Mass Hierarchy and the JUNO Experiment

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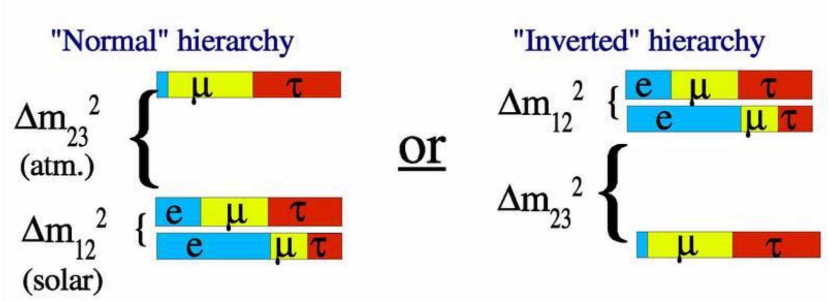
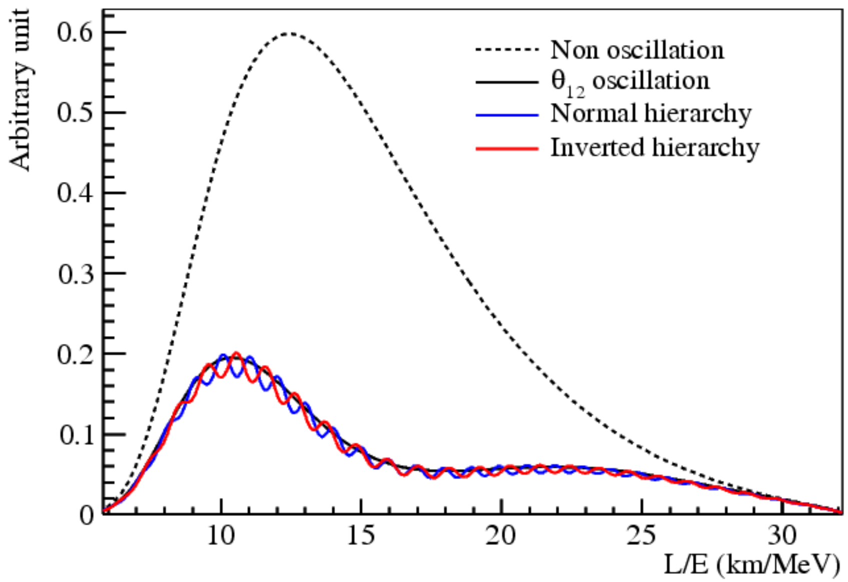
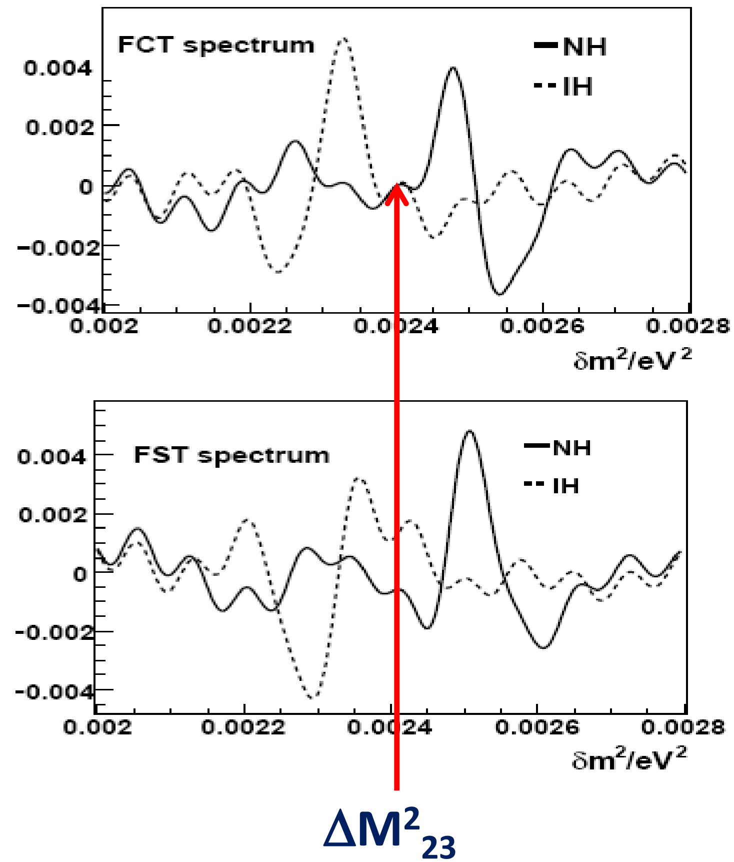
FCPPL, March 31 , 2016

Mass Hierarchy at Reactors



$$\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$$
$$\text{NH}: \; |\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$$
$$\text{IH}: \; |\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$$



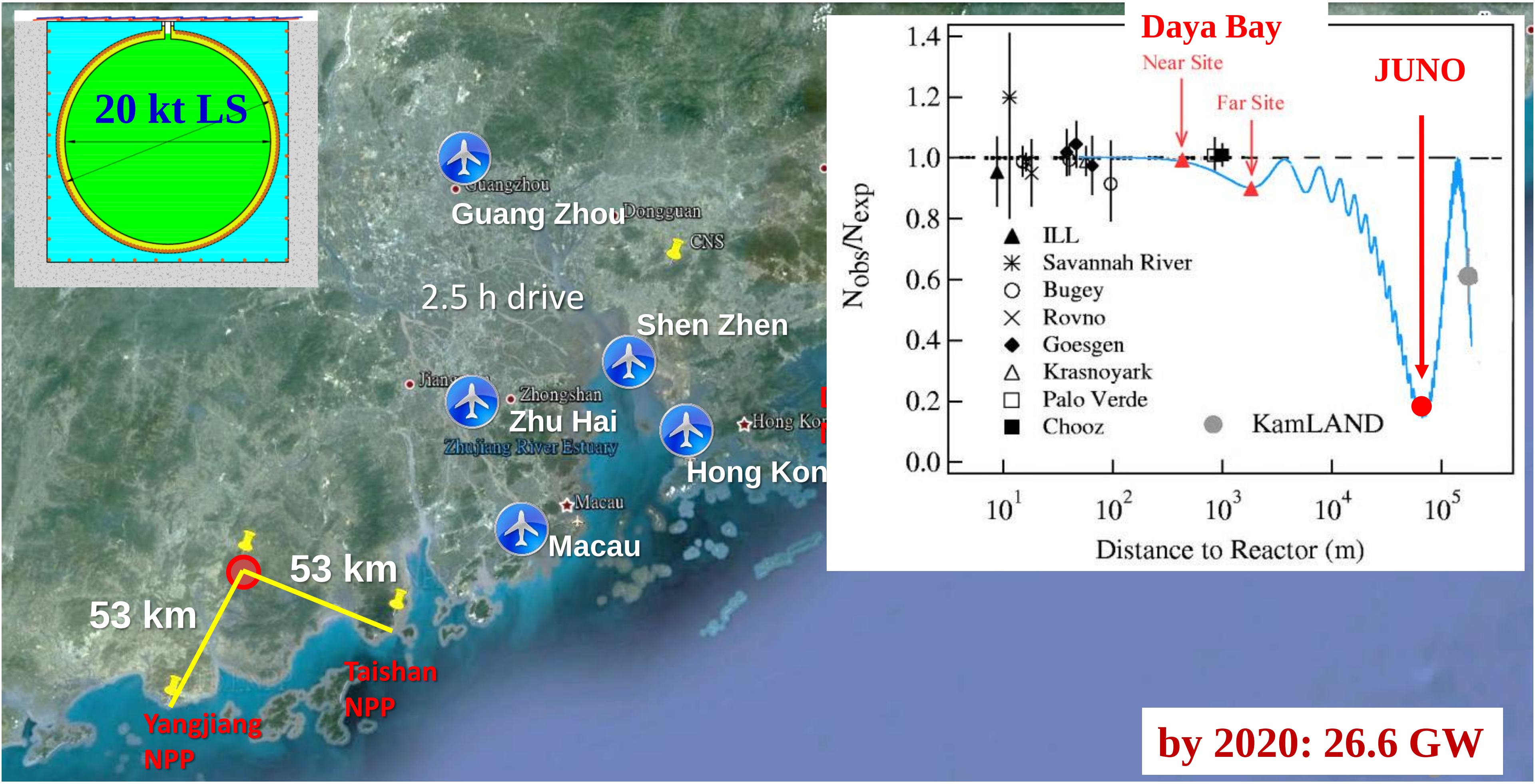


$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21})$$
$$P_{31} = \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31})$$
$$P_{32} = \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32})$$

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

The JUNO Experiment

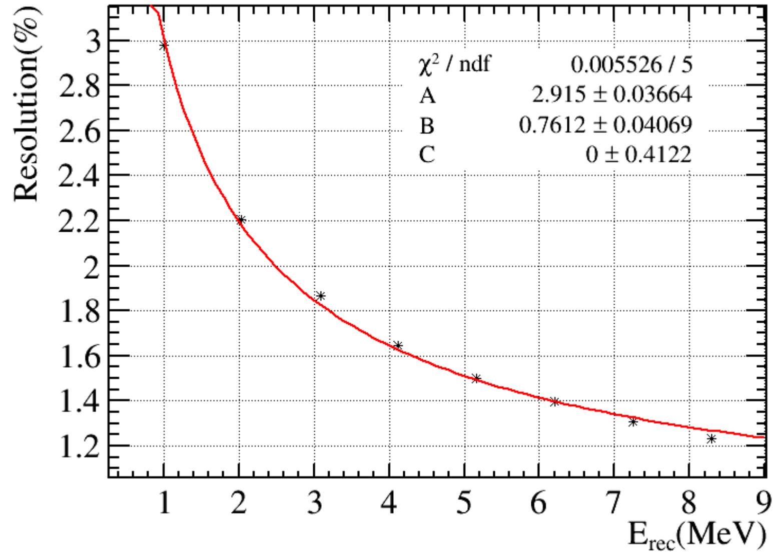
NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



MC Study：Energy Scale & Resolution

- **Resolution based on DYB with:**
  - **JUNO Geometry**
  - **80% photocathode coverage**
  - **PMT QE from 25% ➔ 30%**
  - **Attenuation length of 20 m ➔ abs. 60 m + Rayleigh scatt. 30m**

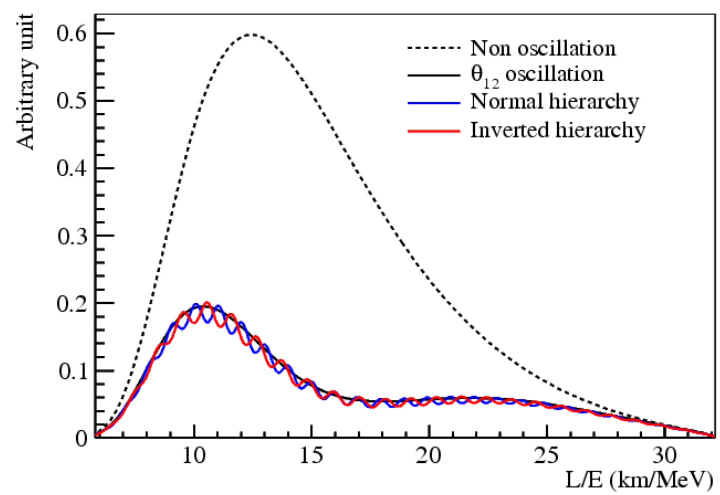
$$\frac{\sigma}{E_{rec}} = \sqrt{\frac{A^2}{E_{rec}} + B^2 + \frac{C^2}{E_{rec}^2}}$$



- **Energy scale**
  - **By introduce a self-calibration (based on ΔM^2_{ee} periodic peaks), effects can be corrected and sensitivity is un-affected**

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

  - **Application of this method: Relatively insensitive to continuous backgrounds, non-periodic structures**



Rayleigh Scattering Length

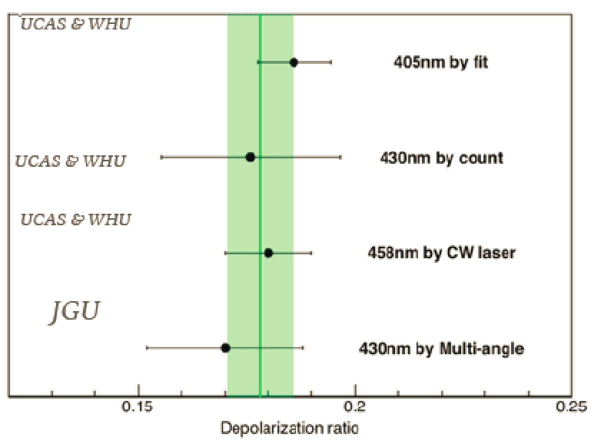
$$\frac{1}{l_{atten}} = \frac{1}{l_{abs}} + \frac{1}{l_{sca}} + \frac{1}{l_{etc.}} \qquad \frac{1}{l_{Ray}} = f(\lambda; T, n, \beta_T, \delta)$$

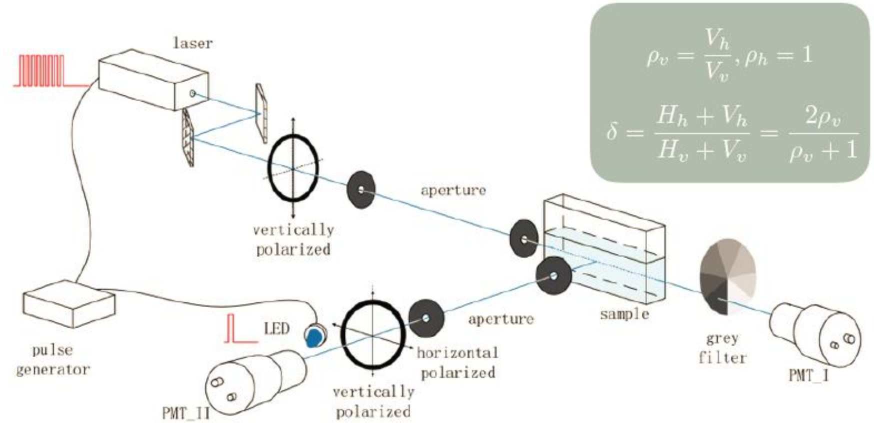
- Rayleigh scattering is measured under ESC model:

$$\beta_{tot}(\theta) = \beta_{iso}(\frac{\pi}{2})(\frac{6+6\delta}{6-7\delta})(1+\frac{1-\delta}{1+\delta}\cos^2\theta)$$

- Four experiments gave consistent results.

$$\overline{\rho_v} = 0.178 \pm 0.008 \qquad l_{ray} = 29.0 \pm 1.0 \text{ m}$$





- Model independent experiments are ongoing in JGU, WHU and UCAS.

Signals & Backgrounds

- **LS without Gd-loading for** $\tau \sim 200\ \mu s$
  - ⇨ Better attenuation length ➔ better resolution
  - ⇨ Lower irreducible accidental backgrounds from LS, important for a larger detector:
    - ✓ With Gd: $\sim 10^{-12}$ g/g ➔ 50,000 Hz
    - ✓ Without Gd: $\sim 10^{-16}$ g/g ➔ 5 Hz
- **IBD Signal and Backgrounds**

Overburden 700m:
$E_{\mu} \sim 211$ GeV, $R_{\mu} \sim 3.8$ Hz
Single rates:
5 Hz by LS and 5Hz by PMT
muon efficiency ~ 99.5%

<table>
<tr><th>Selection</th><th>IBD efficiency</th><th>IBD</th><th>Geo-νs</th><th>Accidental</th><th>^{9}Li/^{8}He</th><th>Fast n</th><th>(α, n)</th></tr>
<tr><td>-</td><td>-</td><td>83</td><td>1.5</td><td>$\sim 5.7 \times 10^{4}$</td><td>84</td><td>-</td><td>-</td></tr>
<tr><td>Fiducial volume</td><td>91.8%</td><td>76</td><td>1.4</td><td rowspan="3">410</td><td>77</td><td rowspan="5">0.1</td><td rowspan="5">0.05</td></tr>
<tr><td>Energy cut</td><td>97.8%</td><td rowspan="3">73</td><td rowspan="3">1.3</td><td rowspan="3">71</td></tr>
<tr><td>Time cut</td><td>99.1%</td></tr>
<tr><td>Vertex cut</td><td>98.7%</td><td>1.1</td></tr>
<tr><td>Muon veto</td><td>83%</td><td>60</td><td>1.1</td><td>0.9</td><td>1.6</td></tr>
<tr><td>Combined</td><td>73%</td><td>60</td><td colspan="5">3.8</td></tr>
</table>

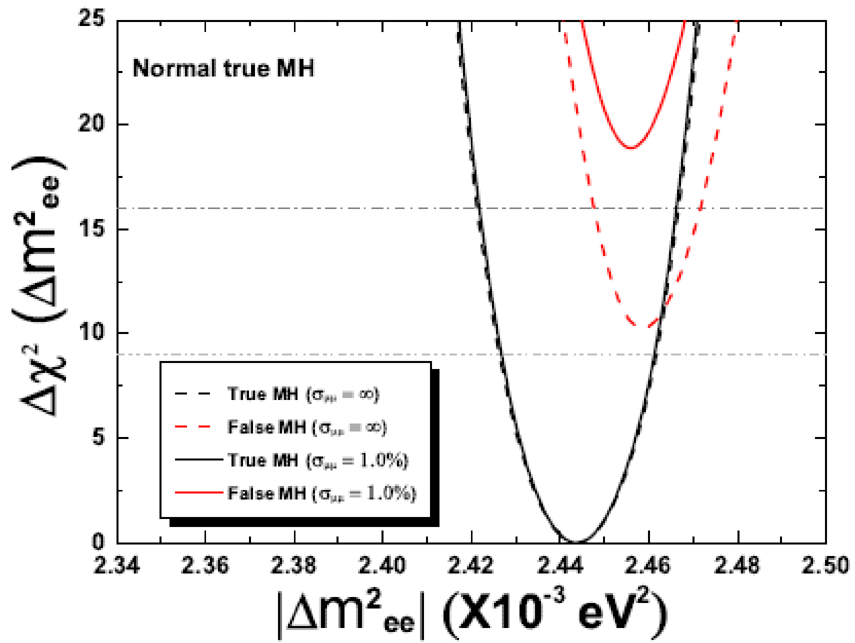
Physics Reach

Thanks to a large θ_{13}

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

For 6 years,

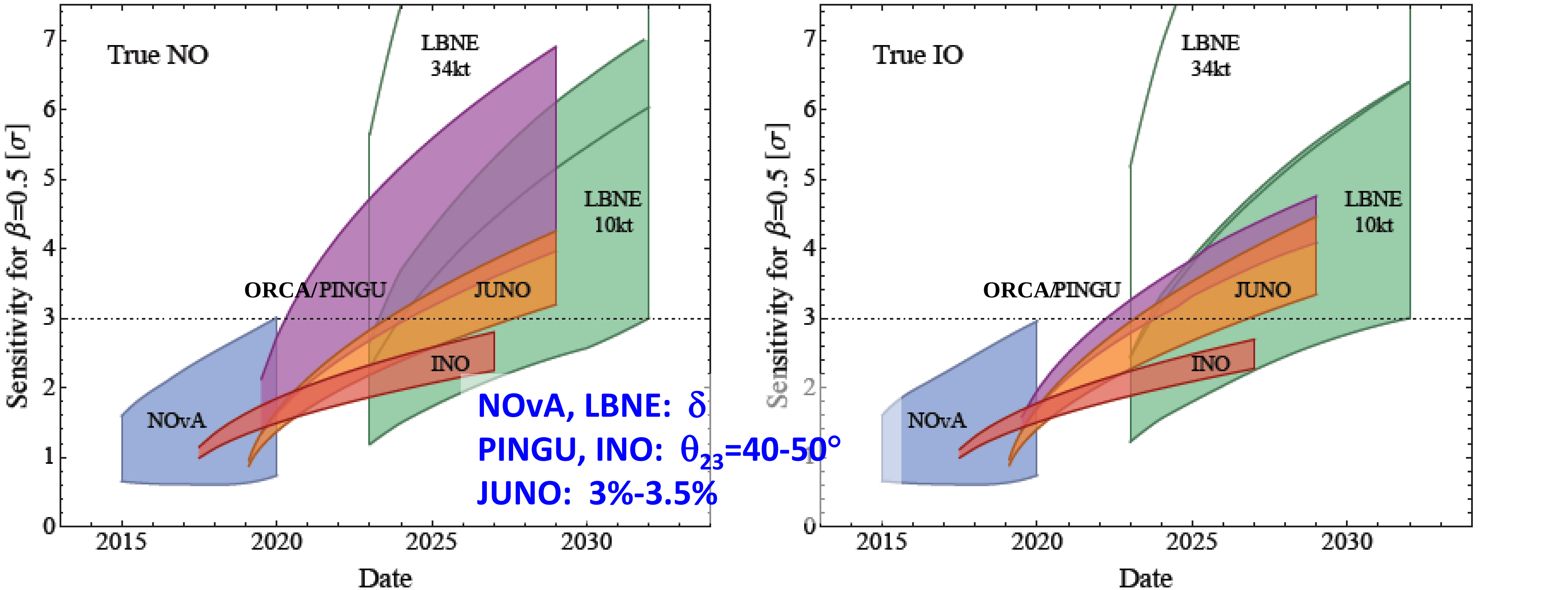
- **Ideally, The relative measurement can reach a sensitivity of 4σ, while the absolute measurement (with the help of $\Delta m^2_{\mu\mu}$ ~ 1%) can reach 5σ**
- **Due to the spread of reactor core distribution, relative measurement can reach a sensitivity of 3σ, while the absolute measurement can reach 4σ**



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

Comparison with Other Experiments

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

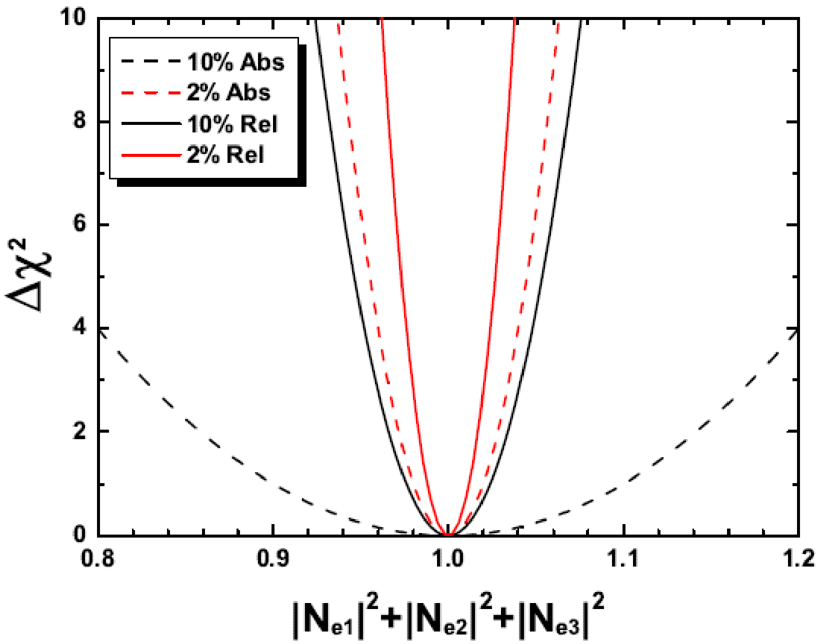


- **JUNO is unique for measuring MH using reactor neutrinos**
  - **Independent of the CP phase and free from the matter effect: complementary to accelerator-based experiments**
  - **competitive in time**
- **Many other science goals**

Precision Measurement of Mixing Parameters

- **Fundamental to the Standard Model and beyond**
- **Probing the unitarity of U_{PMNS} to ~1% level !**
  - ⇨ **Uncertainty from other oscillation parameters and systematic errors, mainly energy scale, are included**

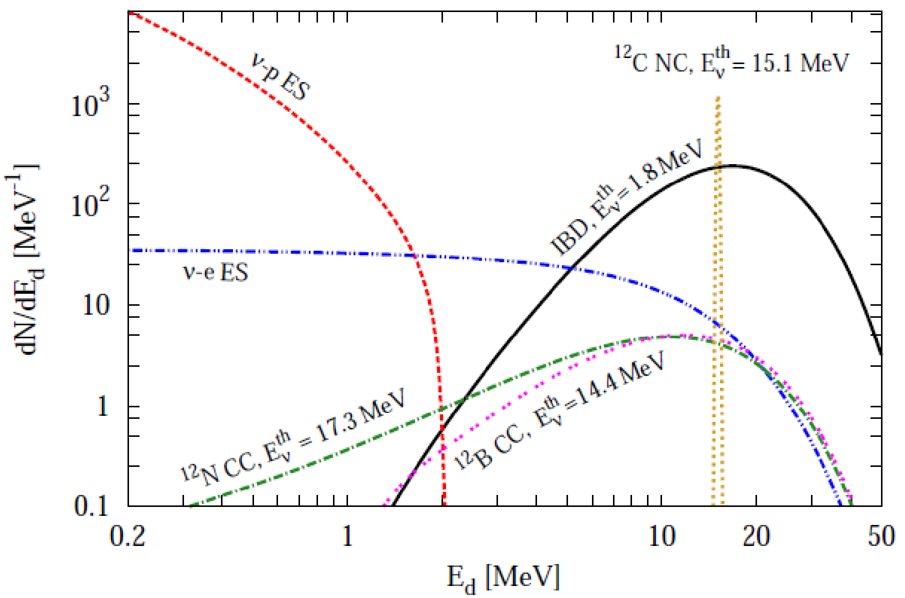
	Current	JUNO
Δm^2_{12}	3%	0.6%
Δm^2_{23}	3%	0.6%
$\sin^2\theta_{12}$	4%	0.7%
$\sin^2\theta_{23}$	11%	N/A
$\sin^2\theta_{13}$	10%	-



More precise than CKM matrix elements !

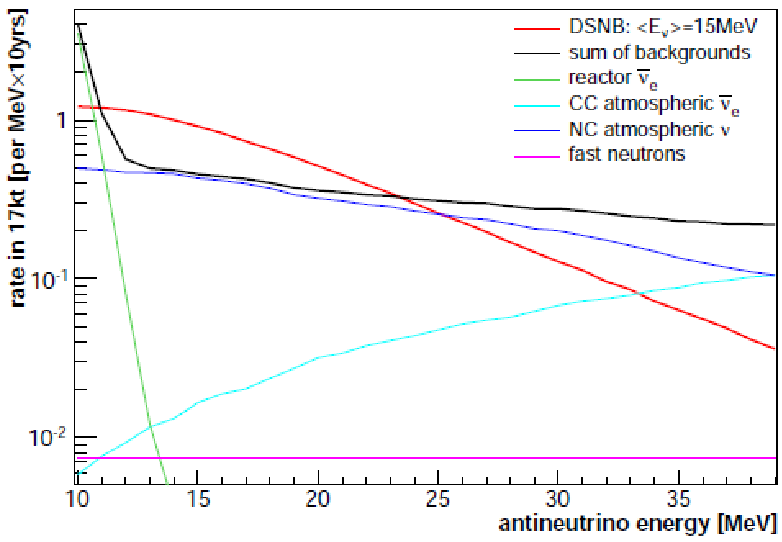
Supernova Neutrinos at JUNO

- Very high statistics
  - Several 10^3 vs 10's for 1987A
- Sensitive to different types of neutrinos
- Hugh implications to astrophysics and particle physics



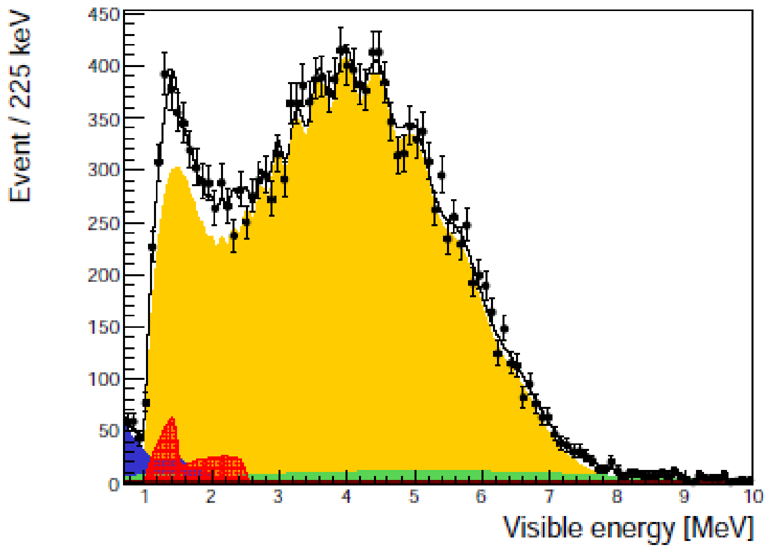
Diffused Supernova Neutrinos

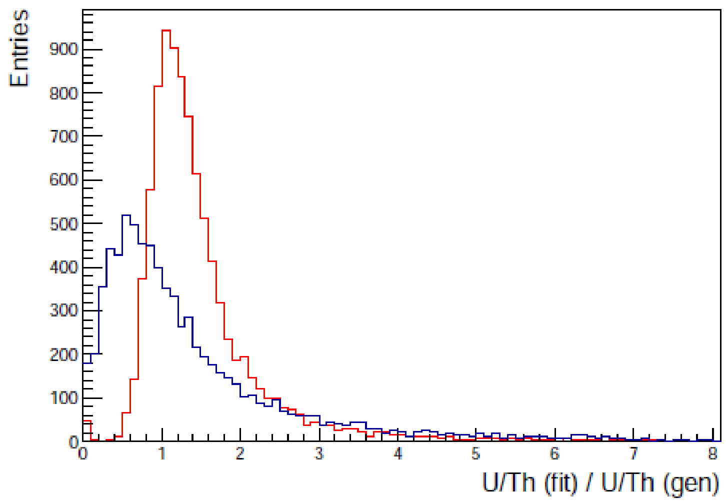
- Important for star-formation rate, average core-collapse neutrino spectrum, rate of failed SNe, etc.
- Very likely to see them above the 3σ level if ⟨E⟩ > 15 MeV
- Significantly improve the current limit by SuperK



Other Physics with Giant LS detector

- **Geo-neutrinos**
  - **Current results:**
    KamLAND: 30±7 TNU *(PRD 88(2013)033001)*
    Borexino: 38.8±12.0 TNU *(PLB 722(2013)295)*
  - **JUNO:**
    - ~ 10% precision for 3 years
    - ~ 6% precision for 10 years
  - **Possible to determine U/Th ratio**
- **Solar neutrinos**
  - need LS purification, low threshold
  - background handling
- **Atmosphere neutrinos**
- **Nucleon Decay**
- **Sterile neutrinos**



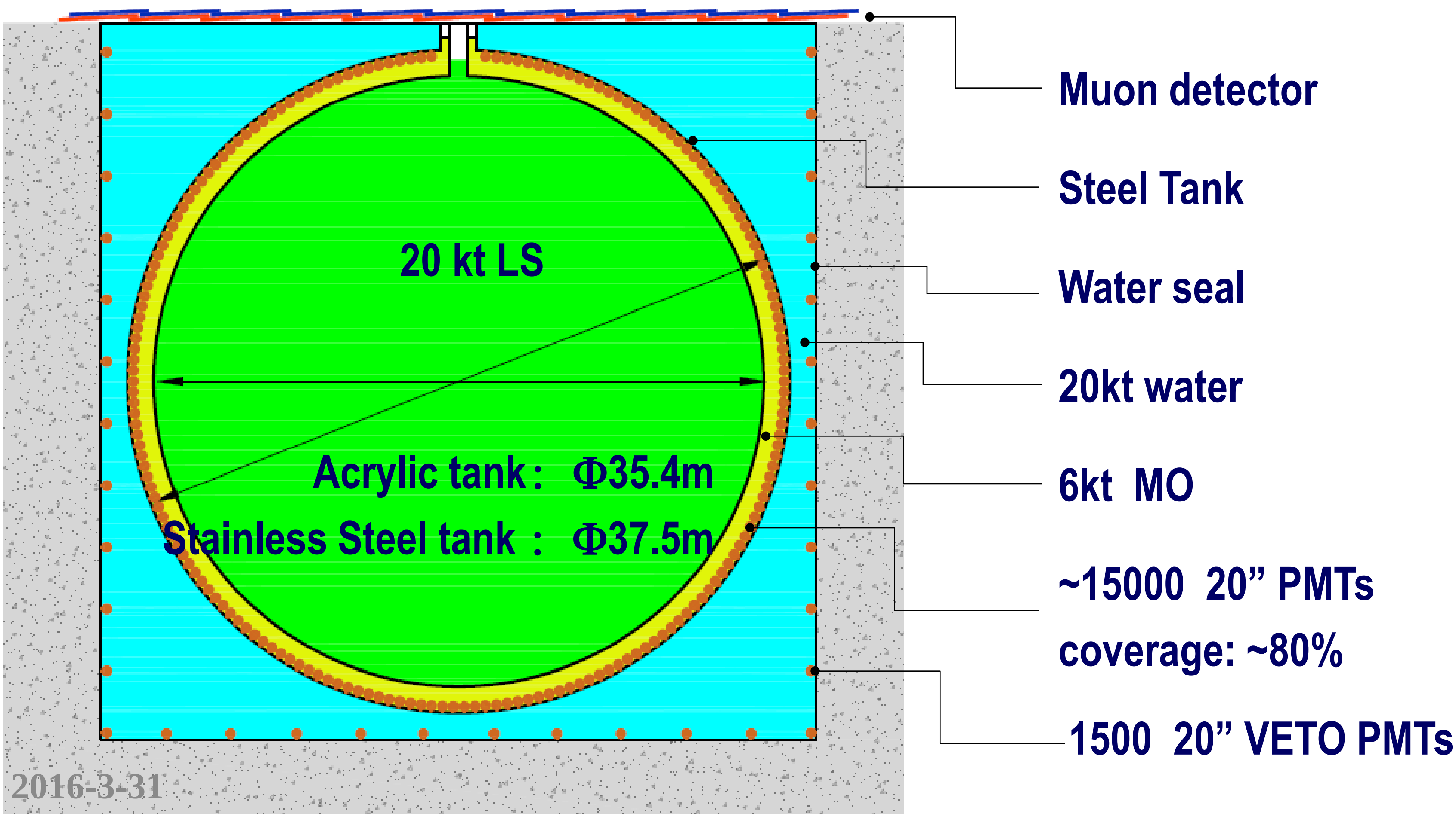


JUNO Physics Book: arXiv: 1507.05613

Detector Concept

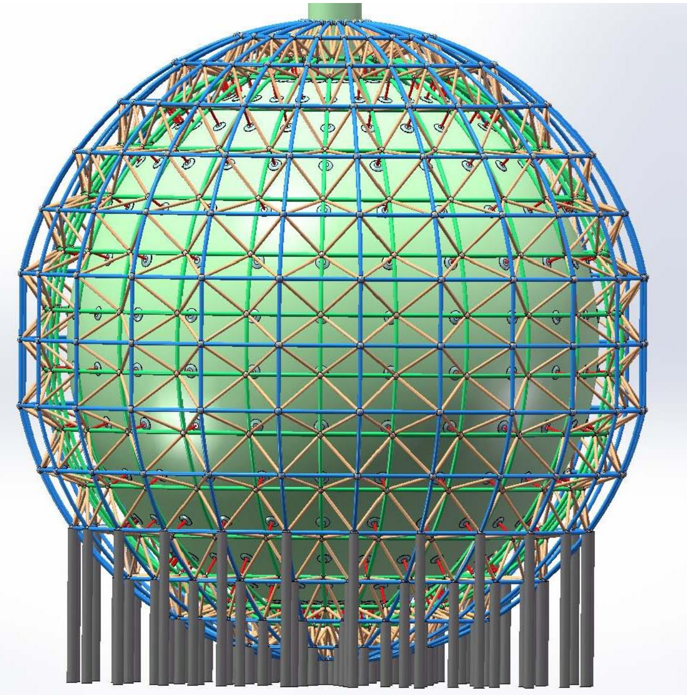
JUNO CDR:
arXiv:1508.07166

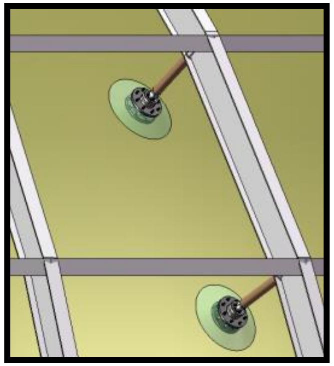
- A large cavern with an overburden > 700 m rock
- LS volume: × 20 KamLAND ➔ for more statistics
- light(PE) × 5 KamLAND ➔ for better resolution ($\Delta M^2_{12}/\Delta M^2_{23}$ ~ 3%)

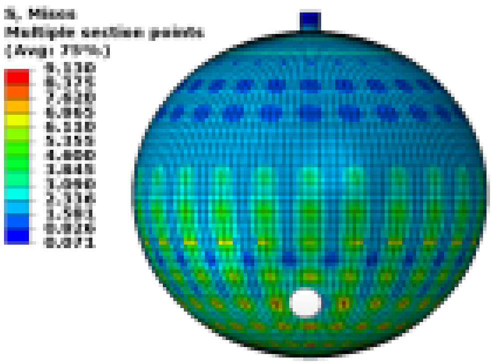


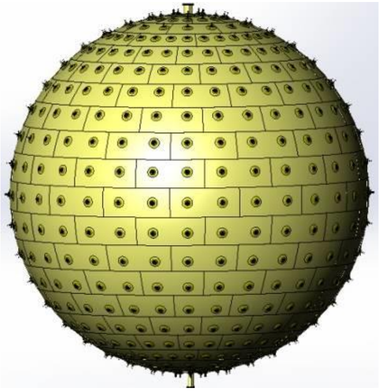
Central Detector

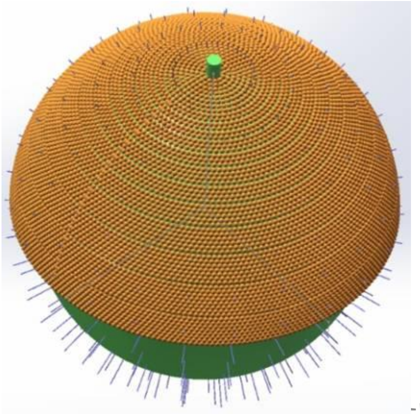
- **A huge detector in the water pool:**
  - **Mechanics，optics, chemistry, …**
  - **How to keep it clean ?**
  - **Possibility of assembly within 1 years**
- **Two main options: acrylic vs balloon**
- **Final choice: A SS structure to hold the acrylic sphere and to mount PMTs**
  - **Detailed FEA calculation in agreement with experimental data, particularly at the supporting point**
  - **Acrylic sheets: 9m × 3m ×12 cm**
  - **Stress less than 5 MPa everywhere**





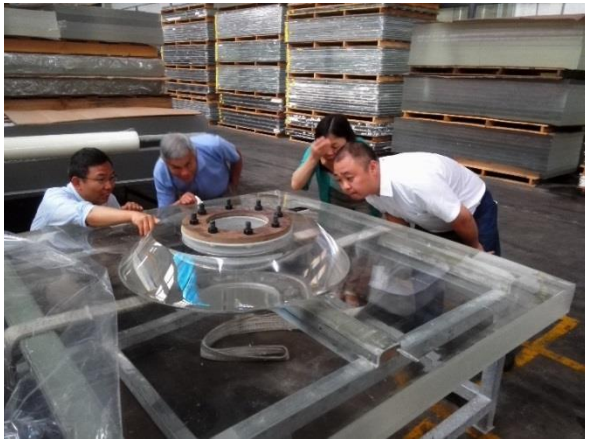


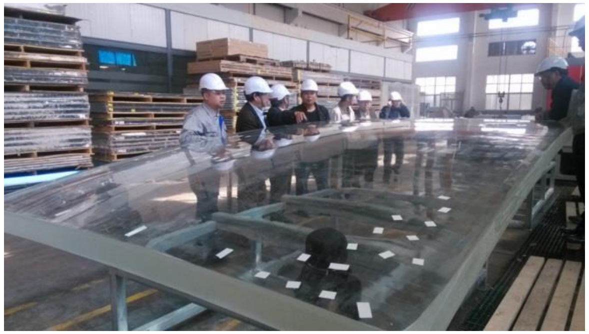




R&D and Prototyping

- **Study of acrylic:**
  - **Property test: aging, creep, crazing,**
    - **80% after 20 years**
    - **No creep & crazing under 5.5 Mpa**
  - **Bonding test: fast bonding, T-shape bonding**
    - **70 -80 % strength**
  - **Strength of the supporting point:**
    - **~ 50 t (safety factor ~ 4)**
- **Prototyping:**
  - ⇨ **Thermal shaping of acrylic sheets**
  - ⇨ **Bonding of large sheets: ~ 1/100 in area**
- **Manufacturing method understood:**
  - ⇨ **SS Truss from bottom to top (2~3 months)**
  - ⇨ **Acrylic sphere from top to bottom(8 months)**



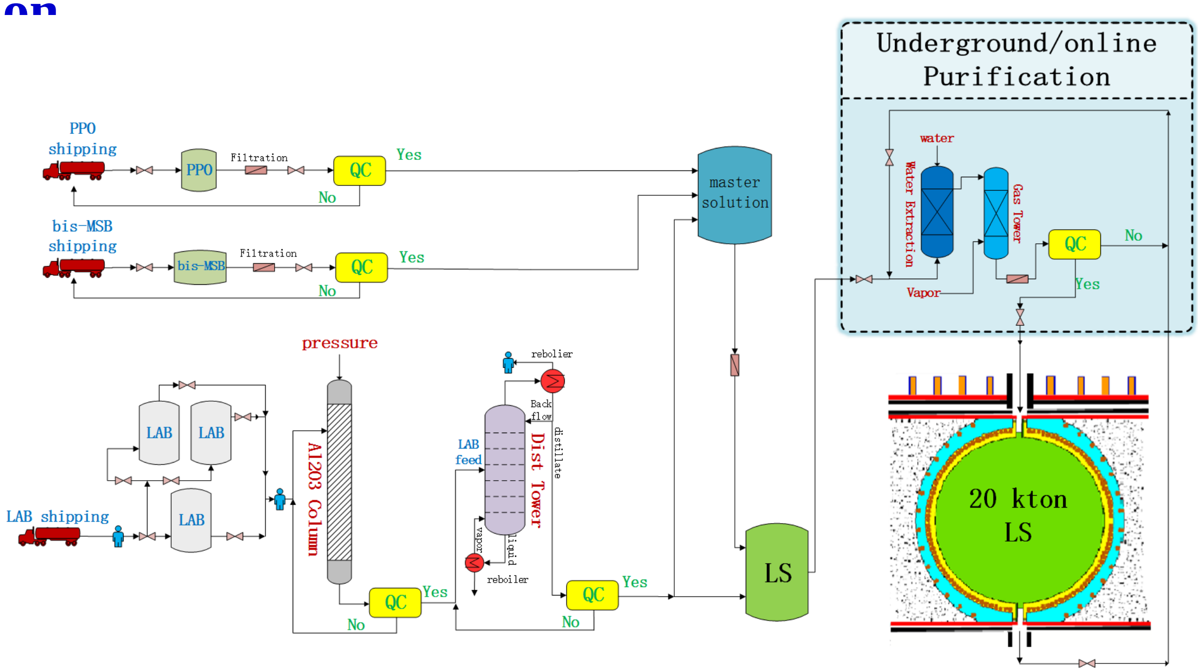


Liquid Scintillator

- **Current Choice: LAB+PPO+BisMSB**
- **Requirements and R&D:**
  - **Long attenuation length: 15m → 30m**
    - ✓ **Improve raw materials**
    - ✓ **Improve the production process**
    - ✓ **Purification**
      - – **Distillation, Filtration, Water extraction, Nitrogen stripping…**
  - **High light yield: Optimization of PPO & BisMSB concentration**

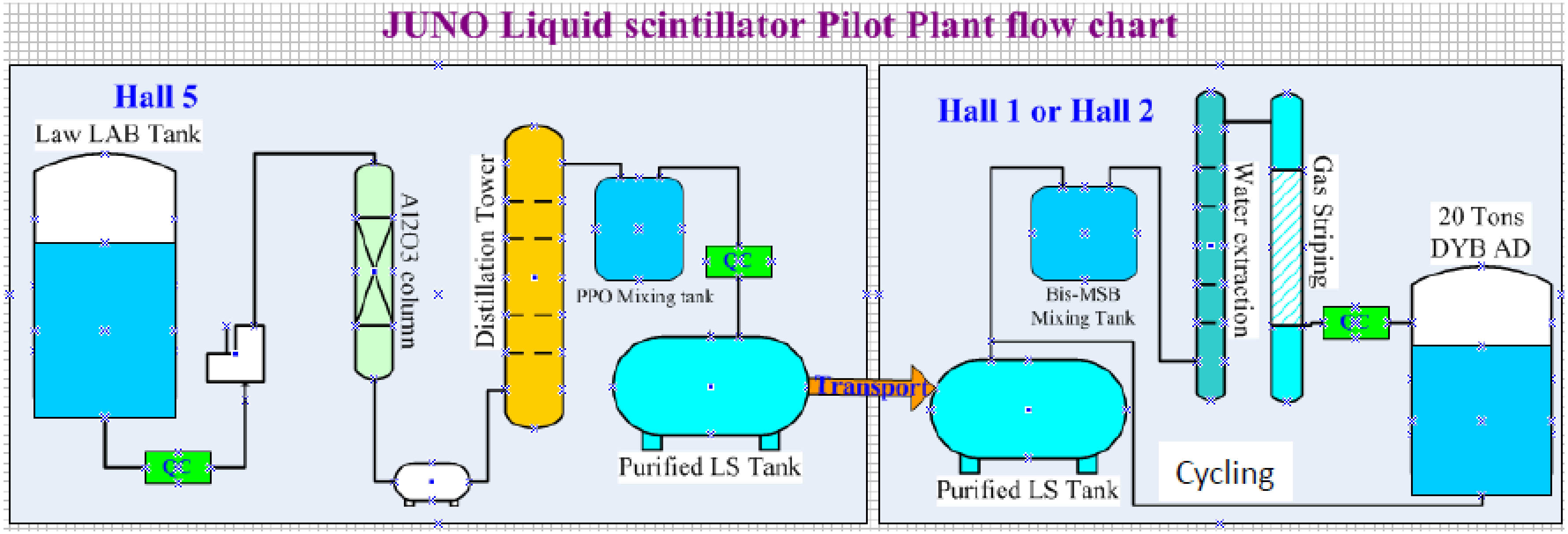
Linear Alky Benzene	Atte. L(m) @ 430 nm
RAW	14.2
Vacuum distillation	19.5
SiO_2 coloum	18.6
Al_2O_3 coloum	22.3
LAB from Nanjing, Raw	20
Al_2O_3 coloum	25

Engineering issues:
Equipment & handling for 20kt
Raw material selection:
BKG & purity issues



A pilot LS system at Daya Bay

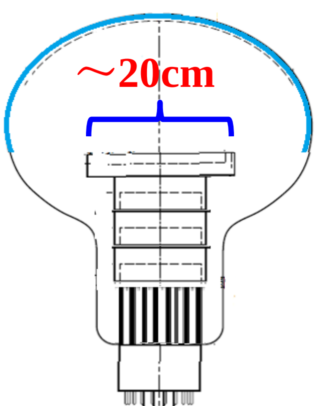
- **Test purification principles**
- **System and components prototyping**
- **All 4 purification methods will be tested:**
  - Al2O3 column, vacuum distillation, water extraction, steam striping
- **Online purification will be tested**
  - water extraction, steam striping



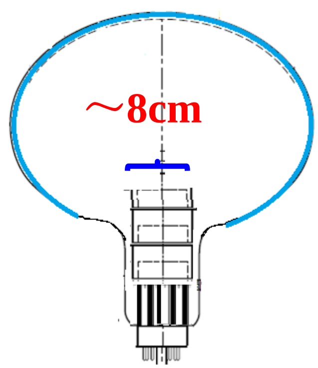
High QE PMT

- A new type of PMT developed by NNVC based on MCP to collect photoelectrons:
  - ⇨ Intrinsically high collection efficiency
    - ✓ No wire mesh in front of dynode
    - ✓ transparent + reflective photocathode
  - ⇨ Easy for mass production

Dynode PMT

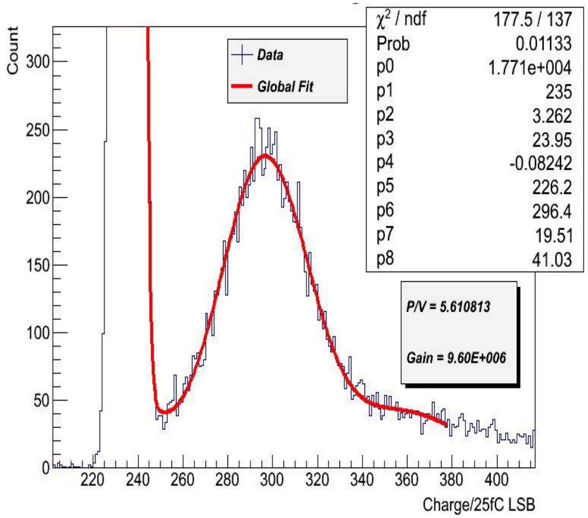


MCP-PMT

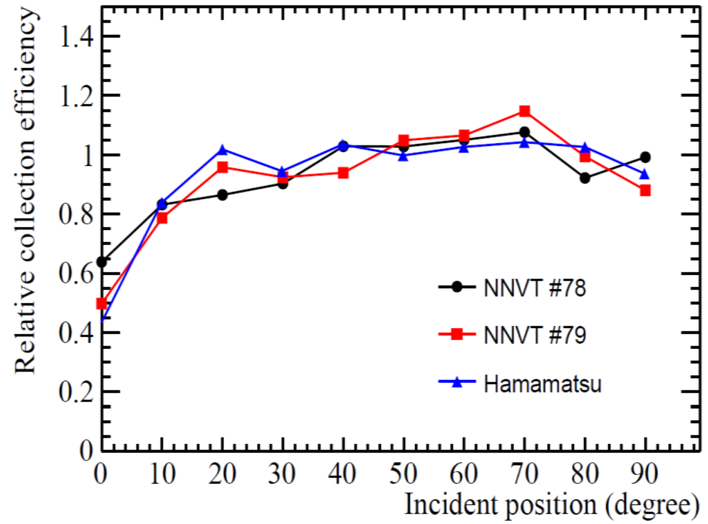


Performance of MCP-PMT

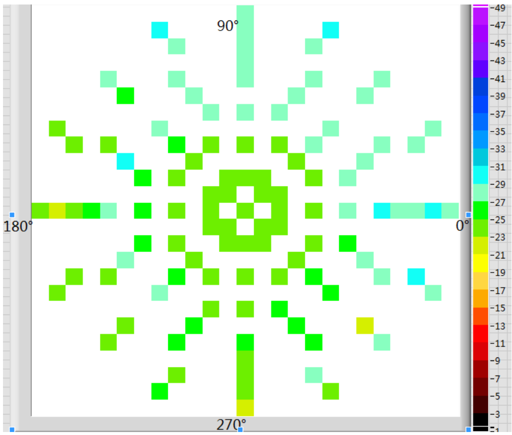
SPE



Angular response

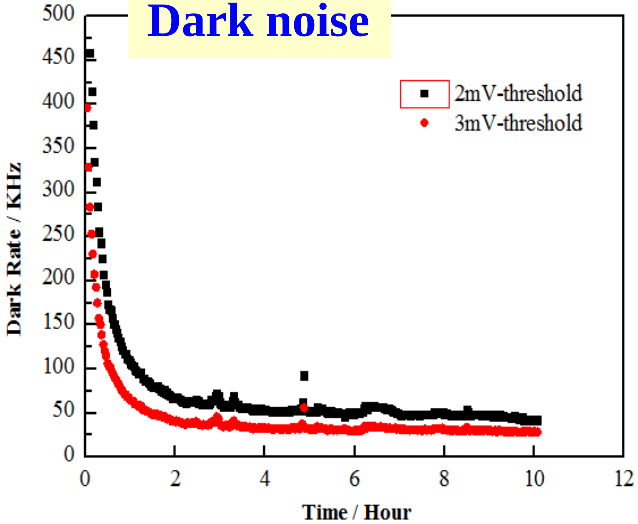


QE & uniformity

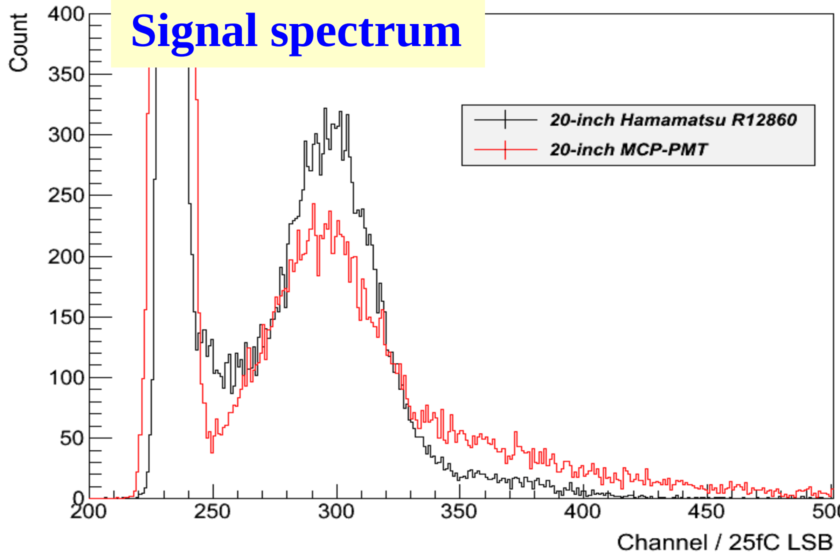


Min:24.5%; Max:29%
Average:26.5%

Dark noise



Signal spectrum



Final Decision

	R12860	MCP-PMT
QE@410nm	~ 30% (T)	~ 26%(T), 30%(T+R)
Collection eff.	90%	100%
Total eff.	27%	26-30 %
P/V of SPE	> 3	> 3
Rise time	7 ns	2ns
TTS	3 ns	~10 ns
Dark noise	30K	30K
After pulse	< 10%	< 3 %

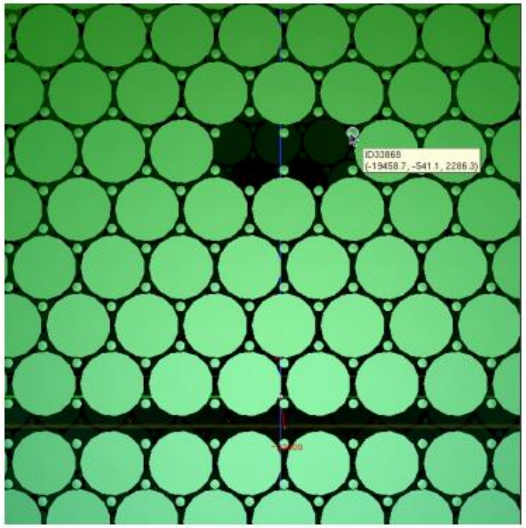
Two vendors:

NNVC: 15000

Hammamatzu: 5000

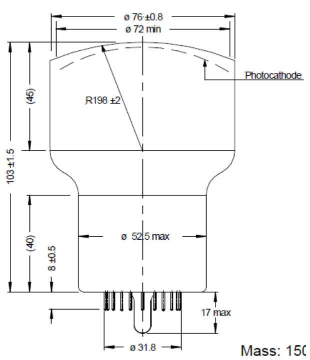
Small PMT system

- Calibrate non-uniformity and non-linearity of Large-PMTs
  - ⇨ Reduce energy scale uncertainty
  - ⇨ Improve energy resolution (non-stochastic term)
- Increase optical coverage (~5%)
  - ⇨ Improve energy resolution (stochastic term)
- Extend energy measurement
  - ⇨ Improve muon physics
- Supernova

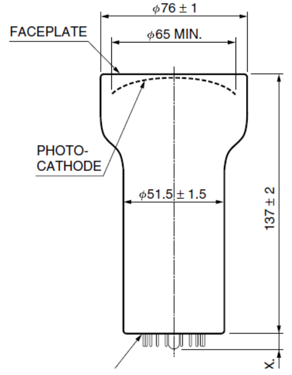


- 20” PMTs: 17746
- 3” PMT: 35794

HCZ XP53B20

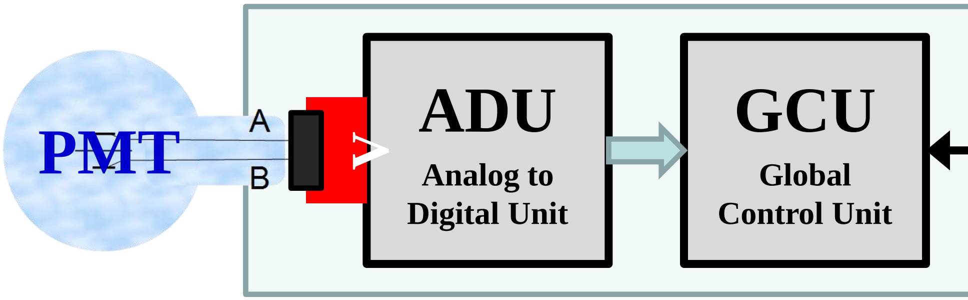


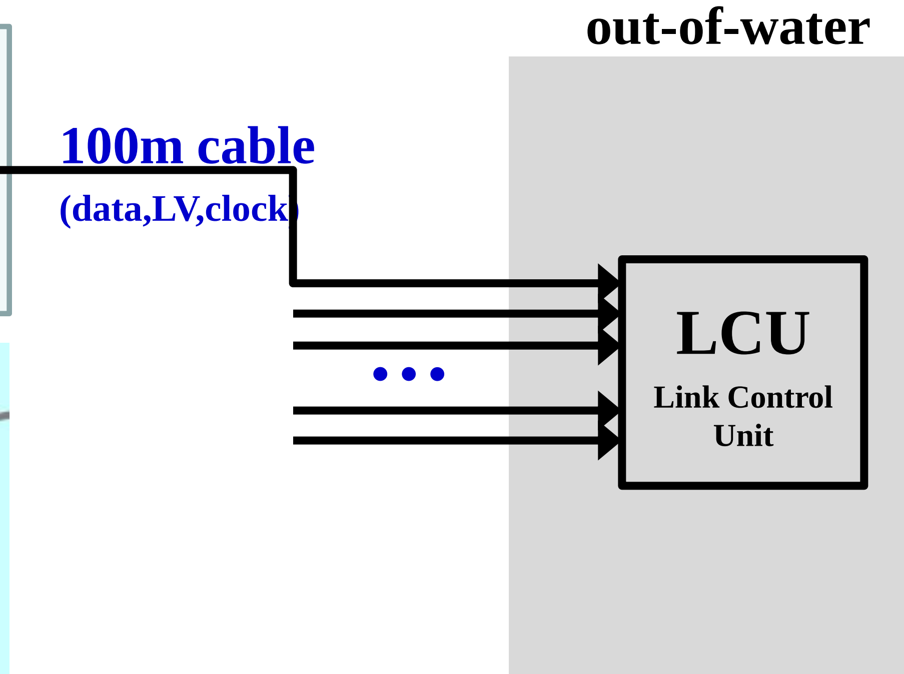
Hamamatsu R6091

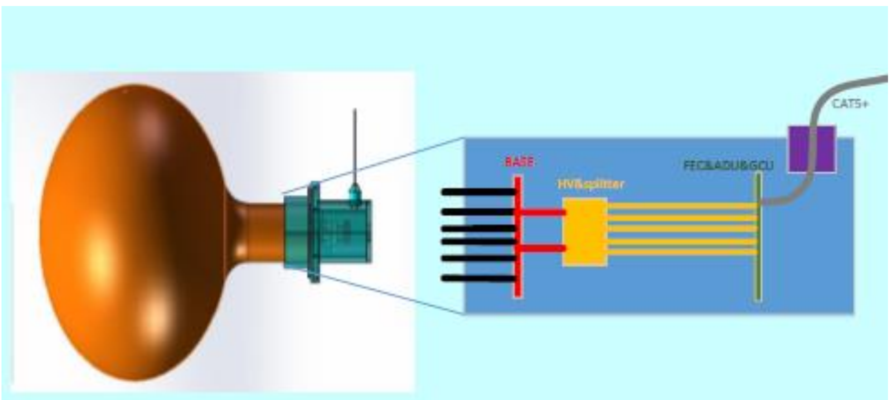


Anatael’s talk

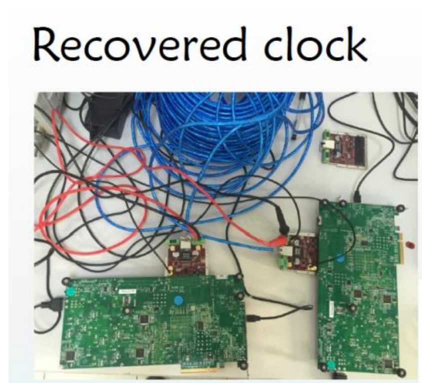
Electronics





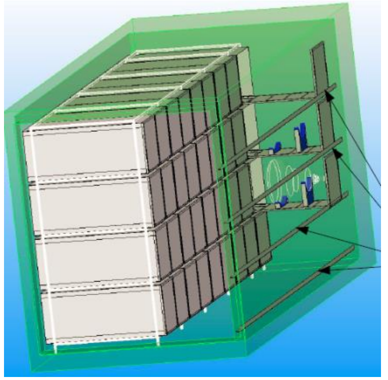


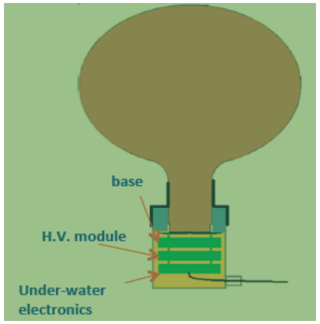
- HV, FADC, FPGA, clock/data transmission, etc.
- Allowed failure rate: 0.5%/6 years
- Issues: power, reliability, etc

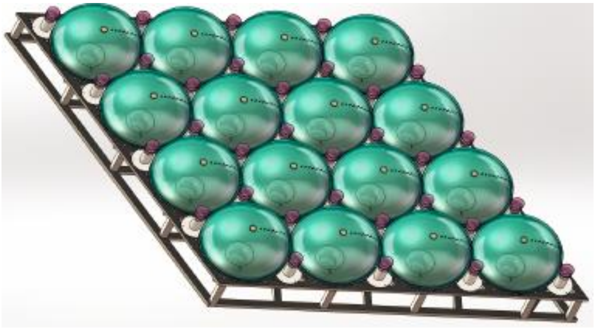


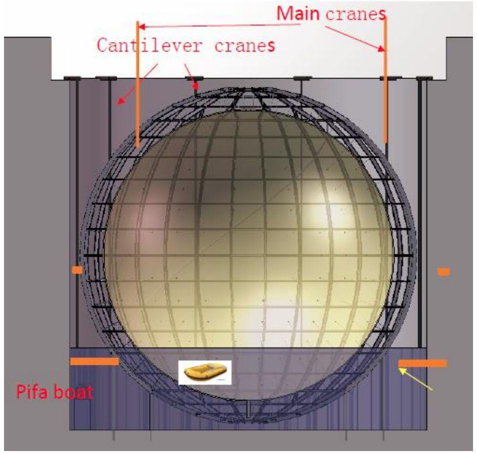
PMT Instrumentation

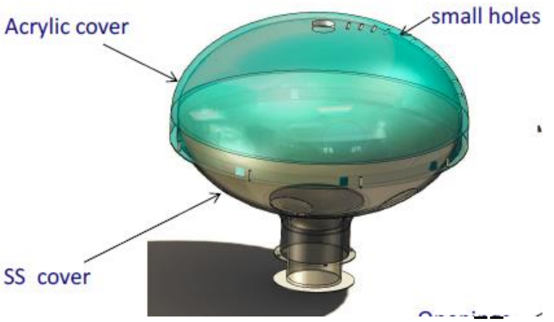
- **PMT testing**
  - 18,000 20” PMTs & 36,000 3” PMTs
  - 4 instrumented Containers for mass testing
- **PMT potting**
  - With base/HV/electronics
  - Failure rate < 0.5%/6 years
- **PMT protection**
  - Mechanism & requirements understood
  - Acrylic + steel cover with holes(plus film ?)
- **PMT installation**





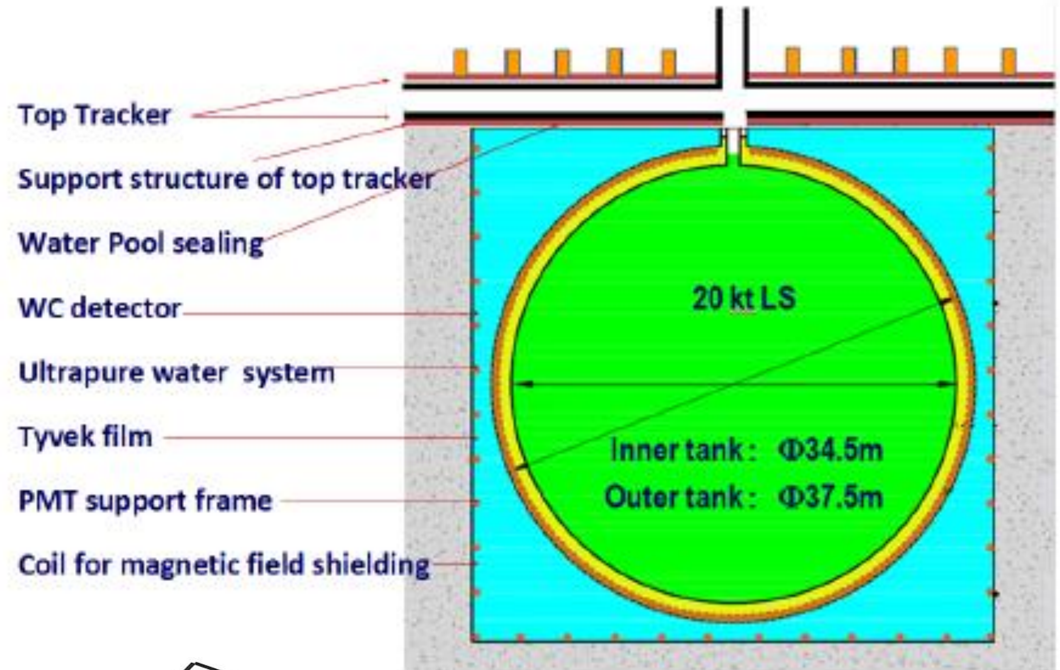


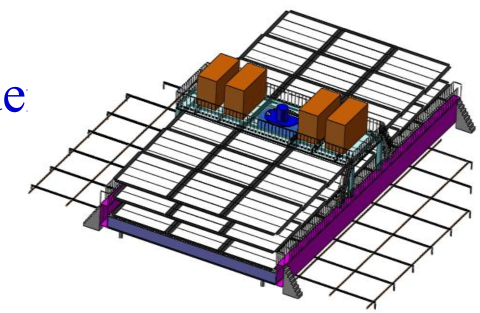


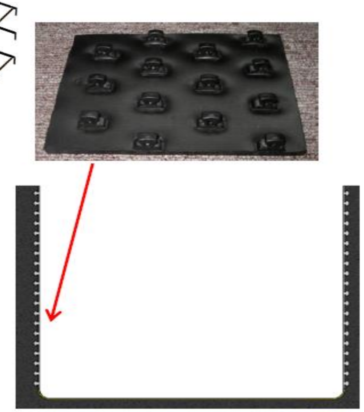


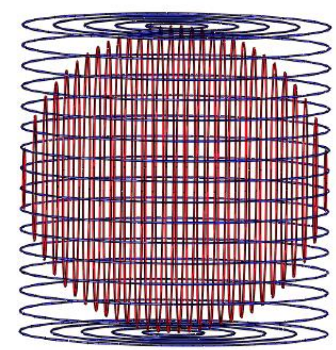
VETO

- **Tasks:**
  - Shield rock-related backgrounds
  - Tag & reconstruct cosmic-rays tracks
- **Detector:**
  - Top tracker: refurbished OPERA scintillators
  - Water Č detector under optimization
- **Pool lining: HDPE**
- **Coil for magnetic field shielding: under design**



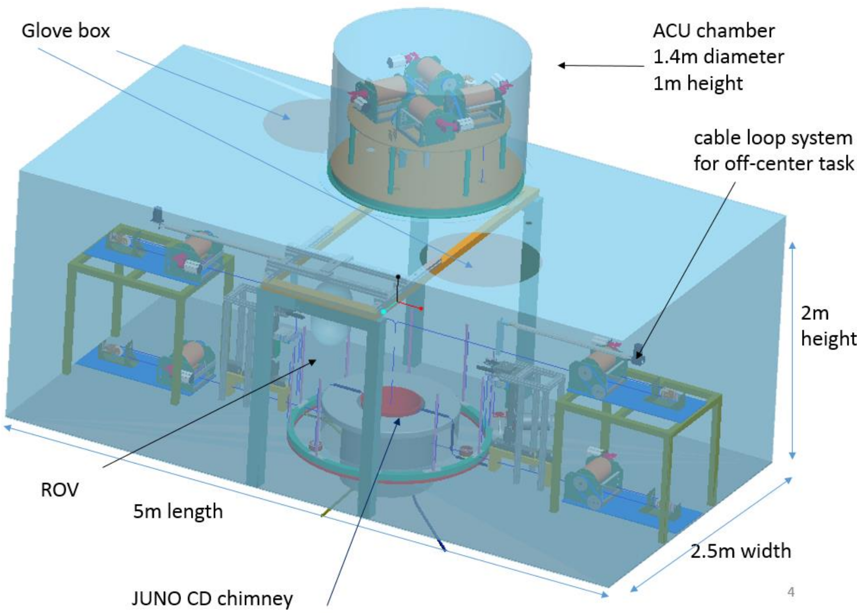


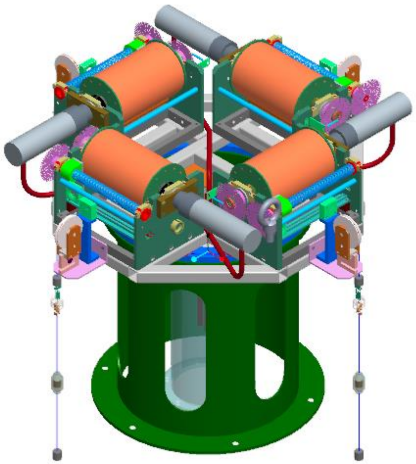


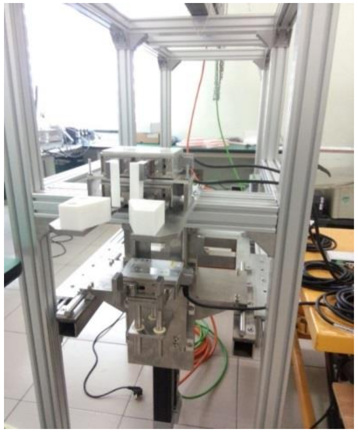


Calibration

- **Main method**
  - ⇨ Routinely Source into LS by
    - ✓ ACU
    - ✓ rope loop
    - ✓ “sub-marine”
  - ⇨ Source into Guided tube
  - ⇨ Mini-balloon
  - ⇨ Pulsed light source
- **Under discussion**
  - ⇨ Diffused short-lived isotopes
  - ⇨ Pelletron-based beam
- **Key technical issues**
  - ⇨ Source deployment
  - ⇨ Source locating system

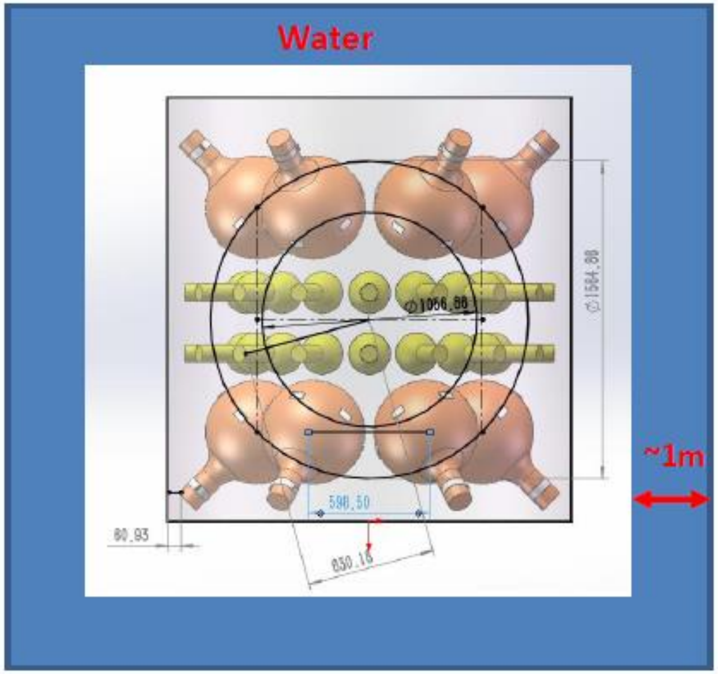


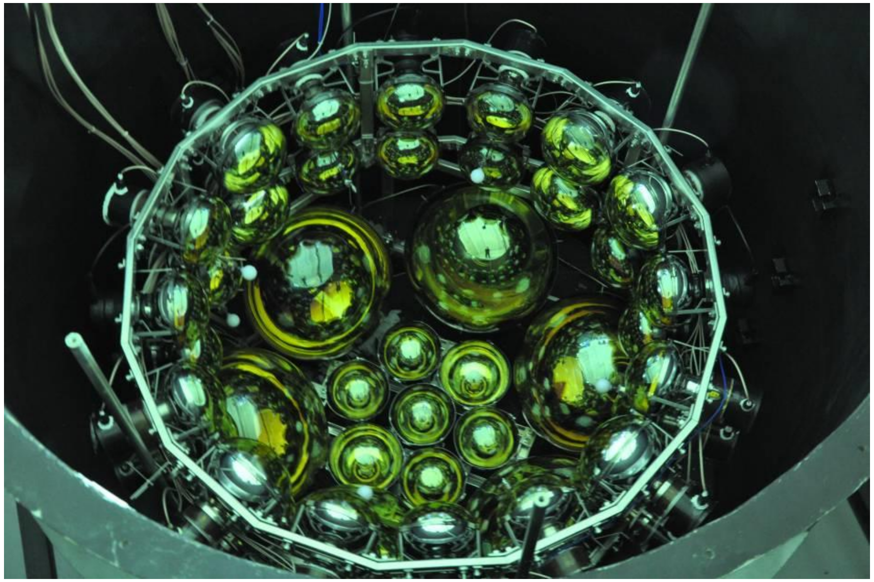




A Prototype to Test Everything

- Test all parts to the CD
  - Type of PMTs
  - PMT supporting structure
  - HV, PMT base and potting
  - Readout electronics & DAQ
  - LS & water system
  - Calibration system



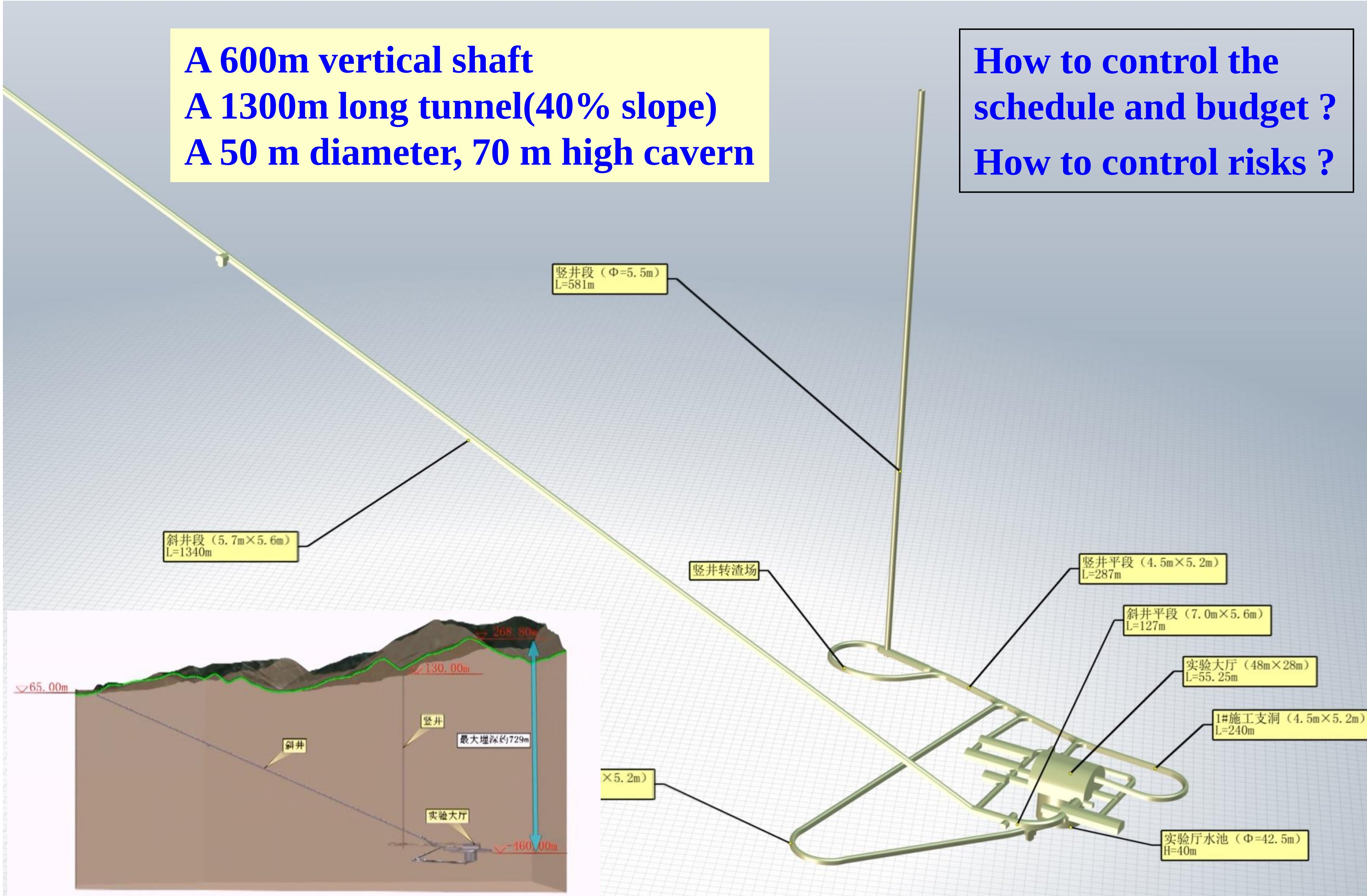


Civil Construction

A 600m vertical shaft
A 1300m long tunnel(40% slope)
A 50 m diameter, 70 m high cavern

How to control the schedule and budget ?

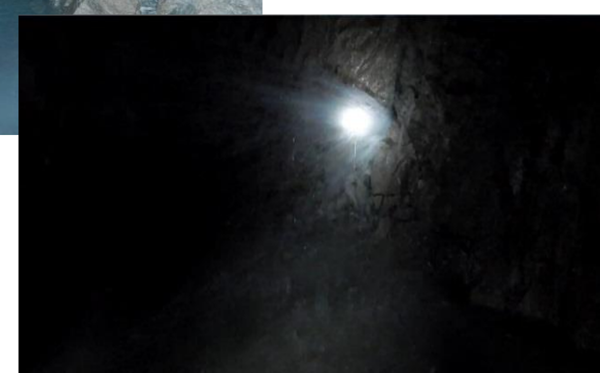
How to control risks ?



Status of Civil Construction

- **Completed:**
  - ✓ **Sloped tunnel: 870 m**
    - – Delayed by ~ 1 month
  - ✓ Vertical shaft: 290m
    - – Delayed by ~ 6 month
- **Issues:**
  - ✓ **More water than anticipated, ~ 200 m^3/h**

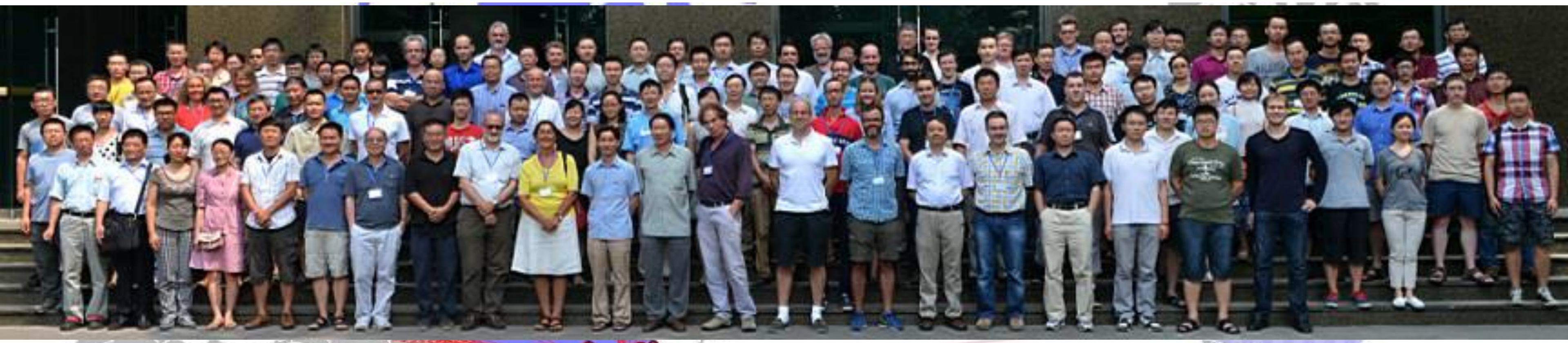
Grounding breaking on Jan. 10, 2015



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

JUNO collaboration established



Europe (27)

Armenia(1)
Yerevan Phys. Inst

Belgium(1)
ULB

Czech(1)
Charles U

France(5)
APC Paris
CPPM Marseille
IPHC Strasbourg
LLR Paris
Subatech Nantes

Finland(1)
U.Oulu

Italy(8)
INFN-Catania
INFN-Frascati
INFN-Ferrara
INFN-Milano
INFN-Mi-Bicocca
INFN-Padova
INFN-Perugia
INFN-Roma 3

Germany(7)
FZ Jülich
RWTH Aachen
TUM
U.Hamburg
IKP FZI Jülich
U.Mainz
U.Tuebingen

Russia(3)
INR Moscow
JINR
MSU

America(4)

US(2)
UMD
UMD-Geo

Chile(2)
Catholic Univ. of Chile
BISEE

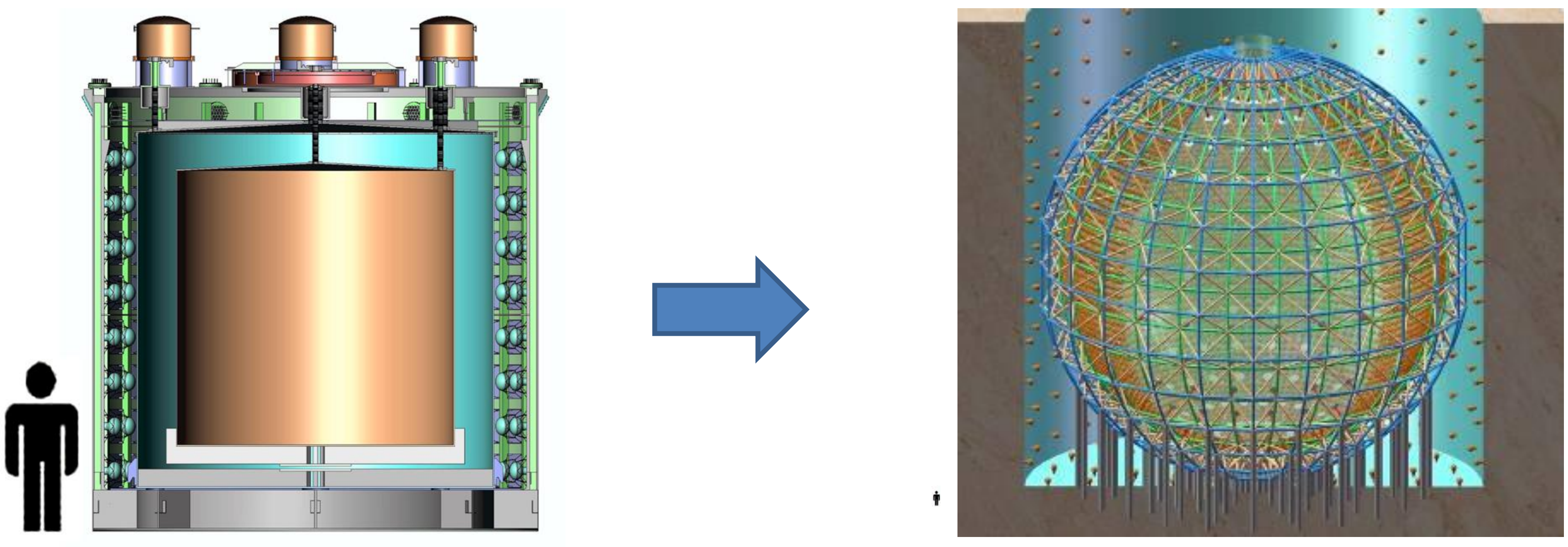
Thailand(1)
SUT

Asia (31)

BJ Nor. U.
CAGS
Chongqing U.
CIAE
DGUT
ECUST
Guangxi U.
HIT
IHEP
Jilin U.
Ninan U.
Nanjing U.
Natl. Chiao-Tung U.
Natl. Taiwan U.
Natl. United U.
Nankai U.
NCEPU
Pekin U.
Shandong U.
Shanghai JT U.
Sichuan U.
SYSU
Tsinghua U.
UCAS
USTC
U. Of South China
Wuhan U.
Wuyi U.
Xi'an JT U.
Xiamen U.

Summary

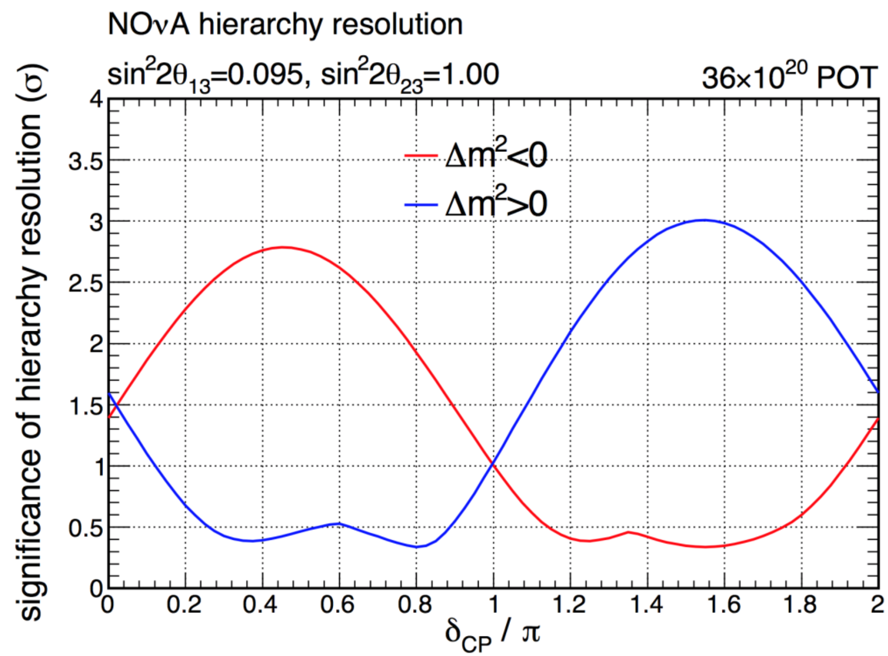
- As the next generation reactor neutrino experiment, JUNO is now moving ahead at a full speed
- European's contributions are essential ➔ next talks
  - Electronics, HV, Slow control, …
  - Top tracker veto
  - 3" PMTs, PMT testing
  - Liquid Scintillator purification
  - …

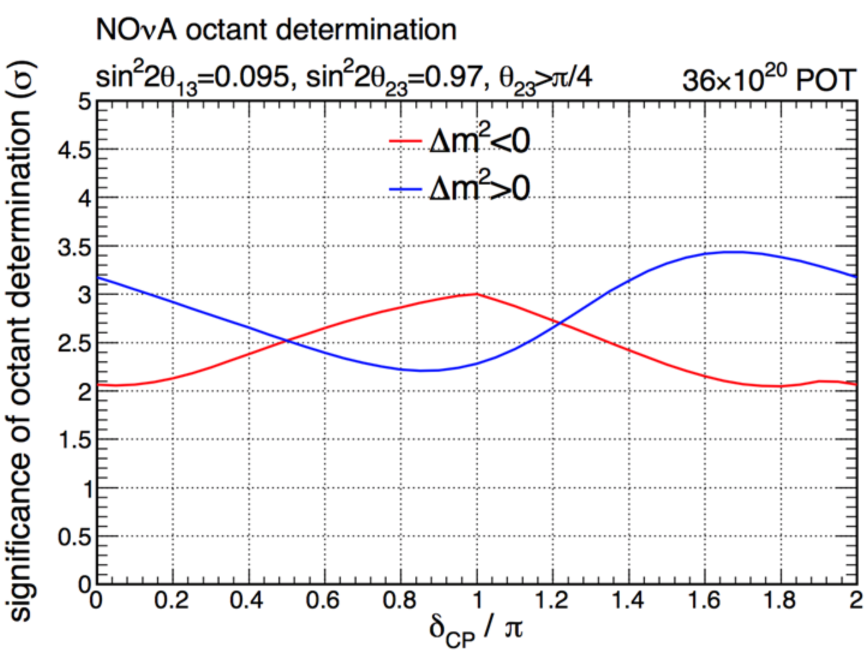


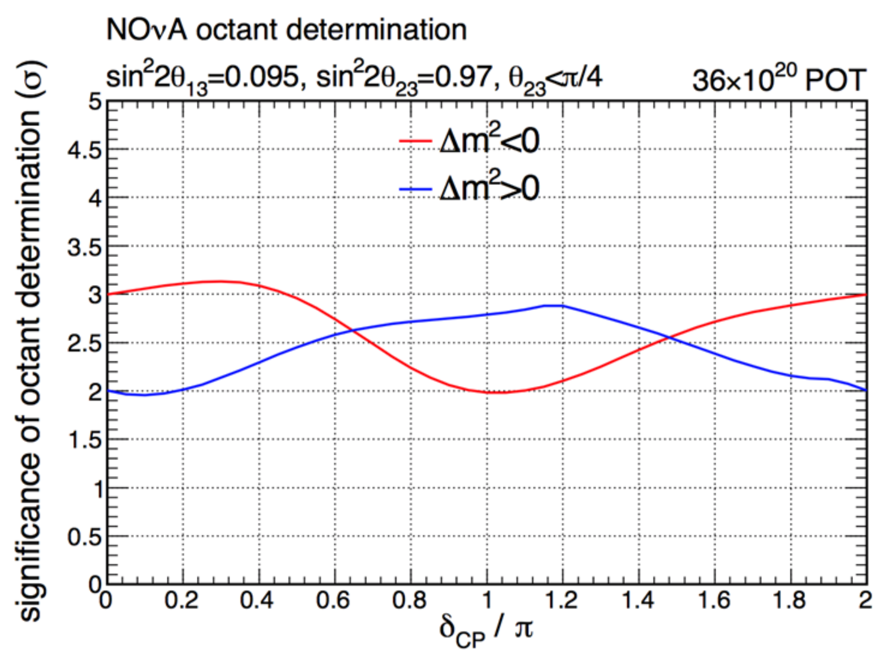
backup

NOVA

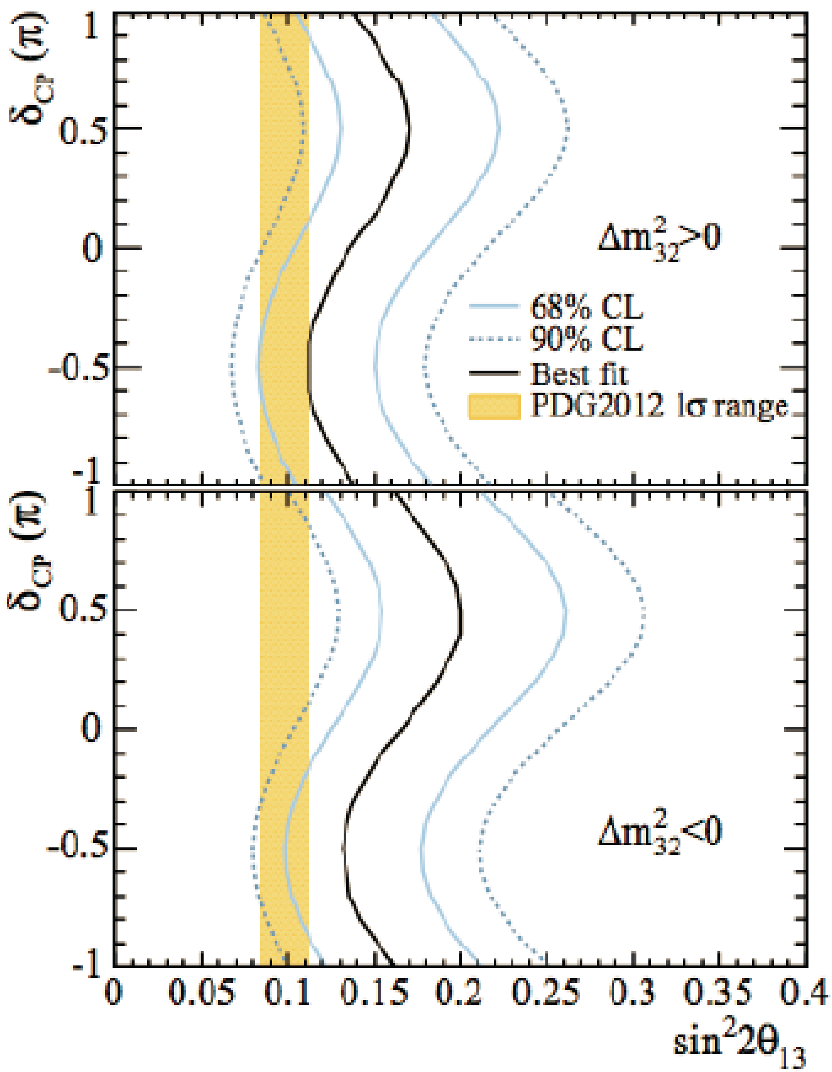
- May get mass hierarchy if lucky
- For non-maximal θ_{23} octant determination: > 95% CL for all δ_{CP} @ $\sin^2 2\theta_{23} = 0.97$

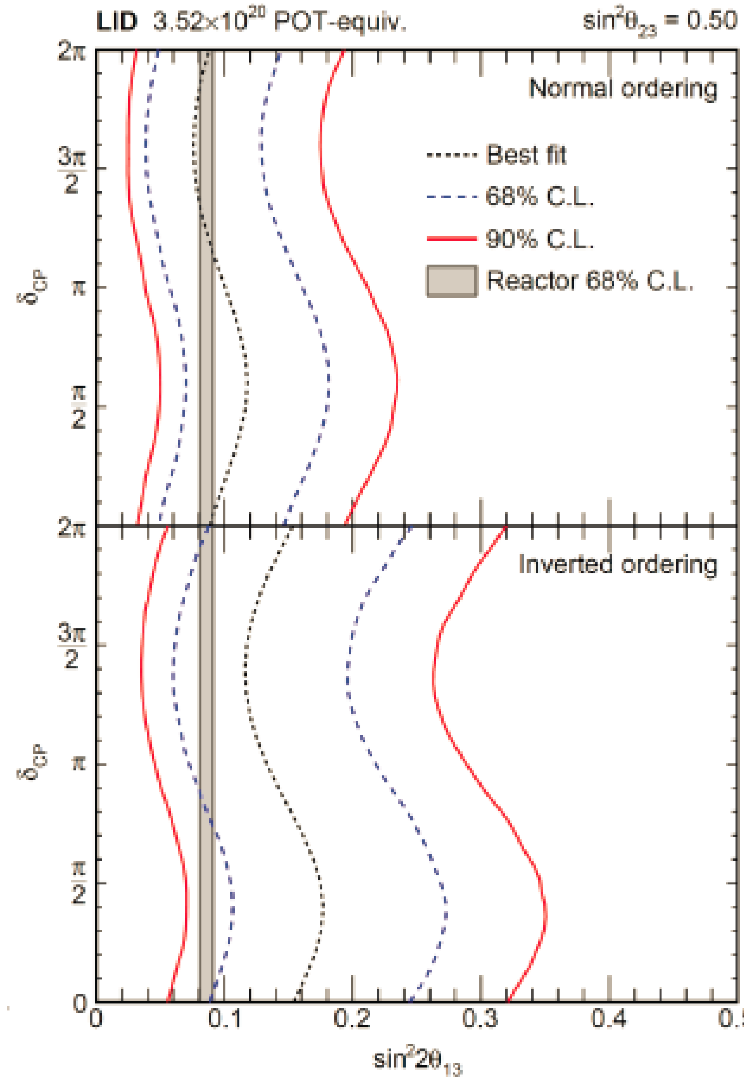






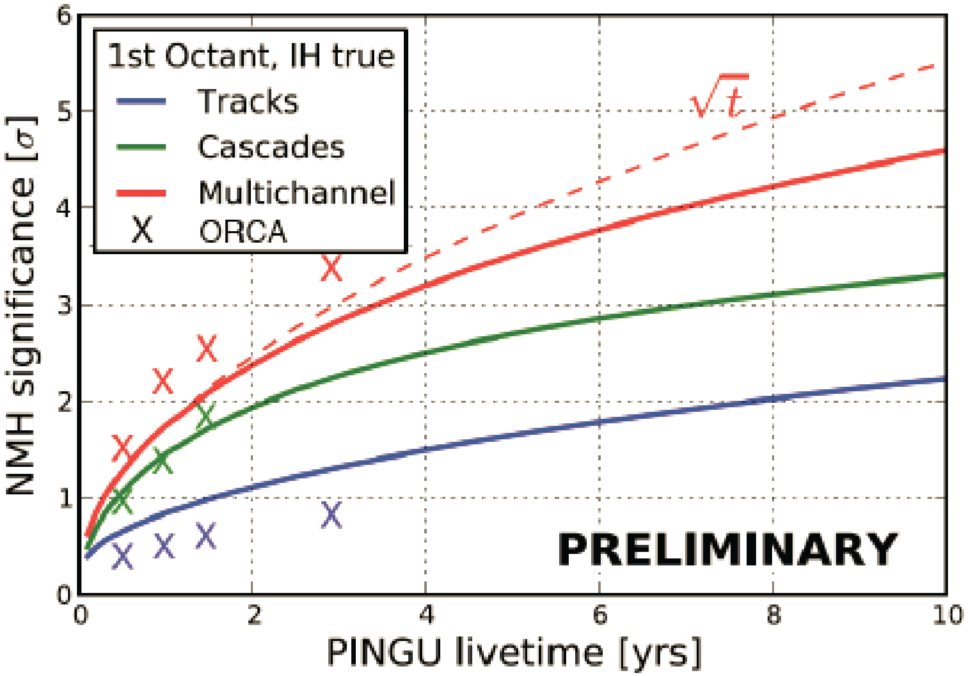
T2K and Nova: CP is known?

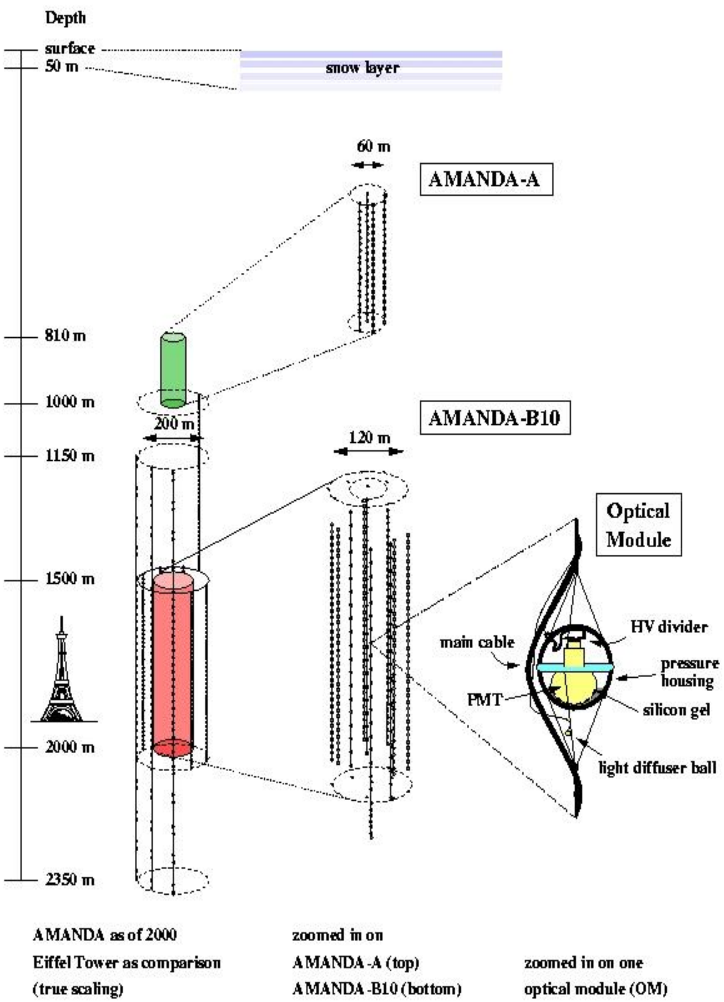




C. Water@neutrino2014

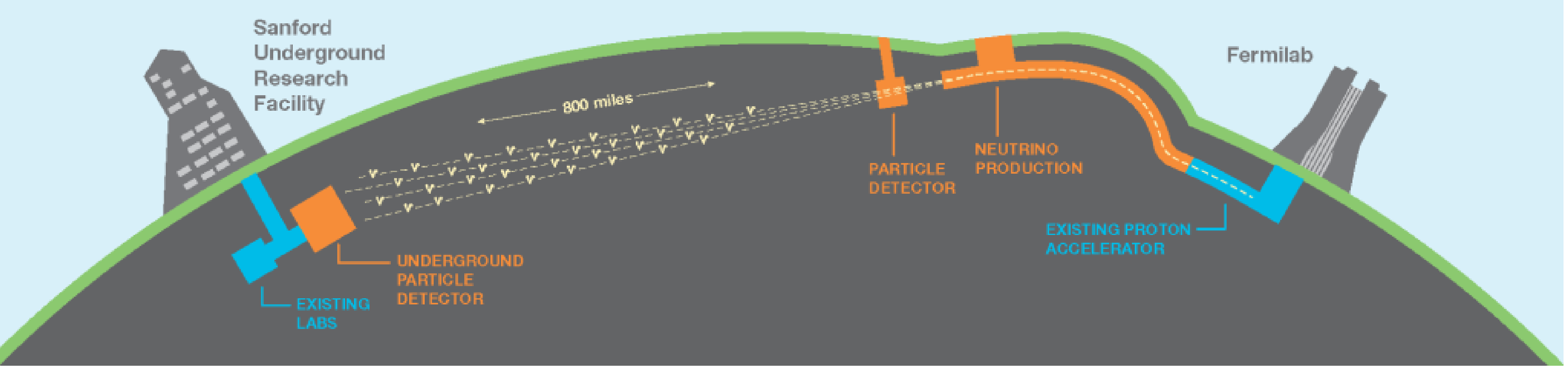
PINGU & ORCA

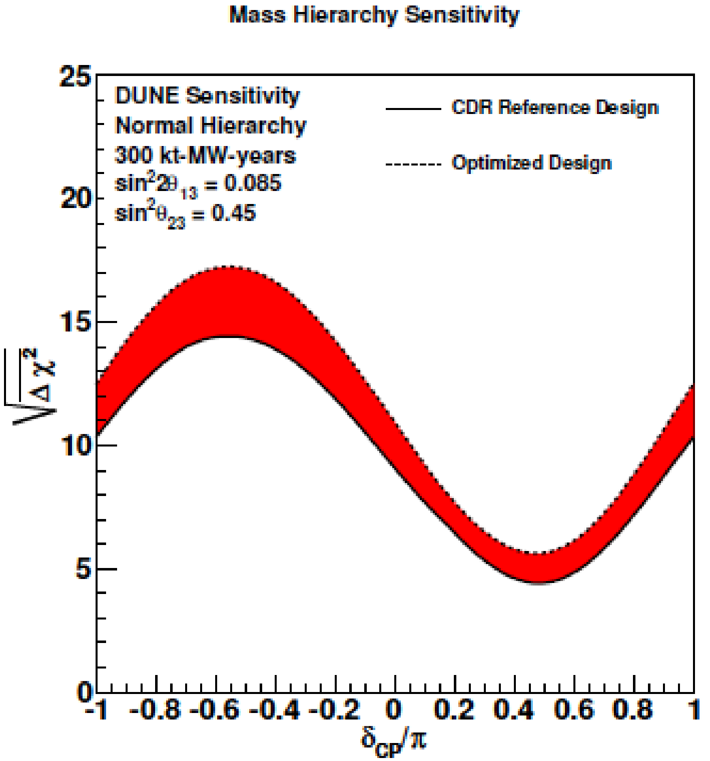


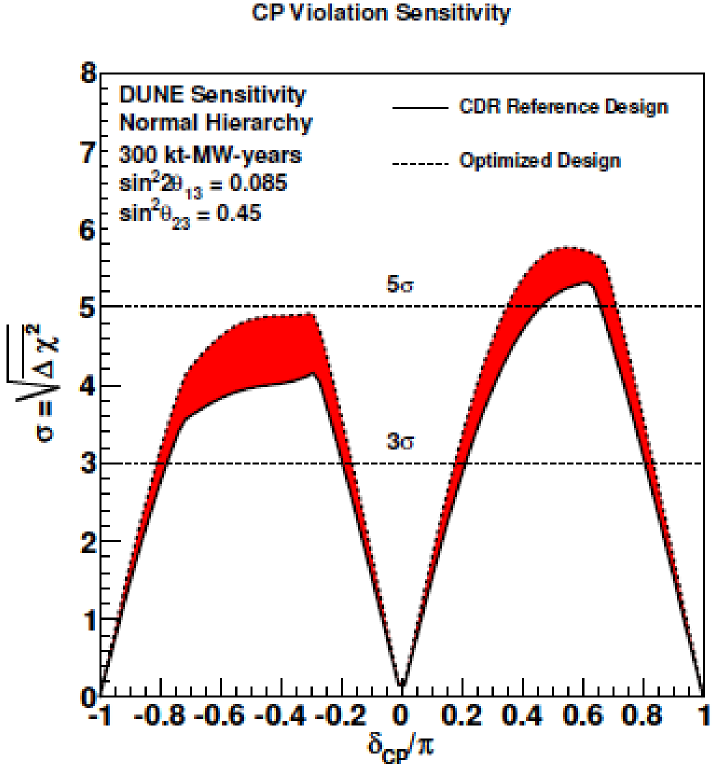


- **PINGU: determine MH at ~ 3σ level with ~3 years of data**
- **ORCA: similar**

LBNF/DUNE


Sanford Underground Research Facility
800 miles
Fermilab
PARTICLE DETECTOR
NEUTRINO PRODUCTION
EXISTING PROTON ACCELERATOR
UNDERGROUND PARTICLE DETECTOR
EXISTING LABS


Mass Hierarchy Sensitivity
DUNE Sensitivity
Normal Hierarchy
300 kt-MW-years
$\sin^2 2\theta_{13} = 0.085$
$\sin^2\theta_{23} = 0.45$
CDR Reference Design
Optimized Design
$\sqrt{\Delta\chi^2}$
δ_{CP}/π


CP Violation Sensitivity
DUNE Sensitivity
Normal Hierarchy
300 kt-MW-years
$\sin^2 2\theta_{13} = 0.085$
$\sin^2\theta_{23} = 0.45$
CDR Reference Design
Optimized Design
5σ
3σ
$\sigma = \sqrt{\Delta\chi^2}$
δ_{CP}/π