Review of current status and focus on future km baseline reactor anti-neutrinos experiments

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on behalf of JUNO collaboration

NuPhys 2023

Neutrino oscillation

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

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

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

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

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

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

E: Neutrino energy
L: baseline

- In the case of anti-neutrinos reactor, we can only observe the disappearance and the probability can be written as:

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

- Studying oscillation with anti-neutrinos reactor does not rely on δ_{CP} and θ_{23} which allow for a clean measurements of the other parameters.

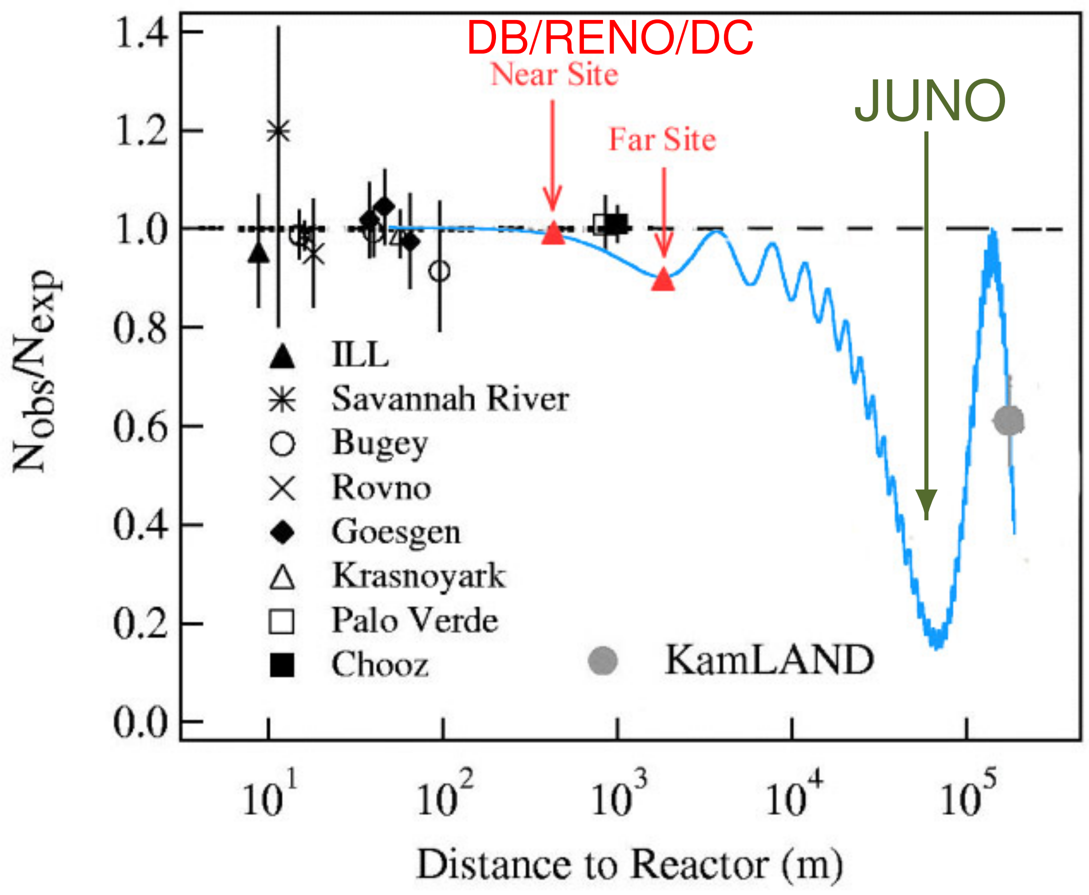
Reactor neutrino oscillation

Short baseline

Medium baseline

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

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



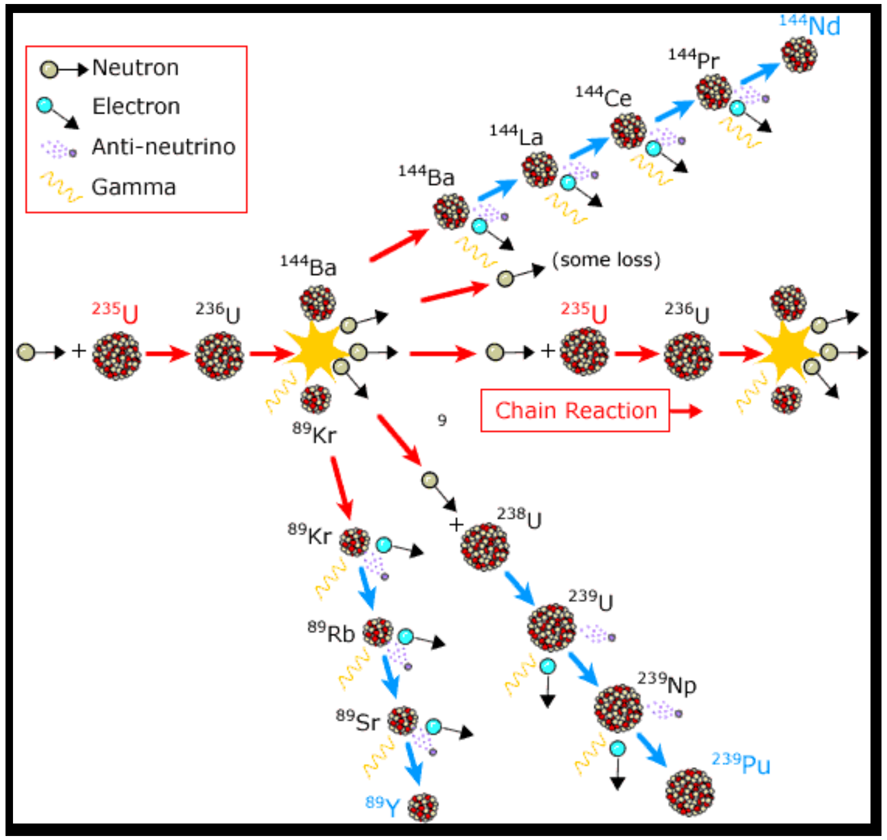
- There are 3 oscillations components which correspond to 3 oscillation frequencies in the L/E space which are proportional to $|\Delta m^2_{ij}|$ respectively:
  - Medium baseline (50 km): driven by (θ_{12}, Δm^2_{12}) parameters.
  - Short baseline (1 km): driven by (θ_{13}, Δm^2_{13}) parameters.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

- Baselines are short enough to neglect matter effects.

Reactor as a copious source of neutrinos

- Nuclear reactors are an intense and pure source of electronic anti-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



Reactor neutrino spectrum prediction

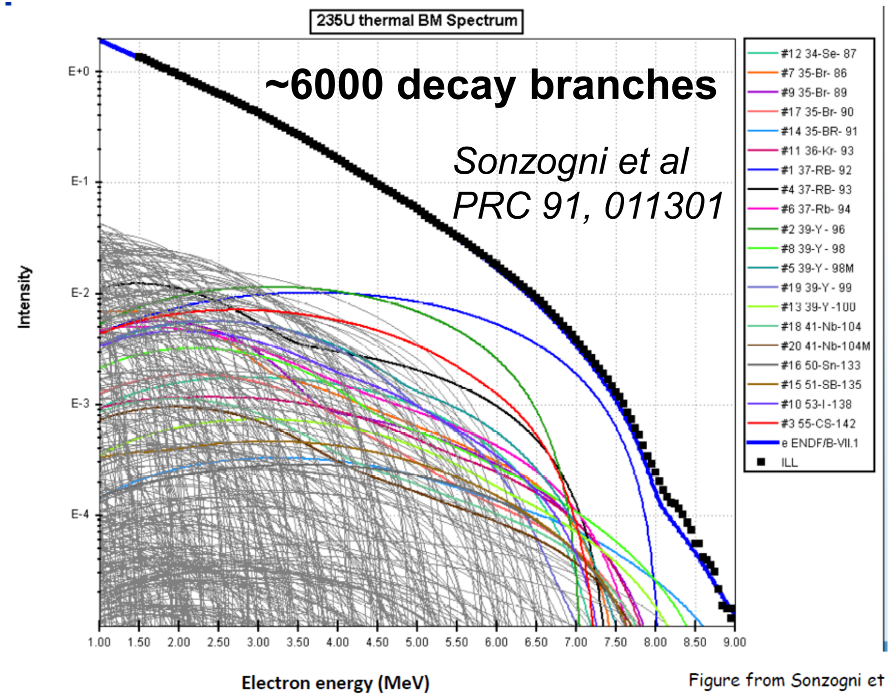
- Taking into account the time evolution and the numerous branching, the prediction of the flux and spectrum are not easy.

Summation (ab initio) method

- The spectrum can be computed as the sum of the contributions from all fission products.

$$S_{\mathrm{tot}}(E) = \sum_{k={}^{235}\mathrm{U},{}^{238}\mathrm{U},{}^{239}\mathrm{Pu},{}^{241}\mathrm{Pu}} \alpha_k \times S_k(E)$$

- This requires a huge amount of nuclear data.



~6000 decay branches

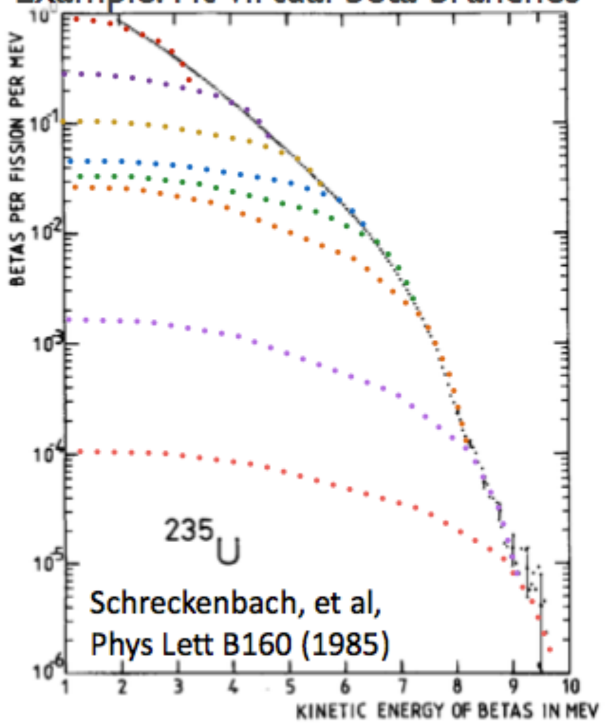
Sonzogni et al PRC 91, 011301

Figure from Sonzogni et

Conversion method

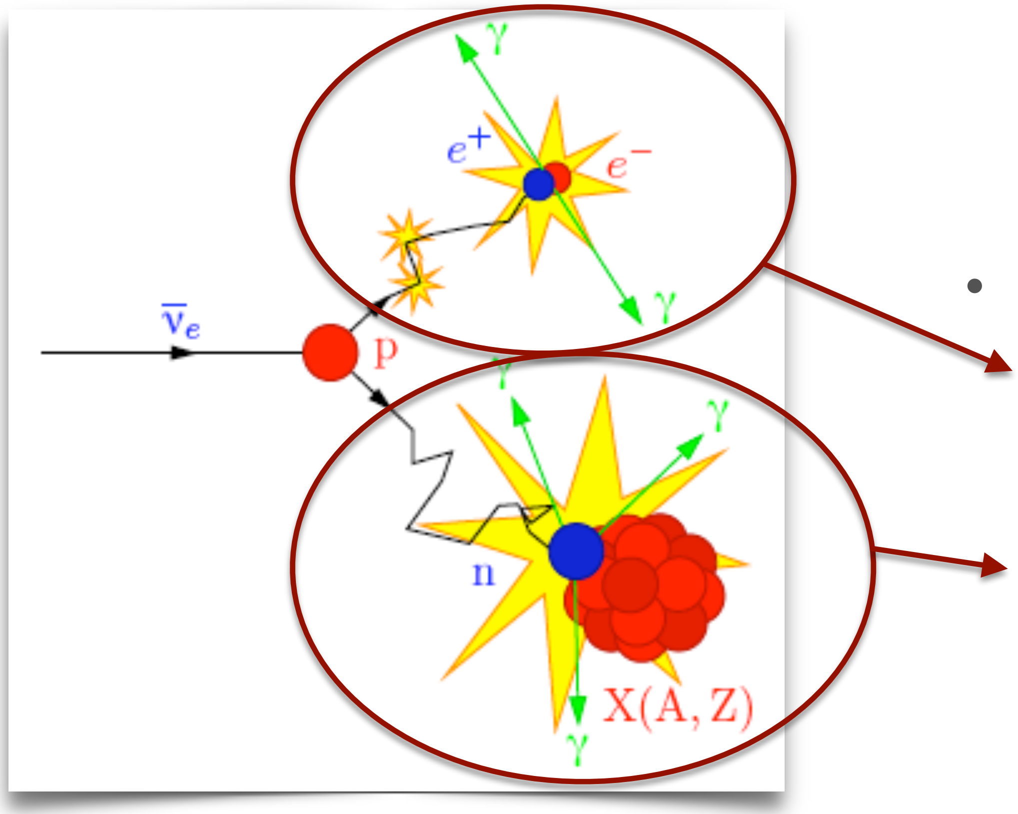
- It is based on the measured beta spectra of fissile isotopes at ILL.
- This spectrum can be converted to determine the anti-neutrino spectrum using virtual branches.
- Several difficulties to include effective branches (charge, forbiddenness).

Example: Fit virtual beta branches



Schreckenbach, et al, Phys Lett B160 (1985)

Measure reactor anti-neutrino

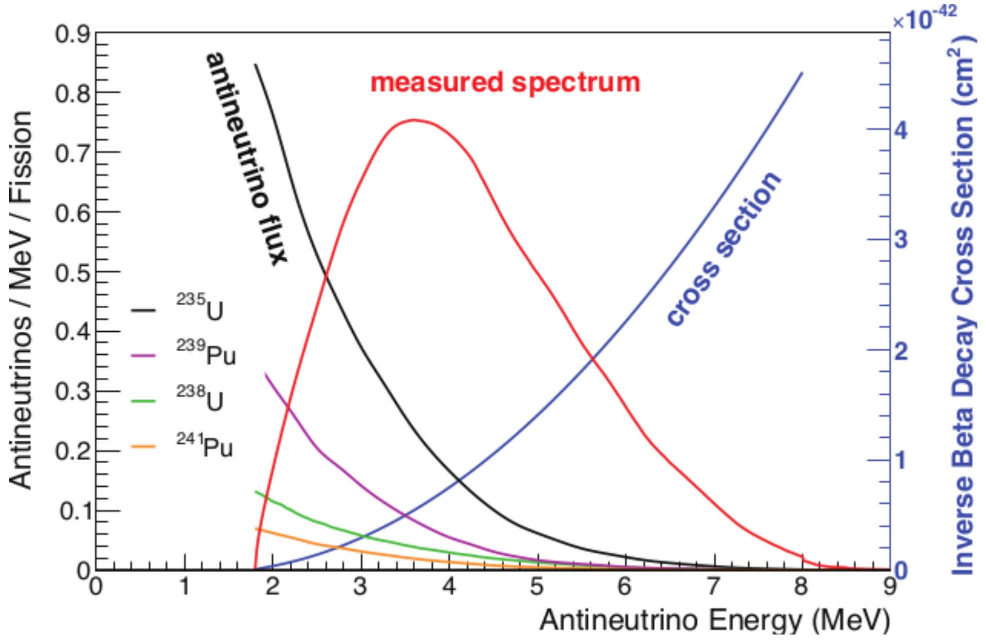


- The preferred channel to observe neutrinos is via Inverse Beta Decay (IBD):

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

- 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:

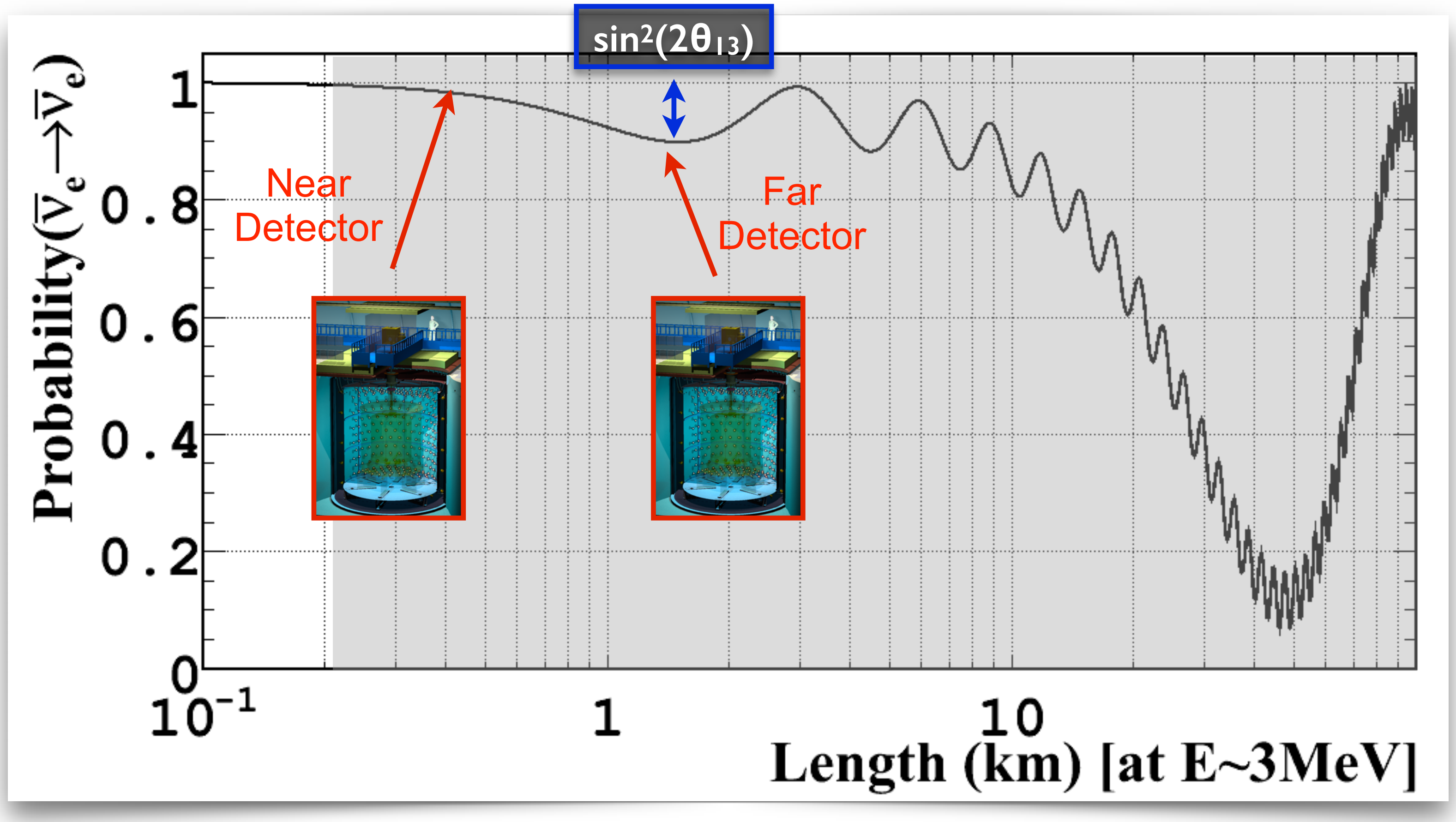
$$\boxed{E_{prompt}=E_{\nu}-T_{n}-0.8\ \text{MeV}}$$

Short baselines :

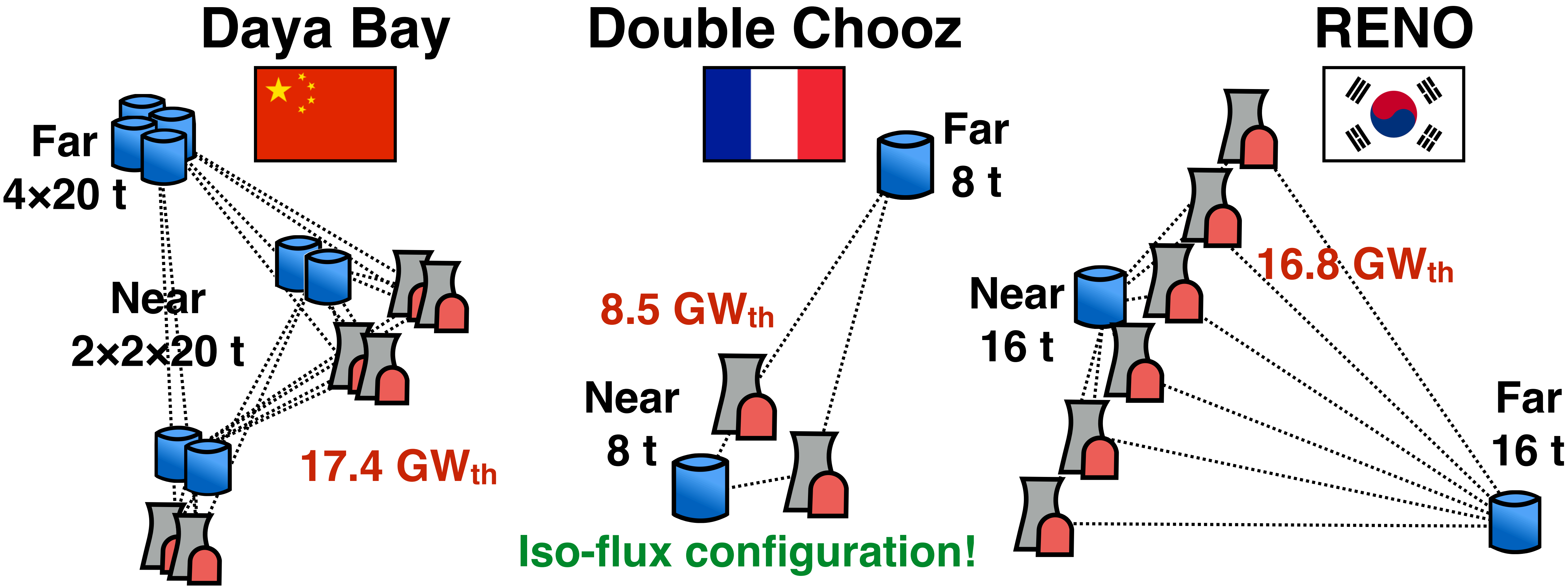
θ_{13} measurements and spectral anomaly

Discovery of θ_{13} mixing angle

- Short baseline allows the determination of θ_{13} :
  - Mixing angle governs the overall size of $\overline{\nu}_e$ deficit.
  - Effective mass squared difference | Δm^2_{ee}| determines the deficit dependance on L/E.
- The use of near and far detectors allows to measure the flux before and after the oscillation to cancel out the associated systematics.



θ_{13} measurement experiments



Daya Bay

Far
4×20 t

Near
2×2×20 t

17.4 GW_{th}

Double Chooz

Far
8 t

8.5 GW_{th}

Near
8 t

RENO

16.8 GW_{th}

Near
16 t

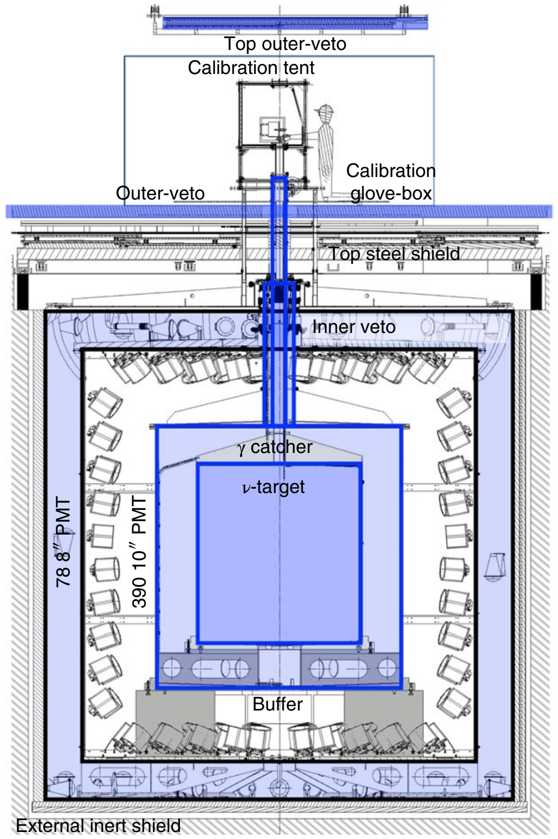
Far
16 t

Iso-flux configuration!

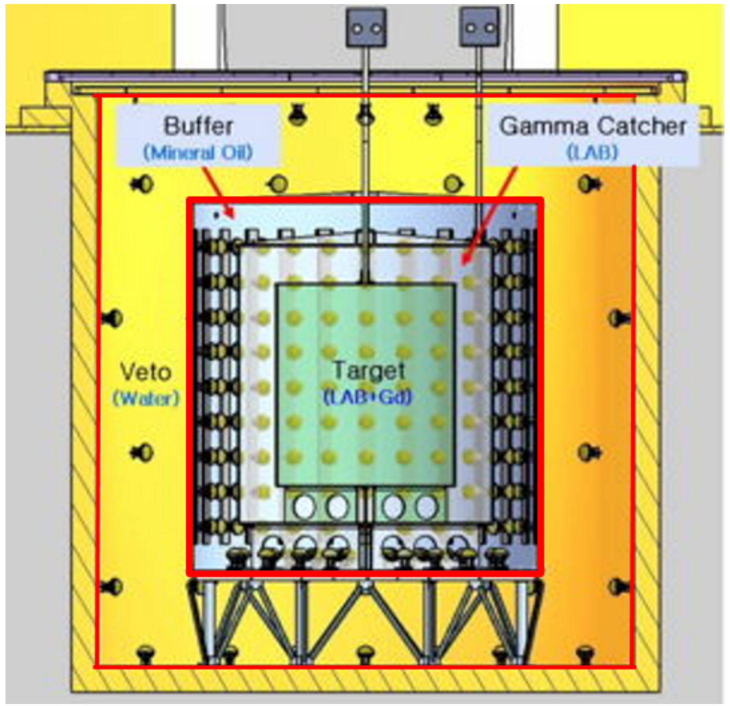
	Power [GWth]	GdLS mass Near/Far [t]	Distance Near/Far [m]	Overburden [mwe]
Daya Bay	17.4	2x2x20 4x20	365,490 1650	250 860
Double Chooz	8.5	8 8	400 1050	120 300
RENO	16.8	16 16	290 1380	120 450

Detector design

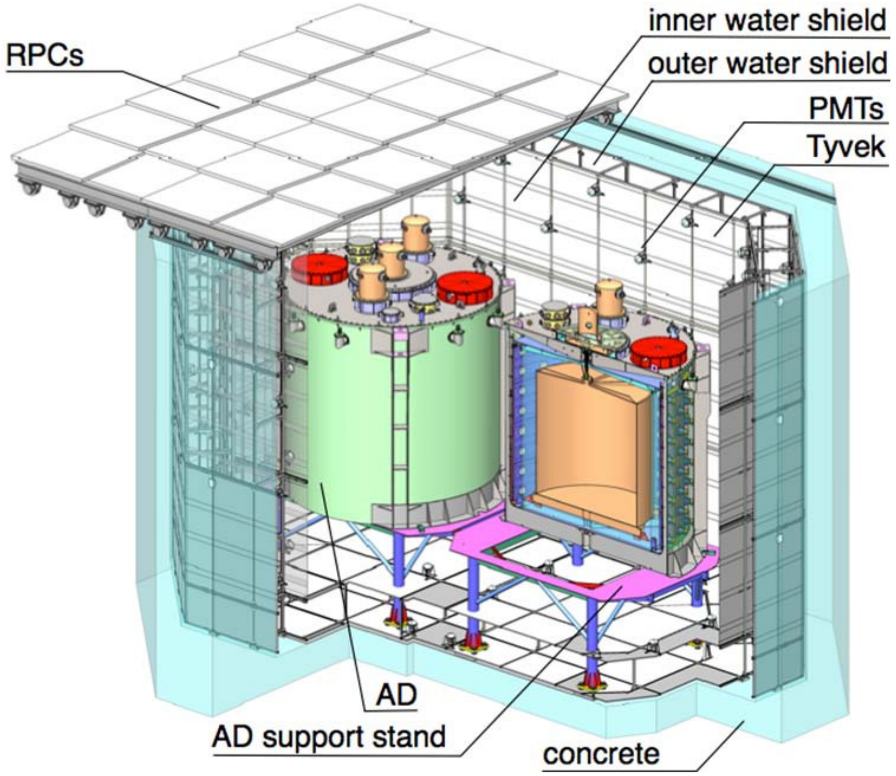
Double Chooz



RENO

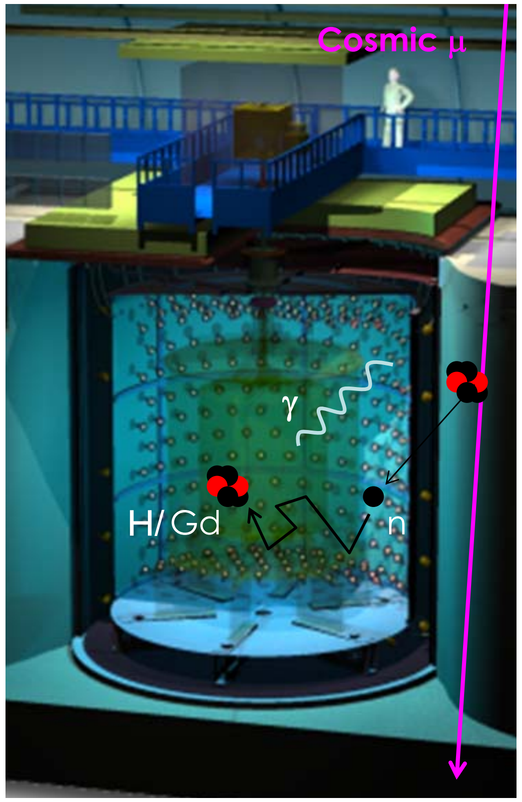
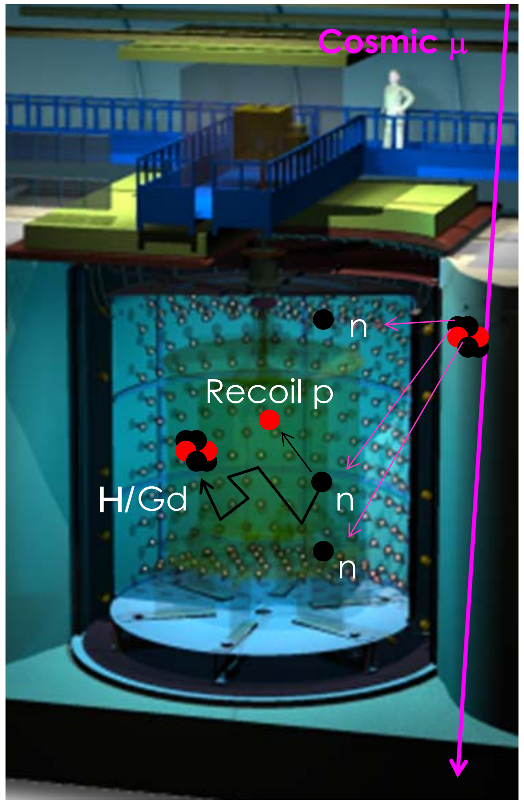
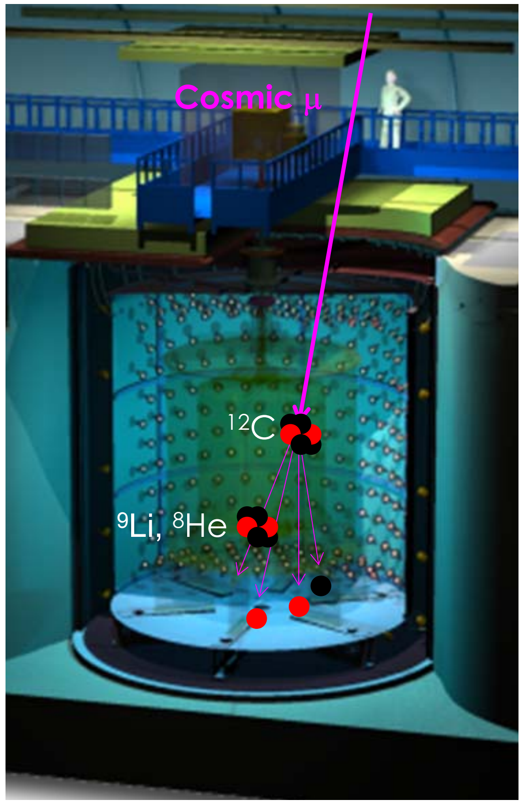


Daya Bay



- The 3 detectors had the same onion structure:
  - Target: Gadolinium-doped liquid scintillator.
  - Gamma-Catcher: Liquid scintillator. Can be used as target for n-H analysis.
  - Buffer: non-scintillating transparent mineral oil with PMTs.
  - Veto for cosmic muon and fast neutron detection (Cherenkov detector or liquid scintillator).
  - Top veto to tag muons (RPC or plastic scintillator strips).

IBD Background

	Accidental BG	Correlated BG	
		Fast neutrons	**Cosmogenics**
			
Prompt	Radioactivity from materials, PMTs, surrounding rock (^{208}Tl).	Neutrons from cosmic μ spallation gives recoil protons (low energy).	Electrons from ^{9}Li/^{8}He β + n decays.
Delay	Neutrons from cosmic μ spallation captured on Gd/H, or γ like prompt fake signal in case of H analysis.	Neutrons from cosmic μ spallation captured on Gd/H, or γ like prompt fake signal in case of H analysis.	Neutrons from ^{9}Li/^{8}He β + n decays captured on Gd/H.

Spectrum measurement

Daya Bay

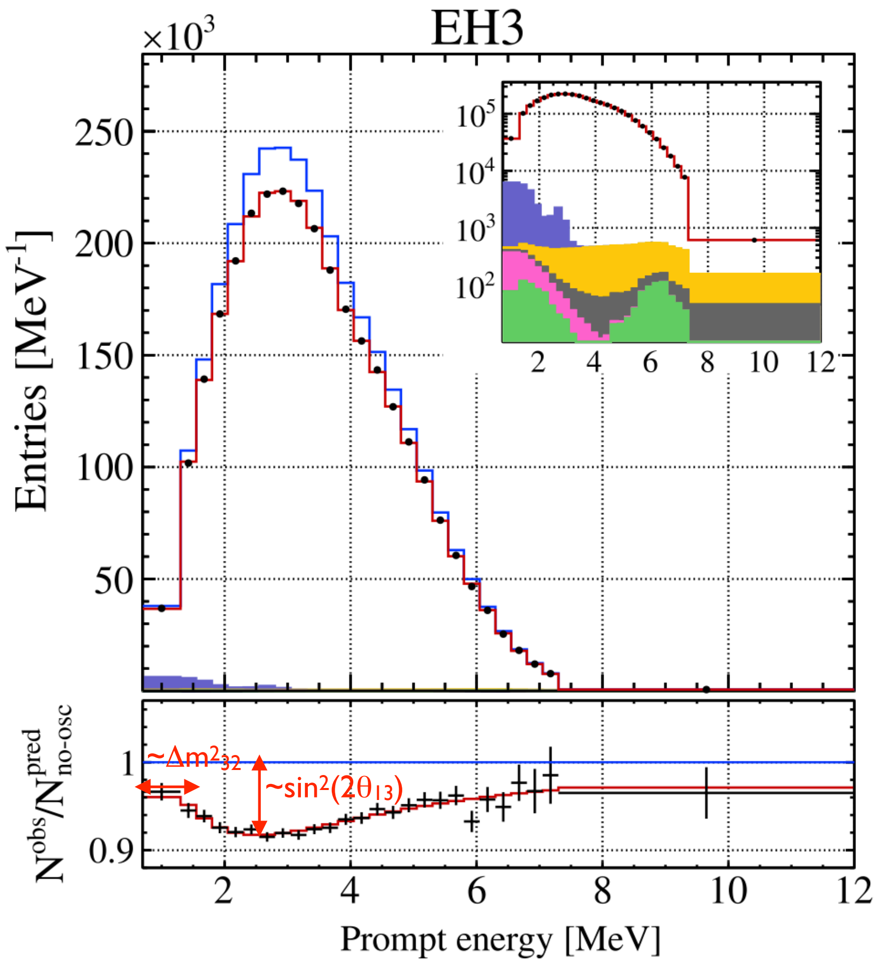
Phys.Rev.Lett. 130 (2023) 16, 161802

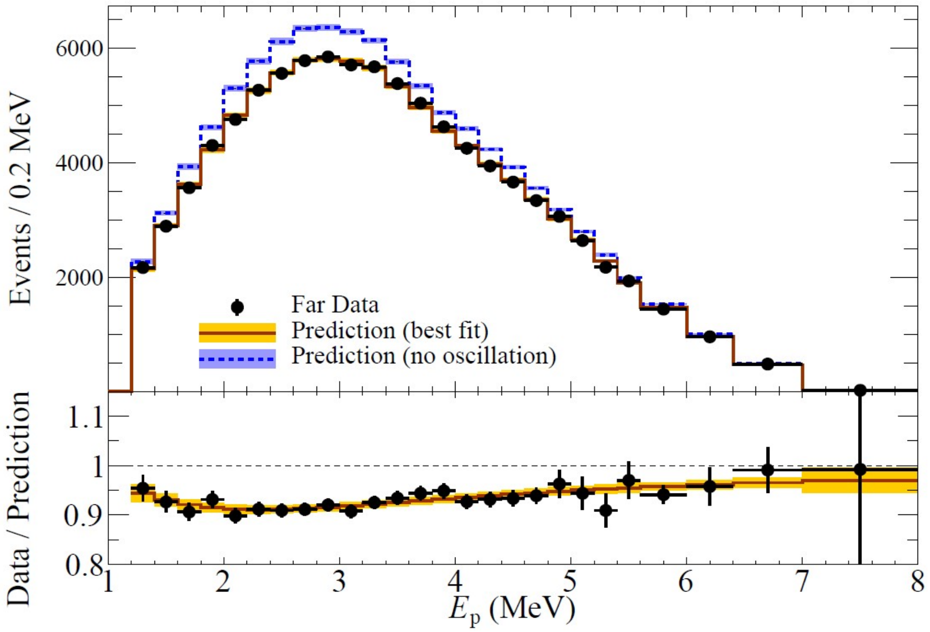
RENO,

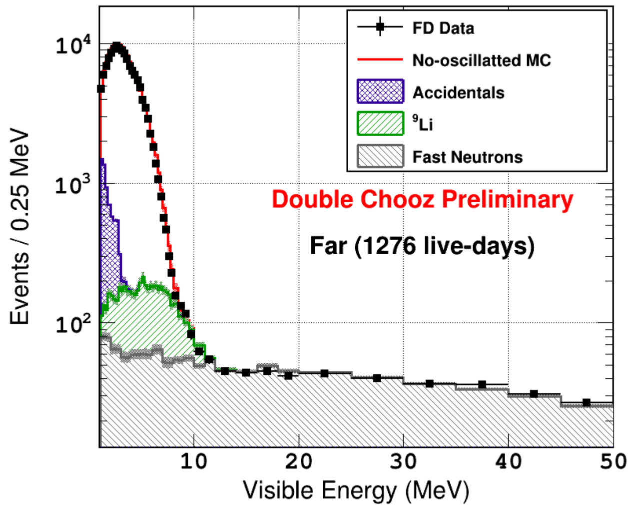
Phys.Rev.Lett. 121 (2018) 20, 201801

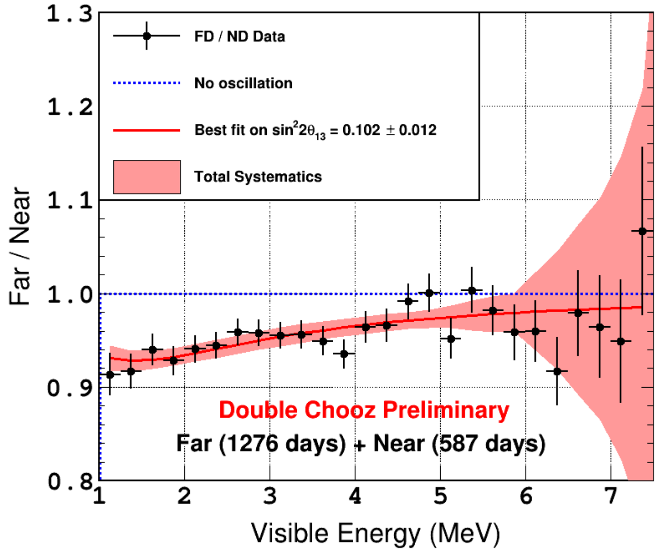
Double Chooz

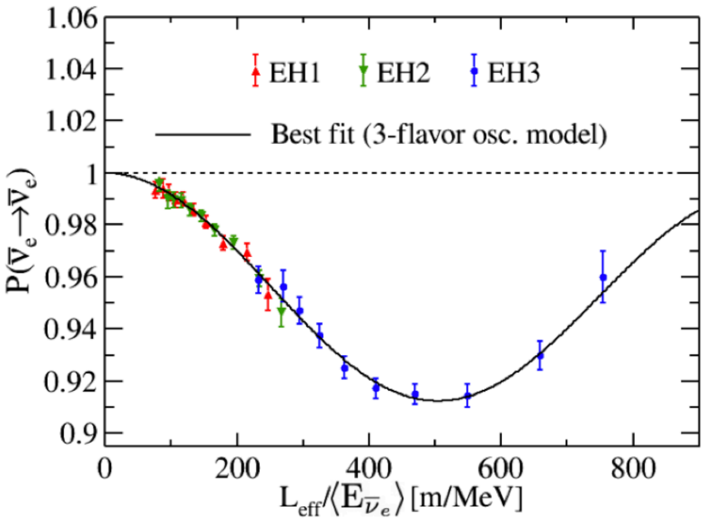
Nature Phys. 16 (2020) 5, 558-564



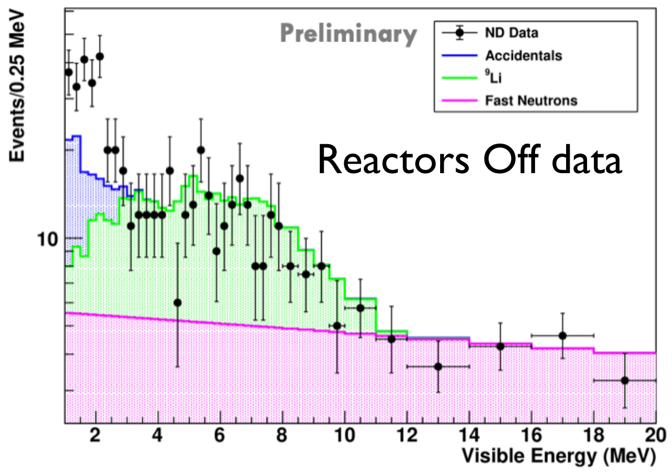








The 3 experiments have observed a deficit which is compatible with neutrino oscillation and which permit to measure θ_{13} as well as Δm^2_{32} (Daya Bay and RENO).

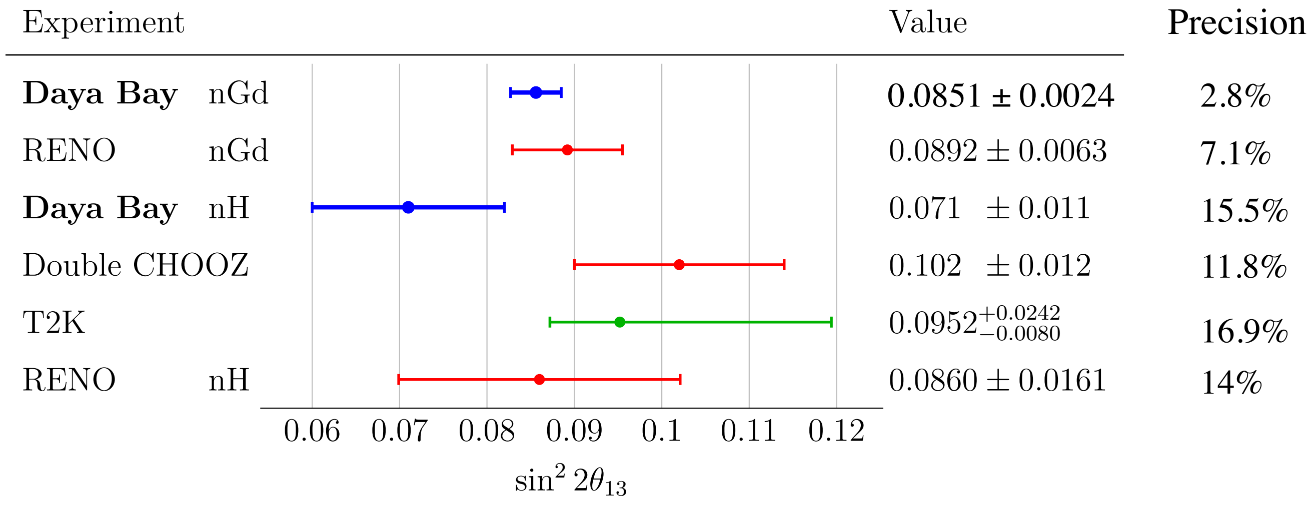


Reactors Off data

Oscillation Results

$\sin^2(2\theta_{13})$

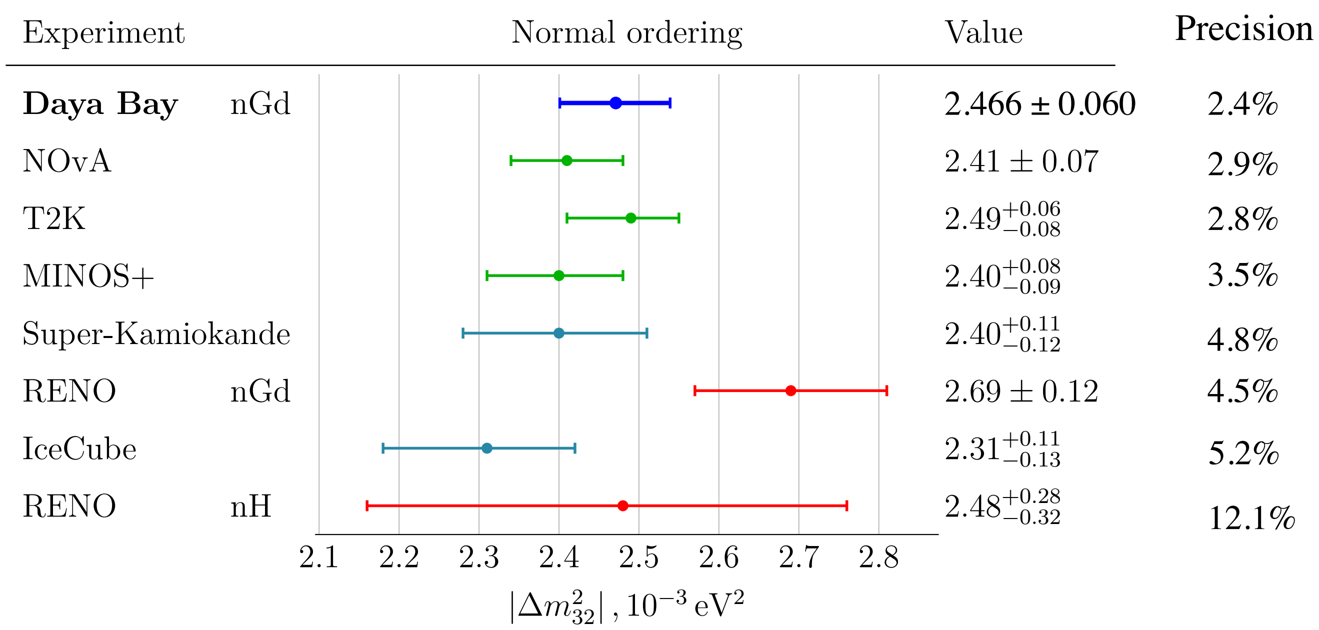
- All experiments have measured a non zero value of θ_{13} doing analysis both studying n-H and n-Gd captures.
- The pdg value is: $\sin^2(\theta_{13})=(2.20\pm0.07)\times10^{-2}$



Experiment		Value	Precision
Daya Bay	nGd	0.0851 ± 0.0024	2.8%
RENO	nGd	0.0892 ± 0.0063	7.1%
Daya Bay	nH	0.071 ± 0.011	15.5%
Double CHOOZ		0.102 ± 0.012	11.8%
T2K		$0.0952^{+0.0242}_{-0.0080}$	16.9%
RENO	nH	0.0860 ± 0.0161	14%

Δm^2_{32}

- Values measured by reactor experiments are consistent with ones from accelerator experiments.



Experiment		Value	Precision
Daya Bay	nGd	2.466 ± 0.060	2.4%
NOvA		2.41 ± 0.07	2.9%
T2K		$2.49^{+0.06}_{-0.08}$	2.8%
MINOS+		$2.40^{+0.08}_{-0.09}$	3.5%
Super-Kamiokande		$2.40^{+0.11}_{-0.12}$	4.8%
RENO	nGd	2.69 ± 0.12	4.5%
IceCube		$2.31^{+0.11}_{-0.13}$	5.2%
RENO	nH	$2.48^{+0.28}_{-0.32}$	12.1%

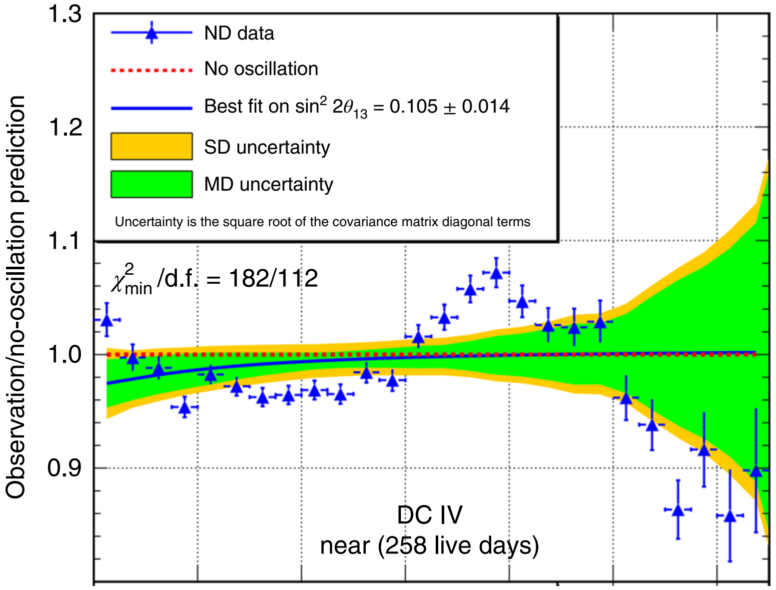
from Snowmass 2021 - Letter of Interest
Legacy of the Data Bay Reactor Neutrino Experiment
and updated results for Daya Bay (PRL 130, 1618021 (2023))

Spectrum comparison with prediction

- A shape distortion with respect to predicted spectrum has been observed but the 3 experiments: both at near and far site a bump at ~ 4-6 MeV is observed.
- This is a new « shape anomaly ».

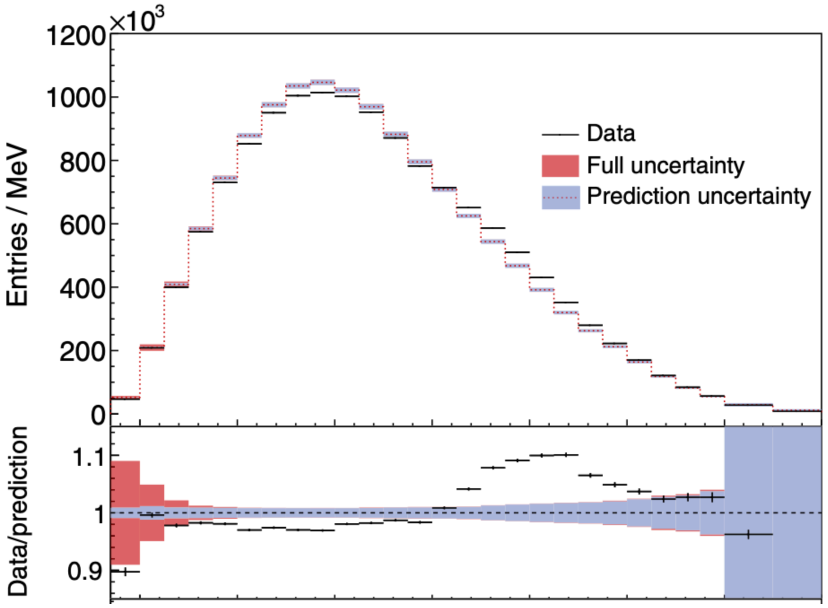
Double Chooz

Nature Phys. 16 (2020) 5, 558-564



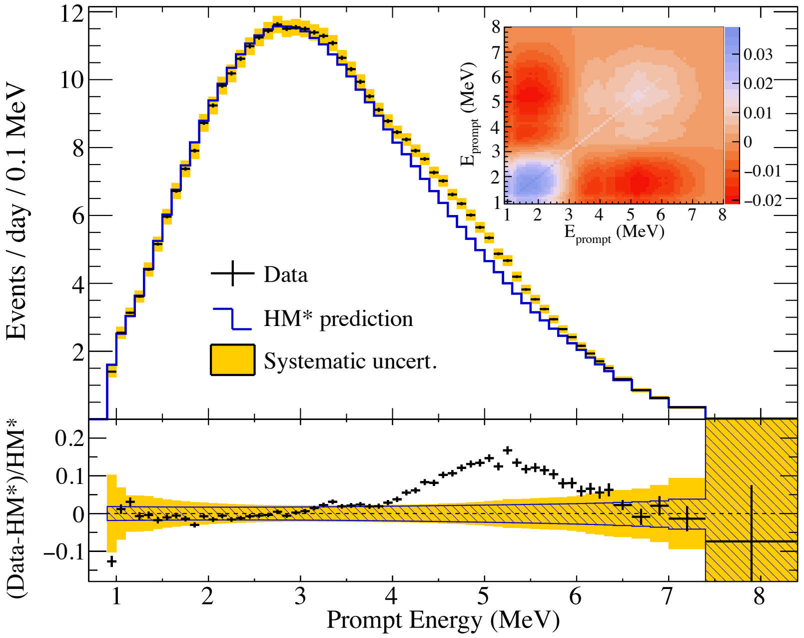
Daya Bay

Phys.Rev.Lett 123(2019) 111801



RENO,

Phys.Rev.D 104 (2021) 11, L111301

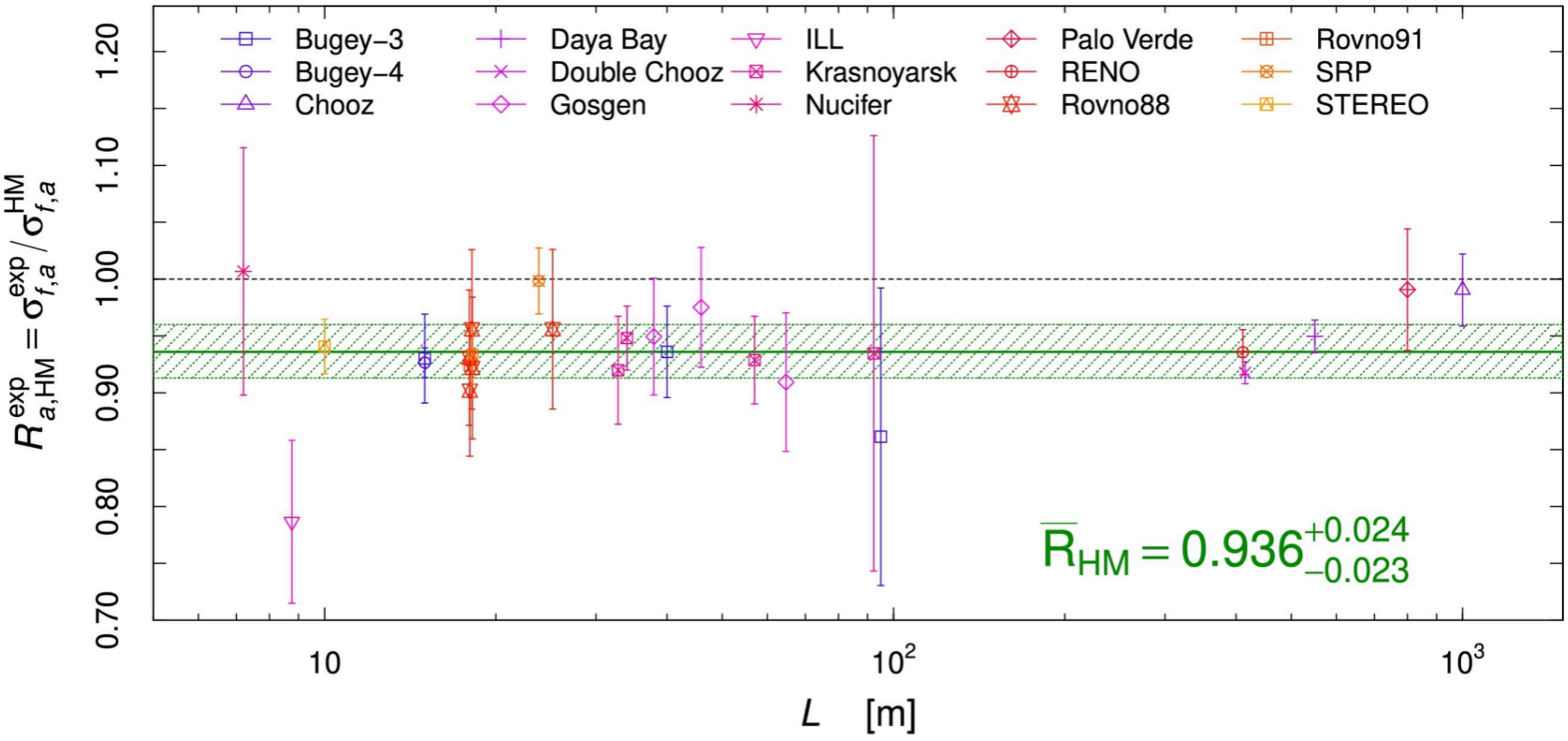


- This bump is not due to a detector effect.
- Sterile hypothesis is not consistant with an excess at 5 MeV.

Rate comparison with prediction

- The 3 experiments measured a deficit of the rate compared to predictions: R= 0.952±0.014(*exp*) ±0.023(*model*) for Daya Bay, R=0.940±0.020 (*exp*) for RENO, R=0.943±0.022 (*exp*) for Double Chooz.
- Total neutrino yield measurements have achieved great precision.

Giunti et al.
PLB 829 (2022) 137054

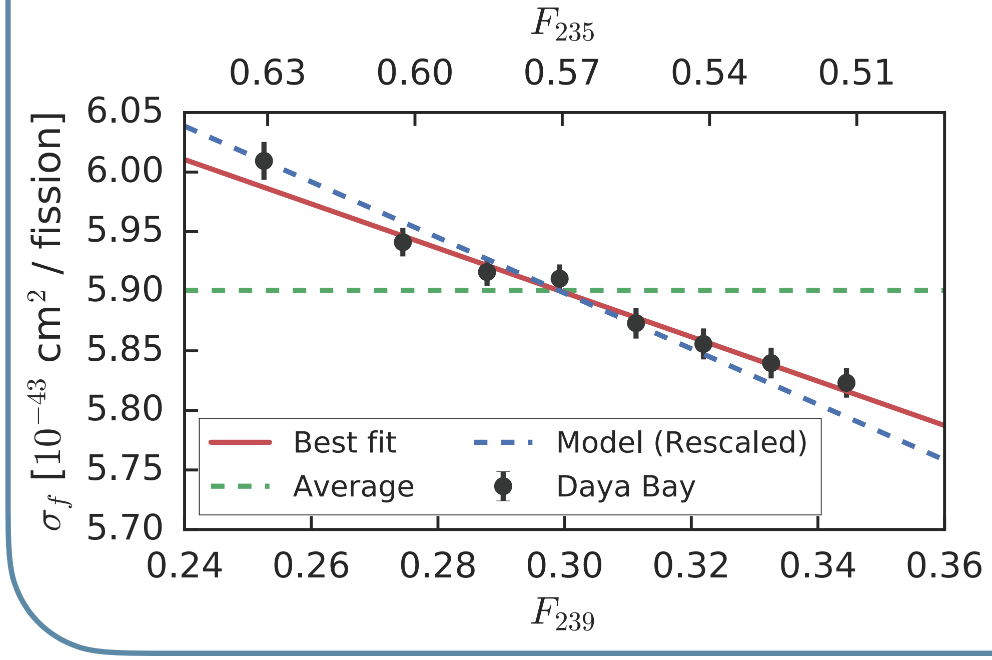


Shape Anomaly and Fuel Evolution

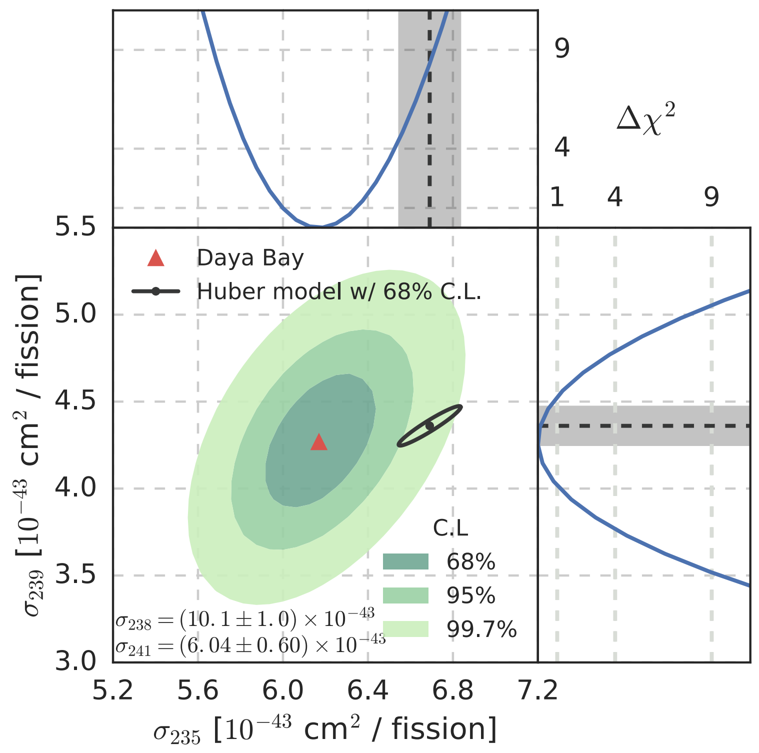
- In 2017, Daya Bay measured the fuel evolution allowing to disentangle ^{235}U and ^{239}Pu yields:
  - The fuel evolution ($d\sigma_f/dF_{239}$) is incompatible with predictions at 3.1σ.
  - ^{235}U fissions produced 7.8% fewer antineutrinos than predicted while ^{239}Pu is consistent.
- In 2019, RENO reinforce the conclusion.

Daya Bay

Phys.Rev.Lett. 118 (2017) 25, 251801



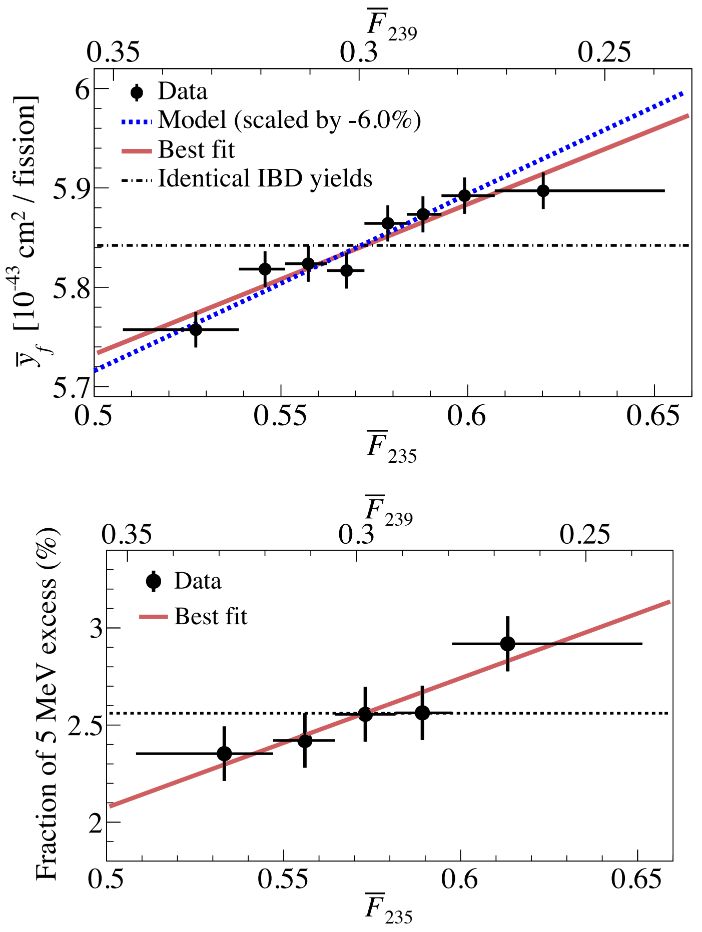
IBD Yield per fission



^{235}U and ^{239}Pu IBD yields per fission

RENO

Phys.Rev.Lett. 122 (2019) 23, 232501



- From DayaBay spectra: In the [4-6] MeV region, a 7% (9%) excess of events is observed for the ^{235}U (^{239}Pu) compared to HM normalized model *(Phys.Rev.Lett. 123(2019) 11, 111801)*.

Medium Baseline : JUNO Experiment

Mass hierarchy determination with reactor

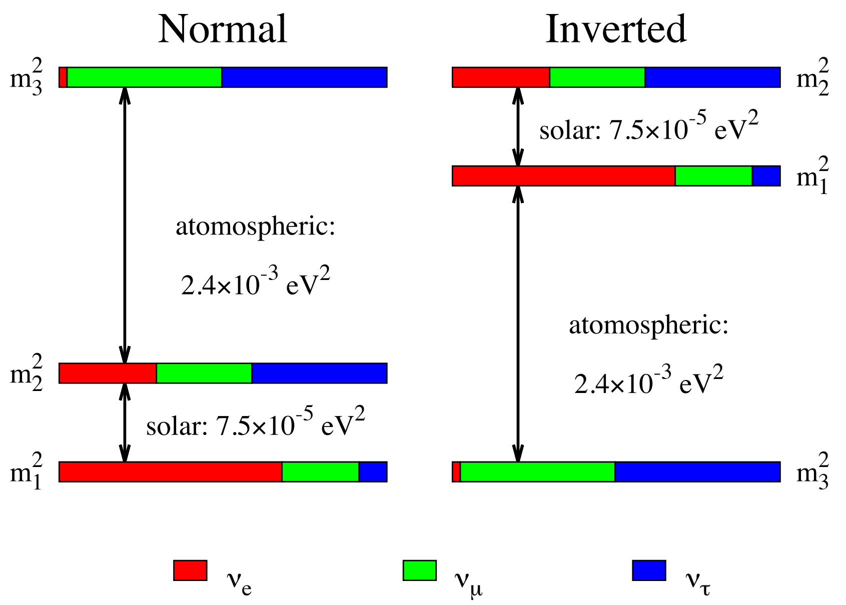
- Reactor anti-neutrinos experiment allow to determine the mass hierarchy doing a clean measurement since it is independent of the CP phase

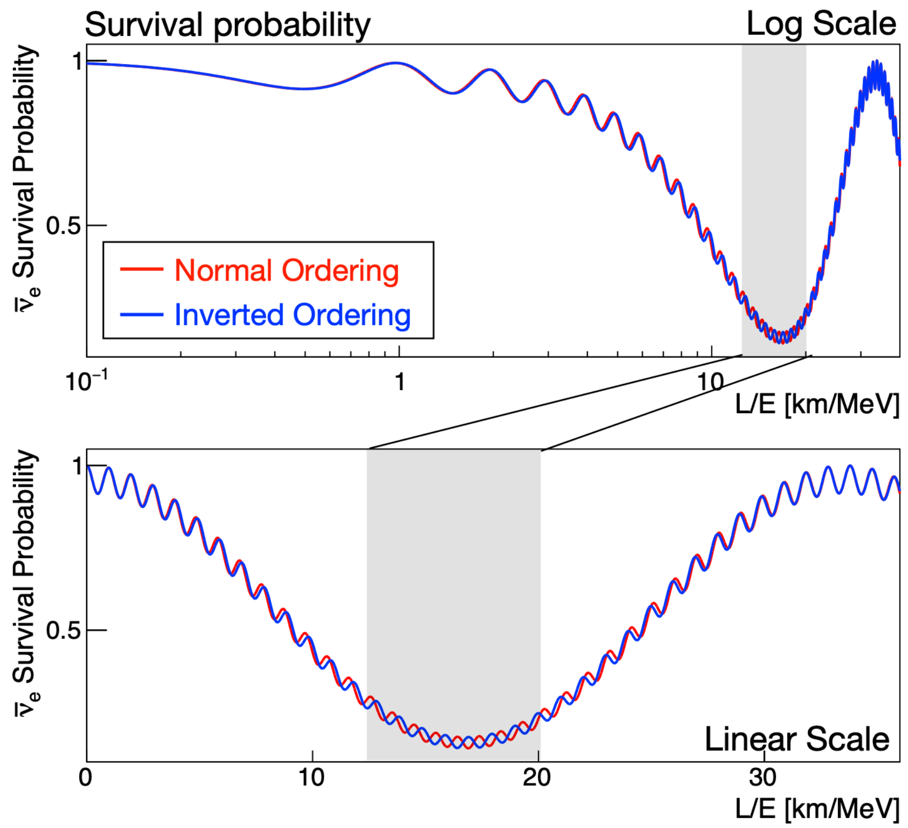
+ Normal hierarchy

- Inverted hierarchy

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

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

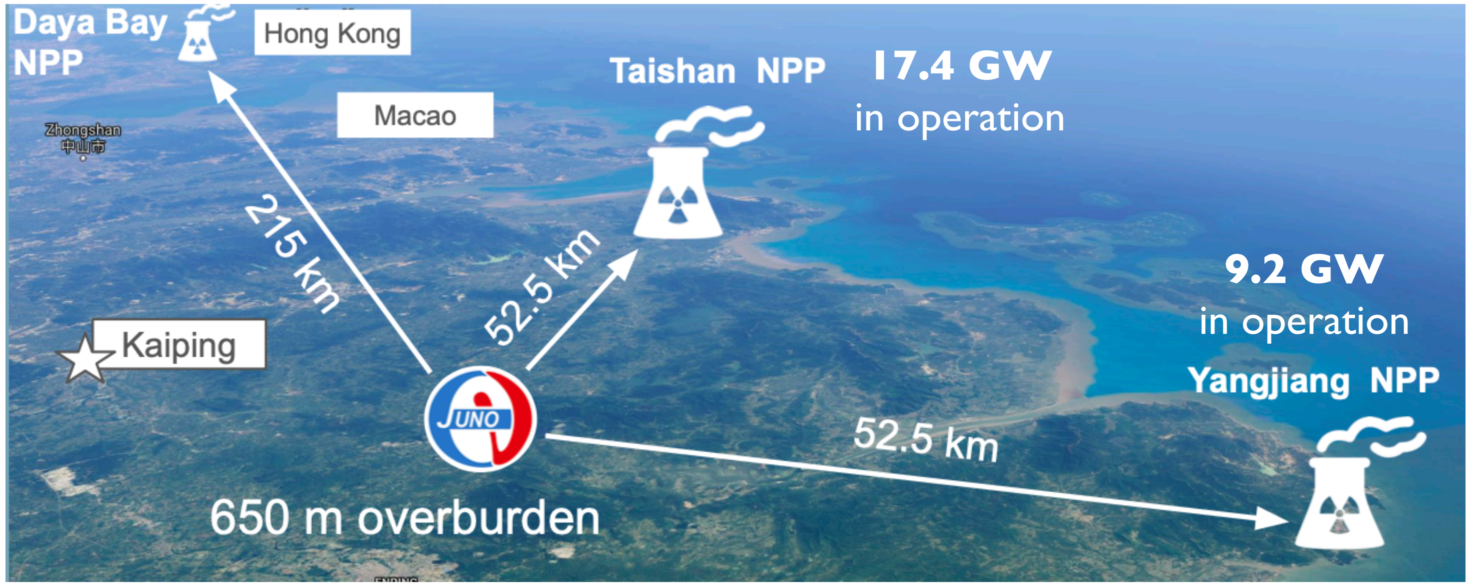


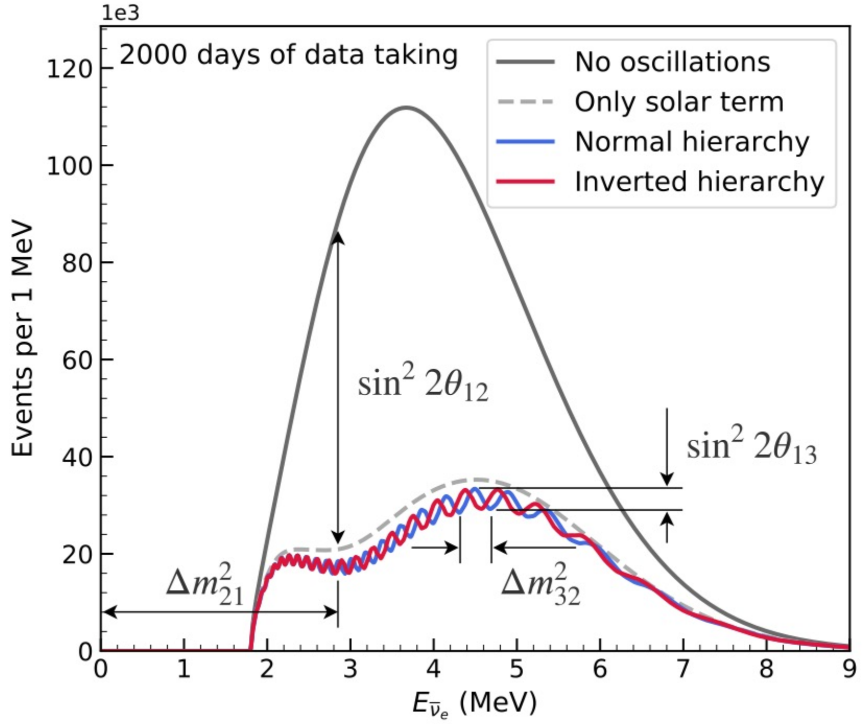


- Several conditions on baseline and energy resolution are necessary to perform such a measurement.
- At 53 km from the source, the oscillation is dominated by the terms (Δm^2_{12}, θ_{12}).
- If the energy resolution is high enough, it is possible to see the oscillation dominated by (Δm^2_{23}, θ_{13}) 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).

will the main goal of :

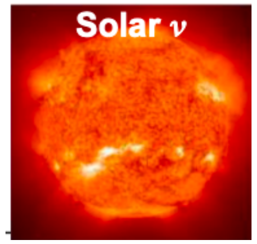
- perform a relative measurement on the mass ordering (no constraint on Δm^2_{31}, $\Delta\chi^2>9$) or an absolute measurement ($\Delta\chi^2>16$) accounting for constraints from long baseline experiments.

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

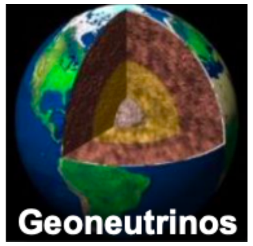
>~100 evts/day



^{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



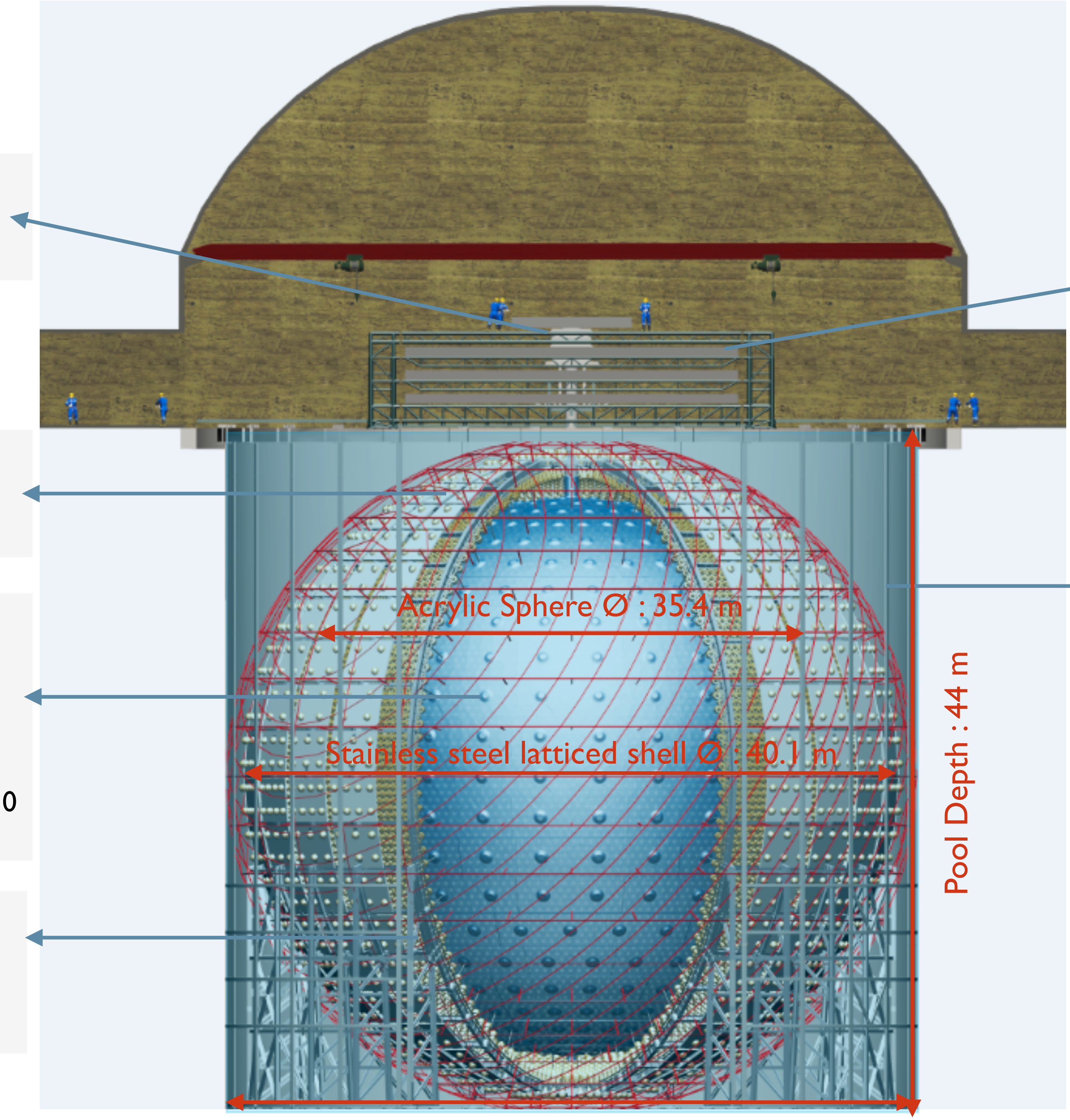
400 evts/year

→Neutrino mass ordering
→Precision measurement of solar oscillation parameters

JUNO detector

High energy precision

Backgrounds reduction



Water Pool Ø : 43.5 m

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
→~ 78% coverage

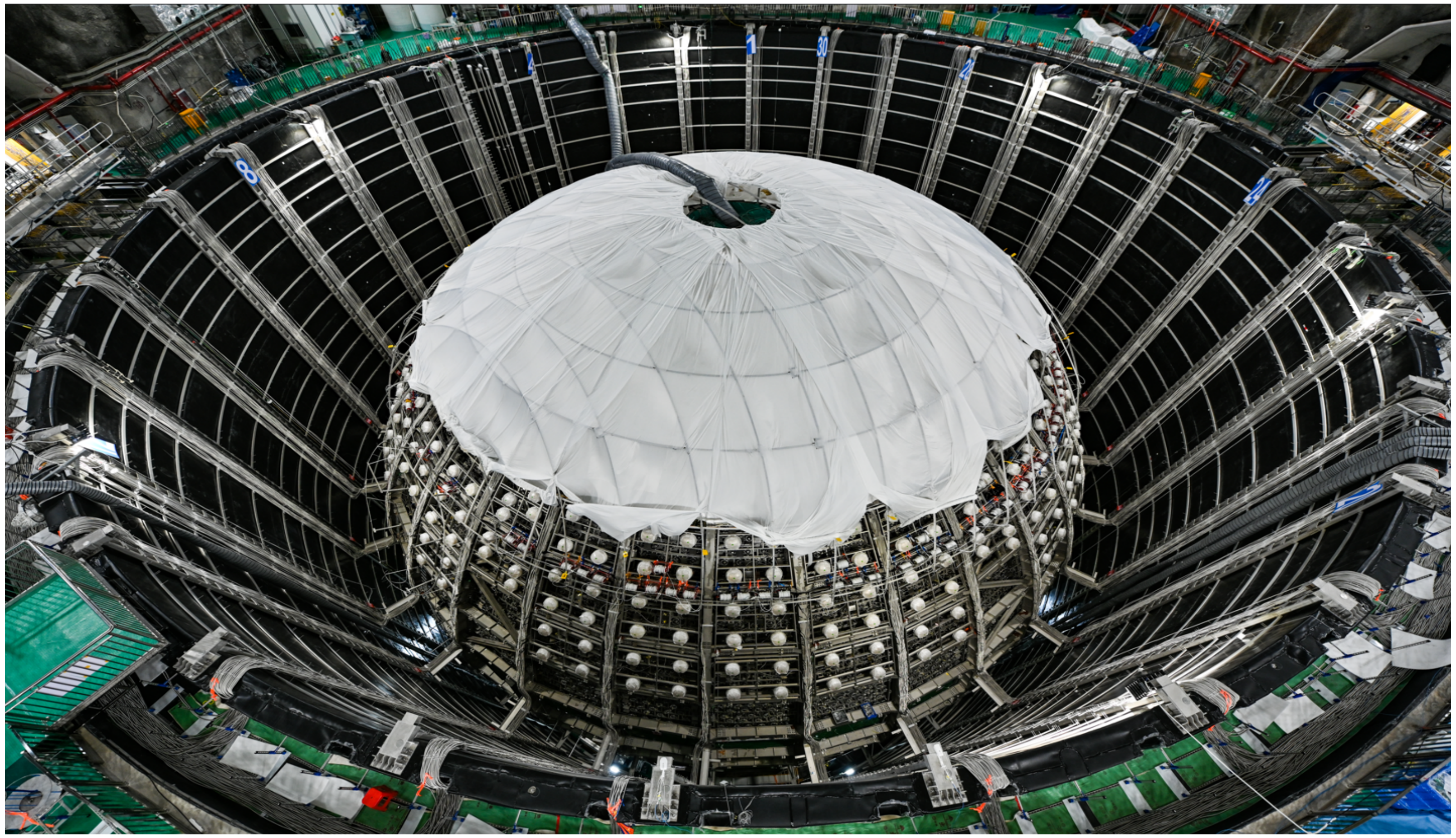
Top Tracker
3 layers of plastic scintillator (cover ~60% of Water Pool)
→Precise muon tracker

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.
- 2022-2023 : installation and commissioning.
- 2024 : Filling and start of data taking.

Current status



Central Detector PMTs view

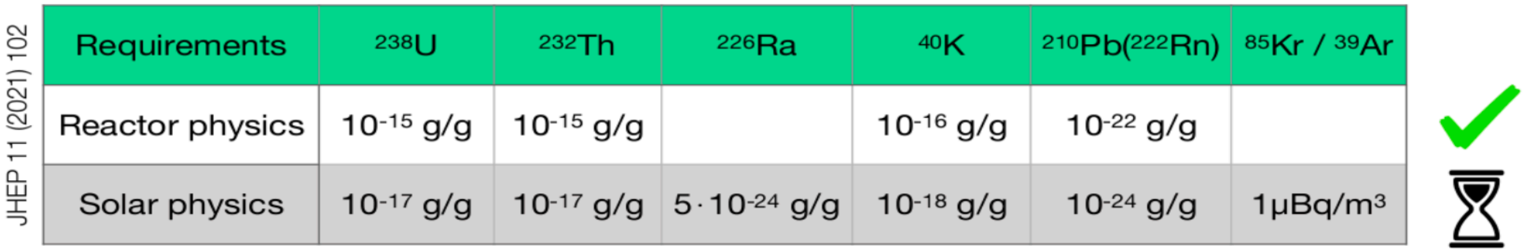
Liquid scintillator of JUNO

- 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	$5 \cdot 10^{-24}$ g/g	10^{-18} g/g	10^{-24} g/g	1µBq/m³	⌛

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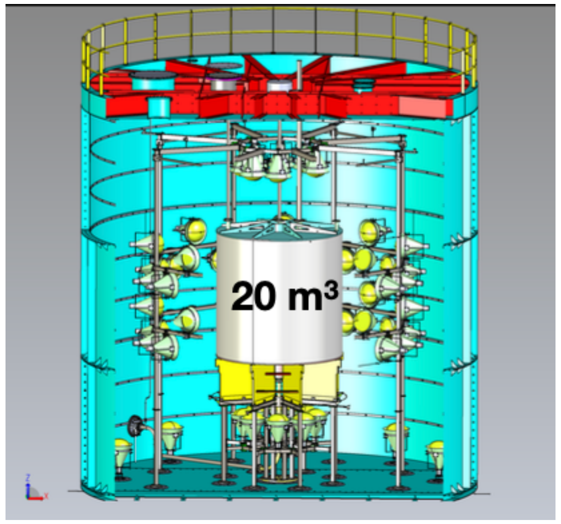
- Radio-purity will be ensured **during the filling** : an ancillary detector of 20 m³ will monitor batches of LS.

OSIRIS

Online Scintillator Internal Radioactivity Investigation System



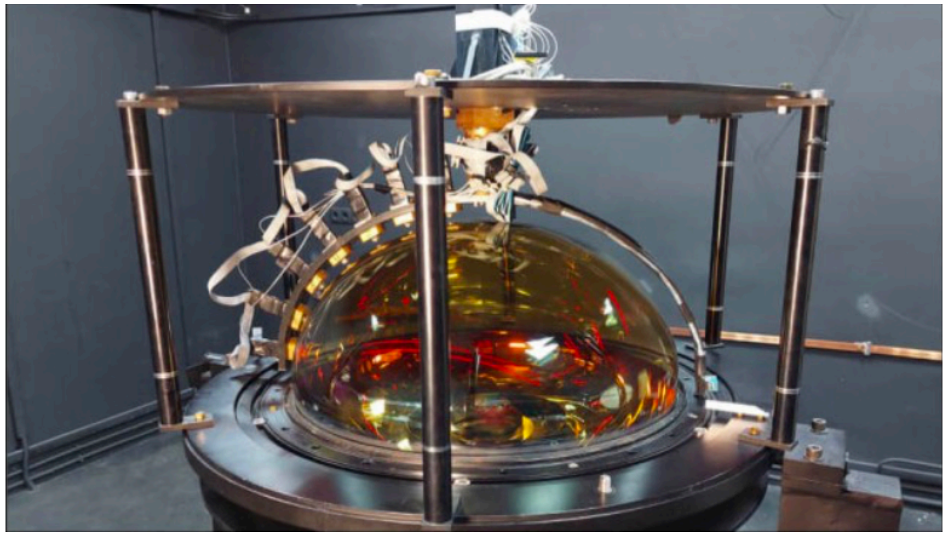
- Exploit Bi-Po decay in ^{238}U and ^{232}Th chains.
- Few days (weeks) needed to verify compliance to 10^{-15} (10^{-16}) g/g.

More details in N. Rodpai and Z.Wang poster

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

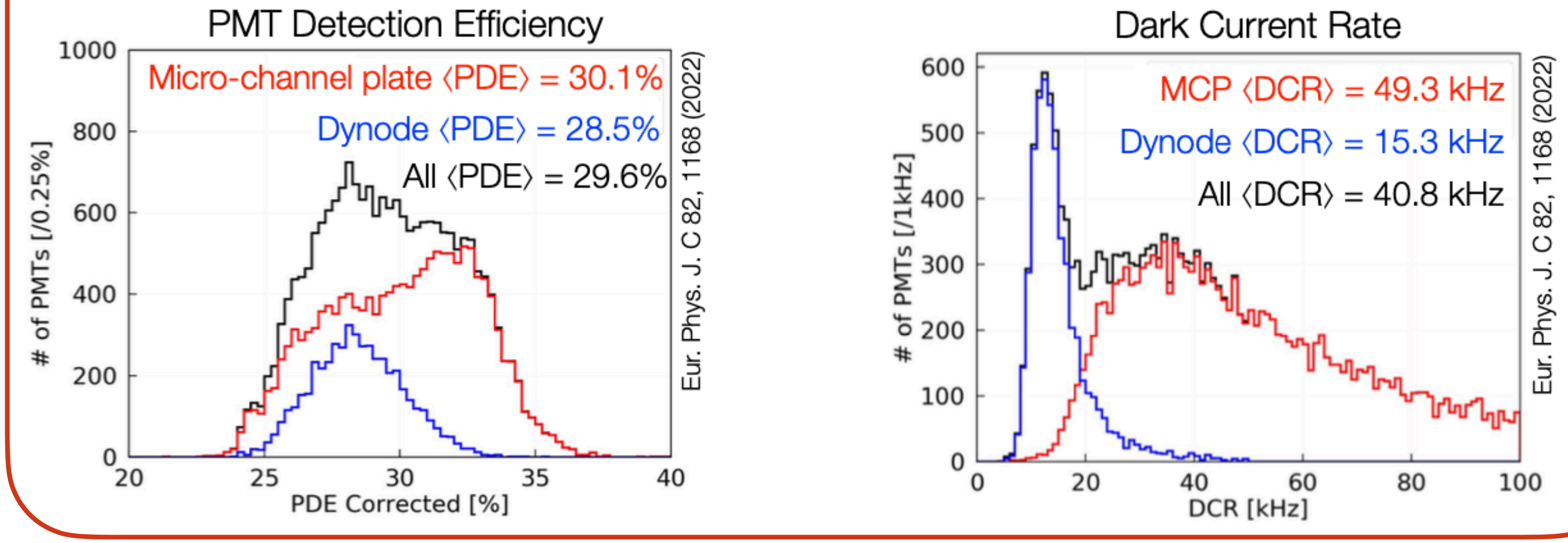


3” PMT

XP72B22

	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



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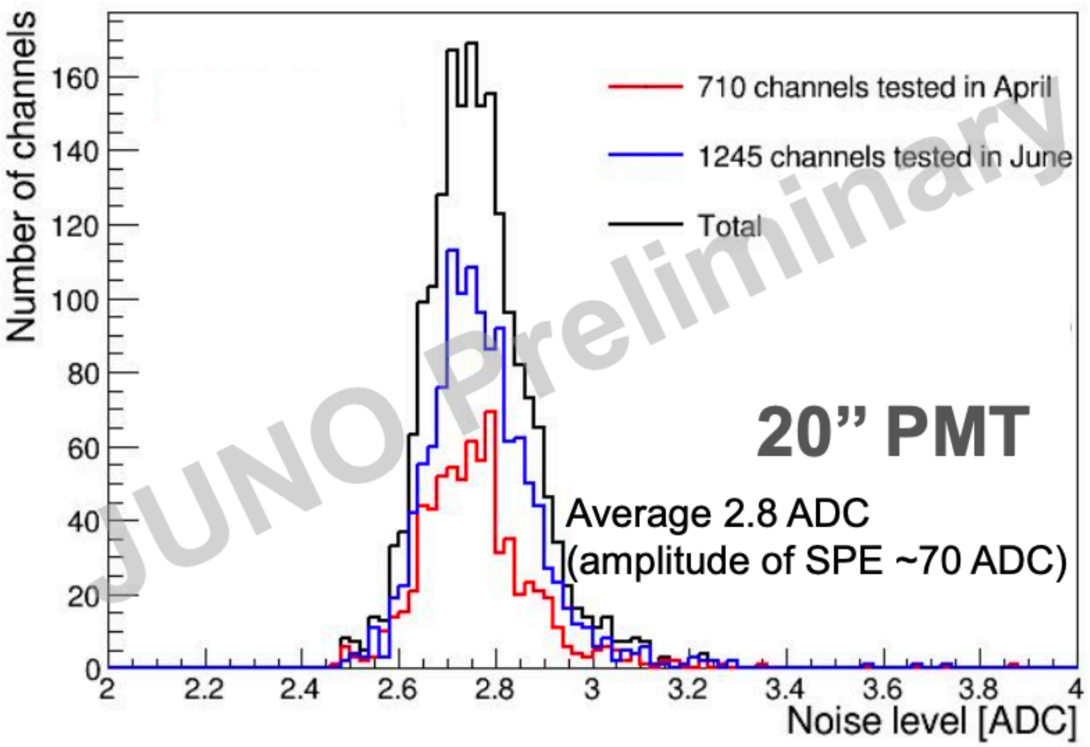
Photomultipliers system: commissioning

➡ All tested PMTs are working well.

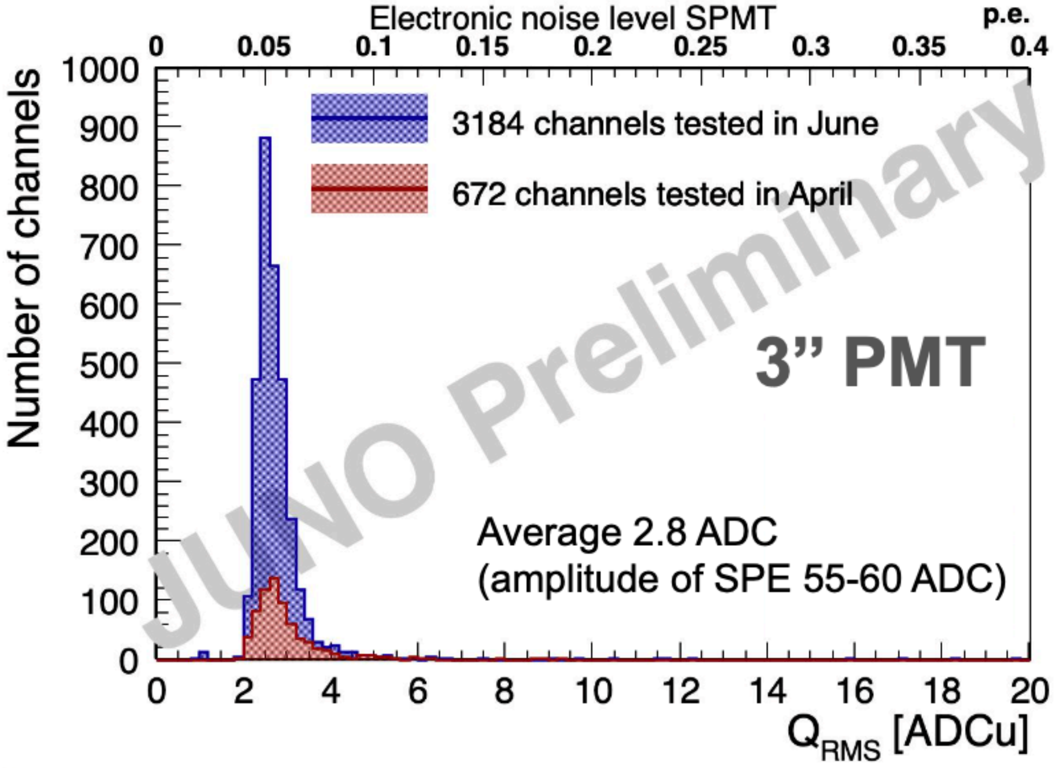
- Regular light-off/on tests during detector assembly
  - Light off tests: full data taking and processing chain with PMT HV on
  - Light on tests: joint elec/trigger/DAQ/DCS test with PMT HV off

    ➡ Very good electronics, shielding and grounding



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

↳much better than the design of 10%



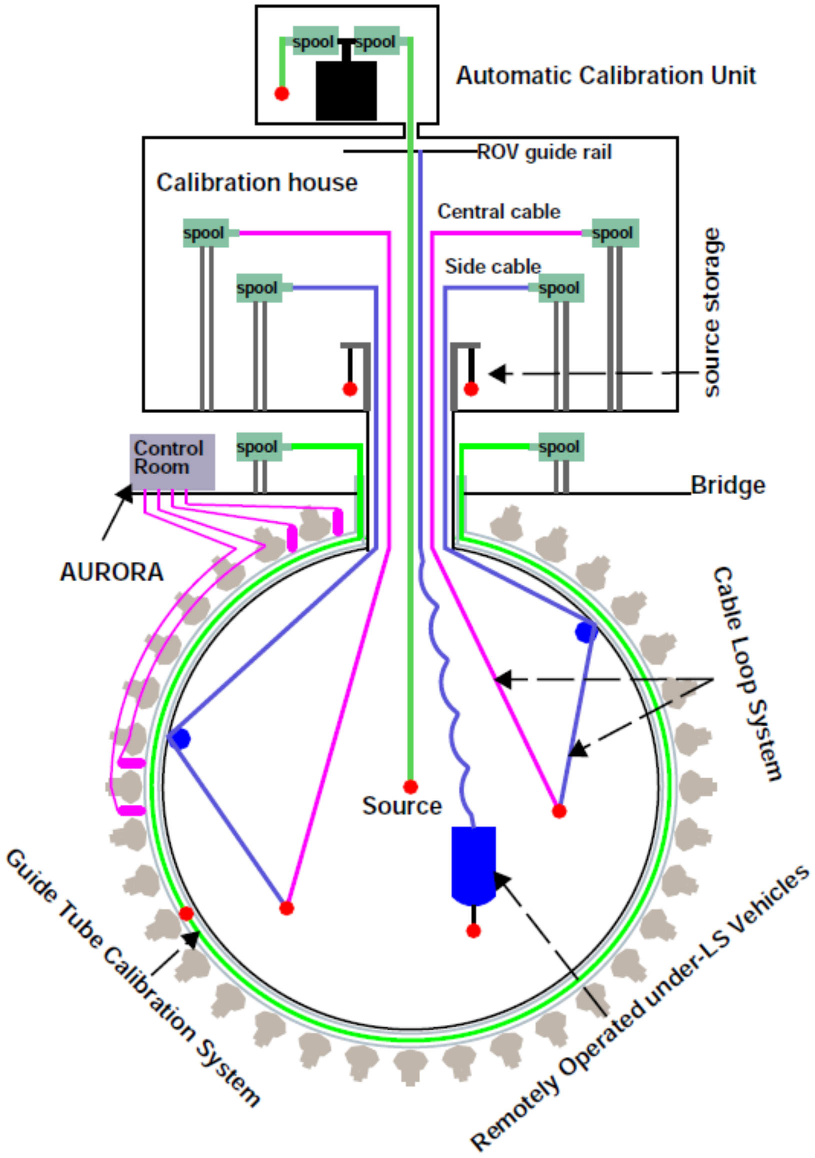
Electronics noise: 2.8 ADC counts corresponding to ~5% of SPE

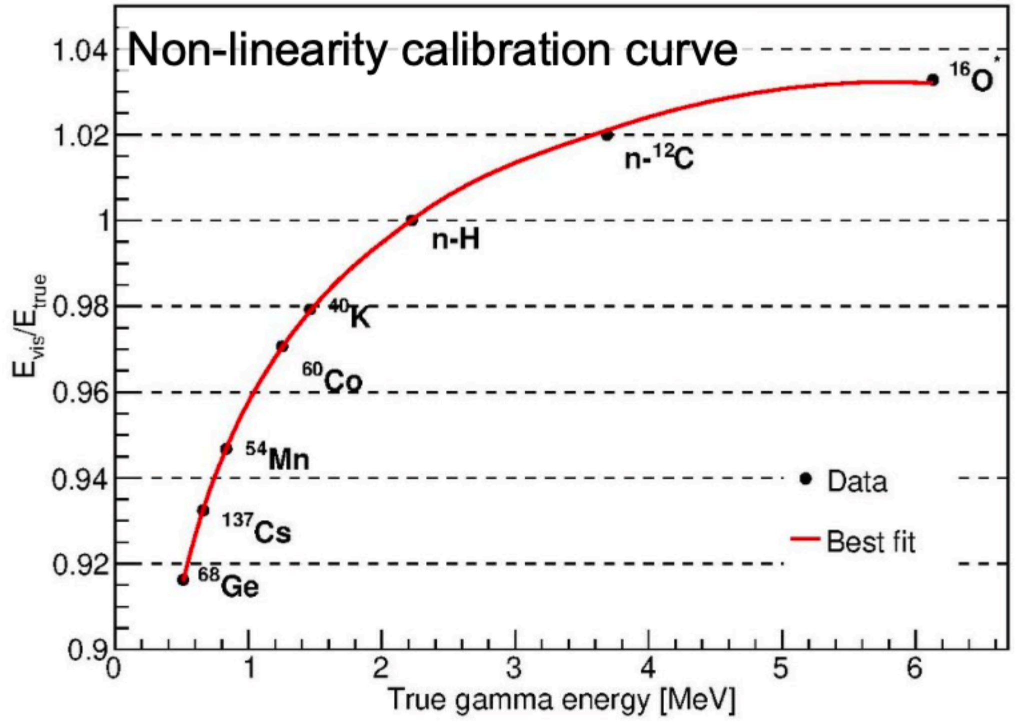
↳much lower than the trigger threshold of 1/3 pe.

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.





Efficiency and backgrounds for reactor neutrino signal

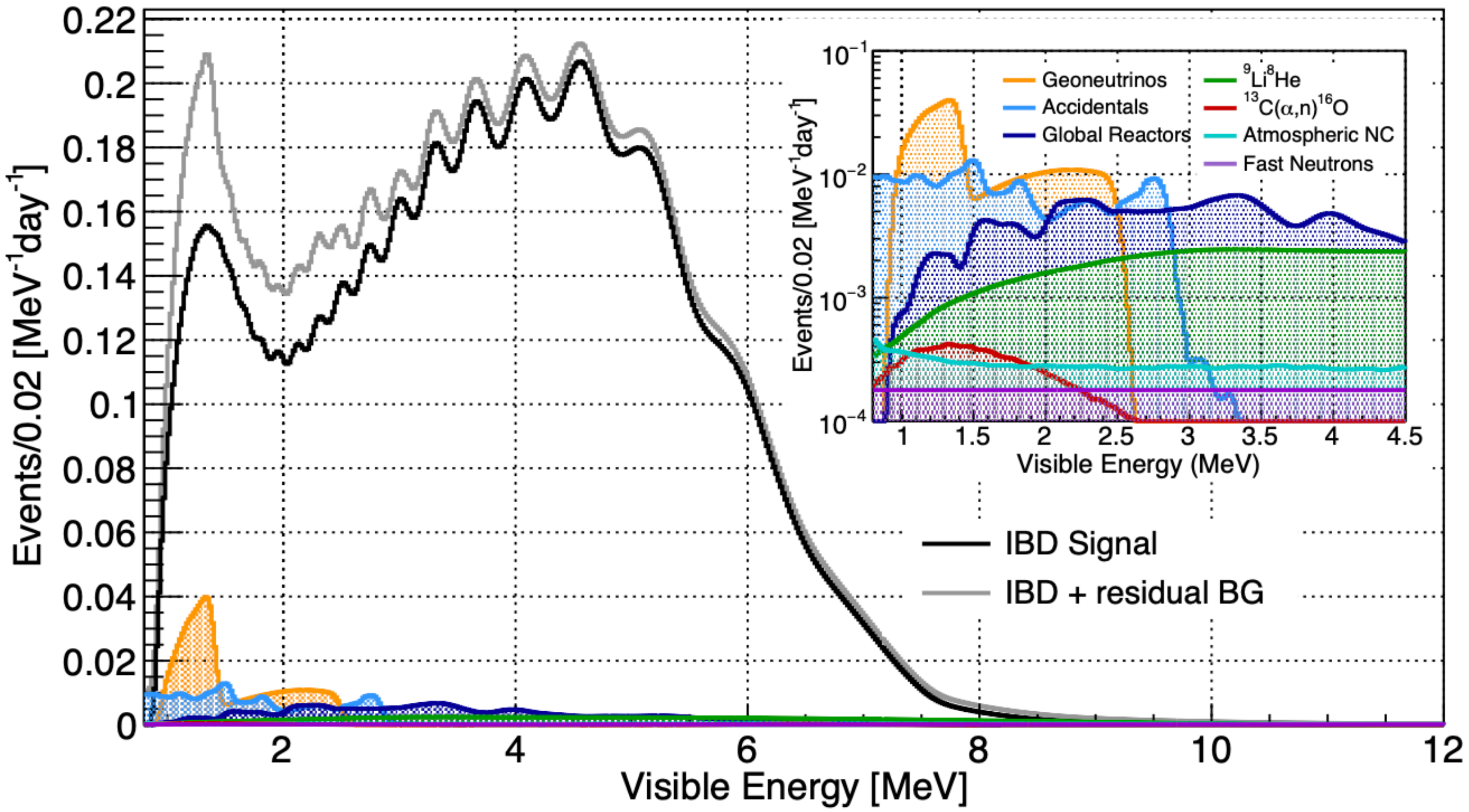
Selection cuts and IBD efficiency

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
$^{9}\text{Li}/^{8}\text{He}$	0.8
Atmospheric neutrinos	0.16
Fast neutrons	0.1
$^{13}\text{C}(\alpha,\text{n})^{16}\text{O}$	0.05
Total background	4.11

JUNO IBD Spectrum

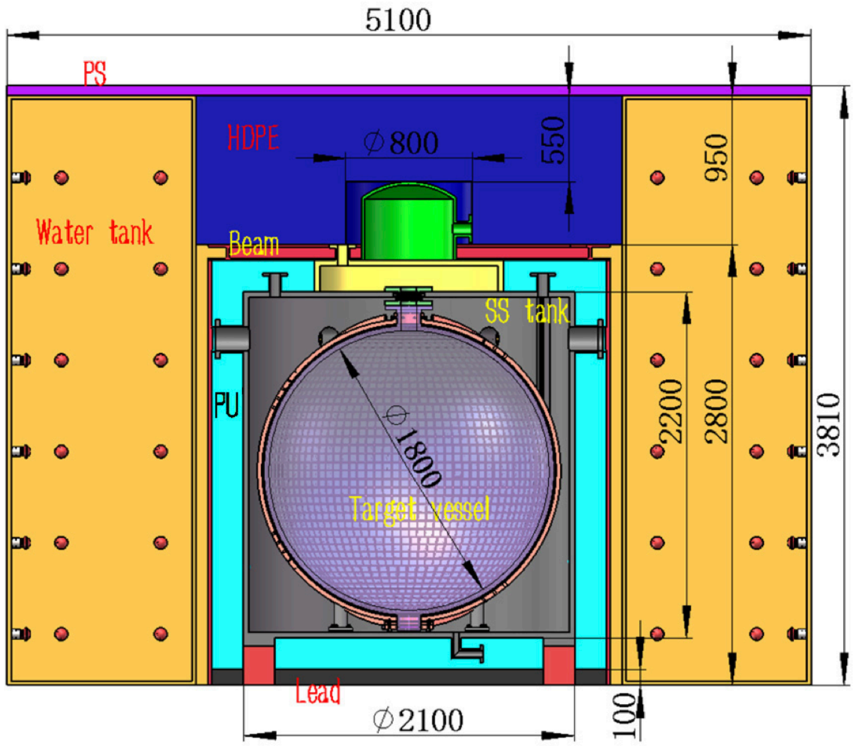


TAO detector: reactor neutrino source understanding

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.

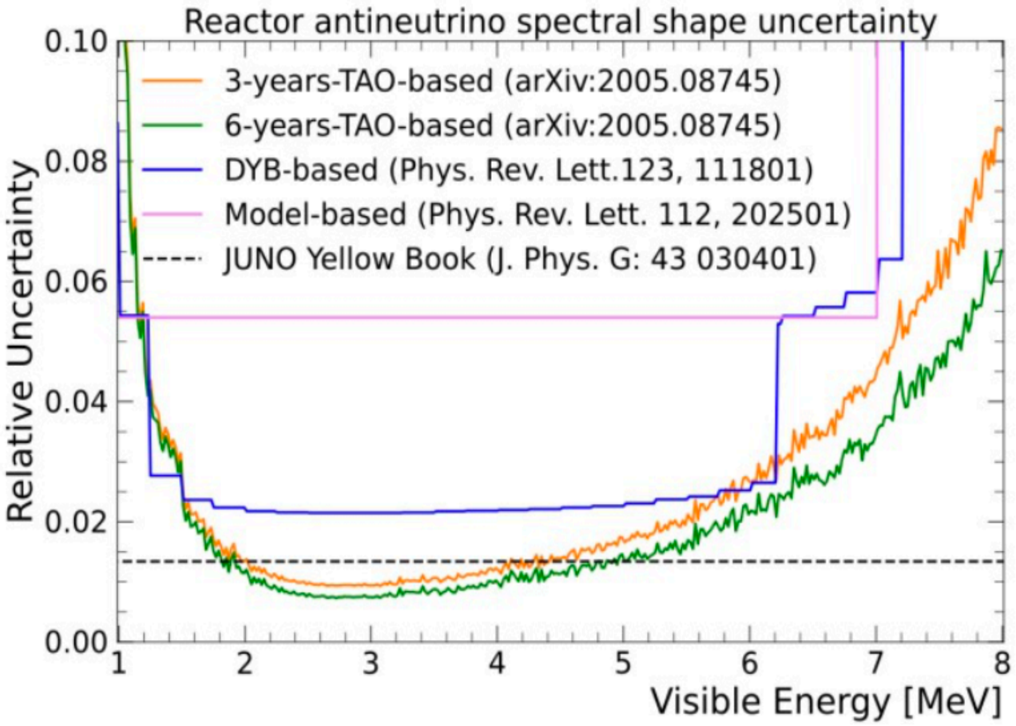
Detector Design

- 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.



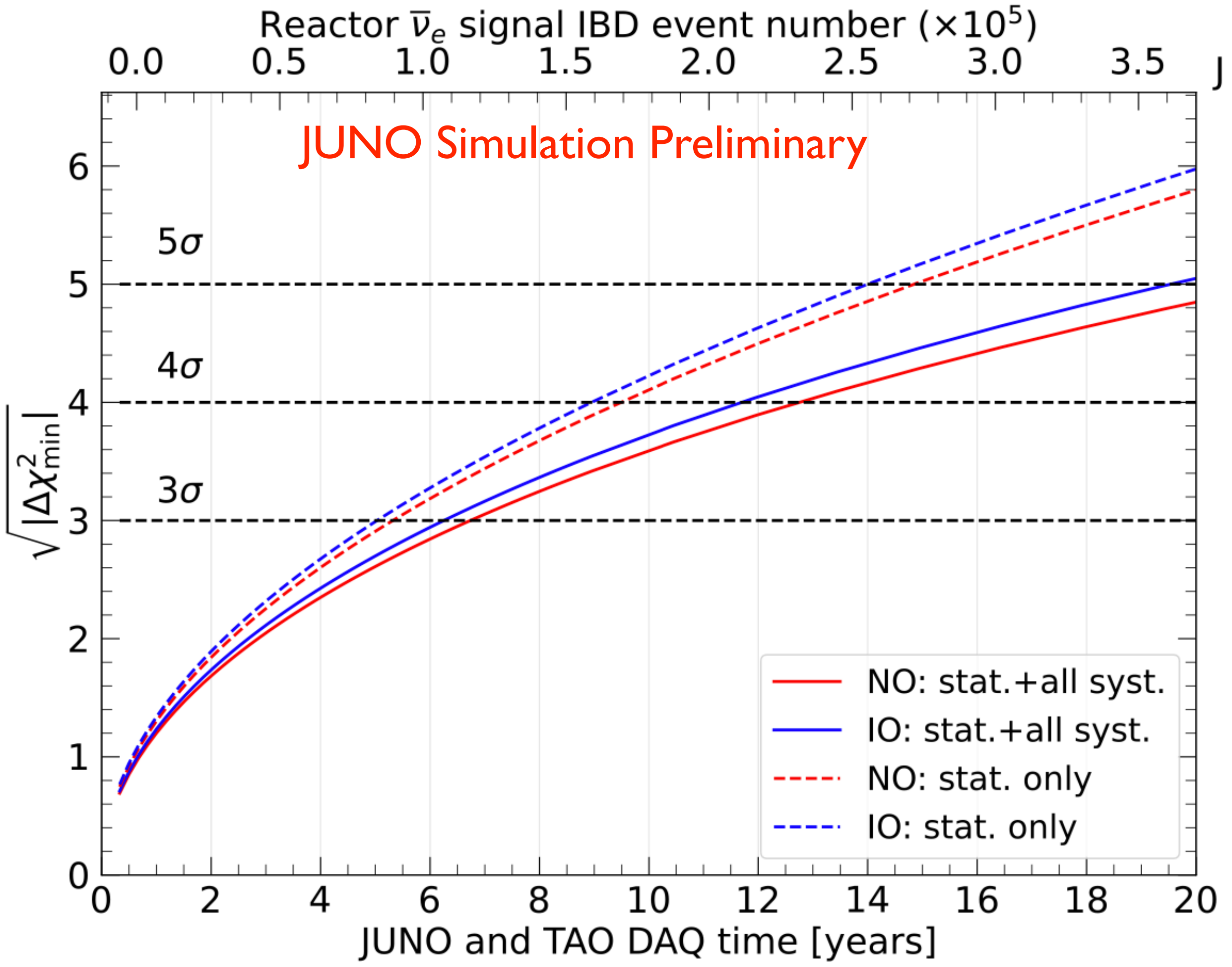
Purposes

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



Neutrino mass ordering

- The experiment will start data taking in 2024.
- The median sensitivity to reject the wrong mass ordering is 3σ ($\Delta\chi^2=9$) with an exposure of 6 years × 26.6 $\mathrm{GW_{th}}$ assuming normal ordering (3.1σ if inverted ordering is true).

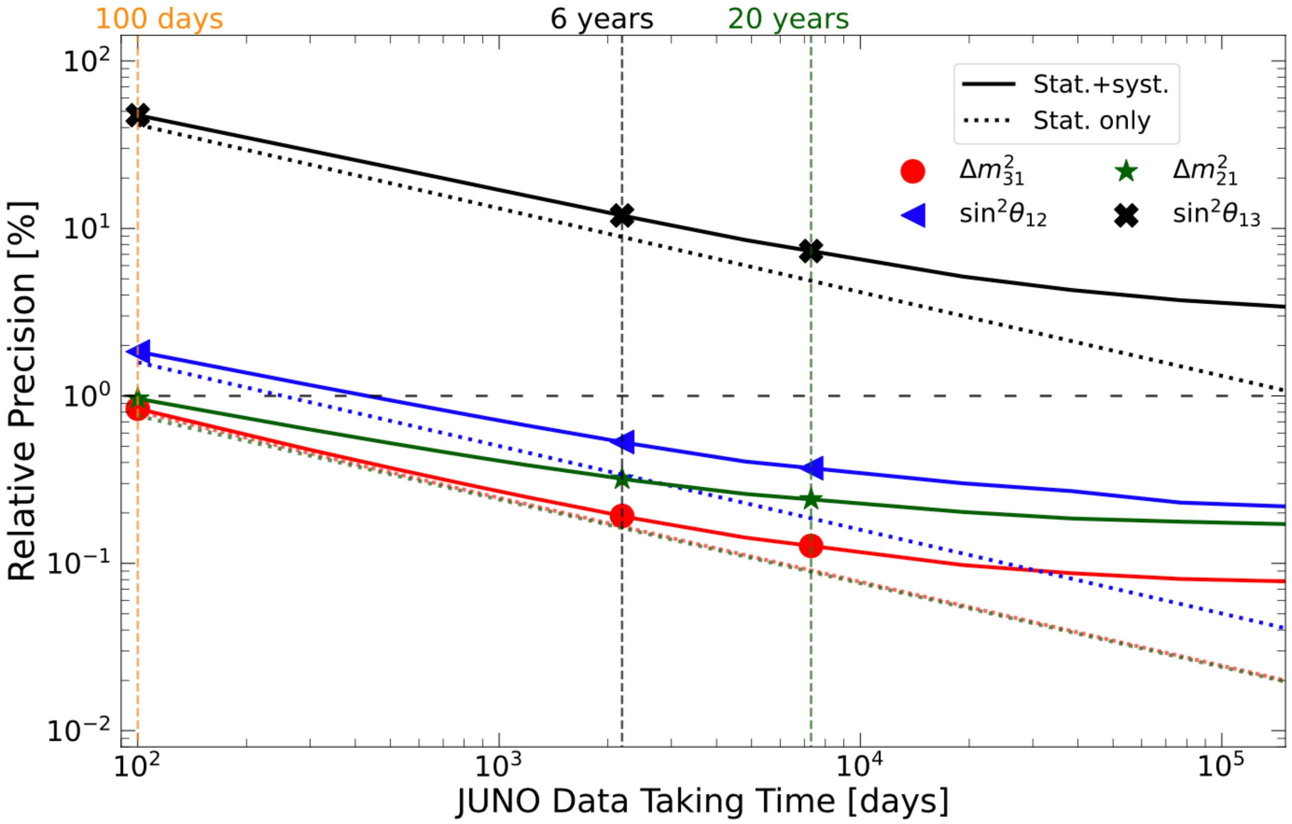


- The sensitivity can be enhanced doing :
  - combinaison with external Δm^2_{31} long baseline experiment constraint.
  - combinaison reactor+atmospheric neutrino analysis ongoing.

More details in V.Cerrone poster

Precision measurement of oscillation parameters

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



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

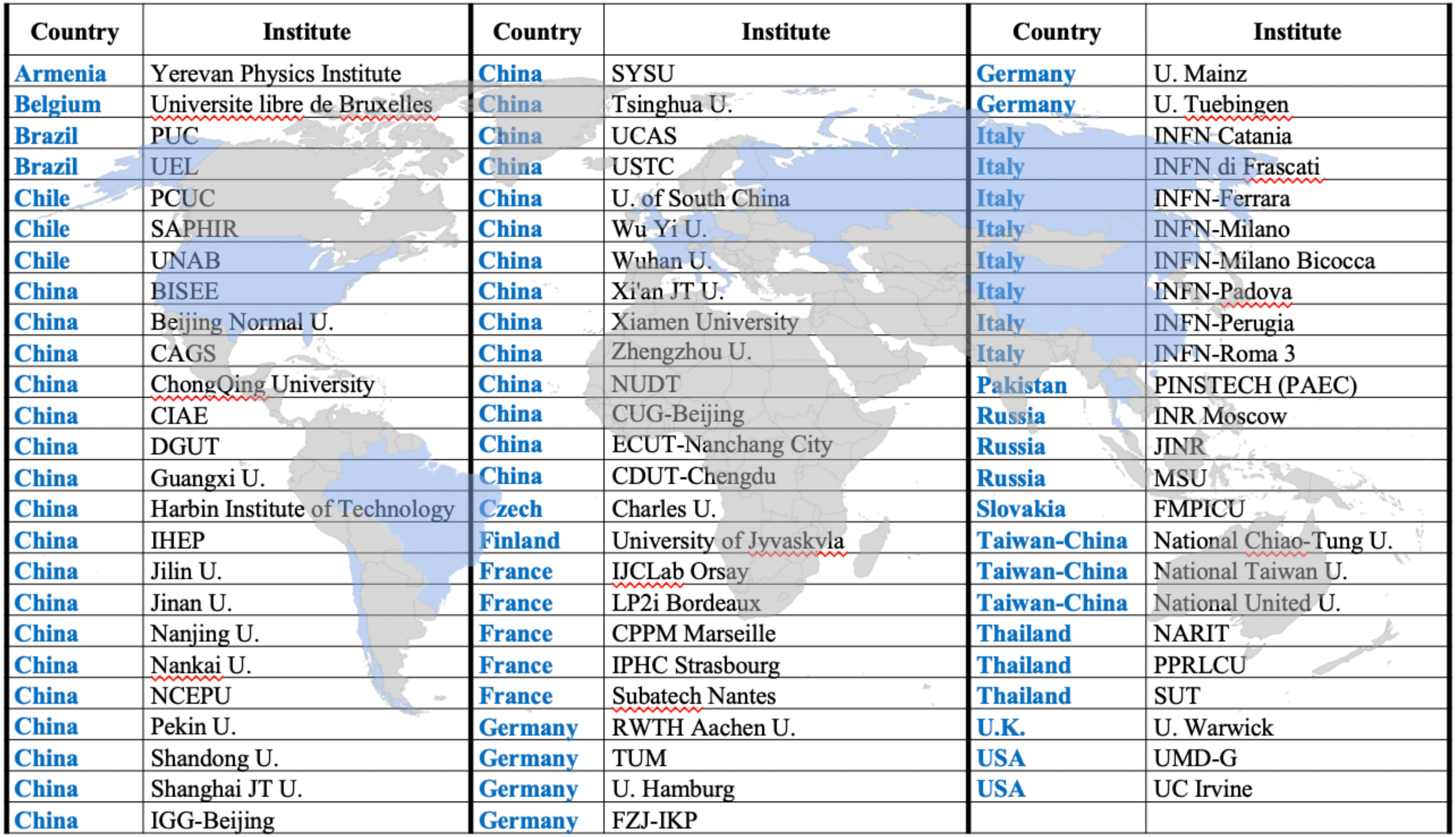
		Central Value	PDG2020	100 days	6 years	20 years
●	Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	± 0.034 (1.3%)	± 0.021 (0.8%)	± 0.0047 (0.2%)	± 0.0029 (0.1%)
★	Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	± 0.18 (2.4%)	± 0.074 (1.0%)	± 0.024 (0.3%)	± 0.017 (0.2%)
◀	$\sin^2\theta_{12}$	0.307	± 0.013 (4.2%)	± 0.0058 (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%)

More details in V.Cerrone poster

Conclusions

- Daya Bay, Double Chooz and RENO successfully measured θ_{13} and improved our knowledge of anti-neutrinos reactor spectrum.
- 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 will be finalized this year and the filling of liquid scintillator and the start of data taking are foreseen next year.
- 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})
  - $> 3\sigma$ with long baseline and/or atmospheric neutrinos.
- TAO program will improve the knowledge of reactor antineutrino fluxes and spectra.

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		

Backup slides

Solar neutrino measurements

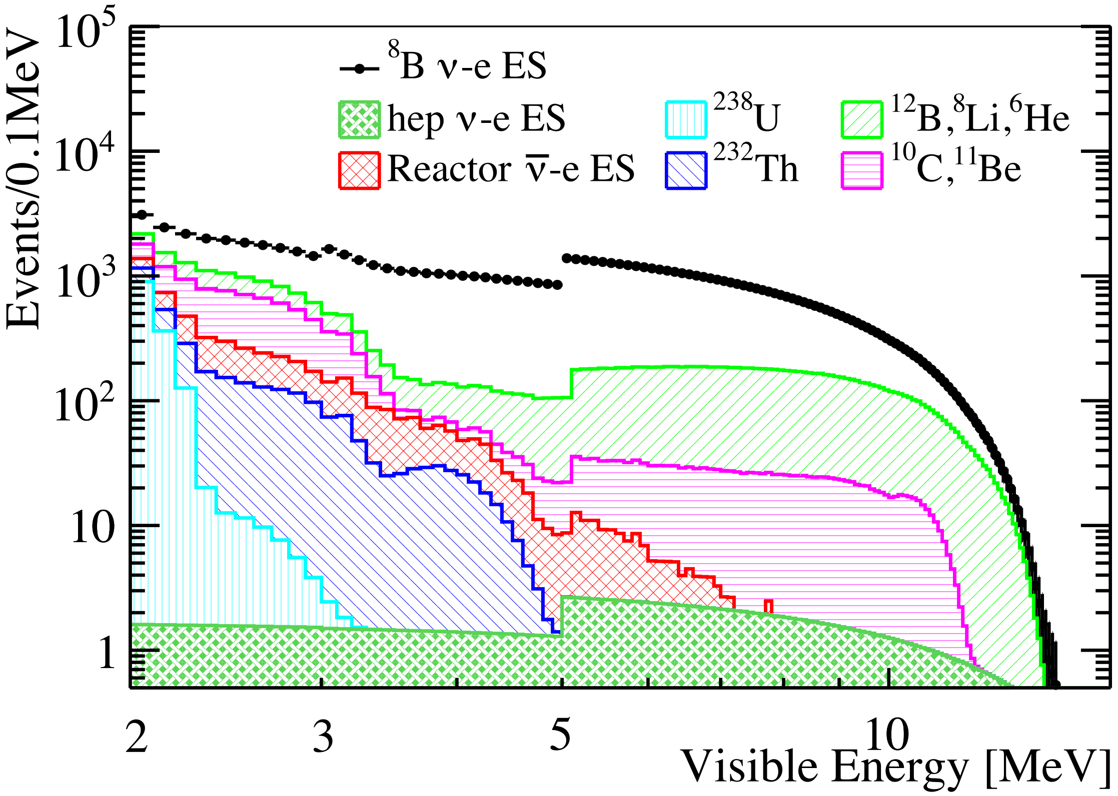
Challenging measurement due to:

- low overburden but new veto strategies for cosmogenic isotopes.
- detection via neutrino-elastic scattering, so higher requirements in terms of radiopurity:
  - assuming an intrinsic ^{238}U and ^{232}Th radioactivity level of 10^{-17} g/g, a 2 MeV analysis threshold can be achieved.

^{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.

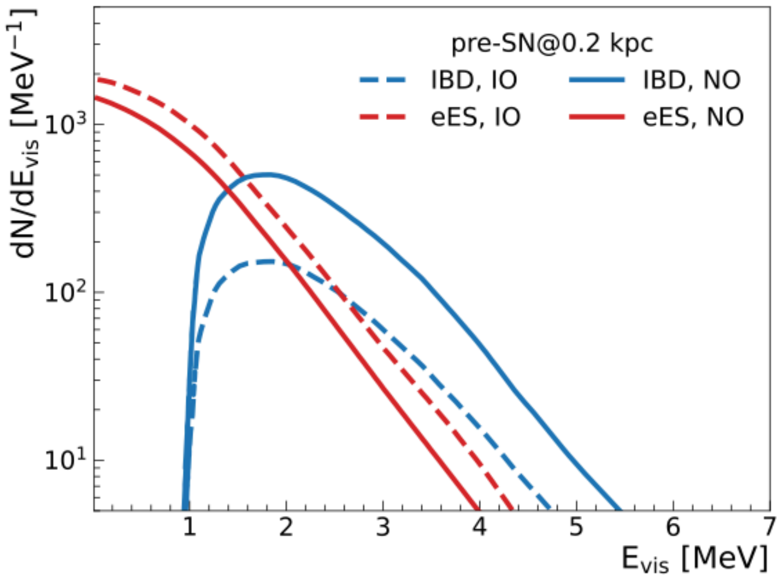


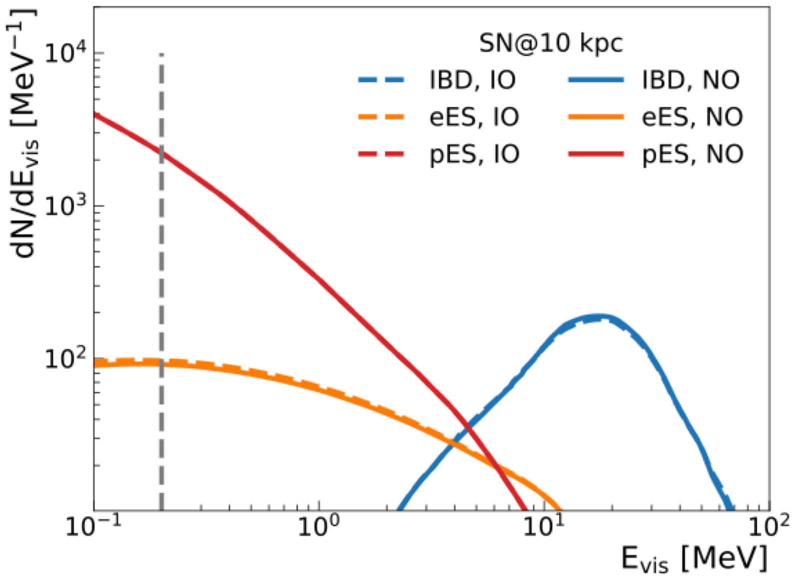
- Observation of intermediate energy solar neutrinos (pep, ^{7}Be, CNO) feasible only if LS purity within specifications.

Supernova neutrinos

Core collapse neutrinos

multi-channel detection, all flavors





at 10kpc:

~5000 IBD

~ 300 eES

~ 2000 pES

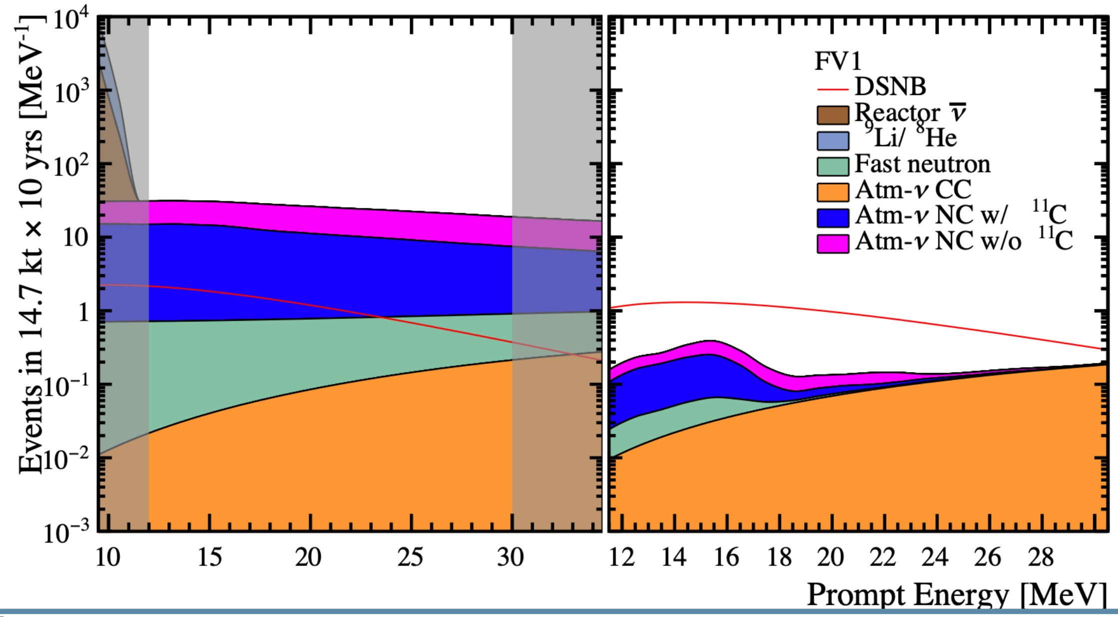
~ 200 CC

~ 300 NC

Diffuse supernova neutrino background

Integrated neutrino signal from all the SN explosions in the Universe

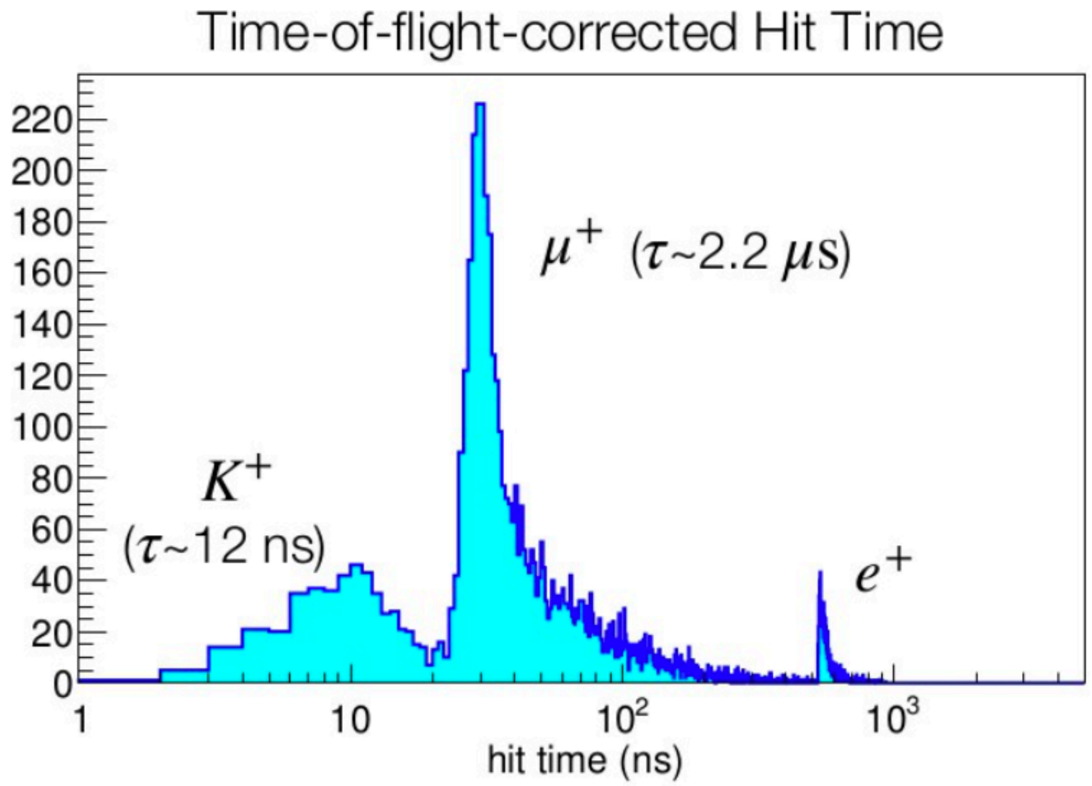
Signal: IBD (2~4/year) for an expected significance of 3σ in 3 years

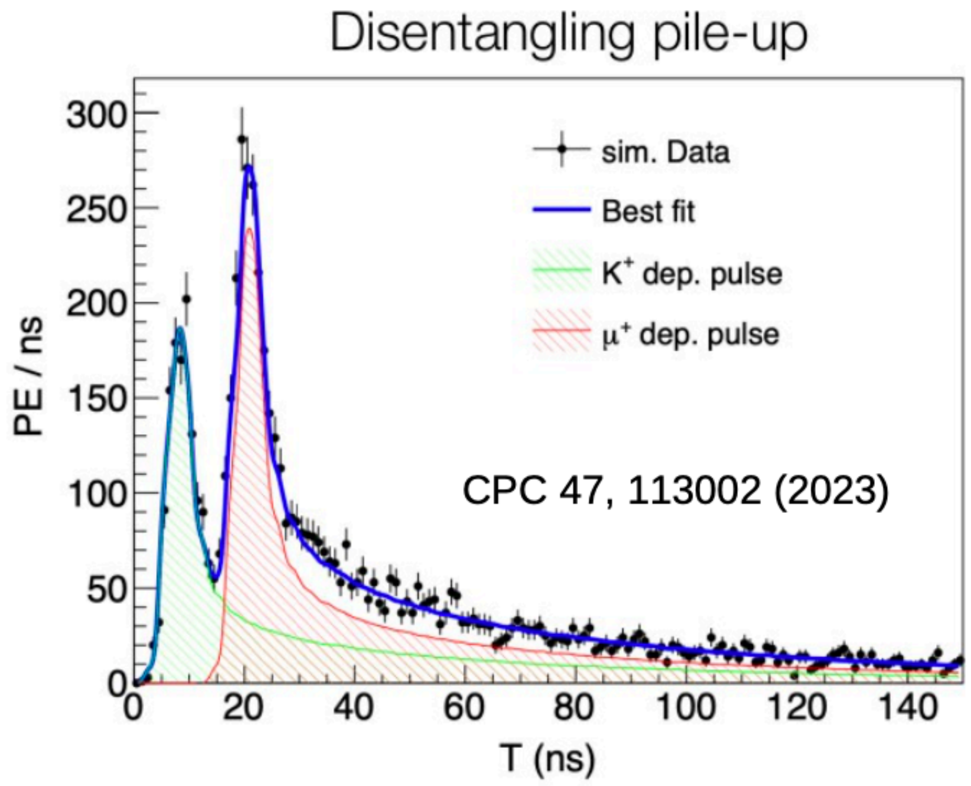


Proton decay

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

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


Time-of-flight-corrected Hit Time


Disentangling pile-up

CPC 47, 113002 (2023)

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