The results of the Daya Bay experiment and the status of the JUNO experiment

Maxim Gonchar for the JUNO / Daya Bay collaboration

Joint Institute for Nuclear Research

International Session-Conference
Section of Nuclear Physics
PSD RAS
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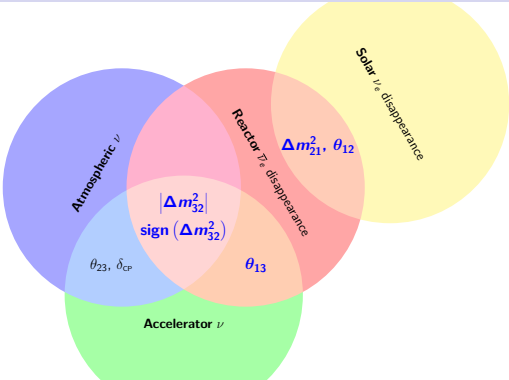


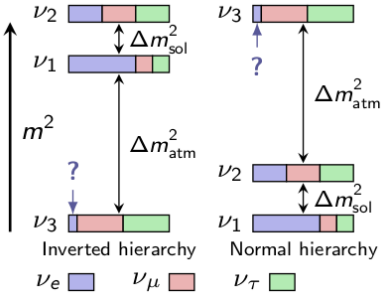
1 Introduction
- Neutrino masses and mixing
- Reactor $\overline{\nu}_e$ oscillations

2 Daya Bay, TAO and JUNO
- IBD selection
- Map
- Detectors
- Backgrounds

3 Daya Bay

4 JUNO and TAO
- Status
- Schedule
- Physics with JUNO

Mandatory slide I: Neutrino mixing



Weak and mass eigenstates differ:

$$|\nu_\alpha\rangle = \sum U^*_{\alpha i}|\nu_i\rangle$$

α – flavor states

i – mass states

Mixing parametrized by:

- three mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$,
- CP-violating phase: $\delta_{\rm CP}$.

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix:

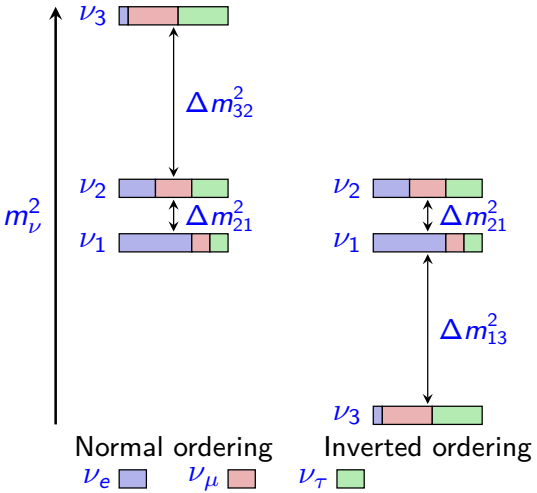
✓ $\theta_{23} \approx 45^\circ$ established through atmospheric and accelerator experiments: possibly maximal.

✓ $\theta_{12} \approx 34^\circ$ established through solar experiments and KamLAND: large, but not maximal.

✓ $\theta_{13} \approx 8^\circ$ established by reactor: **Daya Bay**, RENO, Double Chooz, T2K and MINOS.

- $\delta_{\rm CP} \sim \frac{3\pi}{2}$ probably: NOvA and T2K.

Mandatory slide II: Neutrino mass and ordering



Neutrino mass

- Neutrinos are massive
- Neutrino mass has not been measured
- $\sum m_\nu \lesssim 1\,\text{eV}$ (cosmology)
- $m_e < 2.2\,\text{eV}$ (direct)
- $\langle m_{\beta\beta} \rangle < 0.25\,\text{eV}$ ($0\nu\beta\beta$)

Mass splitting

From oscillation experiments:

- $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\,\text{eV}^2$
- $|\Delta m^2_{32}| = (2.42 \pm 0.06) \times 10^{-3}\,\text{eV}^2$
- $|\Delta m^2_{32}| / \Delta m^2_{21} \sim 32$

Mass ordering

Which neutrino is the lightest one: ν_1 or ν_3?

Reactor electron anti-neutrino production

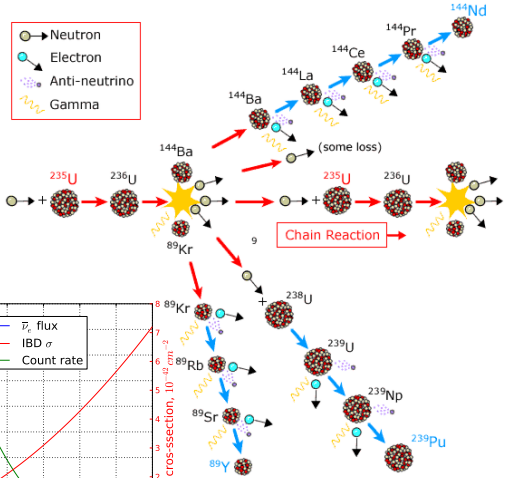
Reactor as $\overline{\nu}_e$ source

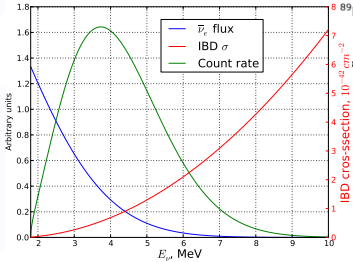
- ✓ **Strong**: produces $\sim 10^{20}\,\overline{\nu}_e/\mathrm{s}/\mathrm{GW_{th}}$
- ✓ **Clean**: only $\overline{\nu}_e$
- ✓ **"Free"** artificial antineutrino source
- **Complex spectrum**: a lot of constituents, time dependence
- $E_\nu < 10\,\mathrm{MeV}$

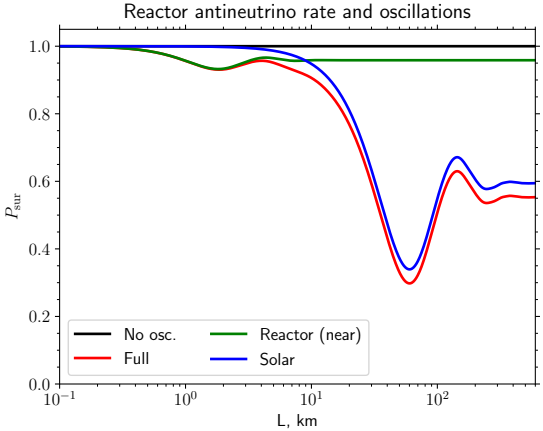
Reactor $\overline{\nu}_e$ production

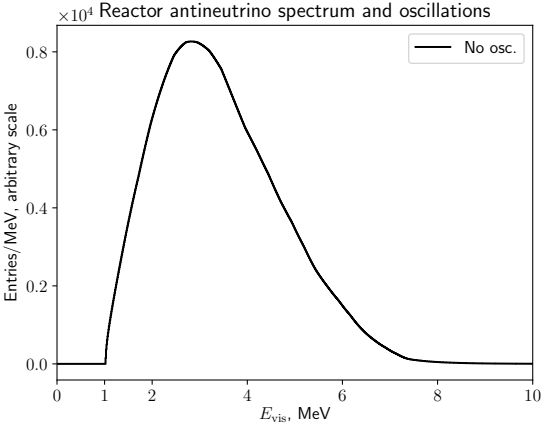
in beta decays of fission products of

- $^{235}\mathrm{U}$, $^{239}\mathrm{Pu}$ and $^{241}\mathrm{Pu}$ (slow n)
- $^{238}\mathrm{U}$ (fast n)
- $\sim 6\ \overline{\nu}_e$/fission (+ 200 MeV of heat)





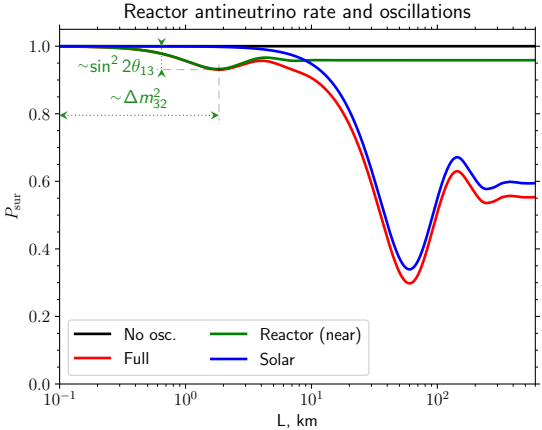


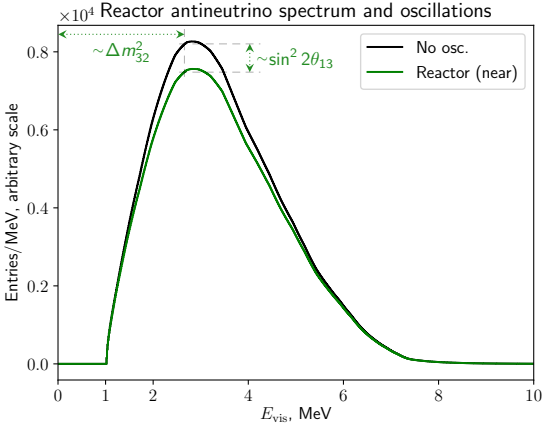


$$1 - P_{\nu_e \to \nu_e} = \sin^2 2\theta_{13} \left(\sin^2 \theta_{12} \sin^2 \frac{\Delta m^2_{32} L}{4E} + \cos^2 \theta_{12} \sin^2 \Delta_{31} \right) + \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 \Delta_{21}$$

~~δ_{CP}, θ_{23}~~

$E_{\rm vis} \approx E_\nu - 0.78\,\text{MeV}$





deficit value

minimum location

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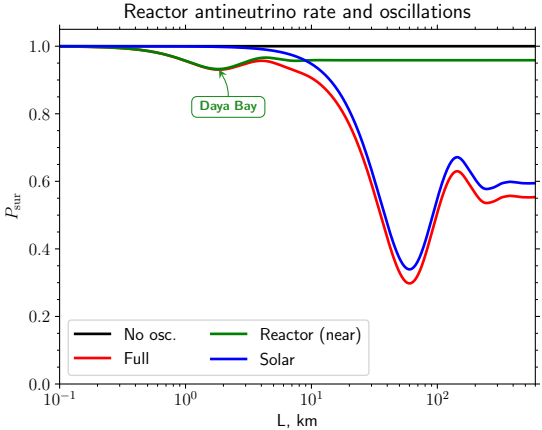

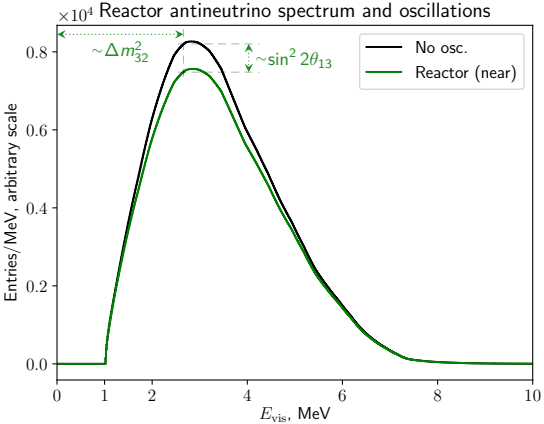

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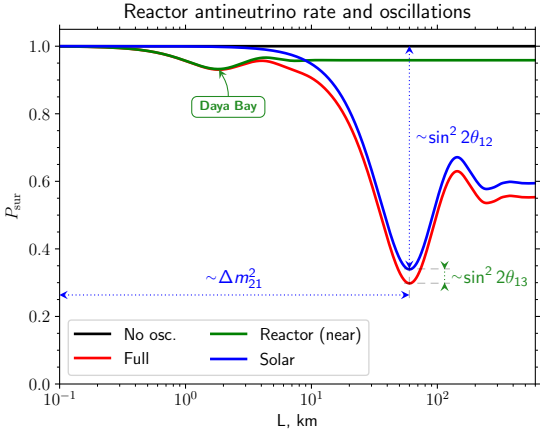

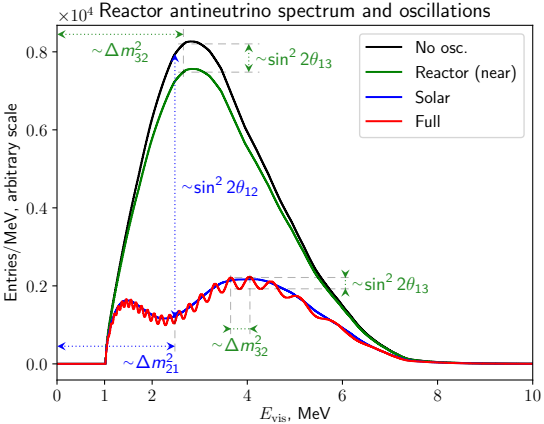

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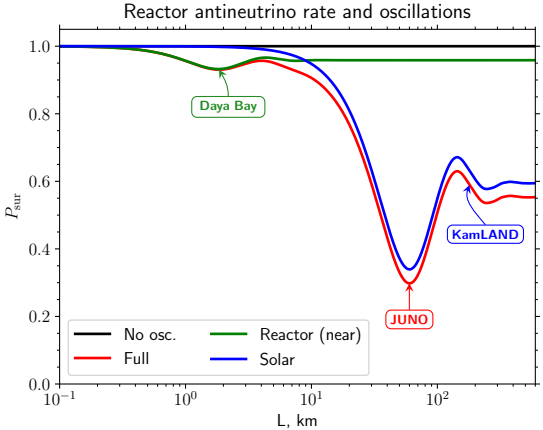

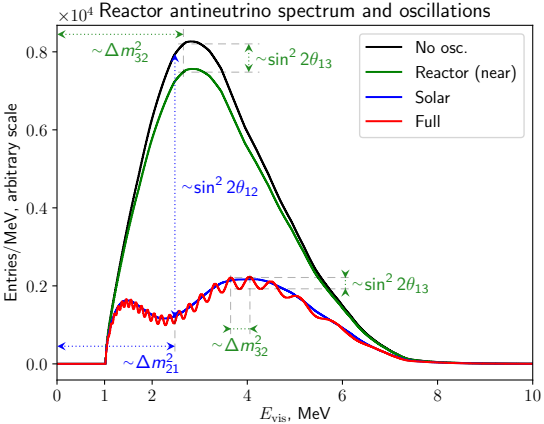

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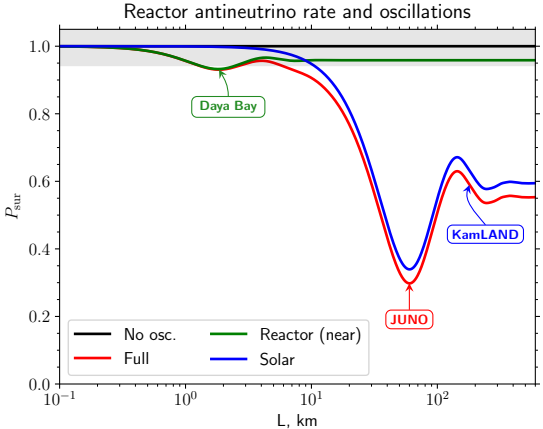
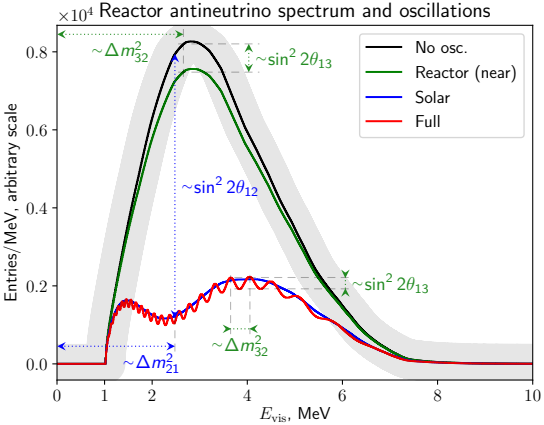


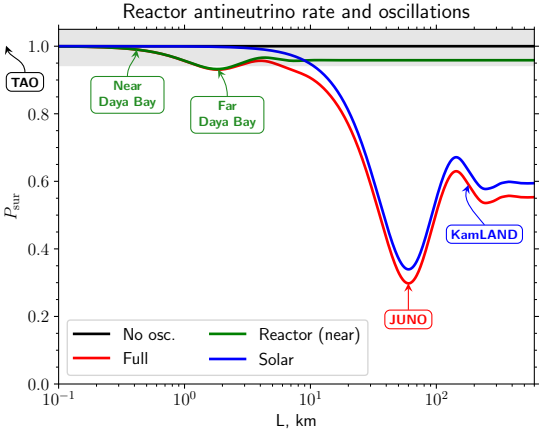


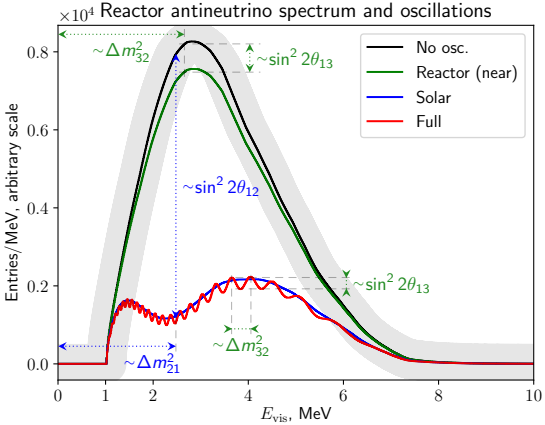
Challenges:

- Unreliable spectrum model

Daya Bay
total flux, spectrum shape

JUNO
fine structure?





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$\lesssim 0.2\%$ uncorrelated

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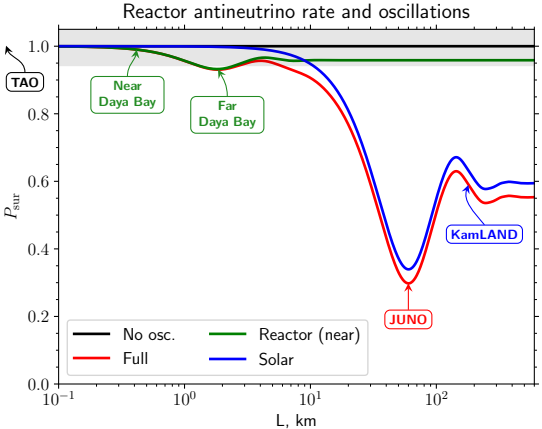

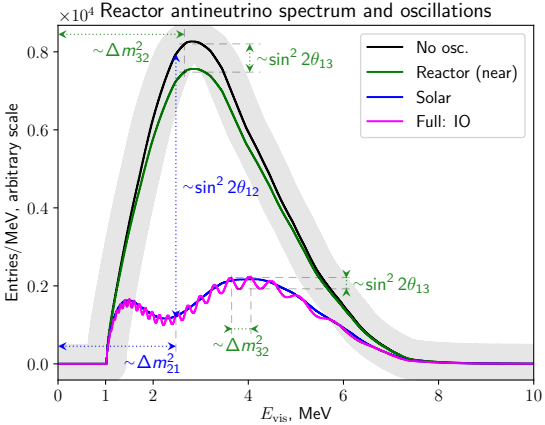

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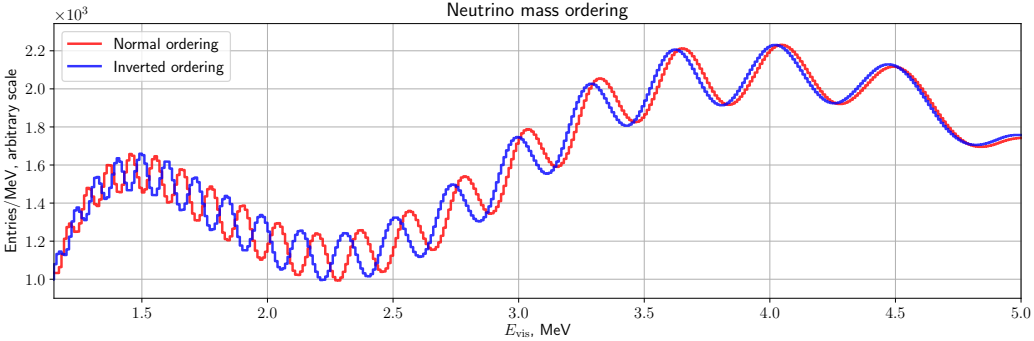
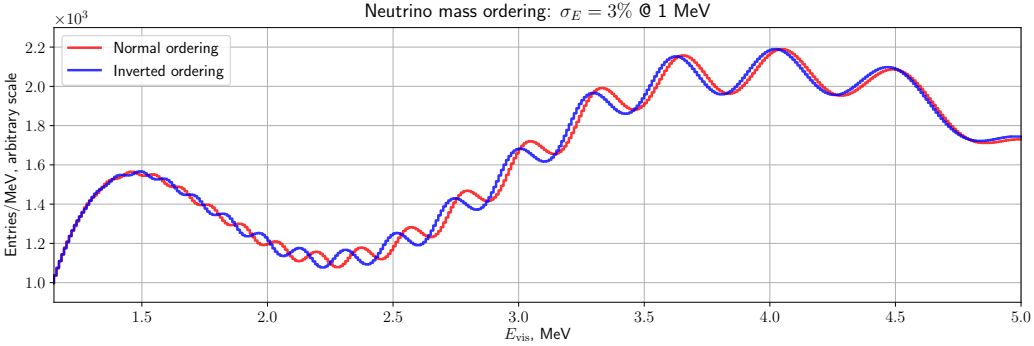


(same Δm^2_{ee})

Challenges:

- Unreliable spectrum model
- Efficiency uncertainty
- Energy scale uncertainty
- Energy resolution

	Daya Bay	**JUNO**
Unreliable spectrum model	total flux, spectrum shape	fine structure?
Efficiency uncertainty	$\lesssim 0.2\%$ uncorrelated	
Energy scale uncertainty		$<1\%$
Energy resolution		$<3\%$ at 1 MeV



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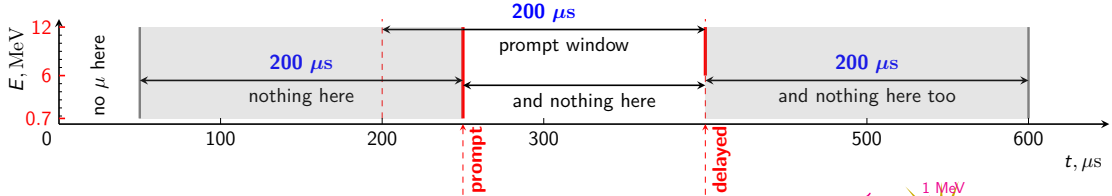
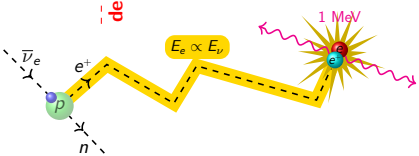
Inverse beta decay and selection criteria



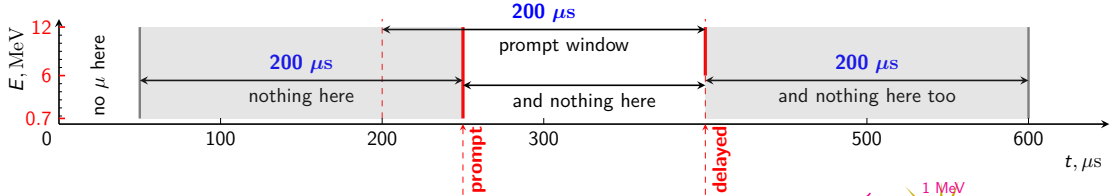
Plot: Daya Bay



Cherenkov: $< 5\%$

Cut	Daya Bay nGd	JUNO nH
Instrumental	Flashers	
Fiducial volume	natural	$R < 17$ m
Time	200 μs	1 ms
Prompt E, MeV	0.7 – 12	
Delayed E, MeV	6 – 12	1.9 – 2.5
Distance, m	no	1.5
Muon veto	0.6 ms – 1 s	TBD
Multiplicity veto, us	±200	TBD

Inverse beta decay and selection criteria



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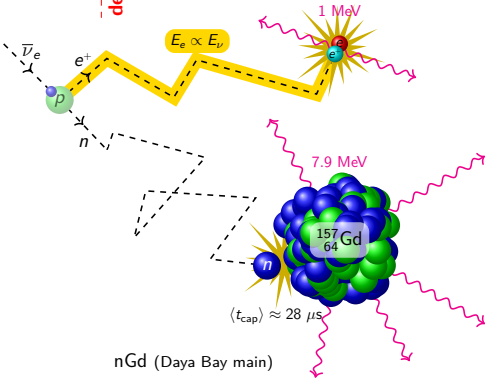
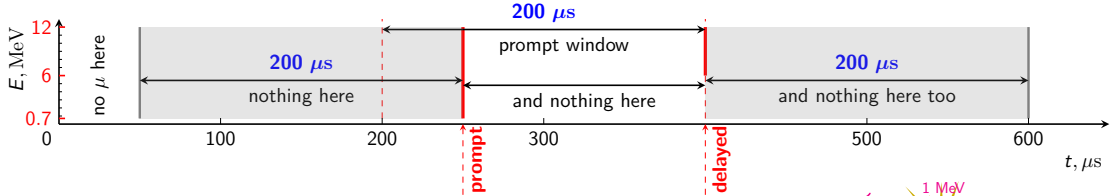


nGd (Daya Bay main)

Inverse beta decay and selection criteria



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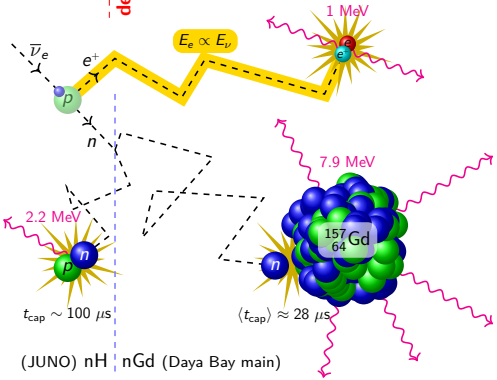
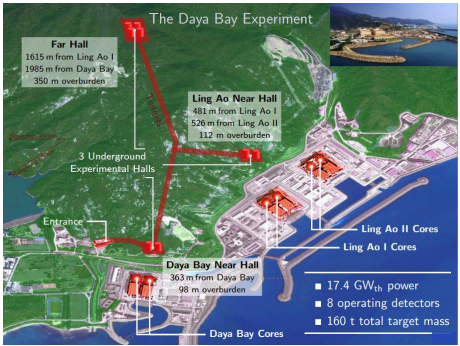


Plot: Daya Bay

Cherenkov: < 5%

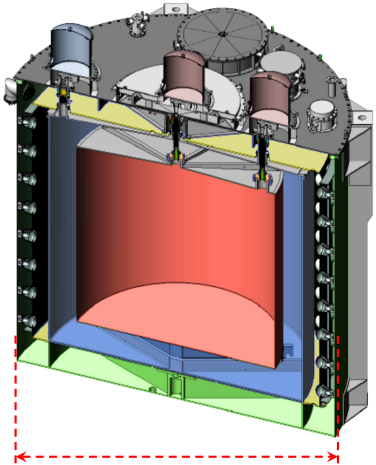
Daya Bay, JUNO and TAO location

- JUNO — Jiangmen Underground Neutrino Observatory
- TAO — Taishan Antineutrino Observatory



	Yangjian	Taishan	Daya Bay	Ling Ao	Ling Ao II	Huizhou
Thermal power, GW	2.9×6	4.6×~~4~~2	2.9×2	2.9×2	2.9×2	2.9×6
Total, GW	~~35.8~~ 26.6			17.4		17.4 ?

Antineutrino Detectors (AD)



	Daya Bay	TAO	JUNO
Attention	**Uncorr. ε unc.**	Energy resolution	
Method	**Identical ADs**	Light collection	
	3 zones	Dark noise	
Scintillator	**GdLS/LS**	GdLS @ -50°C	LS
PMTs	**192 8"**	SiPM 1.5M 5 mm	18k 20" +26k 3"
Coverage, %	**12**	94	78
Light col. p.e./MeV	**160**	4500	~~1200~~ 1350
E res. at 1 MeV, %	**8.7**	2	3
Detectors	**4/4** far near	1	1
Thermal power, GW	**17.4**	4.6	~~35.8~~ 26.6
Baseline	**0.5 km–2 km**	30 m	52 km
IBD/day/AD	**75/635** far near	2000	60

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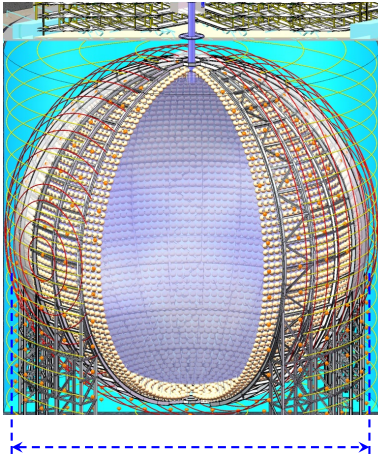

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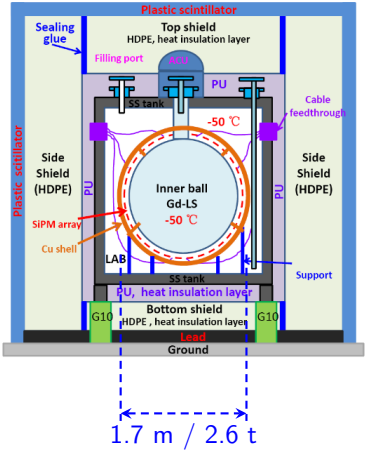

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Attention	Uncorr. ε unc.	**Energy resolution**	
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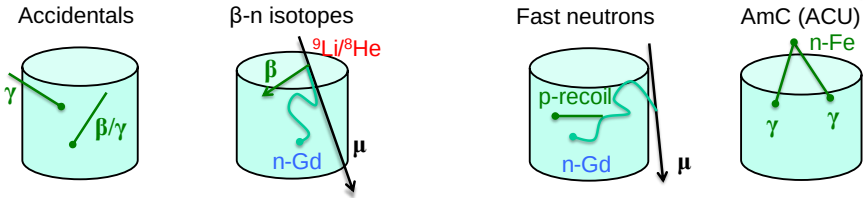
Background events

		DB Near S/N	DB Far S/N	Unc.	JUNO S/N	Unc.
• IBD	events/AD	635	75		60	
• Geo ν	%	negligible	negligible	negligible	1.8	30
• Accidentals	%	1.3	1.6	1	1.5	negligible
• $^{8}\mathrm{He}/^{9}\mathrm{Li}$	%	**0.3**	**0.2**	**30**	2.7	20
• Fast neutrons	%	0.08	0.07	17	0.2	100
• $^{241}\mathrm{Am}$-$^{13}\mathrm{C}$	%	0.03	0.07	45	no	no
• $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$	%	0.01	0.07	50	0.1	50
• Total bkg	%	1.72	2.01		6.5	



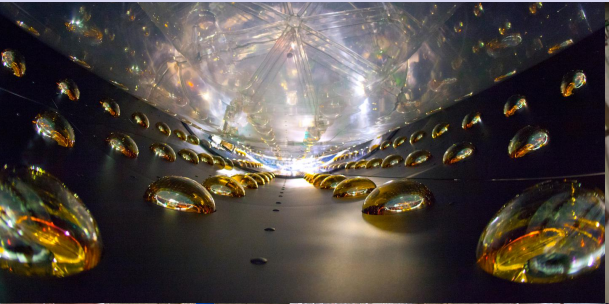
1 Introduction

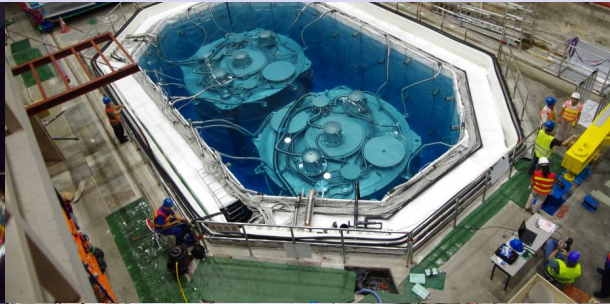
2 Daya Bay, TAO and JUNO

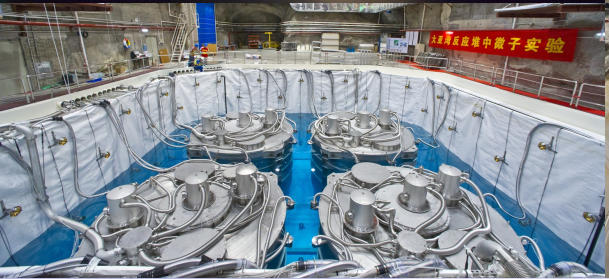
3 Daya Bay

4 JUNO and TAO

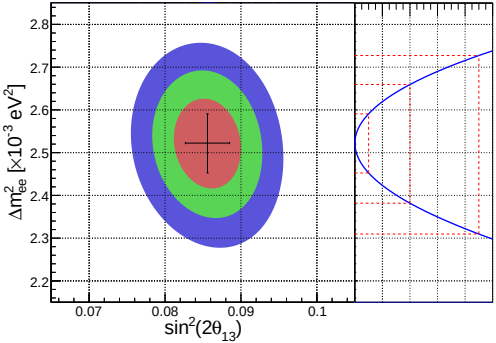
Daya Bay detectors







Daya Bay oscillation result: 500K/4M events

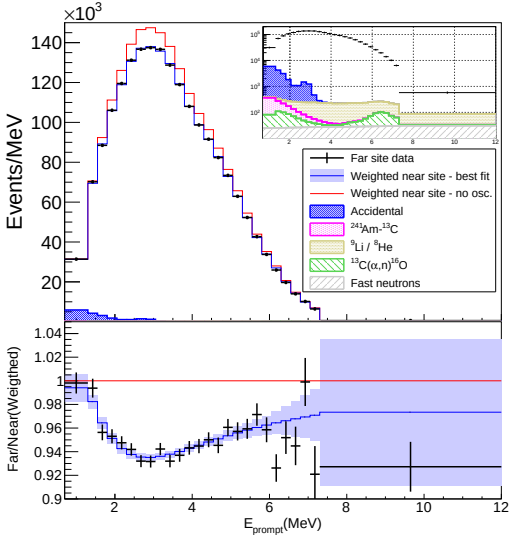


$\sin^2 2\theta_{13} = 8.56 \pm 0.29 \quad \times 10^{-2} \quad 3.4\%$

$|\Delta m^2_{ee}| = 2.522^{+0.068}_{-0.070} \quad \times 10^{-3}\ \text{eV}^2 \quad 2.8\%$

$\chi^2/\text{NDF} = 148.0/154$ precision

✓ Consistent with 3ν oscillations



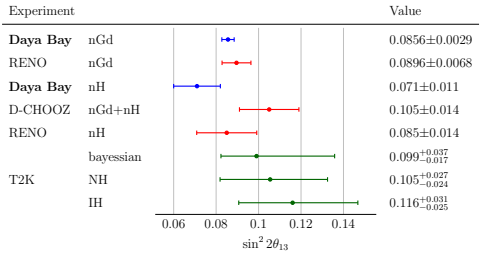
1958 days, arXiv:1809.02261, PRL

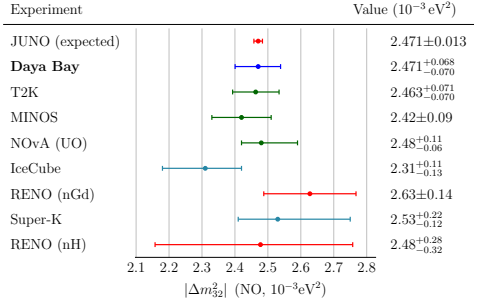
Daya Bay oscillation result

nH, 621 days, arXiv:1603.03549, PRD

nGd, 1958 days, arXiv:1809.02261, PRL

- Most precise $\sin^2 2\theta_{13}$ measurement.
- $\sin^2 2\theta_{13} = 0$ is excluded at almost 30σ.
- nH $\sin^2 2\theta_{13}$ measurement is world's third in precision.
- Second world's measurement of Δm^2_{32}.
- Δm^2_{32} is consistent with and complementary to accelerator measurements.
- Negligible correlation between $\sin^2 2\theta_{13}$ and Δm^2_{ee}.





Comparison updated: 2019.09.11

Light sterile neutrino search

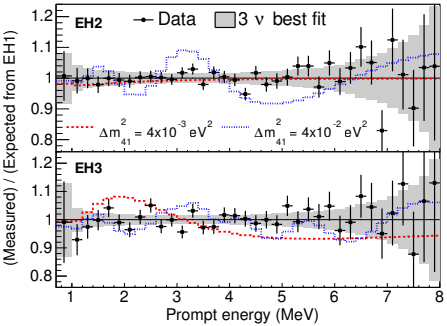
621 days, arXiv:1607.01174, PRL

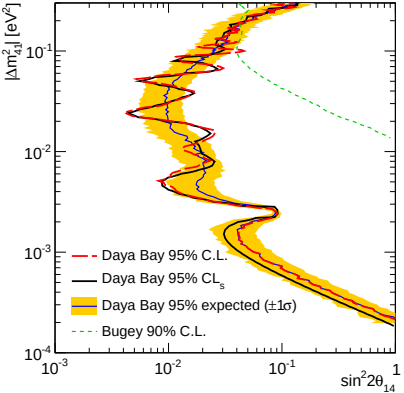
- Sterile neutrino cause spectral distortions, different at the near and far sites.

✓ Relative measurement.

✓ independent of reactor related systematics.

- **Consistent with 3-flavor oscillations.**





Light sterile neutrino search update

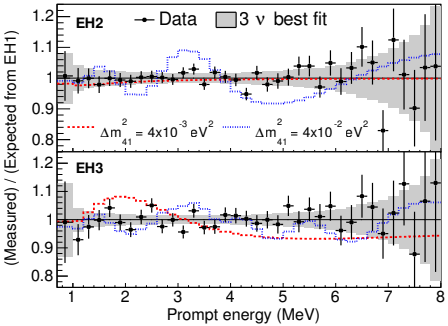
1230 days+MINOS, arXiv:2002.00301

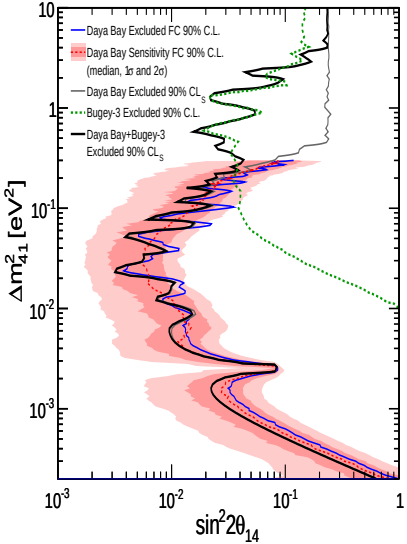
- Sterile neutrino cause spectral distortions, different at the near and far sites.

✓ Relative measurement.

✓ independent of reactor related systematics.

- **Consistent with 3-flavor oscillations.**





Y-scaled for consistency

Light sterile neutrino search update

1230 days+MINOS, arXiv:2002.00301

- Daya Bay and Bugey-3 strongly constrain Δm^2_{41} and $\sin^2 2\theta_{14}$.
- Daya Bay, Bugey-3 and MINOS data allows to constrain Δm^2_{41} and $\sin^2 2\theta_{14} \sin^2 \theta_{24}$.

✓ LSND and MiniBooNE parameters space is excluded at the 90% C.L.

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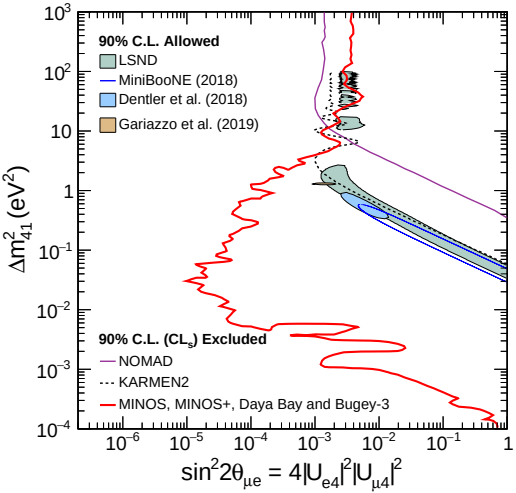

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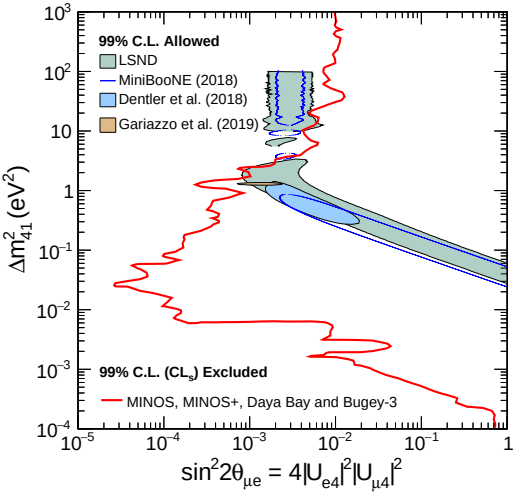
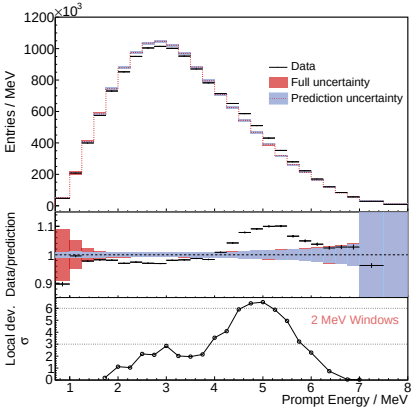


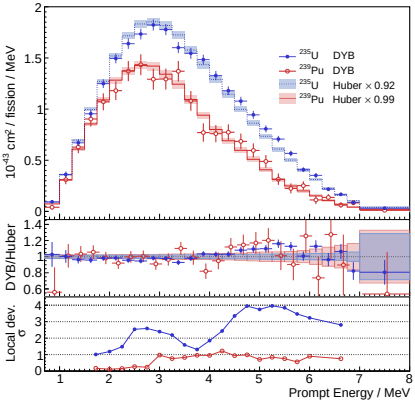
Individual spectra of ^{235}U and ^{239}Pu

Observed positron spectrum



- Disagreement with Huber+Mueller: 5.3σ global/6.3σ local.

Extracted antineutrino spectra



- $4-6$ MeV excess: 7% ^{235}U/9% ^{239}Pu.
- ^{235}U shape discrepancy: 4σ.

1958 days, arXiv:1904.07812, PRL

Daya Bay status and prospects

DAQ status

✓ Stable operation.

- December 2020: shutdown ceremony.

Prospects

- Combined analysis with PROSPECT: reactor spectrum and sterile.
- Studies to be updated:
  - $\sin^2 2\theta_{13}$ and Δm^2_{32} measurement on nH.
  - Final oscillation parameters measurement.
- Search for GW related neutrino events.

Highlights

✓ Individual measurement of $^{235}\mathrm{U}/^{239}\mathrm{Pu}$ spectra.

✓ New oscillation result, 3% precision, 12% improvement:

$$\sin^2 2\theta_{13} = 8.56 \pm 0.29 \times 10^{-2}$$

$$|\Delta m^2_{ee}| = 2.522^{+0.068}_{-0.070} \times 10^{-3}\ \mathrm{eV}^2$$

Recent publications:

1808.10836 PRD	$\overline{\nu}_e$	reactor flux
1809.02261 PRL	$\overline{\nu}_e$	osc. pars. (nGd)
1809.04660 PRD	$\overline{\nu}_e$	time variation

New publications:

1904.07812 PRL	$\overline{\nu}_e$	$^{235}\mathrm{U}/^{239}\mathrm{Pu}$ spectra
2002.00301	$\overline{\nu}_s$	DB+MINOS

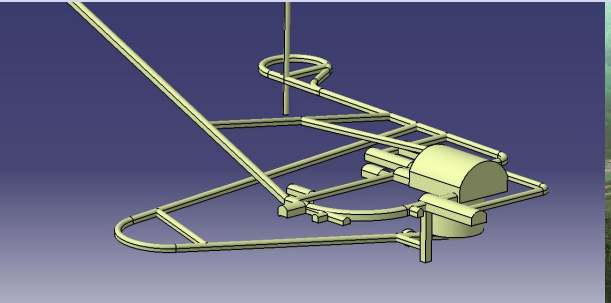
1 Introduction

2 Daya Bay, TAO and JUNO

3 Daya Bay

4 JUNO and TAO
- Status
- Schedule
- Physics with JUNO

Civil construction



Office
Hall
Hall
Hall

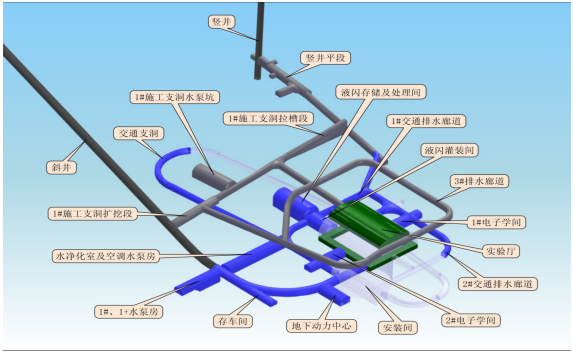
JUNO construction status

Civil construction

- Most of the tunnels finished.
- Transportation tunnel 389/506 m.
- Exp hall: above hall almost finished.
- TODO: detector cavern.
- Expect to finish by June 2020 (?).

Experiment preparation

- 1:12 prototype at IHEP: 600 tons.
- TAO: CDR coming soon.
- OSIRIS R&D: Online Scintillator Internal Radioactivity Investigation System
  - Sensitivity: 10^{-16} g/g for U/Th within 24 h.



Detector assembly technique:
https://www.youtube.com/watch?v=B_uPQZPgU00

JUNO PMT status

Large 20" PMT system

- 12 768 MCP PMTs by NNVT: delivered.
- 5 000 Dynode PMTs by Hamamatsu: delivered.
- Testing: mostly done.
- Protection cover: production started.

Small 3" PMT system

✓ Complementary PMT system:

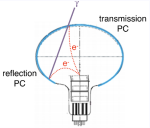
- Increase dynamic range.
- Control systematics.

- 26 000 PMTs by HZC: produced.

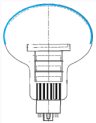
	NNVT	Hamamatsu	HZC
PDE, %	28.3	28.1	24
TTS, ns	12	2.7	1.5

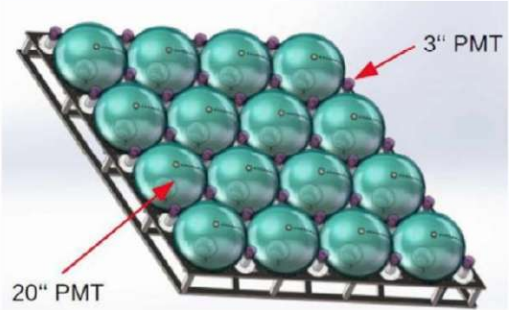
NNVT MCP

Photograph of MCP-PMT

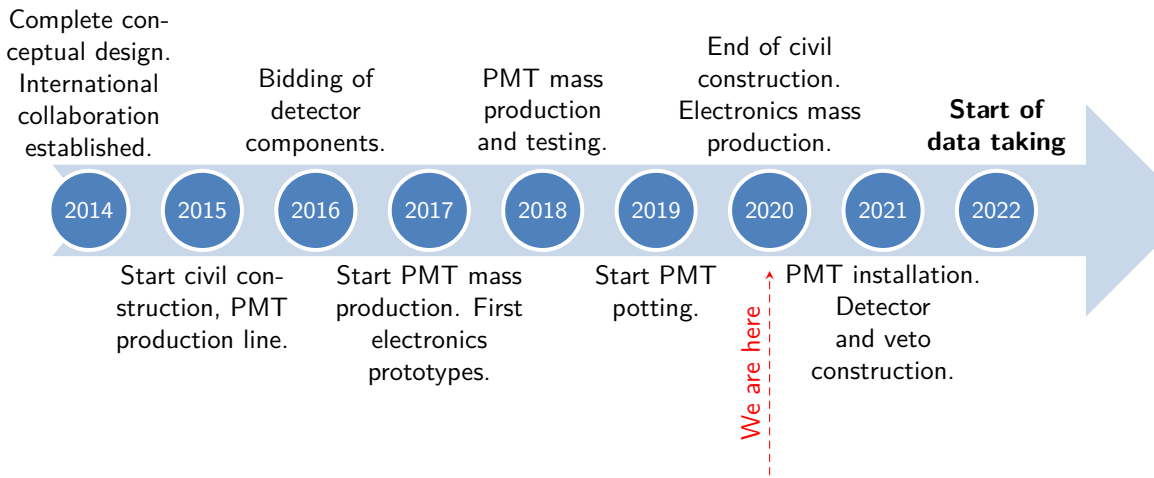


Hamamatsu Dynode





JUNO SCHEDULE

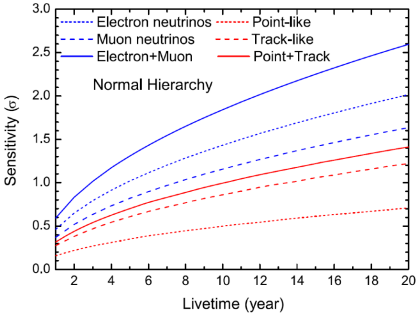


Neutrino physics at JUNO I

- Neutrino mass ordering (NMO)
  - 3σ NMO sensitivity within ~~6~~ 8 years.
  - 4σ with Δm^2_{32} input from accelerator experiments.
  - $> 5\sigma$ combined analysis with IceCube within 3–7 years or PINGU in 2 years.
  - Combination with accelerator experiments — promising.
- Neutrino oscillation parameters measurement
  - ~ 20 oscillation cycles in a single experiment.
  - Expected precision for $\Delta m^2_{32/21}$ and $\sin^2 2\theta_{12} < 0.7\%$.
  - $\sin^2 2\theta_{13}$ precision only 15%. (Daya Bay: $< 3\%$).
  - Test U_{PMNS} unitarity on $< 1\%$ level.
- Atmospheric neutrinos ▶
  - Measure θ_{23} with 6° precision.
  - Complimentary NMO sensitivity.

Physics with TAO

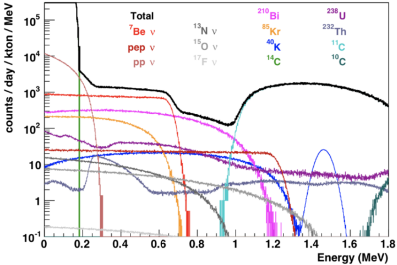
- Precise reactor $\overline{\nu}_e$ spectra:
  - Total spectrum.
  - $^{235}\mathrm{U}/^{239}\mathrm{Pu}$ spectra.
- Search for sterile neutrino.

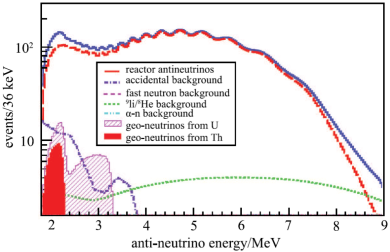


JUNO, IceCUBE, PINGU, arXiv:1911.06745

Neutrino physics at JUNO II

- Solar neutrino ▶
  - $10 - 1000$ ^{7}Be and ^{8}B neutrino interactions per day.
- SuperNOVA
  - Sensitivity: flavor content, energy spectrum, time evolution.
  - 10k events (5k via IBD) for SN @ 10kpc.
- Diffuse SuperNOVA background (DSNB)
  - 3σ sensitivity in 10 years or strongest constraint.
- Geo neutrino ▶
  - $400 - 500$ neutrinos per year.
  - Largest statistics. Precision 5% in 10 years.
- Proton decay
  - Competitive sensitivity via $p \to \overline{\nu} + K^+$.
  - Triple coincidence signal.





Thank you for your attention!

Spare slides:

5 Daya Bay
- Dataset summary
- Systematics summary
- Energy model
- Relative efficiency and energy scale

6 JUNO
- PMT lab

Data set: 1958 DAQ days

	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
$\overline{\nu}_e$ candidates	830036	964381	889171	784736	127107	127726	126666	113922
DAQ live time (days)	1536.621	1737.616	1741.235	1554.044	1739.611	1739.611	1739.611	1551.945
$\varepsilon_\mu \times \varepsilon_m$	0.8050	0.8013	0.8369	0.8360	0.9596	0.9595	0.9592	0.9595
Accidentals (day^{-1})	8.27 ± 0.08	8.12 ± 0.08	6.00 ± 0.06	5.86 ± 0.06	1.06 ± 0.01	1.00 ± 0.01	1.03 ± 0.01	0.86 ± 0.01
Fast neutron (AD^{-1} day^{-1})	0.79 ± 0.10		0.57 ± 0.07		0.05 ± 0.01			
^{9}Li/^{8}He (AD^{-1} day^{-1})	2.38 ± 0.66		1.59 ± 0.49		0.19 ± 0.08			
Am-C correlated(day^{-1})	0.17 ± 0.07	0.15 ± 0.07	0.14 ± 0.06	0.13 ± 0.06	0.06 ± 0.03	0.05 ± 0.02	0.05 ± 0.02	0.04 ± 0.02
^{13}C(α, n)^{16}O (day^{-1})	0.08 ± 0.04	0.06 ± 0.03	0.04 ± 0.02	0.06 ± 0.03	0.04 ± 0.02	0.04 ± 0.02	0.04 ± 0.02	0.04 ± 0.02
$\overline{\nu}_e$ rate (day^{-1})	659.36 ± 1.00	681.09 ± 0.98	601.83 ± 0.82	595.82 ± 0.85	74.75 ± 0.23	75.19 ± 0.23	74.56 ± 0.23	75.33 ± 0.24

- ✓ 1958 days of DAQ data.
- ✓ Above 3.9M IBD candidates, 0.5M of them are on a far site. (high statistics)
- ✓ Statistical uncertainty in $\overline{\nu}_e$ rates: 0.1% – 0.3%.
- ✓ Background contribution to $\overline{\nu}_e$ rate: 1.5% – 2%. (low background)
- ✓ Background uncertainty in $\overline{\nu}_e$ rates 0.1%. (low systematics)

(+highly redundant)

Systematics: 1958 DAQ days

	Parameters	Uncorr.	Uncertainty	Comment
Free	Oscillation parameters (reactor)	P		
	Oscillation parameters (solar)	P		negligible
Reactor	Thermal power	R	0.5%	
	Fission fractions	RI*	5%	
	Average fission energy	I	0.12% – 0.25%	
	Off-equilibrium correction	RI	30%	
	SNF contribution	R	30%	
	$\overline{\nu}_e$ spectra	IE	2% – 30%	
Detector	**Relative efficiency**	D	**0.13%**	**dominant**
	Relative energy scale	D	**0.2%**	part. correlated
	Energy scale non-linearity	P	<1%	
	Energy resolution	P	30%	negligible
	IAV energy distortion	D	4%	
Background	Accidentals rate	D	0.4%	
	$^{8}\mathrm{He}/^{9}\mathrm{Li}$ rate	S	30%	**secondary**
	$^{9}\mathrm{Li}$ contribution to $^{8}\mathrm{He}/^{9}\mathrm{Li}$		5%	negligible
	Fast neutrons rate	S	10% – 17%	
	$^{241}\mathrm{Am}$-$^{13}\mathrm{C}$ rate		40% – 45%	
	$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$ rate	D	50%	
	Background spectra shape		no	negligible

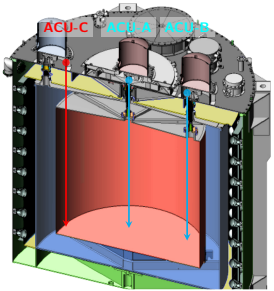
Uncorrelated groups

- **P**arameter
- **R**eactor
- Fissile **I**sotope
- **S**ite
- **D**etector
- **E**nergy bin
- * — part. correlation

Energy response calibration

Automated calibration units (ACU)

- Three ACUs with: ^{60}Co (weekly), ^{68}Ge, ^{241}Am-^{13}C, LED.
- Continuous energy scale calibration with spallation neutrons.



Energy response nonlinearity

- LS nonlinearity (quenching and Cherenkov) + Electronics nonlinearity.

✗ Difficult to disentangle.

Updates

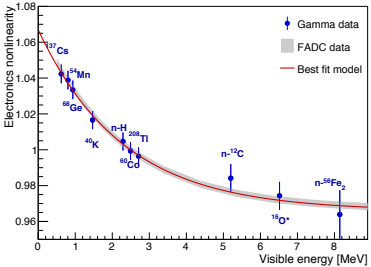
✓ ADC/FADC simultaneous readout in a EH1-AD1 since 2016
↪ measurement of electronics nonlinearity.

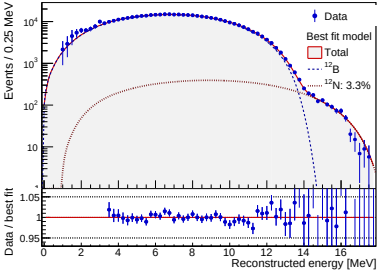
✓ Deployment of ^{60}Co calibration sources with different coating material (early 2017)
↪ measurement of shadowing effects.

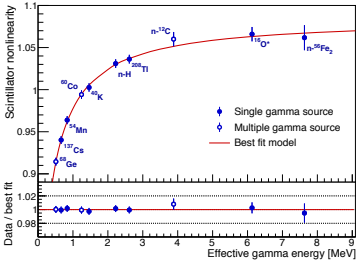
✓ MC simulation of energy loss in ^{60}Co coating material.

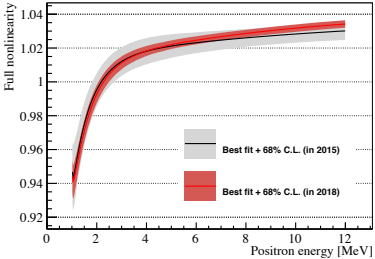
Energy response calibration

arXiv:1902.08241, NIMA





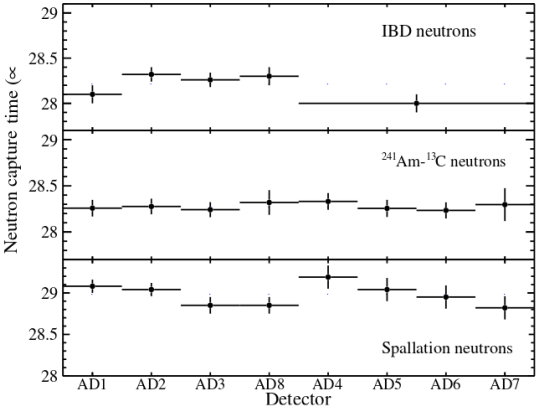




- ✓ Decoupled electronics and scintillator nonlinearity
- ✓ Continuous ^{12}B spectrum
- ✓ Combined positron energy nonlinearity uncertainty: $1\% \rightarrow 0.5\%$

Relative efficiency and relative energy scale

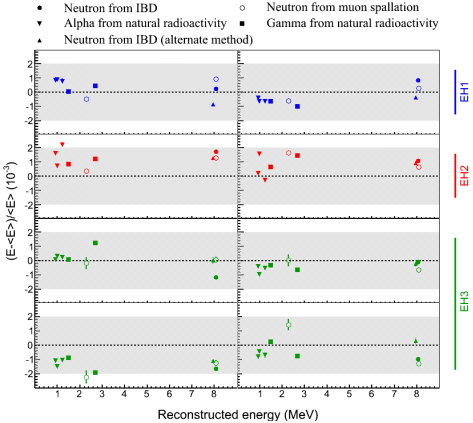
- Relative efficiency $\rightarrow \sin^2 2\theta_{13}$ uncertainty.

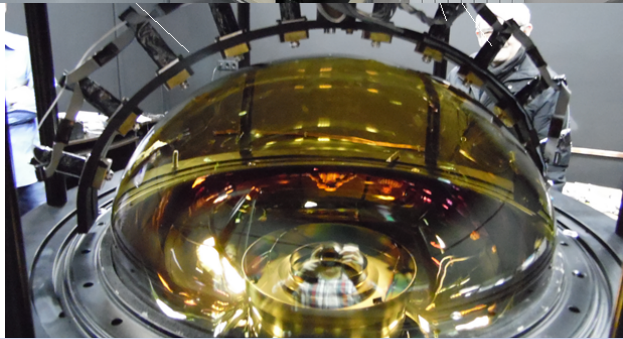


✓ Relative Gd capture fraction unc. $<$ **0.10%**.

✓ Relative efficiency uncertainty $<$ **0.13%**.

- Relative energy scale $\rightarrow \Delta m^2_{32}$ uncertainty.



✓ Relative energy scale uncertainty $<$ **0.2%**.

JINR PMT testing laboratory