Future Reactor Experiments

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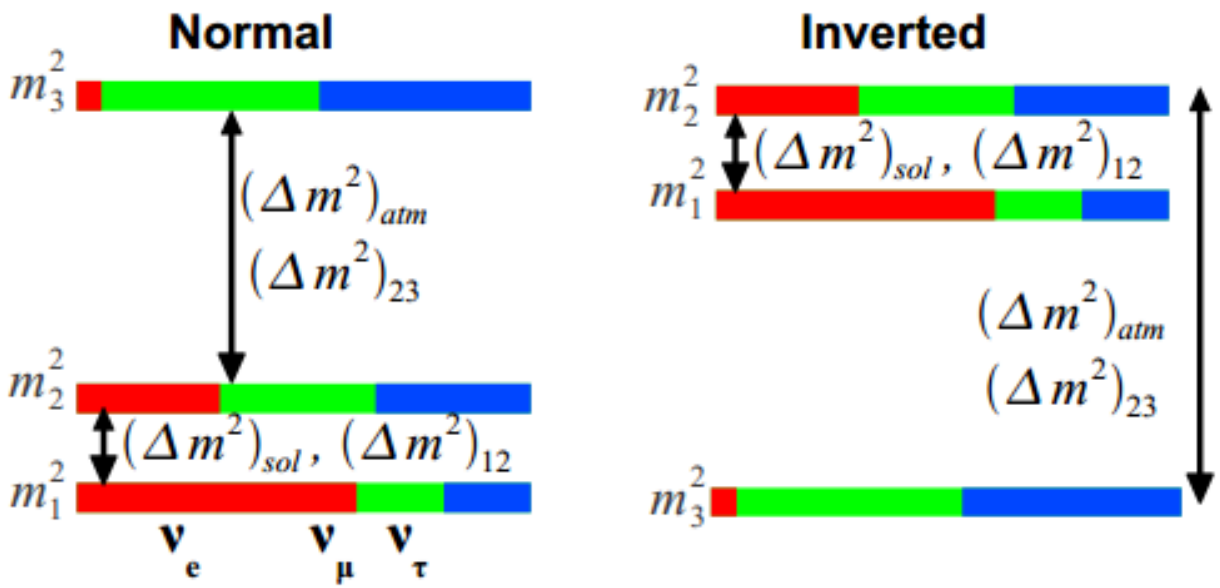
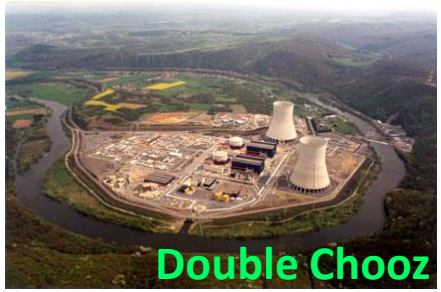
Future Reactor Experiments

that aim at resolving neutrino mass ordering



Running & Future Reactor Neutrino Exp.



θ_{13} companies

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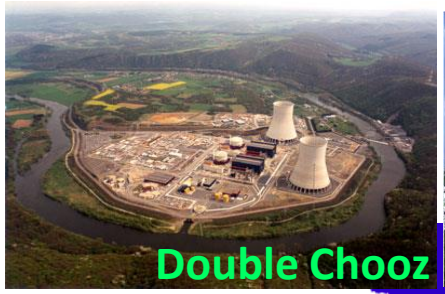

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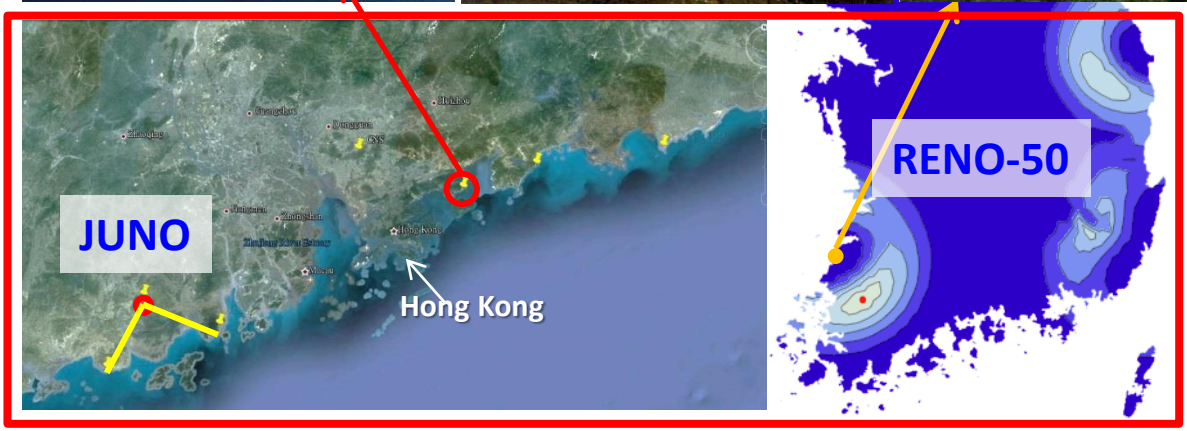

Mass Hierarchy

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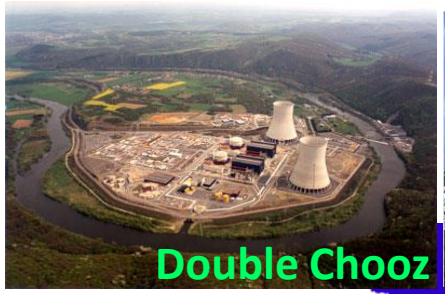

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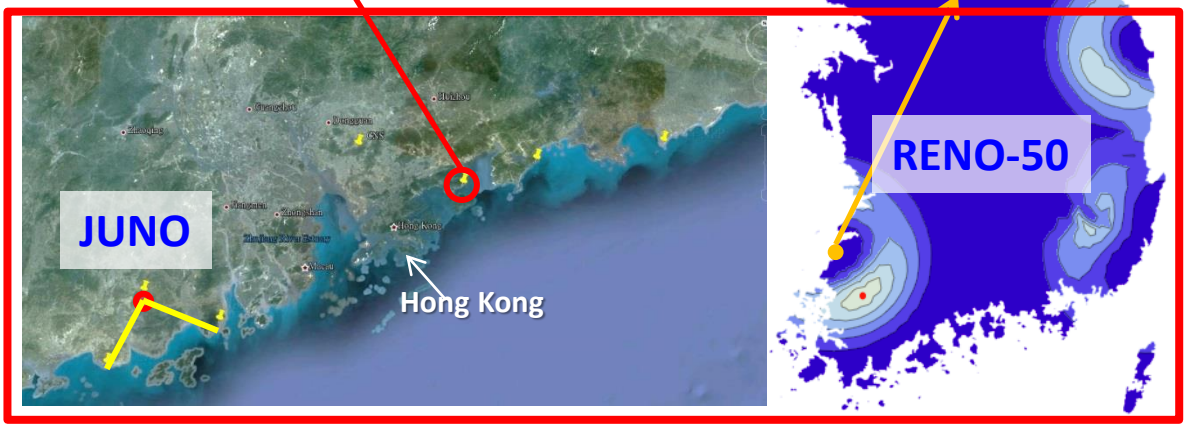
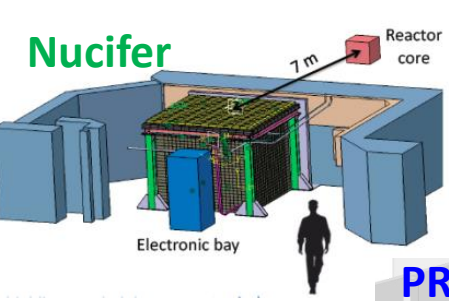


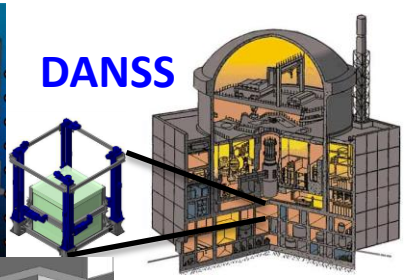
Mass Hierarchy

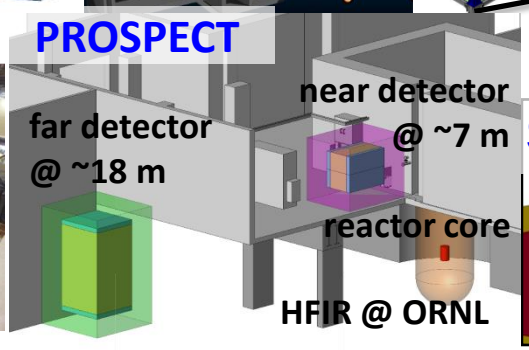
Sterile ν (see D. Lhuillier's talk)

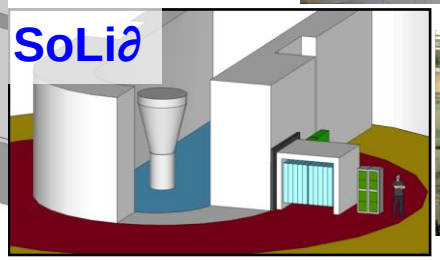
ν Scattering (see P. Barbeau's talk)

Apologies to the projects not be plotted here.

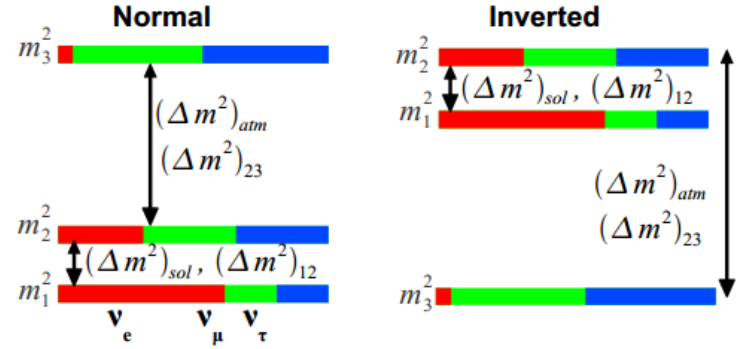




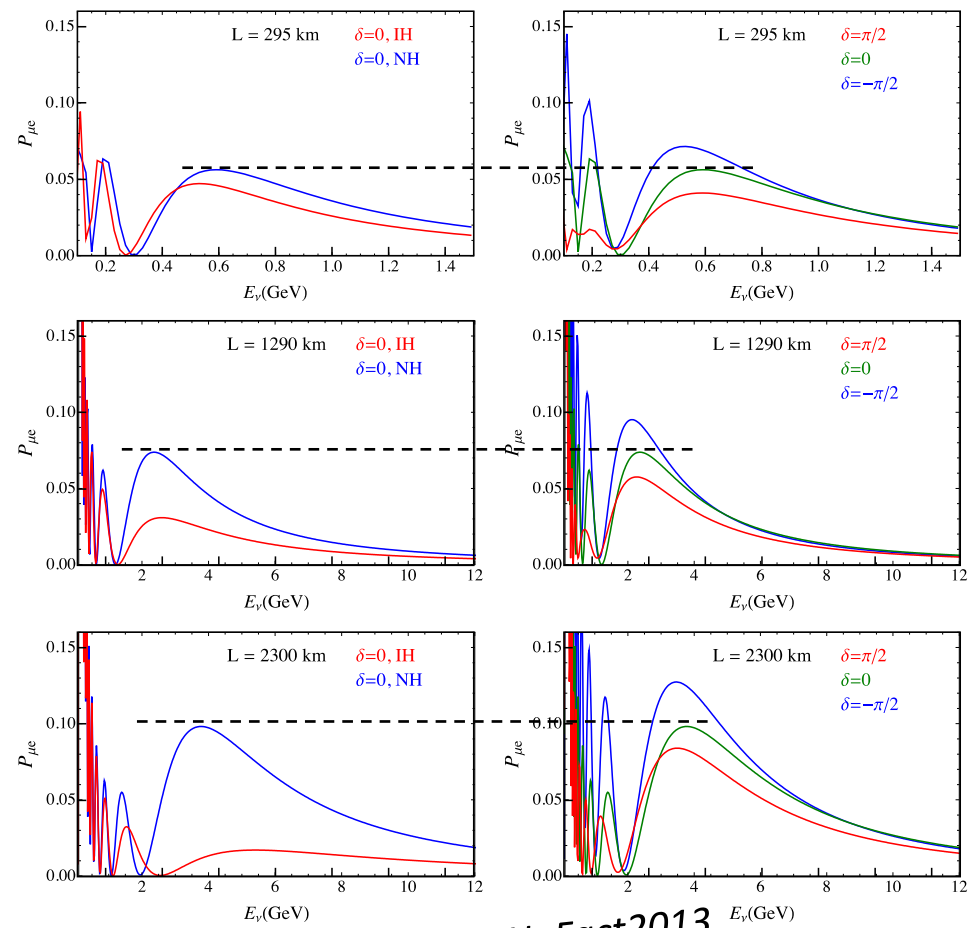




Neutrino Mass Hierarchy



- **Large θ_{13} open doors to MH**
  - **Utilize matter effects**
    - **e-ν CC interactions in the earth modulate the oscillation probability at long baselines (LBNE, LBNO, T2HK)**



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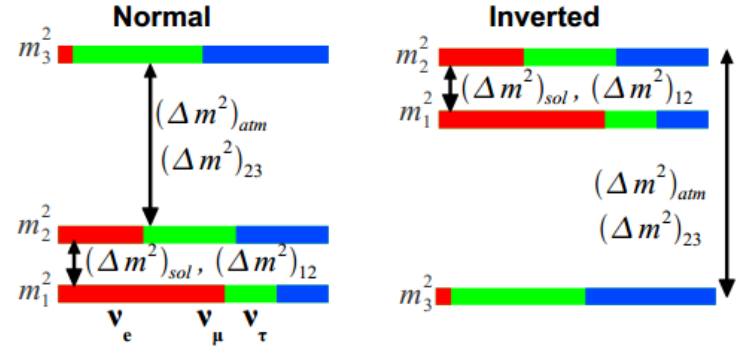

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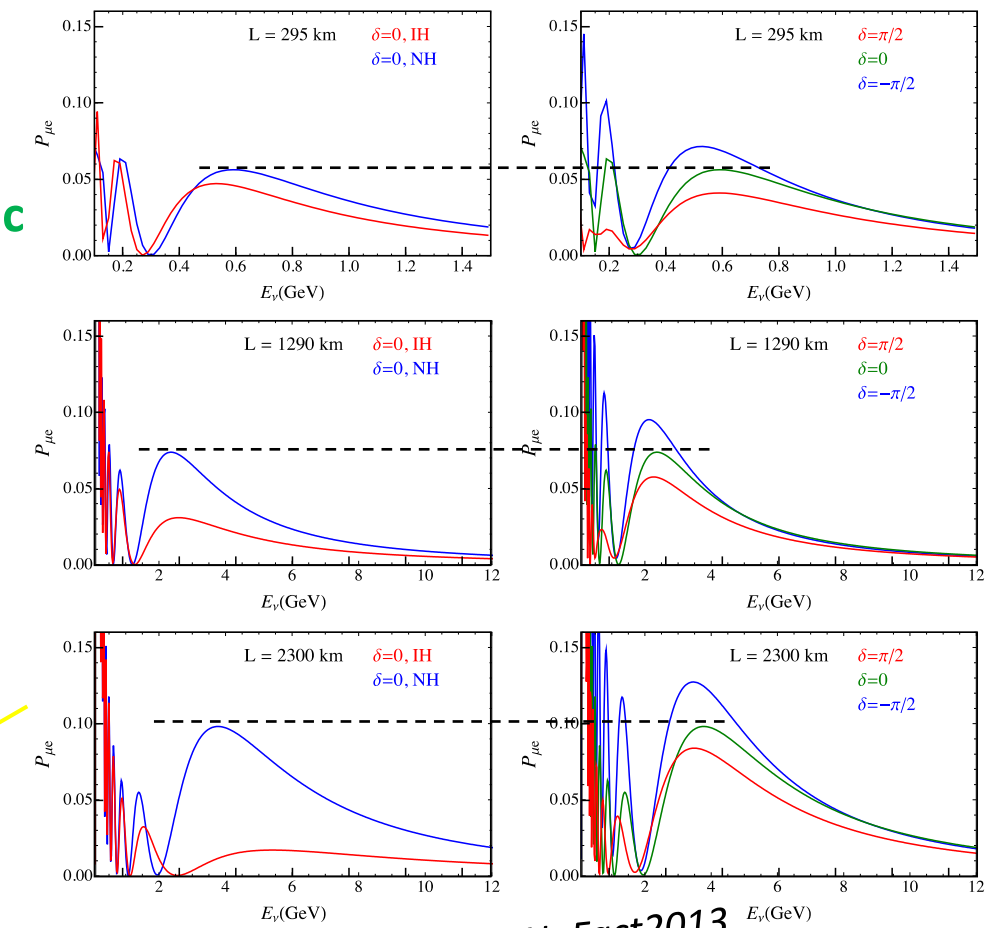

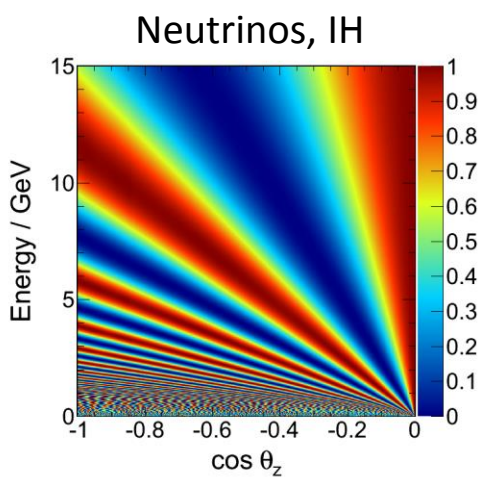

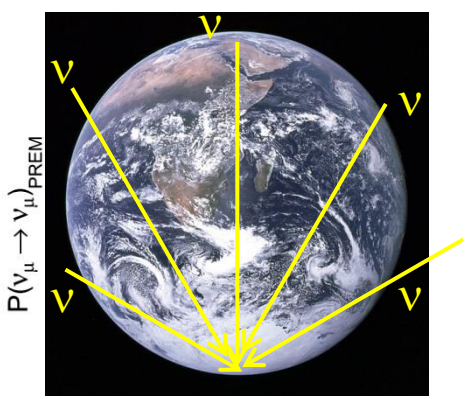

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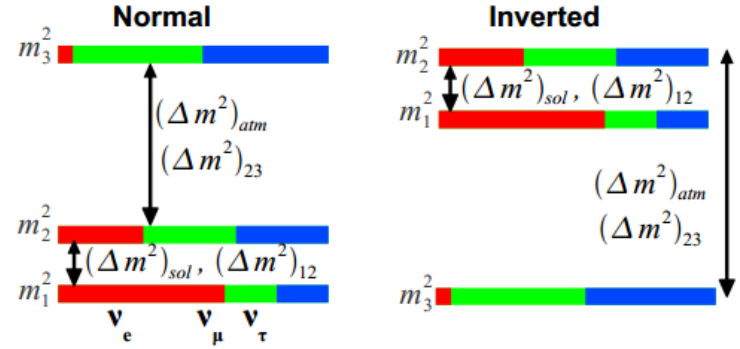

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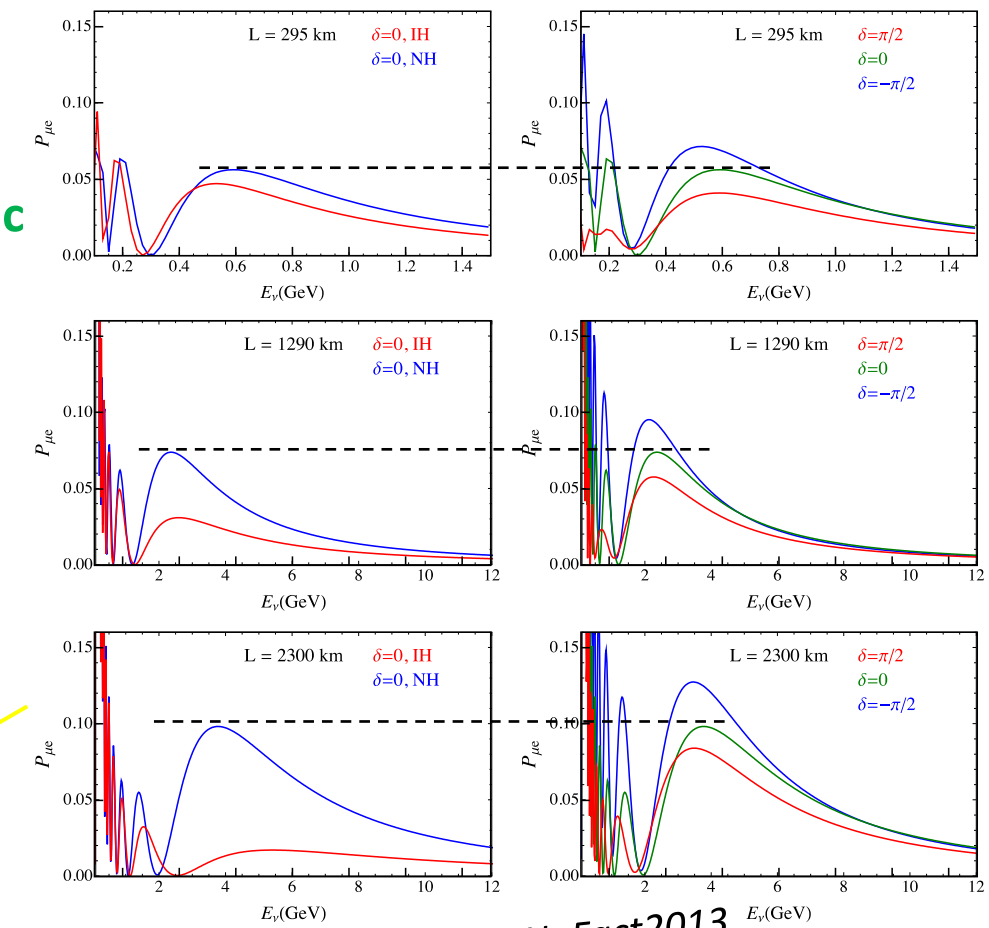
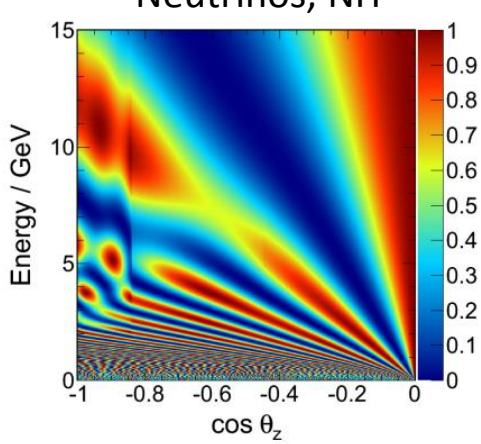
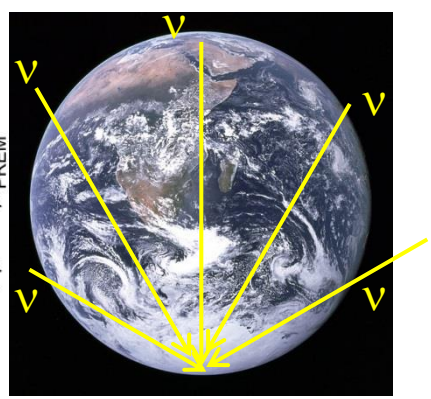


Neutrinos, NH





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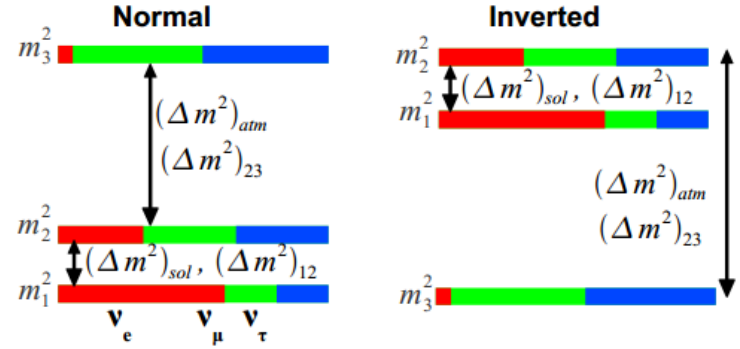

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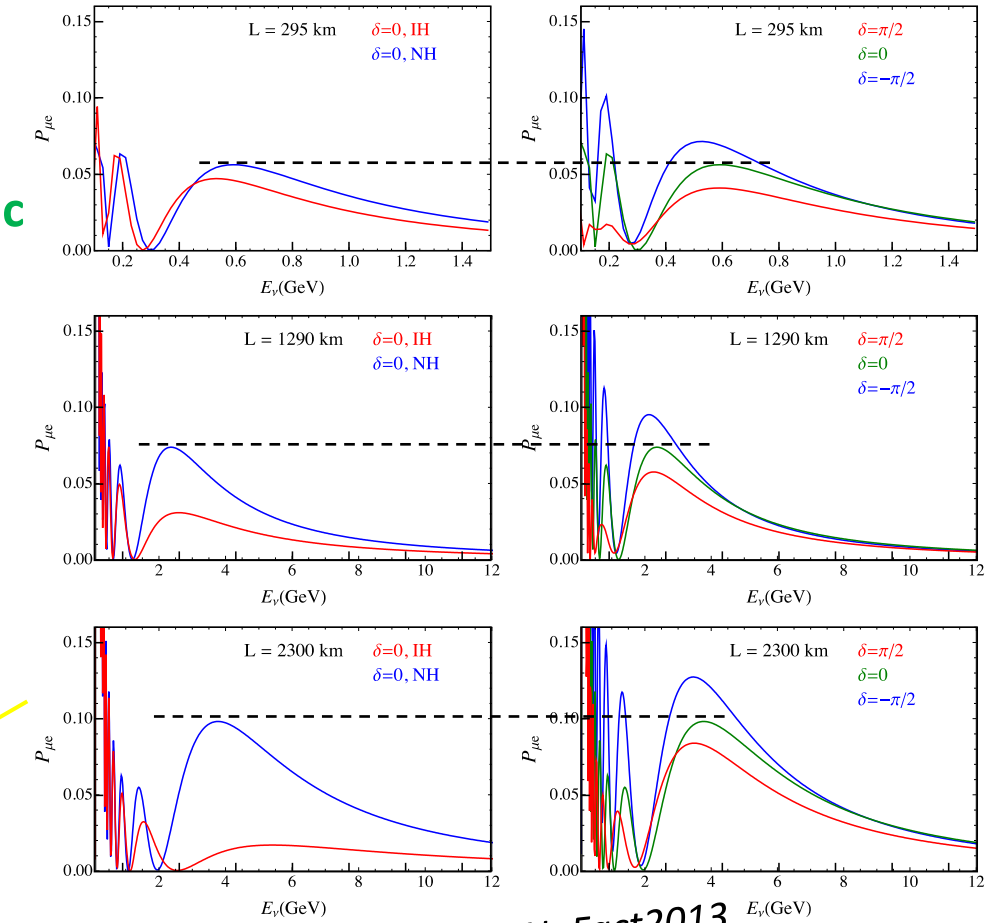
    - **Disappearance in atmospheric neutrinos (PINGU, HK, INO, ORCA)**
    - **Supernovae**



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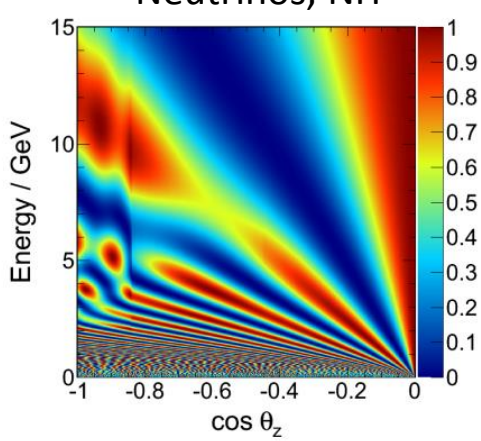

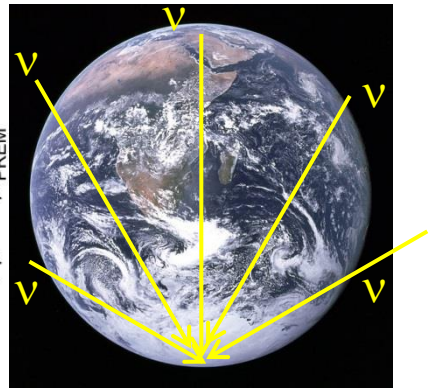

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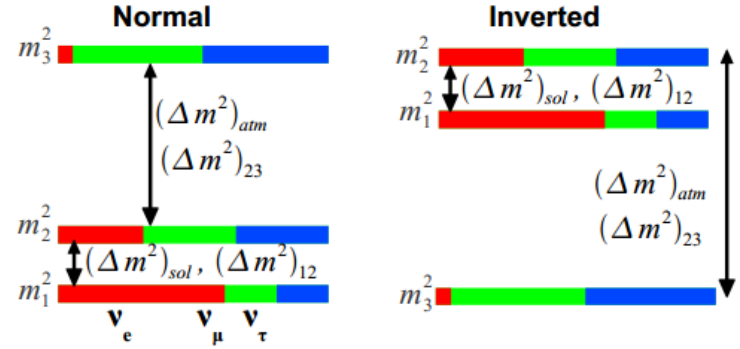

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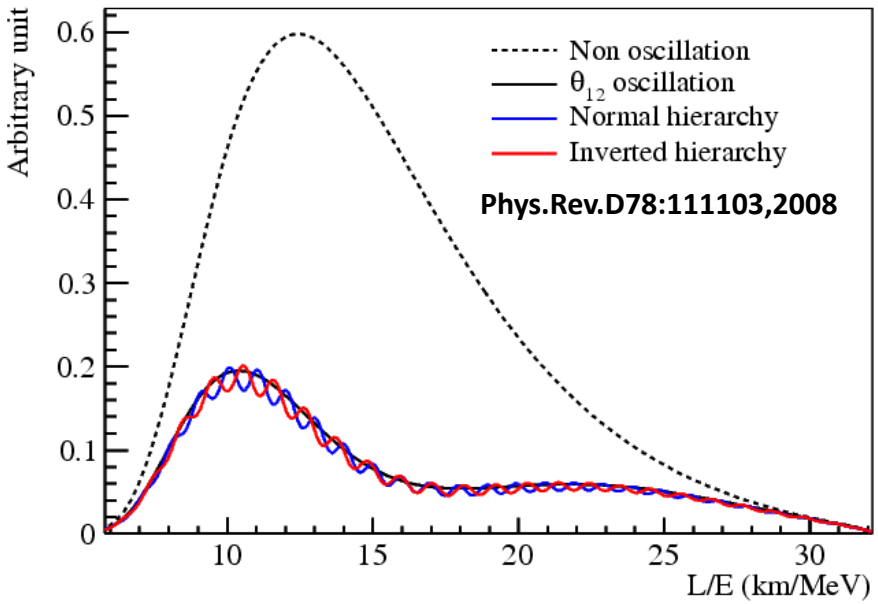

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\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
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S.T. Petcov et al., PLB533(2002)94
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Realistic requirements about determining MH with reactors will be discussed later

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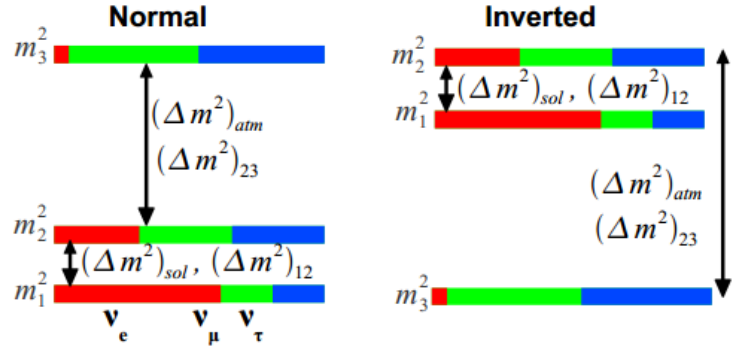

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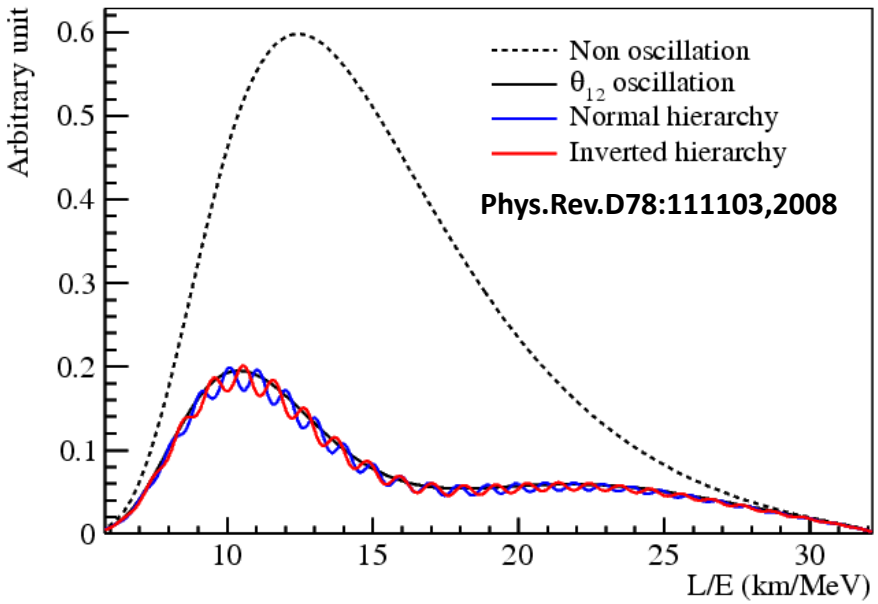

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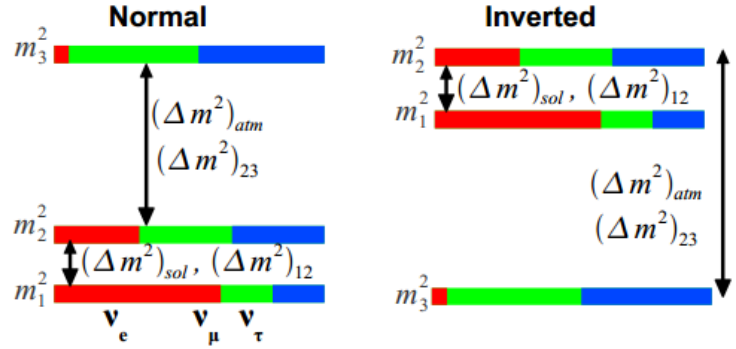

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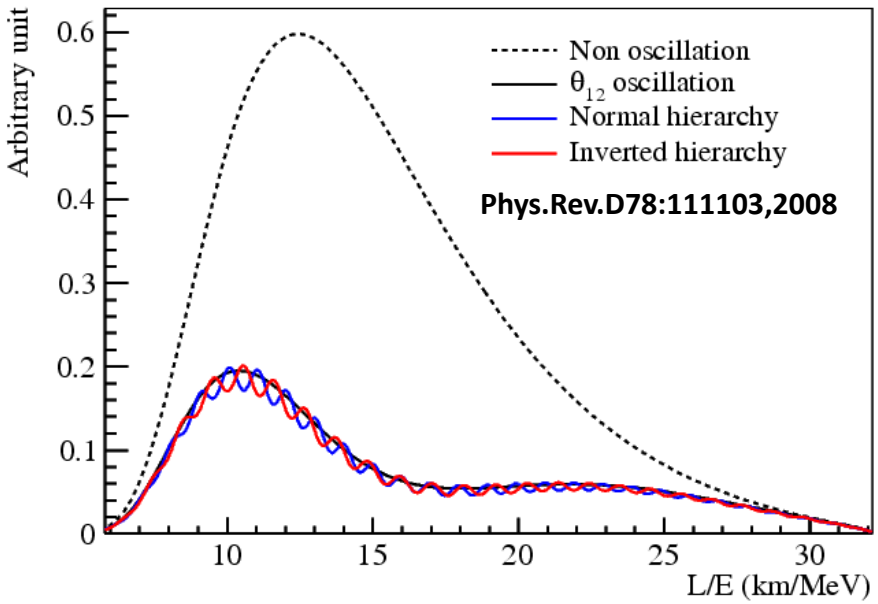

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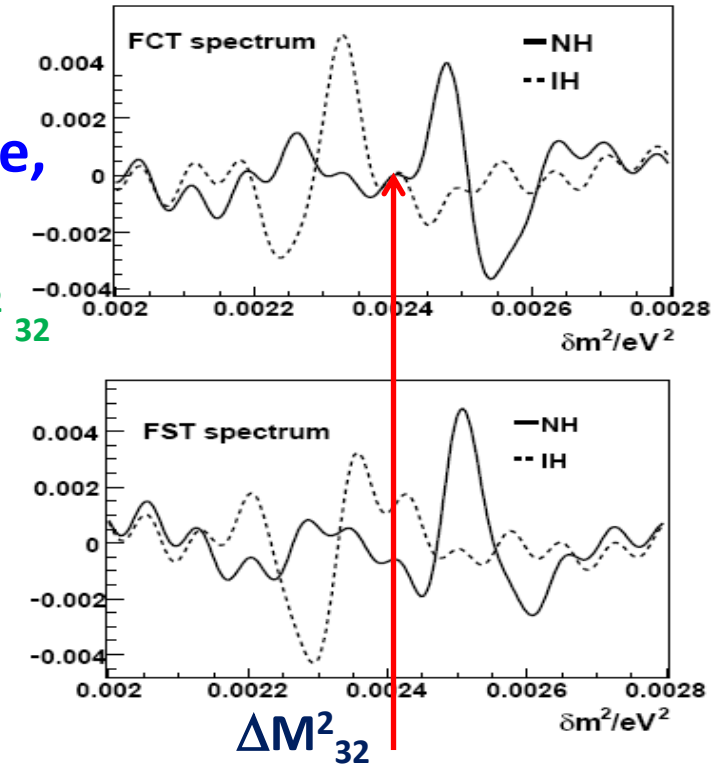
Independent on CP phase and θ_{23} (Acc. & Atm. do)
Energy Resolution is the key

Initial MH Sensitivity with FT method

- **Fourier transform enhances the visible features in ΔM^2 (oscillation frequency) regime, take ΔM^2_{32} as reference**
  - **NH (IH): ΔM^2_{31} peak at the right (left) of ΔM^2_{32}**
- **Distinctive features, no pre-condition of ΔM^2_{32}**



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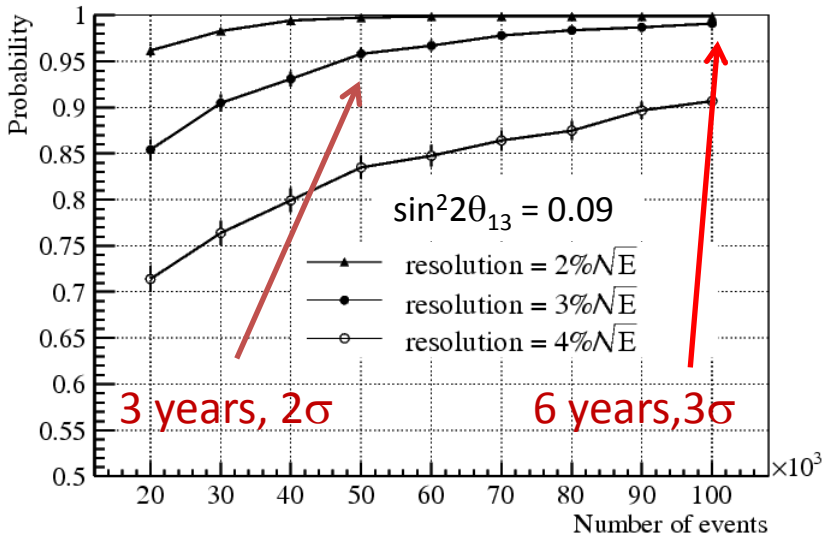

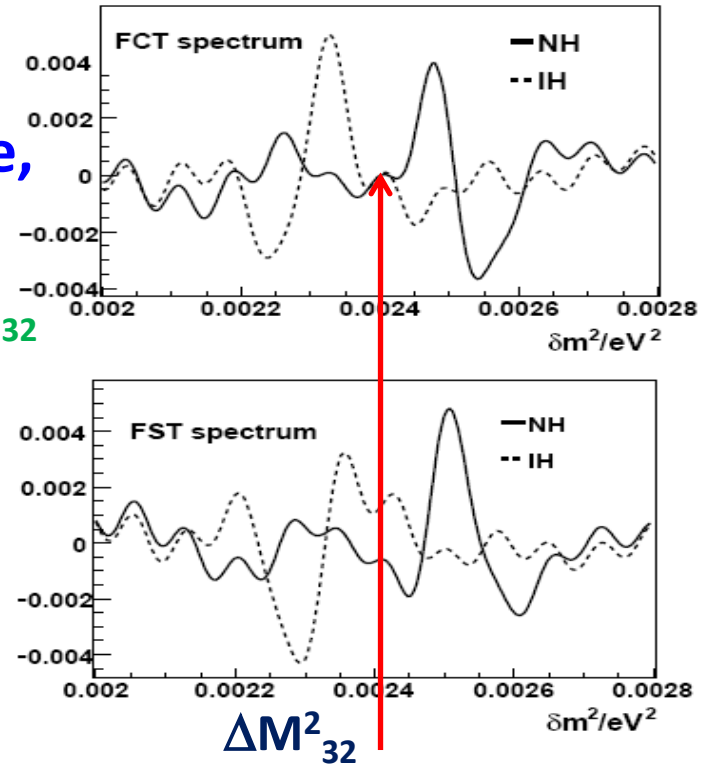

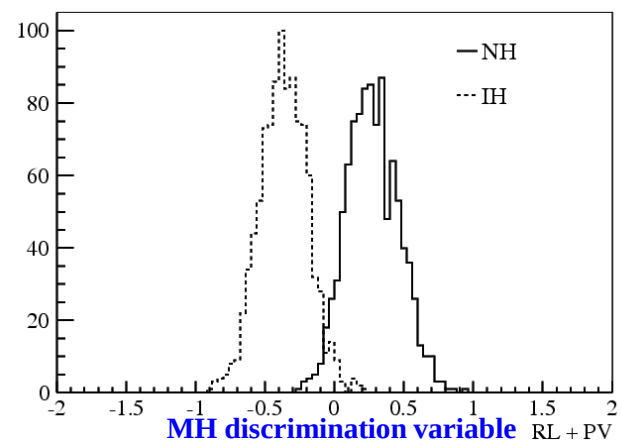

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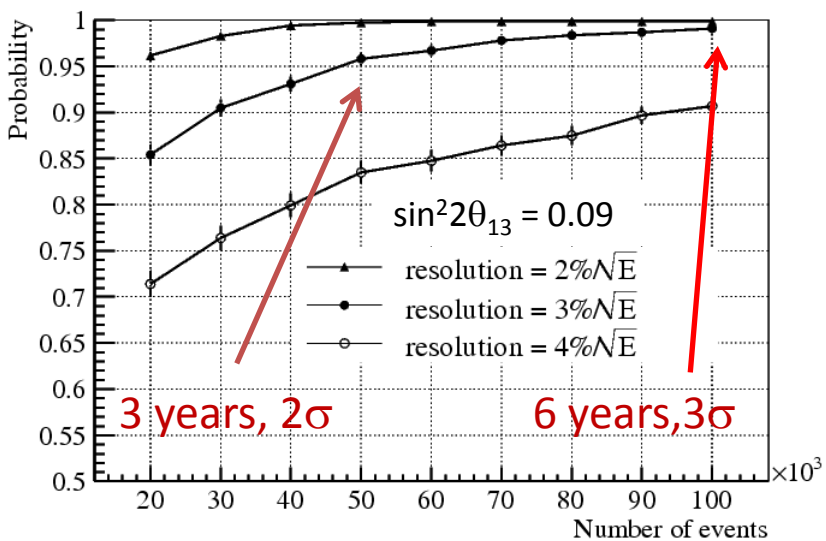
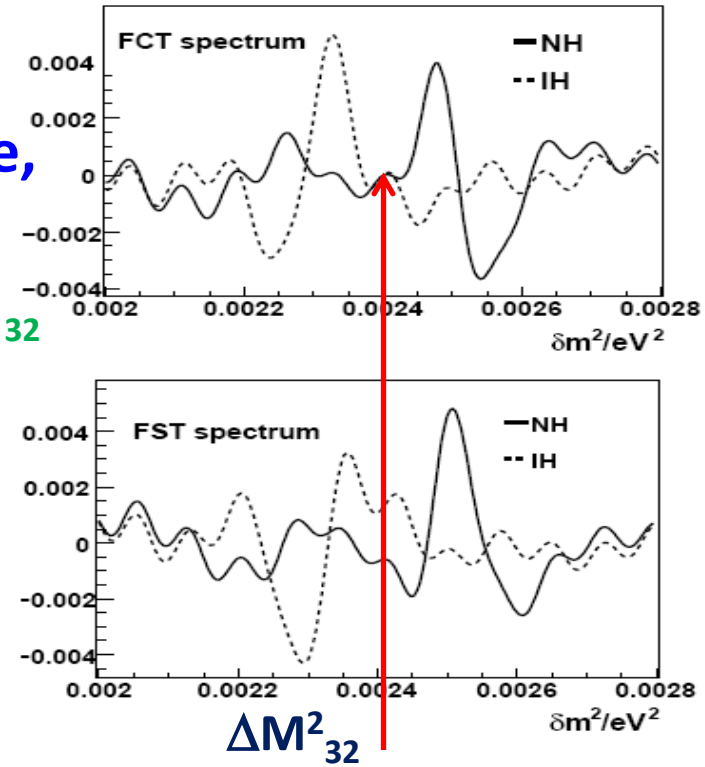
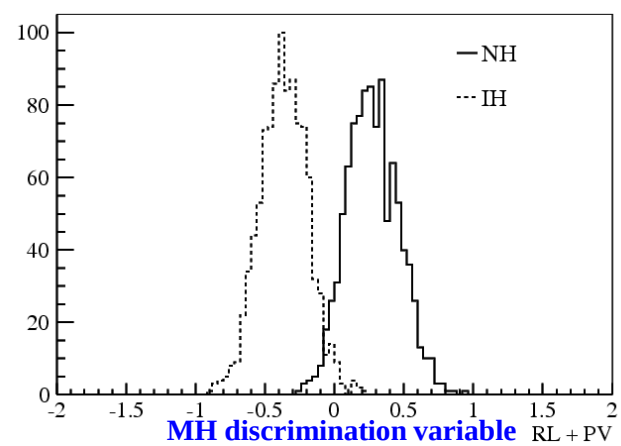






Experiment Concepts:

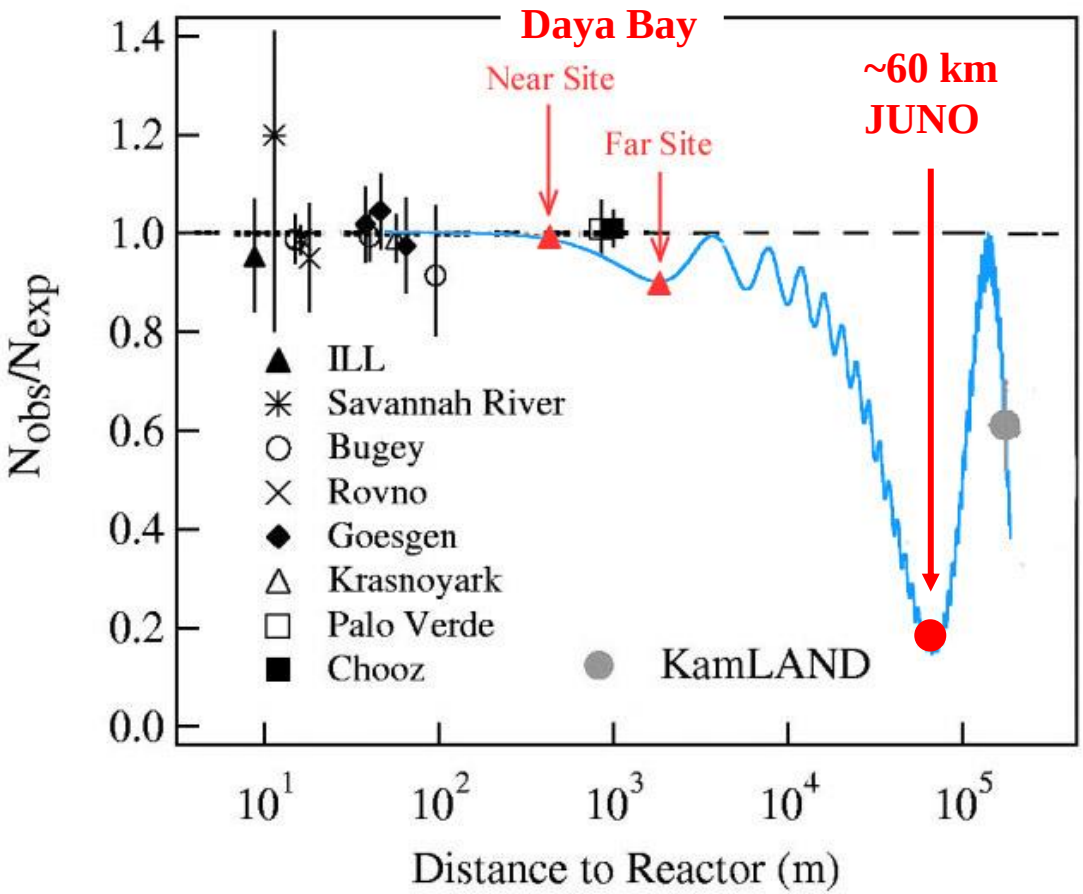
36GW reactors; 58km baseline

20 kton LS; 3%/$\sqrt{E}$ resolution;

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

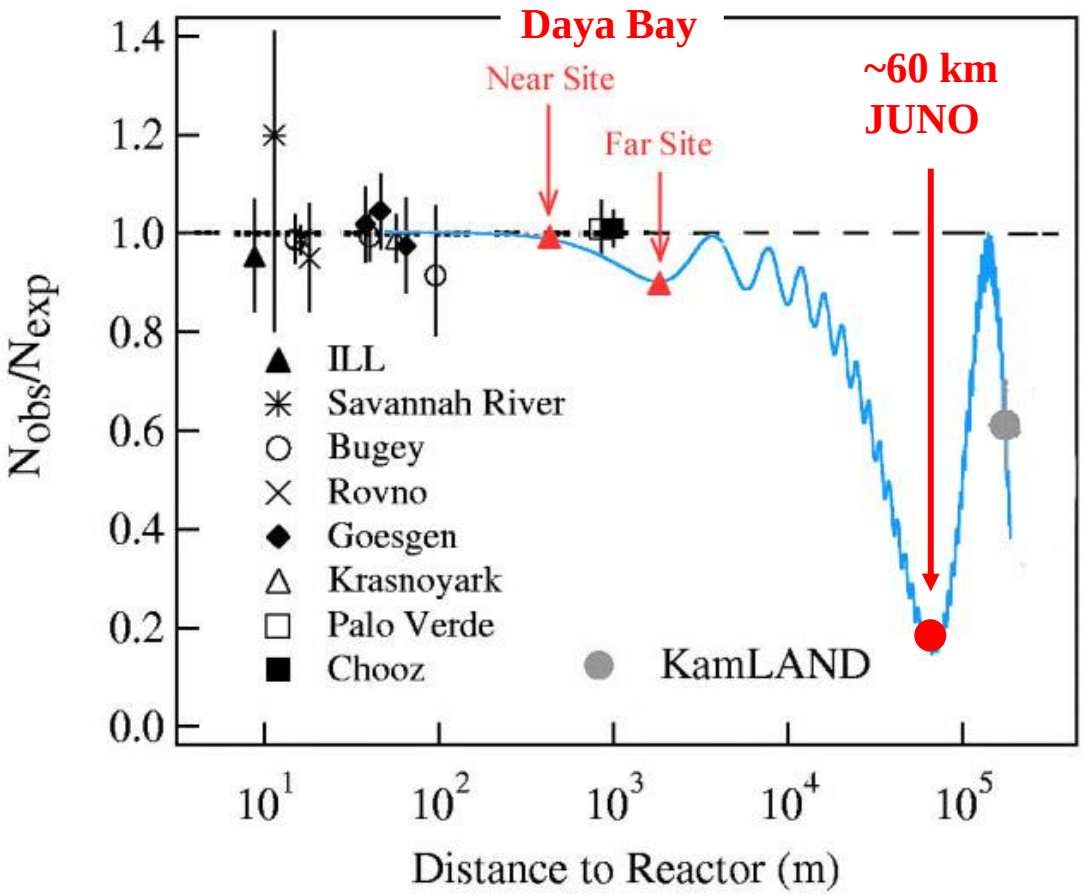
JUNO Experiment

- **Jiangmen Underground Neutrino Observatory** (was Daya Bay II)



JUNO Experiment

- Jiangmen Underground Neutrino Observatory (was Daya Bay II)
- Primary goals: mass hierarchy and precision meas.
  - 20 kton LS detector, 3%/$\sqrt{E}$ energy resolution



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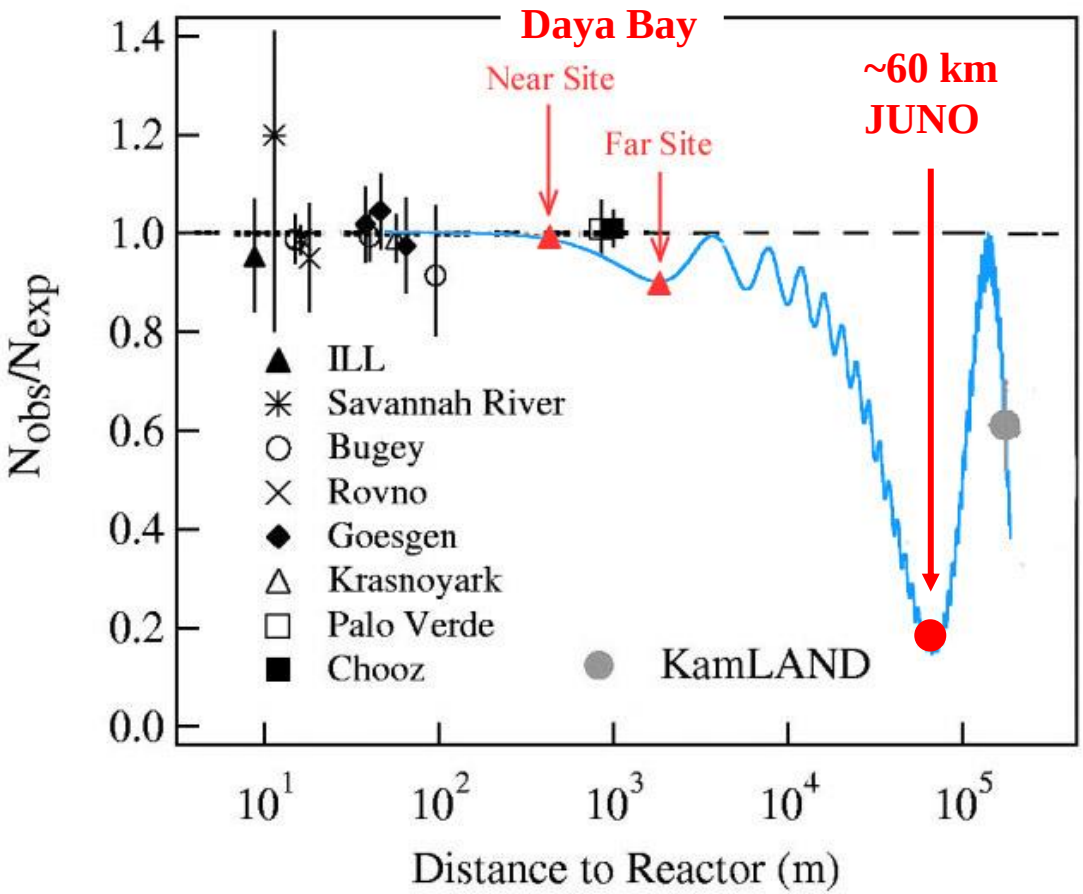
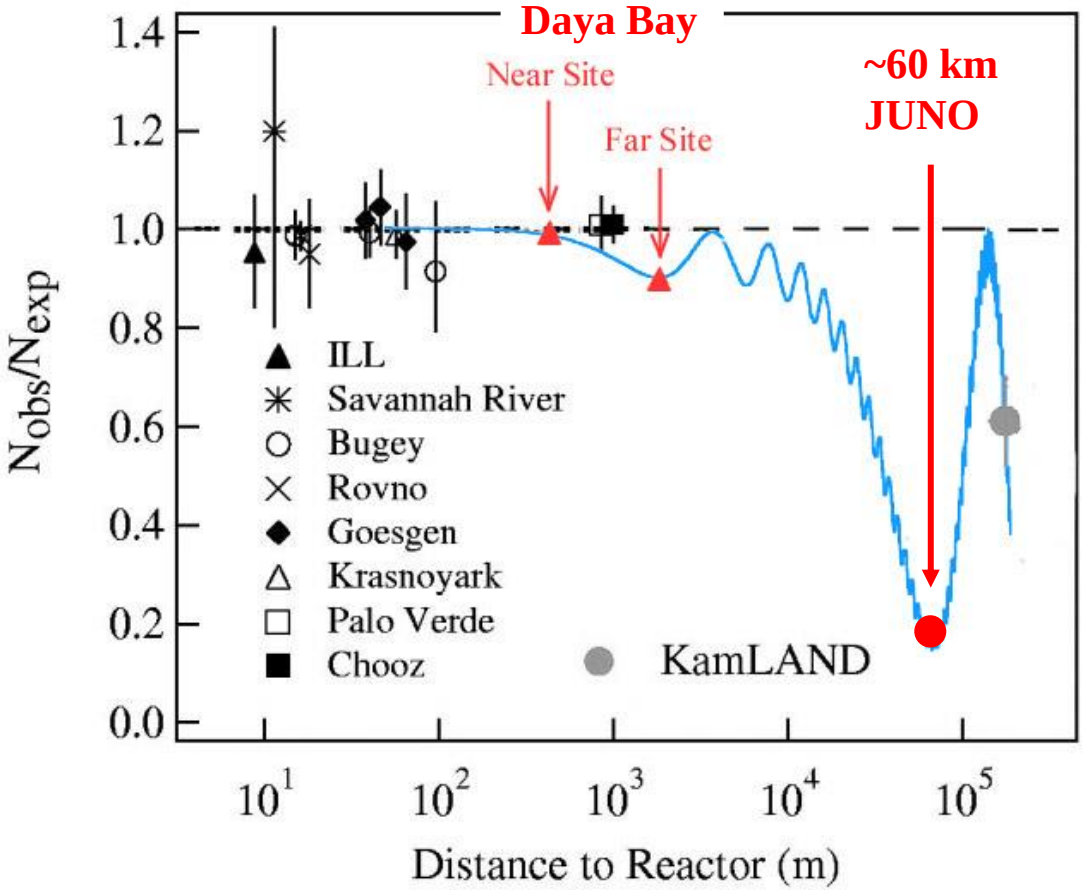


- Rich Physics
  - Mass hierarchy
  - Precision measurement of mixing parameters
  - Supernova neutrinos
  - Geo-neutrinos
  - Solar neutrinos
  - Sterile neutrinos
  - Atmospheric neutrinos
  - Exotic searches

JUNO Experiment

- Jiangmen Underground Neutrino Observatory (was Daya Bay II)
- Primary goals: mass hierarchy and precision meas.
  - 20 kton LS detector, $3\%/\sqrt{E}$ energy resolution
- Proposed in 2008, approved in Feb.2013. ~300M US$



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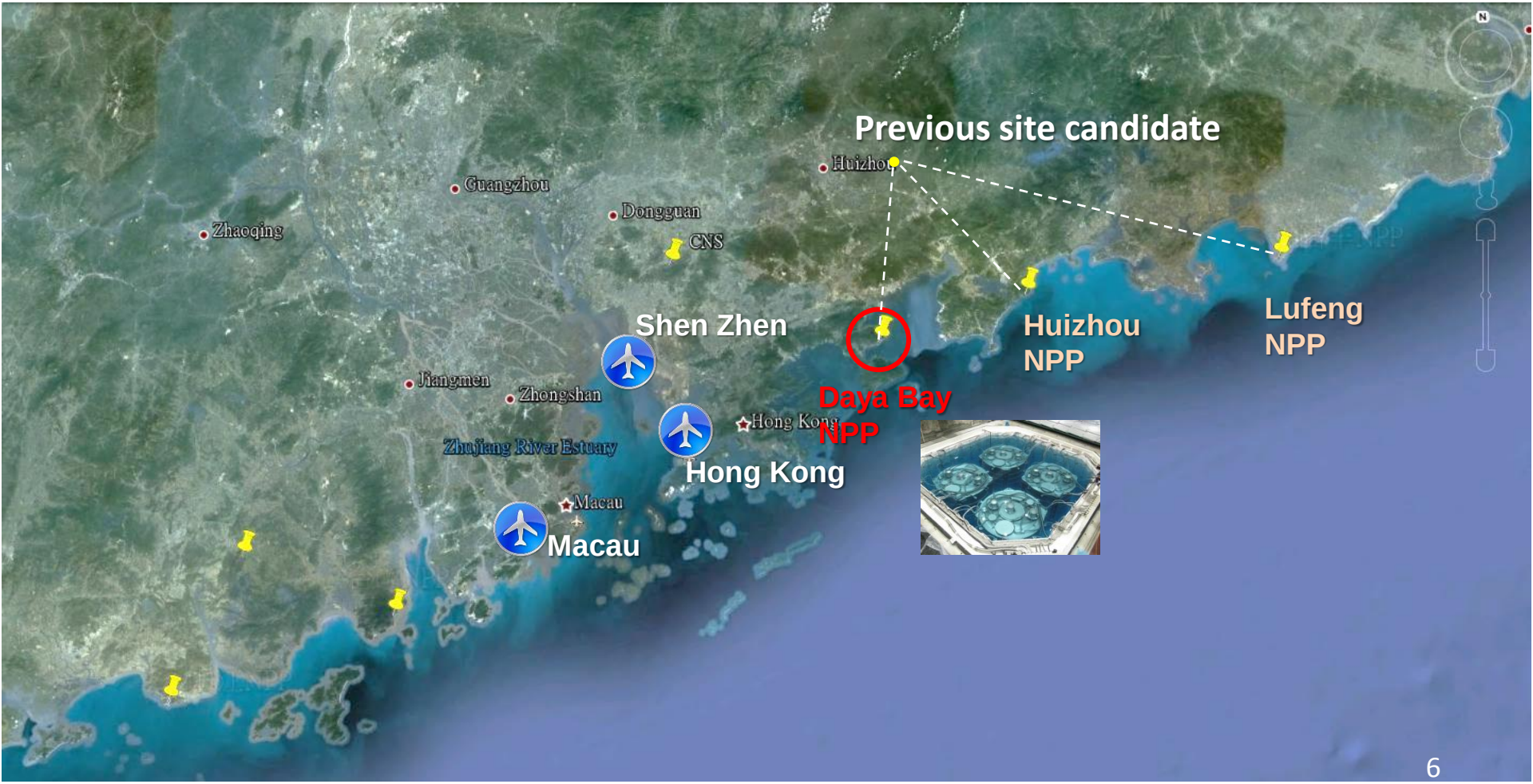
Location of JUNO

NPP	Daya Bay	Huizhou	Lufeng
Status	Operational	Planned	Planned
Power	17.4 GW	17.4 GW	17.4 GW



Location of JUNO

NPP	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

Realistic requirements to MH discrimination

FT method had ambiguities in estimating systematics.
Many studies were performed on the more detailed and realistic requirements on MH determination in the past a couple of years.

Peak structure characteristics,

Exposure & resolution,

Optimum baselines,

Multiple reactor effects,

Energy scale uncertainties,

External constraints on Δm^2,

Statistical test of hypothesis (conventional χ^2 analysis, Bayesian method..),

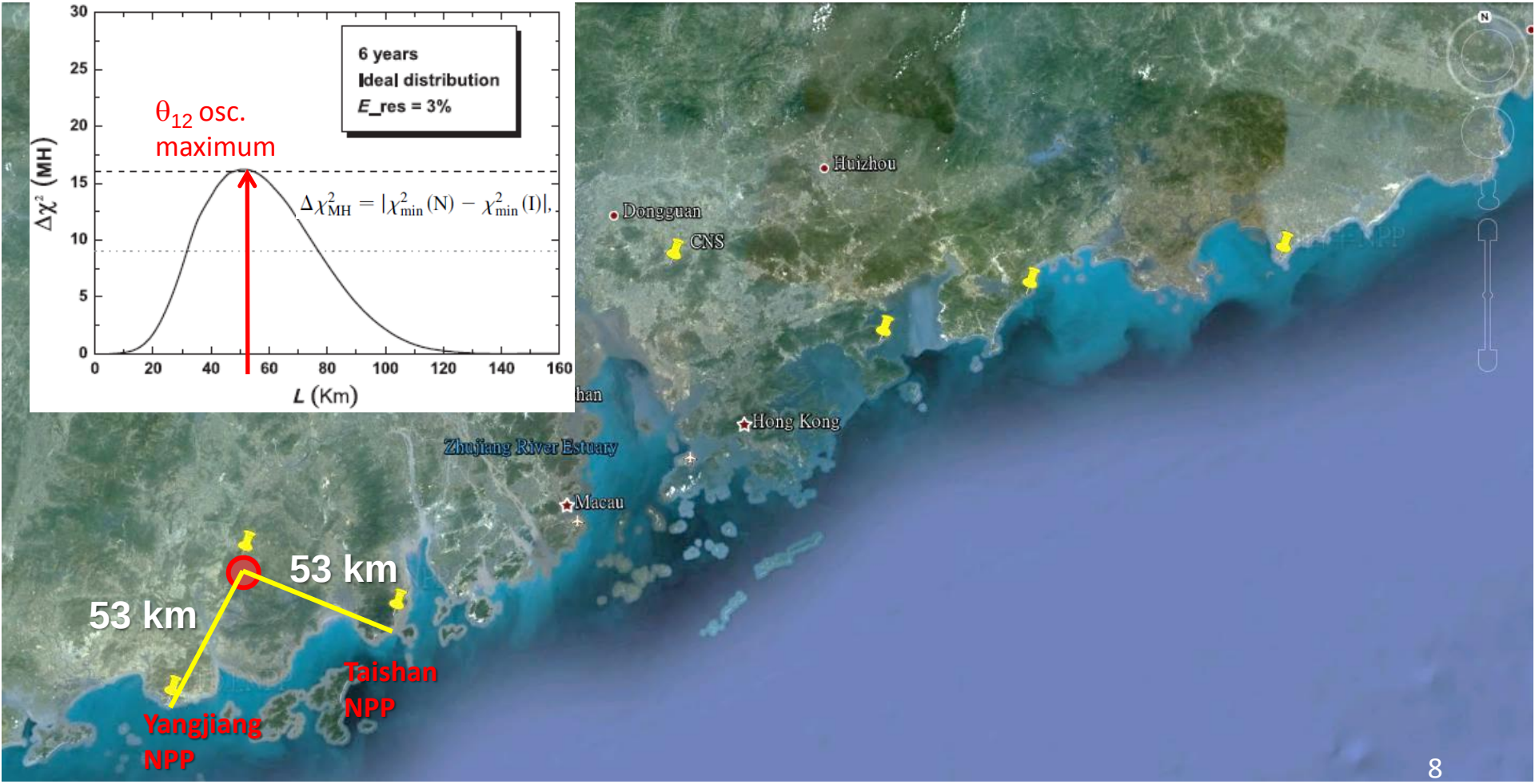
…

… …
P. Ghoshal and S. T. Petcov, JHEP 1103, 058 (2011),
P. Ghoshal, S.T Petcov, JHEP 1209, 115 (2012),
X. Qian et al, Phys. Rev. D 86, 113011 (2012),
E. Ciuffoli at el, JHEP 1212, 004 (2012),
S. F. Ge et al, JHEP 1305, 131 (2013),
E. Ciuffoli et al, JHEP 1303, 016 (2013),
X. Qian et al, PRD, 87, 033005 (2013),
Y. F. Li et al, PRD 88, 013008 (2013),
S. Kettell et al, arXiv:1307.7419,
E. Ciuffoli at el, PRD 88, 033017 (2013),
M. Blennow and T. Schwetz, JHEP 1309 (2013) 089,
E. Ciuffoli et al, JHEP 1401 (2014) 095,
F. Capozzi et al, Phys. Rev. D 89, 013001 (2014),
E. Ciuffoli et al, PhysRevD.89.073006,
M. Blennow et al., JHEP 1403 (2014) 028,
… …

Apologies to the work not be listed here due to my incomplete literature survey.

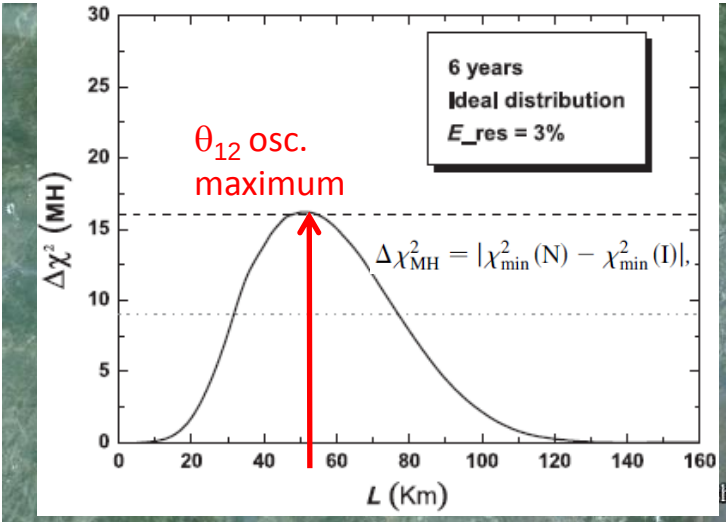
Optimum baseline for MH

- **Optimum at the oscillation maximum of θ_{12}**

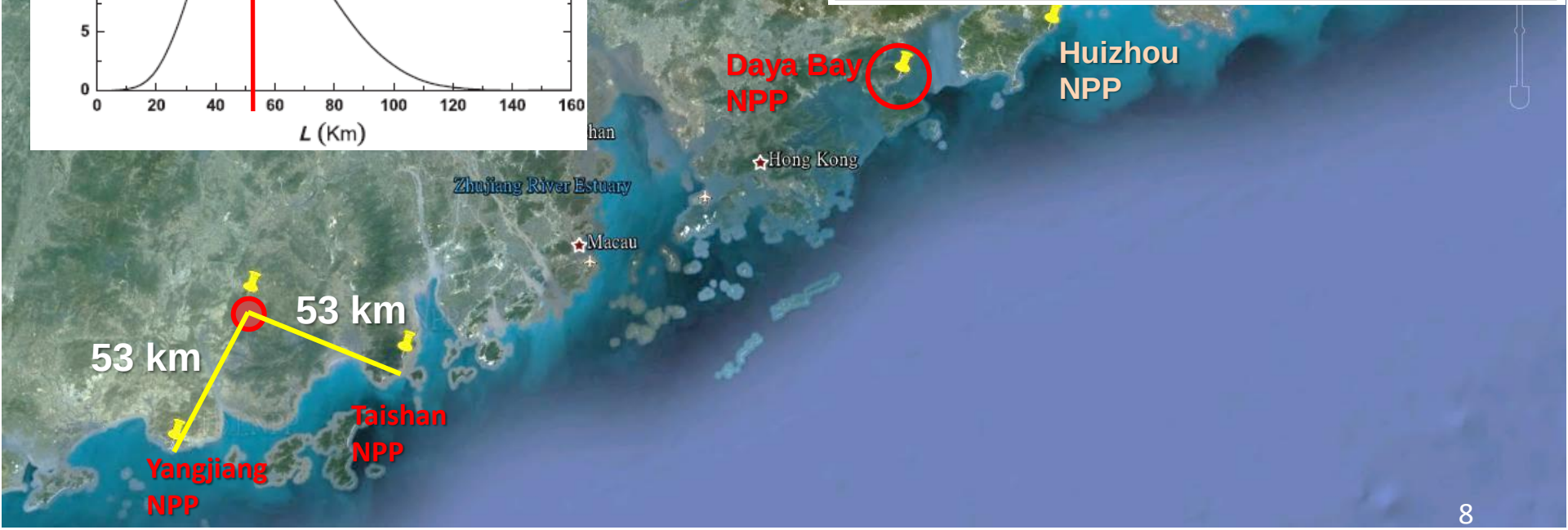


Optimum baseline for MH

- **Optimum at the oscillation maximum of θ_{12}**
- **Multiple reactors**



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



Optimum baseline for MH

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

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
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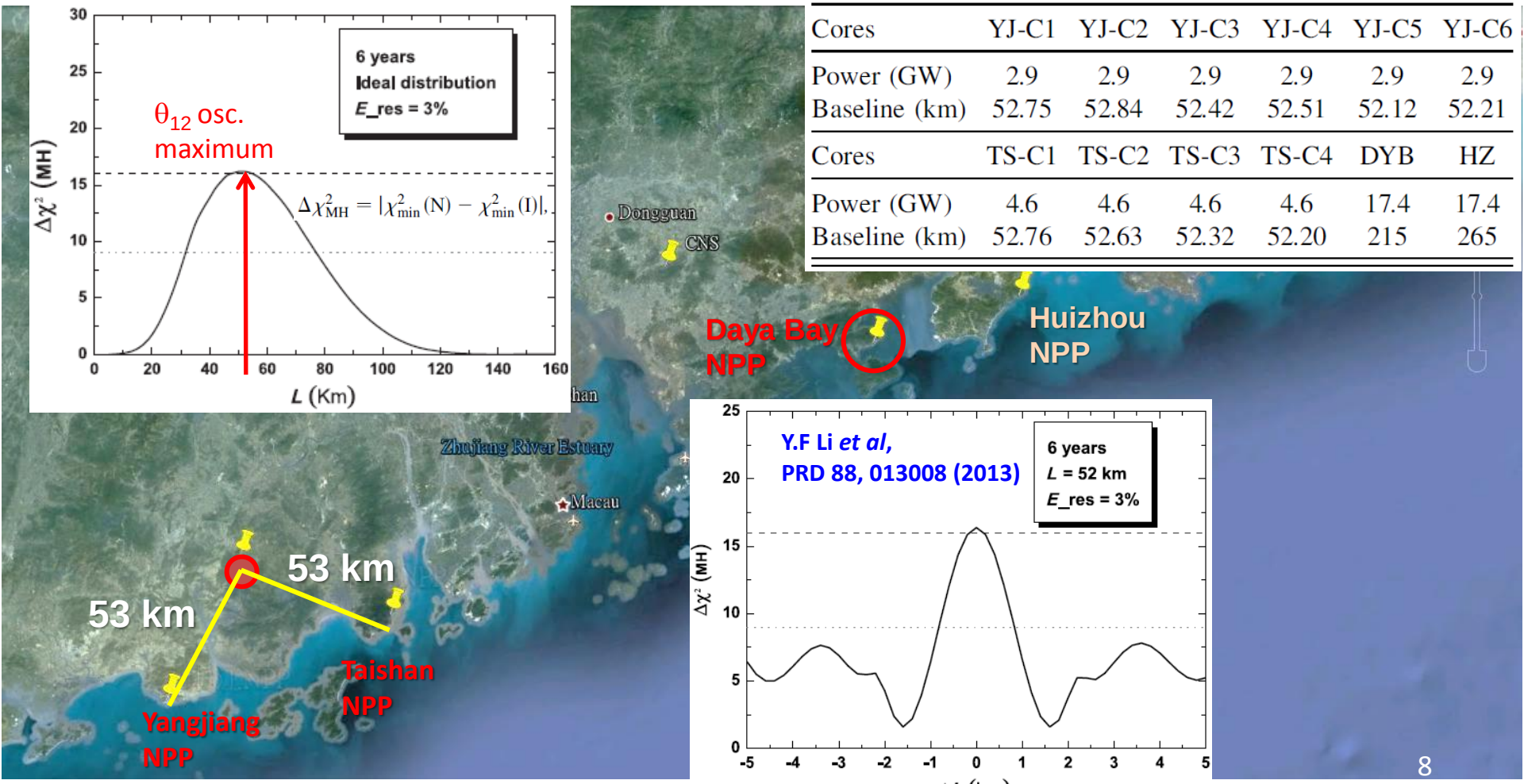

RENO-50

From Soo-Bong Kim

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

- **Goals** : - Determination of neutrino mass hierarchy
  - High-precision measurement of θ_{12}, Δm^2_{21} and Δm^2_{31}
  - Study neutrinos from reactors, the Sun, the Earth, Supernova, and any possible stellar objects

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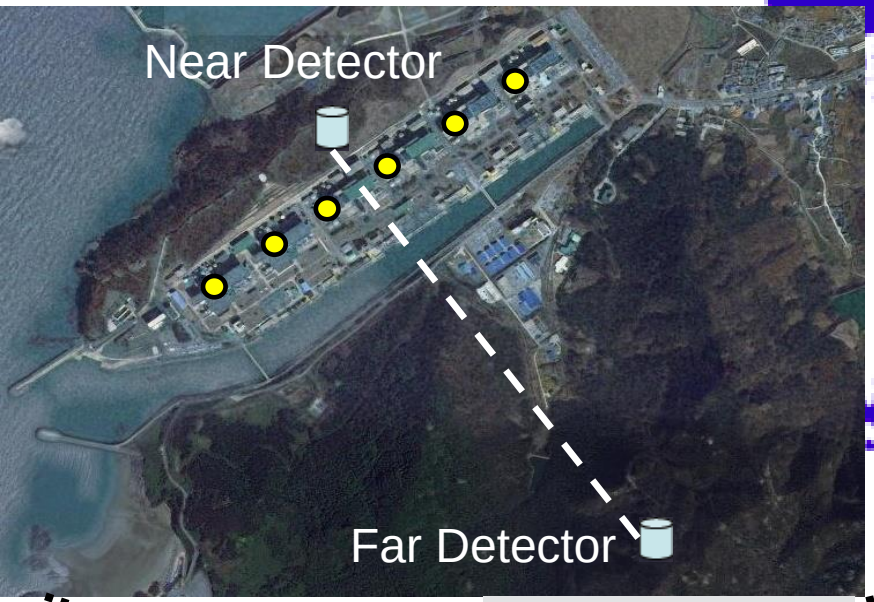
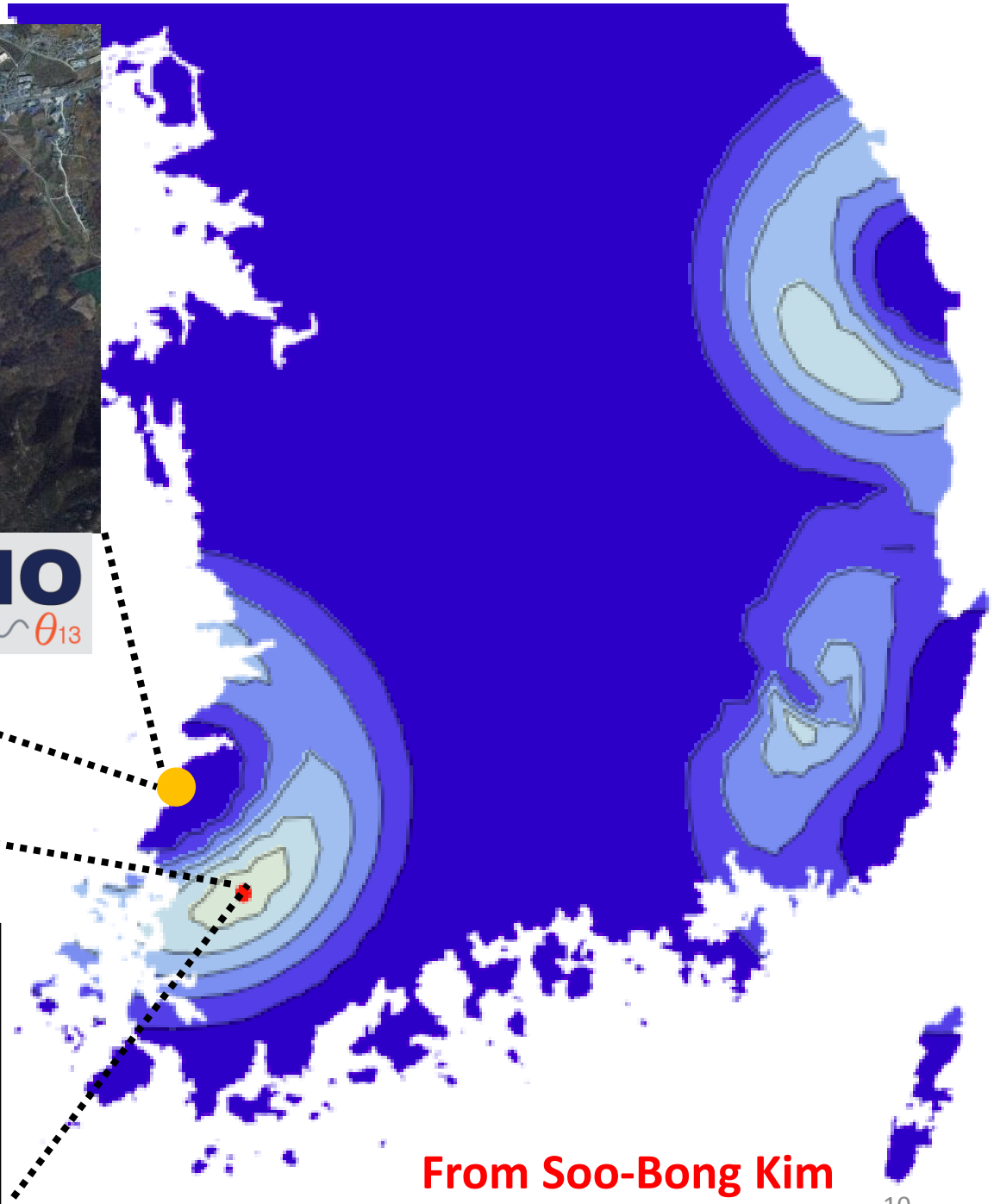
  - High-precision measurement of θ_{12}, Δm^2_{21} and Δm^2_{31}
  - Study neutrinos from reactors, the Sun, the Earth, Supernova, and any possible stellar objects

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

- **Schedule** : 2014 ~ 2019 : Facility and detector construction
  2020 ~ : Operation and experiment





RENO
ν θ_{13}

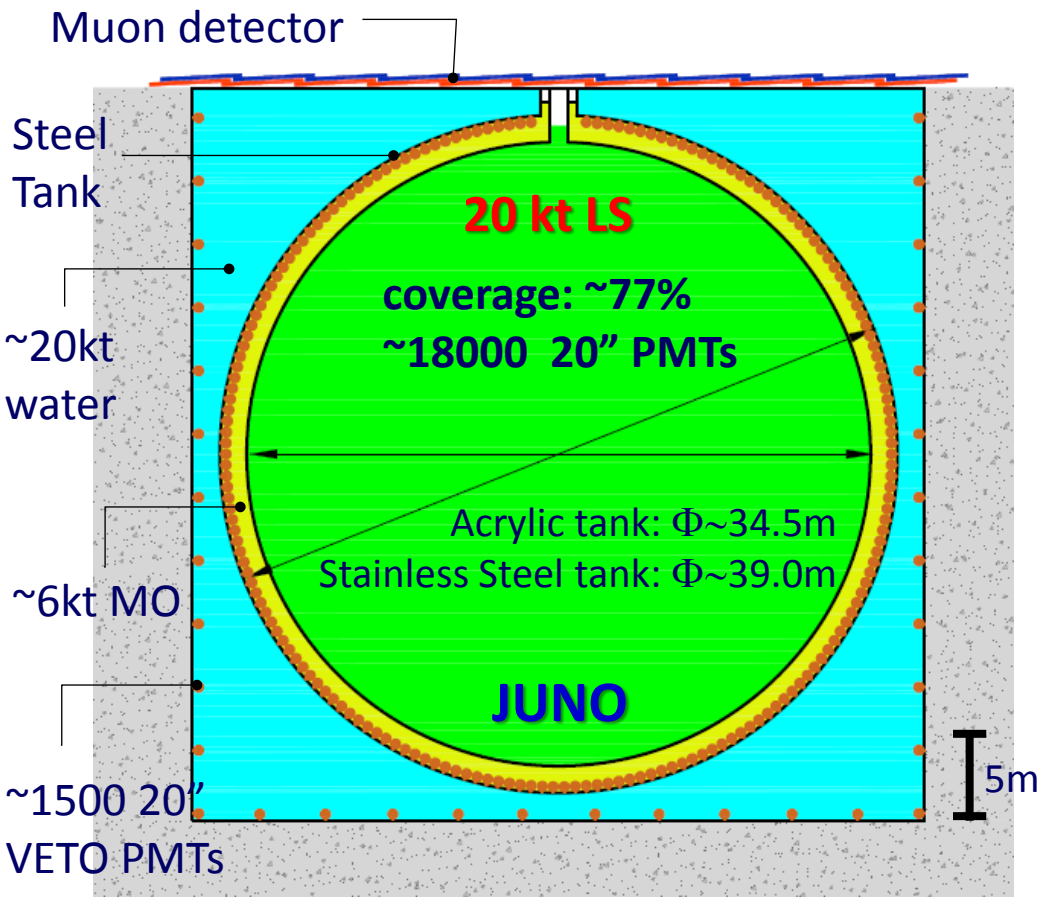
RENO-50

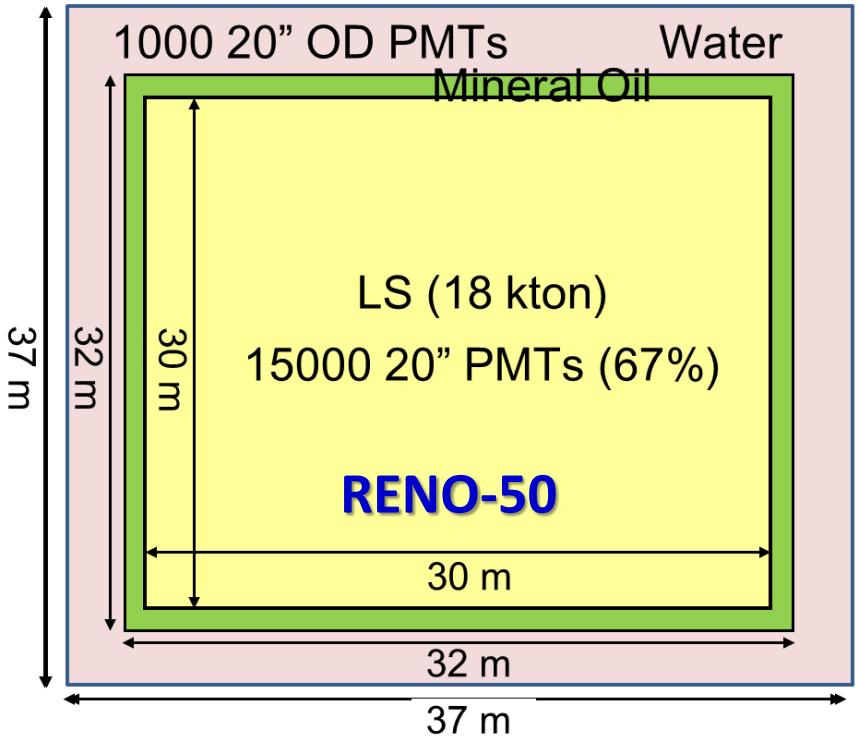
18 kton LS Detector
~47 km from YG reactors

Mt. Guemseong (450 m)
~900 m.w.e. overburden

From Soo-Bong Kim

Challenge: high-precision, giant LS detector





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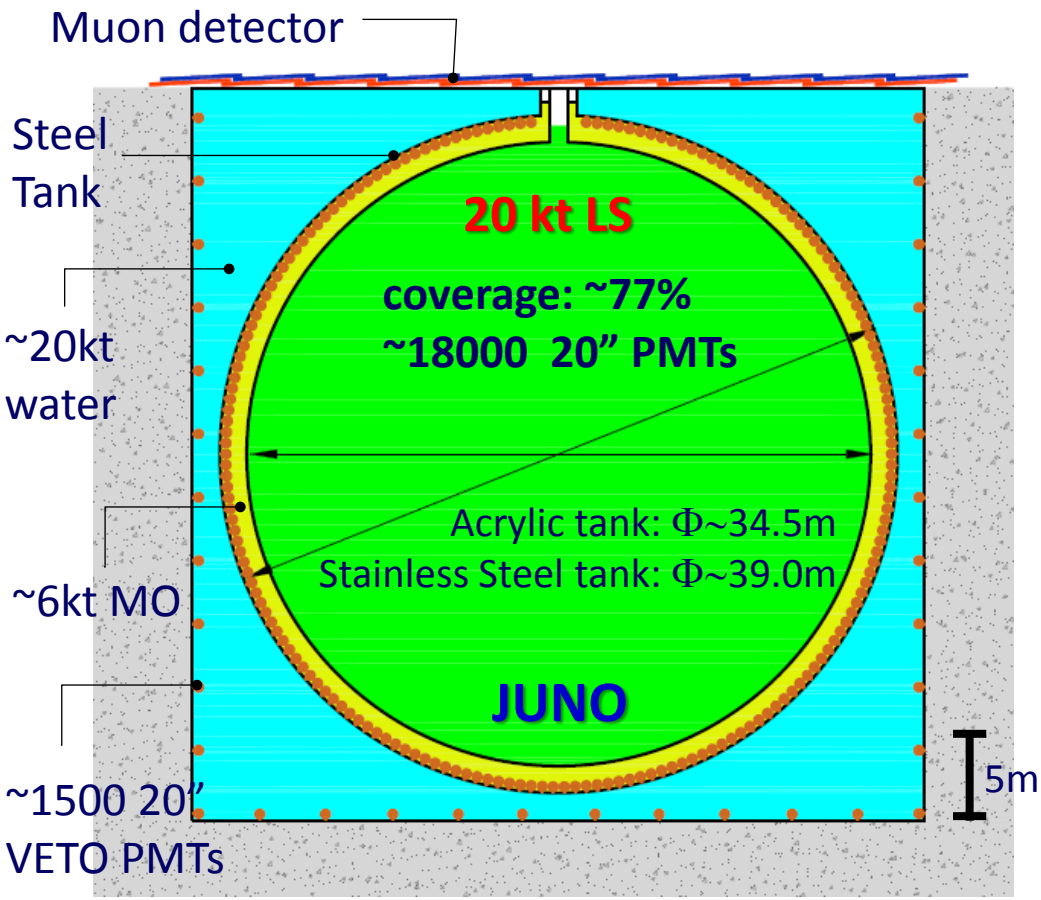
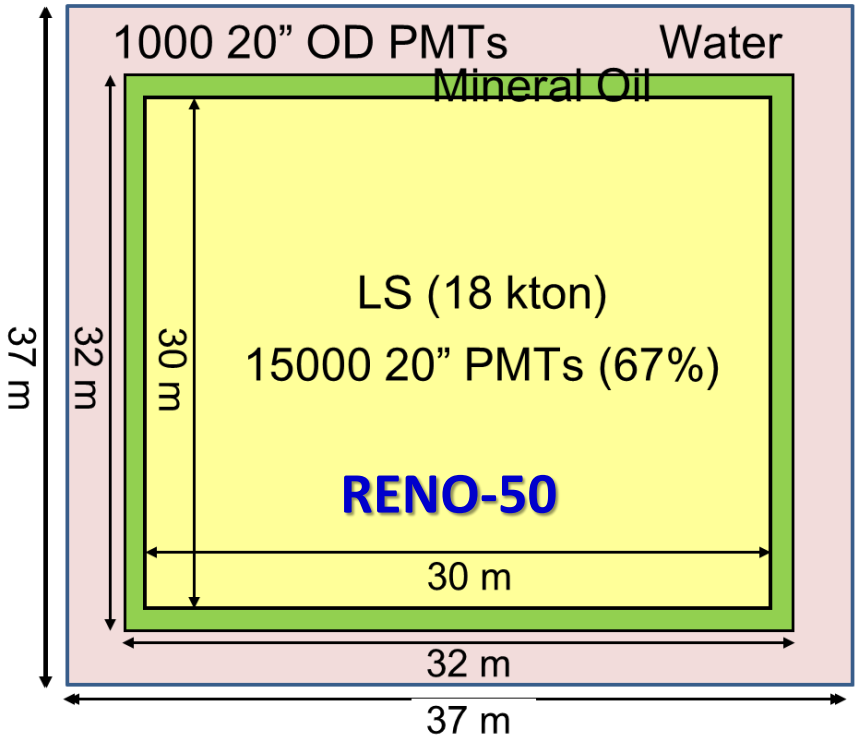
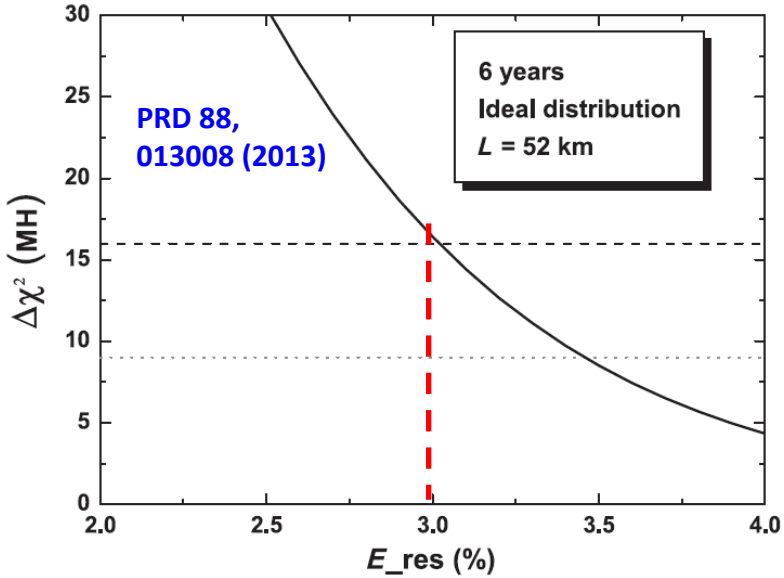




	KamLAND	JUNO	RENO-50
LS mass	~1 kt	20 kt	18 kt
Energy Resolution	$6\%/\sqrt{E}$	$\sim 3\%/\sqrt{E}$	$\sim 3\%/\sqrt{E}$
Light yield	250 p.e./MeV	1200 p.e./MeV	>1000 p.e./MeV

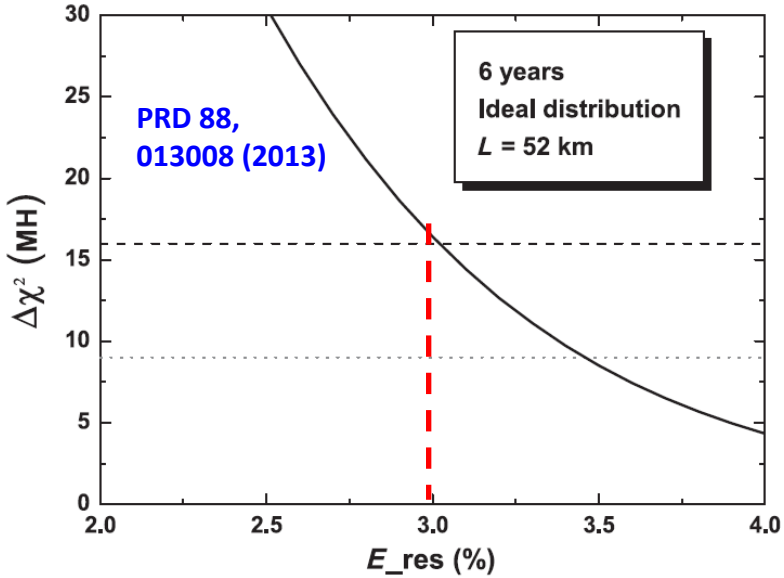
Requirements on Energy Resolution

- **$3\%/\sqrt{E}$ energy resolution**



Requirements on Energy Resolution

- $3\%/\sqrt{E}$ energy resolution
- Take JUNO MC as example
  - Based on DYB MC
  - JUNO Geometry
  - 77% photocathode coverage (KamLAND: ~34%)
  - High QE PMT, QE_{max}: 25% → 35%



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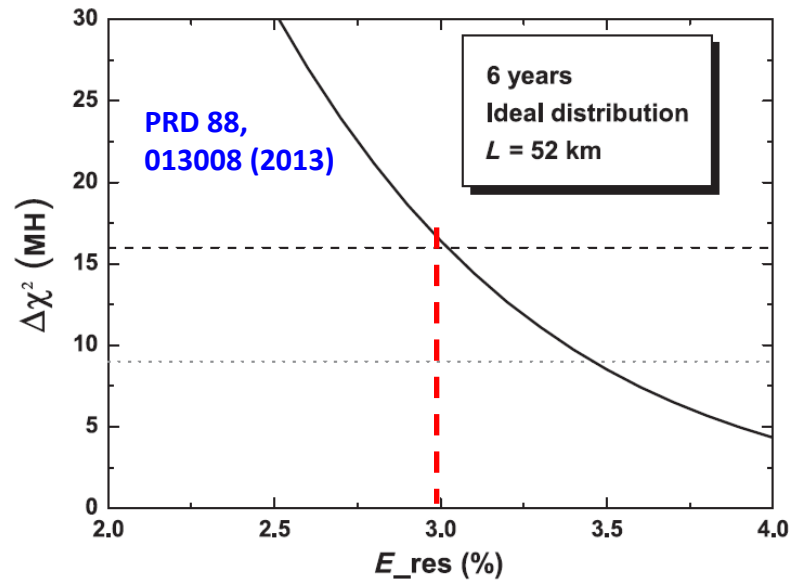
from 15 m

= absorption 30 m + Rayleigh scattering 30 m

to 20 m

= absorption 60 m + Rayleigh scattering 30 m



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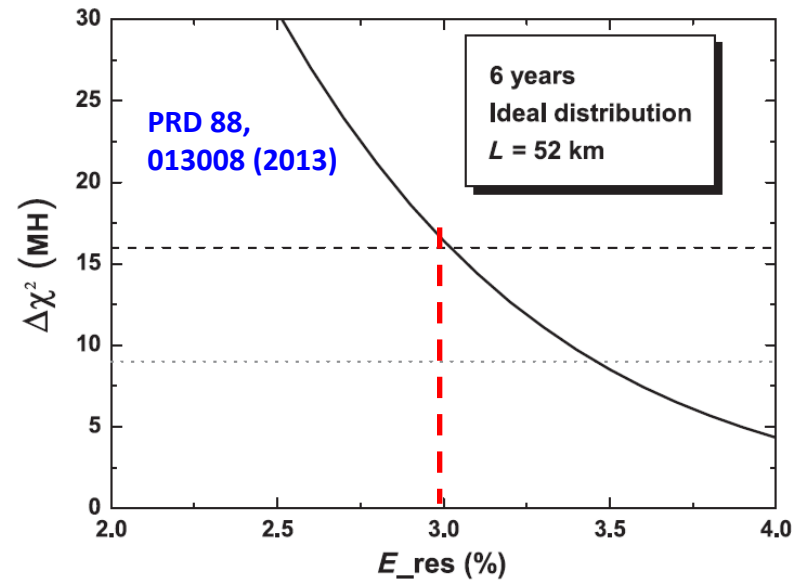
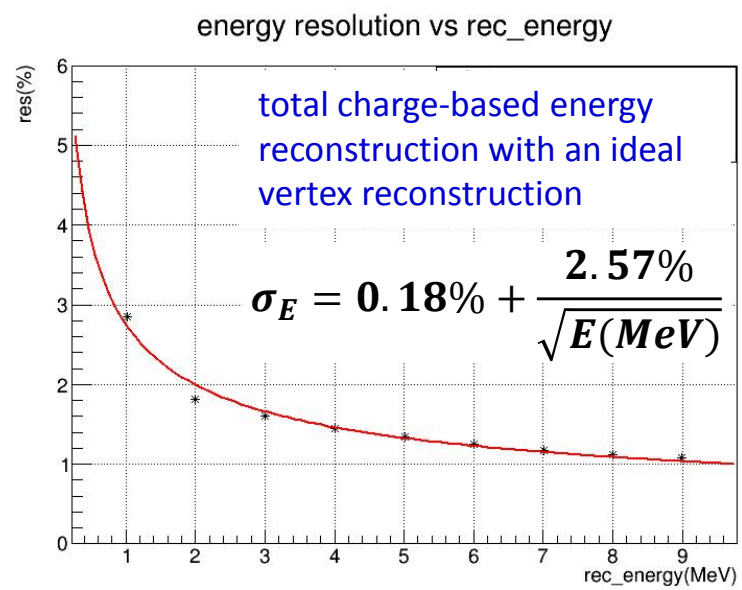
The Highlighted parameters are input to MC

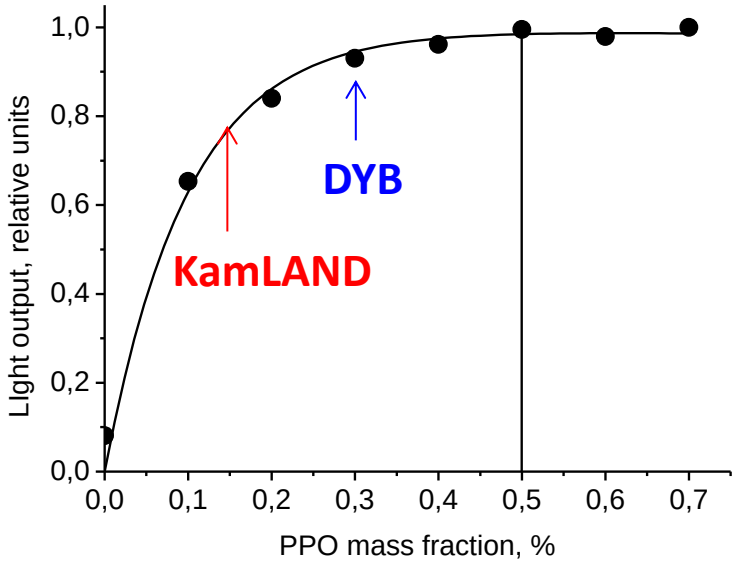




Liquid Scintillator in JUNO

- **Current choice:**

  LAB+PPO+bisMSB (no Gd-loading)
- **Increase light yield**
  - **Optimization of fluors concentration**



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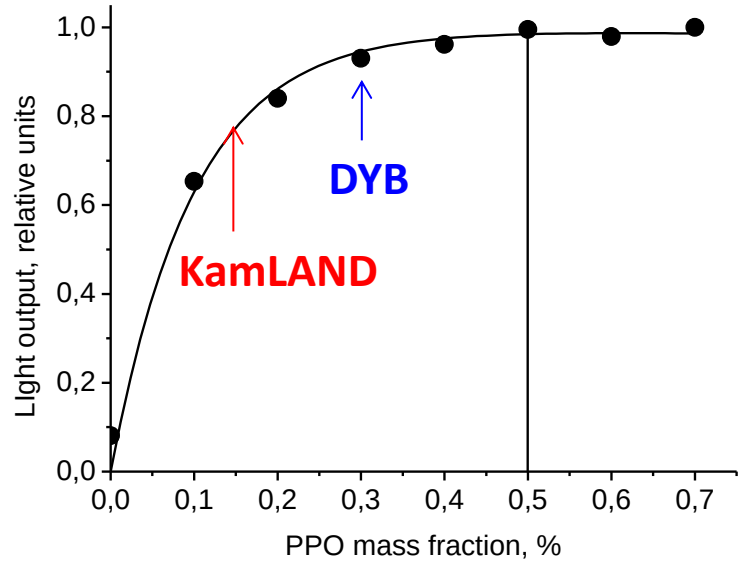
- **Increase transparency**
  - **Good raw solvent LAB**
    - **Improve production processes: cutting of components, using Dodecane instead of MO, improving catalyst, etc**
  - **Online handling/purification**
    - **Distillation, Filtration, Water extraction, Nitrogen stripping, …**



Linear Alky Benzene (LAB)	Atte. Length @ 430 nm
RAW	14.2 m
Vacuum distillation	19.5 m
SiO_2 coloum	18.6 m
Al_2O_3 coloum	22.3 m
LAB from Nanjing, Raw	20 m
Al_2O_3 coloum	25 m

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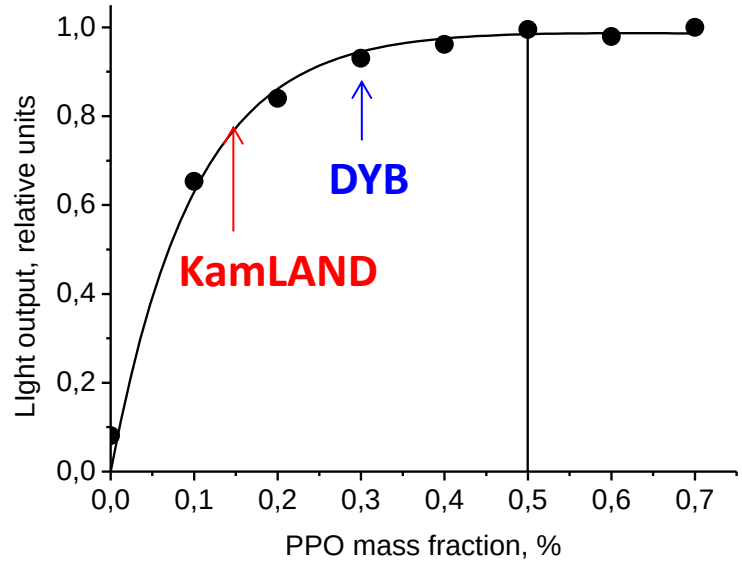
  - **Good raw solvent LAB**
    - **Improve production processes: cutting of components, using Dodecane instead of MO, improving catalyst, etc**
  - **Online handling/purification**
    - **Distillation, Filtration, Water extraction, Nitrogen stripping, …**
- **Reduce radioactivity**
  - **Less risk, since no Gd**
  - **Singles<3Hz (above 0.7MeV), if ^{40}K/U/Th <10^{-15} g/g (preliminary)**



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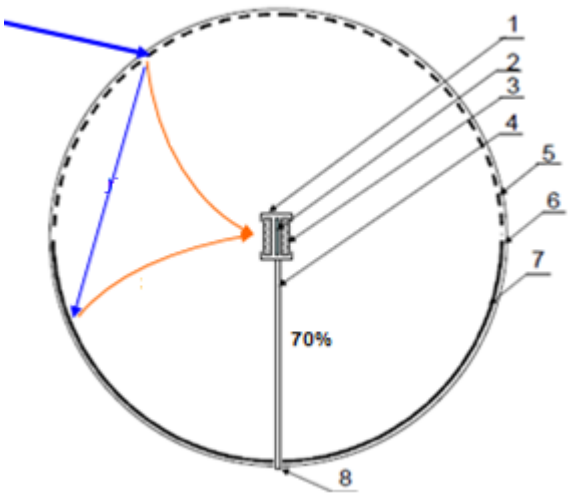
High QE PMT Effort in JUNO

- **High QE 20” PMTs under development:**
  - **A new design using MCP: 4π collection**



High QE PMT Effort in JUNO

- **High QE 20” PMTs under development:**
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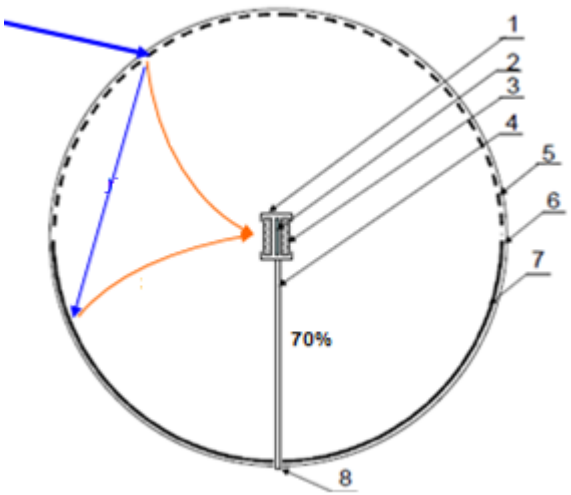
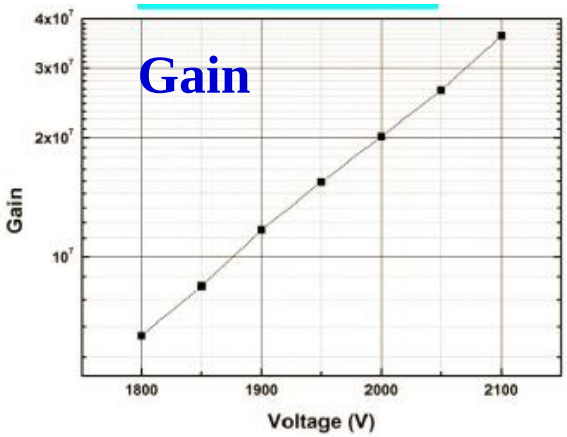
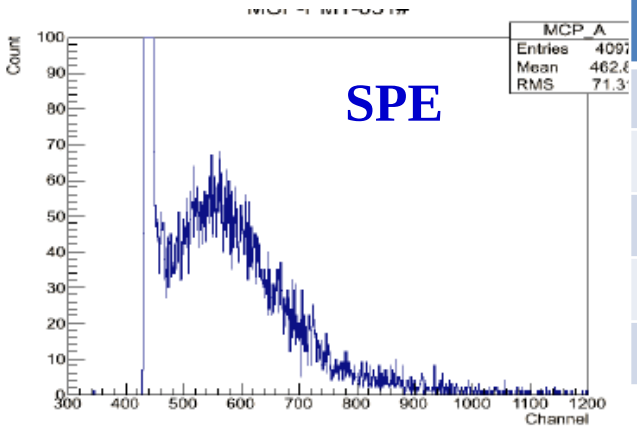
- **MCP-PMT development:**
  - **Technical issues mostly resolved**
  - **Successful 8” prototypes**
  - **A few 20” prototypes**







	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

High QE PMT Effort in JUNO

- **High QE 20” PMTs under development:**
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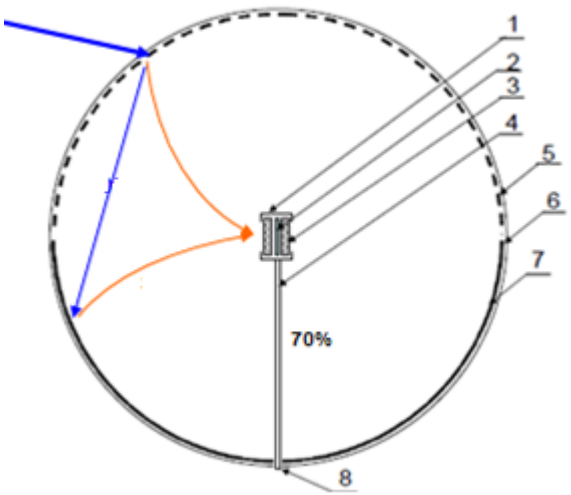
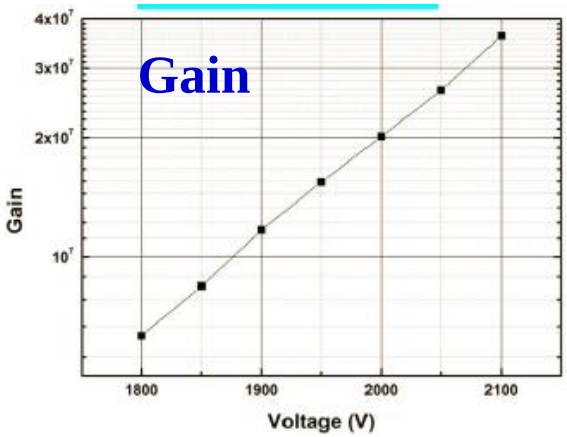
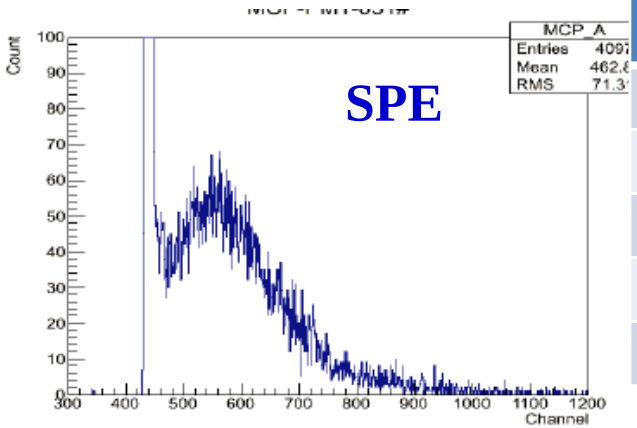
- **Alternative options: Hamamatsu or Photonics**







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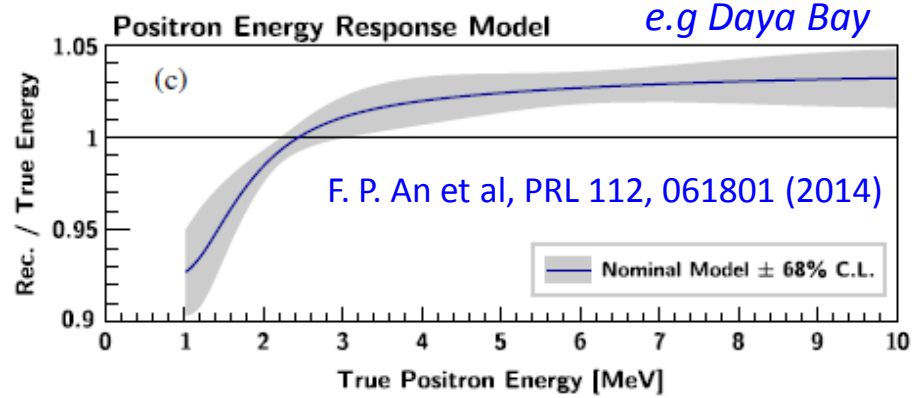
Challenges: Energy non-linearity

- **Non-linear energy response in Liquid scintillator**
  - **Quenching** ***(particle-, E- dep.)***
  - **Cerenkov** ***(particle-, E- dep.)***
  - **Electronics** ***(possible, E- dep.)***

e.g Daya Bay



F. P. An et al, PRL 112, 061801 (2014)

- **Energy non-linearity correction is crucial to spectrum shape analysis**

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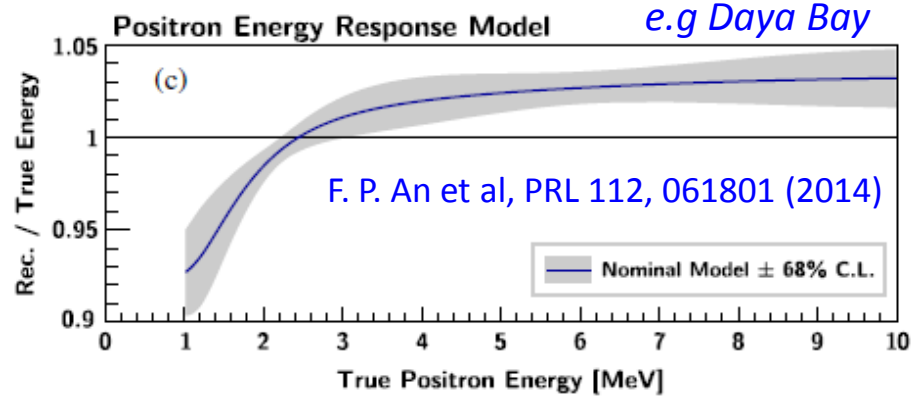

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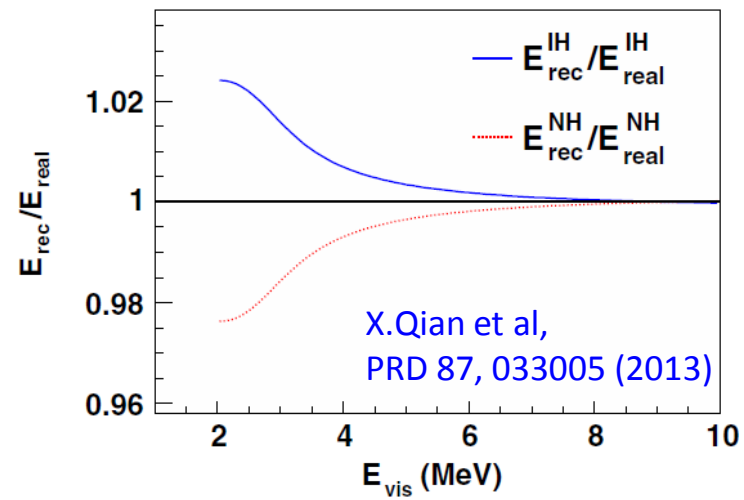
- **Energy non-linearity correction is crucial to spectrum shape analysis**
- **If imperfect correction, particular residual non-linearity shape can fake the oscillation pattern with a wrong MH** ***(X.Qian et al, PRD 87, 033005 (2013))*** **→ Challenge: understand energy scale better than 1%**



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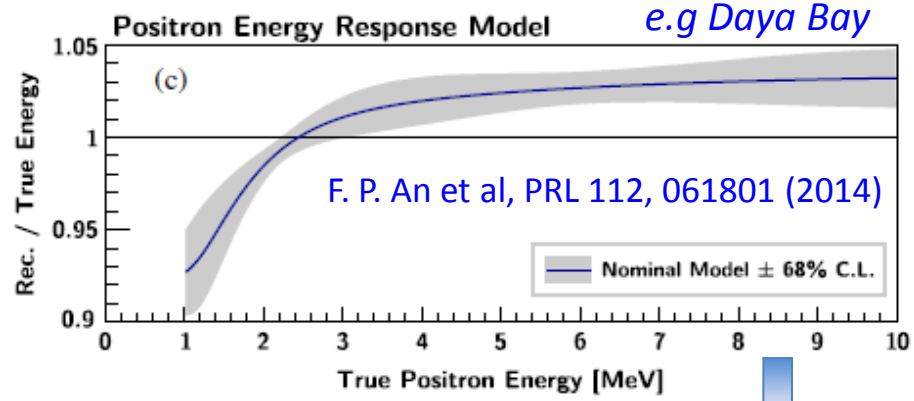

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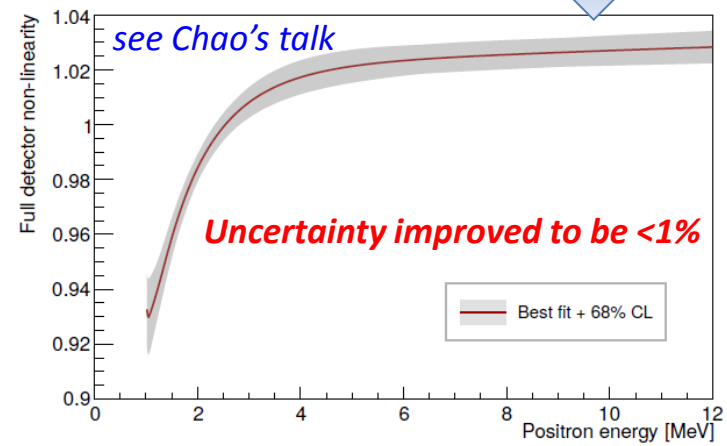

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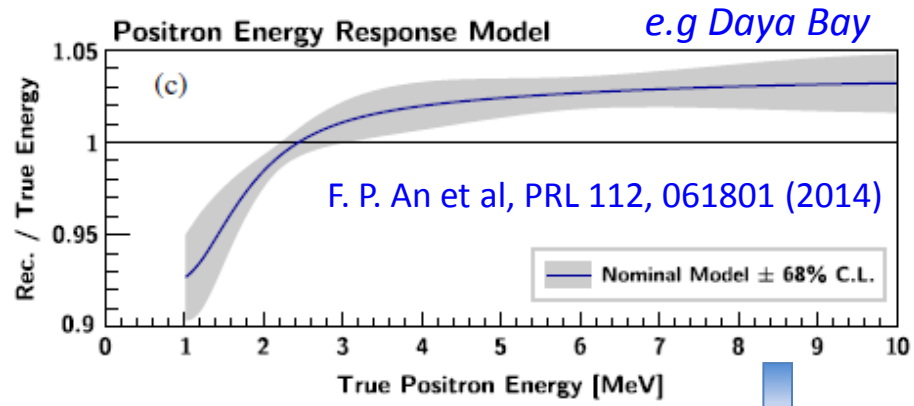

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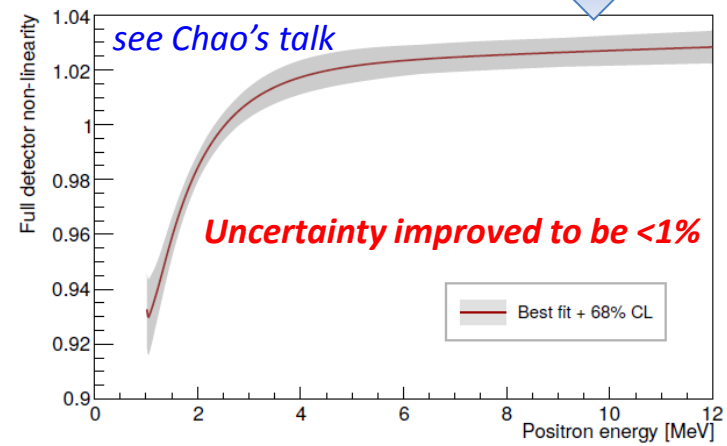
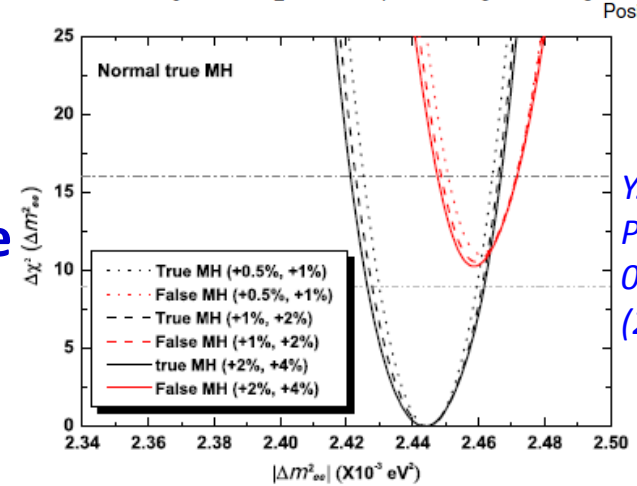


see Chao's talk

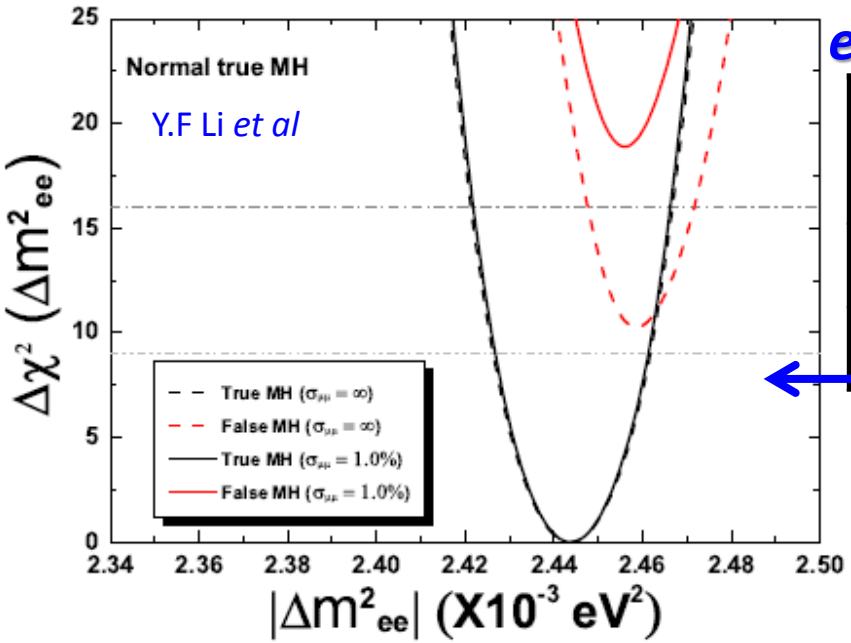
Uncertainty improved to be <1%

- **Energy non-linearity correction is crucial to spectrum shape analysis**
- **If imperfect correction, particular residual non-linearity shape can fake the oscillation pattern with a wrong MH** ***(X.Qian et al, PRD 87, 033005 (2013))*** **→ Challenge: understand energy scale better than 1%**
- **Self-calibration of the spectrum: multiple oscillation peaks can provide good constraints to non-linearity → possibly mitigate the requirement to be <2%**



Y.F.Li et al, PRD 88, 013008 (2013)

Sensitivity on MH and mixing parameters



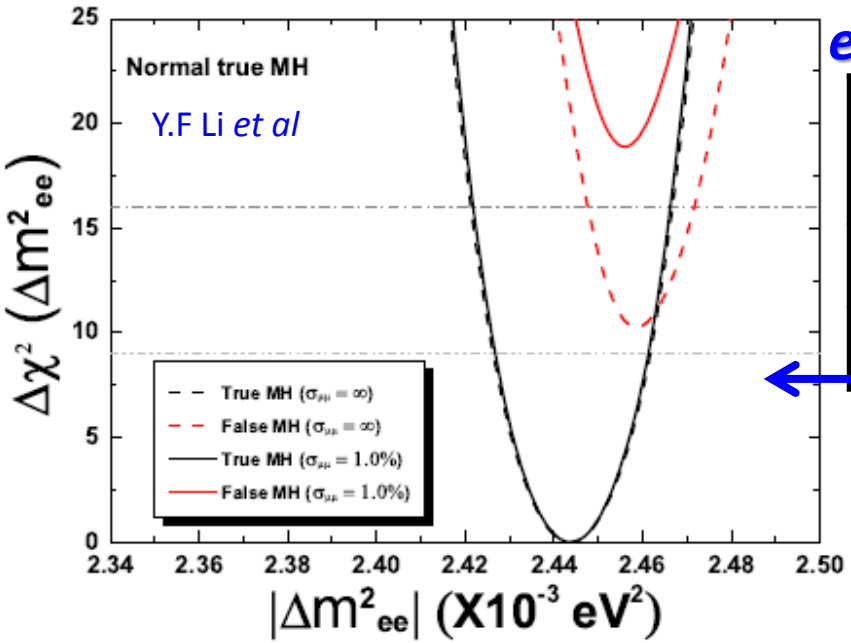
e.g JUNO **MH sensitivity with 6 years' data:**

Ref: Y.F Li et al, PRD 88, 013008 (2013)	**Relative Meas.**	**[a]Use absolute Δm^2**
Ideal case	**4σ**	**5σ**
[b]Realistic case	**3σ**	**4σ**

[a] If accelerator experiments, e.g NOvA, T2K, can measure $\Delta M^2_{\mu\mu}$ to ~1% level

[b] Take into account multiple reactor cores, uncertainties from energy non-linearity, etc

Sensitivity on MH and mixing parameters



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Ideal case	4σ	5σ
[b]Realistic case	3σ	4σ

[a] If accelerator experiments, e.g NOvA, T2K, can measure $\Delta M^2_{\mu\mu}$ to ~1% level

[b] Take into account multiple reactor cores, uncertainties from energy non-linearity, etc

	Current	e.g JUNO
Δm^2_{12}	~3%	~0.5%
Δm^2_{23}	~4%	~0.6%
$\sin^2\theta_{12}$	~7%	~0.7%
$\sin^2\theta_{23}$	~15%	N/A
$\sin^2\theta_{13}$	~6% → ~4%	~ 15%

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

There is nothing new to be discovered in physics.
All that remains is more and more precise measurement,..
William Thompson (1900)

The whole history of physics proves that a new discovery is quite likely lurking at the next decimal place...
F.K. Richtmeyer (1931)

S.L Glashow, arXiv:1305.5482

Supernova neutrinos in Giant LS detector

- **<20 events observed so far**

Giant LS detector →
Measure energy spectra & fluxes of almost all types of neutrinos

Estimated numbers of neutrino events in JUNO (preliminary)
Typical galactic SN assumptions:
10 kpc galactic distance, 3×10^{53} erg, L_ν the same for all types

Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \rightarrow e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \rightarrow \nu + p$	NC	6.0×10^2	1.2×10^3	2.0×10^3
$\nu + e \rightarrow \nu + e$	NC	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}\mathrm{C} \rightarrow \nu + {}^{12}\mathrm{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}$	CC	4.7×10^1	9.4×10^1	1.6×10^2
$\overline{\nu}_e + {}^{12}\mathrm{C} \rightarrow e^+ + {}^{12}\mathrm{B}$	CC	6.0×10^1	1.1×10^2	1.6×10^2

Correlated events.
Better detection in LS than in Water

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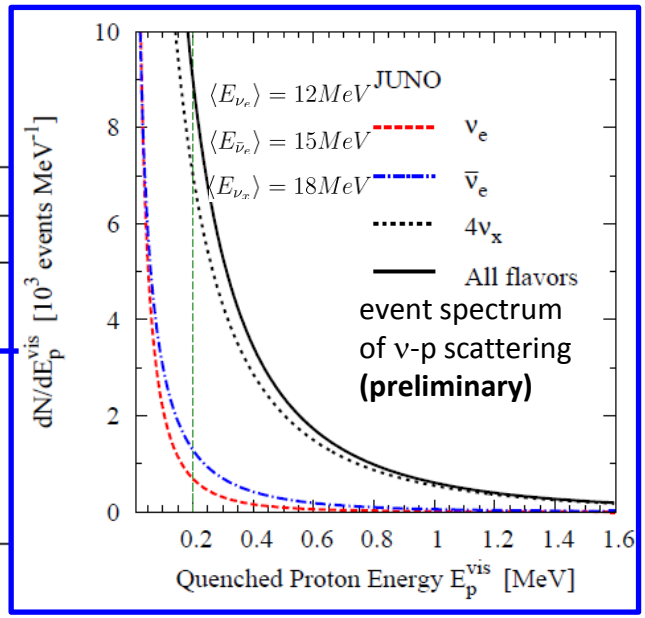

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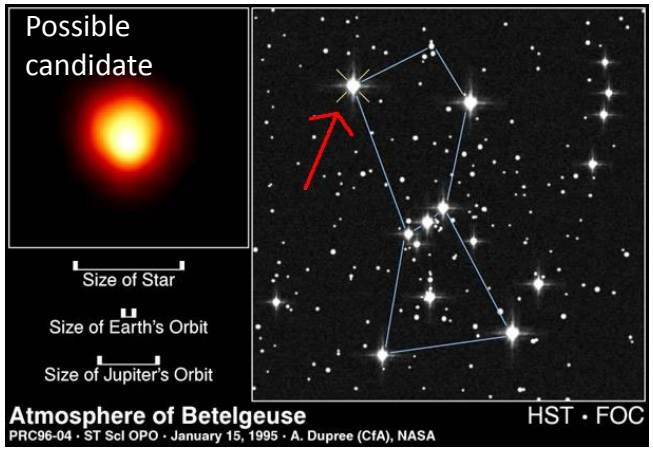

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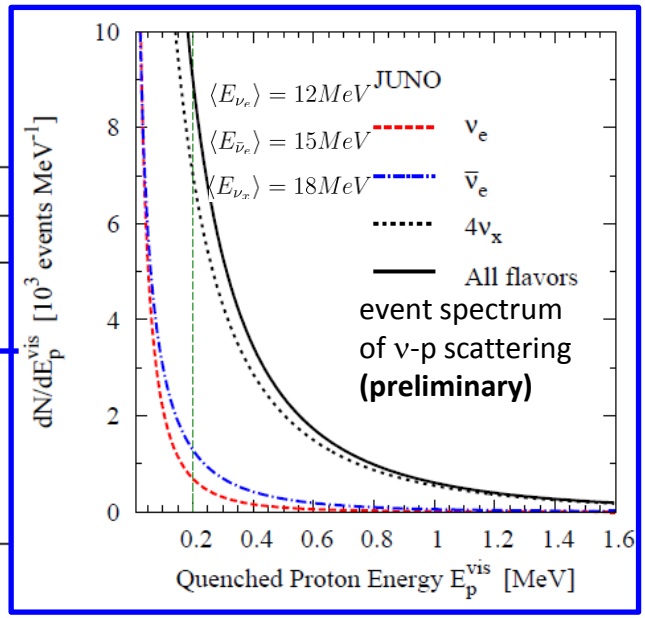

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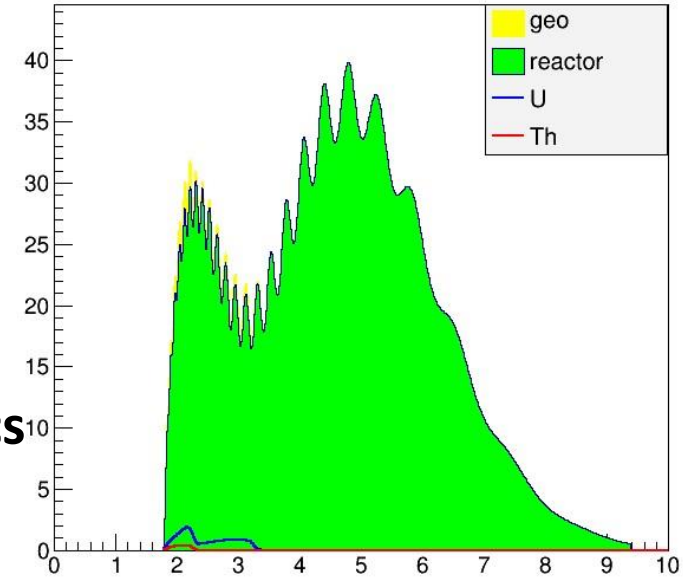
- **Geo-neutrinos**
  - **Current results:**

    KamLAND: 30±7 TNU ***(PRD 88 (2013) 033001)***

    Borexino: 38.8±12 TNU ***(PLB 722 (2013) 295-300)***
  - **JUNO/RENO-50:**

    ~x10 statistics, but challenges on systematics and background from reactor neutrinos



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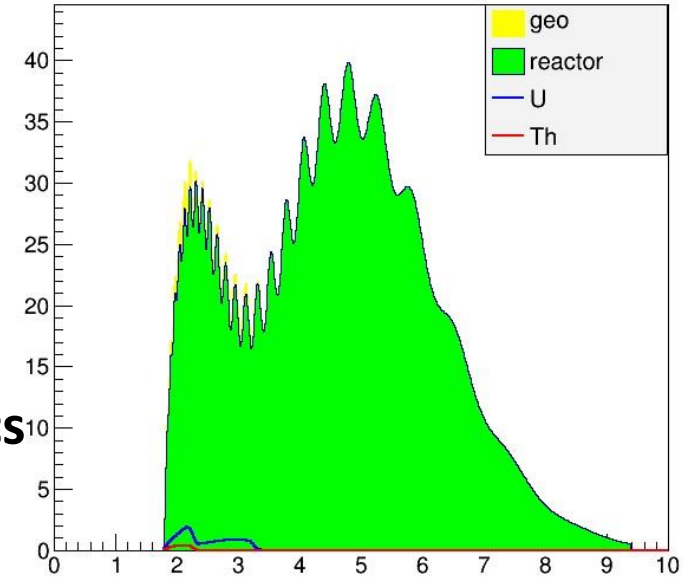

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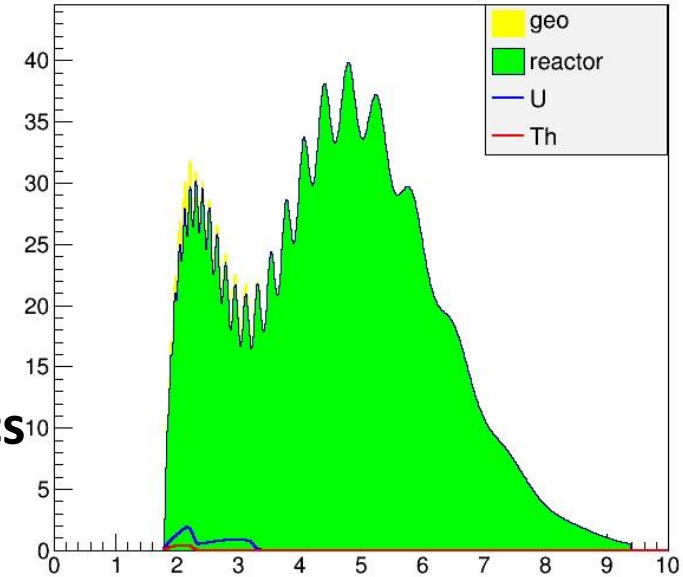

- **Solar neutrinos**
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  - **background handling (radioactivity, cosmogenic)**
- **Atmosphere neutrinos, Nucleon Decay, Sterile neutrinos, etc**
- **RENO-50 specials (from Soo-Bong Kim)**
  - **Detection of J-PARC beam & Neutrino-less double beta decay search**

Poster Session 1

RENO-50: Neutrino Mass hierarchy and Neutrino Observatory (Seon-Hee Seo)

JUNO: Physics Potential (Yufeng Li), Experimental Challenges (Macro GRASSI)

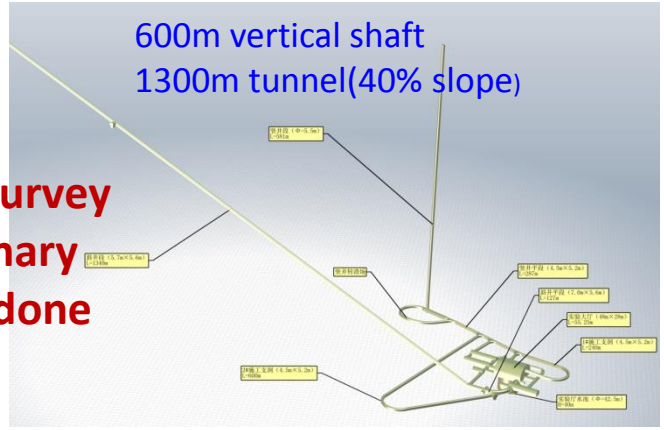
JUNO Progresses and Collaboration

- **Progresses since 2013**

First get-together meeting

Funding(2013-2014) review approved by CAS

Geological survey and preliminary civil design done



2013

2014

Now

Kaiping Neutrino Research Center established

Civil/infrastructure construction bidding

Great support from CAS: “Strategic Leading Science & Technology Programme”, CD1 approved

Yangjiang NPP started to build the last two cores

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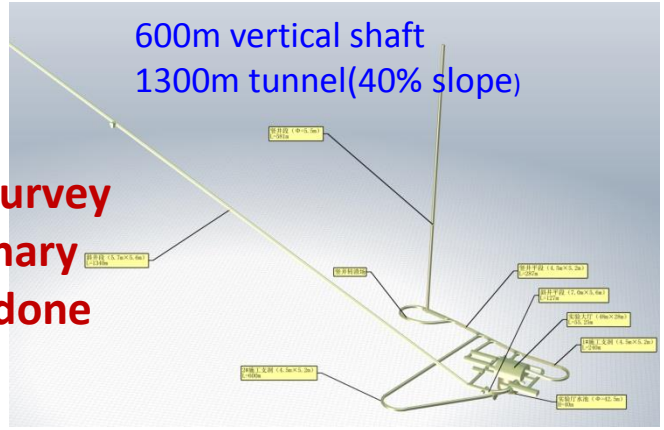

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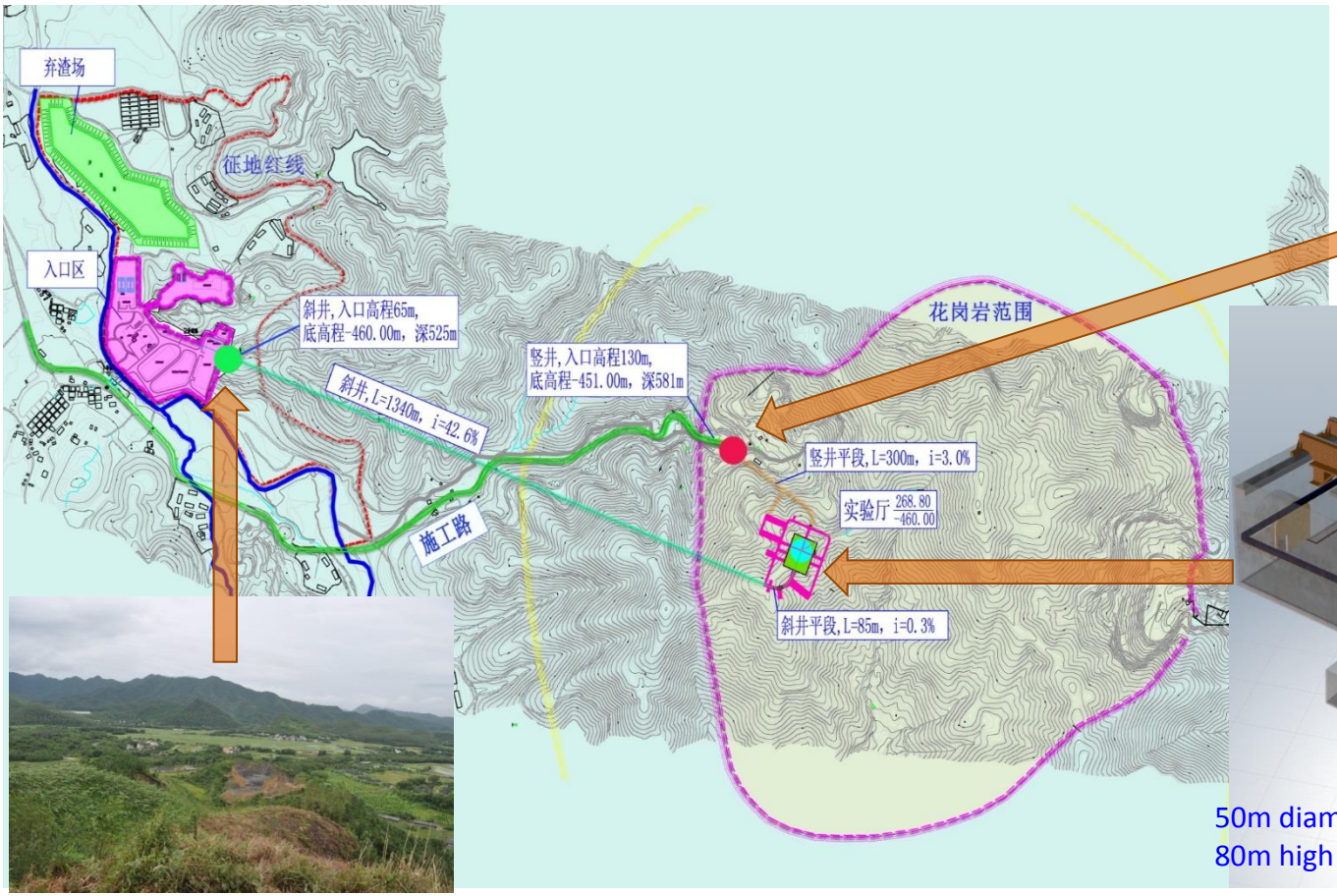
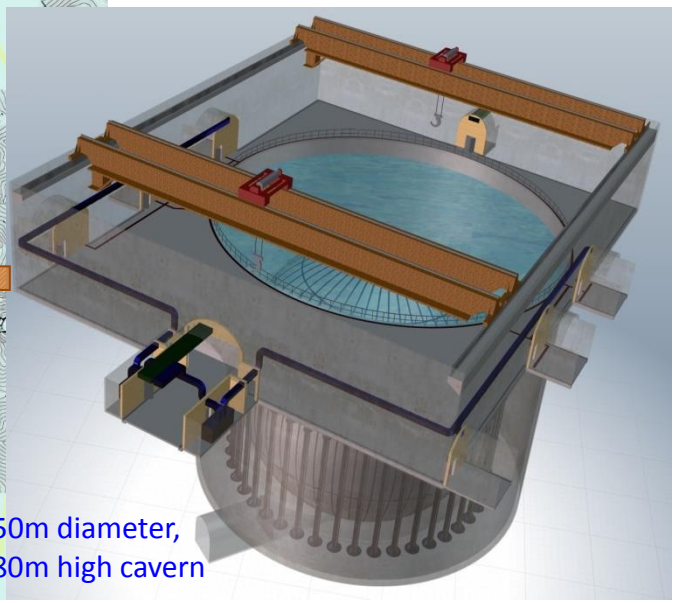
- **Collaboration:**
  - Strong interests from Czech, France, Germany, Italy, Russia, U.S … The proto-collaboration welcome new collaborators
  - Establish the international collaboration this year

Site of JUNO





Expected in 2014

- **Ground-breaking (civil construction takes 3 years)**
- **Publish a physics book and CDR**
- **Form international collaboration**

JUNO Central Detector

- **Some basic numbers:**
  - **Target: 20 kt LS**
  - **$\bar{\nu}_e$ Signal event rate: ~60/day**
  - **Backgrounds with 700 m overburden:**
    - **Accidentals(~10%), ^{9}Li/^{8}He(<1%), fast neutrons(<1%)**

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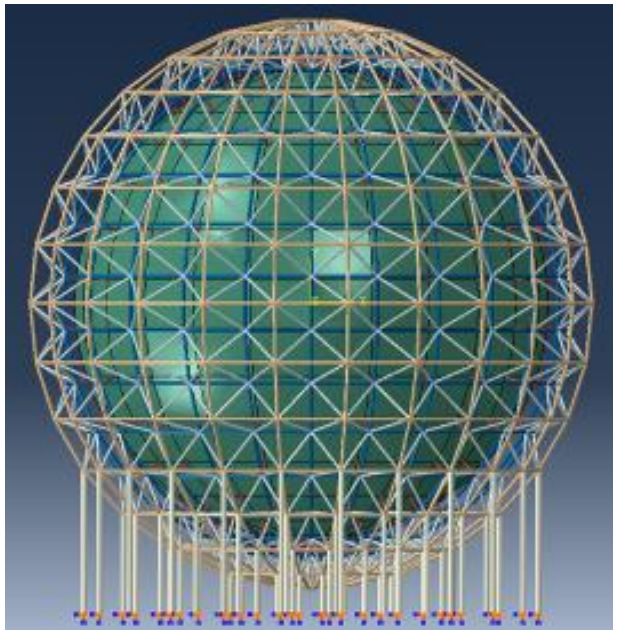

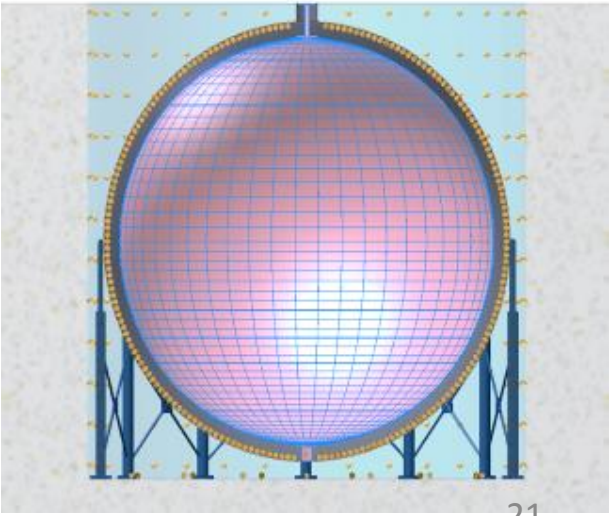

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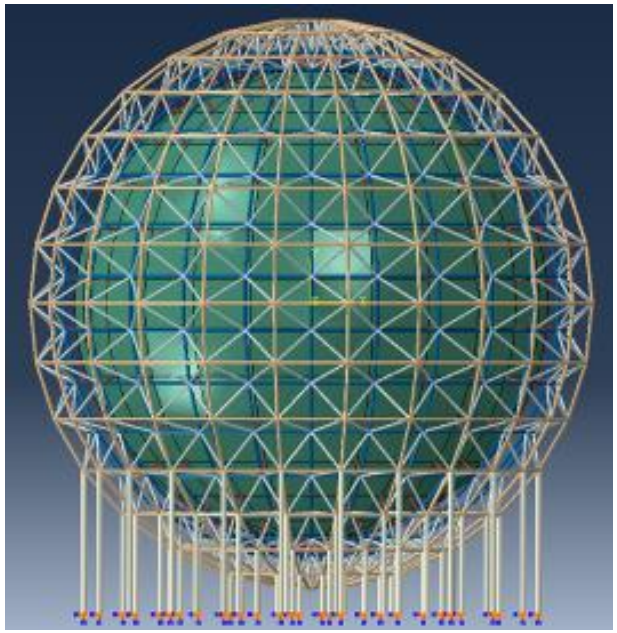
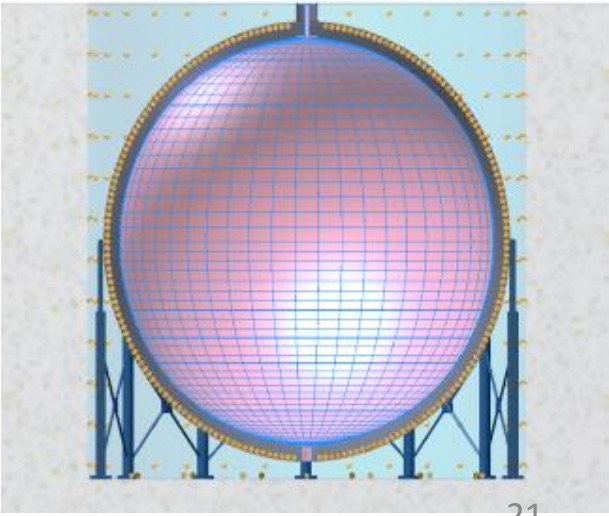
- **Issues:**
  - **Engineering: mechanics, safety, lifetime, …**
  - **Physics: cleanness, light collection, …**
  - **Assembly & installation**
- **Design & prototyping underway**

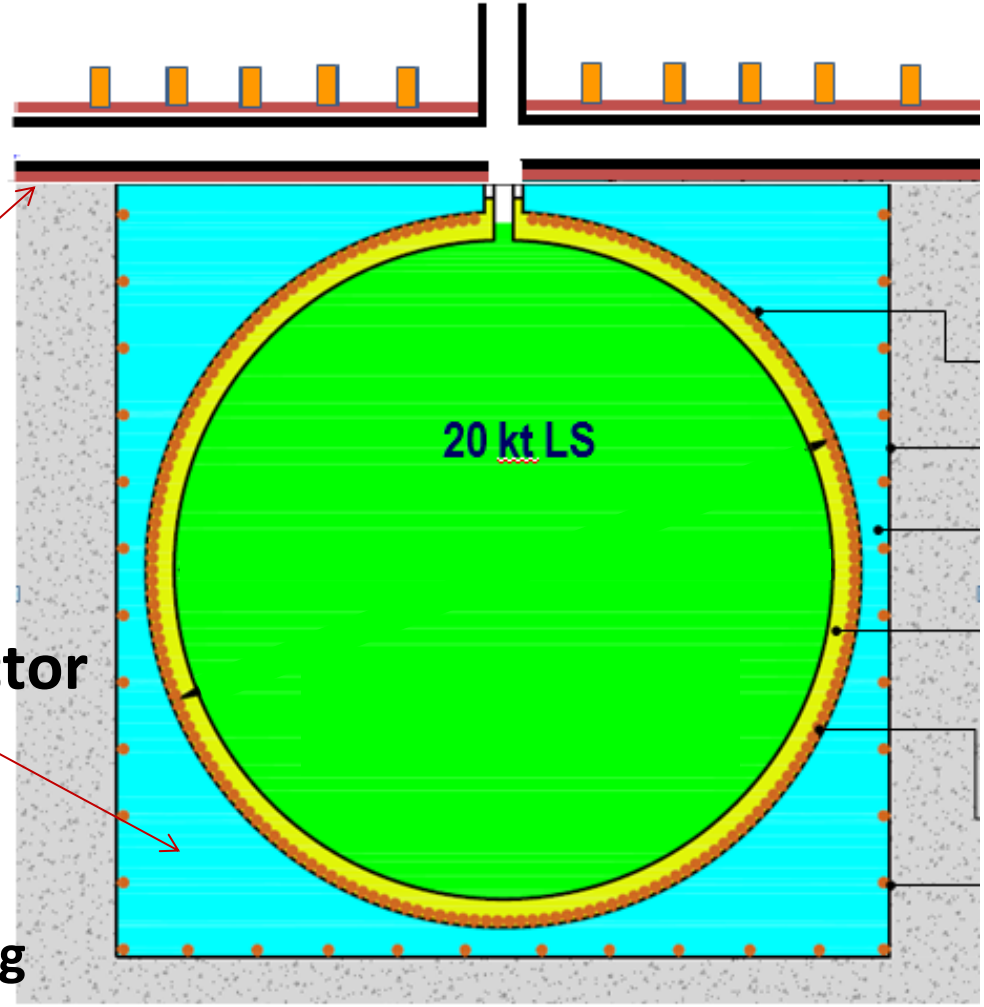




JUNO Muon VETO detector

Top tracker
(OPERA Target Tracker)

Tracker Support



Water Cerenkov Detector

- ✓ **Tyvek**
- ✓ **PMT support**
- ✓ **Water Pool liner**
- ✓ **Earth Magnetic shielding**

JUNO/RENO-50 Schedules

JUNO Schedule:

Civil preparation： 2013-2014

Civil construction： 2014-2017

Detector component production： 2016-2017

PMT production： 2016-2019

Detector assembly & installation： 2018-2019

Filling & data taking： 2020

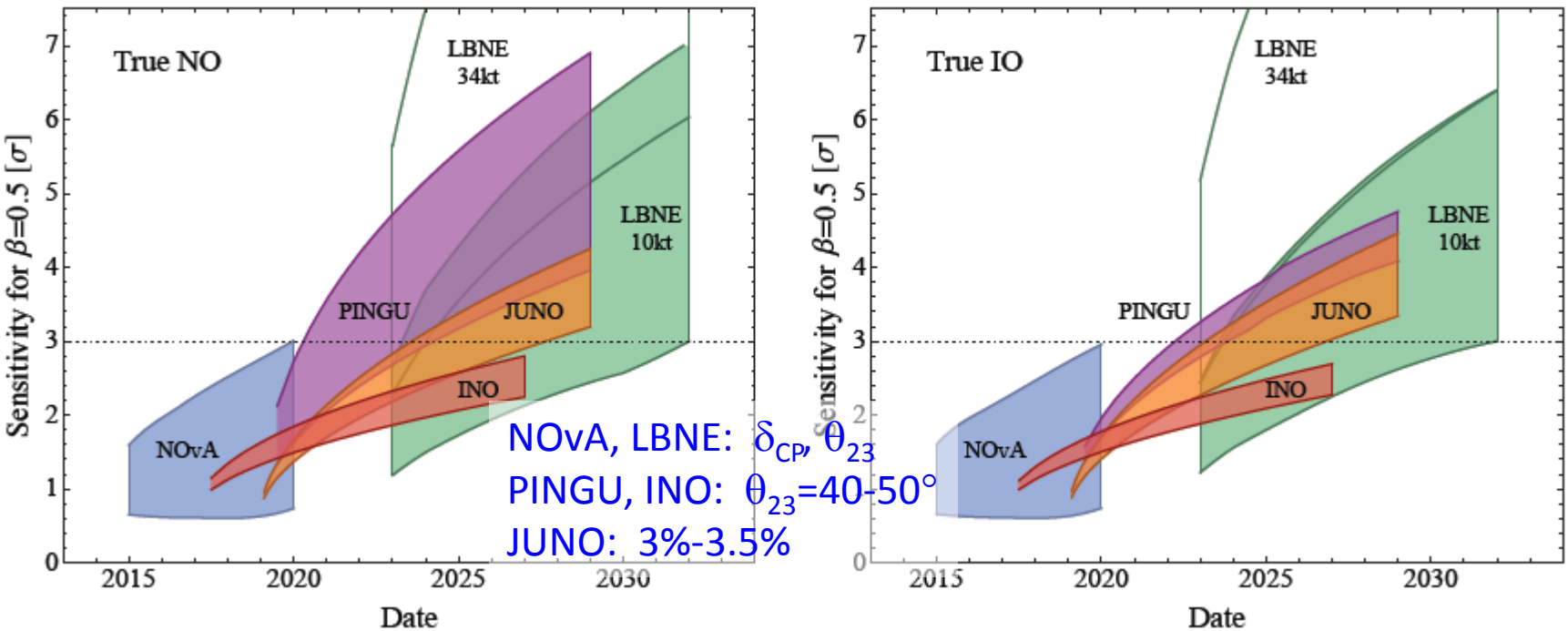
- **RENO-50 Schedule** **From Soo-Bong Kim**

2014 ~ 2019 : Facility and detector construction

2020 ~ : Operation and experiment

Summary

M. Blennow et al., JHEP 1403 (2014) 028



NOvA, LBNE: δ_{CP}, θ_{23}

PINGU, INO: θ_{23}=40-50°

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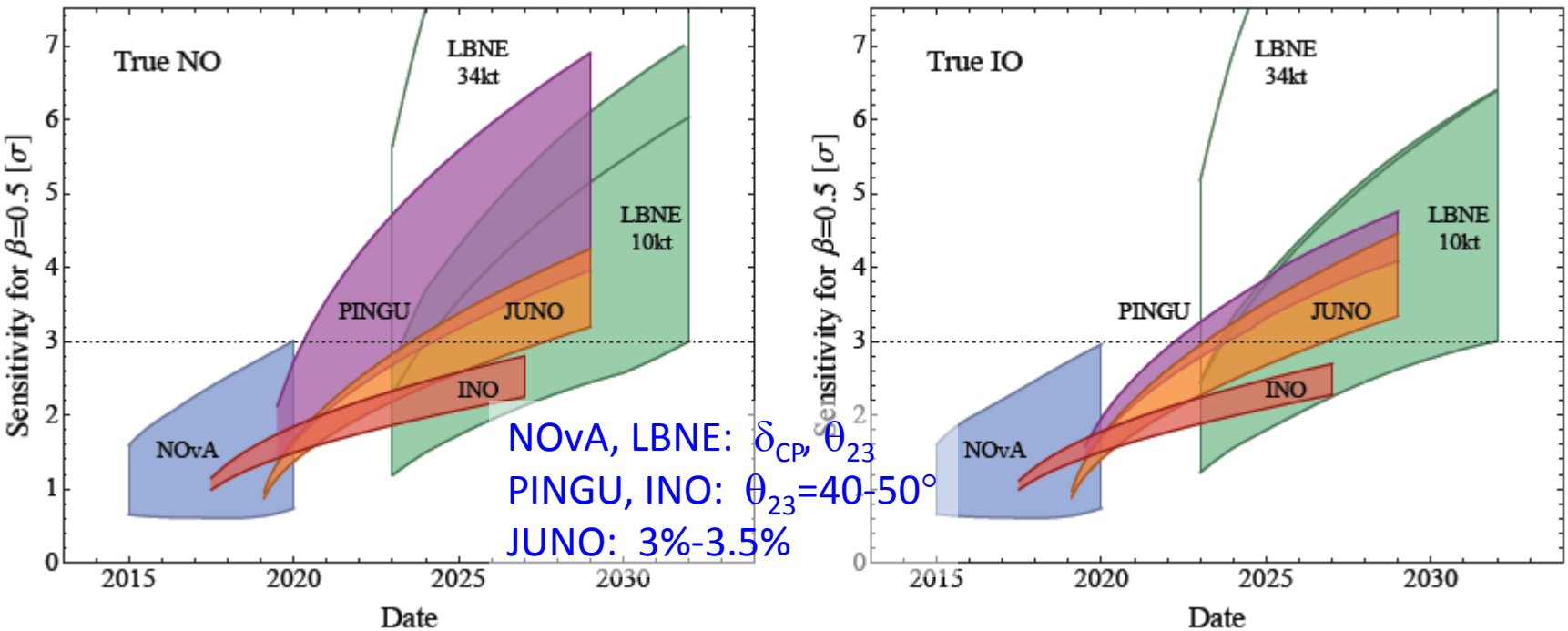

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Measuring MH with reactors is Competitive in schedule and Complementary in physics.

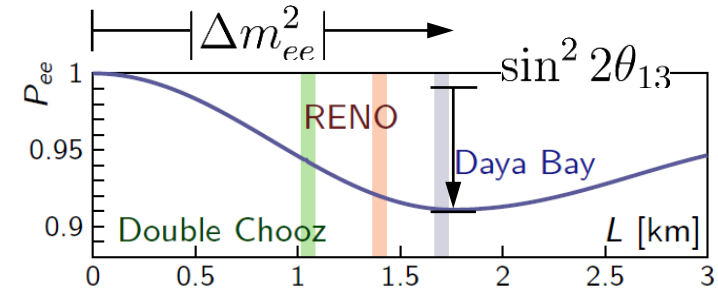
- **Independent of the unknown CP phase and θ_{23}**

Other rich physics

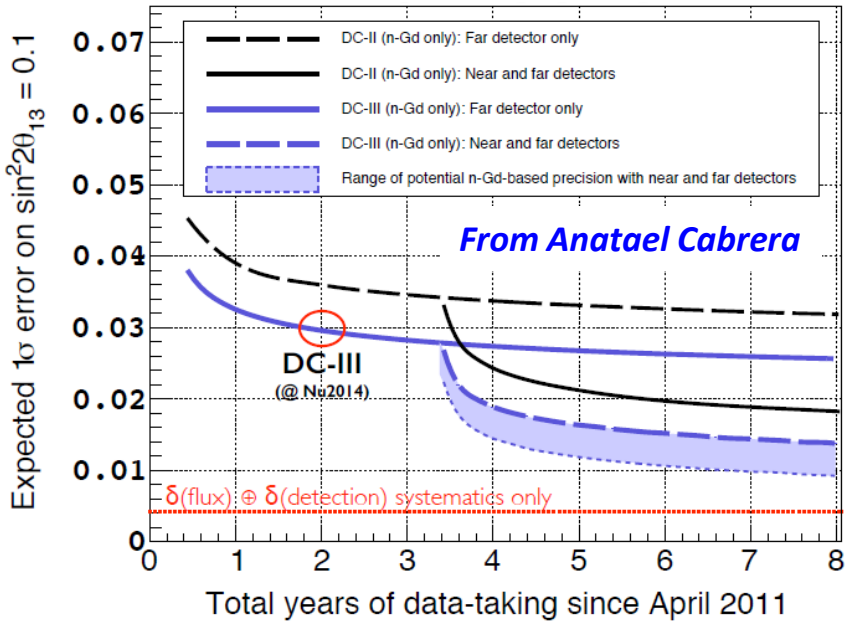
- **Precise Δm_{31}^2, θ_{12}, Δm_{21}^2, Geo-, solar, supernovae, …, neutrinos**

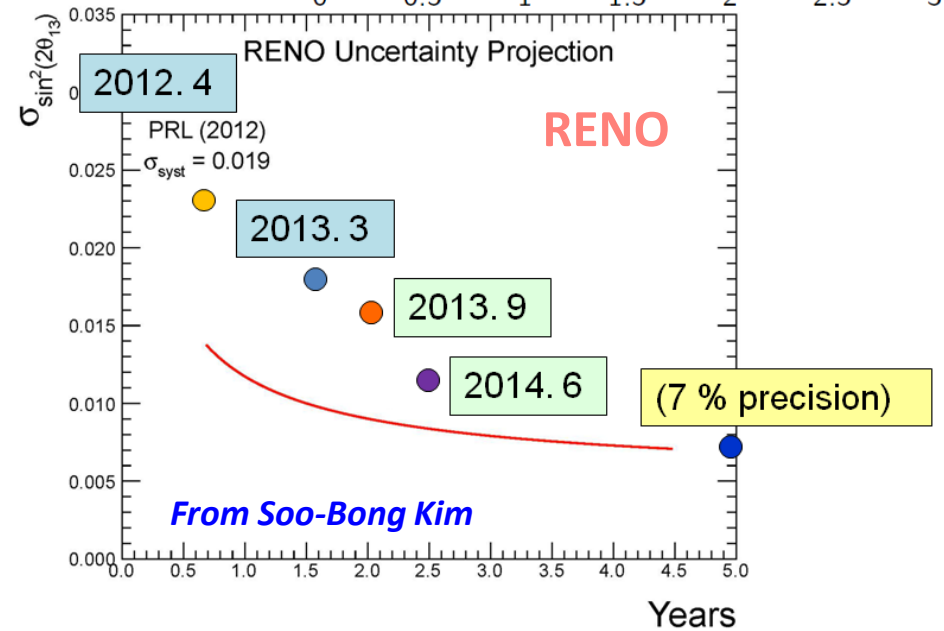
Spares

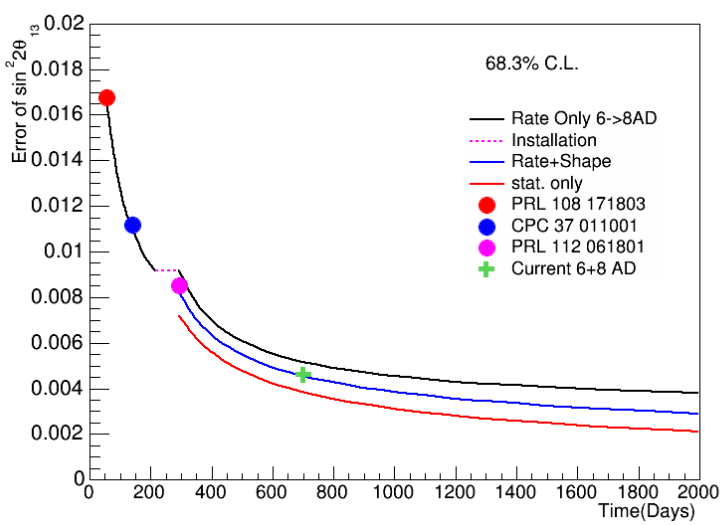
Projections of θ_{13} companies

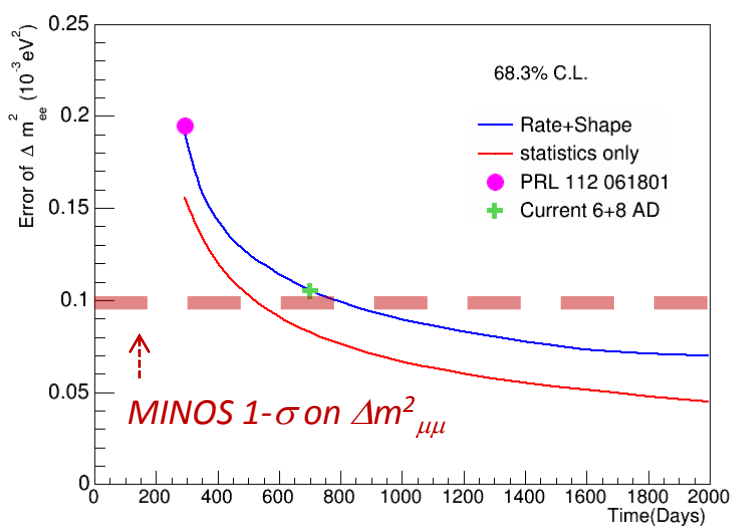


Double Chooz









Daya Bay

RENO-50 Technical Challenges

	KamLAND	RENO-50
LS mass	**~1 kt**	**18 kt**
Energy Resolution	**6.5%/√E**	**3%/√E**
Light yield	**500 p.e./MeV**	**>1000 p.e./MeV**

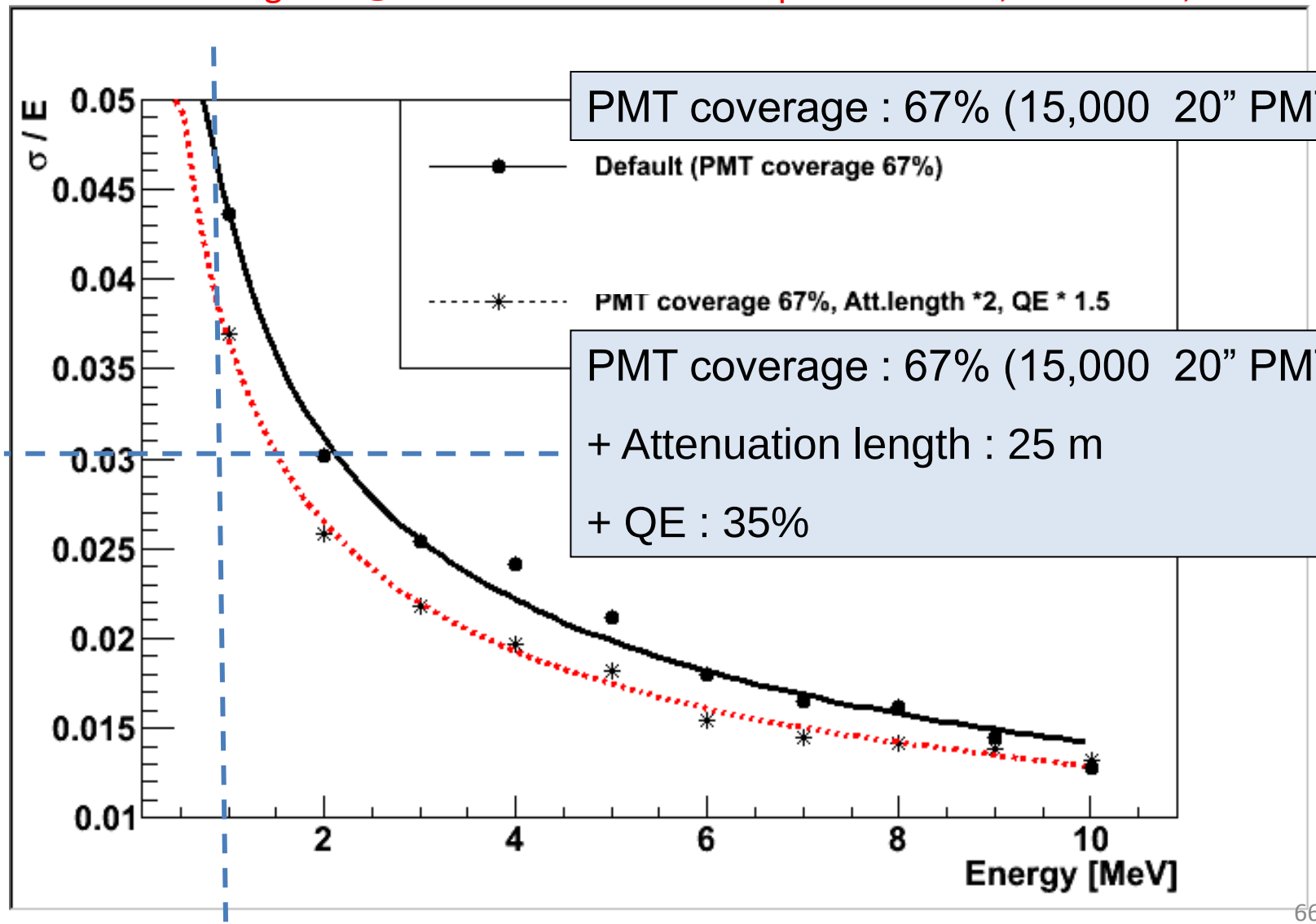
- Large detector (18 ktons) : D=30m, H=30m

- 3% energy resolution :
  - High transparency LS : 15 m → 25 m (purification & better PPO)
  - Large photocathode coverage : 34% → 67% (15,000 20" PMT)
  - High QE PMT : 20% → 35% (Hamamatsu 20" HQE PMT)
  - High light yield LS : ×1.5 (1.5 g/ℓ PPO → 5 g/ℓ PPO)

From Soo-Bong Kim

RENO-50 Expected Energy Resolution

From Soo-Bong Kim @ "International Workshop on RENO-50, June13-14, 2013"



Additional Physics with RENO-50

- Neutrino burst from a Supernova in our Galaxy
  - ~5,600 events (@8 kpc)
  - A long-term neutrino telescope

From Soo-Bong Kim

- Geo-neutrinos : ~ 1,000 geo-neutrinos for 5 years
  - Study the heat generation mechanism inside the Earth

- Solar neutrinos : with ultra low radioacitivity
  - MSW effect on neutrino oscillation
  - Probe the center of the Sun and test the solar models

- Detection of J-PARC beam : ~200 events/year

- Neutrinoless double beta decay search : possible modification like KamLAND-Zen

JUNO: Energy scale can be self-calibrated

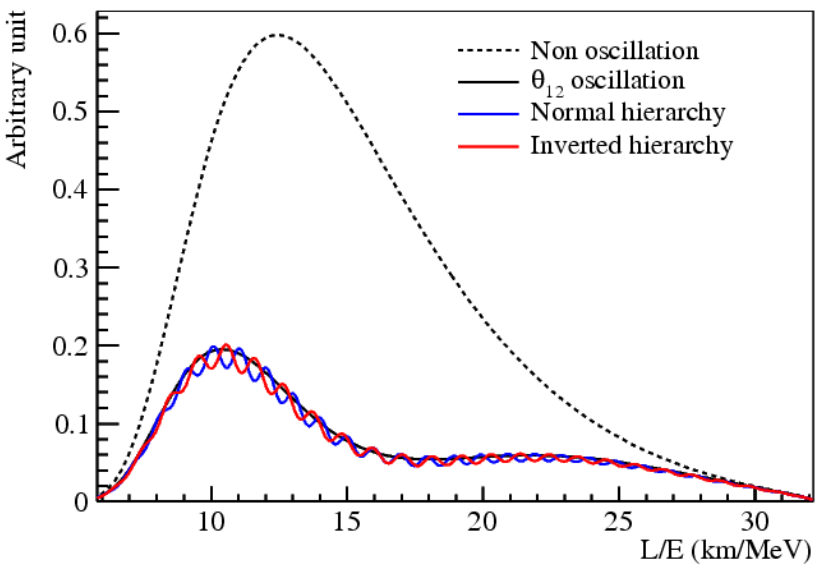
If existing a residual non-linearity:

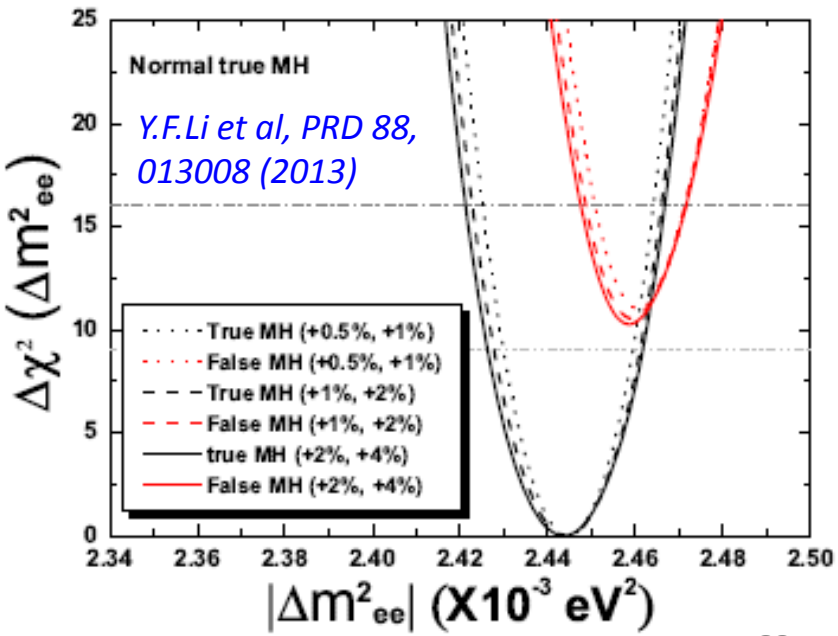
$$\frac{E_{\rm rec}}{E_{\rm true}} \simeq 1 + q_0 + q_1 E_{\rm true} + q_2 E_{\rm true}^2 \,,$$

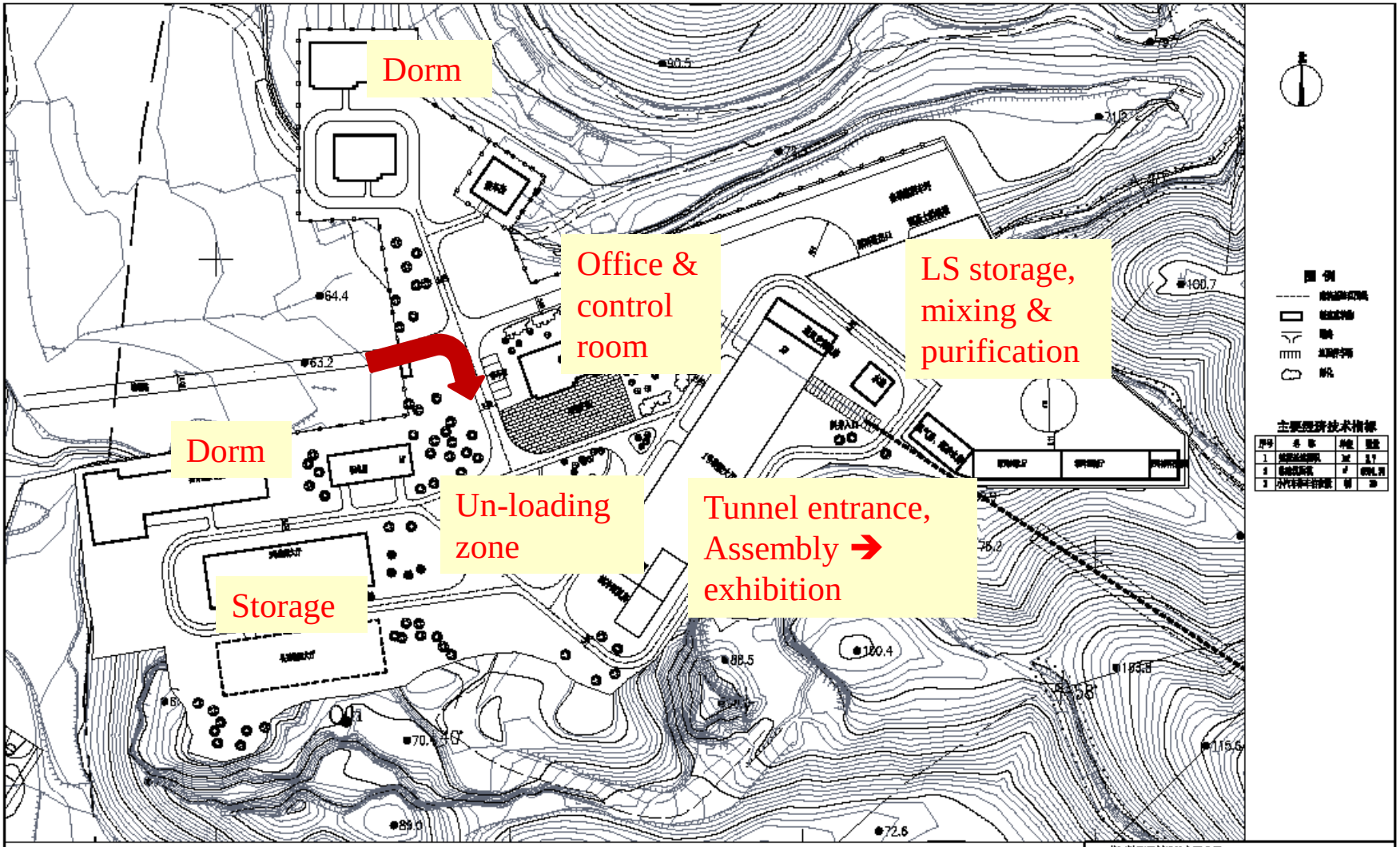
by introduce a self-calibration(based on ΔM^2_{ee} peaks):

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

effects can be corrected and sensitivity is un-affected



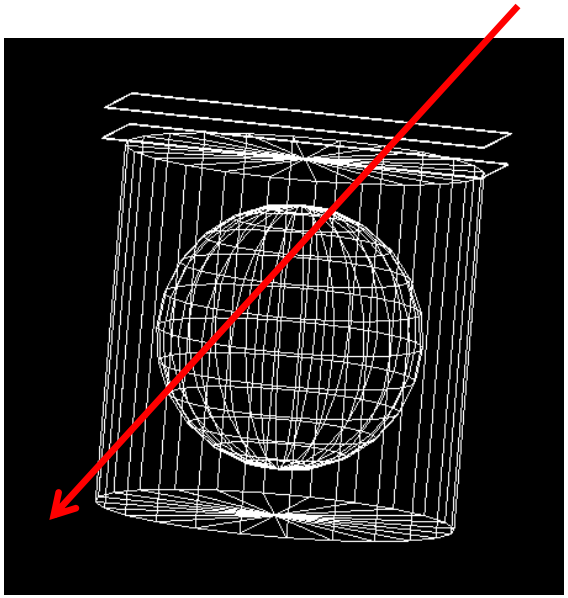




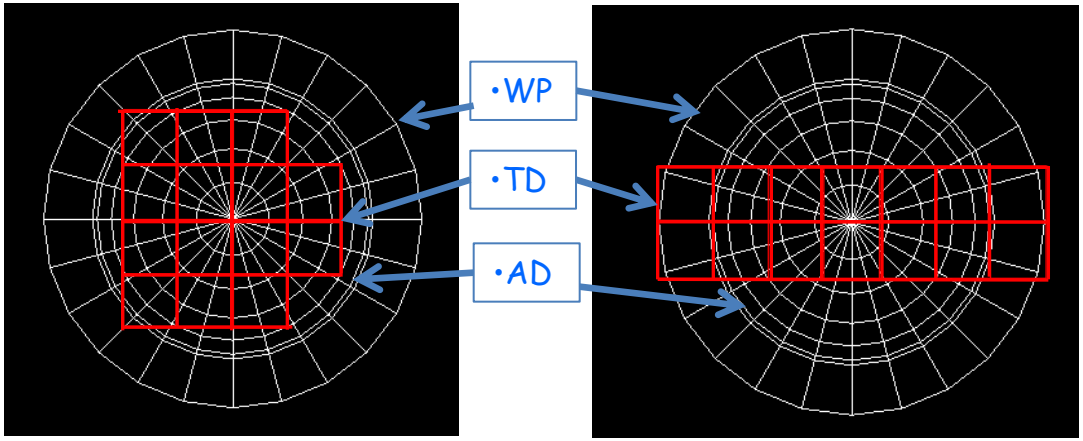
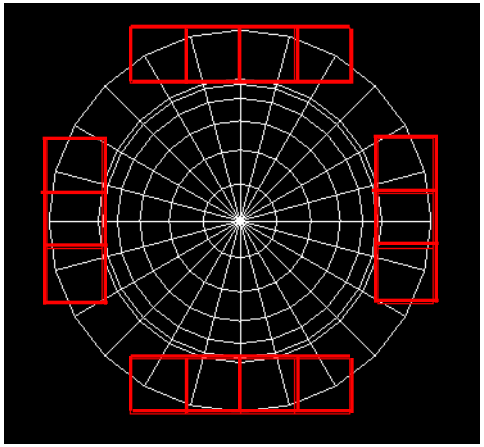
JUNO Experiment Site Layout (Preliminary)

OPERA Target Tracker for JUNO 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)