Group Report T 80.1:

Neutrino Physics with JUNO

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on behalf of

the JUNO Collaboration

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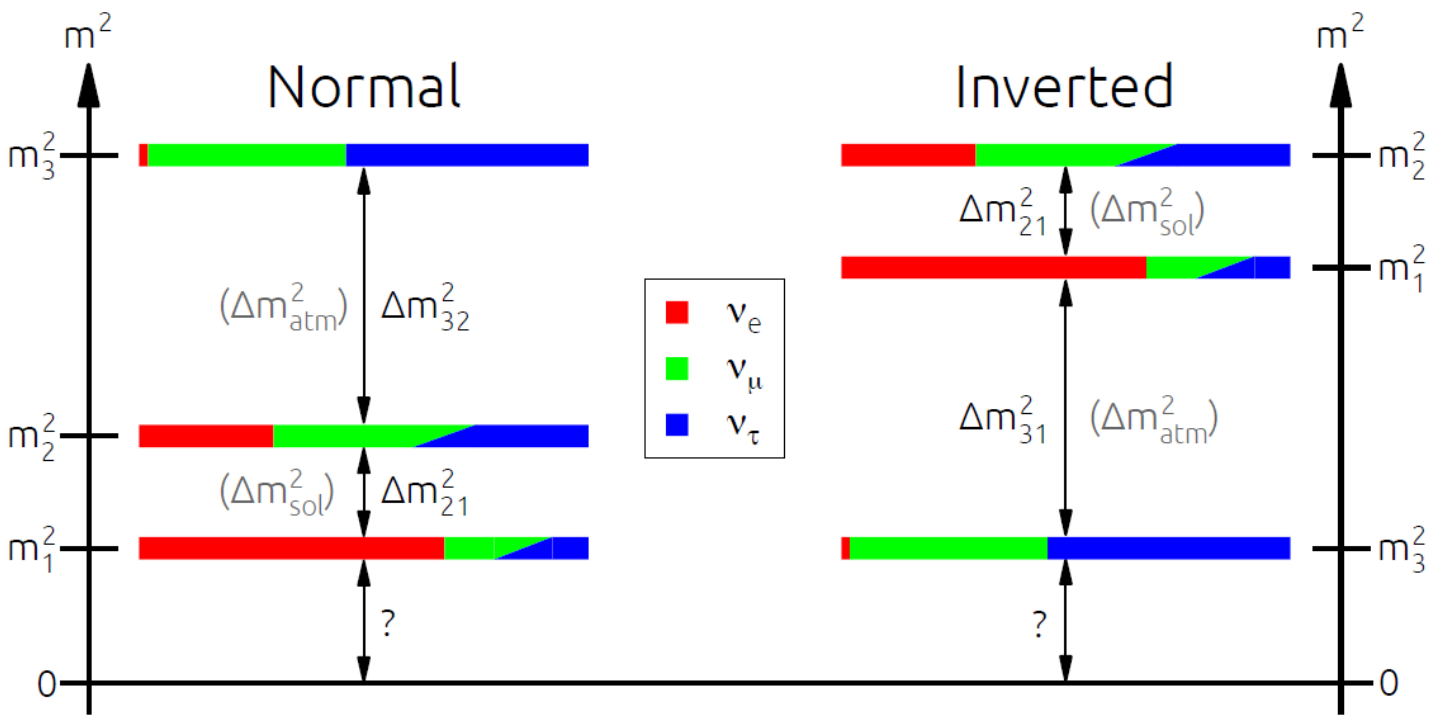
Mass Ordering (MO)



$m_1 < m_2 < m_3$

$m_3 < m_1 < m_2$

$\Delta m^2_{sol} = 7.5 \times \mathbf{10^{-5}} \mathrm{eV}^2$
$\Delta m^2_{atm} = 2.4 \times \mathbf{10^{-3}} \mathrm{eV}^2$

Why measure MO?

- helps to resolve δ_{CP}
- define 0νββ sector
- hint origin of neutrino masses

… and how to measure it

$$P_{\bar{\nu}_e\rightarrow\bar{\nu}_e} = 1 - \sin^2 2\Theta_{13}\left(\cos^2\Theta_{12}\,\mathbf{\sin^2\Delta_{31}} + \sin^2\Theta_{12}\,\mathbf{\sin^2\Delta_{32}}\right) - \cos^4\Theta_{13}\sin^2 2\Theta_{12}\sin^2\Delta_{21}$$

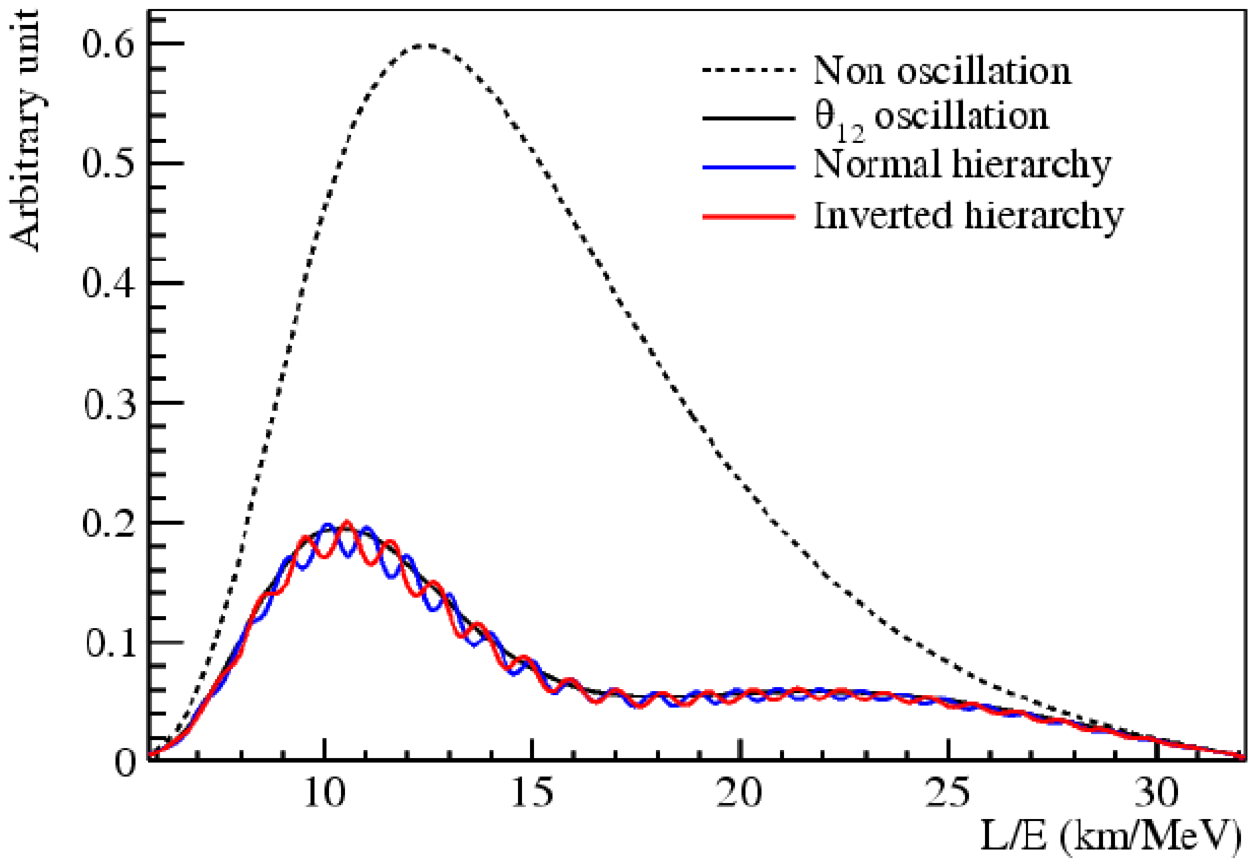
$$\Delta_{ij} = \Delta m_{ij} L/4E$$

E: neutrino energy
L: distance to source

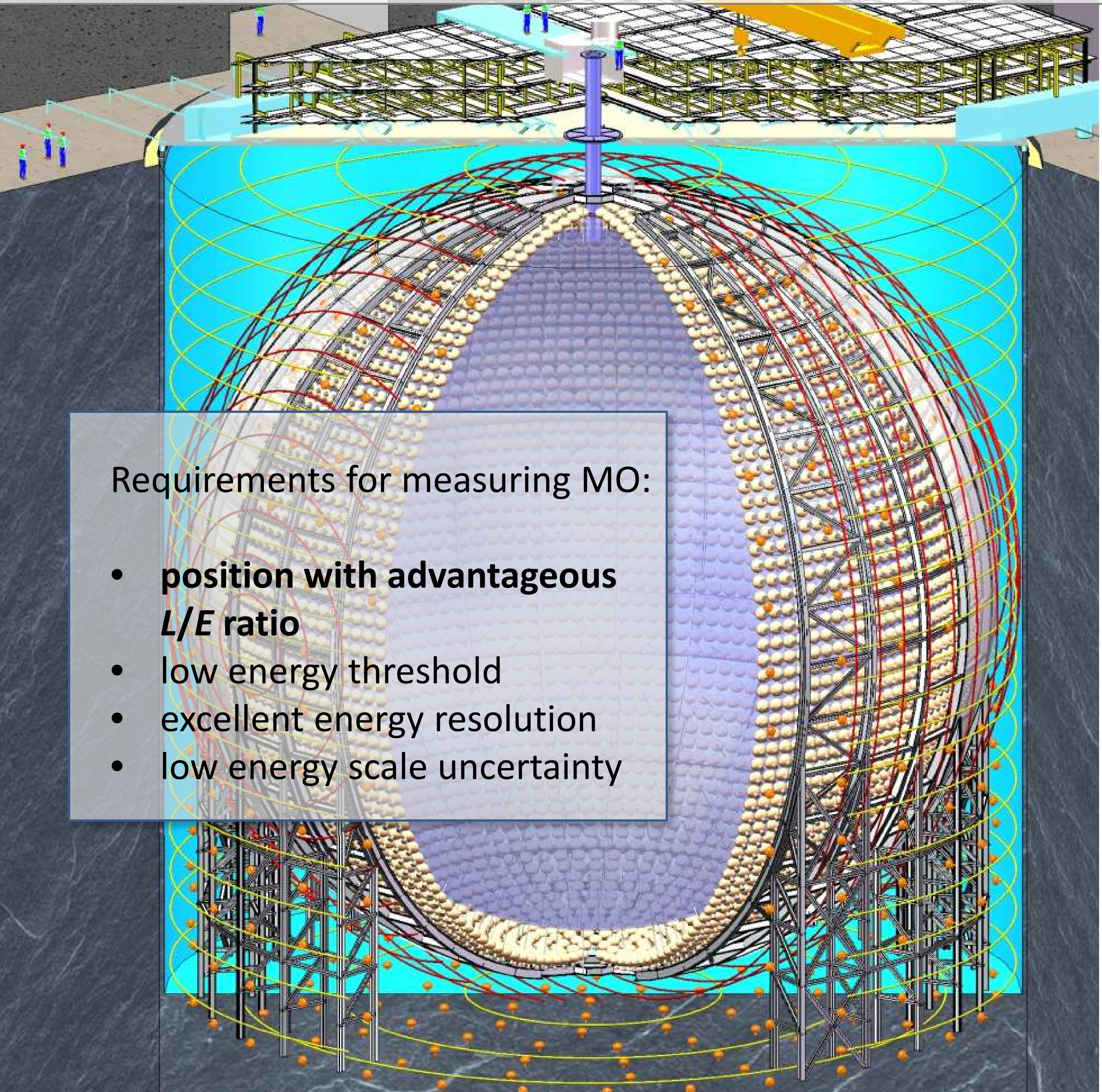
Requirements for measuring MO:

- position with advantageous L/E ratio
- low energy threshold
- excellent energy resolution
- low energy scale uncertainty

reactor $\bar{\nu}_e$ spectrum



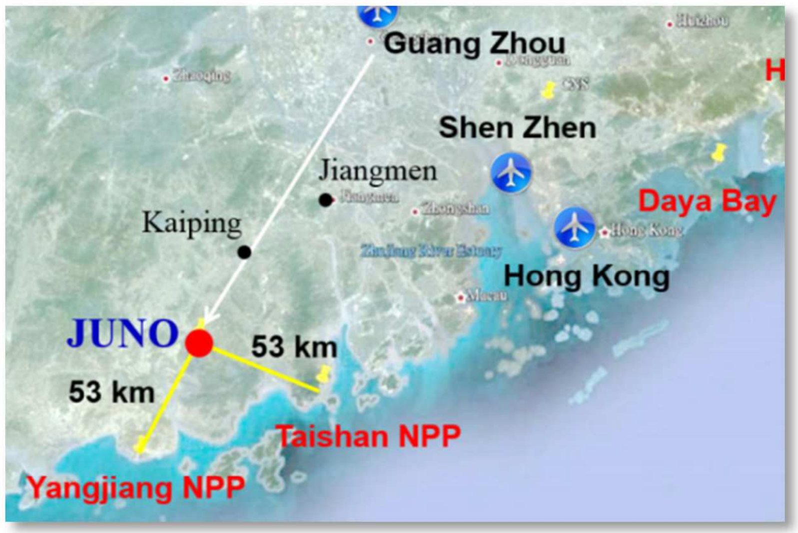
JUNO Overview

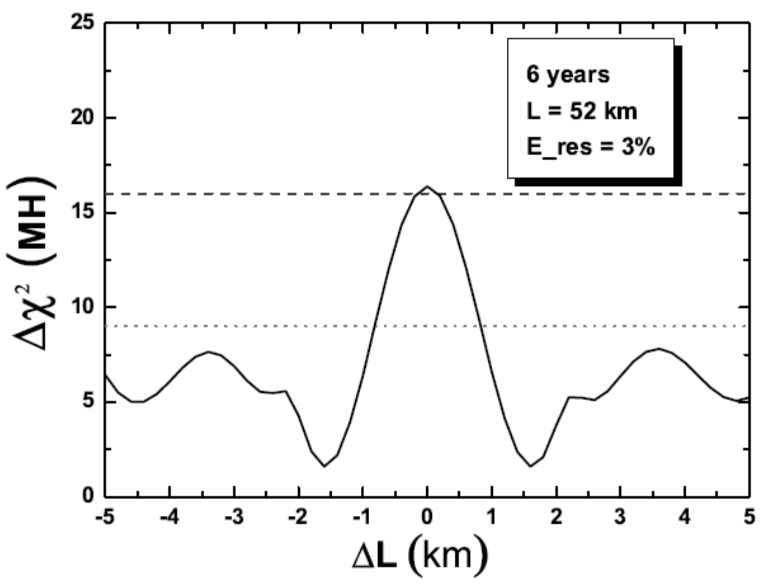


Requirements for measuring MO:

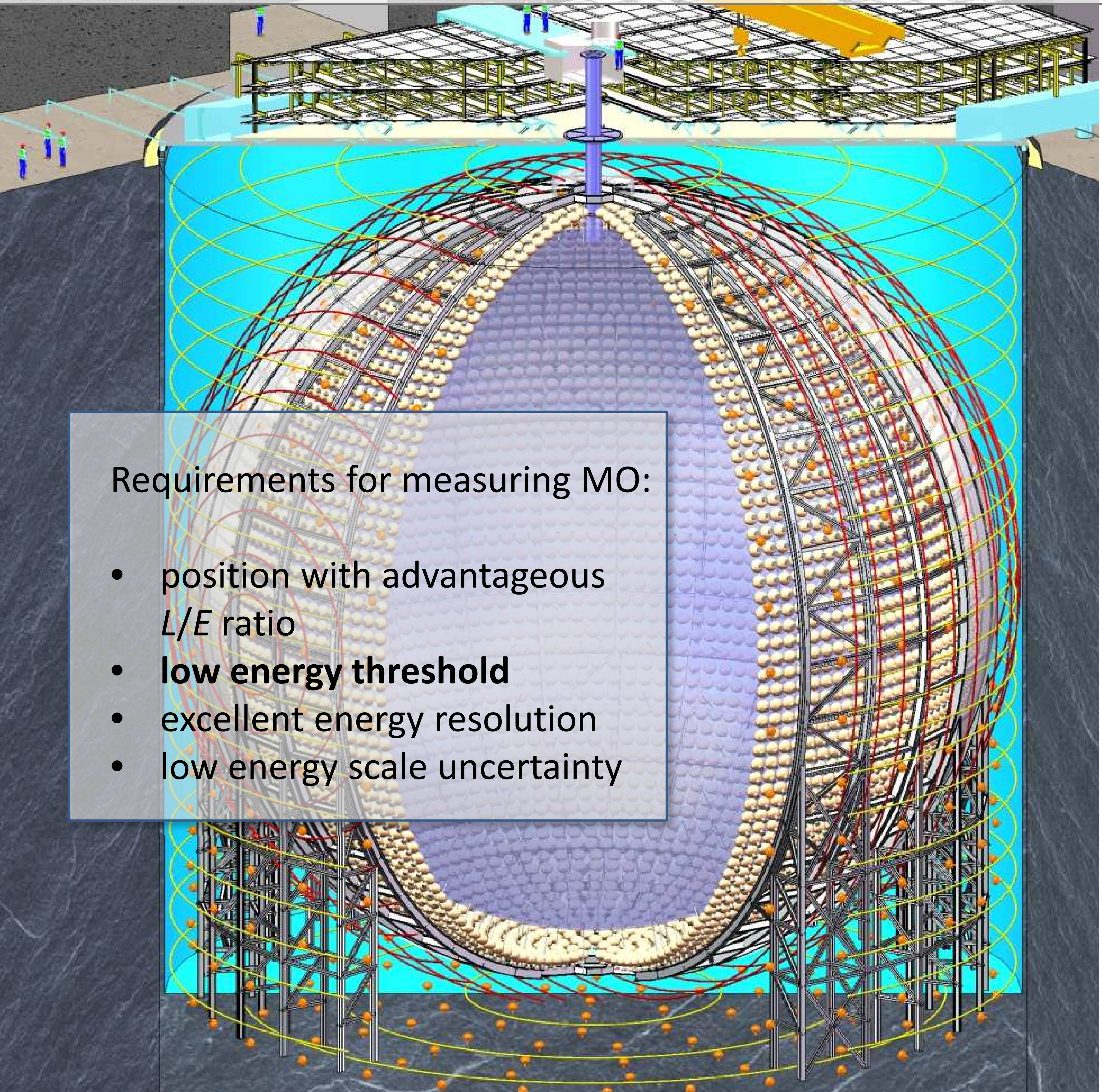
- ***position with advantageous L/E ratio***
- low energy threshold
- excellent energy resolution
- low energy scale uncertainty

- ~53 km distance to two nuclear power plants (35.8 GW P_{th})





JUNO Overview

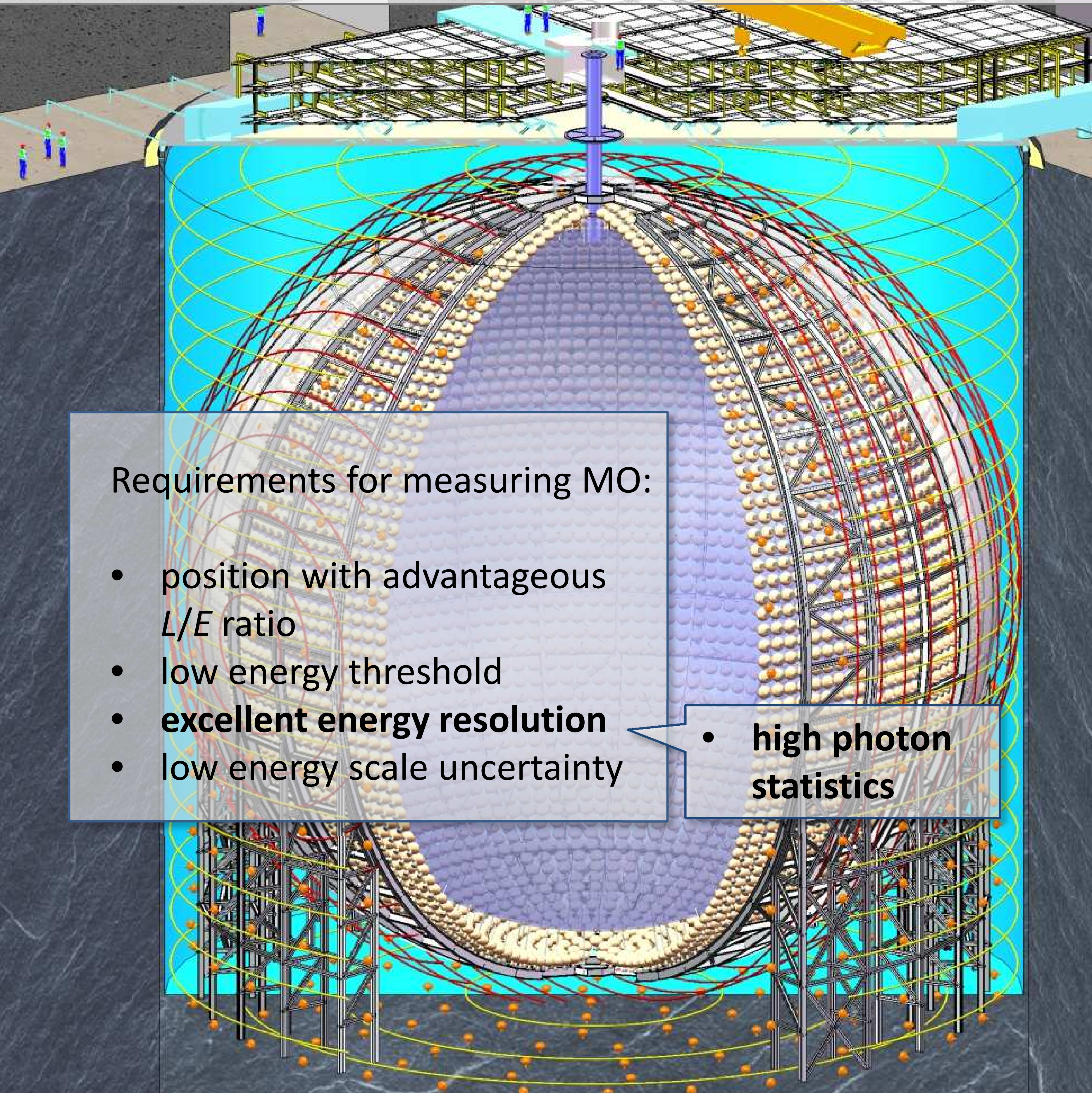


Requirements for measuring MO:

- position with advantageous *L*/*E* ratio
- **low energy threshold**
- excellent energy resolution
- low energy scale uncertainty

- ~53 km distance to two nuclear power plants (35.8 GW P_{th})
- 20 kt liquid scintillator

JUNO Overview



Requirements for measuring MO:

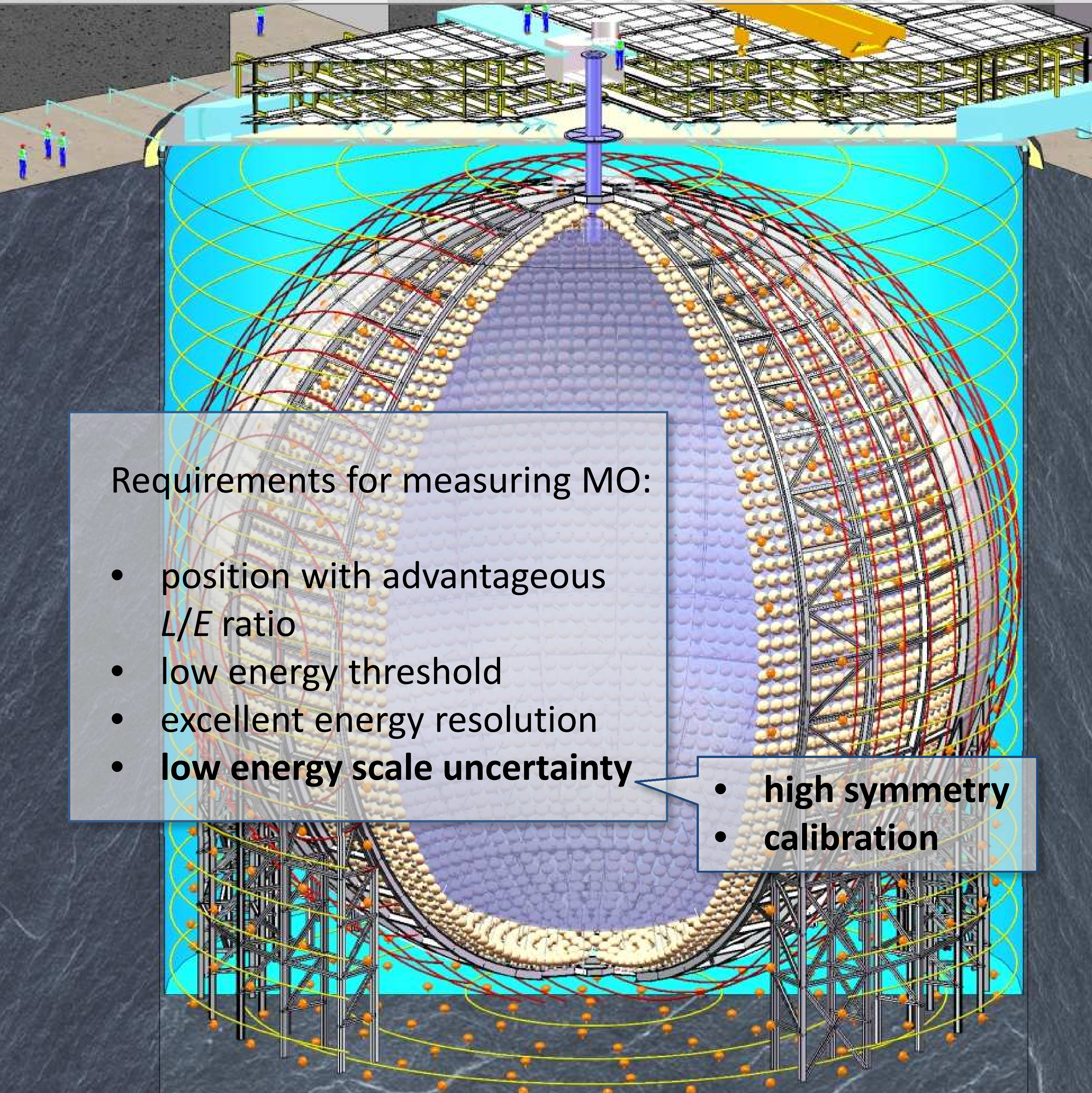
- position with advantageous *L*/*E* ratio
- low energy threshold
- **excellent energy resolution**
- low energy scale uncertainty

- **high photon statistics**

- ~53 km distance to two nuclear power plants (35.8 GW P_{th})
- 20 kt liquid scintillator
- acrylic tank: Ø 35.4 m (PMT sphere: Ø 40.1 m)
- ~18,000 20” PMTs, ~36,000 3” PMTs
  → 77% coverage
- $QE \approx 30\%$
- coils to shield EMF

→ $\Delta E/E = 3\%/\sqrt{E(\mathrm{MeV})}$

JUNO Overview



Requirements for measuring MO:

- position with advantageous *L/E* ratio
- low energy threshold
- excellent energy resolution
- **low energy scale uncertainty**

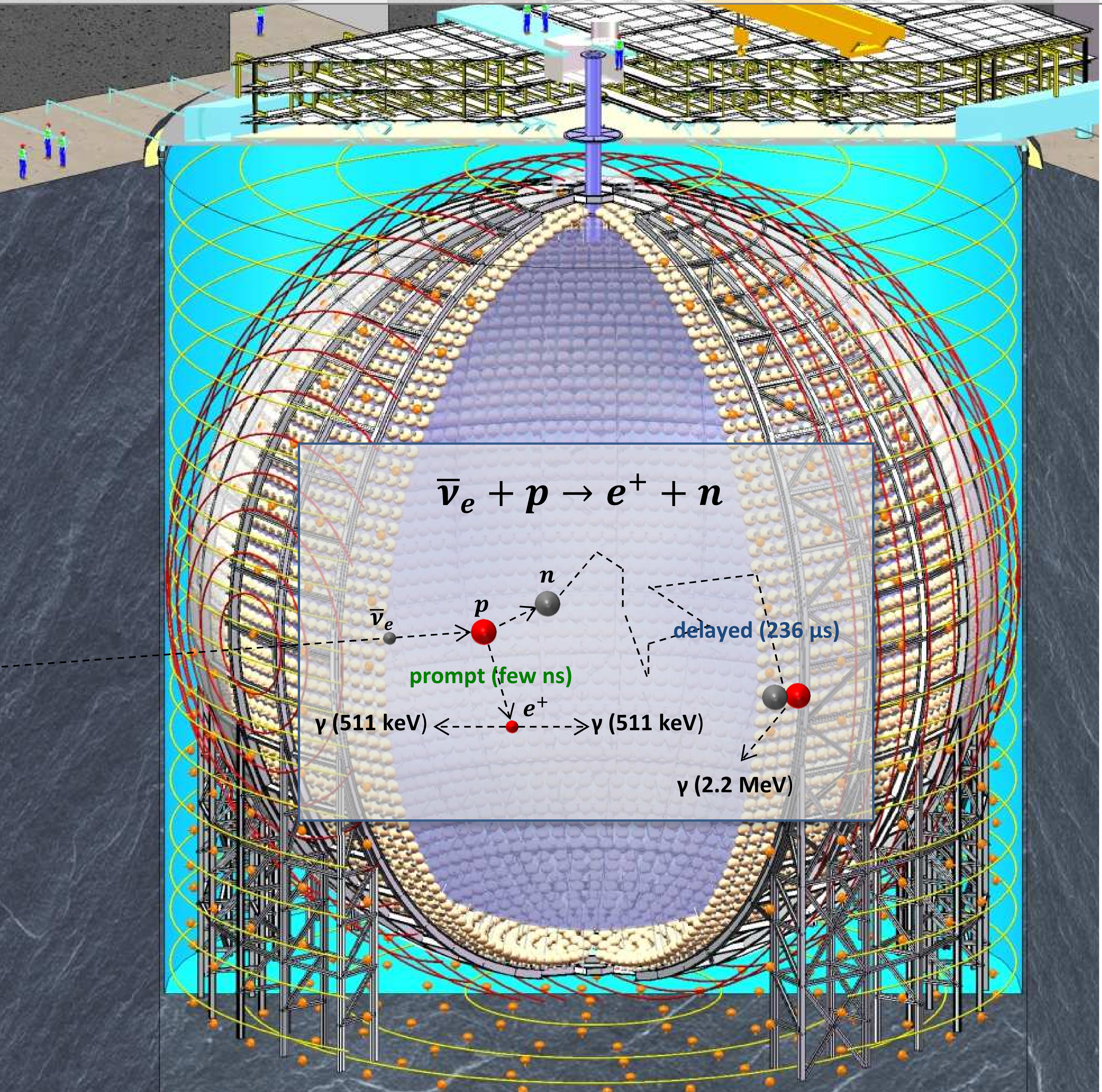
- **high symmetry**
- **calibration**

- ~53 km distance to two nuclear power plants (35.8 GW P_{th})
- 20 kt liquid scintillator
- acrylic tank: Ø 35.4 m (PMT sphere: Ø 40.1 m)
- ~18,000 20” PMTs, ~36,000 3” PMTs
  → 77% coverage
- $QE \approx 30\%$
- coils to shield EMF

→ $\Delta E/E = 3\%/\sqrt{E(\mathrm{MeV})}$

- energy scale uncertainty < 1%

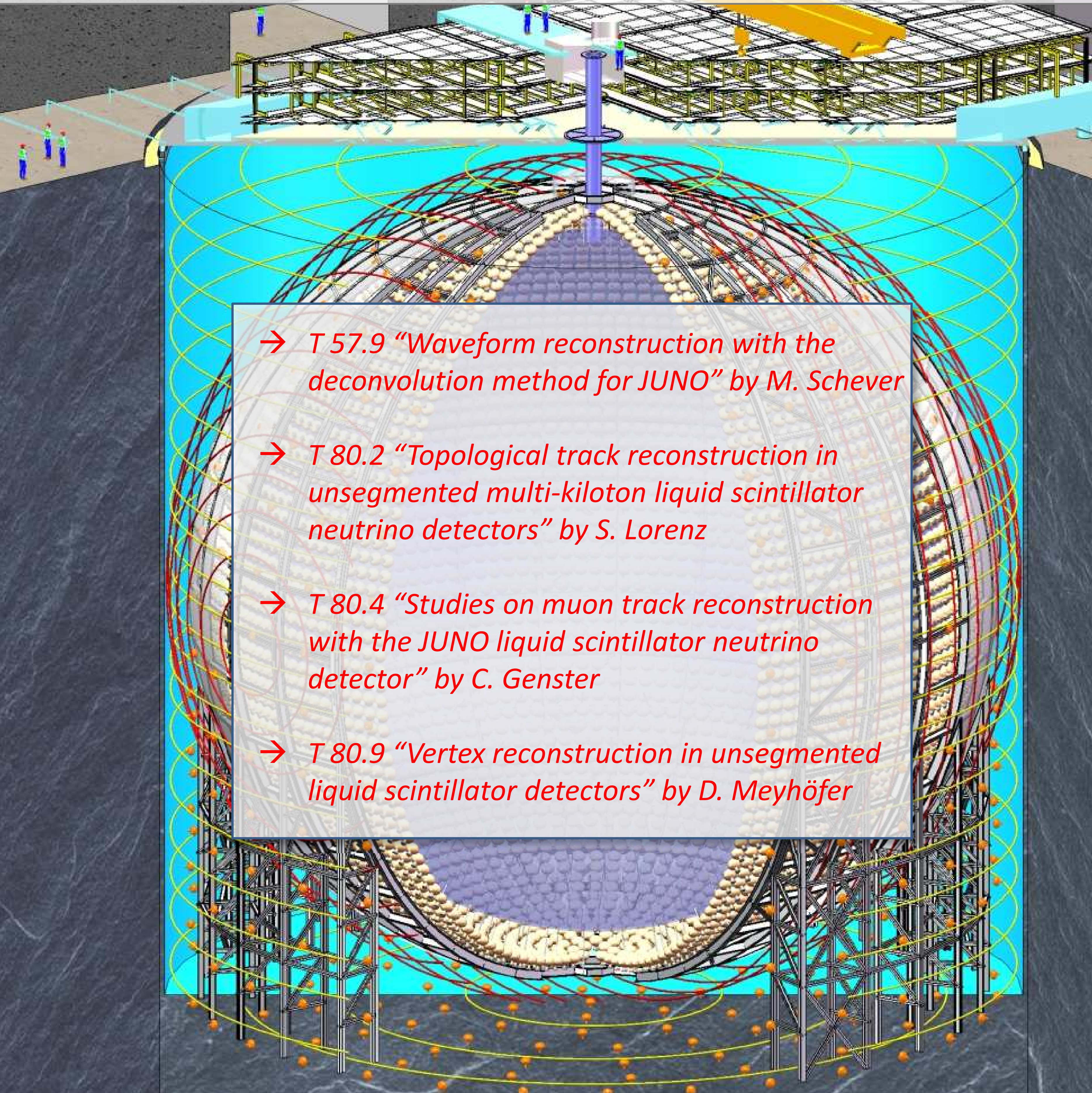
JUNO Overview



signal channel:

- inverse beta decay (IBD)
- delayed coincidence signature

JUNO Overview



→ *T 57.9 "Waveform reconstruction with the deconvolution method for JUNO" by M. Schever*

→ *T 80.2 "Topological track reconstruction in unsegmented multi-kiloton liquid scintillator neutrino detectors" by S. Lorenz*

→ *T 80.4 "Studies on muon track reconstruction with the JUNO liquid scintillator neutrino detector" by C. Genster*

→ *T 80.9 "Vertex reconstruction in unsegmented liquid scintillator detectors" by D. Meyhöfer*

signal channel:

- inverse beta decay (IBD)
- delayed coincidence signature

further background reduction:

- ~700 m rock overburden (≙1900 m.w.e.)

→ 3 muons/s

  - top tracker (OPERA)
  - ultra pure water buffer as Cherenkov veto (2400 20" PMTs)

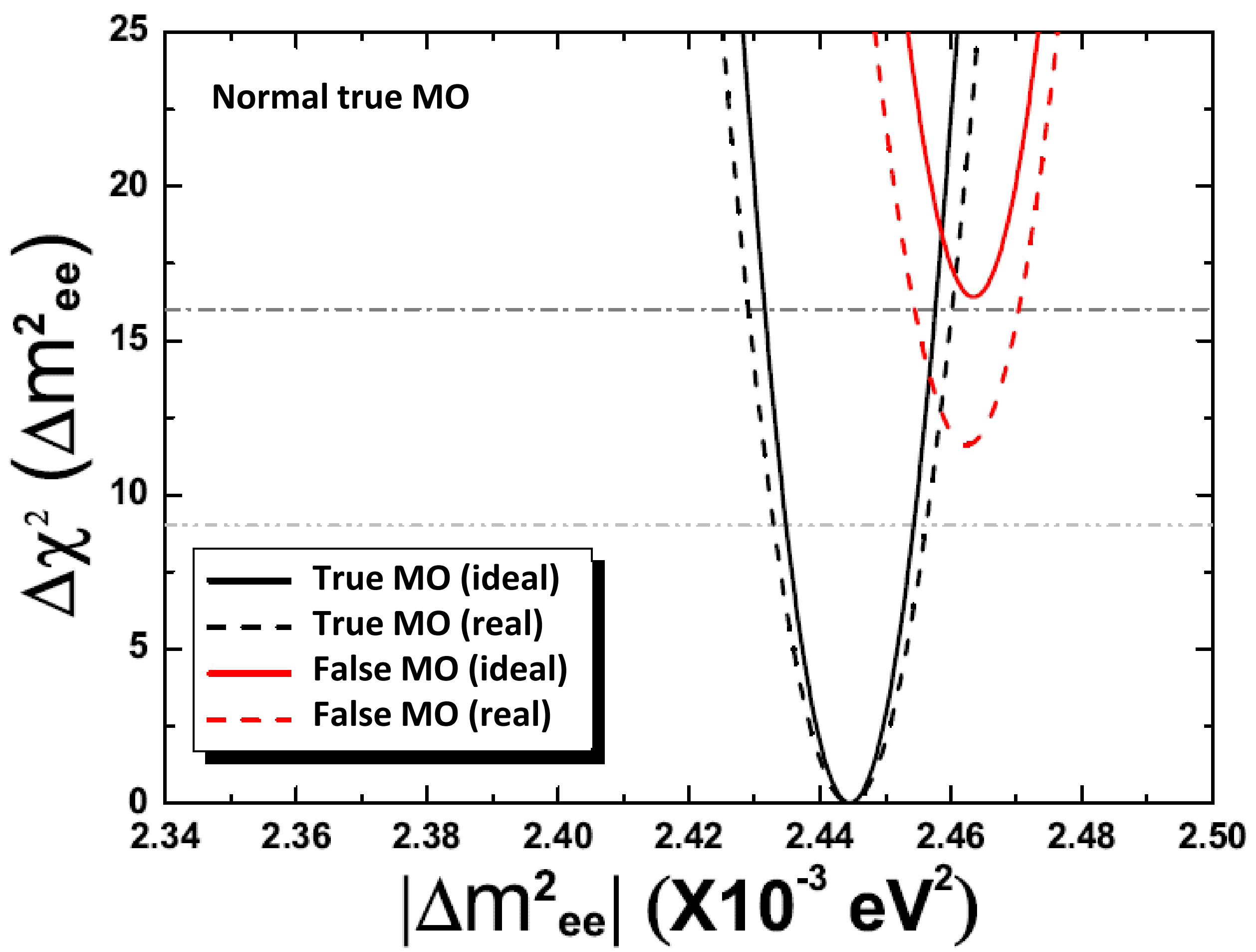
- after cuts: 60 IBD/day vs 3.8 background events/day

MO Sensitivity

$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \sin^2 2\Theta_{13}\underbrace{(\cos^2\Theta_{12}\sin^2\Delta_{31} + \sin^2\Theta_{12}\sin^2\Delta_{32})}_{:=\,\Delta m^2_{ee}} - \cos^4\Theta_{13}\sin^2 2\Theta_{12}\sin^2\Delta_{21}$$

$$\Delta_{ij} = \Delta m_{ij} L/4E$$

E: neutrino energy
L: distance to source



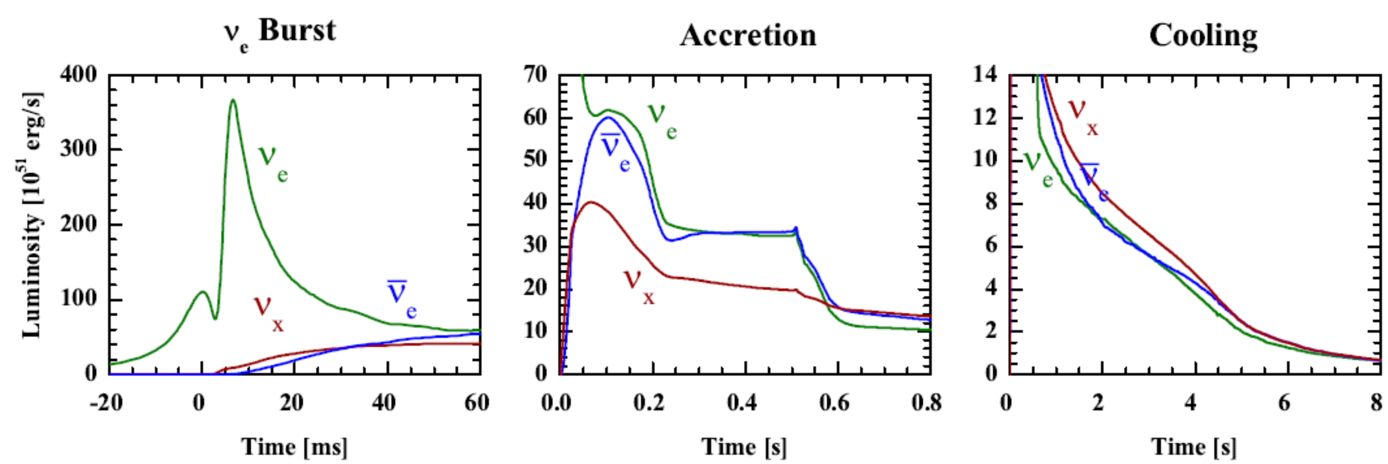
median **sensitivity on MO** after 100k IBD (6 yr of running):

- $\sim 3\sigma$ w/o external input
- 3.7σ - 4.4σ w/ external input

precision of measurement of **solar oscillation parameters**:

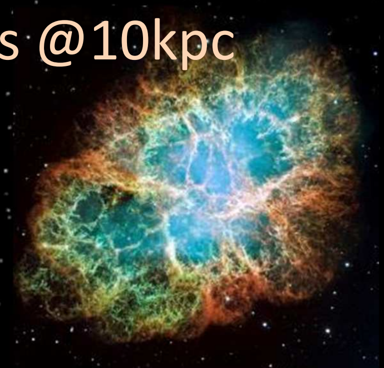
- $\sin^2\Theta_{12}$: 0.54% (current: 4.1%)
- Δm^2_{21}: 0.59% (current: 2.6%)

Further Studies



Core-collapse supernovae

5000 IBD/10 s @10kpc



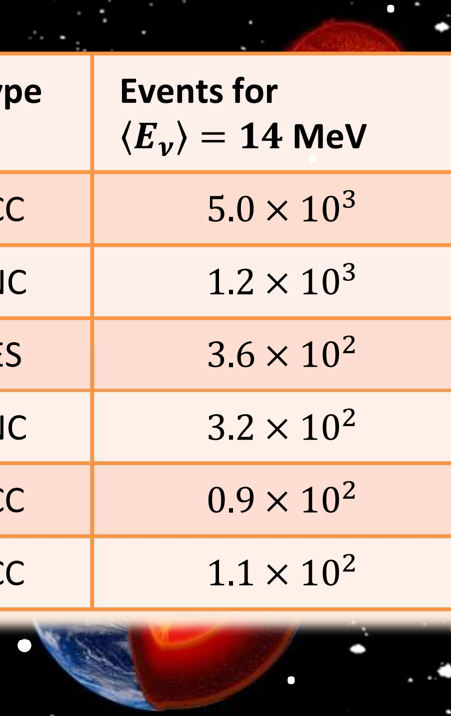
- huge statistics (~ Super K)
- separate detection of $\nu_e, \bar{\nu}_e, \nu_x$
- probe models w.r.t.
    - time evolution
    - energy spectra
    - flavor contents

DSNB

1-2 evts/year

Solar ν

tens of ^{8}B-ν/day

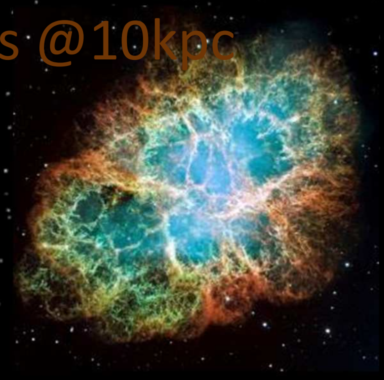


Channel	Type	Events for $\langle E_\nu \rangle = 14$ MeV
$\bar{\nu}_e + p \rightarrow e^+ + n$	CC	5.0×10^3
$\nu_x + p \rightarrow \nu_x + p$	NC	1.2×10^3
$\nu_x + e \rightarrow \nu_x + e$	ES	3.6×10^2
$\nu_x + {}^{12}\mathrm{C} \rightarrow \nu_x + {}^{12}\mathrm{C}^*$	NC	3.2×10^2
$\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}$	CC	0.9×10^2
$\bar{\nu}_e + {}^{12}\mathrm{C} \rightarrow e^+ + {}^{12}\mathrm{B}$	CC	1.1×10^2

Physics Potential

Core-collapse supernovae

5000 IBD/10 s @10kpc



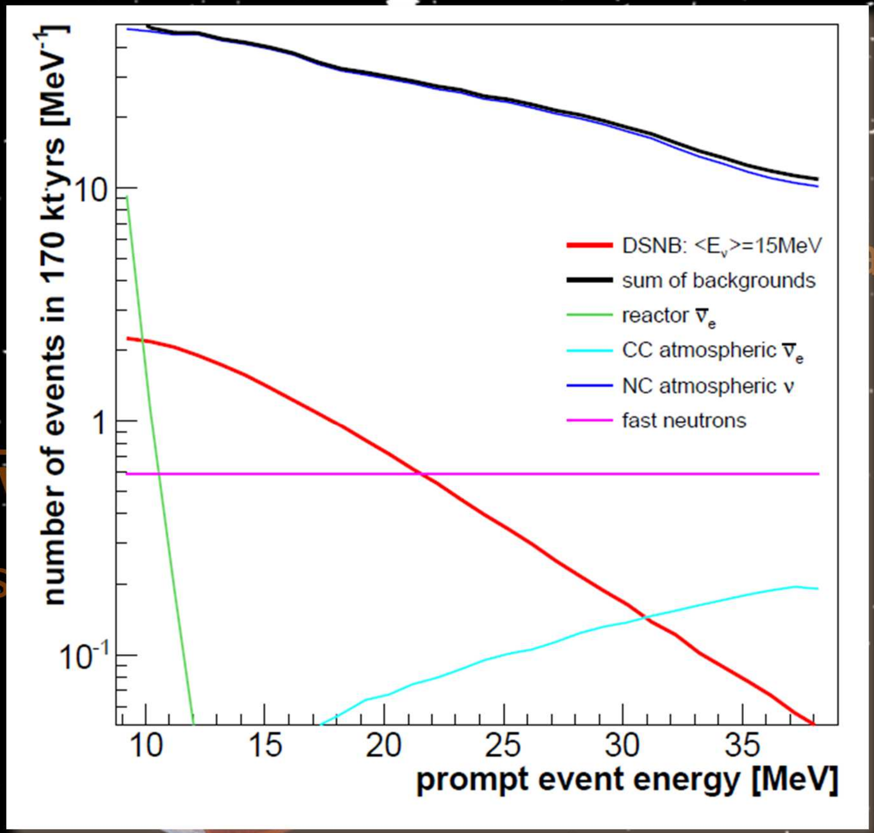
DSNB

1-2 evts/year

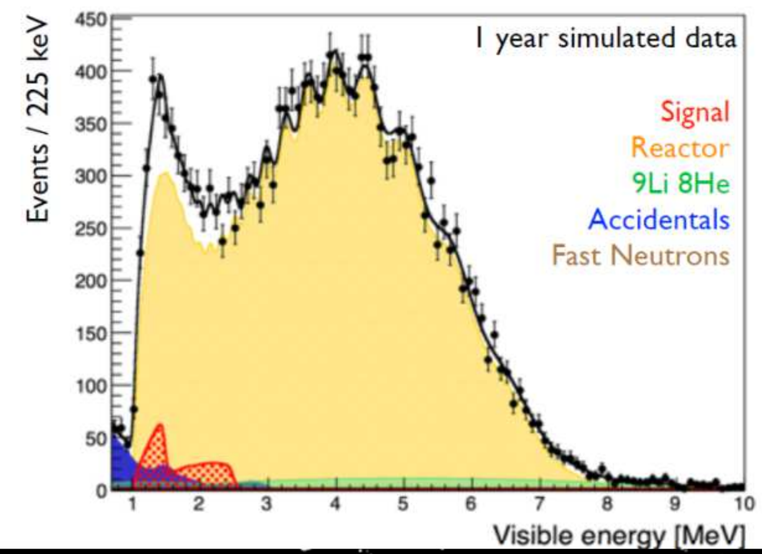
- core collapse SN rate
- average spectrum
- strong atmospheric ν background
- 3σ expected for observation after 10 yr
- even non-detection could tighten current limits

Geo

400 evts



Physics Potential



Core-collapse supernovae

5000 IBD/10 s @10kpc

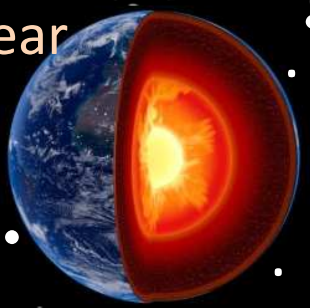
- $\bar{\nu}_e$ from U- and Th-chains from Earth
- look directly into mantle
- primordial vs radioactive sources
- large background from reactor $\bar{\nu}_e$
- JUNO could match present world sample in less than 1 yr

Solar ν

tens of ^{8}B-ν/day

Geo $\bar{\nu}$

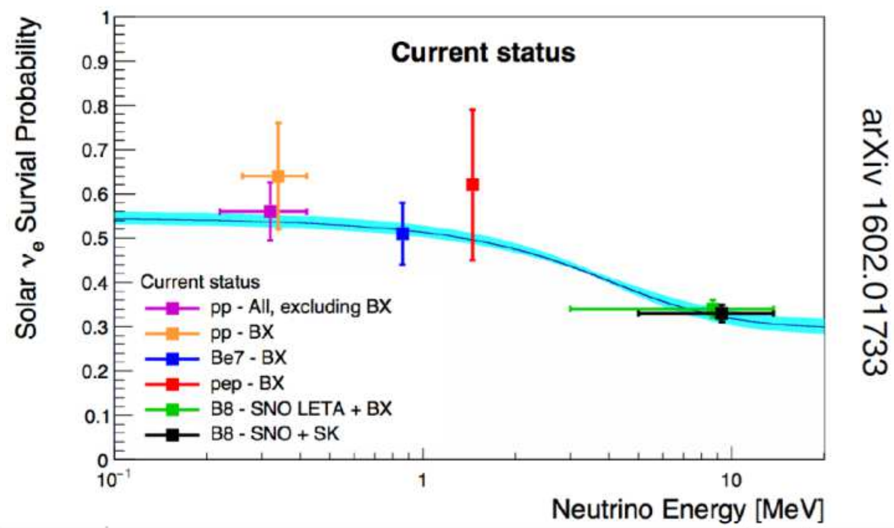
400 evts/year



DSNB

1-2 evts/year

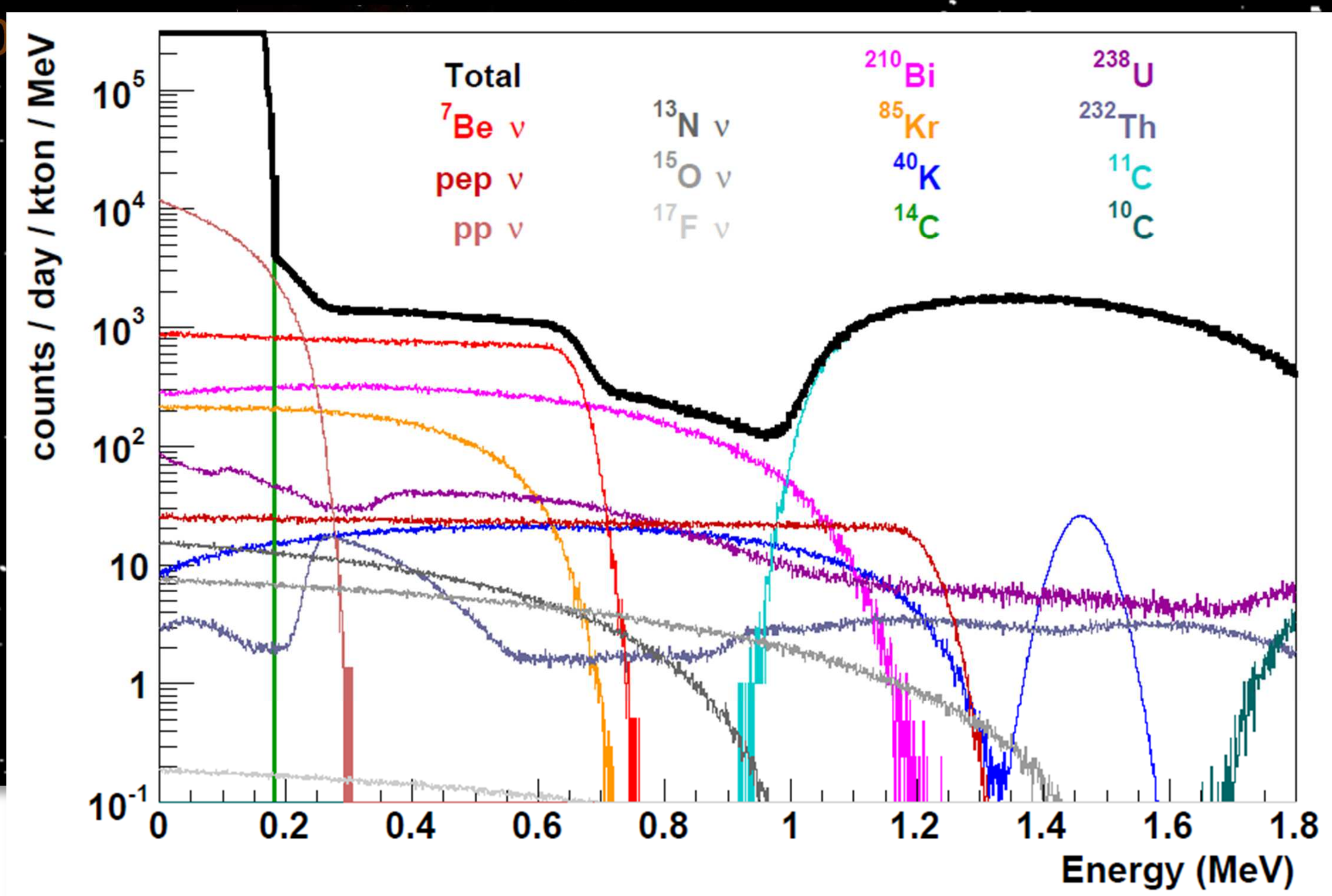
Physics Potential



- LSc: low threshold, high energy resolution
- elastic scattering open to all flavors
- background: radioactivity
- probe transition region of MSW paradigm
- study solar metallicity

Core-collapse supernovae

500

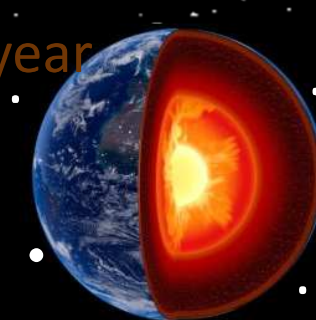


Solar ν

tens of ^{8}B-ν/day

Geo $\bar{\nu}$

400 evts/year

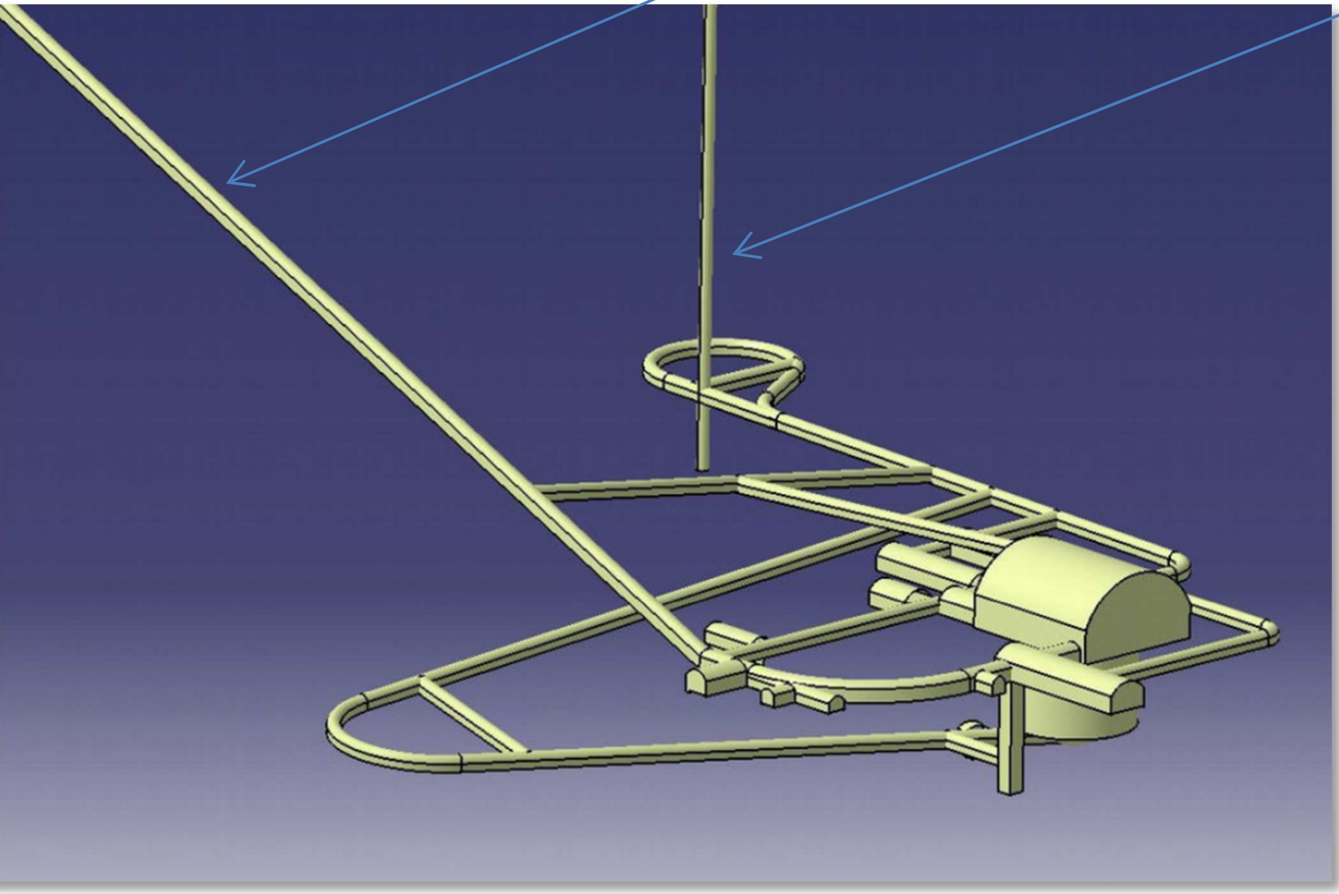


Civil Construction

Groundbreaking on Jan 10, 2015

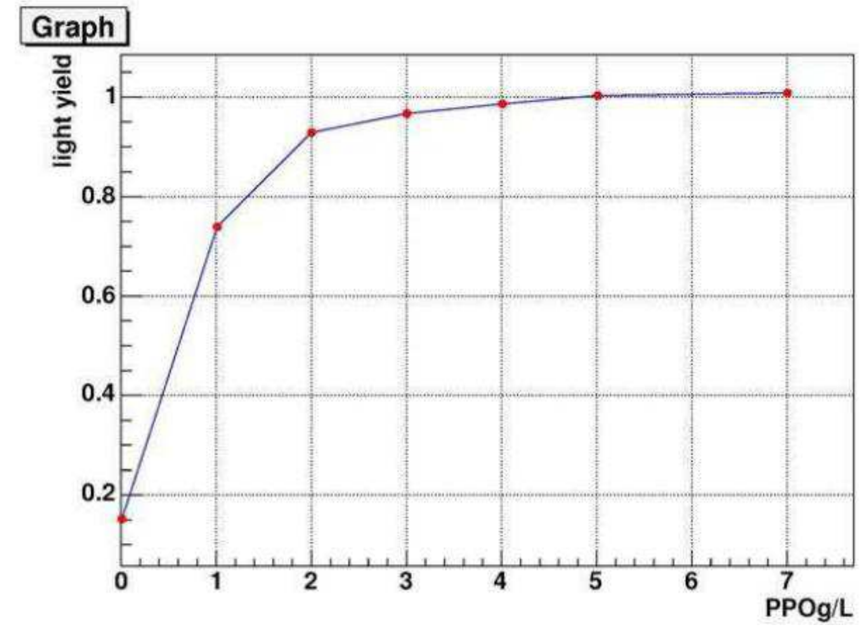
slope tunnel: 1055m out of 1340m

vertical shaft: 513m out of 630m



Liquid Scintillator (LSc)

- **20 kt LSc**: organic linear alkylbenzene (**LAB**) solvent
  + 3 g/l **PPO**
  + 15 mg/l **bis-MSB**
- specifications:
  - high light yield: $\sim 10^4$ ph/MeV
    → 1,100 pe/MeV
  - high attenuation length L_{att}: > 20 m
  - low radioactivity: $< 15^{-15}$g/g (U, Th)



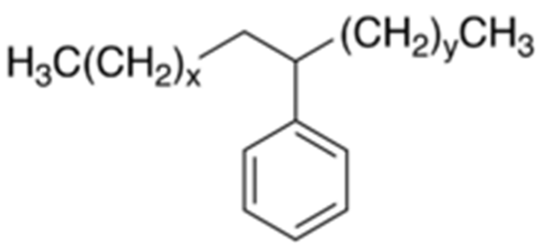
→ *T 57.6 "Determination of the kB parameter of LAB based scintillators for the JUNO experiment" by K. Schweizer*

→ *T 57.7 "Online monitoring system for the liquid scintillator transparency in the JUNO Central Detector" by W. Depnering*

→ *T 80.3 "Status of the PALM Experiment for JUNO" by S. Prummer*

→ *T 112.6 "Positronium Lifetime Determination in Linear Alkylbenyene based Scintillator for JUNO" by M. Schwarz*

- precise measurement of L_{att} and quenching
- online monitoring of transparency



→ *T 57.8 "An On-line Attenuation length Monitor for JUNO" by H. Enzmann*

→ *T 112.5 "Radon Monitoring in gaseous Nitrogen used for the Filling of the Central Detector of JUNO" by P. Landgraf*

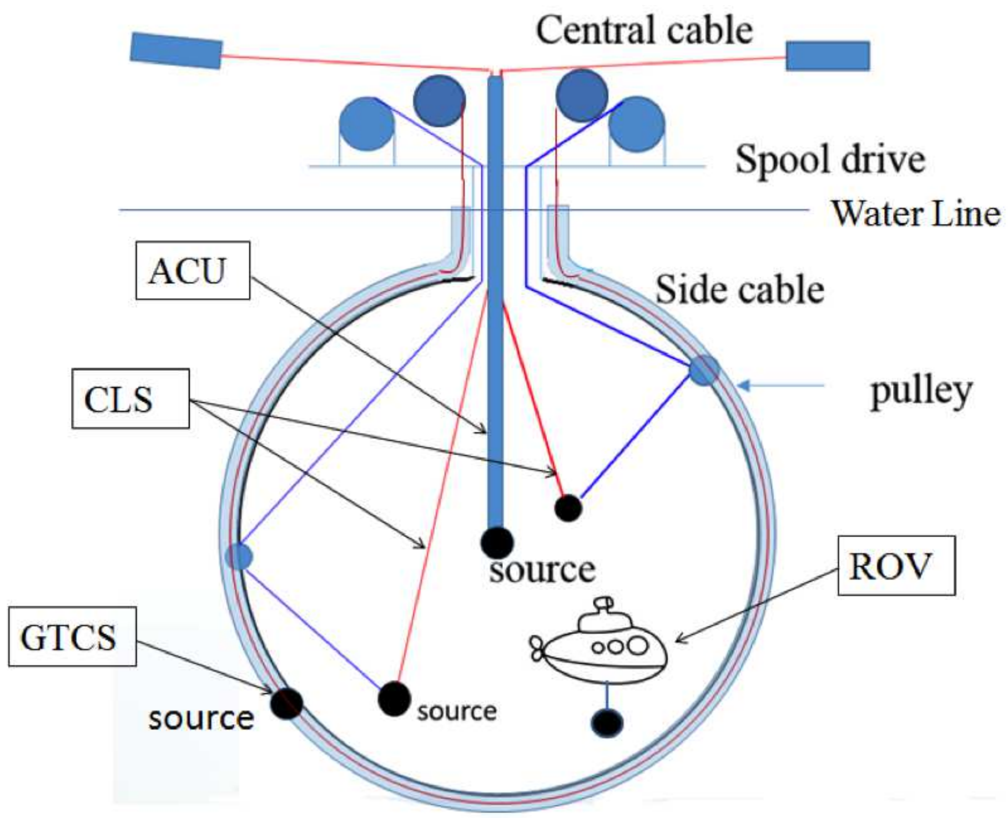
→ *T 112.7 "Monitoring Systems for the Filling of the Central Detector of JUNO" by H. Steiger*

LSc Filling

- gaseous nitrogen used to prevent radon contamination and contact with oxygen
- online monitoring of gas pressure, radon, L_{att}, mech. stress, filling levels

Calibration System

- **1D**: Automatic Calibration Unit (**ACU**)
- **2D**: Cable Loop System (**CLS**),
  Guide Tube Calibration System (**GTCS**)
- **3D**: Remotely Operated Vehicle (**ROV**)



Sources

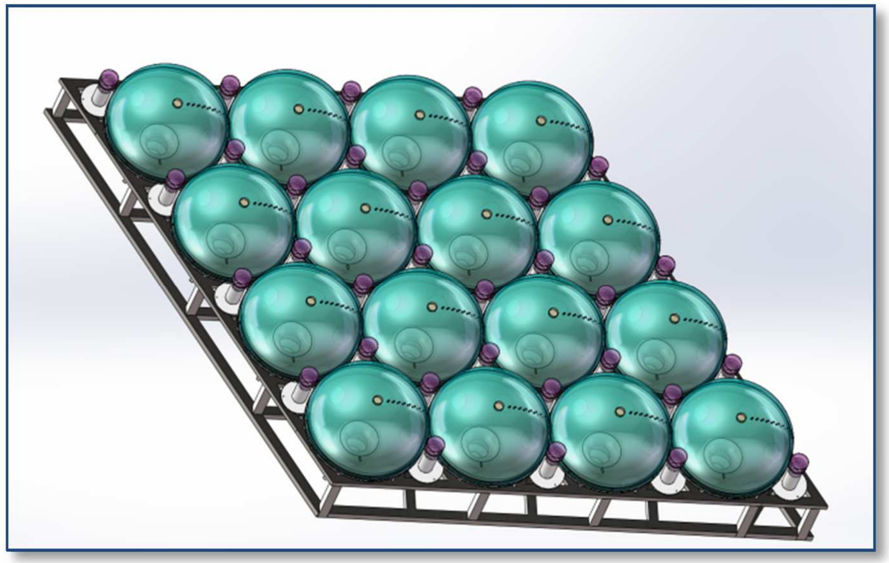
photons: ^{40}K, ^{54}M, ^{60}Co, ^{137}Cs
positrons: ^{22}Na, ^{68}Ge
neutrons: ^{241}Am-Be, ^{241}Am- ^{13}C, ^{241}Pu- ^{13}C, ^{252}Cf

PMT System: Double Calorimetry

size	20”	20”	3”
manufacturer	NNVT	Hamamatsu	?
type	MCP	dynode	
units	15k	5k	36k
QE@400nm	26(T) + 4(R)%	30%	
TTS	12 ns	3 ns	short

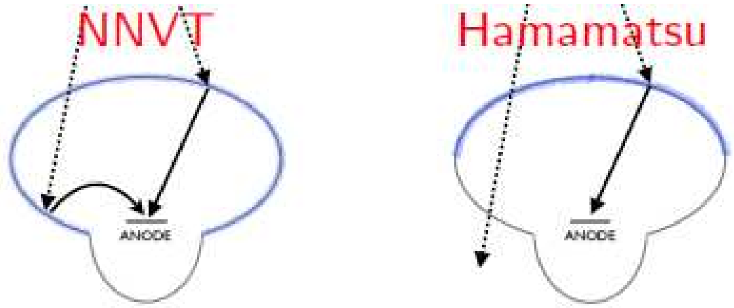
75% coverage (20” PMTs) 3% coverage (3” PMTs)

proposed PMT module



large PMTs:

- requires characterization of every single PMT
- mass testing about to start

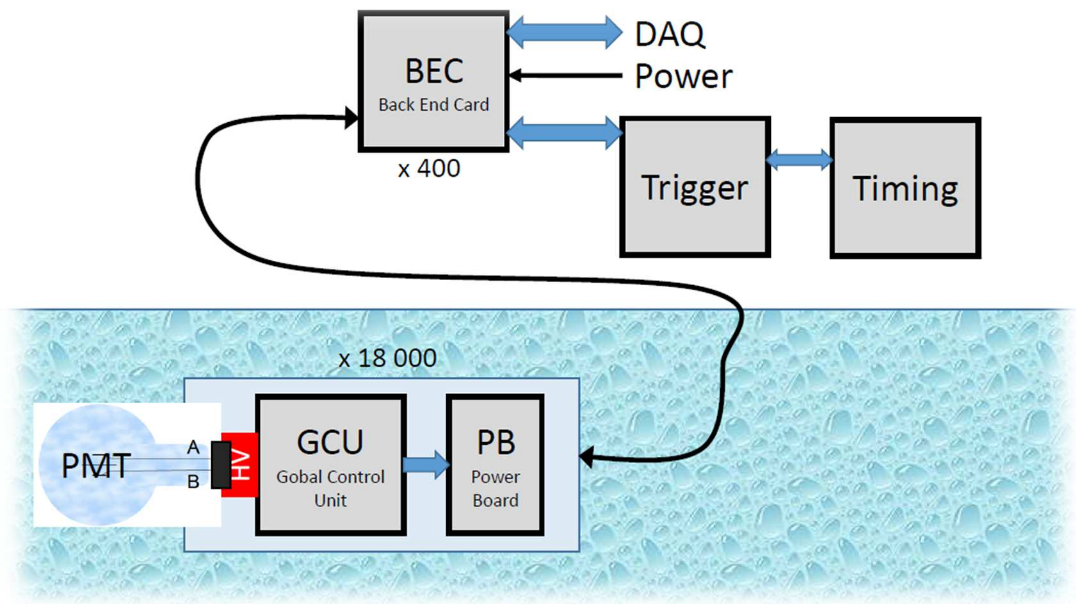


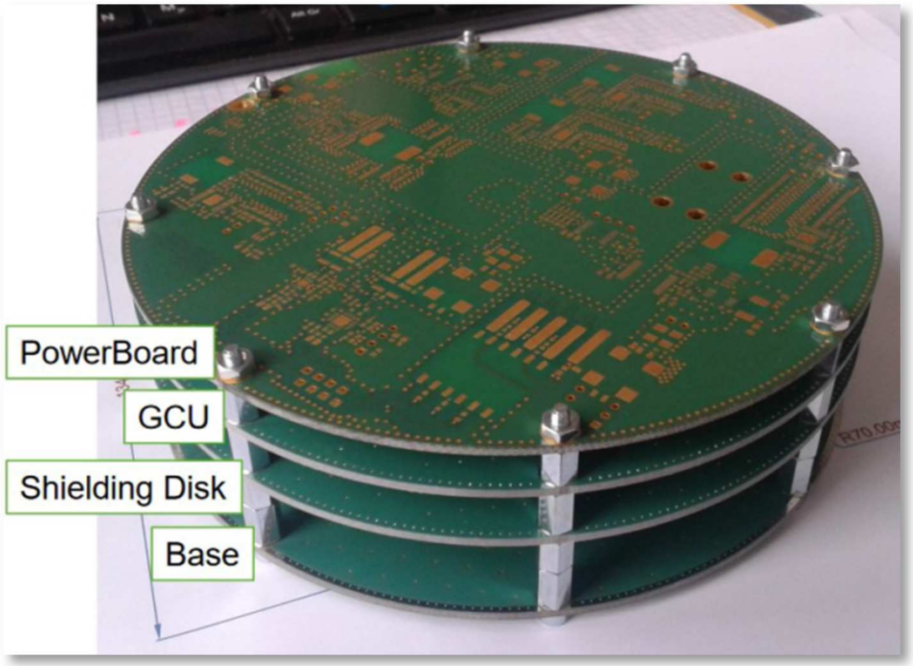
small PMTs:

- better timing properties
- higher energy dynamic range
- no supplier chosen yet

→ *T 57.5 “A PMT Mass Testing Setup for the JUNO Experiment using commercial shipping containers” by A. Tietzsch*

Readout Electronics





- control and readout integrated into PMT housing: intelligent PMTs
- highly-integrated receiver chip including FADC
- further data management in FPGA

→ *T 96.5 "Development of intelligent Photomultipliers for the JUNO Detector" by F. Lenz*

→ *T 96.6 "A Highly-Integrated Receiver Chip for the JUNO Experiment" by A. Zambanini*

→ *T 96.7 "The Digital Control Unit of the highly-Integrated Receiver Chip for JUNO" by P. Muralidharan*

Summary and Outlook

- **JUNO**: A next generation, **20kt LSc** detector in China with the purpose to determine the neutrino **mass ordering** with **reactor anti-neutrinos**

  ("*Neutrino physics with JUNO*" - J. Phys. G 43 (2016) 030401)

- Furthermore, high potential regarding **terrestrial and astrophysical neutrinos**

- Significance: $\geq \mathbf{3\sigma}$ after **100k IBD events** ($\triangleq$ 6 yr of data taking)

- funded project

- Collaboration: 71 international member institutes, 486 scientists