Strategy for Precise Calibration in JUNO

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On behalf of the JUNO collaboration

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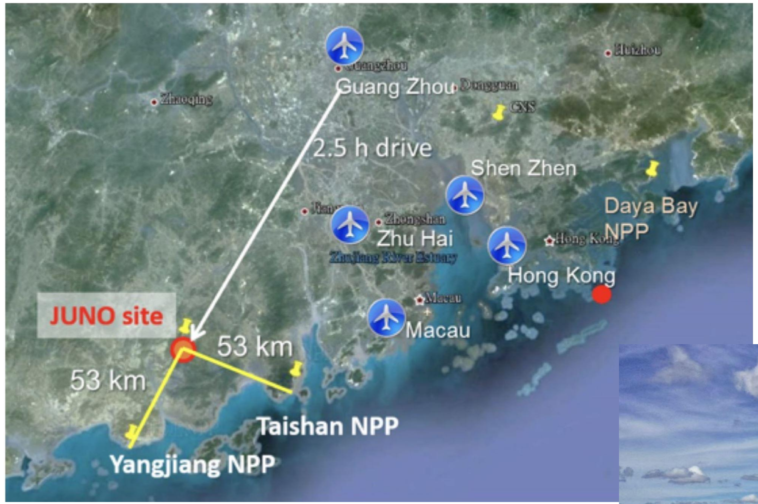
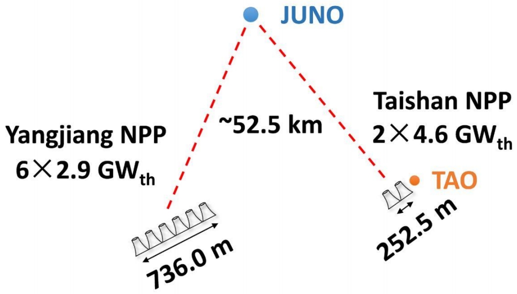
JUNO Experiment Overview

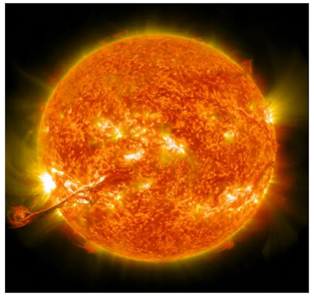
JUNO is a multi-purpose liquid scintillator experiment

- Oscillation physics:
  - Neutrino Mass Ordering (NMO), $|\Delta m^2_{31}|$, Δm^2_{21}, $sin^2\theta_{12}$, $sin^2\theta_{13}$, ...
- Non-oscillation physics:
  - Core-collapse SN, Solar neutrino fluxes, DSNB, Geoneutrinos, Nucleon decay, Dark matter, ...

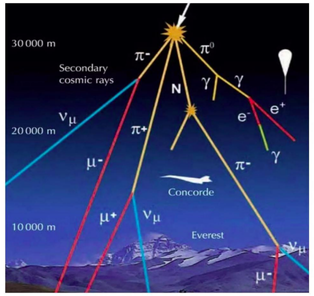




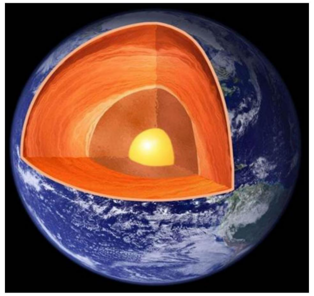
$\sim$ 50/day



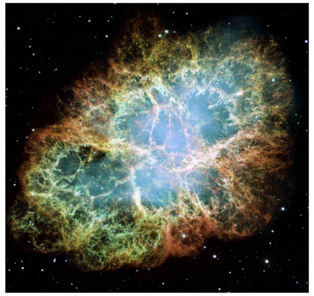
$\mathcal{O}(1000)$/day



$\sim$ 10 - 20/day



$\sim$ 1 - 2/day

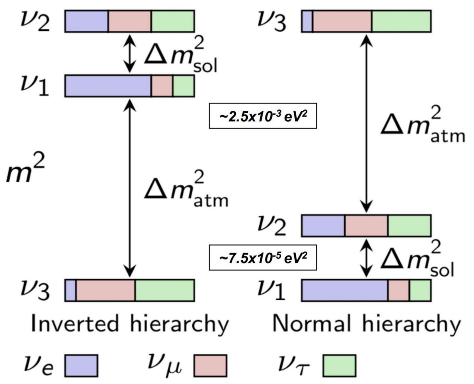


CCSN @10kpc : $\mathcal{O}(1000)$/s
DSNB: few/year

New Physics

Proton decay
etc

Neutrino Mass Ordering (NMO)

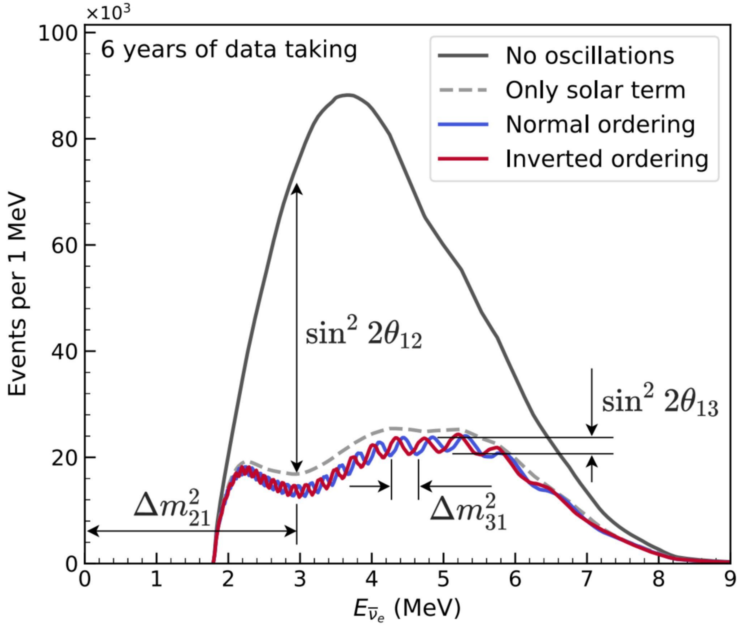


$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$

Slow $P_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$

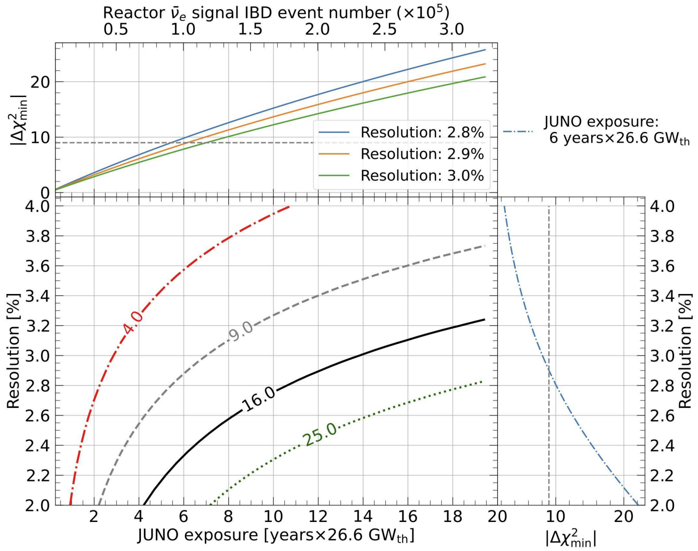
Fast $P_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31})$

$P_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32}),$



How to determine the NMO in JUNO?

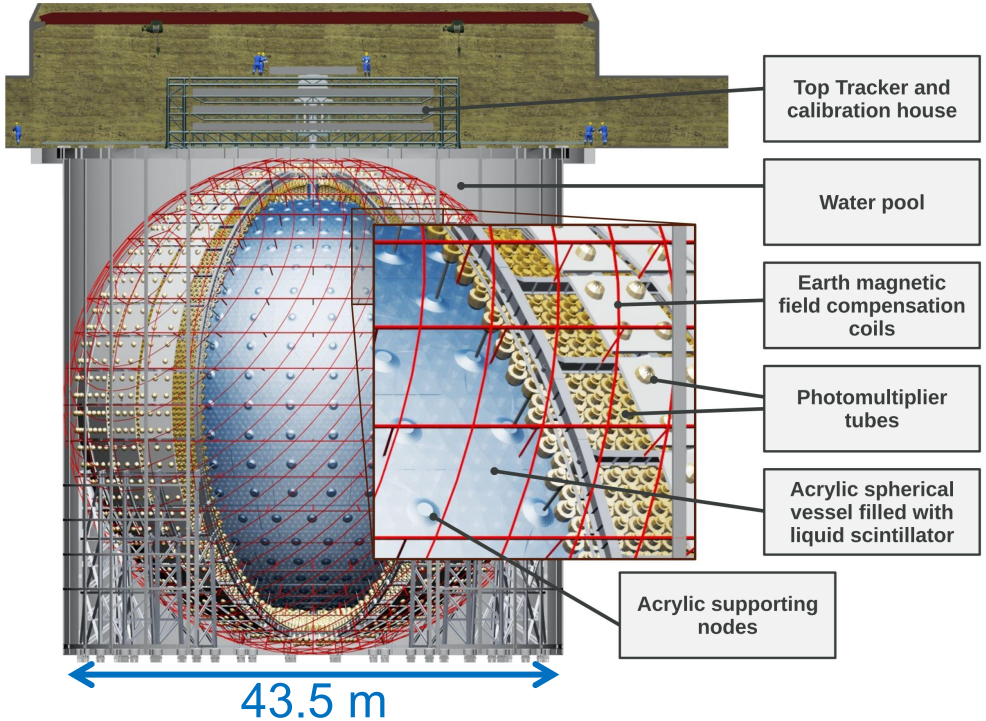
- Measuring the fast and slow oscillations of the reactor $\bar{\nu}_e$ spectrum simultaneously
- Distinguishing the tiny structural difference of energy spectrum oscillation caused by different mass ordering
- Key requirements to detector:
  - Energy scale uncertainty < 1%
  - Effective energy resolution < 3% @ 1MeV

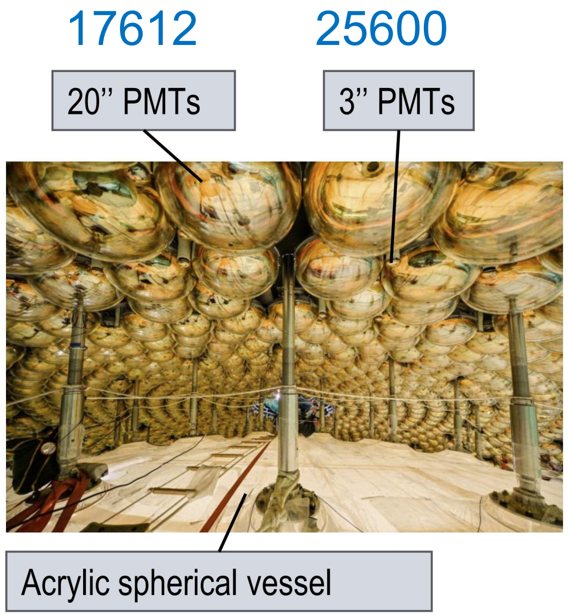


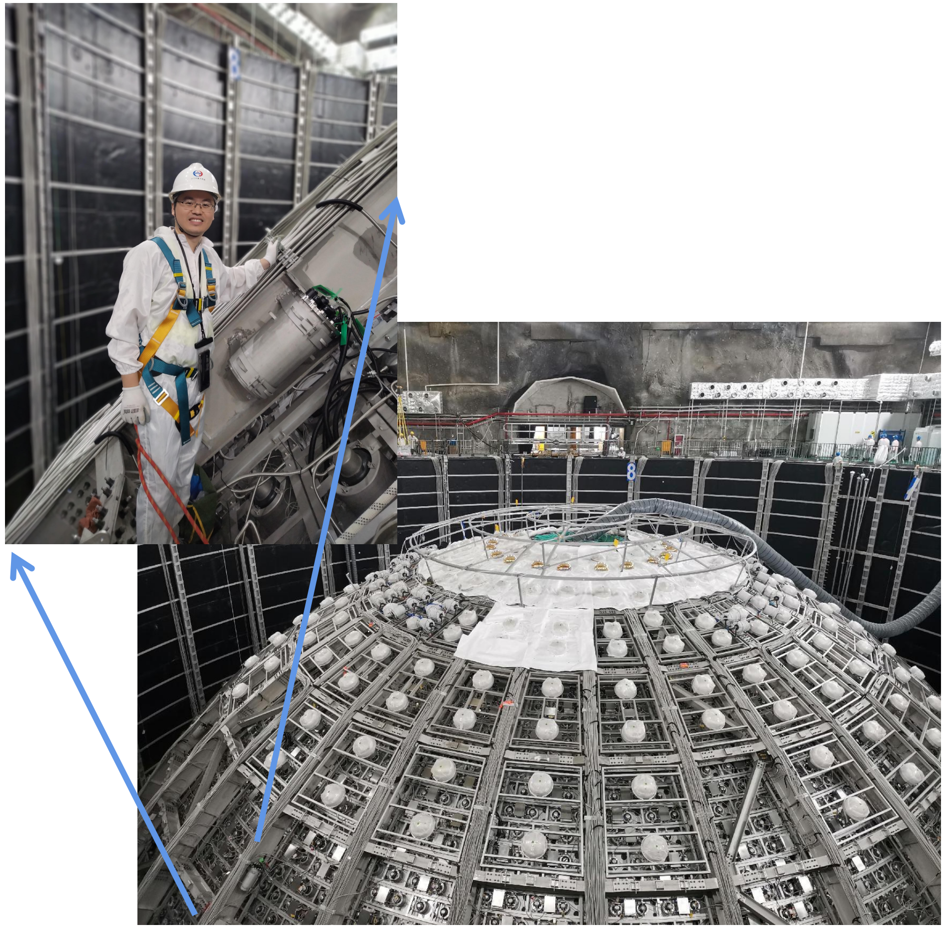
How to achieve the key requirements ?

- The detectors are well designed and optimized
  - Highly transparent LS: attenuation length >20m@430nm
  - Highly efficient PMT: average PMT detection efficiency: ~30%
  - Very high PMT photo-coverage: 78%
  - Dual Calorimetry technique (20-inch and 3-inch PMTs): well-controlled in single channel level
  - ……

JUNO Detector







Experiment	Daya Bay	Borexino	KamLAND	JUNO
LS mass	20 ton	~300 ton	~1 kton	20 kton
PMT coverage	~12%	~34%	~34%	~78%
Light yield	~160 p.e./ MeV	~500 p.e./ MeV	~250 p.e./MeV	> 1345 p.e./ MeV
Energy scale uncertainty	0.5%	1%	2%	**< 1%**
Energy resolution	~8%	~5%	~6%	**~3%**

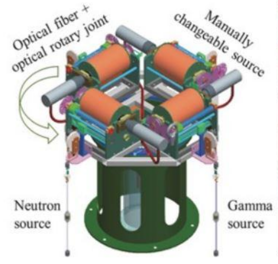
How to achieve the key requirements ?

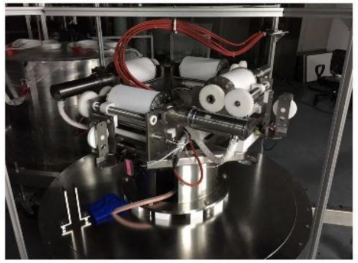
- The detectors are well designed and optimized
- A comprehensive calibration system is designed (multi-dimensional scan)
  - Automatic Calibration Unit (ACU): 1D calibration
  - Cable Loop System (CLS): 2D calibration
  - Remotely Operated under-LS Vehicles (ROV): 3D calibration
  - Guide Tube Calibration System (GTCS): boundary calibration
  - Multiple radioactive sources and Laser source

Calibration system

Automatic Calibration Unit (ACU)

- 1D central axis scan with gamma sources, neutron sources and laser automatically

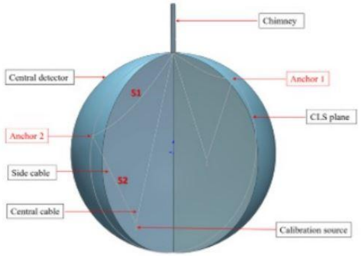




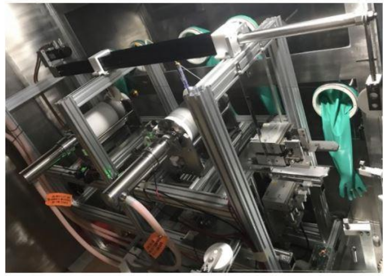
ACU prototype

Cable Loop System (CLS)

- 2D plane source scan with cable loops assembled on both semisphere sides

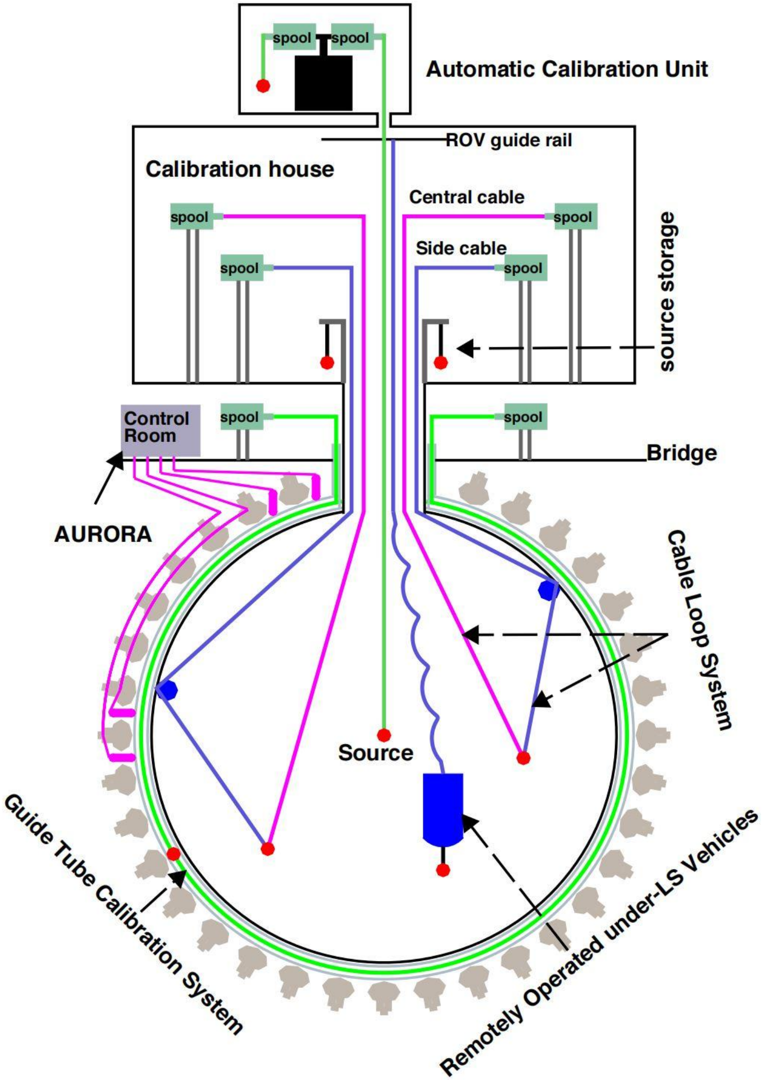


CLS layout



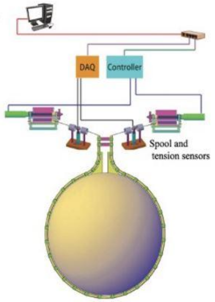
CLS motor prototype

ACU: JINST 16 (2021) 08, T08008
CLS: Nucl.Instrum.Meth.A 988 (2021) 164867
GT: JINST 14 (2019) 09, T09005



Guide Tube Calibration System (GTCS)

- Calibrate boundary area and provide boundary condition for the CD

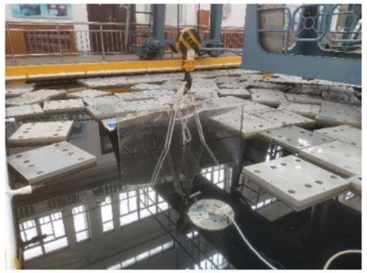


1:1 GTCS prototype

GTCS: JINST 16 (2021) T07005

Remotely Operated Vehicle (ROV)

- 3D source scan with a self-driven vehicle unit



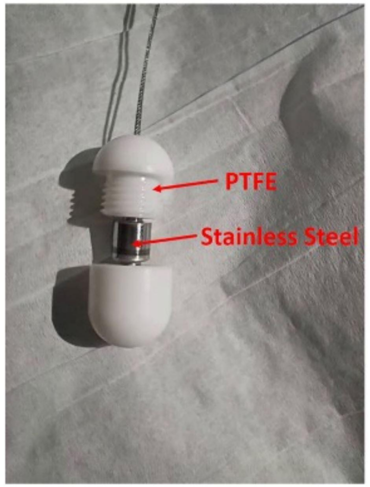
ROV water test

ROV test in LS

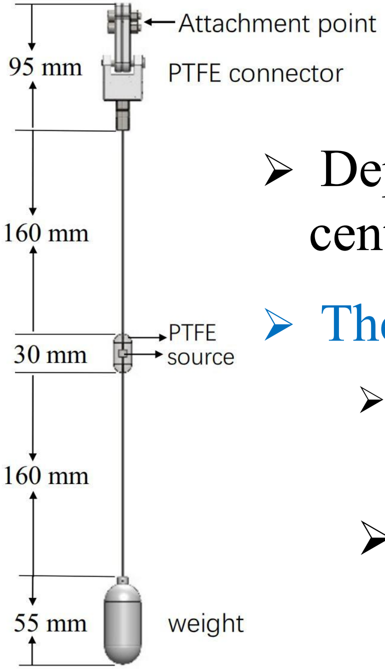
Calibration sources

Source capsule and hanging fixture

PTFE capsule

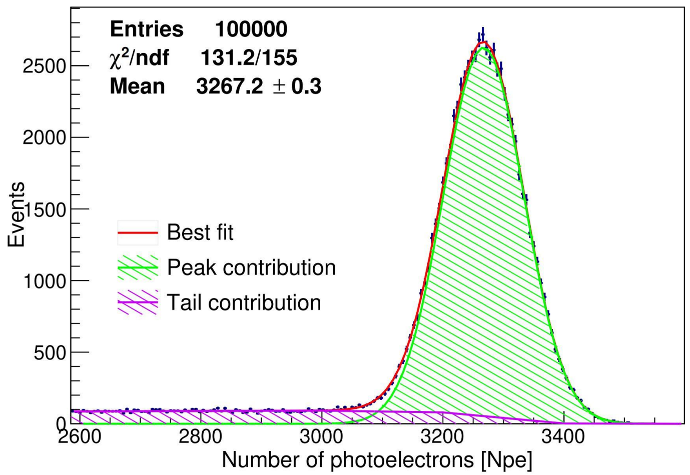


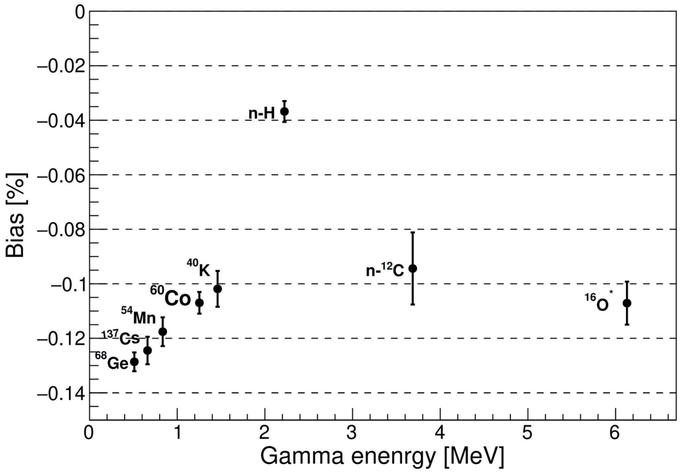
Double layer SS capsule



- Deploying multiple radioactive sources in various locations inside/outside of the central detector (CD)
- The potential energy deviation is carefully estimated
  - Energy loss effect (< 0.06%)
    - Some energy can be deposited in the non-scintillating material, e.g. the enclosure
  - Shadowing effect (< 0.15%)
    - Some optical photons can be absorbed by material surfaces
- Radioactive sources in several tens to hundreds keV range are also being studied

Sources/Processes	Type	Radiation
^{137}Cs	γ	0.662 MeV
^{54}Mn	γ	0.835 MeV
^{60}Co	γ	1.173 + 1.333 MeV
^{40}K	γ	1.461 MeV
^{68}Ge	e^+	annihilation 0.511 + 0.511 MeV
^{241}Am-Be	n, γ	neutron + 4.43 MeV (^{12}C*)
^{241}Am-^{13}C	n, γ	neutron + 6.13 MeV (^{16}O*)
(n,γ)p	γ	2.22 MeV
(n,γ)^{12}C	γ	4.94 MeV or 3.68 + 1.26 MeV



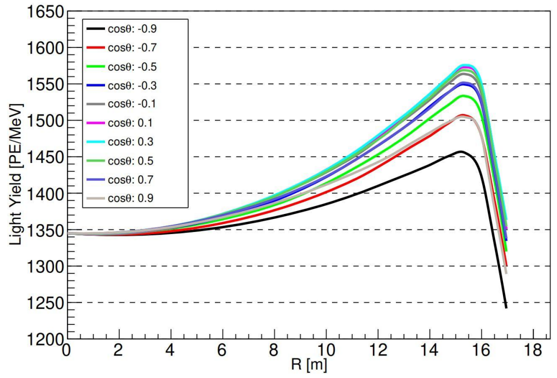


How to achieve the key requirements ?

- The detectors are well designed and optimized
- A comprehensive calibration system is designed (multi-dimensional scan)
- A comprehensive calibration strategy is developed -- *JHEP 03 (2021) 004*

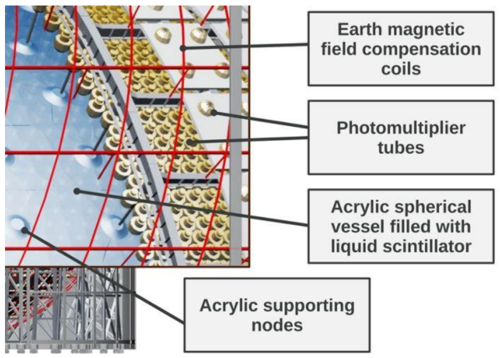
  (precisely understand the energy response of the detector)
  - Energy non-uniformity
  - Energy non-linearity
  - Energy resolution

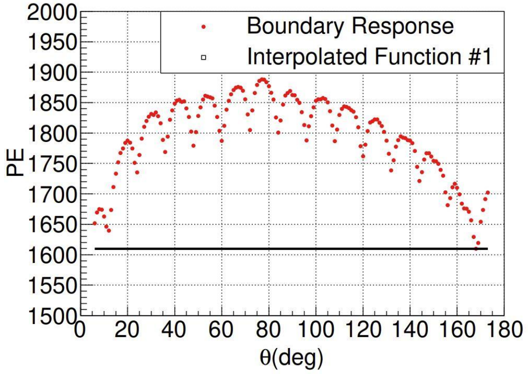
Calibration strategy -- Energy non-uniformity

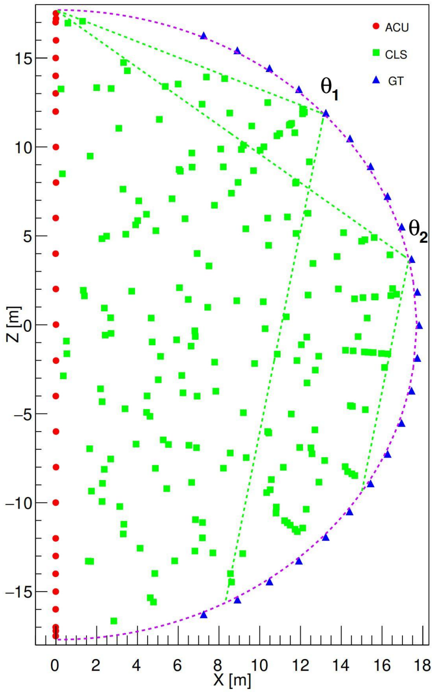


The energy response is position-dependent

- PMT solid angles
- Optical attenuation effects
- Reflections at material interfaces
  - Total reflection at R > 15.6 m region
- Shadowing due to opaque materials
  - Especially some of the support structures



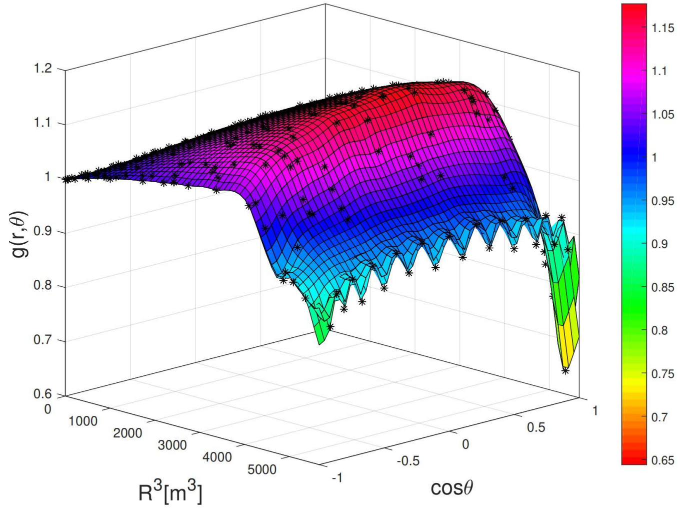




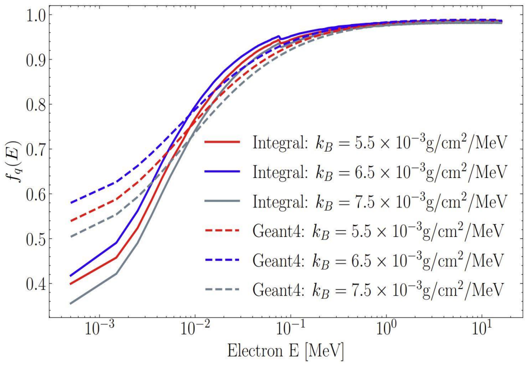
A multi-positional calibration is required

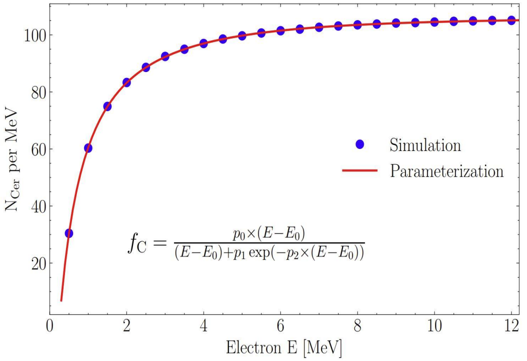
- Deploying multiple radioactive sources in various locations inside/outside of the central detector (CD)
- Obtain radial-angular function $g(r,\theta)$ from calibration and then non-uniformity could be corrected

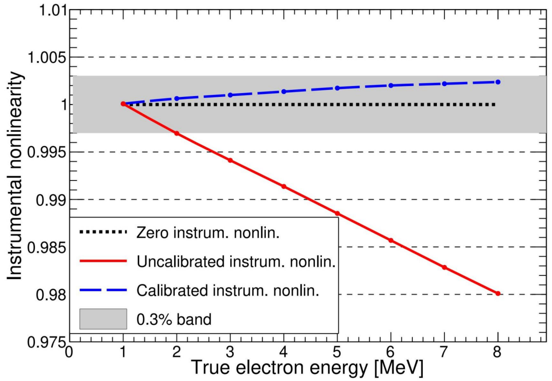
Ø-symmetry is assumed



Calibration strategy -- Energy non-linearity





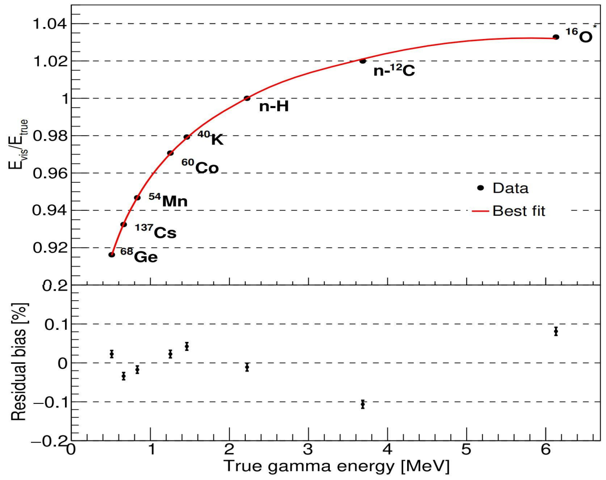


The energy response is energy-dependent

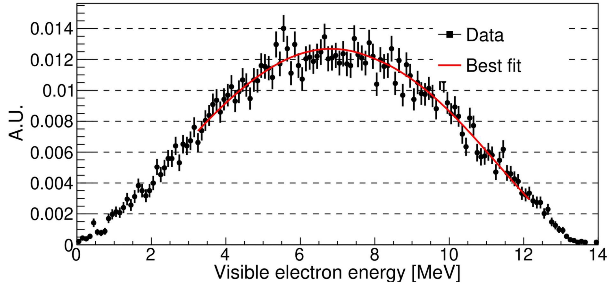
- ➢ Ionization quenching reduces scintillator light yield
  - ➢ Birks' law
- ➢ Cherenkov radiation contributes additional photons
  - ➢ Further through the absorption and re-emission process
- ➢ Instrumental non-linearity
  - ➢ Imperfect charge reconstruction

Construct an energy response model

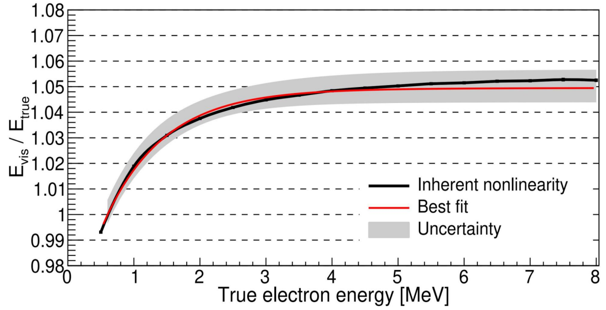
- ➢ Determine the relationship between E_{true} and E_{vis}
  - ➢ Different approaches to model non-linearity
    - ➢ (1) Parametrization based on empirical formula
    - ➢ (2) Birks' law + Cherenkov curve
- ➢ Multiple gamma sources and cosmogenic background (^{12}B) used to calibrate non-linearity
- ➢ Dual calorimetry technique
  - ➢ Calibrate instrumental non-linearity by comparing LPMTs and SPMTs response



(a) Gamma non-linearity



(b) Boron Spectrum



(c) Electron non-linearity

Calibration strategy -- Energy resolution

$$\frac{\sigma_{E_{\mathrm{vis}}^{\mathrm{prompt}}}}{E_{\mathrm{vis}}^{\mathrm{prompt}}} = \sqrt{\left(\frac{a}{\sqrt{E_{\mathrm{vis}}^{\mathrm{prompt}}}}\right)^2 + b^2 + \left(\frac{c}{E_{\mathrm{vis}}^{\mathrm{prompt}}}\right)^2}$$

- a term: Poisson statistical fluctuations (~2.6%)
- b term: a constant independent of energy, dominated by the position non-uniformity (~0.8%)
- c term: background noise (~1%)

For the NMO determination, the impact of the b term is ~1.6 times larger than that of the a term, and the impact of the c term is ~1.6 times smaller than that of the a term. For convenience, an effective energy resolution can be defined as

$$\tilde{a} \equiv \sqrt{(a)^2 + (1.6 \times b)^2 + \left(\frac{c}{1.6}\right)^2} \leqslant 3\%$$

Assumptions	a	b	c	$\tilde{a} = \sqrt{a^2 + (1.6b)^2 + (\frac{c}{1.6})^2}$	energy bias (%)
Central IBDs	2.62(2)	0.73(1)	1.38(4)	2.99(1)	-
Ideal correction	2.57(2)	0.73(1)	1.25(4)	2.93(1)	-
Azimuthal symmetry	2.57(2)	0.78(1)	1.26(4)	2.96(1)	-
Single gamma source	2.57(2)	0.80(1)	1.24(4)	2.98(1)	-
Finite calibration points	2.57(2)	0.81(1)	1.23(4)	2.98(1)	-
Vertex smearing(8 cm/$\sqrt{E(\mathrm{MeV})}$)	2.60(2)	0.82(1)	1.27(4)	3.01(1)	-
PMT QE random variations	2.61(2)	0.82(1)	1.23(4)	3.02(1)	0.03(1)
1% PMT death (random)	2.62(2)	0.84(1)	1.23(5)	3.04(1)	0.09(1)
1% PMT death (asymmetric)	2.63(2)	0.86(1)	1.20(4)	3.06(1)	0.23(1)
Y_0 reduced by 1%	2.62(2)	0.85(1)	1.25(4)	3.05(1)	0.09(1)
Y_0 reduced by 5%	2.68(2)	0.85(1)	1.28(5)	3.11(1)	0.09(1)
Absorption length reduced by 4%	2.62(2)	0.82(1)	1.27(4)	3.03(1)	0.07(1)
PMT single photon charge resolution (30%)	2.72(2)	0.83(1)	1.23(5)	3.12(1)	0.08(1)

Mock neutrino energy spectra were generated assuming different values of a, b and c to investigate the impact of the energy resolution.

Calibration program

Comprehensive calibration

Source	Energy [MeV]	Points	Travel time [min]	Data taking time [min]	Total time [min]
Neutron (Am-C)	2.22	250	680	1262	1942
Neutron (Am-Be)	4.4	1	58	17	75
Laser	/	10	58	333	391
^{68}Ge	0.511×2	1	58	17	75
^{137}Cs	0.662	1	58	17	75
^{54}Mn	0.835	1	58	17	75
^{60}Co	1.17+1.33	1	58	17	75
^{40}K	1.461	1	58	100	158
Total	/	/	1086	1780	2866 ($\sim$ 48 h)

Weekly calibration

Source	Energy [MeV]	Points	Travel time [min]	Data taking time [min]	Total time [min]
Neutron (Am-C)	2.22	5	58	5	63
Laser	/	10	58	20	78
Total	/	/	116	25	141 ($\sim$2.4 h)

Monthly calibration

System	Source	Points	Travel time [min]	Data taking time [min]	Total time [min]
ACU	Neutron (Am-C)	27	93	27	120
ACU	Laser	27	93	54	147
CLS	Neutron (Am-C)	40	293	40	333
GT	Neutron (Am-C)	23	50	23	73
Total	/	/	529	144	673 ($\sim$11.2 h)

Summary

- A comprehensive calibration system is designed in JUNO
  - Multi-dimensional calibration

- JUNO developed a comprehensive calibration strategy to understand the energy response of the detector
  - Energy non-uniformity, non-linearity, resolution

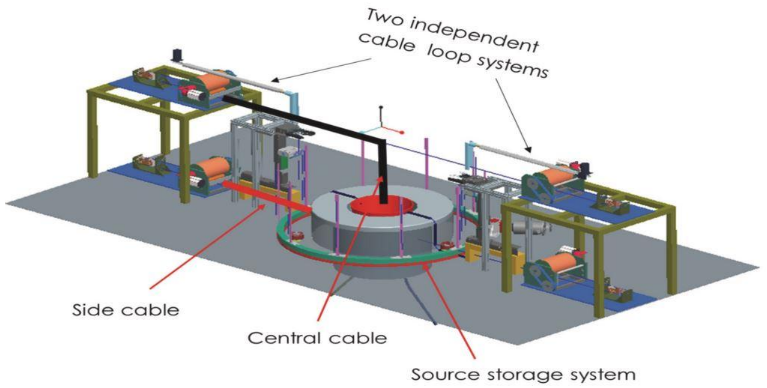
- With the calibration scheme, JUNO can achieve an excellent energy resolution of 3% /√E(MeV) and an accuracy of the energy scale at 1% level or better

Backup

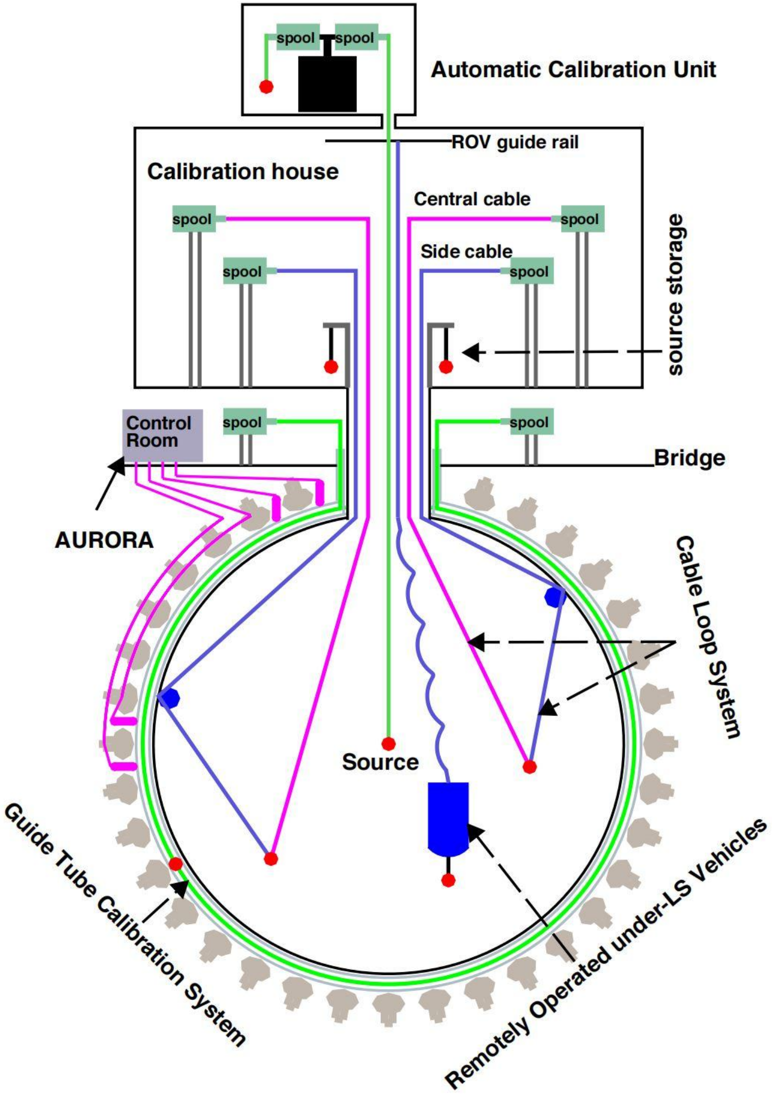
Calibration system -- Auxiliary systems

Calibration house

- Source storage, motors to control CLS system, ROV rail, etc



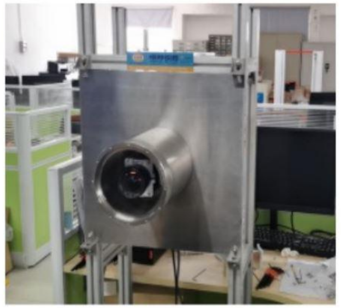
Calibration house



Ultrasonic sensor system (USS) and CCD

- positioning ROV and CLS

USS prototype



CCD prototype

AURORA (A Unit for Researching Online the LSc tRAnsparency)

- Monitor and determine LS attenuation length, scattering length and absorption length with laser system