

JUNO Oscillation Physics Program



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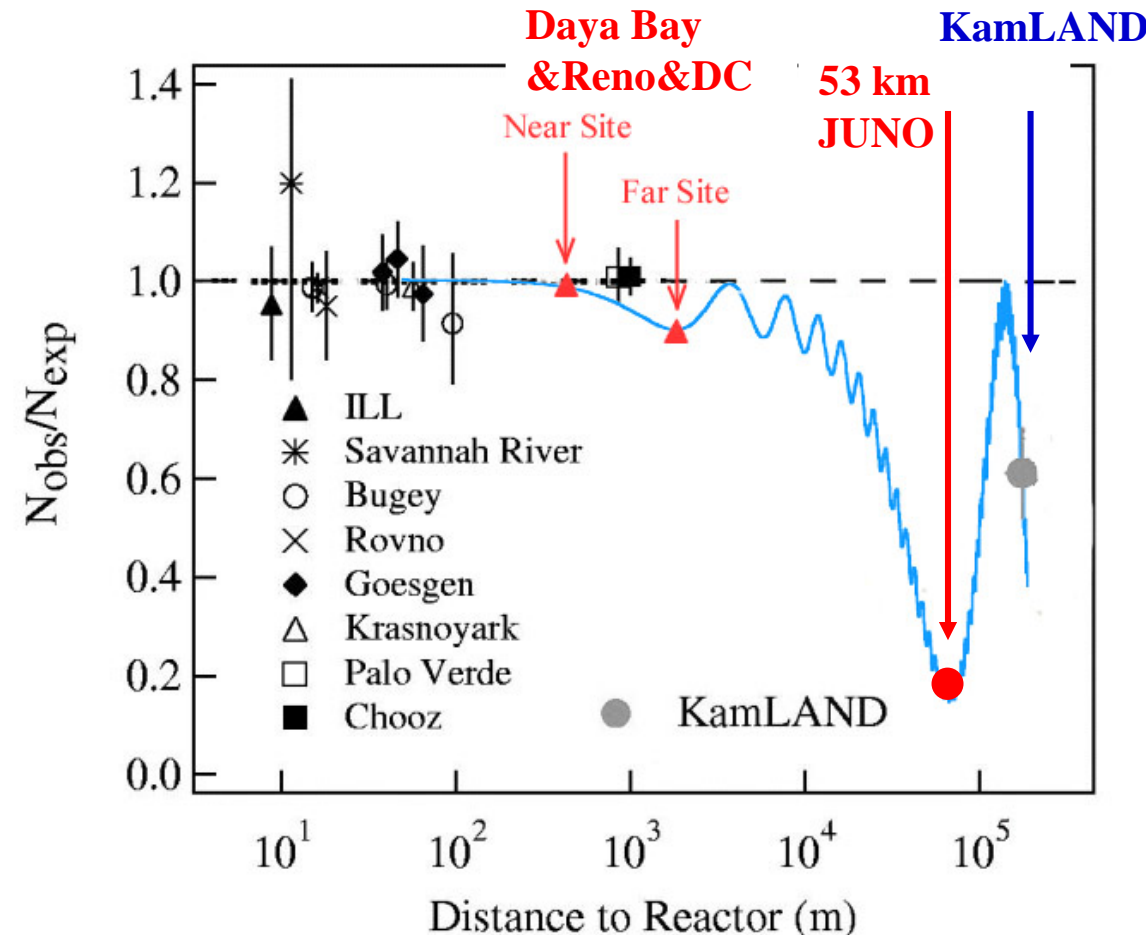
NOW 2018
September 11, 2018

Rosa Marina (Ostuni, Italy)

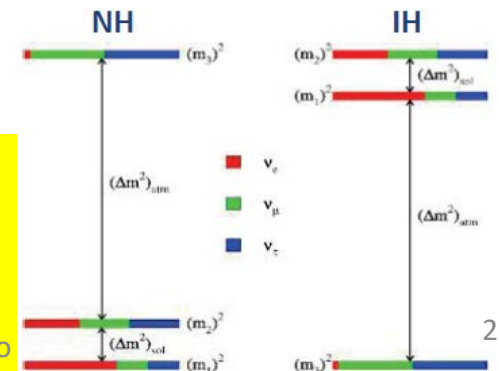
On behalf of the JUNO Collaboration

- 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 (out of the scope of this talk)
- 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 physics with 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"

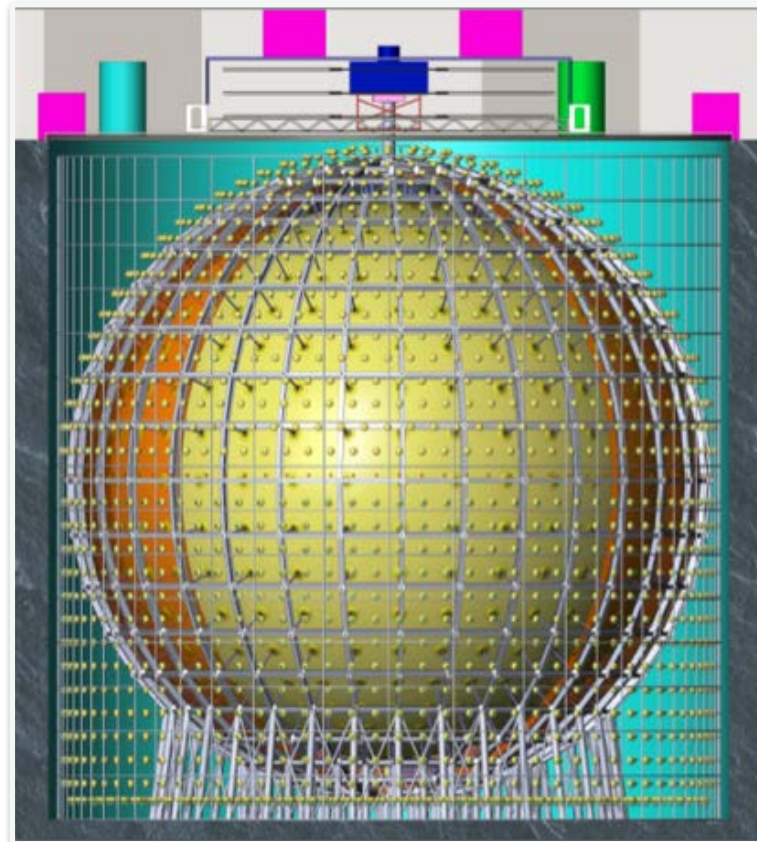
18000 Inner

2000 veto

~25000 x 3"

Acrylic Sphere

filled with 20 kt LS



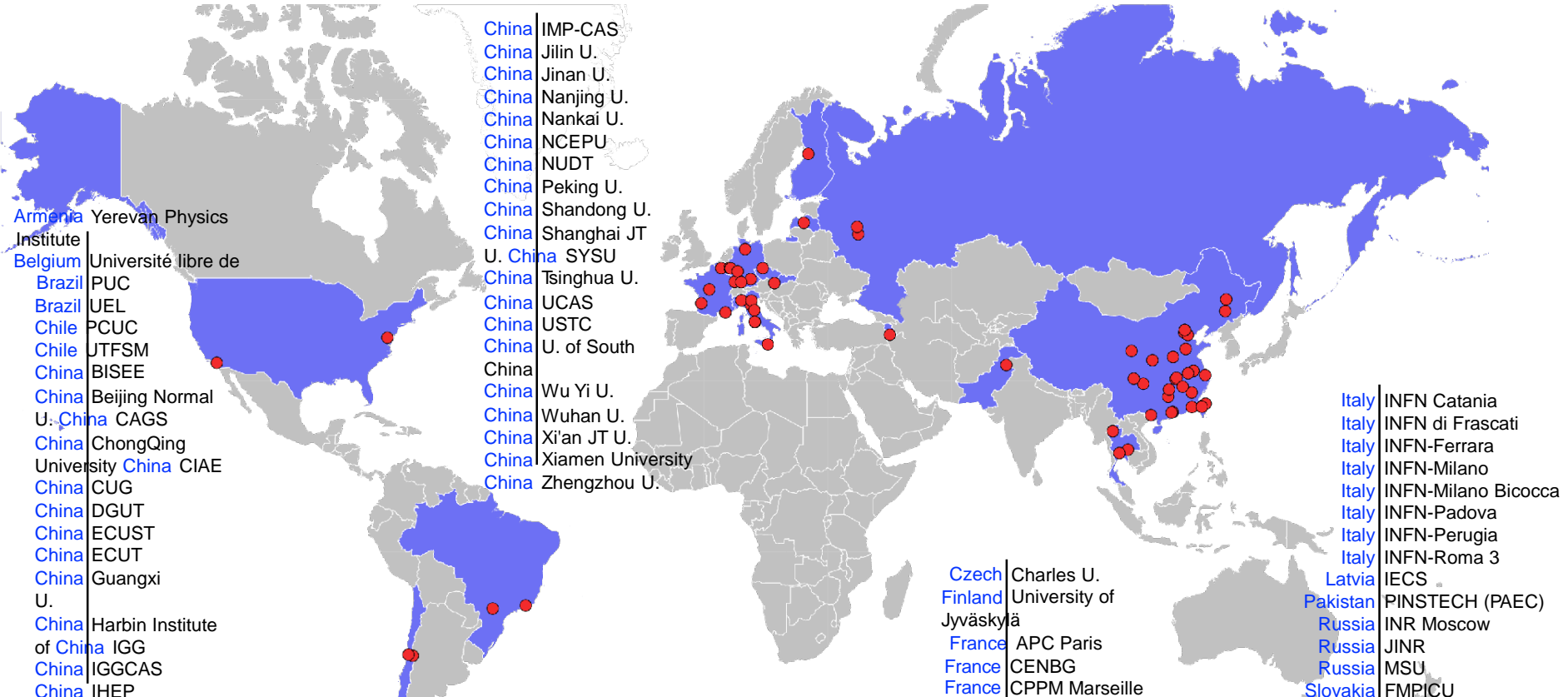
JUNO has been approved in China in Feb. 2013

Participation and contributions from several other countries:

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



JUNO collaboration



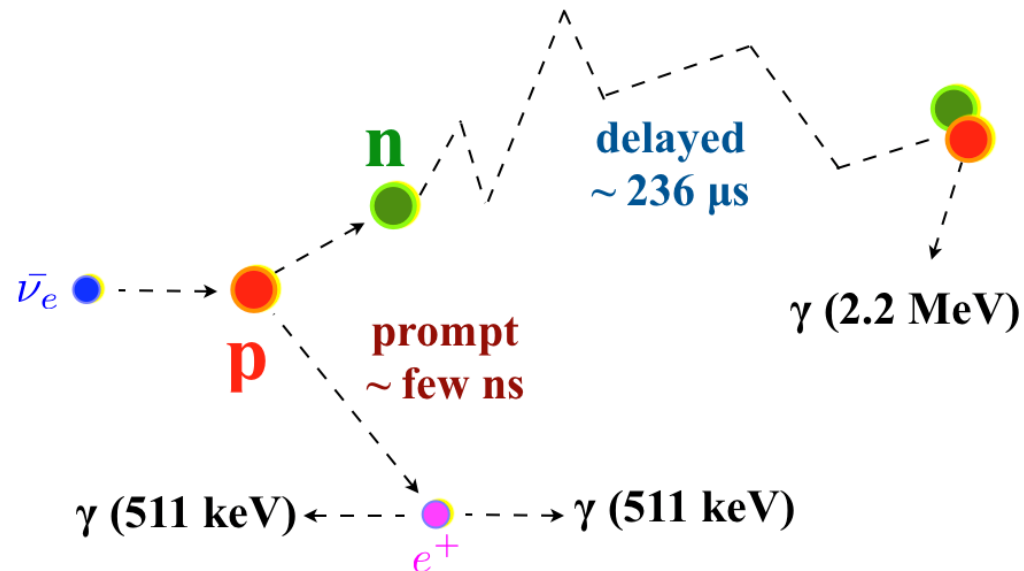
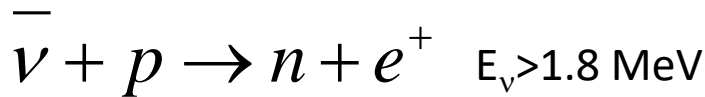
Rosa Marina, September 11, 2018

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



The time coincidence between the positron and the γ from the capture rejects the uncorrelated background

The “observable” for the mass hierarchy determination is the positron spectrum
 It results that $E_{\text{vis}}(e^+) = E(\nu) - 0.8 \text{ MeV}$

MH and Survival probability

arXiv 1210.8141

$$\begin{aligned}
 P_{ee} &= \left| \sum_{i=1}^3 U_{ei} \exp\left(-i \frac{m_i^2}{2E_i}\right) U_{ei}^* \right|^2 \\
 &= 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 (\Delta_{21}) \\
 &\quad - \cos^2 \theta_{12} \sin^2 2\theta_{13} \sin^2 (\Delta_{31}) \\
 &\quad - \sin^2 \theta_{12} \sin^2 2\theta_{13} \sin^2 (\Delta_{32})
 \end{aligned}$$

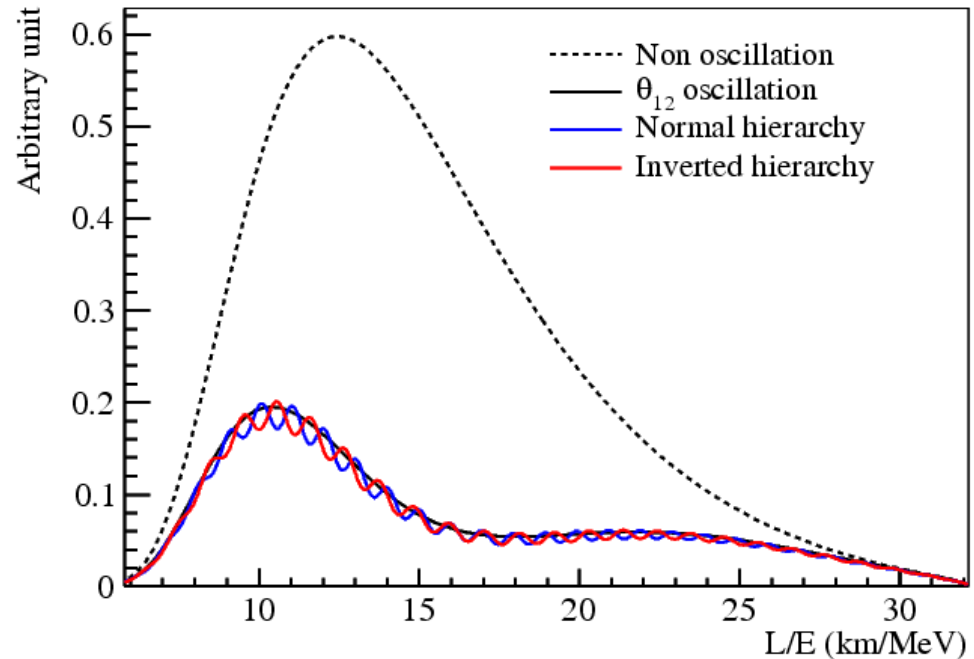
$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E_\nu}, \quad (\Delta m_{ij}^2 \equiv m_i^2 - m_j^2)$$

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

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

+ NH

- IH



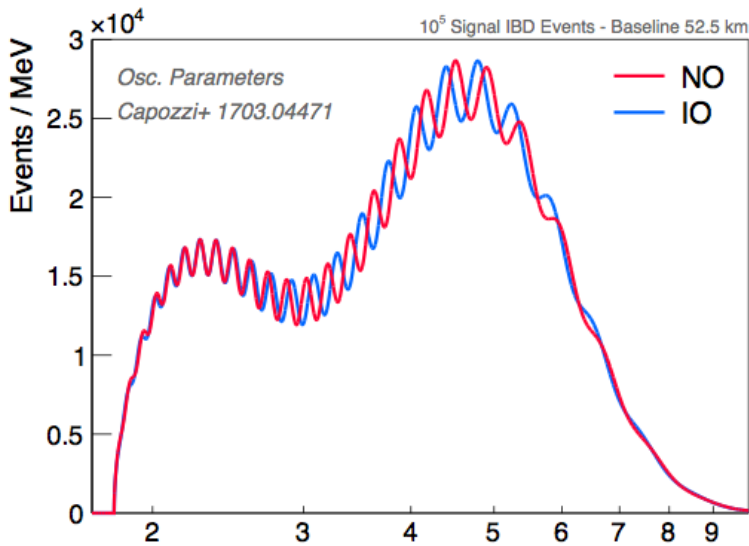
The big suppression is due to the
“solar” oscillation $\rightarrow \Delta m_{21}^2, \sin^2 \theta_{12}$
The ripple is the “atmospheric”
oscillation $\rightarrow |\Delta m_{31}^2|$ from frequency
MH encoded in the phase
“high” value of θ_{13} crucial

Example of Neutrino & Positron Spectra

Spectrum in term of neutrino energy – no energy resolution



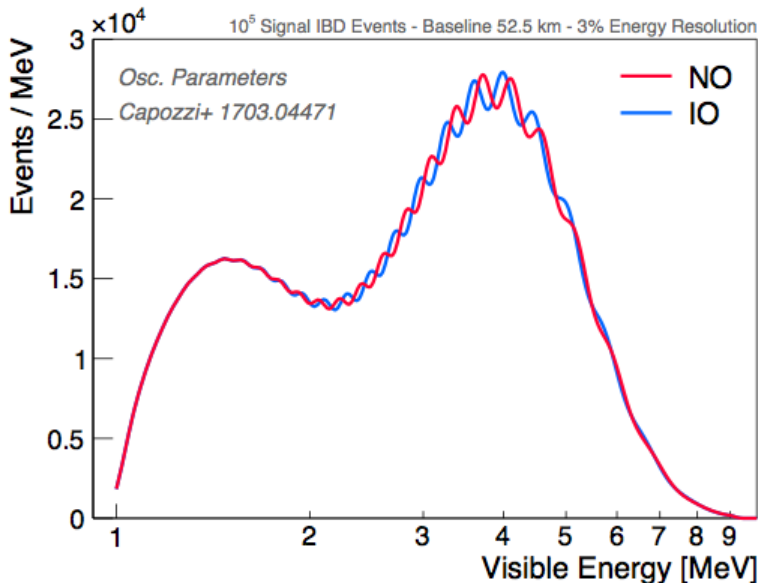
- Three neutrino framework
- Baseline: 52.5 km
- Fiducial Volume: 20 kt
- Thermal Power: 36 GW
- Exposure Time: 6 years
- Nominal JUNO values**



Visible energy due to inverse beta decay

- $E(\text{vis}) \sim E(\nu) - 0.8 \text{ MeV}$
- 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. $|\Delta m_{31}^2|$

Case NH true- average spectrum

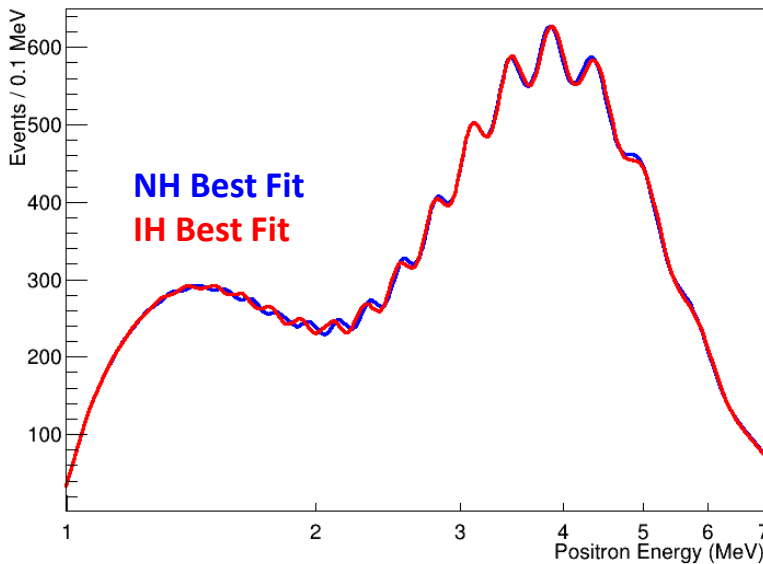
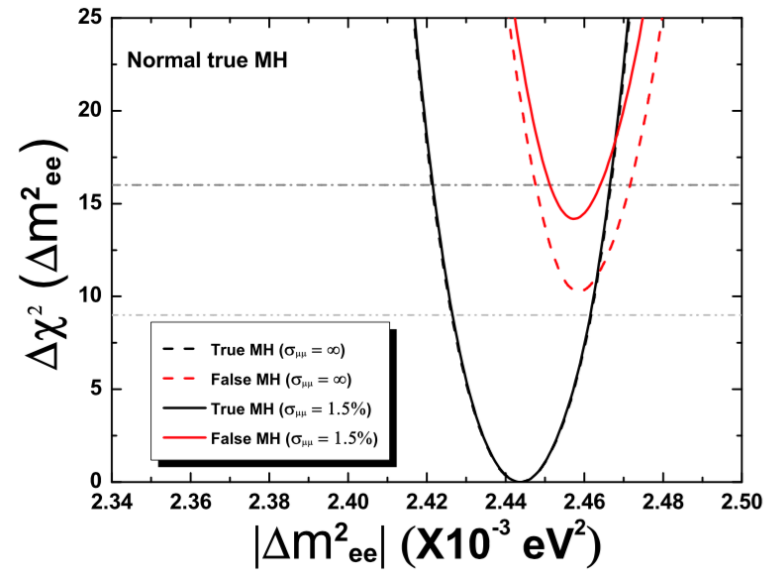
(no fluctuation – **Asimov data set**)

Test statistics $\rightarrow \Delta\chi^2 = \chi^2_{\min}(\text{NH}) - \chi^2_{\min}(\text{IH})$

Fit NH minimum: $1.6 \cdot 10^{-2}$ (practically 0)

FIT IH minimum: 16.0 \rightarrow pure statistical effects

$\overline{\Delta\chi^2} \sim 16.0$



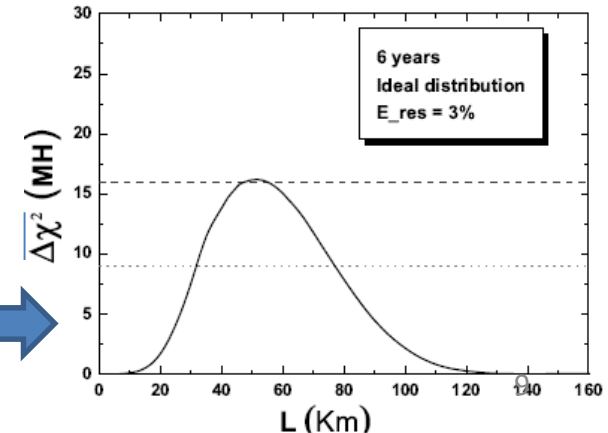
Comparison between IH/NH best fits

The best fit $|\Delta m_{31}^2|$ 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** @ 52.5 km

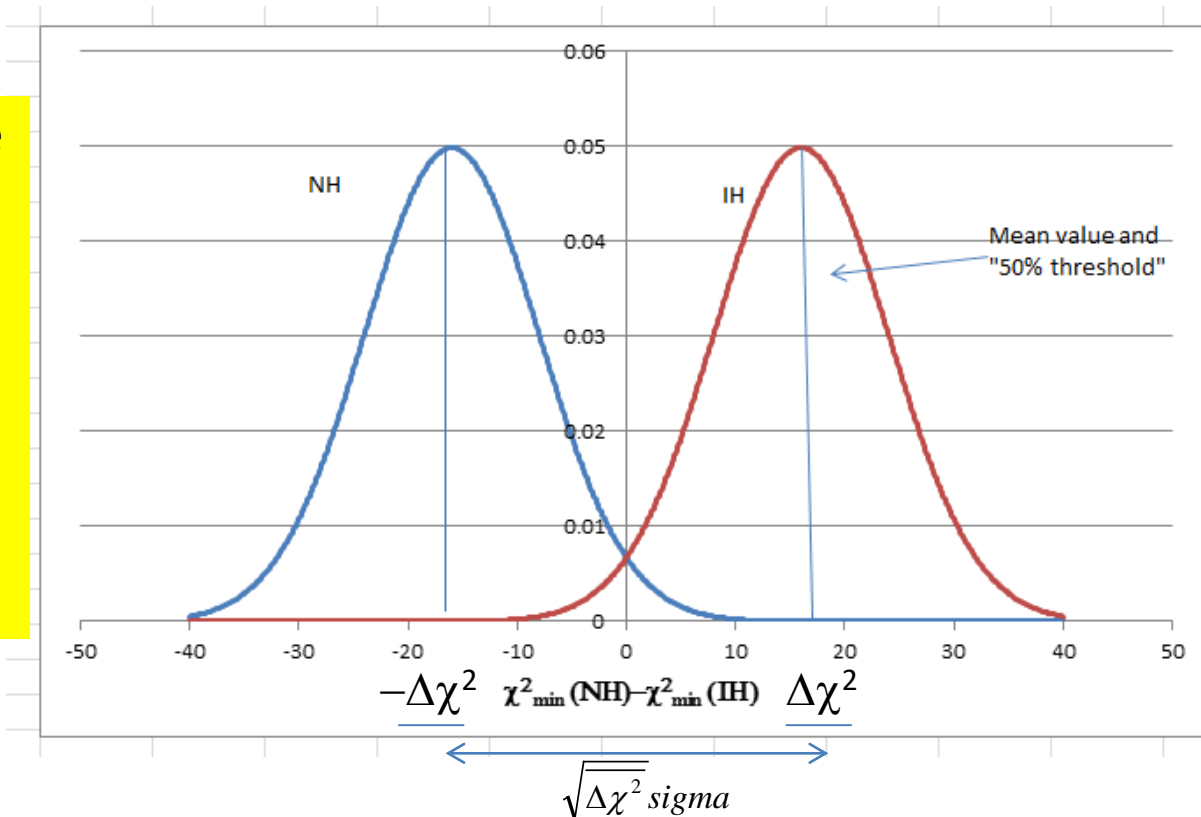
Distribution of test statistics and number of sigmas for discovery

- **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 values of the two curves are displaced of exactly

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

Assumed in a frequentist framework as quantification of discovery capability



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

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 \rightarrow 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%



MH sensitivity systematic effects

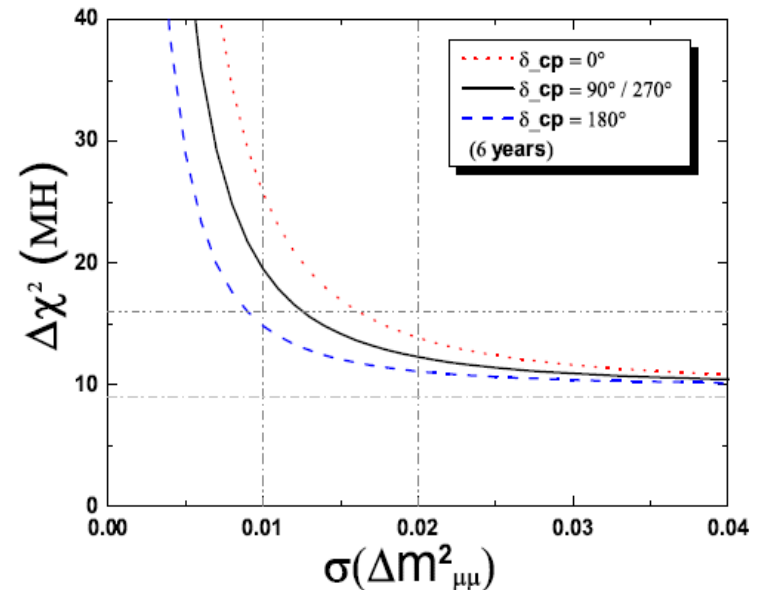
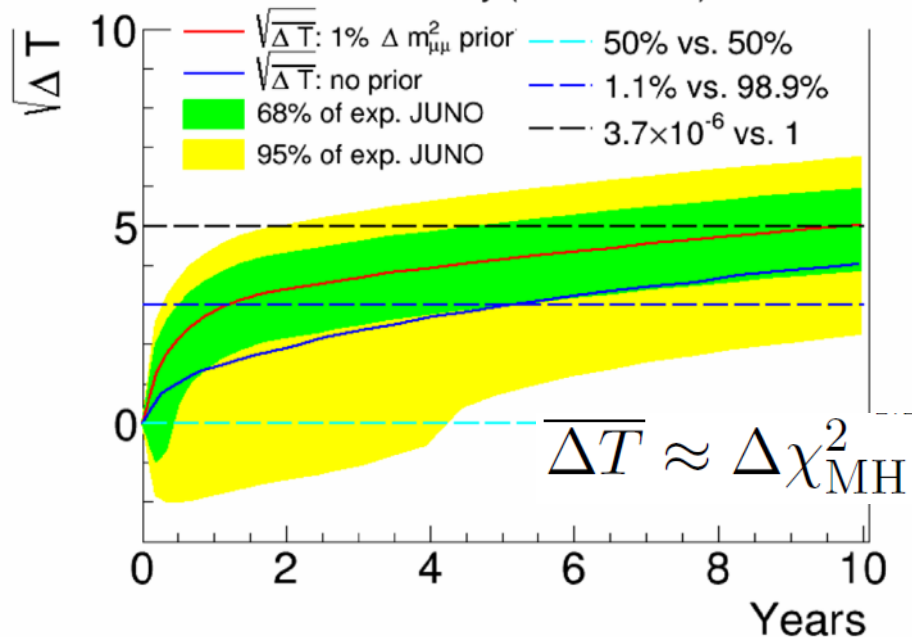
- Spread of the distances ~ 500 from the cores (interference of the signals) **-3 $\Delta\chi^2$ loss**
- Reactor shape uncertainty (1%)
- Statistical and shape uncertainties of backgrounds
- **Non linearity of energy scale (sub-percent precision)**
Other experiments already achieved $<1\%$ accuracy
(Daya Bay $\sim 0.5\%$, Double Chooz 0.74% , Borexino $<1\%$ (at low energies), KamLAND 1.4%)
- **Substructures in the reactor spectrum**

Added a pull in the χ^2 to account for the improved precision on the effective parameter $\Delta m_{\mu\mu}^2 \sim 1\%$ at time of data taking

Summary of MH Sensitivity

<i>PRD 88, 013008 (2013)</i>	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)	$ \Delta m^2_{\mu\mu} $
Size	52.5 km	Tab. 1-2	Tab. 1-2	1%	6.3%	0.4%	1%
$\Delta \chi^2_{MH}$	+16	-3	-1.7	-1	-0.6	-0.1	+(4 - 12)

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 → 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

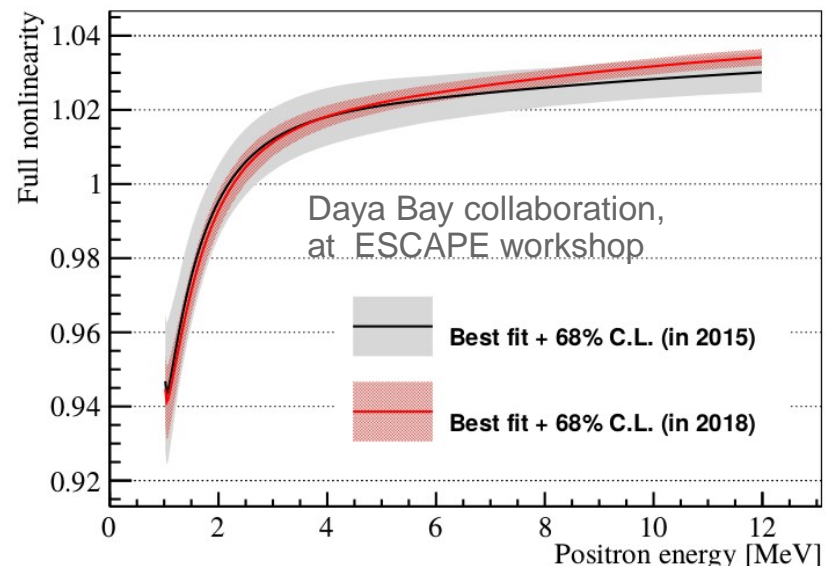
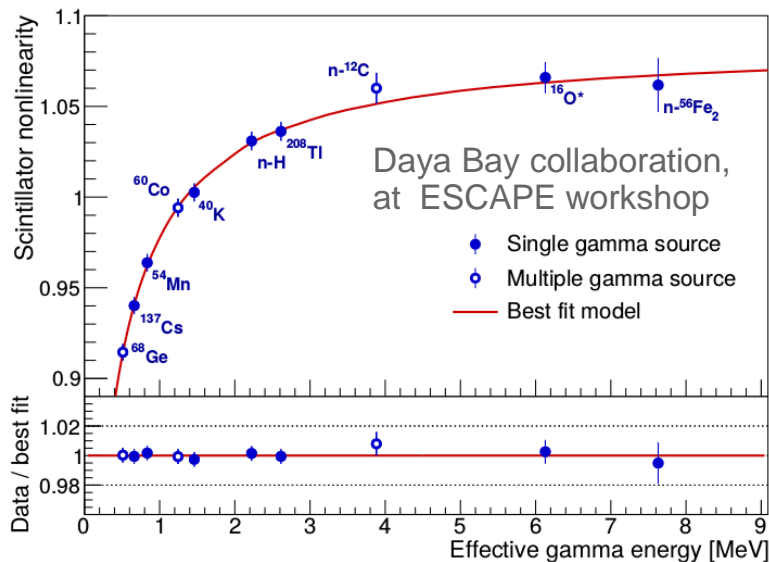
How to Control the Energy Scale Uncertainties

With accurate and extensive calibration procedures

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

and additional handle to control the systematic effects →
3" PMTs system

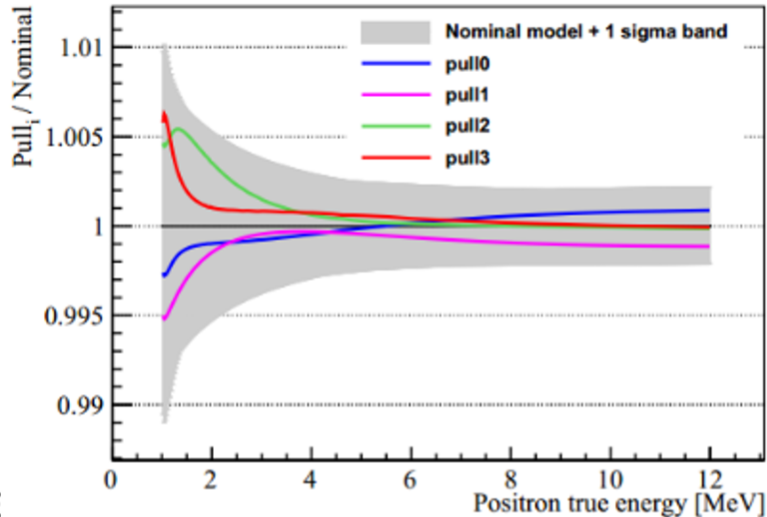
**New calibration results from Daya Bay at ESCAPE workshop
@Heidelberg June 2018**



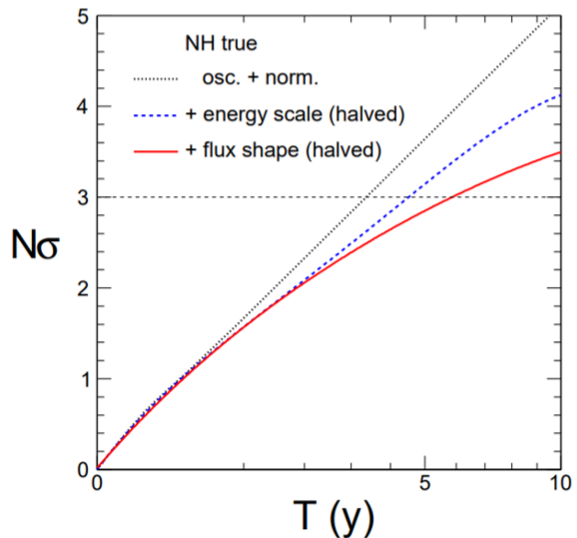
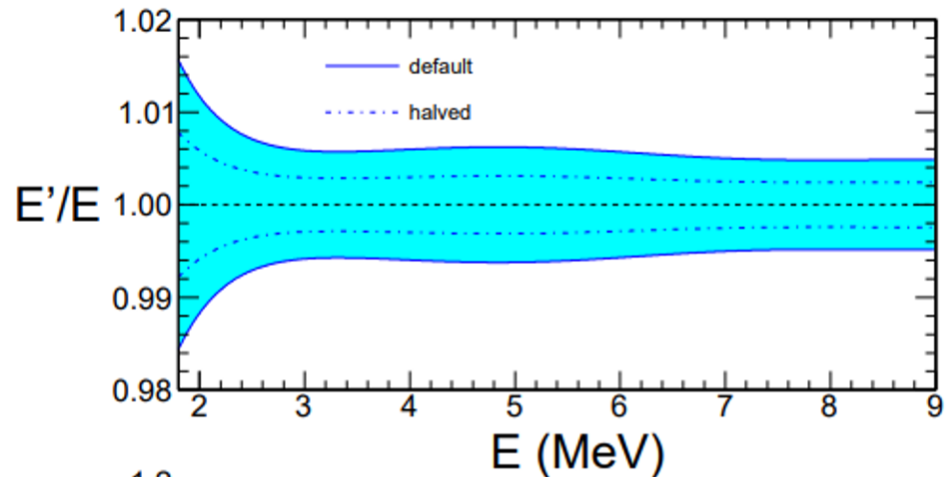
Uncertainty band substantially shrunk in this recent release

Impact of energy scale uncertainty

Updated Daya Bay relative uncertainty



Uncertainty in arxiv:1508.01392

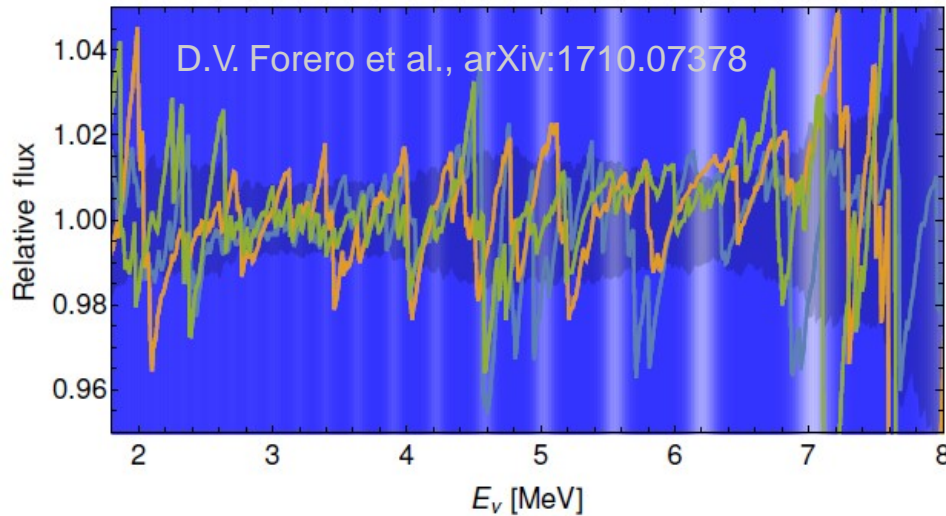


The updated uncertainty band from Day Bay at Escape (top left) is close to the reduced band assumed in arXiv:1508.01392 (top right) the corresponding calculation in the same paper is on the left (dashed line)

→ 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

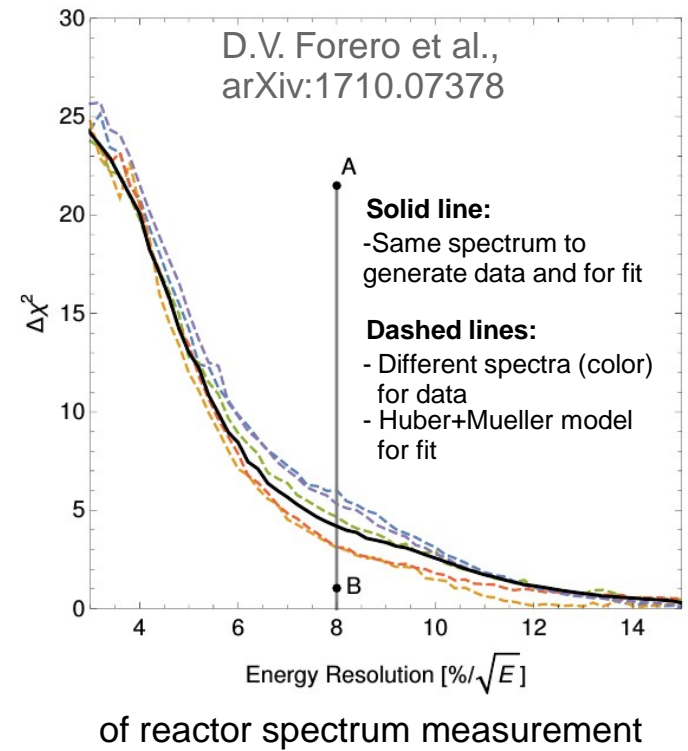
Implications of the reactor shape uncertainty

- “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 degrade the MH sensitivity by mimicking periodic oscillation pattern



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

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



Near (reference) Detector Concept

Gd-LS in diameter of 1800 mm

Surface 10.2 m²

Volume 3.05 m³, 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%

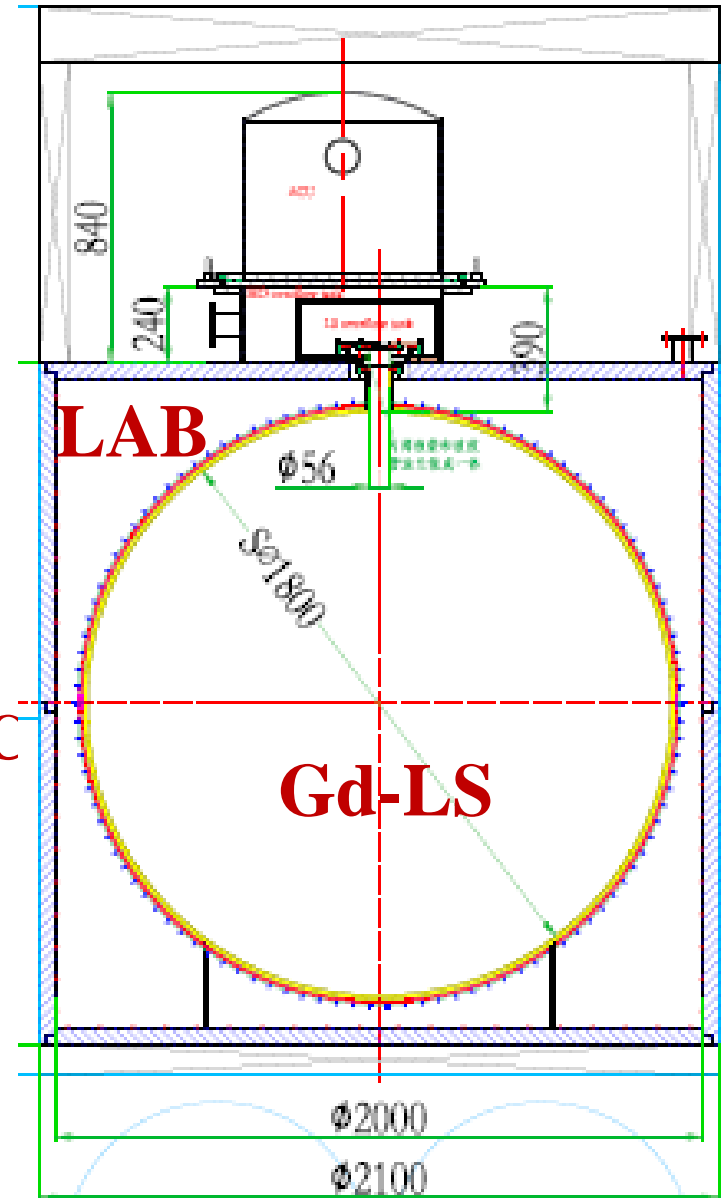
Nylon bag w/ acrylic support (JUNO backup option)

10 m² SiPM of 50% PDE, operated at -50°C

LAB+quencher as buffer

Cryogenic vessel

DYB Automatic Calibration Unit



More about the conjectured effect

Danielson, Hayes and Garvey

Reactor Neutrino Spectral Distortions Play Little Role in Mass Hierarchy Experiments

[arxiv.1808.03276](https://arxiv.org/abs/1808.03276)

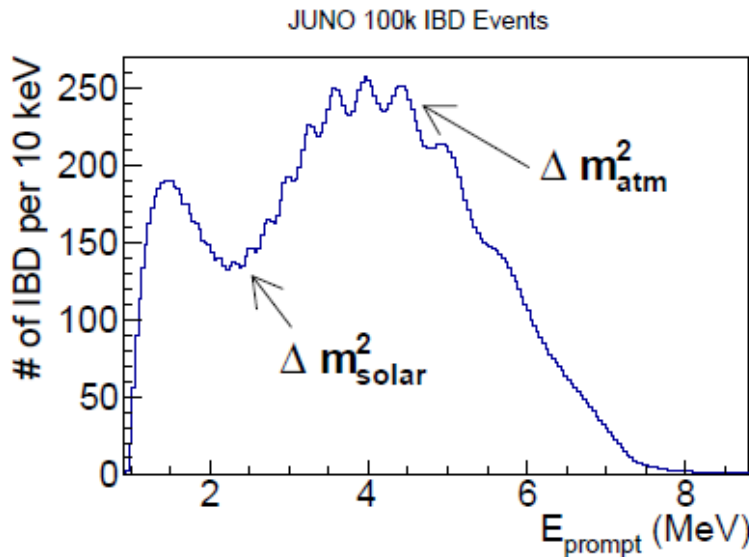
...these sawtooth-like distortions are found to contribute at a magnitude of only a few percent relative to the mass hierarchy-dependent oscillation pattern

..... the features that encode a neutrino mass hierarchy dominate by over sixteen (twenty-five) times in prominence to the maximal contribution of the sawtooth-like distortions from the detailed energy spectrum

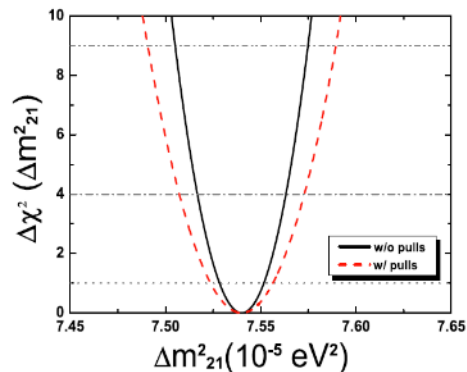
with accurate knowledge of detector energy response, **the sawtooth-like features in reactor antineutrino spectra will not significantly impede neutrino mass hierarchy** measurements using reactor antineutrinos

Precision Measurements

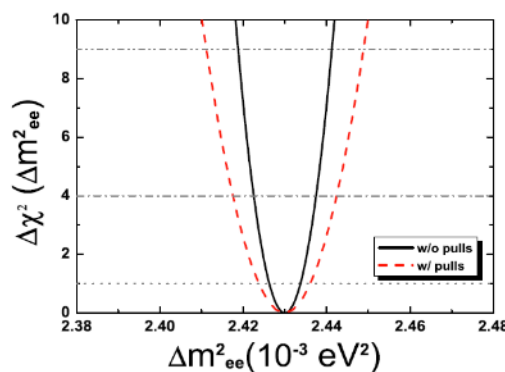
Probing the unitarity of U_{PMNS} to $\sim 1\%$
more precise than CKM matrix elements !



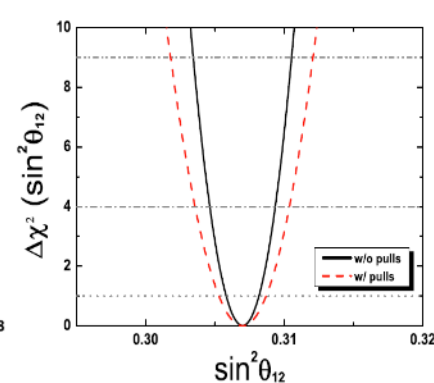
	Statistics	+BG +1% b2b +1% EScale +1% EnonL
$\sin^2 \theta_{12}$	0.54%	0.67%
Δm^2_{21}	0.24%	0.59%
Δm^2_{ee}	0.27%	0.44%



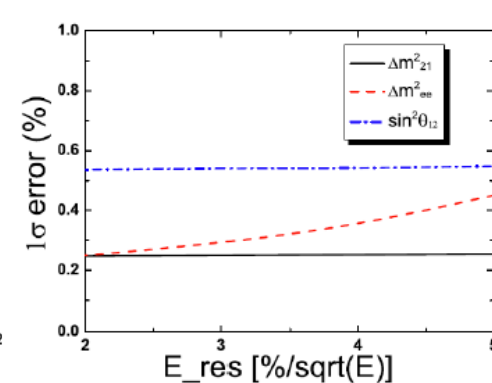
0.16% \rightarrow 0.24%



0.16% \rightarrow 0.27%



0.39% \rightarrow 0.54%



E resolution

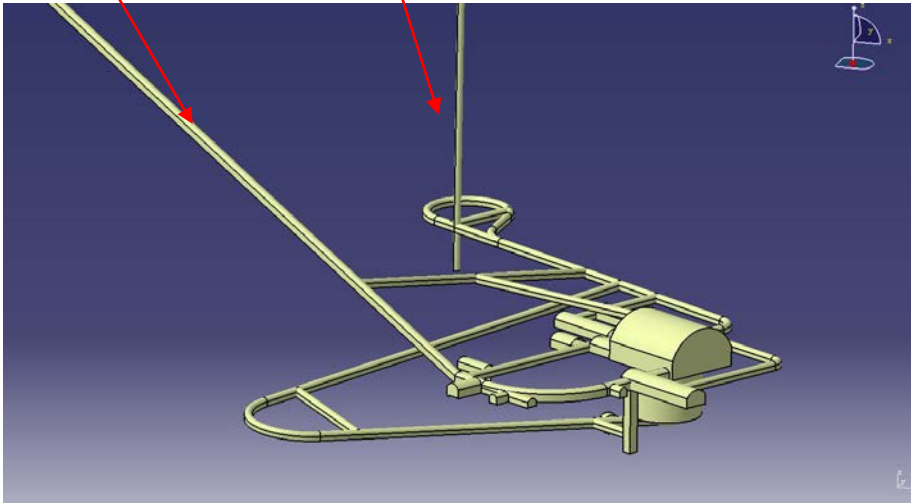
Correlation among parameters

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

Layout of the site

Slope tunnel

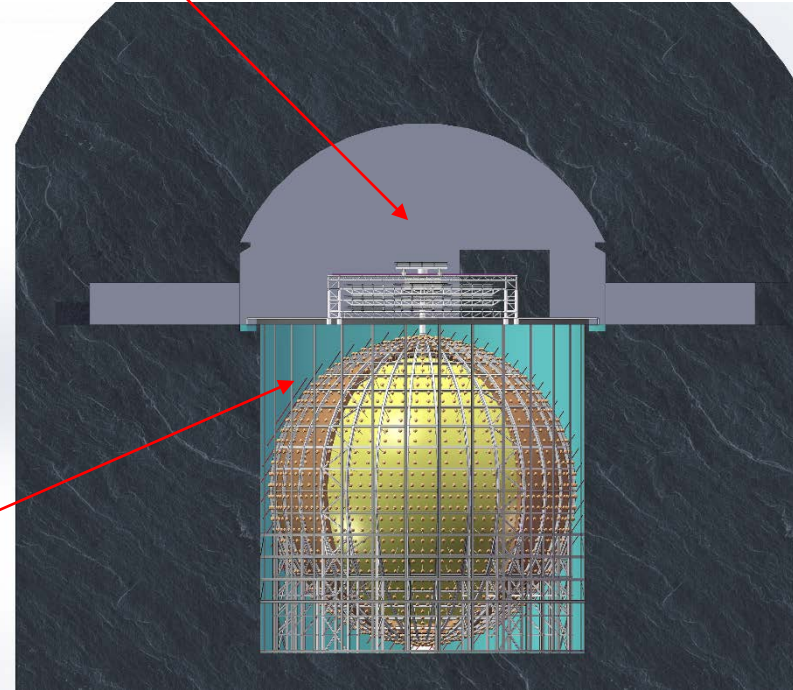
Vertical shaft



overburden ~ 700 m

Experimental Hall

Pool



Surface buildings

Central detector

- Acrylic sphere with 20k t liquid scintillator
- PMTs in water buffer on a stainless steel truss - 18k 20" and 25k 3"
- 78% PMT coverage

Water Cherenkov muon veto

- 2000 20" PMTs
- 35 ktons ultra-pure water
- Efficiency > 95%
- Radon control → less than 0.2 Bq/m³

Compensation coils

- Earth's magnetic field <10%
- Necessary for 20" PMTs

Top tracker

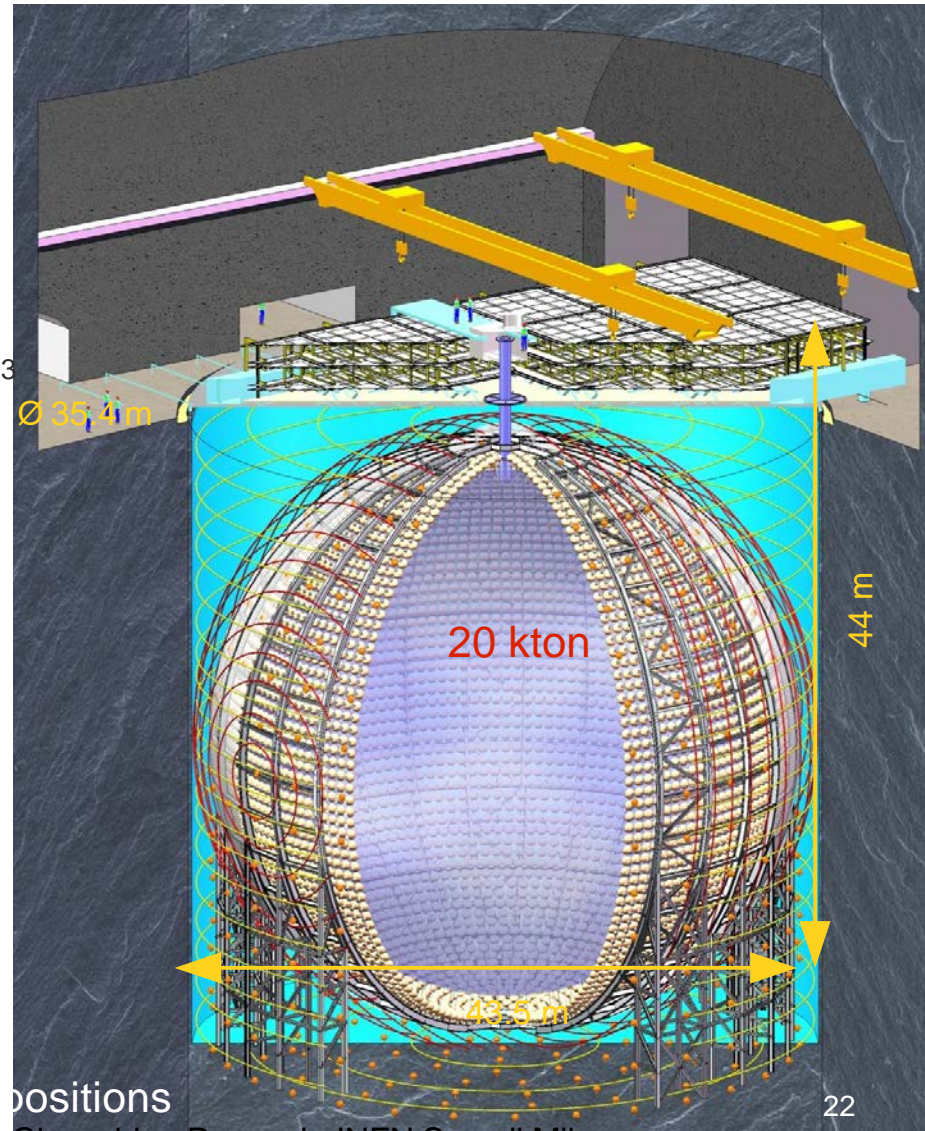
- Precision muon tracking
- 3 plastic scintillator layers
- Covering half of the top area

Calibration System

- 4 complementary sub-systems
- various particle types, ranges and positions

Detector's layout

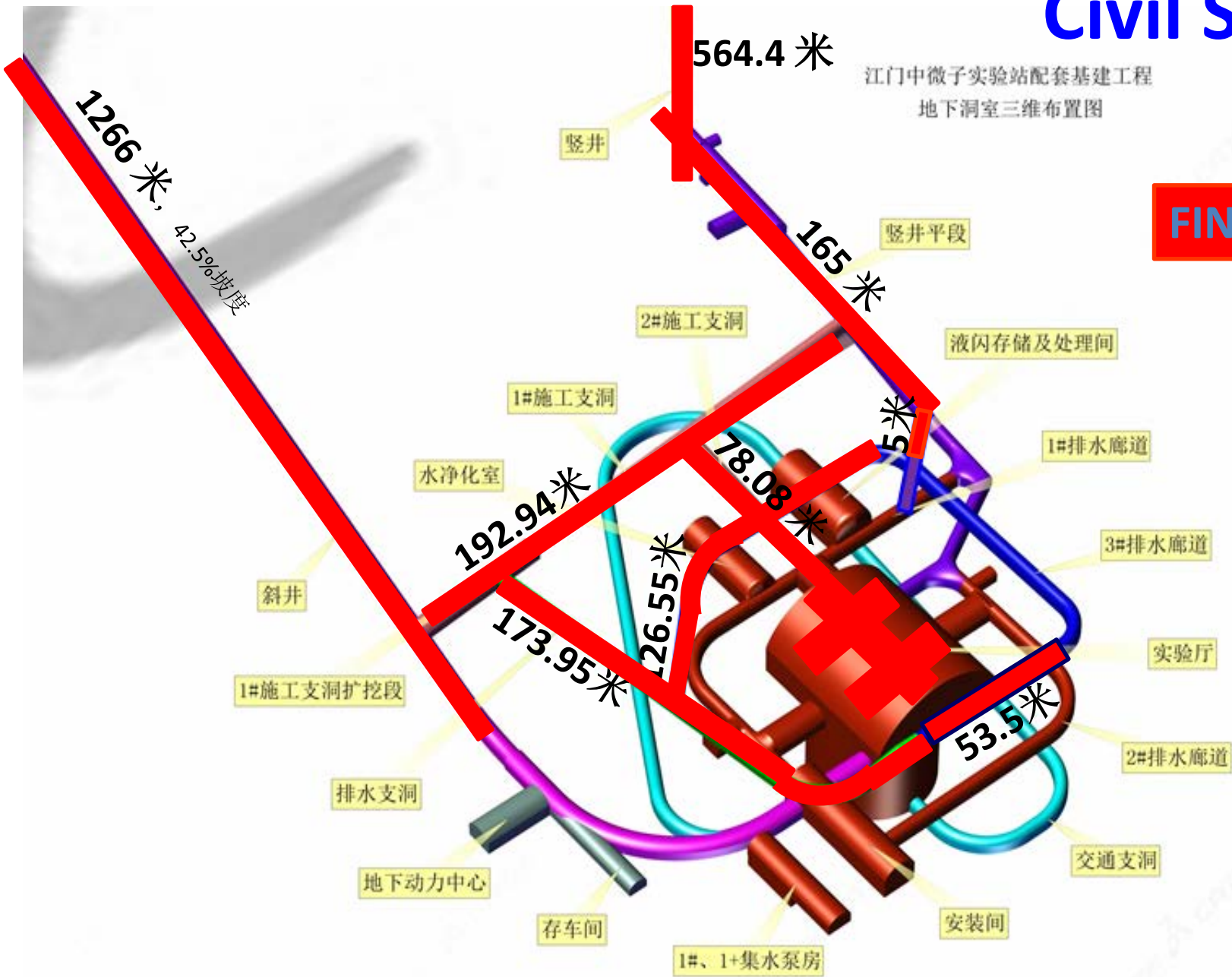
Everywhere background control and monitor



Civil Status

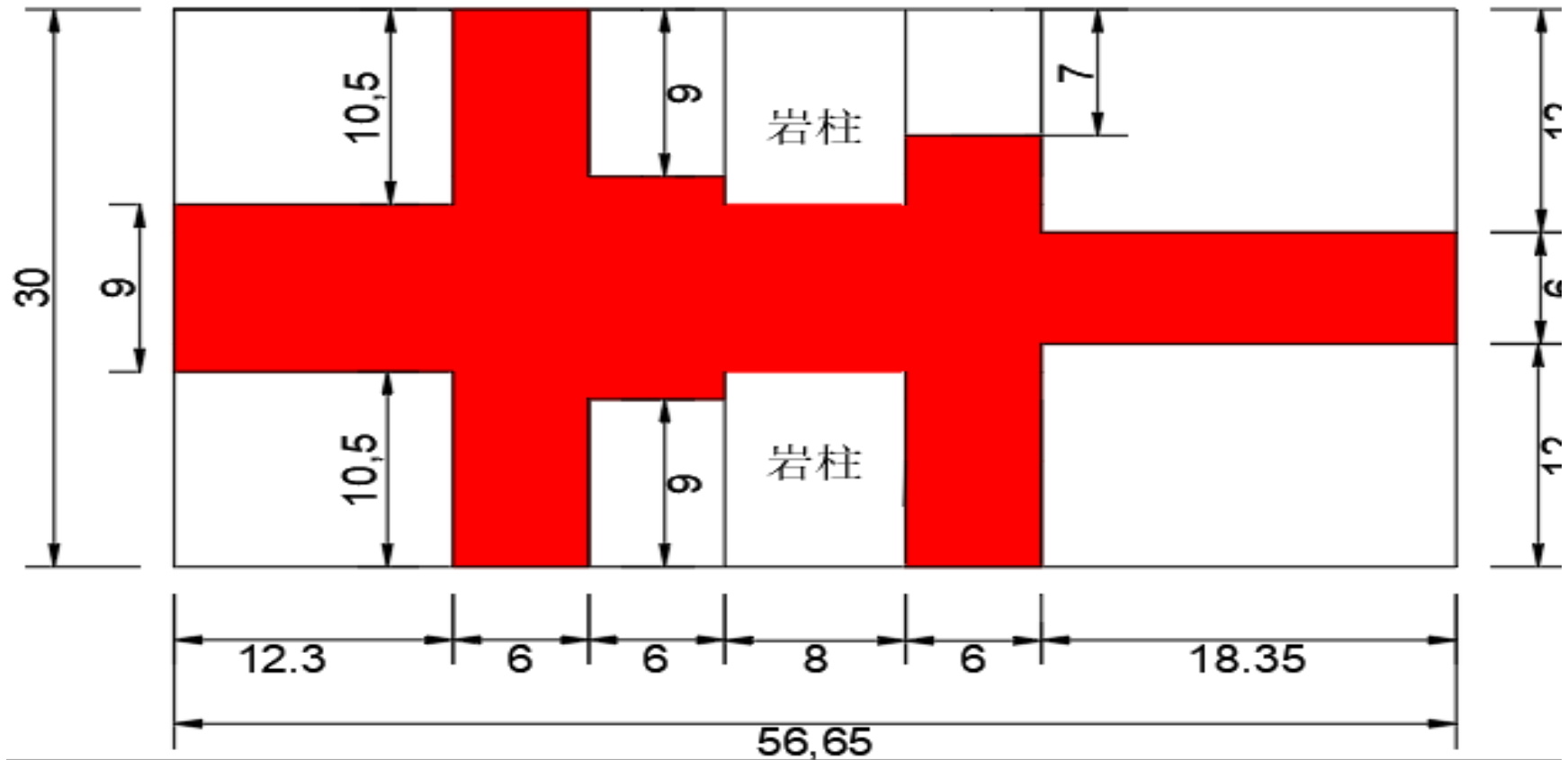
江门中微子实验站配套建设工程
地下洞室三维布置图

FINISHED



Top of EH Construction

FINISHED



Experimental hall



Access tunnel to the experimental hall



Vertical shaft



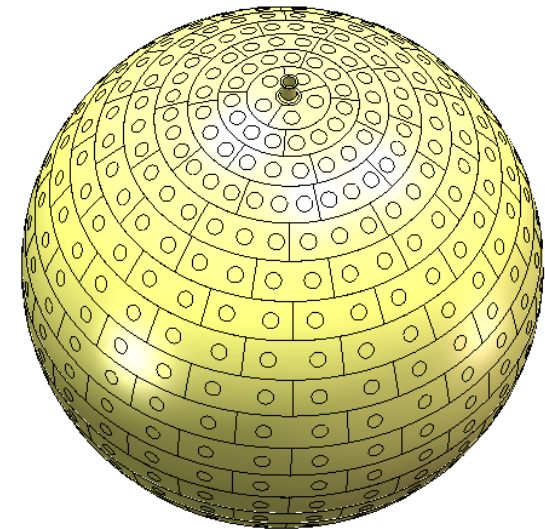
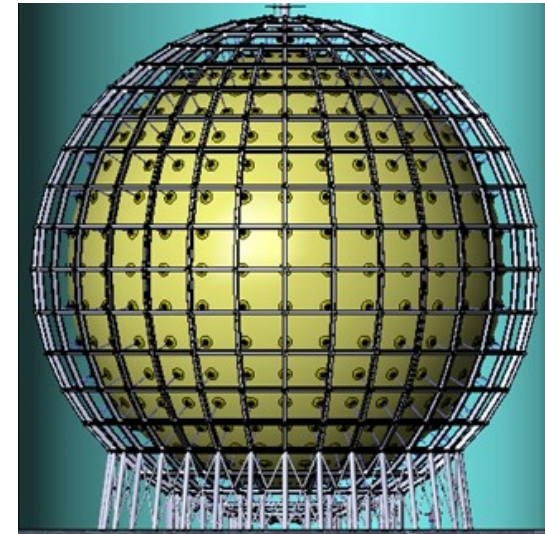
One of the service tunnels





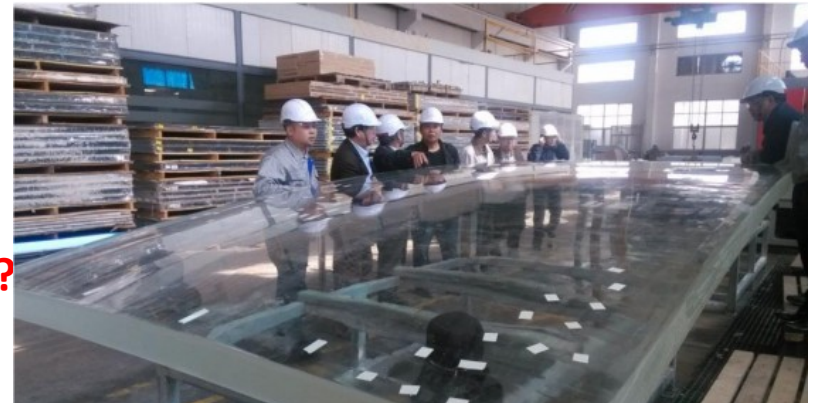
Center Detector

- Liquid scintillator based calorimeter
 - Req.: **3% resolution & <1% en. scale precision**
- **SS** supporting **PMTs + Acrylic Sphere(AS)**
 - Outside AS: water (shielding PMT/SS γ s)
 - Inside AS: LS (scintillation matter)
- Scintillation **photon** detector:
 - 18k 20" PMTs + 25k 3" PMTs
 - 1200 pe/MeV
- Electronics:
 - **1 GHz, 14 bit**, 1~4000 p.e. dynamic range
- Coils for Earth's magnetic field compensation
- **All construction elements contracted**



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

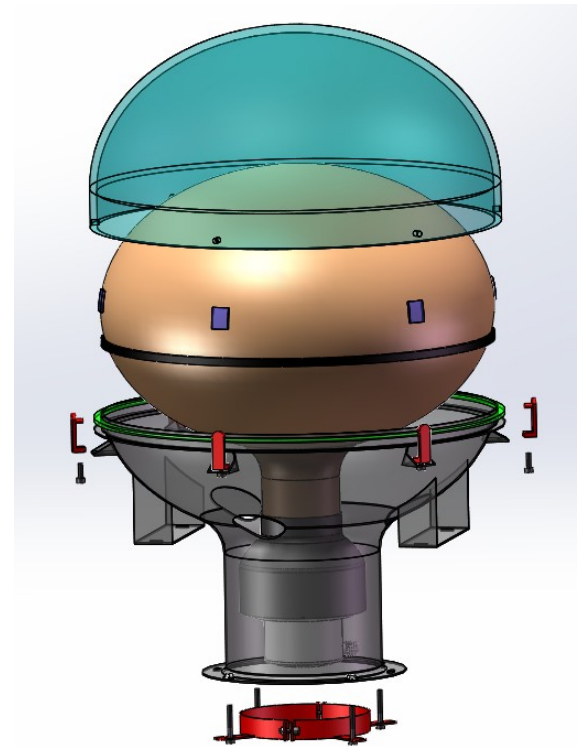


1:12
prototype

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

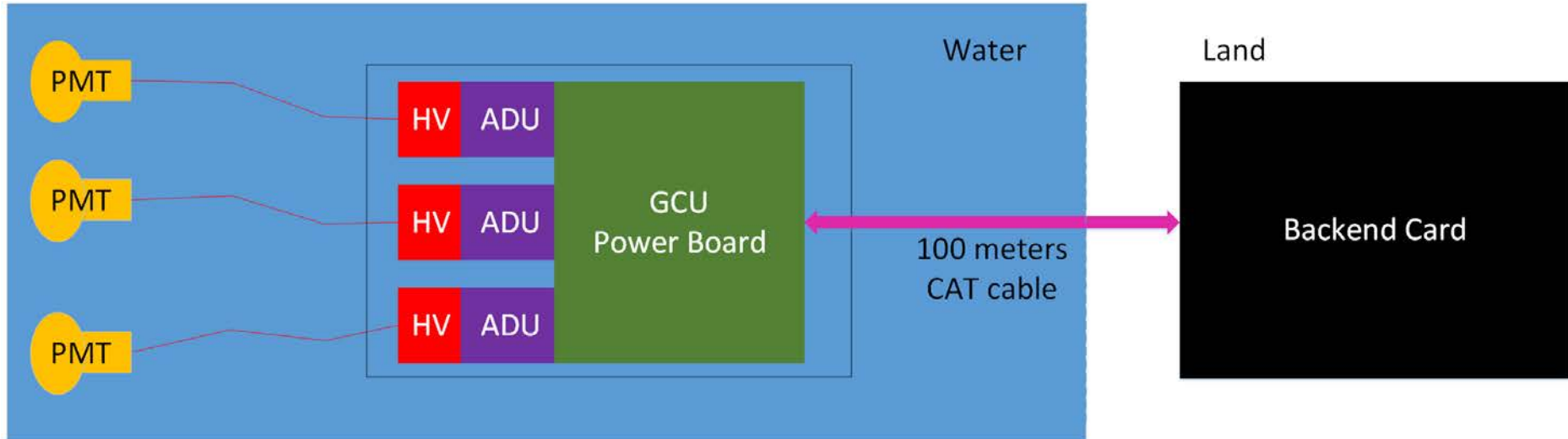


JUNO PMT with implosion protection cover

New HQE MCP-PMT this year: **another 10% improvement** in PDE 27%→30%
 Average PDE of HAMAMATSU 28%

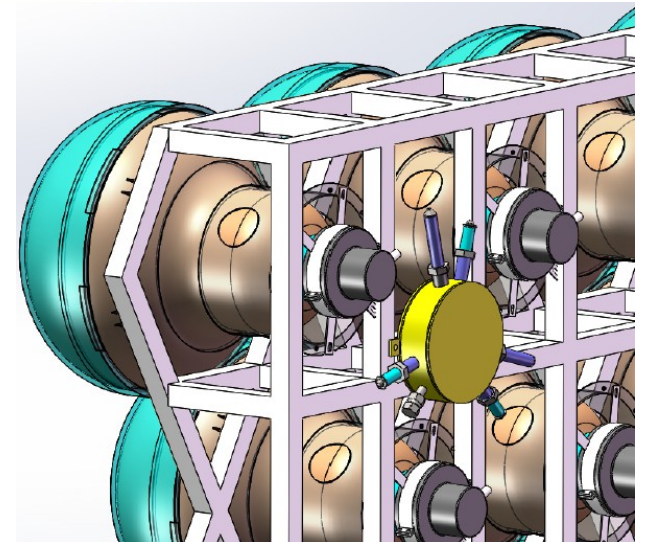
Readout Electronics

1F3 scheme



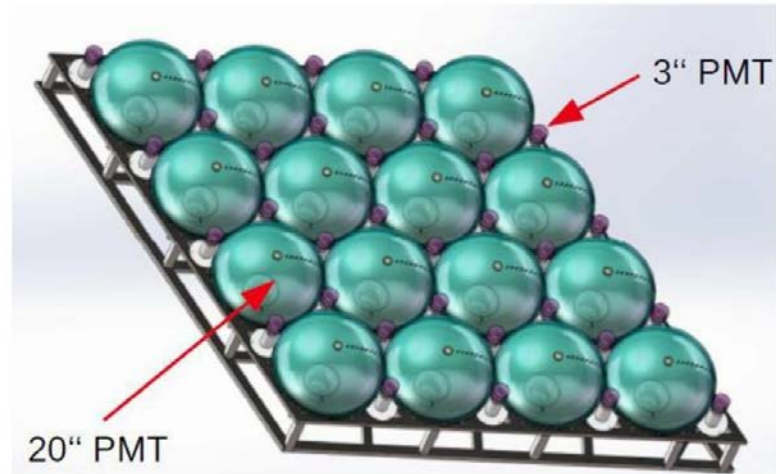
- PMT: photomultiplier tubes
- HV: High Voltage units
- ADU: Analog to Digital Unit
- GCU: Global Control Unit
- CAT cable: Category 5e cable
- High reliability needed
- Severe constraints by power consumption

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



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)



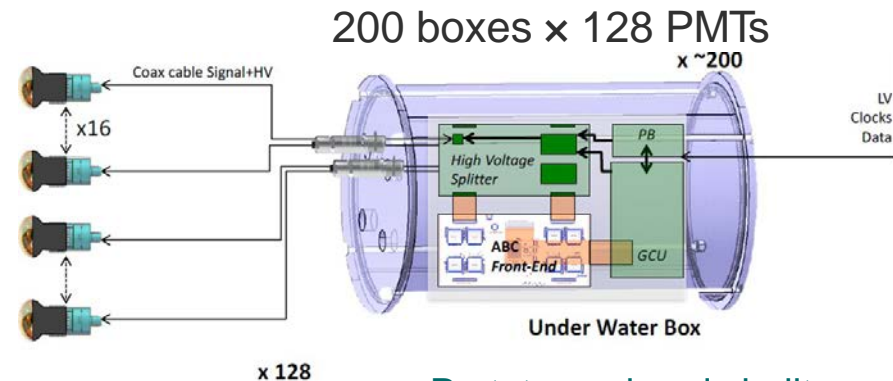
- 25000 PMTs contracted to HZC
- 8000 produced and tested at HZC

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

JUNO custom design:
XP72B22

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



Prototype already built

Veto Detectors

- **Cosmic muon flux**
 - Overburden: **~700 m**
 - Muon rate: **0.003Hz/m²**
 - Average energy: **214 GeV**
- **Water Cherenkov Detector**
 - ~4 m water shielding, Radon: **<0.2 Bq/m³**
 - ~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

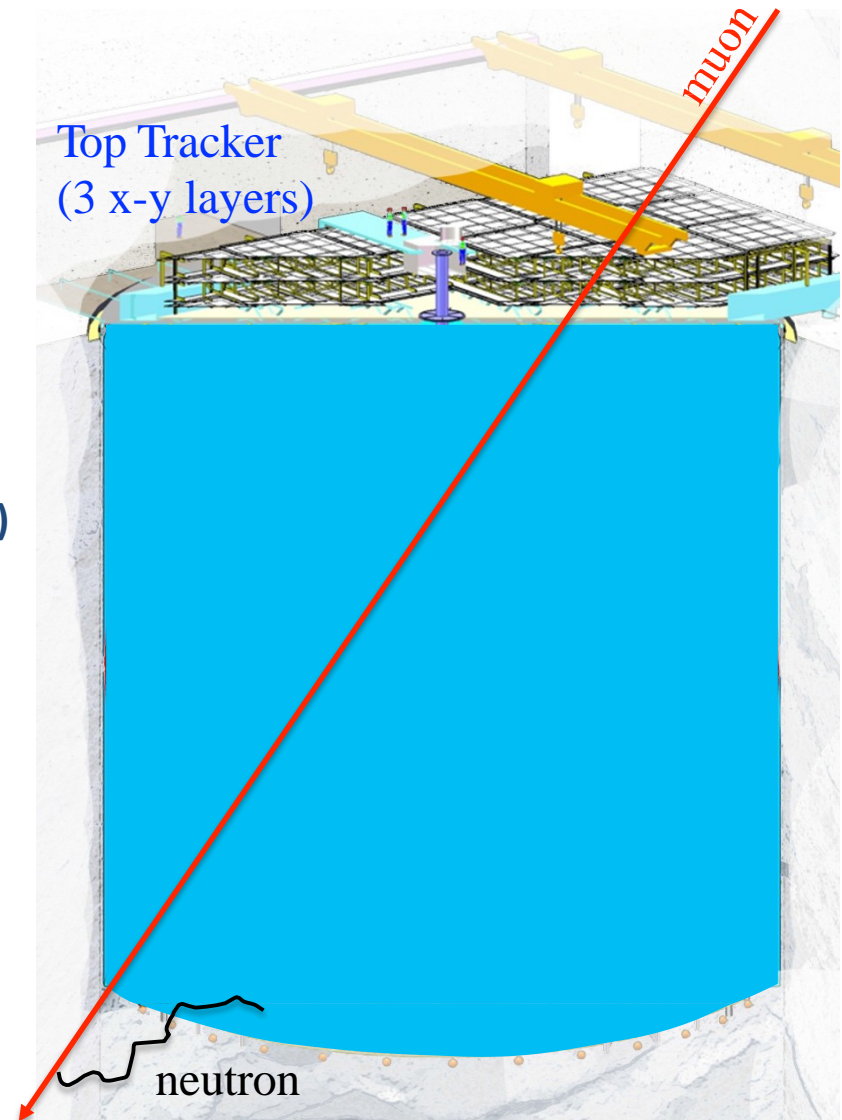
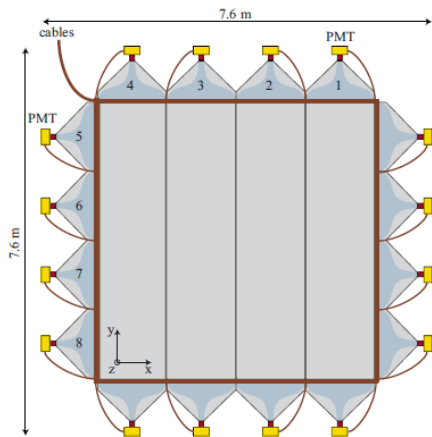


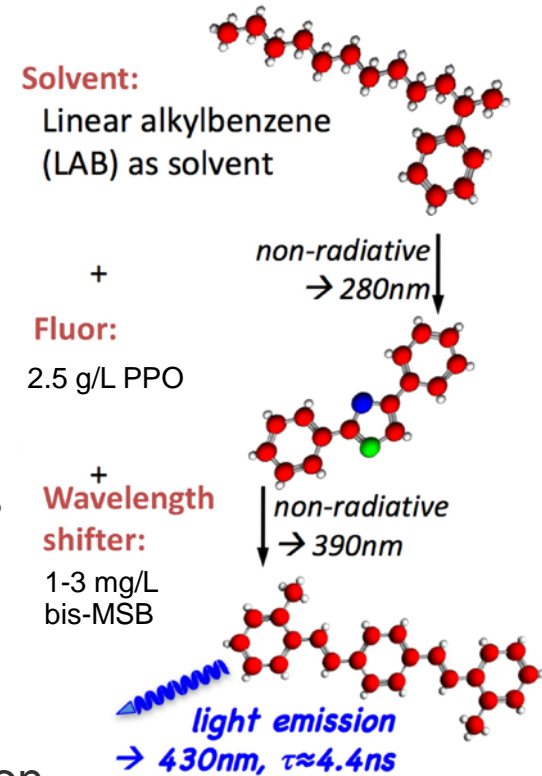
Fig. 3. Schematic view of a plastic scintillator strip wall.

Scintillator

- Requirement for $3\%/\sqrt{E}$
 - High light-yield: $\sim 10^4$ photons/MeV
 - High transparency:
Attenuation Length (A.L.) > **25m** @430nm

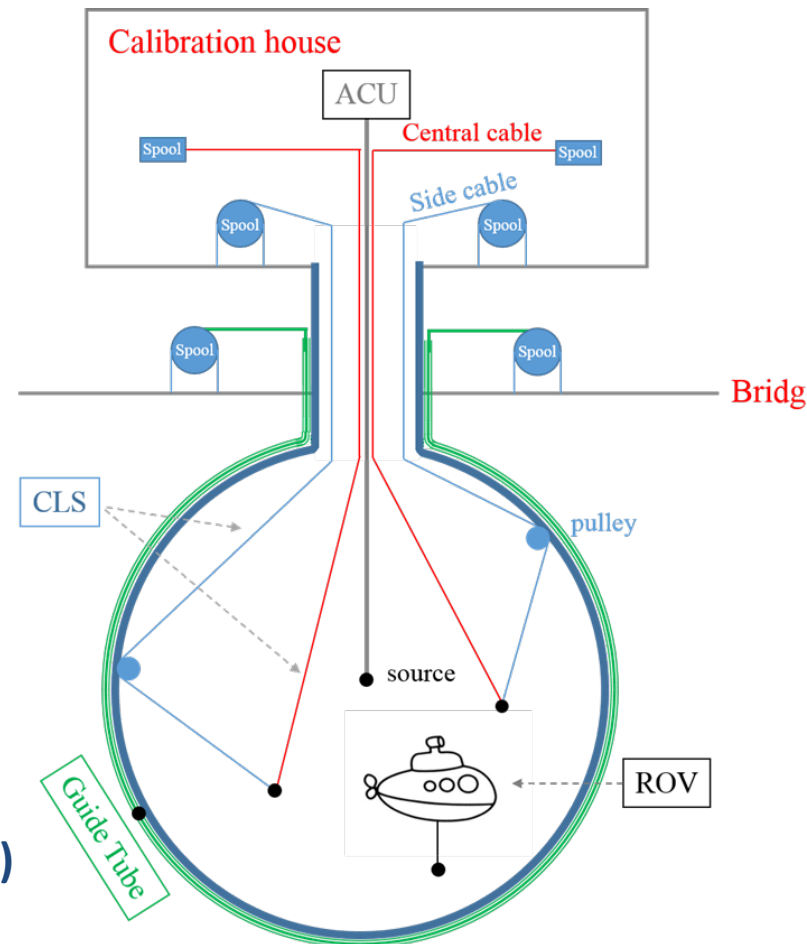


- Purification pilot plants
 - Check of purification effectiveness U/Th/K and radioactive gases
 - Targeted at least 10^{-15} g/g
 - Under operation at Daya Bay
 - Distillation, Al_2O_3 column purification, water extraction and gas stripping
 - > **25 m** A.L. after filling (measured)
 - Optimizing LS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



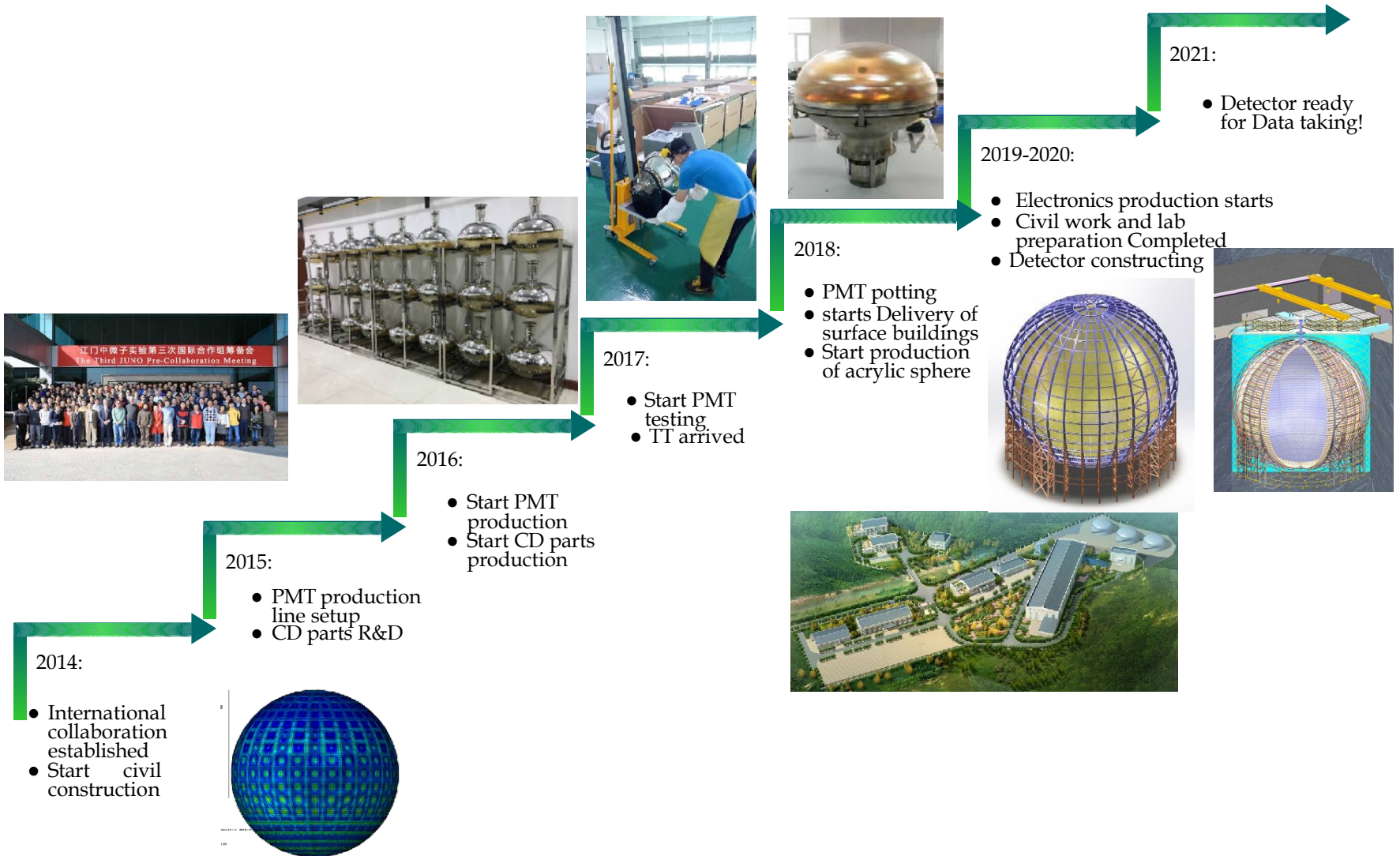
Calibration system

- The goal:
 - Overall energy resolution: $\leq 3\%/VE$
 - Energy scale uncertainty: $<1\%$
- Radioactive sources:
 - γ : ^{40}K , ^{54}Mn , ^{60}Co , ^{137}Cs
 - e^+ : ^{22}Na , ^{68}Ge
 - n : $^{241}\text{Am-Be}$, $^{241}\text{Am-}^{13}\text{C}$ or $^{241}\text{Pu-}^{13}\text{C}$, ^{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





Milestone & schedule





Conclusion

- 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
- **Needed precise understanding of the detector response and of the energy scale**
- Near detector planned for precise reference reactor spectrum
- Project well along the realization path
- Expected data taking start time: **2021**