Status and Prospects of JUNO

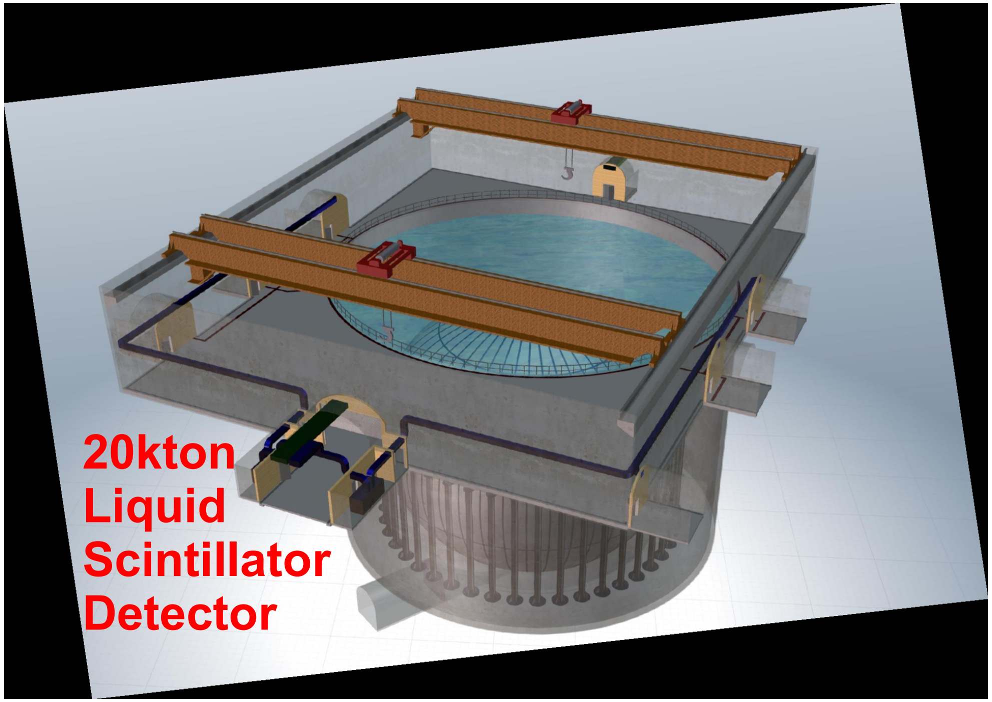
Neutrino 2018 in Heidelberg

Björn Wonsak
on behalf of the JUNO collaboration

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Jiangmen Underground Neutrino Observatory

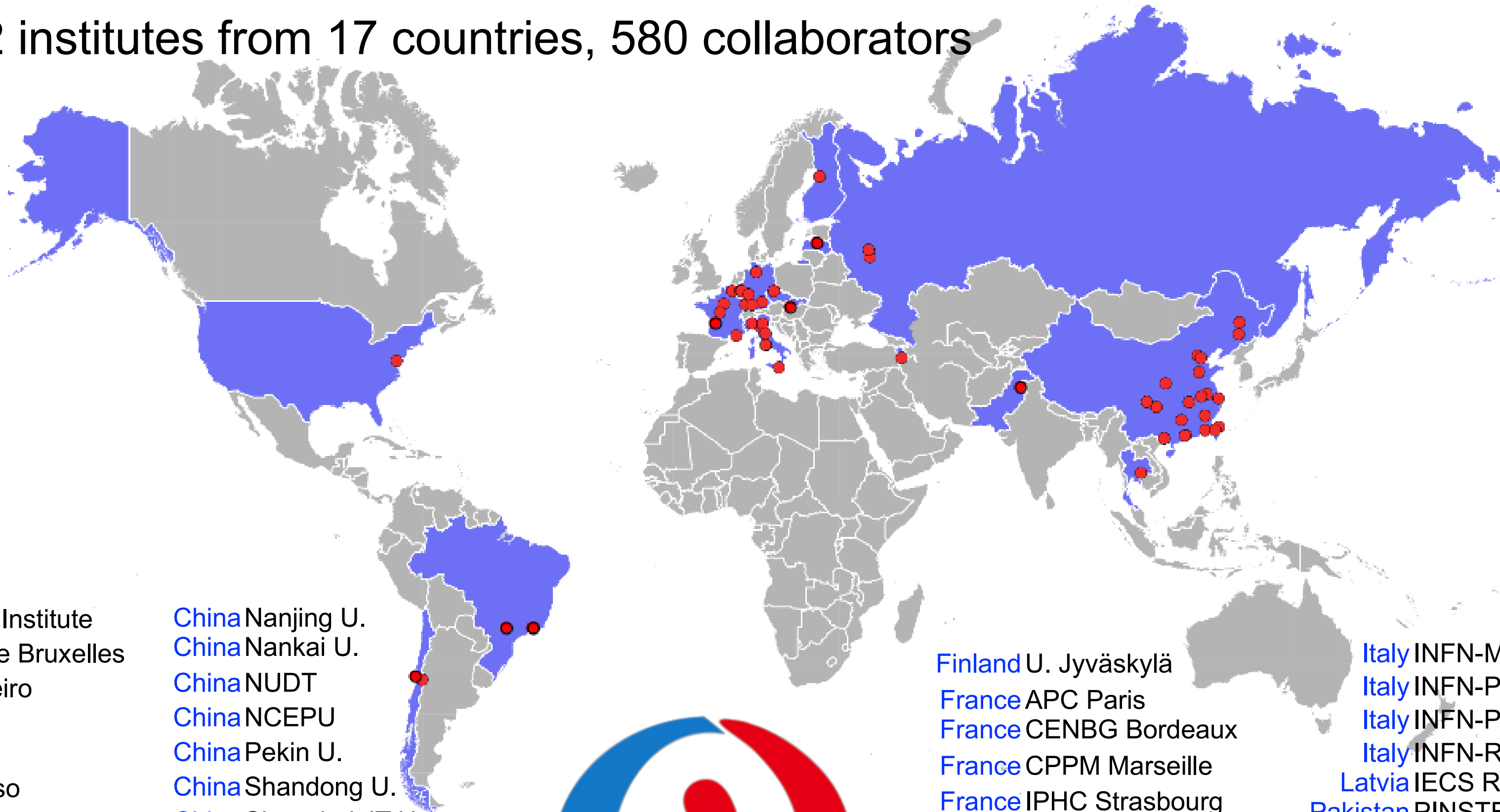
Main goal: Mass Hierarchy (MH)



High power nuclear power plants
(26.6 GW total power)

The JUNO Collaboration

72 institutes from 17 countries, 580 collaborators

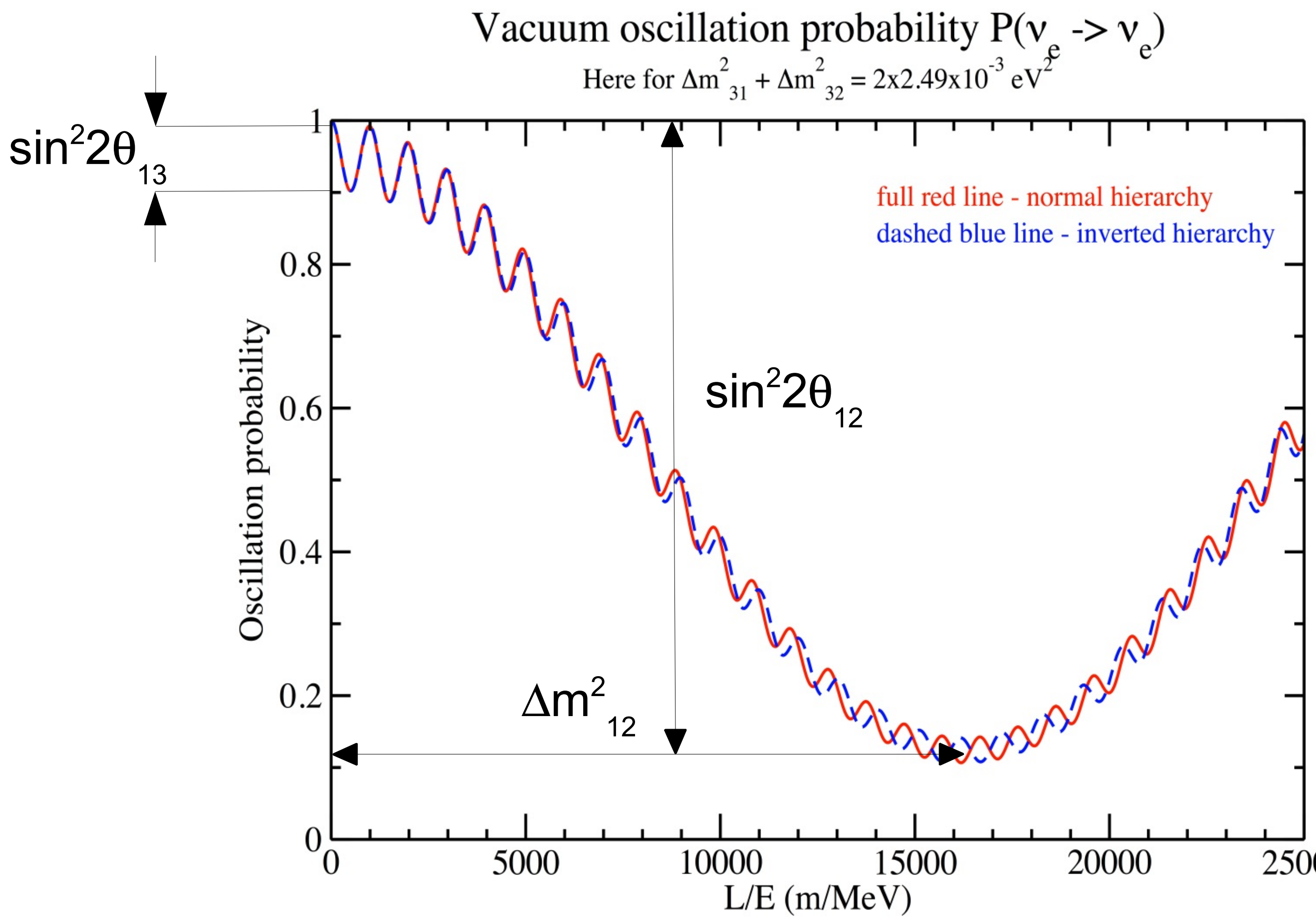


Armenia	Yerevan Physics Institute
Belgium	Université libre de Bruxelles
Brazil	PUC Rio de Janeiro
Brazil	UE Londrina
Chile	PCUC
Chile	UTFSM Valparaiso
China	BISEE
China	Beijing Normal U.
China	CAGS
China	ChongQing University
China	CIAE
China	DGUT
China	ECUST
China	Guangxi U.
China	Harbin Institute of Technology
China	IHEP
China	IMP-CAS
China	Jilin U.
China	Jinan U.
China	Nanjing U.
China	Nankai U.
China	NUDT
China	NCEPU
China	Pekin U.
China	Shandong U.
China	Shanghai JT U.
China	SYSU
China	Tsinghua U.
China	UCAS
China	USTC
China	U. of South China
China	Wu Yi U.
China	Wuhan U.
China	Xi'an JT U.
China	Xiamen University
China	Zhengzhou U.
Czech	R. Charles U. Prague
Finland	U. Jyväskylä
France	APC Paris
France	CENBG Bordeaux
France	CPPM Marseille
France	IPHC Strasbourg
France	Subatech Nantes
Germany	ZEA FZ Julich
Germany	RWTH Aachen U.
Germany	TUM
Germany	U. Hamburg
Germany	IKP-2 FZ Jülich
Germany	U. Mainz
Germany	U. Tuebingen
Italy	INFN Catania
Italy	INFN di Frascati
Italy	INFN-Ferrara
Italy	INFN-Milano
Italy	INFN-Milano Bicocca
Italy	INFN-Padova
Italy	INFN-Perugia
Italy	INFN-Roma 3
Latvia	IECS Riga
Pakistan	PINSTECH Islamabad
Russia	INR Moscow
Russia	JINR
Russia	MSU
Slovakia	U. Bratislava FMPICU
Taiwan	National Chiao-Tung U.
Taiwan	National Taiwan U.
Taiwan	National United U.
Thailand	NARIT
Thailand	PPRLCU Bangkok
Thailand	SUT
USA	UMD1
USA	UMD2

Measuring the MH with Reactor Neutrinos

$$\mathbf{P}(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \boxed{\cos^4\theta_{13}\,\sin^2 2\theta_{12}\,\sin^2\Delta m^2_{21}\frac{\mathbf{L}}{4\mathbf{E}}} - \boxed{\sin^2 2\theta_{13}\left(\cos^2\theta_{12}\,\sin^2\Delta m^2_{31}\frac{\mathbf{L}}{4\mathbf{E}} + \sin^2\theta_{12}\,\sin^2\Delta m^2_{32}\frac{\mathbf{L}}{4\mathbf{E}}\right)}$$

P_{21} $\quad$ $P_{31} + P_{32}$



Measuring the MH with Reactor Neutrinos

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta m^2_{21}\frac{L}{4E} - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\Delta m^2_{31}\frac{L}{4E} + \sin^2\theta_{12}\sin^2\Delta m^2_{32}\frac{L}{4E}\right)$$

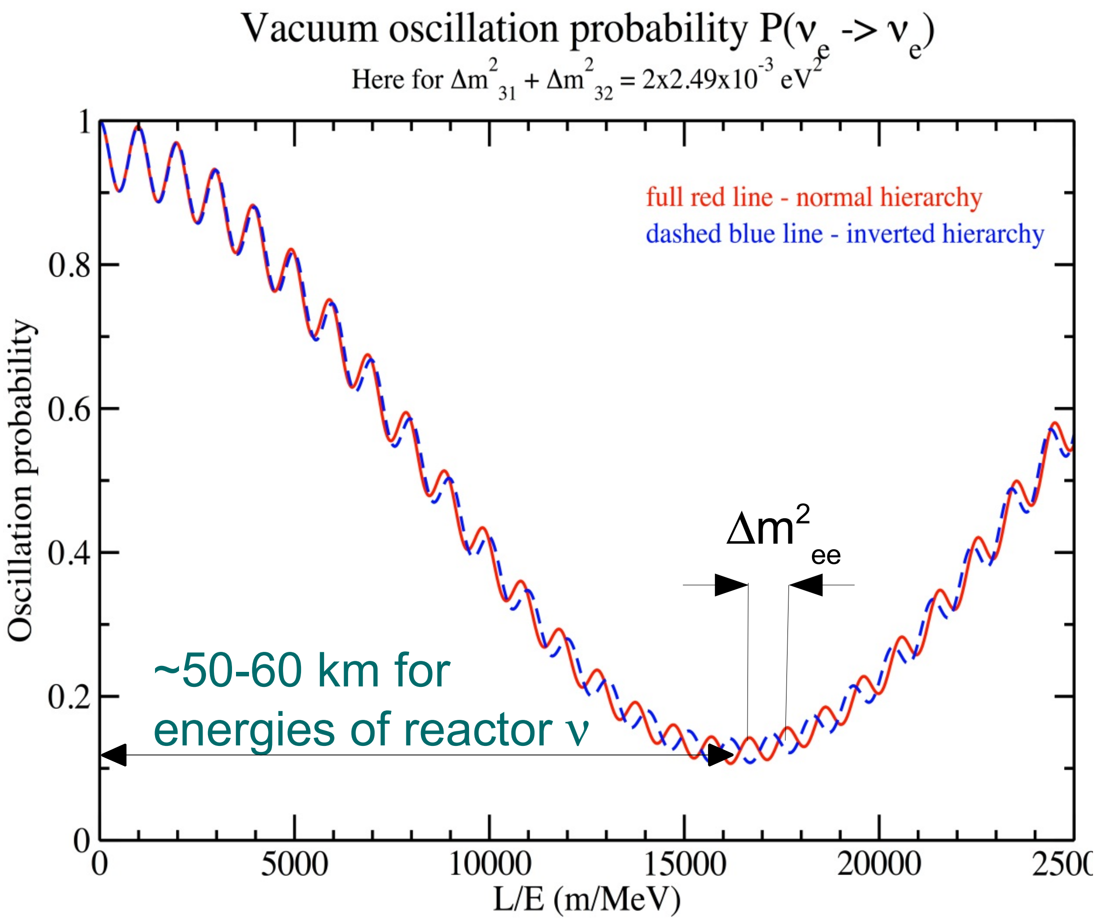
$$\approx 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta m^2_{21}\frac{L}{4E} - \sin^2 2\theta_{13}\sin^2\Delta m^2_{ee}\frac{L}{4E} \quad ,\text{for} \quad \Delta m^2_{12} \ll \Delta m^2_{32}$$

Δm^2_{ee} = effective neutrino mass-squared difference
(beat frequency)

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

with $\Delta m^2_{12} << \Delta m^2_{32}$

→ different beat frequency (Δm^2_{ee}) for both hierarchies



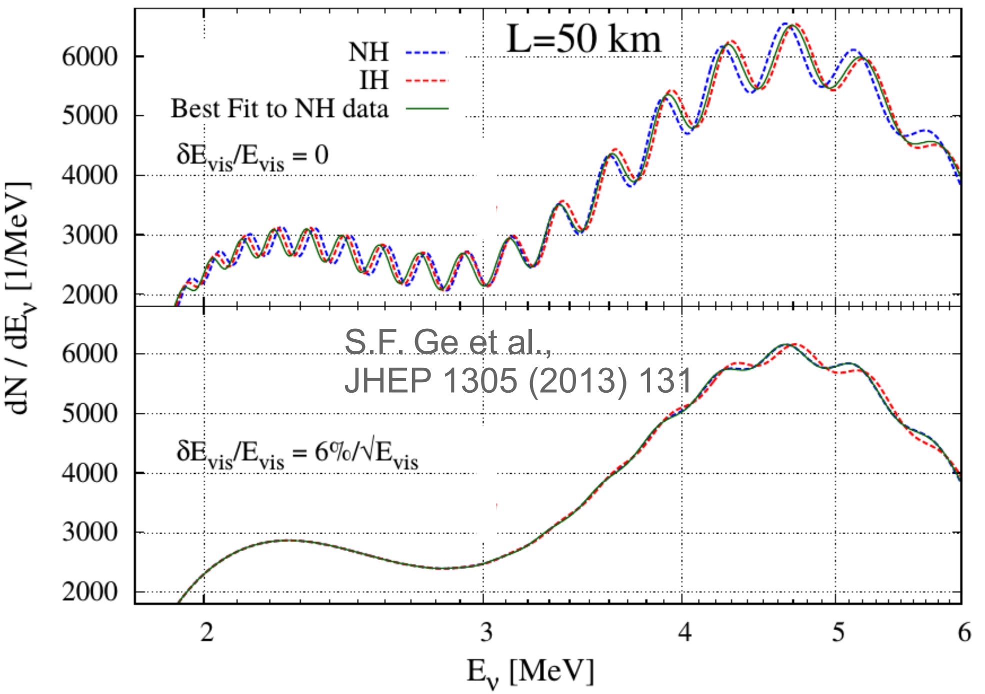
Requirements for JUNO

- **Reactor baseline variation: < 0.5 km**
  - JUNO site meets this requirement

- **Energy resolution: ~ 3%/√E**
  - The crucial parameter

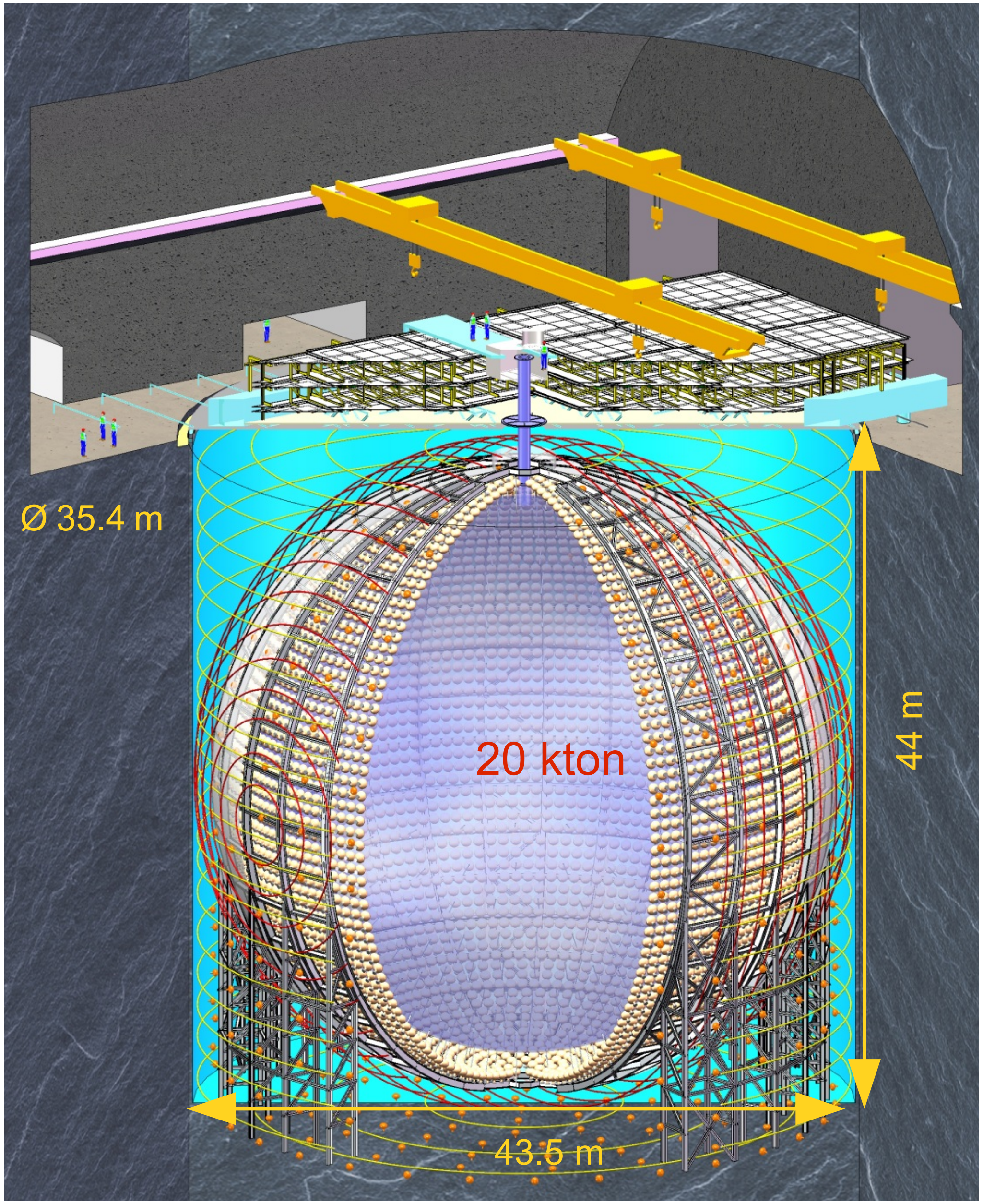
- **Energy scale uncertainty: < 1%**
  - Large uncertainties could lead to wrong answer

- **Statistics: 100k events in 6 yrs**
  - 26.6 GW reactor power
  - 20 kton detector (→ ~60 evts/day)
  - Precision muon tracking to maximize exposure (minimize vetoed volume)



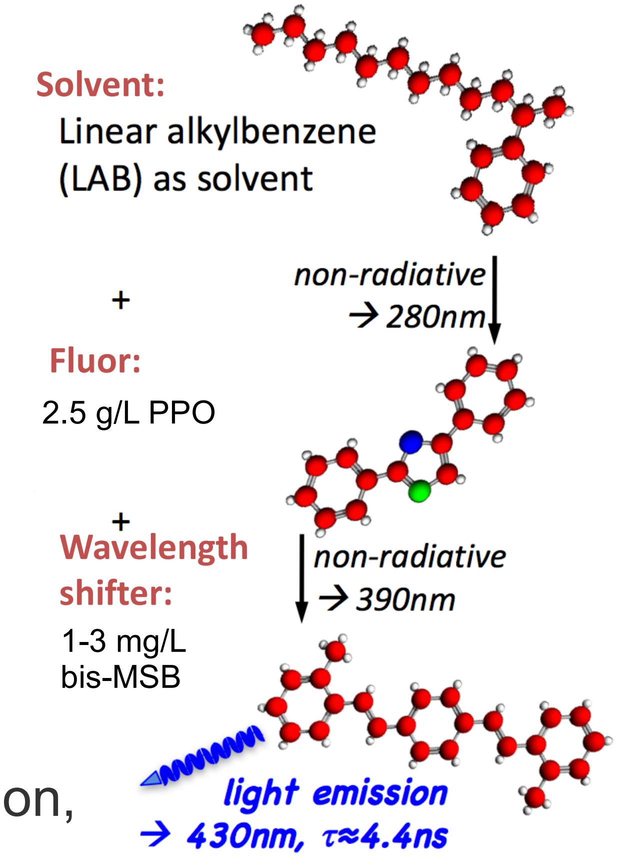
Overall Detector Design + Veto

- **Central detector**
  - Acrylic sphere with liquid scintillator
  - PMTs in water buffer
  - 78% PMT coverage
- **Water Cherenkov muon veto**
  - 2000 20” PMTs
  - 35 ktons ultra-pure water
  - Efficiency > 95%
  - Radon control → less than 0.2 Bq/m^3
- **Compensation coils**
  - Earth magnetic field <10%
  - Necessary for 20” PMTs
- **Top tracker**
  - Precision muon tracking
  - 3 plastic scintillator layers
  - Covering half of the top area



JUNO Liquid Scintillator

- **Requirement for 3%/√E**
  - High light-yield: 10^4 photons/MeV
  - High transparency:
    Attenuation Length (A.L.) > 20m @430nm

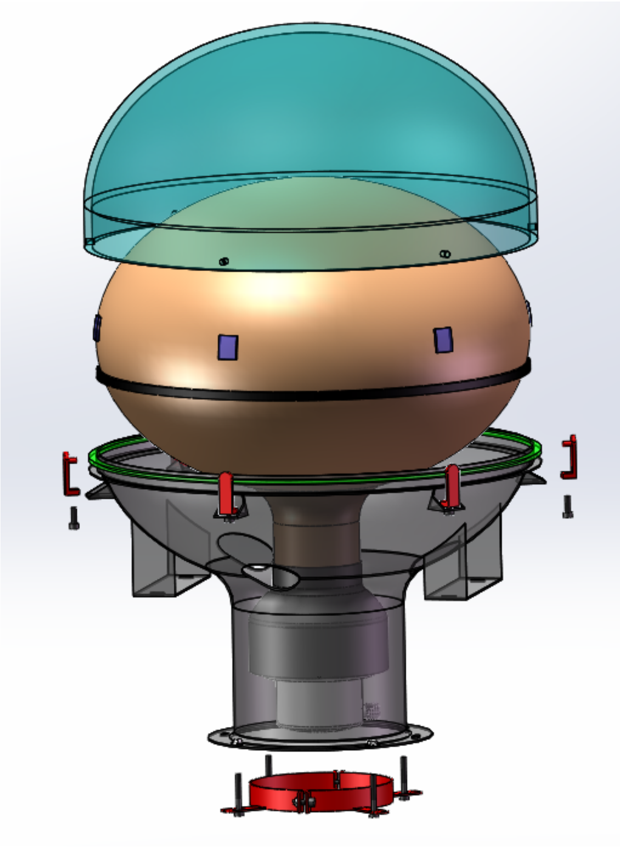


- **Purification pilot plant**
  - Under operation at Daya Bay
  - Distillation, Al_2O_3 column purification, water extraction and gas stripping
  - > 23 m A.L. after filling (measured)
  - Optimizing LS recipe
  - Studying radio-purity

JUNO 20" PMTs

- **15000 MCP-PMTs from NNVT** (Northern Night Vision Technology)
- **5000 dynode PMTs from Hamamatsu**
- **In production since 2016**
- **Already >9000 delivered**
- **More than 5000 tested**

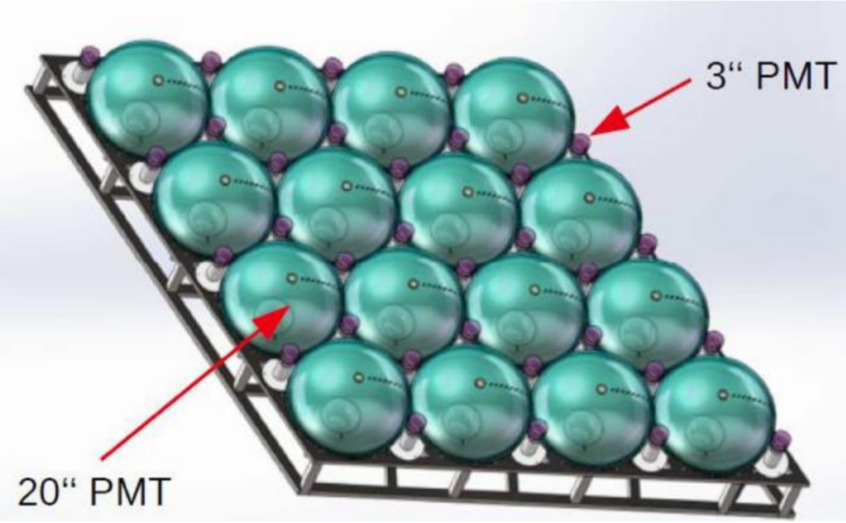
Characteristics	unit	MCP-PMT （NNVT）	R12860 （Hamamatsu）
Detection Efficiency (QE*CE)	%	27%	27%
P/V of SPE		3.5, > 2.8	3, > 2.5
TTS on the top point	ns	~12, < 15	2.7, < 3.5
Rise time/ Fall time	ns	R~2, F~12	R~5,F~9
Anode Dark Count	Hz	20K, < 30K	10K, < 50K
After Pulse Rate	%	1, <2	10, < 15
Radioactivity of glass	ppb	238U:50 232Th:50 40K: 20	238U:400 232Th:400 40K: 40



JUNO PMT with implosion protection cover

3” PMTs

- **Double calorimetry**
  - Always photon counting
    → Better control of systematics
    (Calibration of non-linear response of large PMTs)
  - Increased dynamic range
    → Helps with large signals
    (e.g. muons, supernova signal)

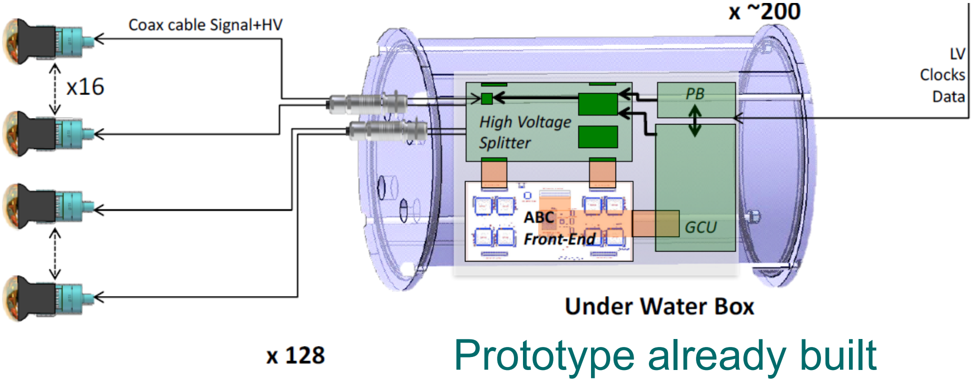


- **25000 PMTs contracted to HZC**
- **4000 produced, 3000 tested at HZC**

JUNO custom design:
XP72B22

QE 24% , P/V 3.0
SPE resolution 30%
TTS 2-5 ns

200 boxes × 128 PMTs



Prototype already built

How to Control the Energy Scale Uncertainties

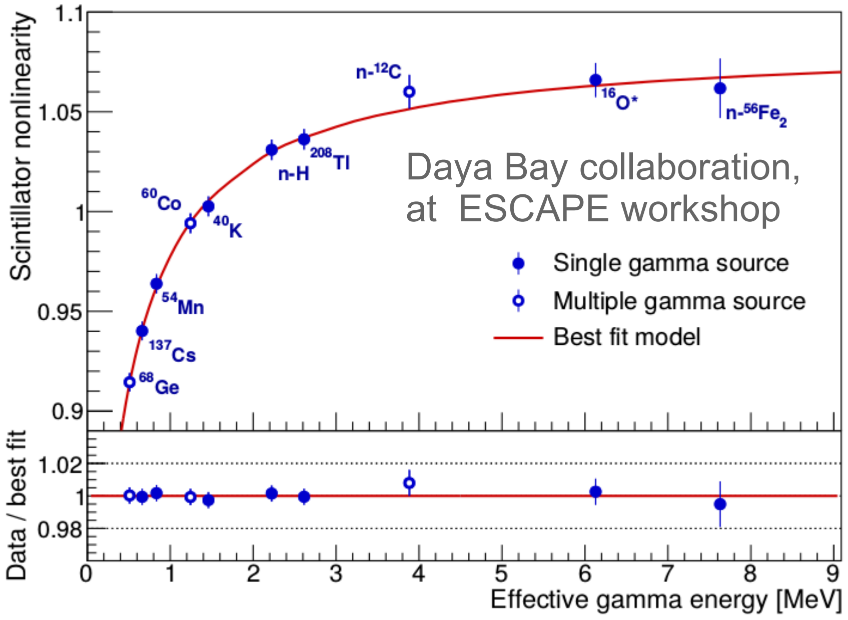
- **Answer:** Meticulous calibration

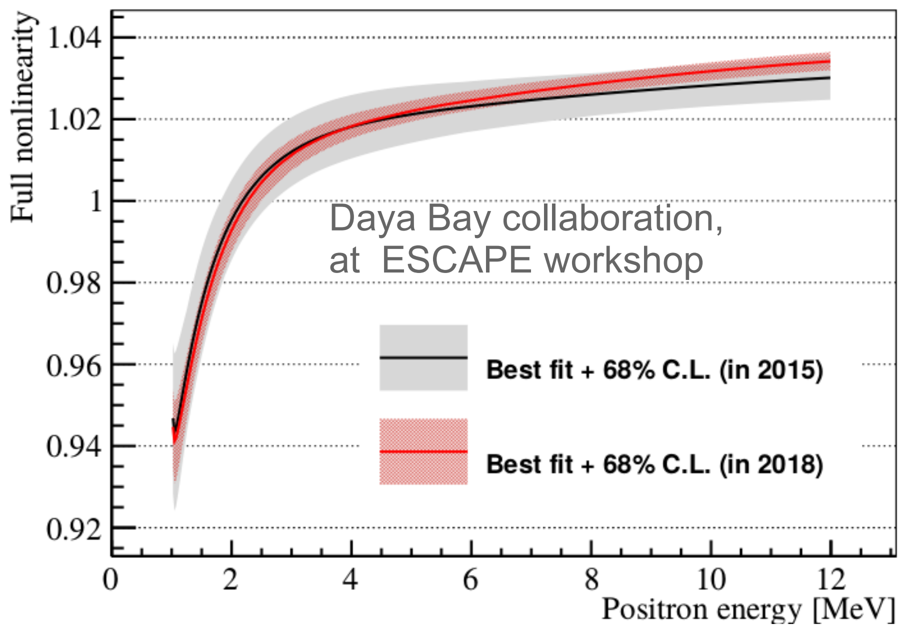
  (Different sources, over whole energy range, continuously, ...)

- Other experiments already achieved 1% accuracy

  (Daya Bay ~0.5%, Double Chooz 0.74%, Borexino <1% (at low energies), KamLAND 1.4%)

New results from ESCAPE workshop

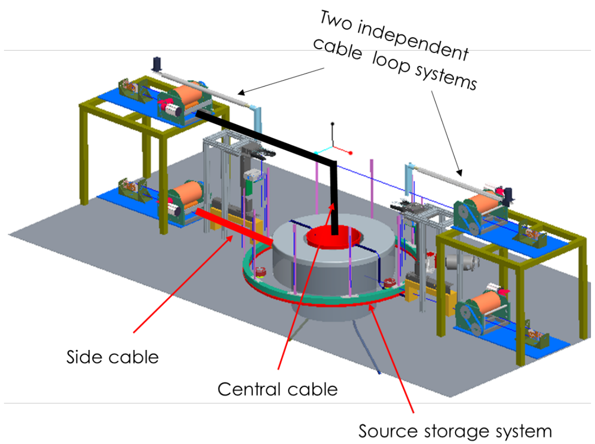




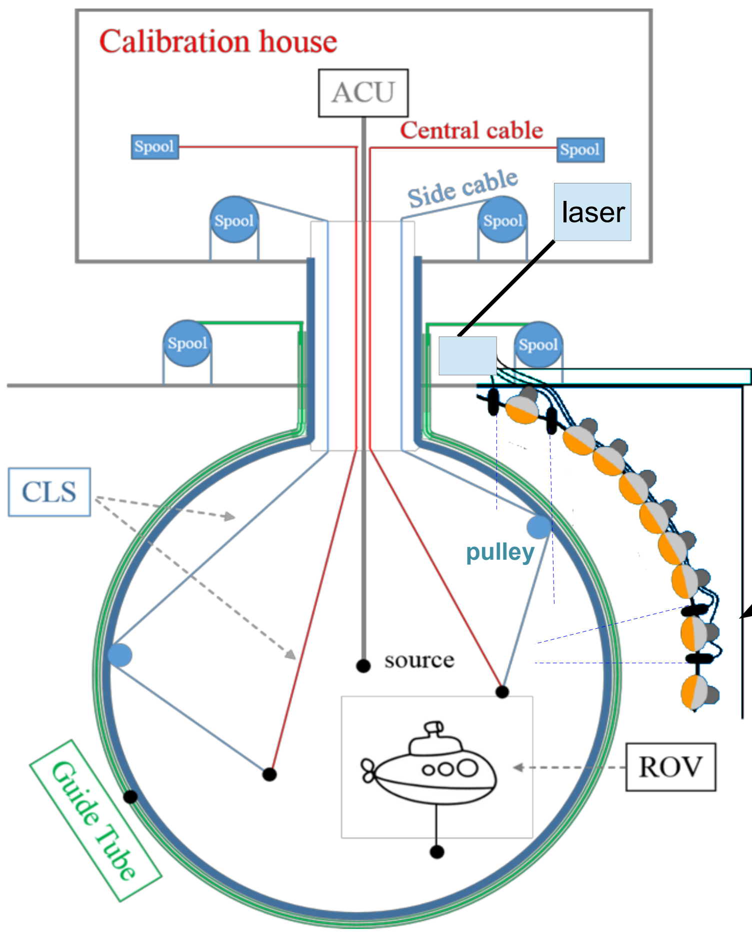
For more information see: Daya Bay collaboration, Phys. Rev. D 95, 072006 (2017)

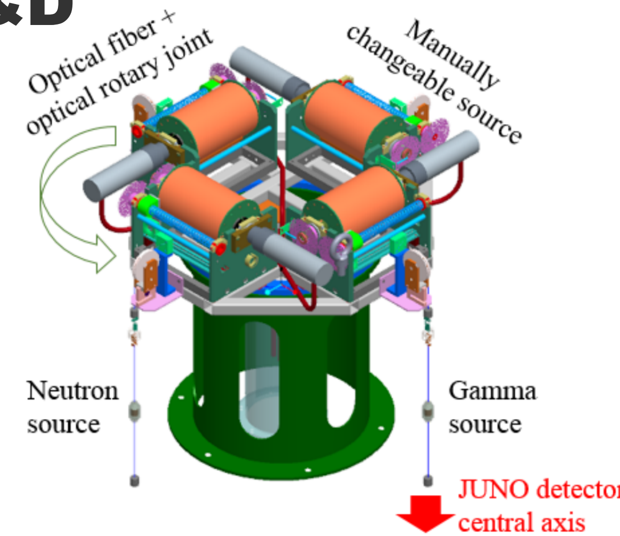
Calibration

- **Five complementary systems under R&D**

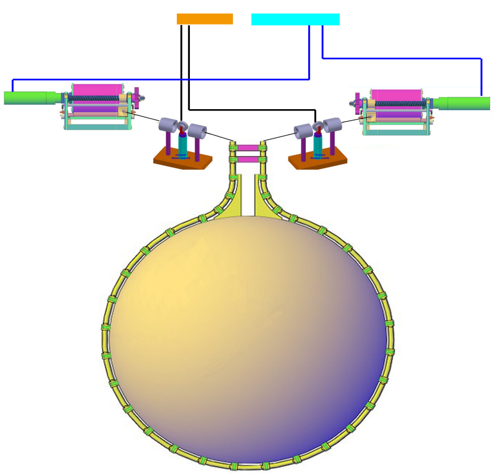


Cable Loop System (CLS)

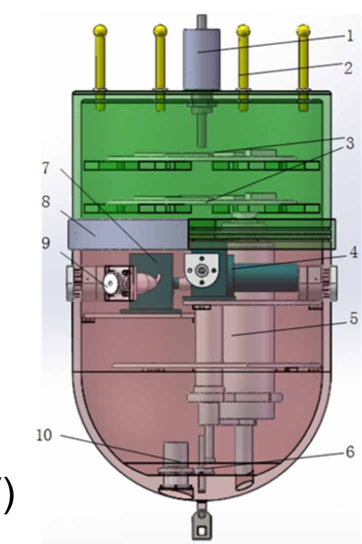




Automatic Calibration Unit (ACU)



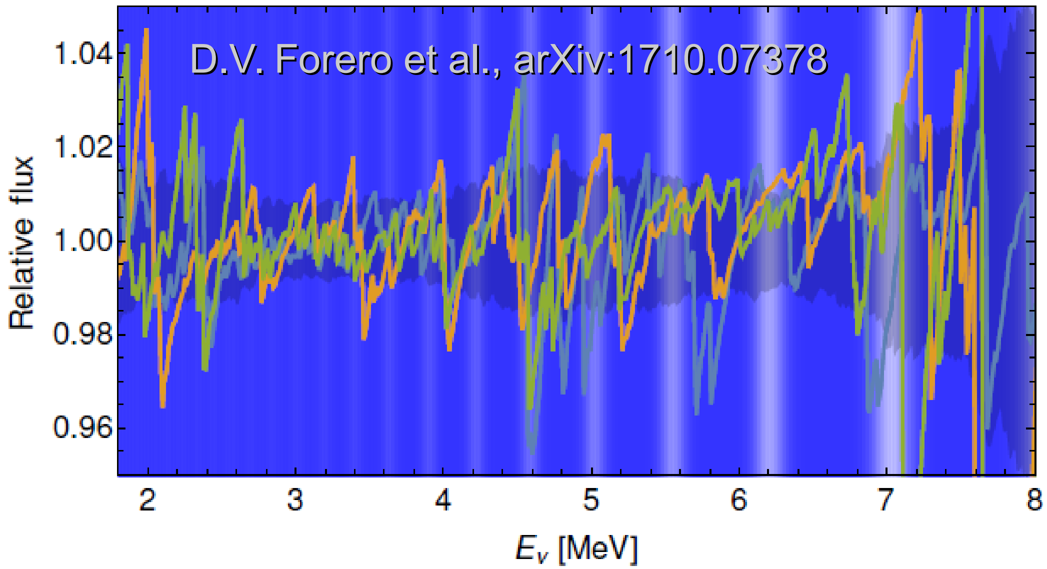
Guide tube system



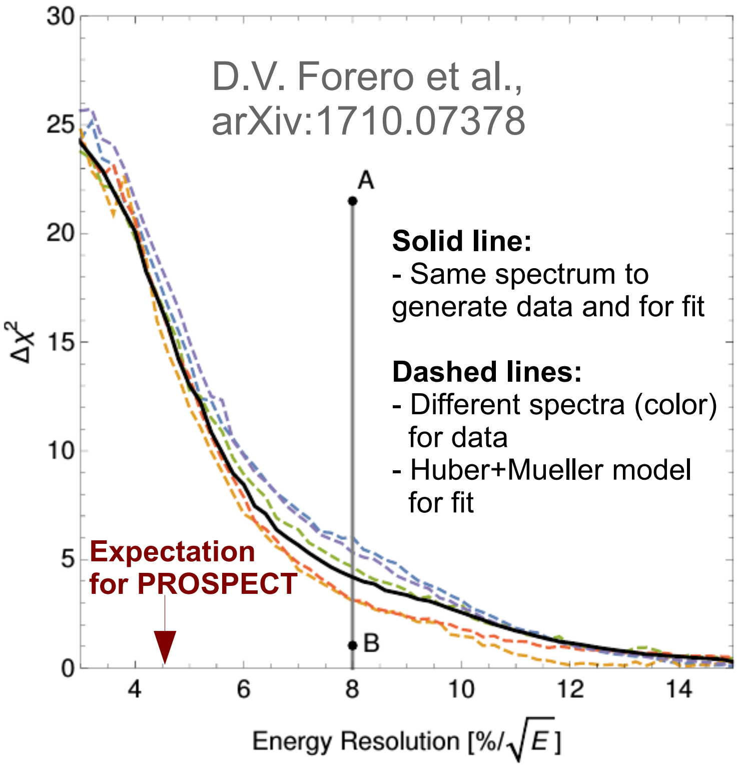
Remotely Operated Vehicle (ROV)

Reactor Spectrum Uncertainties

- Reactor spectrum might show micro-structure
  (see e.g. A.A.Sonzogni, et al. arXiv:1710.00092, D. A. Dwyer &T. J. Langford, Phys. Rev. Lett. 114,012502 (2015))
- It might degrade the MH sensitivity by mimicking the periodic oscillation structures



Relative difference of 3 synthetic spectra to spectrum predicted from ILL data (Huber+Mueller model)



of reactor spectrum measurement

→ Need reactor spectrum with energy resolution similar to JUNO

Solution: A JUNO Near Detector

For more information see:

ESCAPE 2018 workshop
Talk by Liang Zhan

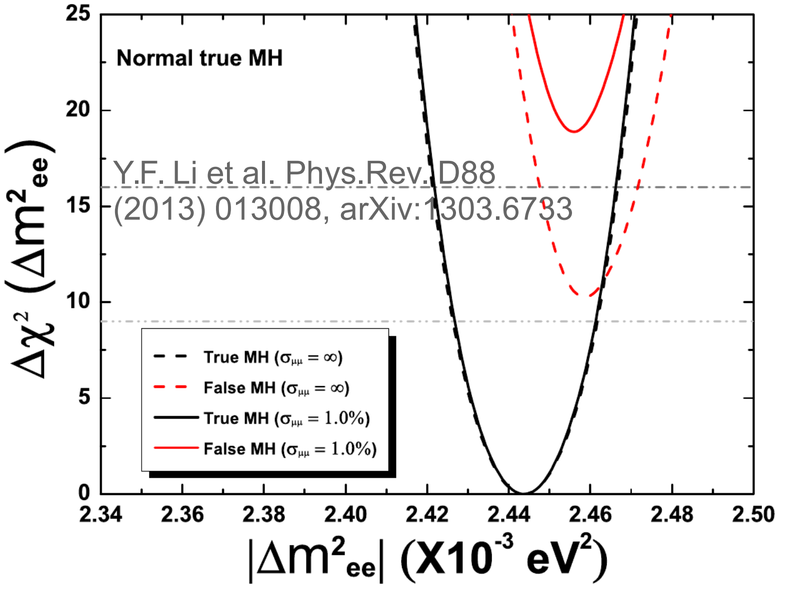
- **Started near detector R&D**
  - 2.9 ton Gd-LS in spherical vessel
  - Outer buffer oil in stainless steel vessel
  - → Central detector size ~ 2 m x 2 m x 2 m
  - → @35 m to reactor (4.6GW): 10x JUNO statistics (6yr) after 1 year

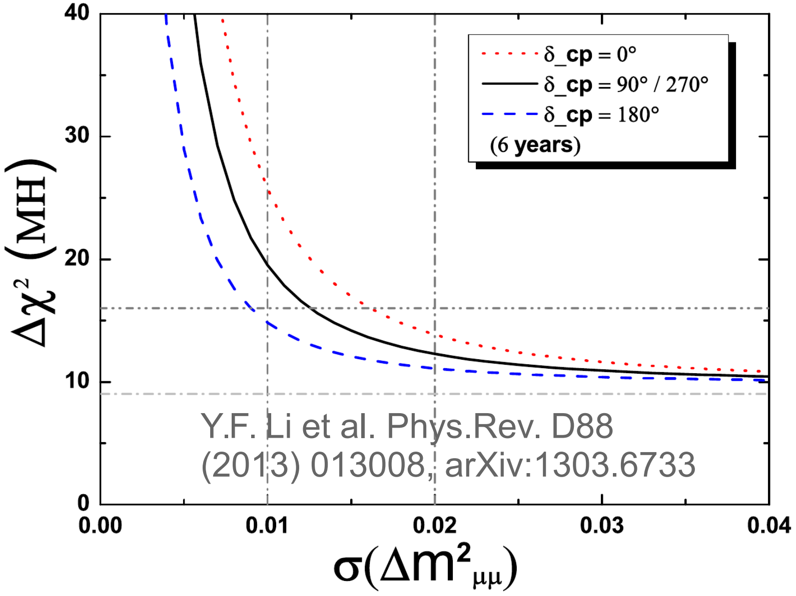
- **Two sensor types under consideration:**
  - SiPM → need -50°C → 1.7% energy resolution
  - 2300 3.5” PMTs → 2.5% energy resolution

- **Additional motivation:**
  - Shed light on reactor spectrum anomaly (5 MeV bump)
  - Serve as benchmark to test nuclear databases

Mass Hierarchy Sensitivity

- **Measurement with or without constraint on $\Delta m^2_{\mu\mu}$**





- **Sensitivity with 100k events (~6 yrs):**
  - No constraint: $\overline{\Delta\chi^2} > 9$
  - With 1% constraint: $\overline{\Delta\chi^2} > 16$
- **Reason for synergy:**

$$|\Delta m^2_{ee}| - |\Delta m^2_{\mu\mu}| = \pm \Delta m^2_{21} \cdot (\cos(2\theta_{12}) - \sin(2\theta_{12}) \sin(\theta_{13}) \tan(\theta_{23}) \cos(\delta))$$

Sign defined by MH

See H. Nunokawa et al, Phys.Rev. D72 (2005) 013009

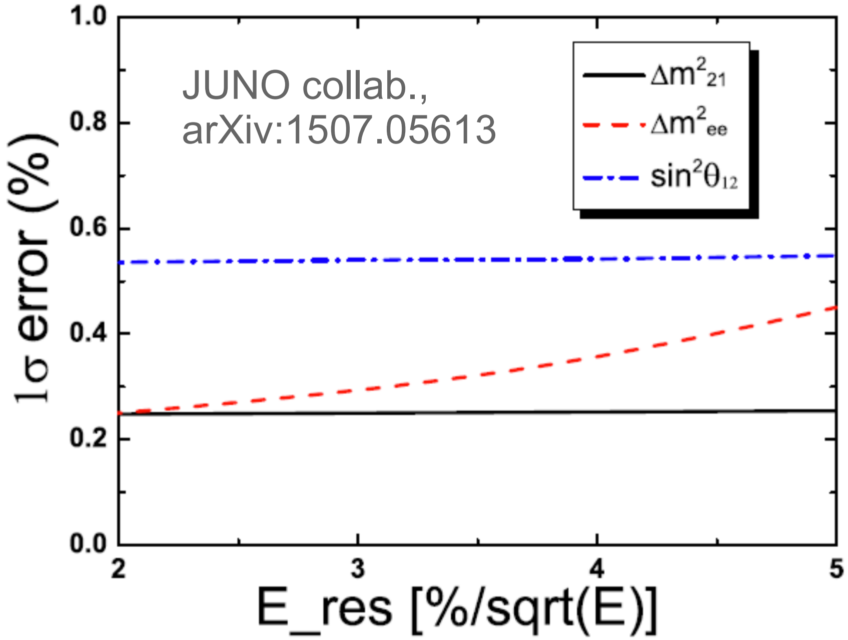
Precision Measurement of Oscillation Parameters

	Δm^2_{21}	$\sin^2\theta_{12}$	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$
Dominant experiment	KamLAND	SNO	T2K & NOvA /Daya Bay	Daya Bay	T2K
Individual 1σ	2.4%	6.7%	3.2%/3.5%	4.0%	9.8%
Global 1σ *	2.2%	3.9%	1.2%	3.4%	5%
JUNO expected 1σ	**0.6%**	**0.7%**	**0.4%**	**~15%**	**-**

Δm^2_{ee}

- Sub-percent accuracy warranted for θ_{12}, Δm^2_{21} & Δm^2_{ee}
- Complementary to long-baseline experiments

  (precision measurement of θ_{23}, θ_{13} & Δm^2_{31})



* For global fits see e.g. F. Capozzi et. al., arXiv:1804.09678 or I. Esteban et al., JHEP 01 (2017) 087 / NuFIT 3.2 (2018), www.nu-fit.org

Other Physics with JUNO

- **JUNO will be an exceptional detector**

	KamLAND	Borexino	Daya Bay	JUNO
Mass [t]	~1000	~300	~170	20000
Light yield [p.e./MeV]	250	500	200	1200
Energy resolution	6%/√E	5%/√E	7.5%/√E	3%/√E
Energy calibration	1.4%	1%	1%	< 1%

→ Rich additional physics program:

- Supernova ν
- Diffuse supernova ν
- Geo-neutrinos
- Solar ν
- Proton decay
- Atmospheric ν
- Sterile ν
- Indirect dark matter searches
- Other exotic searches

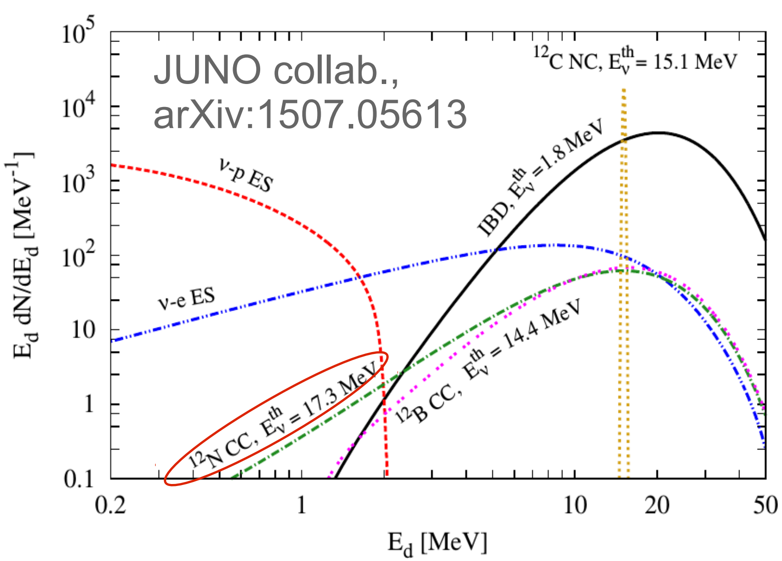
Supernova Neutrinos in JUNO

- **Core-collapse SN at 10kpc**
- **Opens new physics window:**
  - Test SN models
  - Information about MH
  - Multi-messenger astronomy
  - ...

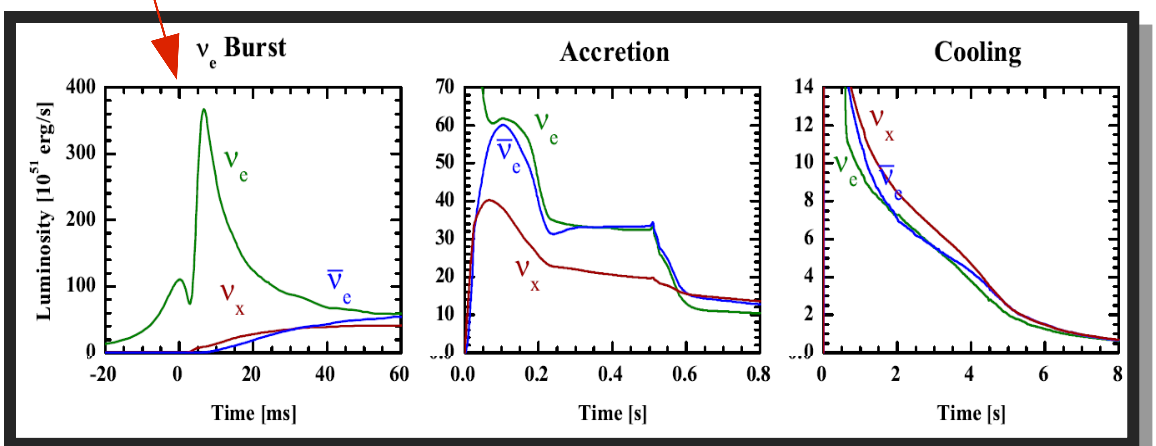
Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \rightarrow e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \rightarrow \nu + p$	NC	0.6×10^3	1.2×10^3	2.0×10^3
$\nu + e \rightarrow \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}\mathrm{C} \rightarrow \nu + {}^{12}\mathrm{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}$	CC	0.5×10^2	0.9×10^2	1.6×10^2
$\overline{\nu}_e + {}^{12}\mathrm{C} \rightarrow e^+ + {}^{12}\mathrm{B}$	CC	0.6×10^2	1.1×10^2	1.6×10^2

JUNO collab., arXiv:1507.05613

Huge statistics + Flavour information



Energy spectrum



JUNO collab.,arXiv:1507.05613, based on: L. Hüdepohl, PhD Thesis, TU Munich (2013), A. Mirizzi et. al., arXiv:1508.00785

Time evolution

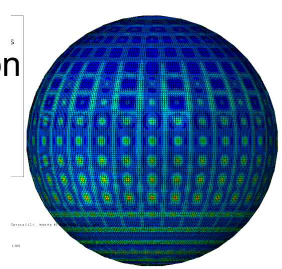
Milestones & Schedule

2014:

- International collaboration established

2015:

- PMT production line setup
- CD parts R&D
- Start civil construction



2016:

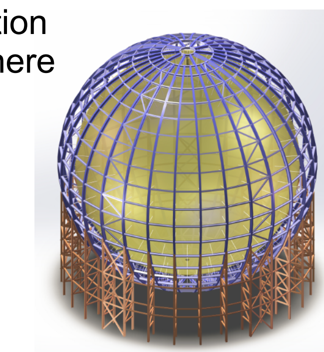
- Start PMT production
- Start CD parts production

2017:

- Start PMT testing
- TT arrived

2018:

- PMT potting starts
- Delivery of surface buildings
- Start production of acrylic sphere

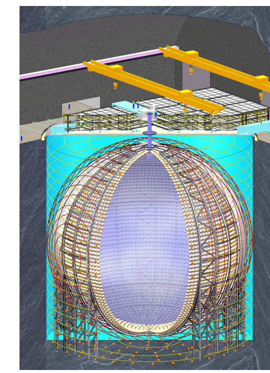


2019-2020:

- Electronics production starts
- Civil work and lab preparation completed;
- Detector constructing

2021:

- Detector ready
- Data taking!



Summary

- **JUNO → Unique physics instrument**
- **MH sensitivity:** $\overline{\Delta\chi^2}>9$ ($\overline{\Delta\chi^2}>16$ with 1% constraint on $\Delta m^2_{\mu\mu}$)
  - Strong synergy with long-baseline ν program
- **Sub-percent measurement of θ_{12}, Δm^2_{21} & Δm^2_{ee}**
  - Complementary to long-baseline ν program
- **Rich additional physics program**
- **Very active R&D program**
  - Will achieve design goals
- **Data taking will start in 2021**
- **Started near detector R&D**
  - Energy resolution < 3%

List of Posters

Monday Session, Poster Wall #175 (Ballroom)
ASAVAPIBHOP, Burin (Chulalongkorn University)
SUWONJANDEE, Narumon (Chulalongkorn University)
Earth Magnetic Field Compensation Coils System for JUNO

Monday Session, Poster Wall #183 (Ballroom)
ATHAYDE MARCONDES DE ANDRÉ, João Pedro (IPHC/CNRS/IN2P3)
The Top Tracker detector of the JUNO Experiment

Monday Session, Poster Wall #157 (Ballroom)
CAO, Guofu (Institute of High Energy Physics)
Introduction to Monte Carlo Simulation at JUNO

Monday Session, Poster Wall #186 (Ballroom)
CHENG, Yaping (FZJ IKP2)
GNA fitter and Detector response impact on MH sensitivity study

Monday Session, Poster Wall #91 (Auditorium Gallery Left)
DEPNERING, Wilfried (JGU Mainz)
A Liquid Scintillator Transparency monitoring Laser System for JUNO

Monday Session, Poster Wall #174 (Ballroom)
ENZMANN, Heike (Johannes Gutenberg-Universität, Mainz)
attenuation length monitor for the JUNO filling system

Monday Session, Poster Wall #181 (Ballroom)
GUO, Cong (Institute of High Energy Physics)
The water system and radon measurement system of JUNO veto detector

Monday Session, Poster Wall #204 (Ballroom)
HAN, Ran (BISEE)
Potential of geo-neutrino measurements at JUNO and the Local 3D model

Monday Session, Poster Wall #107 (Auditorium Gallery Left)
HAN, Yang (Lab APC, Paris)
Stereo Calorimetry in JUNO: Physics Motivation and Instrumentati on

Monday Session, Poster Wall #105 (Auditorium Gallery Left)
HU, Bei-Zhen (National Taiwan University)
The 3-inch PMTs of the JUNO experiment

Monday Session, Poster Wall #190 (Ballroom)
LU, Haoqi (Institute of High Energy Physics,CAS)
WANG, Ruiguang (Institute of High Energy Physics, CAS)
Water Cherenkov detector of the JUNO Veto System

Monday Session, Poster Wall #170 (Ballroom)
QIN, ZHONGHUA (Institute of High Energy Physics, China)
the 20-inch PMT instrumentation for the JUNO experiment

Monday Session, Poster Wall #200 (Ballroom)
SCHEVER, Michaela (Forschungszentrum Juelich GmbH)
Waveform Reconstruction of IBD and Muon Events in JUNO

Monday Session, Poster Wall #185 (Ballroom)
SISTI, Monica (University and INFN of Milano-Bicocca)
Radioactive background control for the JUNO experimental setup

Monday Session, Poster Wall #182 (Ballroom)
STEIGER, Hans Th. J. (TUM)
The Filling System Slow Control for JUNO

Monday Session, Poster Wall #176 (Ballroom)
TIETZSCH, Alexander (Uni Tübingen)
WONSAK, Björn (UniHH)
The PMT Mass Testing System for JUNO

Monday Session, Poster Wall #163 (Ballroom)
WANG, Zhimin (Institute of High Energy phisics, CAS)
The study of JUNO CD with a prototype detector

Monday Session, Poster Wall #177
WONSAK, Björn (UniHH)
3D Topological Reconstruction for the JUNO Detector

Monday Session, Poster Wall #179 (Ballroom)
ZHANG, Haiqiong (IHEP)
Tested Performance of JUNO 20"PMTs

Wednesday Session, Poster Wall #36 (Auditorium Gallery Right)
DING, Xuefeng (Gran Sasso Science Institute)
Clusterization algorithm for sub-MeV events reconstruction in J UNO

Wednesday Session, Poster Wall #11 (Robert-Schumann-Room)
JEN, Kuo-Lun (National Chiao Tung University)
Simulation Studies on Supernova Neutrino Detections in JUNO

Wednesday Session, Poster Wall #4 (Robert-Schumann-Room)
LI, Huiling (Shandong University)
Towards a complete reconstruction of supernova neutrino spectra in future large liquid-scintillator detectors

JUNO Collaborators

APC, CNRS, FRANCE

BEIJING NORMAL UNIVERSITY 1902

CASC 中国航天

CENBG

CHONGQING UNIVERSITY 1929

Chulalongkorn University
จุฬาลงกรณ์มหาวิทยาลัย
Pillar of the Kingdom

EAST CHINA UNIVERSITY OF SCIENCE AND TECHNOLOGY

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

IPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM

DONGGUAN UNIVERSITY OF TECHNOLOGY

UNIVERSITAS COMENIANA BRATISLAVENSIS MCMXIX

JÜLICH FORSCHUNGSZENTRUM

UH Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

HIT 1920

ELEKTRONIKAS UN DATORZINĀTŅU INSTITŪTS
INSTITUTE OF ELECTRONICS AND COMPUTER SCIENCE

Chinese Academy of Geological Sciences

AE

JILIN UNIVERSITY CHINA 1946

NATIONAL UNIVERSITY OF DEFENSE TECHNOLOGY 1953

Institute of High Energy Physics
Chinese Academy of Sciences

IMP

JINR

Joint Institute for Nuclear Research
SCIENCE BRINGING NATIONS TOGETHER

INFN

PONTIFICIA UNIVERSIDAD CATÓLICA DE CHILE

JINAN UNIVERSITY 1906

NANKAI UNIVERSITY 1919

Lomonosov Moscow State University

NARIT

PUC RIO

NORTH CHINA ELECTRIC POWER UNIVERSITY

NANJING UNIVERSITY 1902

TSINGHUA UNIVERSITY 1911

CHINESE ACADEMY OF SCIENCES

NATIONAL UNITED UNIVERSITY

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Pakistan Institute of Nuclear Science & Technology ISLAMABAD

北京大学物理学院
School of Physics, Peking University

SUN YAT-SEN UNIVERSITY

UNIVERSITAS AMOIENSIS

University of Science and Technology of China 1958

UNIVERSITY OF SOUTH CHINA

SHANDONG UNIVERSITY 1901 山东大学

SHANGHAI JIAO TONG UNIVERSITY 1896

cnrs IN2P3 Les deux infinis

RWTH AACHEN UNIVERSITY

มหาวิทยาลัยเทคโนโลยีสุรนารี

TUM

WUHAN UNIVERSITY

ULB UNIVERSITÉ LIBRE DE BRUXELLES

UNIVERSITY OF MARYLAND 1856

EX UMBRA IN SOLEM

ZHENGZHOU UNIVERSITY 郑州大学

西安交通大學 XI'AN JIAOTONG UNIVERSITY

WUYI UNIVERSITY

A. ALIKHANYAN National Laboratory

Universidade Estadual de Londrina

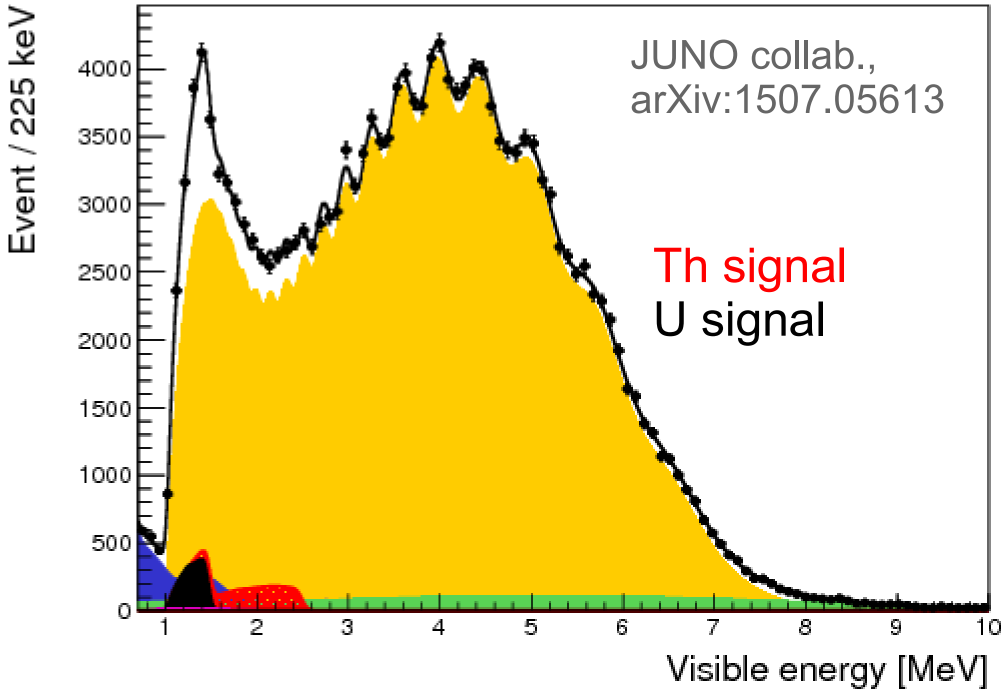
Backup Slides

Geo-Neutrinos in JUNO

- **Exploring origin and thermal evolution of the Earth**
- **Uncertainty on flux:** 17% (1 yr) / 6% (10 yr) U/TH ratio fixed
- **For comparison:**
  - KamLAND 14.3±4.4 evts PLB 722 (2013) 295
  - Borexino 116+28-27 evts PRD 88 (2013) 033001

- **Uncertainty for U/TH flux:**
  - U: 11% (JUNO 10 yr)
  - Th: 24% (JUNO 10yr)

JUNO10 year free U/TH-ratio



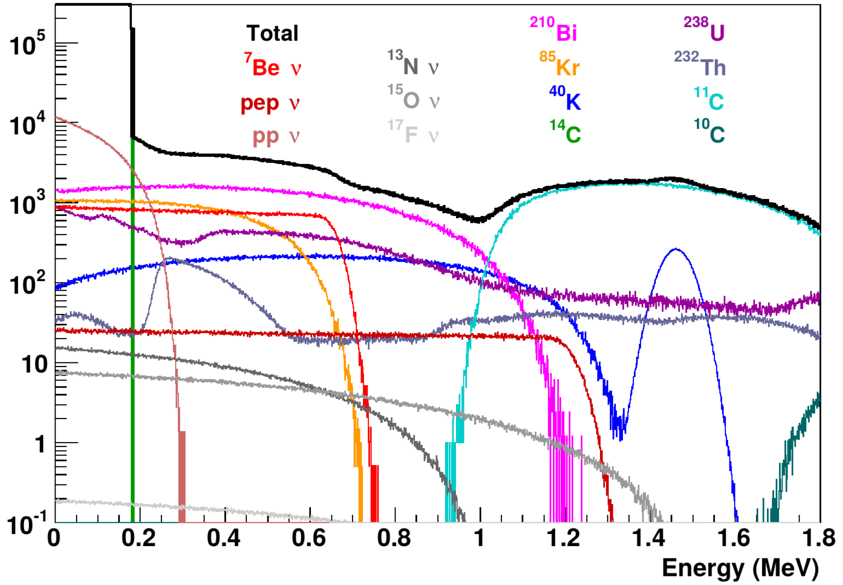
Solar Neutrinos

- **Main challenge:**
  - Radio-purity
  - Cosmogenic background, e.g. long living spallation ^{11}C
- **Potential:**
  - ^{7}Be and low tail ^{8}B (large mass)
  - Discriminate pp from ^{14}C (energy resolution)

Internal radiopurity requirements		
	baseline	ideal
^{210}Pb	5×10^{-24} [g/g]	1×10^{-24} [g/g]
^{85}Kr	500 [counts/day/kton]	100 [counts/day/kton]
^{238}U	1×10^{-16} [g/g]	1×10^{-17} [g/g]
^{232}Th	1×10^{-16} [g/g]	1×10^{-17} [g/g]
^{40}K	1×10^{-17} [g/g]	1×10^{-18} [g/g]
^{14}C	1×10^{-17} [g/g]	1×10^{-18} [g/g]
Cosmogenic background rates [counts/day/kton]		
^{11}C	1860	
^{10}C	35	
Solar neutrino signal rates [counts/day/kton]		
pp ν	1378	
^{7}Be ν	517	
pep ν	28	
^{8}B ν	4.5	
^{13}N/^{15}O/^{17}F ν	7.5/5.4/0.1	

KamLAND-like Borexino-like

JUNO collab., arXiv:1507.05613

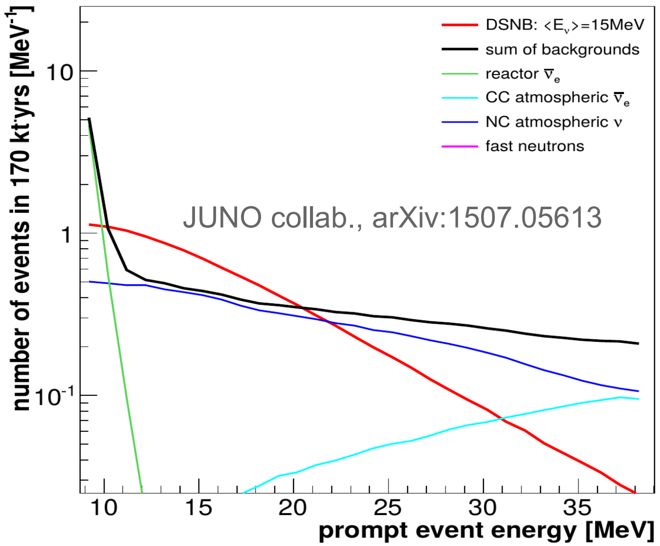


Baseline background

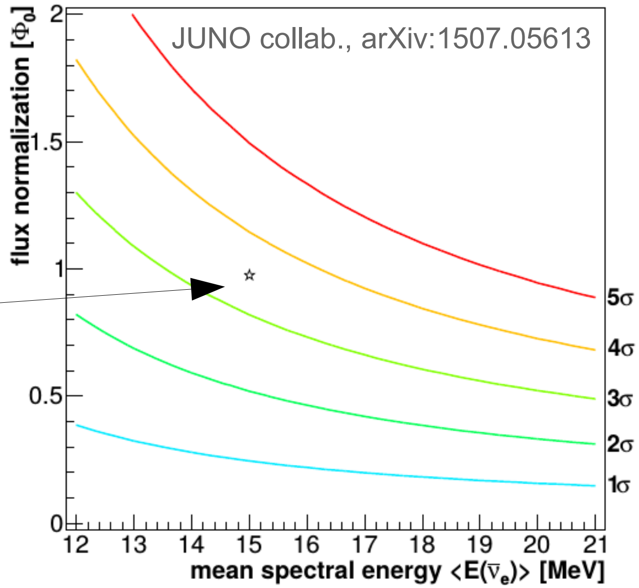
Diffuse Supernova Neutrinos

- **Combines Neutrino signal of past SN**
- **Encoded information:**
  - Star formation rate
  - Average core-collapse neutrino spectrum
- **Advantage JUNO:** Pulse-shape discrimination

  → 3σ conceivable after 10 yr

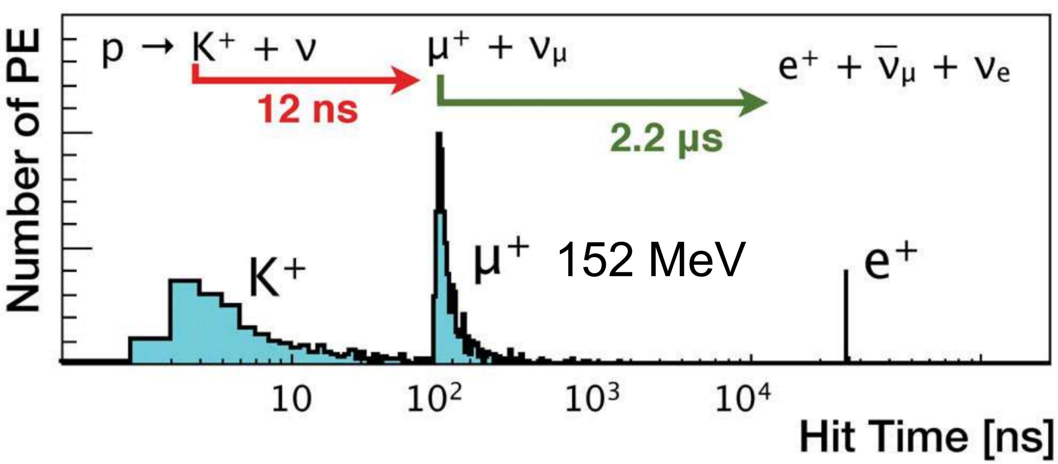


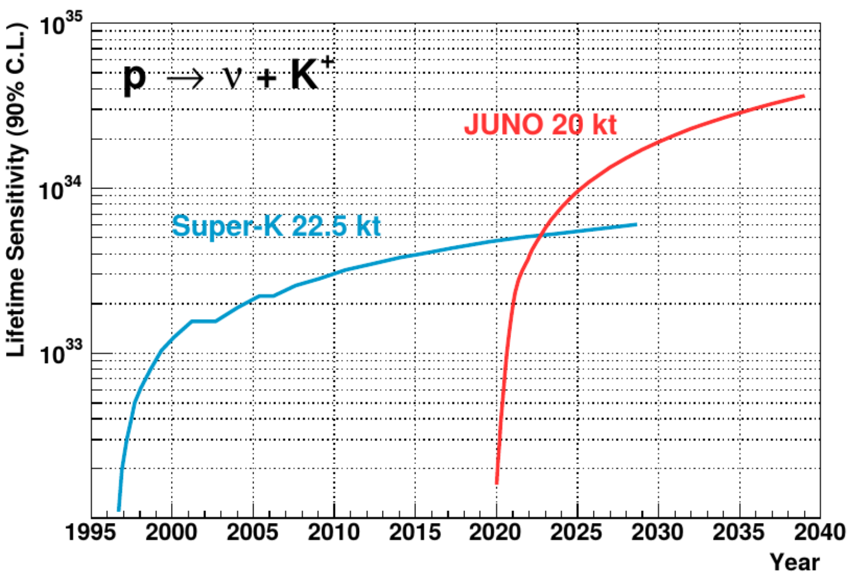
Typical DSNB parameters



Proton Decay

- A prompt signal from K + and a delayed signal from its decay daughters with a time coincidence of 12 ns.
- Both the prompt and delayed signals have well-defined energies.
- There is one and only one decay positron with a time coincidence of 2.2 μs from the prompt signals.





Reactor Flux Spectrum Uncertainty

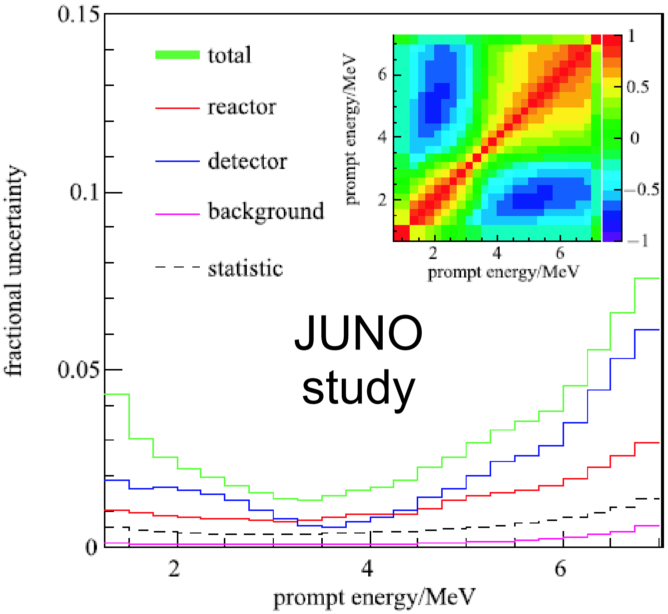
F. Capozzi, E. Lisi, A. Marrone, PRD92, 093001 (2015)

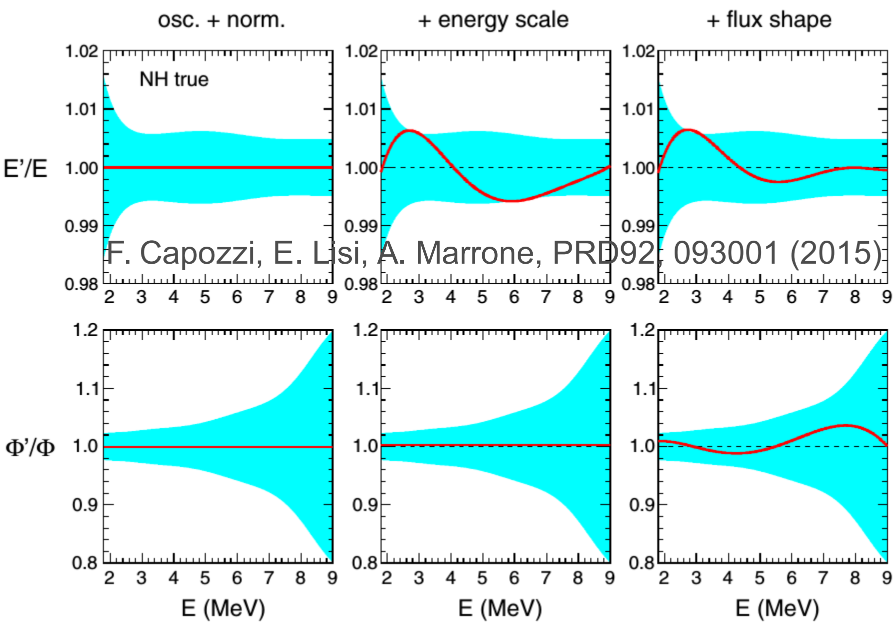
- **Smooth deformation of energy scale & reactor flux shape**

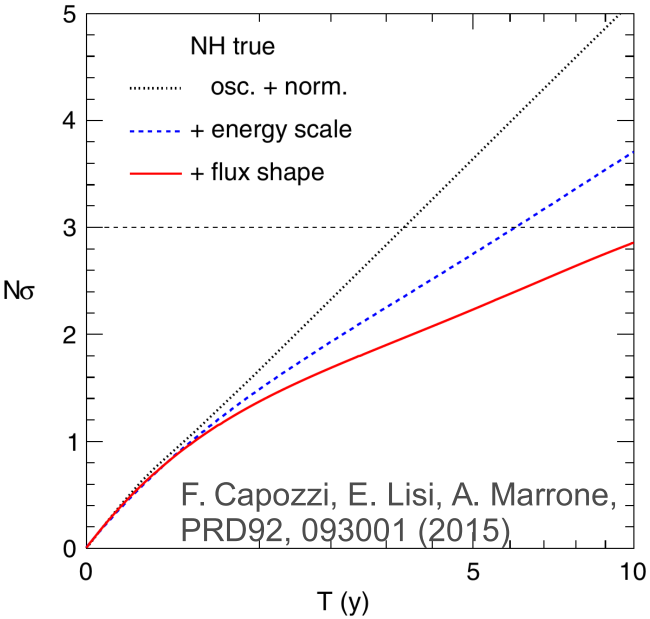
  → Significant effect on MH sensitivity

- **We found:**
  - Uncertainty of energy scale and the measured reactor flux shape are strongly correlated

- **Near detector will help**





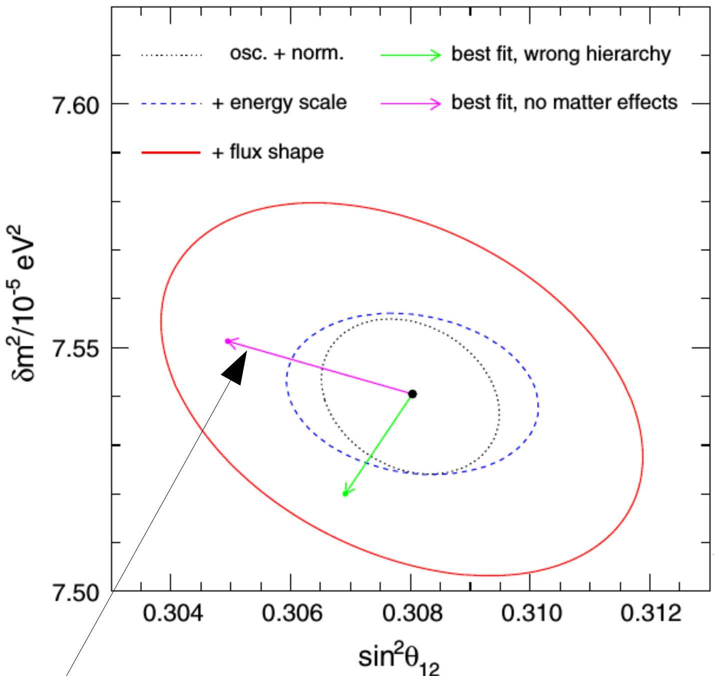


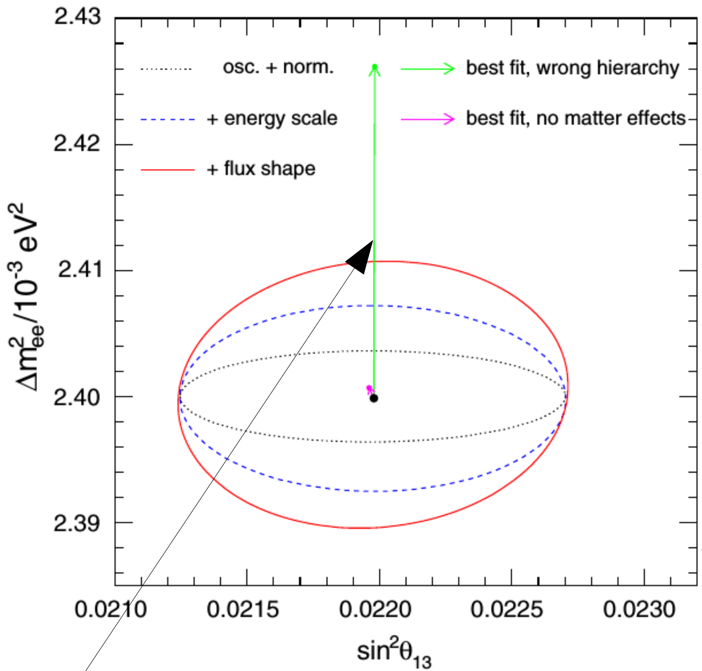
Flux Shape & Precision Measurement

F. Capozzi, E. Lisi, A. Marrone, PRD92, 093001 (2015)

- **Flux shape also has large impact**
- **2% prior on Δm^2_{ee}**

→ Results better than our official ones (unconstrained)





Matter effects become important!

Synergy to $\Delta m^2_{\mu\mu}$ visible

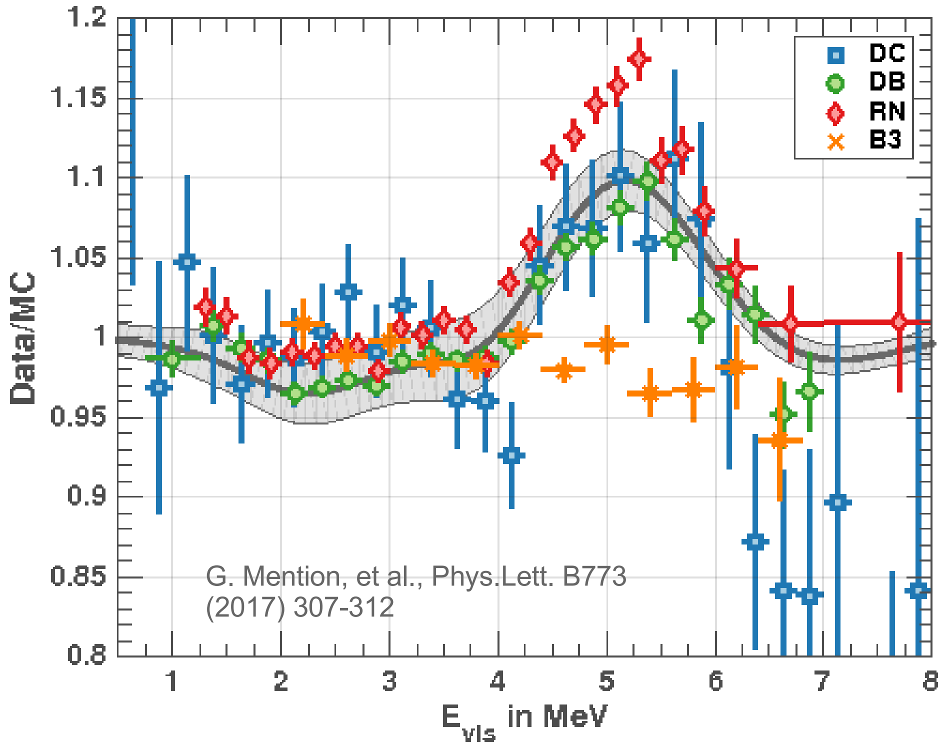
5 MeV Bump and Calibration

- **Many different possible explanations in literature:**
  - Deviation/distortion of energy scale G. Mention, et al., Phys.Lett. B773 (2017) 307-312
  - Missing β-decays e.g.: A.A.Sonzogni, et al. arXiv:1710.00092
  - ...

- **Effects seems reproducible**

  → Can be calibrated

- **Will not affect JUNO MH**



Effective Mass-Squared Differences

- ν_e and ν_μ disappearance experiments measure different effective atmospheric mass-squared differences

$$\Delta m^2_{ee} \simeq \cos^2(\theta_{12}) \cdot \Delta m^2_{31} + \sin^2(\theta_{12}) \cdot \Delta m^2_{32}$$

$$\Delta m^2_{\mu\mu} \simeq \sin^2(\theta_{12}) \cdot \Delta m^2_{31} + \cos^2(\theta_{12}) \cdot \Delta m^2_{32} + \sin(2\theta_{12}) \sin(\theta_{13}) \tan(\theta_{23}) \cos(\delta) \cdot \Delta m^2_{21}$$

- With precision measurements of Δm^2_{ee} and $\Delta m^2_{\mu\mu}$, the difference

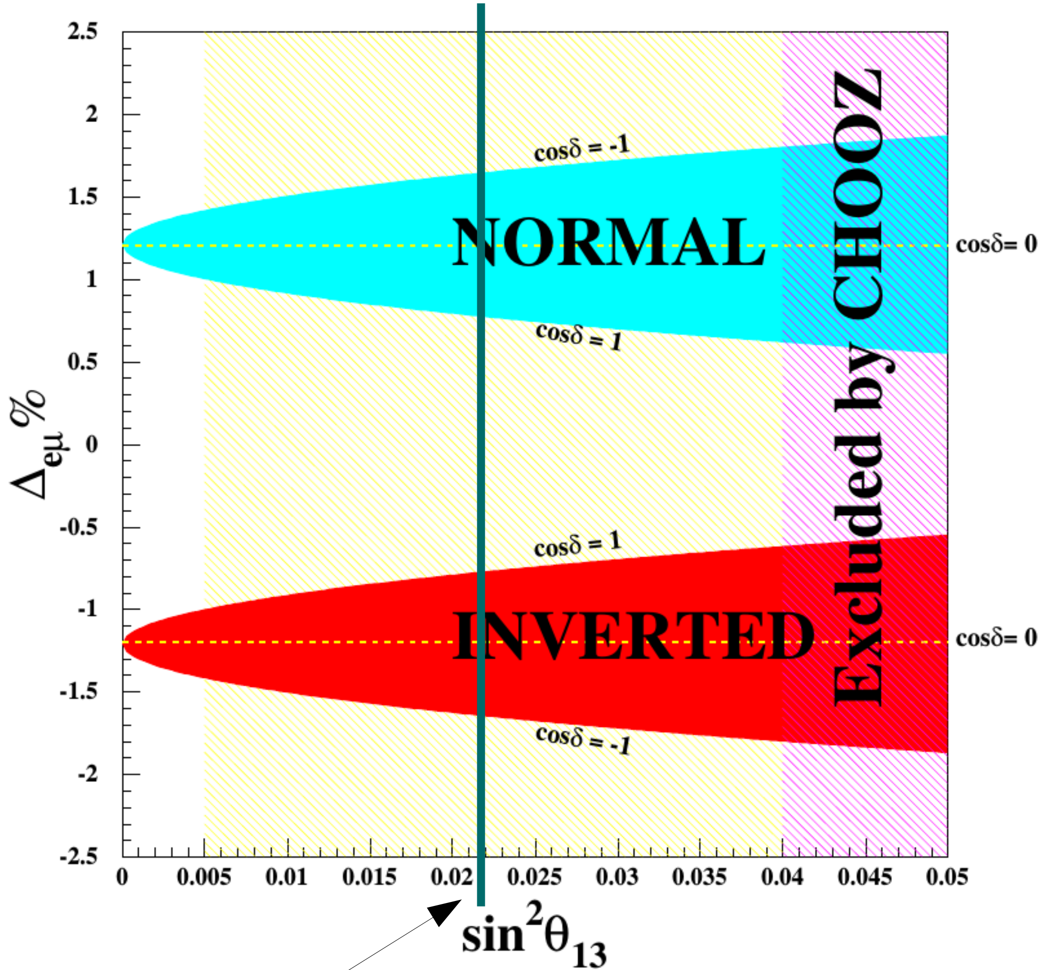
$$|\Delta m^2_{ee}| - |\Delta m^2_{\mu\mu}| = \pm \Delta m^2_{21} \cdot (\cos(2\theta_{12}) - \sin(2\theta_{12}) \sin(\theta_{13}) \tan(\theta_{23}) \cos(\delta))$$

(+: NH, -: IH) allows to determine the MH and possibly even cosδ at high precision of Δm^2_{ee} and $\Delta m^2_{\mu\mu}$

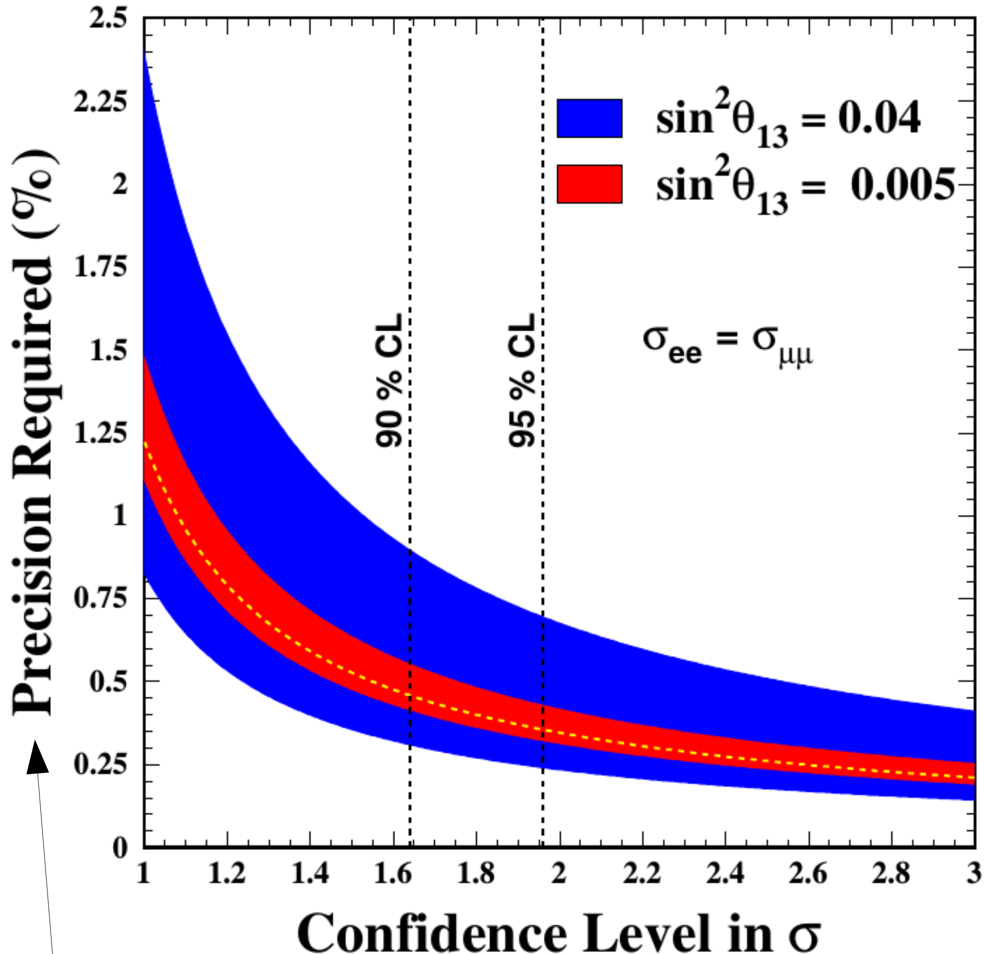
H. Nunokawa et al, Phys.Rev. D72 (205) 013009

Reason for Synergy

H. Nunokawa et al, Phys.Rev. D72 (2005) 013009



Current global best fit



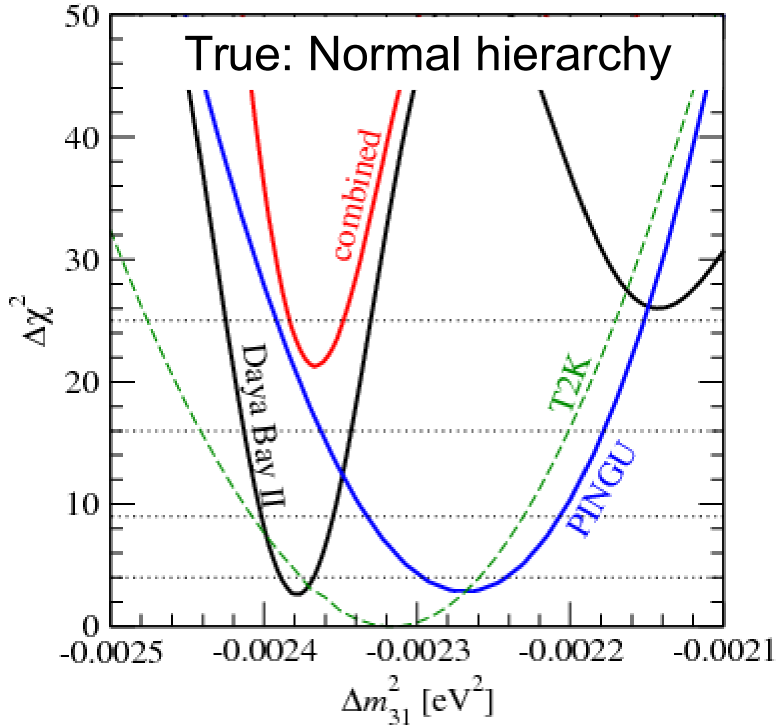
on $\Delta_{e\mu}$ (difference of both effective mass splittings)

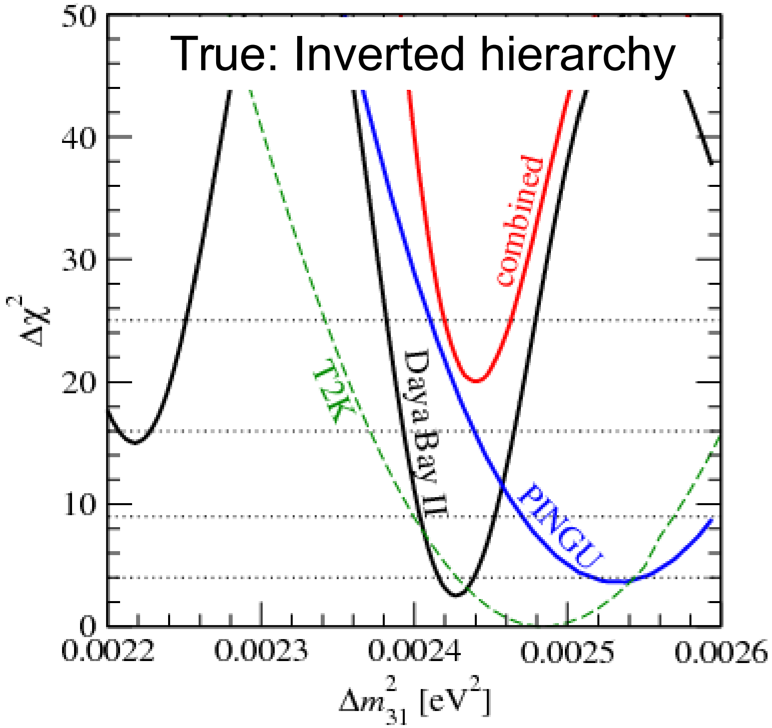
Complementarity to other Experiments

- Different systematics compared to MH from matter effects
  → Combined analysis very effective

$$\Delta \chi^2_{Combined} \approx \Delta \chi^2_{JUNO,\,min} + \Delta \chi^2_{Atm,\,min} + \frac{\left(|\Delta m^2_{31,\,JUNO}| - |\Delta m^2_{31,\,Atm}|\right)}{\sigma^2_{JUNO} + \sigma^2_{Atm}}$$

Synergy term





M. Blennow and T. Schwetz., JHEP 1309 (2013) 089

Statistical Significance

- **Test between two discrete hypotheses**
- **Two consequences:**
  - $\Delta\chi^2$ cannot be interpreted in normal way
    → Need additional "estimator" to get significance
  - Also need to know statistical power

$\Delta\chi^2$ still good to compare experiments & study systematic effects

	Median sens.	Standard sens.	Crossing sens.
Normal MH	3.4 σ	3.3 σ	1.9 σ
Inverted MH	3.5 σ	3.4 σ	1.9 σ

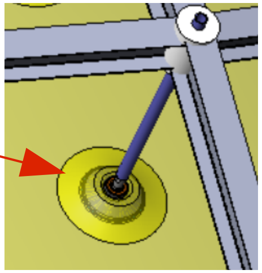
- **Could also be a chance**
  - Use 'tailored' estimator instead of χ^2
    → Can lead to better significance

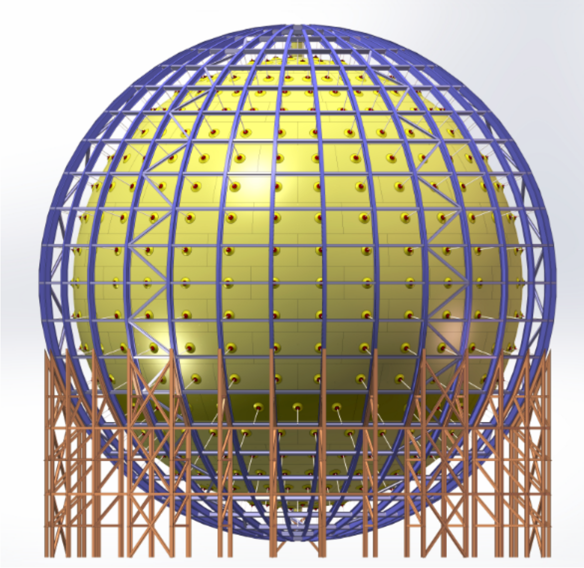
See L.Stanco, et al., arXiv:1707.07651

Acrylic Sphere & Steel Truss

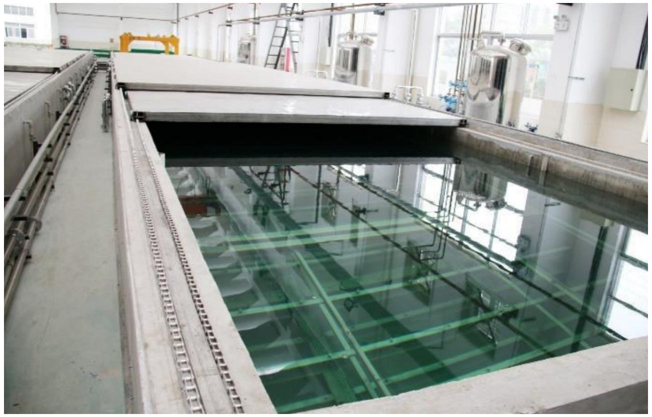
- **Engineering & design completed**
  - 265 acrylic sheets (12 cm thick)
  - ~600 connection nodes
  - 1200 tons of weight

  (Rigorous radioactivity control)

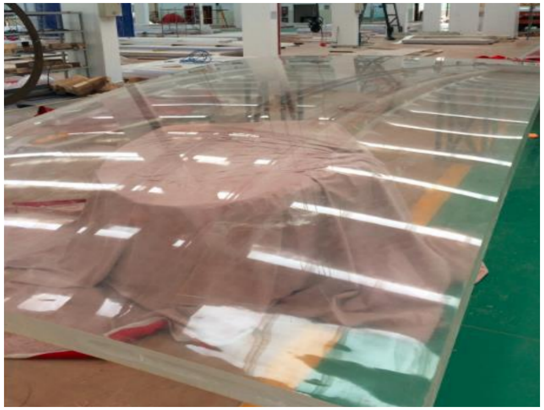




- **Bidding finished and contract signed**
- **Mass production of acrylic sheets under preparation**



water pool for acrylic polymerization

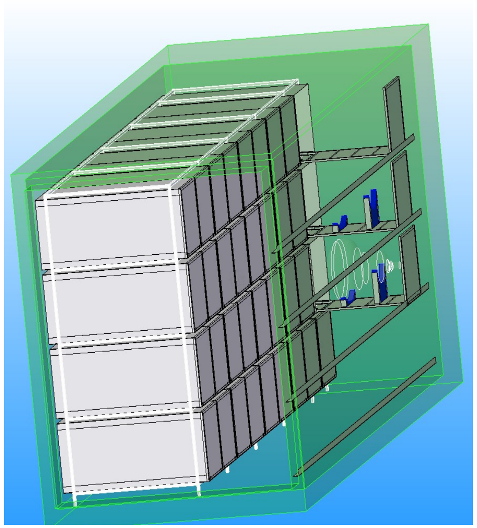


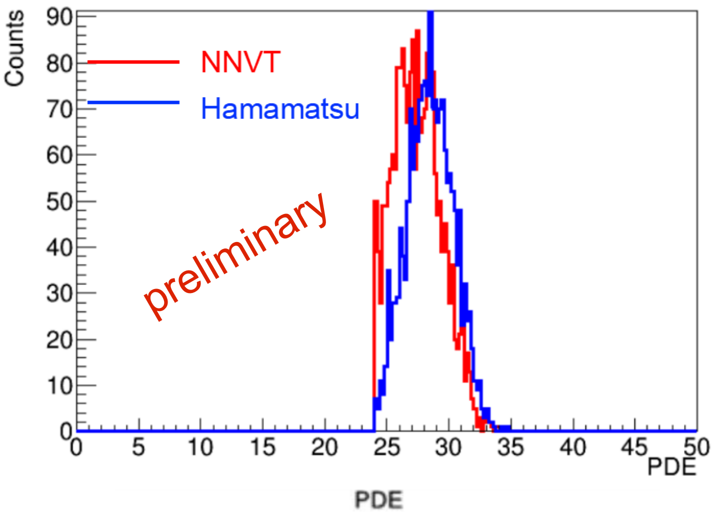
thermal bending

Meticulous PMT Quality Control

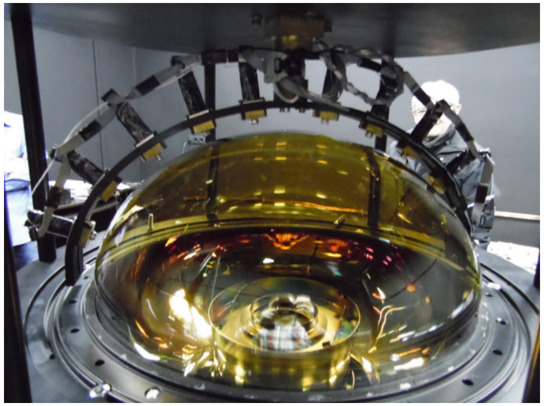
- **Every PMTs will be fully characterized**
- **More than 5000 PMT already tested**

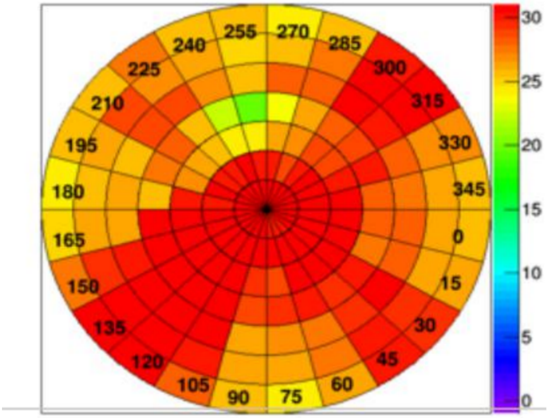
Container-based mass test
→ all PMTs





Scanning station
→ 5-10% of PMTs





Average photon detection efficiency > 27% !

Self-Calibration in JUNO

Have a lot of peaks induced by Δm^2_{ee}

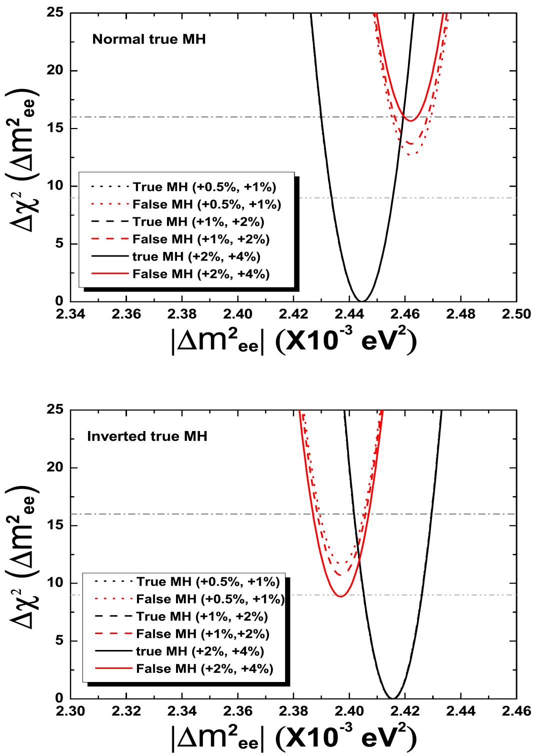
→ Redundancy allows to measure at different energies

→ Do not need true energy scale

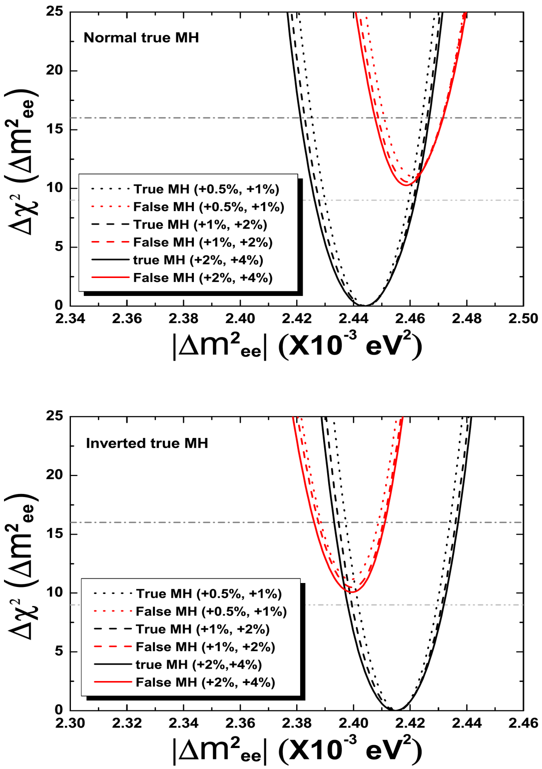
→ Can leave non-linearity as fit-parameters → Relative calibration within the detector (cannot get constant term)

Need absolute calibration to use constraints from other experiments

→ Calibration must be as good as quality of constraints



Sensitivity **without** self-calibration



Sensitivity **with** self-calibration

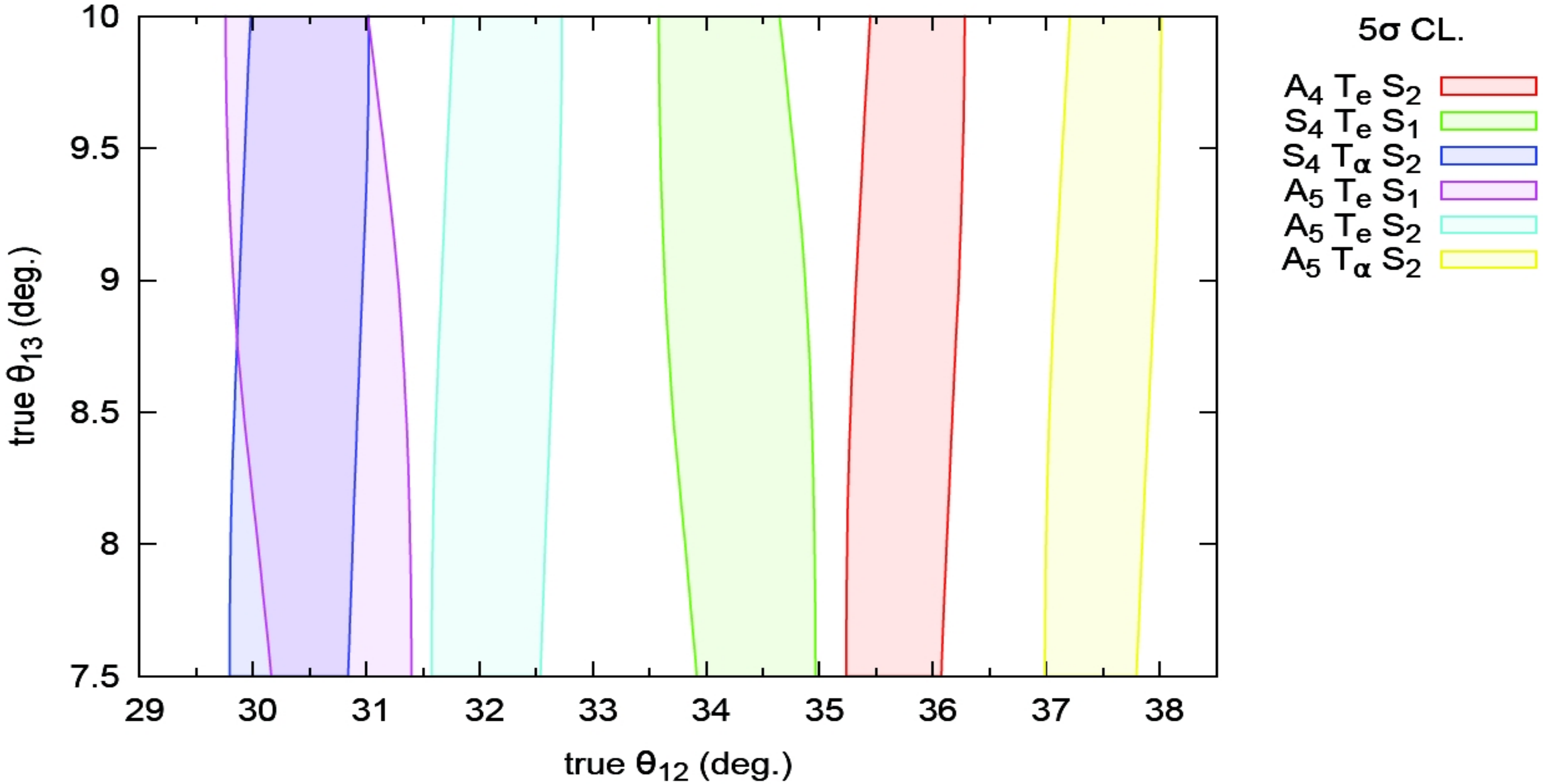
Form of detector non-linearity in fit

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

Y.F. Li et al., Phys.Rev. D88 (2013) 013008

Motivation for Precision

5σ allowed regions for solar predictions of JUNO (after 6 years)

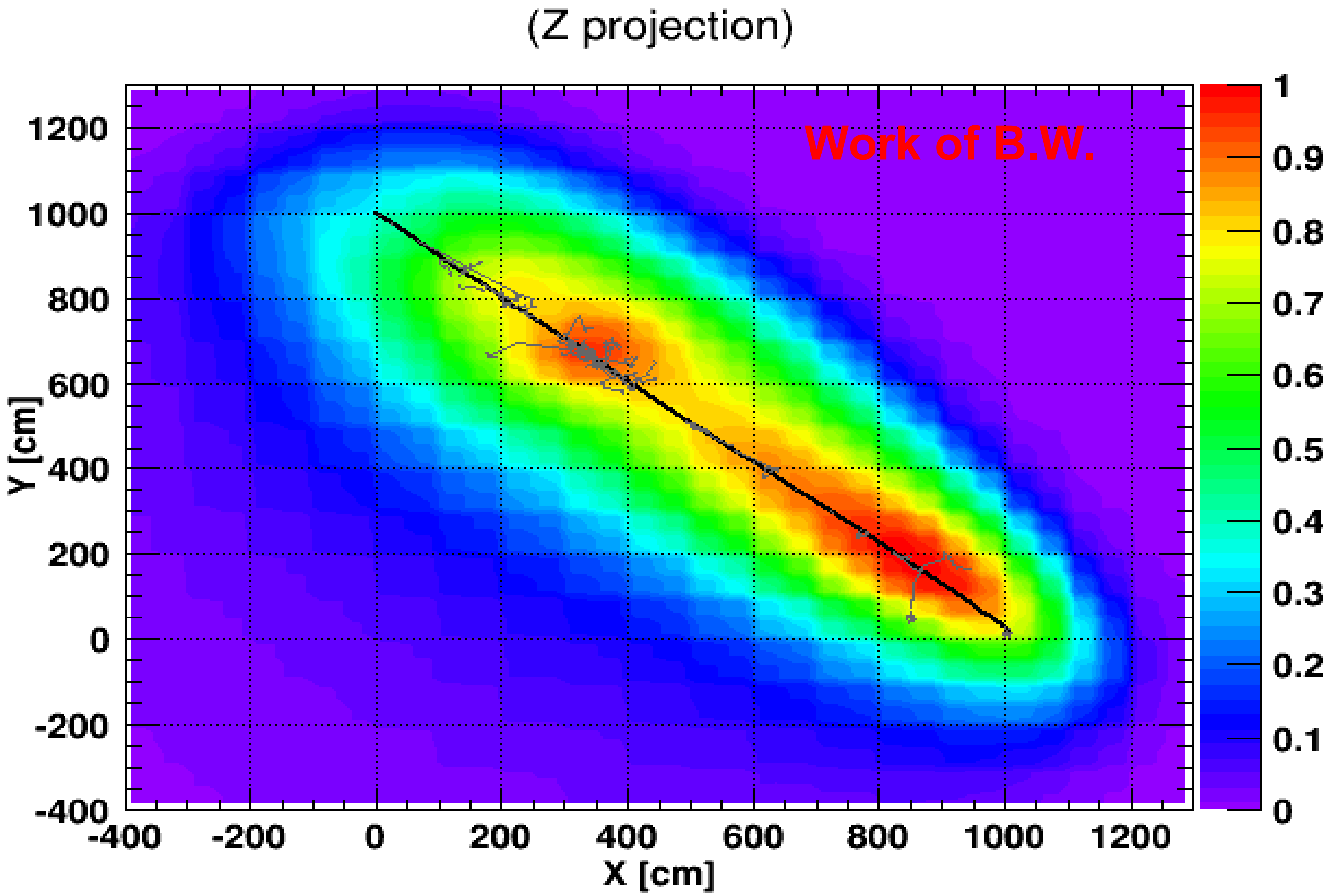


P. Ballet, S.F. King, C. Luhn, S. Pascoli and M.A. Schmidt: arXiv:1406.0308

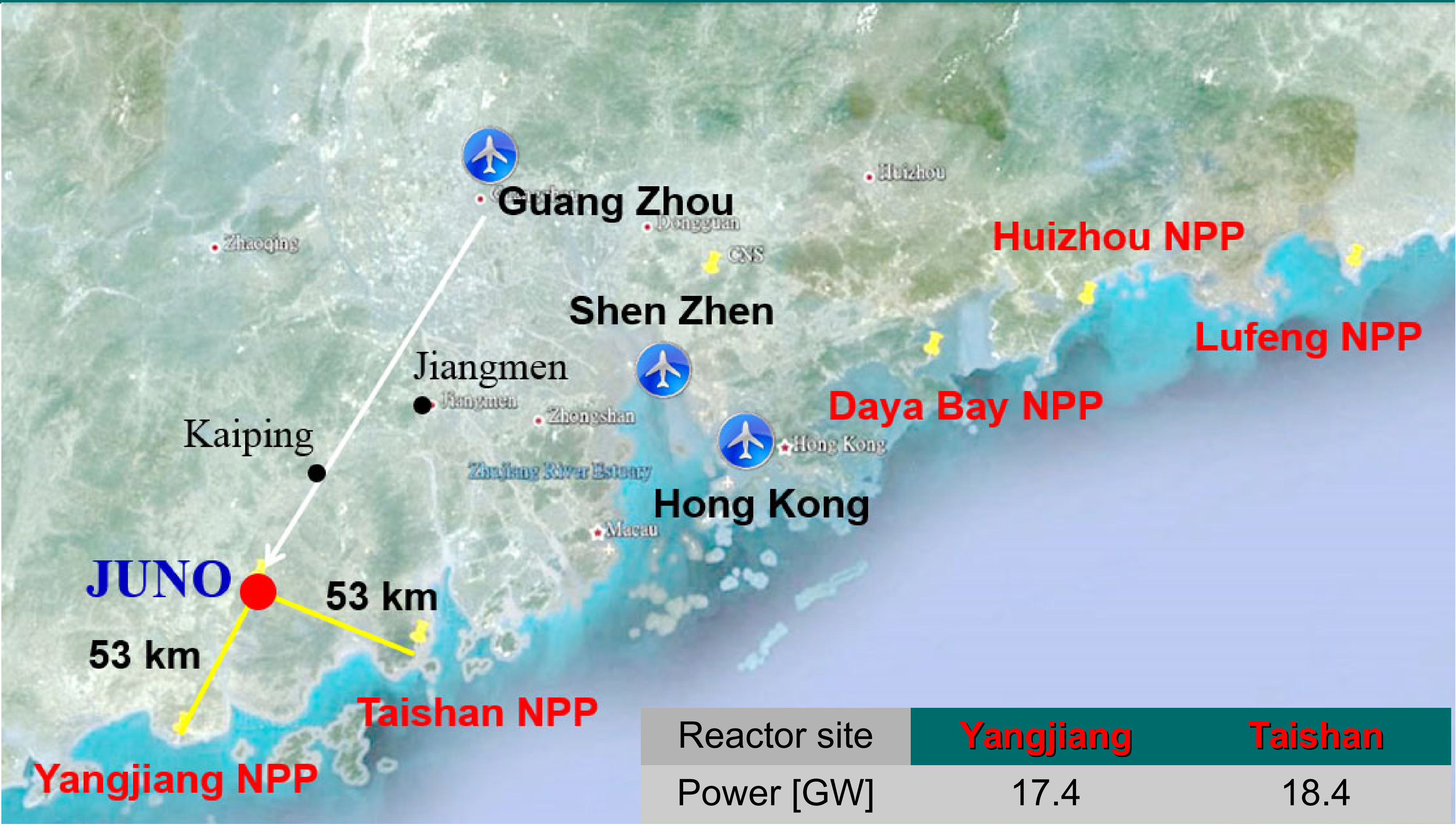
Only one example!

My Work: Tracking

- Developing **3d topological tracking**
- Only input: Vertex position and time
- dE/dx accessible



JUNO Site

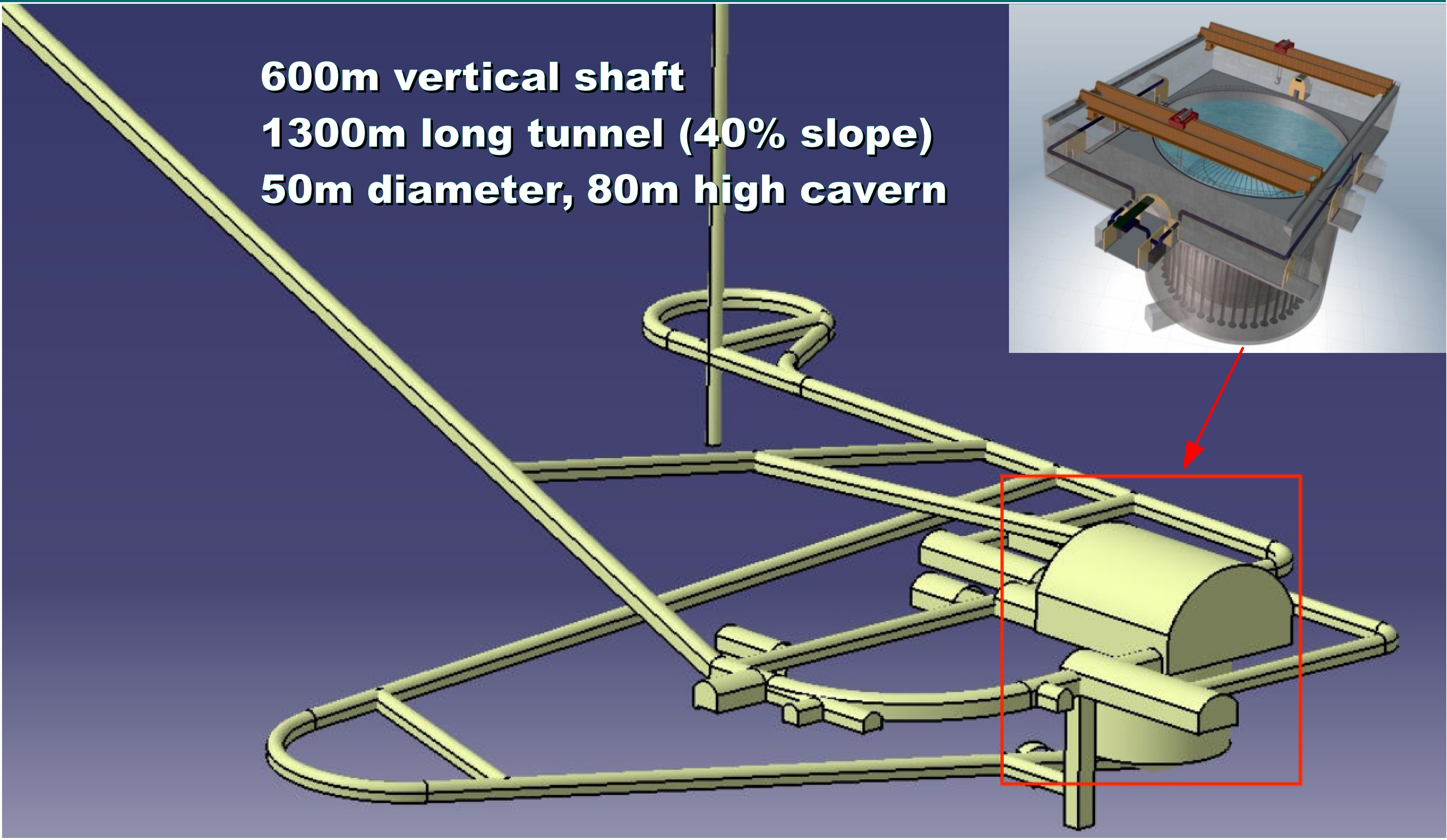


Reactor site	Yangjiang	Taishan
Power [GW]	17.4	18.4

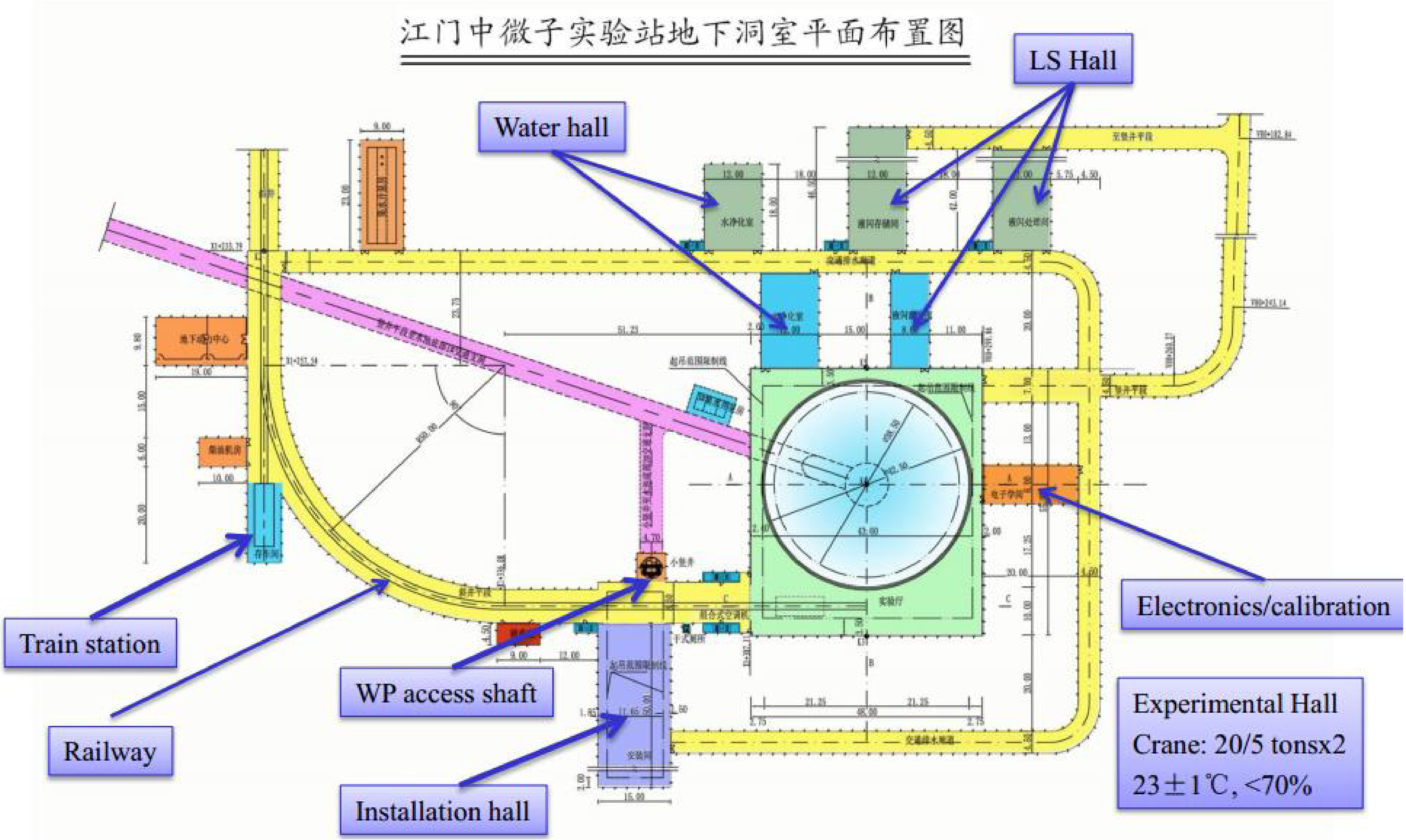
Civil Construction

Jiangmen Underground Laboratory

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



Detector Hall

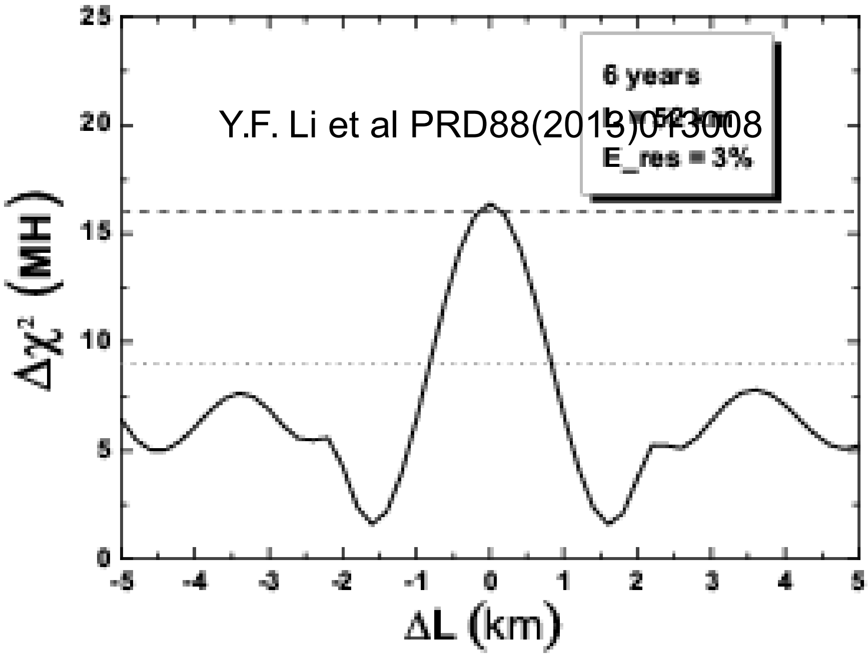


Baseline Optimisation

- Baseline varies between different reactor cores
- Shift of half an oscillation length

  → Oscillation cancels
- → optimisation of baseline

  → difference <= 500m



Y.F. Li et al PRD88(2013)013008

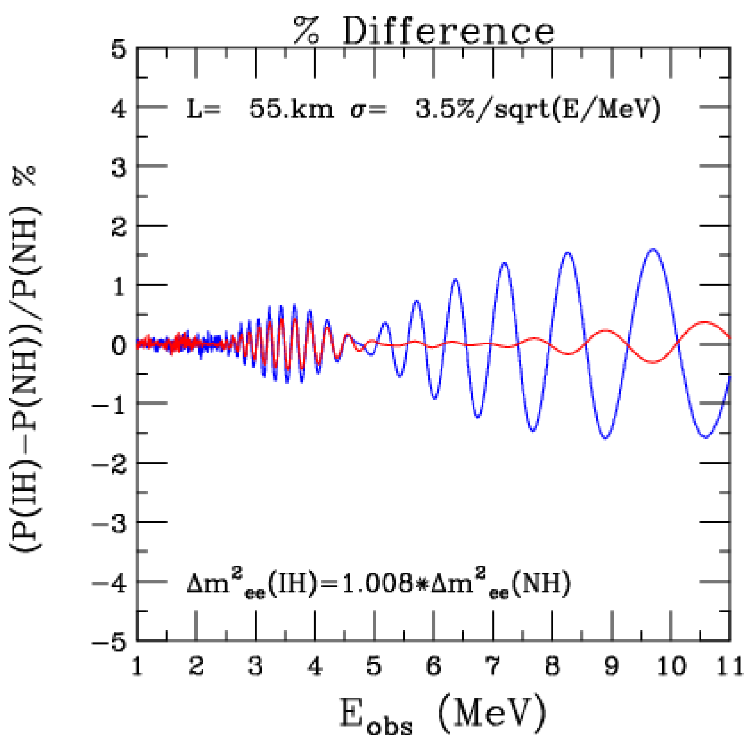
Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline(km)	52.75	52.84	52.42	52.51	52.12	52.21

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

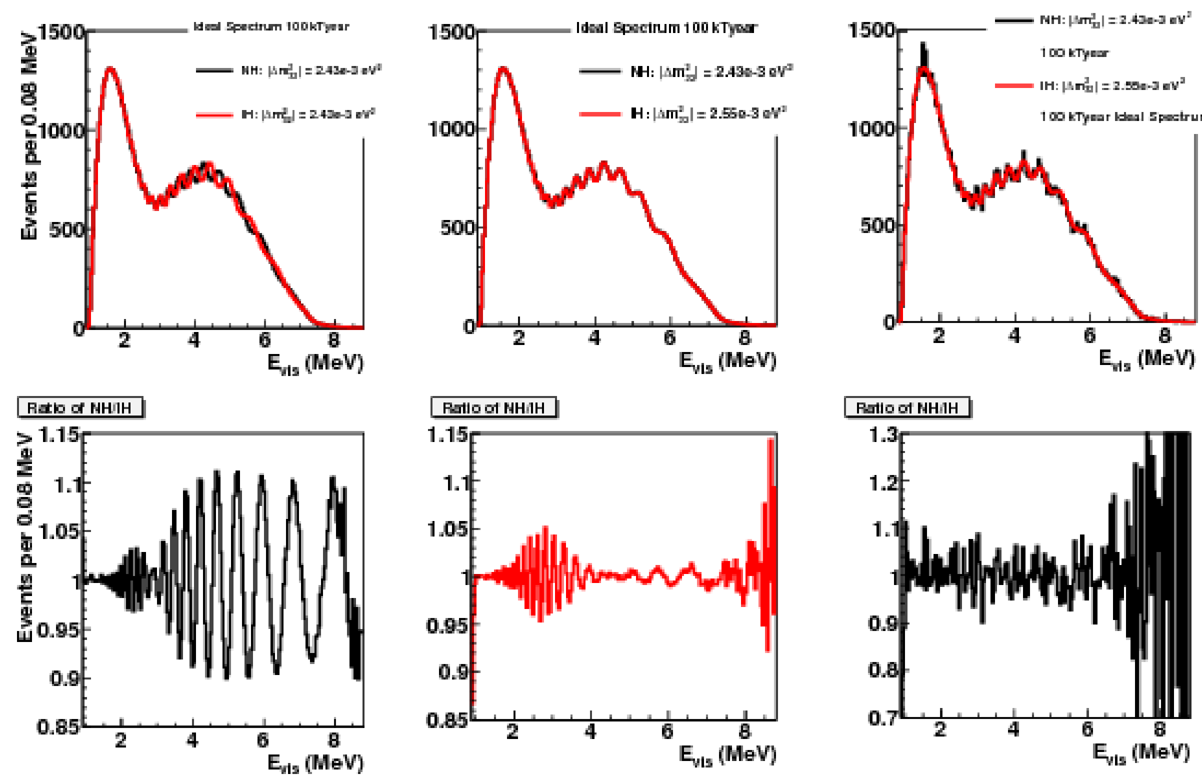
Non-Linearities

- **Energy reconstruction has bias or non-linearity residuals**
  → Signals might disappear or lead to wrong solution

- **Various studies show <= 1% uncertainty is needed**

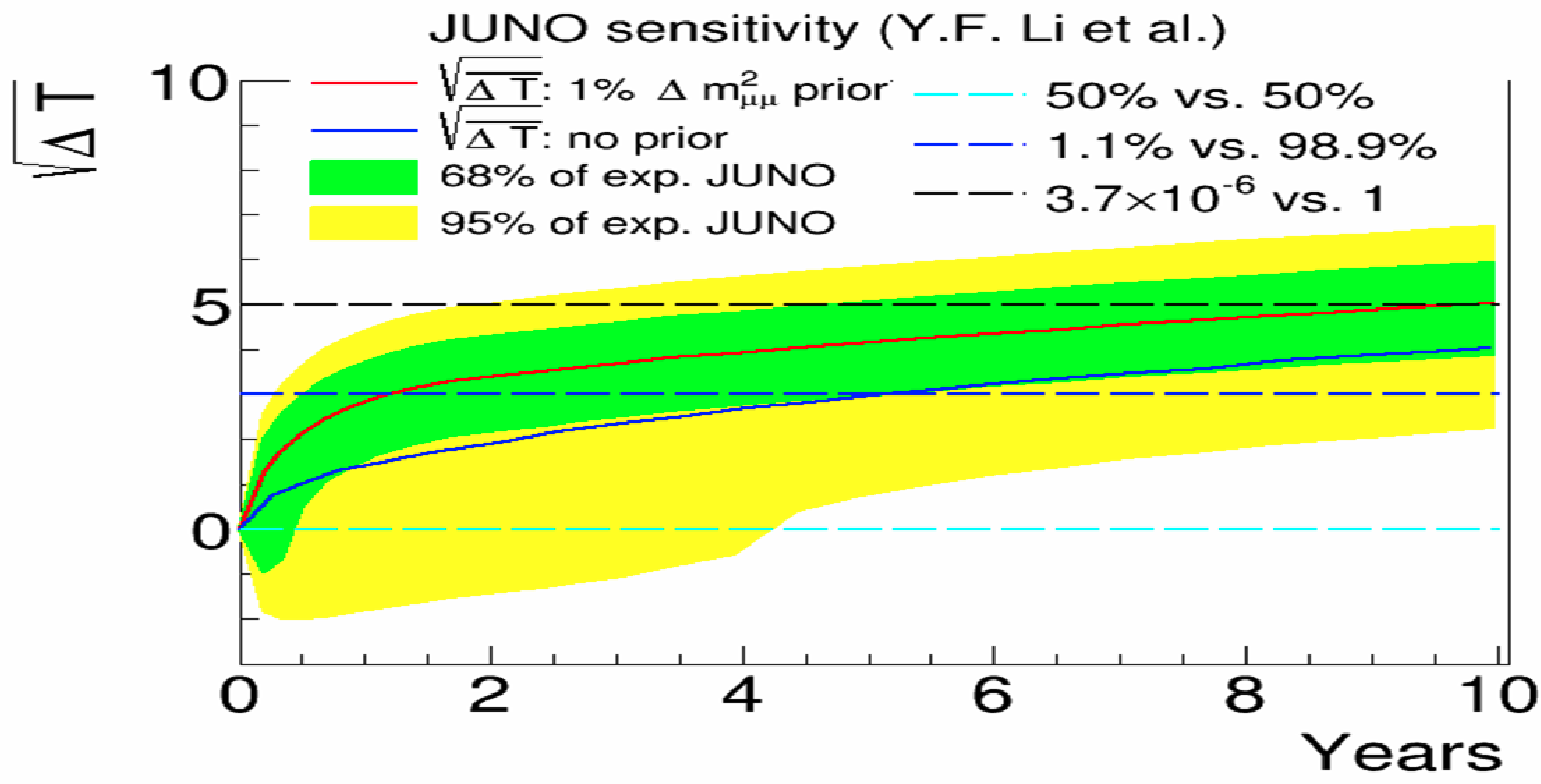


S.J. Parke et al,
Nucl.Phys.Proc.Suppl. 188 (2009)



X. Qian et al, PRD87(2013)3, 033005

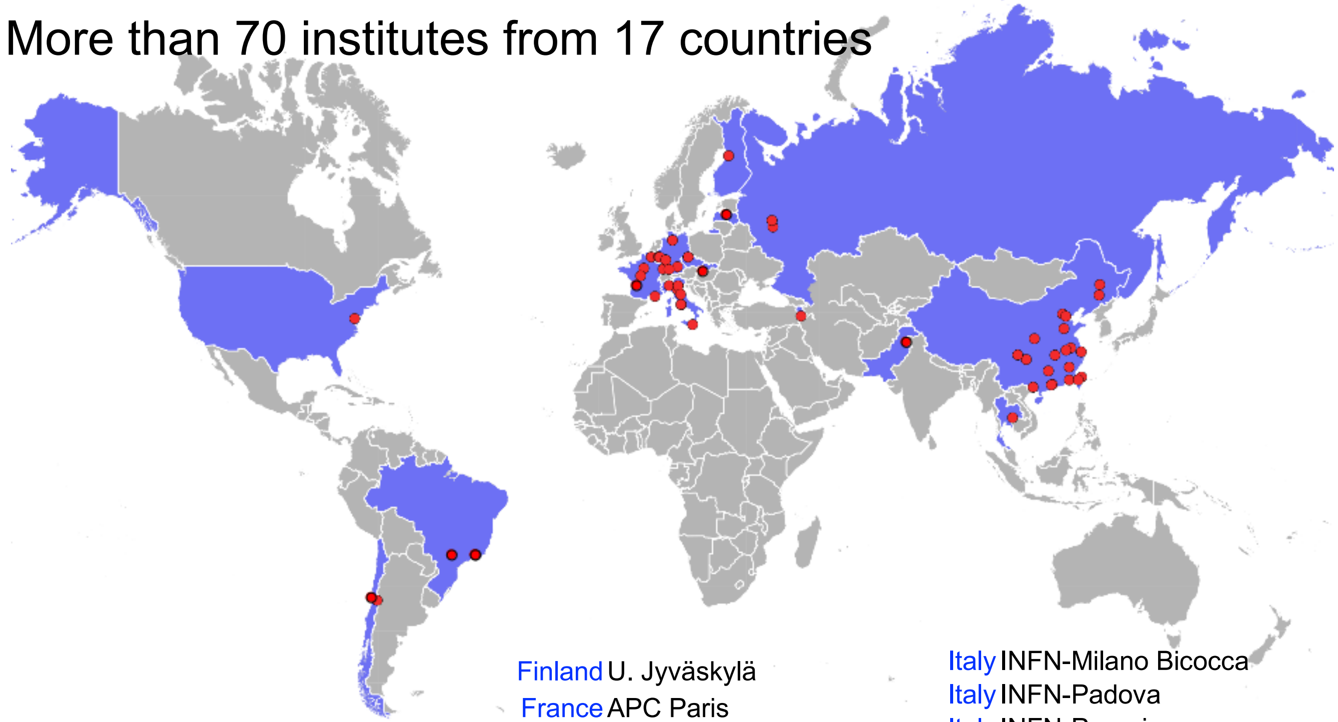
JUNO Sensitivity



See also Qian, Xin et al. Mod.Phys.Lett. A29 (2014) 1430016 arXiv:1405.7217

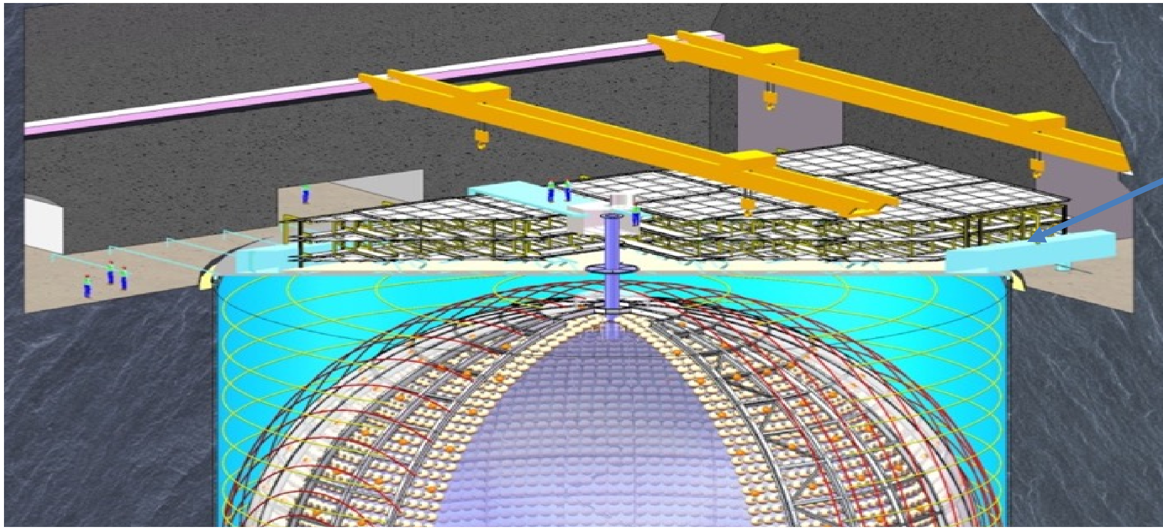
The JUNO Collaboration

More than 70 institutes from 17 countries



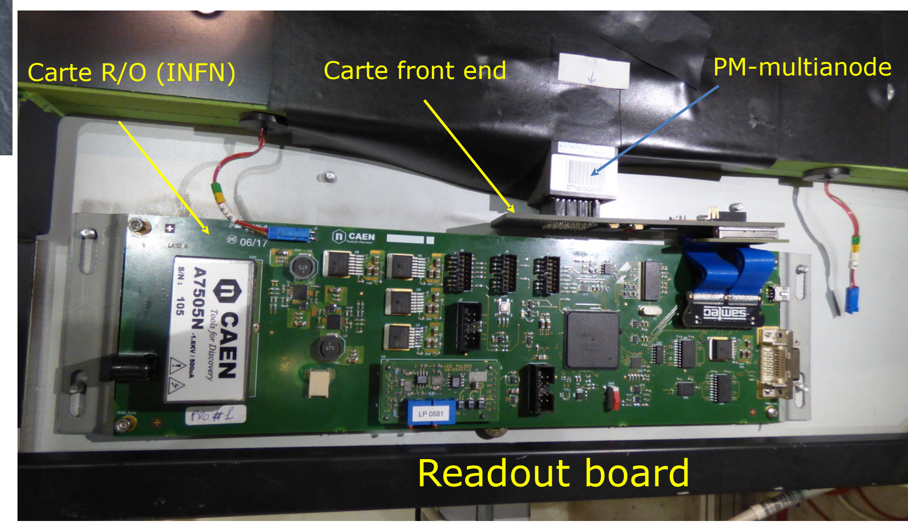
Armenia Yerevan Physics Institute
Belgium Université libre de Bruxelles
Brazil PUC Rio de Janeiro
Brazil UE Londrina
Chile PCUC
Chile UTFSM Valparaiso
China BISEE
China Beijing Normal U.
China CAGS
China ChongQing University
China CIAE
China DGUT
China ECUST
China Guangxi U.
China Harbin Institute of Technology
China IHEP
China IMP-CAS
China Jilin U.
China Jinan U.
China Nanjing U.
China Nankai U.
China NUDT
China NCEPU
China Pekin U.
China Shandong U.
China Shanghai JT U.
China SYSU
China Tsinghua U.
China UCAS
China USTC
China U. of South China
China Wu Yi U.
China Wuhan U.
China Xi'an JT U.
China Xiamen University
China Zhengzhou U.
Czech R. Charles U. Prague
Finland U. Jyväskylä
France APC Paris
France CENBG Bordeaux
France CPPM Marseille
France IPHC Strasbourg
France Subatech Nantes
Germany ZEA FZ Julich
Germany RWTH Aachen U.
Germany TUM
Germany U. Hamburg
Germany IKP-2 FZ Jülich
Germany U. Mainz
Germany U. Tuebingen
Italy INFN Catania
Italy INFN di Frascati
Italy INFN-Ferrara
Italy INFN-Milano
Italy INFN-Milano Bicocca
Italy INFN-Padova
Italy INFN-Perugia
Italy INFN-Roma 3
Latvia IECS Riga
Pakistan PINSTECH Islamabad
Russia INR Moscow
Russia JINR
Russia MSU
Slovakia U. Bratislava FMPICU
Taiwan National Chiao-Tung U.
Taiwan National Taiwan U.
Taiwan National United U.
Thailand NARIT
Thailand PPRLCU Bangkok
Thailand SUT
USA UMD1
USA UMD2

The JUNO Top Tracker



3 layers of plastic scintillators (OPERA Target Tracker)

- Cosmic muon tagging,
- Studies of cosmogenic background to reduce the JUNO systematics,
- Studies of central detector reaction to cosmic rays.

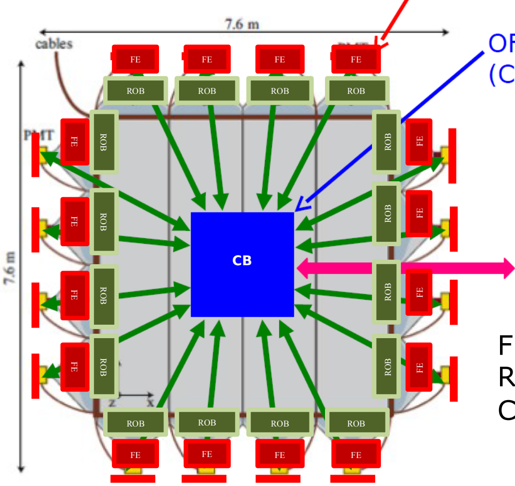


New electronics for higher radioactivity environment than at LNGS

ON-DETECTOR ELECTRONICS (MAROC3 + READOUT BOARD)

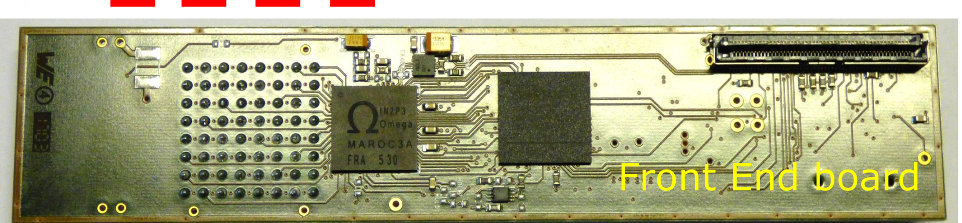
OFF-DETECTOR ELECTRONICS (CONCENTRATOR/TRIGGER BOARD)

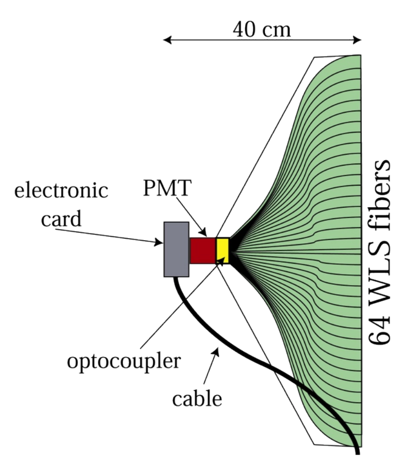
- Data concentrator (ADC/TDC)
- Trigger board (Lev1 WALL TRIGGER)
- Event time stamp
- Slow control

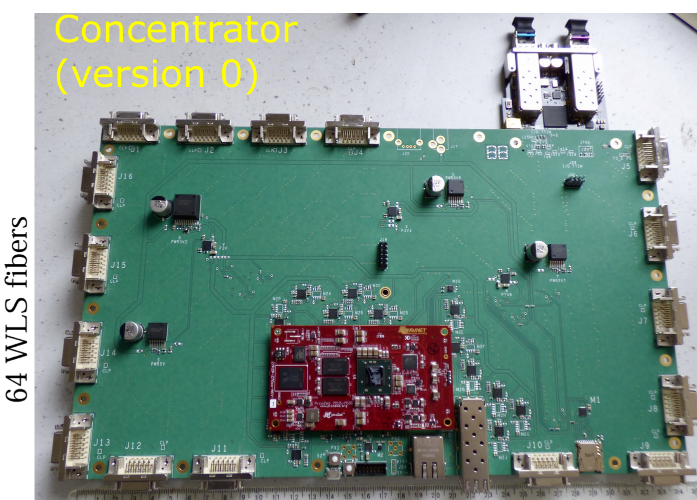


DATA & SLOW CTRL

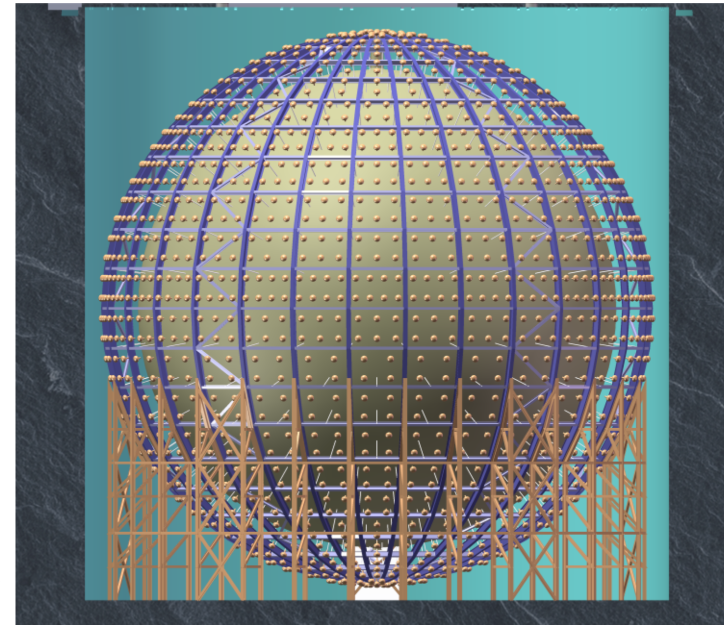
FE : Front end card: IPHC
ROB : Read out board: INFN/CAEN
CB : Concentrator board: IPHC/INFN







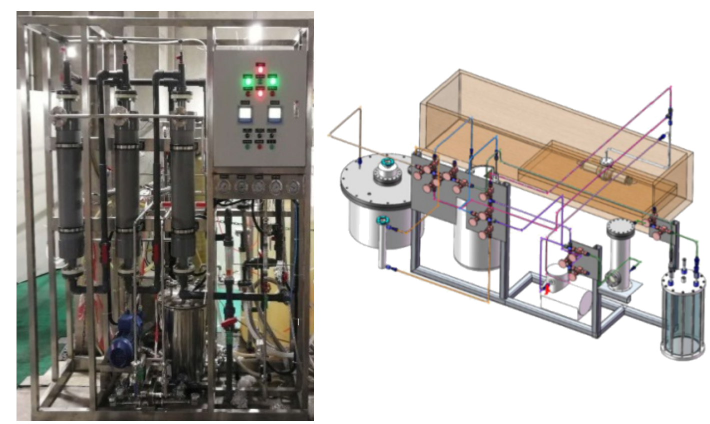
Water Cherenkov detector



- **Detector Characteristics**
  - 20 inch MCP-PMT used for veto system with number~2400
  - PMTs put on the surface of the stainless steel frame
  - ~35 kton ultrapure water in the pool
  - Tyvek reflector film coated on surface to increase light collection efficiency
  - Muon detection efficiency is expected to be > 95%
- Water system
  - Employ a circulation/polishing water system (~2 week one volume circulation)
  - Keep a good water quality including radon control (<0.2 Bq/m3)
  - Water system radon control R&D is under test.
- Compensation coils system used for earth magnet field shielding to keep PMT performance.

Background Estimation:

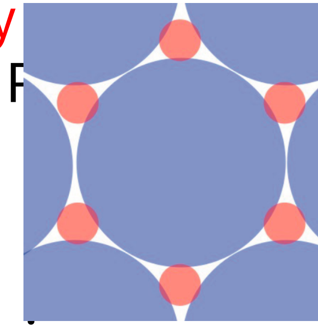
- Fast neutron background ~0.1/day
- Water buffer is 3.2m at equator from rock to central detector
- Radioactive background from rock is 7.4 Hz @3.2m water buffer



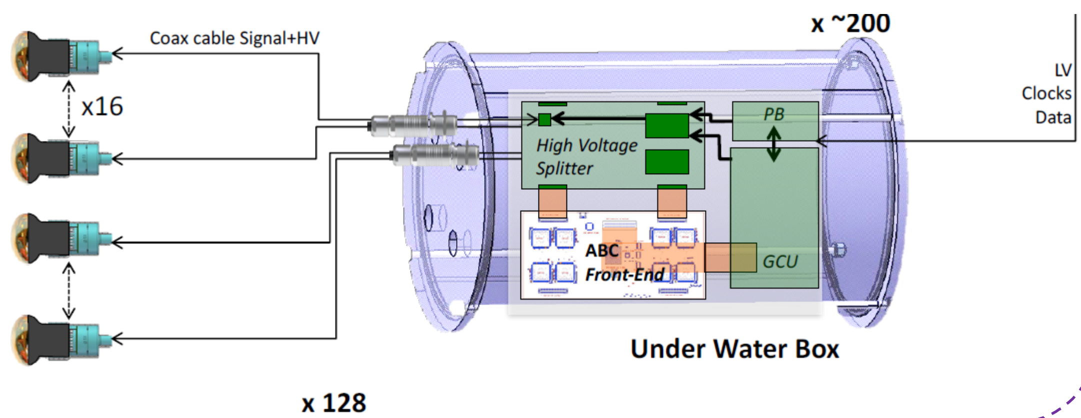
Radon control R&D

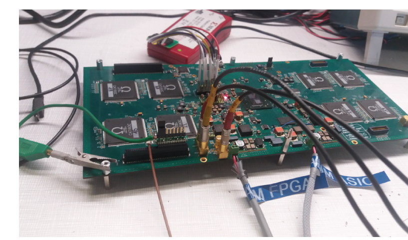
Small PMT

- Calibration of non-linear response of large PMT: double calorimetry
- International bidding done in 2017: 25,000 (+1,000 spares) 3.1-inch PMTs (XP72B22) contract with HZC Photonics
- Mass production on going: ~4,000 produced, 3,000 tested at HZC
- 128-channel readout by an ASIC Battery Card (ABC) with 8 CatiROC
- Underwater box with multi-channel connectors as electronics containers



System overview: 200 boxes × 128 PMTs



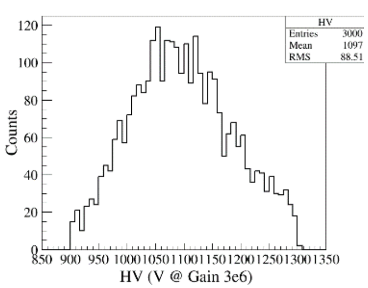


Prototype of ABC

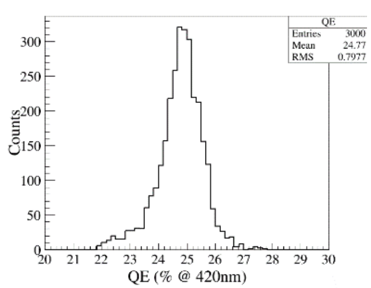
Prototype of underwater box

Prototype of connector

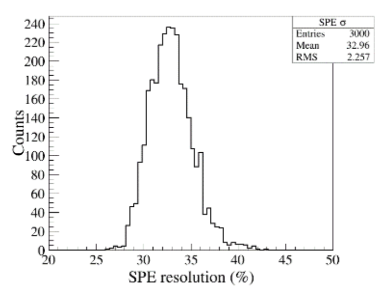
Performances highlight of 3,000 PMTs



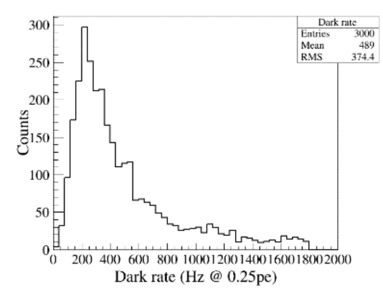
HV: 900-1300V



$\overline{QE}$=24.8%



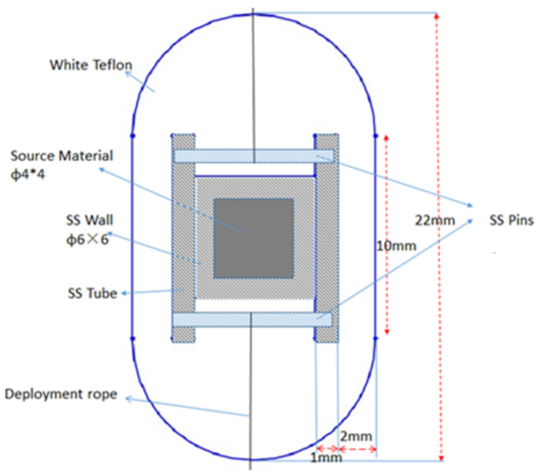
$\overline{\sigma_{SPE}}$=33.0%

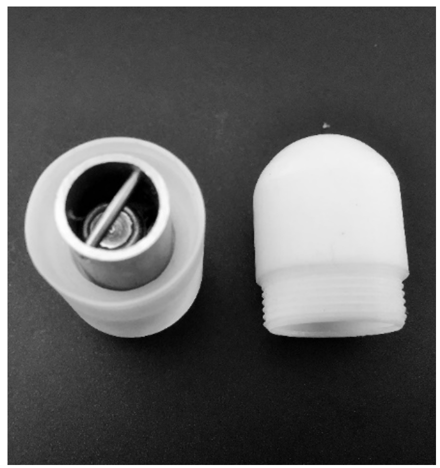


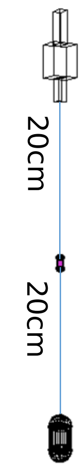
$\overline{dark\ rate} < 500\text{Hz}$

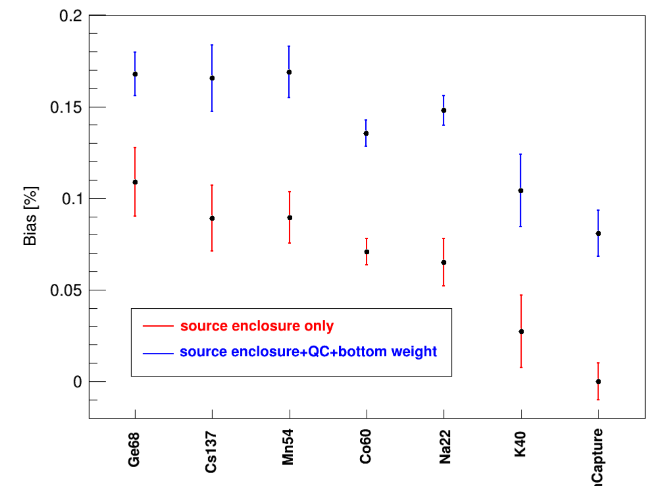
Calibration (radioactive & optical) Sources

- Main issues: the shadowing effects (more important) and the energy loss on the dead volume (less important);
- Solution: make the source to be small (generic SS enclosure Ø6×6 mm) and with highly reflective surface

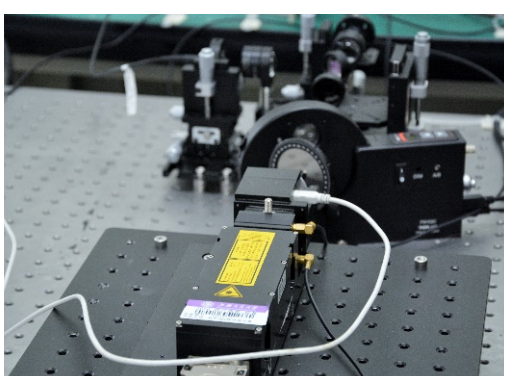








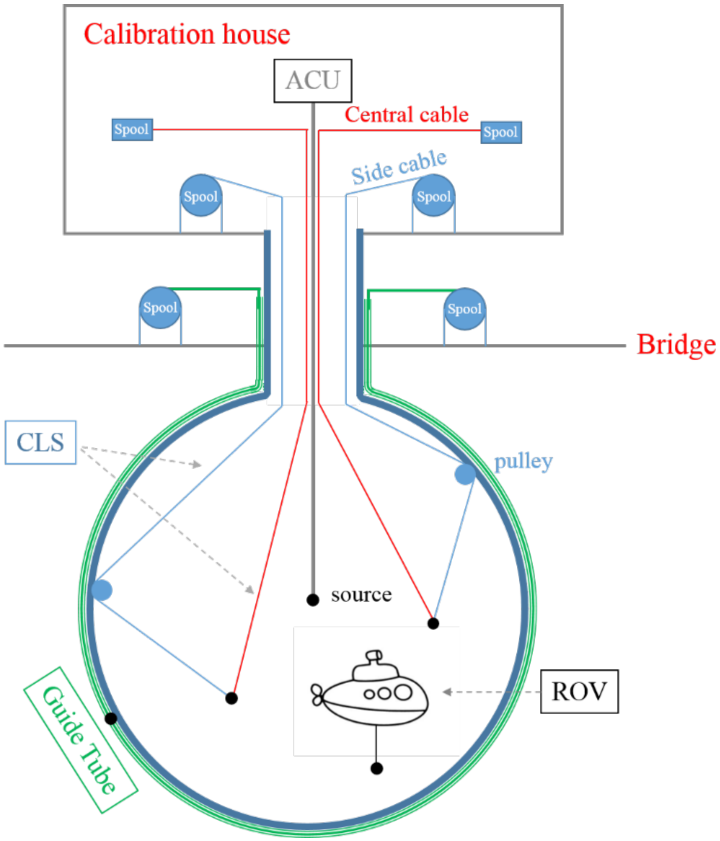
➢ Bias due to the enclosure <0.2% (validated with Daya Bay detector and can be further corrected) .

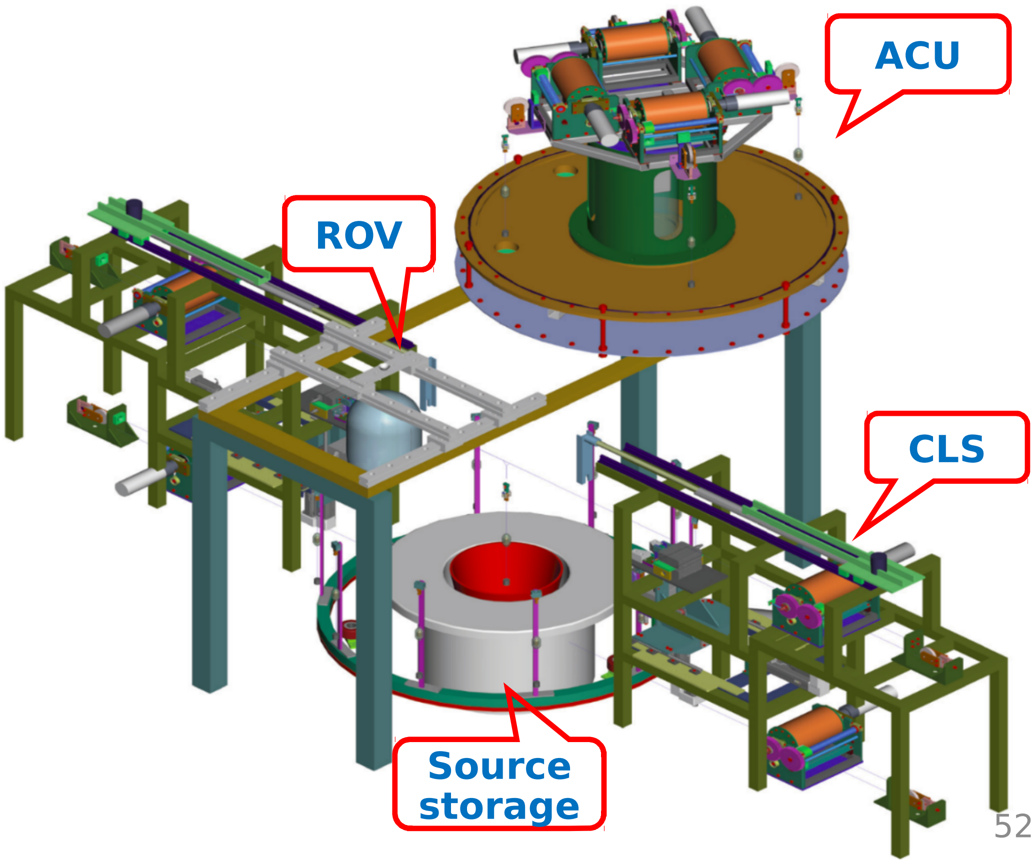


- Optical source for PMTs calibration.
- Fast (<1ns) and large energy coverage (MeV~TeV) : for electronics timing calibration and non-linearity calibration.
- Non-linearity of laser prototype can be controlled to <1% .

Source Deployment Systems

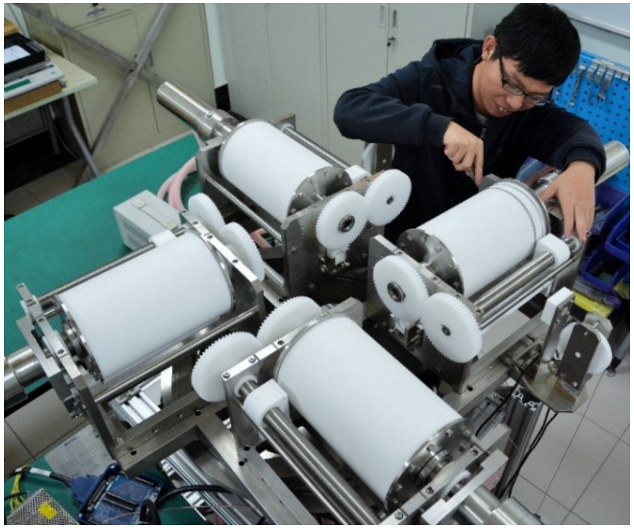
- Internal source deployment:
  - **ACU** (Automatic Calibration Unit): scan the central axis (**1D**)
  - **CLS** (Cable Loop System): scan one vertical plane (**2D**)
  - **ROV** (Remotely Operated Vehicle): scan “everywhere” (**3D**)
- External source deployment:
  - **GT** (Guide Tube): scan CD outer surface (**boundary**)



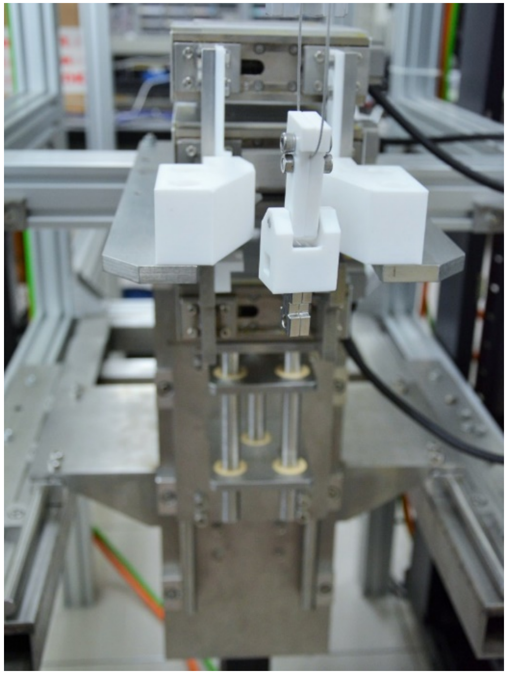


System Construction (Prototype)

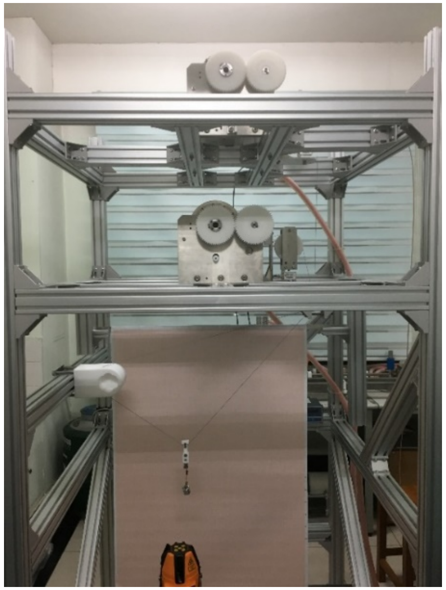
ACU

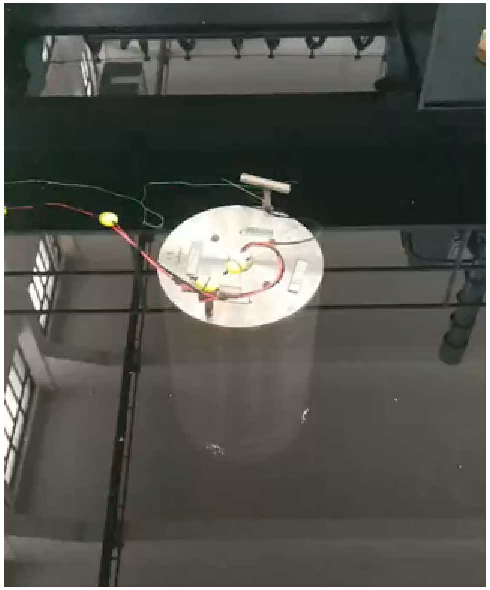


Source Auto-change



CLS





ROV

Guide tube