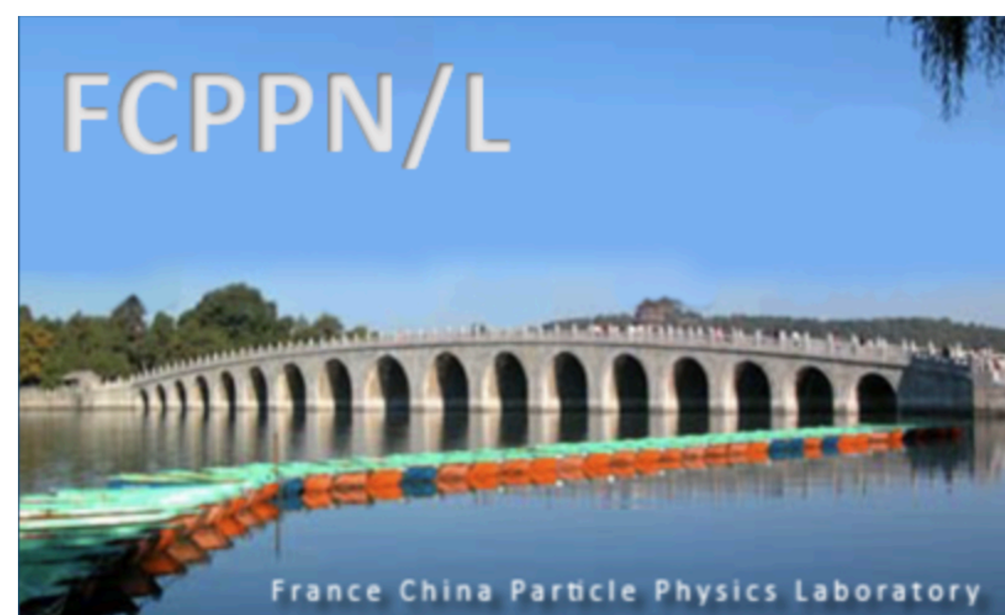
JUNO Physics program

Cécile Jollet (Bordeaux university, LP2iB - CNRS/IN2P3)
on behalf of JUNO collaboration

FCPPN/L Bordeaux 11-14 June 2024



JUNO Collaboration

Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	SYSU	Germany	U. Mainz
Belgium	Universite libre de Bruxelles	China	Tsinghua U.	Germany	U. Tuebingen
Brazil	PUC	China	UCAS	Italy	INFN Catania
Brazil	UEL	China	USTC	Italy	INFN di Frascati
Chile	PCUC	China	U. of South China	Italy	INFN-Ferrara
Chile	SAPHIR	China	Wu Yi U.	Italy	INFN-Milano
Chile	UNAB	China	Wuhan U.	Italy	INFN-Milano Bicocca
China	BISEE	China	Xi'an JT U.	Italy	INFN-Padova
China	Beijing Normal U.	China	Xiamen University	Italy	INFN-Perugia
China	CAGS	China	Zhengzhou U.	Italy	INFN-Roma 3
China	ChongQing University	China	NUDT	Pakistan	PINSTECH (PAEC)
China	CIAE	China	CUG-Beijing	Russia	INR Moscow
China	DGUT	China	ECUT-Nanchang City	Russia	JINR
China	Guangxi U.	China	CDUT-Chengdu	Russia	MSU
China	Harbin Institute of Technology	Czech	Charles U.	Slovakia	FMPICU
China	IHEP	Finland	University of Jyvaskyla	Taiwan-China	National Chiao-Tung U.
China	Jilin U.	France	IJCLab Orsay	Taiwan-China	National Taiwan U.
China	Jinan U.	France	LP2i Bordeaux	Taiwan-China	National United U.
China	Nanjing U.	France	CPPM Marseille	Thailand	NARIT
China	Nankai U.	France	IPHC Strasbourg	Thailand	PPRLCU
China	NCEPU	France	Subatech Nantes	Thailand	SUT
China	Pekin U.	Germany	RWTH Aachen U.	U.K.	U. Warwick
China	Shandong U.	Germany	TUM	USA	UMD-G
China	Shanghai JT U.	Germany	U. Hamburg	USA	UC Irvine
China	IGG-Beijing	Germany	FZJ-IKP		

Neutrino oscillation

- The relationship between the flavor eigenstates and the mass eigenstates is expressed using the PMNS matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} e^{i\xi_1/2} & 0 & 0 \\ 0 & e^{i\xi_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$s_{ij} = \sin(\theta_{ij})$
$c_{ij} = \cos(\theta_{ij})$
$\delta =$ phase CP
$\xi_1, \xi_2 =$ phases de Majorana

- The oscillation probability between flavors can be computed and expressed as:

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2(1.27\Delta m^2_{ij}L/E)$$
$$+2\sum_{i>j} Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin(2.54\Delta m^2_{ij}L/E)$$

E: Neutrino energy
L: baseline

$$\Delta m^2_{ij} \equiv m^2_i - m^2_j$$

- The measured parameters (PDG 2022) are:

	Ref. [182] w SK-ATM	
NO	Best Fit Ordering	
Param	bfp $\pm 1\sigma$	3σ range
$\frac{\sin^2\theta_{12}}{10^{-1}}$	$3.03^{+0.13}_{-0.13}$	$2.63 \to 3.45$
$\theta_{12}/^\circ$	$33.40^{+0.80}_{-0.82}$	$30.85 \to 35.97$
$\frac{\sin^2\theta_{23}}{10^{-1}}$	$4.55^{+0.18}_{-0.15}$	$4.16 \to 5.99$
$\theta_{23}/^\circ$	$42.4^{+1.0}_{-0.9}$	$40.2 \to 50.7$
$\frac{\sin^2\theta_{13}}{10^{-2}}$	$2.23^{+0.07}_{-0.06}$	$2.04 \to 2.44$
$\theta_{13}/^\circ$	$8.59^{+0.13}_{-0.12}$	$8.21 \to 8.99$
$\delta_{CP}/^\circ$	223^{+32}_{-23}	$139 \to 355$
$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.36^{+0.16}_{-0.15}$	$6.93 \to 7.93$
$\frac{\Delta m^2_{32}}{10^{-3}\ eV^2}$	$2.448^{+0.023}_{-0.031}$	$2.367 \to 2.521$

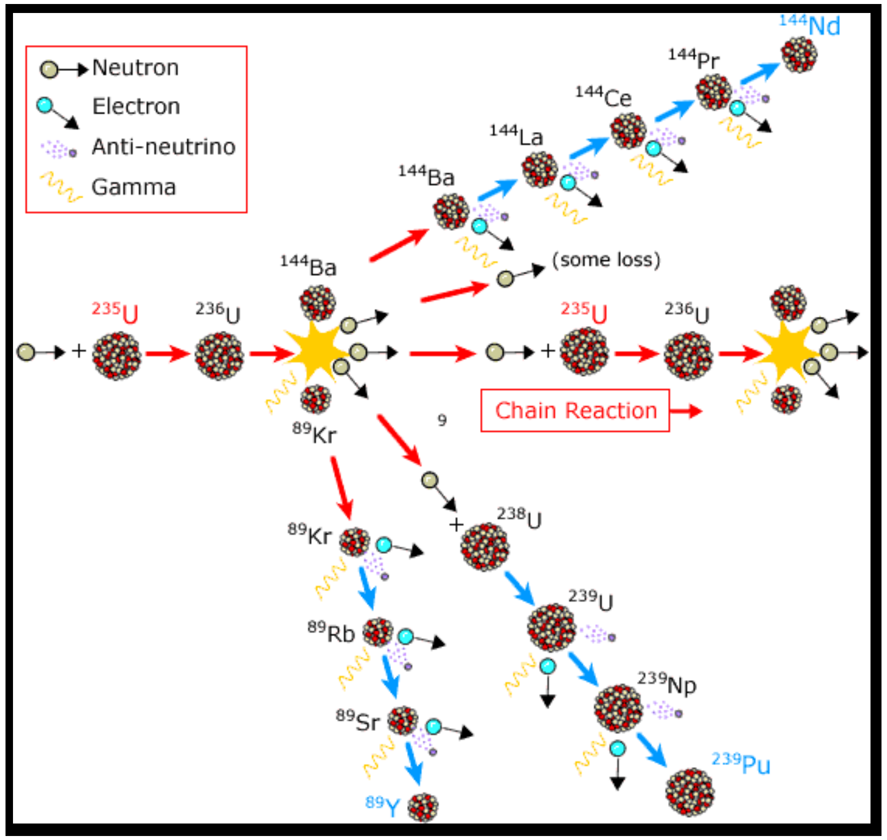
precision > 1%

sign of $\Delta^2 m_{32}$ unknown

Reactor as a copious source of neutrinos

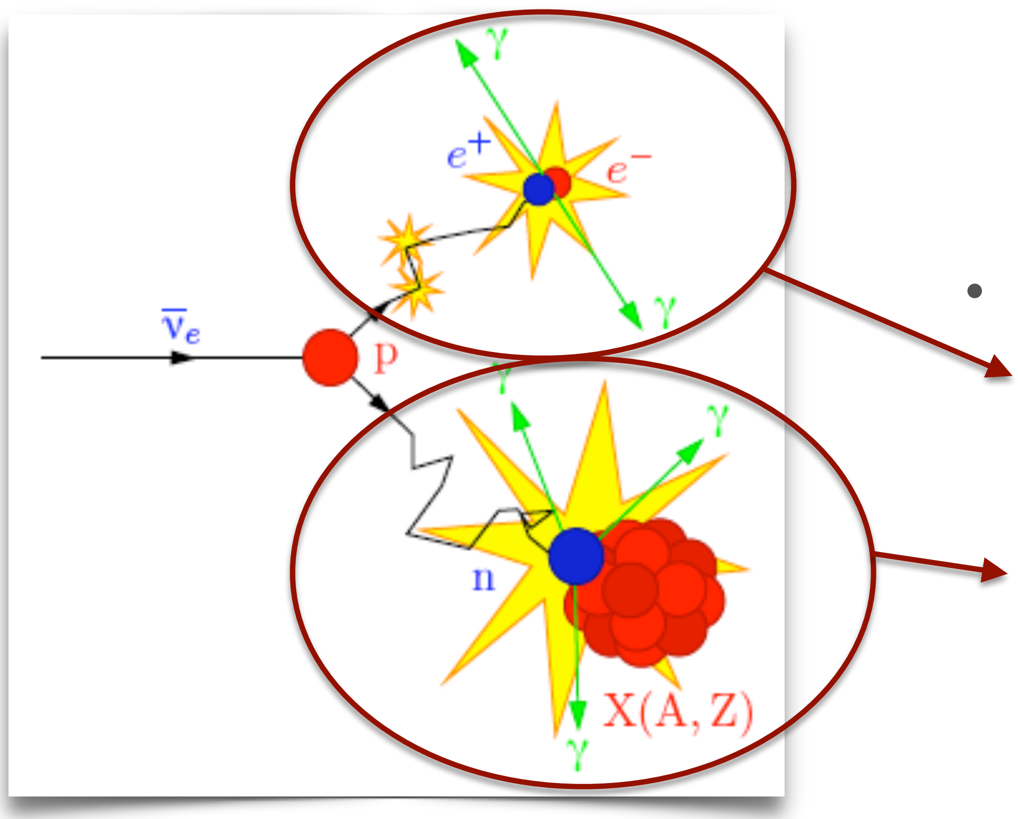
- Nuclear reactors are an intense source of neutrinos.
- Neutrinos come from beta-fission fragments from the fission of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu.
- All the fission products are neutron-rich nuclei and all decays are beta-type, leading to a **pure electronic anti-neutrino** flux.
- For 1 GW_{th} reactor (thermal power) we expect **2×10^{20} ν/s** emitted in 4π solid angle.

Nuclear chain reaction



- Taking into account the time evolution and the numerous branching, the prediction of the flux and spectrum are not easy.

Measure reactor anti-neutrino

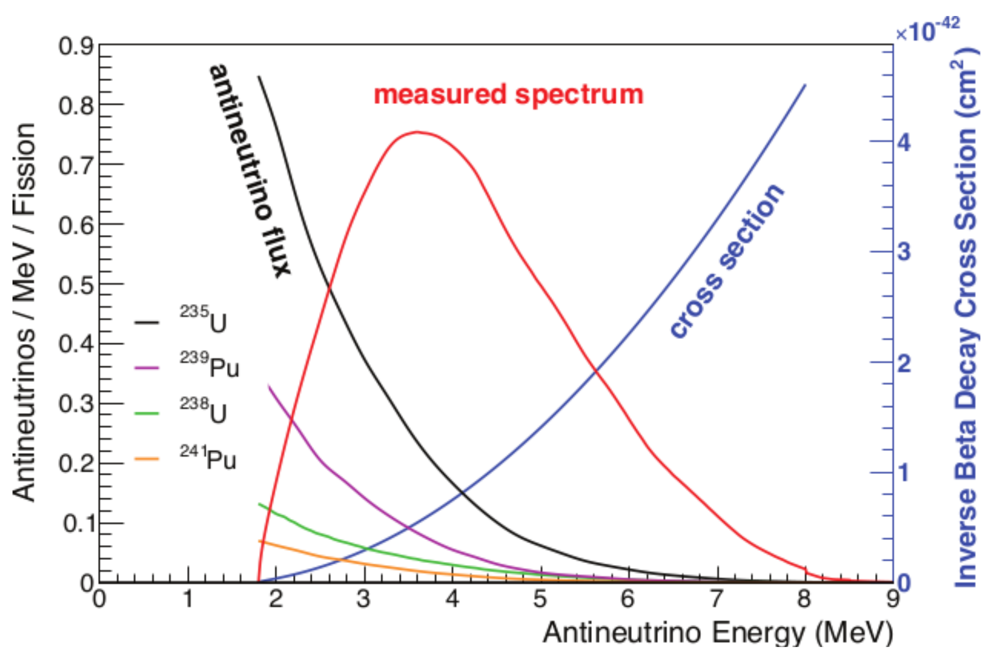


- The preferred channel to observe neutrinos is via Inverse Beta Decay (IBD):

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

- The signal signature is given by a **twofold coincidence**:

1. **Prompt** photons from e^+ ionisation and annihilation (1-8 MeV).
2. **Delayed** photons from n capture on Gadolinium (~8 MeV) or H (2.2 MeV), or signal from n capture on ^{6}Li.
3. Time correlation: Δt ~200 μs in LS.
4. Space correlation (< 1m).



- The energy spectrum is a convolution of flux and cross section (threshold at 1.8 MeV).

- The prompt energy is related to $\bar{\nu}_e$ energy:

$$E_{prompt}=E_{\nu}-T_{n}-0.8 \text{ MeV}$$

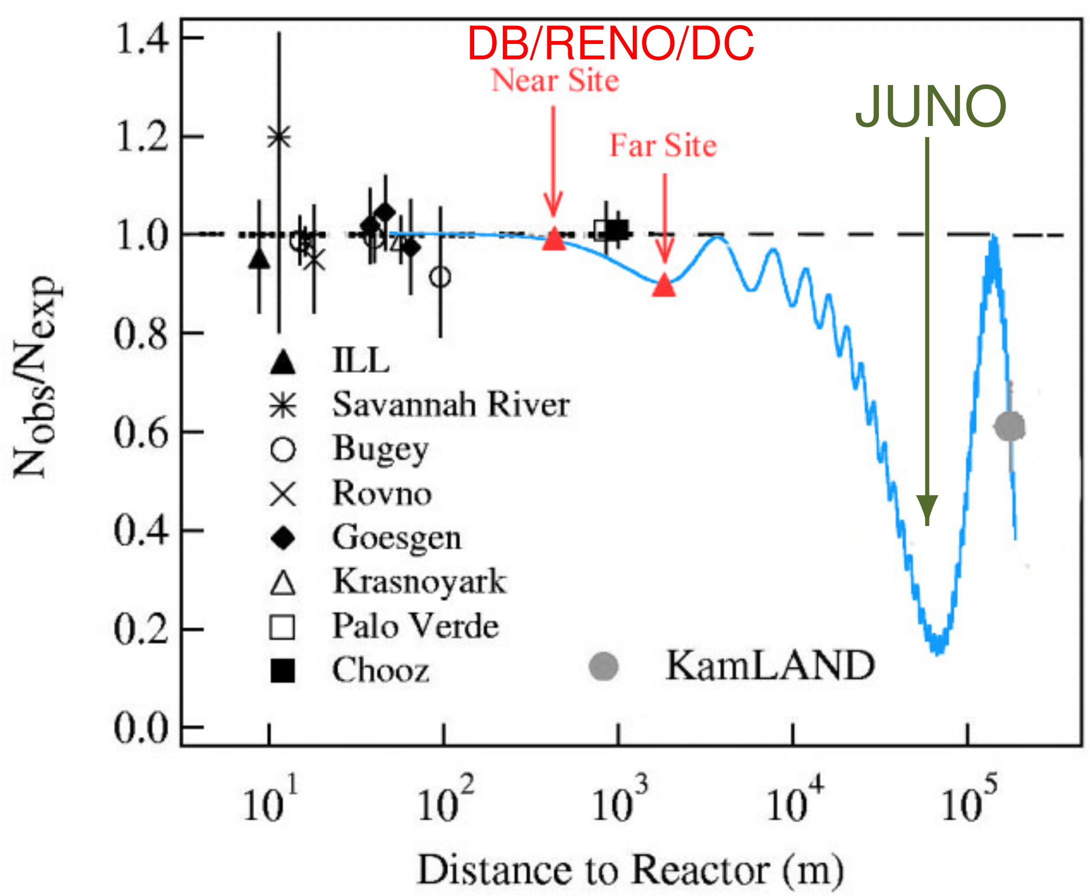
Reactor neutrino oscillation

- In the case of reactor anti-neutrinos, we can only observe the disappearance and the oscillation does not rely on δ_{CP} and θ_{23} which allow for a clean measurement of the other parameters.
- The probability can be written as:

Short baseline — Medium baseline

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{ee}L}{4E}\right) - \sin^2(2\theta_{12})\cos^4(\theta_{13})\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right)$$

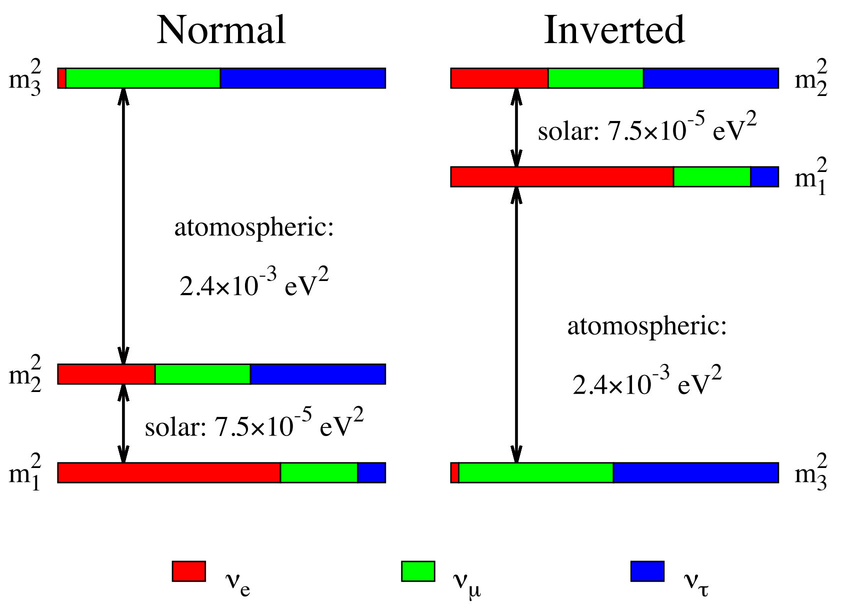
with $\sin^2\left(\frac{\Delta m^2_{ee}L}{4E}\right) \equiv \cos^2(\theta_{12})\sin^2(\frac{\Delta m^2_{31}L}{4E}) + \sin^2(\theta_{12})\sin^2(\frac{\Delta m^2_{32}L}{4E})$



- There are 3 oscillation components which correspond to 3 oscillation frequencies in the L/E space which are proportional to $|\Delta m^2_{ij}|$ respectively:
  - Medium baseline (50 km): driven by (θ_{12}, Δm^2_{12}) parameters.
  - Short baseline (1 km): driven by (θ_{13}, Δm^2_{13}) parameters.
  - Very short baseline (few meters): sterile neutrinos searches.

Mass hierarchy determination with reactor

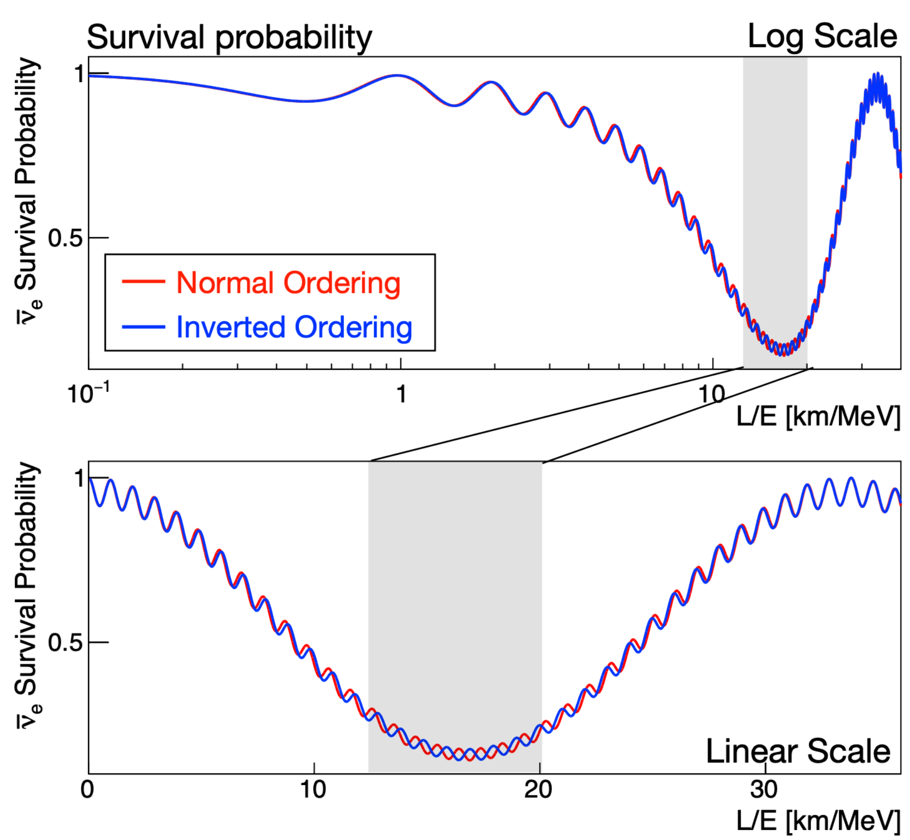
- Since the sign of $\Delta^2 m_{32}$ unknown, there are two hypothesis for the mass hierarchy:



$$P_{ee} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21}) - \sin^2 2\theta_{13}\sin^2(|\Delta_{31}|) - \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{21})\cos(2|\Delta_{31}|) \pm \frac{\sin^2\theta_{12}}{2}\sin^2 2\theta_{13}\sin(2\Delta_{21})\sin(2|\Delta_{31}|),$$

$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E_\nu}, \quad (\Delta m^2_{ij} \equiv m_i^2 - m_j^2)$$

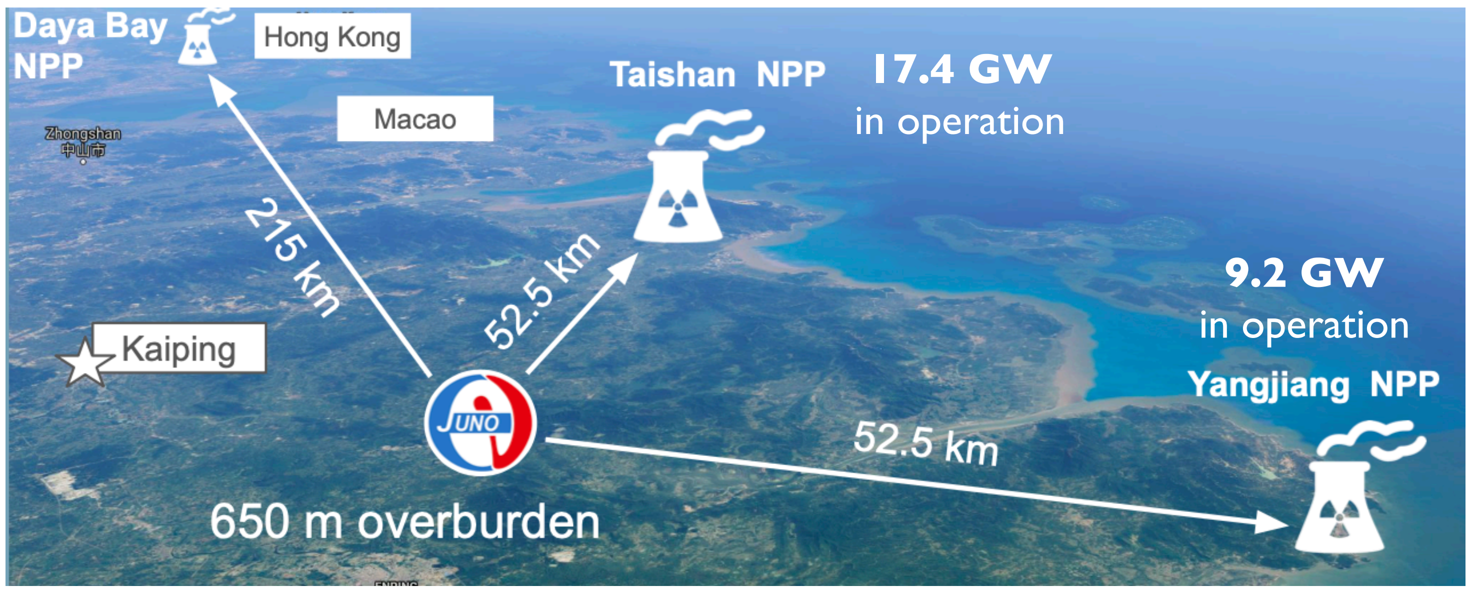
+ Normal hierarchy
- Inverted hierarchy

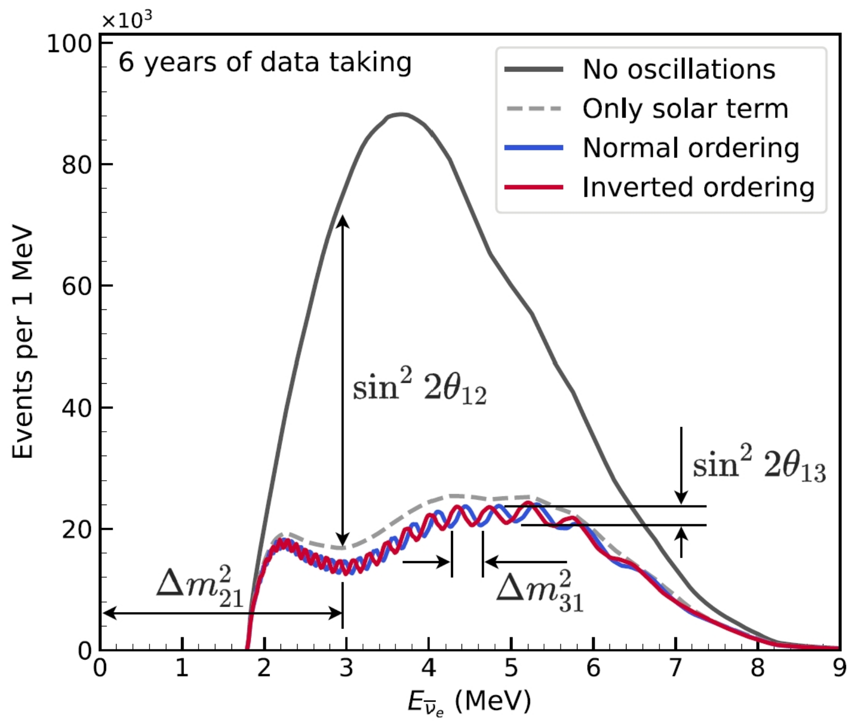


- Several conditions on baseline and energy resolution are necessary to perform such a measurement.
- At 52.5 km from the source, the oscillation is dominated by the terms (Δm^2_{12}, θ_{12}).
- If the energy resolution is high enough, it is possible to see the oscillation dominated by (Δm^2_{23}, θ_{13}) and a spectral analysis will permit to discriminate between the 2 hierarchies.

JUNO experiment

- JUNO (Jiangmen Underground Neutrino Observatory) is a medium-baseline (52.5 km) reactor neutrino experiment.
- Its position has been optimized to resolve the neutrino mass ordering (conditions on baseline).





The detector has been designed to :

- ensure large statistics (20 kilo-ton liquid scintillator target) and unprecedented energy resolution (3% at 1 MeV).

with the main goal of :

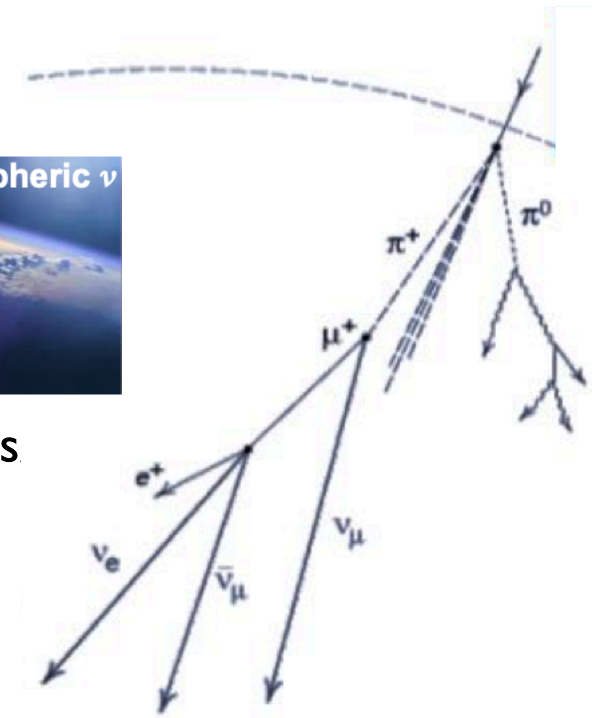
- perform a relative measurement on the mass ordering (no constraint on Δm^2_{31}, $\Delta\chi^2>9$) or an absolute measurement ($\Delta\chi^2>16$) accounting for constraints from long baseline experiments.

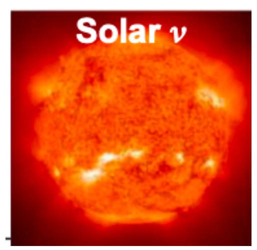
JUNO physics program

- JUNO is a multipurpose Neutrino Observatory and it has a rich program in neutrino physics and astrophysics studying neutrinos in a large energy range.

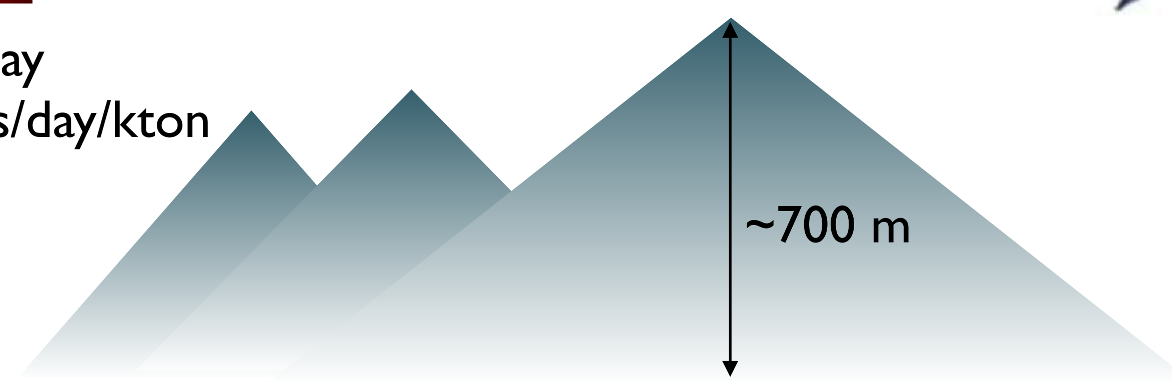
10^4 evts at 10 kpc
DSNB : 2-4 evts/year

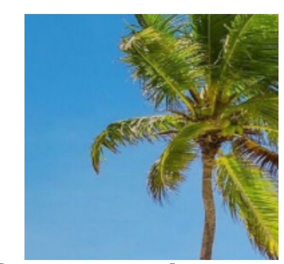
>~100 evts





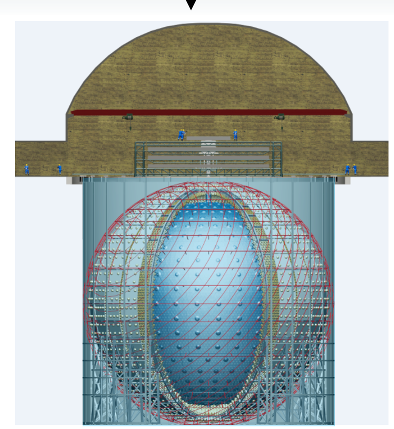
^{8}B : 16 evts/day
^{7}Be : 490 evts/day/kton

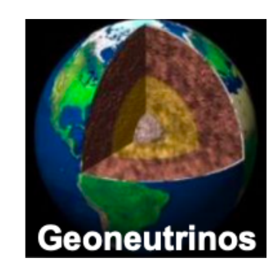




Proton decays : $p \rightarrow \bar{\nu} + K^+$
Indirect Dark Matter Searches

45 evts/day
→Neutrino mass ordering
→Precision measurement of solar oscillation parameters





400 evts/year

JUNO detector

High energy precision

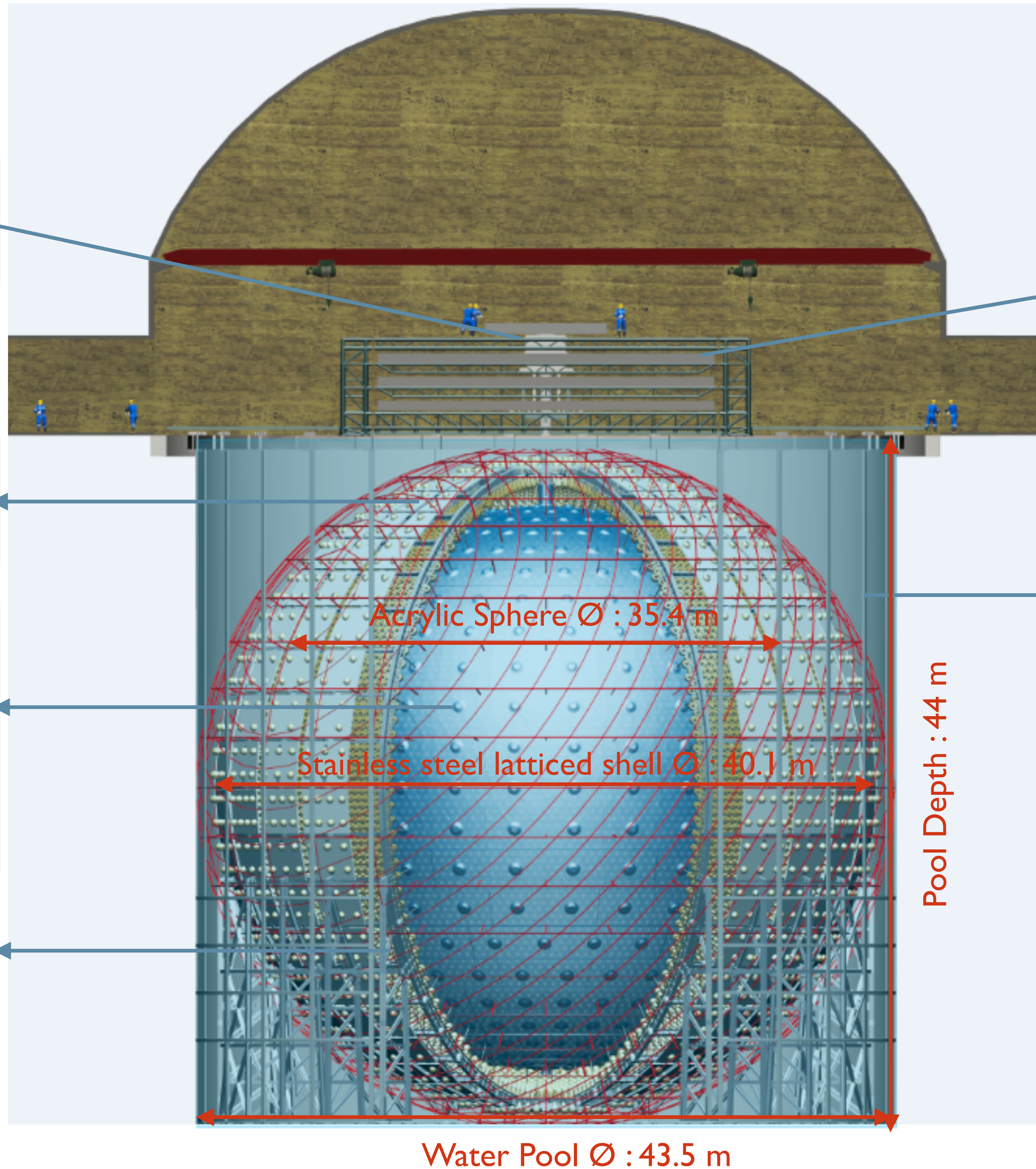
Backgrounds reduction

Calibration room
multi-dimension calibration systems

Central Detector (CD)
SS latticed shell
Acrylic sphere

Liquid Scintillator (LS)
20 kilo-ton based LAB LS
→High light yield : ~ 10 000 photons/MeV
→ High transparency : ~ 20 meters attenuation length at 430 nm

Photomultipliers (PMTs)
17 612 20" PMTs
25 600 3" PMTs
See F. Perrot's talk
→~ 78% coverage



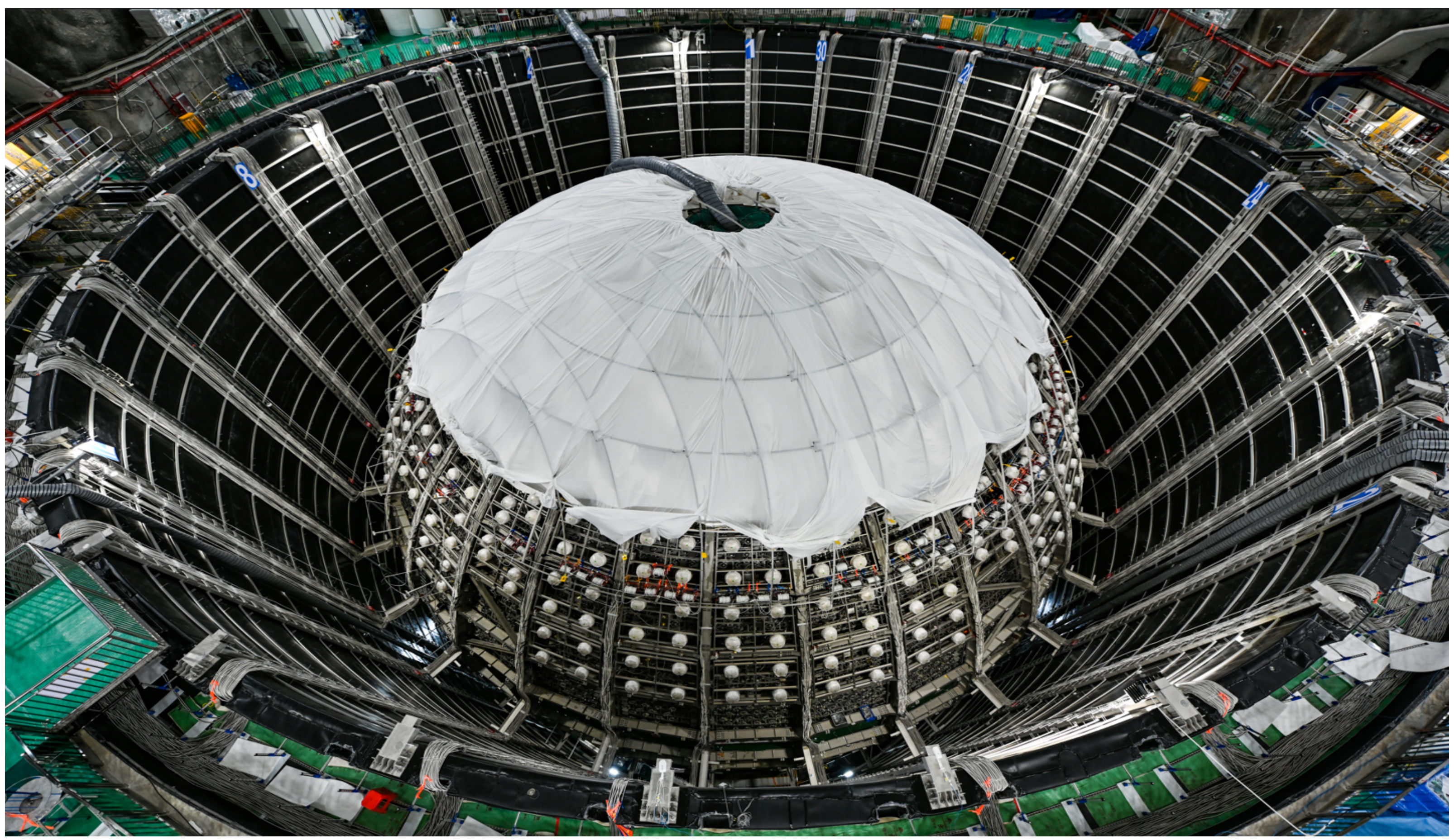
Top Tracker
3 layers of plastic scintillator (cover ~60% of Water Pool)
→Precise muon tracker
See J.P. de Andre's talk

Water Pool (WP)
35 kilo-ton pure water
2400 20" PMTs on CD surface
→High muon detection efficiency
→Protects CD against external radioactivity

JUNO detector

- Civil construction of a dedicated laboratory started in 2015 to host the JUNO detector.
- 2022-2024 : installation and commissioning.
- 2025 : Filling and start of data taking.

Status in December 2023



Central Detector PMTs view

More details about Detector and Installation in Y. Wang's talk

Liquid scintillator of JUNO

- The composition of the LS is: LAB *(solvant)* + 2.5 g/L PPO *(fluor)* + 3 mg/L bis-MSB *(wavelength shifter)*
- The LS will be purified from optical impurities (transparency) and radioactivity contaminants (background events) **before filling** the detector.

4 steps of purification

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

radioactivity components requirements

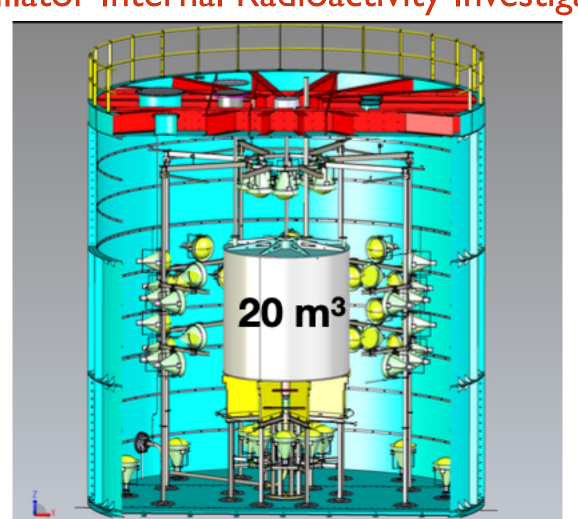
Requirements	^{238}U	^{232}Th	^{226}Ra	^{40}K	$^{210}Pb(^{222}Rn)$	^{85}Kr / ^{39}Ar
Reactor physics	10^{-15} g/g	10^{-15} g/g		10^{-16} g/g	10^{-22} g/g	
Solar physics	10^{-17} g/g	10^{-17} g/g	$5\cdot10^{-24}$ g/g	10^{-18} g/g	10^{-24} g/g	1μBq/m^3

JHEP 11 (2021) 102

- Radio-purity will be ensured **during the filling** : an ancillary detector of 20 m^3 will monitor batches of LS.

OSIRIS

Online Scintillator Internal Radioactivity Investigation System



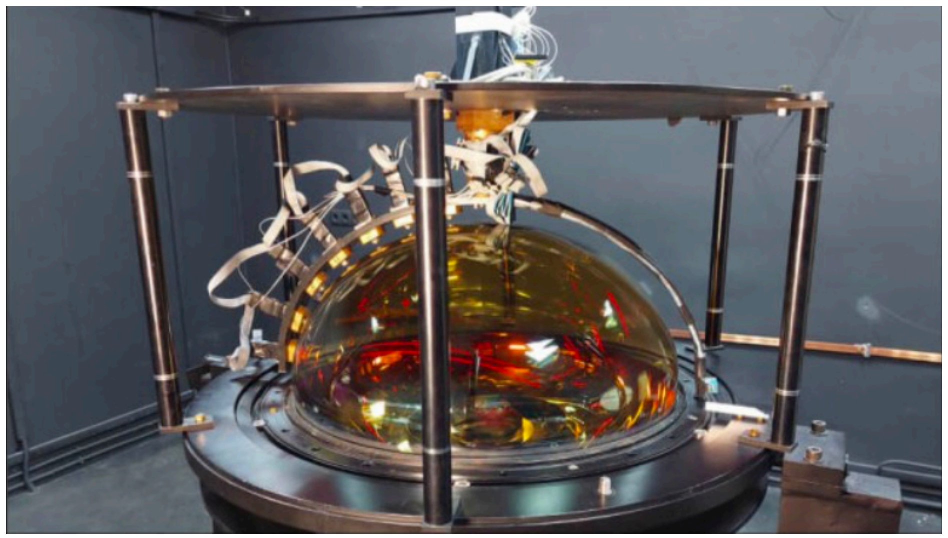
- Exploit Bi-Po decay in ^{238}U and ^{232}Th chains.
- Few days (weeks) needed to verify compliance to 10^{-15} (10^{-16}) g/g.

EPJ C 81 (2021)11, 973

Photomultipliers system

- The goal is to have a high photo statistics in order to reach the requirement of the energy resolution : large coverage and high efficiency of photon detection.
- All 20" and 3" PMTs tested before installation.

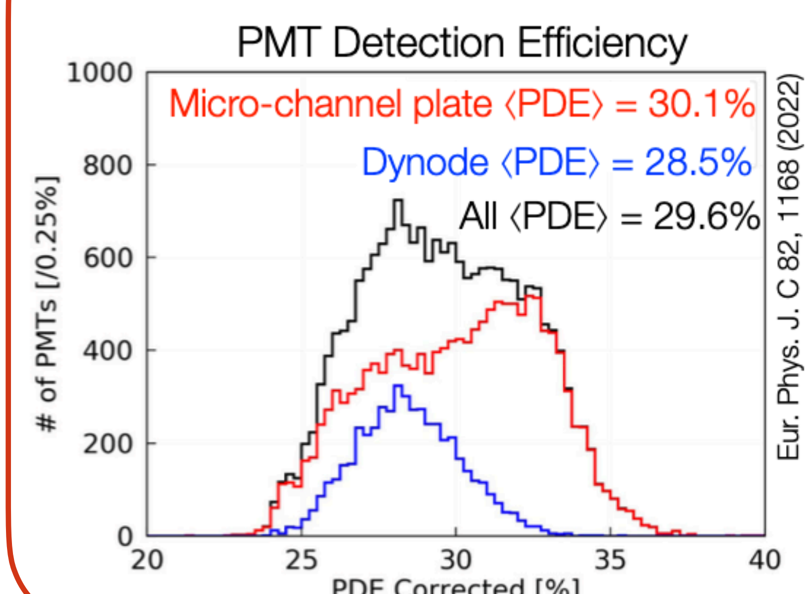
20" PMT

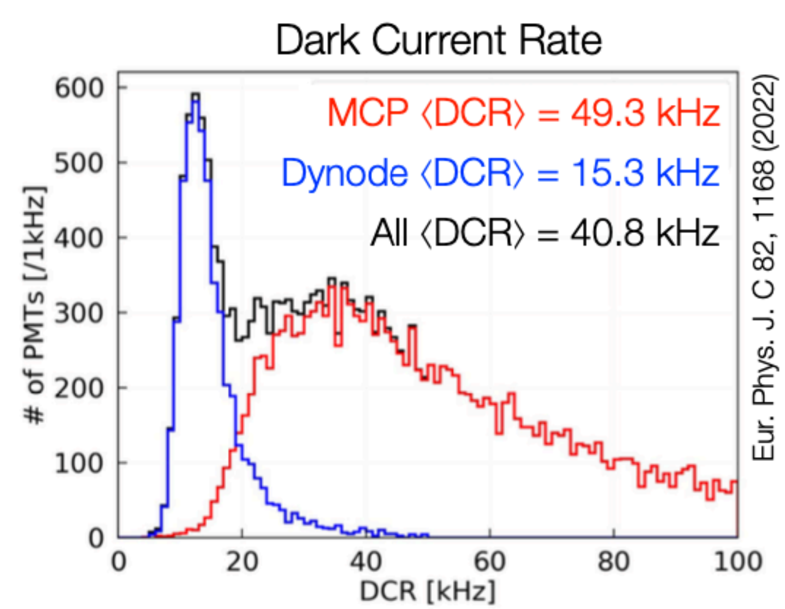


3" PMT

	20" PMTS ~ 75% coverage ~ 1500 p.e./MeV		3" PMTS ~ 3% coverage ~ 40 p.e./MeV
Quantity	5000	15000	25600
Manufacturer	Hamamatsu (JP)	NNVT (CN)	HZC (CN)
Charge Collection	Dynode	Micro-channel plate	Dynode
Transit Time Spread	σ 1.3 ns	σ 7.0 ns	σ 1.5 ns

20" PMT



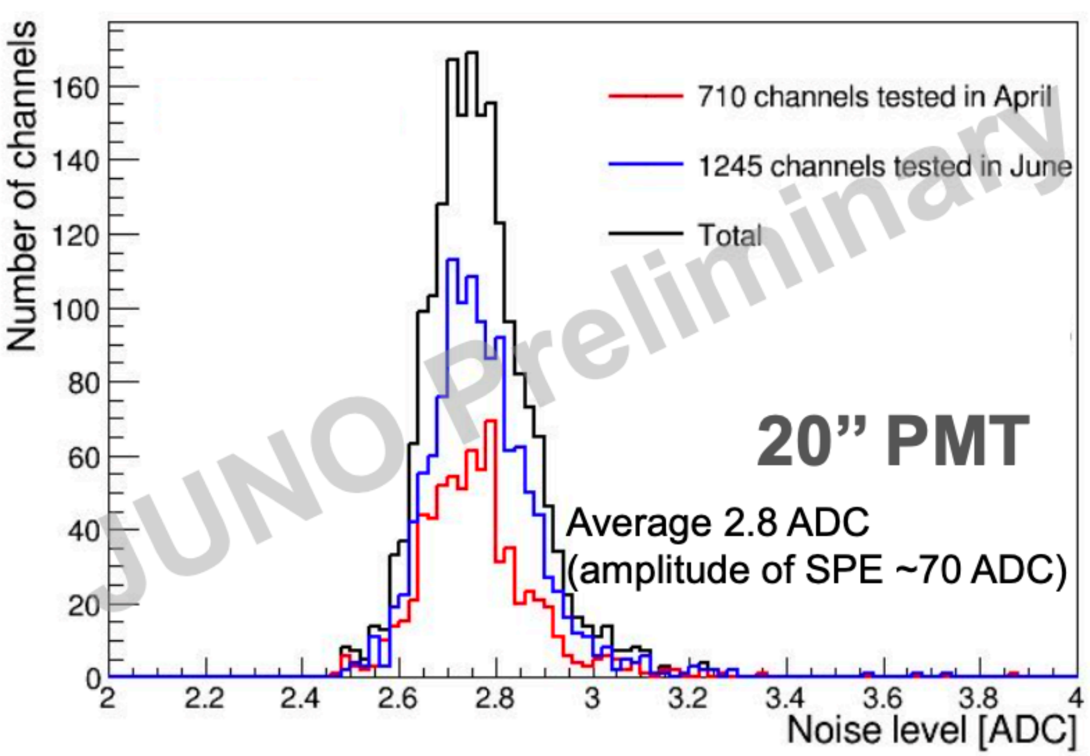


Photomultipliers system: commissioning

➡ All tested PMTs are working well.

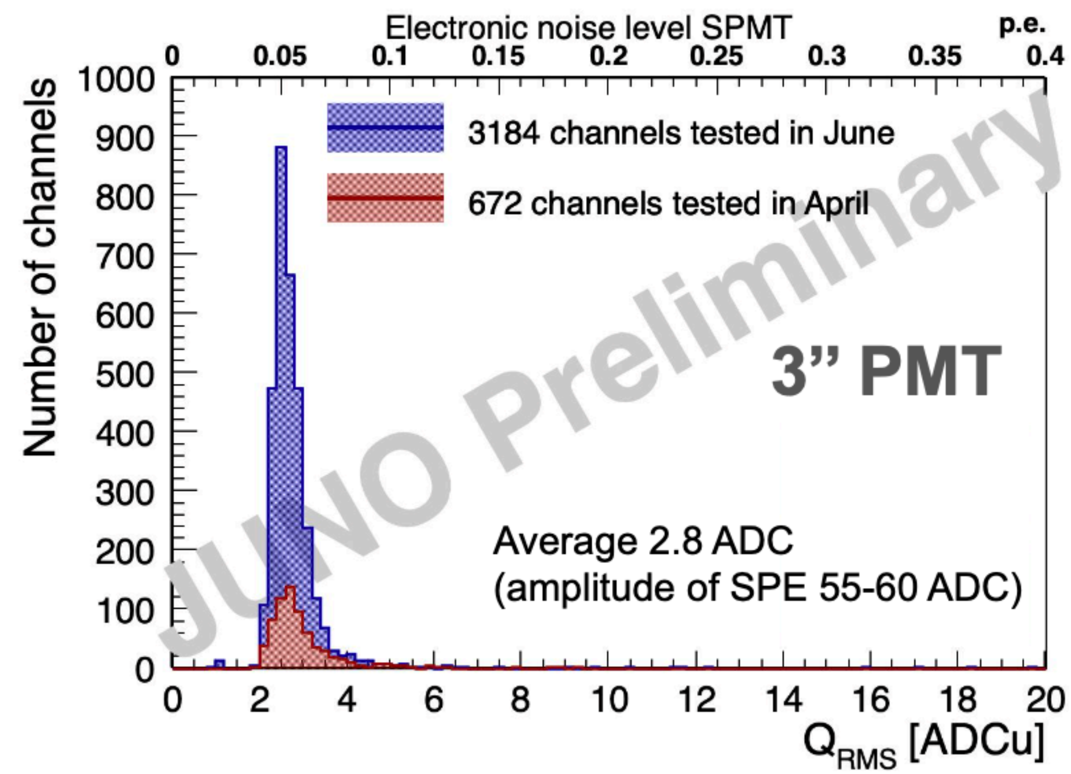
- Regular light-off/on tests during detector assembly
  - Light off tests: full data taking and processing chain with PMT HV on
  - Light on tests: joint elec/trigger/DAQ/DCS test with PMT HV off

    ➡ Very good electronics, shielding and grounding



Electronics noise: 2.8 ADC counts corresponding to ~4% of SPE

↳much better than the design of 10%



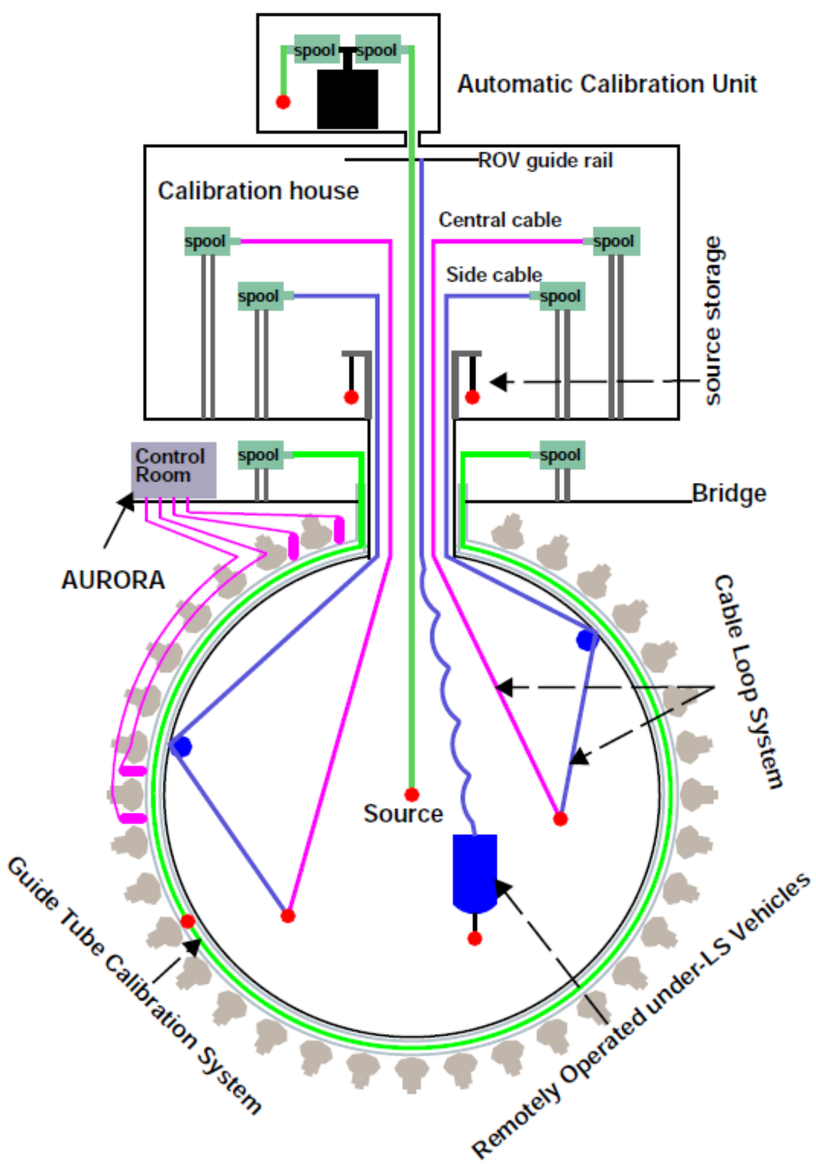
Electronics noise: 2.8 ADC counts corresponding to ~5% of SPE

↳much lower than the trigger threshold of 1/3 pe.

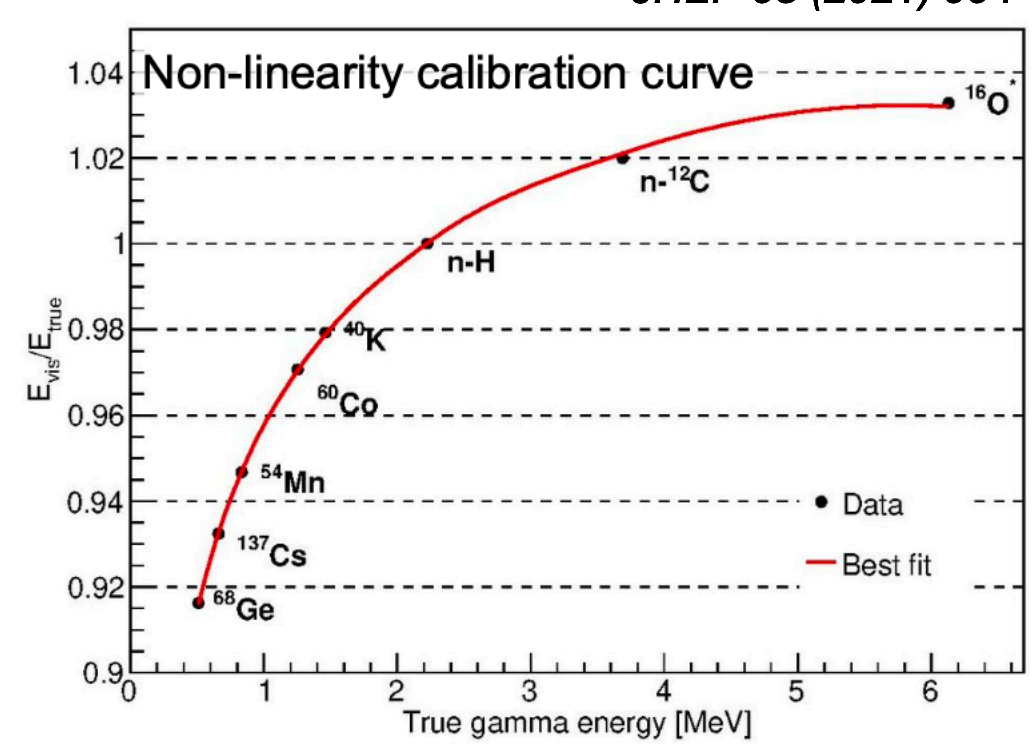
Energy scale calibration

To keep energy scale uncertainty below 1%, **four calibration systems** will be used:

- 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.



JHEP 03 (2021) 004



Efficiency and backgrounds for reactor neutrino signal

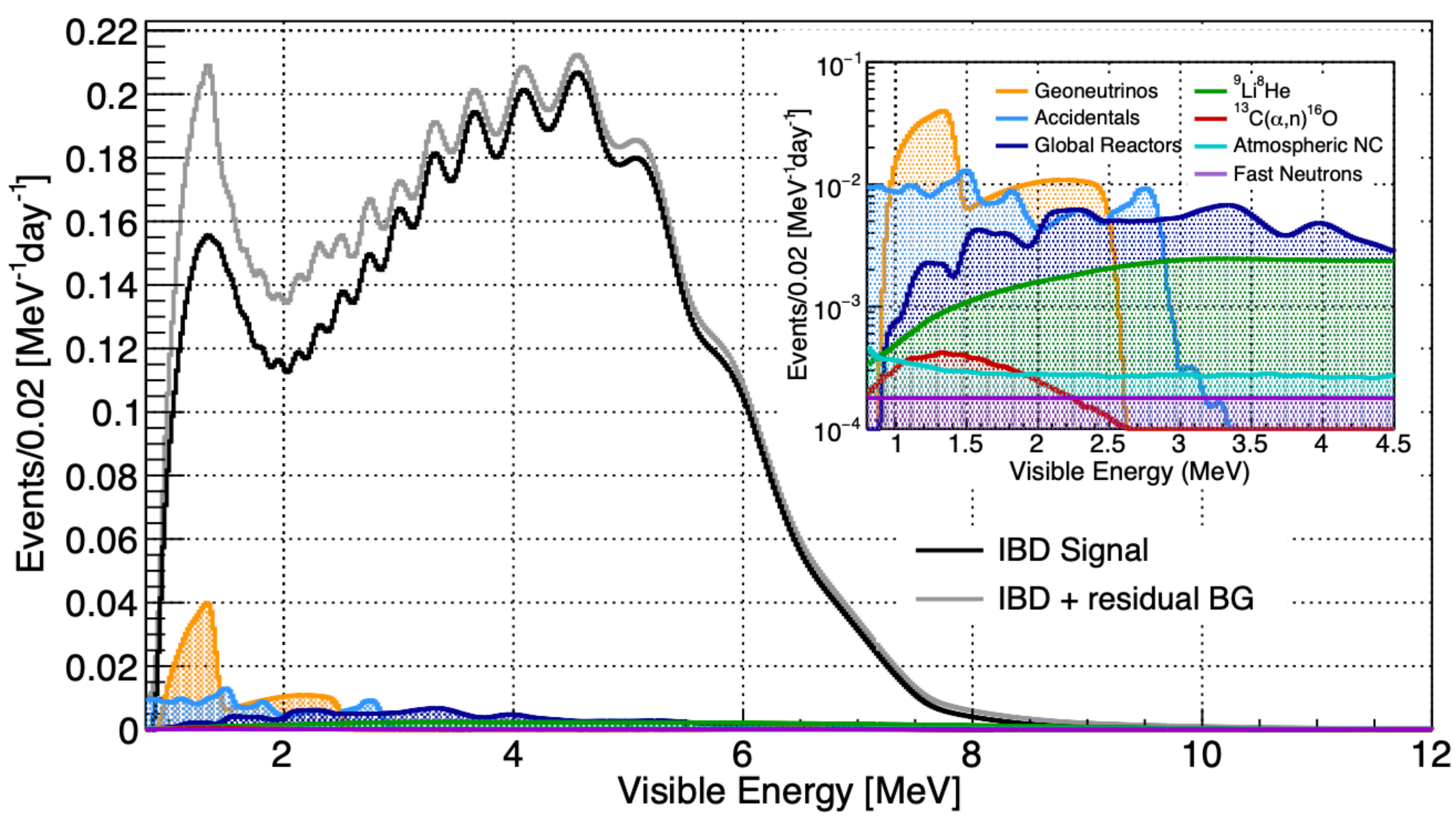
Selection cuts and IBD efficiency

Selection Criterion	Efficiency (%)	IBD Rate (day^{-1})
All IBDs	100.0	57.4
Fiducial Volume	91.5	52.5
IBD Selection	98.1	51.5
Energy Range	99.8	-
Time Correlation (ΔT_{p-d})	99.0	-
Spatial Correlation (ΔR_{p-d})	99.2	-
Muon Veto (Temporal⊕Spatial)	91.6	47.1
Combined Selection	82.2	47.1

Background rates

Background	Rate (day^{-1})
Geoneutrinos	1.2
World reactors	1.0
Accidentals	0.8
^{9}Li/^{8}He	0.8
Atmospheric neutrinos	0.16
Fast neutrons	0.1
^{13}C(α,n)^{16}O	0.05
Total background	4.11

JUNO IBD Spectrum

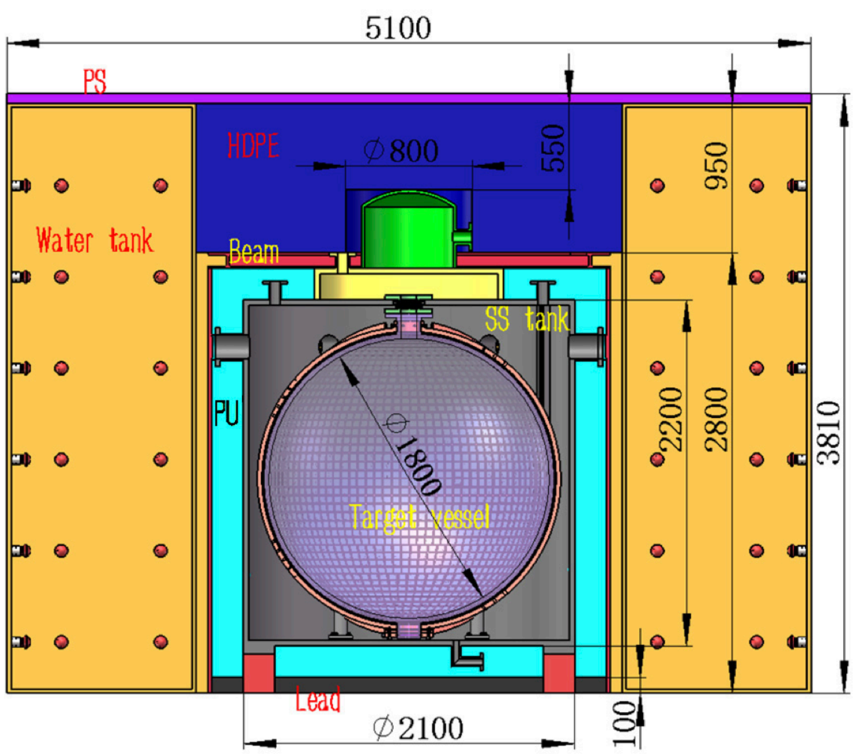


TAO detector: reactor neutrino source understanding

Taishan Antineutrino Observatory (TAO), is a ton-level, high energy resolution LS detector at ~44 meters from one of the Taishan reactor cores (4.6 GW_{th}). It is a satellite detector of JUNO.

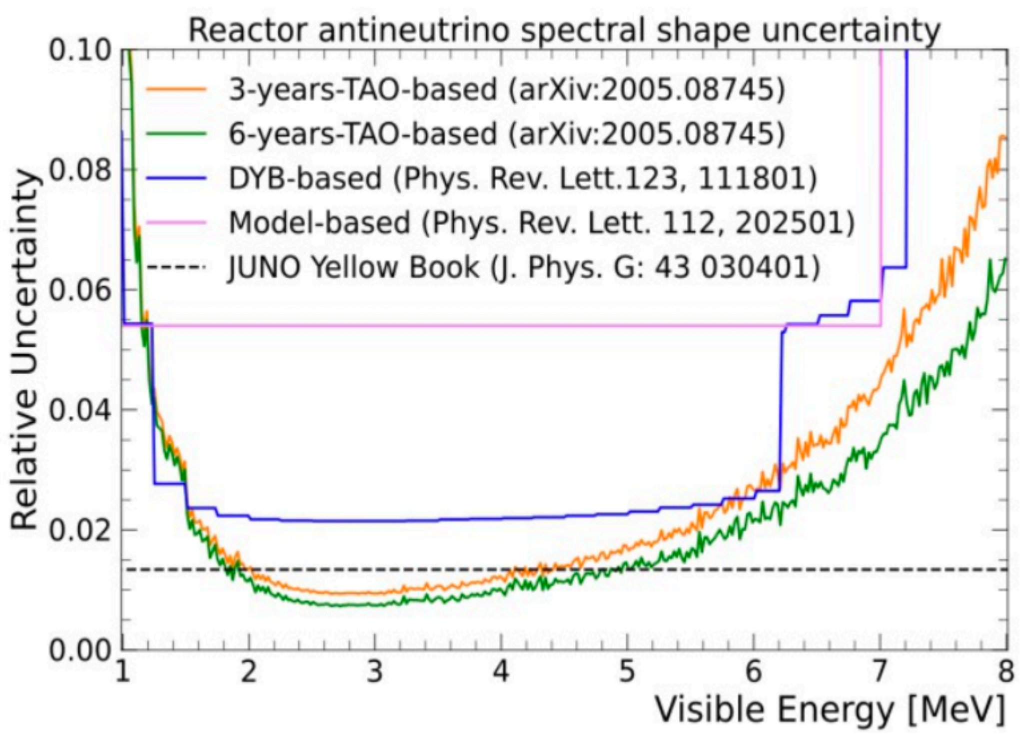
Detector Design

- 2.8 ton (1 ton fiducial volume) Gd-LS operated at -50°C
- 10 m^2 of SiPM for a > 90% coverage
- 4500 p.e./MeV.



Purposes

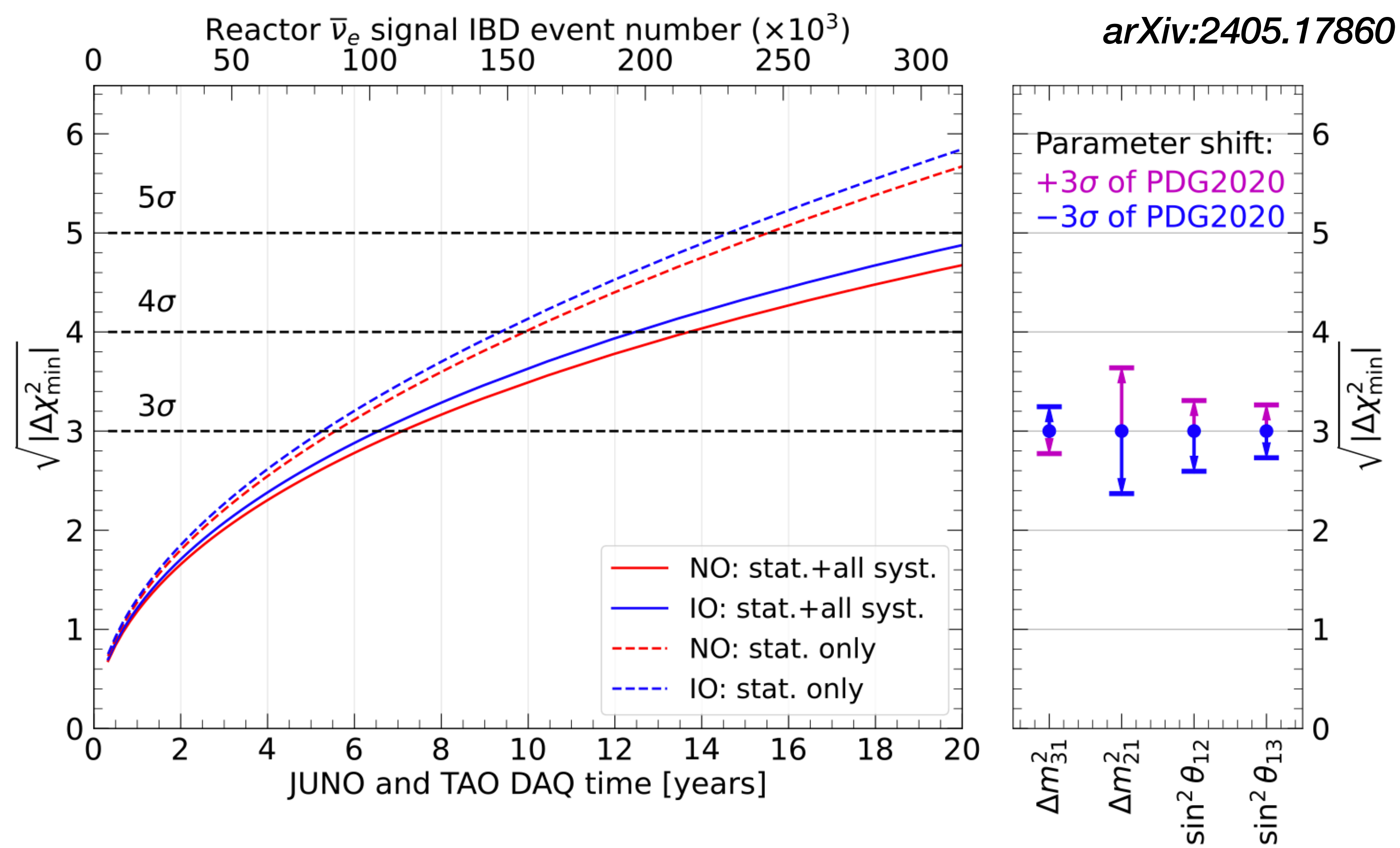
- Provide a model-independent reference spectrum for JUNO
- benchmark for investigation of the nuclear database.



Production is ongoing, start of operation at the same time than JUNO.

Neutrino mass ordering

- The median sensitivity to reject the wrong mass ordering is **3σ ($\Delta\chi^2=9$)** with an exposure of **6 years × 26.6 GW_{th}** assuming normal ordering (3.1σ if inverted ordering is true).

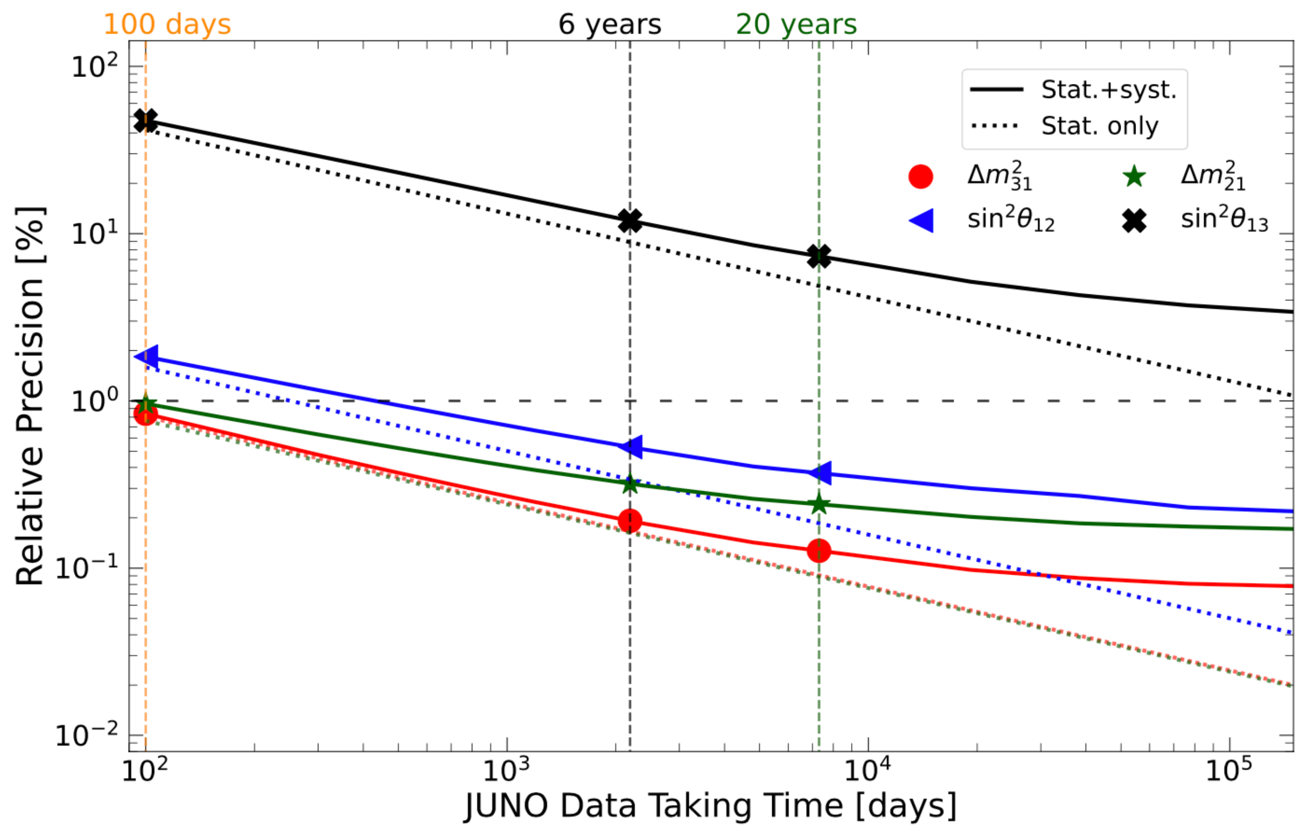


- The sensitivity can be enhanced doing :
  - combination with external Δm^2_{31} long baseline experiment constraint.
  - combination reactor+atmospheric neutrino analysis ongoing.

Precision measurement of oscillation parameters

- By measuring the energy spectrum, JUNO will be also sensitive to solar parameters and will perform precision measurements.

Chin.Phys.C 46 (2022) 12, 123001



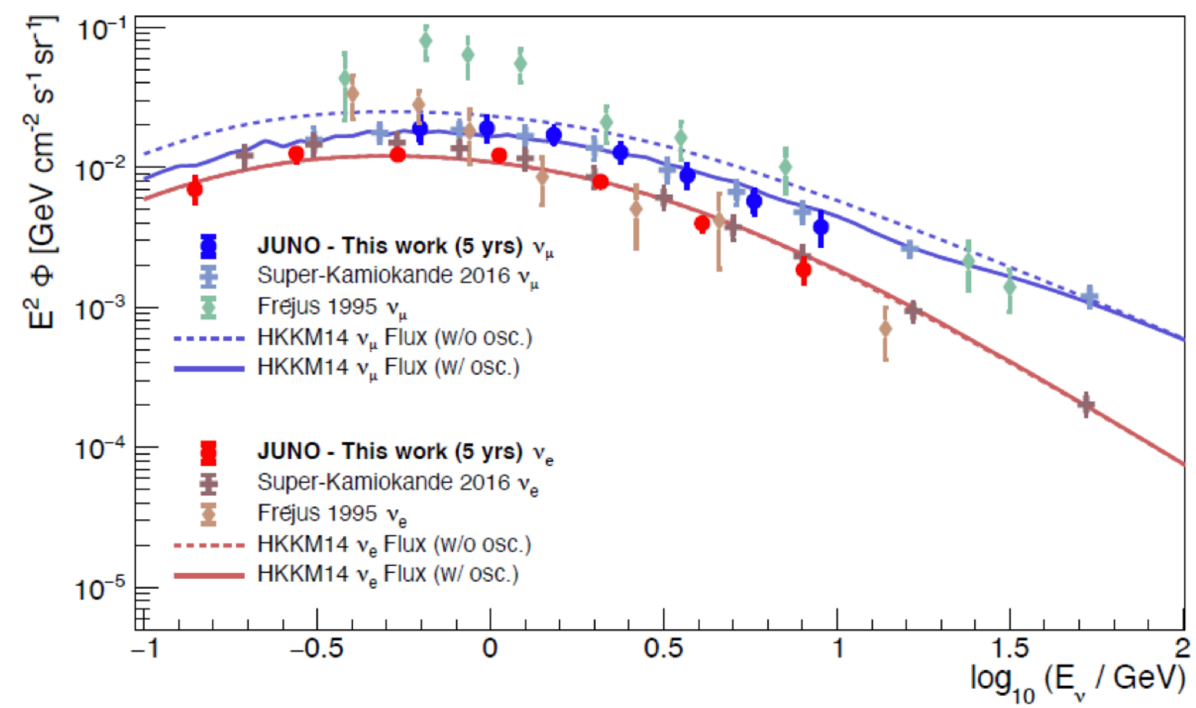
- Sub-percent precision measurement for Δm^2_{31}, Δm^2_{21}, $\sin^2\theta_{12}$

		Central Value	PDG2020	100 days	6 years	20 years
●	Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
★	Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
◀	$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (0.5%)	±0.0010 (0.3%)
✖	$\sin^2\theta_{13}$	0.0218	±0.0007 (3.2%)	±0.010 (47.9%)	±0.0026 (12.1%)	±0.0016 (7.3%)

Atmospheric neutrinos

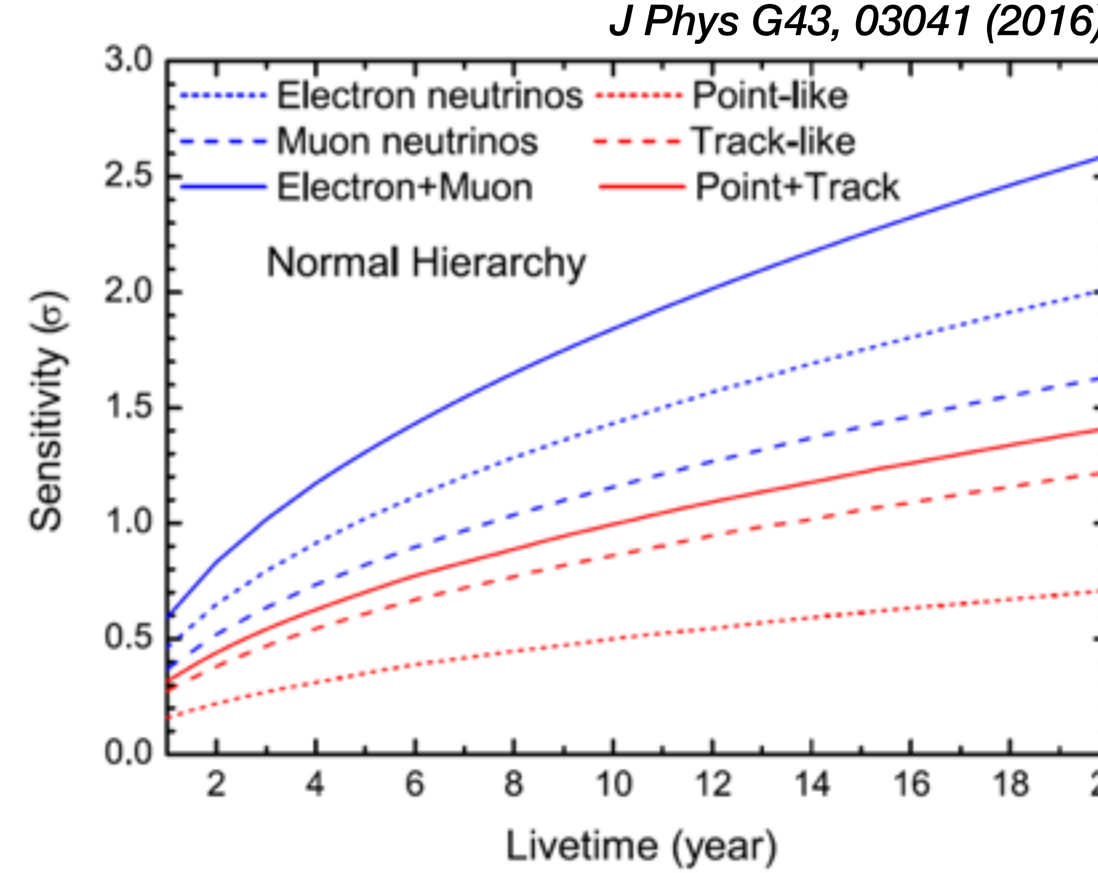
- Importance of reconstructing neutrino direction/ flavor/energy.
- Good ability to reconstruct atmospheric spectrum.
- Provide constraints to models.

EPJ-C 81 87 (2021)



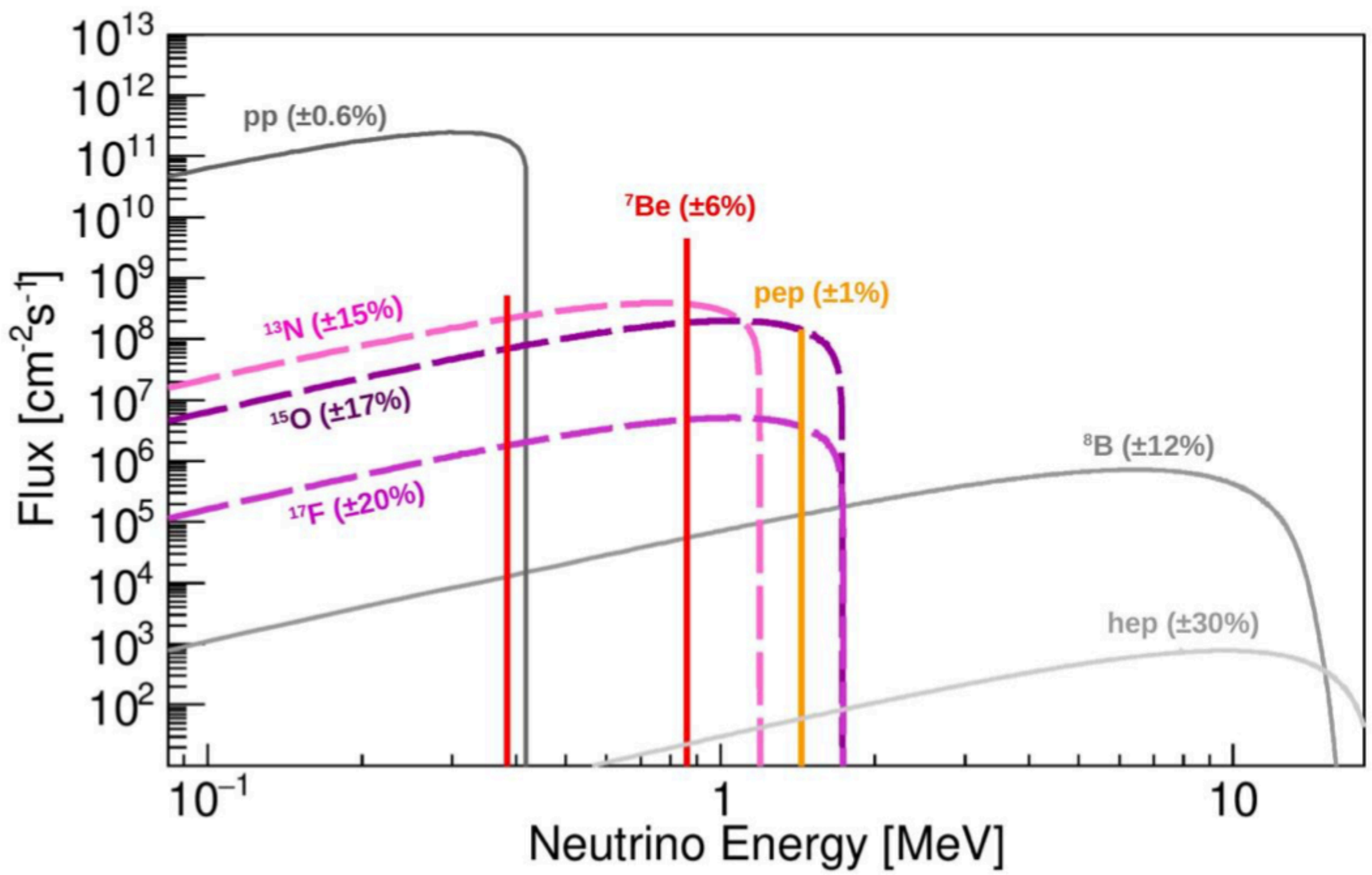
- Independent measurement of Neutrino hierarchy via matter effect.
- Sensitivity to θ_{23}.
- ~1σ sensitivity in 1 year.
- Reevaluation of sensitivity in progress.
- A combined analysis with reactor anti-neutrino can reach >3σ in 6 years.

J Phys G43, 03041 (2016)



Solar neutrinos measurements

- Neutrinos are produced in Sun from fusion reactions (pp chain and CNO cycle).



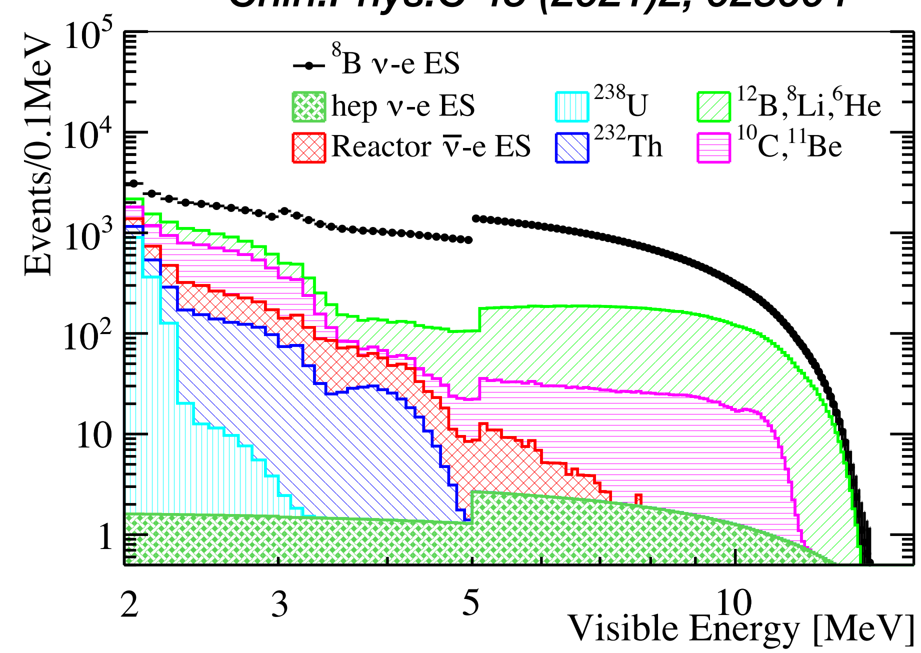
- JUNO can measure solar neutrino in the Elastic Scattering channel: $e^- + \nu \rightarrow e^- + \nu$.
- Challenging measurement due to:
  - low overburden but new veto strategies for cosmogenic isotopes.
  - detection via neutrino-elastic scattering, so higher requirements in terms of radiopurity

Solar neutrinos measurements

^{8}B neutrino observation

- With 10 years of data taking, about 60000 signal and 30000 background events are expected.
- Shed new light on current tension in Δm^2_{21} between solar and reactor neutrinos measurement with the same detector.

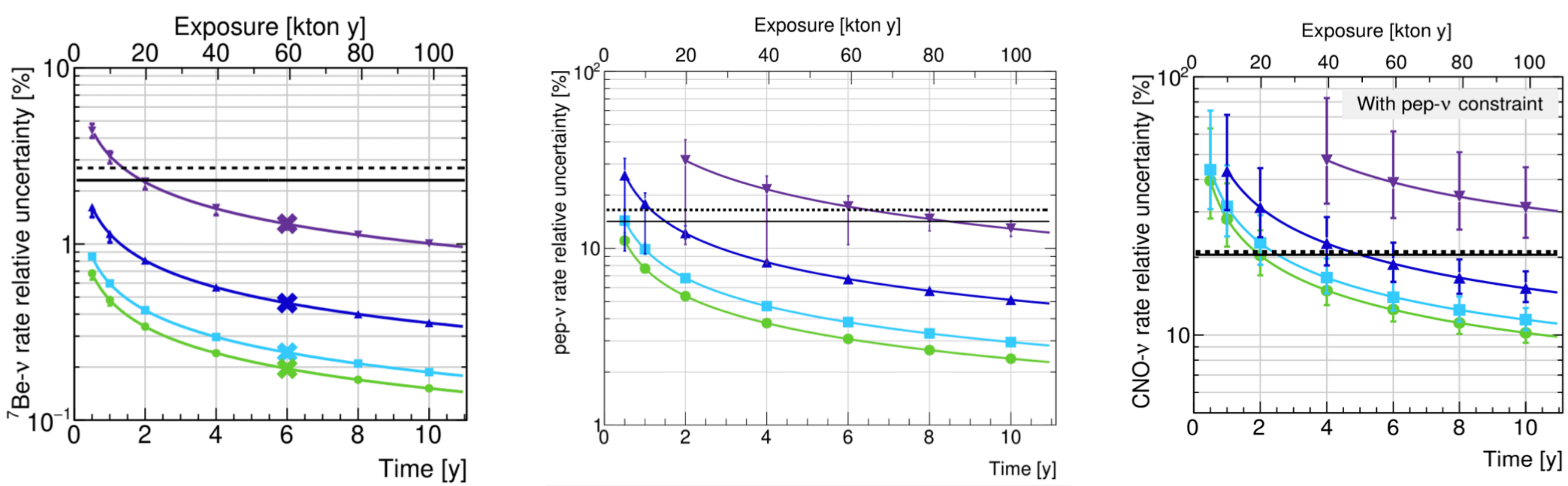
Chin.Phys.C 45 (2021)2, 023004



^{7}Be, pep, CNO neutrino observation

- Sensitivity depends strongly on the scintillator radiopurity.

JCAP 10 (2023) 022

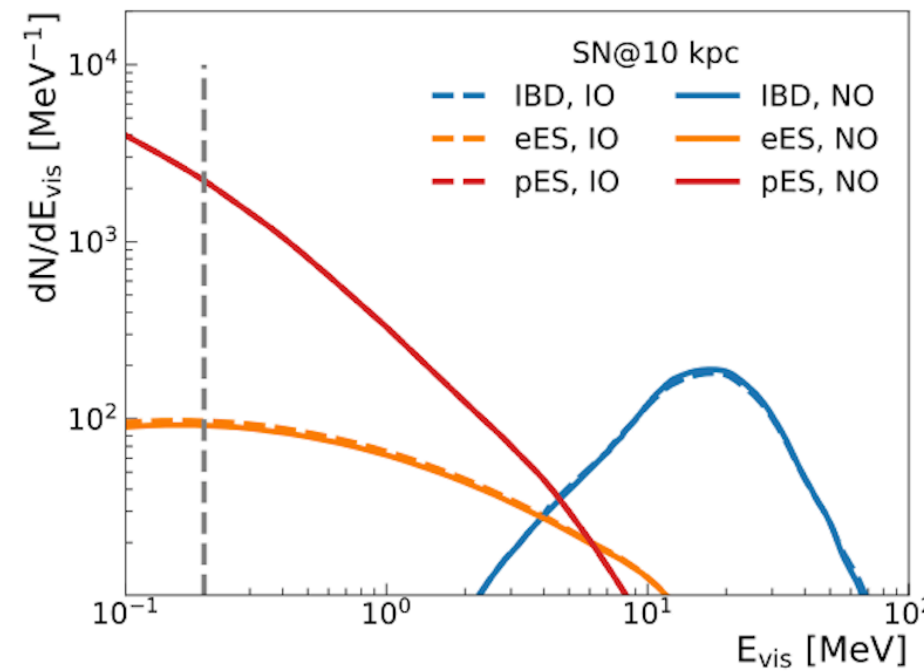


Supernova neutrinos

Core collapse neutrinos

JCAP 01 (2024) 057

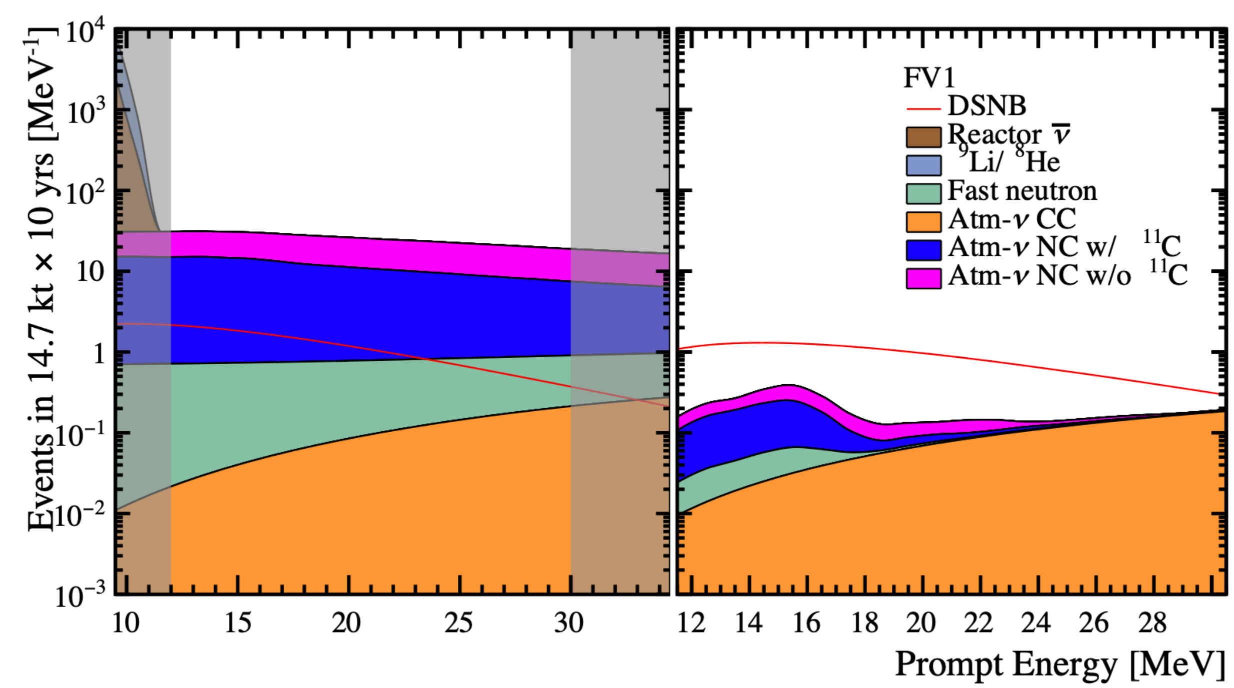
- SN rate: ~ 3 per century
- Core-collapse SN emits ~99% of the energy via neutrinos.
- Multi-channel detection : all flavors.
- Expected rate @ 10 kpc: 5000 IBD, 2000 pES, 300 eES, 300 NC, 200 CC
- Determination of the time evolution, energy spectra and flavor content.



Diffuse supernova neutrino background

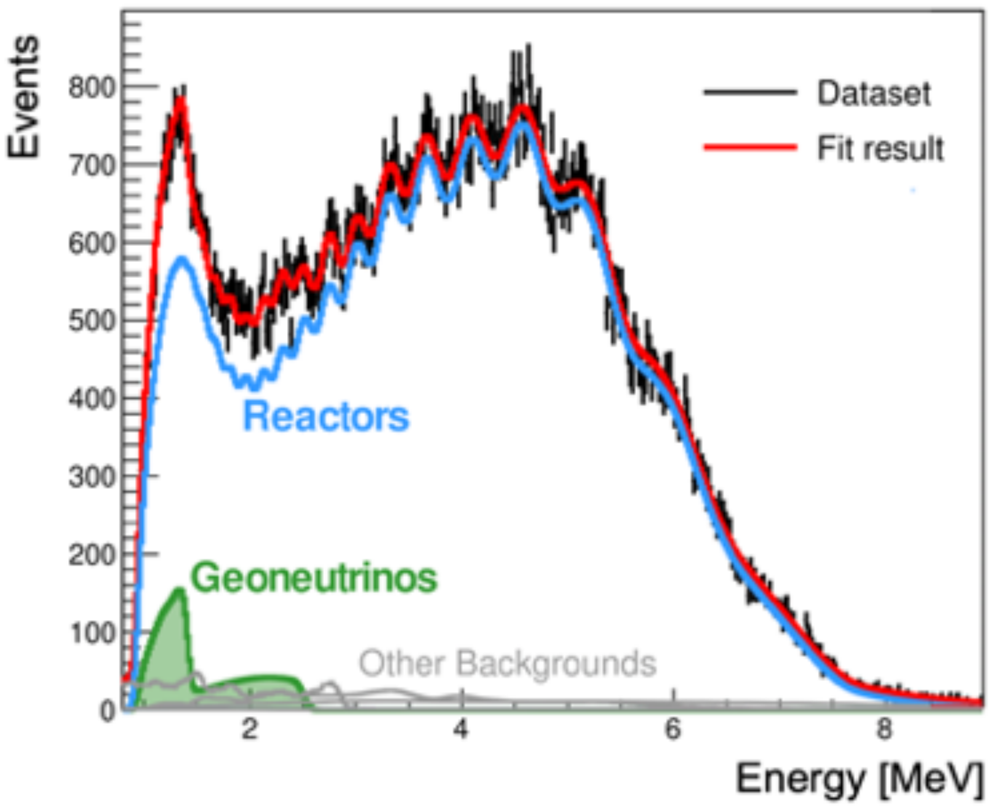
JCAP 10 (2022) 033

- Integrated neutrino signal from all the SN explosions in the Universe.
- Many background sources
- Expected rate: IBD (2~4/year)
- Expected significance of 3σ in 3 years.



Geoneutrinos

- Geoneutrinos originate from β-decays of U, Th and K present in the Earth.
- Geoneutrinos are detected via IBD (threshold 1.8 MeV).
- The largest background is due to reactor neutrinos.



- JUNO will collect the largest dataset of geoneutrinos in about 1 year : ~400 geo-neutrinos/year.
- The precision of total geoneutrino signal is ~ 8% in 10 years with Th/U ratio fixed (KamLAND: ~15%, Borexino: ~17%).
- Expected precision for U+Th, U, Th and Th/U ratio:

	6 years	10 years
^{232}Th:	~40%	~35%
^{238}U:	~35%	~30%
^{232}Th+^{238}U:	~18%	~15%
^{232}Th/^{238}U ratio:	~70%	~55%

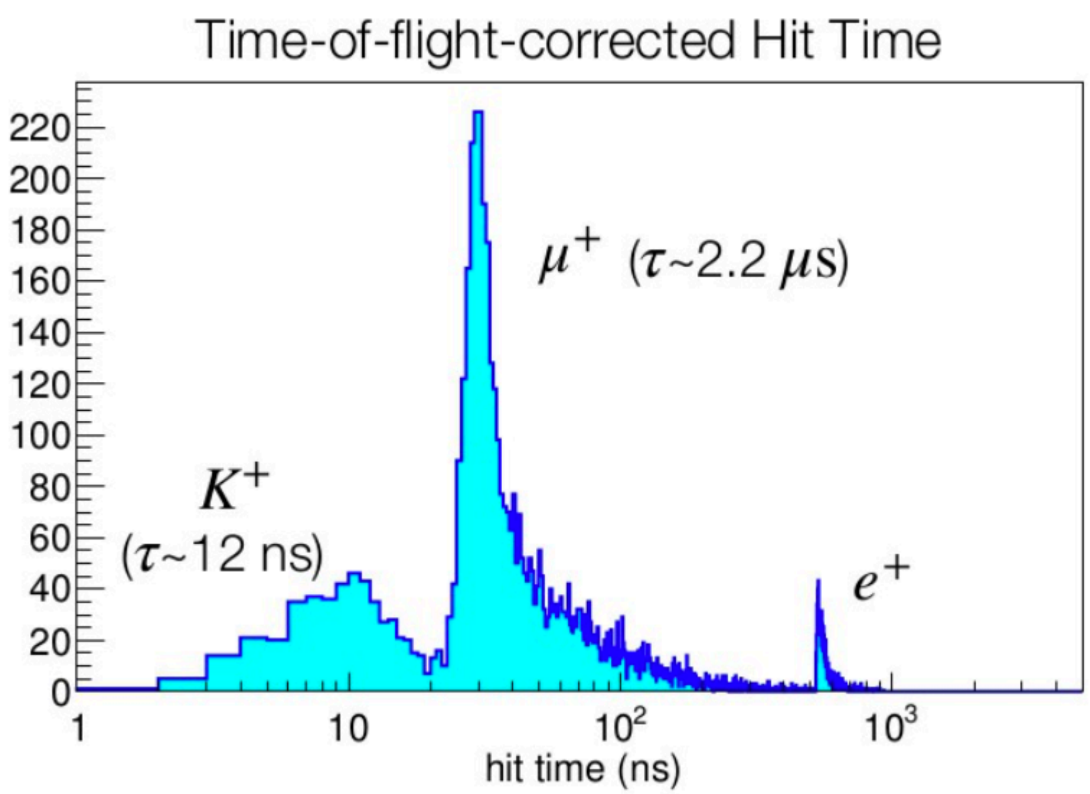
PRELIMINARY

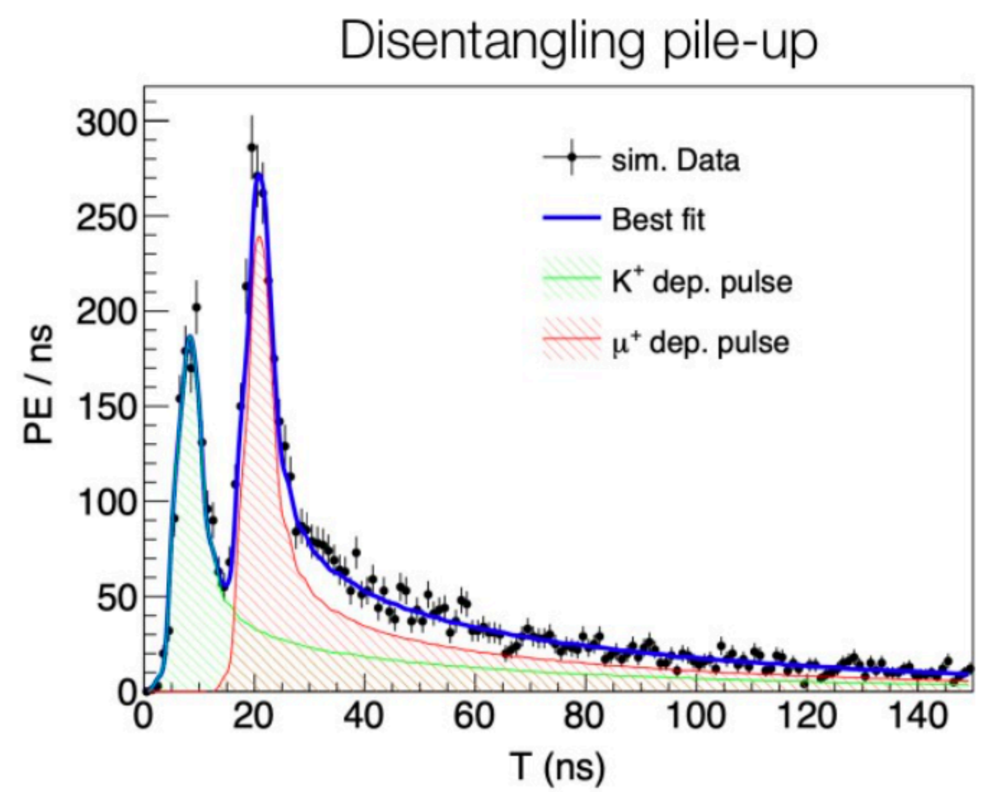
Proton decay

Competitive sensitivity to proton decay searches exploiting the $p \to \bar{\nu} + K^+$

- clear identification: 3 signals in coincidence.
- background from atmospheric neutrinos.

CPC 47, 113002 (2023)





Expected sensitivity: 9.6 ×10^{33} years at 90% CL in 10 years of data taking (200 ton.yr).

Conclusions

- JUNO will be the largest reactor anti-neutrino detector ever built (20 kilo-ton of liquid scintillator) with an unprecedented energy resolution (3% @ 1 MeV).
- The construction is on-going and the start of data taking is foreseen next year.
- Data taking with OSIRIS to measure the LS radioactivity is on-going.
- JUNO has a vast physics program in particle physics and astrophysics.
- The parameters Δm^2_{31}, Δm^2_{21}, $\sin^2\theta_{12}$ will be measured with sub-percent precision.
- The mass ordering determination in 6 years × 26.6 GWth will be given with :
  - ~ 3σ with reactor neutrinos only (completely independent from CP-violation and θ_{23})
  - > 3σ with long baseline and/or atmospheric neutrinos.
- TAO program will improve the knowledge of reactor antineutrino fluxes and spectra.