Status and perspectives of JUNO

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INFN - Milano

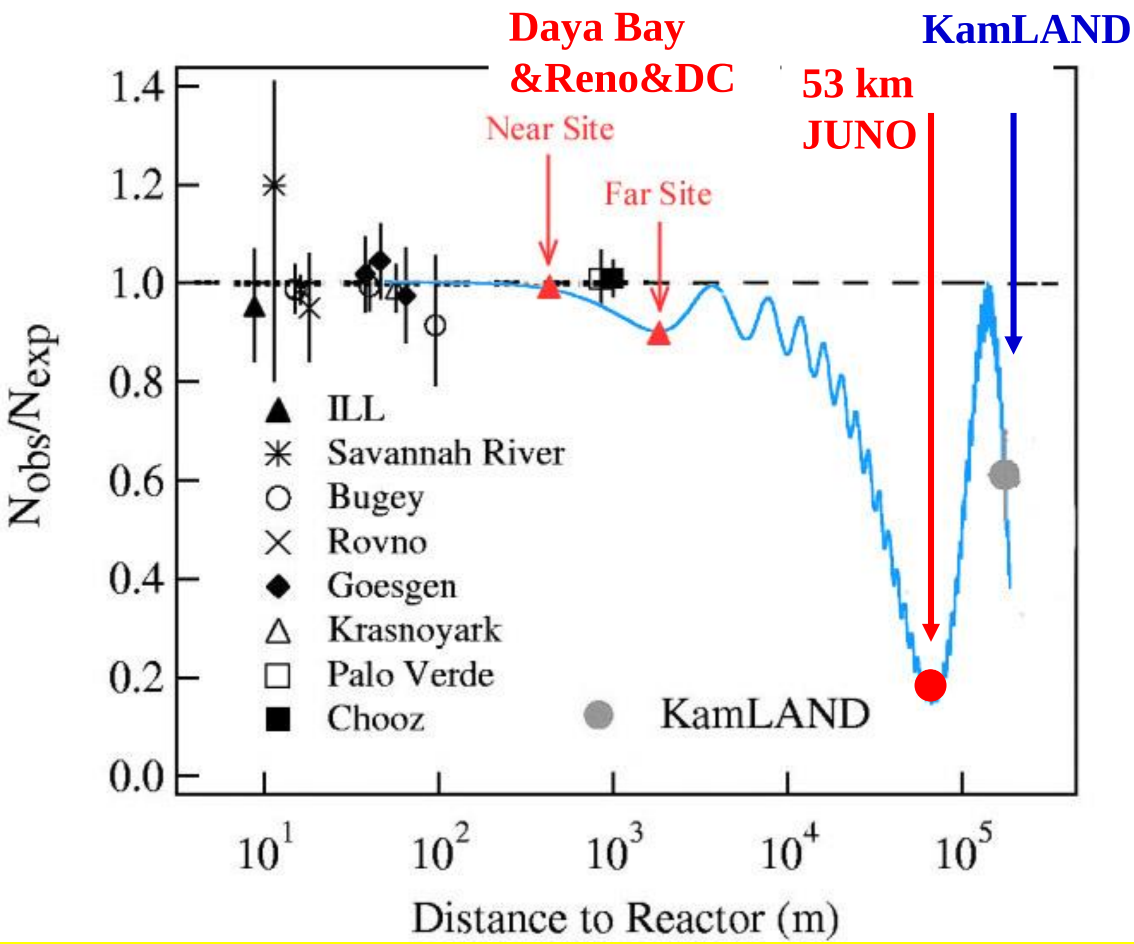
Colloquium Prague ν 19
October 24, 2019

J. Heyrovsky Institute of Physical Chemistry

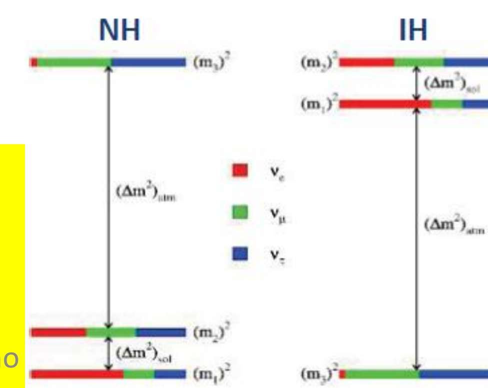
On behalf of the JUNO Collaboration

- Determination of the neutrino mass hierarchy with a large mass liquid scintillation detector located at medium distance – 53 km – from a set of high power nuclear complexes
- Precise measurements of oscillation parameters
- Vast astroparticle program
- Technical challenges and status of the construction

JUNO physics summary



- **20 kton LS detector**
- **~3 % energy resolution-the greatest challenge**
- Rich physics possibilities
  - ⇨ **Mass hierarchy**
  - ⇨ **Precision measurement of 3 mixing parameters**
  - ⇨ **Supernovae neutrinos**
  - ⇨ **Geoneutrinos**
  - ⇨ **Diffuse Supernovae ν's**
  - ⇨ **Atmos&sol neutrinos**
  - ⇨ **Nucleon Decay**
  - ⇨ **Exotic searches**



Neutrino Physics with JUNO, J. Phys. G 43, 030401 (2016)

The tension between the solar and KamLAND Δm^2 has further boosted the importance of the precision Δm^2_{21} measurement

The tool: a large LS spherical detector

- LS large volume: ➔ for statistics
- High Light(PE) ➔ for energy resolution 1200 pe/MeV

Both crucial for the physics capabilities

Steel Truss

Holding PMTs

~20000 x 20"

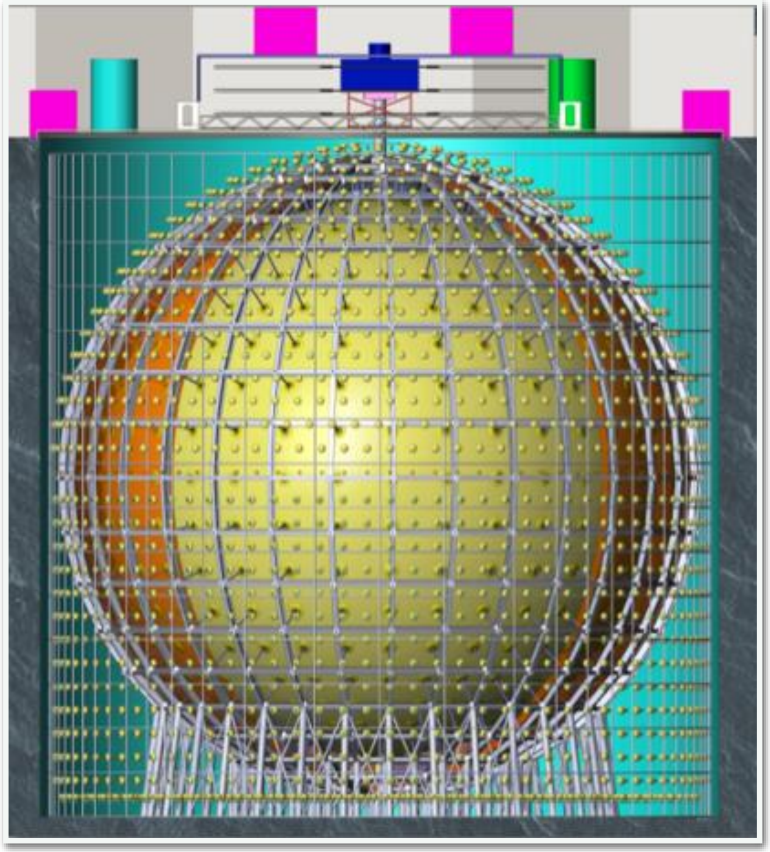
18000 Inner

2000 veto

~25000 x 3"

Acrylic Sphere

filled with 20 kt LS



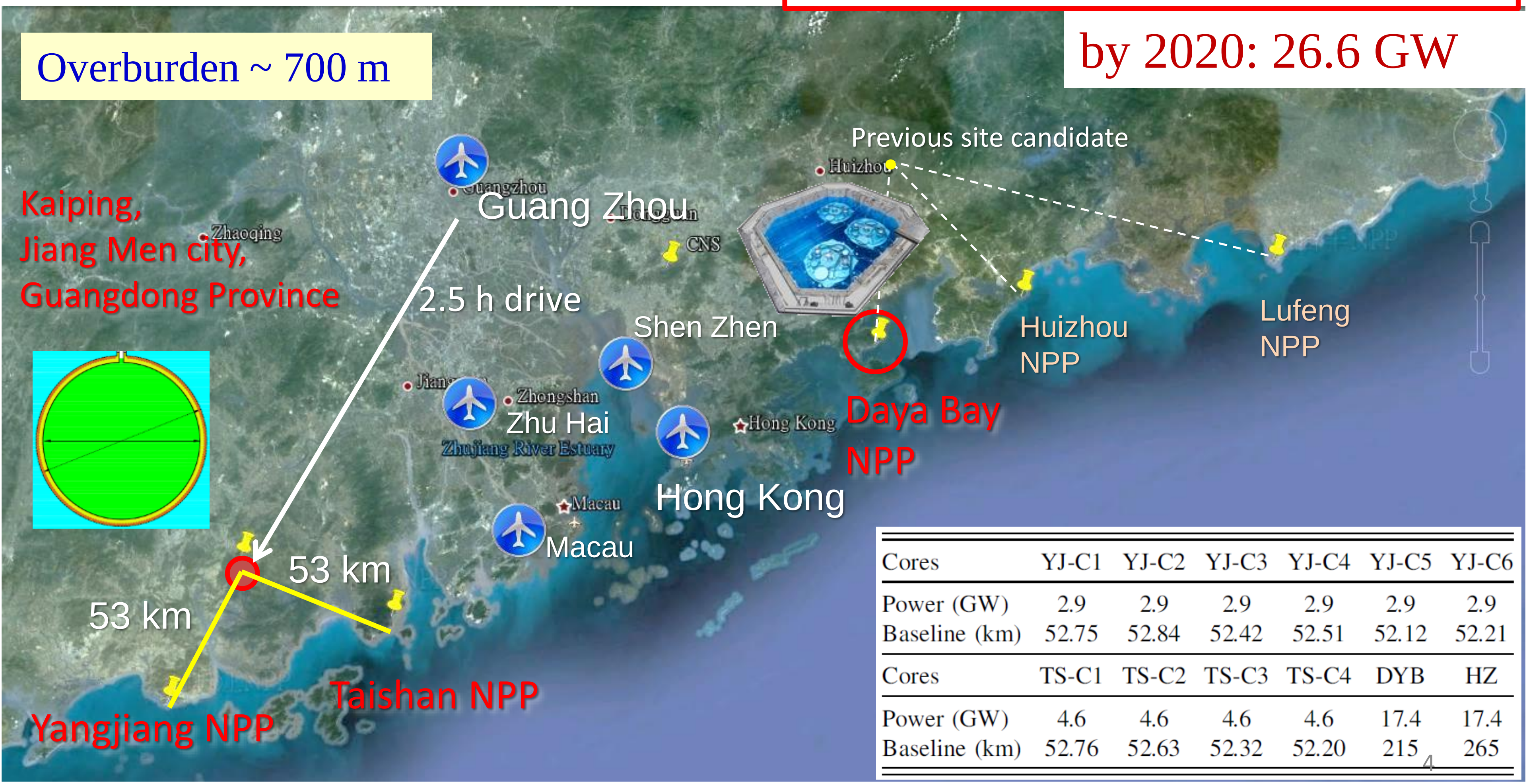
JUNO has been approved in China in Feb. 2013

Participation and contributions from several other countries:

- **Armenia**
- **Belgium**
- **Brazil**
- **Chile**
- **Czech Republic**
- **Finland**
- **France**
- **Germany**
- **Italy**
- **Latvia**
- **Pakistan**
- **Russia**
- **Slovakia**
- **Taiwan**
- **Thailand**
- **USA**

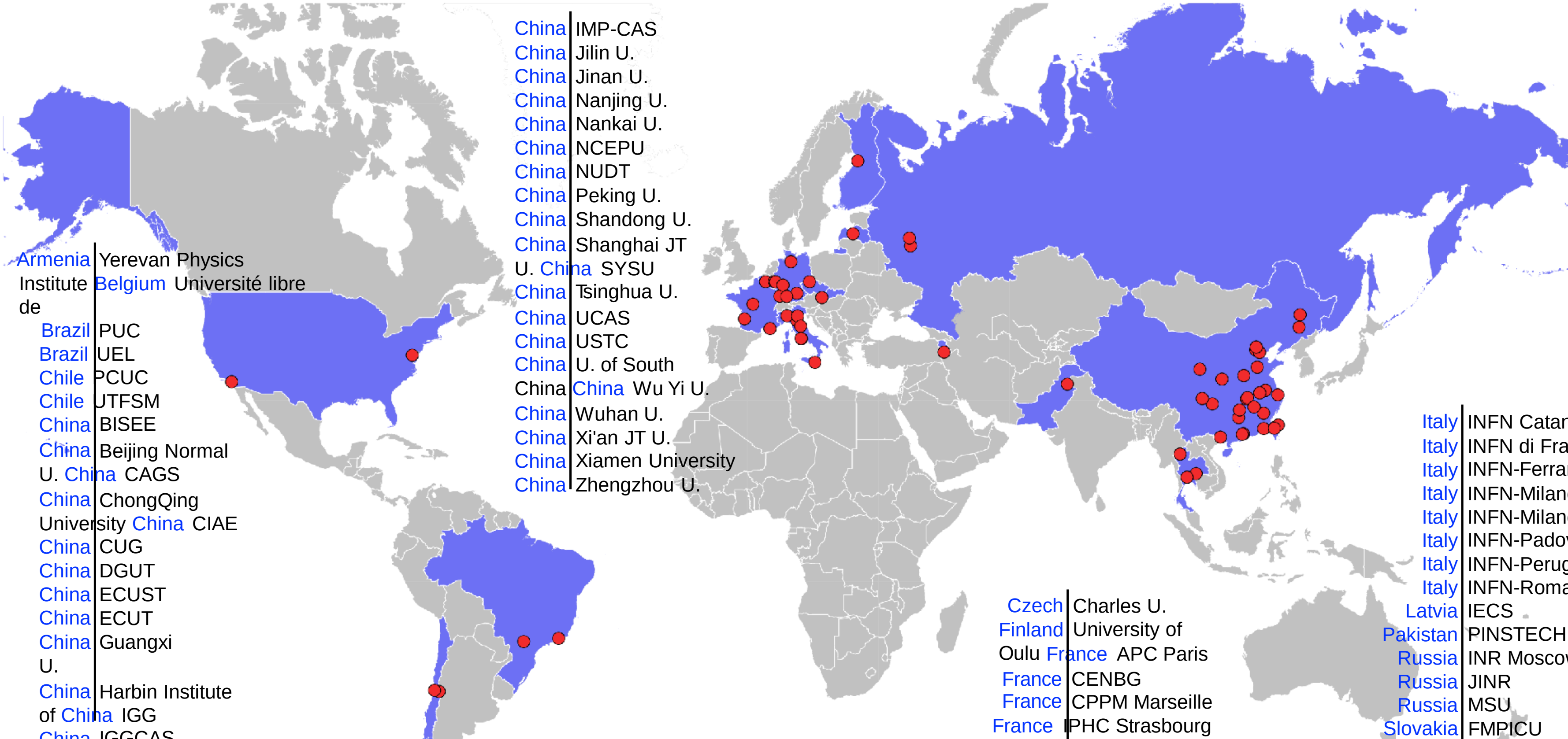
The importance of the location

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



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

JUNO collaboration



Armenia Yerevan Physics Institute
Belgium Université libre de
Brazil PUC
Brazil UEL
Chile PCUC
Chile UTFSM
China BISEE
China Beijing Normal U.
China CAGS
China ChongQing University
China CIAE
China CUG
China DGUT
China ECUST
China ECUT
China Guangxi U.
China Harbin Institute of China
IGG
China IGGCAS

China IMP-CAS
China Jilin U.
China Jinan U.
China Nanjing U.
China Nankai U.
China NCEPU
China NUDT
China Peking 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 Charles U.
Finland University of Oulu
France APC Paris
France CENBG
France CPPM Marseille
France IPHC Strasbourg
France Subatech Nantes
German ZEA FZ Julich
German RWTH Aachen U.
German TUM
German U. Hamburg
German IKP FZ Jülich
German U. Mainz
German 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
Pakistan PINSTECH (PAEC)
Russia INR Moscow
Russia JINR
Russia MSU
Slovakia FMPICU
Taiwan National Chiao-Tung U.
Taiwan National Taiwan U.
Taiwan National United U.
Thailand NARIT
Thailand PPRLCU
Thailand SUT
USA UMD1
USA UMD2
USA UCI

Collaboration established on July 2014

Now 77 institutions ~600 collaborators

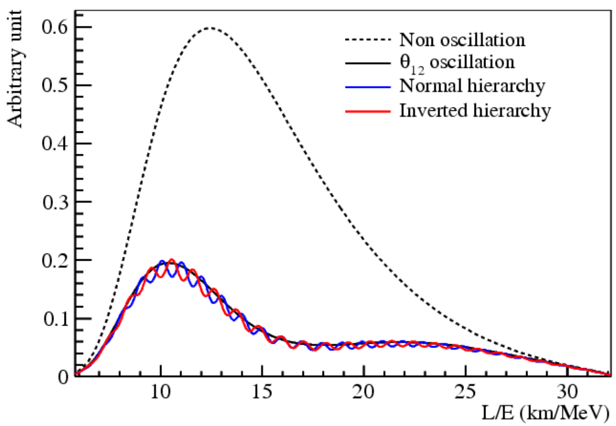
Methodology to infer the Mass Hierarchy

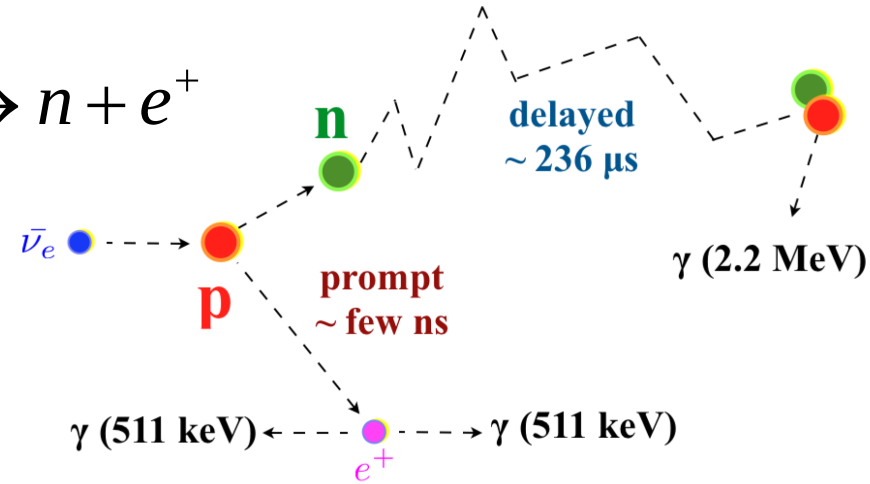
The determination of the mass hierarchy relies on the identification on the positron spectrum of the “imprinting” of the anti-ν_e survival probability

Detection through the classical inverse beta decay reaction

$$\bar{\nu} + p \rightarrow n + e^{+}$$

E_ν>1.8 MeV

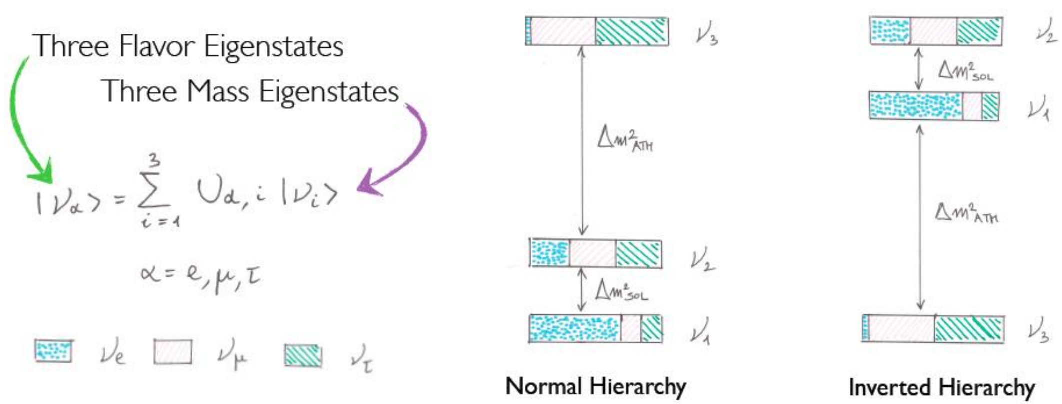




The “observable” for the mass hierarchy determination is the positron spectrum

It results that $E_{vis}(e^+)=E(\nu)-0.8$ MeV

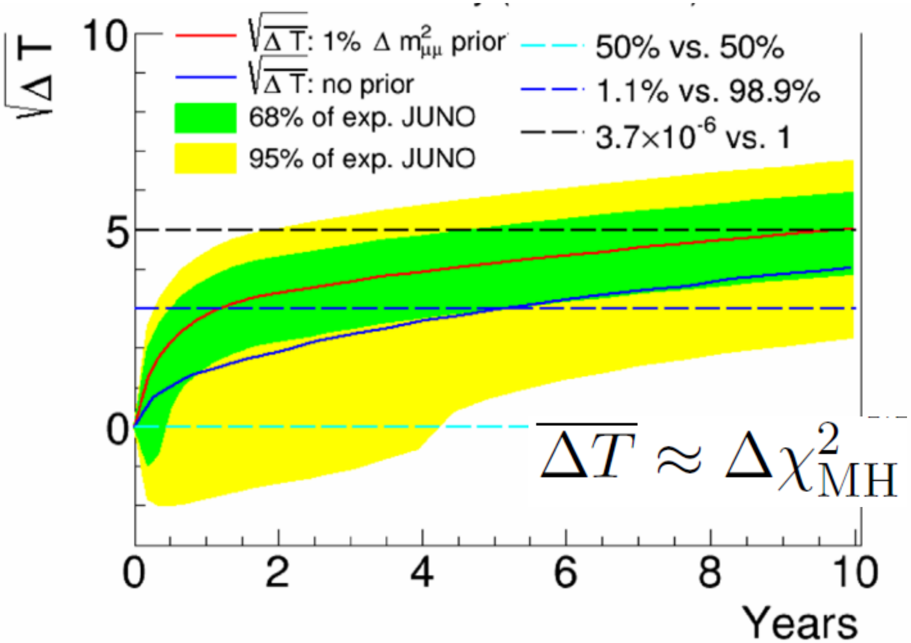
The wiggles are the key!

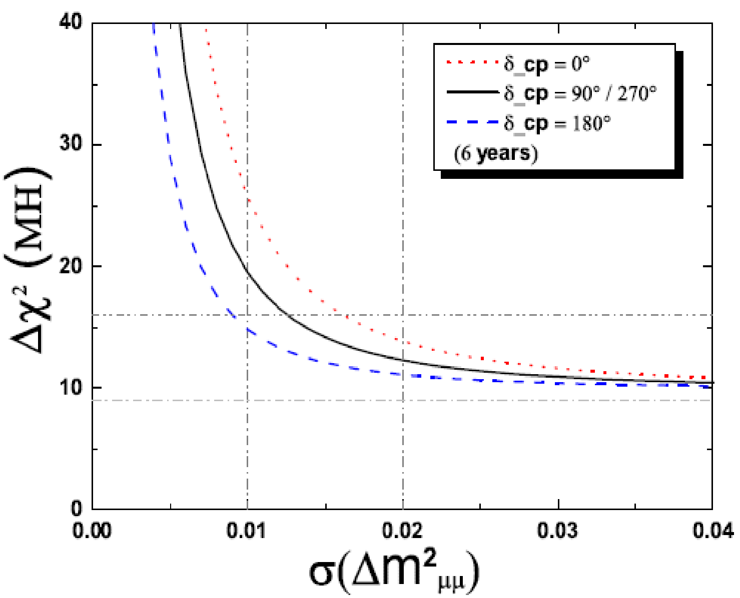


Summary of MH Sensitivity

PRD 88, 013008 (2013)	Relative Meas.	Use absolute Δm^2
Statistics only	4σ	5σ
Realistic case	3σ	4σ

JUNO **MH sensitivity with 6 years' data (nominal power):**





	Stat.	Core dist.	DYB & HZ	Shape	B/S (stat.)	B/S (shape)	$\lvert\Delta m^2_{\mu\mu}\rvert$
Size	52.5 km	Tab. 1-2	Tab. 1-2	1%	6.3%	0.4%	1%
$\Delta\chi^2_{\rm MH}$	+16	−3	−1.7	−1	−0.6	−0.1	+(4 − 12)

Near (reference) Detector Concept

Recent addition to measure with great accuracy the initial spectrum and control the systematic effect

Gd-LS in diameter of 1800 mm

- **Surface 10.2 m^2**
- **Volume 3.05 m^3, or 2.63 ton**
- **1 ton fiducial volume w/ a 25cm cut**
- **Event rate 30 times of JUNO**
- **~30 m from the core**
- **Resolution better than 1.7%**

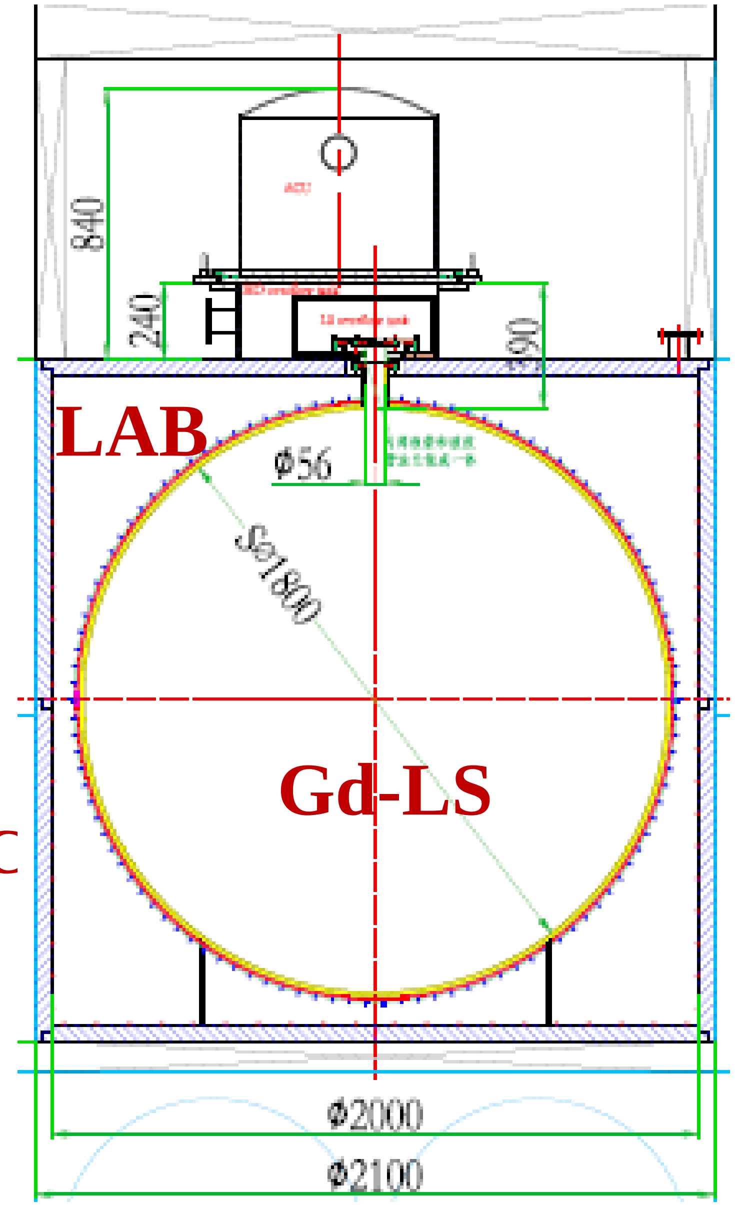
Nylon bag w/ acrylic support (JUNO backup option)

10 m^2 SiPM of 50% PDE, operated at -50°C

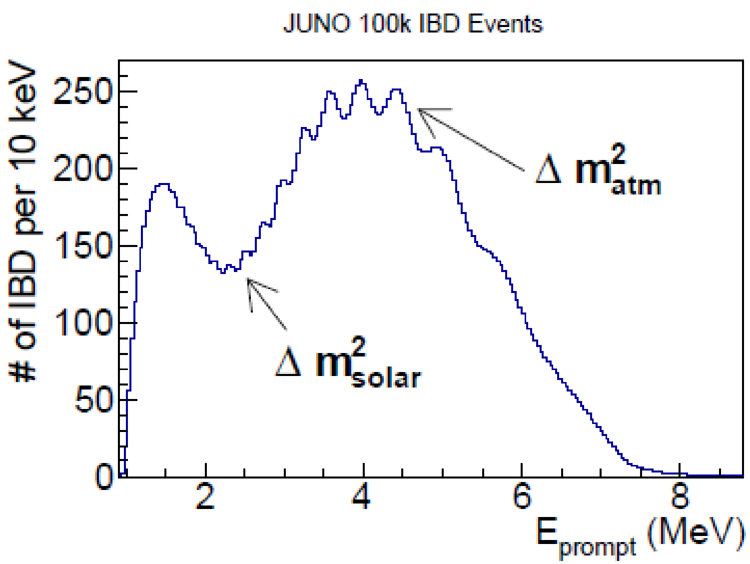
LAB+quencher as buffer

Cryogenic vessel

DYB Automatic Calibration Unit

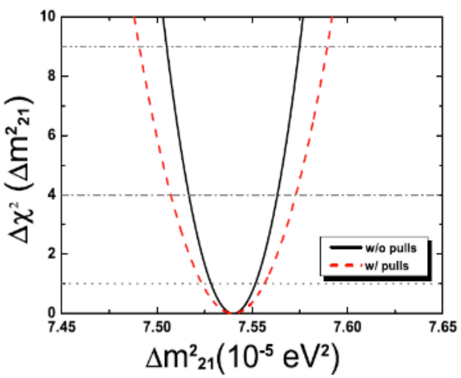


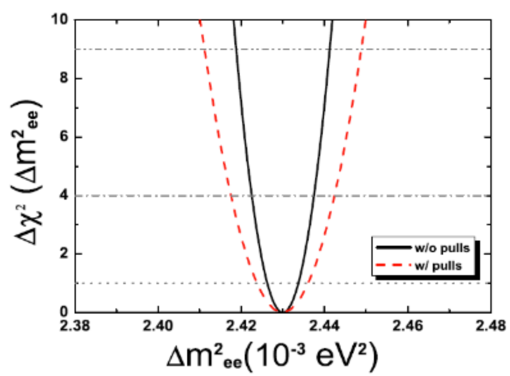
Precision Measurements

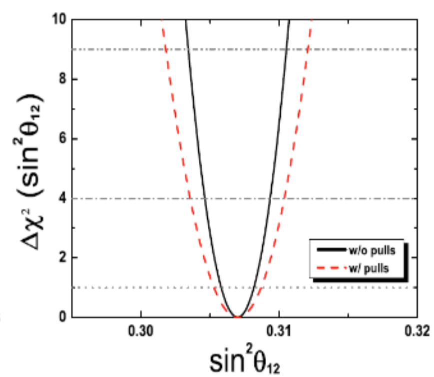


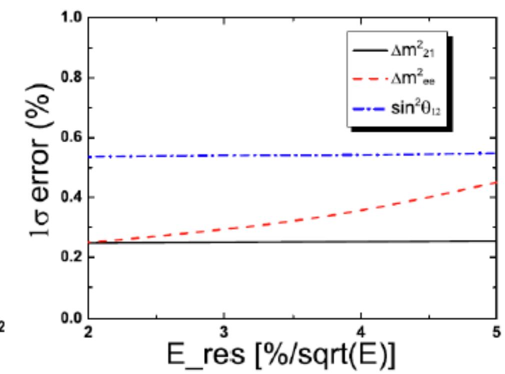
Probing the unitarity of U_{PMNS} to ~1%
more precise than CKM matrix elements !

	Statistics	+BG +1% b2b +1% EScale +1% EnonL
$\sin^2\theta_{12}$	0.54%	0.67%
Δm^2_{21}	0.24%	0.59%
Δm^2_{ee}	0.27%	0.44%









0.16%→0.24%

0.16%→0.27%

0.39%→0.54%

E resolution

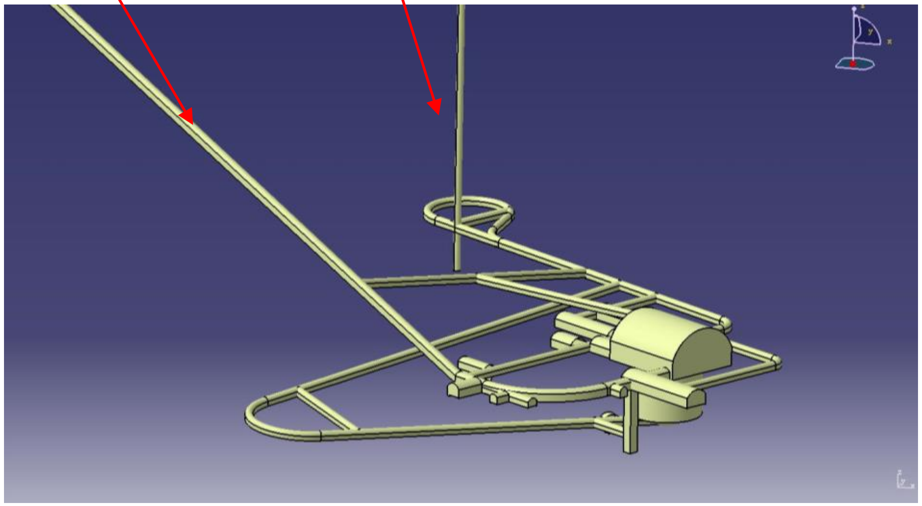
Correlation among parameters

$$\Delta m^2_{ee} = \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

Layout of the site

Slope tunnel

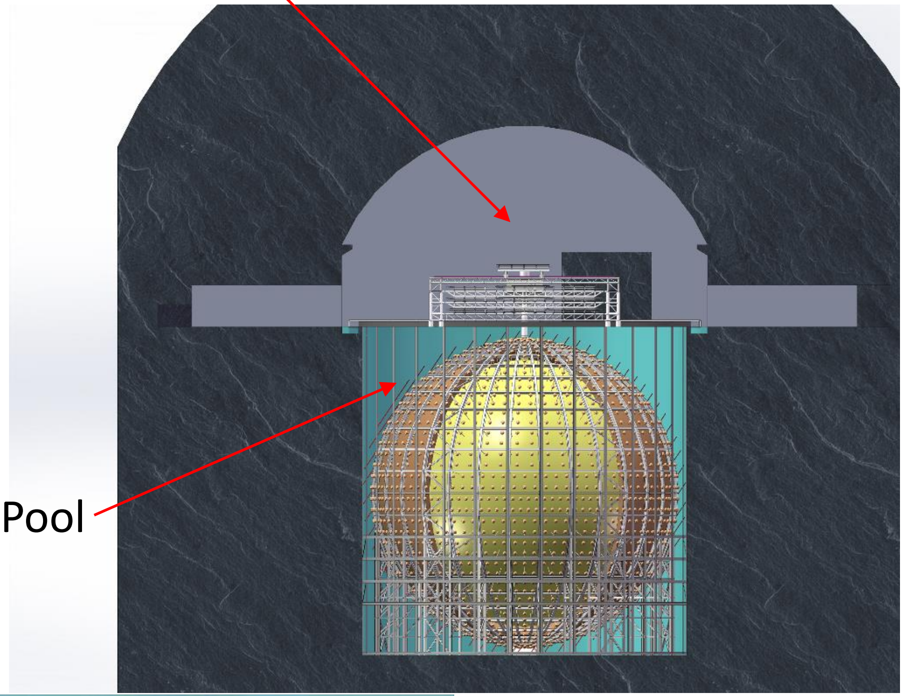
Vertical shaft



overburden ~ 700 m

Experimental Hall

Pool

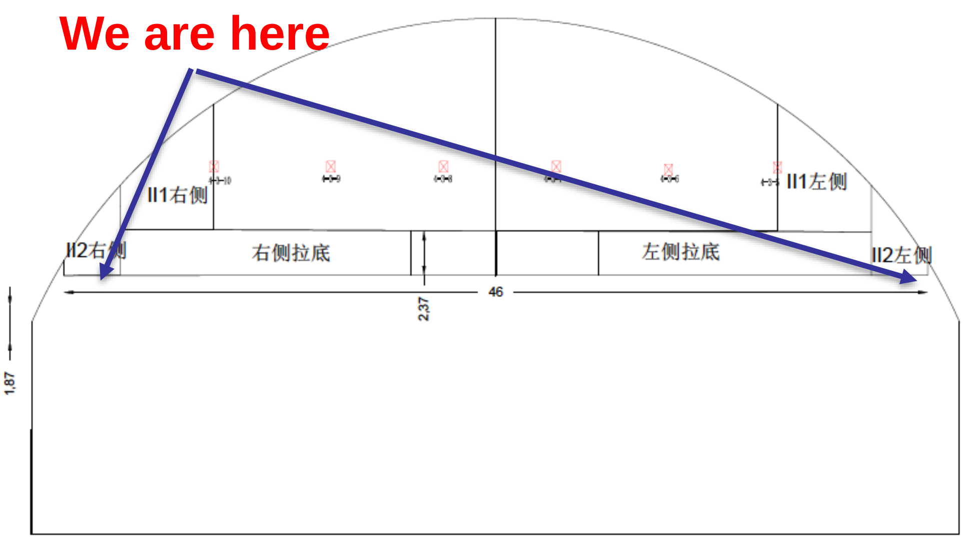


Surface buildings

Status of Civil Construction

- **Experimental Hall is only 1.5 m short to the final top arc structure**
- **Schedule**
  - Surface buildings will be completed at end of 2019
  - The experimental hall will be completed on 2020.6.30

Work in the Experimental Hall

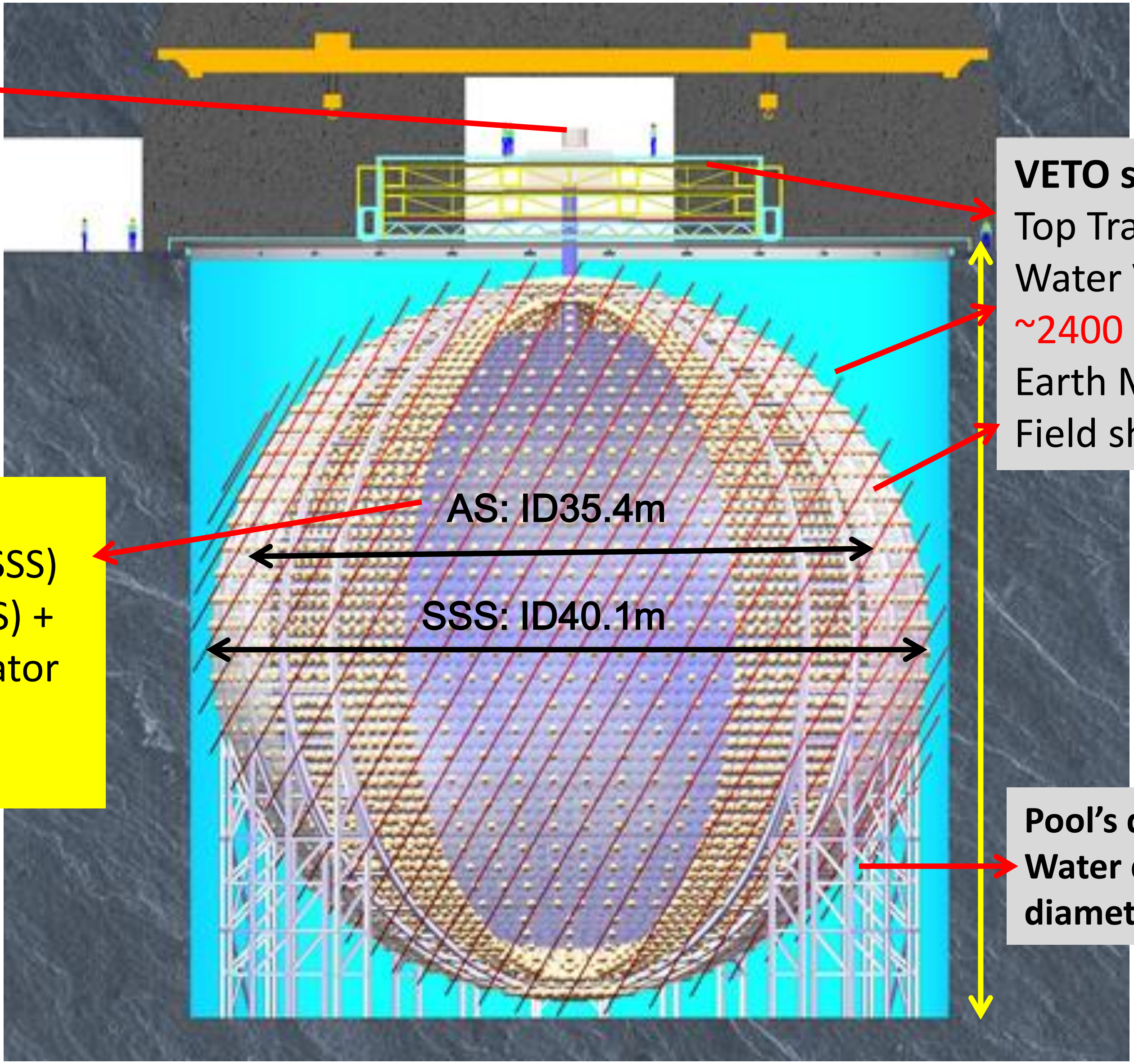


下端墙断面图

Status of the underground civil construction

Vertical shaft

JUNO Detectors



Calibration

VETO system
Top Tracker
Water VETO with
~2400 20'' PMT
Earth Magnetic
Field shielding coils

Central detector
- Steel structure (SSS)
- Acrylic sphere(AS) +
20kt Liquid scintillator
- ~18000 20" PMT
- ~25000 3'' PMT

Pool's depth: 44m
Water depth and diameter: 43.5m

Central Detector：Acrylic sphere

- **Acrylic:**
  - Panel: No plasticizer, no anti-UV
  - Thermoforming\annealing process
  - Transmittance: > 96% in LS
  - Dimension & shapes OK
  - 4 new bending molds ready
- **Bonding**
  - Creeping >30year under 5.5MPa in LS
  - 1:1 size panel bonding tested
  - 10m diameter ring bonding tested
- **Acrylic node**
  - Tensile and compression force > 90t
  - Creep performance better than material
- **Radiopurity and cleanliness**
  - Dedicated production line to control radioactivity (water, air, tools, mold,…)
  - All surfaces will be grinded and protected
  - BKG is tested to be less than ~ 1ppt
- **Mass production on schedule**

Batch test of acrylic node

First panel of acrylic sphere: measurement

Thermoforming mold

Panels storage: Anti-pollution and protected from light

1:1 size panel bonding

10m diameter ring bonding

Central Detector: Stainless Steel Structure

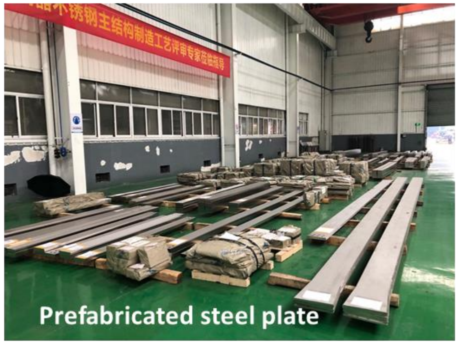
- All materials basically ready, background for all batches are OK.
- Production of steel structure in good shape
  - 50% completed
  - Weld quality inspection: self 100%, third party 20%
  - Pre-assembled for the support section
- Critical issues resolved
  - high-strength stainless steel fastener for structure.
  - surface treatment for disc spring.
- PRR for the connecting parts between the steel structure and the acrylic sphere was passed, about 6 months to finish all production. The PDR of the axial force monitoring system passed.

Prototype performance test

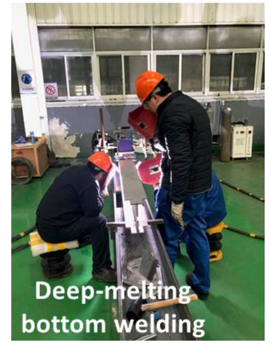
Key component prototype

Production readiness review for the connecting components

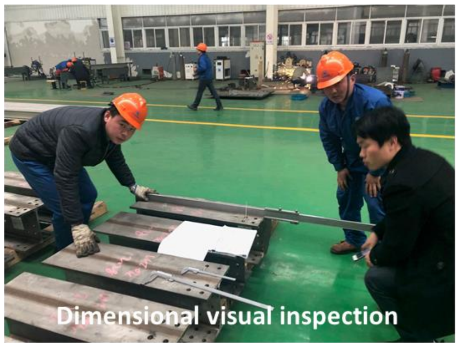
Stainless Steel Structure Production in good shape


Prefabricated steel plate

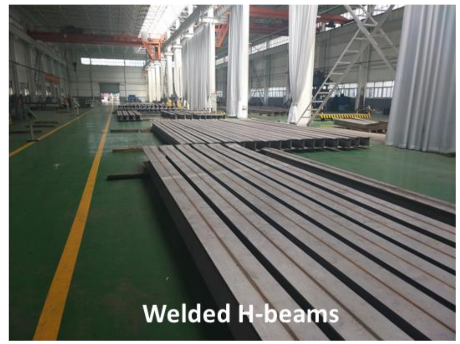

Assembly and spot welding

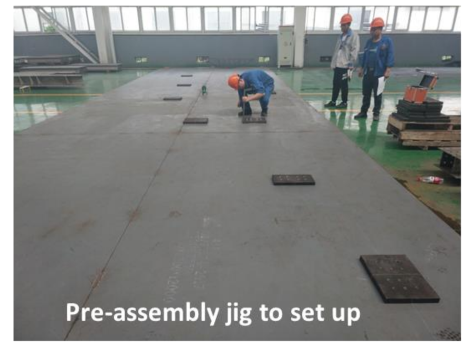

Deep-melting bottom welding


submerged-arc welding H-beams


Dimensional visual inspection


Ultrasonic inspection


Welded H-beams

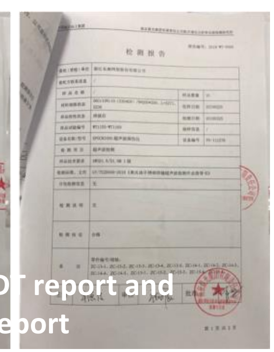

Pre-assembly jig to set up


Joints welding


Welded H-beams

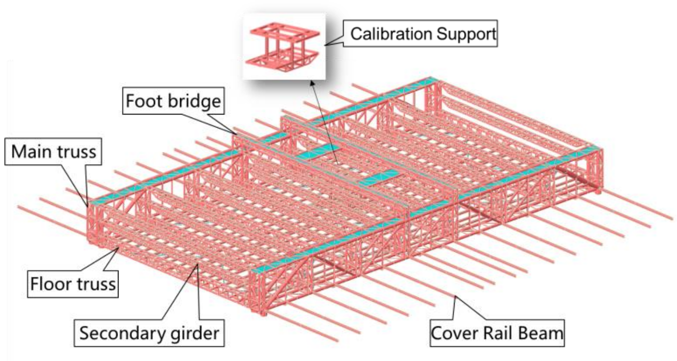

Pre-assembly support section

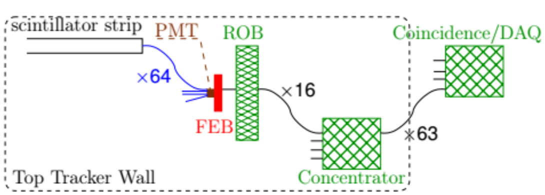

PDR for axial force monitoring system

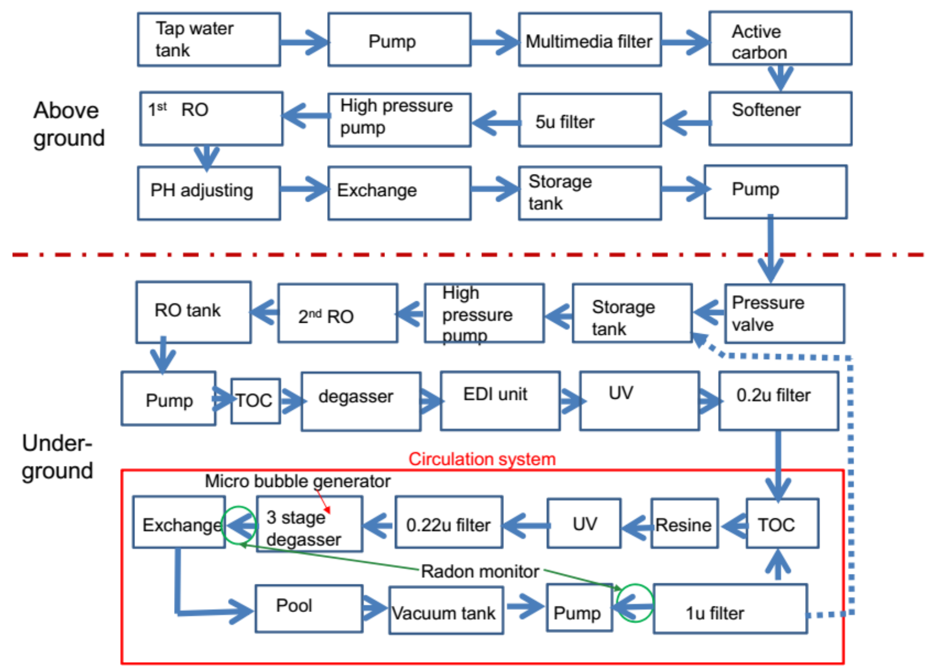

Material properties & NDT report and third party test report

Veto system

- Completed the bidding of the Ultrapure water system, including the pipe and water pressure reducing valve system.
- Completed the bidding of TT main structure and TT module structure
- FDR of TT electronics FEB and ROB completed
- The position and fixation design of EMS sensors, veto PMT calibration LEDs, layout of cable trench, pipes in water pool etc. are going on.







Prague, October 24, 2019

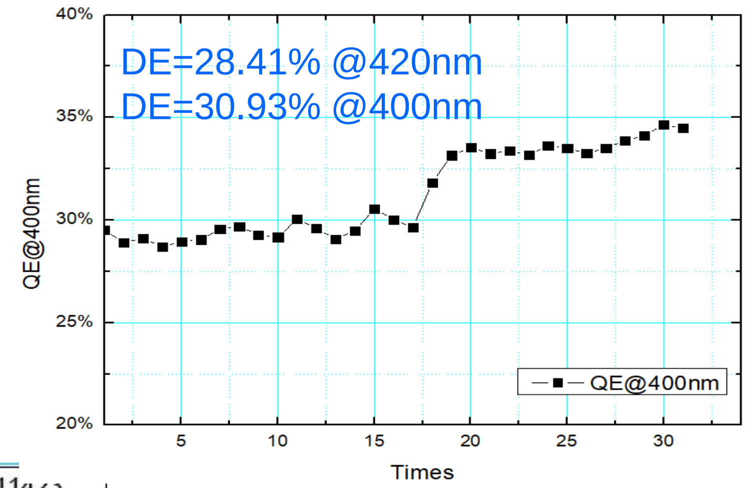
TT support structure and electronics

Ultrapure water system

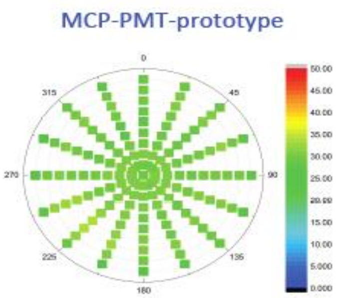
20" MCP-PMT

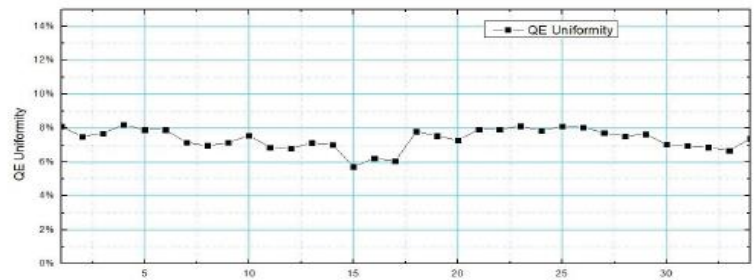
- From 10/2018 to now, 4032 20" MCP-PMTs have been delivered to Fanya test base for testing
- Better performance: higher QE, lower dark noise…

year	Detection Efficiency/%	Dark Rate /KHz	Linearity /10%, pe	P/V
2017	27.23	37.86	1285	7.10
2018	31.04	45.00	1352	7.03
2019	**31.86**	**36.92**	**1405**	**7.04**

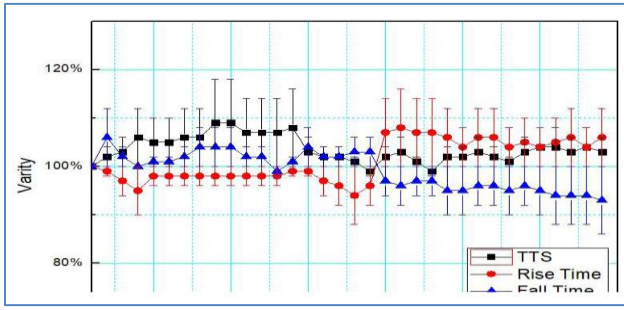


PMTs	Hamamatsu	MCP-PMT prototype	~300 MCP-PMTs	~1000 MCP-PMTs	~10000 MCP-PMTs	~11425 MCP-PMTs
Uni-QE @ 400nm	< 10%	< 10%	8.1%	7.8%	7.42%	7.38%





The Uniformity of the Photocathode



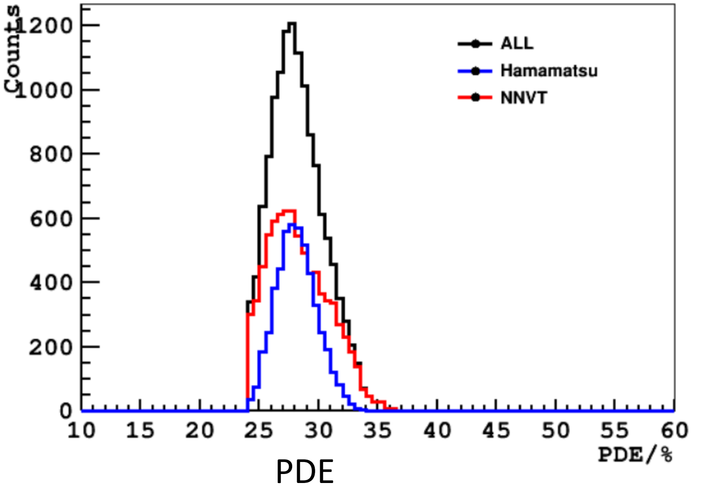
The TTS （FWHM）， RT， FT

20” PMT Instrumentation (1)

- PMT testing
  - 16000 (out of 20000) PMTs were delivered, including 11000 MCP PMTs from NNVT and 5000 dynode PMTs from Hamamatsu
  - Acceptance test for visual quality and performance up to the delivery
  - The average PDE reaches 28%

PDE	Mean（%）
All	28.2
HAMAMATSU	28.1
NNVT	28.3

PMTs @ Fanya test base



PDE

- Base
  - Production was started at Tianjin Centre company from June
  - So far, 4000 pieces have been delivered to Pan-Asia station, and 6000 pieces are under aging test

Base production

20” PMT Instrumentation (2)

- Potting
  - Potting lab. was fully prepared: 600 m^2 in size, 10 operators , 50 PMTs/day
  - Potting of JUNO PMTs started from July
  - So far, 500 PMTs have been potted, no leaking found after leakage test

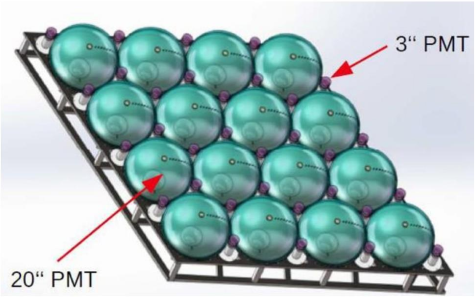
The potting process

PMTs after potting

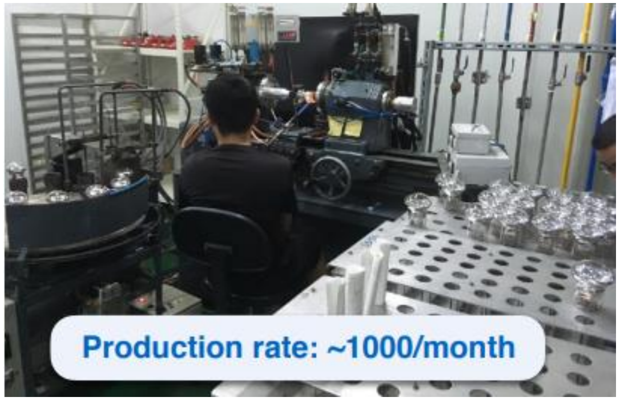
- Implosion protection
  - Testing with a PMT module shows no chain reaction and no damage to the module
  - Machining of the mold for cover production was started

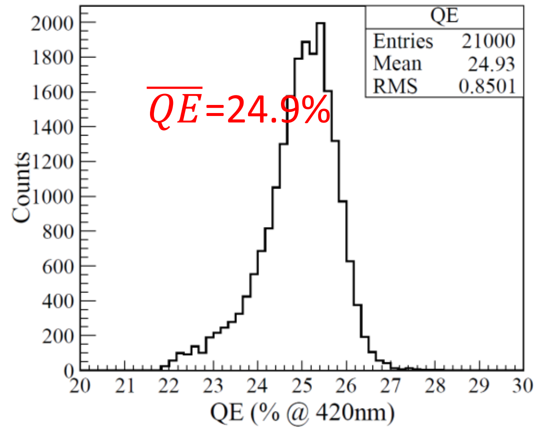
Implosion test with a PMT module

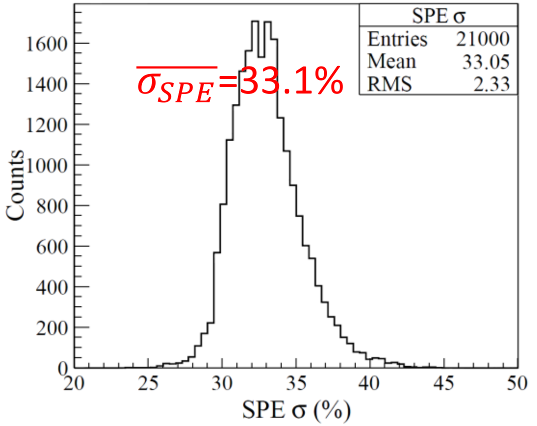
Small PMT system



- SPMT production and characterization
  - Stable production rate and quality
  - 21,000 out of 26,000 produced and tested so far, to be finished this year



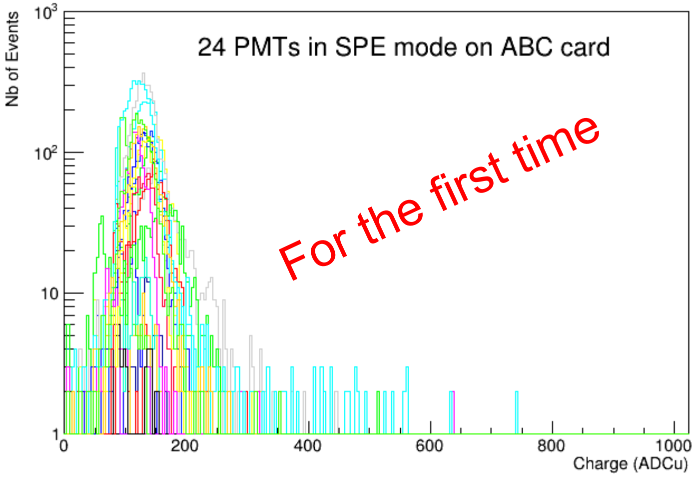




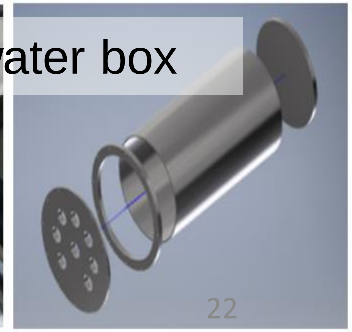
- SPMT instrumentation: production partially start
  - HV divider: 6,000 pieces produced, ~10% tested without any problem
  - Potting, cable and connector: FDR passed, PRR conditionally passed, mass production soon
  - SPMT acceptance test in Guangxi University: laboratory construction almost ready

Small PMT system

- Electronics
  - Catiroc Chip is OK for JUNO and 1,800 over 2,000 have been tested with success
  - Testing Firmware with ABC v0 for Guangxi is working ➔ testing station to be delivered in November
  - ABC v1 received and testing starts soon
  - SPMT-GCU started design with ABC and HV splitter interface
  - HV splitter exhaustively testing: everything OK
  - Full electronics architecture under discussion

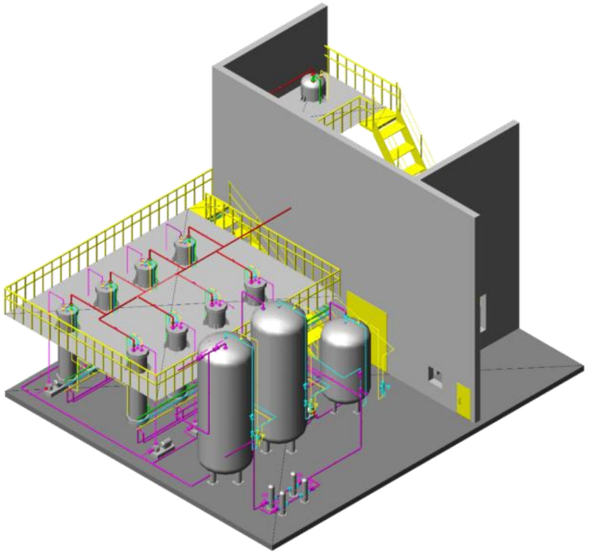


- Underwater box
  - Design finalizing: one removable lid with 3 O-rings
  - 10 prototypes produced and at intense testing stage, successful so far

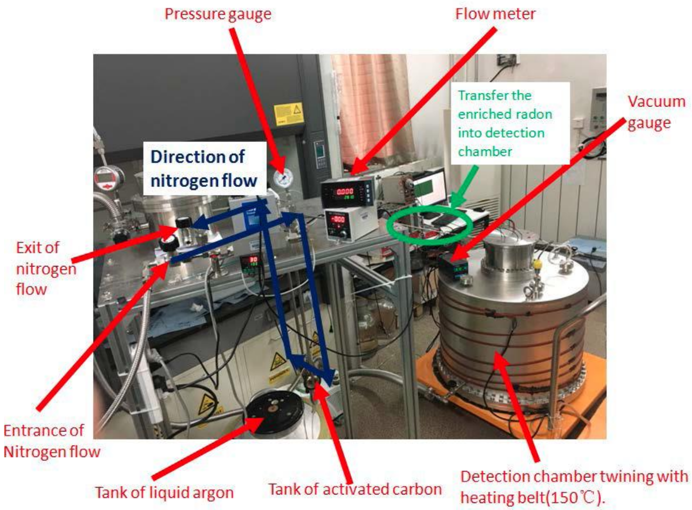



Liquid Scintillator

- The contract of LS surface building (including 5 kt LAB storage tank and pipes down to the detector） signed and passed the PRR. The onsite construction will start this December.
- The **Distillation** and **Gas Stripping** plants are under construction and in good shape.
- The contract of $\mathbf{Al_2O_3}$ column plant signed and will have PRR soon.
- The **Water Extraction** plant and LS Mixing system with **PPO purification** passed the Pre-bidding review and will start bidding this month.
- The radioactive background of raw PPO has been reduced from 8ppt to 0.5ppt.
- The pilot plant of **high purity** $\mathbf{N_2}$ system satisfied requirements, and PBR will start soon.



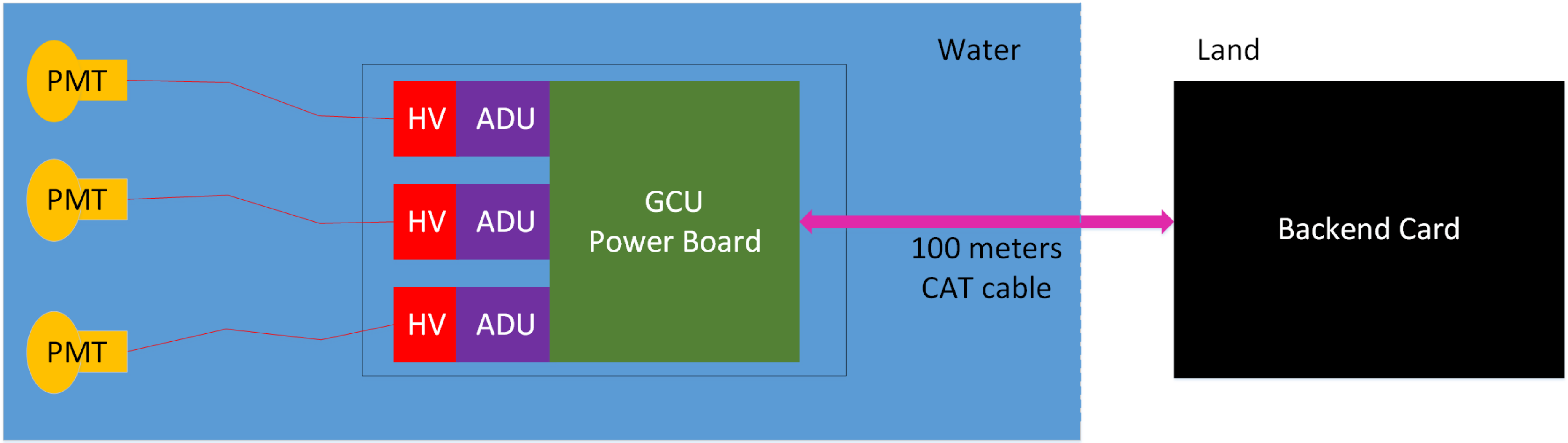
The Al_2O_3 column plant



The Rn enrich and measurement system

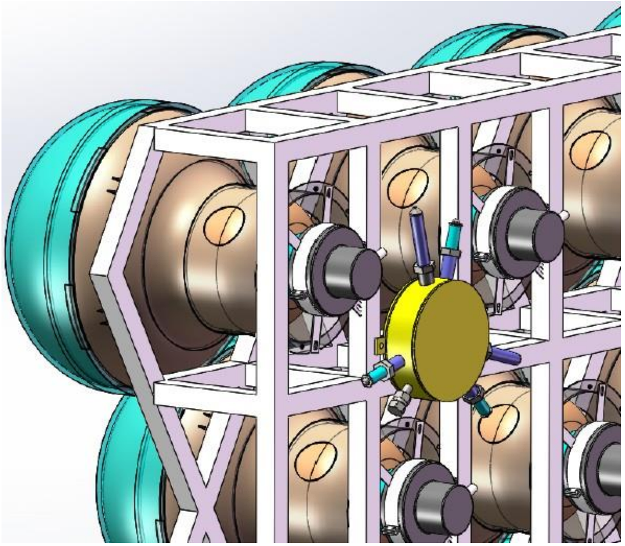
Readout Electronics

1F3 scheme



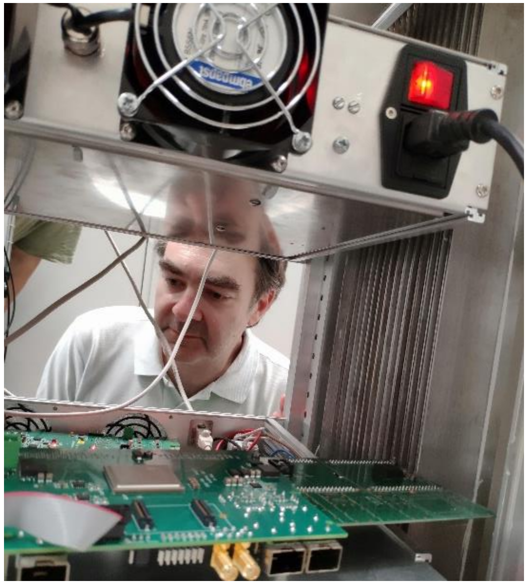
- PMT: photomultiplier tubes
- HV: High Voltage units
- ADU: Analog to Digital Unit
- GCU: Global Control Unit
- CAT cable: Category 5e cable
- High reliability needed
- Severe constraints by power consumption

PMT signals' waveform are read out by FADC, which is near PMT and guarantee the quality of the analog signals.

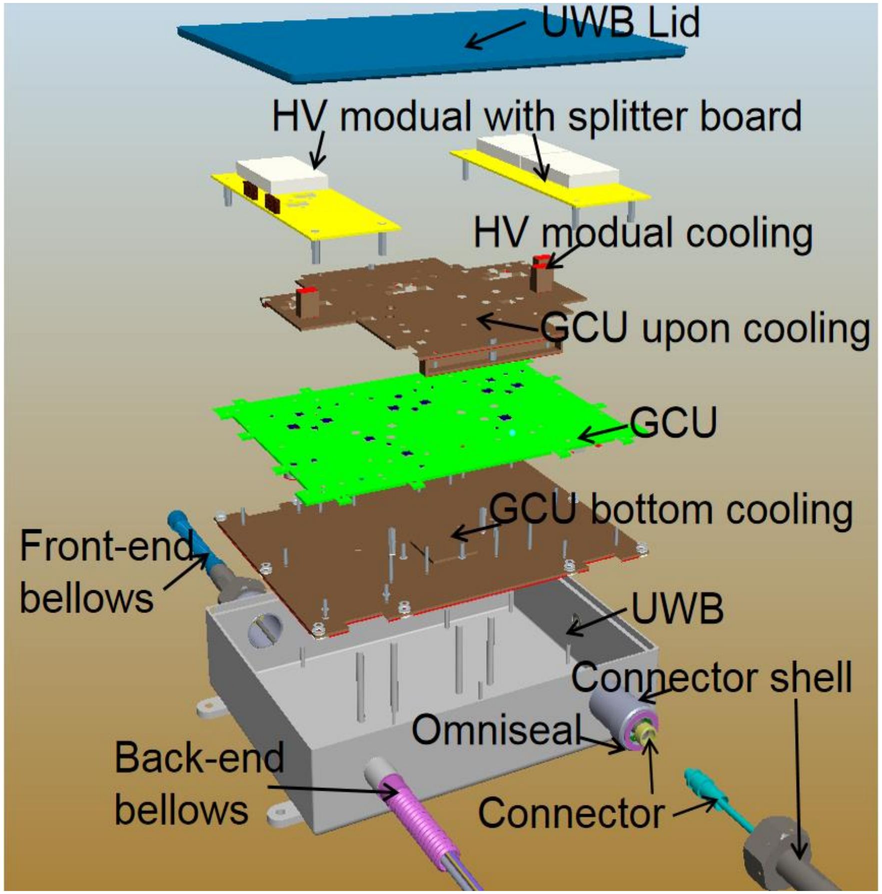


Electronics System

- HV already went into the production phase
- First full path of PMT-BASE-GCU-CABLE-BEC-DAQ worked
- Front end mechanical structure is in production phase
- Back end mechanical structure close to finish the design



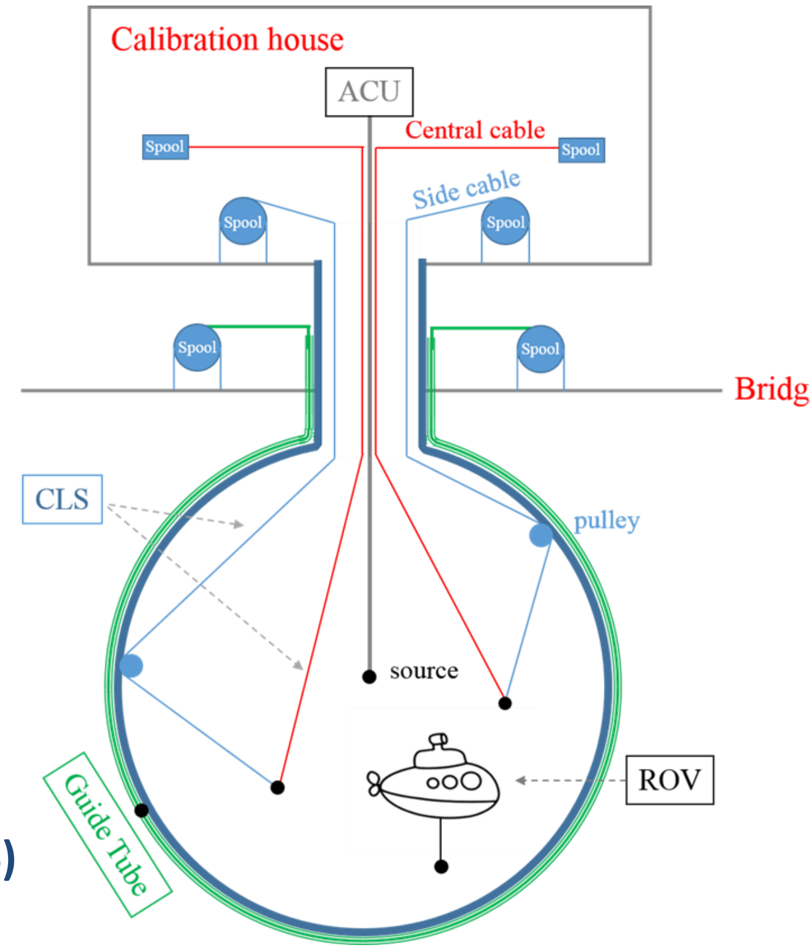
48-chs system running



Everything in electronics box

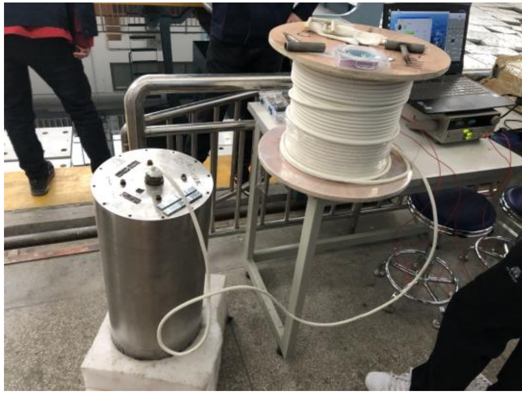
Calibration system

- **The goal:**
  - **Overall energy resolution: ≤ 3%/√E**
  - **Energy scale uncertainty: <1%**
- **Radioactive sources:**
  - **γ ： ^{40}K, ^{54}Mn, ^{60}Co, ^{137}Cs**
  - **e+ ： ^{22}Na, ^{68}Ge**
  - **n ： ^{241}Am-Be, ^{241}Am- ^{13}C or ^{241}Pu- ^{13}C, ^{252}Cf**
- **Four complementary calibration systems**
  - **1-D: Automatic Calibration Unit (ACU) → for central axis scan,**
  - **2-D:**
    - **Cable Loop System (CLS) → scan vertical planes,**
    - **Guide Tube Calibration System (GTCS) → CD outer surface scan,**
  - **3-D: Remotely Operated under-LS Vehicle (ROV) → full detector scan**

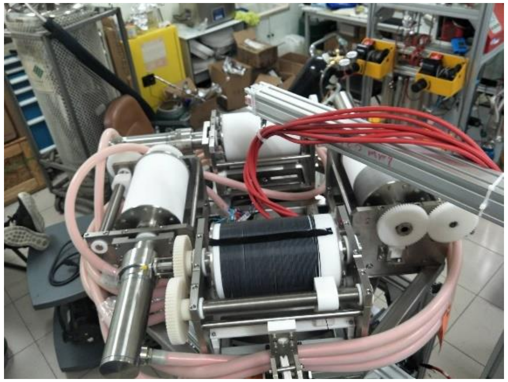


Calibration System

- **ACU:** Production of the bell jar has been completed and delivered. Main parts of hardware installation and software framework are ready, and extra optimizations are needed; Radioacitve source capsules testing is ongoing.
- **CLS:** Whole 4-m and 8-m , partial 18-m and 35.4-m CLS prototypes are investigated. Calibration strategy has established based on the tests;
- **ROV:** Submarine is ready; Zero buoyance cable suitable for LS is under design; More tests will be performed.
- **GTCS:** Whole system works smoothly in a 5-m mock-up test; Control software function test were completed.
- **Calibration house:** The bidding was completed.

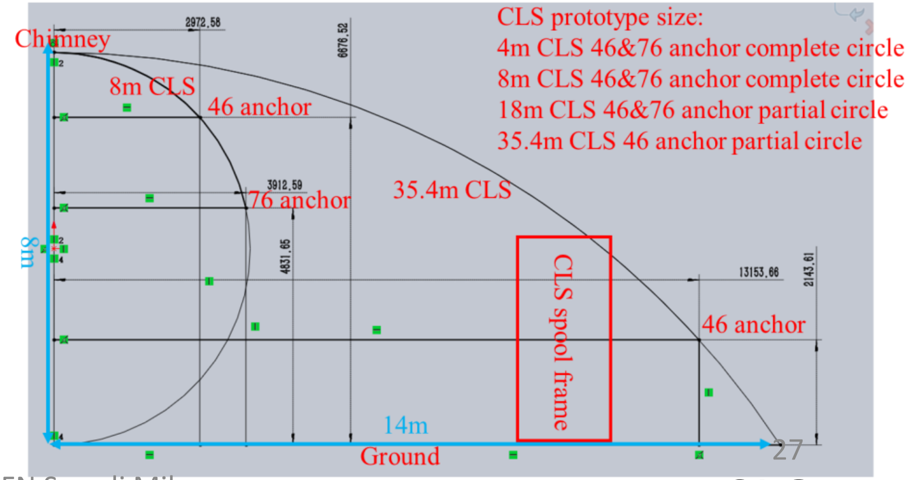


ROV



ACU

- **Software interface:** established communication protocols with DAQ and DCS considering the physics, calibration, supernova cases.
- **Hardware interface:** FDR of hardware were passed, and determined the interfaces with CD, TT and filling systems.

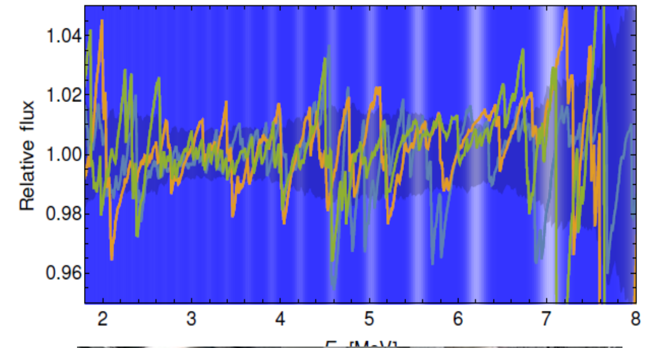


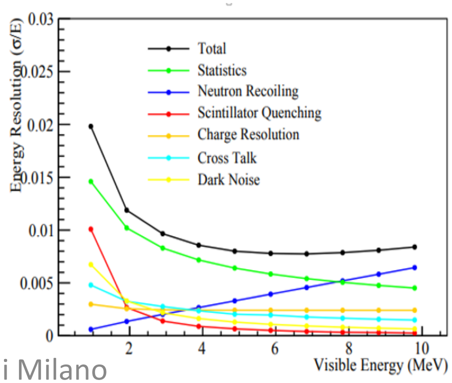
Section of experimental hall

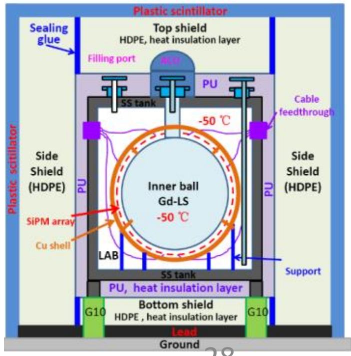
CLS

JUNO-TAO

- Goal
  - To guarantee that MH measurement will not be affected by fine structures of the spectrum
  - To measure reactor nu spectrum with highest resolution (1%) for nuclear data base studies
- Detector
  - Laboratory in a basement at -10 m, 30-35 m from Taishan core (4.6 GW)
  - 2.6 ton Gd-LS + 10 m^2 SiPM of 50% PDE
  - Whole detector Operate at -50 °C
- R&D Progresses
  - Recipe of LS works well at -50 °C
  - SiPM readout
  - Prototype at -50 °C ready for test
  - Ideal laboratory near the core
  - CDR ready in early 2020

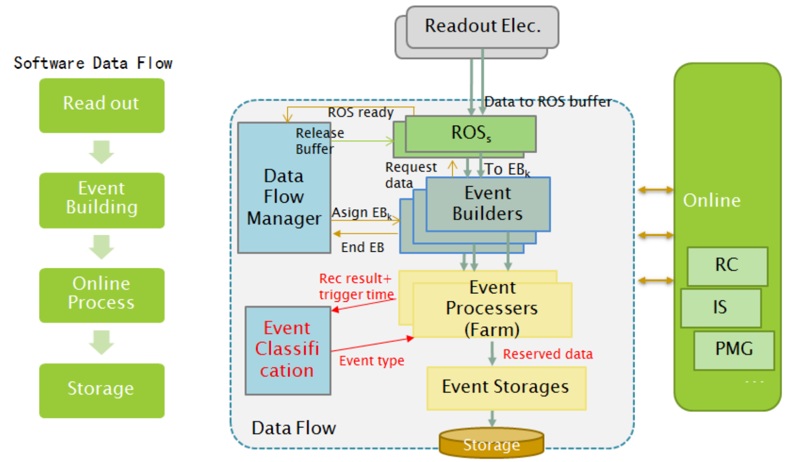


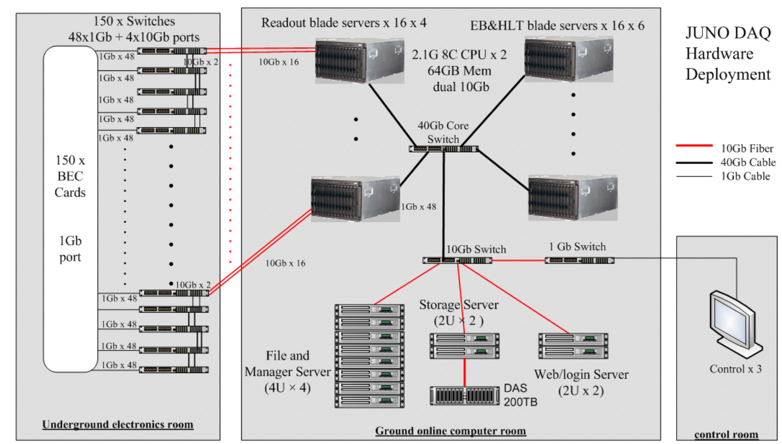


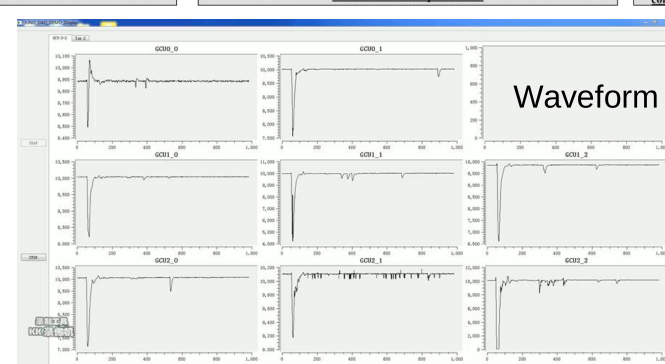


DAQ

- **Normal readout: 40GB/s, Links: 7000**
  - New hits data stream for MM and supernova
- **Major R&D finished**
  - Data flow meet requirements
  - New online software architecture design
- **Passed final design review**
  - Complete requirements of each subsystems
  - Final SW&HW architecture design
    - ✓ New data flow and data compression policy
    - ✓ New solution for MM and Supernova
    - ✓ New solution for automatic calibration
- **Joint test with electronics**
  - Basic readout function, readout -> 50MB/s per channel

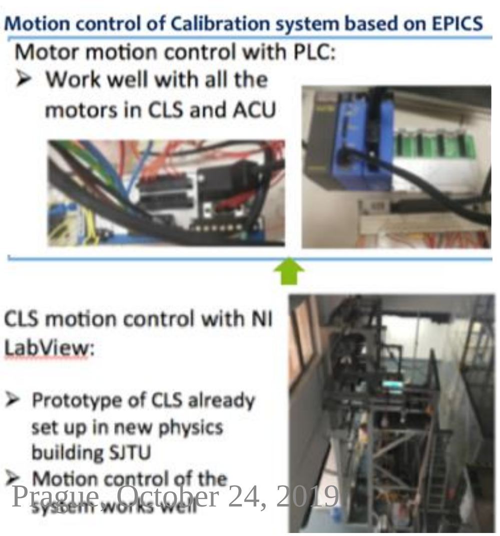




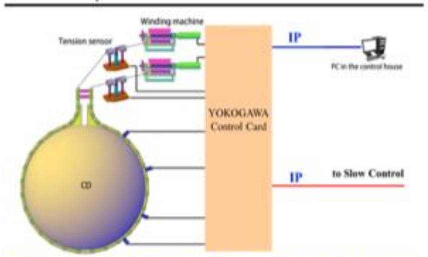


Detector Control System (DCS)

- Integration with subsystems
  - CD, Calibration, LS filling, LS purification， Veto， etc.
  - High Voltage and power control (26k PMT ch.+7k low voltage ch.)
  - Fiber based sensor of temperature & humidity
  - Function realization & PLC-EPICS driver development
- Database disaster tolerance： ~10k tables of 20TB storage self-healing
- Compatibility & simulation test
  - Simulation of the distributed IOCs: ~300k pv points
  - Compatibility Test of Operating System: SL6/6.5/7 CentOS 6/7
  - Protocol supported： Networked (TCP/UDP), Serial (RS-232, RS485), IPBus(PMT elec.), SNMP, GPIB (IEEE-488)， etc.
- Remote control: function realization of web based control & monitoring



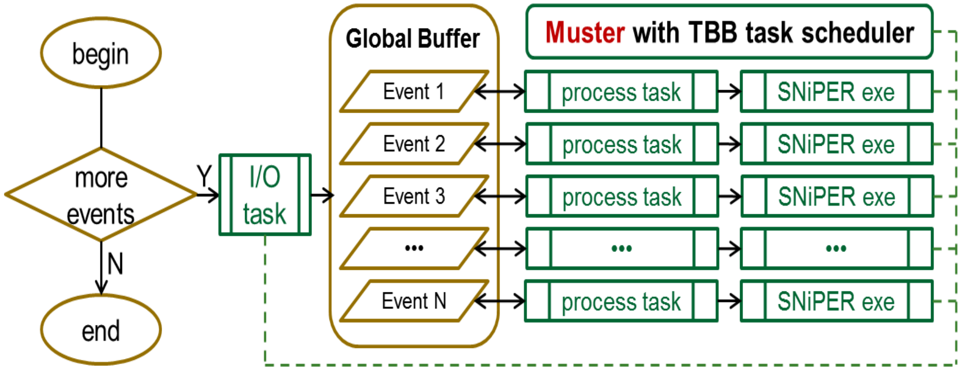
Data of GTCS	type	Number of channels
Position of motors	double	2
Source position	double	1
Position Sensor state	bool	20
Tension sensor output	double	2



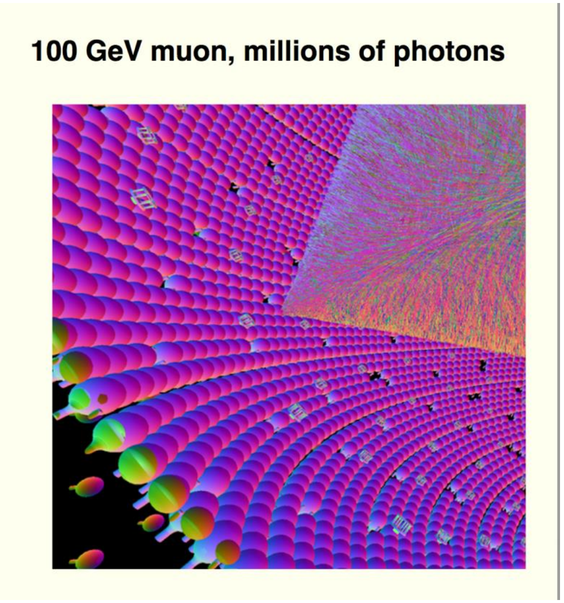
New prototype works well under new GTCS control system based on EPICS

Software and Computing (1)

- **Multi-threaded Software**
  - Multi-threaded software framework developed based on Intel Threading Building Blocks (TBB)
  - concurrent event processing by many worker threads
  - processing and event I/O synchronized by a Global Buffer

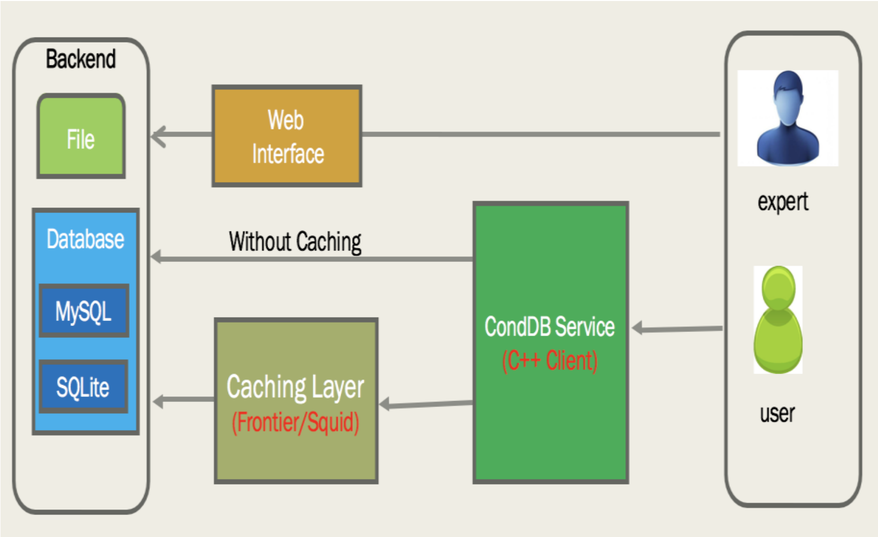


- **Simulation and Reconstruction**
  - More realistic simulation: updated geometry and PMT parameters from test measurements
  - Optical photon simulation speedup > 1000 times by applying state-of-the-art GPU ray tracing toolkit (NVIDIA OptiX)
  - Event reconstruction performance optimized and new deep learning approaches are being explored

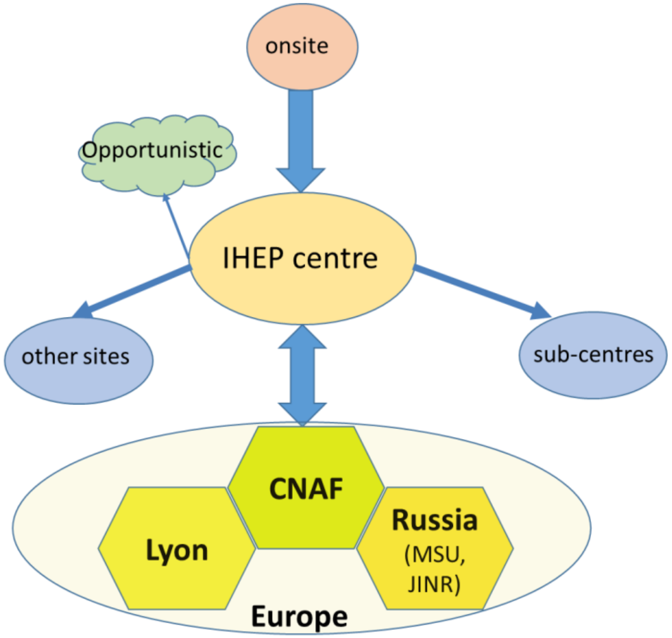


Software and Computing (2)

- **Calibration/Conditions Database**
  - Data model developed, including: Payload, Interval of Validity, Tag and Global Tag etc.
  - Management, access and retrieval applications developed
  - System is deployed and in use to develop calibration workflows.

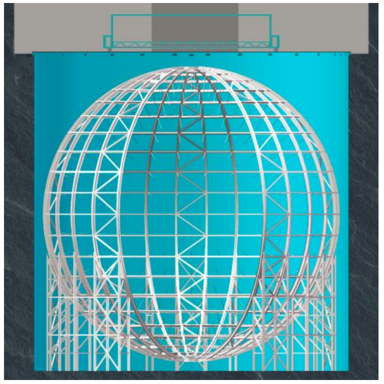


- **Distributed Computing**
  - Prototype integrating resources from CNAF, IN2P3, IHEP, and JINR was created based on DIRAC middleware software.
  - Software releases distributed via CVMFS
  - All data center representatives reached agreement on future roadmap at Shanghai meeting in Jan 2019.
  - Planning application to join LHCONE for improved network performance

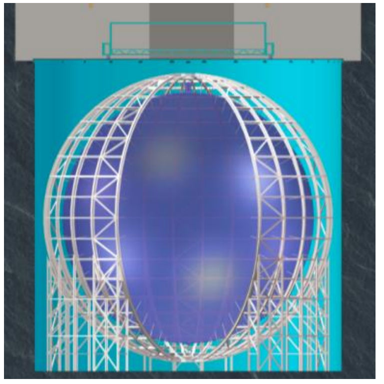


Installation

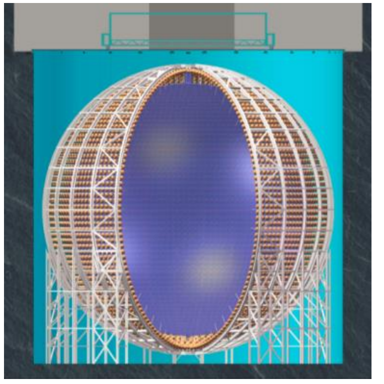
- Completed the final design review of Installation



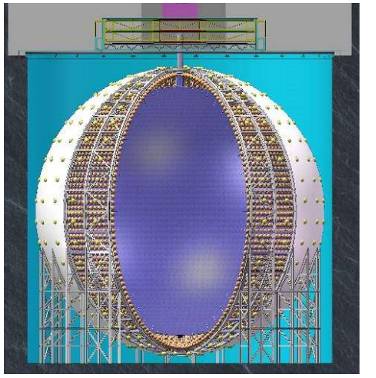
SS MAIN STRUCTURE



+ACRYLIC SPHERE



+PMT



+VETO+CALI.

SS Main Structure | Acrylic sphere | Clean | LS Filling

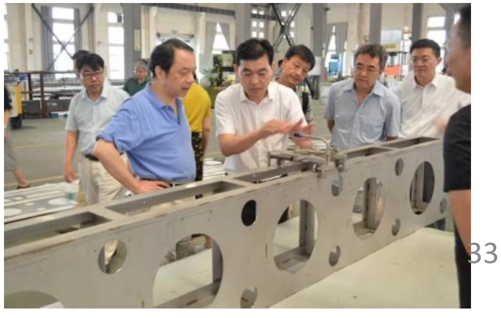
Acrylic sphere Installation platform

PMT Module

pool lining、Earth magnetic field shielding coils、Tyvek etc.

cover、Bridge、Cali.、TT

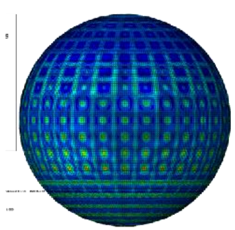
- Completed the production readiness review
- Completed twice installation tests
- Some On-site Facilities prepared



Milestone & schedule

2014:

- International collaboration established
- Start civil construction



2015:

- PMT production line setup
- CD parts R&D

2016:

- Start PMT production
- Start CD parts production

2017:

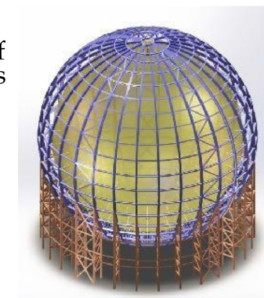
- Start PMT testing
- TT arrived

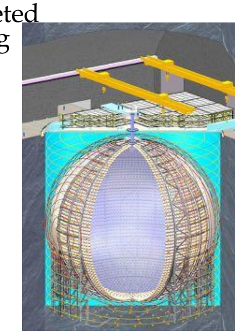
2018:

- 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





2021-2022:

- Detector ready for fill and Data taking!

Conclusions

- The JUNO experiment provides vast physics opportunities with its **large mass** and **unprecedented energy resolution**
- Neutrino Mass Ordering sensitivity in 6 yrs:
  - $>3\sigma$ and can **reach $>4\sigma$ with 1% constraint on $\Delta m_{\mu\mu}^2$**
- **Sub-percent measurement** of $\sin^2\theta_{12}$ Δm_{12}^2 and Δm_{ee}^2
- Near detector planned for precise reference reactor spectrum
- **Project well along the realization path**
- **All systems and subsystems designed and under construction**
- Detector ready for Fill and Data Taking : **2021 - 2022**

Back up

Method from Petcov and Piai, Physics Letters B 553, 94-106 (2002)

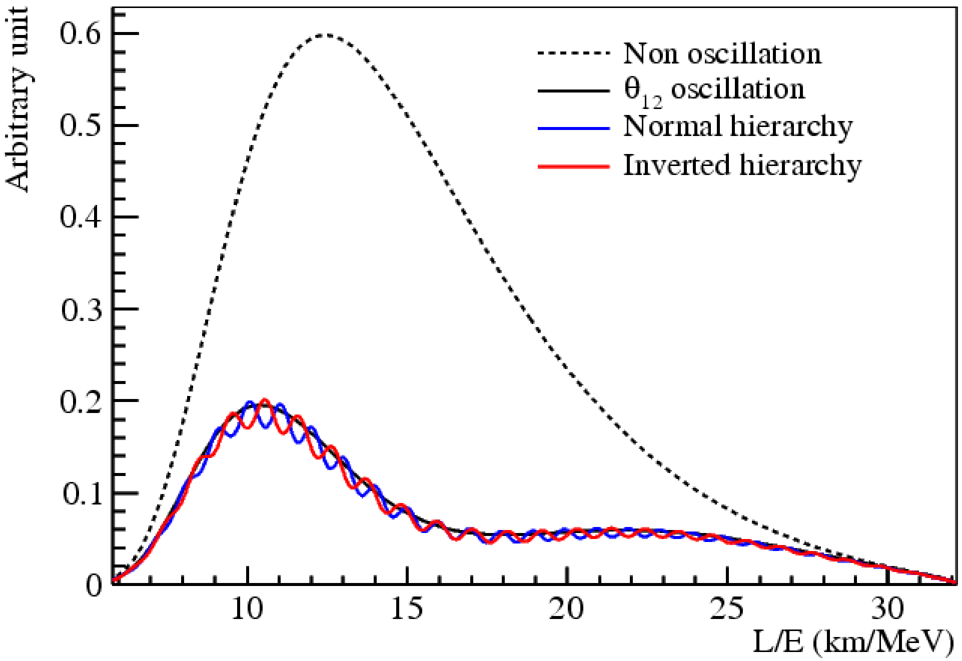
MH and Survival probability

arXiv 1210.8141

$$P_{ee} = \left| \sum_{i=1}^{3} U_{ei} \exp\left(-i \frac{m_i^2}{2E_i}\right) U_{ei}^* \right|^2$$

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

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E_\nu}, \quad (\Delta m_{ij}^2 \equiv m_i^2 - m_j^2)$$



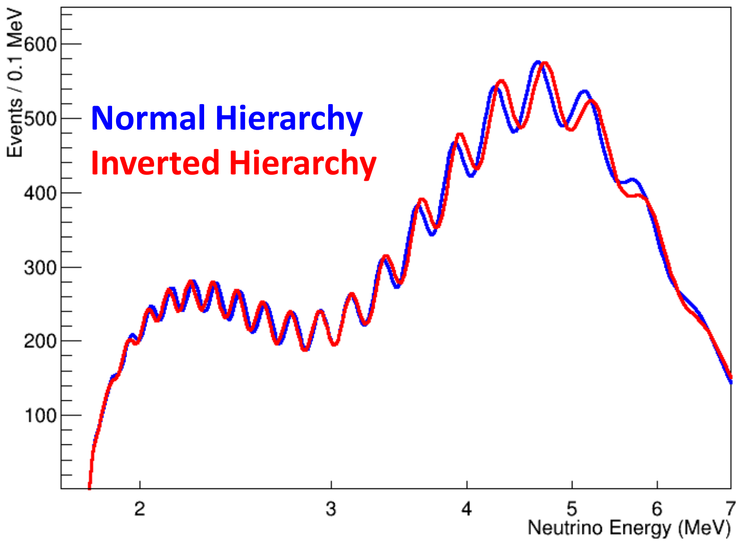
Or to make the effect of the mass hierarchy explicit, exploiting the approximation $\Delta m^2_{32} \approx \Delta m^2_{31}$:

$$P_{ee} = 1 - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(\Delta_{21}) - \sin^2 2\theta_{13} \sin^2(|\Delta_{31}|) - \sin^2\theta_{12} \sin^2 2\theta_{13} \sin^2(\Delta_{21}) \cos(2|\Delta_{31}|) \pm \frac{\sin^2\theta_{12}}{2} \sin^2 2\theta_{13} \sin(2\Delta_{21}) \sin(2|\Delta_{31}|),$$

+ NH
- IH

The big suppression is due to the "solar" oscillation → Δm^2_{21} , $\sin^2\theta_{12}$
The ripple is the "atmospheric" oscillation → $|\Delta m^2_{31}|$ from frequency
MH encoded in the phase
"high" value of θ_{13} crucial

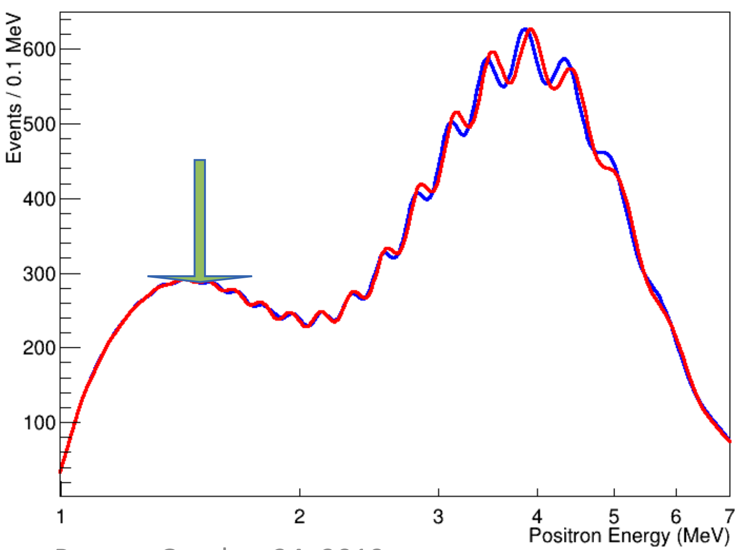
Example of Neutrino & Positron Spectra



Spectrum in term of neutrino energy – no energy resolution

Replicating sensitivity study in arXiv 1210.8141

- Three neutrino framework (no effective Δmee Δmμμ)
- Baseline: 50 km
- Fiducial Volume: 5 kt
- Thermal Power: 20 GW
- Exposure Time: 5 years
- **more pessimistic than the JUNO values**



Visible energy due to inverse beta decay

- E(vis) ~ E(ν) – 0.8 MeV
- Assuming 3% / sqrt(E) resolution
- Assuming negligible constant term in resolution

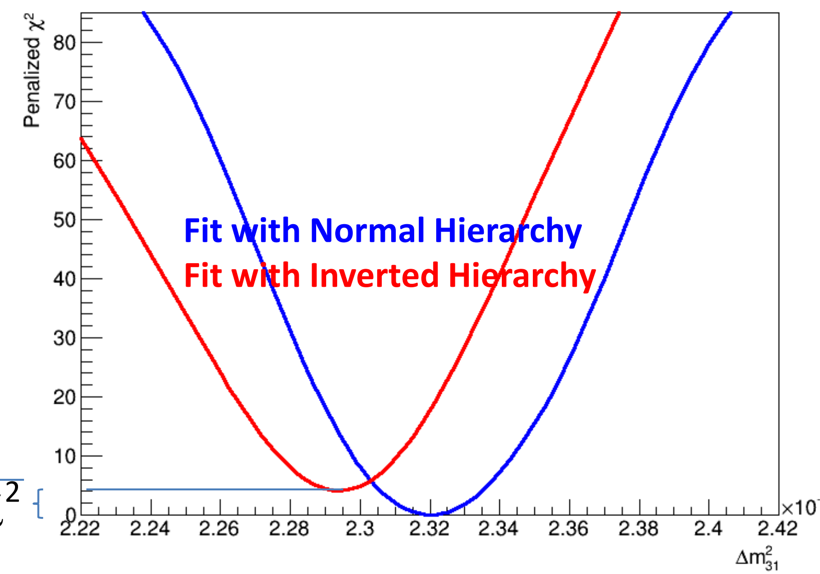
Spectrum in term of positron visible energy – with energy resolution

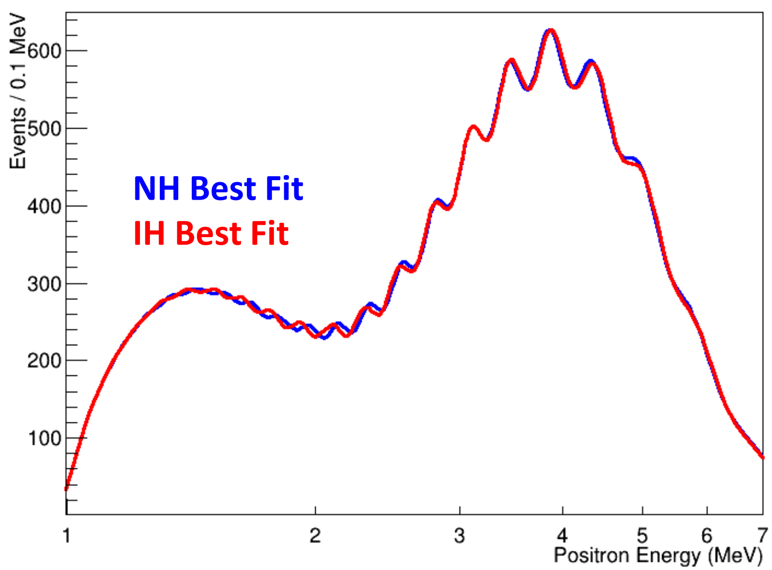
Example of χ^2 comparison – NH true

Numerical values as before
Scan of penalized (i.e. marginalized over the other minimization parameters) χ^2 vs. $|\Delta m^2_{31}|$

Case NH true- average spectrum
(no fluctuation –**Asimov data set**)
Test statistics → $\Delta\chi^2=\chi^2_{min}(NH) - \chi^2_{min}(IH)$

Fit NH minimum: 1.6 10^{-2} (practically 0)
FIT IH minimum: 4.0
$\overline{\Delta\chi^2}$ ~4.0





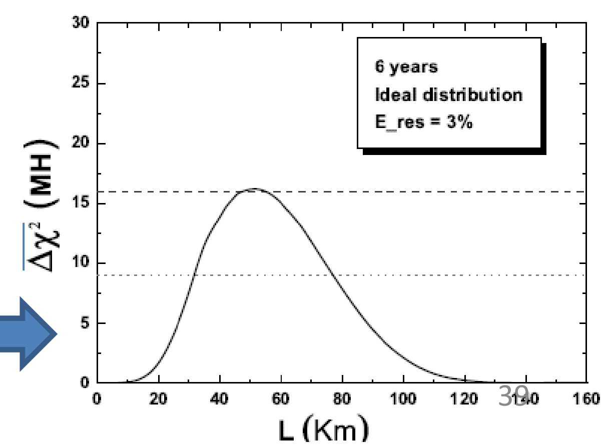
Comparison between IH/NH best fits

The best fit $|\Delta m_{31}|$ is different in the two cases

Fit almost succeeds in accommodating IH spectrum to NH data

The two solutions are fully degenerate but in a limited range of distances

Optimum distance to maximize $\overline{\Delta\chi^2}$

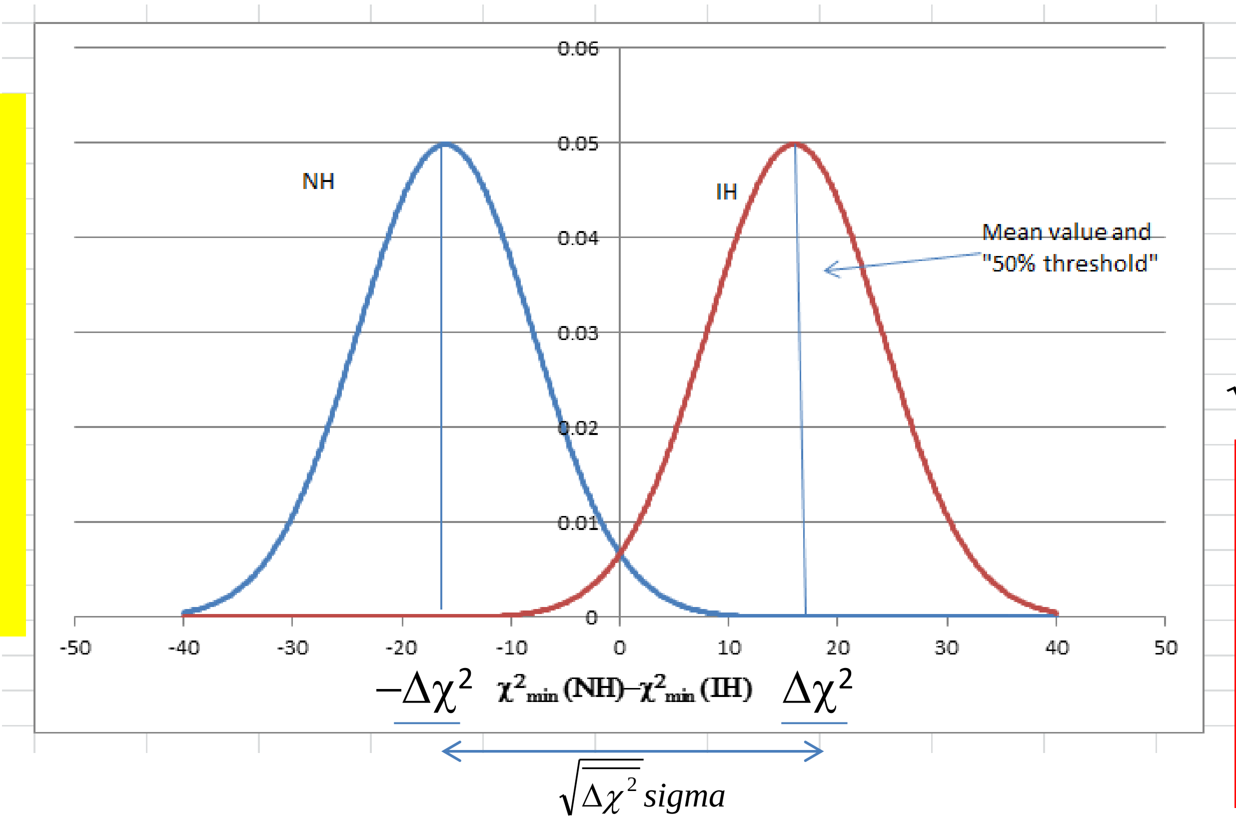


From arXiv:1303.6733v1 [hep-ex] JUNO
$\overline{\Delta\chi^2}$ can be as high as **16** @ 53 km

Distribution of test statistics and number of sigmas for discovery

- **Not unique answer**
- It depends upon the assumed framework (**frequentist or Bayesian**)
- However the actual information is fully encoded in the amount of overlap of the two Gaussian independently from how it is summarized as number of σ
- General result: sigma of each Gaussian = $2\sqrt{\Delta\chi^2}$ **arXiv: 1210.8141v2**

The mean value of the Gaussian curves is taken as representative of the **JUNO** capability at 53 Km arXiv:1303.673



The mean values of the two curves are displaced of exactly

$\sqrt{\Delta\chi^2}\, sigmas$

Assumed in a frequentist framework as quantification of discovery capability

arXiv:1311.4076

Frequentist considerations for the number of σ

The special relation between sigma and mean value of the two distributions implies that the median sensitivity according to the frequentist framework is automatically equal to

$$\sqrt{\Delta\chi^2}\,\sigma$$

This means that if the actual outcome of the experiment is more extreme than the expected mean value one get a positive indication for one of the two hierarchies (IH if the outcome is positive or NH if the outcome is negative) with a CL better than $\sqrt{\Delta\chi^2}\,\sigma$ i.e. with a probability of making a mistake (type I error according to the statistical terminology) equal to the corresponding one-tailed p-value on the Gaussian curve

3 σ → p-value (1-0.9973)/2 instead of the standard 1-0.9973

In summary for JUNO

- If the outcome is as typically expected, the MH will be determined rather unambiguously
- Even better if there will be an upward fluctuation
- A downward fluctuation will produce an ambiguous result

With these characteristics JUNO can achieve a 4 σ sensitivity with the above meaning (spectrum with about 100000 events) →

Baseline: 53 km

Fiducial Volume: 20 kt

Thermal Power: 36 GW

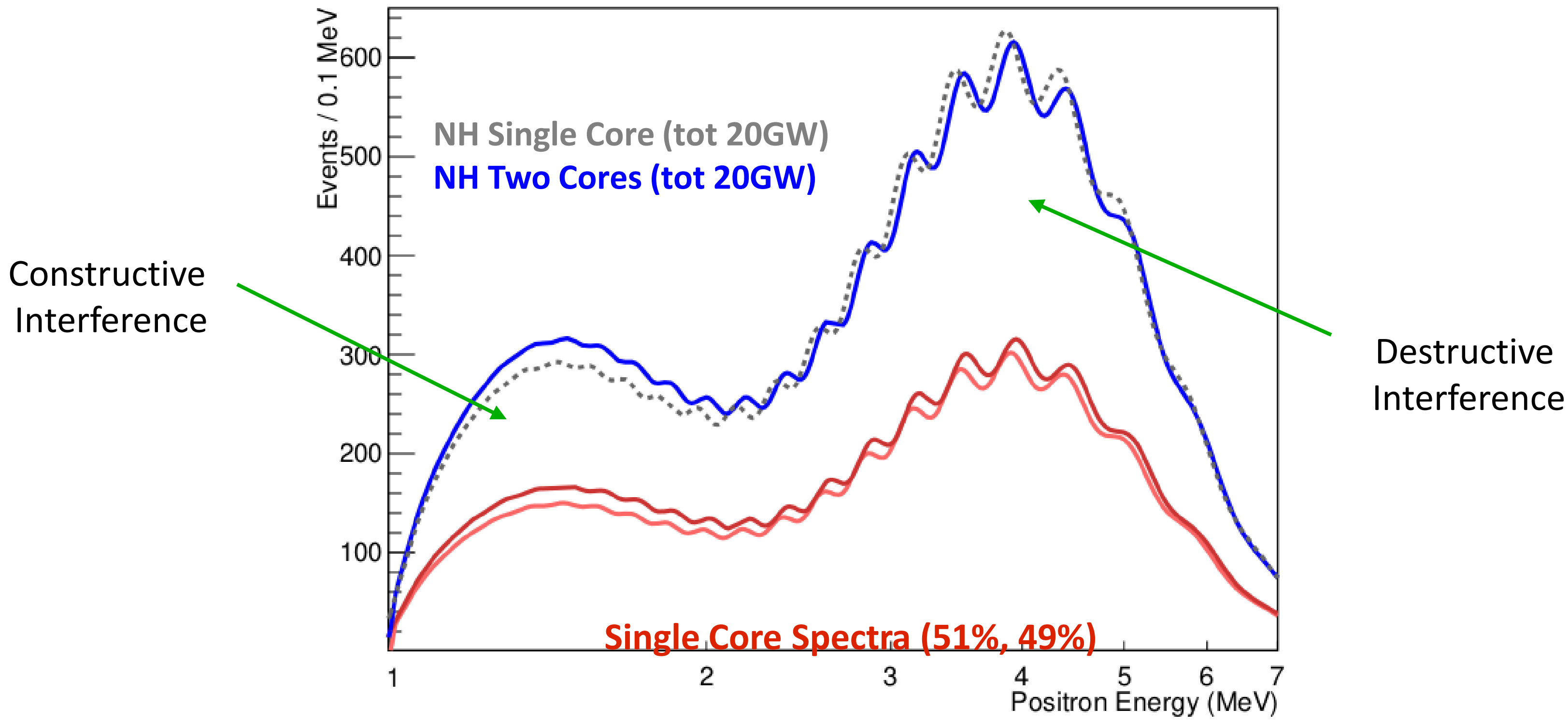
Exposure Time: 6 years

Proton content 12% in mass , en. res. 3%

Caveat: Multiple Cores

Reduction in sensitivity might arise from actual spatial distribution of nuclear reactor cores

Eg. two cores with 51% (49%) of tot. power, placed at 50 km (50.5km) distance from detector

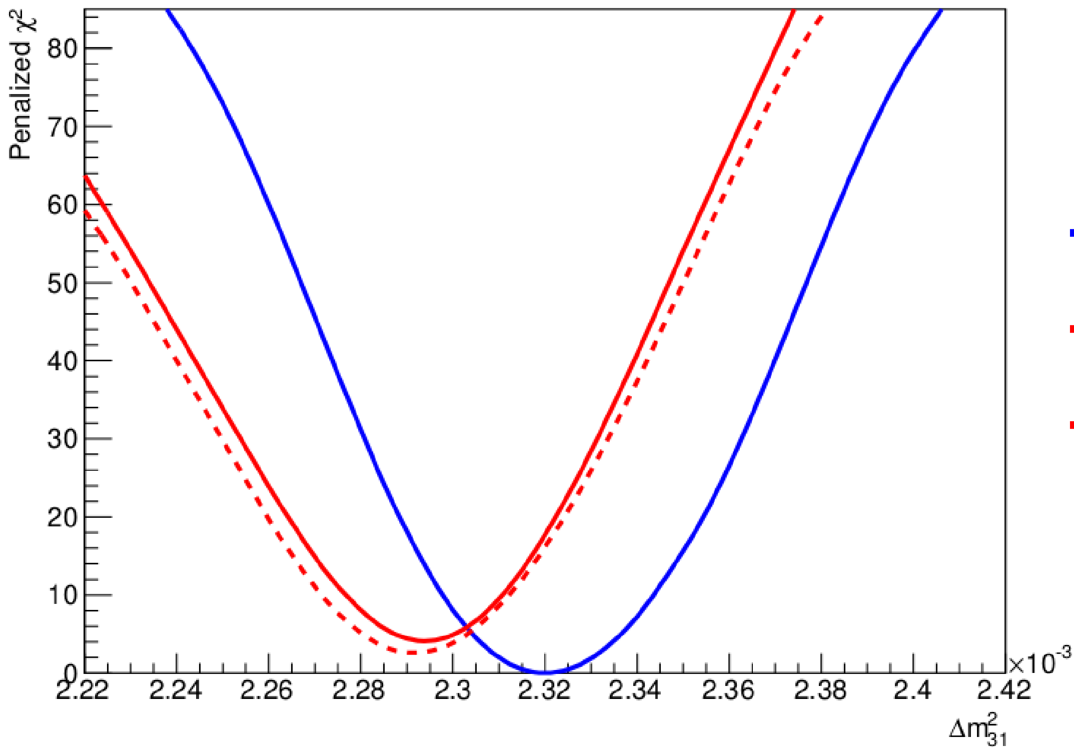


Baseline difference results in destructive interference in the most sensitive region of the spectrum

Important effect since JUNO will detect neutrinos from several cores

Multiple Cores: χ^2

Sensitivity loss is measured through the new χ^2 minimum



For JUNO this defines the location (only two reactors) and the maximum baseline difference : 500 m

$\overline{\Delta\chi^2}$ between IH and NH in this numerical exercise is reduced from 4.0 to 2.6

In the JUNO set-up the spread of the cores is 500 m $\rightarrow$ $\overline{\Delta\chi^2}$ reduction of about **3**

Other effects

❖ Adverse effects

- **Non linearity of the energy scale**

  This clearly impacts the ability to distinguish the true from false Hierarchy since distorts the experimental spectrum, therefore a very careful calibration is required better than 1% **arXiv:1307.7419**, as well as the long term stability of the detector - see also **arXiv:1508.01392**

Other experiments already achieved <1% accuracy

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

- **Reactor shape uncertainty** (1%) ➡ more on this later
- **The statistical and shape uncertainties of backgrounds**

❖ Favorable element for analysis

Improved knowledge of $|\Delta m_{31}|$ by other experiments specifically T2K and NOνA ~1%

Exploited by adding a pull in the χ^2 definition thus increasing globally the $\overline{\Delta\chi^2}$

This is better done using the effective parameter $|\Delta m^2_{\mu\mu}|$

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

❖ In conclusion arXiv:1303.6733v1 demonstrates that JUNO can reach the value $\overline{\Delta\chi^2}$ in the range 15-20 ➡ **crucially dependent upon the resolution (this assumes 3%) which is by far the challenge of the experiment**

Energy non linearity and residual energy scale uncertainty

Implications thoroughly discussed in the JUNO Yellow Book arXiv:1507.05613

The loss on $\overline{\Delta\chi^2}$ depends upon the assumed form of the residual non linearity and also on the procedure to deal with in the χ^2 computation - this is why is not included in the summary table $\rightarrow$ main message : calibrate as better as possible (sub percent level)

A general approach to deal with this issue devised in arXiv:1508.01392

- based on the knowledge of the residual uncertainty band and on the introduction of a corresponding pull in the χ^2 definition

Example: residual energy scale uncertainty in Day Bay calibration

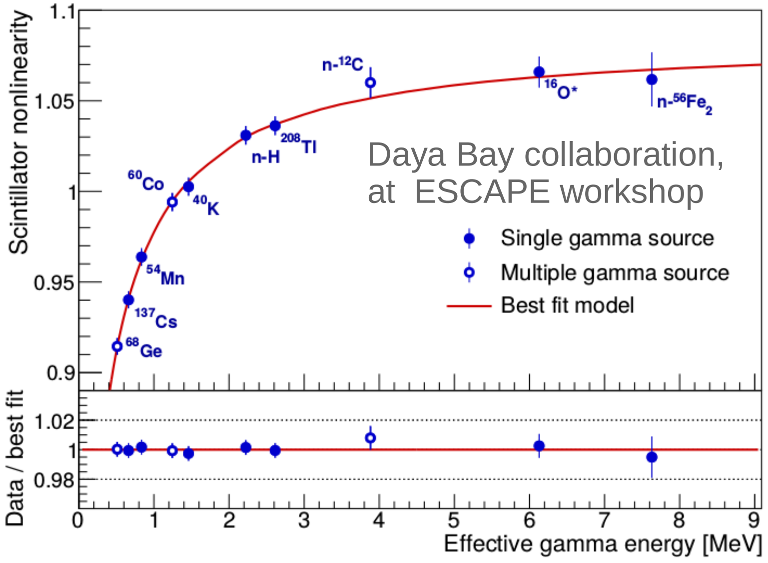
How to Control the Energy Scale Uncertainties

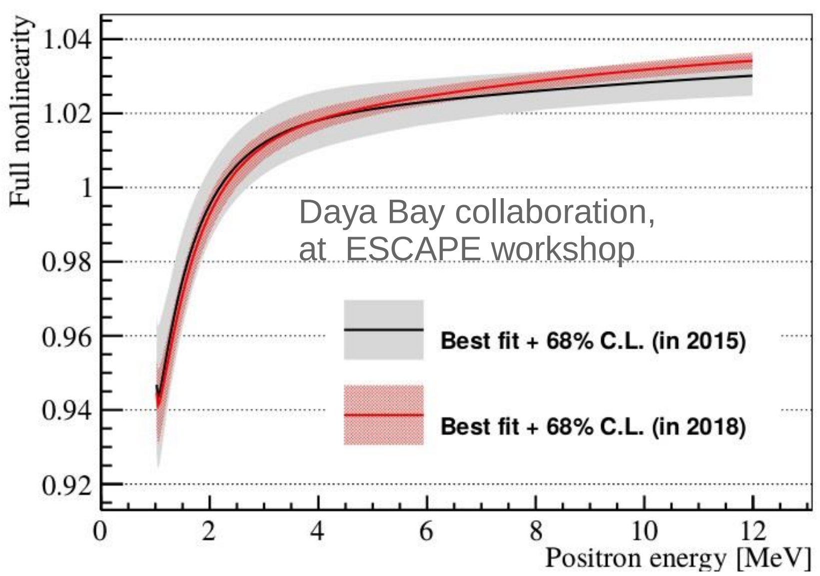
With accurate and extensive calibration procedures

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

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

New calibration results from Daya Bay at ESCAPE workshop @Heidelberg June 2018

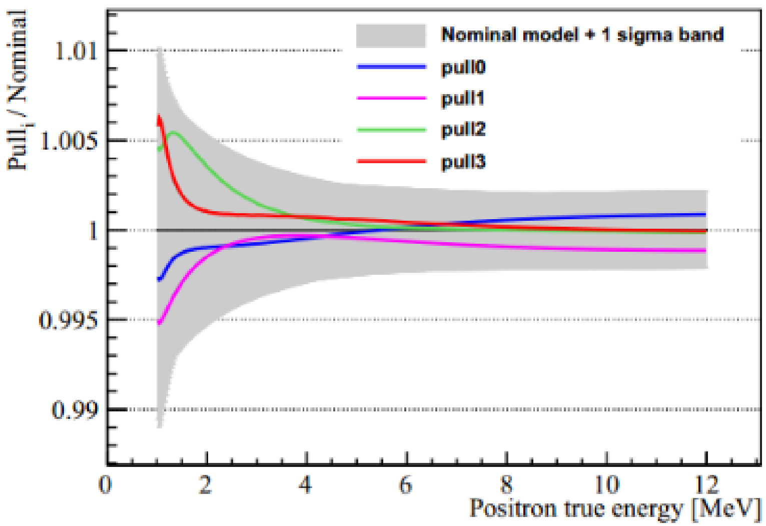




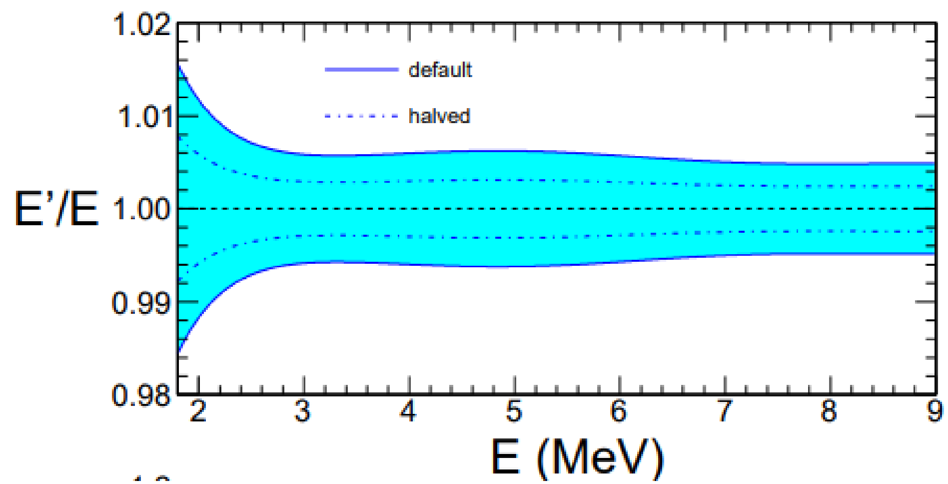
Uncertainty band substantially shrunk in this recent release

Impact of energy scale uncertainty

Updated Daya Bay relative uncertainty



Uncertainty in arxiv:1508.01392



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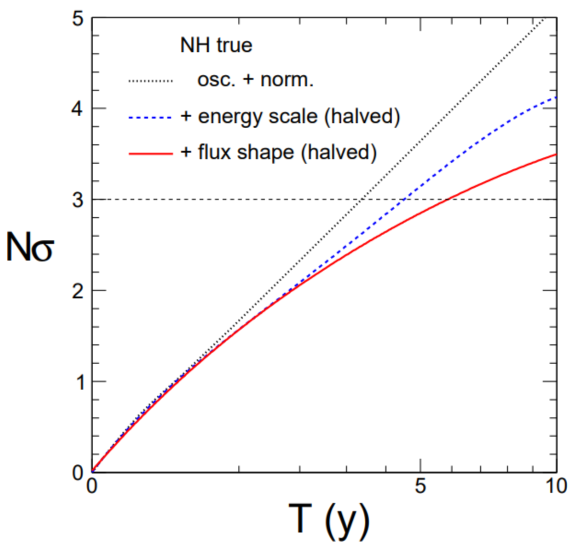
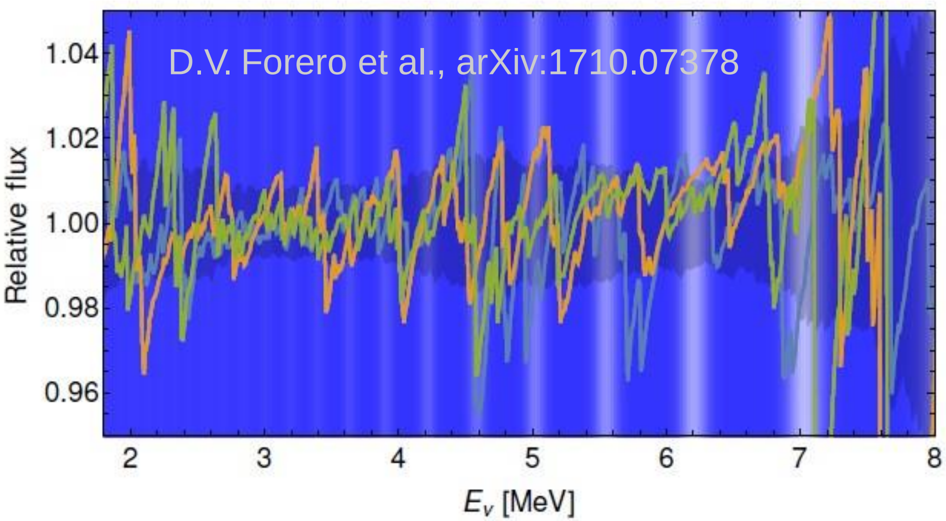


The updated uncertainty band from Day Bay at Escape (top left) is close to the reduced band assumed in arXiv:1508.01392 (top right) the corresponding calculation in the same paper is on the left (dashed line)

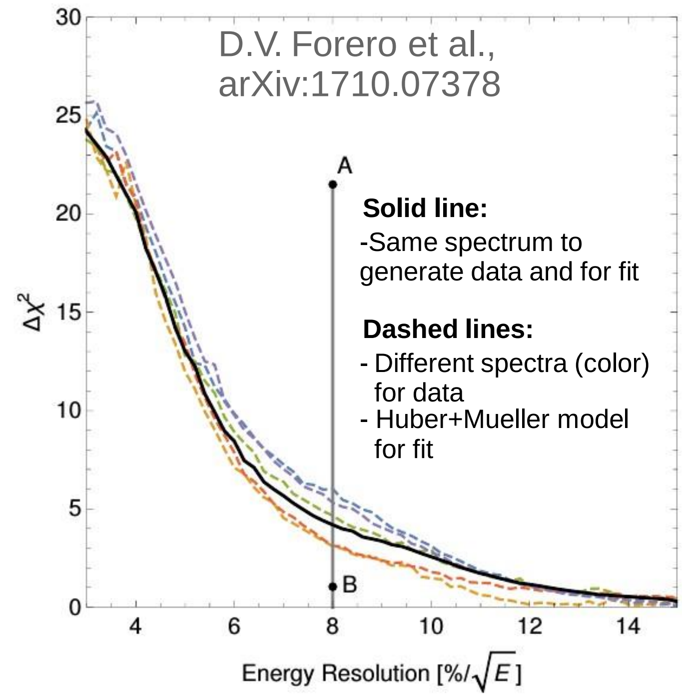
→ The impact on the MO sensitivity is modest and confirms that with proper calibration the effect of the energy scale uncertainty can be taken under control

Implications of the reactor shape uncertainty

- "Standard" reactor shape uncertainty has minor impact on the sensitivity
- But reactor spectrum might show micro-structures
  (see e.g. A.A.Sonzogni, et al. arXiv:1710.00092, D. A. Dwyer &T. J. Langford, Phys. Rev. Lett. 114,012502 (2015))
- micro-structures might degrade the MH sensitivity by mimicking periodic oscillation pattern



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



of reactor spectrum measurement

→ Reactor spectrum with energy resolution at least similar to JUNO avoids in principle this potential issue

Experimental hall

Access tunnel to the experimental hall

One of the service tunnels

R&D about acrylic

- **How about the life time of acrylic?**
  - Strength reduce to ~70% for 20 years @ 5.5 Mpa
  - Creep: over 100 years
- **Can the spherical panel be made?**
  - 3 companies made samples
  - 2017.2 Donchamp won the bid.
- **How about the max stress control on acrylic?**
  - ≤ 3.5 Mpa, less than 5 Mpa in Daya Bay
- **How strong the acrylic node need to be?**
  - Max pulling load: ~ 8 tons
  - Break at load: ~100 tons
- **How to control the radiation back- ground and the quality of acrylic?**
- **How to make the bulk-polymerization on site**

Thermoforming the spherical panel: 3m x 8m x 120mm

Test for bulk-polymerization

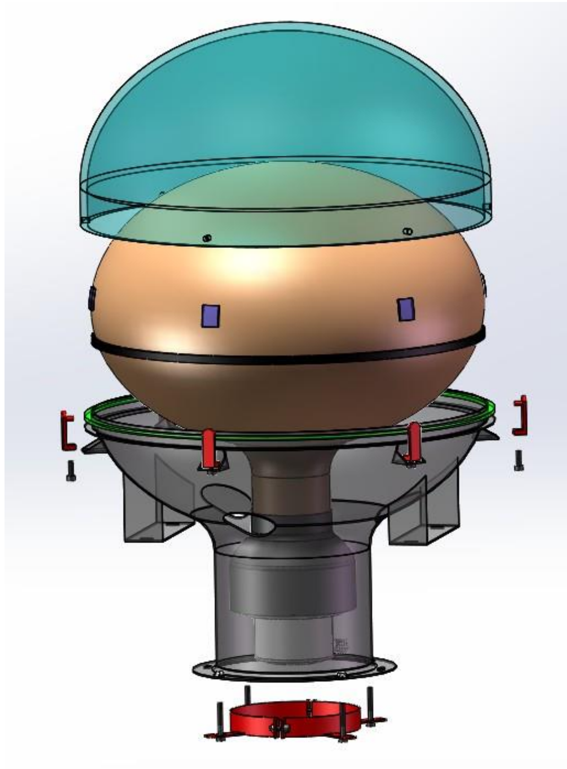
Load test of node: break at 100 tons

1:12 prototype

Photomultipliers

- **15000 MCP-PMTs from NNVT** (Northern Night Vision Technology)
- **5000 dynode PMTs from Hamamatsu**
- **In production since 2016**
- **About 10000 delivered**
- **More than 6000 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

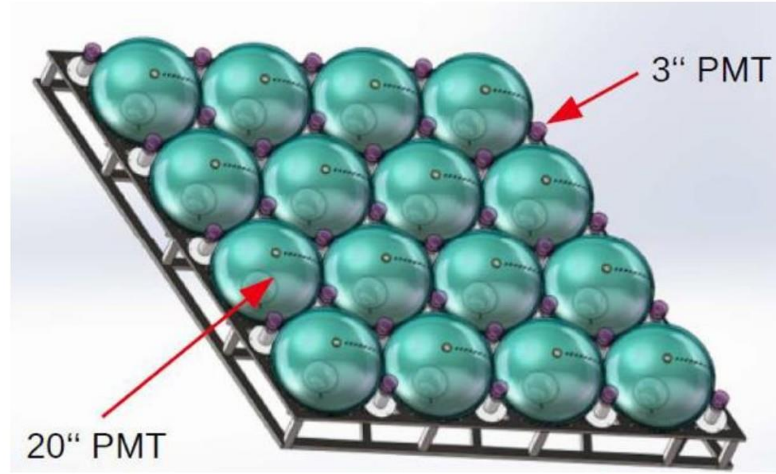


JUNO PMT with implosion protection cover

New HQE MCP-PMT this year: **another 10% improvement** in PDE 27%->30%

Average PDE of HAMAMATSU 28%

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)

Detector Resolution: $$\frac{\sigma_E}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2}$$

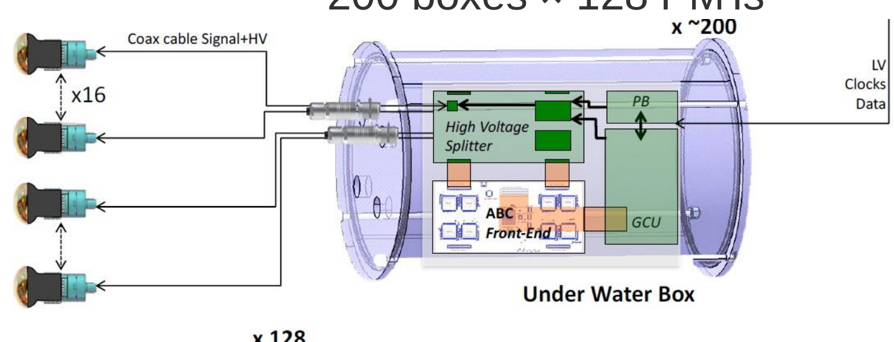
b and *c* non stochastic terms

- **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

Veto Detectors

- **Cosmic muon flux**
  - Overburden: ~700 m
  - Muon rate: 0.003Hz/m^2
  - Average energy: 214 GeV
- **Water Cherenkov Detector**
  - ~4 m water shielding, Radon: <0.2 Bq/m^3
  - ~2000 20”PMTs
  - 40 kton pure water, HDPE lining on pool
  - Similar technology as Daya Bay (99.8% efficiency)
- **Compensation Coil for EMF shield**
- **Top muon tracker**
  - Decommissioned OPERA plastic scintillator

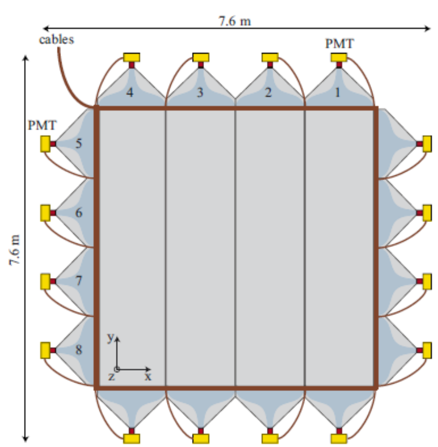
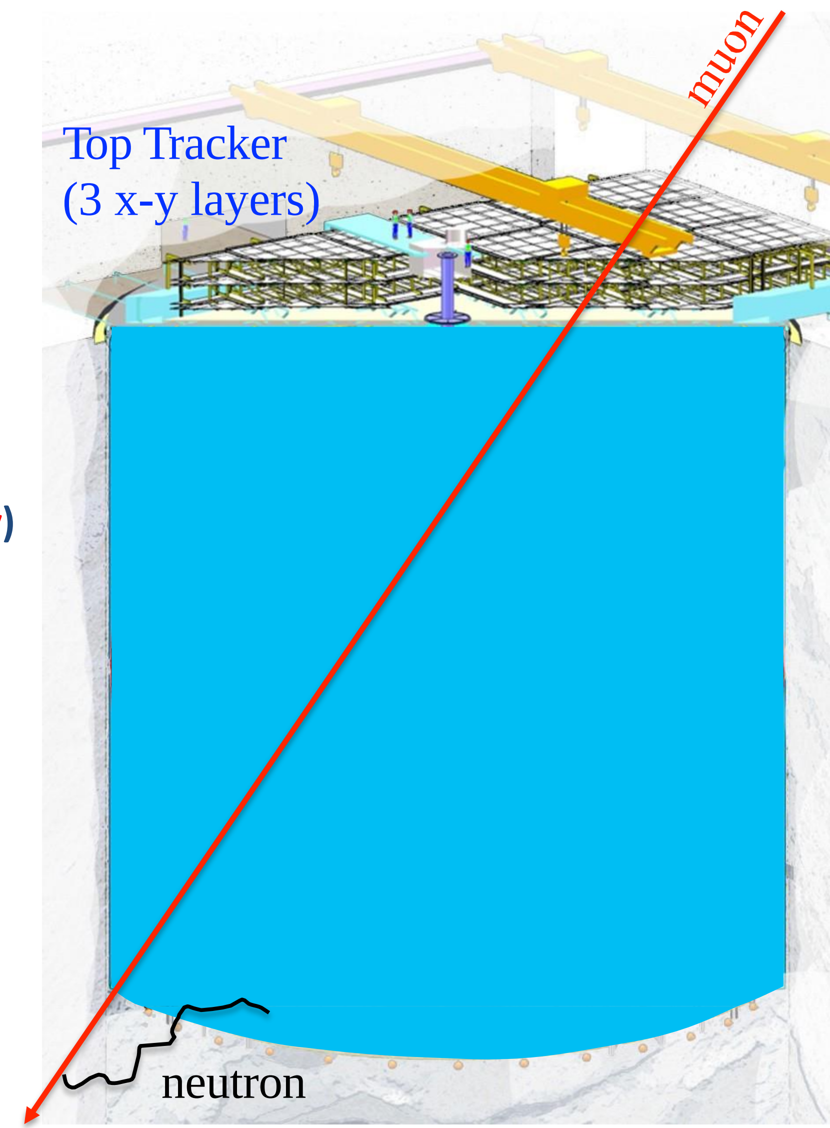


Fig. 3. Schematic view of a plastic scintillator strip wall.



Scintillator

- **Requirement for 3%/√E**
  - High light-yield:~10^4 photons/MeV
  - High transparency:

    Attenuation Length (A.L.) > **25m** @430nm

- **Purification pilot plants**
  - Check of purification effectiveness U/Th/K and radioactive gases
  - Targeted at least **10^{-15} g/g**
  - Under operation at Daya Bay
  - Distillation, Al_2O_3 column purification, water extraction and gas stripping
  - > **25 m** A.L. after filling (measured)
  - Optimizing LS recipe
  - Studying radio-purity
  - Same plants scaled for JUNO