JUNO

- Sebastian Lorenz -

on behalf of the JUNO Collaboration

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

PRISMA Cluster of Excellence

10th Terascale Detector Workshop 2017

DESY Hamburg, April 13th 2017

Outline

- Determining the neutrino mass ordering with the **J**iangmen **U**nderground **N**eutrino **O**bservatory
- The JUNO detector
  - Liquid Scintillator + Container
  - PMT System & Electronics
  - Cherenkov Veto
- Mass ordering sensitivity and other physics
- Summary

Neutrino Oscillations: What we know

We know that…

- …the three known neutrino flavors oscillate...
- …as a function of
  - three mixing angles θ_{ij},
  - **three (two independent) mass-squared differences Δm^2_{kl}** ,
  - one phase factor δ_{CP},
  - source distance L,
  - neutrino energy E.
- **…neutrinos have mass! (Nobel Prize 2015)**

	Any Ordering
	3σ range
$\sin^2\theta_{12}$	$0.273 \to 0.348$
$\theta_{12}/^\circ$	$31.52 \to 36.18$
$\sin^2\theta_{23}$	$0.388 \to 0.632$
$\theta_{23}/^\circ$	$38.6 \to 52.7$
$\sin^2\theta_{13}$	$0.01938 \to 0.02396$
$\theta_{13}/^\circ$	$8.00 \to 8.90$
$\delta_{CP}/^\circ$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.02 \to 8.08$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$\begin{bmatrix}+2.413 \to +2.645\\ -2.630 \to -2.409\end{bmatrix}$

Δm^2_{31} or Δm^2_{32}, depending on mass ordering

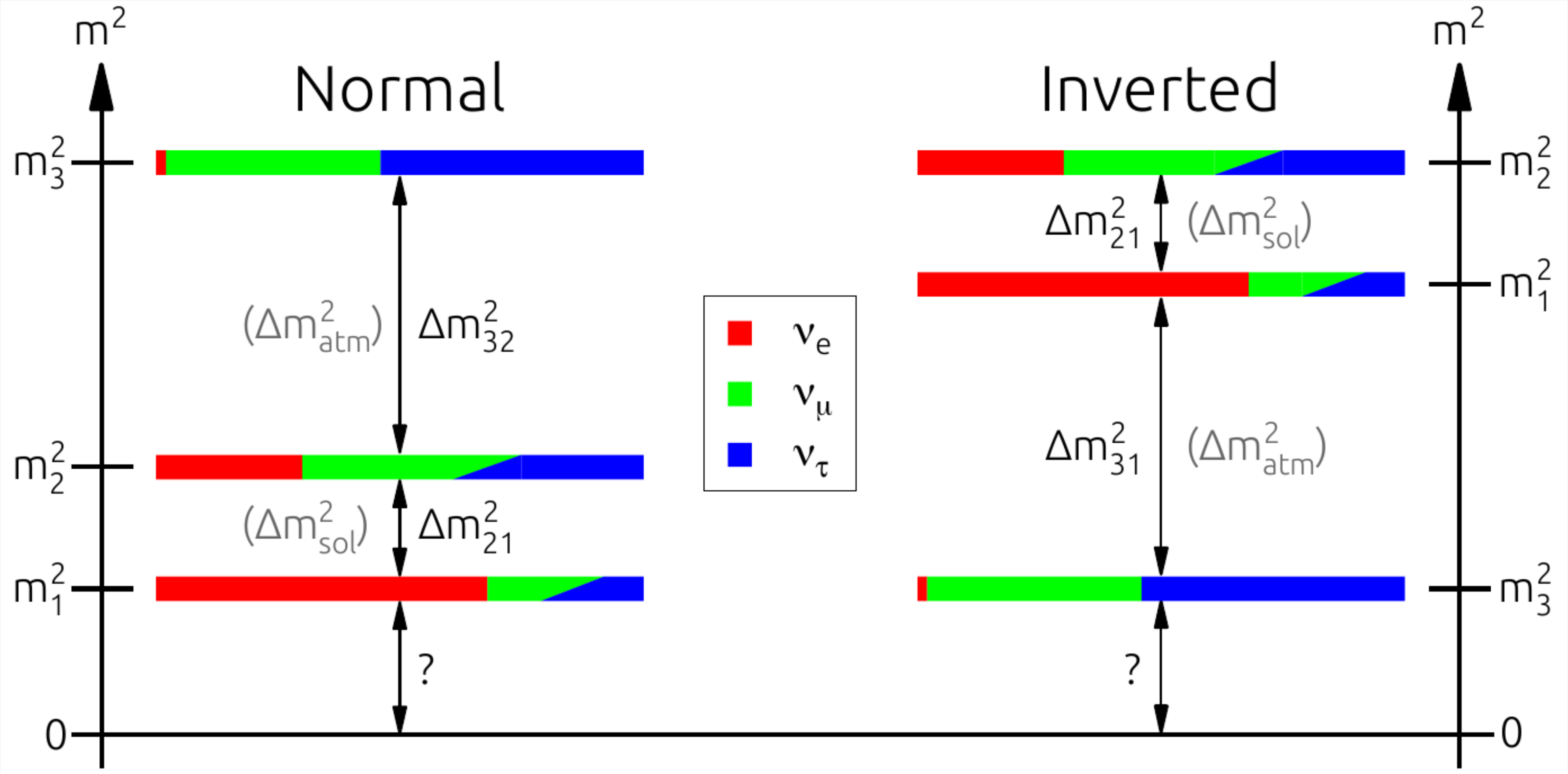
JHEP 11 (2014) 052, NuFit 2.2 (2016), www.nu-fit.org

$$P(\ell \to \ell') = \sin^2(2\theta)\ \sin^2\left(\frac{\Delta m^2 L}{4E}\right), \quad \ell \neq \ell'$$

(Two-flavor oscillation formula in vacuum; natural units)

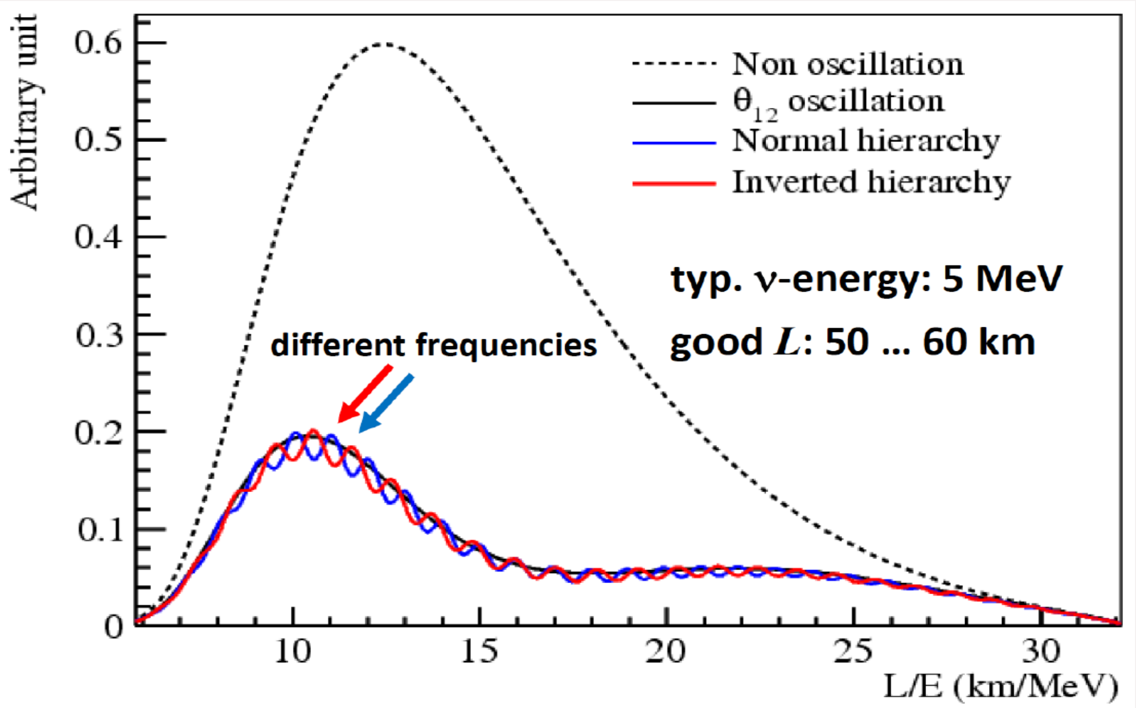
We don‘t know…

- …the value of δ_{CP} (leptonic CP-violation / conservation).
- …the **neutrino mass ordering** (MO) (road to δ_{CP}; mass model building).
- ...if there are sterile neutrinos (physics beyond the SM).



Measuring the MO with JUNO

- **Approach:** probe oscillatory fine structure in survival probability of reactor $\bar{\nu}_e$ at a baseline length of ~53 km



Method: Petcov and Piai, Phys. Letters B 533, 94-106 (2002)

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

- **Requirements:**
  - large target mass (20 kt)
  - low energy threshold for $\bar{\nu}_e$
  - very good energy resolution ($\leq 3\%$ @ 1 MeV)
  - low energy scale uncertainty (< 1%)

Measuring the MO with JUNO

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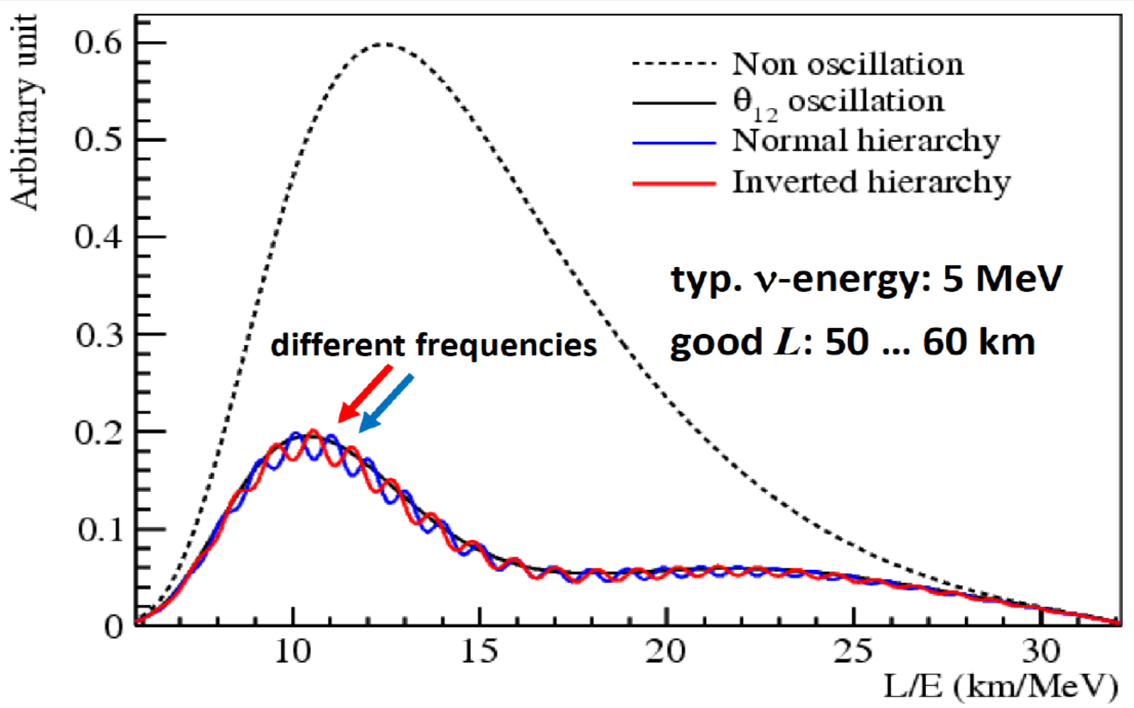

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- large target mass (20 kt)
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- very good energy resolution ($\leq$ 3% @ 1 MeV)
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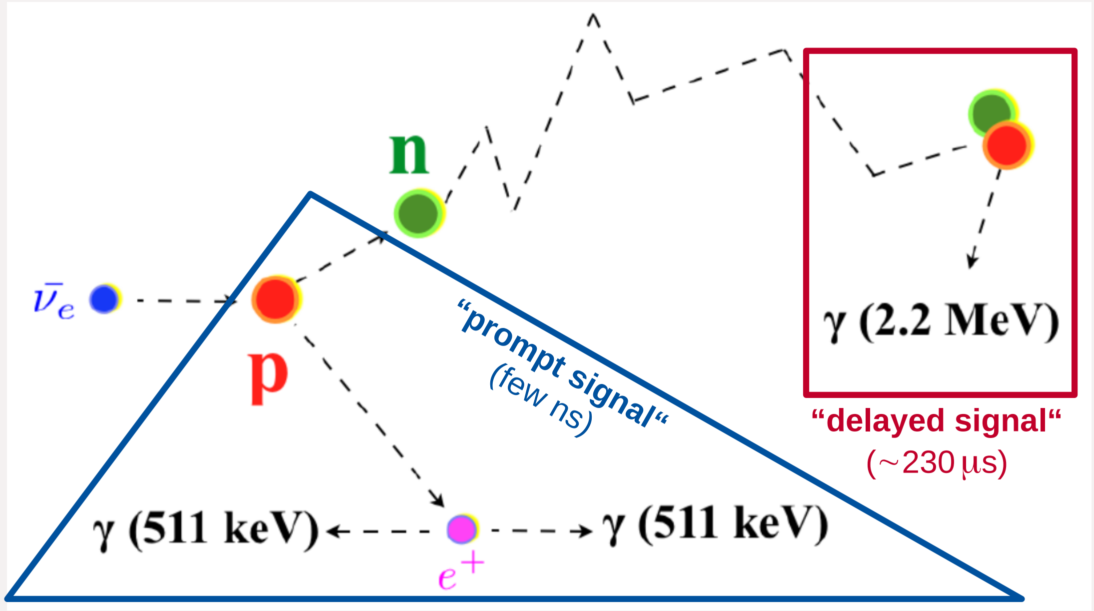
➔ **Liquid scintillator (LS) technology!**

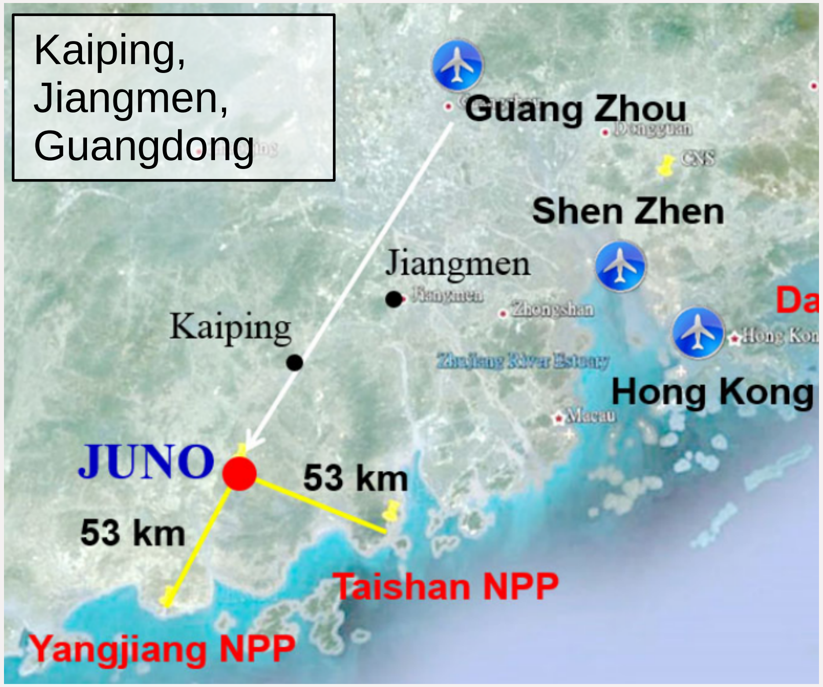
$\overline{\nu}_e$ Detection in Liquid Scintillator

- LS is the best technology for low-energy neutrino detection (Borexino), especially for reactor $\overline{\nu}_e$ (Daya Bay, Double Chooz, KamLAND, RENO)
- Primary $\overline{\nu}_e$ detection channel in LS: **inverse beta decay** (IBD)
  → delayed coincidence signature

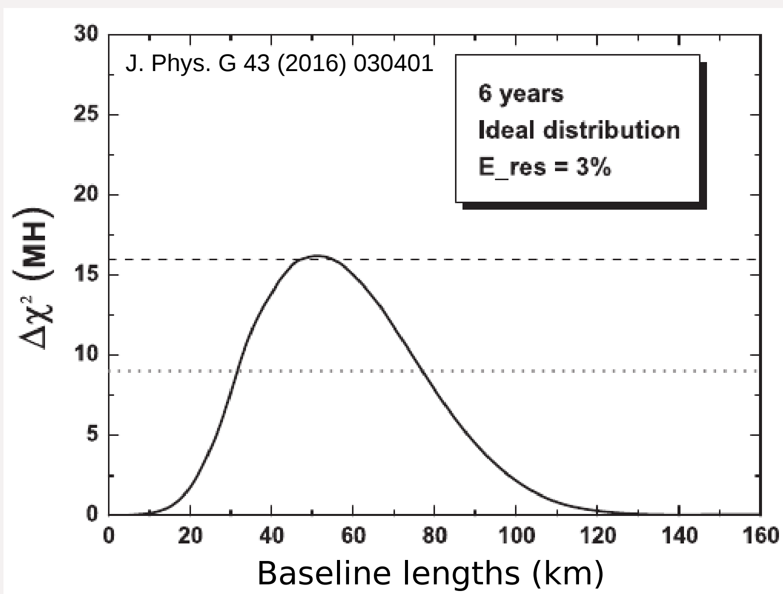


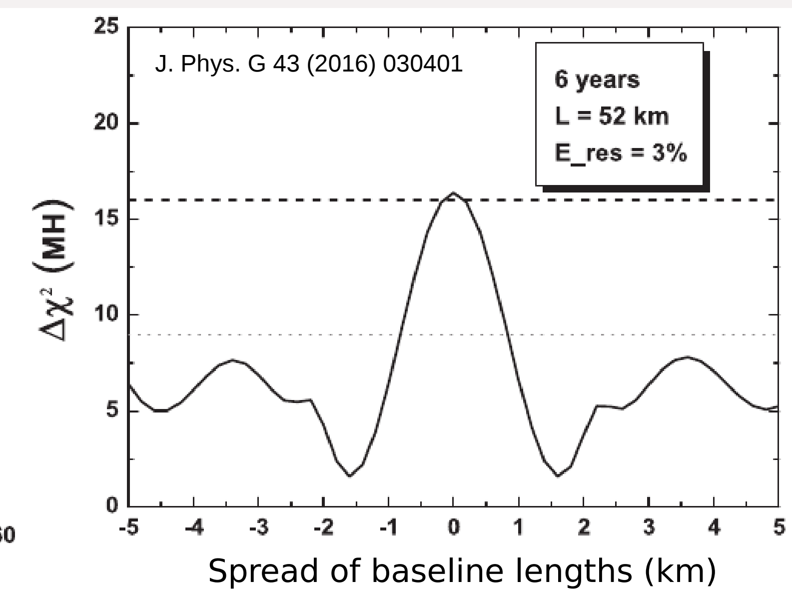
- Calorimetric measurement of $\overline{\nu}_e$ energy E_ν: $E_\nu = E_{prompt} + 0.784$ MeV

JUNO Experimental Site



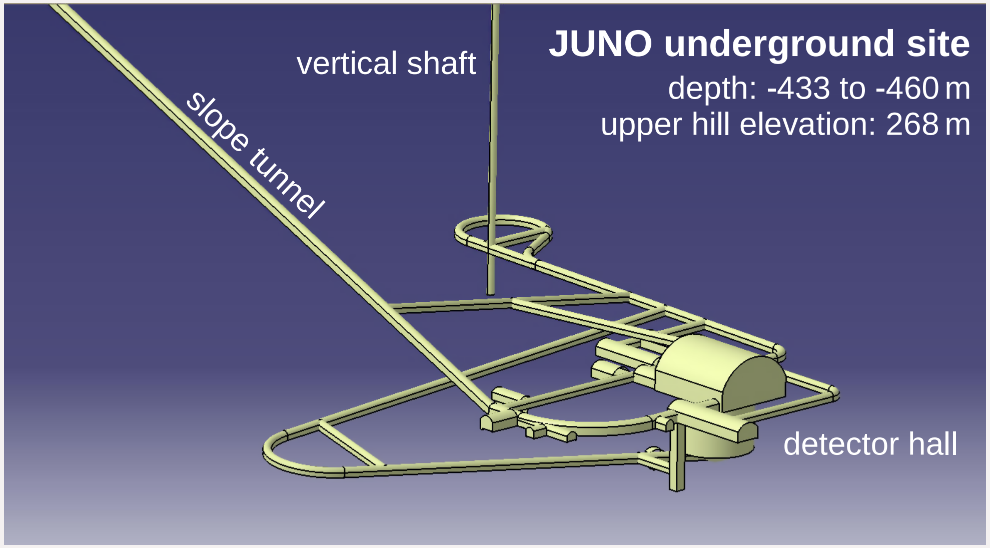
- $\bar{\nu}_e$ source: 2 nuclear power plants at ~53 km distance; 10 cores with a total of 35.8 GW thermal power
  (26.6 GW by start of data taking around 2020)
- Expected $\bar{\nu}_e$ event rate: 83 per day
- Detector site chosen with respect to:
  - optimal mean distance to the cores
  - low spread in core-detector distances





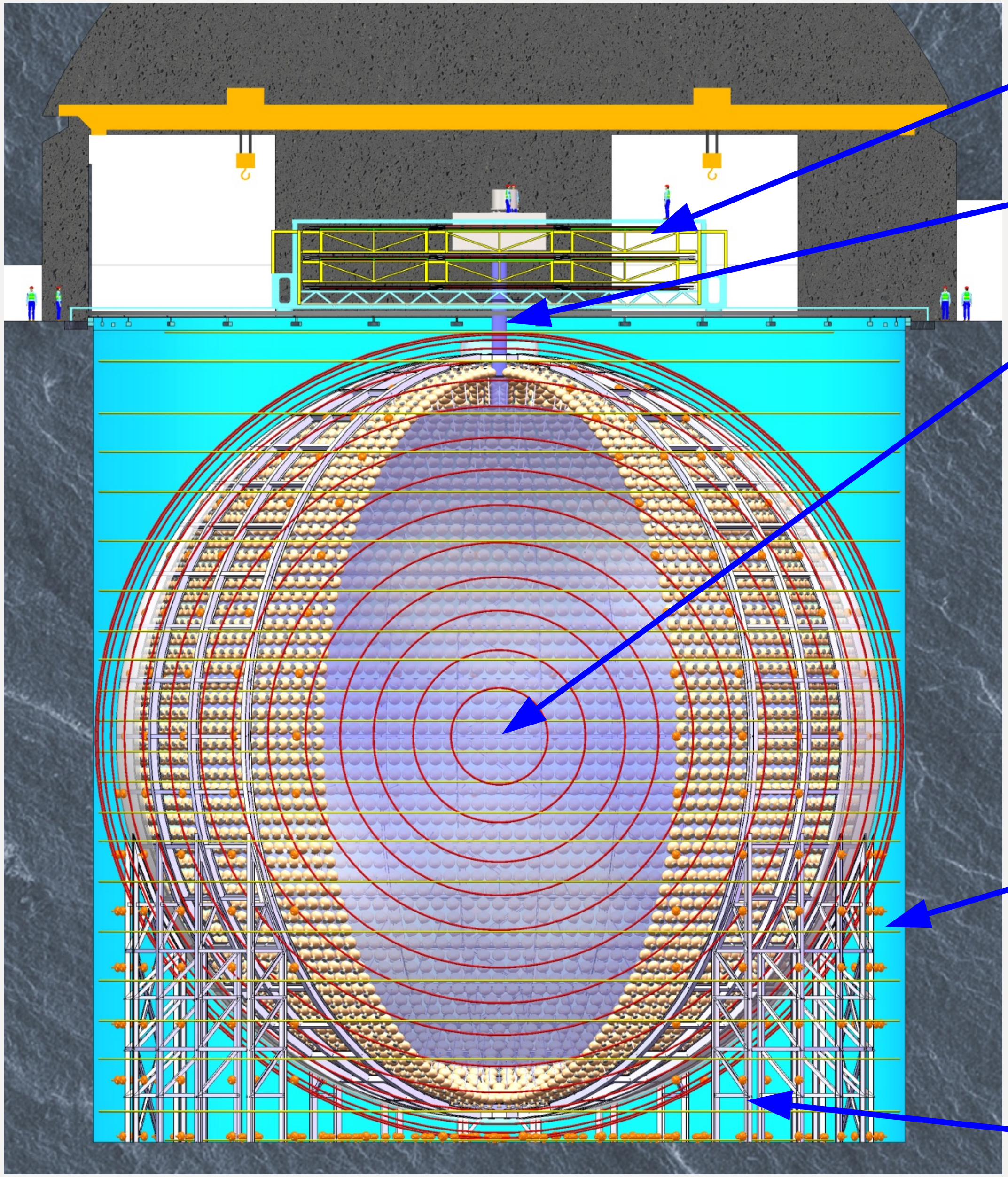
JUNO Underground Site

- JUNO is a funded project
- Civil construction for underground site started early 2015
- Tunnels ~80% completed; will be finished in 1-5 months



- About 700 m overburden
- Muon event rate: ~3 per second
- Signal to cosmogenic background ratio of 1:1 expected

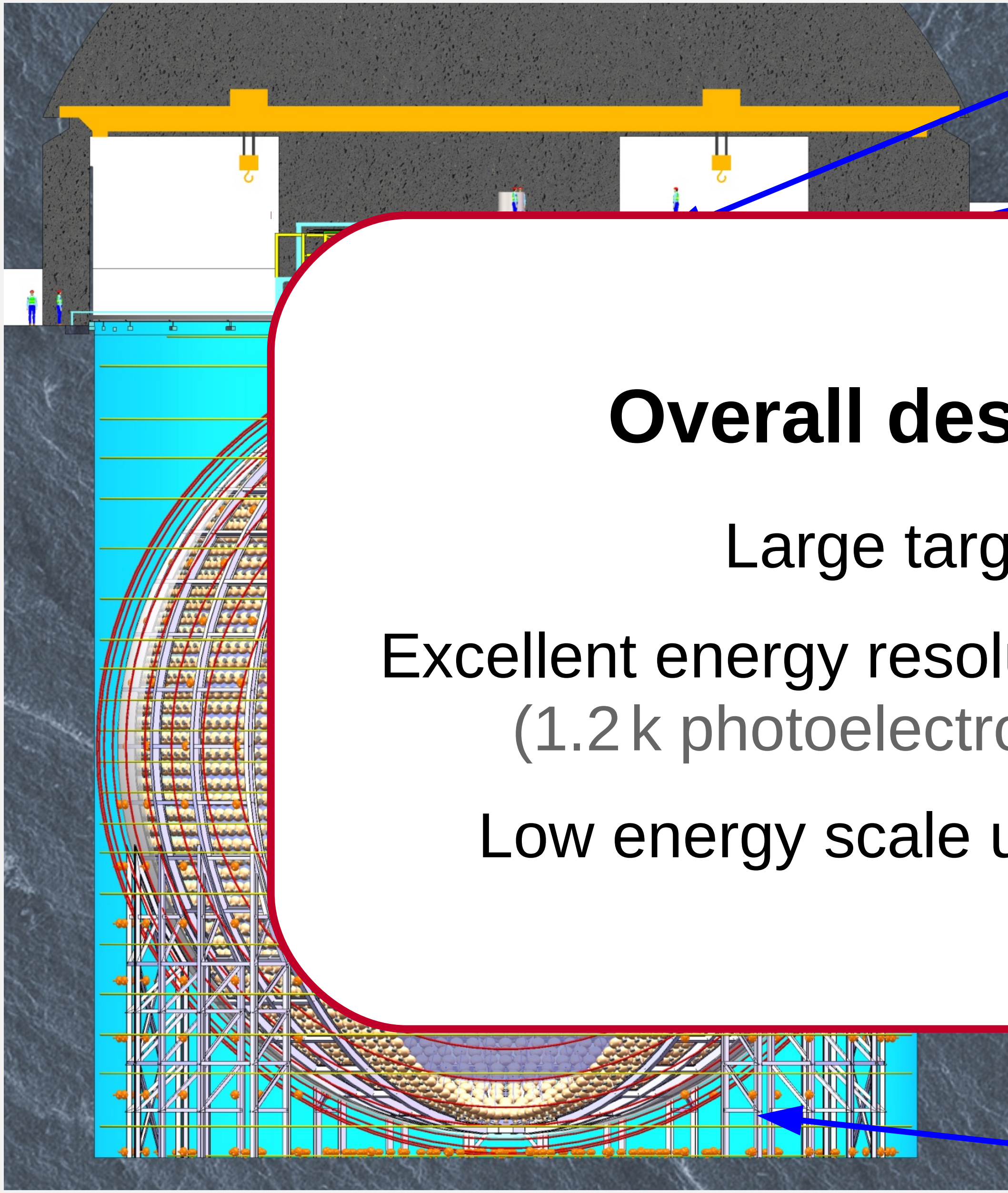
JUNO Detector Design



“*JUNO Conceptual Design Report*“ - arXiv: 1508.07166

- Top tracker (solid scintillator)
- Calibration system, chimney
- **Central detector** (CD)
  - LS in acrylic vessel (35.4 m diam.)
  - Ultra-pure water buffer (2 m)
  - Stainless steel latticed shell (40.1 m diam.)
  - Optical separation
  - ∼18 k 20’’ and ∼36 k 3’’ PMTs
  - Earth magnetic field shielding coils
- Water Cherenkov veto pool
  - 44 m deep, 43.5 m wide
  - ∼2 k 20’’ PMTs
- Anchoring against buoyancy

JUNO Detector Design



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- Top tracker (solid scintillator)
- Calibration system, chimney

diam.)

(40.1 m diam.)

s

g coils

ol

- Anchoring against buoyancy

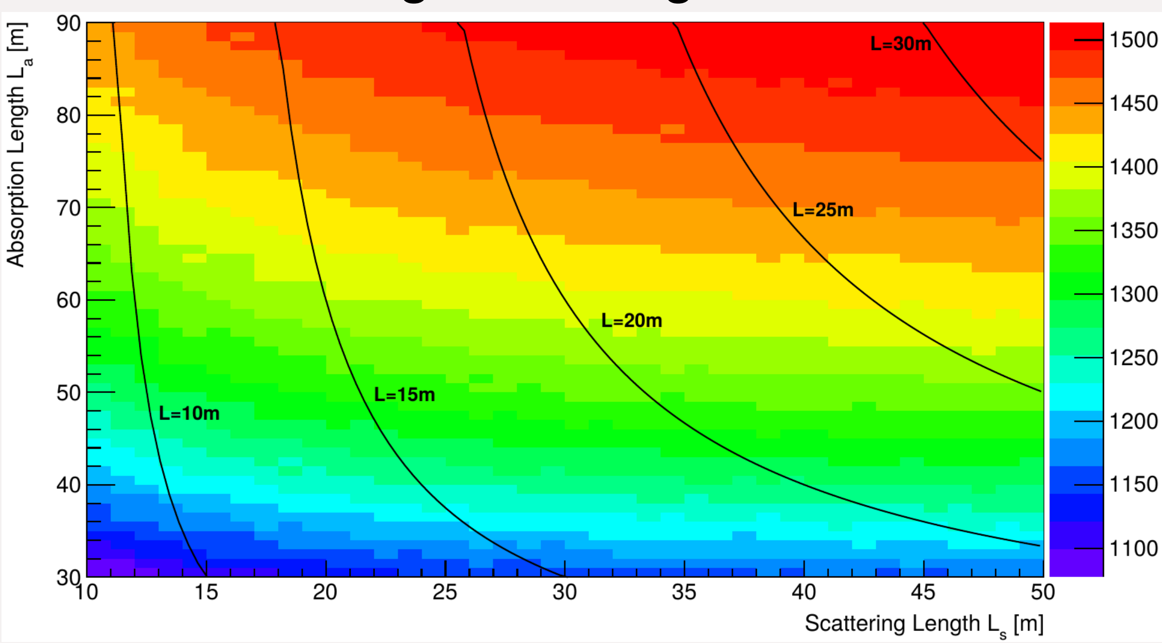
Overall design goals

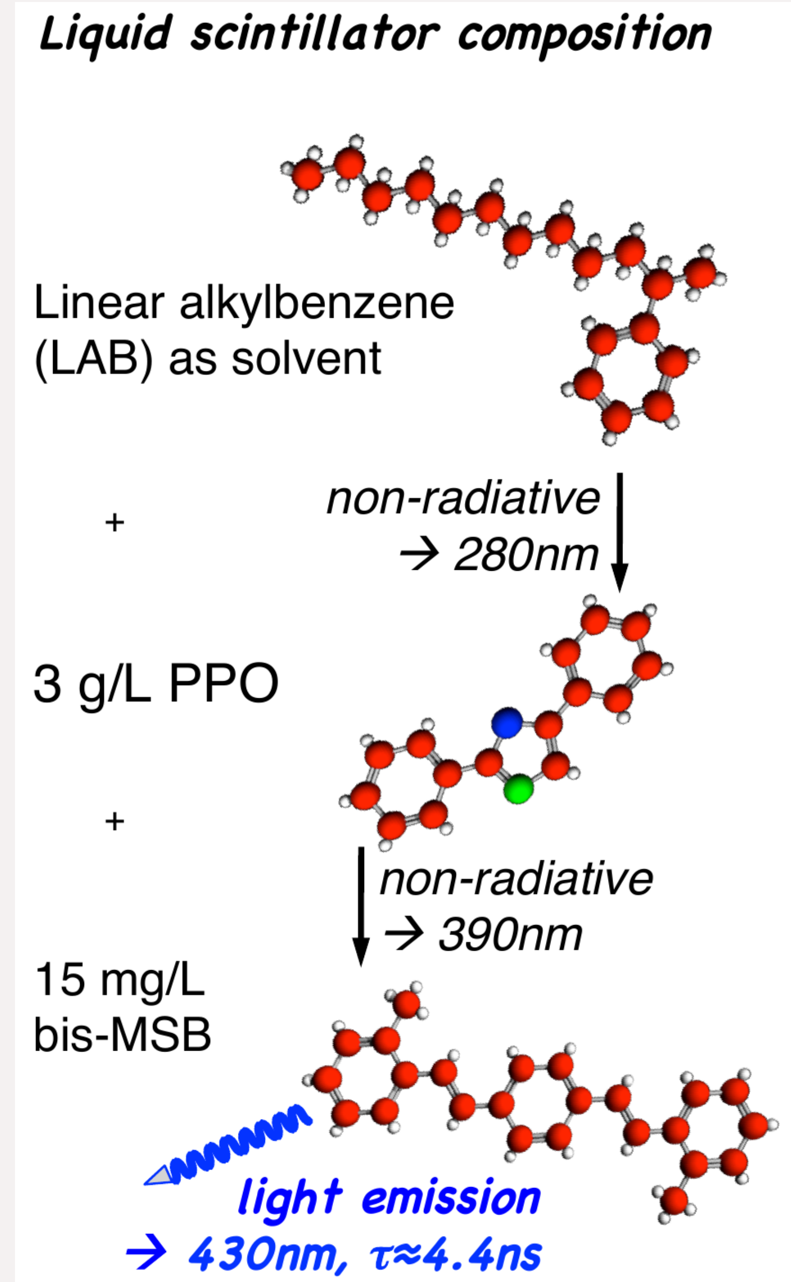
Large target mass

Excellent energy resolution: ≤ 3% / sqrt(E)
(1.2 k photoelectrons (p.e.) / MeV)

Low energy scale uncertainty: < 1%

- **Design goal:** 1.2k p.e. / MeV
- **Requirements:**
  - High light yield: ~10k photons / MeV
    - ➔ Pure organic solvent
    - ➔ High fluor (PPO) concentration
  - High transparency: $L_{att} > 20\,m$ @ 430 nm
    - ➔ High-quality, transparent solvent → LAB
    - ➔ Shift to long wavelengths → bis-MSB



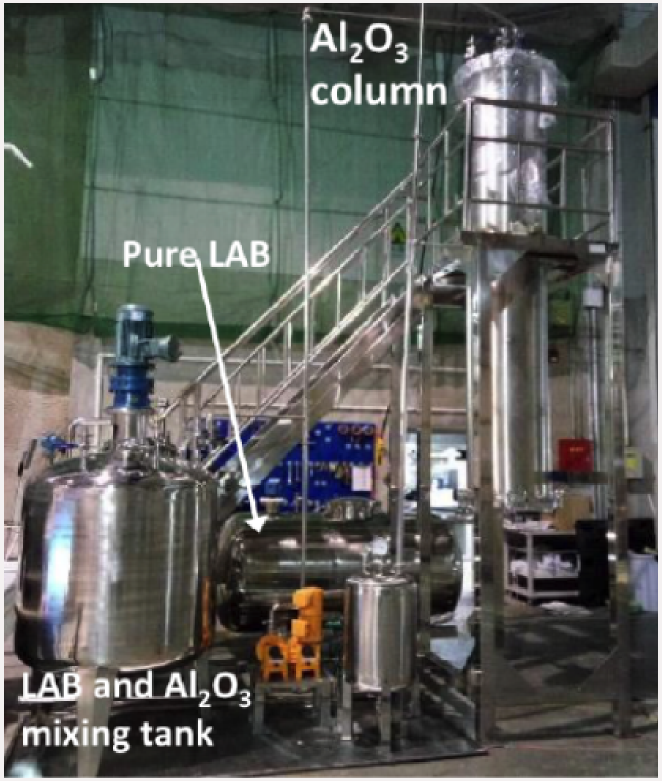


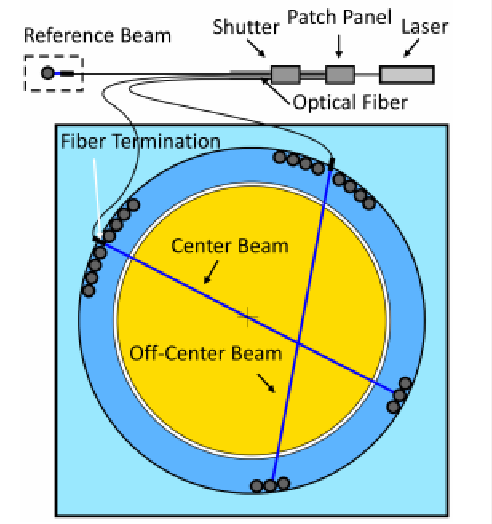
JUNO Liquid Scintillator R&D

- LS characterization
  Scattering, attenuation, light quenching,...

- LS purification test at Daya Bay
  - Al_2O_3 column → remove organic impurities
  - Distillation → remove radioactive metal ions
  - Gas stripping → remove volatile impurities (Ar, Kr, Rn)
  - Water extraction → remove polarized impurities (U, Th)
  - ➔ Reach transparency and radiopurity goal of $\leq 10^{-15}$ g/g (U/Th)
    Borexino expertise on board!

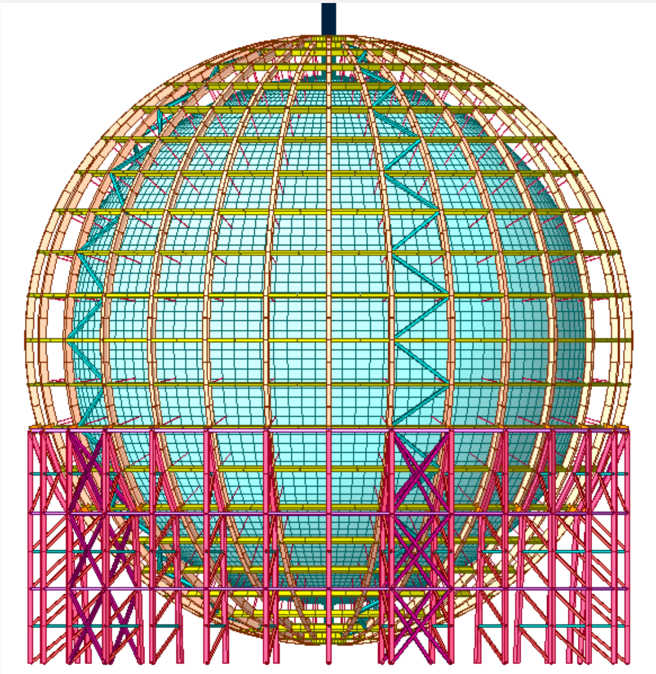
- Development of online LS monitoring systems
  - Test optical properties before CD filling
  - In-situ monitoring of changes
    e.g., due to aging, temperature gradient,...

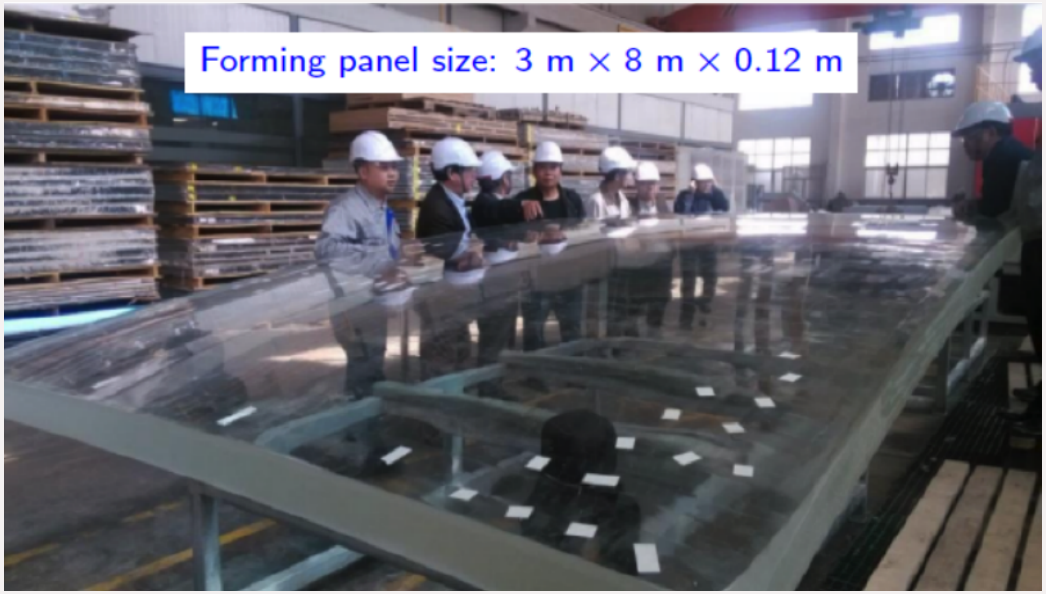




JUNO Central Detector

- Several options for CD discussed
- Safety was given priority
- Acrylic sphere + stainless steel latticed shell
- Sphere made of ~260 panels with 12 cm thickness
- 590 connecting nodes, 60 pillars
- Total weight: ~600 t acrylic + ~590 t steel

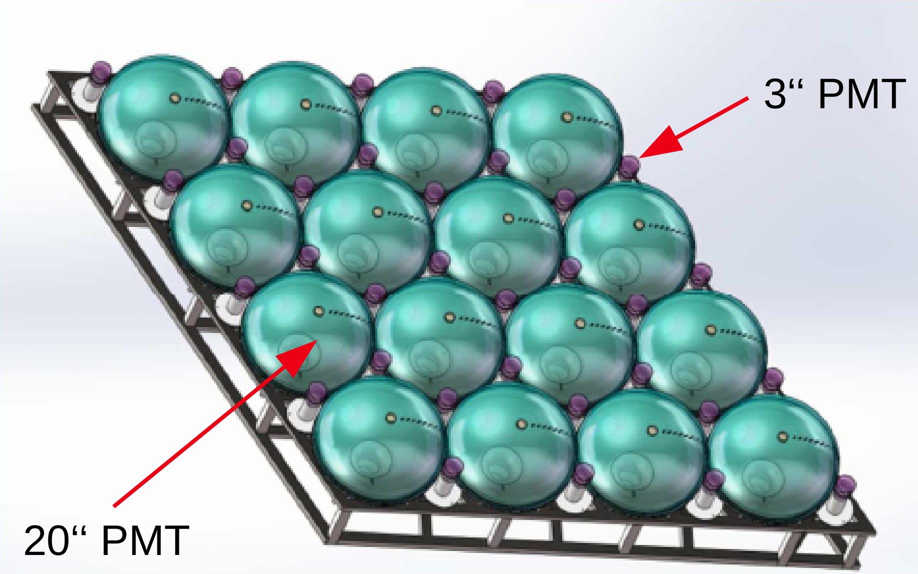




JUNO Double Calorimetry PMT System

- **Design goal:** 1.2k p.e. / MeV
- **Requirements:**
  - High optical coverage
  - High photon detection efficiency
  - Acceptable noise / radiopurity levels
  - Acceptable time resolution (event reco)
  - Broad dynamic range
    (IBD → muons → Supernova-ν burst)

Proposed PMT module



- **JUNO will have two independent CD PMT systems! (“Double calorimetry“)**

18 k large 20“ PMTs
- 75% coverage
- Stochastic term: 3% / sqrt(E)
- Slower + worse p.e. resolution
- High dark noise

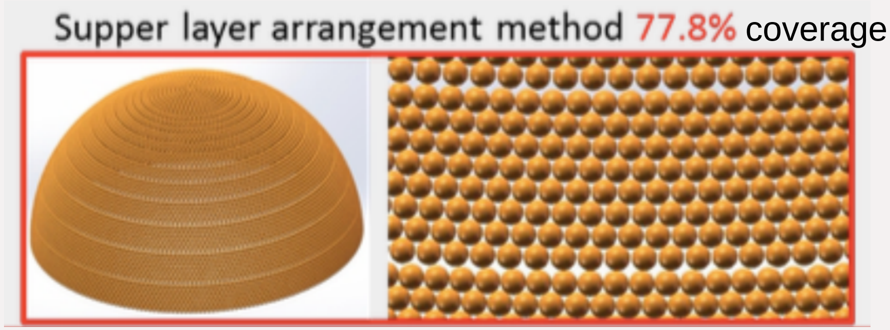
+

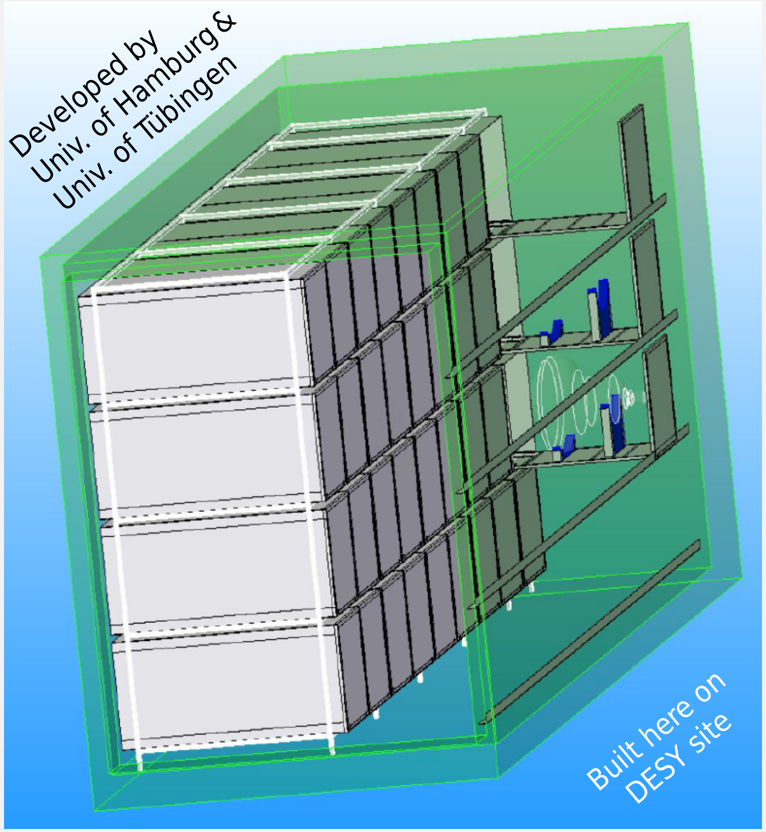
36 k small 3“ PMTs (under optimization)
- 3% coverage
- Stochastic term: 10% / sqrt(E)
- Faster + better p.e. resolution
- Low dark noise

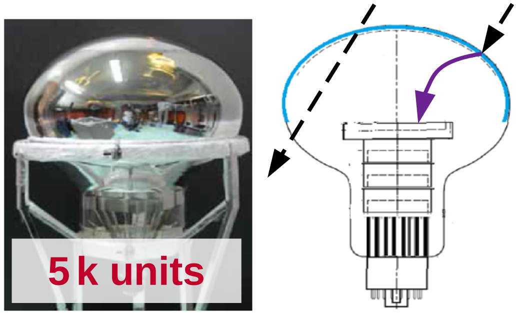
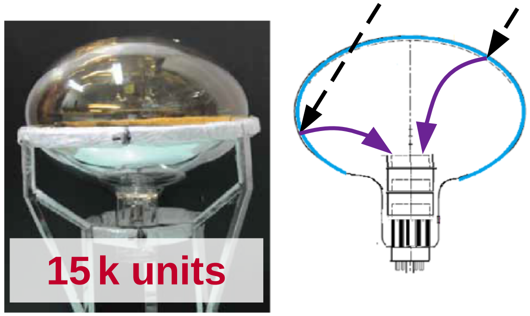
No supplier chosen yet!

JUNO 20“ PMT System

- Maximum coverage
- Two different types
- Integrated control and readout
  → “intelligent PMTs“
- Mass-testing about to start

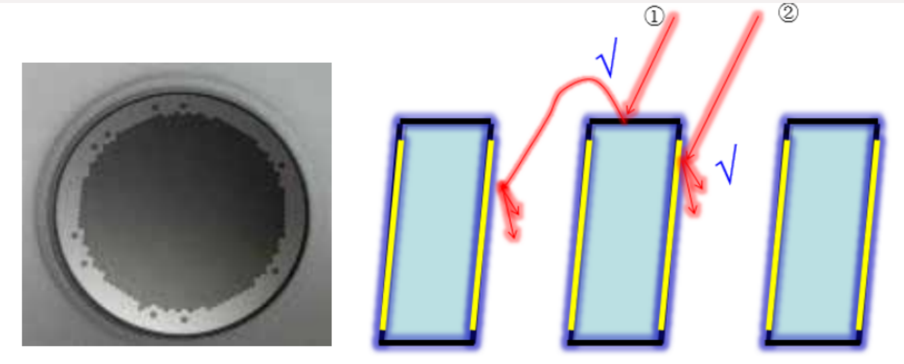


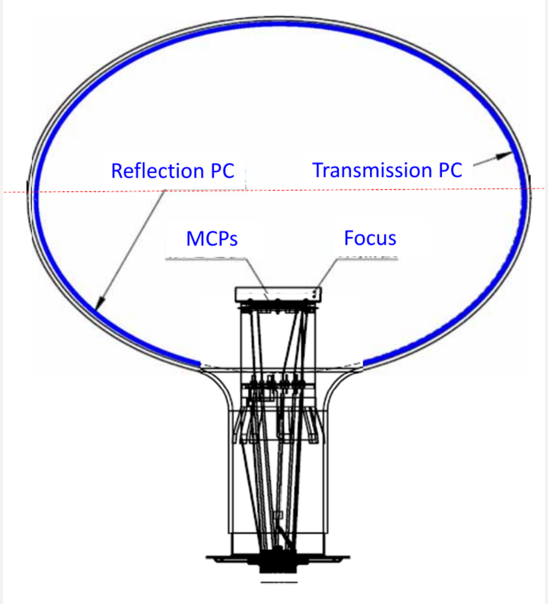


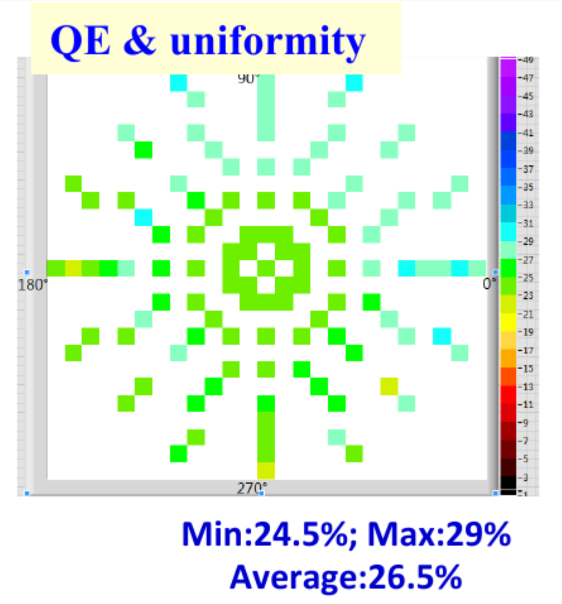
	20’’ Hamamatsu PMT (JPN)	20’’ IHEP-NNCV MCP-PMT (CHN)
		
Photo-cathode	transmission	transmission + reflection
Relative collection eff.	100%	110%
QE (400 nm)	30%	26% (T) + 4% (R)
TTS (FWHM)	~3 ns	~12 ns
Dark rate	~30 kHz	~30 kHz

JUNO MCP-PMT

- In development since 2009;
  5“, 12“ and 20“ prototypes produced
- Latest MCP design: ~100% collection efficiency but ~12ns TTS (FWHM)
- Material selection important to control intrinsic background (e.g., ^{40}K in glass)
- Mass production started

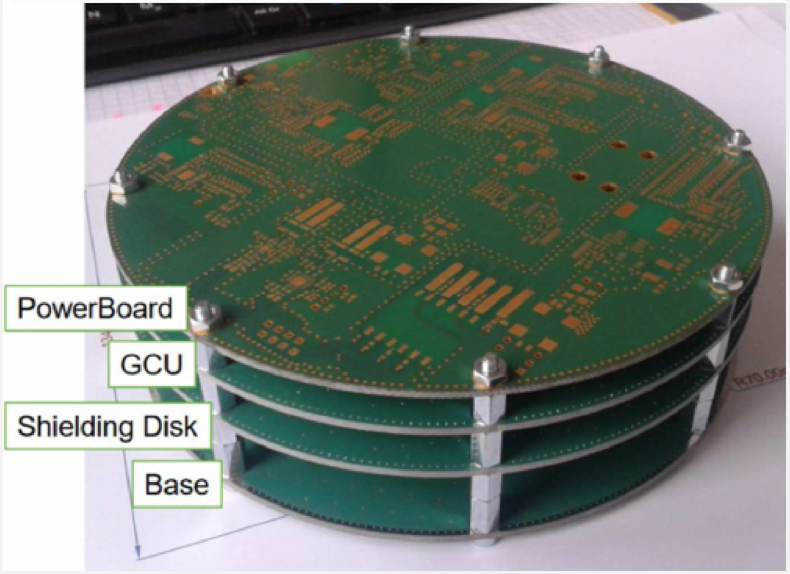


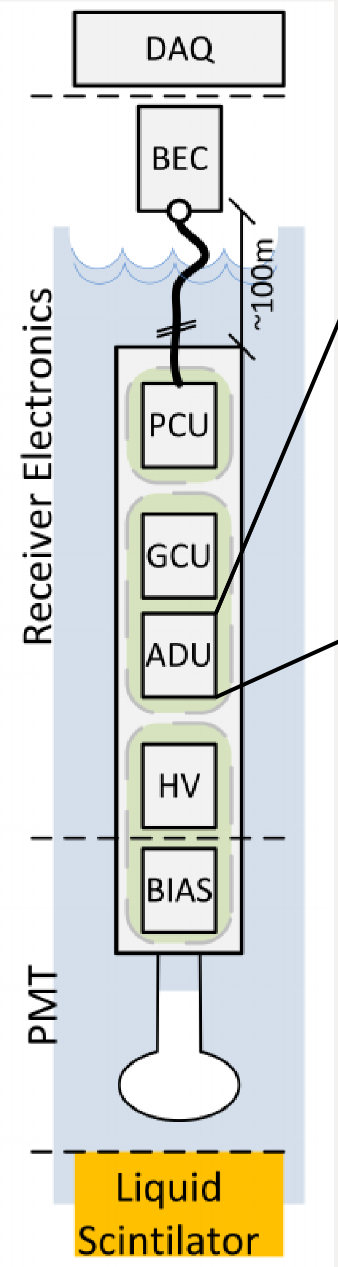




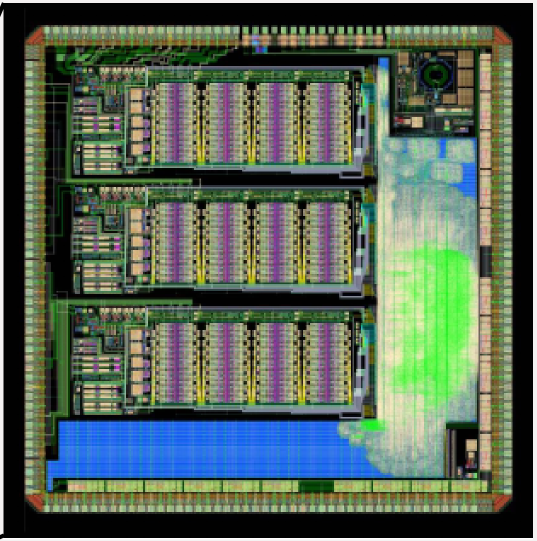
JUNO DAQ & Electronics ("Intelligent PMTs")

- VULCAN: highly-integrated receiver chip
- Three large dynamic range ADCs
- Highly configurable alternative operating modes
- Internal buffer memory
- Optional overshoot compensation





VULCAN chip

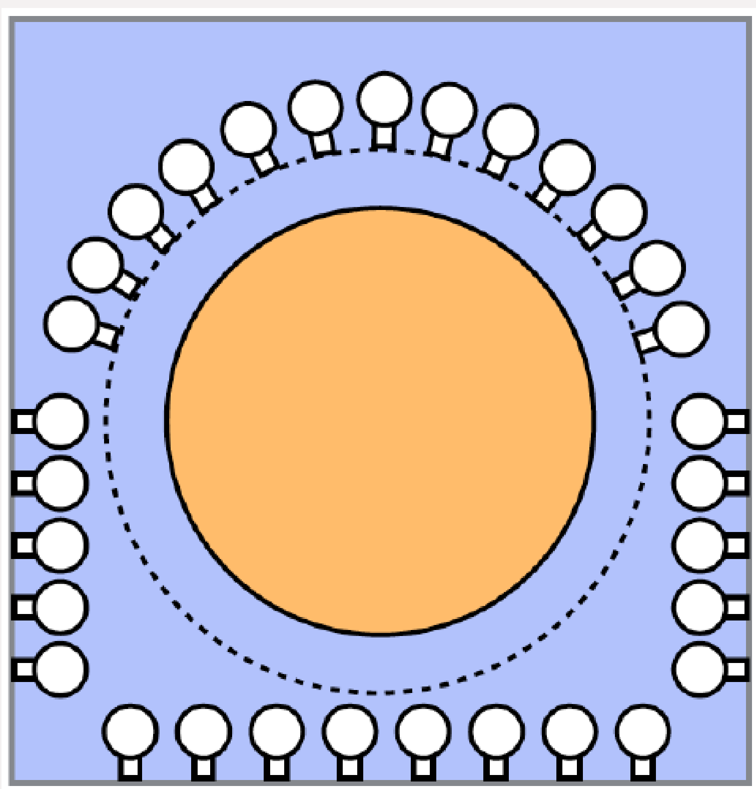


developed by ZEA, Forschungszentrum Jülich, Germany

Sampling rate	1 GHz
Bandwidth	500 MHz
Input impedance	<10 Ω
Dynamic range	$\frac{1}{16}$ - 2000 p.e.
ADC resolution	8 bit [3 ×]
High gain	0.06 p.e./bit
Medium gain	0.4 p.e./bit
Low gain	8 p.e./bit
Power	1 W
Area	22.09 mm^2

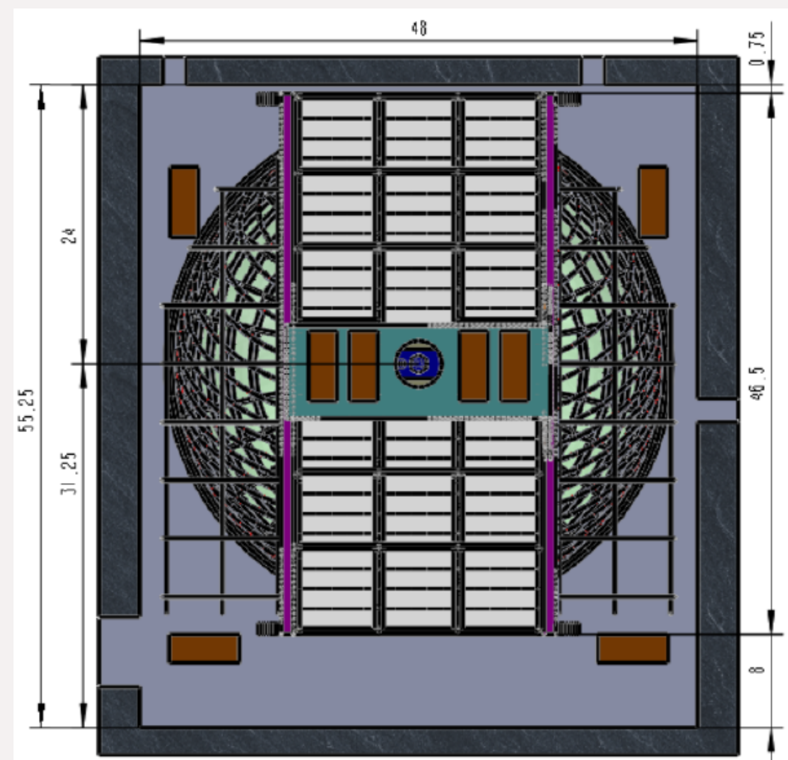
Water Cherenkov veto

- 20 kt ultra-pure water
- Shielding + Cherenkov detector
- 2 k large 20“ PMTs
- Optimized detection efficiency for Cherenkov light from cosmic muons



Top Tracker

- Three layers of OPERA plastic scintillator (49 m^2 / module)
- Only partial coverage due to available modules
- Tag ~50% of muons; provides sample to test reconstruction in CD



JUNO Sensitivity and Other Physics

- Median sensitivity to neutrino MO (100 k IBD events, ~6 years of running):

w/o external input on $|\Delta m^2_{\mu\mu}|$: ~3σ || **w/ external input on $|\Delta m^2_{\mu\mu}|$ at 0.5-1% level** (NOνA + T2K)**: 3.7–4.4σ**

- Precision measurements of flavor oscillation parameters:

Parameter	$\sin^2\theta_{12}$	Δm^2_{21}	$\lvert\Delta m^2_{ee}\rvert$
Precision (Current)	4.1%	2.6%	1.9%
Precision (JUNO)	0.67%	0.50%	0.44%

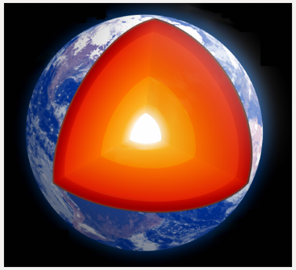
← effective atm. mass splitting

- Other physics (some examples):

Geo ν

~400 events / year

→ radiogenic heat, U / Th ratio



Core-collapse supernova ν

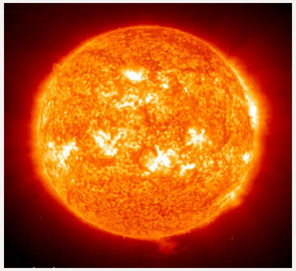
@ 10 kpc dist: ~5000 IBD in 10 s

→ test supernova models

Solar ν

some tens of ^{8}B-ν / day

→ solar metallicity, flavor oscil.



Diffuse supernova ν bkg.

~1-2 events / year after cuts

→ discovery, SN rate, ...

JUNO Timeline & Collaboration

- **2013**: Complete conceptual design; complete civil design & bidding
- **2014**: Start civil construction; complete protoyping (PMT & detector)
- **2015**: PMT production line manufacturing
- **2016**: Start PMT production; start detector Production or bidding
- **2017**: Complete civil construction; start detector construction & assembly
- **2018**: Start LS production
- **2019**: Complete detector assembly, installation & LS filling
- **~2020**: Start data taking

International JUNO Collaboration: formally established August 2014

Currently: 71 institutions, 486 scientists

Summary

- With its 20 kt LS detector, the medium-baseline experiment JUNO in China aims to determine the neutrino mass ordering by measuring the fine structure in the reactor $\bar{\nu}_e$ survival probability

- JUNO is a funded, international project; data taking will start around 2020

- Critical items: energy resolution $\leq 3\%/\mathrm{sqrt}(E)$ and energy scale uncertainty $< 1\%$

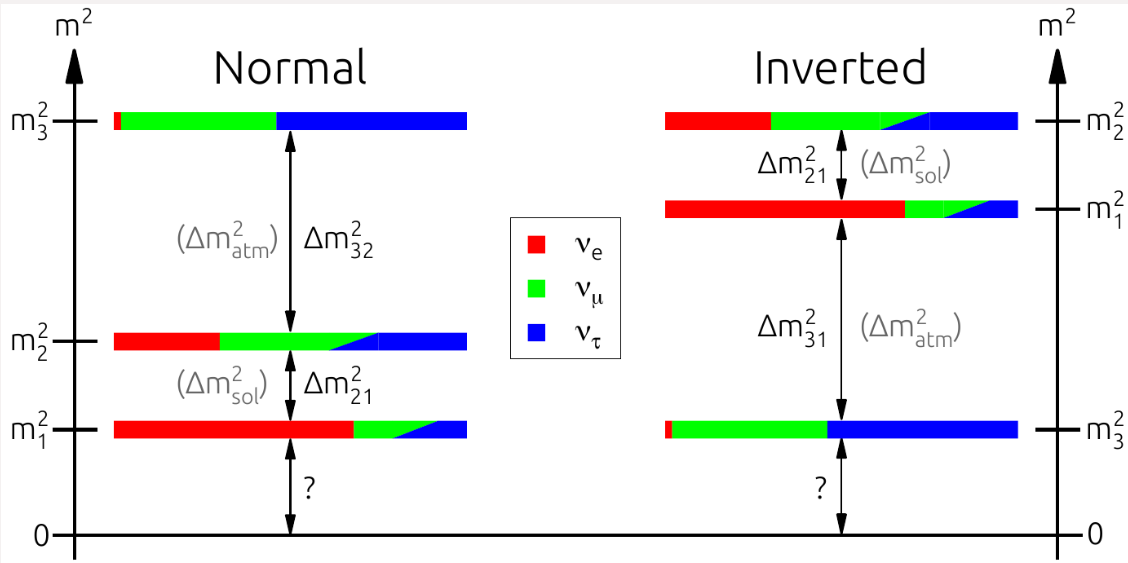
- Median sensitivity to neutrino mass ordering with 100 k IBD events: $\geq 3\sigma$

- Moreover, measurements...
  - ... of oscillation parameters at sub-percent level precision
  - ... with terrestrial and astrophysical neutrinos

Thank you for your kind attention!

Further Information

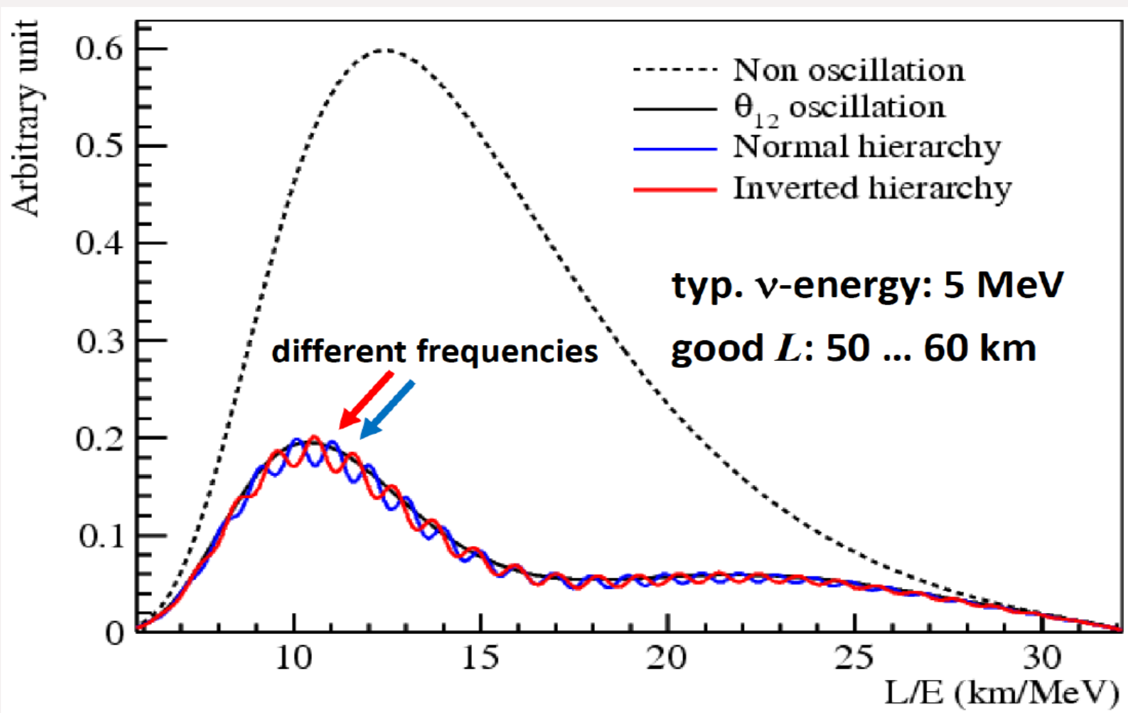
Medium-Baseline $\bar{\nu}_e$ Oscillations



$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$$
$$P_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31})$$
$$P_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})$$
$$\Delta_{ij} = 1.27\Delta m^2_{ij} L/E$$

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

$$\frac{|\Delta m^2_{21}|}{|\Delta m^2_{32}|} \sim 0.03$$



Precision of $\sin^2\theta_{12}$, Δm^2_{21} and $|\Delta m^2_{ee}|$ from the nominal setup to those including additional systematic uncertainties. The systematics are added one by one from left to right.

	Nominal	+B2B (1%)	+BG	+EL (1%)	+NL (1%)
$\sin^2\theta_{12}$	0.54%	0.60%	0.62%	0.64%	0.67%
Δm^2_{21}	0.24%	0.27%	0.29%	0.44%	0.59%
$\lvert\Delta m^2_{ee}\rvert$	0.27%	0.31%	0.31%	0.35%	0.44%

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

Energy Resolution Model

$$\frac{\Delta E}{E} = \sqrt{a^2 + \frac{b^2}{E} + \frac{c^2}{E^2}}$$

- a^2: Energy leakage & non-uniformity
- $\frac{b^2}{E}$: Photon statistics
- $\frac{c^2}{E^2}$: Noise (~ background)

- **High, uniform photoelectron yield (~1200 p.e. / MeV)**
  - Spherical detector (easier non-uniformity correction)
  - High light yield scintillator + low attenuation (**no Gd loading**)
  - High photocathode coverage (~75%)
  - PMTs with high detection efficiency (~30%)
- **Low noise** → clean materials and quiet PMTs
- **Comprehensive calibration program**

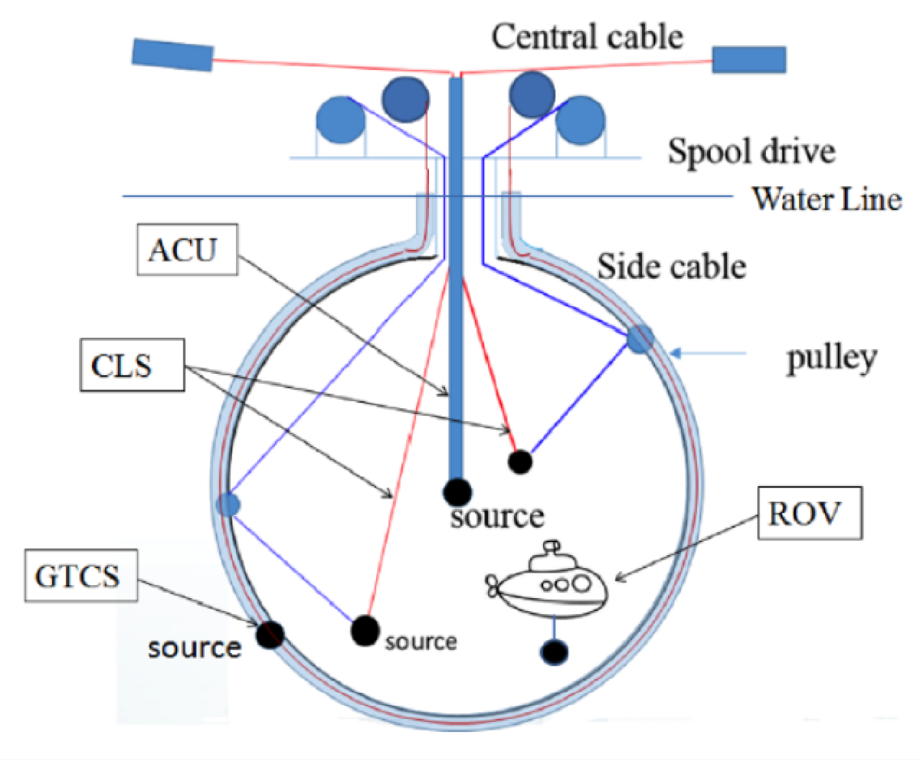
JUNO Calibration

- The challenge:
  - overall energy resolution: ≤ 3% / sqrt(E)
  - energy scale uncertainty: <1%
- Four complementary calibration systems
  - **1D**: *Automatic Calibration Unit* (ACU)
    → central axis scan
  - **2D**: *Cable Loop System* (CLS)
    → scan vertical planes

    Guide Tube Calibration System (GTCS)
    → CD outer surface scan
  - **3D**: *Remotely Operated under-liquid-scintillator Vehicle* (ROV)
    → whole detector scan

Method	System
Rope Length Calculation	CLS, ACU and GTCS
Ultrasonic receiver	ROV, CLS
CCD(Independent)	ROV, CLS

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



Concept of the iPMT

High Voltage Unit:
- Provides the HV for the PMT
- Programmable by the control unit

Signal Board:
General Control Unit (FPGA, RAM)
ADU

Power Board:
Provides all voltage for HVU, GCU, ADU