeV} < E_{prompt} < 12.0\text{MeV}$**
  - **$6.0\text{MeV} < E_{delayed} < 12.0\text{MeV}$**
  - **$1\mu s < \Delta t_{e^+\text{-}n} < 200\mu s$**



Daily Neutrino Rate

- **Three halls taking data synchronously allows near-far cancellation of reactor related uncertainties**
- **Rate changes reflect the reactor on/off.**



Prediction:

- **Baseline（ 3.5cm，~0.002%）**
- **Target mass（3kg，0.015%）**
- **Reactor neutrino flux**

Predictions are absolute, multiplied by a normalization factor from the fitting

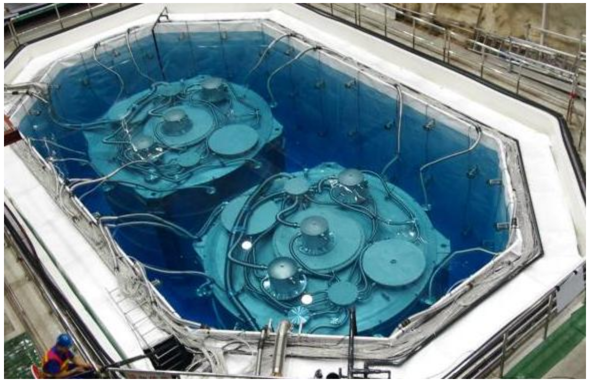
The Most Precise Neutrino Experiment

Detector			
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Combined	78.8%	1.9%	0.2%

Design: (0.18 - 0.38) %

Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

Side-by-side Comparison



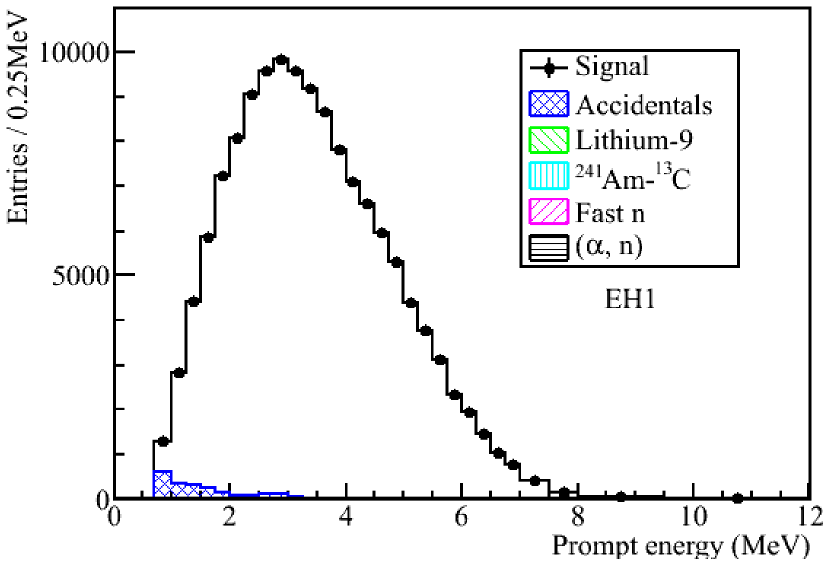
Expectation:

R(AD1/AD2) = 0.981

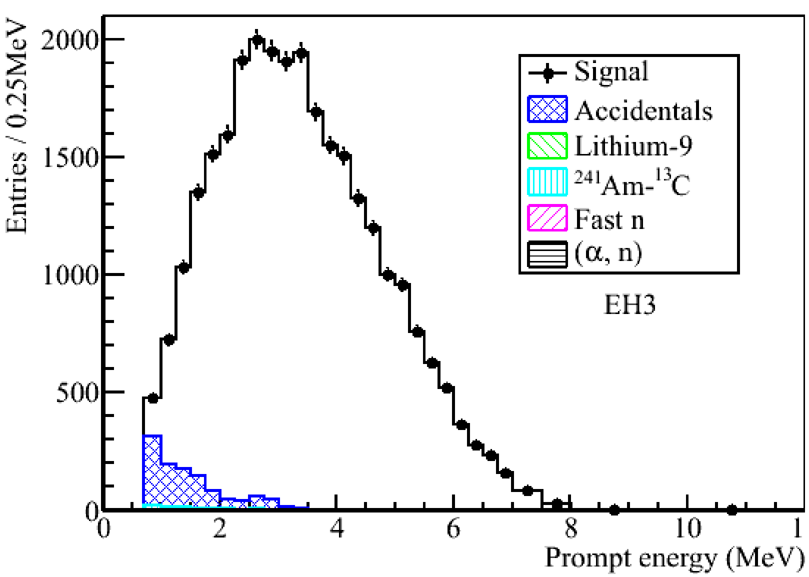
Measurement:

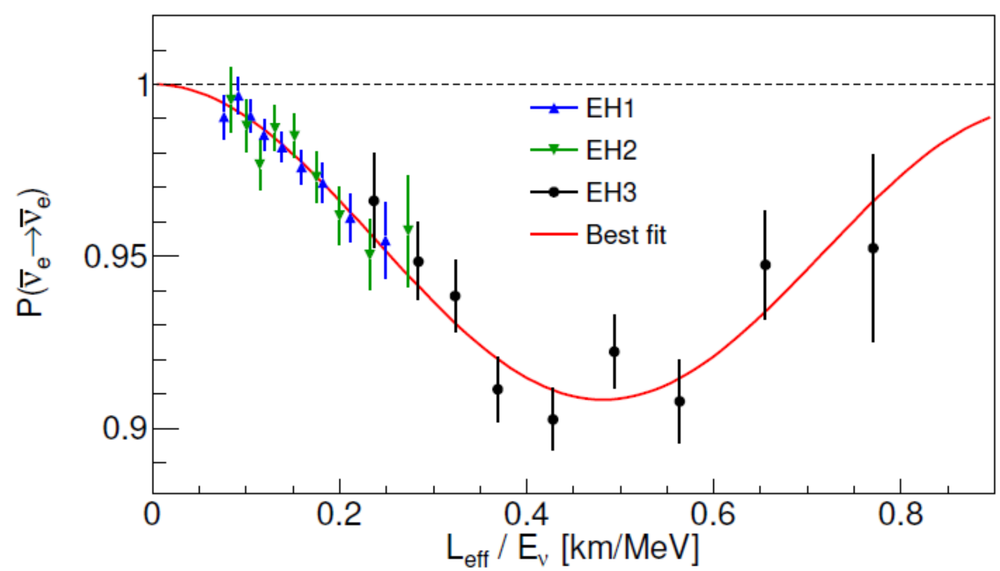
0.984 ± 0.004(stat) ± 0.002(syst)

Latest Results：Spectral Analysis



- Each energy bin is an oscillation measurement
- Precise energy measurement is a key
- Issues of non-linearity…





Energy Response Model

arXiv:1310.6732

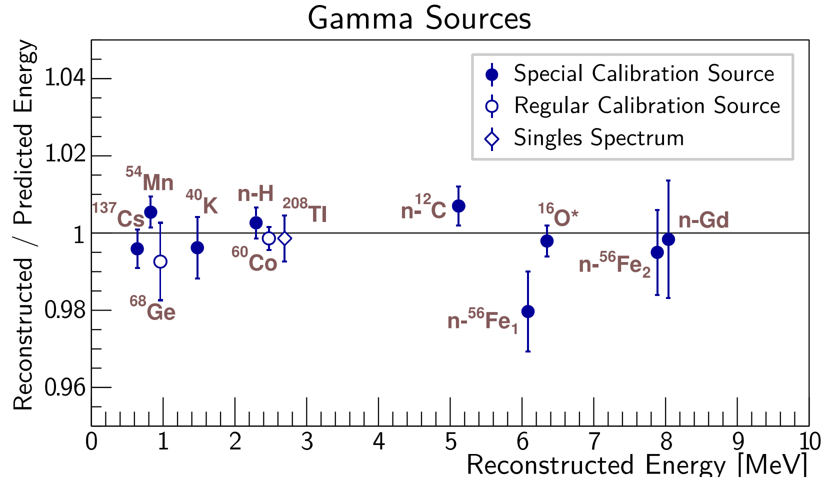
Mapping the true energy E_{true} to the reconstructed kinetic energy E_{rec}:

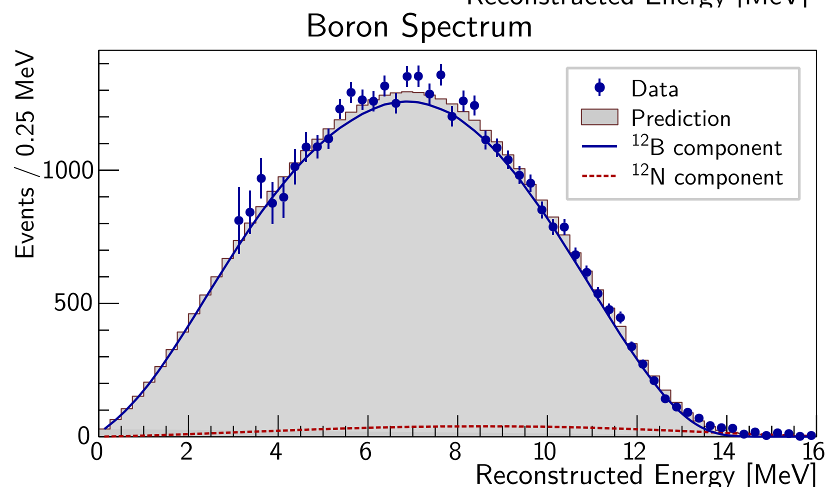
$$f = \frac{E_{rec}}{E_{true}} = \frac{E_{rec}}{E_{vis}} \cdot \frac{E_{vis}}{E_{true}}$$

1 Electronics non-linearity → $\frac{E_{rec}}{E_{vis}}$

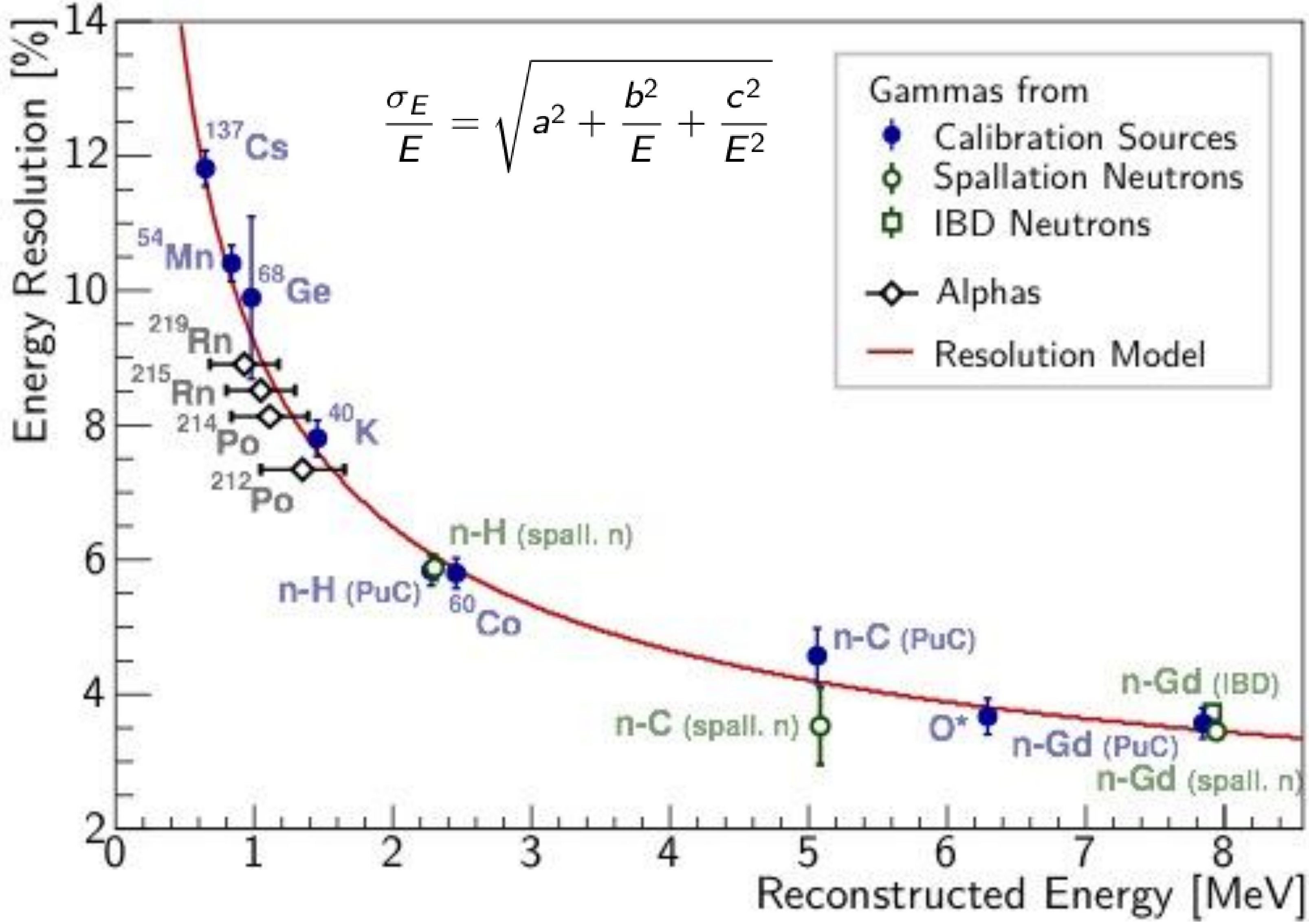
2 Scintillator non-linearity → $\frac{E_{vis}}{E_{true}}$

- **Build models taking into account:**
  - **Electronics non-linearity: time-dependent charge collection efficiency**
  - **Scintillator non-linearity: Quench effect & Cerenkov radiation**
  - **Complicated e^+, e^-, γ's interactions in LS, from simulation**
- **Constraint parameters by a fit to**
  - **all calibration data**
  - **Standalone measurement on**
    - **scintillator quenching using compton e- and n beams**
    - **Calibrate readout electronics by Flash ADC**

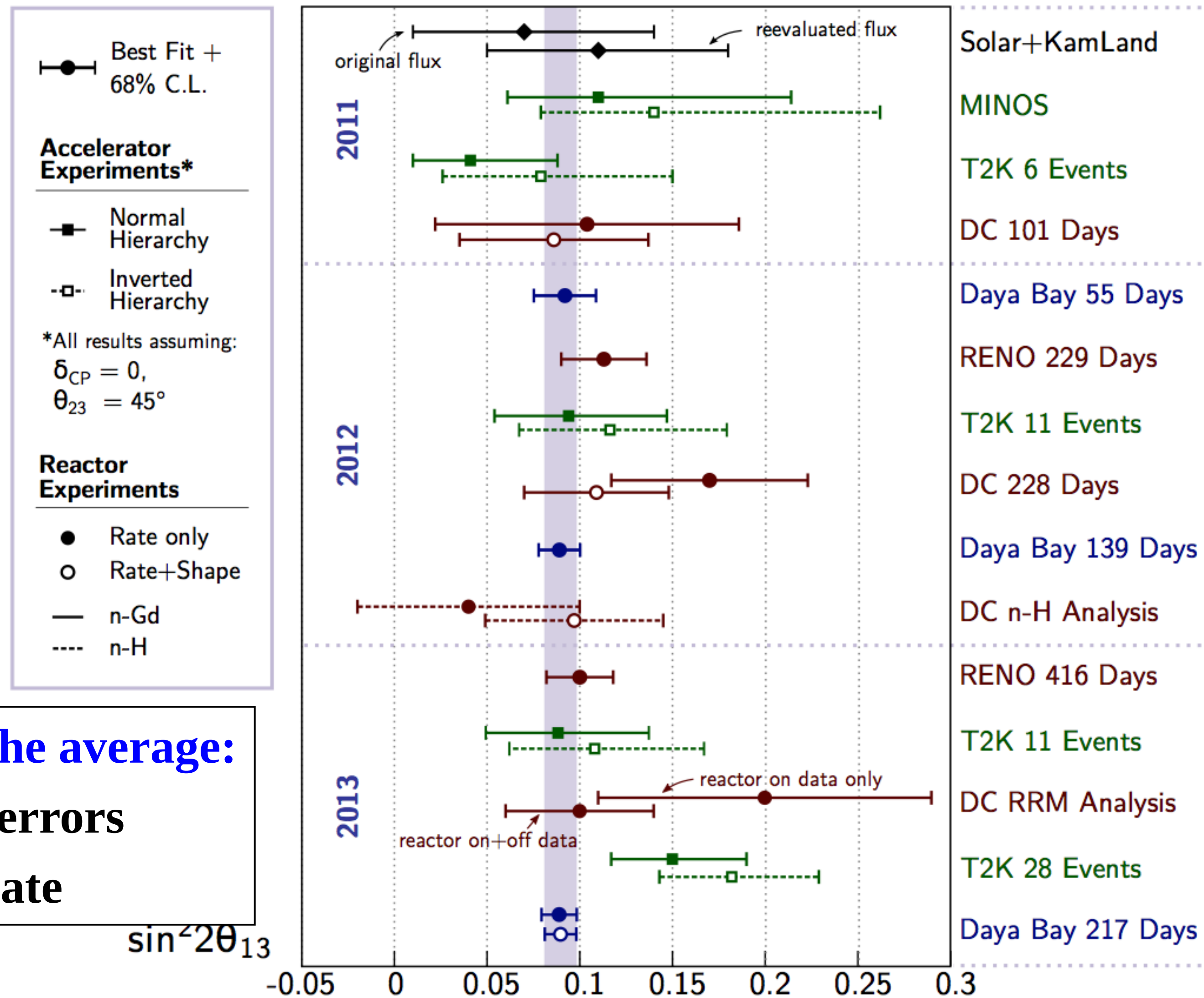




Energy Resolution Model



Global Comparison of θ_{13} Measurements



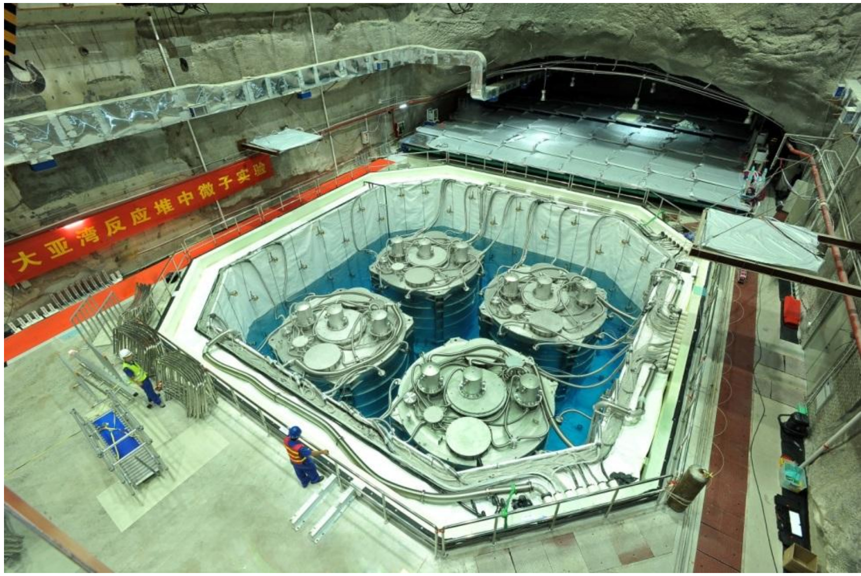
Be careful to take the average:

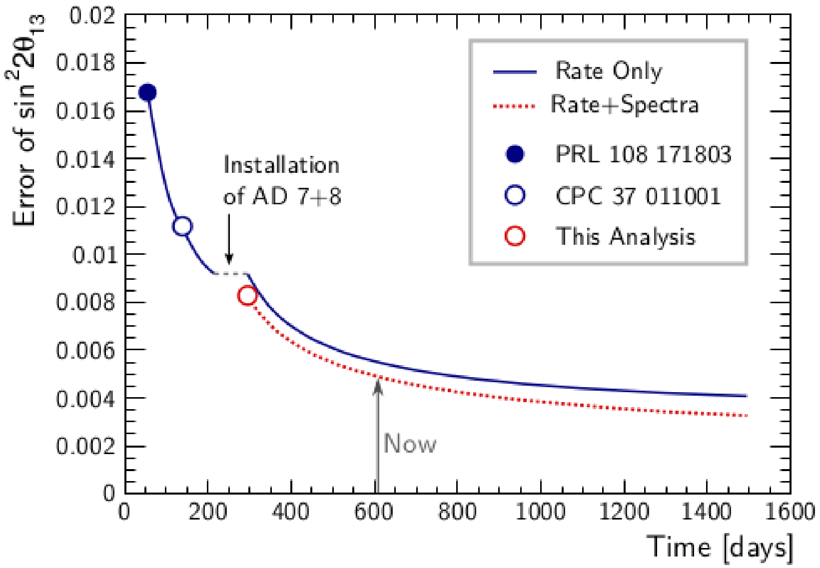
- Correlated errors
- Error estimate

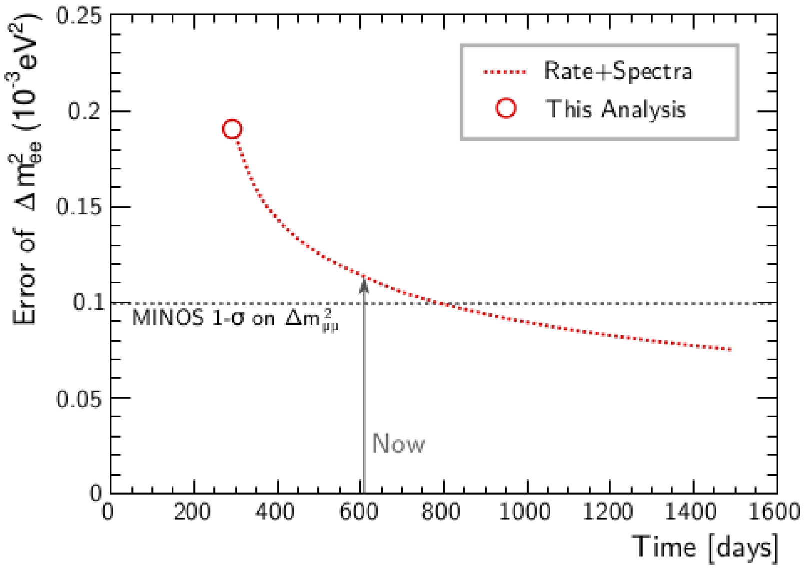
The three reactor experiments will work together to report results in a coherent way, and probably can report a combined result.

Current status and future plan

- **Summer(2012) maintenance completed**
  - ⇨ **Two new AD modules installed**
  - ⇨ **Special Automatic & Manual calibration completed**
- **Data taking resumed in Oct.**
- **Precision results in three years, $\Delta(\sin^2 2\theta_{13}) \sim 4\%$**







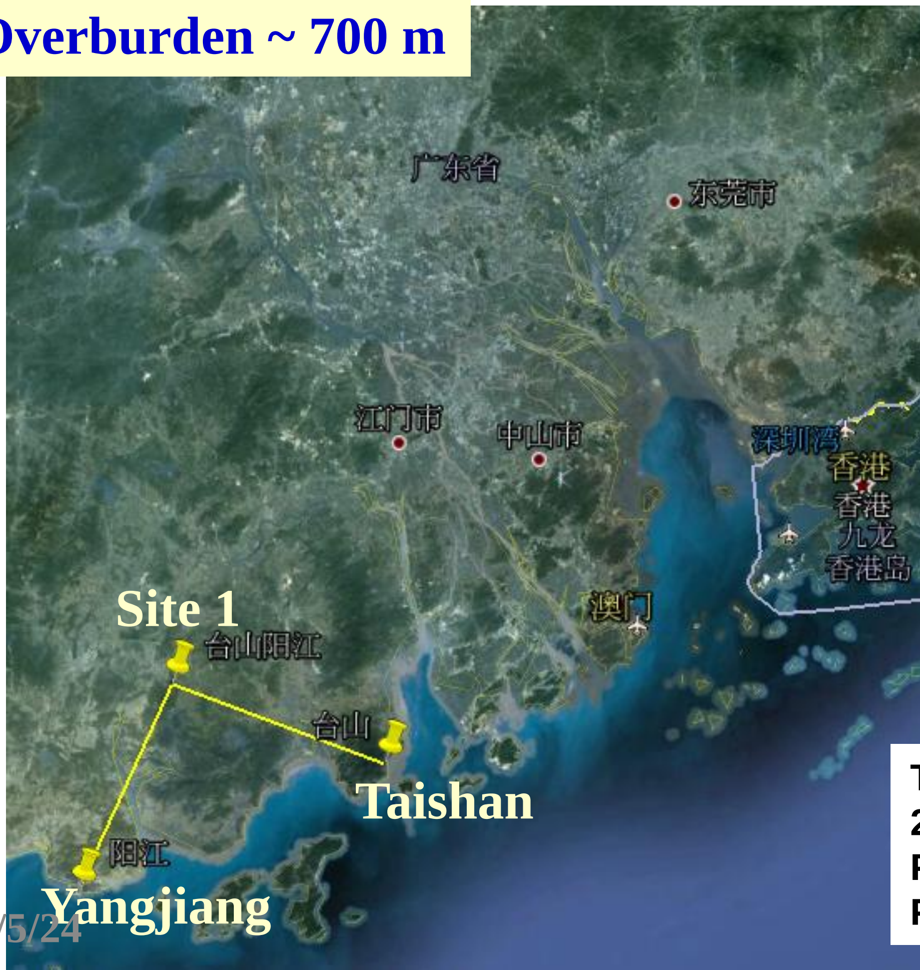
Still a lot of unknowns

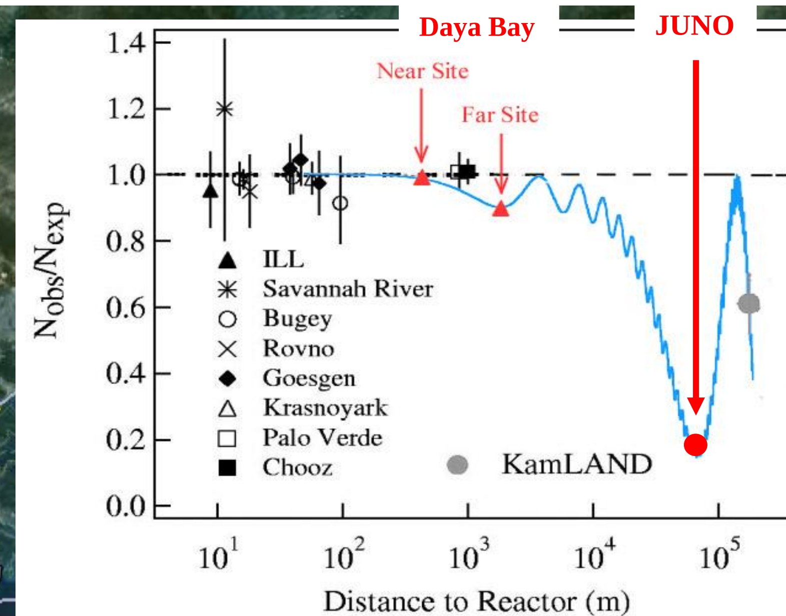
- **Neutrino oscillation:**
  - **Neutrino mass hierarchy ?**
  - **Unitarity of neutrino mixing matrix ?**
  - **Θ_{23} is maximized ?**
  - **CP violation in the neutrino mixing matrix as in the case of quarks ? Large enough for the matter-antimatter asymmetry in the Universe ?**
- **What is the absolute neutrino mass ?**
- **Neutrinos are Dirac or Majorana ?**
- **Are there sterile neutrinos?**
- **Do neutrinos have magnetic moments ?**
- **Can we detect relic neutrinos ?**
- **……**

Next Experiment: JUNO

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

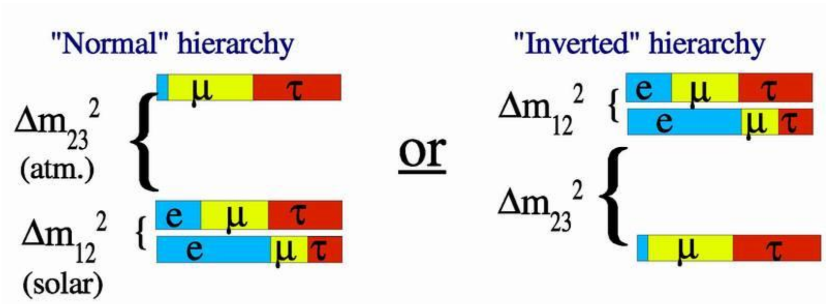
Overburden ~ 700 m



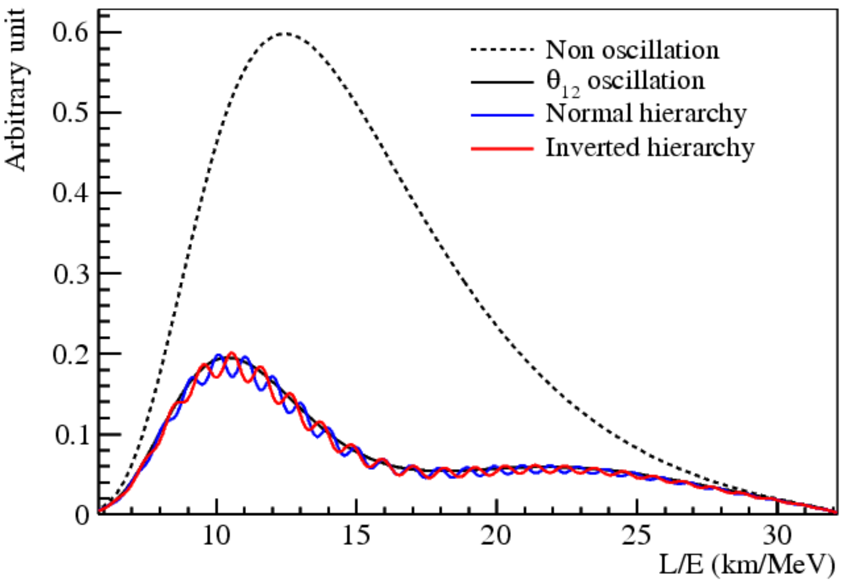


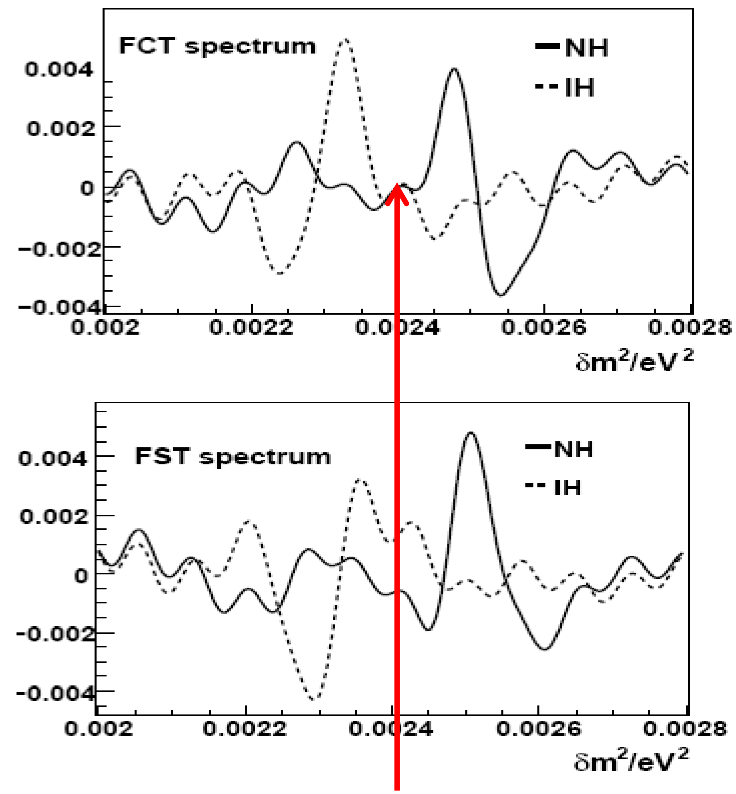
Talk by Y.F. Wang at ICFA seminar 2008, Neutel 2011; by J. Cao at Nutel 2009, NuTurn 2012 ; Paper by L. Zhan, Y.F. Wang, J. Cao, L.J. Wen, PRD78:111103,2008; PRD79:073007,2009

Mass Hierarchy at Reactors



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





ΔM^2_{23}

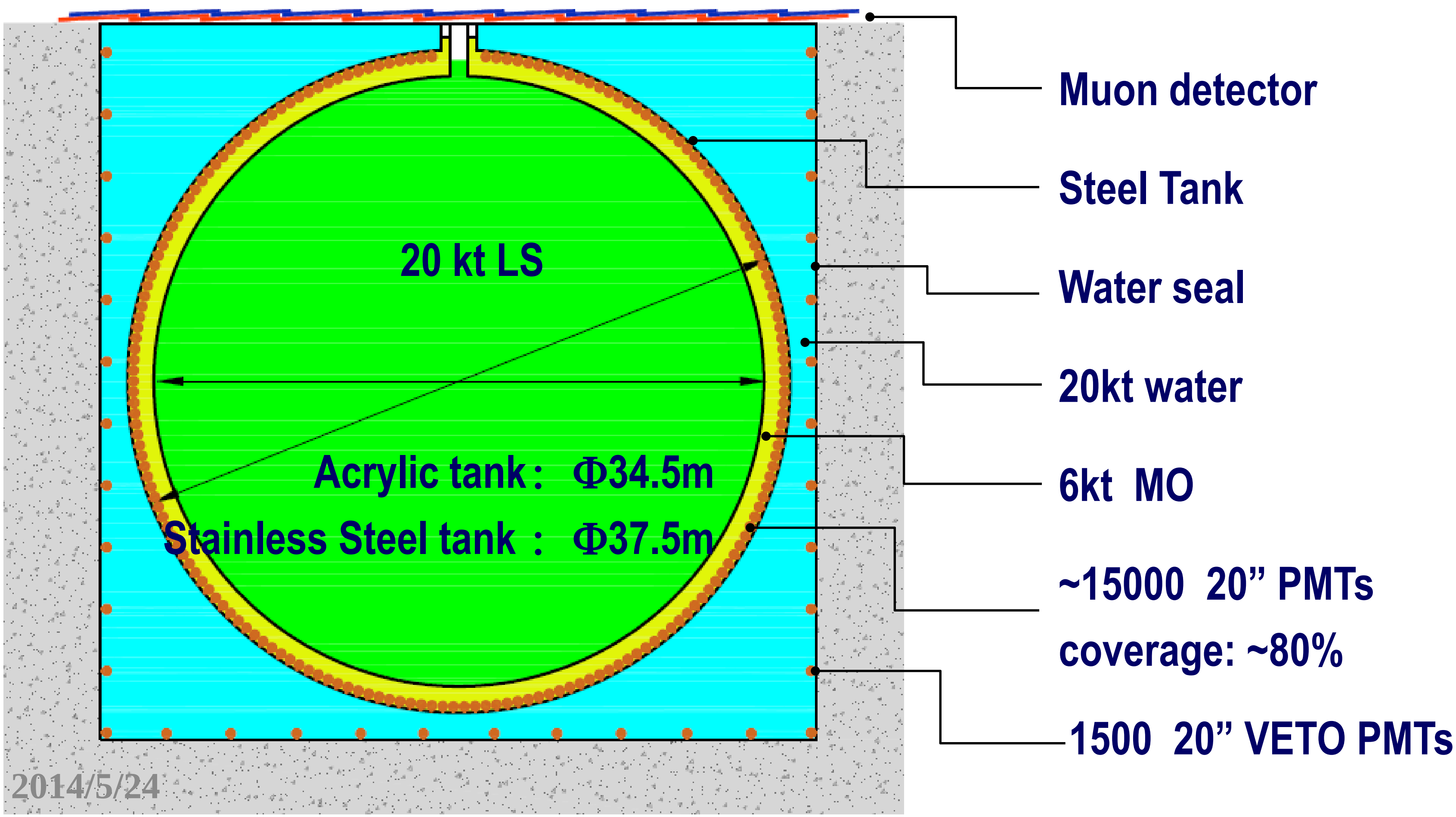
$$\begin{aligned} P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\ P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\ P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\ P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32}) \end{aligned}$$

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

The plan: a large LS detector

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

40 events/day



Physics Reach

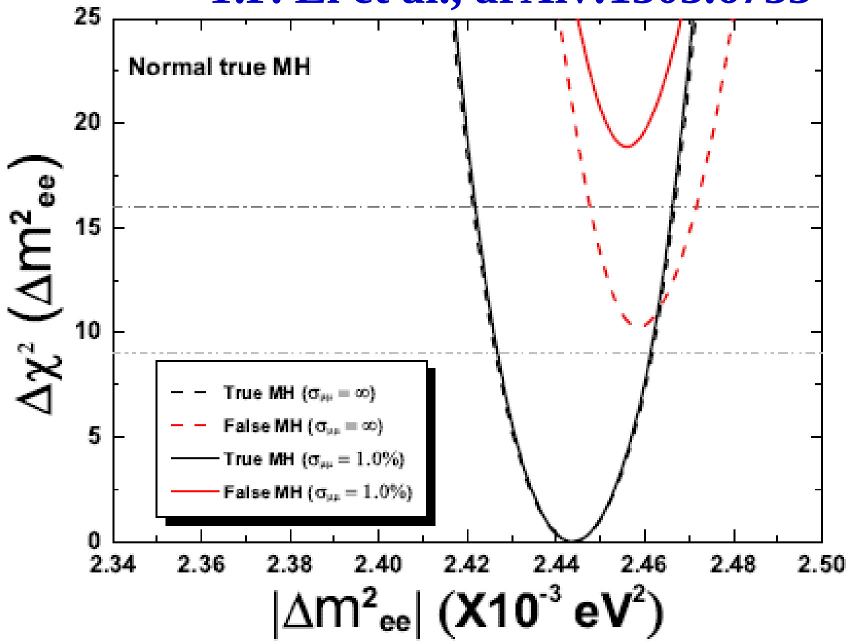
Thanks to a large θ_{13}

- **Mass hierarchy**
- Precision measurement of mixing parameters
- Supernova neutrinos
- Geoneutrinos
- Sterile neutrinos
- ……

	Current	Daya Bay II
Δm^2_{12}	3%	0.6%
Δm^2_{23}	5%	0.6%
$\sin^2\theta_{12}$	5%	0.7%
$\sin^2\theta_{23}$	5%	N/A
$\sin^2\theta_{13}$	14% ➔ 4%	~ 15%

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

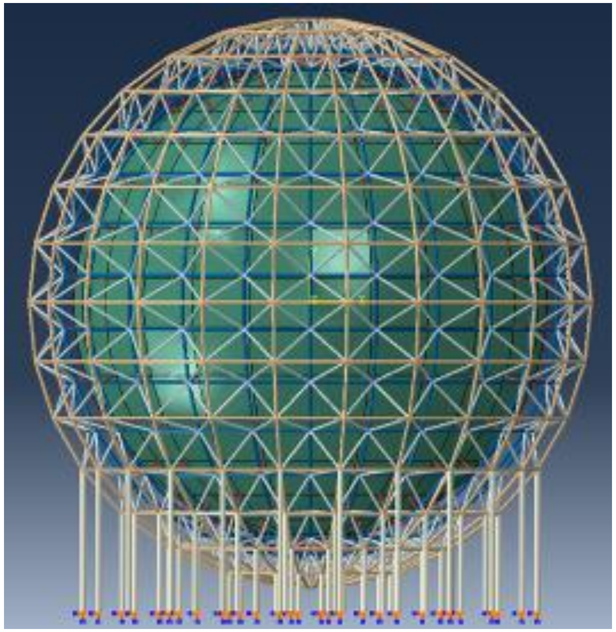
Y.F. Li et al., arXiv:1303.6733

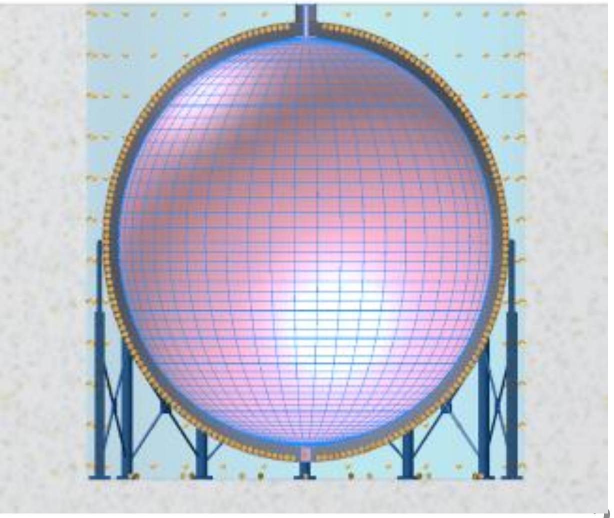


For 6 years, mass hierarchy can be determined at 4σ level, if $\Delta m^2_{\mu\mu}$ can be determined at 1% level

Central Detector

- **Some basic numbers:**
  - ⇨ **20 kt liquid scintillator as the target**
  - ⇨ **Signal event rate: 40/day**
  - ⇨ **Backgrounds with 700 m overburden:**
    - ✓ **Accidentals(~10%), $^{9}Li/^{8}He$(<1%), fast neutros(<1%)**
- **A huge detector in a water pool:**
  - ⇨ **Default option: acrylic tank(D~35m) + SS structure**
  - ⇨ **Backup option: SS tank(D~38m) + acrylic structure + balloon**
- **Issues:**
  - ⇨ **Engineering: mechanics, safety, lifetime, …**
  - ⇨ **Physics: cleanness, light collection, …**
  - ⇨ **Assembly & installation**
- **Design & prototyping underway**

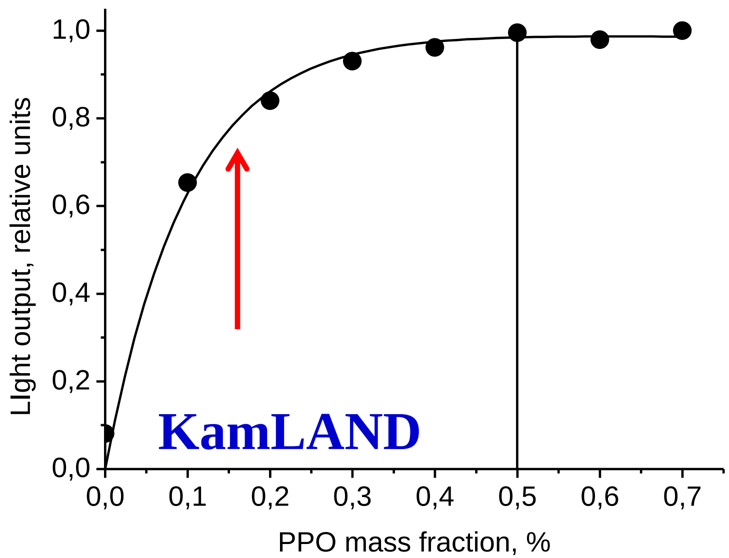




Liquid Scintillator

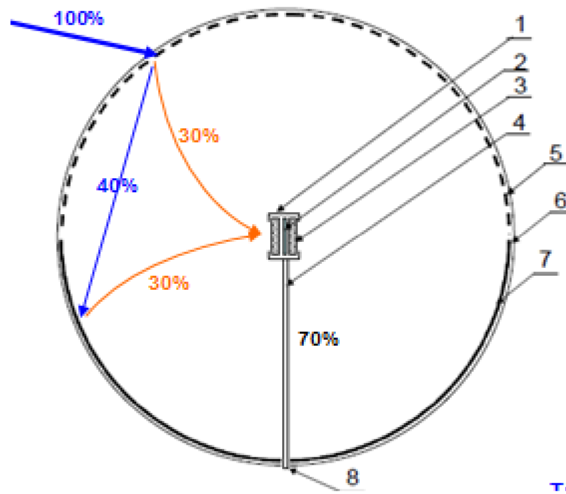
- **Requirements:**
  - Low background: ➔ No Gd-loading
  - Long attenuation length: 15m ➔ 30m
    - ✓ Improve raw materials
    - ✓ Improve the production process
    - ✓ Purification
  - High light yield: optimize fluor concentration
- **Current Choice: LAB+PPO+BisMSB**

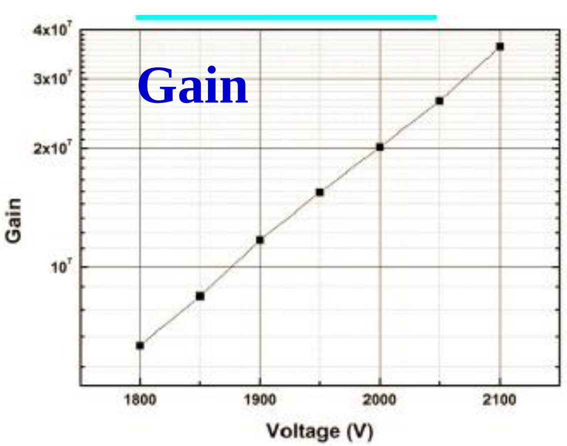
Linear Alky Benzene	Atte. L(m) @ 430 nm
RAW	14.2
Vacuum distillation	19.5
SiO_2 coloum	18.6
Al_2O_3 coloum	22.3
LAB from Nanjing, Raw	20
Al_2O_3 coloum, fourth time	27
Al_2O_3 coloum, second time	25
Al_2O_3 coloum, 8th time	24

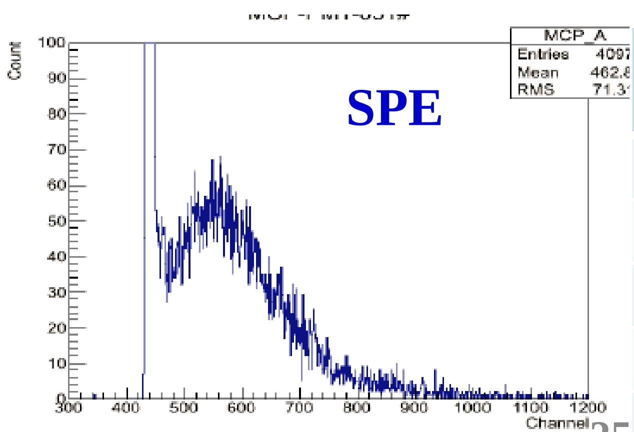


High QE PMT

- Two types of high QE 20” PMTs under development:
  - ⇨ Hammamatzu R5912-100 with SBA photocathode
  - ⇨ A new design using MCP: 4π collection
- MCP-PMT development:
  - ⇨ Technical issues mostly resolved
  - ⇨ Successful 8” prototypes
  - ⇨ 20” prototypes soon



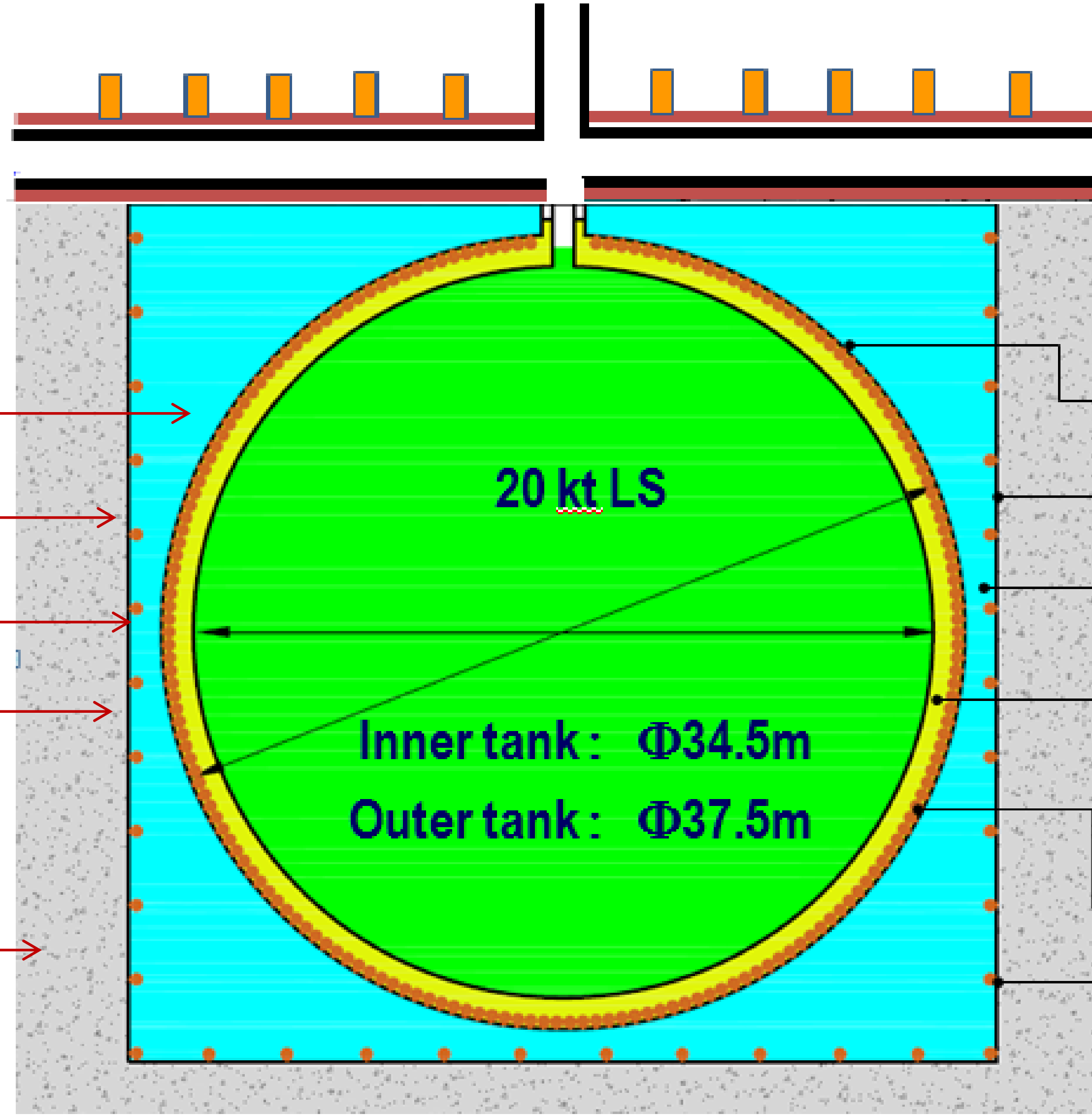




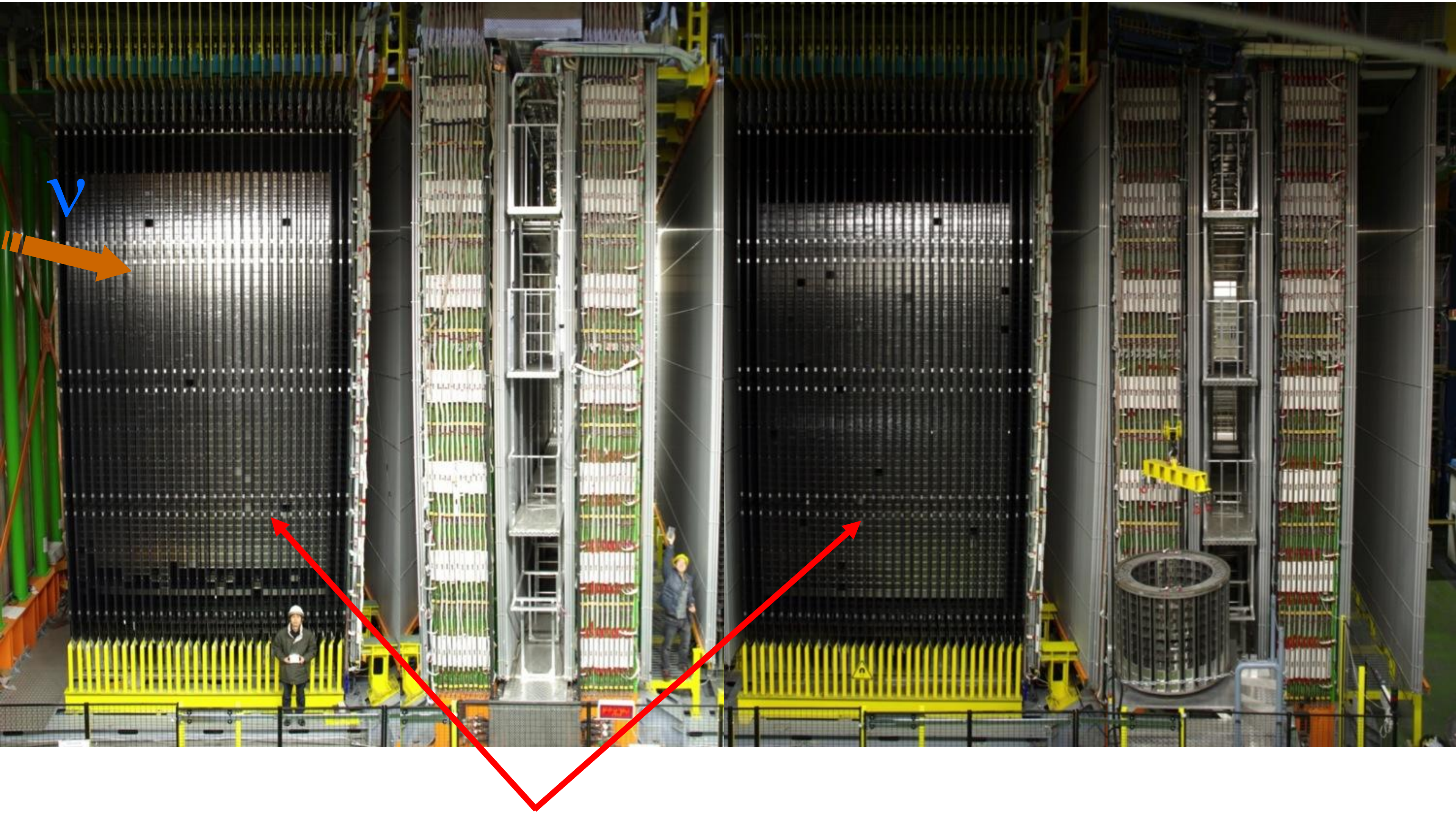
	R5912	R5912 -100	MCP -PMT
QE@410nm	25%	35%	25%
Rise time	3 ns	3.4ns	5ns
SPE Amp.	17mV	18mV	17mV
P/V of SPE	>2.5	>2.5	`2
TTS	5.5ns	1.5 ns	3.5 ns

Muon VETO detector

- Top tracker
- Tracker support
- Water system
- Tyvek
- PMT support
- Water pool liner
- Earth magnetic shielding



The OPERA Target Tracker in JUNO



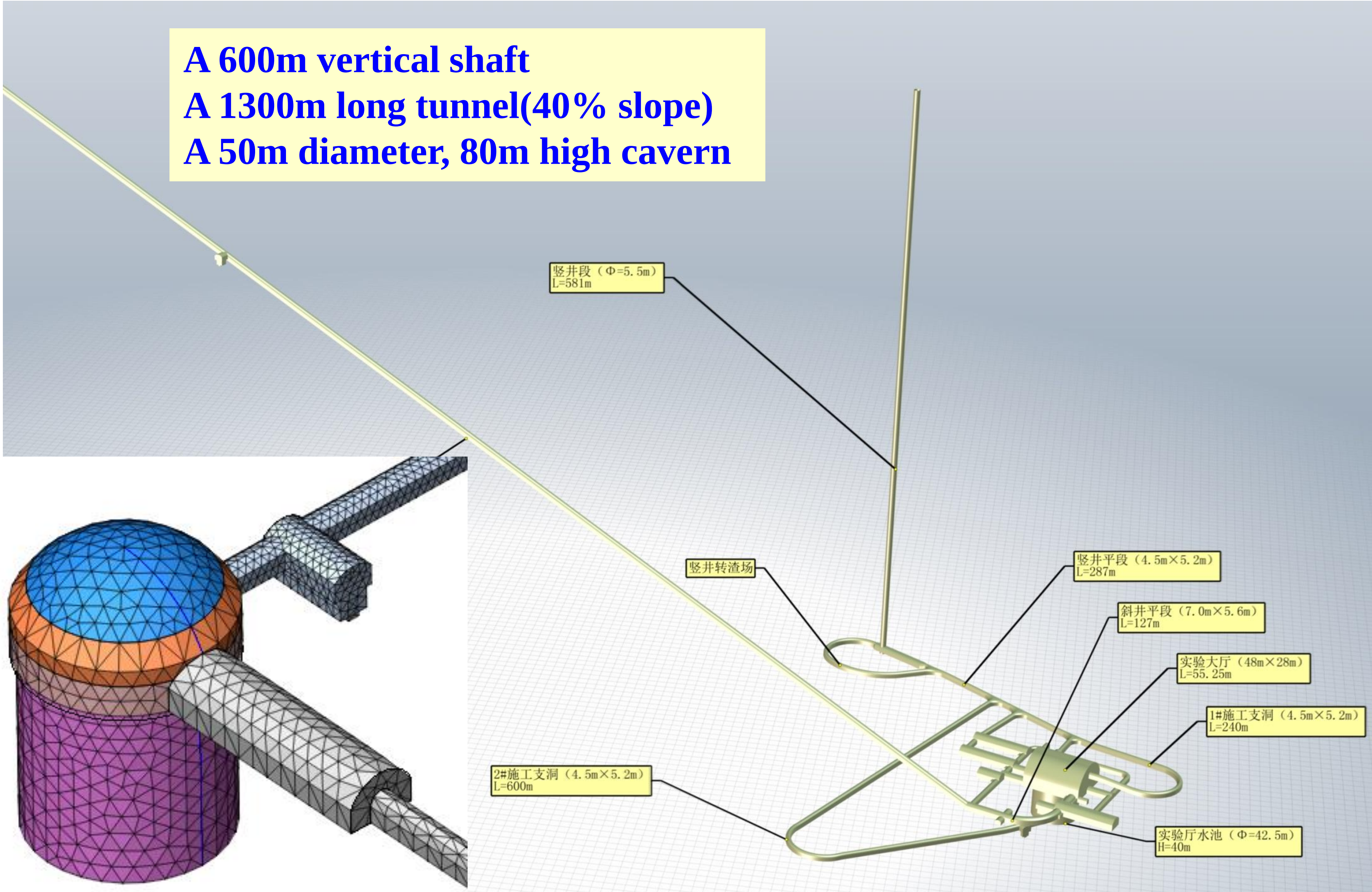
2x31 Target Tracker x-y walls (4.5 M€)

TT dismounting schedule

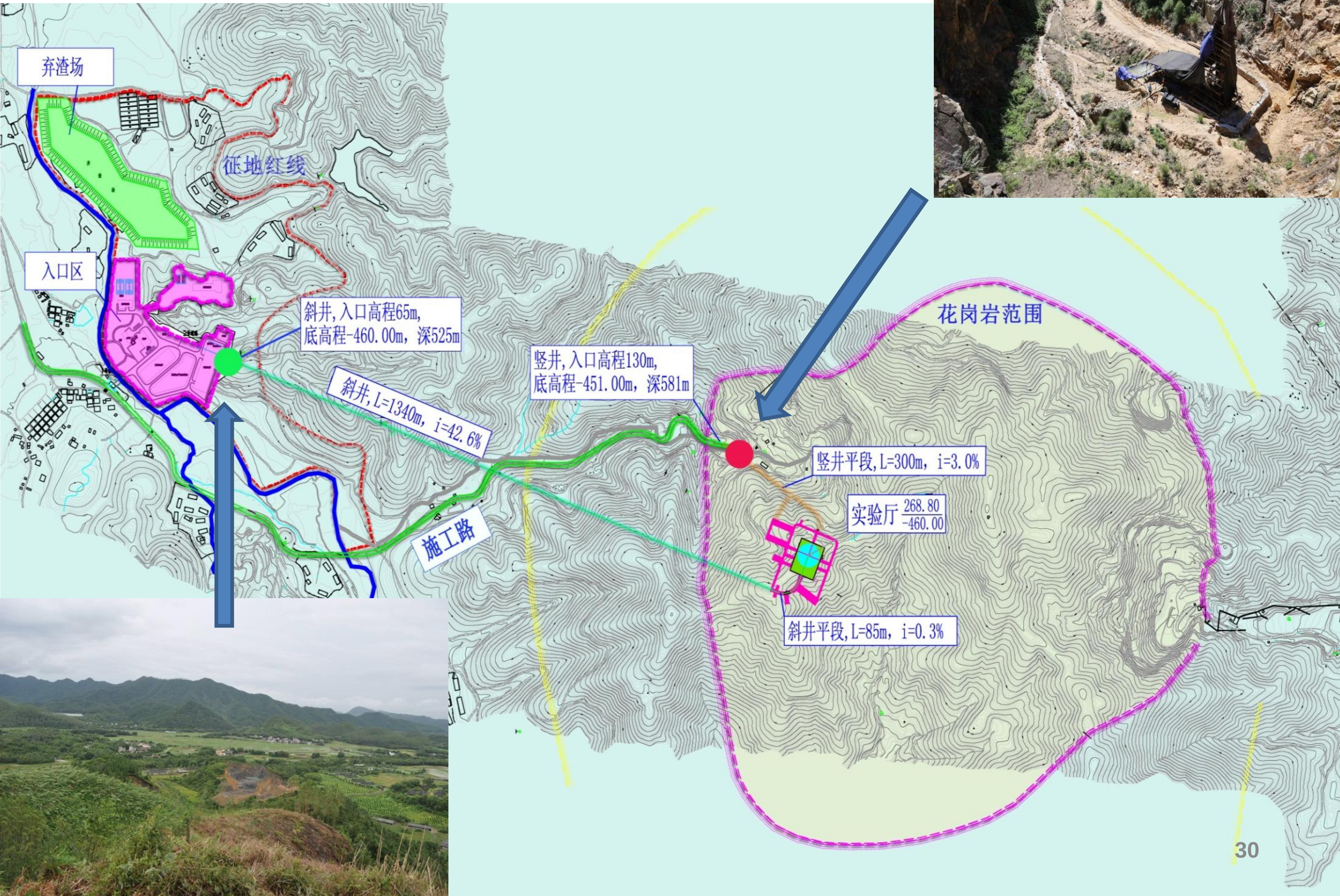
- Dismounting schedule:
  - mid-2015: first OPERA super module (31 TT walls, 248 modules)
  - beginning 2016: second OPERA super module (31 TT walls, 248 modules)
  - storage of all TT modules in Gran Sasso in containers up to the moment all dismounting is finished
  - send all TT containers (10) to Kaiping ~Spring 2016 if storage buildings already available
- Mounting in JUNO: ~2019

Civil Construction

A 600m vertical shaft
A 1300m long tunnel(40% slope)
A 50m diameter, 80m high cavern



Layout


弃渣场
入口区
征地红线
斜井, 入口高程65m,
底高程-460.00m, 深525m
斜井, L=1340m, i=42.6%
竖井, 入口高程130m,
底高程-451.00m, 深581m
花岗岩范围
竖井平段, L=300m, i=3.0%
实验厅 268.80 / -460.00
斜井平段, L=85m, i=0.3%
施工路

Current Status & Brief Schedule

- **Project approved by CAS for R&D and design**
- **Geological survey completed**
  - Granite rock, tem. ~ 31 ^{o}C, little water
- **Engineering design underway**
- **Detector design and R&D underway**
- **International Collaboration: China, Czech, France, Germany, Italy, Russia, US, …**

Schedule:

Civil preparation：2013-2014

Civil construction：2014-2017

Detector R&D：2013-2016

Detector component production：2016-2017

PMT production：2016-2019

Detector assembly & installation：2018-2019

Filling & data taking：2020

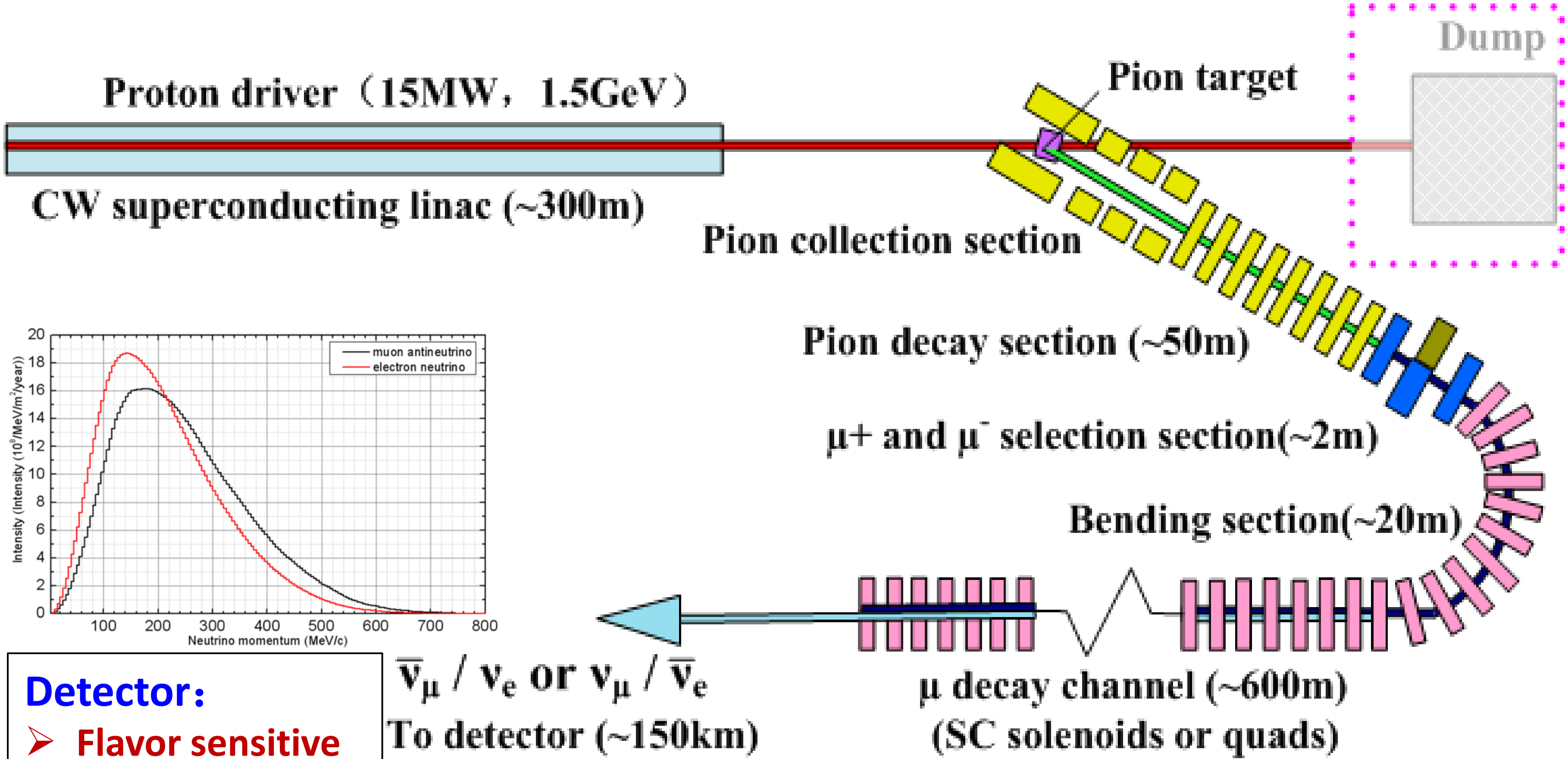
Summary

- Neutrino physics is very exciting
- We know θ_{13} now
- We will soon know mass hierarchy

Thanks

谢谢

A New Type of Neutrino Beam for CP (MOMENT)



Detector:

- Flavor sensitive
- Charge sensitive
- NC/CC sensitive

Neutrinos after the target/ collection/decay:

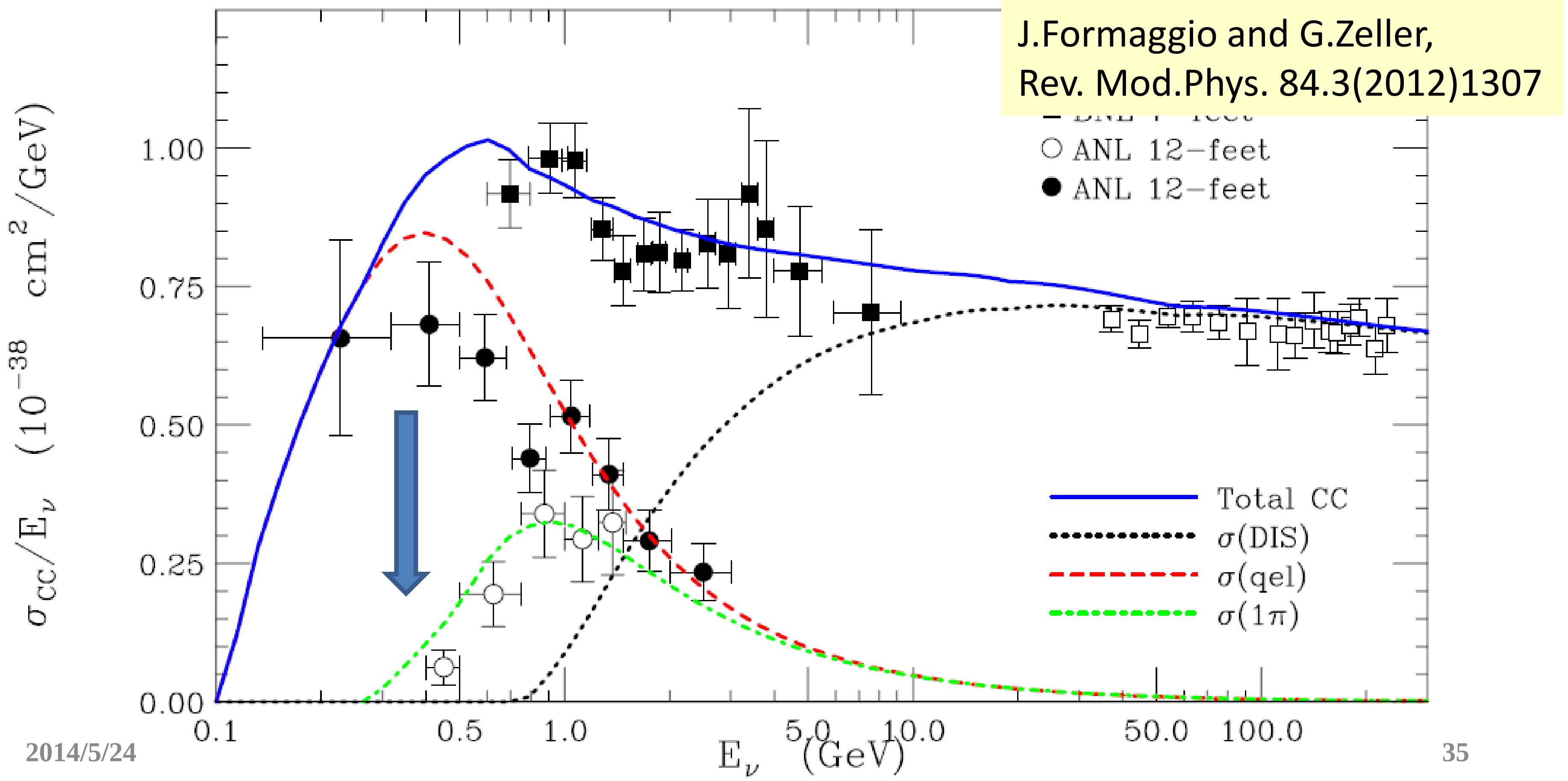
〉 10^{21} ν/year

Comparison

	ν Factory	Super pi beam	MOMENT
Neutrino energy	2-4 GeV	0.3-0.7， 2-4 GeV	300 MeV
Neutrino source	Muon decay	Pi decay	Muon decay
Beam backgrounds	no	high	low
Neutrino flux	10^{21}/year	10^{18-21}/year	5×10^{21}/year
Proton driver	Pulsed 8-16 GeV 4 MW	Pulsed 5-400 GeV 1-5 MW	CW 1.5 GeV 15 MW
Target	Mercury	Mercury	?
Collection	Horn	Horn	SC magnet
Decay pipe	Storage ring	Vacuum pipe	SC magnet
cooling	yes	No	No
Muon acceleration	yes	No	No
cost	High	low	low

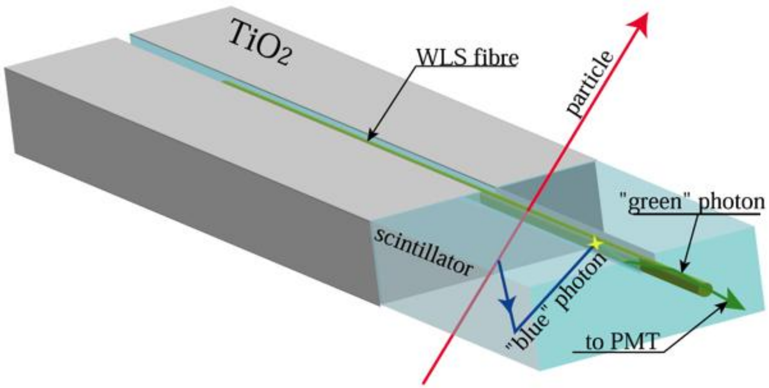
Best energy for CP ?

- **Below in-elastic threshold: ~ 300 MeV ➔ baseline = 150 km**
- **Such a threshold is similar for CC/NC & ν/νbar**
- **Although we loose statistics due to the lower cross section, but we have less systematics by being π^0 free**



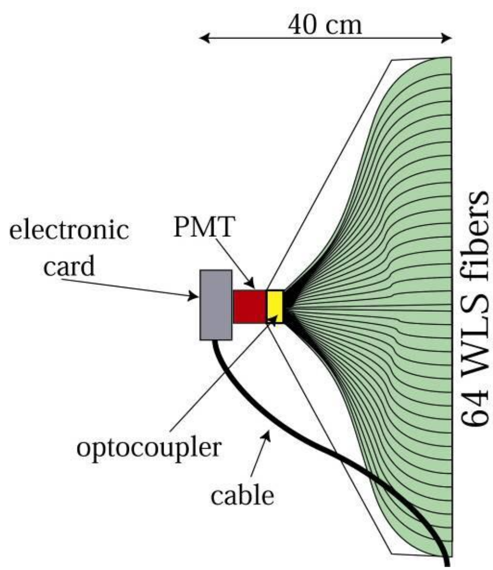
Target Tracker

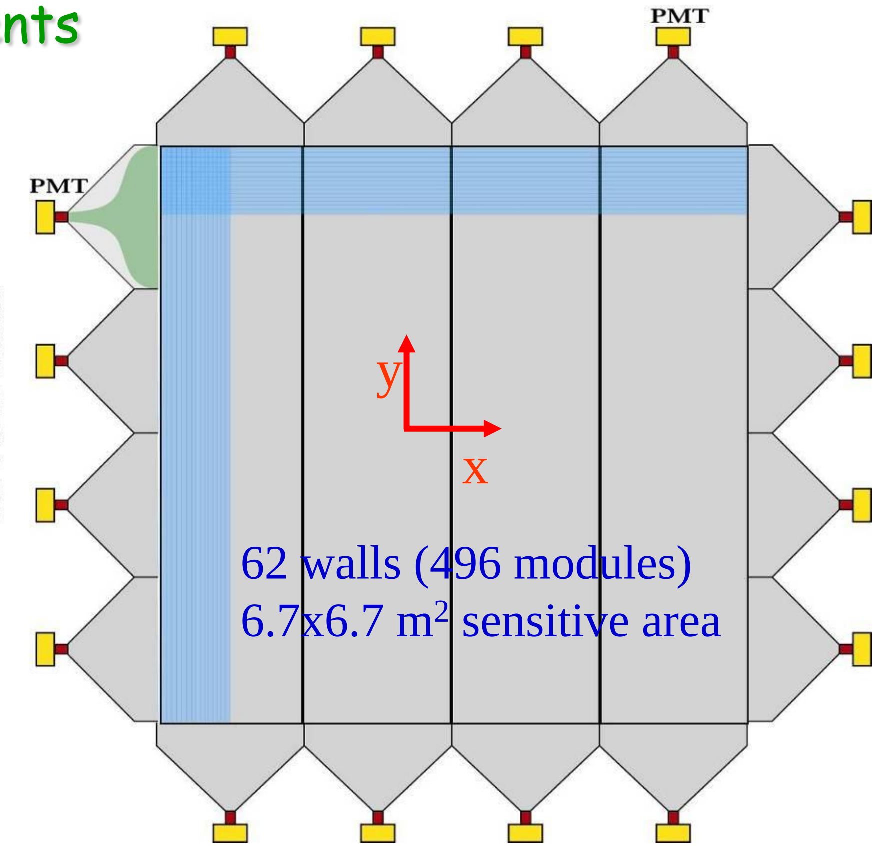
(Bern, Brussels, CERN, Dubna, Neuchâtel, Orsay, Strasbourg)



- detection technique: polystyrene scintillating strips (plastic)
- role:
  - find the "good" Pb/emulsion brick
  - calorimetric information on neutrino events

992 Hamamatsu
MA-PMTs
(64 channels)
3x3 cm^2





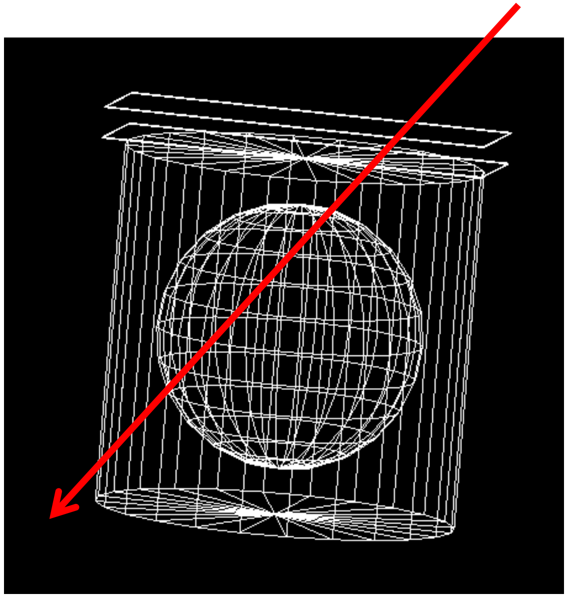
62 walls (496 modules)
6.7x6.7 m^2 sensitive area

The TT in JUNO
(motivation)

- OPERA TT will be a very good tracker for JUNO
  - Strip width is 2.63 cm, with a position resolution ~ 7.8 mm
  - Many layers can be used for cosmic muon tracking
  - Will give better precision than JUNO water pool (WP) and anti-neutrino detector (AD).
- The addition of top tracker (TT) above AD and WP can help to do many physics studies
  - Measure precisely the muon angle distribution
  - Verify the muon reconstruction with the rest of the JUNO detector
  - Monitor WP or AD running stability
  - Measure neutron background muon distance in AD (more precisely than WP or AD)
  - Measure rock neutrons (placed at the edges to measure rock neutron background and then deduce the whole rock neutron background for JUNO)
  - Measure $^{9}Li/^{8}He$ background.
    - $^{9}Li/^{8}He$ production is the main background source for mass hierarchy measurement in JUNO.
    - Partly measurement of $^{9}Li/^{8}He$ background produced in AD
    - Partly measurement of $^{9}Li/^{8}He$ background produced in water pool
- The TT will also help to simulate the cosmogenic background

Possible Configuration of the Top Tracker

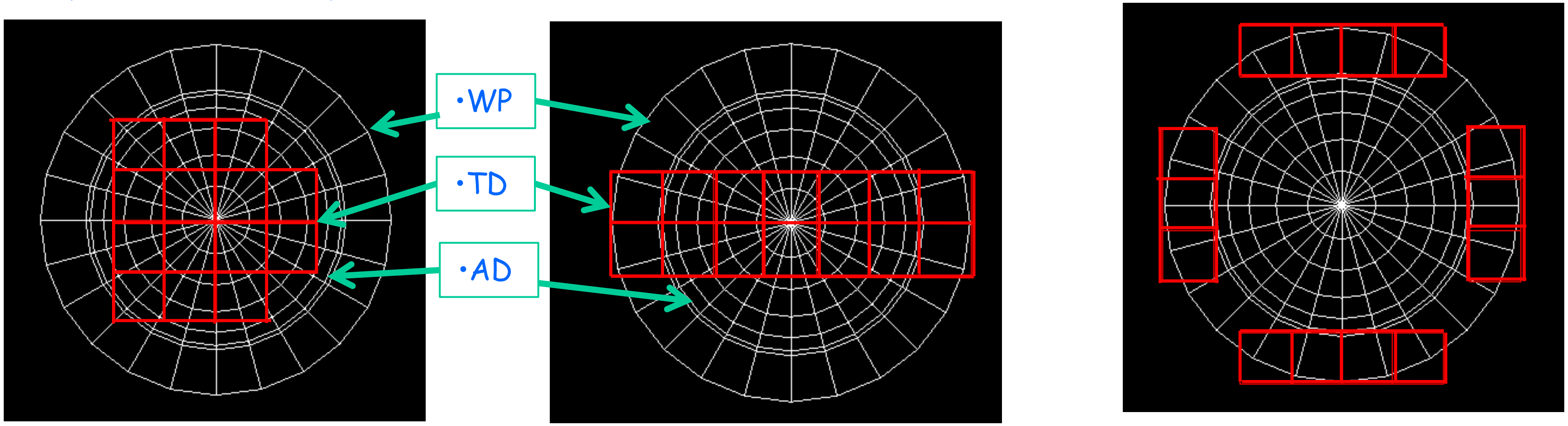
- 56 x-y walls (6.7m × 6.7m each)
- 14 TT stations, 4 walls each.
- each station is composed of 2 layers of 2 TT walls separated by 4 m distance.
- Distance of lowest and upper wall: 4 m
- Distance of lowest plane from water pool: 1 m.
- Different configurations (Middle, Rectangle, Around)
- Covered area is about $630m^2$.



- 4XY Middle (Mid)
- (3 × 4+2 modules)

- 4XY Rectangle(Rtg)
- (2 × 7 modules)

- 4XY Around("O")
- (2 × 4+2 × 3 modules)

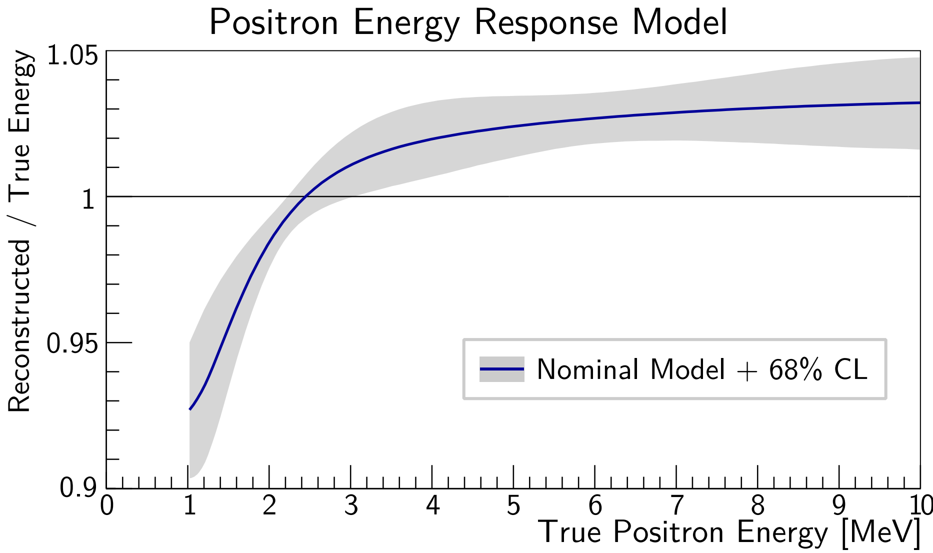


Building Non-Linearity Models

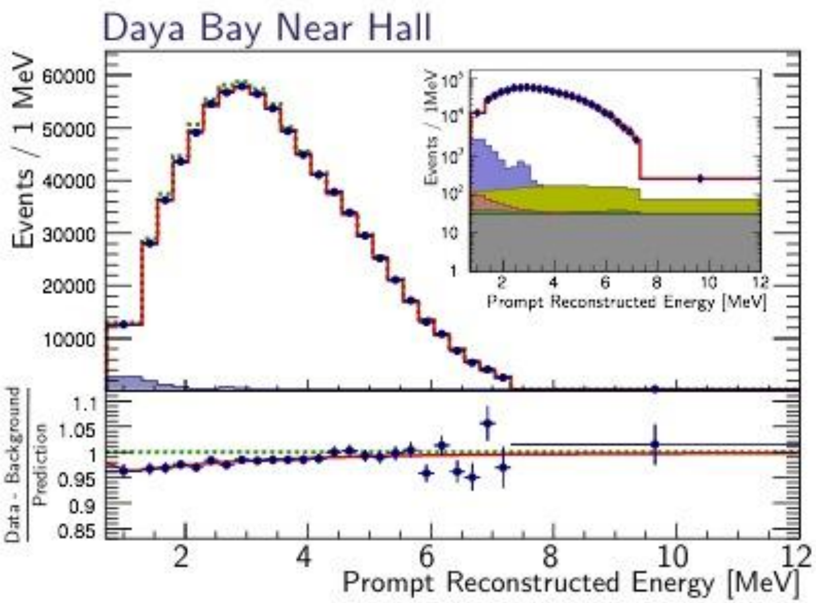
- Method 1:
  - All parameters determined by simultaneous fit
- Method 2
  - Birks constant and Cherenkov contribution by bench measurements
  - Electronics response from quadratic fit to gamma data
- Method 3
  - Birks constant by bench measurements
  - Cherenkov and electronics from exponential fit to all 4 + spectra

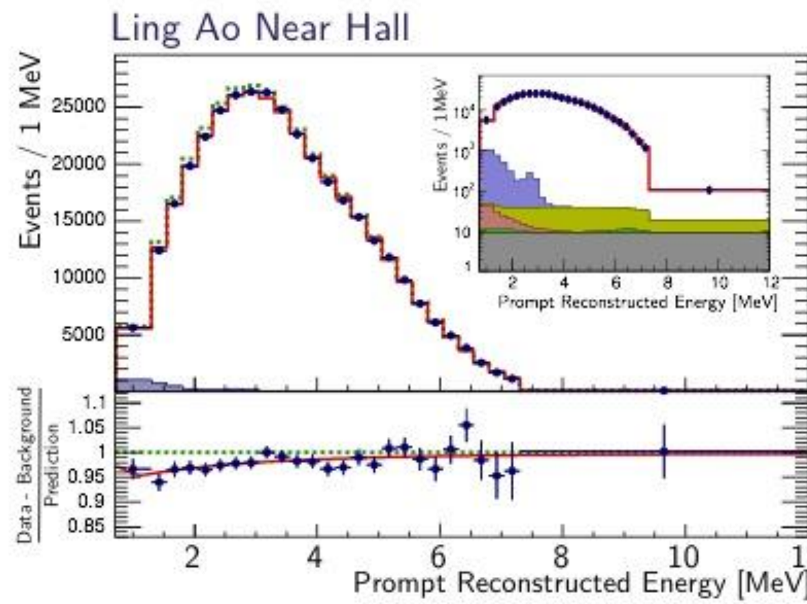
Non-linearity models by different parameterizations & weighting of data constraints:

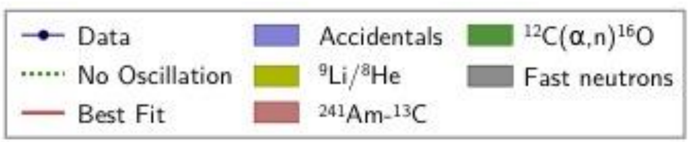
- ✓ 5 Models with minimum correlations selected, consistent within 1.5%
- ✓ Uncertainty is conservatively estimated by the curves+uncertainties in 68% C.L.

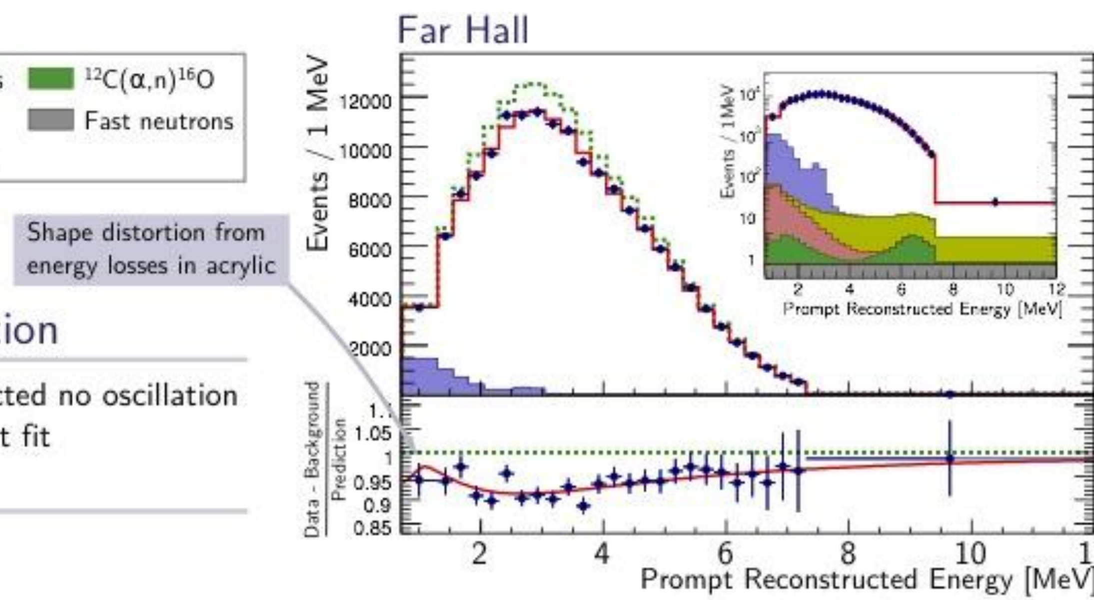


Prompt IBD spectra (~E_ν)





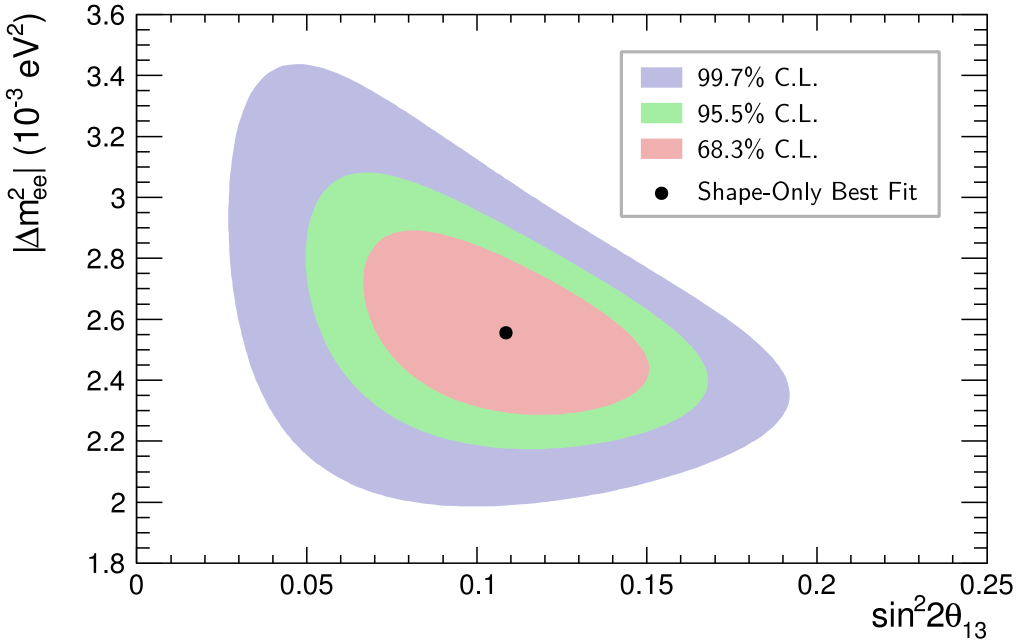




Spectral distortion consistent with oscillation

- Both background and predicted no oscillation spectrum determined by best fit
- Errors statistical only

Pure Spectral Analysis



$$\sin^2 2\theta_{13} = 0.108 \pm 0.028$$

$$|\Delta m^2_{ee}| = 2.55^{+0.21}_{-0.18} \cdot 10^{-3}\,\mathrm{eV}^2$$

$$\chi^2/N_{\mathrm{DoF}} = 161.2/148$$

θ_{13} = 0 can be excluded at > 3σ from spectral information alone

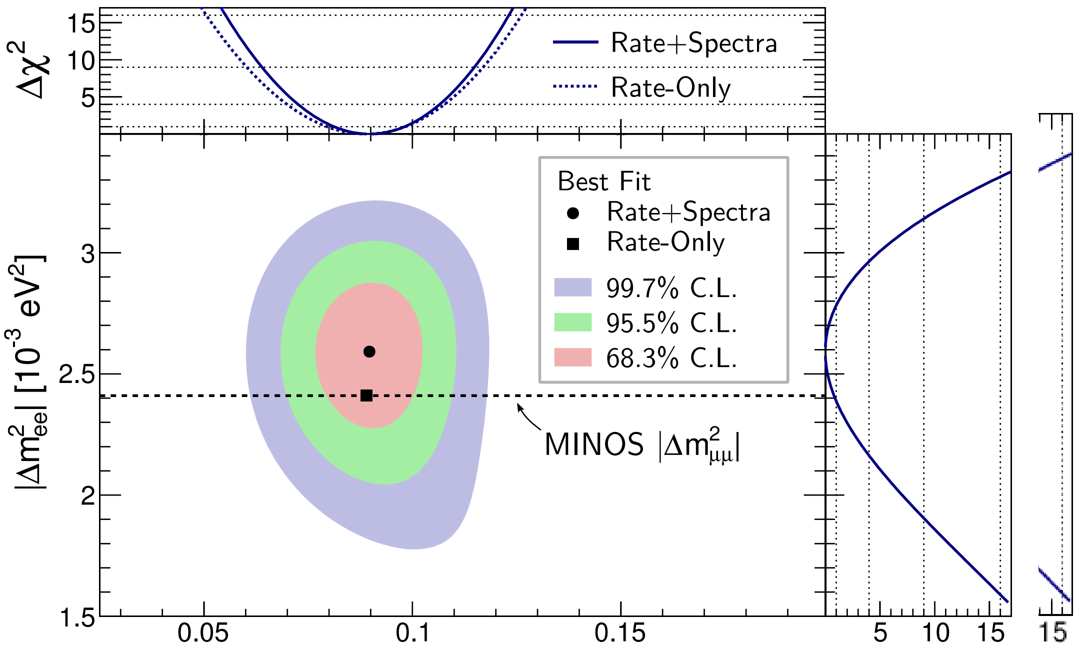
- For each AD, total event prediction fixed to observed data:

1	θ_{13} free-floating:	$\chi^2/N_{\mathrm{DoF}} = 161.2/148$
2	$\theta_{13} = 0$:	$\chi^2/N_{\mathrm{DoF}} = 178.5/146$

$\Rightarrow \Delta\chi^2/N_{\mathrm{DoF}} = 17.3/2$, corresponding to $p = 1.75 \cdot 10^{-4}$

Rate+Spectra Oscillation Results

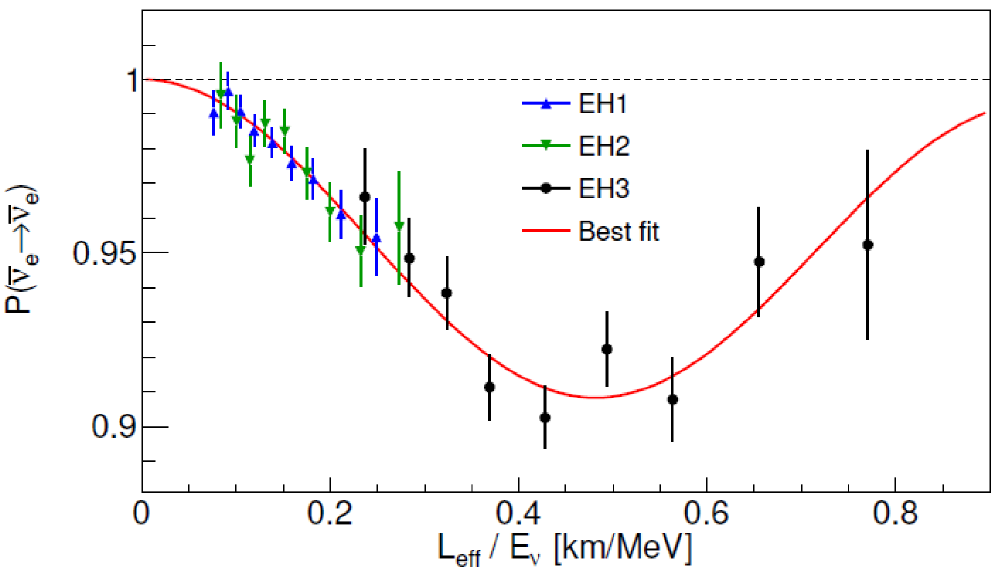
arXiv:1310.6732



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

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

$$\chi^2/N_{\mathrm{DoF}} = 162.7/153$$



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

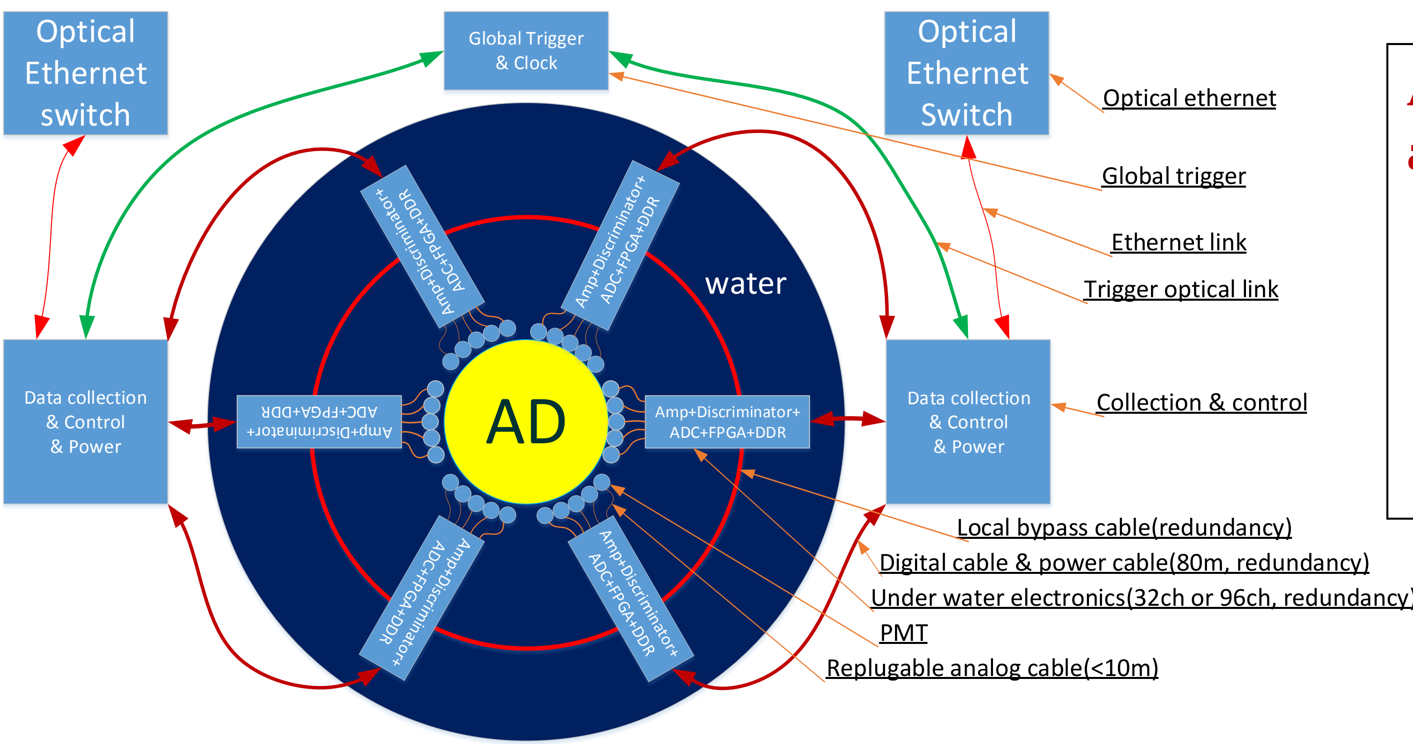
$$\Delta m^2_{\mu\mu} \sim 0.3\Delta m^2_{31} + 0.7\Delta m^2_{32} + CP$$

Readout Electronics and Trigger

- **Charge and timing info. from 1 GHz FADC**

Total No. channel	20,000
Event rate	~ 50 KHz
Charge precision	1 – 100 PE: 0.1 – 1 PE; 100-4000PE: 1-40PE
Noise	0.1 PE
Timing	0-2us: ~ 100 ps

- **Main Choice to be made: in water or on surface**



An option to have a box in water:

- ~100 ch. per box
- Changeable in water
- Global trigger on surface

Interests from APC & others

JUNO-FR: APC+Omega+Subatech laboratories…

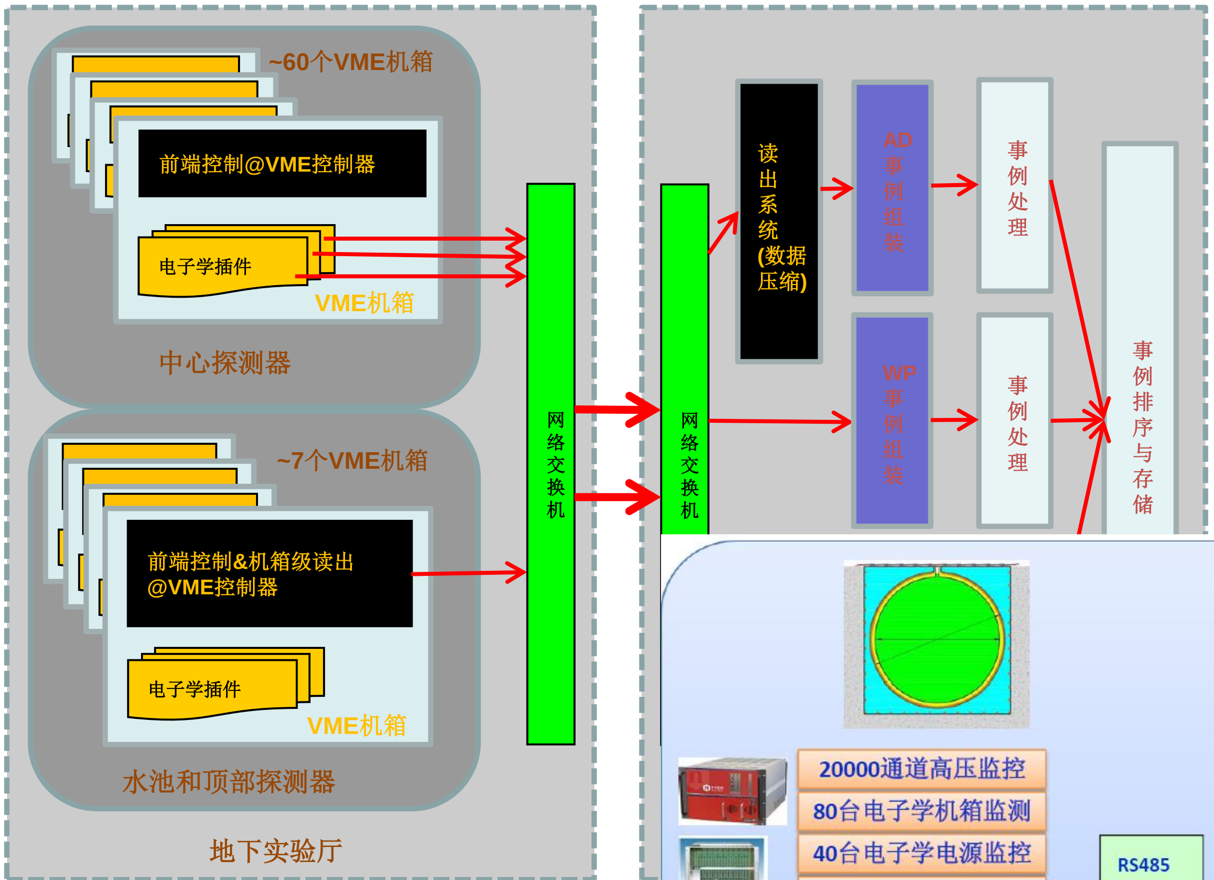
- **France:** 3 laboratories so far (not coming from OPERA) [see OPERA slides]
    - **APC** (Paris): A. Cabrera + H. de Kerret [Double Chooz]
    - **Omega** (Paris): C. de la Taille [ASIC development→ many application]
    - **Subatech** (Nantes): F. Yermia [Solid/Double Chooz/Nucifer]

- **relevant expertise towards JUNO…**
    - **Double Chooz experience [APC + Subatech]**
        - expertise on detector, systematics, energy, backgrounds, MC, etc.
    - **electronics + online systems expertise [Omega+APC]**
        - (Omega) ASIC development: electronics for many experiments (CERN, etc)
        - (APC) Double Chooz FADC electronics (with CAEN) and DAQ
    - **reactor flux expertise [Subatech+APC]**
        - world's unique knowledge/techniques on reactor flux systematics (→Double Chooz input)

- **possible involvement in JUNO…**
    - DAQ's "event builder farm(s)" (à la SK-IV) + data-monitoring [APC+Subatech]
    - reactor flux systematics (AREVA reactors)→ solar high precision measurements [Subatech+APC]
    - electronics design [Omega+APC in tight collaboration with Aachen+Jüllich]

- **(beyond OPERA) tight partnership by 3 laboratories in France→ more members are welcome!**

DAQ and Detector Monitoring



Readout:2GB/s,

Storage:200MB/s