JUNO experiment and the neutrino mass hierarchy measurement

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GSSI Astroparticle Physics Colloquia

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Neutrino oscillation landscape

Neutrino flavor oscillation induced by quantum mechanics.
Three neutrino flavors in weak interaction CC coupling ν_α (α=e,μ,τ).
ν_α are linear combinations of neutrino mass states νi (i=1,2,3), eigenstates for vacuum propagation.
The mixing matrix is called Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

c=cos ϑ
s=sin ϑ

Majorana phases omitted because unobservable in neutrino oscillations.

Oscillation probability in vacuum:

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) + 2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

Many experiments have observed neutrino oscillations.....
Their results imply that neutrinos are massive with not degenerate masses.

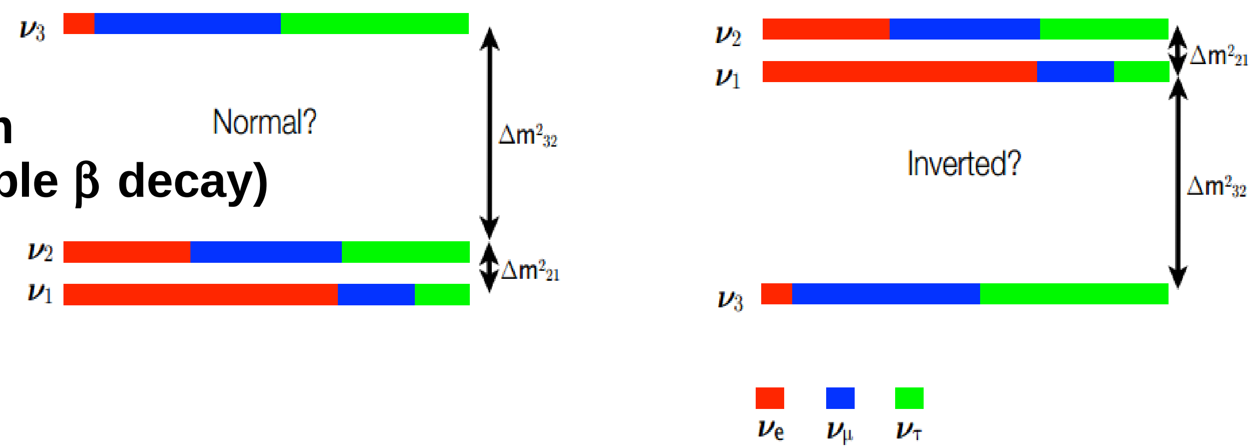
Open issues in neutrino physics

Nowadays, 5 parameters well (few %) measured:

- $\Delta m^2_{21} \approx 7.4\ 10^{-5}\ eV^2$
- $|\Delta m^2_{31}| \approx 2.5\ 10^{-3}\ eV^2$
- $Sin^2\ \theta_{12} \approx 0.3$
- $Sin^2\ \theta_{23} \approx 0.5$
- $Sin^2\ \theta_{13} \approx 0.02$

Global fit papers:
ArXiv 2006.11237 (Valencia group)
ArXiv 2007.14792 (Schwetz, Maltoni et al.)
ArXiv 2107.00532 (Lisi, Capozzi et al.)

Mass hierarchy problem
(connection with neutrinoless double β decay)



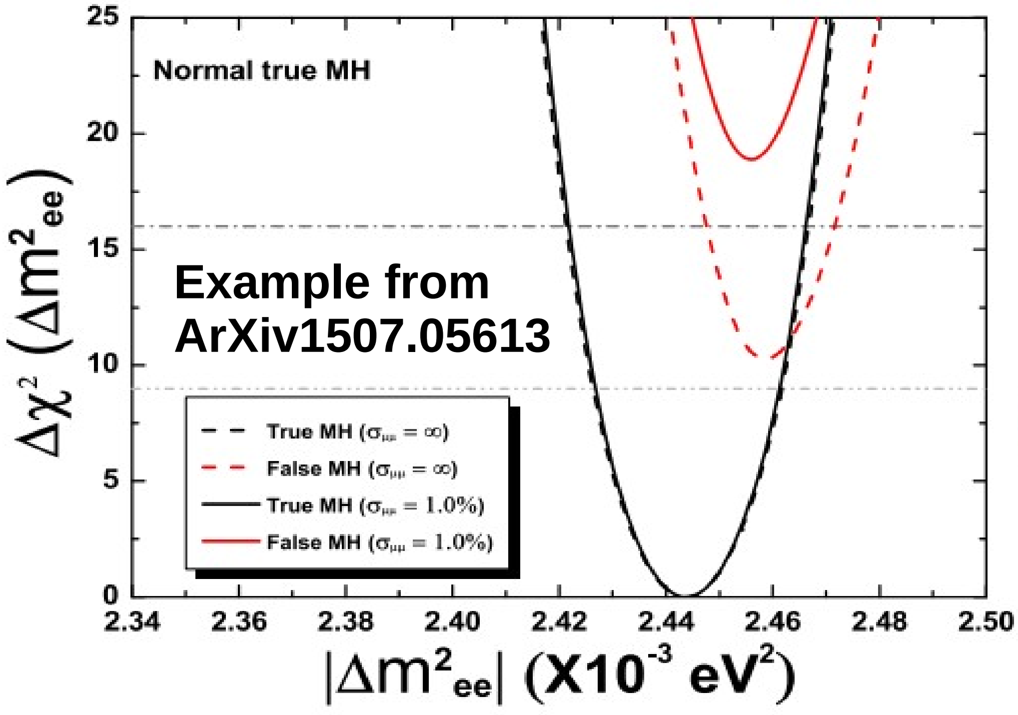
But still open issues:

- **Neutrino mass ordering (normal, inverted) and absolute value?**
- **Mass mechanism and why are so low ?**
- **CP violation (δ) and θ_{23} octant degeneracy ?**
- **Neutrino Dirac or Majorana particle (neutrinoless double β decay) ?**
- **Other BSM physics: sterile neutrinos, Non Standard Interactions, CPT....**

Neutrino mass hierachy measurement

Observe interference effects of oscillations driven by $\pm\Delta m^2_{31}$ and those driven by other quantities of known sign:
1) Δm^2_{21} (medium baseline reactor, as JUNO)
2) $G_F N_e E$ (ν-matter effects in atmospheric and Long-Baseline accelerator experiments).

Fit measured neutrino spectrum for the determination of one (or more) parameter(s) assuming NO or IO, and compare $\chi2_{min}$(IO) with $\chi2_{min}$(NO).



Example from ArXiv1507.05613

Δm^2_{ee} combination of Δm^2_{31} and Δm^2_{32} introduced for reactor neutrino analysis.

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

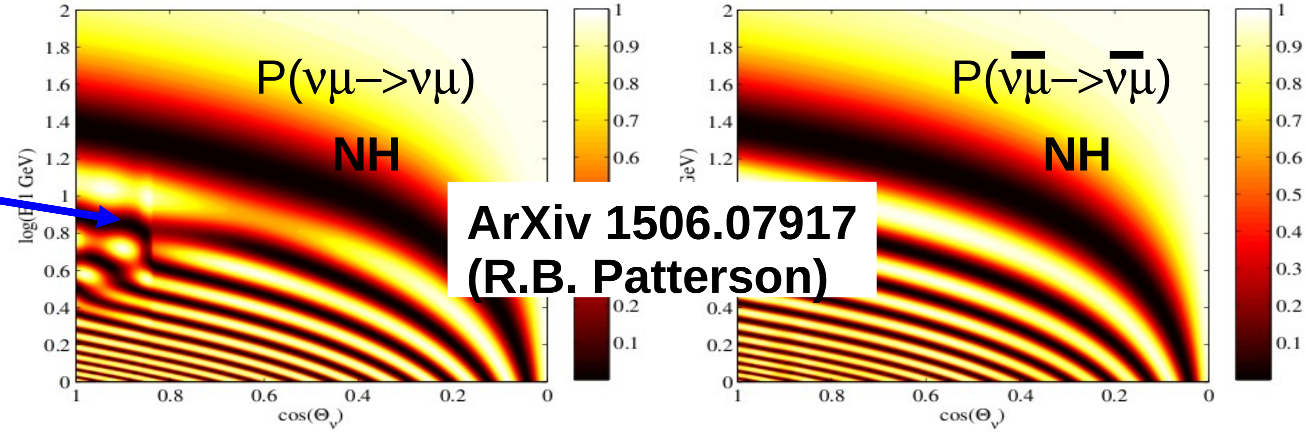
$$|\Delta m^2_{ee}| - |\Delta m^2_{\mu\mu}| = \pm\Delta m^2_{21}(\cos 2\theta_{12} - \sin 2\theta_{12}\sin\theta_{13}\tan\theta_{23}\cos\delta)$$

Sign dependent on NMO

Neutrino mass hierachy measurement

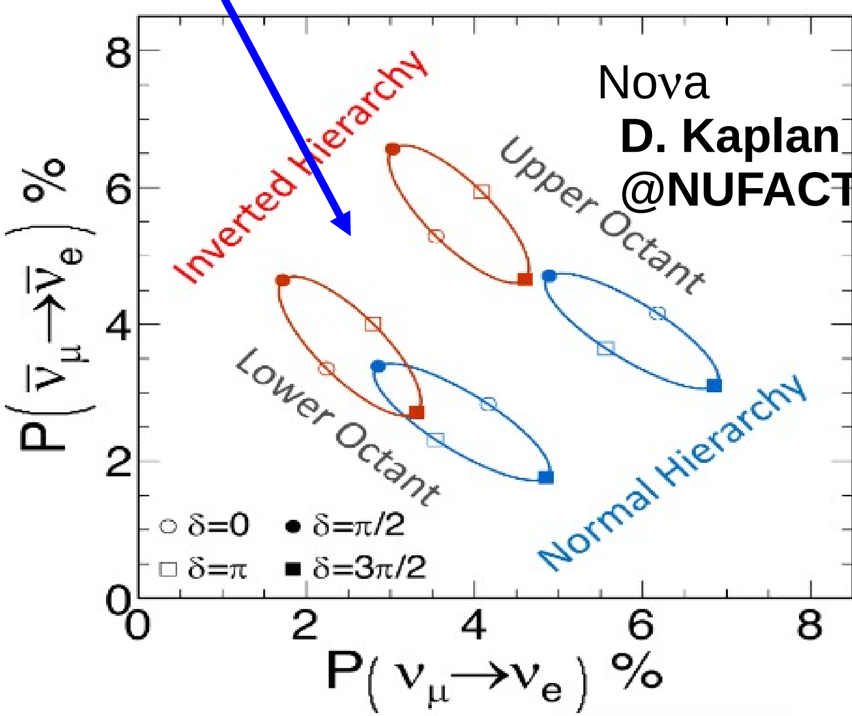
Δm^2_{31} oscillation amplitude interference with Matter Effect or Δm^2_{21} amplitude

Atmospheric neutrinos
Survival probability enhanced for ν_μ in case of NH
(for anti-ν_μ in case of IH)

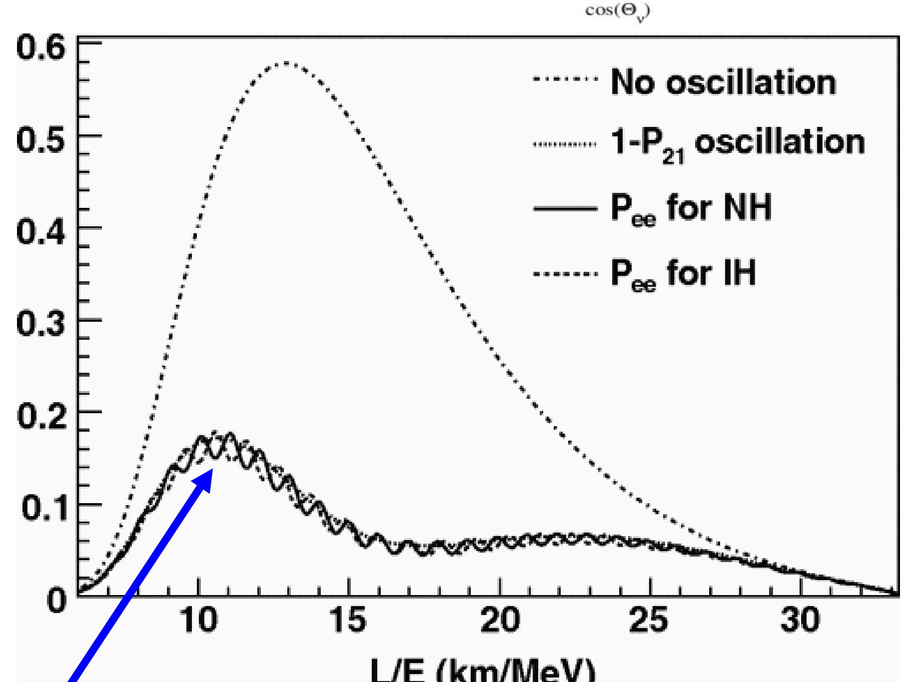


ArXiv 1506.07917
(R.B. Patterson)

Long-Baseline accelerators ν:
Compare oscillations into ν_e and anti–ν_e probability
(Noνa and Dune, L=810 and 1300 km respectively)

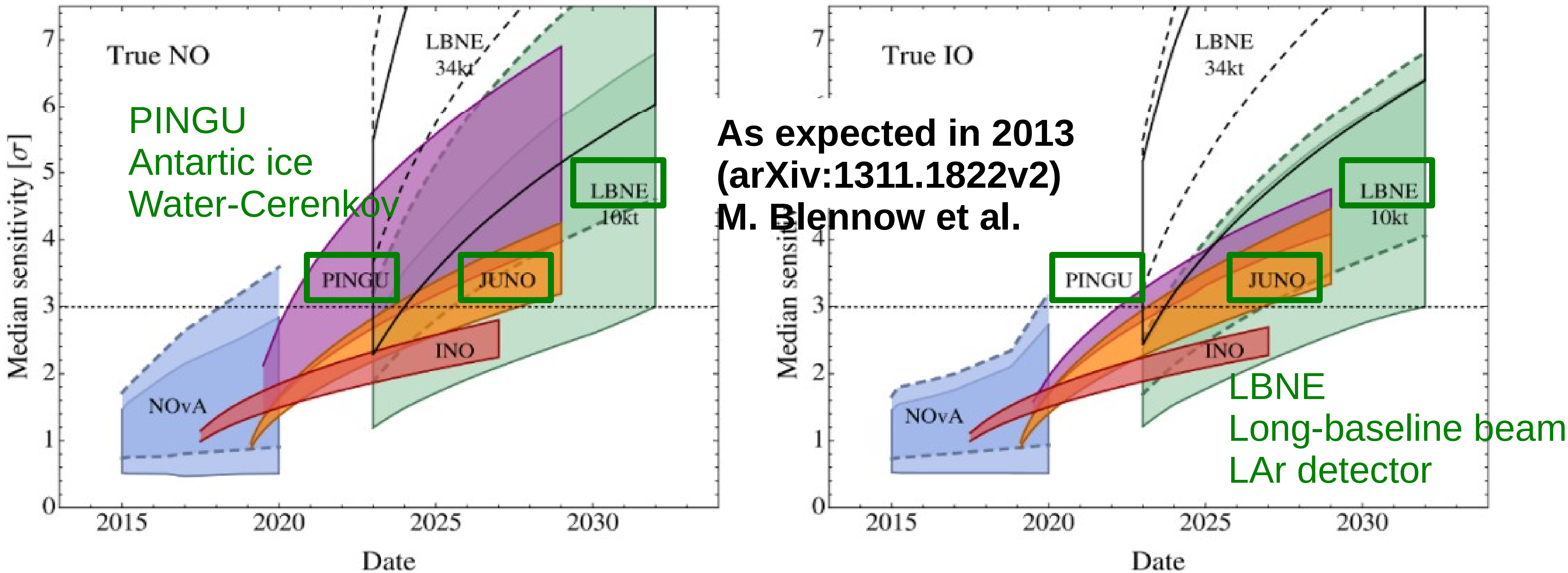


Noνa
D. Kaplan talk @NUFACT2021



Reactor neutrino @ L=50 km (JUNO)
Interference between “solar” and atmospheric oscillations. Independent on θ_{23} and CP phase.
Physics Letters B 533 (2002) 94 (Petcov, Piai)

Neutrino mass hierachy measurement perspectives



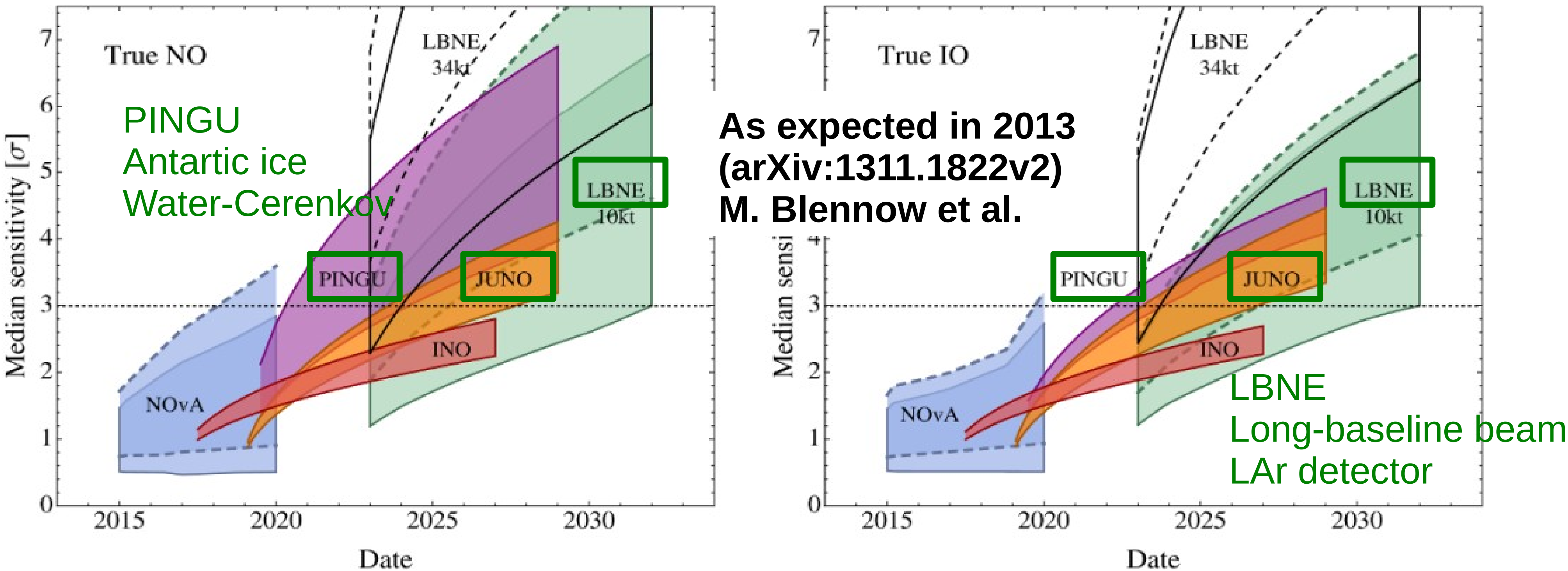
Caveat:

1) **The sensitivities** are from one of the first phenomenological papers on the matter. The sensitivities are estimated by its authors and are **not the ufficial ones from collaborations.**

2) Experiments and starting dates are out-dated. Look only at the NMH sensitivity vs time for different techniques.

3) **NOνA** is running (as **T2K**). **JUNO** fully funded: detector completion before end of 2022. **HyperK/T2HK, ORCA** and **DUNE** approved, but completion foreseen years after JUNO start.

Neutrino mass hierachy measurement perspectives



As expected in 2013 (arXiv:1311.1822v2) M. Blennow et al.

Long baseline experiments: band reflects different δ (CP violation) phase values.
Atmospheric neutrino experiments: band reflects θ_{23} between 40º and 50º.

Asimmetry between Normal and Inverted hierarchy sensitivity.
JUNO: energy resolution between 3% and 3.5% at E=1 MeV (no δ e θ_{23} dependence).

Sinergy JUNO-Atmospheric/Long-Baseline ν_μ disappearance experiments, 5 σ at reach in 2–7 years:
ArXiv:1911.06745 - PINGU+JUNO, ICECUBE upgrade (7 near strings)+JUNO
ArXiv:2108.06293 – ORCA + JUNO
ArXiv:2008.11280 - Juno+NovA+T2K

Nuclear Reactors as antineutrino source

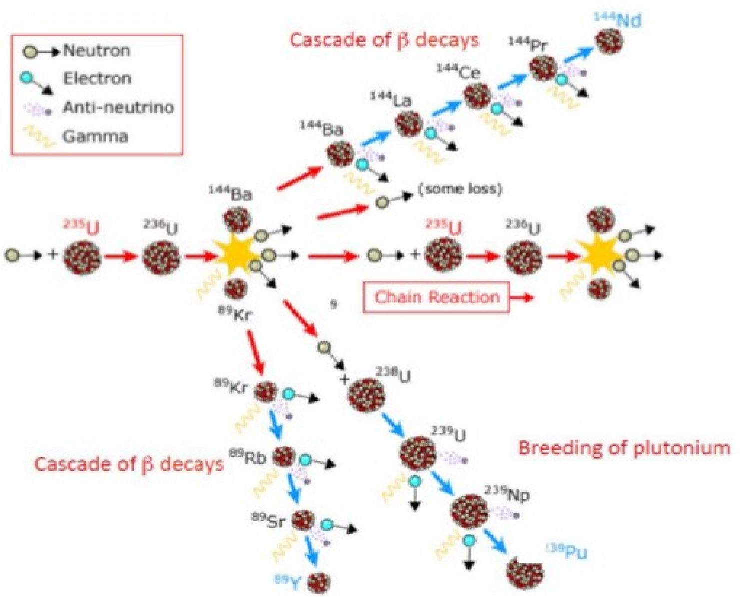
Nuclear reactors are a pure anti-ν_e source from β-decay of fission daughters.

Low energy: E < 10 MeV.

Flux: ≈ 6 anti-ν_e per fission. $2*10^{20}$ anti-ν_e per Gw_{th}.

Commercial reactors are powered with a fuel mixture (^{235}U,^{239}Pu,^{238}U,^{241}Pu).

A precise estimation of anti-ν_e flux on the experimental site requires knowledge of fuel composition evolution in time.



Detected anti-ν_e spectrum:

$$S(E) \sim \sum_j f_j(E) * S_j(E) * P_{ee}(E) * \sigma(E) * \varepsilon(E)$$

$f_j(E)$ = isotope j fission fraction

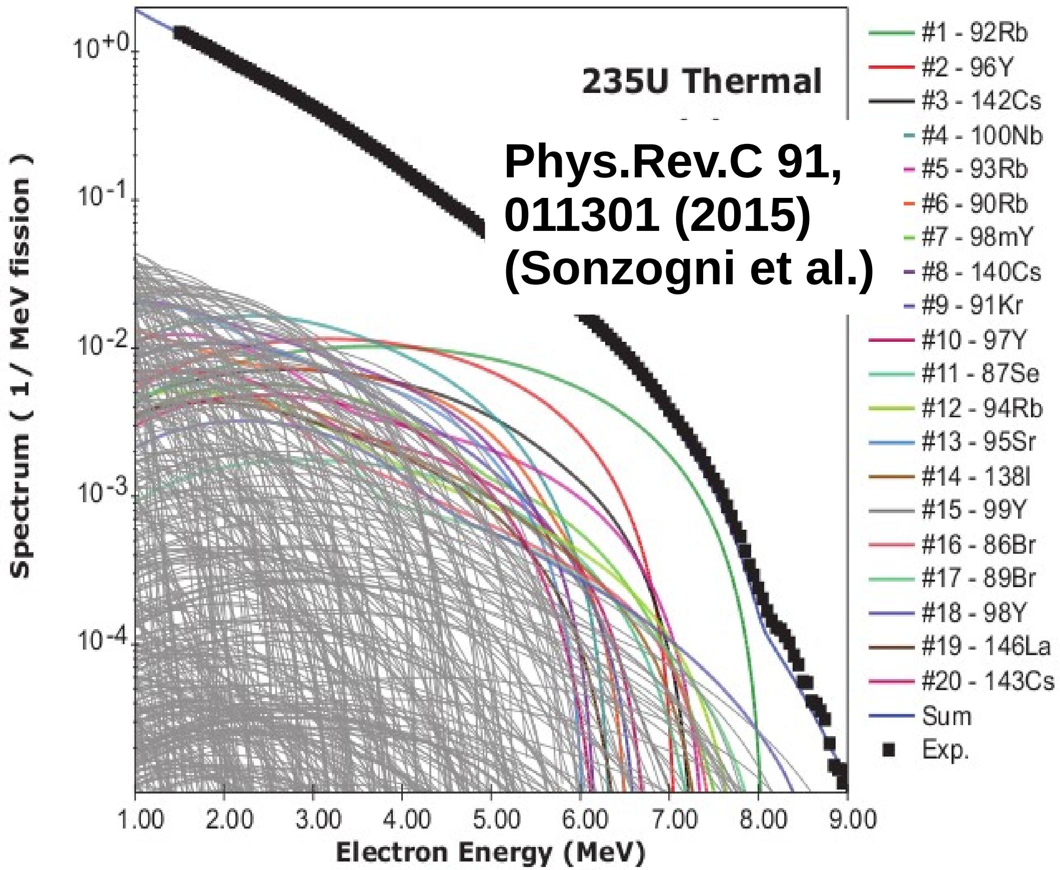
$S_j(E)$ = isotope j fission spectrum

$P_{ee}(E)$ = oscillation survival probability

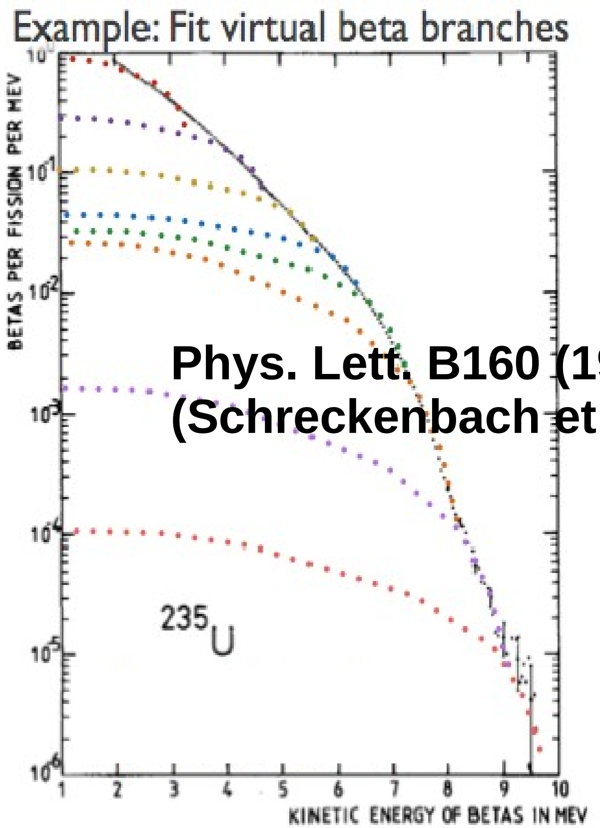
$\sigma(E)$ = Inverse Beta Decay cross section

$\varepsilon(E)$ = selection efficiency

Reactor neutrinos predictions



Phys.Rev.C 91, 011301 (2015) (Sonzogni et al.)



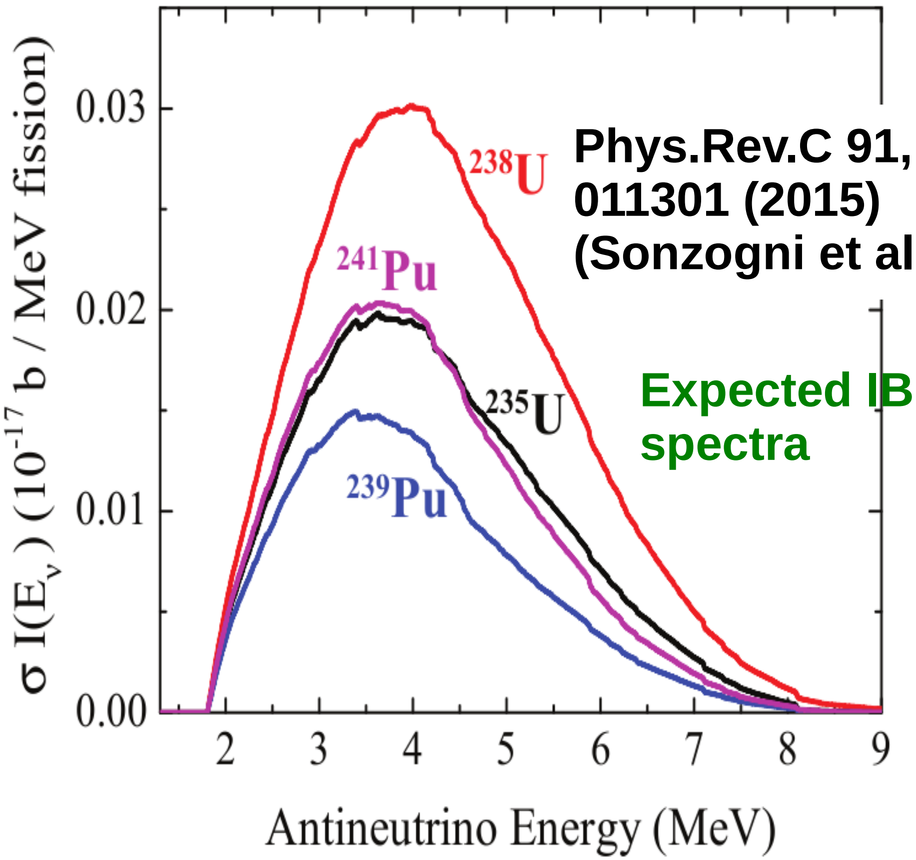
Phys. Lett. B160 (1985) (Schreckenbach et al.)

Summation (ab initio) method:
The spectrum is derived using the nuclear database for thousands of β nuclides.
10% uncertainty.

Conversion method:
Based on measurement of electron energy spectrum, fitted with >30 virtual branches.
2.5% uncertainty.
Used by most reactor neutrino experiments.
Re-analized in 2011 (+5% flux increase).

Other papers (not exhaustive list):
Phys.Rev.C 83 054615 (2011) (Mueller,Lasserre et al.), Phys.Rev.C 84 024617 (2012) (Huber)

Reactor neutrinos predictions



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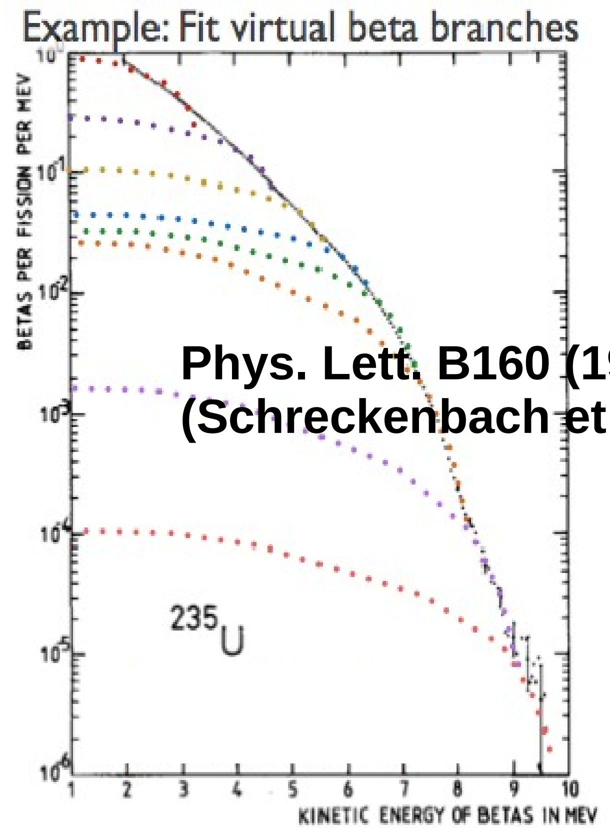
Expected IBD spectra



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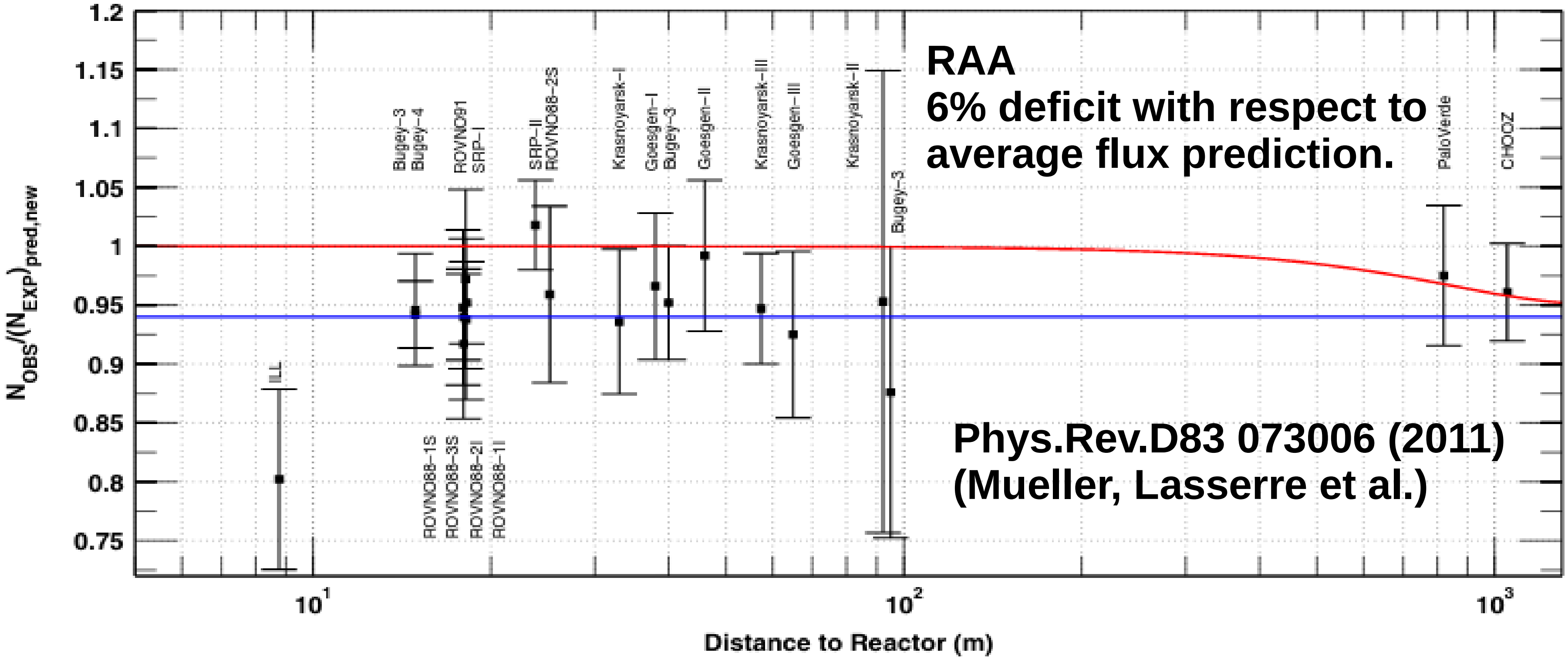
Reactor neutrinos anomalies



Recent reactor neutrino experiments in disagreement with model predictions:

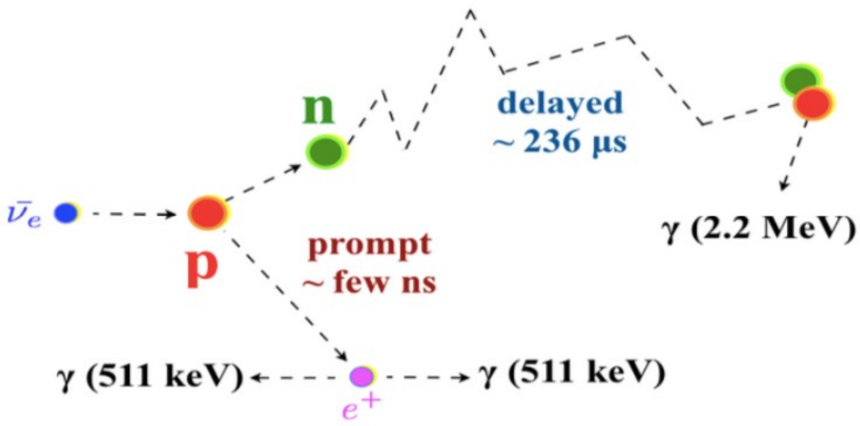
- **Integrated flux deficit: so called Reactor Anti-neutrino Anomaly, RAA. sterile ν ?**
- **Spectral shape difference: 5 MeV bump.**
- **Individual isotope spectra normalization in fuel evolution: from IBD rate vs time.**

Neutrino oscillation measurements safe (near detectors, oscillation pattern).

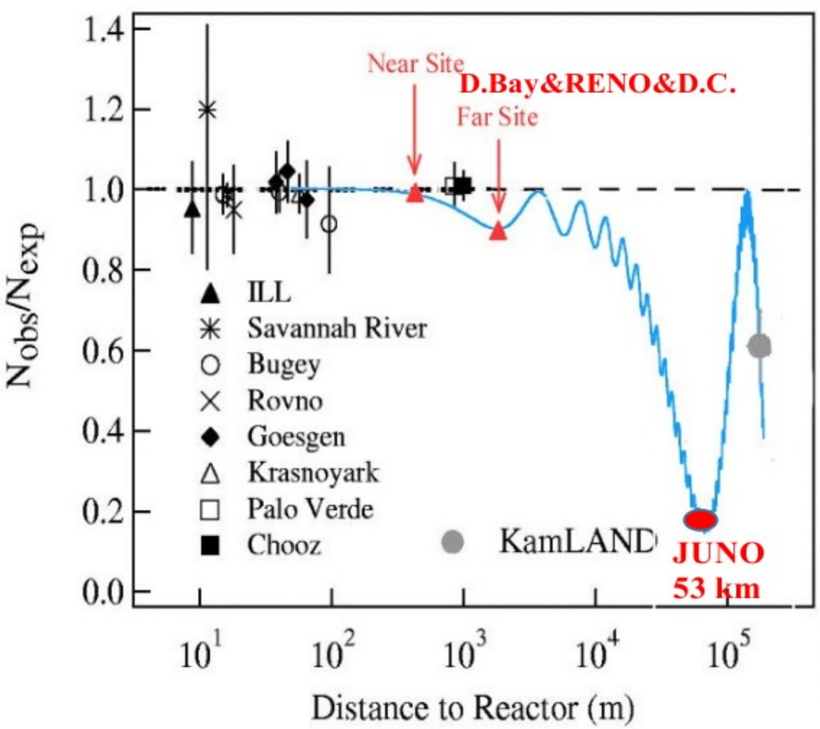
See papers by Daya Bay (largest statistics), RENO, Double CHOOZ and other experiments.
As well as arXiv:2110.06820 (C. Giunti et al.) for a comparison of different model predictions.

Reactor neutrinos IBD

- Antineutrino detection through IBD (Inverse Beta Decay).



- Relatively large cross section
- Background rejection using coincidence between positron (prompt) and neutron (delayed) signals
- $E_{prompt}=E_{\nu} - 0.8$ MeV (neglecting n recoil kinetic energy)



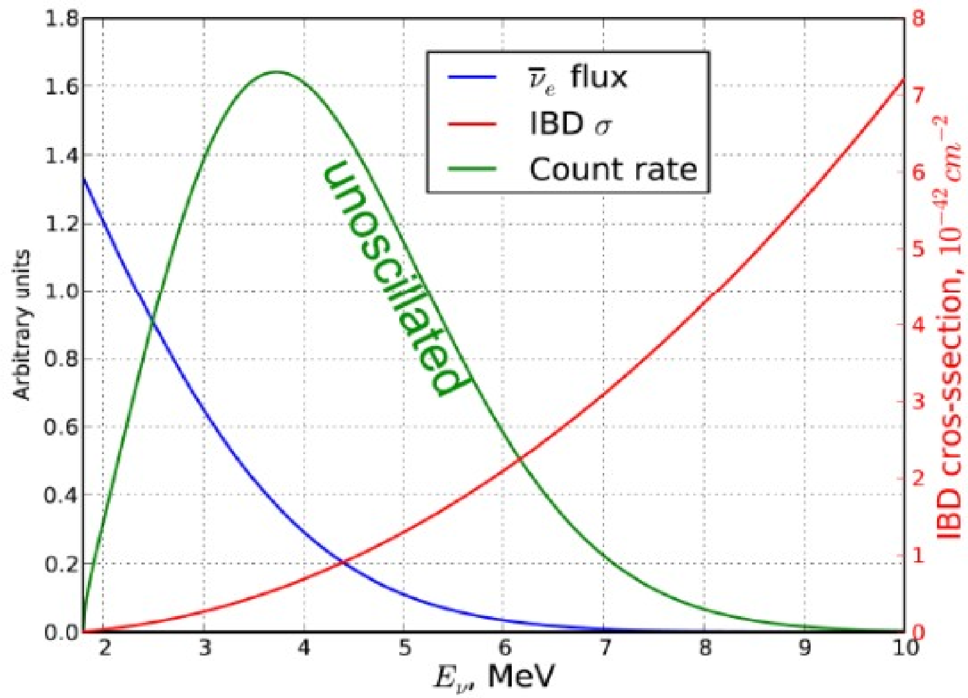
History and perspectives of reactor neutrino physics:
- Neutrino discovery (Reines & Cowan, 1956)
- θ_{12} and Δm^2_{21} meaurement (KamLAND, 2003)
- Precision θ_{13} measurement (Daya Bay, RENO, Double Chooz)
- Neutrino mass hierarchy around the corner (JUNO)

Reactor antineutrino disappearance

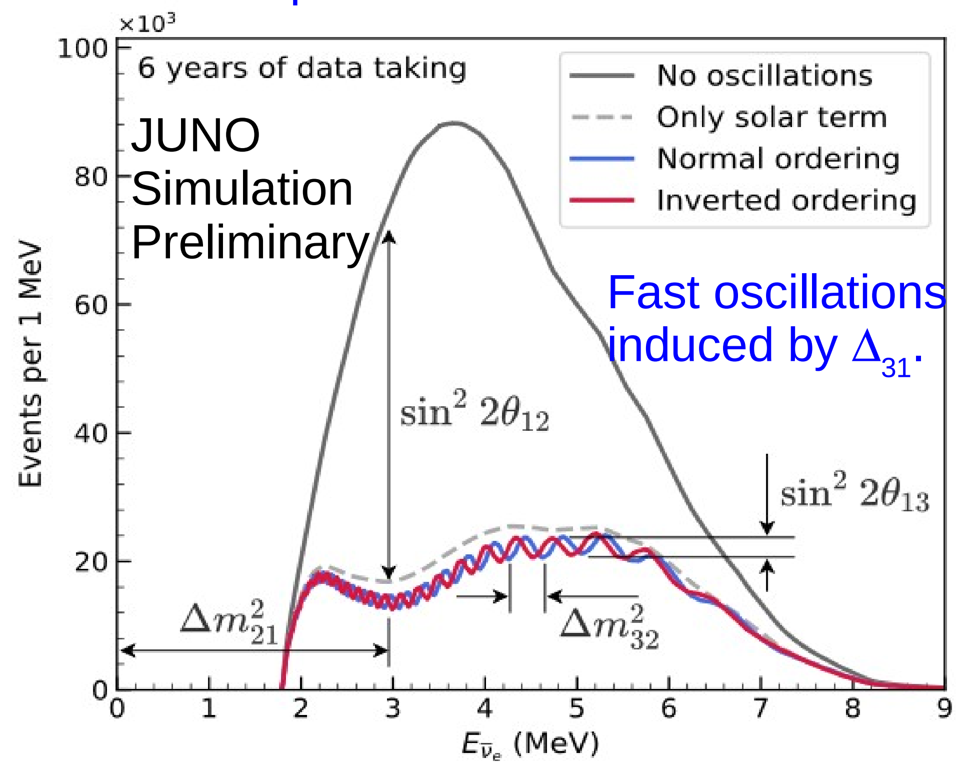
$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32})
\end{aligned}
$$

$$
\begin{aligned}
\Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\
\mathrm{NH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\
\mathrm{IH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}|
\end{aligned}
$$

$\Delta_{ij} = \Delta m^2_{ij}\, L / (4E)$



Antineutrino flux for L=53 km, maximum for solar parameters driven oscillations.



Oscillation probability independent of CPV phase and θ_{23}.

Also matter effect negligible (@L=53 km), at least for NMH measurement.

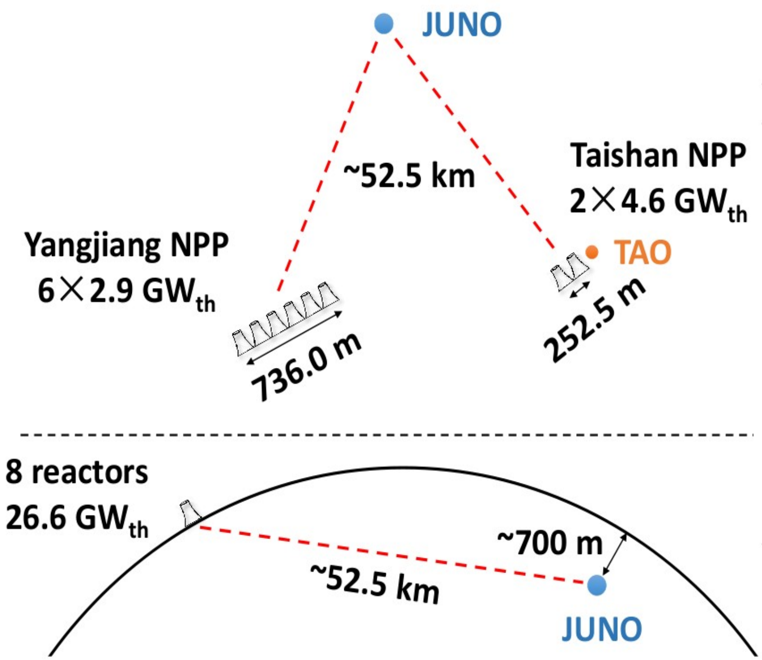
JUNO experiment location

JUNO (Jiangmen Underground Neutrino Observatory) is a multipurpose anti-ν_e detector near Kaiping (South China).

Baseline (≈52.5 km) from Yangjian and Taishan reactors (8 cores) optimized in the region of maximum Δm^2_{21}-driven oscillations.

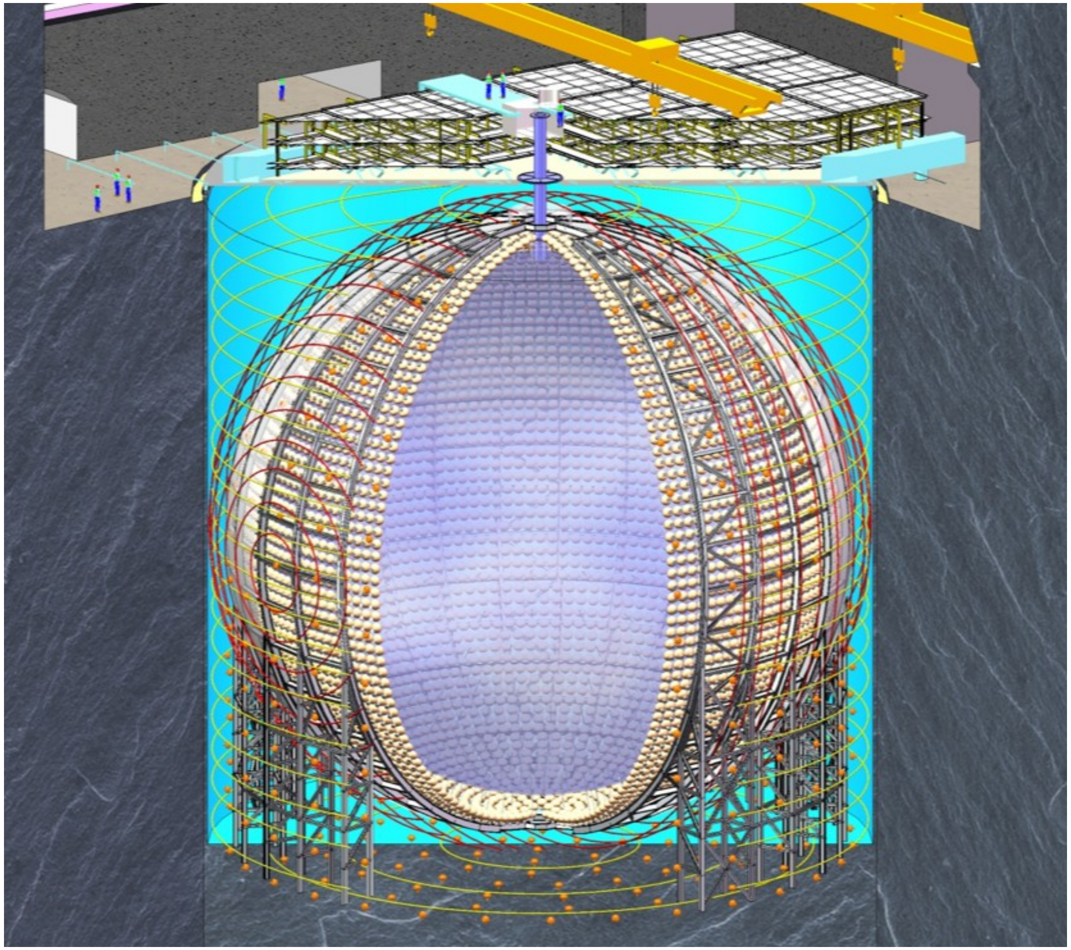
Total power: 26.6 Gwth.

Detector installation expected to finish in 2022.



Reactor	Power (GW_{th})	Baseline (km)	IBD Rate (day^{-1})	Relative Flux (%)
Taishan	9.2	52.71	15.1	32.1
Core 1	4.6	52.77	7.5	16.0
Core 2	4.6	52.64	7.6	16.1
Yangjiang	17.4	52.46	29.0	61.5
Core 1	2.9	52.74	4.8	10.1
Core 2	2.9	52.82	4.7	10.1
Core 3	2.9	52.41	4.8	10.3
Core 4	2.9	52.49	4.8	10.2
Core 5	2.9	52.11	4.9	10.4
Core 6	2.9	52.19	4.9	10.4
Daya Bay	17.4	215	3.0	6.4

JUNO experiment detector concept



10^5 events required in 6 years of data taking: 20 ktons of liquid scintillator in a sphere of about 35 m diameter.

Energy resolution 3%/√E(MeV):

- High liquid scintillator light yield and transparency.
- High photocatode coverage and photon detection efficiency.

Energy scale uncertainty < 1%:

- Calibration systems
- Stereo-calorimetry

JUNO will be the largest scintillator detector ever built !

Experiment	Daya Bay	Borexino	KamLAND	JUNO
LS mass (tons)	20 /detector	~300	~1,000	20,000
Nb of collected p.e. per MeV	~160	~500	~250	~1200
Energy resolution @ 1 MeV	~7.5%	~5%	~6%	~3%

JUNO Collaboration

Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	IMP-CAS	Germany	FZJ-IKP
Belgium	Universite libre de Bruxelles	China	SYSU	Germany	U. Mainz
Brazil	PUC	China	Tsinghua U.	Germany	U. Tuebingen
Brazil	UEL	China	UCAS	Italy	INFN Catania
Chile	PCUC	China	USTC	Italy	INFN di Frascati
Chile	SAPHIR	China	U. of South China	Italy	INFN-Ferrara
China	BISEE	China	Wu Yi U.	Italy	INFN-Milano
China	Beijing Normal U.	China	Wuhan U.	Italy	INFN-Milano Bicocca
China	CAGS	China	Xi'an JT U.	Italy	INFN-Padova
China	ChongQing University	China	Xiamen University	Italy	INFN-Perugia
China	CIAE	China	Zhengzhou U.	Italy	INFN-Roma 3
China	DGUT	China	NUDT	Latvia	IECS
China	ECUST	China	CUG-Beijing	Pakistan	PINSTECH (PAEC)
China	Guangxi U.	China	ECUT-Nanchang City	Russia	INR Moscow
China	Harbin Institute of Technology	Croatia	UZ/RBI	Russia	JINR
China	IHEP	Czech	Charles U.	Russia	MSU
China	Jilin U.	Finland	University of Jyvaskyla	Slovakia	FMPICU
China	Jinan U.	France	IJCLab Orsay	Taiwan-China	National Chiao-Tung U.
China	Nanjing U.	France	CENBG Bordeaux	Taiwan-China	National Taiwan U.
China	Nankai U.	France	CPPM Marseille	Taiwan-China	National United U.
China	NCEPU	France	IPHC Strasbourg	Thailand	NARIT
China	Pekin U.	France	Subatech Nantes	Thailand	PPRLCU
China	Shandong U.	Germany	FZJ-ZEA	Thailand	SUT
China	Shanghai JT U.	Germany	RWTH Aachen U.	USA	UMD-G
China	IGG-Beijing	Germany	TUM	USA	UC Irvine
China	IGG-Wuhan	Germany	U. Hamburg		

Collaboration established in 2014.
At present 77 institutions, more than 600 collaborators.

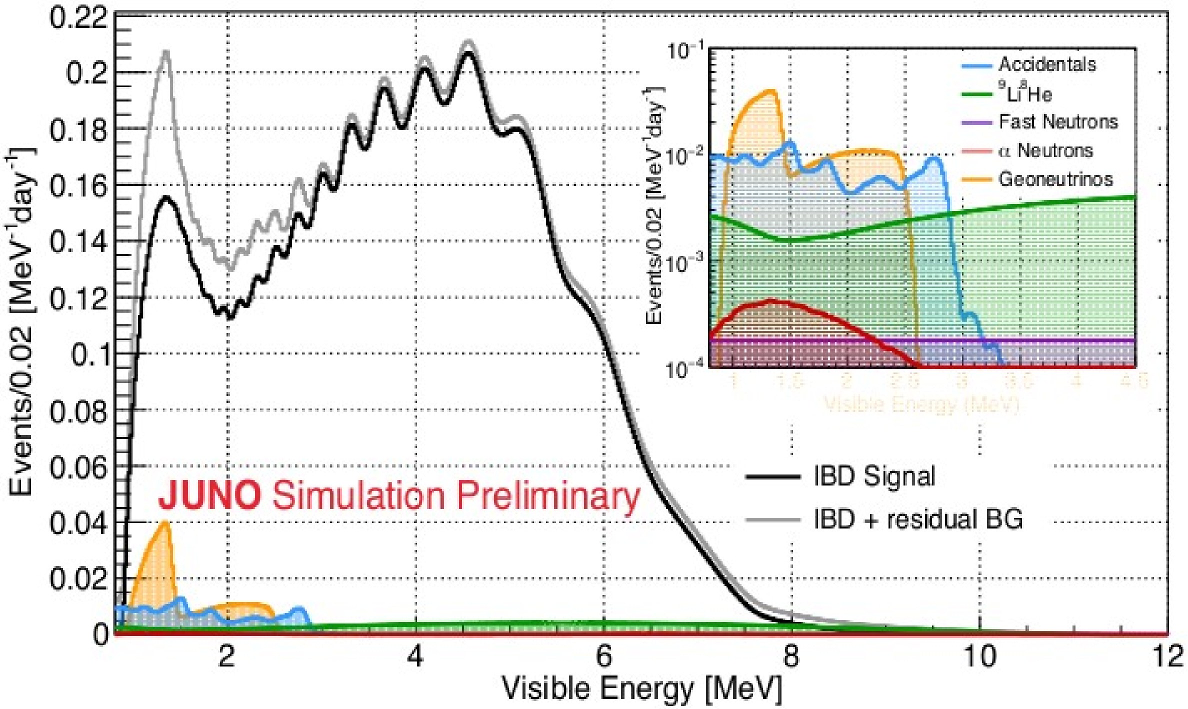
JUNO signal and background

Preliminary selection cuts:

- Fiducial volume: R<17.2 m
- Prompt energy: 0.7 MeV < E_p < 12 MeV
- Delayed energy: 1.9 MeV < E_d < 2.5 MeV
- Prompt-delayed time difference: ΔT < 1 ms
- Prompt-delayed distance: ΔR < 1.5 m
- Muon VETO criteria for rejection of cosmogenic ^{9}Li/^{8}He background.

	Efficiency (%)	IBD Rate (day^{-1})
All IBDs	100	57.4
After Selection	82.2	47.1

JUNO simulation preliminary



After selection cuts:

Background	Rate (day^{-1})
Geo-neutrinos	1.2
Accidentals	0.8
^{9}Li/^{8}He	1.4
Fast neutrons	0.1
^{13}C(α,n)^{16}O	0.05

JUNO simulation preliminary

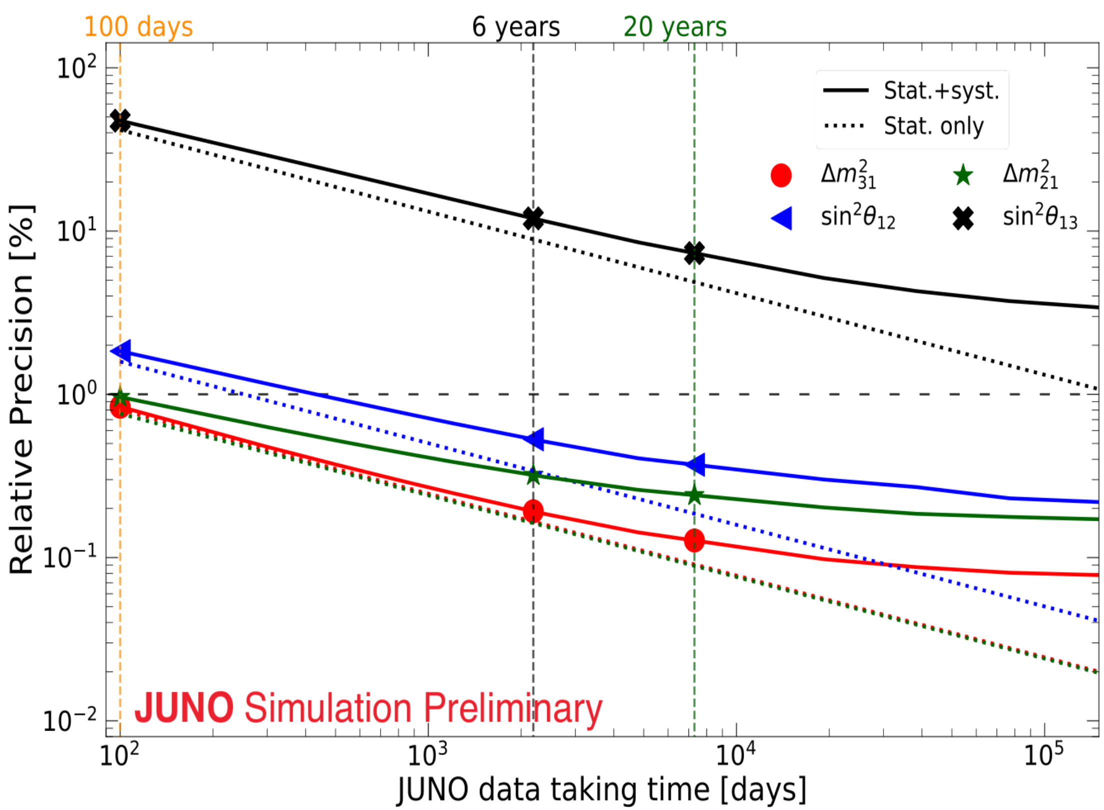
JUNO Physics reach (1)

JUNO designed to reach better than 3 σ precision on MH determination.
But also other measurements possible:

- Oscillation parameters determination (θ_{12}, Δm^2_{21}, Δm^2_{31}) at sub-% level (limited by systematics).

	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
JUNO 6 years	∼0.2%	∼0.3%	∼0.5%	∼12%
PDG2020	1.4%	2.4%	4.2%	3.2%

JUNO simulation preliminary



Sub% systematics effects:

- **Flux knowledge precision**
- **Multiple core distances (and Daya Bay anti-ν_e)**
- **IBD neutron recoil in energy reconstruction**
- **Matter effect in neutrino propagation**

See arXiv:2006.01648 (Capozzi,Lisi,Marrone)

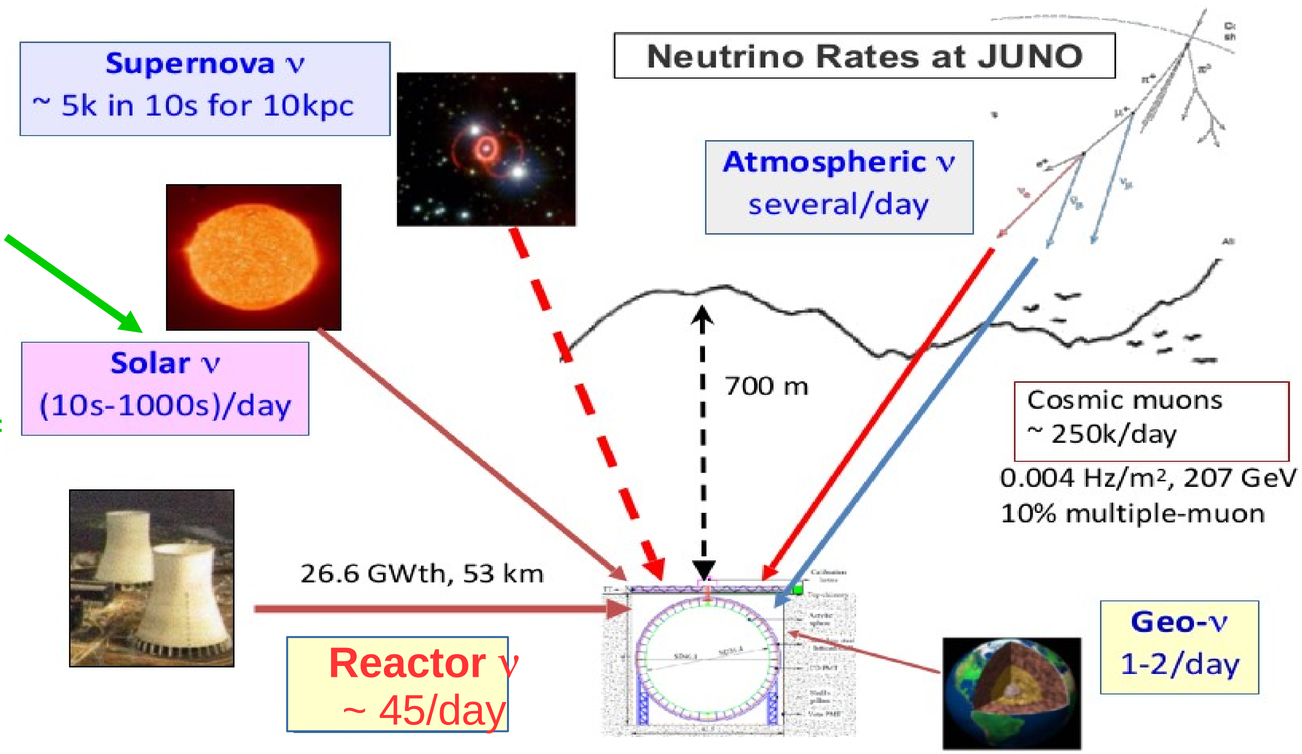
JUNO Physics reach (2)

JUNO designed to reach better than 3 σ precision on MH determination.
But also other measurements possible:

- Oscillation parameters determination (θ_{12}, Δm^2_{21}, Δm^2_{31}) at sub-% level.
- Neutrino observation from natural sources and exotic searches (Lorentz-Invariance-Violation, Proton decay).

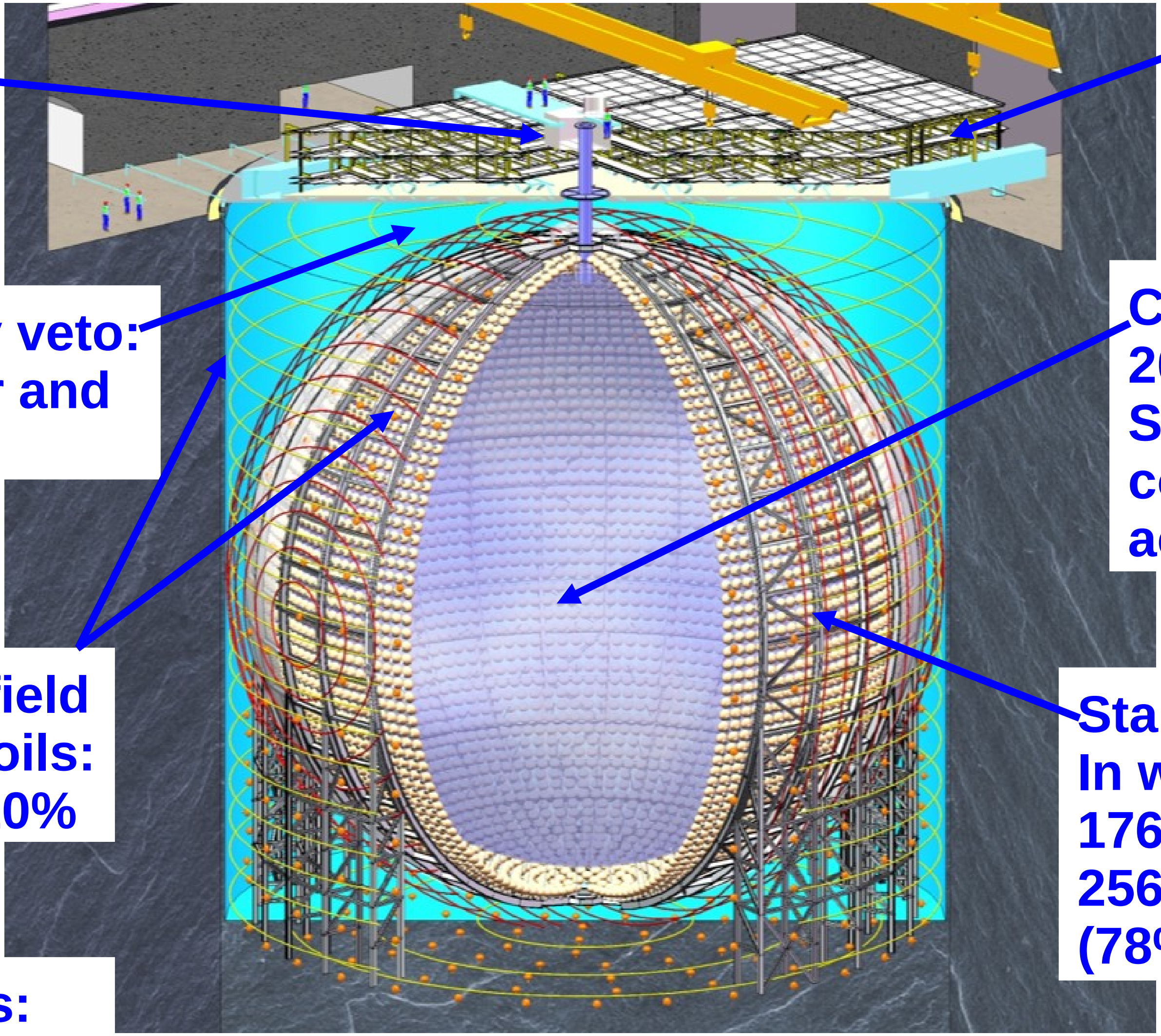
More details in J. Phys. G43 (2016) n.3, 030401
8B Solar neutrino paper: Chin. Phys. C45 (2021)
Atmospheric neutrino paper: Eur. Phys. J. C 81 (2021) 887

Interesting opportunities for solar neutrino measurements (also at low energies depending on reached liquid scintillator purity).
Independent measurement of solar neutrino oscillation parameters measurement.



JUNO Experiment

700 m overburden



Calibration box

Top Tracker:
3 layers of plastic scintillator strips (from OPERA)

Water Cerenkov veto:
35 kton of water and 2400 20” PMTs

Central detector:
20 kton of Liquid Scintillator contained inside an acrylic sphere.

Earth magnetic field compensating coils:
residual field < 10%

Stainless Steel Truss:
In water, holding 17612 20” PMTs 25600 3” PMTs (78% photo-coverage)

Pool dimensions:
- **Height 44 m**
- **Diameter 43.5 m**

JUNO CDR: arXiv:1508.07166 (2015)
Update in arXiv:2104.02565

Civil engineering status

External campus 28 January 2021

Water pool 30 September 2021

Liquid scintillator

JUNO liquid scintillator composition: LAB + PPO (2.5 g/l) + bis-MSB (3 mg/l)

LAB/scintillator purification in four steps:

- Al_2O_3 filtration column (optical properties improvement)
- Distillation (heavy elements removal/transparency improvement)
- Water extraction (U/Th/K radioisotopes removal)
- Steam/Nitrogen stripping (Gaseous impurities -Ar,Kr,Rn- removal)

Dedicated underground detector (OSIRIS) for purity measurement

Underground

Radiopurity requirements:

- **Reactor neutrinos**

$^{238}U/^{232}Th < 10^{-15}$ g/g

$^{40}K < 10^{-16}$ g/g

$^{210}Pb < 10^{-22}$ g/g

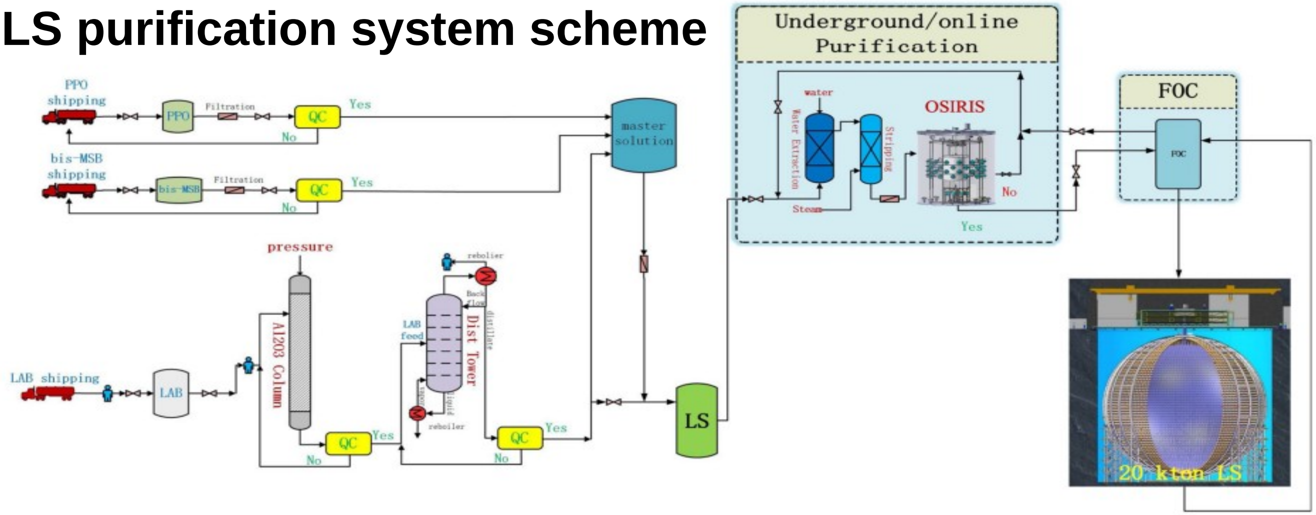
- **Solar neutrinos**

$^{238}U/^{232}Th < 10^{-17}$ g/g

$^{40}K < 10^{-18}$ g/g

$^{210}Pb < 10^{-24}$ g/g

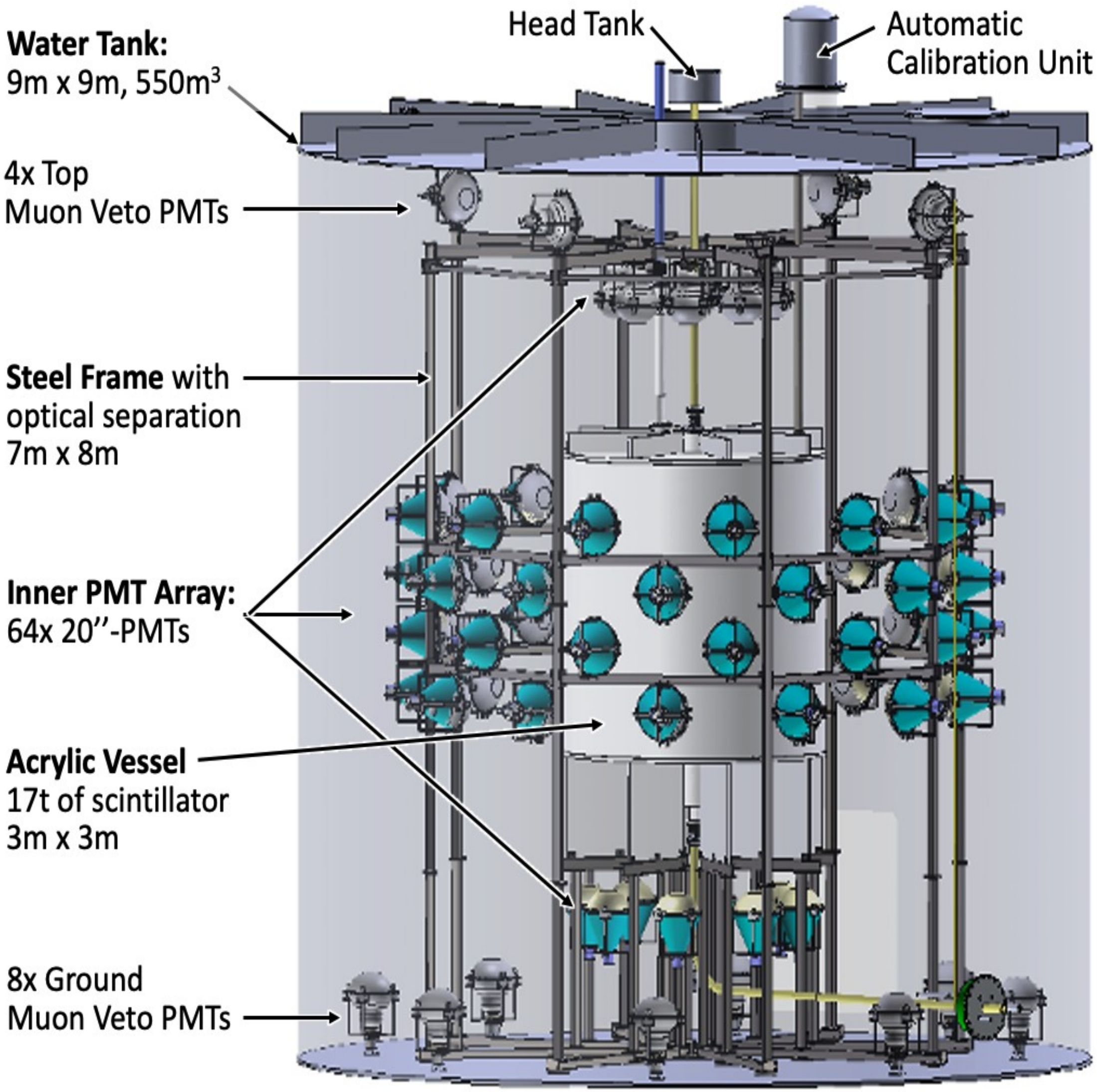
LS purification system scheme



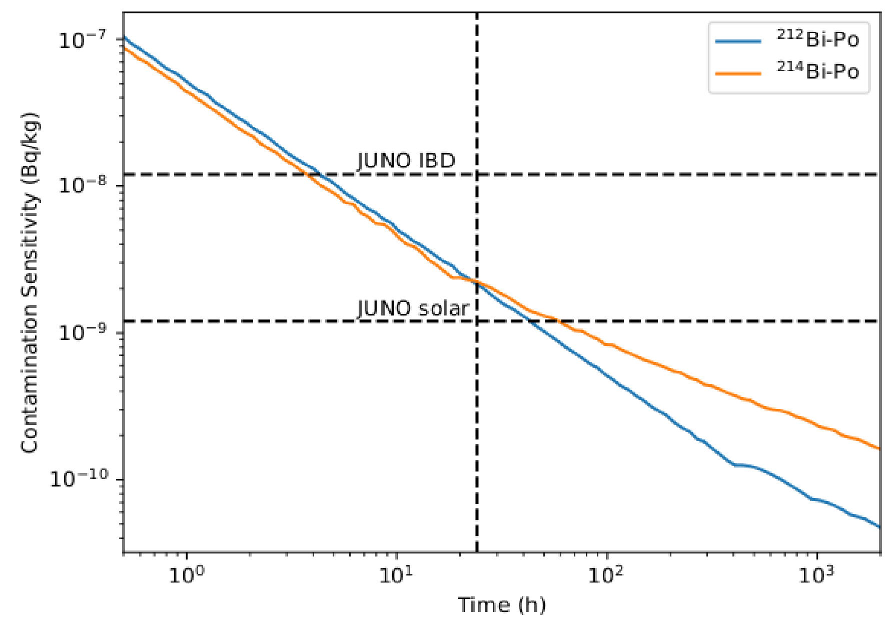
See also NIMA 988, 164823 (2021)

OSIRIS Detector

Online Scintillator Internal Radioactivity Investigation System



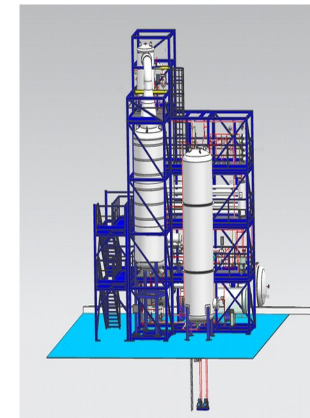
- **Exploits fast coincidences in the U/Th chains.**
- **Few hours needed to verify compliance to JUNO IBD requirements**



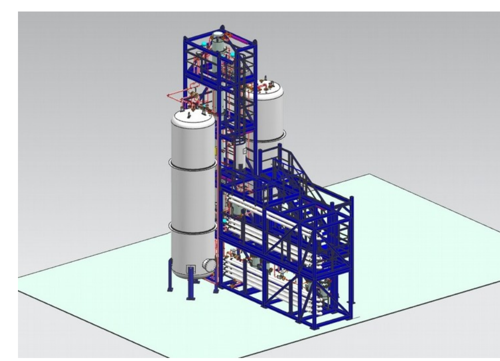
See also Eur. Phys. J. C (2021) 81:973

Liquid scintillator facilities status

Distillation system assembly



Stripping system assembly



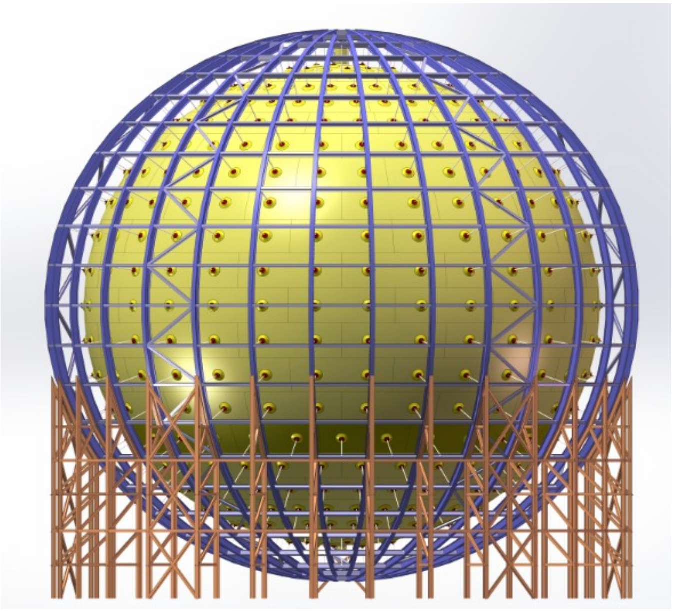
LS ground hall, LN2 towers and 5 kt LAB tank ready on external laboratory.
First LAB batches delivered.
Al_2O_3 filtration plant installed.

Distillation and stripping plants delivered.
Installation of underground systems ready to start.

Central detector: steel truss and acrylic vessel

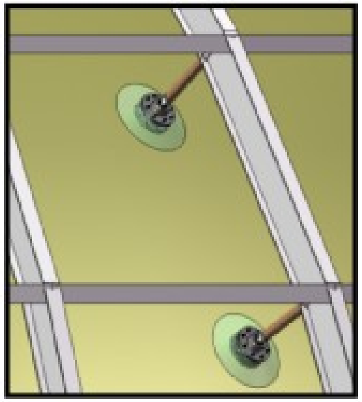
The Stainless Steel Structure is connected to the acrylic vessel and it is the support of the PMTs.

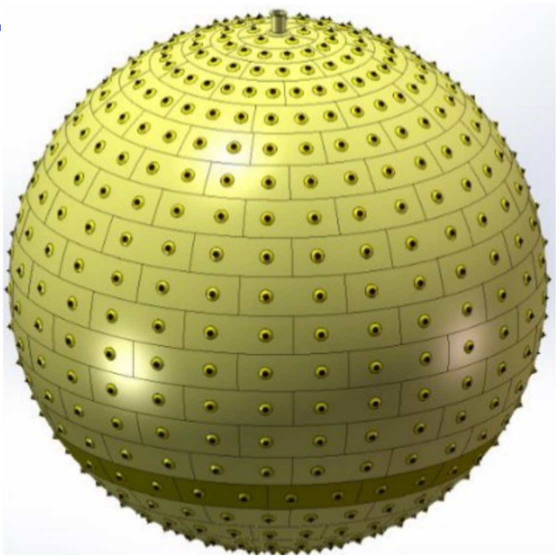
- Rooted on the water pool concrete floor
- Supporting bars to hold the acrylic vessel
- Mechanical precision for 3 mm PMT clearance
- Earthquake safe structure
- Steel radiopurity U/Th/K ≤ ppb



The acrylic vessel built by bulk polymerization of 265 panels (12 cm thickness) for a total weight around 600 tons.

- Maximal stress < 3.5 MPa
- Thermal expansion matching: 21 ^{o}C ± 1 ^{o}C
- Transparency > 96%
- Acrylic radiopurity U/Th/K < 1 ppt

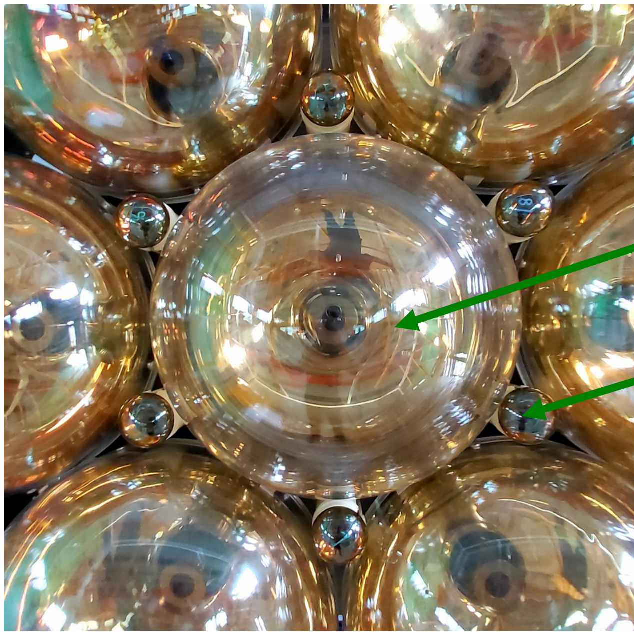




See JHEP11 (2021) 102
for radioactvity control strategy in JUNO.

Large PMT system

JUNO will use 20” Photomultipliers as its main photodetection system.
Water-proof potting (voltage divider) and implosion protection.

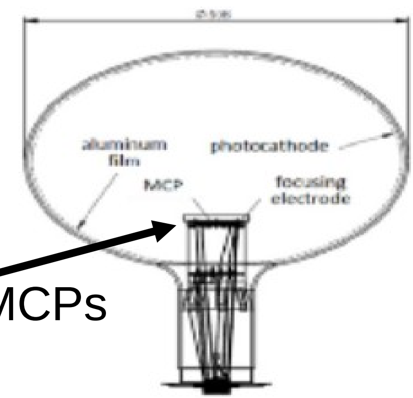


Tight arrangement with photocatode coverage > 75% (78% including Small PMTs).

Large PMT

Small PMT

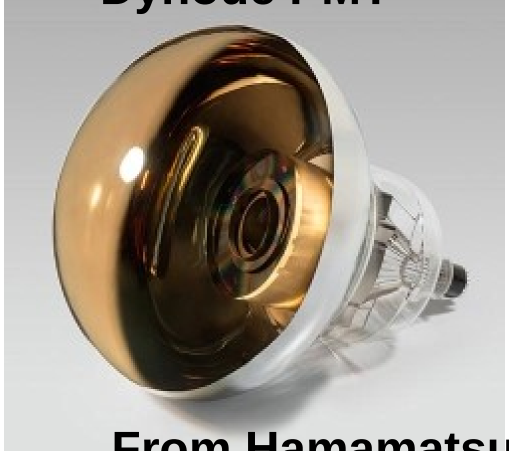
MCP-PMT

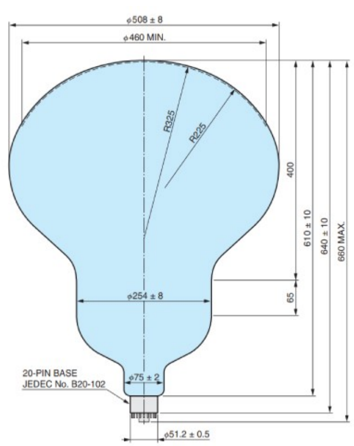


2 Horizontal MCPs

NIMA 971 (2020) 164021

Dynode PMT





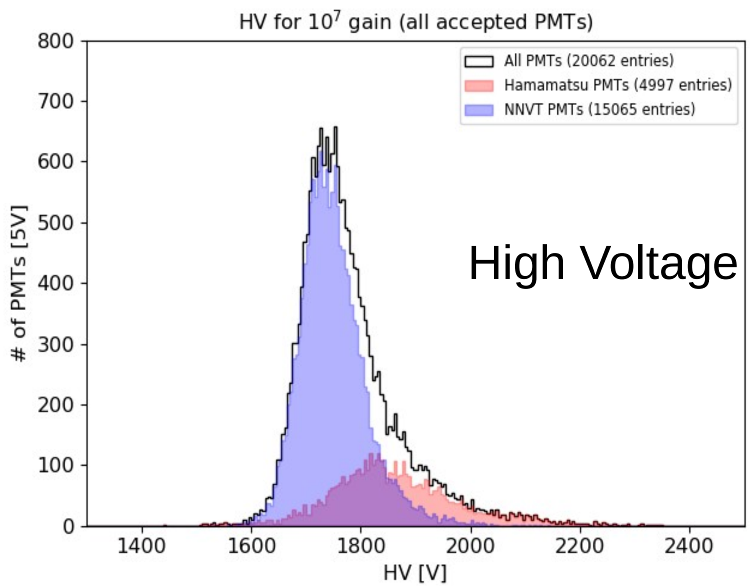
From Hamamatsu R12860 datasheet

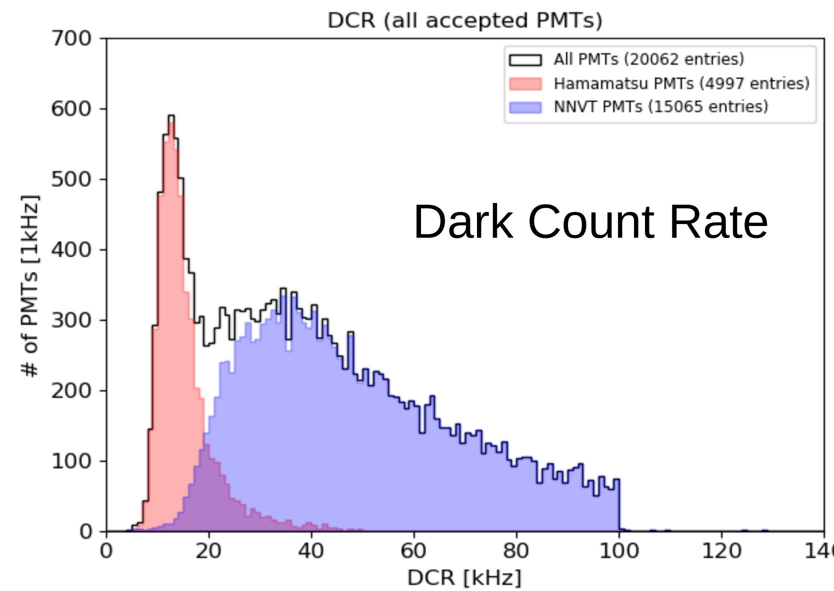
Two complementary LPMT technologies:

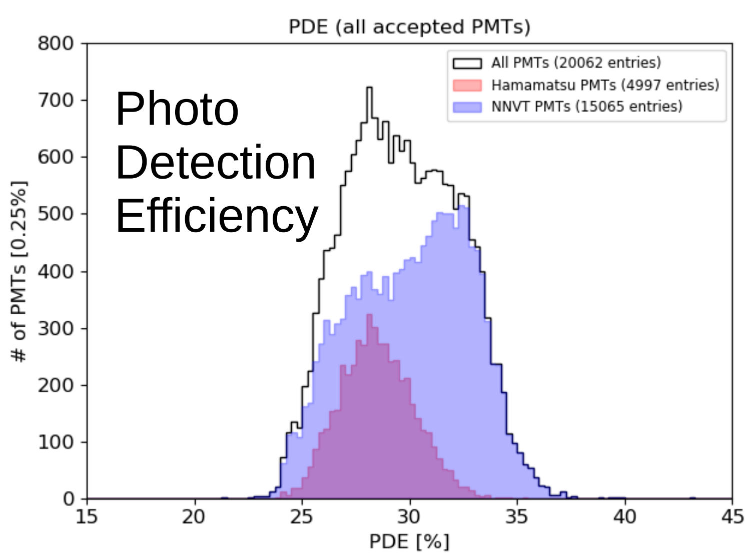
- **15000 MCP-PMTs** from NNVT (Microchannel plates) with larger PhotoDetection Efficiency (energy measurement)
- **5000 dynode PMTs** from Hamamatsu with better Transit Time Spread (vertex reconstruction and tracking in Central Detector)

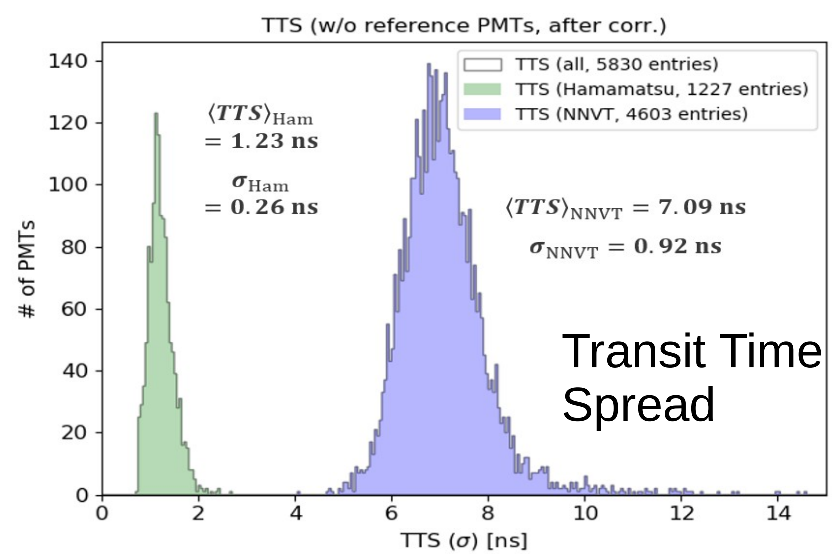
Large PMT performances

Large PMT production and testing at PanAsia facility (ZhongShan) finished.
Design PDE value (critical for mass ordering measurement) reached.







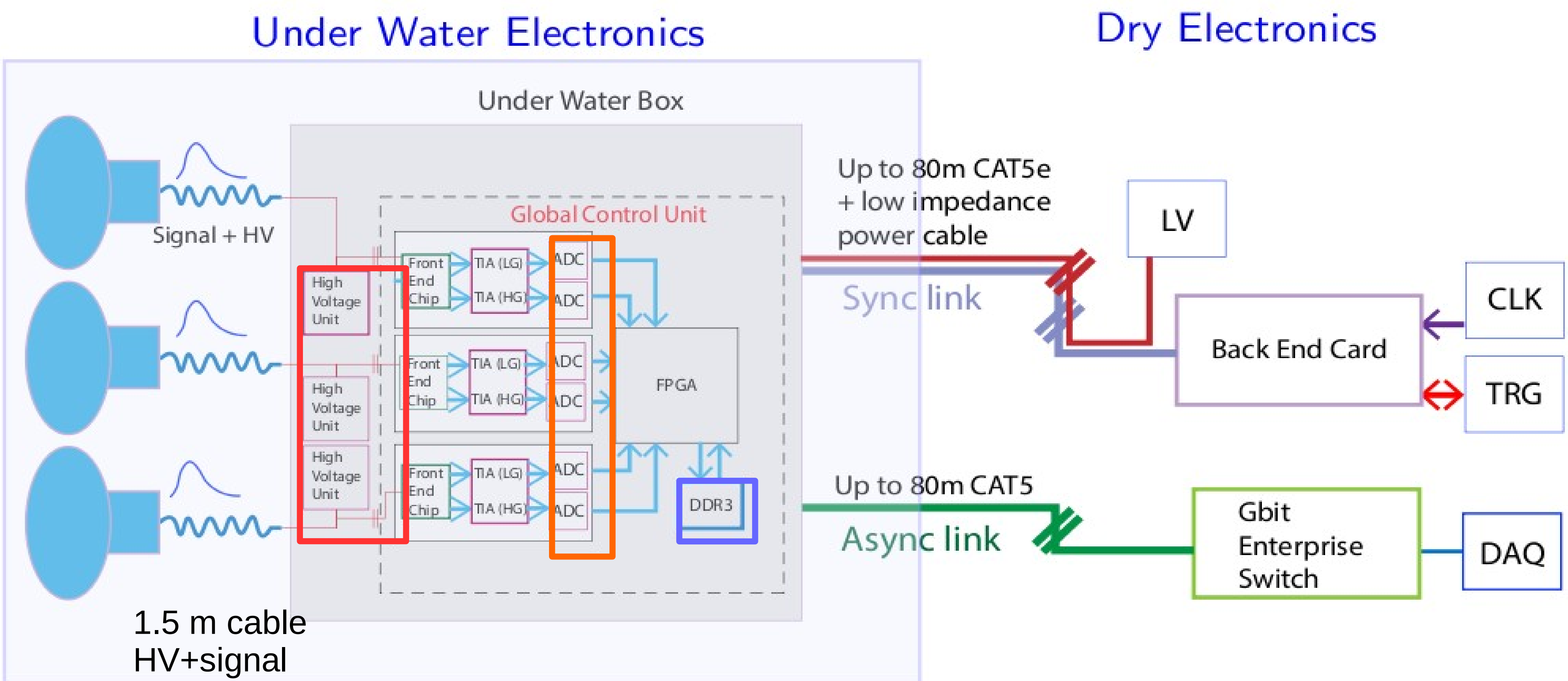


Large PMT electronics

The Large PMTs are read-out with full waveform digitization and operated (HV setting) independently. The signal is digitized near the voltage divider.

Dynamic range: 1-4000 pe
Noise: 10% @ 1 pe

Resolution: 10% @ pe , 1% @ 100 pe
Failure rate: <0.5% over 6 years



Custom HV-unit
0-3kV/300 µA

Custom ADC
12 bit/1 Gsps

2 GB RAM
For SN burst

Small PMT system

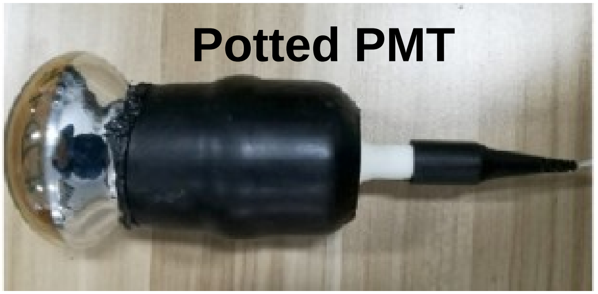
JUNO will use also 3-inch PMTs as a complementary photo-detection system to improve the control of systematics and increase the dynamic range in photon-counting mode.

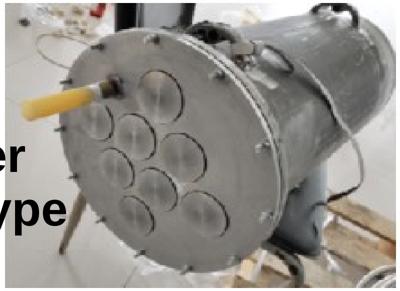
25600 PMTs from HZC company (Hainan, PR China). Production and test completed.

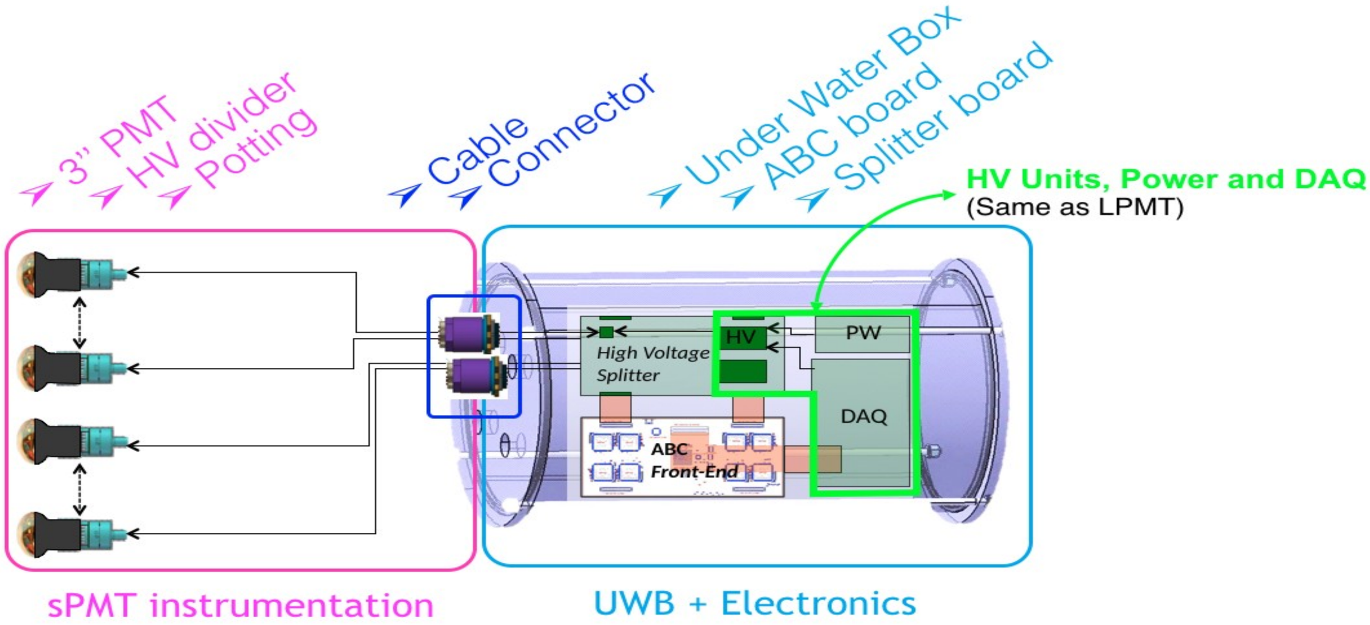
128 PMTs connected to one underwater box, to reduce the electronics channel number. FE electronics based on CATIROC chip.

Independent physics measurements:

- Muon tracking (+ shower muon calorimetry)
- Solar neutrino oscillation parameters measurements
- Supernovae neutrino read-out

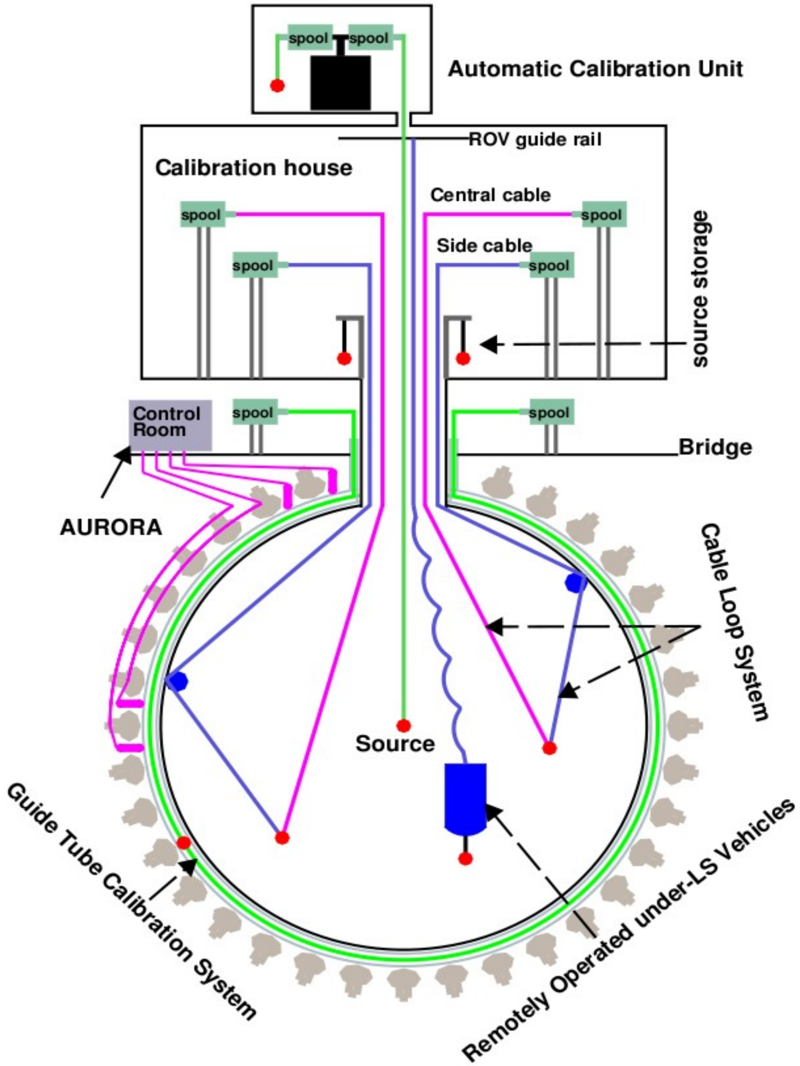






Calibration system

To keep energy scale uncertainty below 1%, **four calibration systems**:
Automatic Calibration Unit (ACU): 1D along z-axis.
Cable Loop System (CLS): 2D plane inside vessel.
Guide Tube (GT): 2D plane inside vessel.
Remotely Operated Vehicle (ROV): 3D anywhere inside vessel.



Source list

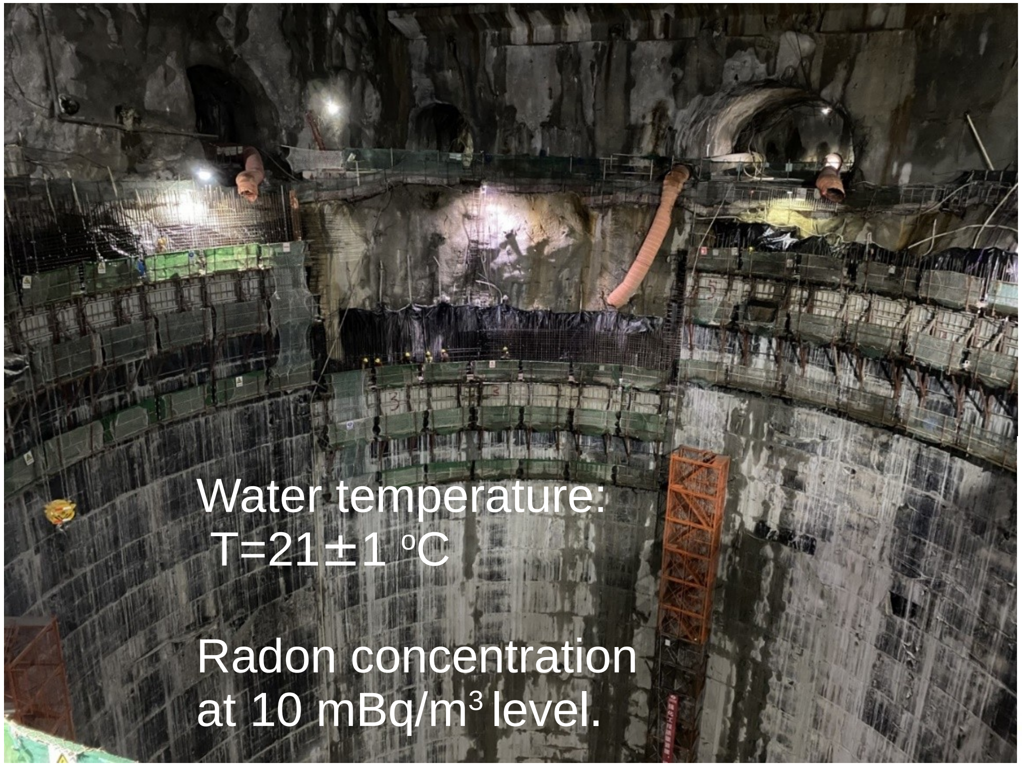
Sources/Processes	Type	Radiation
^{137}Cs	γ	0.662 MeV
^{54}Mn	γ	0.835 MeV
^{60}Co	γ	1.173 + 1.333 MeV
^{40}K	γ	1.461 MeV
^{68}Ge	e^+	annihilation 0.511 + 0.511 MeV
^{241}Am-Be	n, γ	neutron + 4.43 MeV (^{12}C*)
^{241}Am-^{13}C	n, γ	neutron + 6.13 MeV (^{16}O*)
(n,γ)p	γ	2.22 MeV
(n,γ)^{12}C	γ	4.94 MeV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

System strategy:
- Different sources (LS non-linearity)
- Tunable light source: electronics non-linearity
- Many locations (detector non-uniformity)

More details in JHEP 03, 004 (2021)

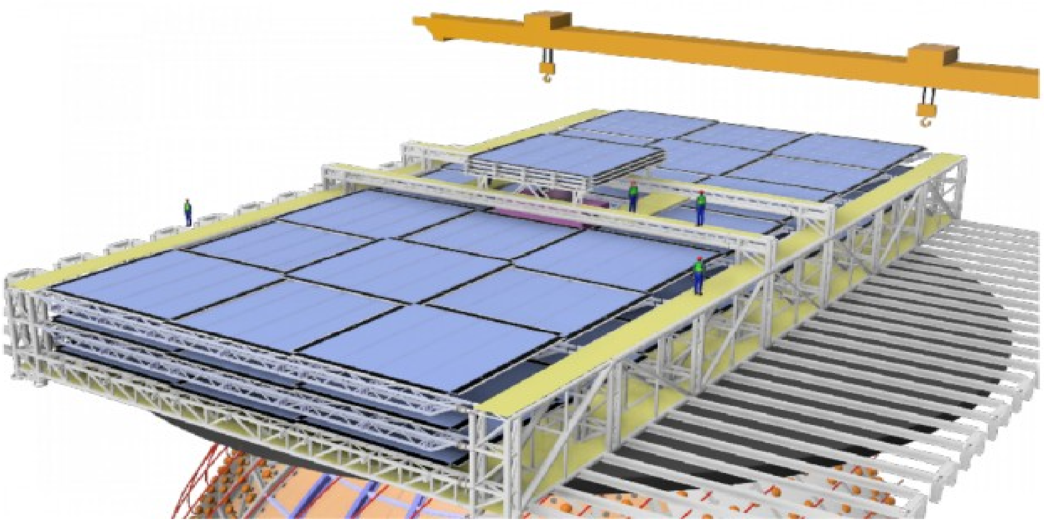
Veto system

VETO system to handle the cosmogenic background
Made by a **water Cerenkov** and a **Top Tracker**.
Earth magnetic shielding coils are also part of the system.



Top Tracker

- Made of scintillator strips refurbished from OPERA.
- Already on JUNO site.
- Precise muon tracking of 1/3 of the muons crossing the Central Detector
- New electronics (based on MAROC3 chip)



Water Cerenkov Detector

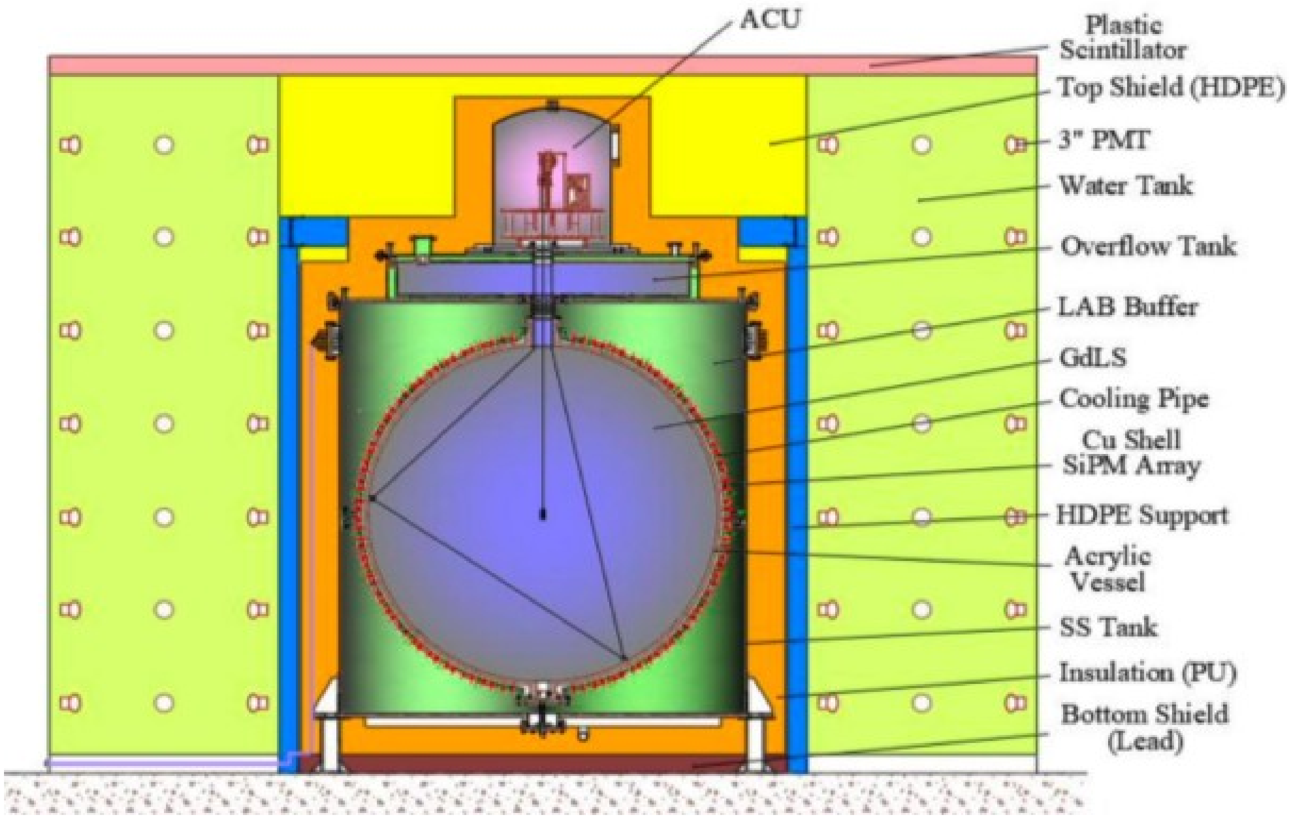
- Around the Central Detector
- Shields environment radioactivity and neutrons induced by cosmic rays
- Instrumented with 2400 20” PMTs
- 35 kton ultra-pure water with circulation
- Muon efficiency > 99%

TAO
(Taishan Anti-neutrino Observatory)

Measure anti-neutrino spectrum at % level to provide:

- **a model-independent reference spectrum for JUNO**
- **a benchmark for investigation of the nuclear database**

2.6 ton (1 ton FV) Gd-doped LS detector at 30 m from a Taishan reactor core (4.6 GW)
Full coverage SiPM read-out (50% PDE)
Liquid Scintillator and SiPM operated at -50 ^{o}C
Effective light yield: 4500 p.e./MeV → energy resolution ~ 1.8%/√E (MeV)



TAO CDR: arXiv:2005.08745

Summary and Conclusions

Neutrino mass hierarchy measurement just around the corner with different experimental techniques.
Reactor neutrino disappearance will play an important role (no θ_{23} and δ_{CP} dependence).

JUNO will be the largest reactor anti-neutrino detector ever built (20 kton of liquid scintillator) with an unprecedented energy resolution (3% @ E=1 MeV).
Civil engineering on the way (water pool civil construction completed, surface laboratory active).
Production/assembly of detector components going on.
Installation is starting, detector completion expected before the end of 2022.

The experiment has been designed for a vast research program in

- **particle physics: neutrino mass ordering and sub-% precision measurement of oscillation parameter (θ_{12}, Δm^2_{21}, Δm^2_{31})**
- **Astrophysics/Geophysics (neutrinos from natural sources)**