JUNO *and* Its Physics Potential

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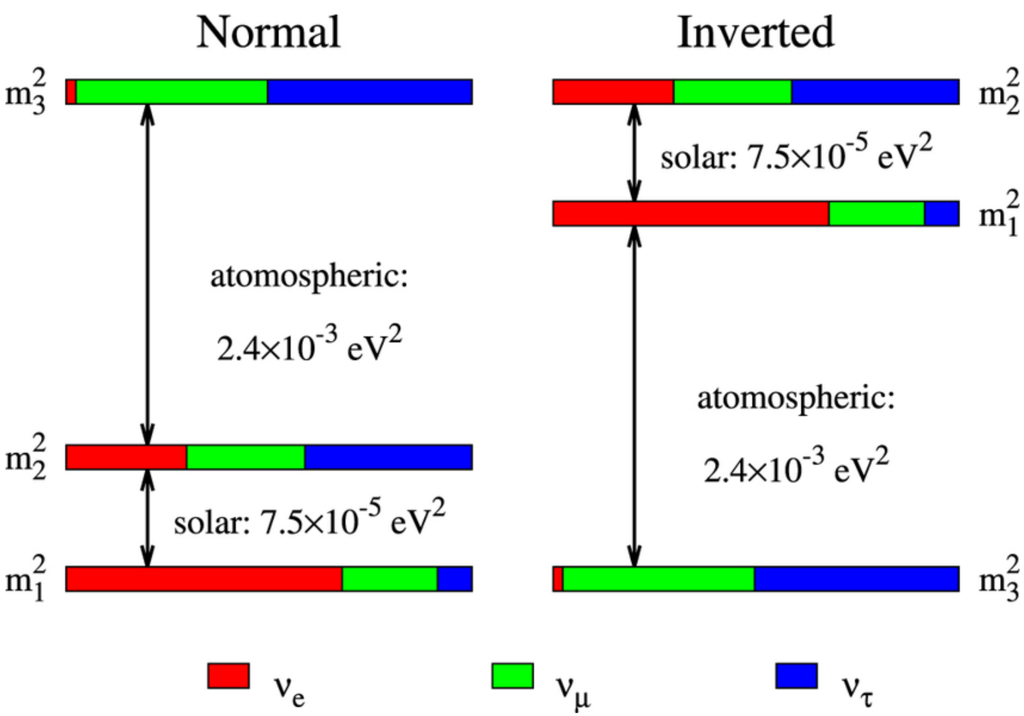
Lake Louise Winter Institute, Feb 21, 2018

- *ν Mass Hierarchy resolution by reactors*
- *JUNO experiment and detector designs*
- *R&D briefing and status of the project*
- *Summary and Outlook*

Neutrino Mass Hierarchy Must be Resolved



MSW Effect tells m_2 from m_1;
No clue for the sign of Δm^2_{32}

- ➡️ Our familiar tool that has helped us telling the m_2 state from m_1 using solar neutrino data: Matter Effect
- ➡️ **Interference between the solar and the atmospheric oscillation terms: JUNO**
- ➡️ Cosmological data
- ➡️ Supernova neutrinos

Global Efforts Resolving ν Mass Hierarchy

Source / Principle	Matter Effect	Interference of Solar&Atm Osc. Terms	Collective Oscillation	Constraining Total Mass
Atmospheric ν	Super-K, Hyper-K, PINGU/IceCUBE, ICAL/INO, ORCA/ KM3NeT, DUNE	Atm ν_μ + JUNO		
Beam ν_μ	T2K, NOνA, T2HKK, DUNE	Beam ν_μ + JUNO		
Reactor ν_e		JUNO, JUNO+Beam ν_μ		
Supernova Burst ν			Super-K, Hyper-K, PINGU/IceCUBE, ORCA/KM3NeT, DUNE, JUNO	
ν during Struc. Form.				Cosmological Data

Known θ13 Enables Neutrino Mass Hierarchy at Reactors

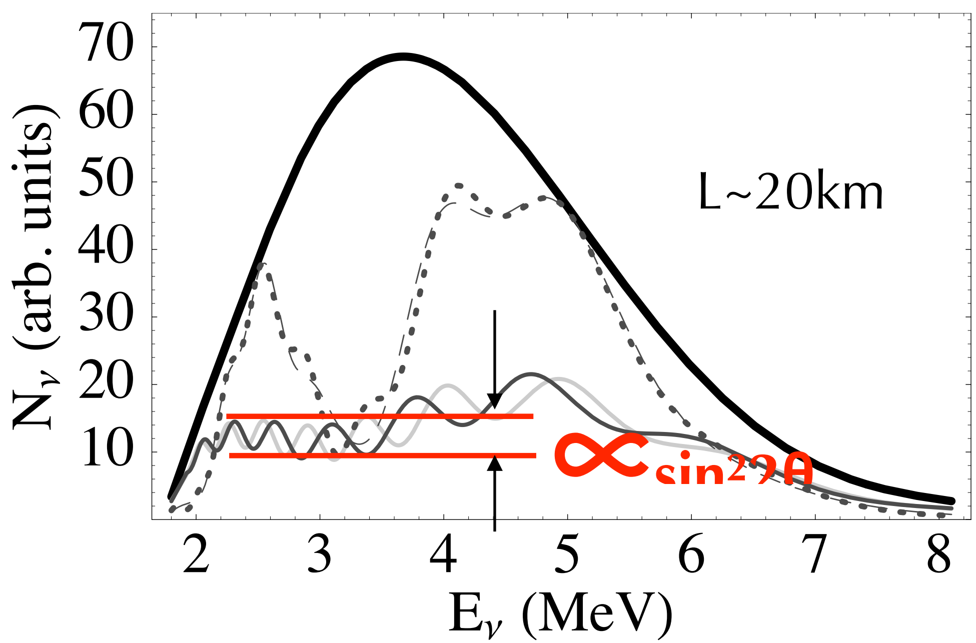
- Recall that reactor neutrinos helped solving ***the solar sector***

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

- Recall that Daya Bay measures ***the most precise atmospheric mass-squared splitting***

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

Petcov&Piai, Phys. Lett. B533 (2002) 94-106



✓ Mass hierarchy is reflected in the survival spectrum

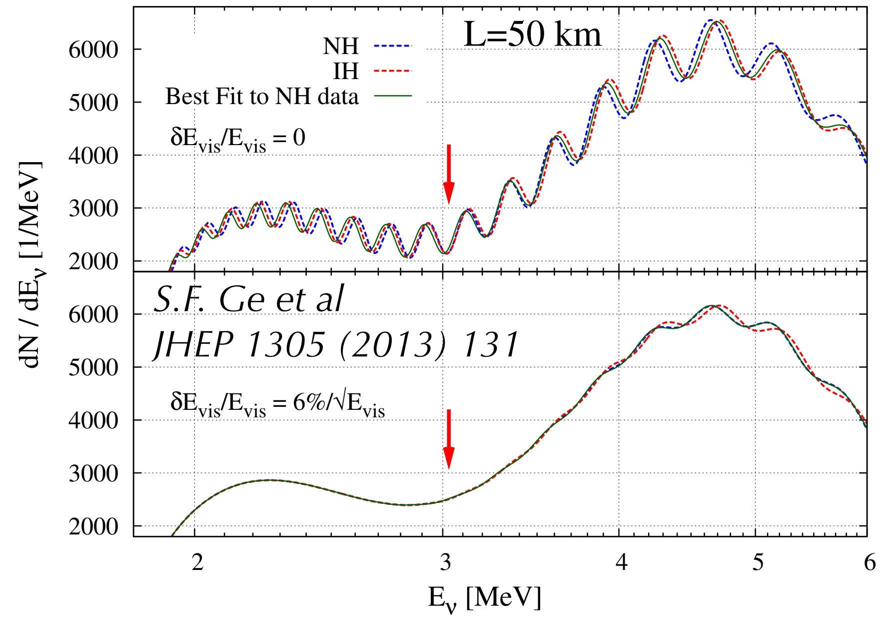
✓ Proportional to $\sin^2 2\theta_{13}$

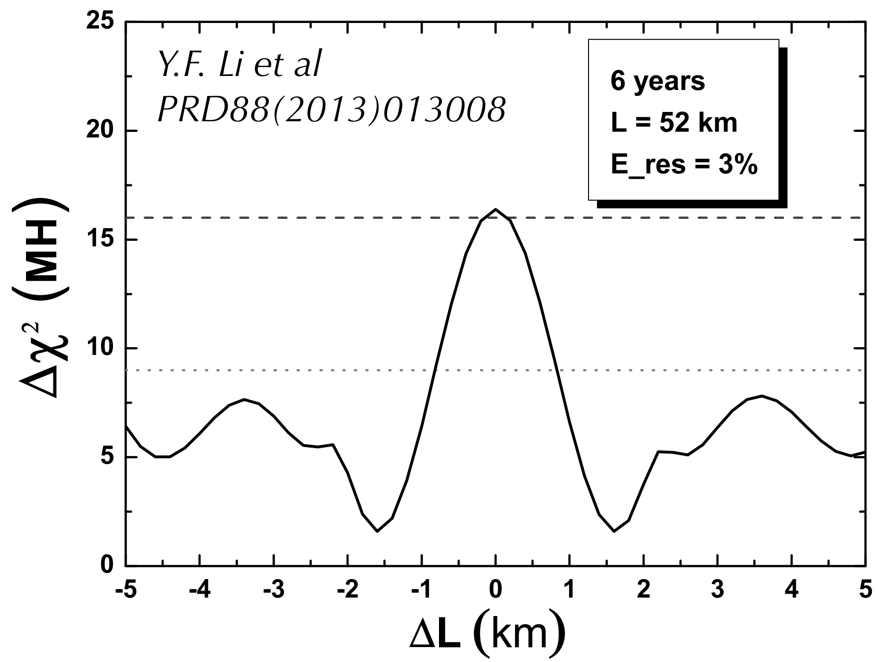
✓ Independent of the unknown CP phase and the θ_{23} octant

✓ Best baseline is ~60km

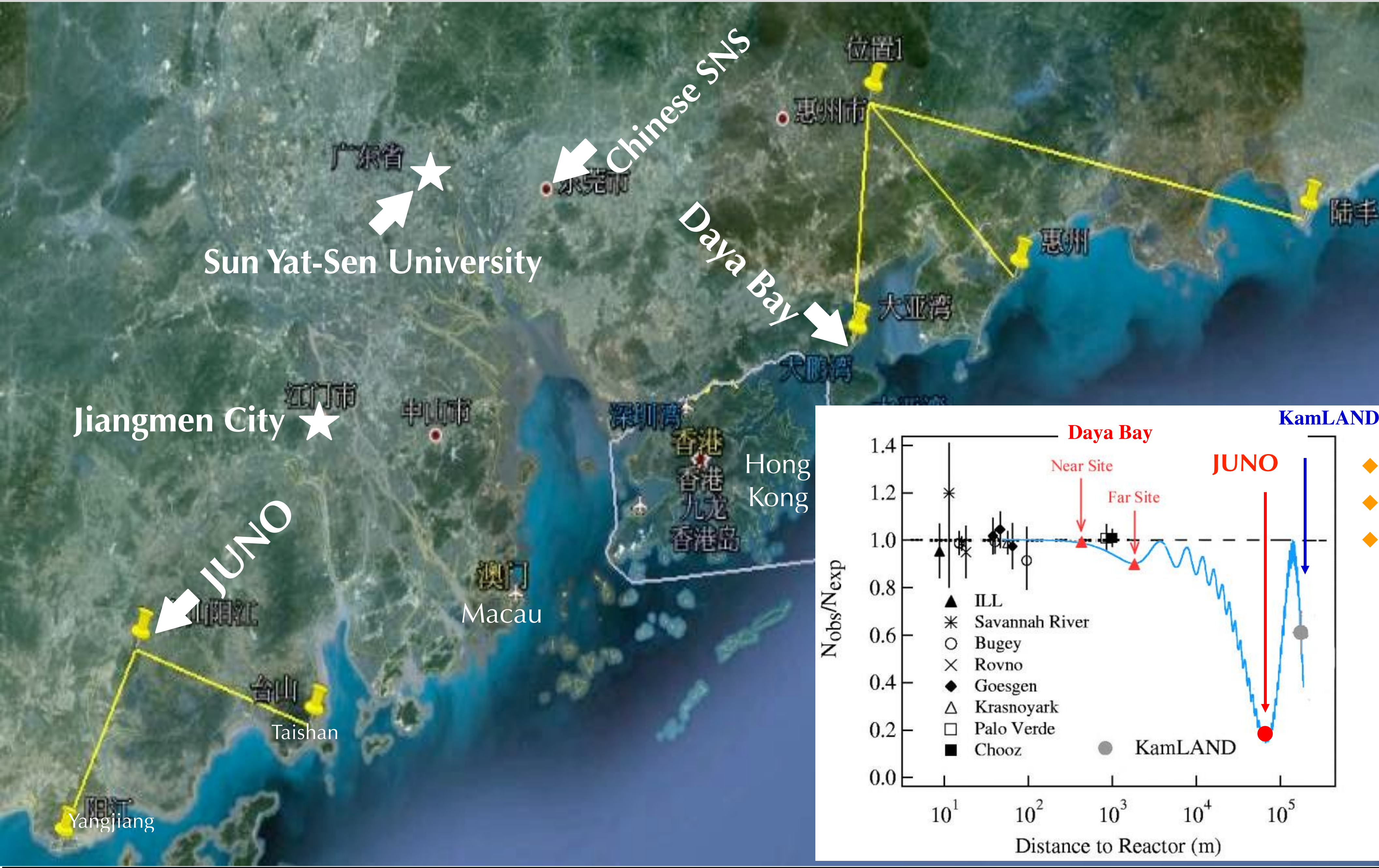
Challenges for the Interference Method using Reactors

- Energy resolution: ~3%/sqrt(E)
  - Bad resolution leads to smeared spectrum and the MH signal practically disappears
- Energy scale uncertainty: <1%
  - Bad control of energy scale could lead to no answer, or even worse, a wrong answer
- Statistics (who doesn't like it?)
  - ~36GW thermal power, a 20kt detector plus precise muon tracking to get the best statistics
- Reactor distribution: <~0.5km
  - If too spread out, the signal could go away due to cancellation of different baselines
  - JUNO baseline differences are within half kilometer.

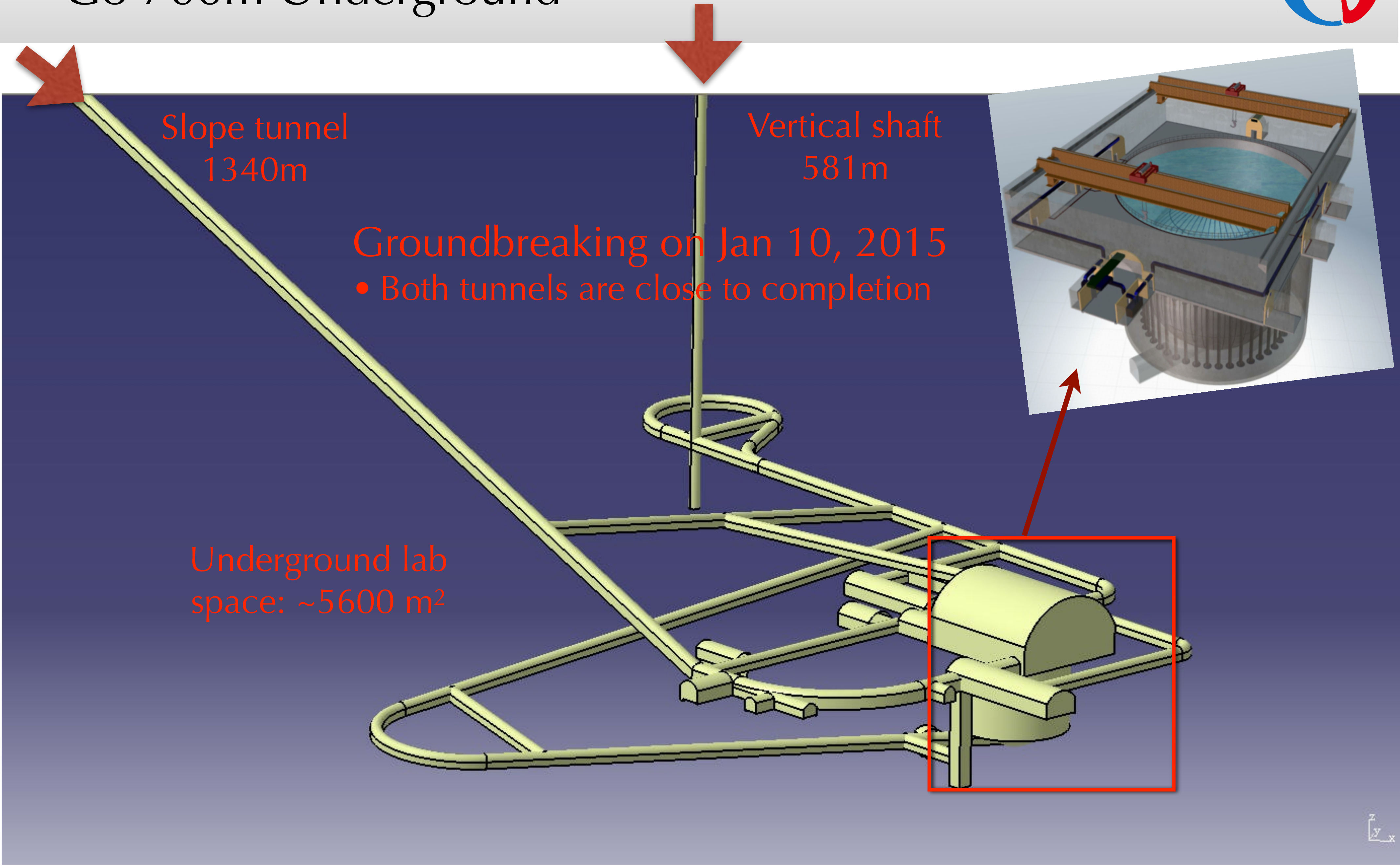




Jiangmen Underground Neutrino Observatory



Go 700m Underground



The JUNO Detector Design

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

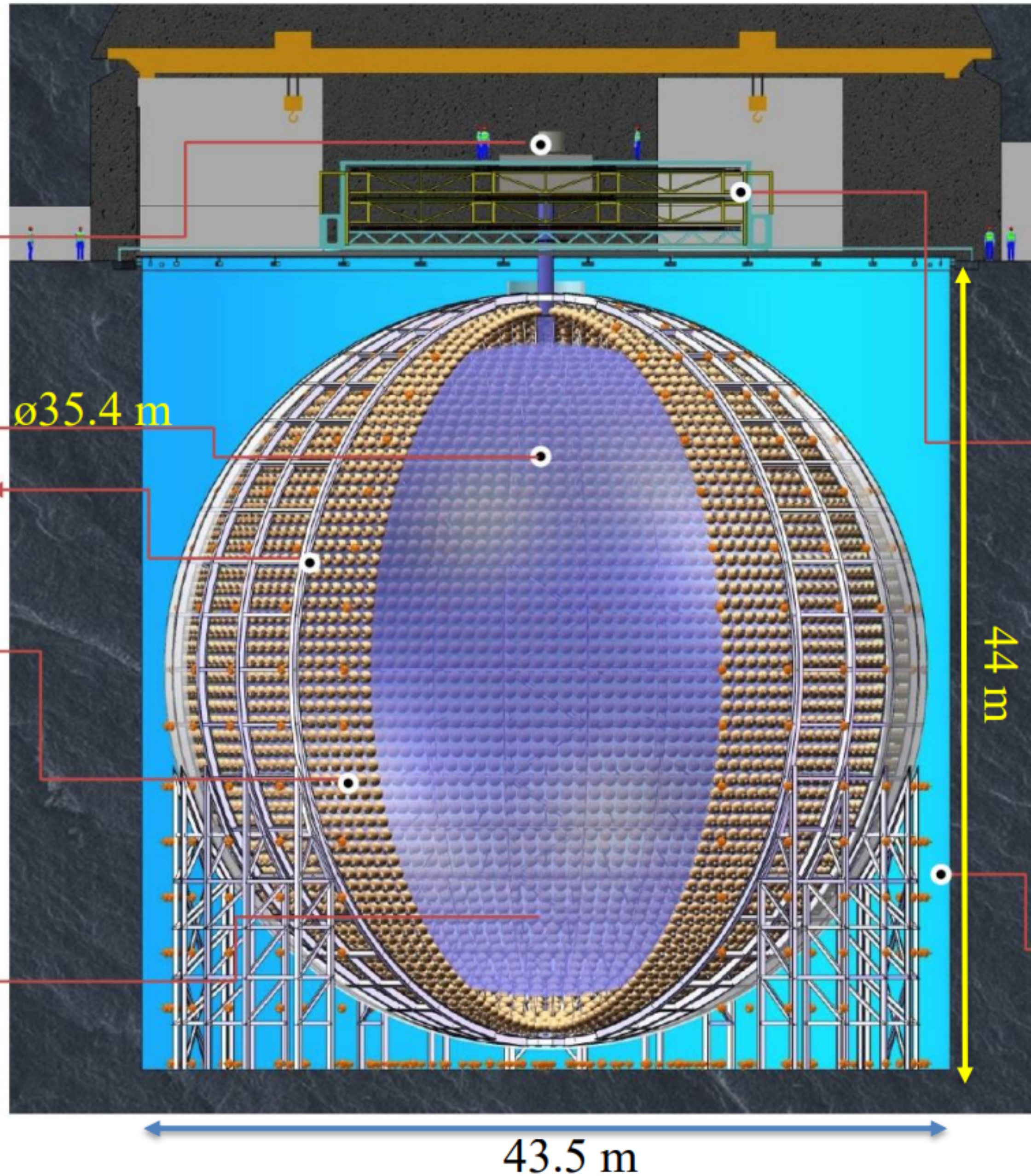
Central detector

Calibration
-ACU, ROV, etc.

Acrylic sphere
Stainless-steel truss

PMT
-18,000 20” PMTs
-25,000 3” PMTs

Liquid scintillator
-20 kton LS



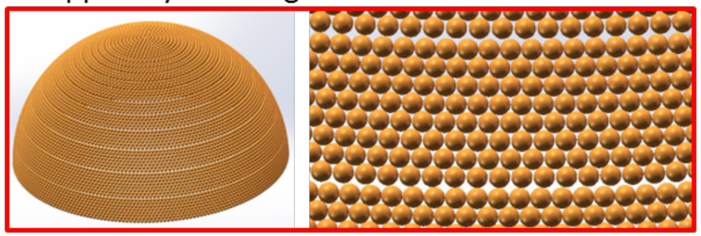
VETO detector

Top Tracker
-62 Plastic scintillator walls

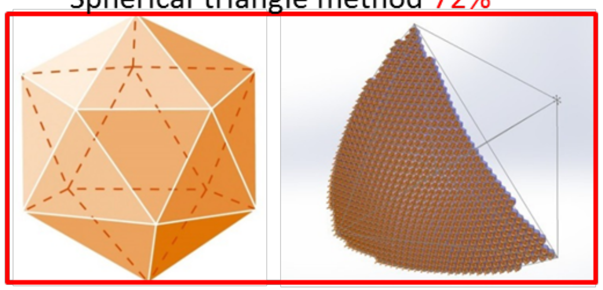
Water Cherenkov
-35 kt high-purity water
-2000 20” PMTs

Generate Light ➤ Collect Light ➤ Convert Light

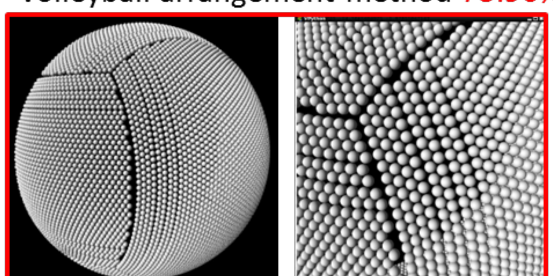
Supper layer arrangement method 77.8%

✓1


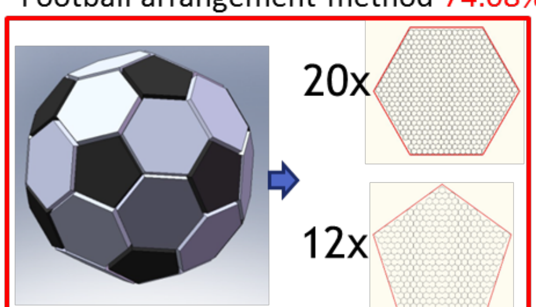
Spherical triangle method 72%

2


Volleyball arrangement method 75.96%

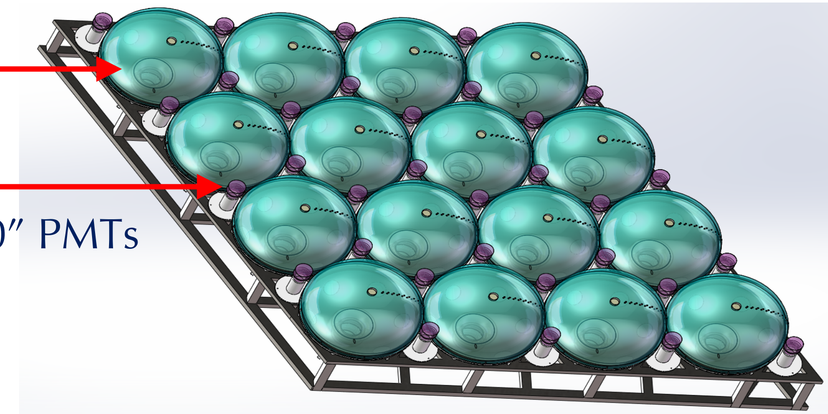
3


Football arrangement method 74.08%

4


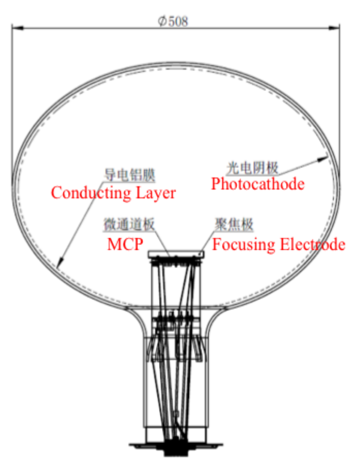
20″ PMT(~17000)

3″ sPMT(~25000)
Arranged between 20″ PMTs



- LAB-based liquid scintillator 10k photon/MeV
- LS transparency reaches ~20m
- High detection efficiency PMT: ~75% coverage

➡ ~3%/√E energy resolution plausible

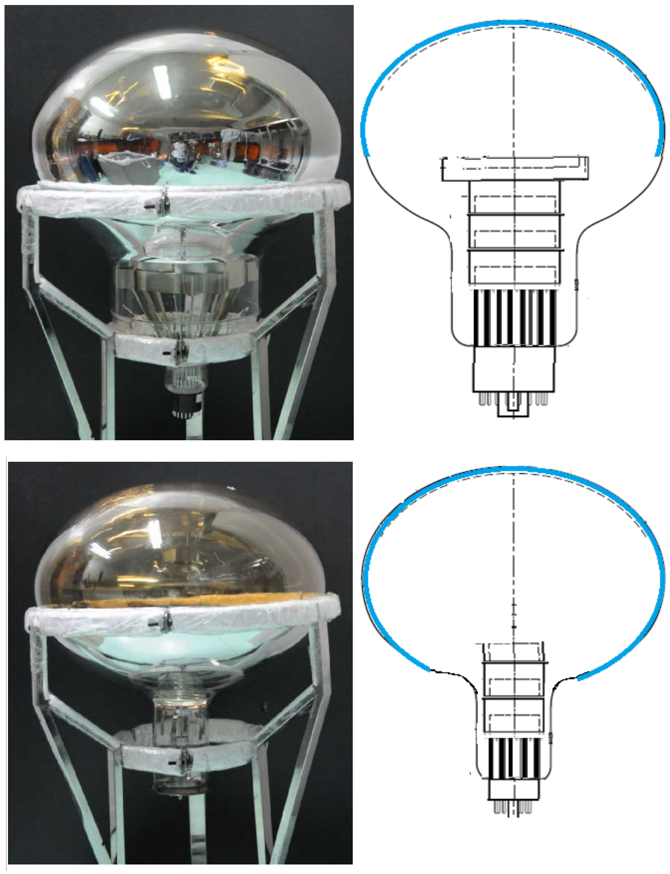


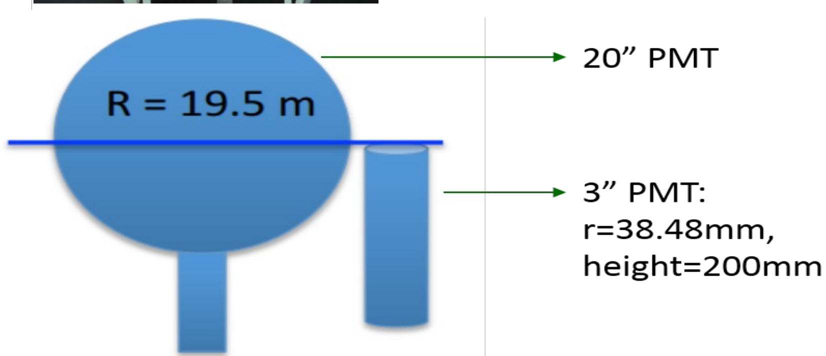
Structure of MCP-PMT

Photograph of MCP-PMT

Hamamatsu R12860-50

More Light: PMT and Photocathode Coverage

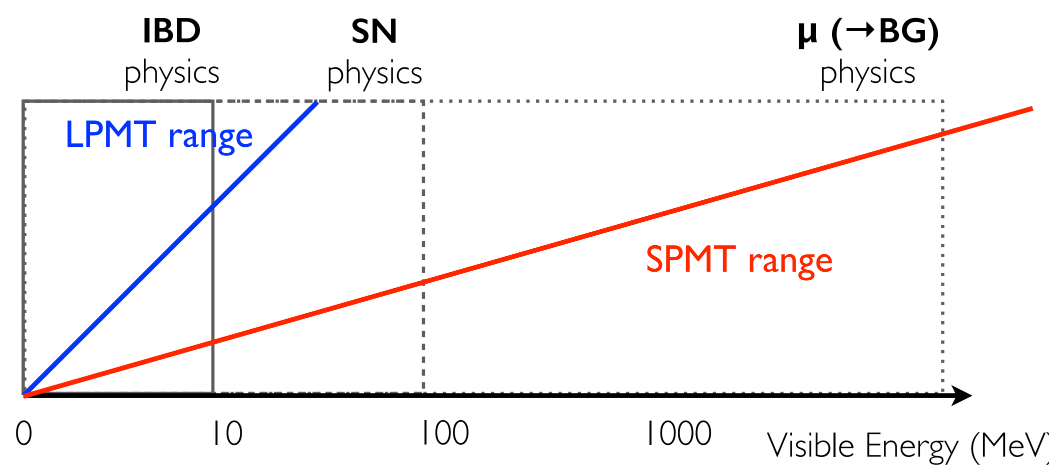




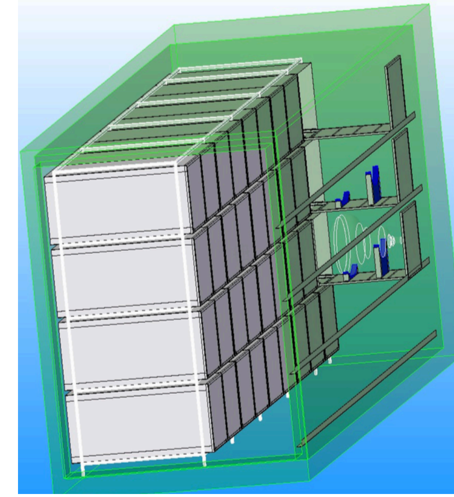
The front end of the 3” PMT is in the same plane as the equatorial plane of 20” PMT

- Large PMTs: 20″ MCP-PMT, ~75%
- Large PMTs: 20″ SBA Hamamatsu, ~25%
- Small PMTs: 3″ PMTs
  - ➡ to further increase the photocathode coverage
  - ➡ to provide a semi-independent calorimetry system for timing
  - ➡ to extend energy dynamic range to avoid saturation, important for high energy events and cosmic muons

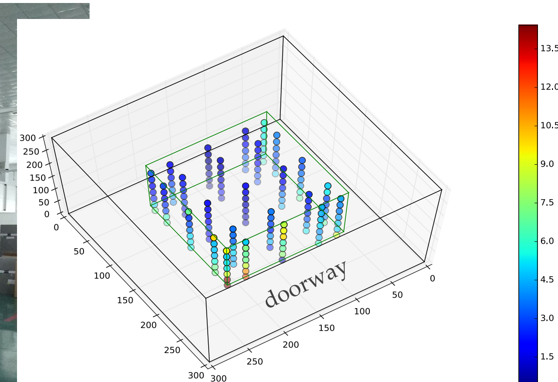
Complementary Roles by SPMTs and LPMTs

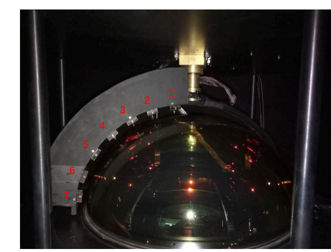


"Meticulous" PMT Quality Control and Characterization



An Earth Magnetic Field (EMF) shielded 36-slot container testing all PMTs

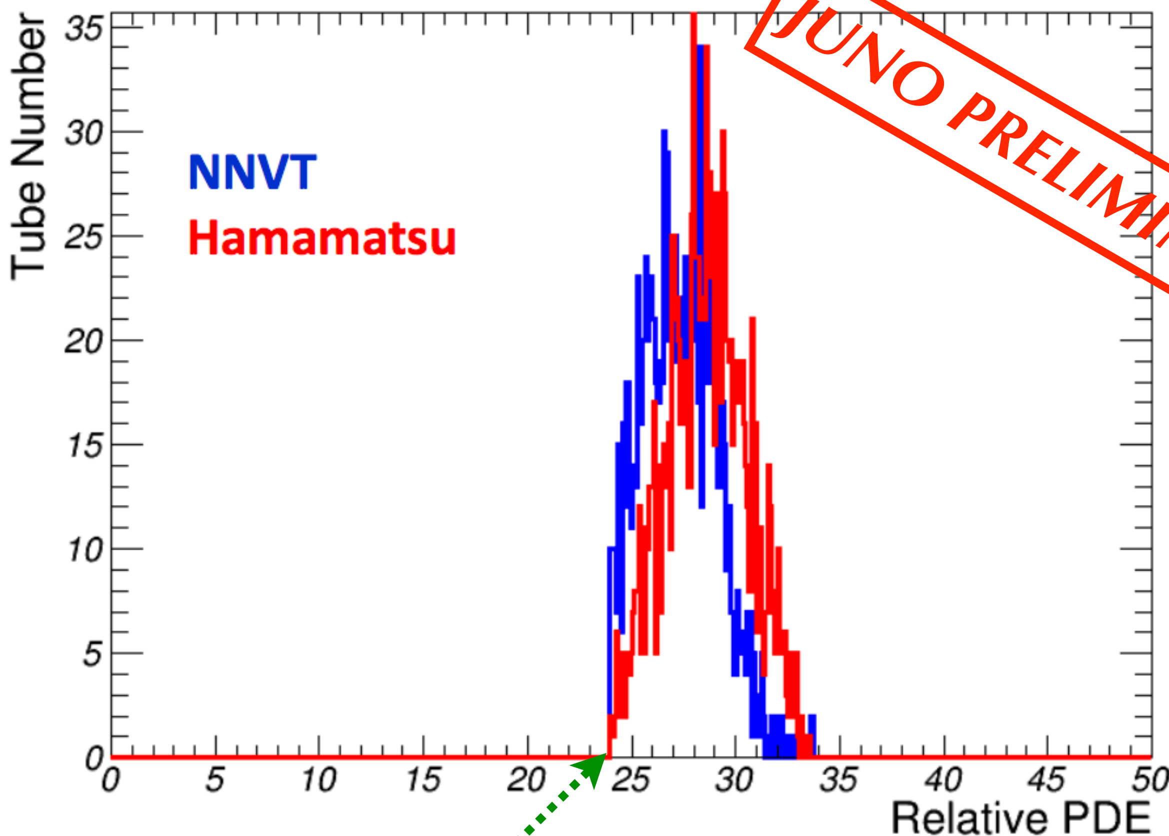




A scanning device in an EMF compensated dark room checking ~10% PMTs photocathode uniformity

Preliminary PMT Detection Efficiency Performance

- Detection Efficiency is the most essential factor



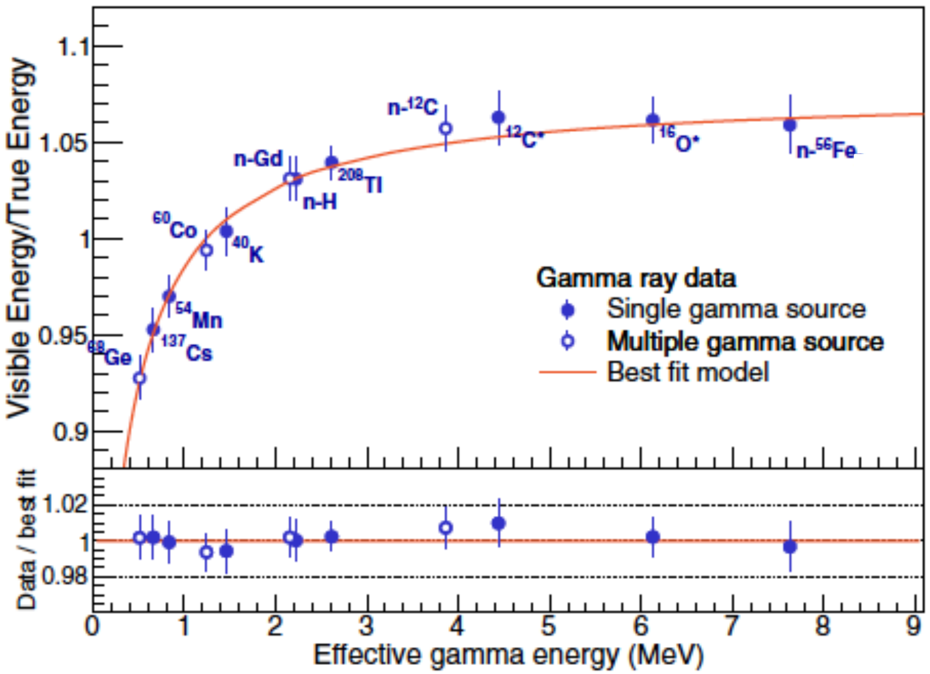
	Delivered	Tested	Prelim. Results
滨松	~3000	1354	27.3% ±1%
北方夜视	~7000	1229	28.6% ±1%

The lower limit on PMT detection efficiency: 24%

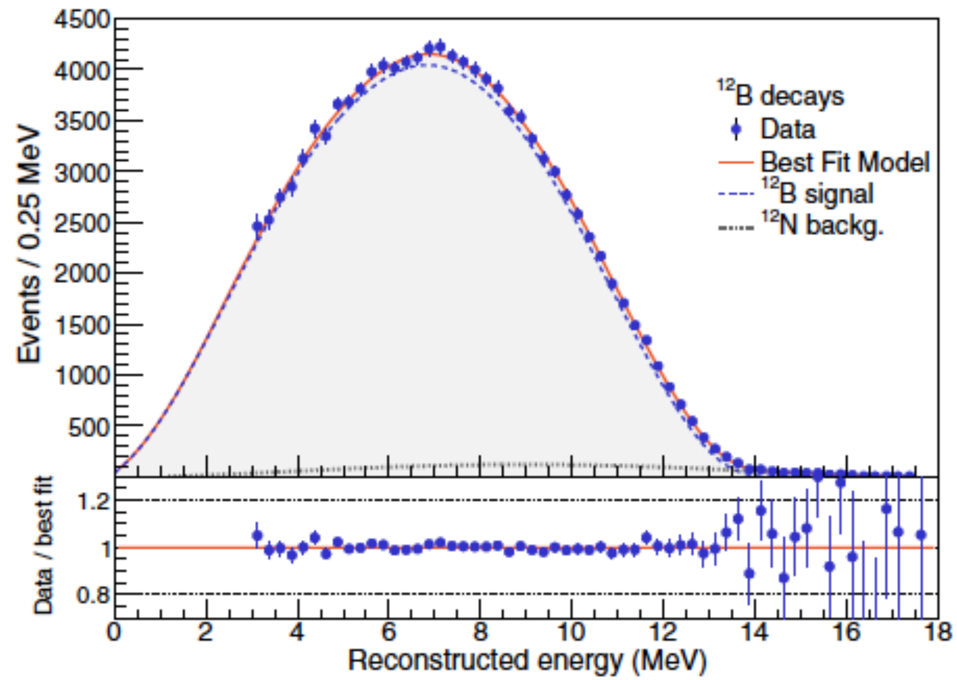
- Other numbers are not as essential to the energy response performance

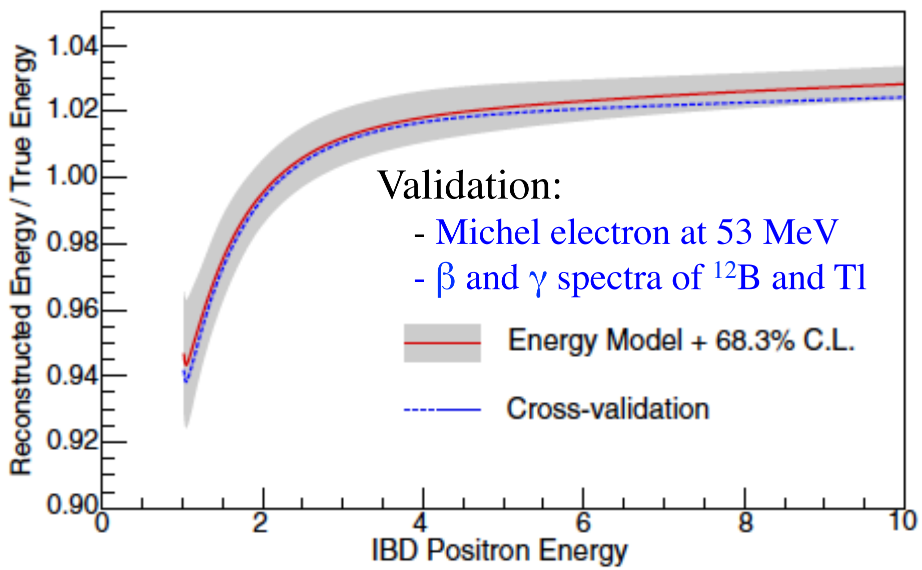
Can One Calibrate Energy to 1%?

Daya Bay by Luk, Erice 2017



Also use electrons from Compton scattering to determine energy non-linearity of liquid scintillator in labs

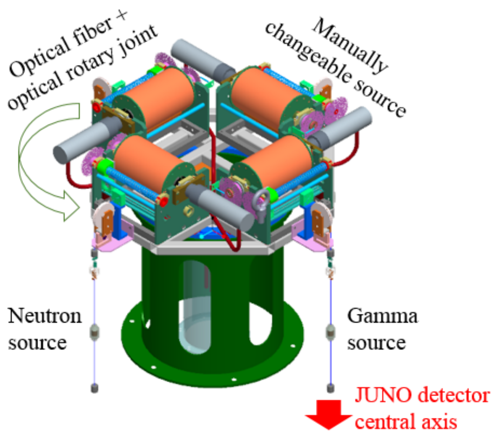




E_{obs}/E_{true} is known to <1% for
1 MeV < E_{e+} < 10 MeV

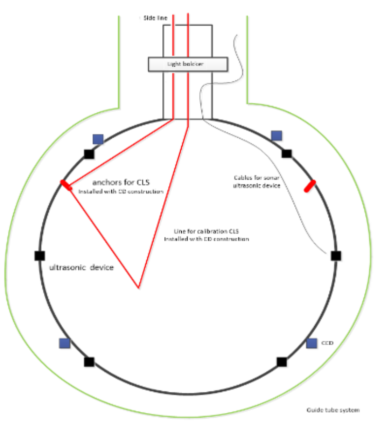
Multiple Calibration Approaches

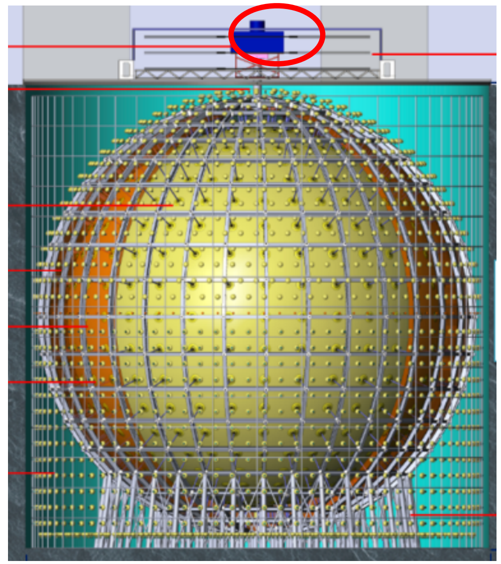
Automatic calibration Unit (ACU) Ø =1.4 m, h=1 m

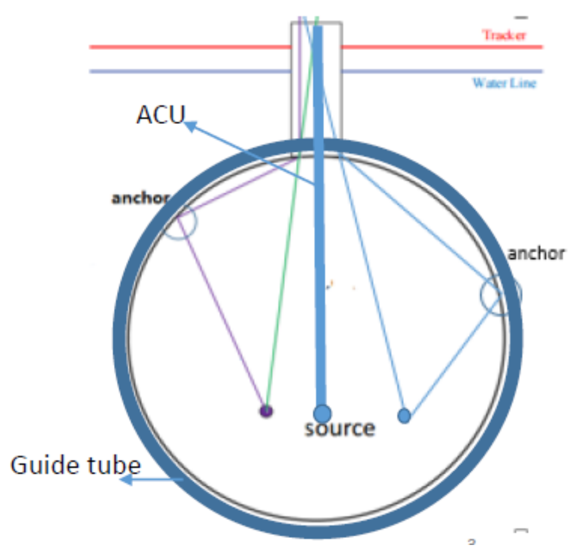


•Regular deployment (every week)
Scan center axis

Cable Loop System (CLS)

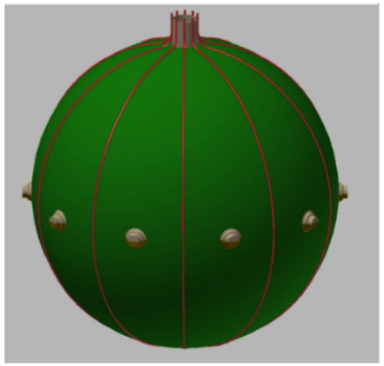






Four units designed

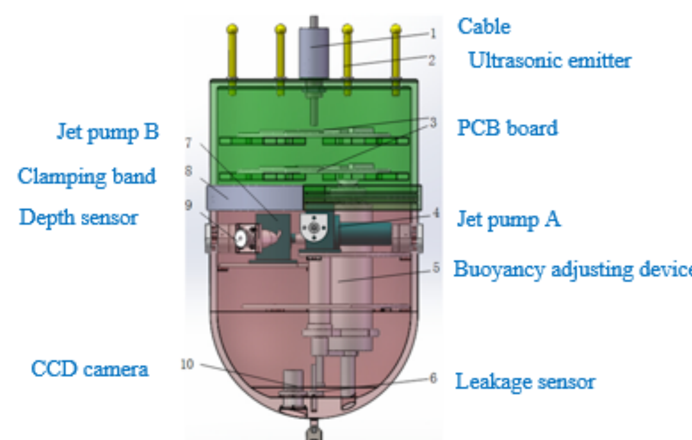
Guide Tube (GT)



Scan outer surface of CD

The source is driven with rope pulled by step motors

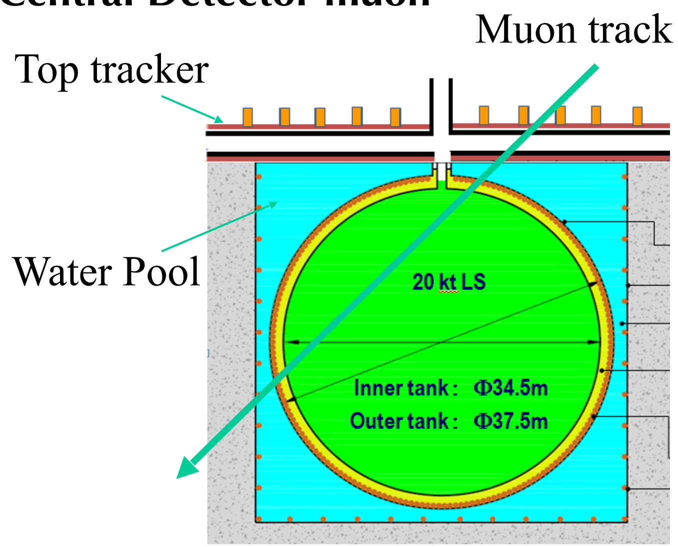
Remotely Operated Vehicle(ROV)



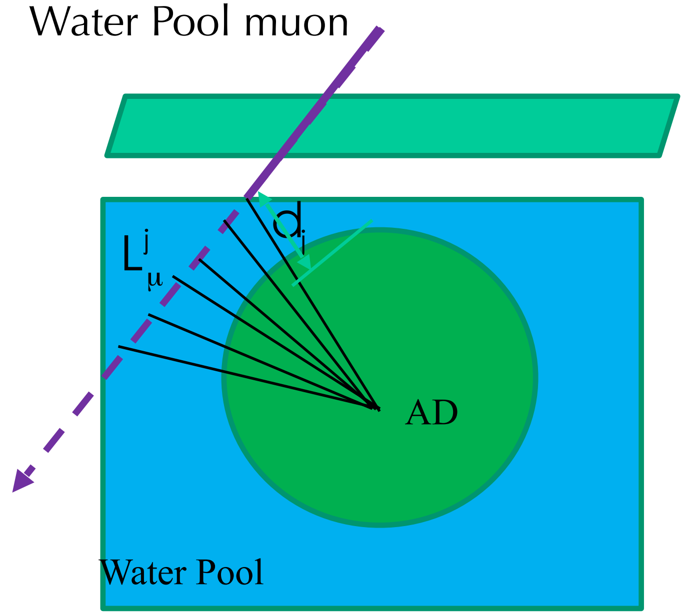
Scan the whole CD if needed

Veto System Considerations and Designs

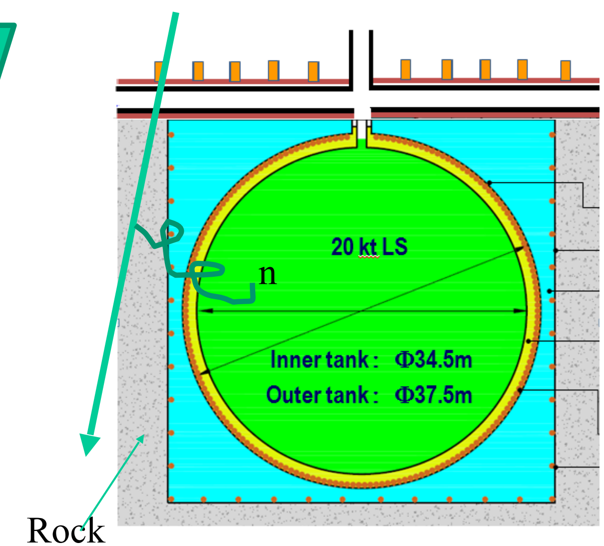
Central Detector muon



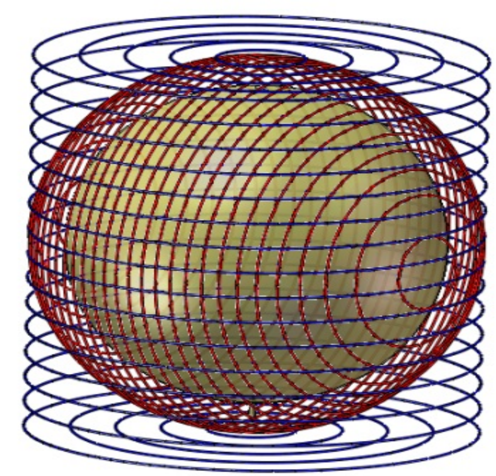
Water Pool muon



Rock muon



- Veto has tracking capability to better understand and remove cosmogenic backgrounds in both space&time
  - A water Cherenkov detector + A Top Tracker (TT, OPERA scintillator calorimeters)
- Earth magnetic field compensation coils
- Radon removal, control and monitoring

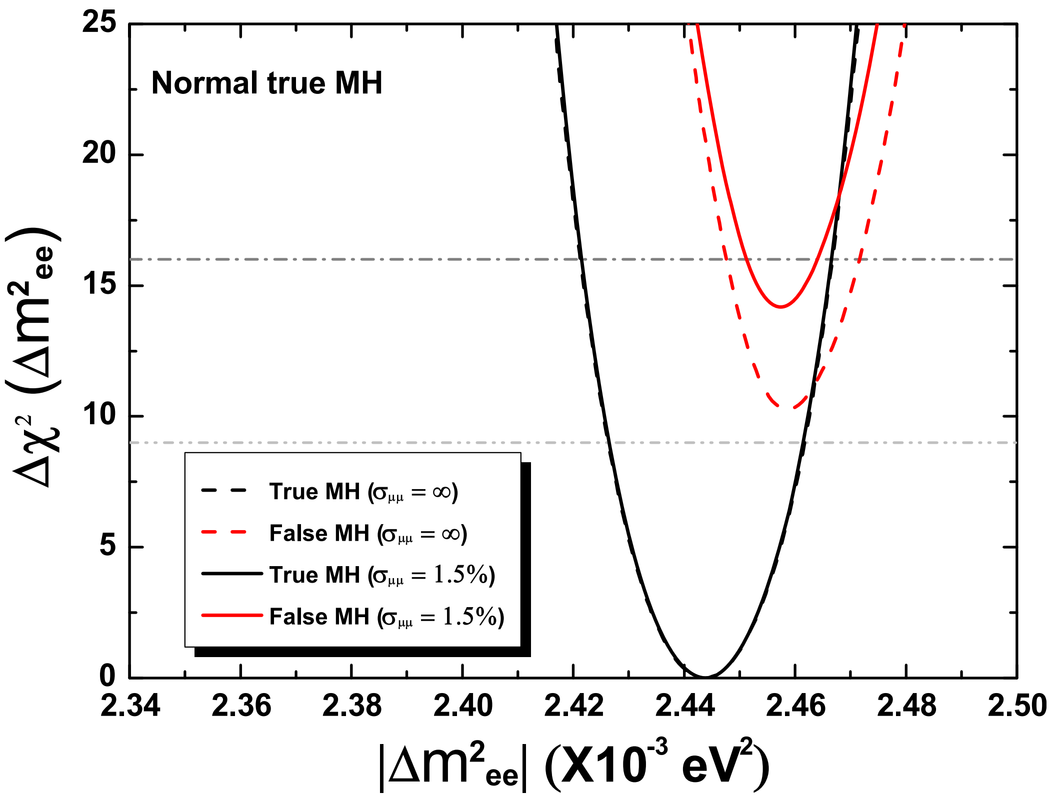


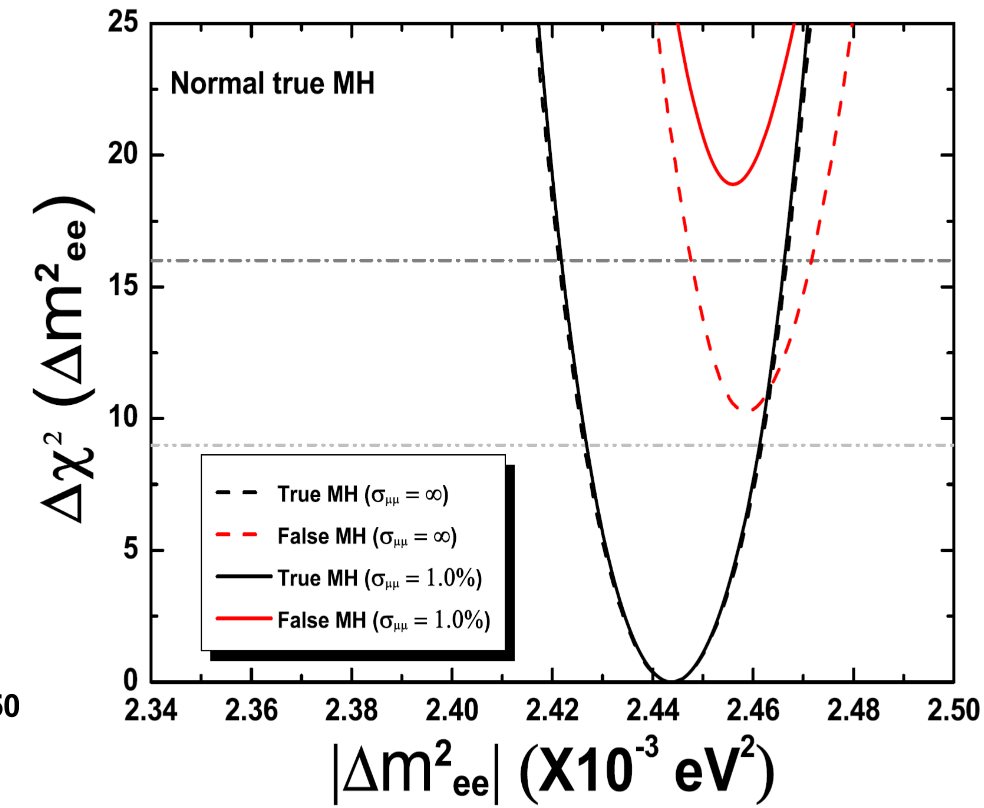
The Detector Performance Goals

	Daya Bay	BOREXINO	KamLAND	JUNO
Target Mass	20t	~300t	**~1kt**	**~20kt**
Photocathode Coverage	~12%	**~34%**	**~34%**	**~80%**
PE Collected	~160 PE/MeV	**~500 PE/MeV**	~250 PE/MeV	**~1200 PE/MeV**
Energy Resolution	~7.5%/√E	**~5%/√E**	~6%/√E	**3%/√E**
Energy Calibration	~1.5%	**~1%**	~2%	**<1%**

➡ An unprecedented LS detector is under development for the JUNO project —> a great step in detector technology

Expected Significance to Mass Hierarchy

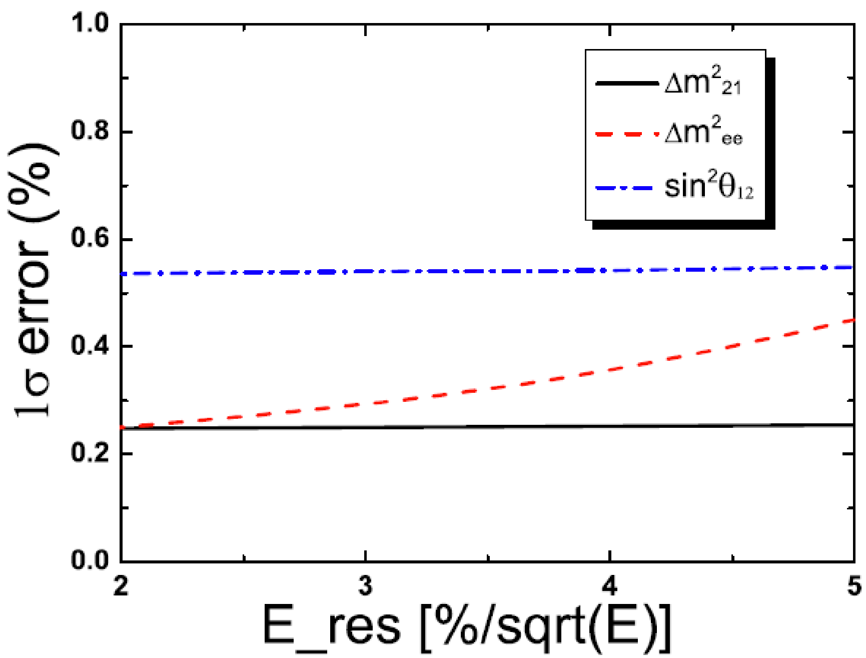




- Reactor neutrino survival spectrum can tell MH to **~3σ**
- JUNO can use help: If T2K+NOvA tells $\Delta m^2_{\mu\mu}$ ~1%, **~4σ**
    - *T2K+NOvA $\Delta m^2_{\mu\mu}$ ~1%, S.K. Agarwalla, S. Prakash, WW, arXiv:1312.1477*

Other Potential: Precision Oscillation Warranted

	Δm^2_{21}	$\|\Delta m^2_{31}\|$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$
Dominant Exps.	KamLAND	MINOS	SNO	Daya Bay	SK/T2K
Individual 1σ	2.7% [121]	4.1% [123]	6.7% [109]	6% [122]	14% [124, 125]
Global 1σ	2.6%	2.7%	4.1%	5.0%	11%



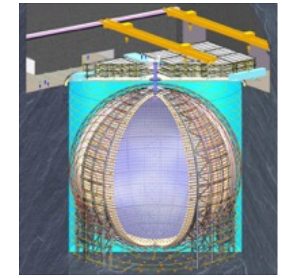
JUNO Yellow Book
arXiv:1507.05613

- Subpercent precision oscillation measurements warranted @ JUNO

JUNO: 100k evts, arXiv:1507.05613

	Nominal	+ B2B (1%)	+ BG	+ EL (1%)	+ NL (1%)
$\sin^2\theta_{12}$	0.54%	0.60%	0.62%	0.64%	0.67%
Δm^2_{21}	0.24%	0.27%	0.29%	0.44%	0.59%
$\|\Delta m^2_{ee}\|$	0.27%	0.31%	0.31%	0.35%	0.44%

JUNO Major Milestones and Progresses



2014: International collaboration established

- start civil construction

2015: PMT production line setup; CD parts R&D

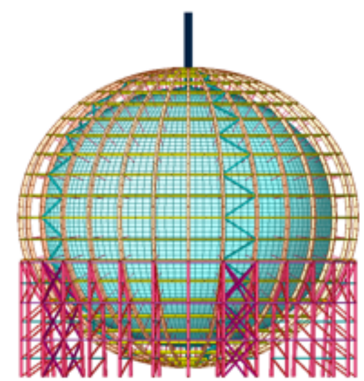
2016: Start PMT and CD parts production

2017: Start PMT testing; TT arrived

2018: PMT potting starts; Electronics production starts

2019 - 2020: Civil work and lab preparation completed; Detector Constructing

2021: Detector Ready; DATA!



Do We Need A Near Detector?

- We do not believe that periodic fine structures could exist. However, a near detector with resolution better than 3%/sqrt(E) could remove the doubts completely from the community
  - GasTPC or LXe (scattering) do not have enough statistics.
  - LS with Gd-doping could be a better choice (PMTs vs SiPM)
- Basic parameters of a Gd-LS near detector:
  - Fiducial Volume: 1 ton
    - Event rate 400k/year @ 50m
    - 3 years data taking yields 10x JUNO 6-year data
  - Additional 28 cm to contain the event
- Two-layer detector:
  - 2.9 t target in spherical acrylic vessel
  - Oil buffer in stainless steel vessel, size ~ 2mx2m.

Welcome New Collaborators!

Summary

- Exciting and steady progresses have been made in the past 20 years in neutrino physics — ***Neutrino Mass is beyond the Standard Model***
- JUNO provides great potential in resolving the neutrino mass hierarchy, ***unique and complementary to other efforts***

  ➡️Pure e-flavor and free of matter effect

- JUNO also provides ***great potential*** in ***precision oscillation measurements, geoneutrino and extraterrestrial neutrino detections***, and other non-neutrino physics like nucleon decay and indirect dark matter searches
- The JUNO project has been ***making steady progresses*** and data taking is expected in 2021

JUNO thanks you all for your attention!

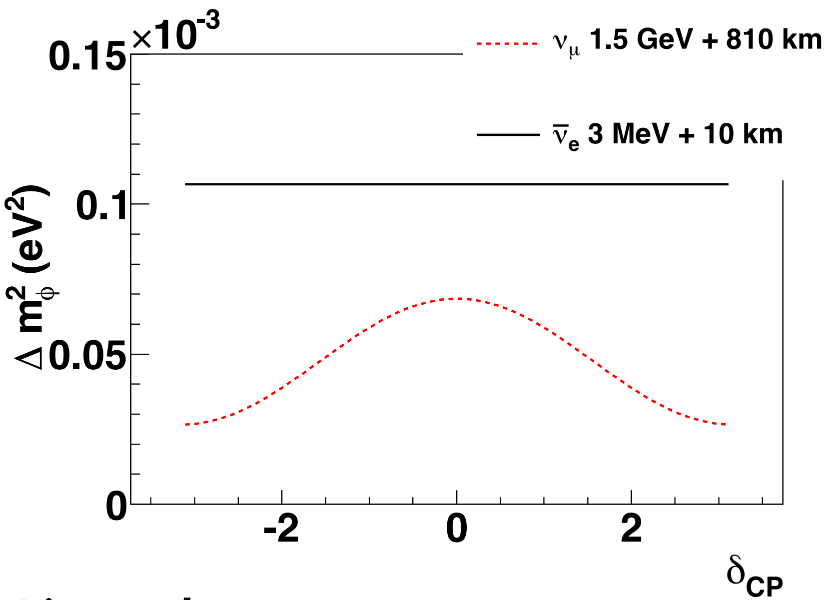
Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	IMP-CAS	Germany	U. Mainz
Belgium	Université libre de Bruxelles	China	SYSU	Germany	U. Tuebingen
Brazil	PUC	China	Tsinghua U.	Italy	INFN Catania
Brazil	UEL	China	UCAS	Italy	INFN di Frascati
Chile	PCUC	China	USTC	Italy	INFN-Ferrara
Chile	UTFSM	China	U. of South China	Italy	INFN-Milano
China	BISEE	China	Wu Yi U.	Italy	INFN-Milano Bicocca
China	Beijing Normal U.	China	Wuhan U.	Italy	INFN-Padova
China	CAGS	China	Xi'an JT U.	Italy	INFN-Perugia
China	ChongQing University	China	Xiamen University	Italy	INFN-Roma 3
China	CIAE	China	NUDT	Latvia	IECS
China	DGUT	China	Zhengzhou University	Pakistan	PINSTECH (PAEC)
China	ECUST	Czech Rep.	Charles U.	Russia	INR Moscow
China	Guangxi U.	Finland	University of Jyvaskyla	Russia	JINR
China	Harbin Institute of Technology	France	APC Paris	Russia	MSU
China	IHEP	France	CENBG	Slovakia	FMPICU
China	Jilin U.	France	CPPM Marseille	Taiwan	National Chiao-Tung U.
China	Jinan U.	France	IPHC Strasbourg	Taiwan	National Taiwan U.
China	Nanjing U.	France	Subatech Nantes	Taiwan	National United U.
China	Nankai U.	Germany	Forschungszentrum Julich ZEA2	Thailand	NARIT
China	NCEPU	Germany	RWTH Aachen U.	Thailand	PPRLCU
China	Pekin U.	Germany	TUM	Thailand	SUT
China	Shandong U.	Germany	U. Hamburg	USA	UMD1
China	Shanghai JT U.	Germany	IKP FZJ	USA	UMD2

72 Institutes, 16 Countries, 4 Continents and ~550 collaborators

Mass Hierarchy by Comparing $\Delta m^2_{\mu\mu}$ and Δm^2_{ee}

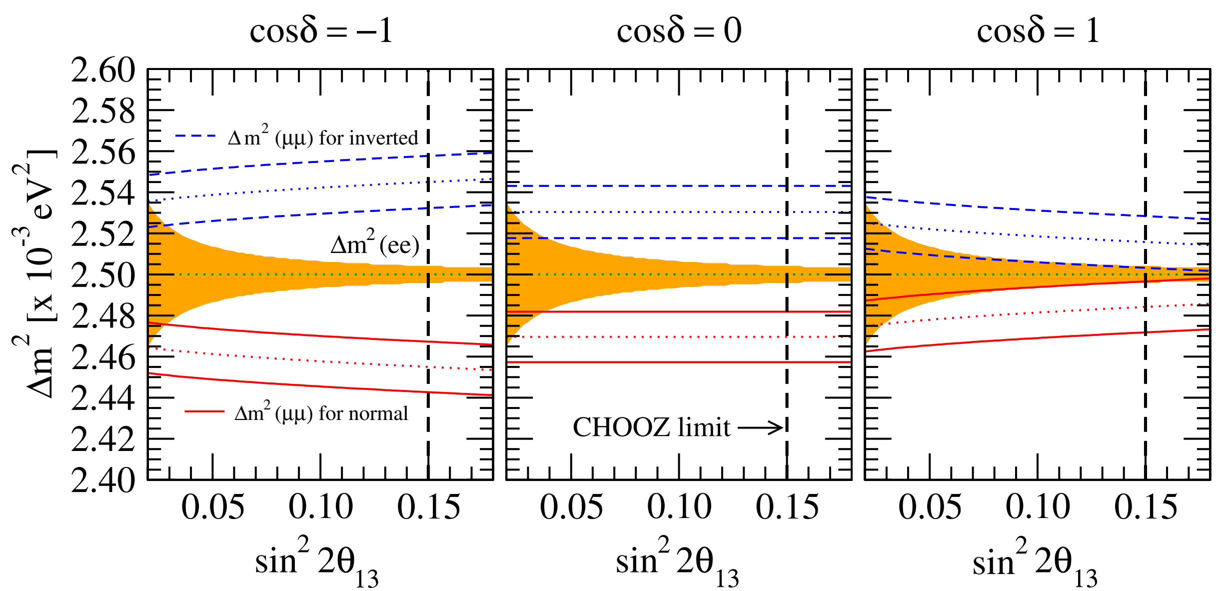
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$= 1 - 2s^2_{13}c^2_{13} - 4c^4_{13}s^2_{12}c^2_{12}\sin^2\Delta_{21} + 2s^2_{13}c^2_{13}\sqrt{1 - 4s^2_{12}c^2_{12}\sin^2\Delta_{21}}\cos(2\Delta_{32} \pm \phi)$$

$$P_{\nu_\mu \to \nu_\mu} = 1 - P^{\mu}_{21} - \cos^2\theta_{13}\sin^2 2\theta_{23}\sin^2\frac{(\Delta m^2_{32} \pm \phi)L}{4E}$$



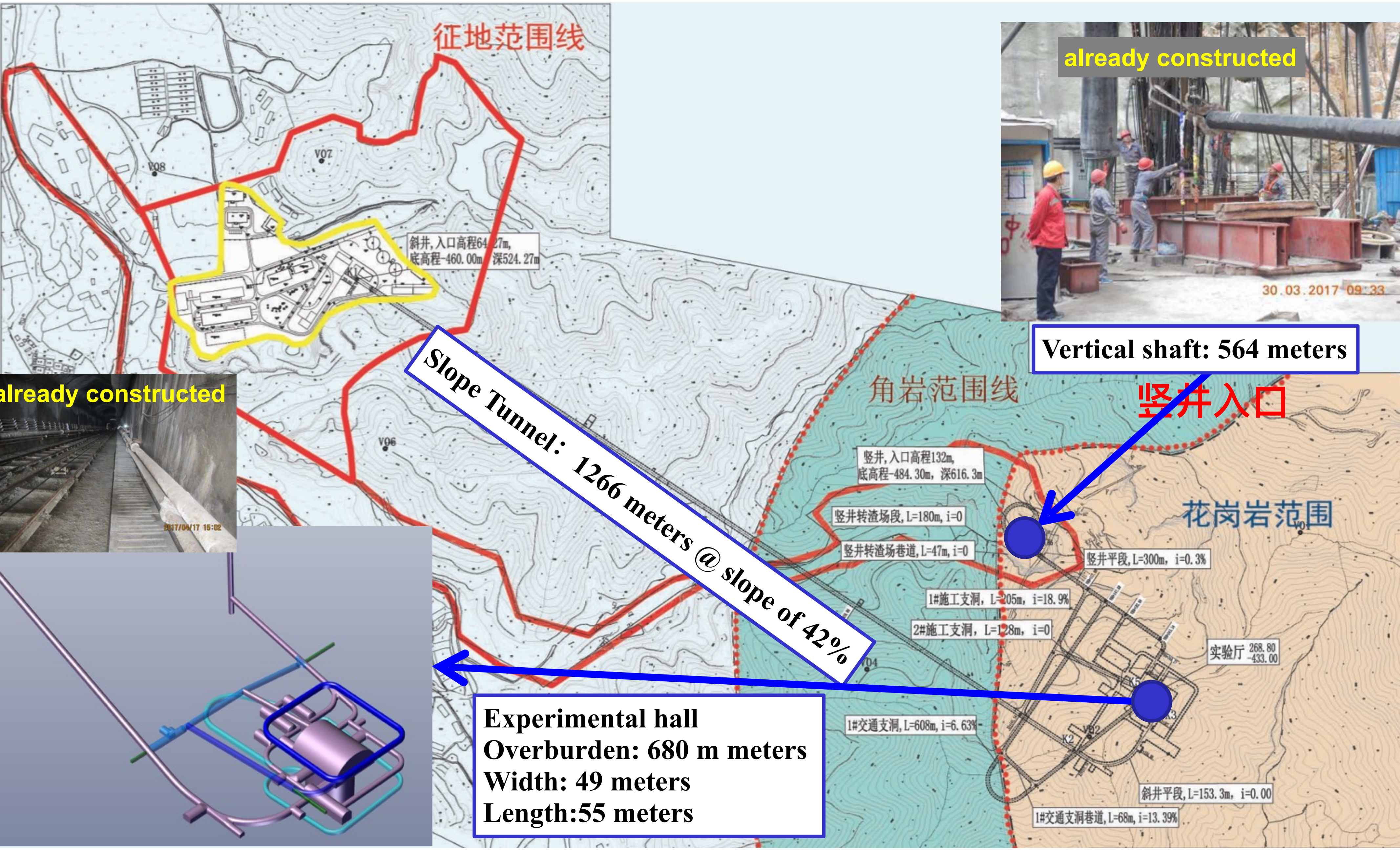
Qian et al, PRD87(2013)3, 033005

FIG. 6: The dependence of effective mass-squared difference $\Delta m^2_{ee\phi}$ (solid line) and $\Delta m^2_{\mu\mu\phi}$ (dotted line) w.r.t. the value of δ_{CP} for $\bar{\nu}_e$ and ν_μ disappearance measurements, respectively.



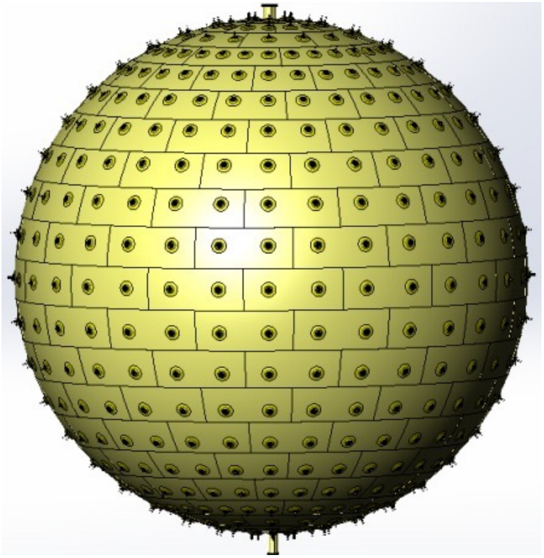
Minakata et al PRD74(2006), 053008

Civil Layout and Status

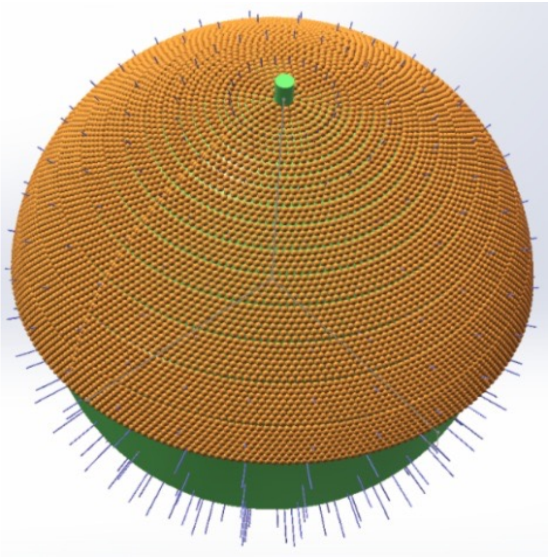


Details of the JUNO Central Detector

Stainless Steel Truss
Inner Diameter:40.1m



Acrylic Sphere
Inner Diameter: 35.4m



PMT Arrangement
~18,000 (20″)+~25,000 (3.1″)

Stainless steel truss
- ID: Ø40.1m
- OD: Ø41.1m
- Weight: ~600t

Acrylic sphere
- ID: Ø35.4m
- Thickness:120mm
- Weight: ~600t

20″ PMT array
- Distance to LS: ~1.6m
- Gap: ~250mm (extremely challenging)

Veto System

Top Tracker

- Re-using the OPERA's Target Tracker (plastic scintillators)
- Three (x-y) layers to ensure good muon tracking (3 muons/s)
- Muon rejection studies
- Cosmogenic background study (^{9}Li, ^{8}He)
- Delivered to China already

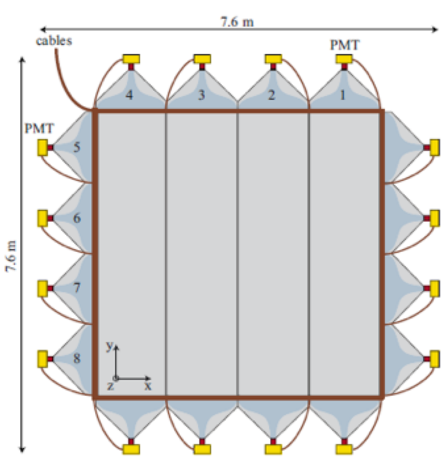
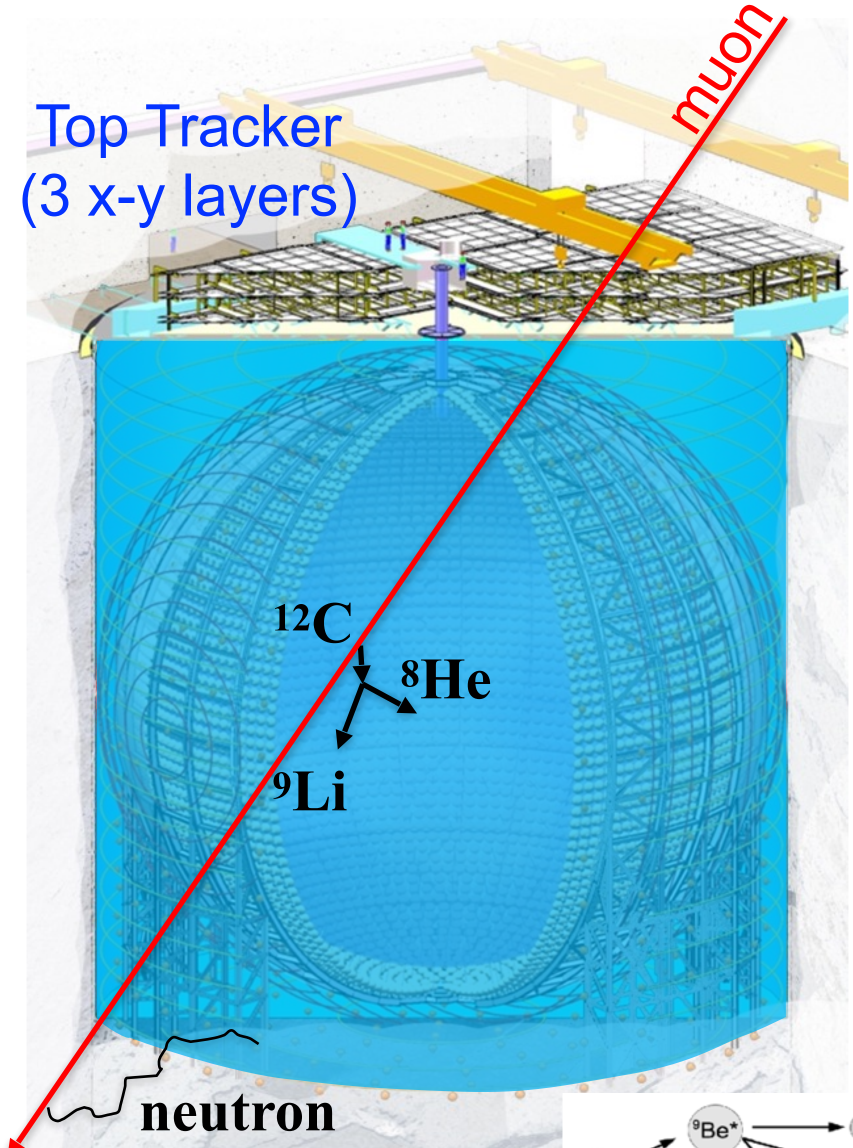
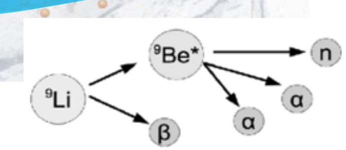


Fig. 3. Schematic view of a plastic scintillator strip wall.

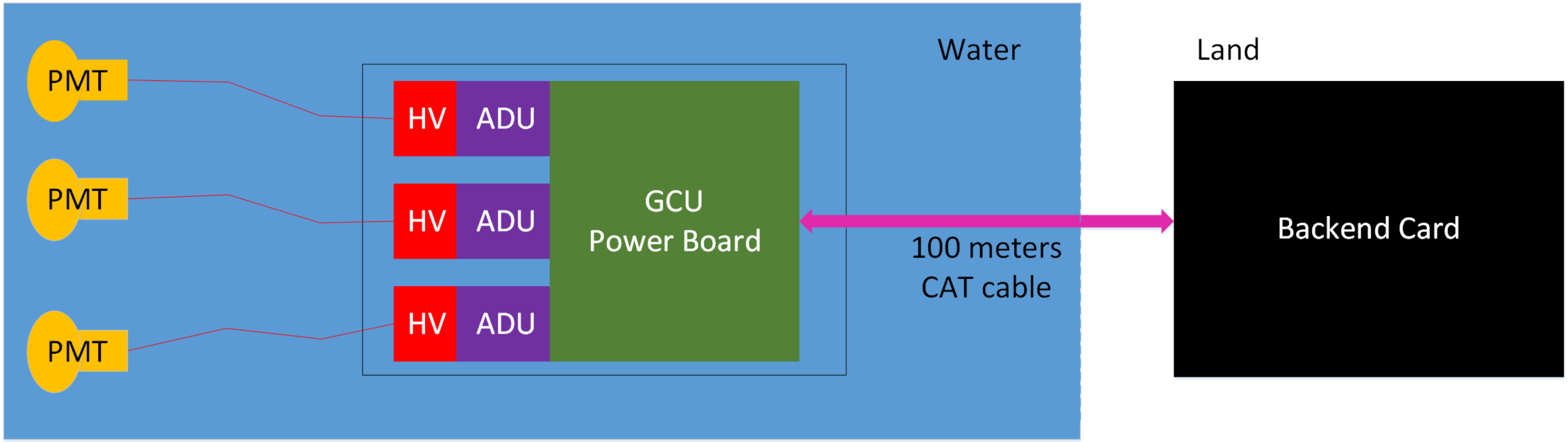


lparaiso

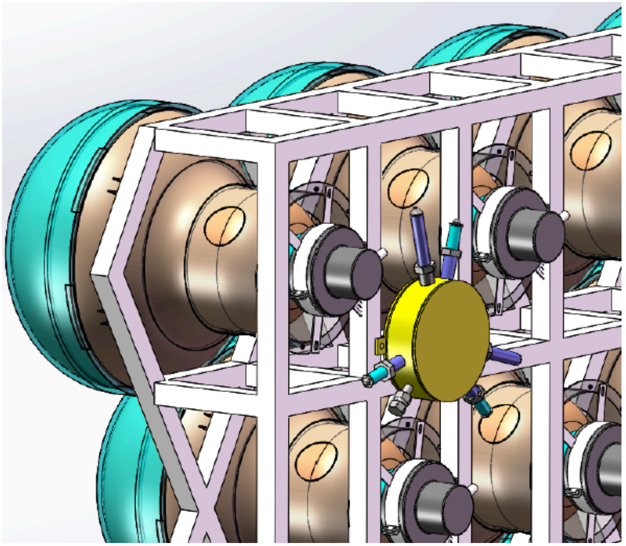


The Electronic Readout Scheme

1F3 scheme



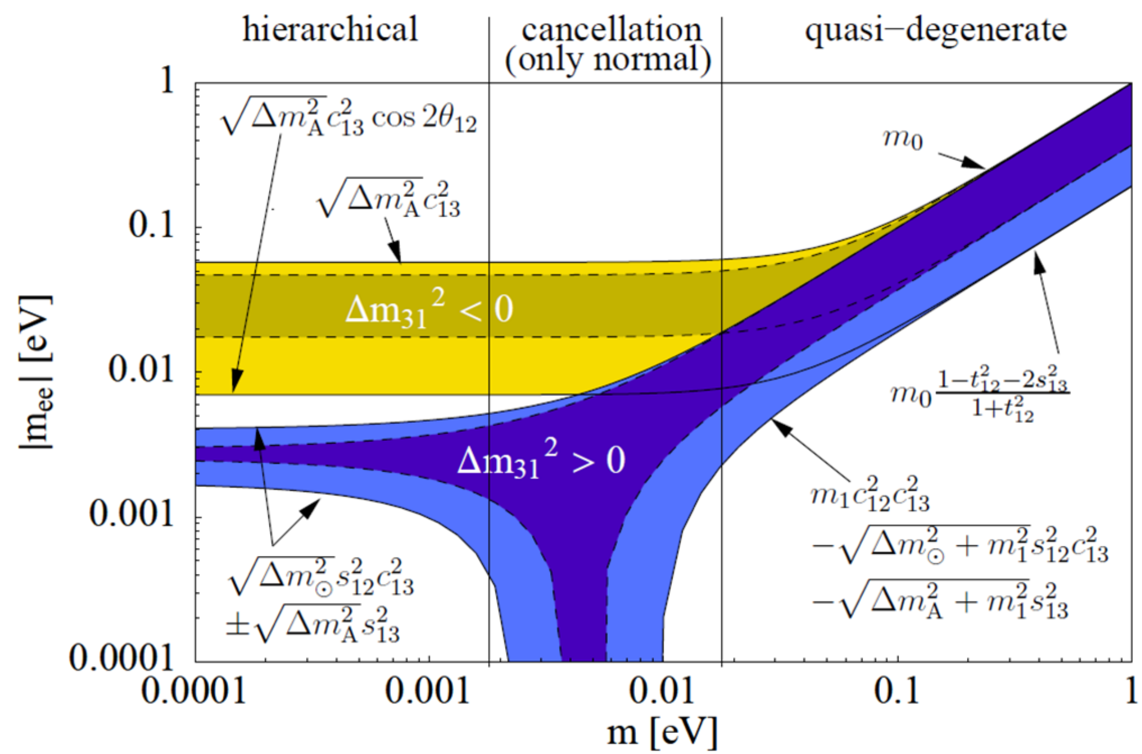
- PMT: photomultiplier tubes
- HV: High Voltage units
- ADU: Analog to Digital Unit
- GCU: Global Control Unit
- CAT cable: Category 5e cable
- High reliability needed
- Severe constraints by power consumption

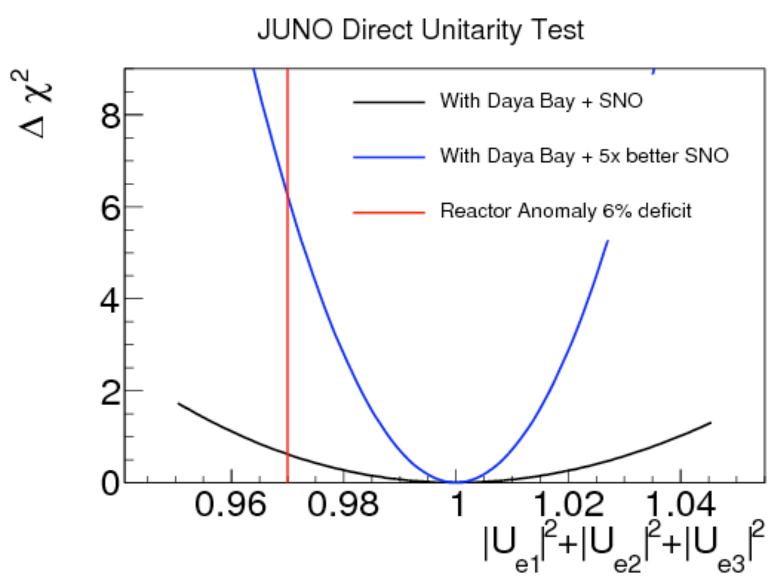


Why Precise Solar Mixing Angle Measurements

- Best solar angle in the foreseeable future
- Valuable input to the neutrinoless double beta decay

M. Lindner, A. Merle, W. Rodejohann, Phys.Rev. D73 (2006) 053005





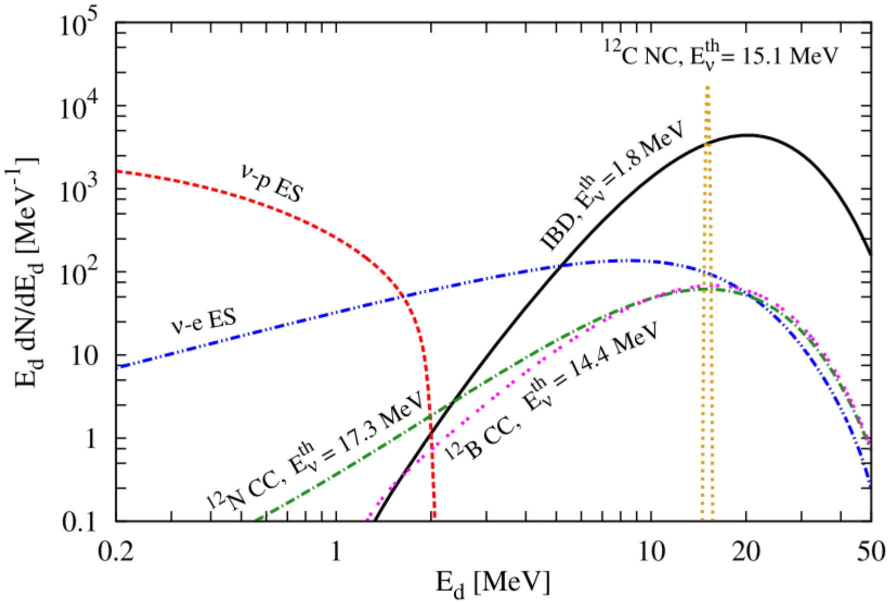
Qian, X. et al. arXiv:1308.5700

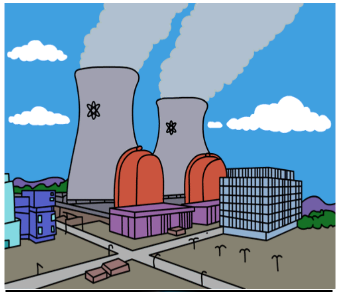
- Three-neutrino paradigm test

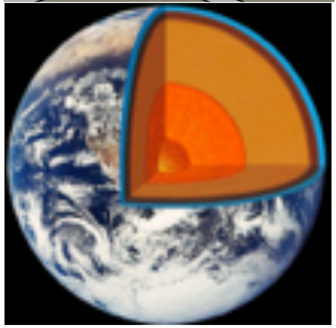
Direct unitarity test of $|U_{e1}|^2+|U_{e2}|^2+|U_{e3}|^2=1$

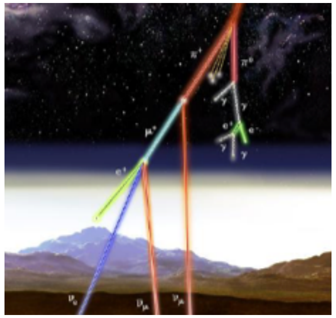
JUNO Physics Program

JUNO Yellow Book
J. Phys. G 43, 030401 (2016)



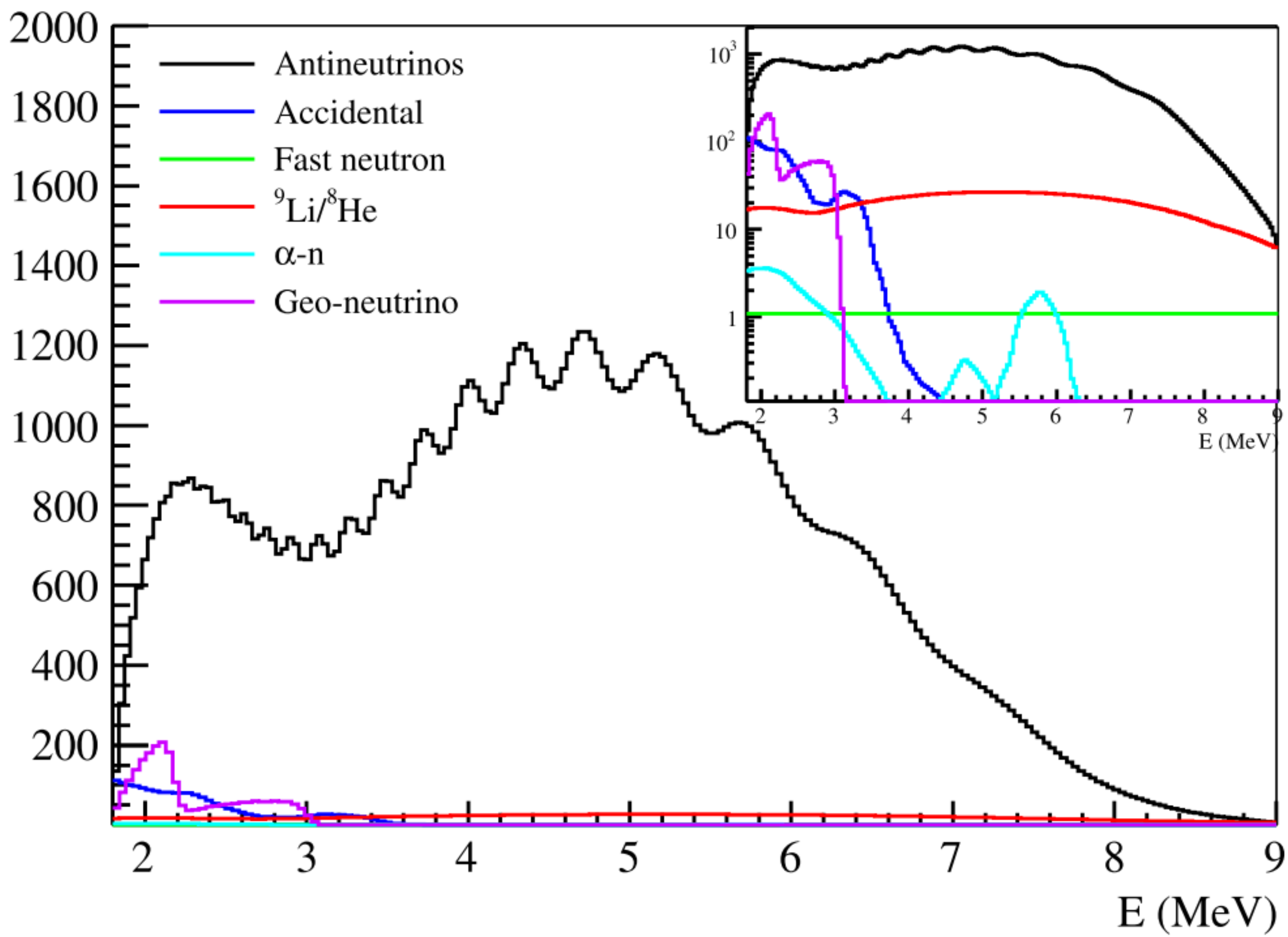






- Reactor neutrinos
  - Mass Hierarchy
  - Precision measurements of oscillation parameters
- Geoneutrinos
- Solar neutrinos
- Atmospheric neutrinos
- Supernovae neutrinos
- Exotic searches

Expected IBD Spectrum of JUNO (MC)



JUNO Sensitivity to DSNB