Reactor neutrino experiments: status and perspectives

Alessandro Paoloni

XXIII Roma3 Topical Seminar on Subnuclear Physics:
“Where we stand and where we go with neutrino physics”

13th December 2021

Nuclear Reactors as antineutrino source

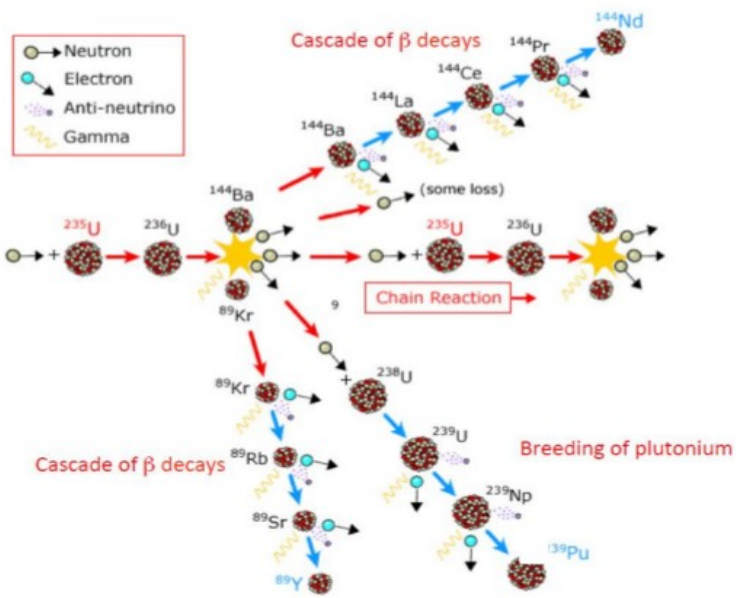
Nuclear reactors are a pure anti-ν_e source from β-decay of fission daughters.

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 by a fuel mixture (^{235}U,^{239}Pu,^{238}U,^{241}Pu) with Low Enriched Uranium content. Research reactors with HEU content.

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:

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

$f_j(E,t)$ = isotope j fission fraction

$S_j(E)$ = isotope j fission neutrino spectrum

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

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

$\varepsilon(E)$ = selection efficiency

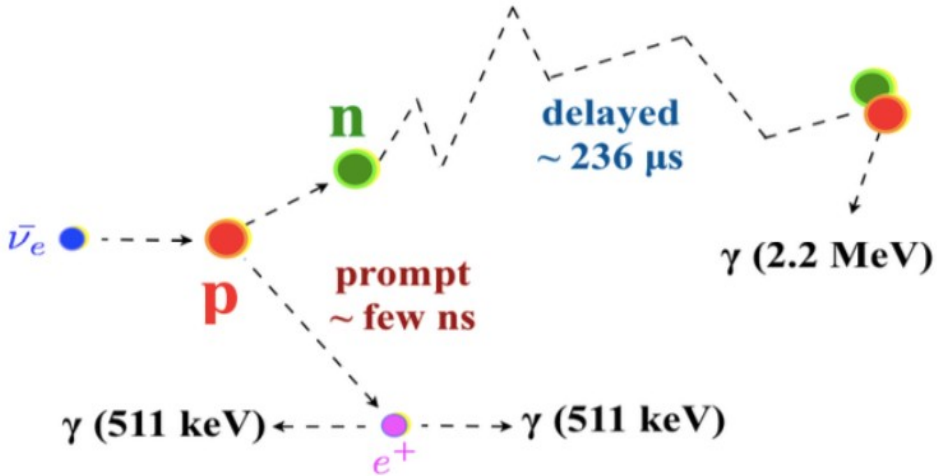
E=neutrino energy, t=time, L=baseline

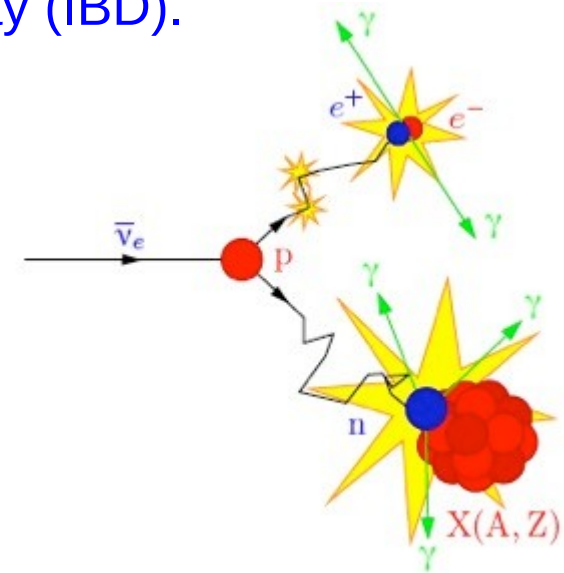
Inverse Beta Decay (IBD)

Antineutrino detection through Inverse Beta Decay (IBD).

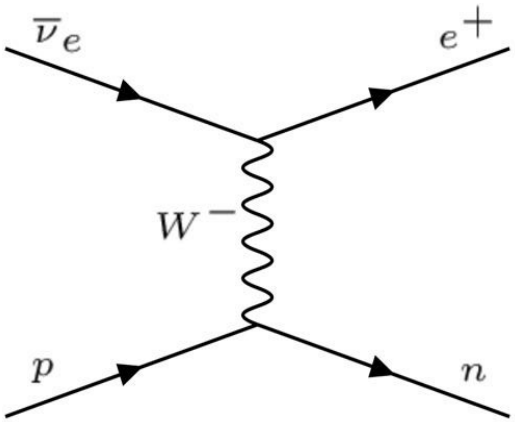
Most experiments use liquid scintillator

as target and detector: n+p-> γ (2.2 MeV).





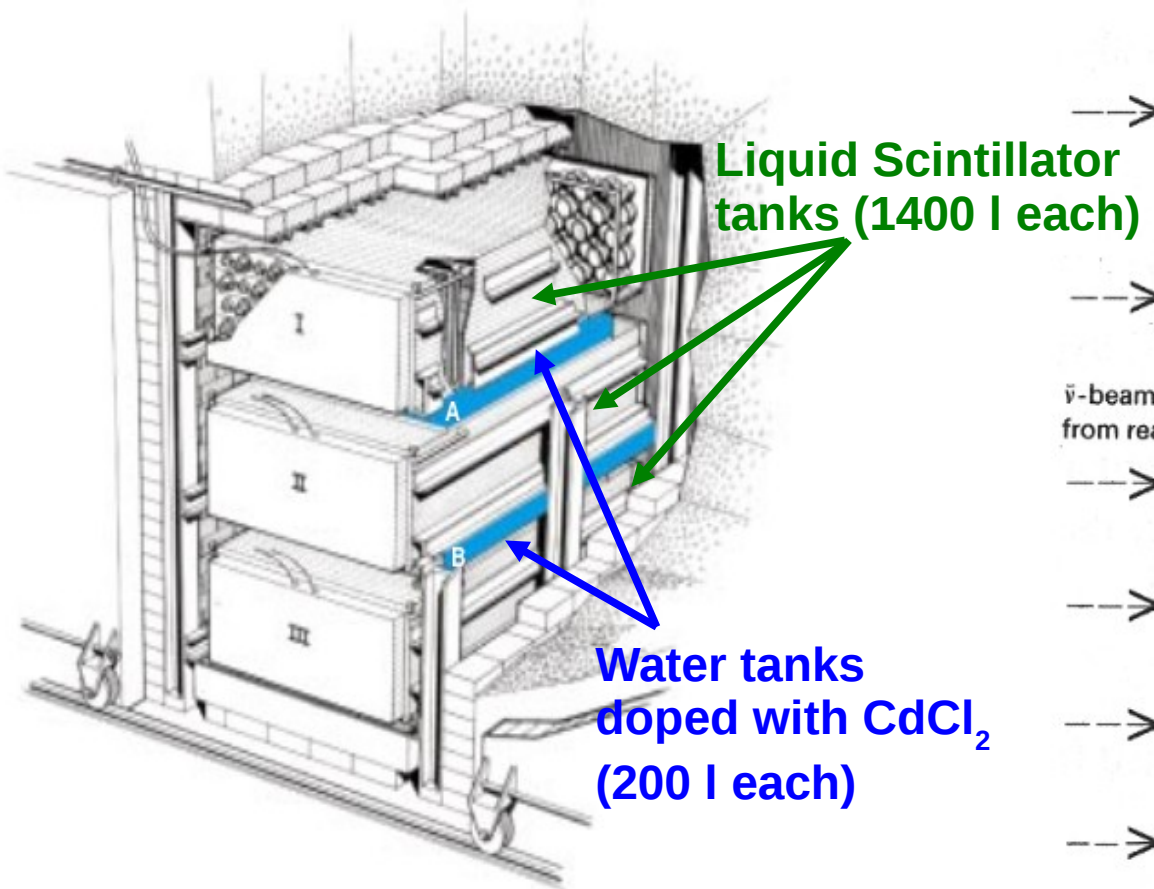
Gadolinium doping for faster neutron capture (tens of μs): n+Gd-> γ-rays (8 MeV).

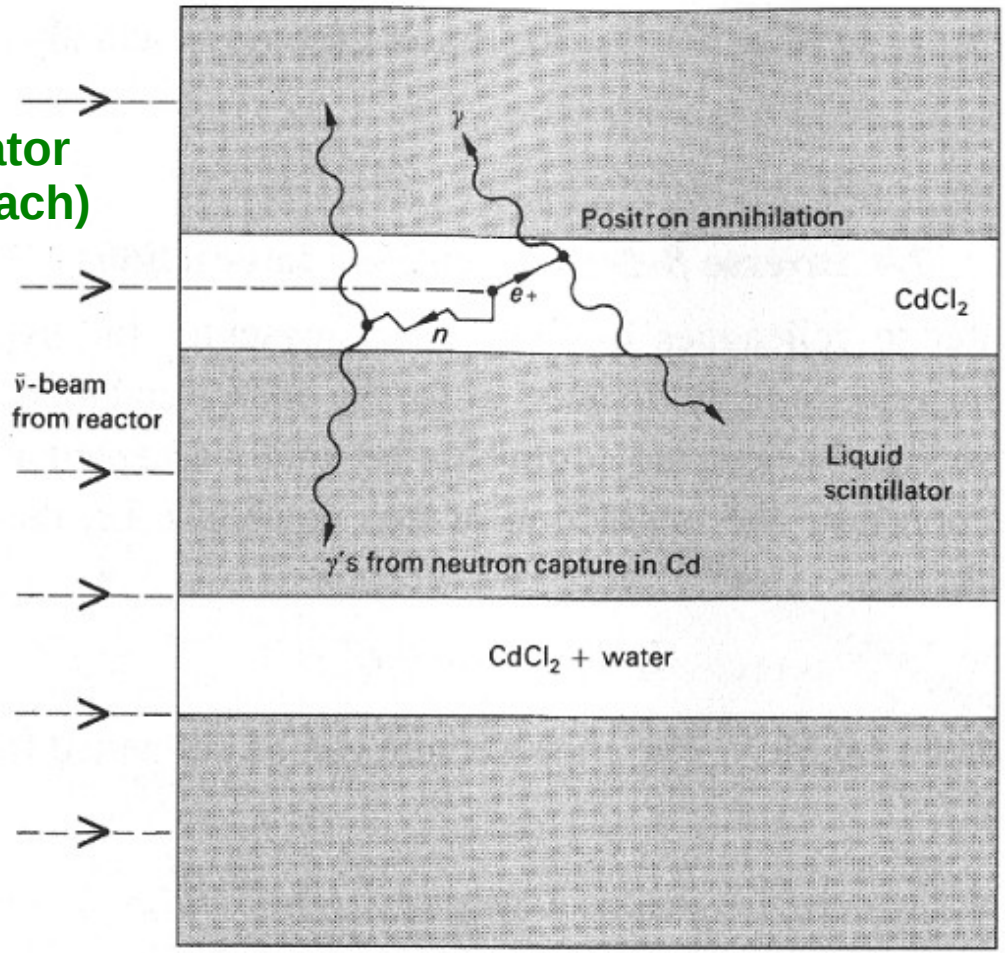


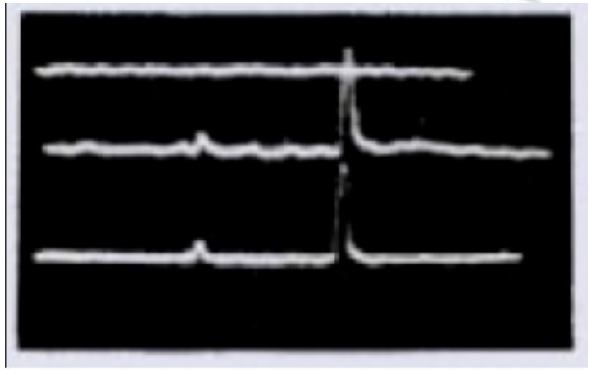
- 1.8 MeV threshold on neutrino energy
- Relatively large cross section
- Background rejection using coincidence between positron (prompt) and neutron (delayed) signals
- $E_{prompt}=E_\nu$ – 0.8 MeV (neglecting n recoil kinetic energy)

First neutrino detection

First neutrino detection by Reines e Cowan (1956) using reactor anti-neutrinos.
H_2O + $CdCl_2$ as target, liquid scintillator tanks as detectors.







Interaction rate: 3 events/hour.

Neutrino oscillations in a nutshell

Neutrino flavor oscillation induced by **quantum mechanics.**
Neutrino flavor tag in production and detection through CC weak interaction (ν_e, ν_μ, ν_τ), but vacuum propagation as combination of mass eigenstates (ν_1, ν_2, ν_3).
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.

Inside the matrix, three mixing angles, $\boldsymbol{\theta_{12}}$,$\boldsymbol{\theta_{13}}$ and $\boldsymbol{\theta_{23}}$, and one phase $\boldsymbol{\delta}$ (**CP violation**).

Oscillation probability in vacuum:

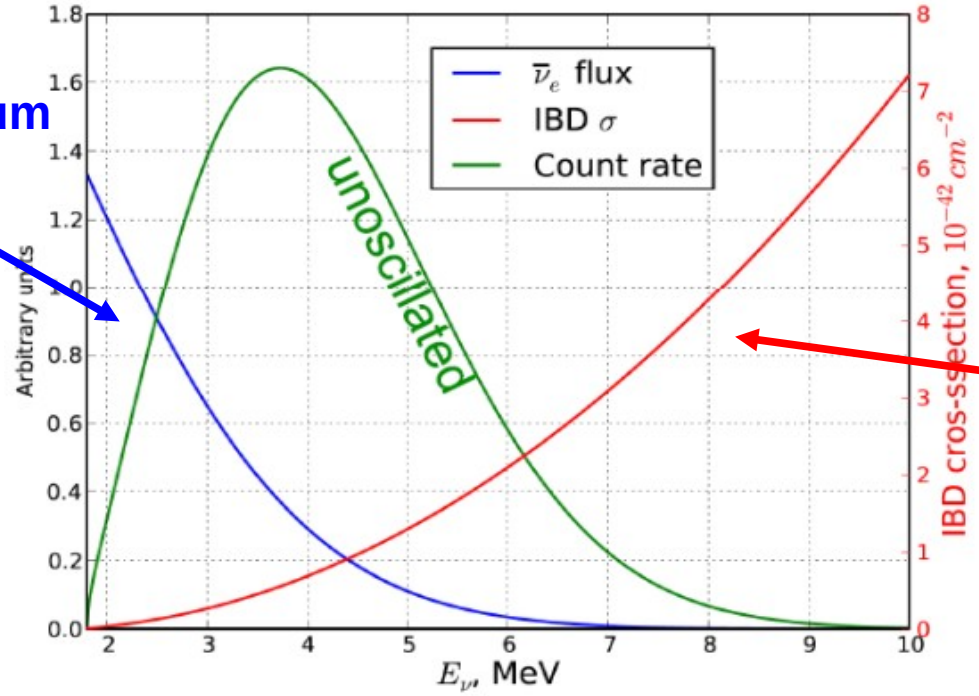
$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) + 2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

Detection of ν-oscillation:

- **Neutrinos have mass**
- **ν mass not degenerate**
- 2 independent $\Delta m^2 \Rightarrow 3\ \nu$

Neutrino oscillations and reactors

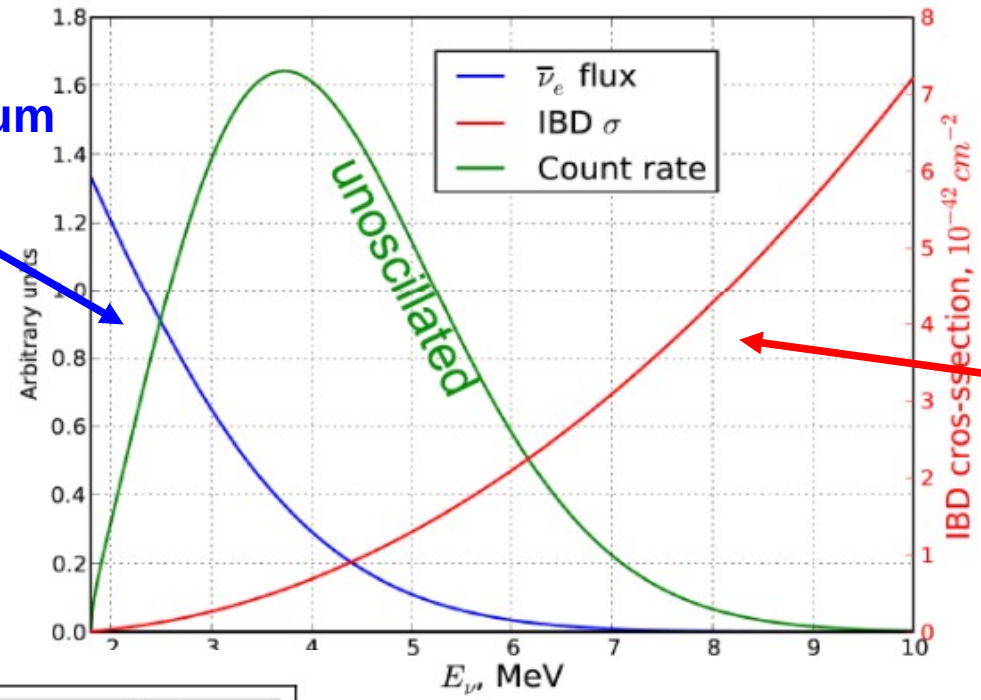
Anti-neutrino spectrum (E < 10 MeV)



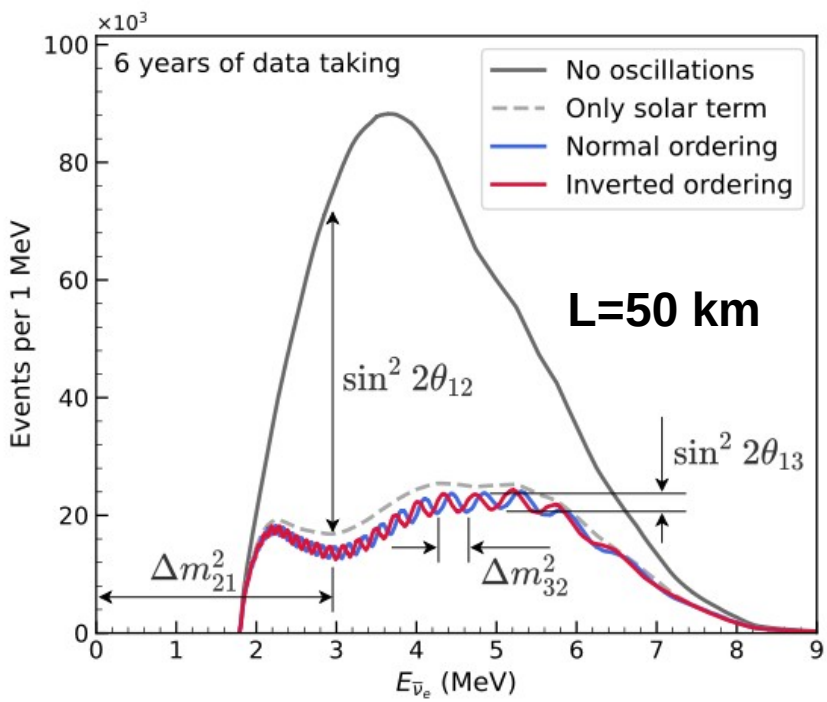
Interaction cross-section

Neutrino oscillations and reactors

Anti-neutrino spectrum (E < 10 MeV)



Interaction cross-section



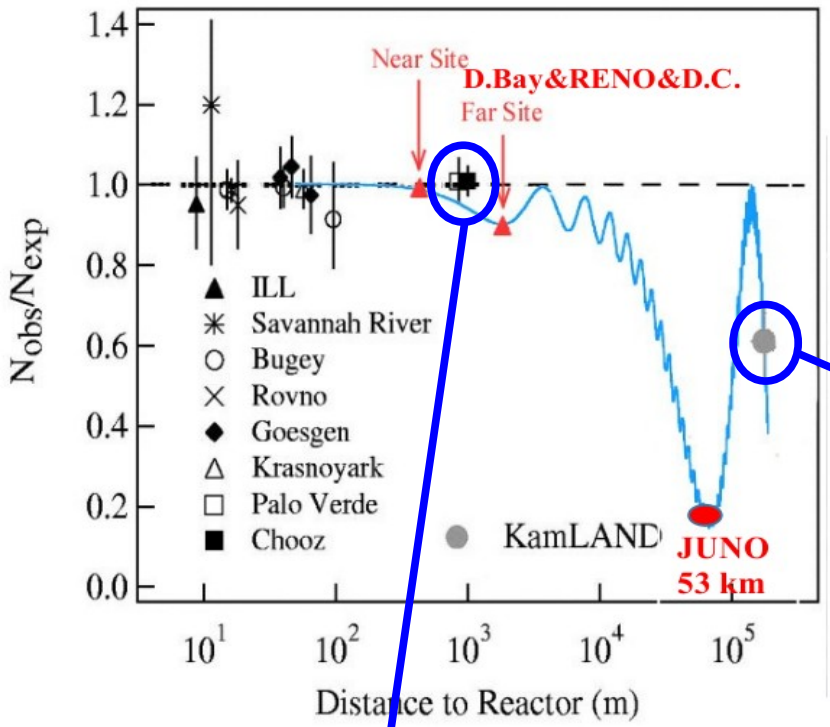
Given the energies, $\nu_{\mu,\tau}$ cannot produce μ,τ in CC interactions.....

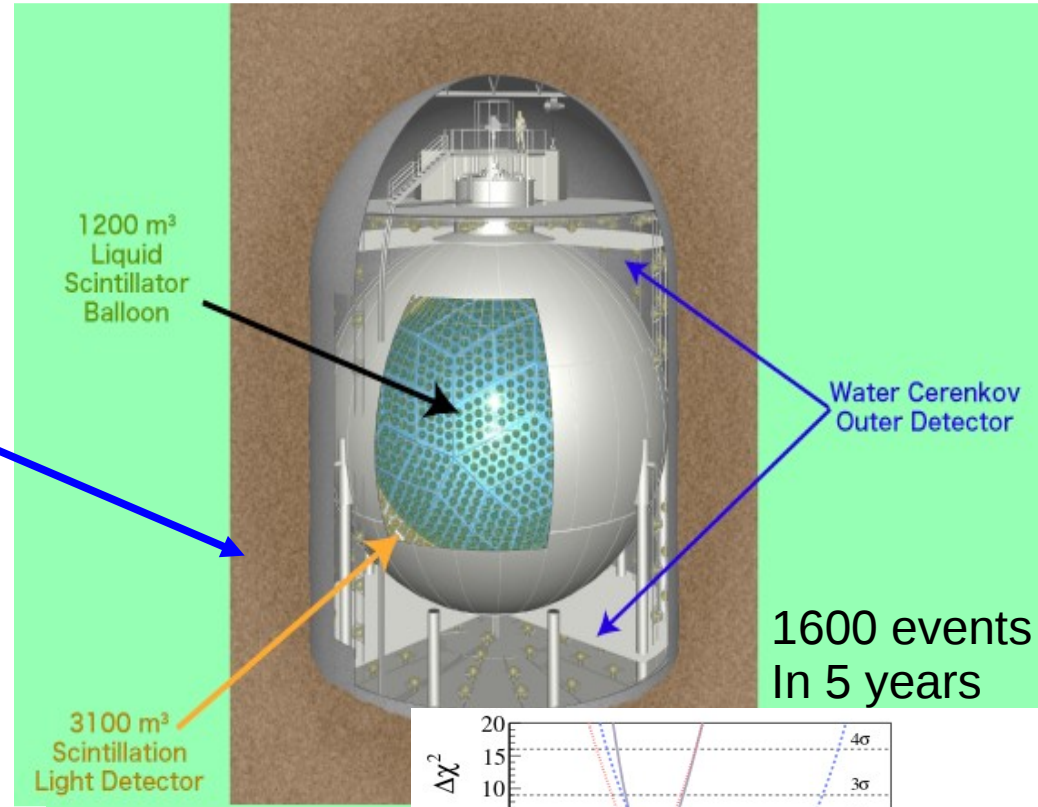
Oscillation (disappearance) probability

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

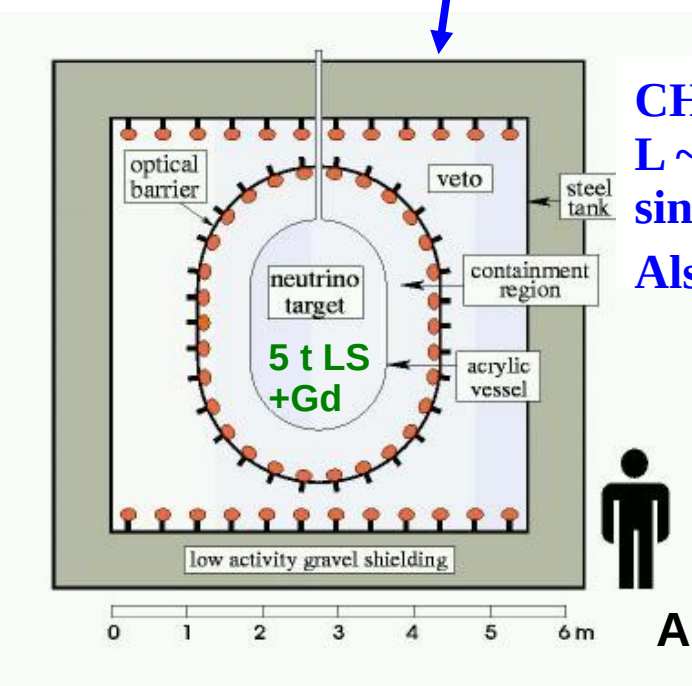
$\Delta_{ij} = \Delta m^2_{ij}\ L / (4E)$

Neutrino oscillation experiments with reactors (1993-2003)

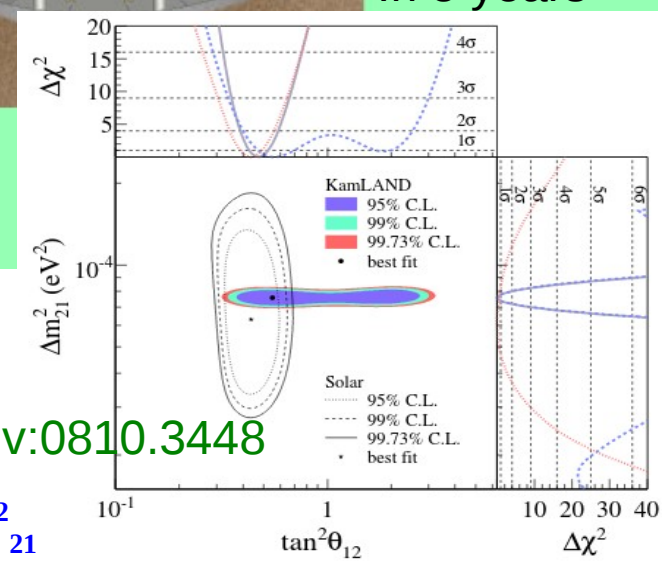




1600 events
In 5 years



CHOOZ (France)
L ~ 1 km.
$\sin^2(2\theta_{13})<0.17$ (90%CL)
Also Palo Verde (USA).

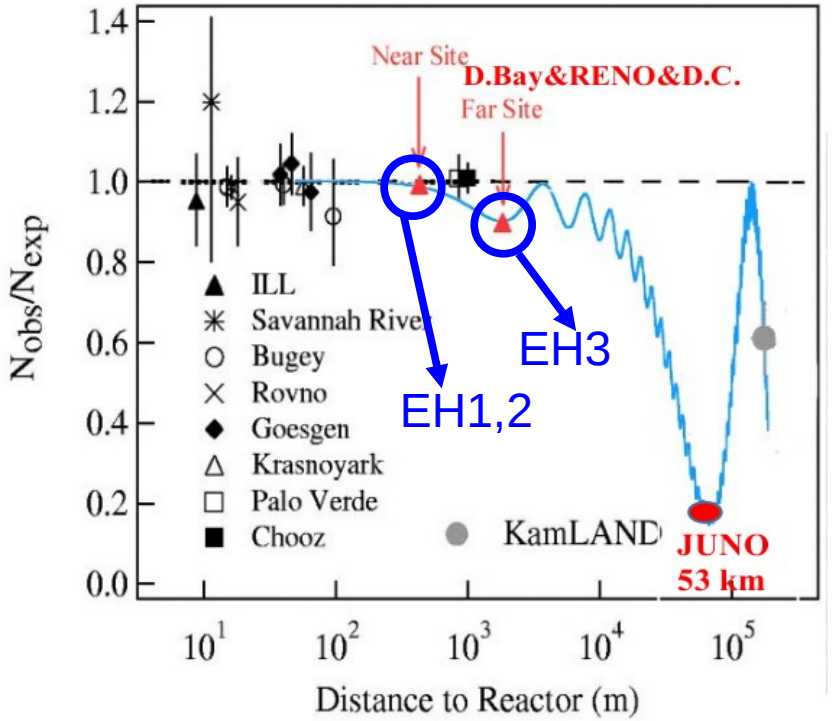


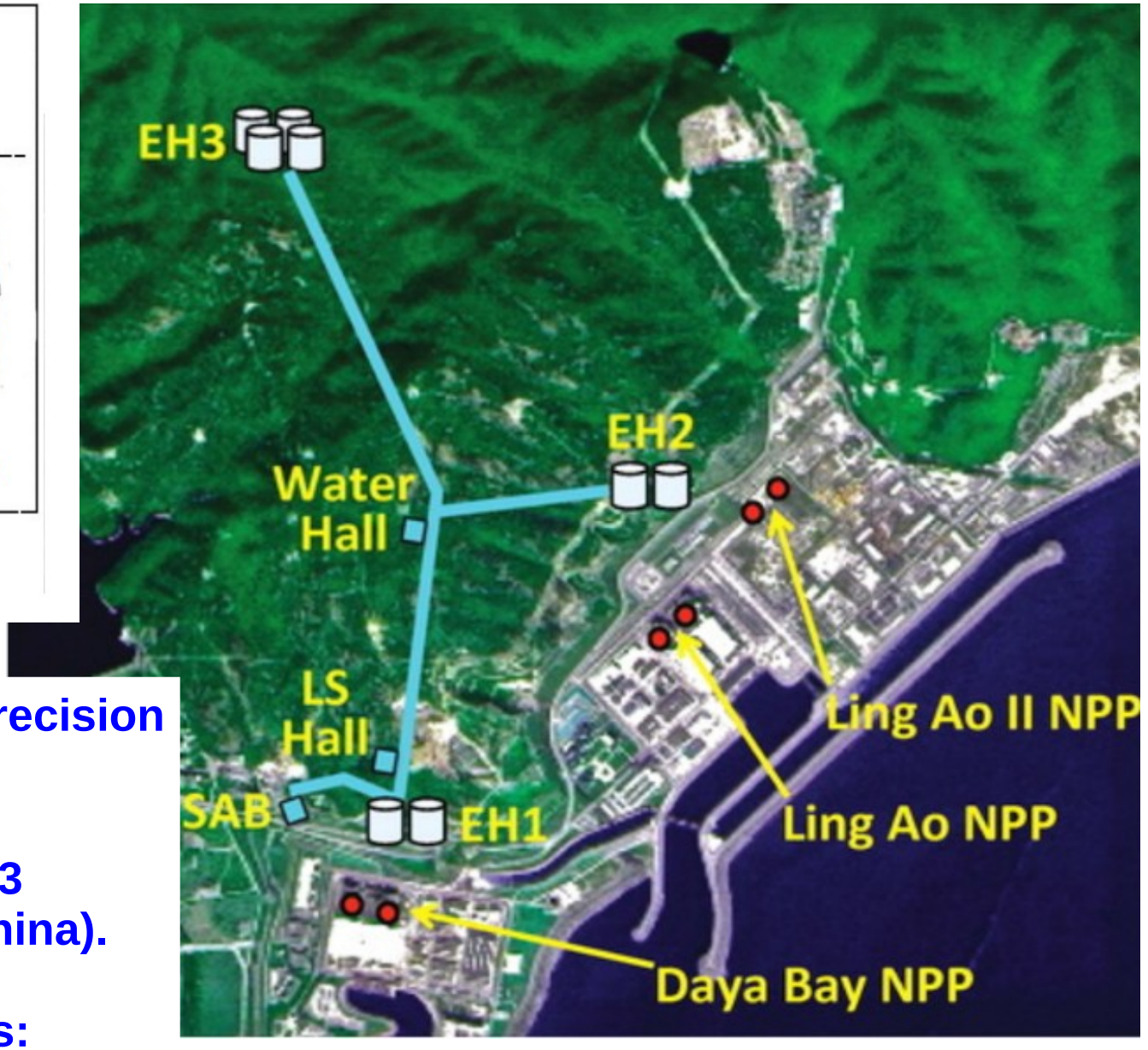
arXiv:0810.3448

KamLAND (Japan)
L ~ 100 km.
Measurement of θ_{12} and Δm^2_{21}
(also measured with solar ν).

Arxiv:hep-ph/0107277 (Bemporad,Vogel,Gratta)

Neutrino oscillation experiments with reactors (>2010)





Daya Bay: dedicated to the precision measurement of θ_{13}.

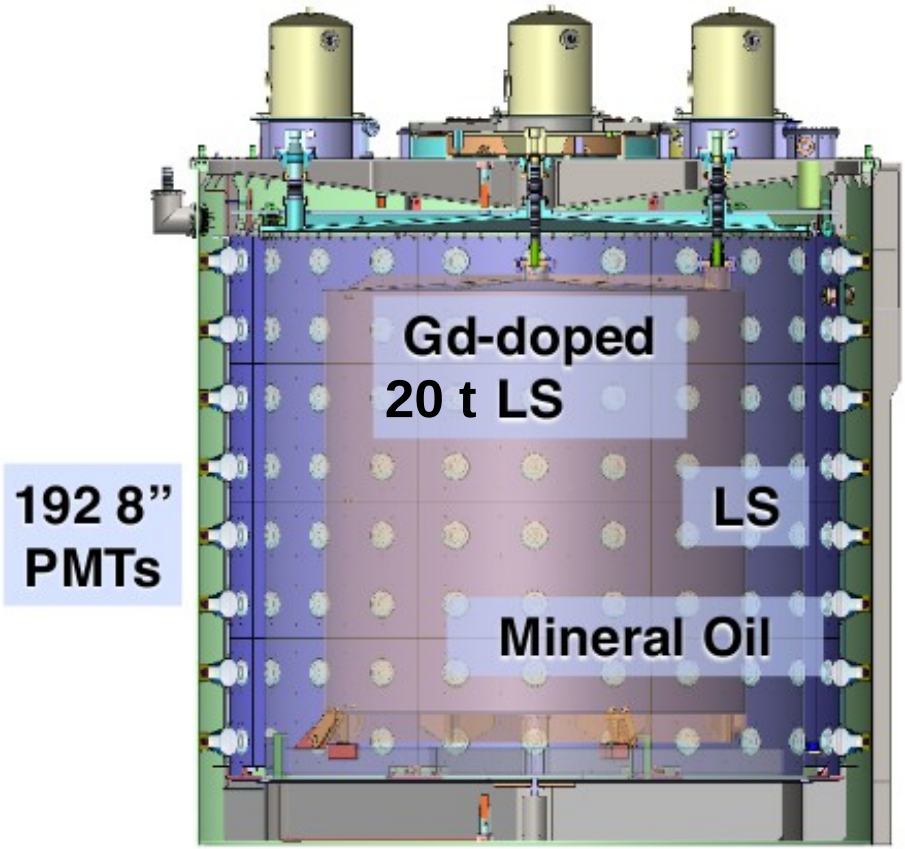
6 reactors (2.9 Gwth each) in 3 Nuclear Power Plants (P.R. China).

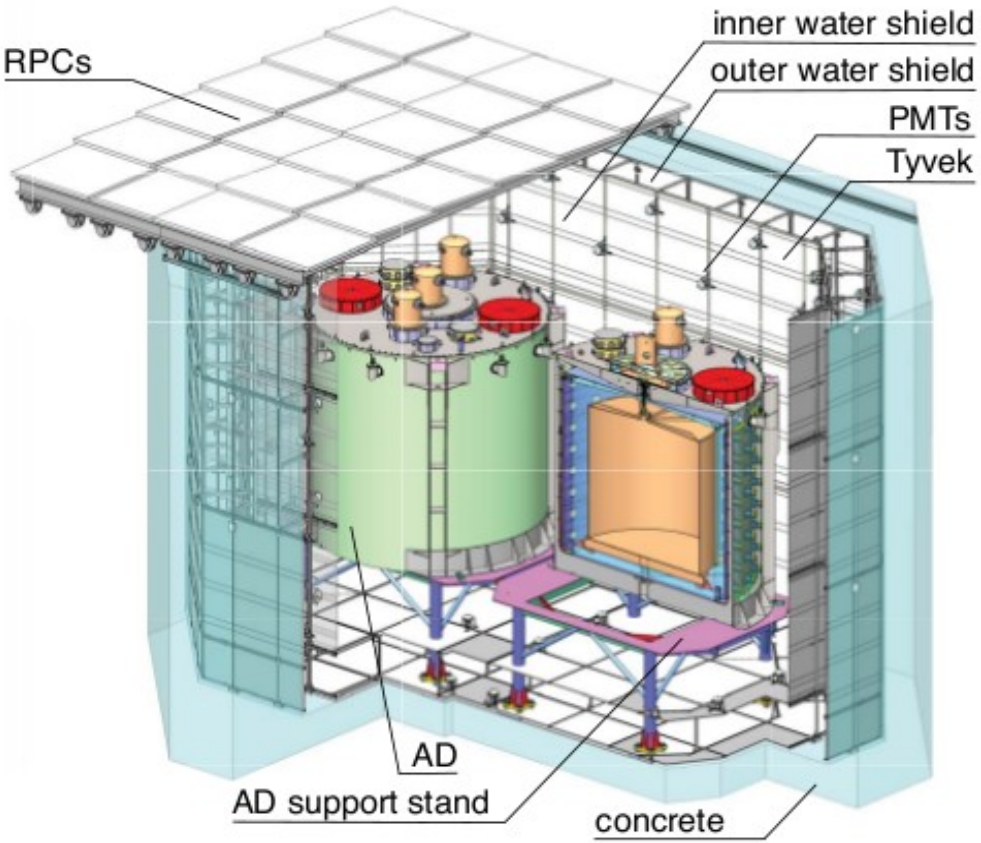
8 identical detectors in 3 sites:

- **EH1, EH2 = near sites**
- **EH3 = far site**

Daya Bay experiment

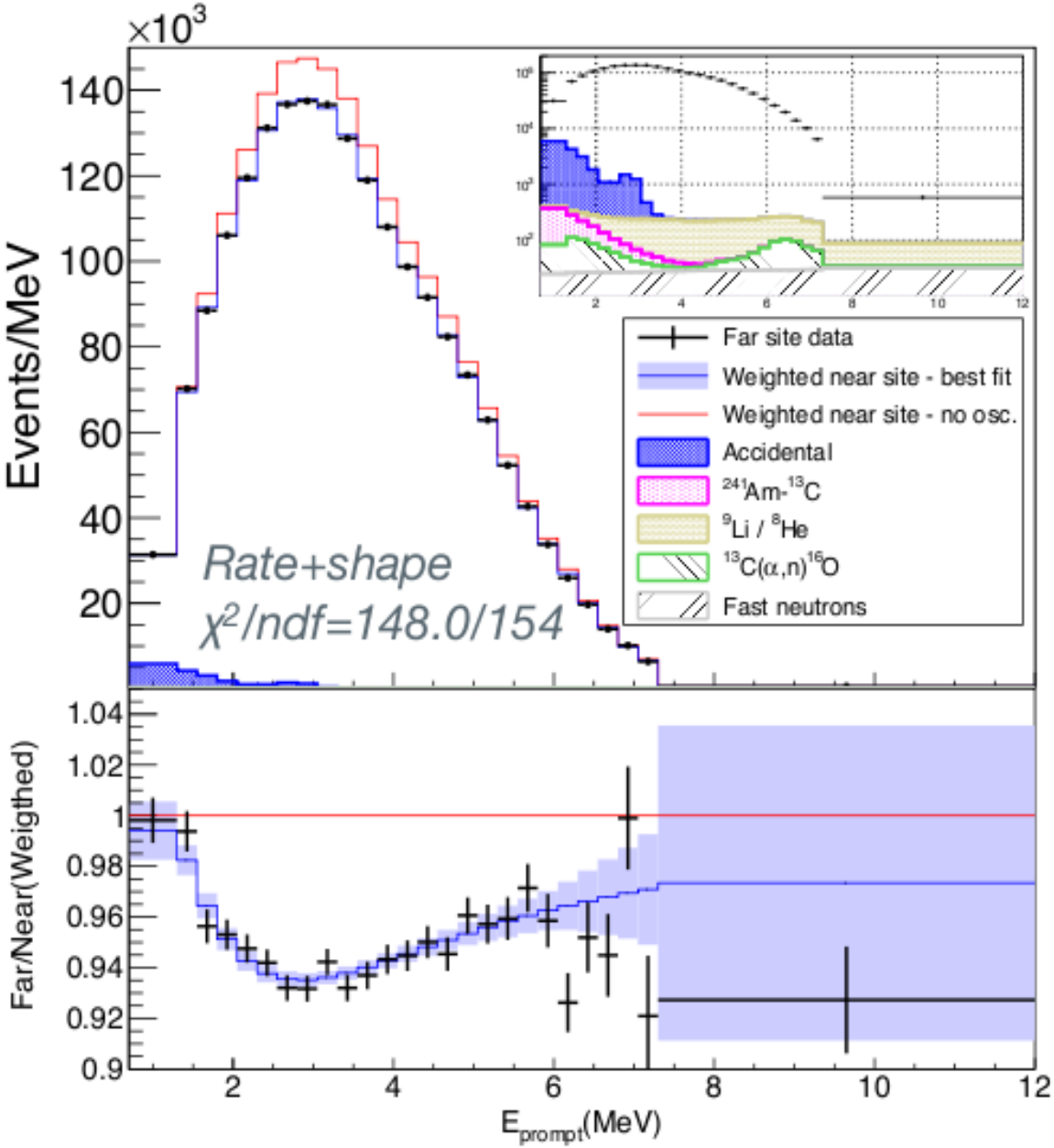
Three Experimental Halls, each with 2 (4) identical Anti-neutrino Detectors (ADs) in near (far) site.
Each AD is a three-zone cylindrical detector, immersed in water (used as Cerenkov VETO and shield). VETO system completed by a Top Tracker.





More on the detectors: NIMA 773, 8 (2015); NIMA 811, 133 (2016)

Daya Bay results



Collected statistics: 3.9 10^6 events.
1958 days of data-taking.
<2% background in all sites.
Relative efficiency error=0.13%

Clear rate and shape distorsion due to ν-oscillations.
Normalization to near detectors measurements.

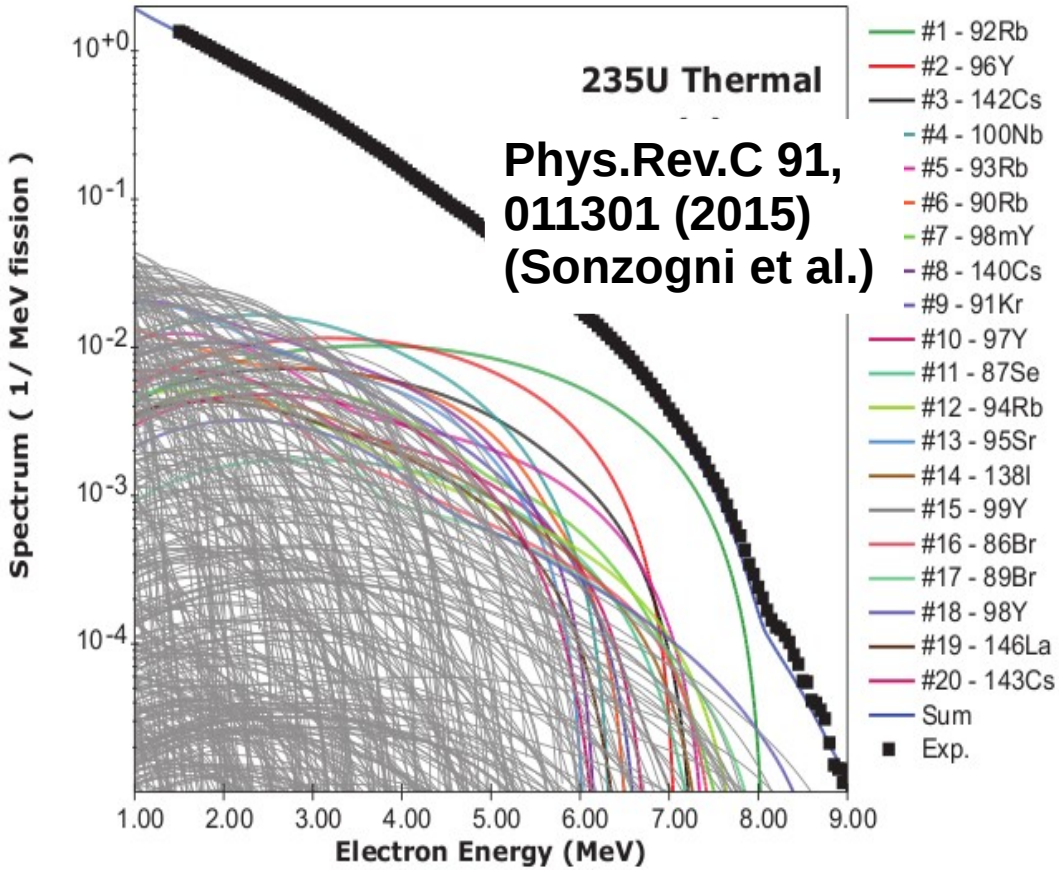
Best measurement in the world of:

$\sin^2(2\theta_{13}) = 0.0856 \pm 0.0029$

(60% of total uncertainty due to statistics)
PRL 121, 241805 (2018)

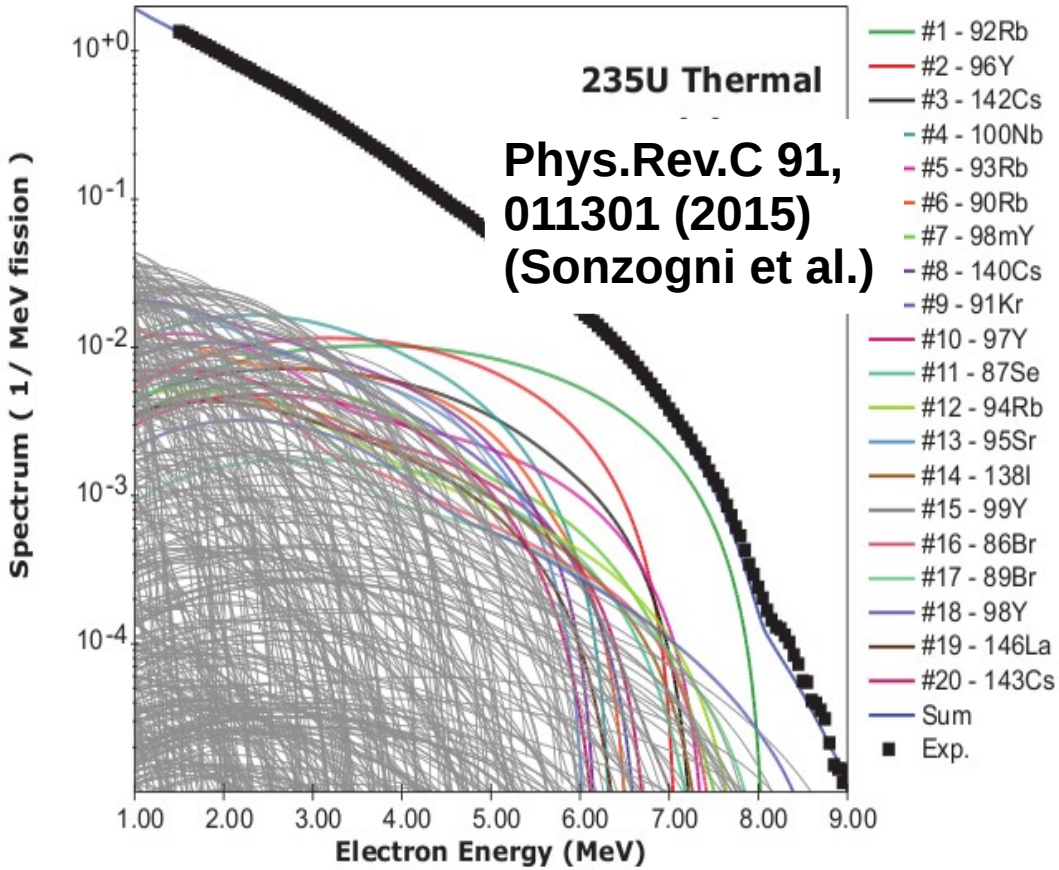
θ_{13} measurement also by: Reno (South Korea) and Double Chooz (France).
Great effort on the experimental side, but also on flux predictions....

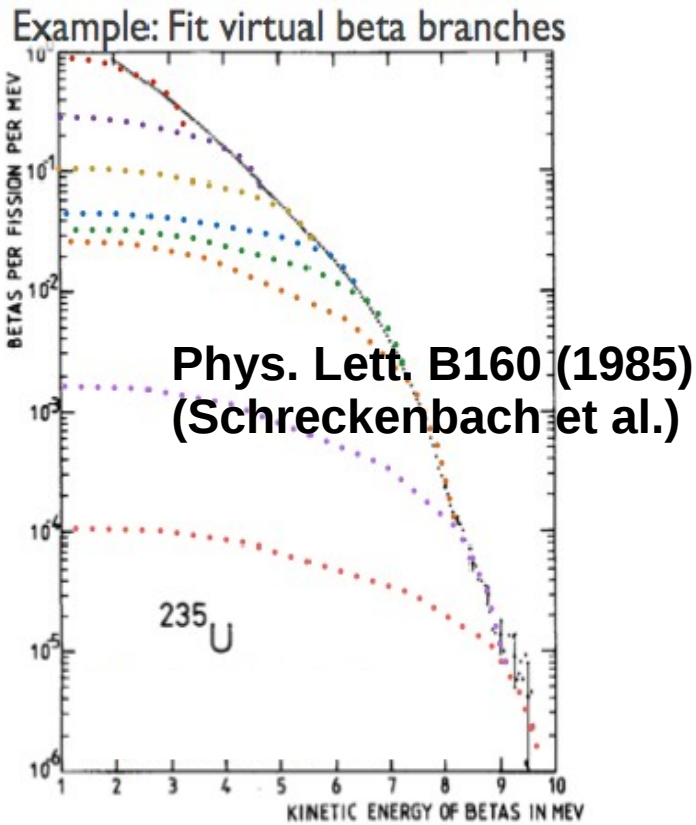
Reactor neutrinos predictions



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

Reactor neutrinos predictions



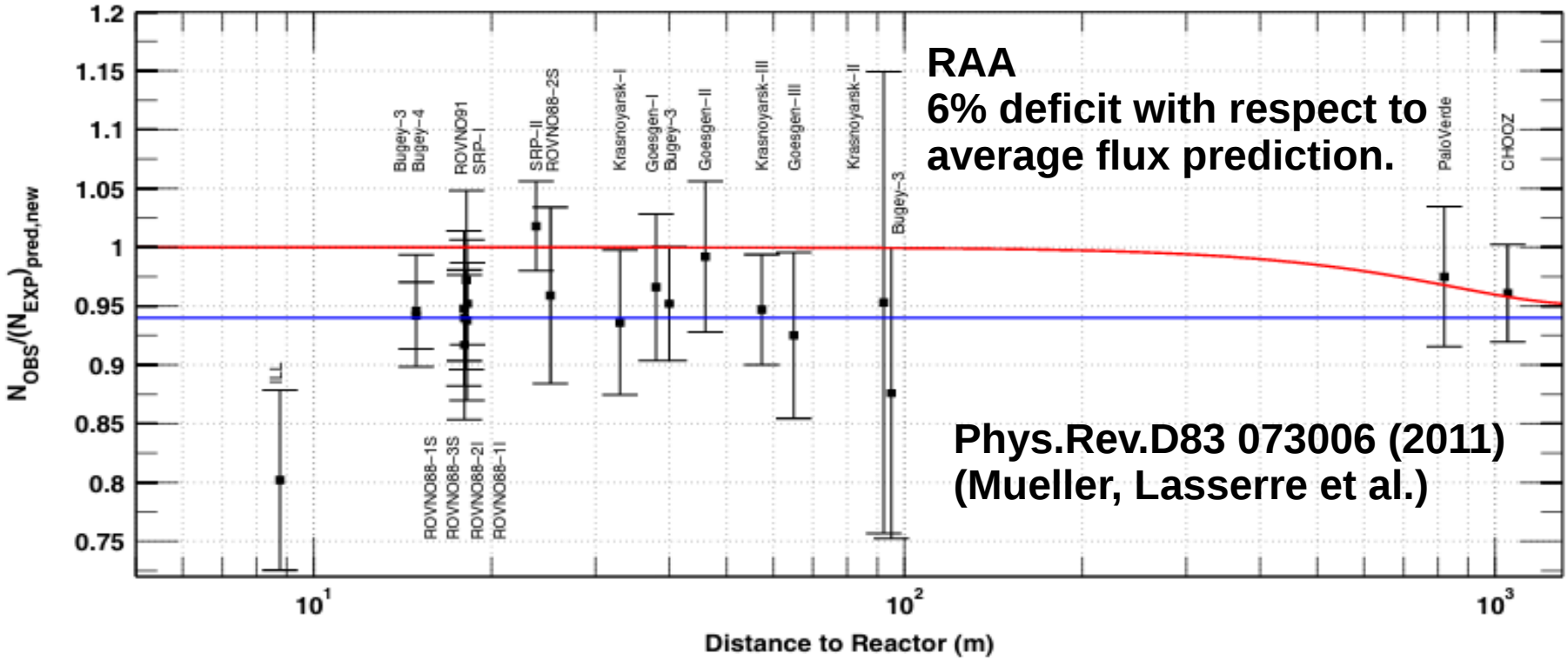


Summation (ab initio) method:
The spectrum is derived using the nuclear database for thousands of β nuclides.
10% uncertainty.

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)

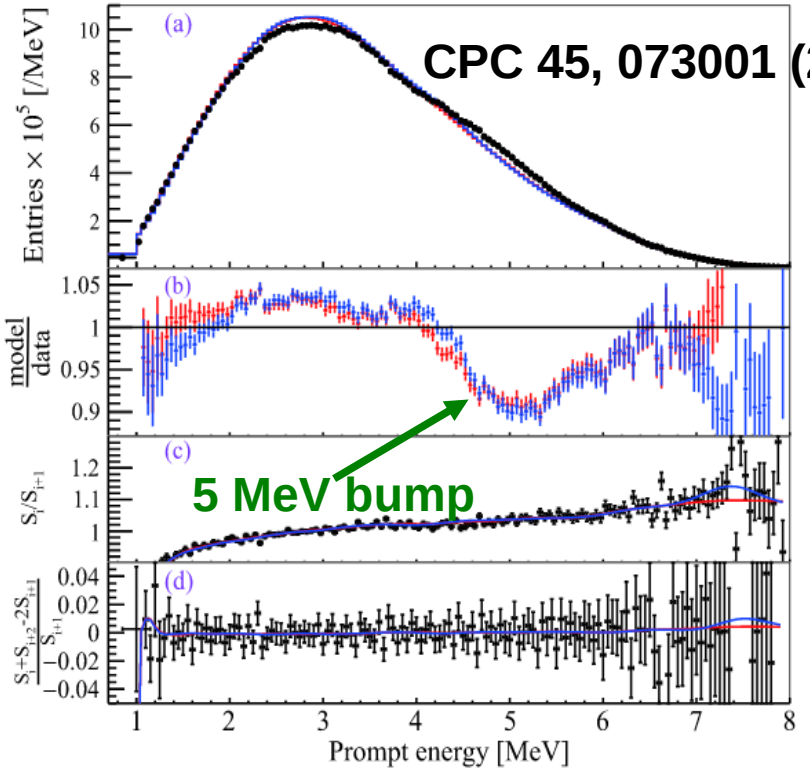
Reactor neutrinos anomalies



Recent reactor neutrino experiments in disagreement with model predictions:

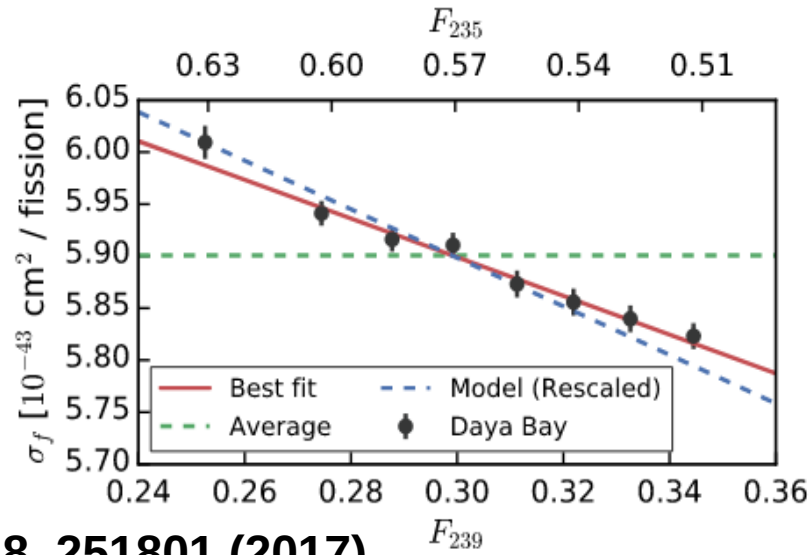
- **Integrated flux deficit: so called Reactor Anti-neutrino Anomaly, RAA. sterile ν ?**

Reactor neutrinos anomalies



IBD Rate vs F239

$$\sigma_f(F_{239}) = \bar{\sigma}_f + \frac{d\sigma_f}{dF_{239}}(F_{239} - \bar{F}_{239})$$



PRL 118, 251801 (2017)

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.

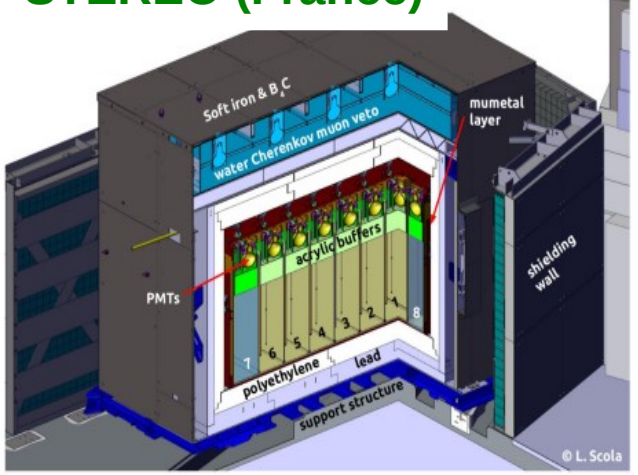
Sterile neutrino searches with reactors

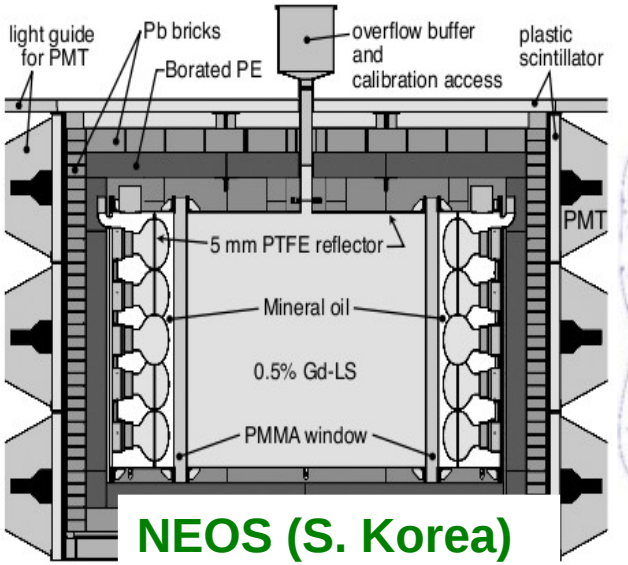
Reactor Anti-neutrino Anomaly can be explained by a 4th (sterile) neutrino with $\Delta m^2_{41} \sim eV^2$.

Investigations with ν_μ beams, but also with reactor ν-experiments.....

New generation (>2014) of experiments. Also reactor physics studies...

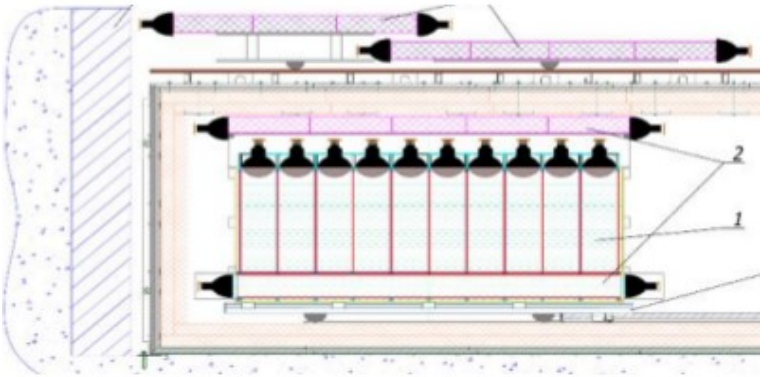
STEREO (France)





NEOS (S. Korea)

Neutrino-4 (Russia)



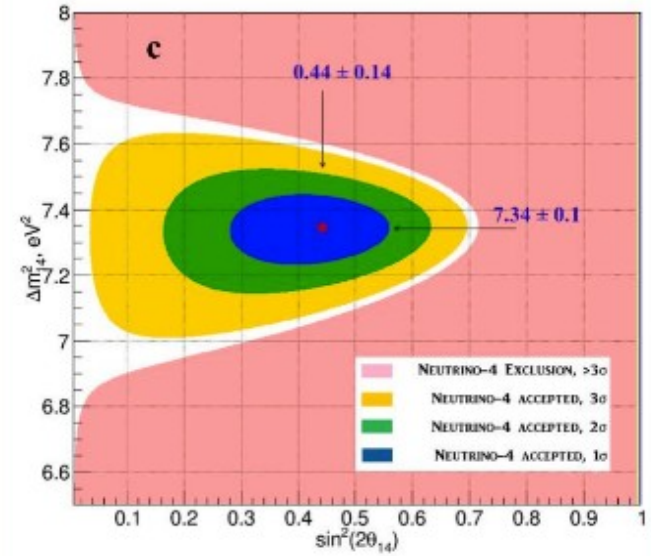
Other experiments:
PROSPECT (USA)
DANSS (Russia)

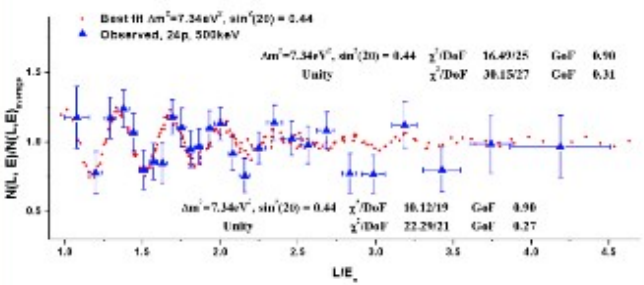
Sterile neutrino reactor experiment "identikit":

- Ton-scale detectors
- Distance L~10 m from reactor
- Liquid scintillator based (DANSS with plastic scintillators)
- Gd doped (PROSPECT uses ^{6}Li) for n-capture
- Read-out with PMTs (DANSS with PMTs+SiPMs)

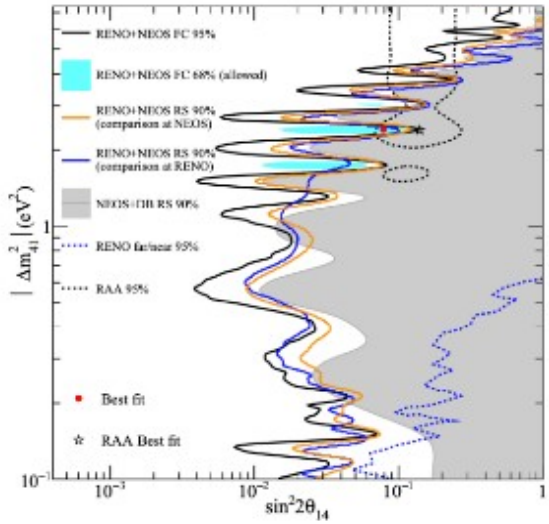
Results from electron-neutrino disappearance

Neutrino-4 arXiv:1809.10561

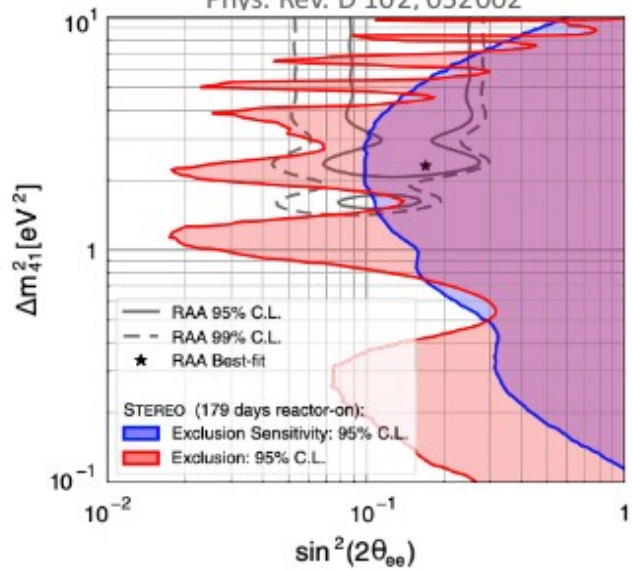




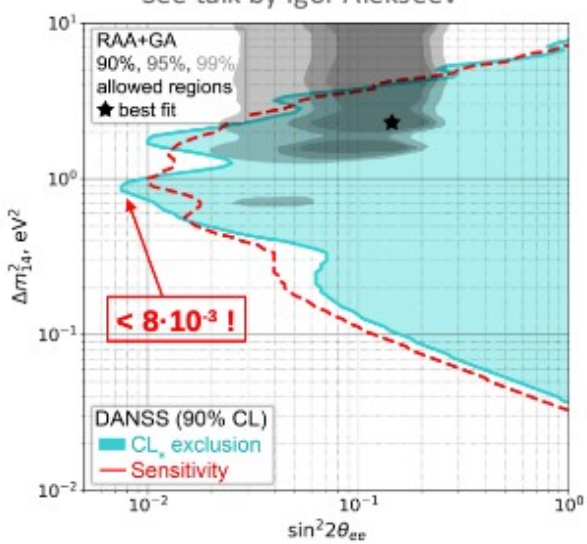
NEOS+RENO
arXiv:2011.00896



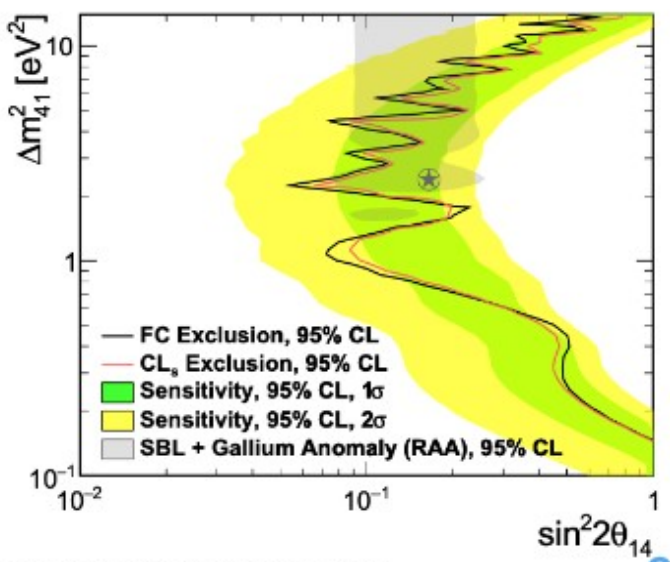
STEREO Collaboration
Phys. Rev. D 102, 052002



DANSS
See talk by Igor Alekseev



PROSPECT
Phys. Rev. D 103, 032001 (2021)



Wiggles or fluctuations?

See C. Giunti arXiv:2101.06785

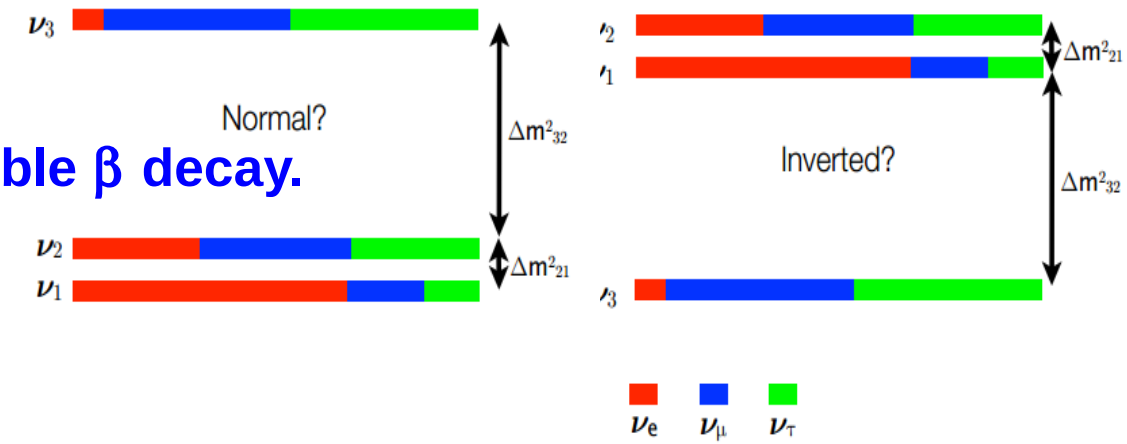
See poster by A. Minotti for a recent summary

See talk by d Galbinski for sensitivity of the Solid experiment

See C. Arguelles talk at NUFACT 2021

Neutrino mass hierachy measurement

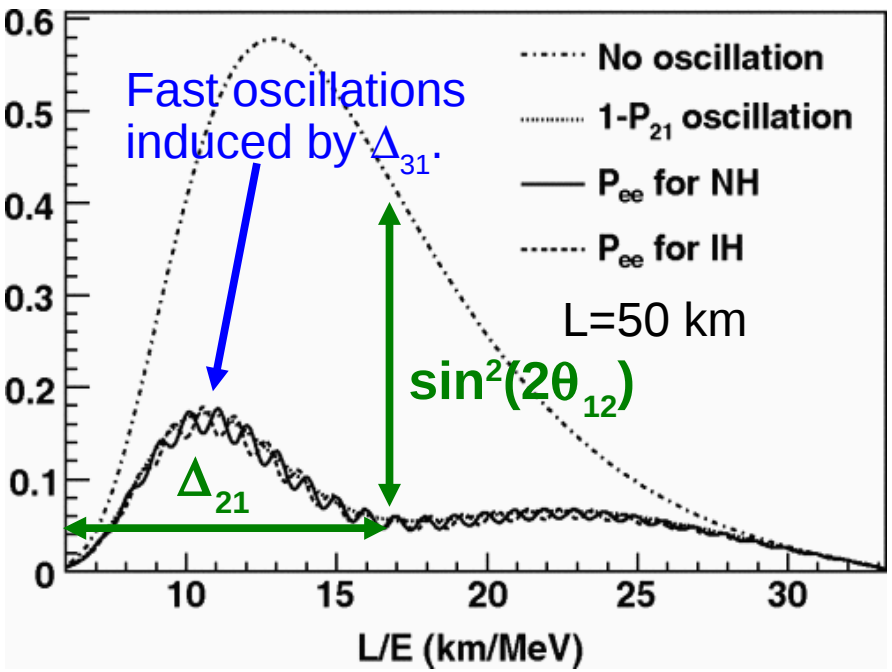
Neutrino Mass Hierarchy puzzle:
ν_3 heavier or lighter than $\nu_{1,2}$.
Consequences on neutrino-less double β decay.



Can be measured also with reactor neutrino experiments, exploiting Δm^2_{31} oscillation amplitude interference with Δm^2_{21} amplitude @L=50 km.
Physics Letters B 533 (2002) 94 (Petcov, Piai)

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

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



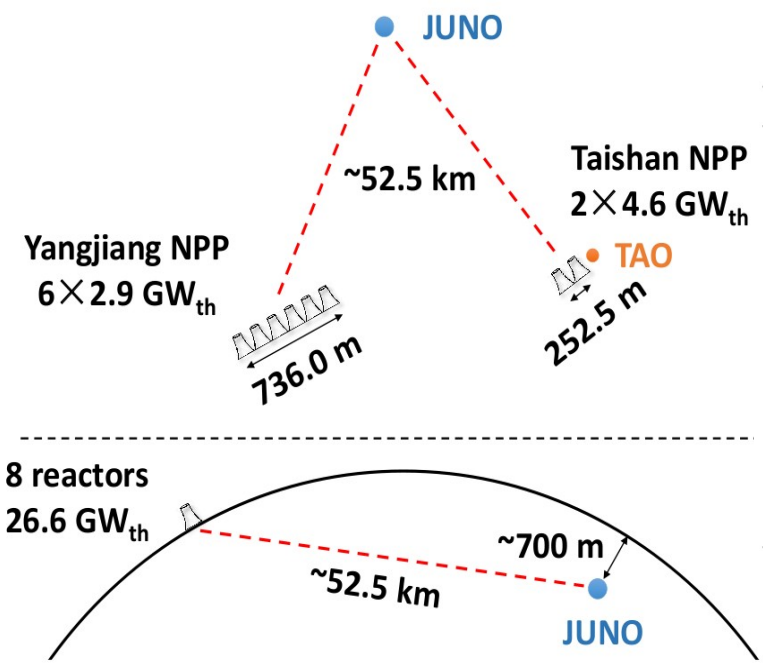
P_{ee} is independent on θ_{23} and δ_{CP} (the less known oscillation parameters).

JUNO experiment location

JUNO (Jiangmen Underground Neutrino Observatory) is a multipurpose anti-ν_e detector near Kaiping (South China), primarily designed for neutrino mass hierarchy measurement.

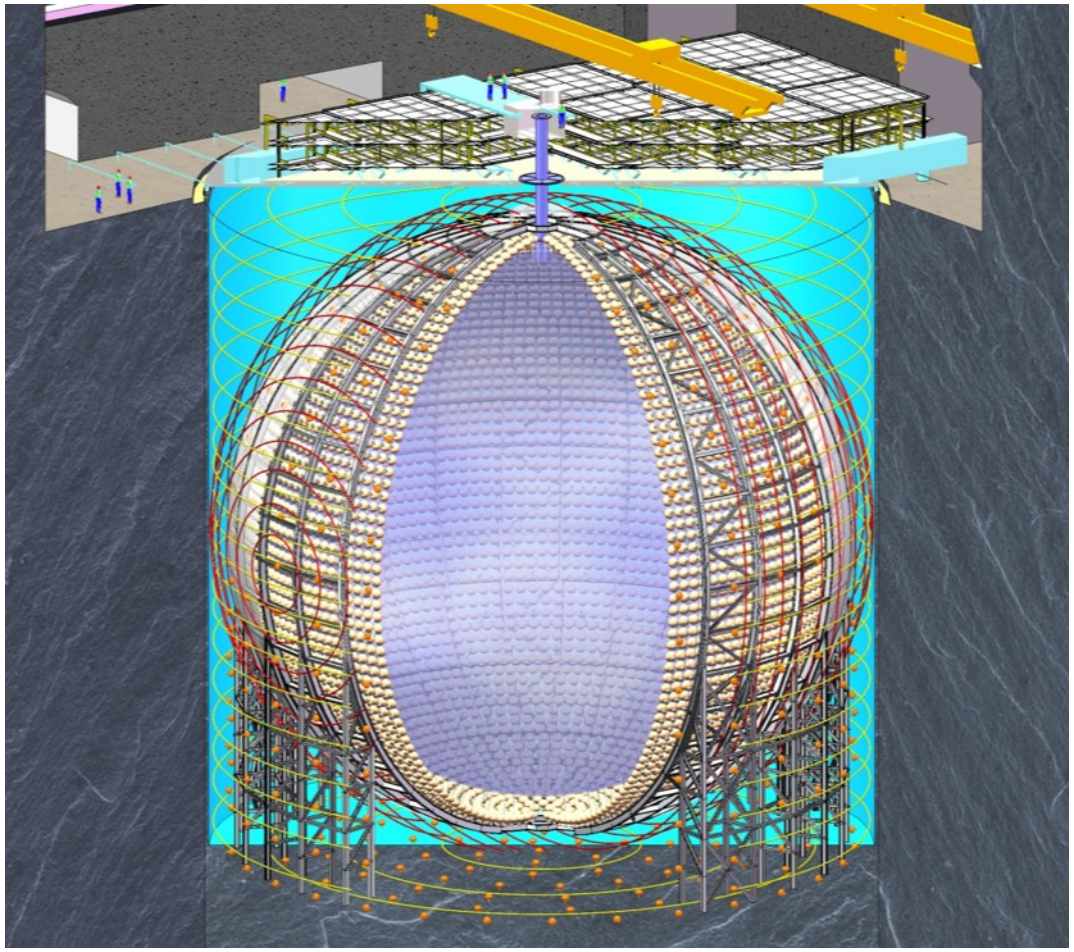
Baseline (≈52.5 km) from Yangjian and Taishan reactors (8 cores) optimized in the region of maximum Δm^2_{21}-driven oscillations.

Total power (2 multi-core Nuclear Power Plants): 26.6 Gwth.



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: 6 years of data taking with 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 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

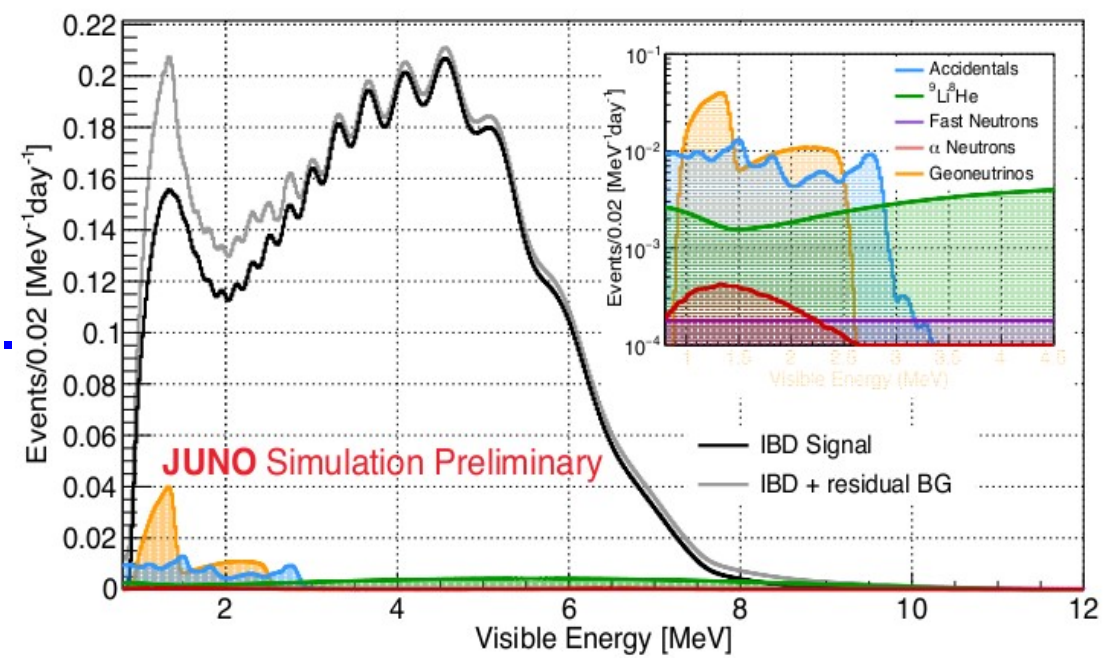
Bakground = 3.6 ev/day (after selection)

JUNO simulation preliminary

JUNO designed to reach 3 σ precision on mass hierarchy determination in 6 years.
Sinergy with 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+NoνA+T2K

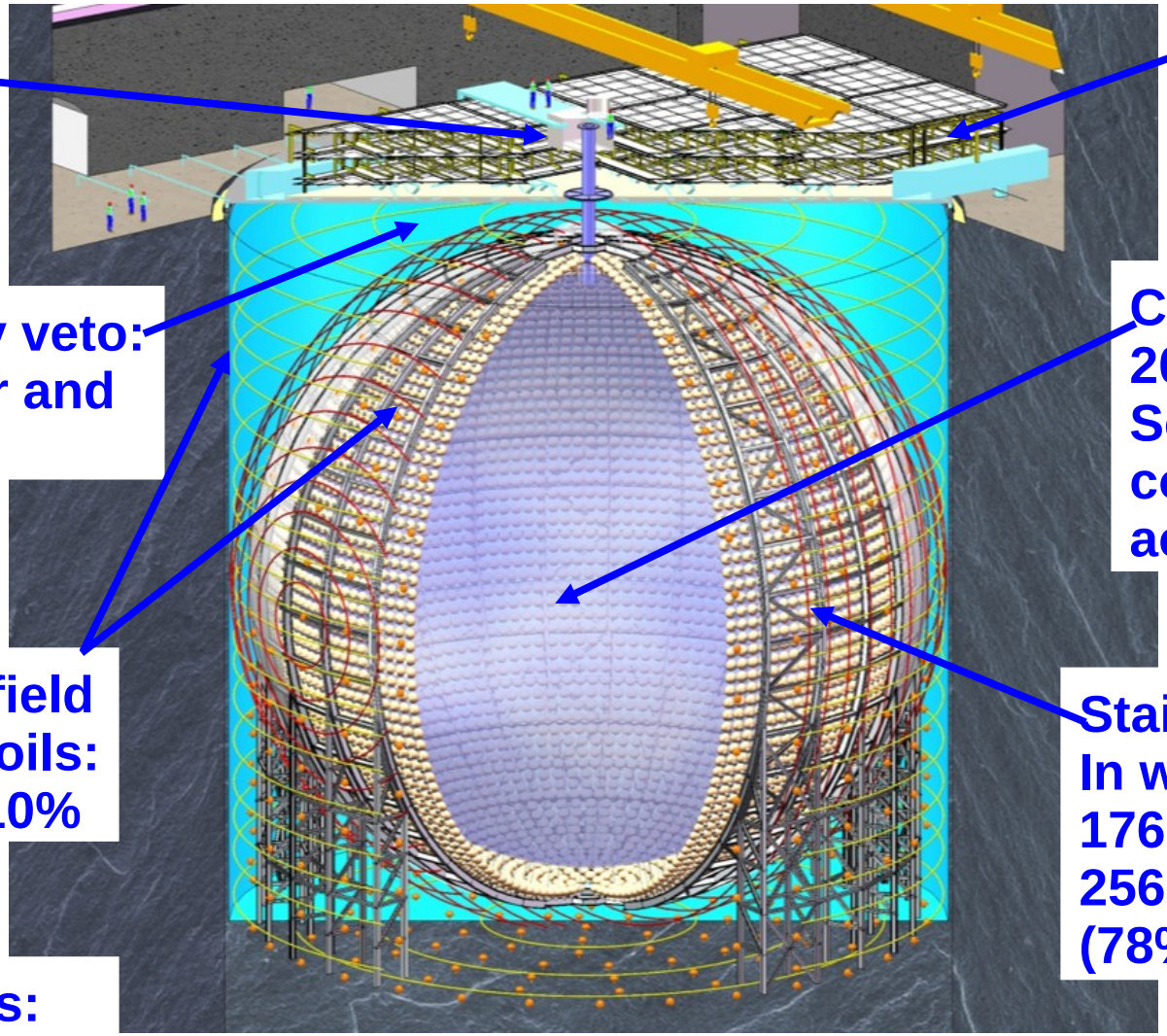
JUNO also designed for:

- **<% precision on Δm^2_{31}, Δm^2_{21}, $\sin^2\theta_{12}$.**
- **ν from natural sources detection.**



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:

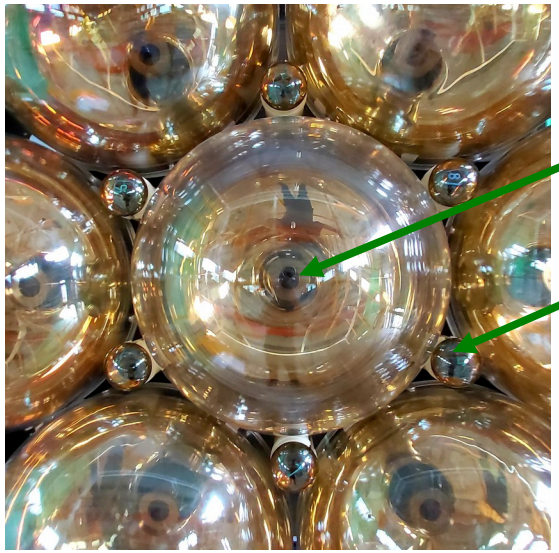
- **Height 44 m**
- **Diameter 43.5 m**

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

JUNO PMT systems

- **JUNO will use 20” Photomultipliers as its main photodetection system.**
- **Water-proof potting (voltage divider) and implosion protection.**
- **Also 3” PMTs: improve the control of systematics and increase dynamic range in photon-counting mode.**

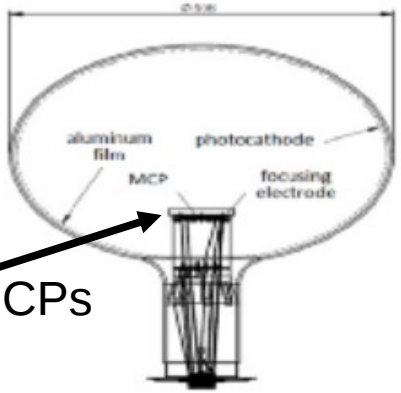
Tight arrangement with photocatode coverage > 75% (78% including Small PMTs).



Large PMT

Small PMT

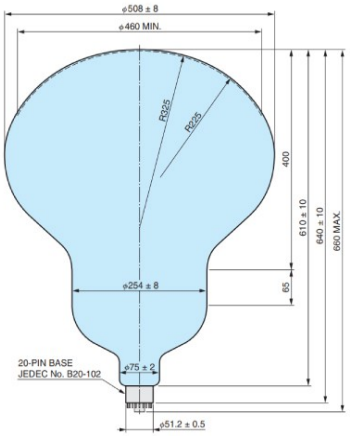
MCP-PMT



2 Horizontal MCPs

NIMA 971 (2020) 164021

Dynode PMT



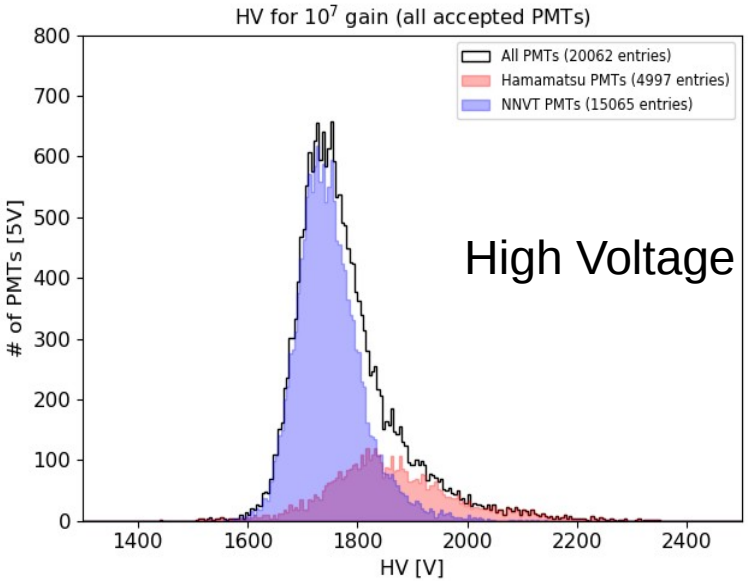
From Hamamatsu R12860 datasheet

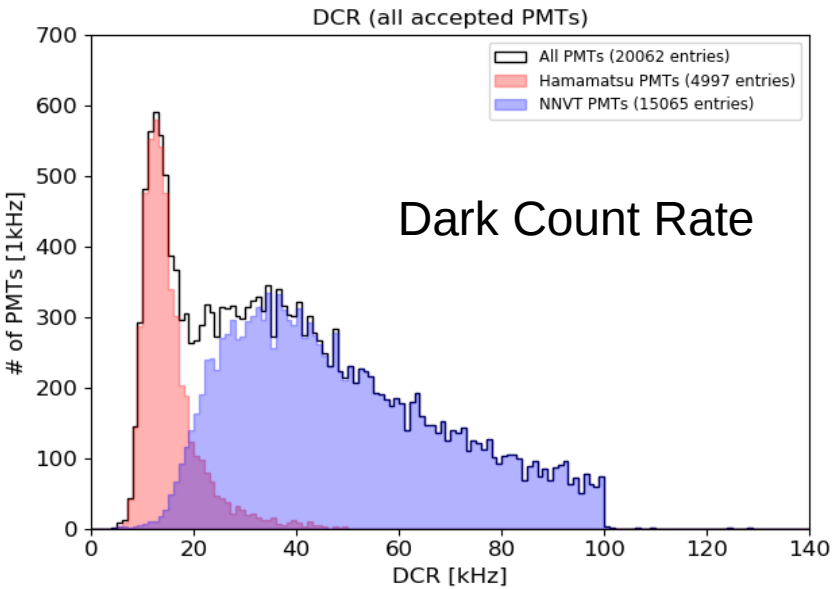
Two complementary LPMT technologies:

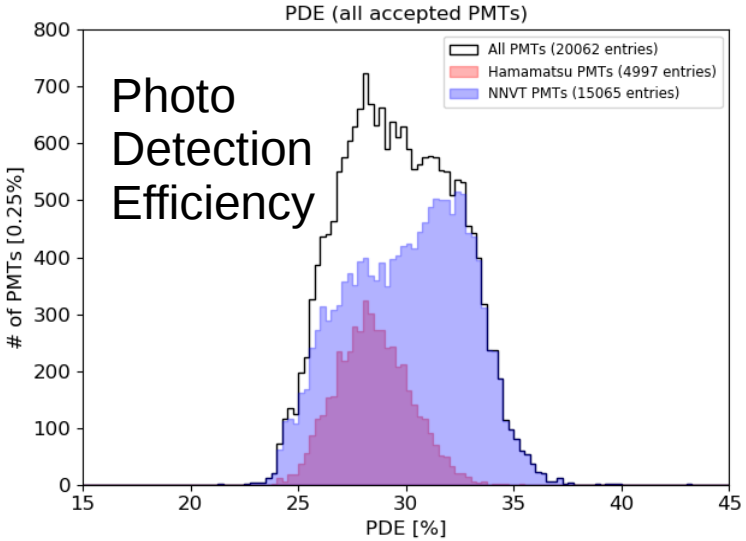
- **15000 MCP-PMTs** from NNVT (Microchannel plates) with larger PhotoDetection Efficiency (energy measurement)
- **5000 dynode PMTs** from Hamamatsu with better Transit Time Spread (vertex reconstruction and tracking in Central Detector)

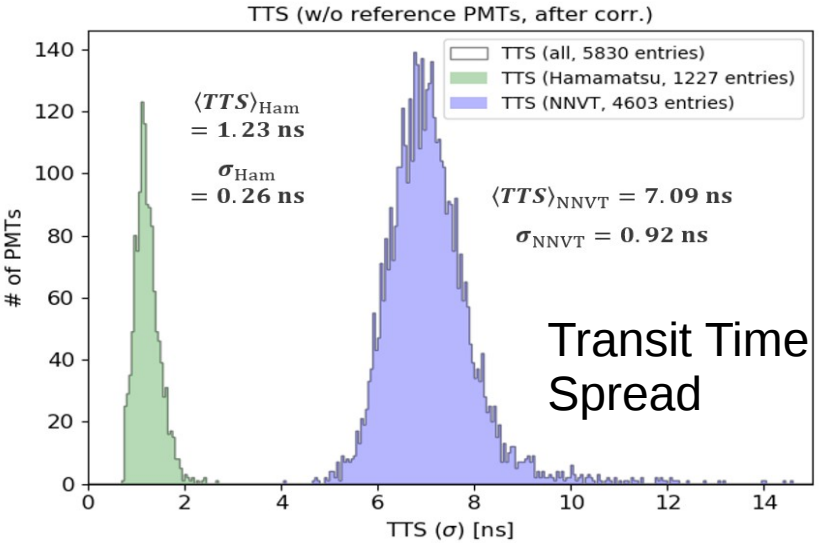
Large PMT performances

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









Detector installation status

External campus 28 January 2021

Water pool 30 September 2021

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.
Detector installation expected to finish in 2022.

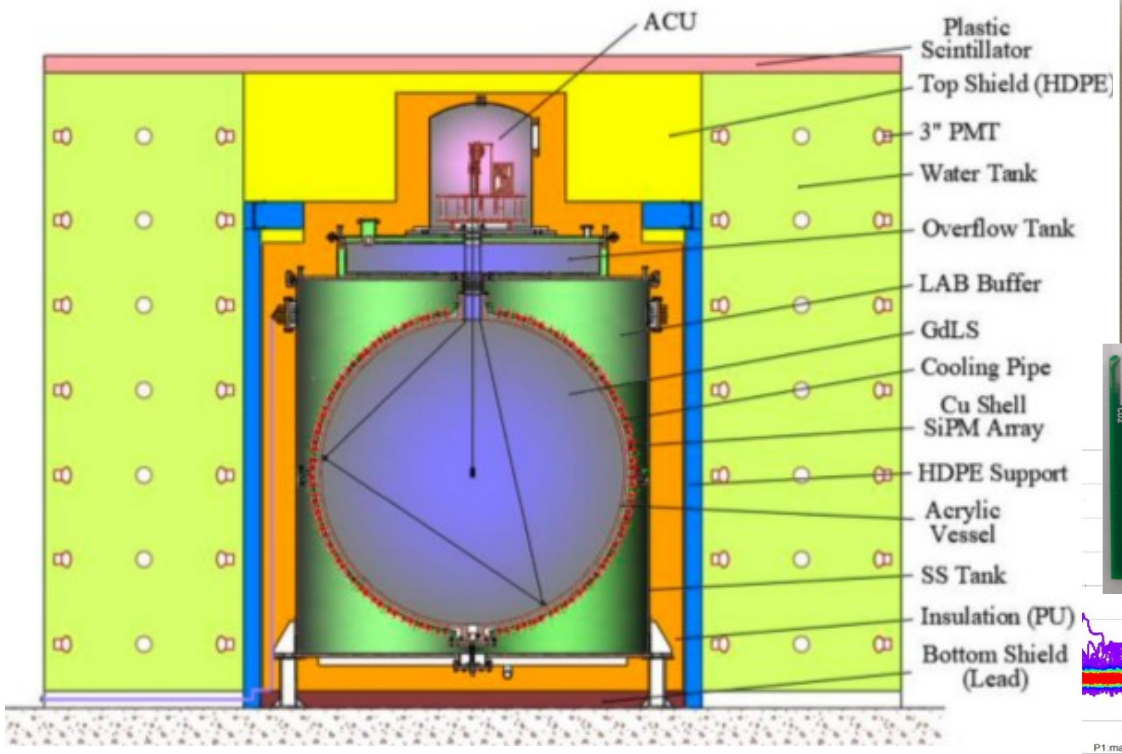
TAO
(Taishan Anti-neutrino Observatory)

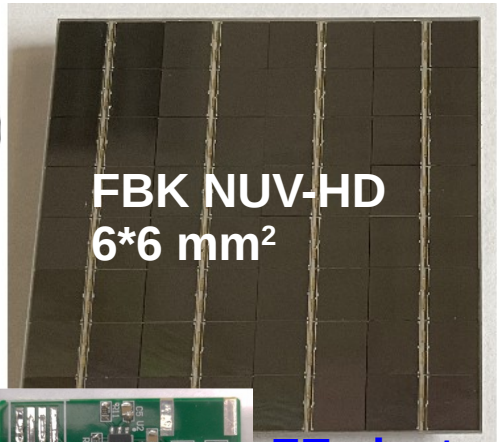
Measure anti-neutrino spectrum at % level to provide:

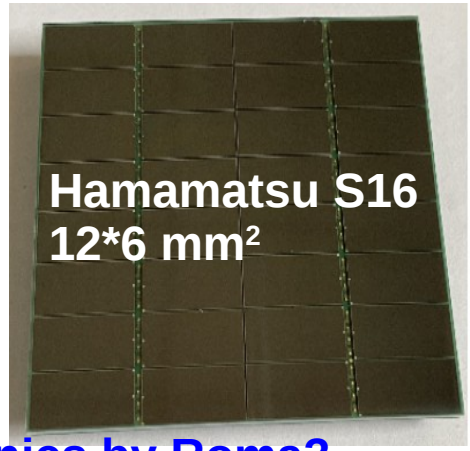
- **a model-independent reference spectrum for JUNO**
- **a benchmark for investigation of the nuclear database**

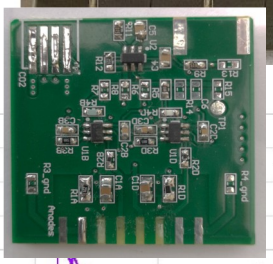
TAO CDR: arXiv:2005.08745

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 ~ 2%/√E (MeV)

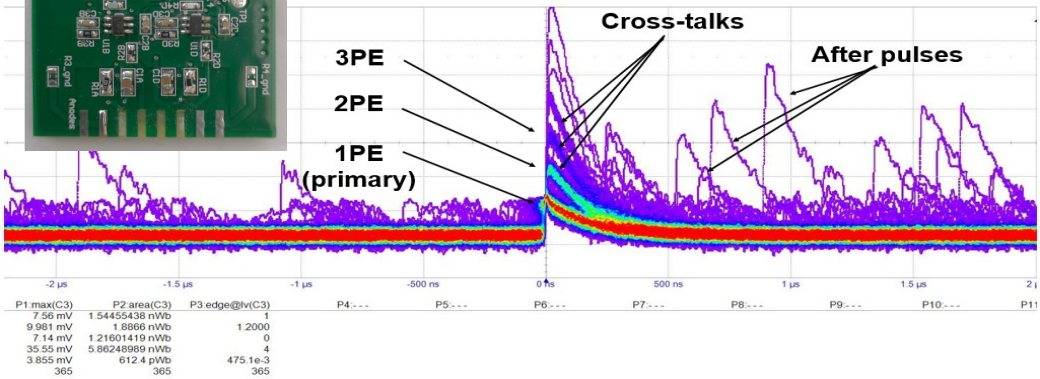








FE electronics by Roma3



Runninng at the end of 2022.

Summary and Conclusions

Reactor anti-neutrinos played an important role in neutrino oscillation measurements:

- **Neutrino discovery (Reines & Cowan, 1956)**
- **θ_{12} and Δm^2_{21} meaurement (KamLAND, 2003)**
- **Precision θ_{13} measurement (Daya Bay, RENO, Double Chooz)**

At present research activity on sterile ν and on reactors physics.

Neutrino mass hierarchy measurement just around the corner with JUNO, which will also measure at sub-% level other oscillation parameters.

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).

Installation started, detector completion expected before the end of 2022.