Neutrino Mass Ordering: JUNO status and plans

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Outline

- Introduction
- Experimental Goals and Strategy
- Collaboration
- Location
- Neutrino Detection
- Experimental Layout
- Overall Schedule
- Conclusion

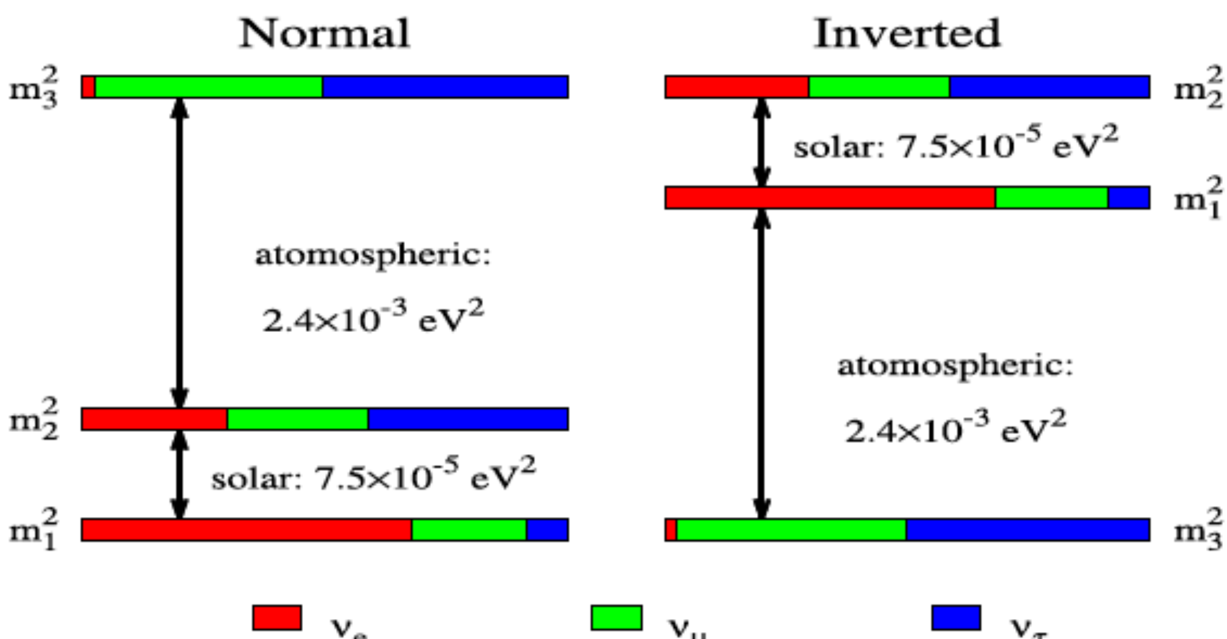
Introduction: PMNS today

What We Know

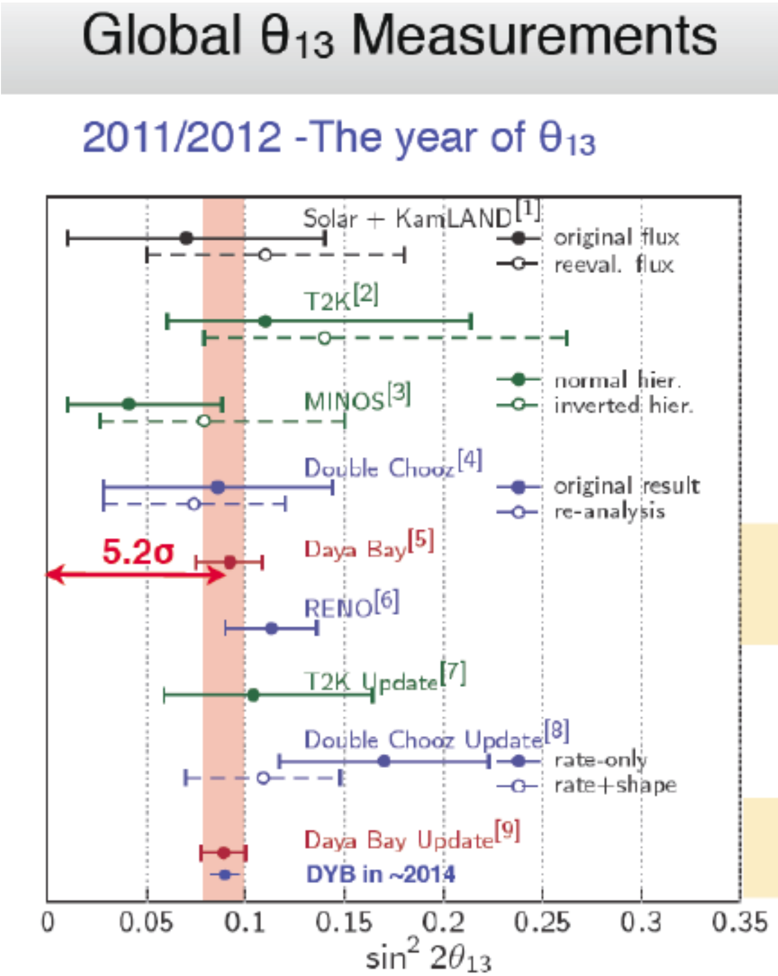
atmospheric accelerator ν_μ	short baseline reactor accelerator ν_e	solar long baseline reactor

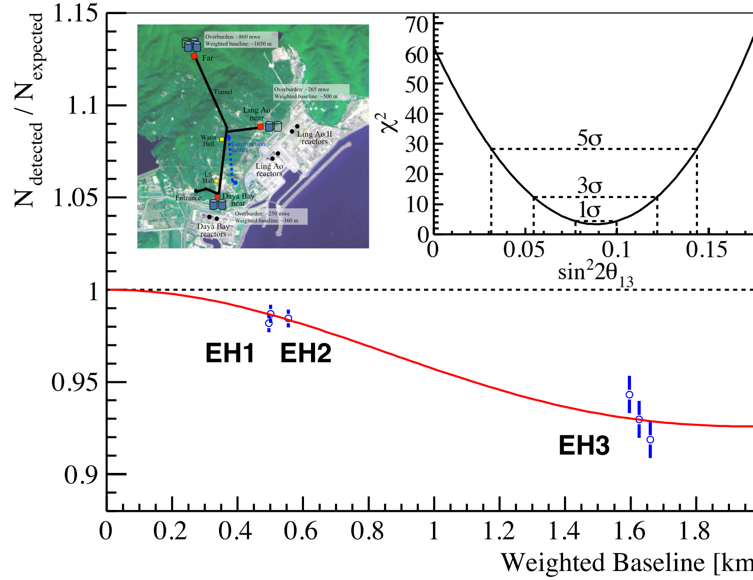
$$\text{Flavor}\quad \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad \text{Mass}$$

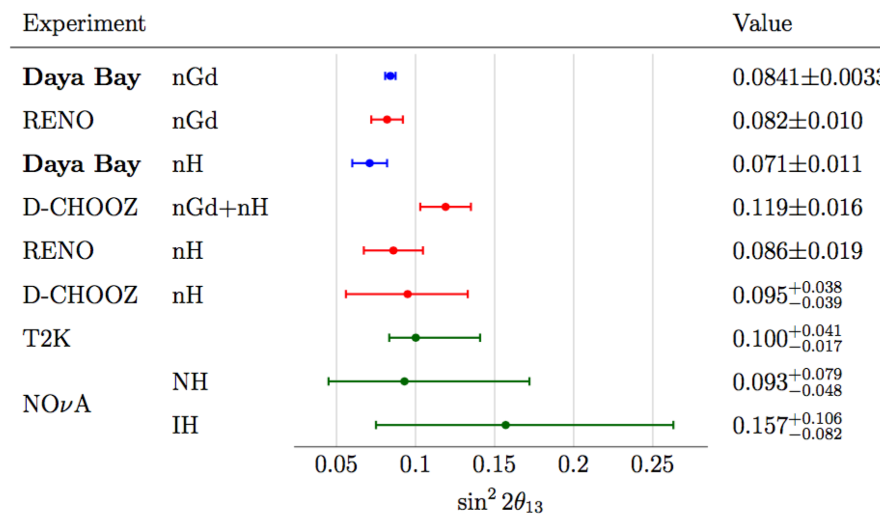
$\theta_{23} \approx 45^\circ$ $\theta_{13} \approx 9^\circ$ $\theta_{12} \approx 34^\circ$



θ_{13} Mixing Angle Measurement







Sensitivities to NMO Determination

Project	ν source	Detector	Goal	Challenges
NOVA	LBL (810 km)	14 kt tracking calorimeter	2σ (2020)	Parameter degeneracy
JUNO	Reactor (53 km)	20 kt LS	$(3-4)\sigma$ (2026)	Energy resolution
PINGU/ORCA	Atmosphere	(1-10) Mt of ice	$(3-5)\sigma$ (unknown)	Energy resolution, systematics
INO	Atmosphere	50 kt magnetized calorimeter	3σ (2030)	Low statistics (10 years)
T2HK	LBL (295 km)	1Mt of water	3σ (2030)	Parameter degeneracy
DUNE	LBL (1300 km)	1kt of liquid argon	$(3-5)\sigma$ (2030)	Parameter degeneracy
Cosmology	Early Universe	CMB-S4 bolometers	4σ (>2023)	Dependence on cosmological models

Comparison of expected median sensitivities to neutrino mass hierarchy determination of various accelerator, atmospheric, reactor and cosmological experiments.

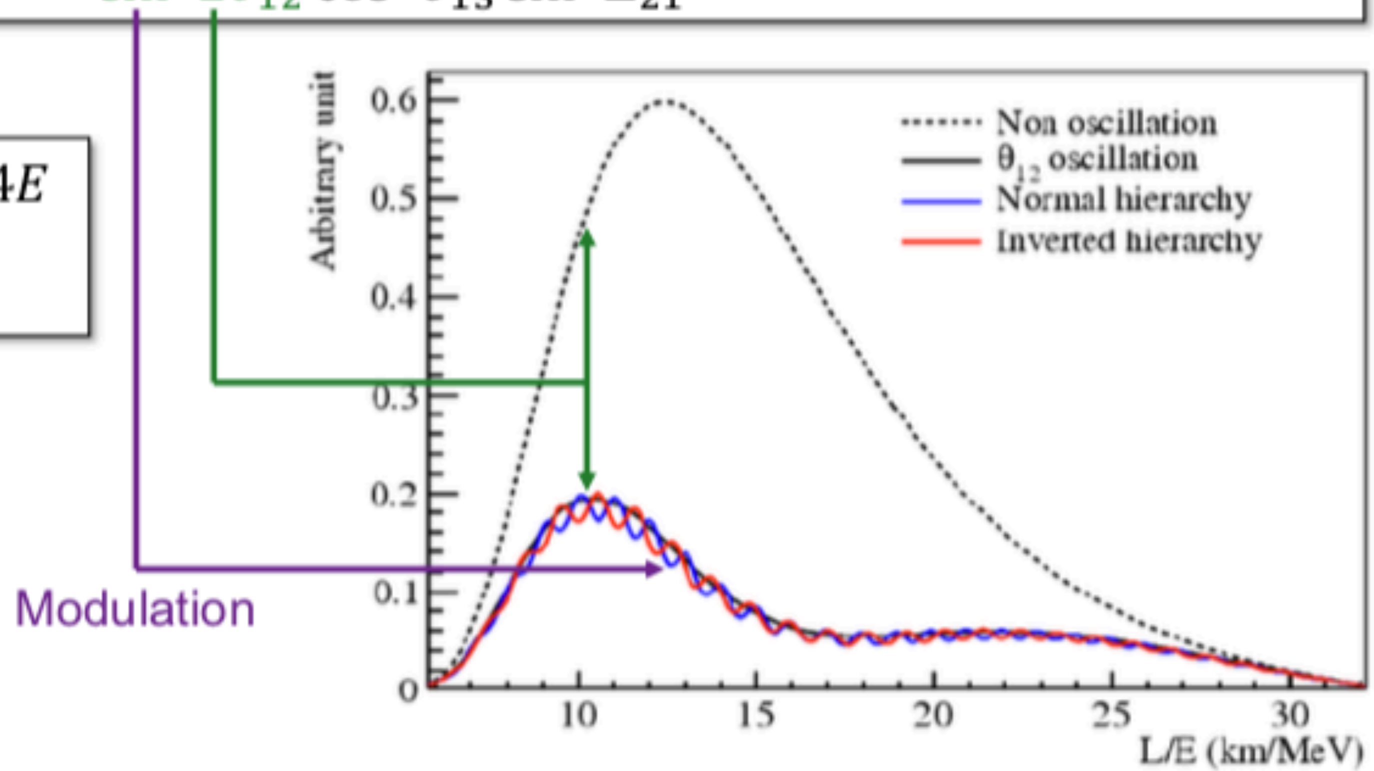
Measurement at Reactors

The mass hierarchy is accessible through reactor antineutrino oscillations

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

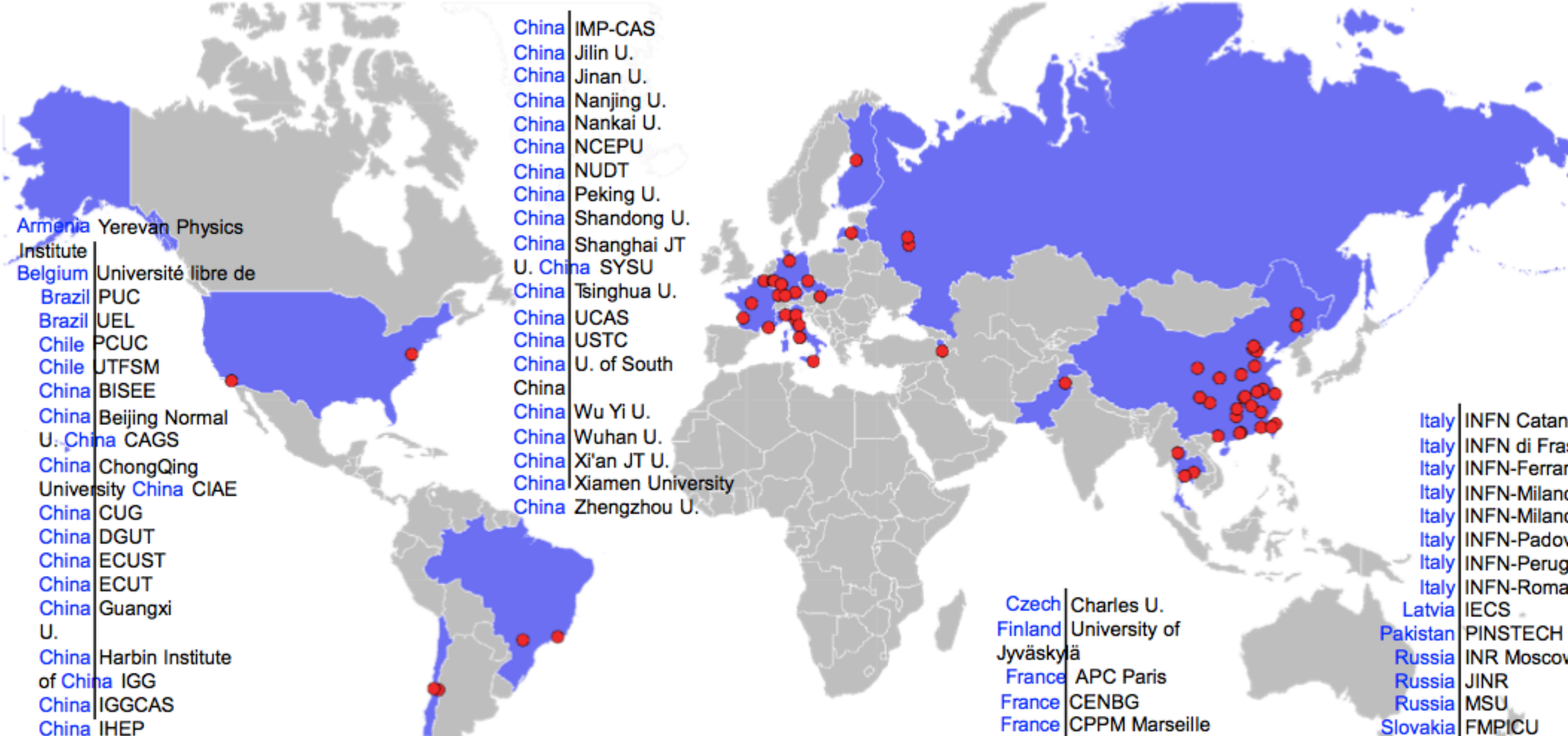
$$\Delta_{ij} = \Delta m_{ij}^2 \, L/4E$$

E: antineutrino energy
L: baseline



First discussion by Bilenky and Petcov (~2000);
Petcov and Piai, Physics Letters B553 (2002) 94-106;

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
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China | IGGCAS
China | IHEP
China | IMP-CAS
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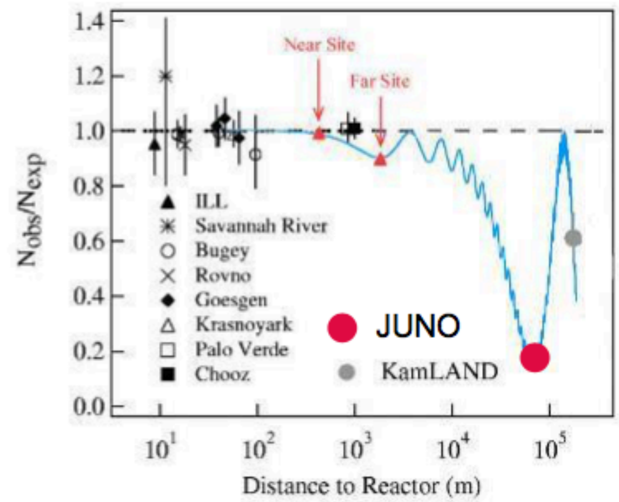
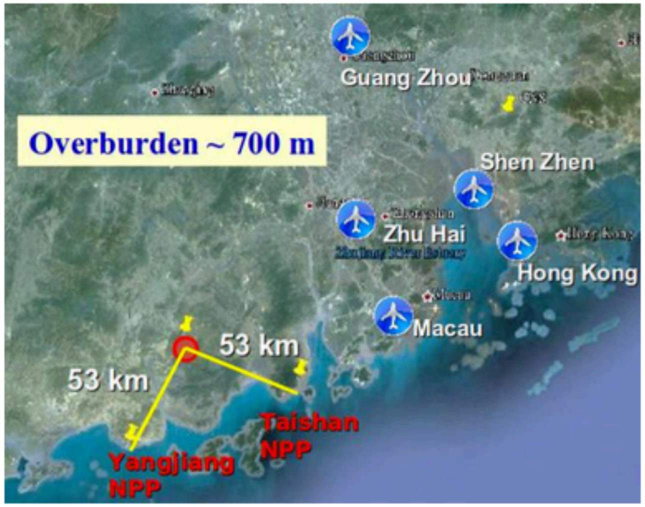
Taiwan | National United U.
Thailand | NARIT
Thailand | PPRLCU
Thailand | SUT
USA | UMD1
USA | UMD2
USA | UCI

Collaboration established on July 2014
Now 77 institutions ~600 collaborators

The Cornerstones for JUNO

- **Optimized reactor baseline**
  - Site chosen with ideal distance of 53 km to two nuclear power plants with multiple cores
  - Distance variation below 0.5 km
- **High statitics needed: 100k events in 6 years**
  - ~36 GW_{th} reactor power
    - At start of data taking ~26.6 GW_{th}
  - 20 kton liquid scintillator
  - Increased exposure by sophisticated muon tracking
- **Very good energy resolution: 3% @ 1 MeV**
  - Corresponds to ~1200 p.e. / MeV
- **Low energy scale uncertainty < 1%**



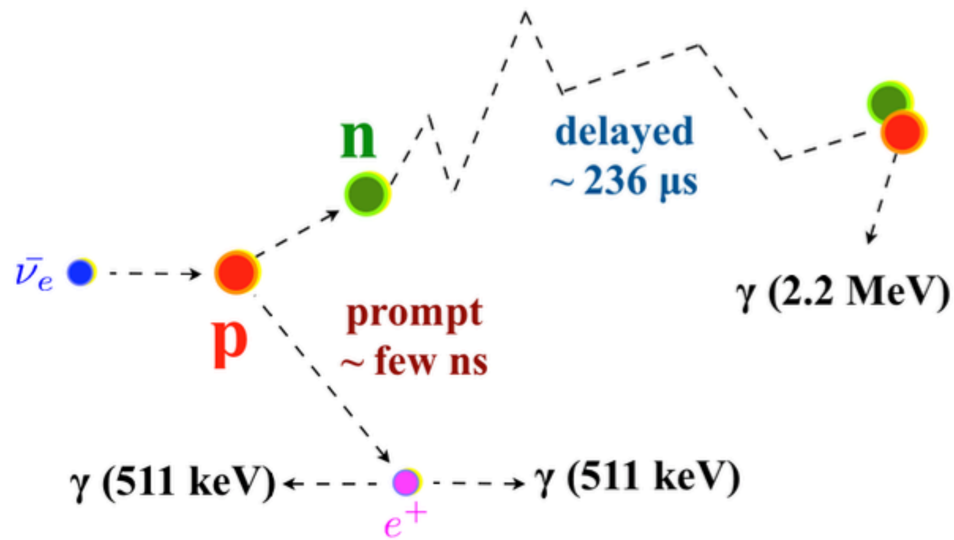


Detection Principle

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

$$\bar{\nu} + p \rightarrow n + e^{+}$$ $E_\nu > 1.8$ MeV

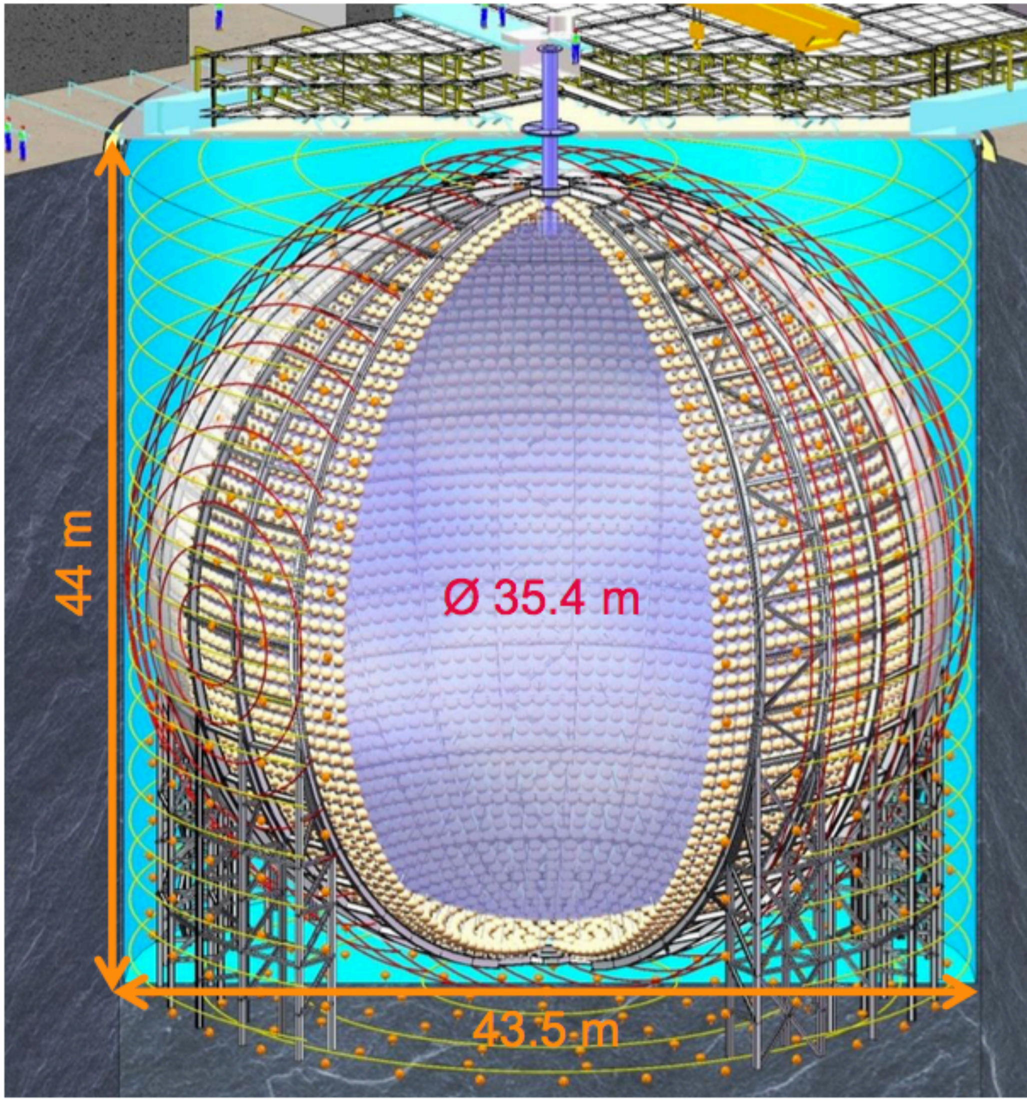


The time coincidence between the positron and the γ from the capture rejects the uncorrelated background

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

The JUNO detectors

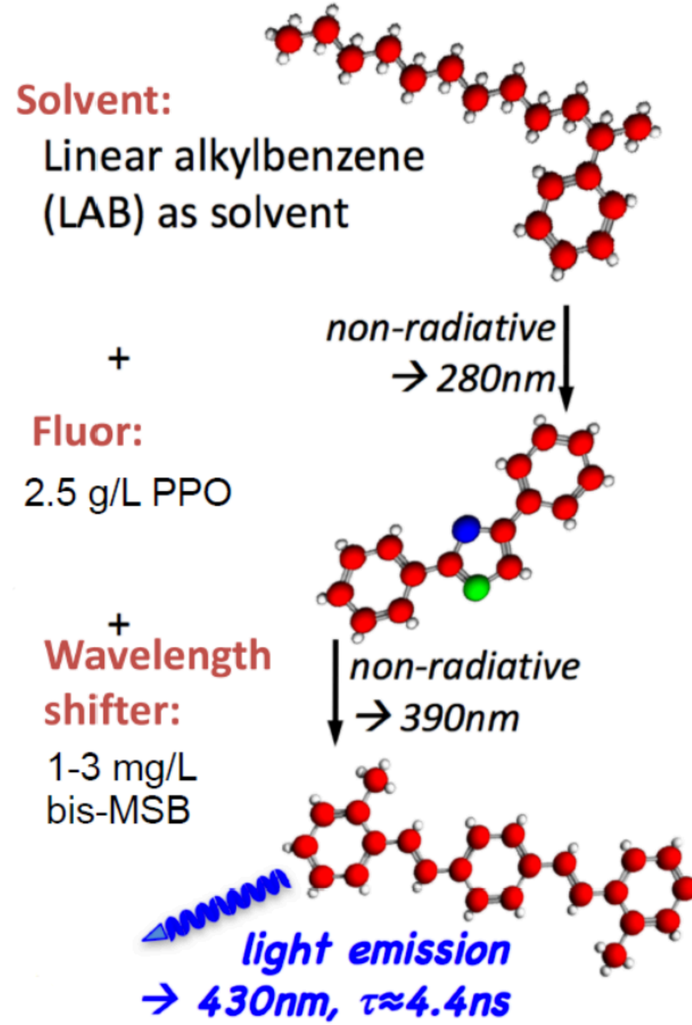
- **Central detector**
  - Acrylic sphere filled with **L**iquid **S**cintillator
  - 18k 20" + 25k 3" PMTs in water buffer
  - 78% coverage of 20 kton LS
- **Water Cherenkov muon veto**
  - 2k 20" PMTs in 35 kton ultra-pure water
  - > 95% efficiency in muon tagging
  - Passive radioactivity shield
- **Top Tracker**
  - Repurpose of former OPERA tracker
  - 3 plastic scintillator layers, x-y-readout
  - Covers 50% of top area
  - High precision muon tracking
- **EMF compensation coils**
  - Needed for operation of 20" PMTs
  - Reduction to 10% of earth magnetic field



The Liquid Scintillator

- **LAB + 2.5g/L PPO + 1-3mg/L bis-MSB**
- High light yield of 10^4 photons/MeV
- **Attenuation length** $L_{att} > 20$ m @ 430 nm
- Low radioactivity $< 10^{-15}$g/g (U/Th)

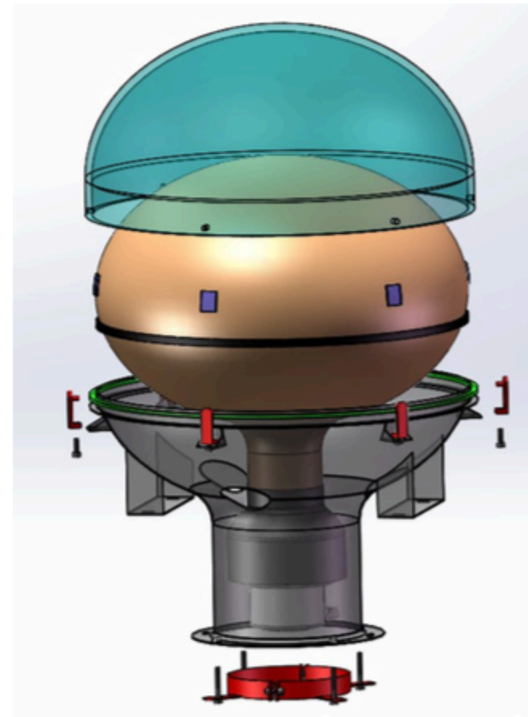
- **Purification pilot plant**
  - Prototype tested at Daya Bay AD1
  - Al_2O_3 column, distillation, water extraction and steam stripping
  - Achieved 23 m attenuation length after filling



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%

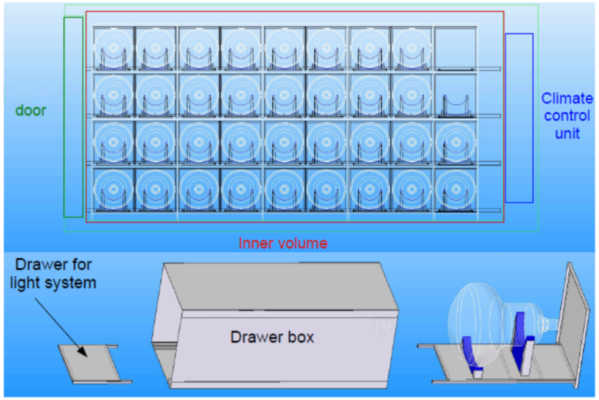
Average PDE of HAMAMATSU 28%

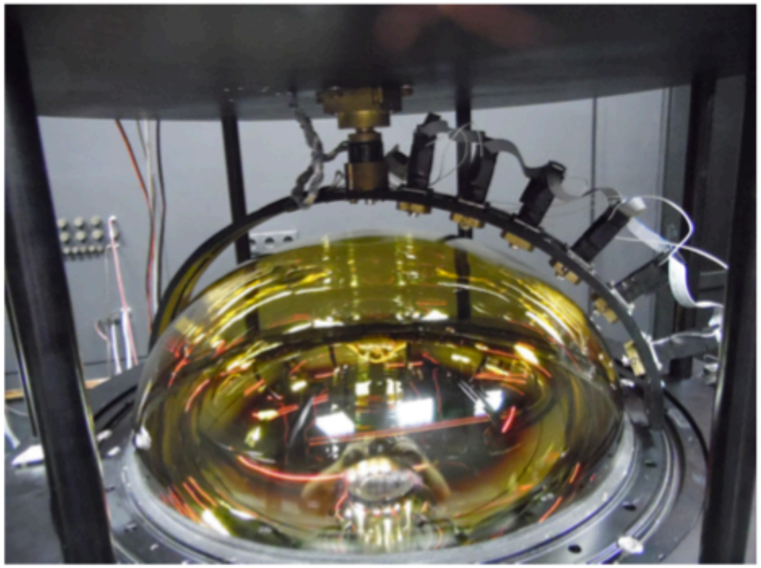
JUNO PMT tests

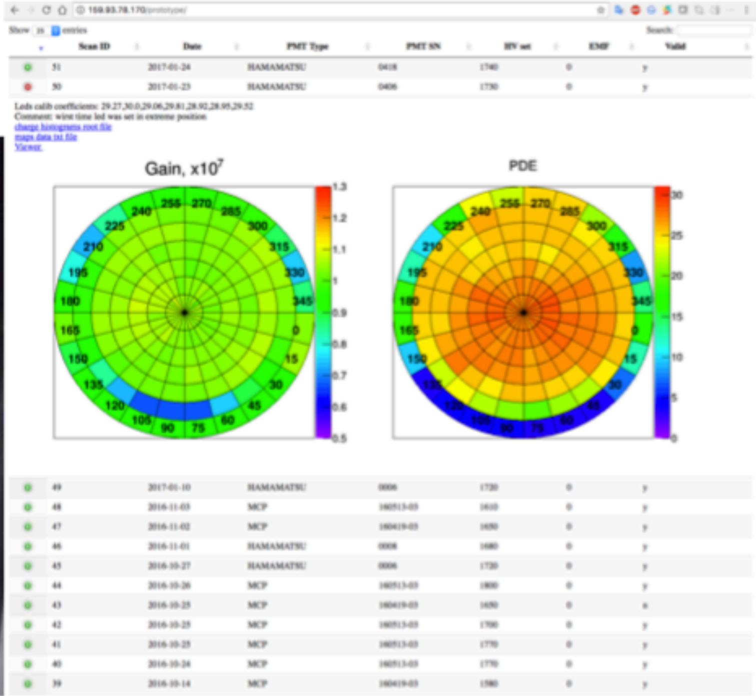
Test of 20’000 (5’000 Hamamatsu and 15’000 NNVT) 20” PMTs is performed at a special facility constructed by JUNO in China.

Acceptance test (visual inspection, test of 100% PMTs in Container and test of ~10% at the Scanning Stations) will be followed by the test of potted PMTs and PMTs with real 1F3 electronics.

Design of the Mass Testing Container System

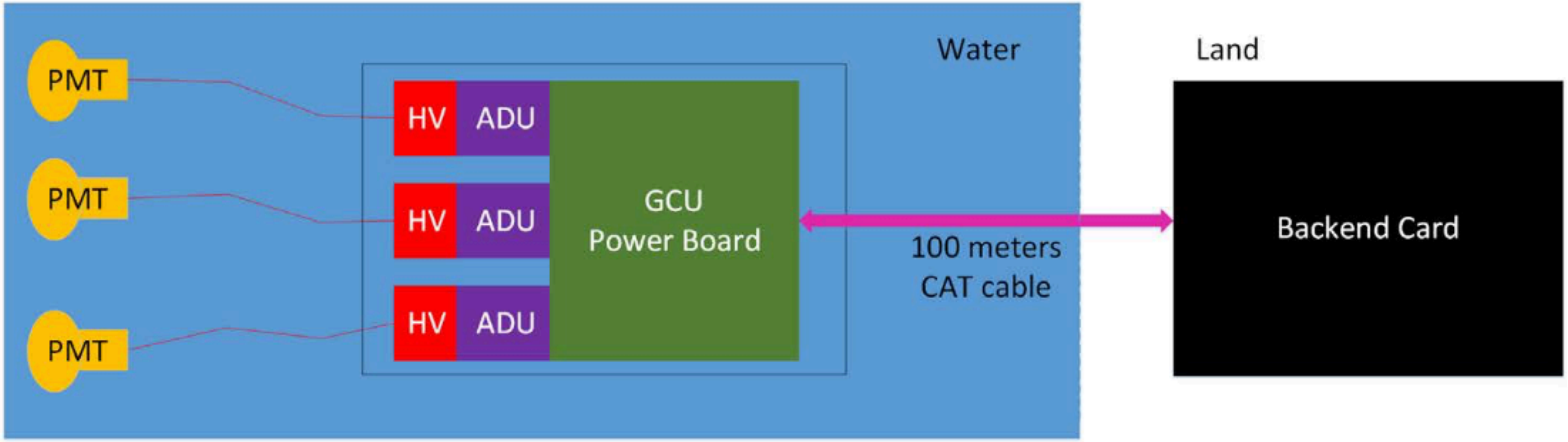






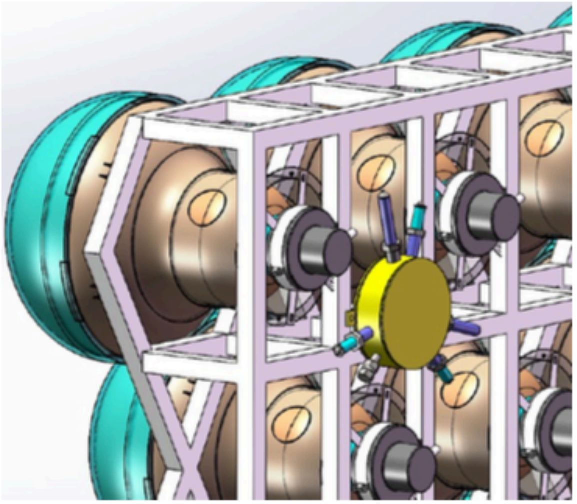
Readout Electronics

1F3 scheme

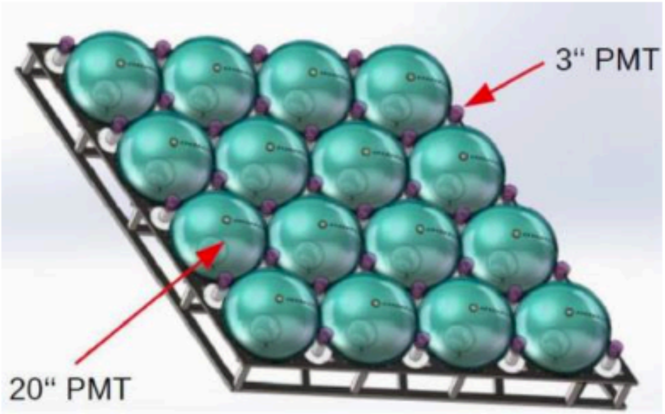


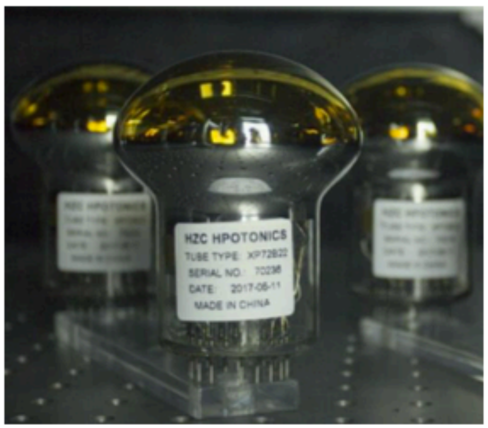
- PMT: photomultiplier tubes
- HV: High Voltage units
- ADU: Analog to Digital Unit
- GCU: Global Control Unit
- CAT cable: Category 5e cable
- High reliability needed
- Severe constraints by power consumption

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

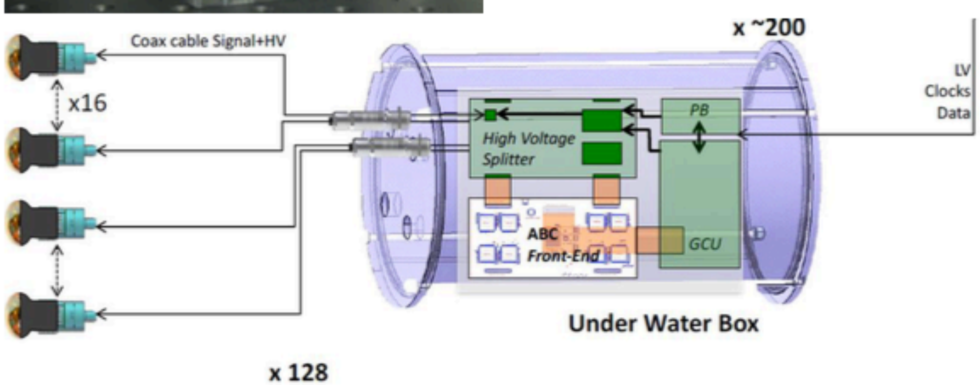


3-inch PMTs





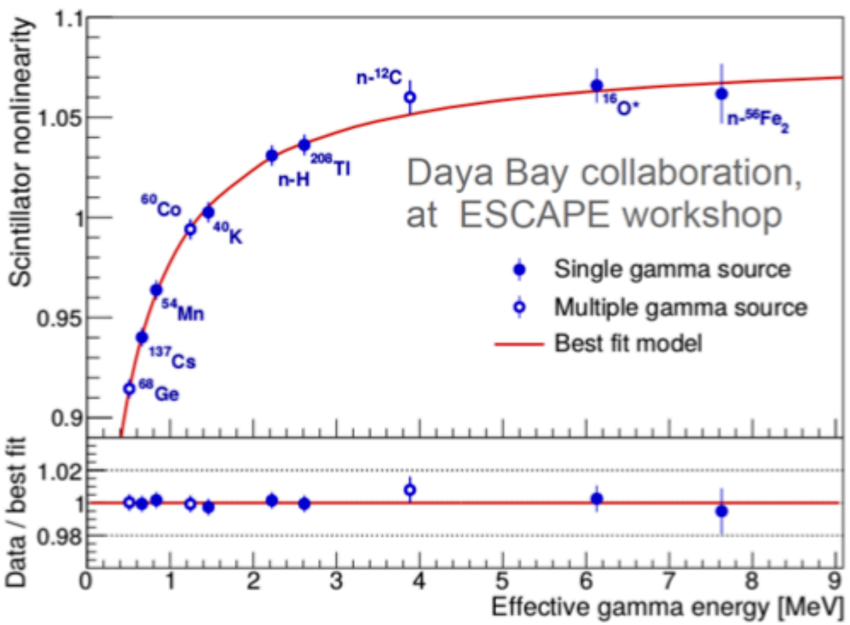
- Independent system -> **Double calorimetry**
  - Always in **photon-counting** mode for reactor antineutrinos
    - Calibration of non-linear LPMT response
  - **Increased dynamic range** beneficial for large signal from muons and supernova
- 25000 PMTs contracted to HZC with JUNO custom design
  - 6000 produced and already tested
- XP72B22: QE 24%, P/V 3.0, SPE resolution 30%, TTS 3.5 ns FWHM

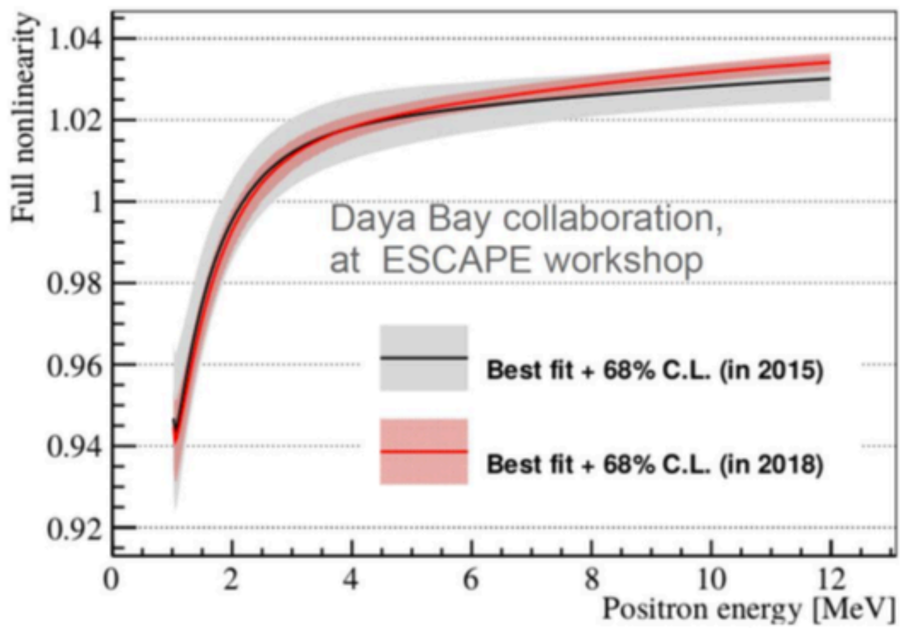


Prototype of underwater box built
200 boxes with 128 PMTs each

Energy Scale Uncertainty

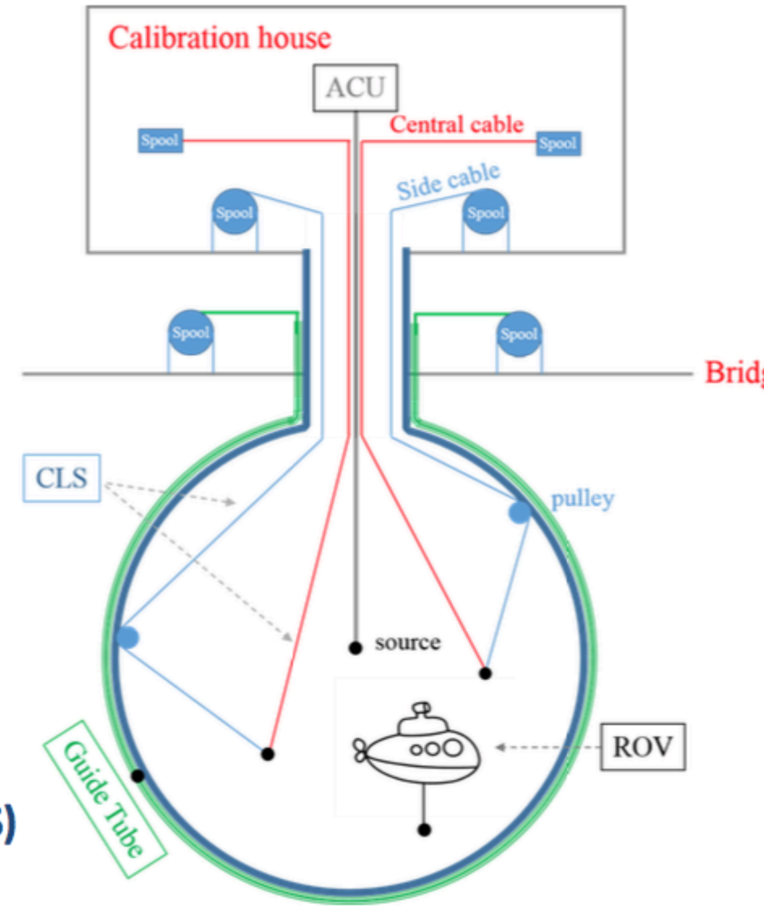
- JUNO needs to achieve an energy scale non-linearity accuracy of < 1%
  - Possible with extremely careful calibration: Utilizing different sources, covering the whole energy range & continuous calibration
- Other experiments already achieved 1% accuracy
  - Daya Bay ~ 0.5%, Double Chooz 0.74%, Borexino <1% (at low energies), KamLAND 1.4%





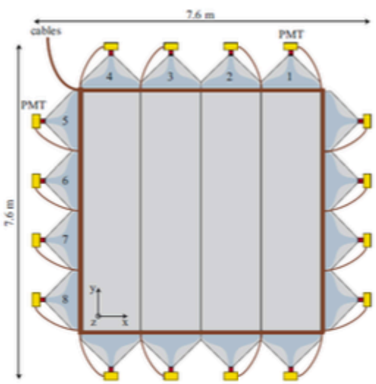
Calibration system

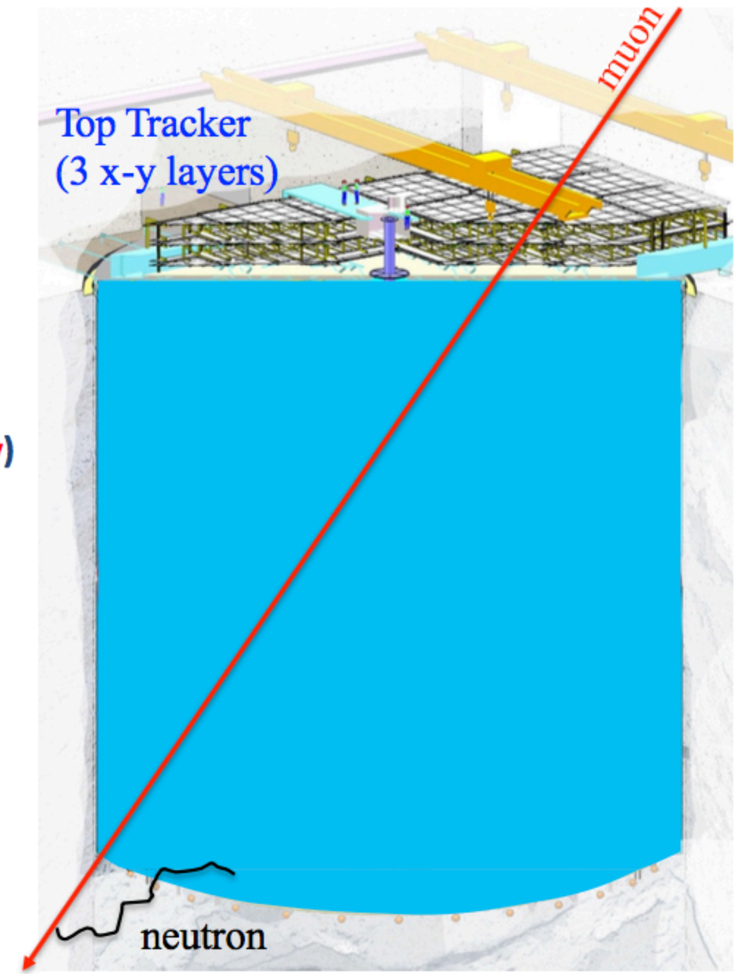
- **The goal:**
  - Overall energy resolution: ≤ 3%/√E
  - Energy scale uncertainty: <1%
- **Radioactive sources:**
  - γ ： ^{40}K, ^{54}Mn, ^{60}Co, ^{137}Cs
  - e+ ： ^{22}Na, ^{68}Ge
  - n ： ^{241}Am-Be, ^{241}Am- ^{13}C or ^{241}Pu- ^{13}C, ^{252}Cf
- **Four complementary calibration systems**
  - 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



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





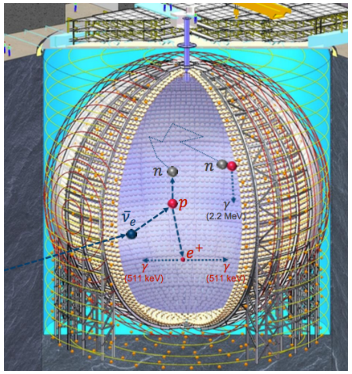
Signal and background in JUNO

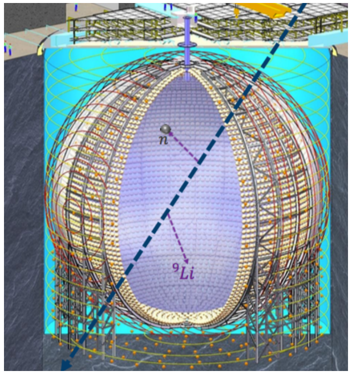
- Reactor $\bar{\nu}_e$ are detected via Inverse Beta Decay (IBD)

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

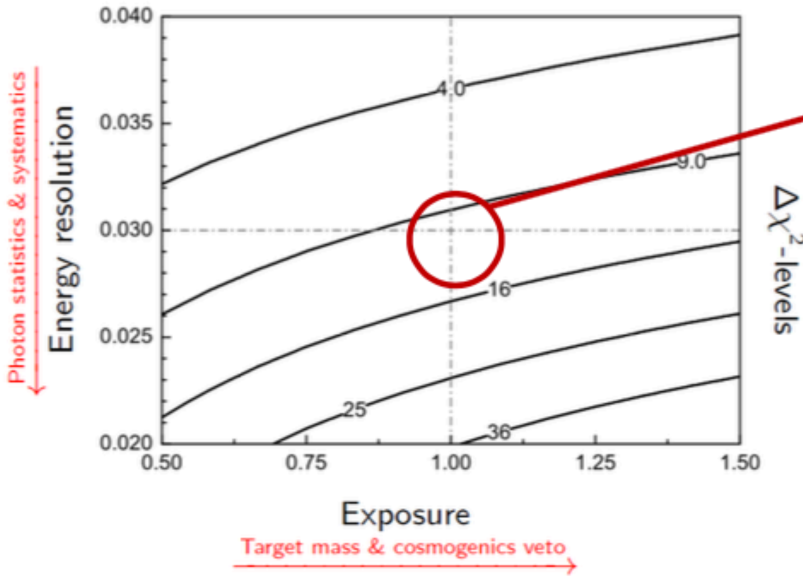
- Delayed coincidence between prompt positron annihilation and delayed neutron capture
- Rate: ~83/day
- Muons create main background:
  - 700 m overburden (≙ 1900 m.w.e.)
  - 3.5 Hz in central detector
  - Decay of ^9Li and ^8He mimic delayed IBD coincidence
  - ~84/day
- Top Tracker (former OPERA)
- Water bufferwith 2000 20-inch PMTs
- Reconstruction in Central Detector
- Other backgrounds include geo-ν (1.5/day), fast neutrons (0.1/day) and (α, n)-decays (0.05/day)
- After all cuts:

  60 IBD / 3.8 background events per day

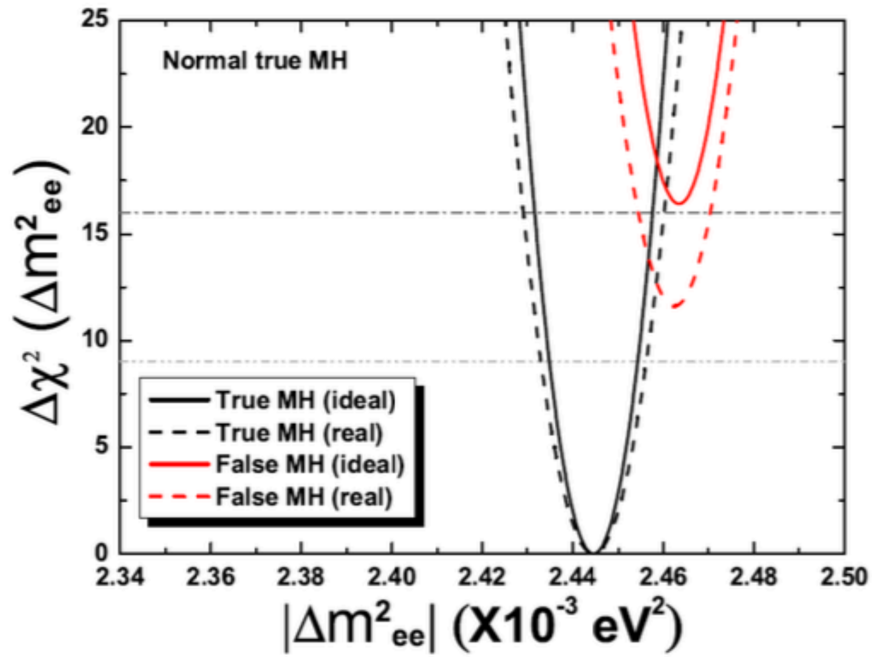




JUNO Sensitivity on Mass Hierarchy and Oscillation Parameters



Nominal exposure = 100k IBD events
≙ 6 years x 20 kt LS x 36 GW_{th}



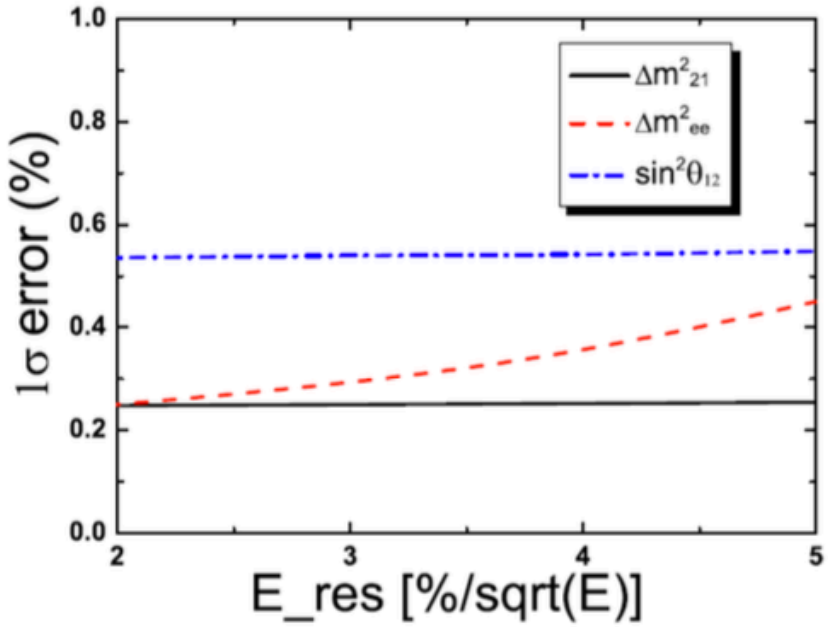
$$\Delta m^2_{ee} = \cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}$$

Sensitivity on MH with nominal exposure and energy resolution

- $\Delta\chi^2 > 9$ with JUNO alone
- $\Delta\chi^2 > 16$ with external input of $\Delta m^2_{\mu\mu}$~ 1%

Precision Measurement of Oscillation Parameters

- JUNO's energy resolution and baseline allow for large improvements on θ_{12}, Δm^2_{21} and Δm^2_{ee} to sub-percent accuracy
- Complementary to long-baseline experiments



Parameter	$sin^2\theta_{12}$	Δm^2_{21}	$\lvert\Delta m^2_{ee}\rvert$
Precision (current)	2.2%	3.9%	1.2%
Precision (JUNO)	0.7%	0.6%	0.4%

Other Physics

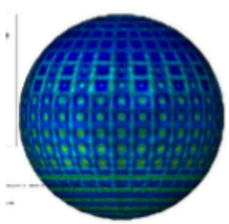
	KamLAND	Borexino	Daya Bay	JUNO
Mass [t]	~1000	~300	~170	20000
Light yield [p.e. / MeV]	250	500	200	**1200**
Energy resolution	$6\%/\sqrt{E}$	$5\%/\sqrt{E}$	$7.5\%/\sqrt{E}$	$\mathbf{3\%/\sqrt{E}}$
Energy calibration	1.4%	<1%	0.5%	<1%

- Rich physics program:
  - **Supernova ν**
  - **Diffuse supernova background**
  - Atmospheric ν
  - **Solar ν**
  - Sterile ν
  - **Geo-ν**
  - Proton decay
  - Indirect dark matter search
  - Other exotic searches

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:

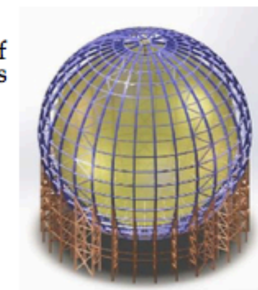
- Start PMT testing
- TT arrived

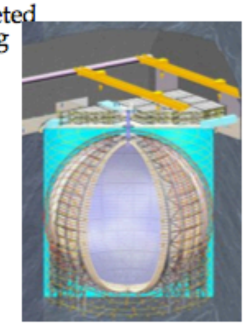
2018:

- 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





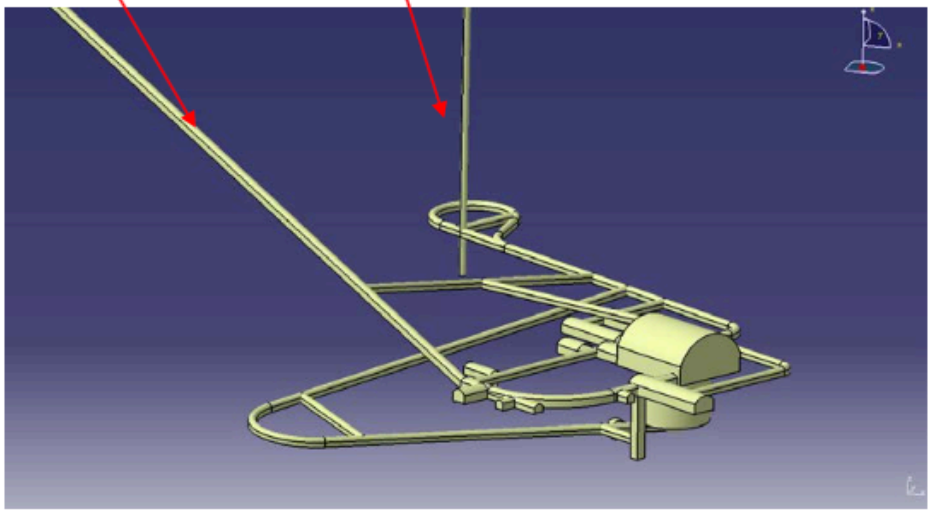
2021:

- Detector ready for Data taking!

Layout of the site

Slope tunnel

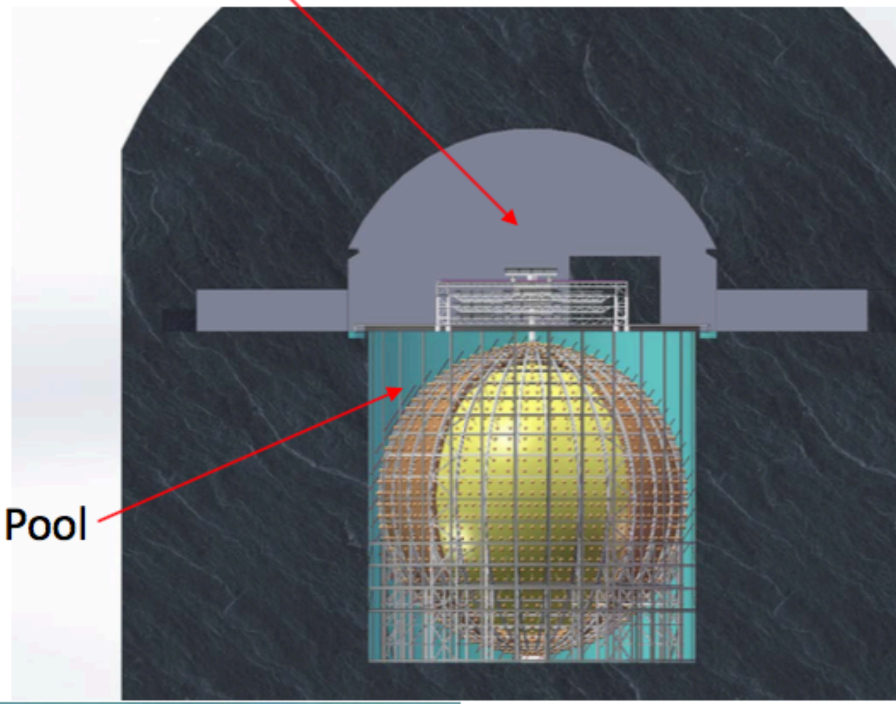
Vertical shaft



overburden ~ 700 m

Experimental Hall

Pool



Surface buildings

Civil Status

Experimental hall

Access tunnel to the experimental hall

Vertical shaft

One of the service tunnels

Conclusion

- JUNO is a unique physics instrument pairing a very **large target mass** with an **unprecedented energy resolution**
- Sensitivity on **neutrino mass ordering**:
  - $\Delta\chi^2 > 9$ after 6 years with JUNO
  - $\Delta\chi^2 > 16$ with external input from $\Delta m^2_{\mu\mu}$ at 1%

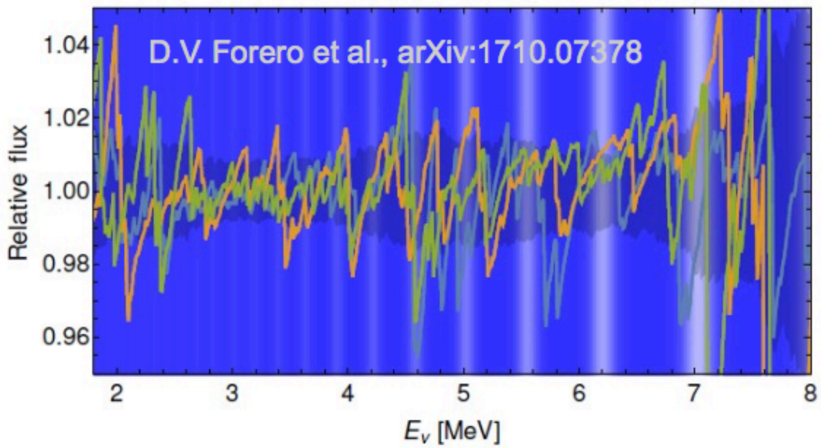
- **Sub-percent** measurement of oscillation parameters $\boldsymbol{\theta_{12}}$, $\Delta \mathrm{m}^2_{21}$ and $|\Delta m^2_{ee}|$
  - Complementary to long baseline experiments

- Rich additional **physics program**
- Large effort in understanding the **detector response** and its **non-linearity**
- R&D for near detector started for **a precise reference reactor spectrum**

- Good project progress and on path to start **data taking in 2021**

Special Comment on
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

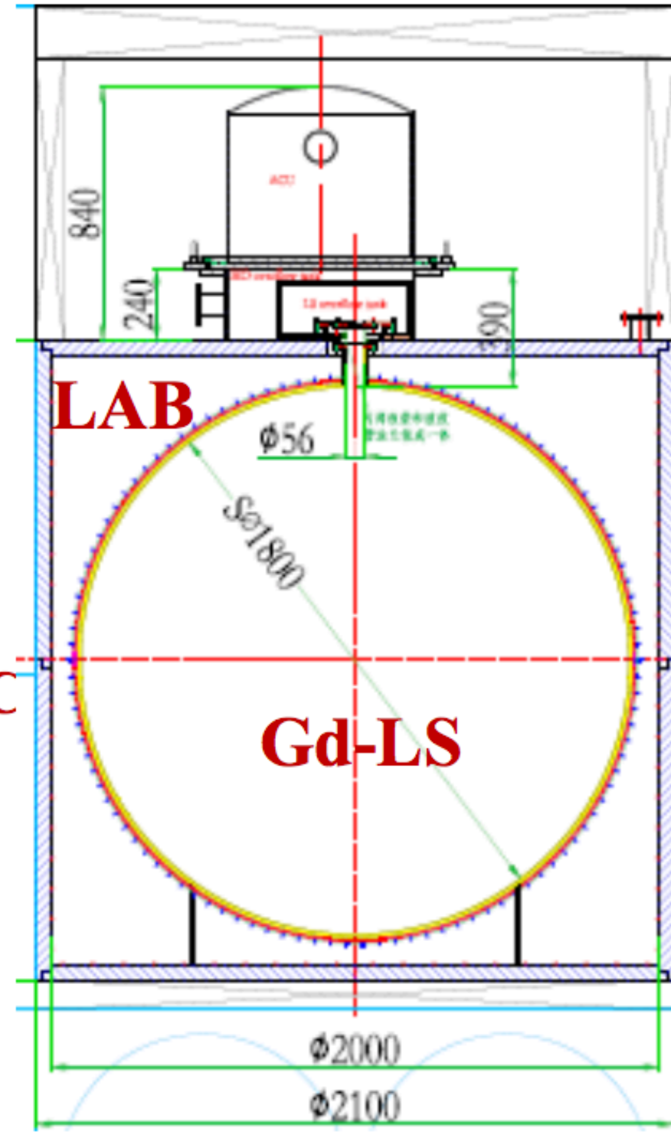
Near (reference) Detector Concept

Gd-LS in diameter of 1800 mm
- Surface 10.2 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

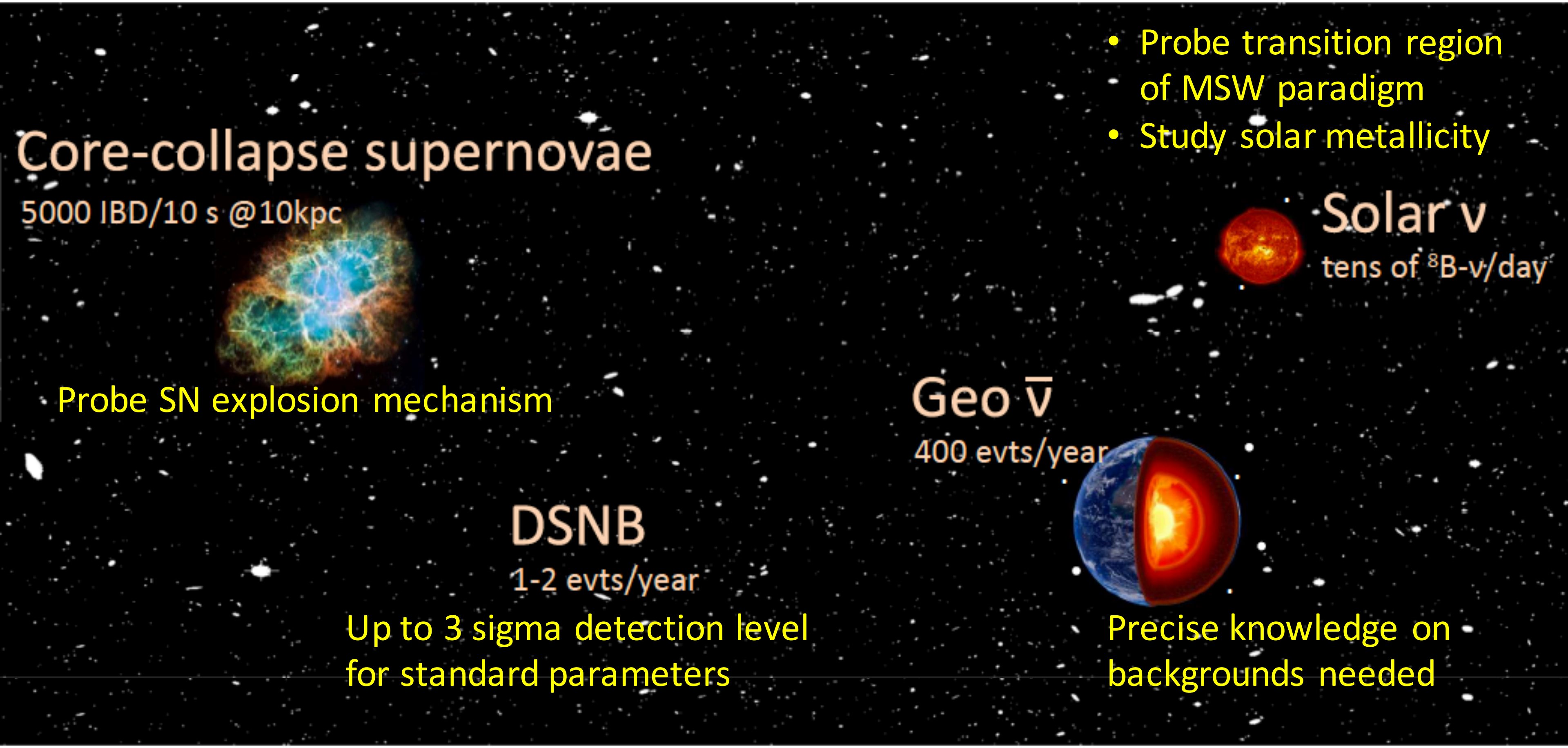
LAB+quencher as buffer
Cryogenic vessel
DYB Automatic Calibration Unit



Thank you

Backup slides

Other Physics

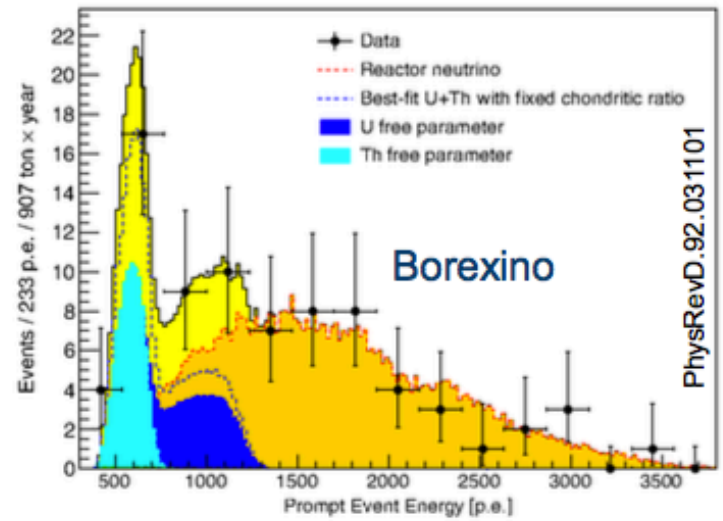


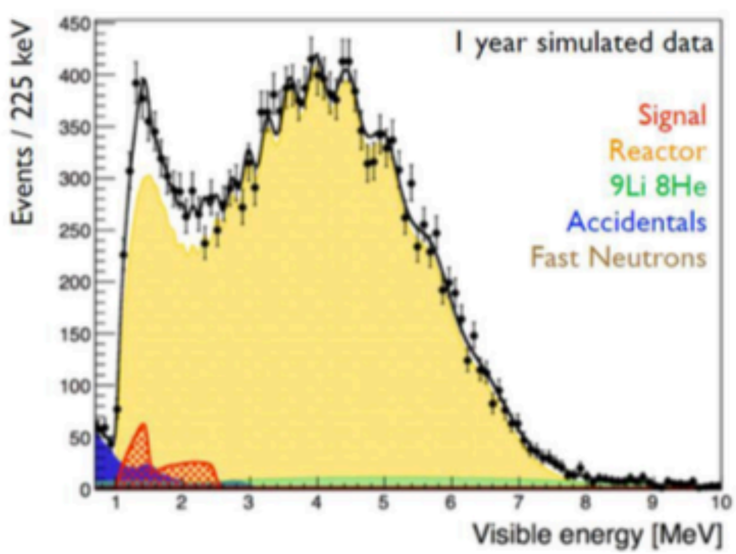
DSNB: Diffuse Supernova Neutrino Background

Extended Physics Program

Geoneutrinos

- $\bar{\nu}_e$ neutrinos from U- and Th-chains in the earth mantle and crust
- Used to study the composition of the Earth & its radiogenic heat production
- Currently only measured by Borexino and KamLAND



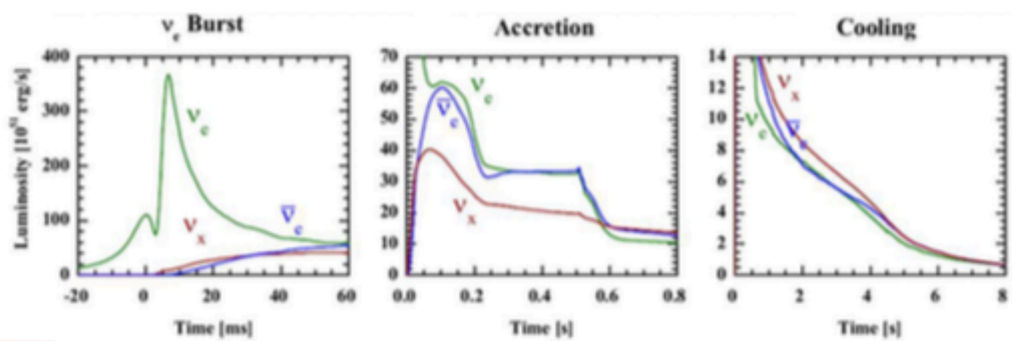


- Expected rate of 400 events/year could match present world sample in less than 1 year
- Challenge: large background from reactor $\bar{\nu}_e$

Extended Physics Program

Core-collapse supernova

- JUNO will be equipped to record a high statistics sample in case of a core collapse SN at d ~10 kpc:
  - 5000 IBD from $\bar{\nu}_e$ & 2000 elastic ν_x-p scatterings within 10 sec
- Separate detection of $\bar{\nu}_e$, ν_e and ν_x
- Probe SN models:
  - Time evolution
  - Energy spectra
  - Flavor mixing



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

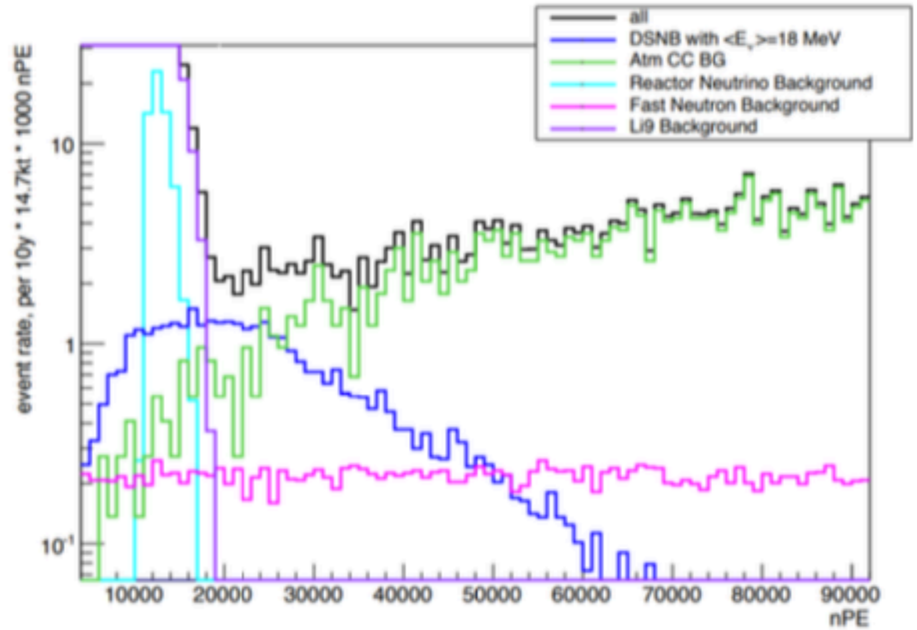
- T 32.9 „*Thermonuclear Supernova Neutrino Signals in JUNO*“ by J. Schulte
- T 93.7 „*Neutrinos from Supernovae collapsing into Black Holes in JUNO*” by M. Büsken

Extended Physics Program

Diffuse supernova background

DSNB is made up of the cumulative neutrino emission of core-collapse SN throughout the universe

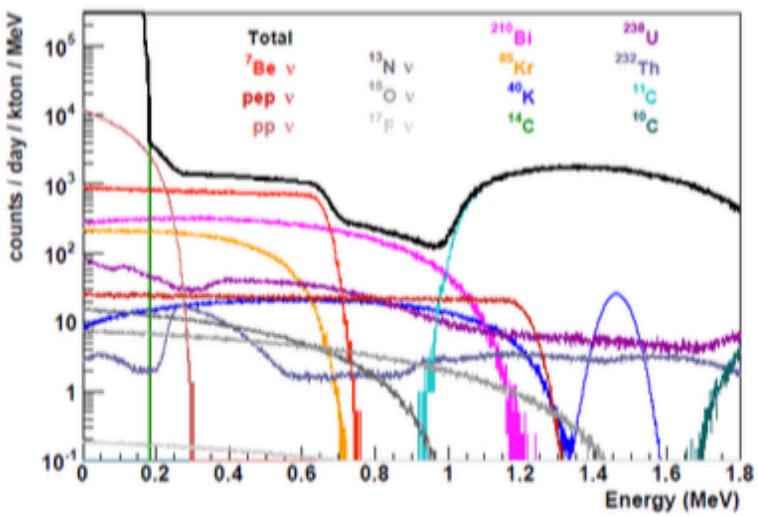
- Detected via IBD channel
- Expected rate 1-4 events per year
- Strong background from atmospheric ν
- Up to 3σ detection level for 10 year measurement
- Improvement of limits even for non-detection

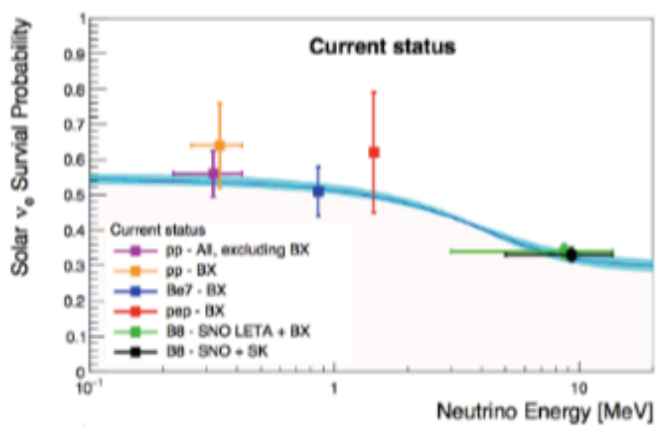


- T 32.10 „*Detection Potential for the Diffuse Supernova Neutrino Background in the Large Liquid Scintillator Detector JUNO*" by J. Sawatzki

Extended Physics Program

Solar neutrinos





arXiv 1602.01733

- The sun is a large source for MeV neutrinos
- LS detector well suited due to low threshold and high energy resolution
- JUNO can measure ^{7}Be and ^{8}B neutrinos
- Elastic scattering possible for all neutrino flavors
- Expected rate O(10) ^{8}B events and O(10^4) ^{7}Be events per day
- Study of the MSW effect and the solar metallicity