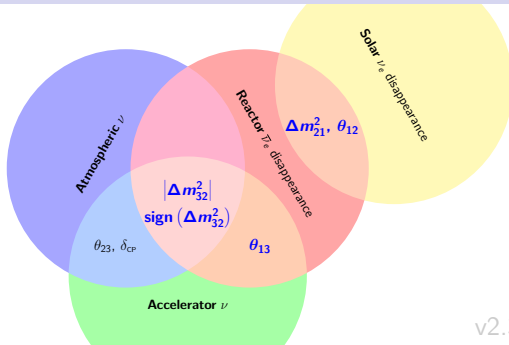
Report on the JUNO/Daya Bay Project
Proposal for the JUNO Project Prolongation and Further Daya Bay Support

Maxim Gonchar for the JINR group

Dzhelepov Laboratory for Nuclear Research

April 13, 2020



v2.3.1

The project update: JUNO and Daya Bay

Daya Bay will stop by the end of 2020

Topic: 2010-2023

- 02-2-1099-2010/2023 Study of Neutrino Oscillations

Past: 2007−2017

- The Daya Bay Project

Present: 2018−2020

- The JUNO/Daya Bay Project

Future: 2021−2023

- The JUNO Project
- The Daya Bay activity

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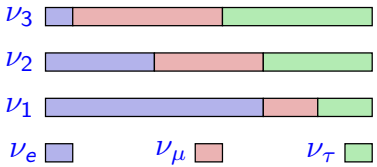
Our team

N. Anfimov, T. Antoshkina, S. Biktemerova, A. Bolshakova, I. Butorov, A. Chetverikov, A. Chukanov, S. Dmitrievsky, D. Dolzhikov, D. Fedoseev, M. Gonchar, Y. Gornushkin, M. Gromov, V. Gromov, D. Korablev, A. Krasnoperov, N. Kutovskiy, K. Kuznetsova, Y. Malyshkin, D. Naumov, E. Naumova, I. Nemchenok, A. Olshevskiy, A. Rybnikov, A. Sadovsky, D. Selivanov, A. Selyunin, V. Sharov, A. Shaydurova, V. Shutov, O. Smirnov, S. Sokolov

36 from JINR

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: δ_{CP}.

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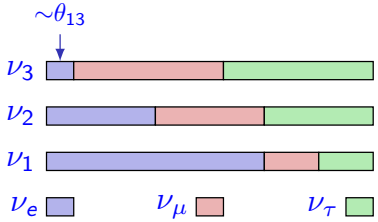

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Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix:

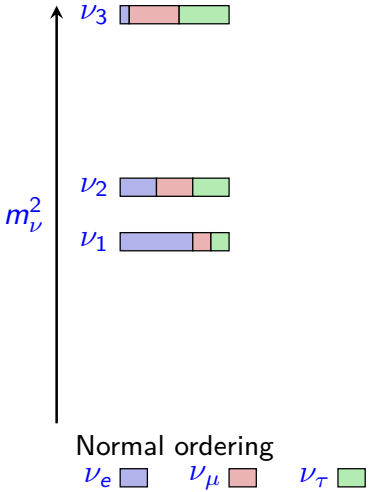
✓ $\theta_{23} \approx 45°$ established through atmospheric and accelerator experiments: possibly maximal.

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

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

- δ_{CP} unknown: 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)
- $\langle m_{\beta\beta} \rangle < 0.25\,\text{eV}$ ($0\nu\beta\beta$)

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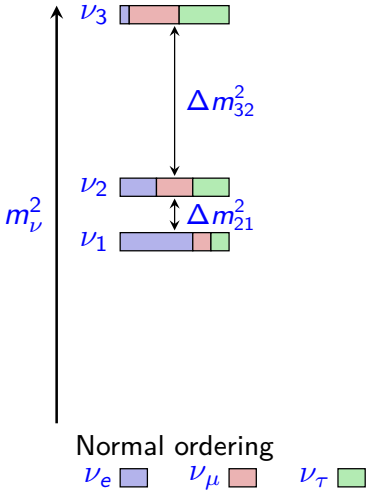

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Mass splitting

From oscillation experiments:

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

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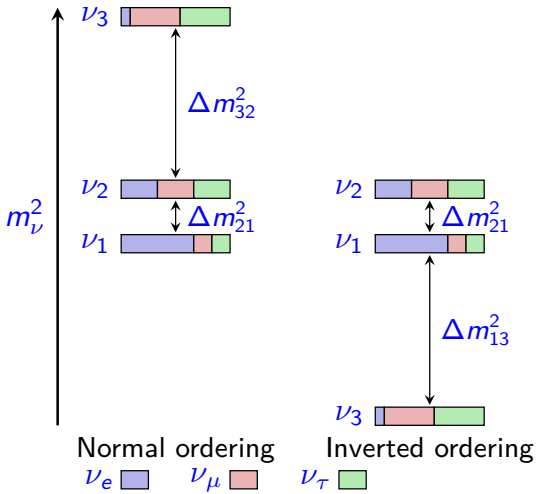

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Mass ordering

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
- $E_\nu < 10\,\mathrm{MeV}$

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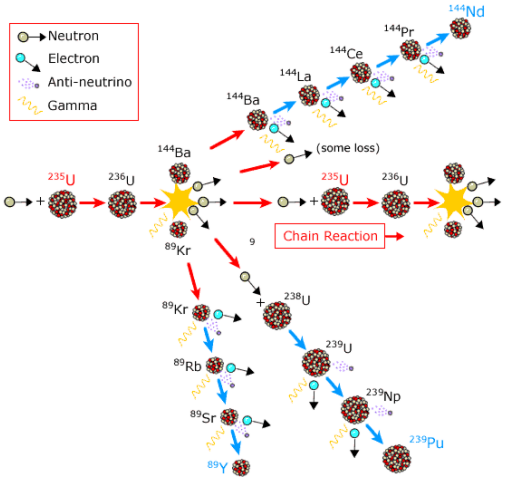
in beta decays of fission products of

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



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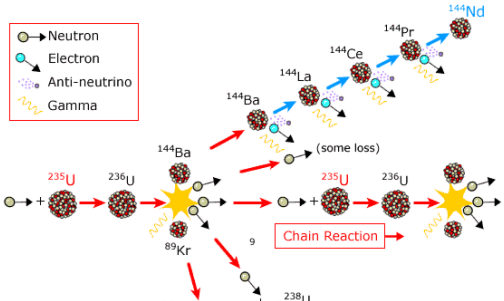
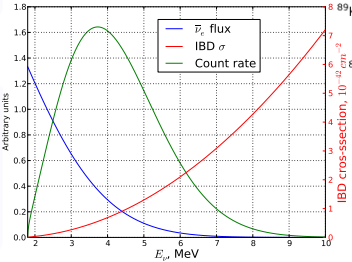
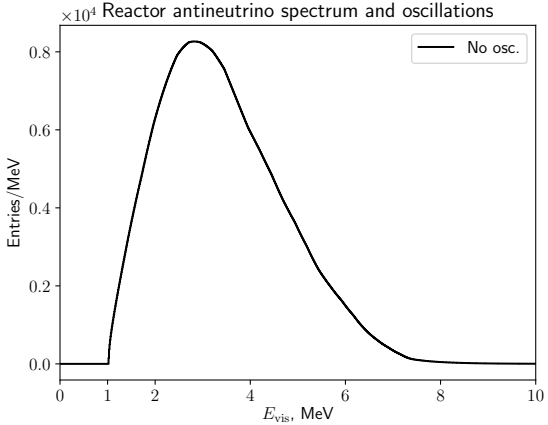
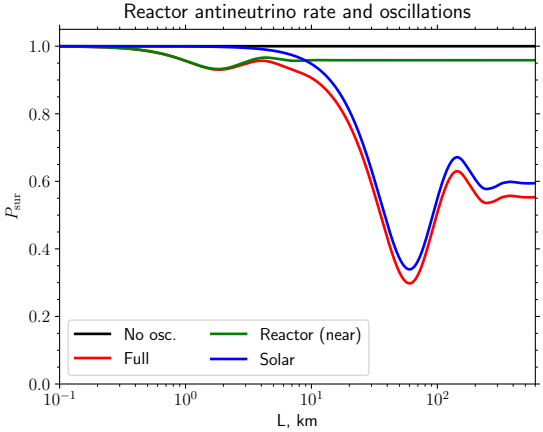
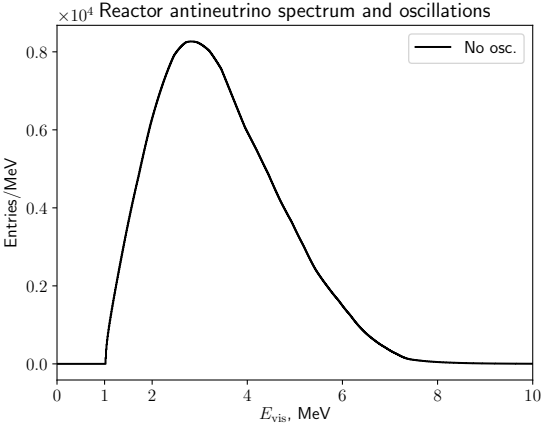






$E_{\text{vis}} \approx E_\nu - 0.78\,\text{MeV}$





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~~δ_{CP}, θ_{23}~~

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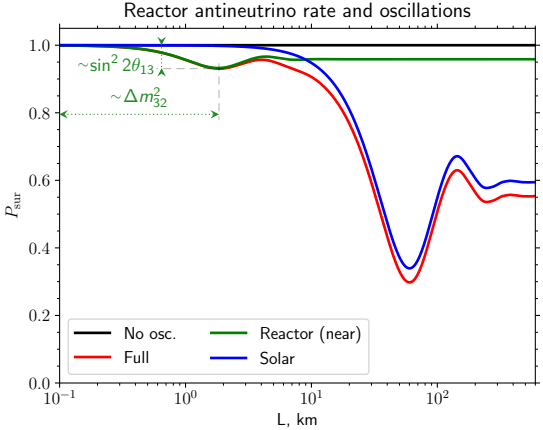

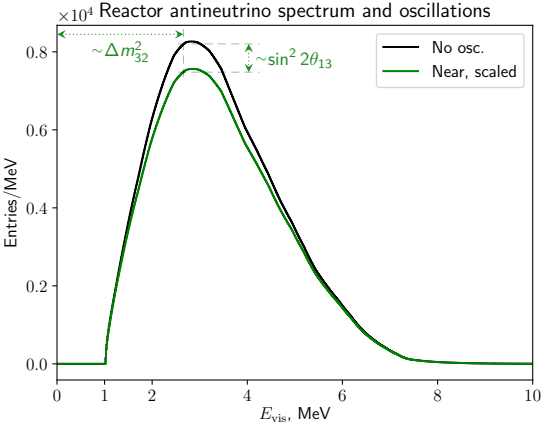

deficit value

minimum location

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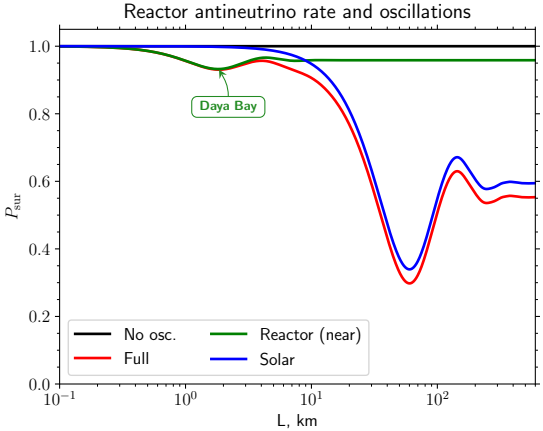

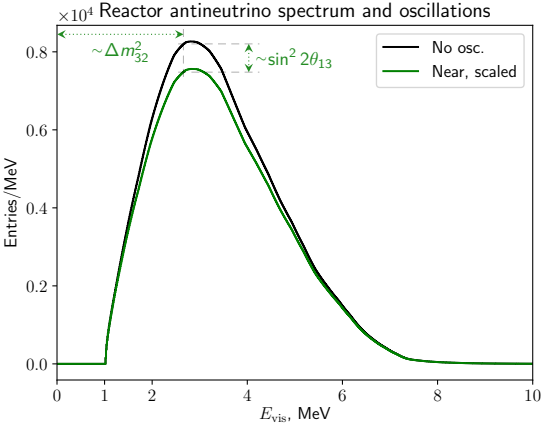

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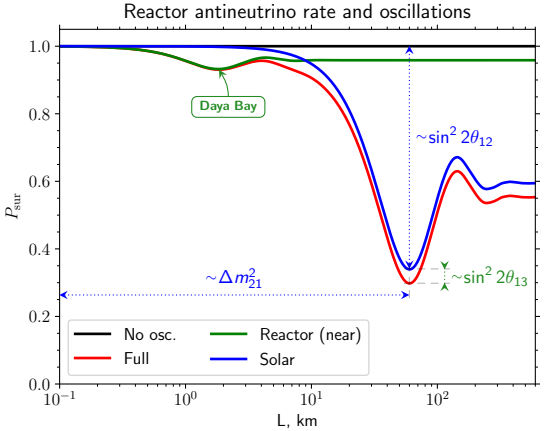

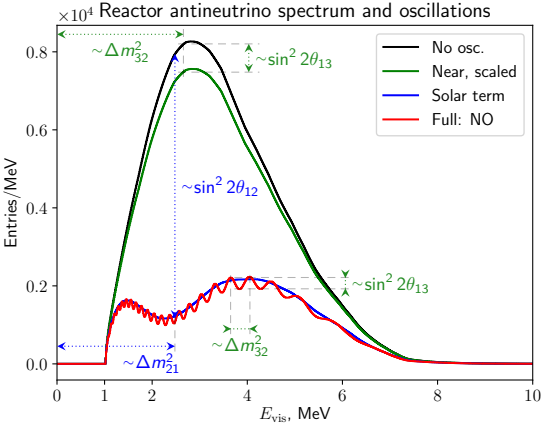

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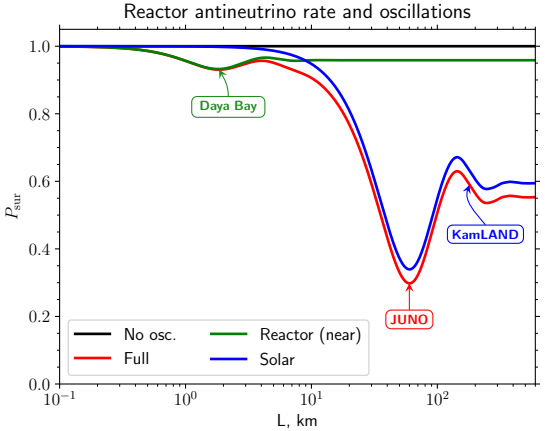

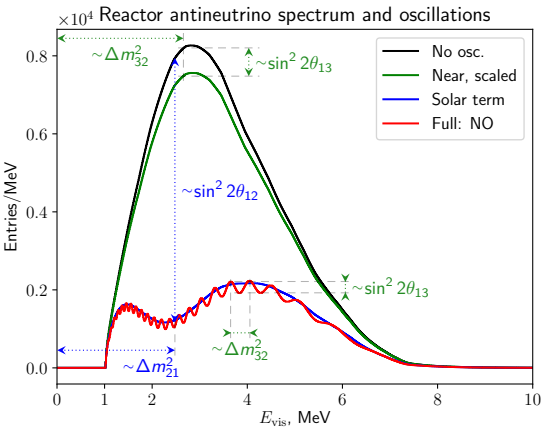

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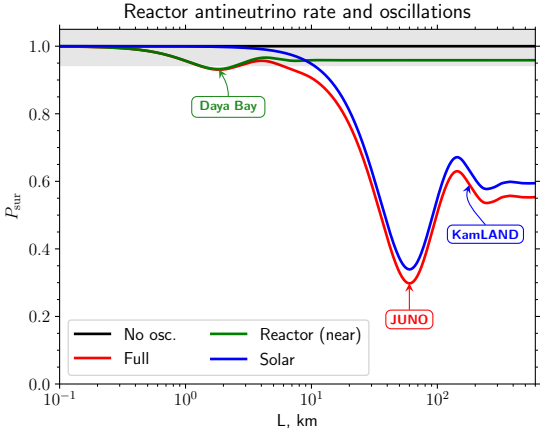

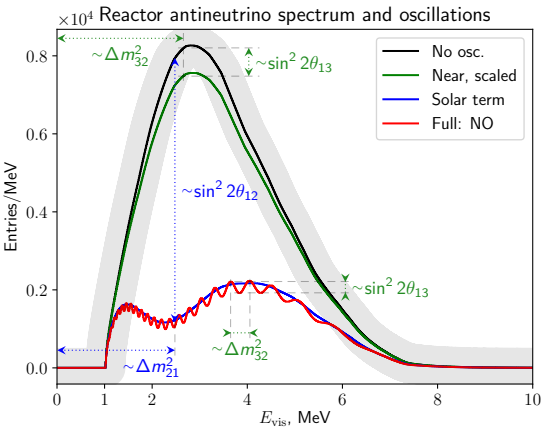

Challenges:

- Unreliable spectrum model

Daya Bay
total flux, spectrum shape

JUNO
fine structure?

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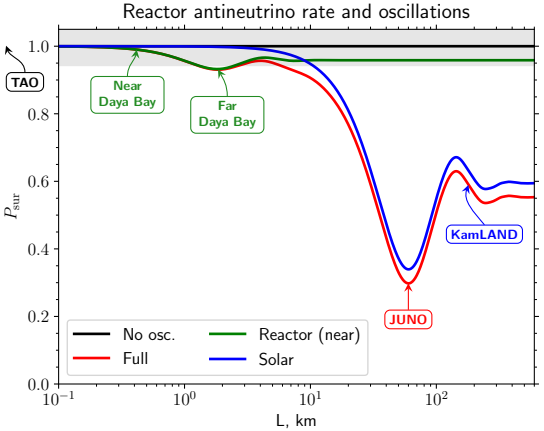

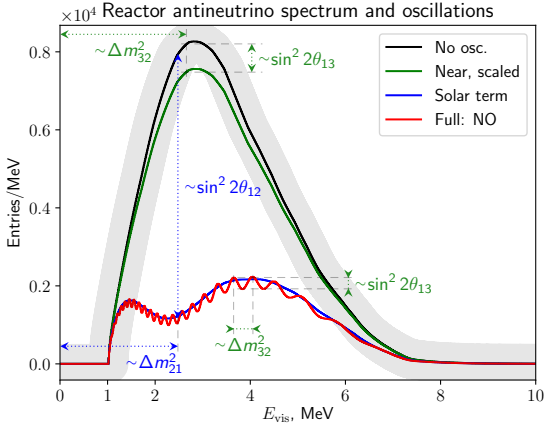

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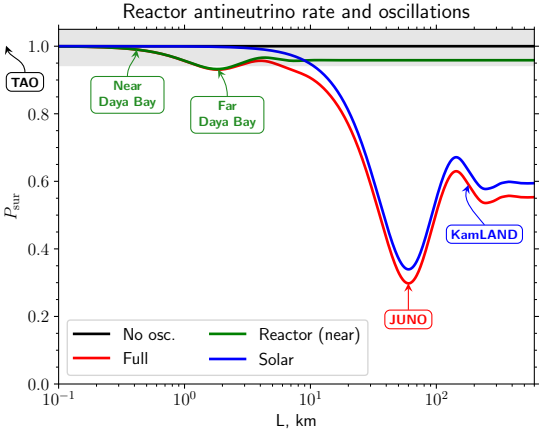

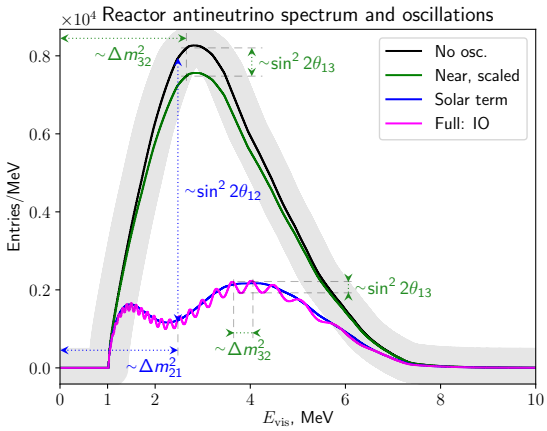

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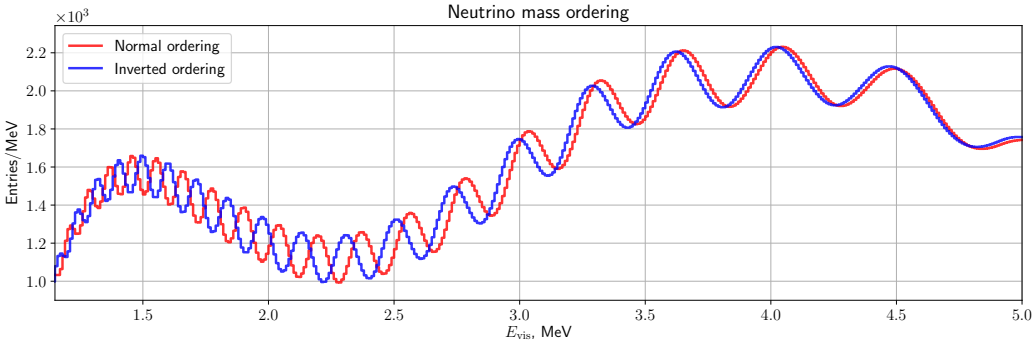

(same Δm^2_{ee})

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$<3\%$ at 1 MeV

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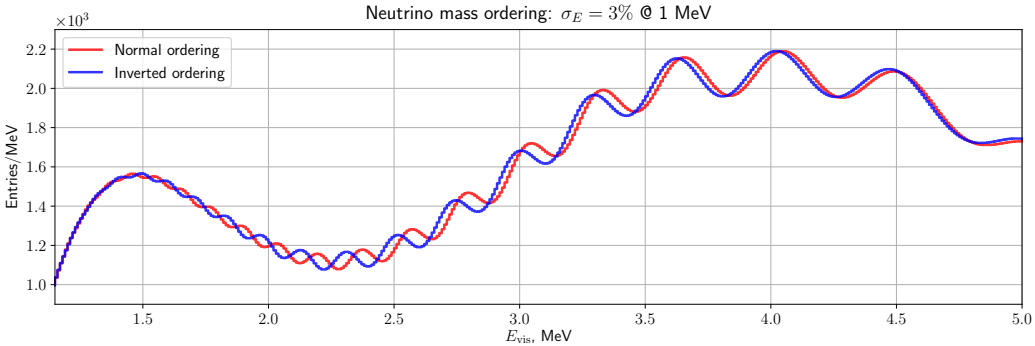

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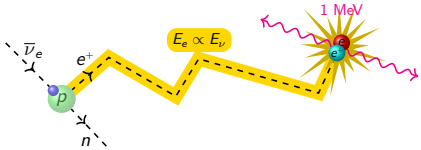
Inverse beta decay and selection criteria



Cherenkov: $< 5\%$

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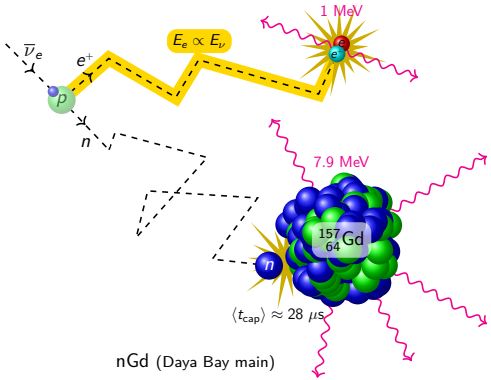

nGd (Daya Bay main)

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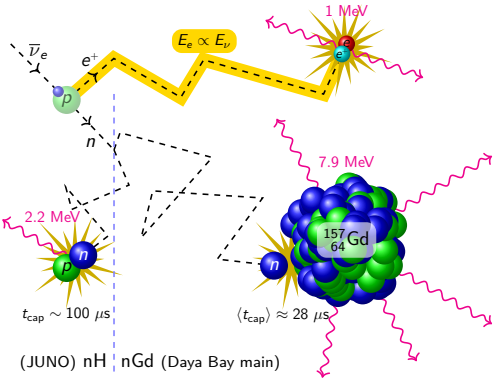

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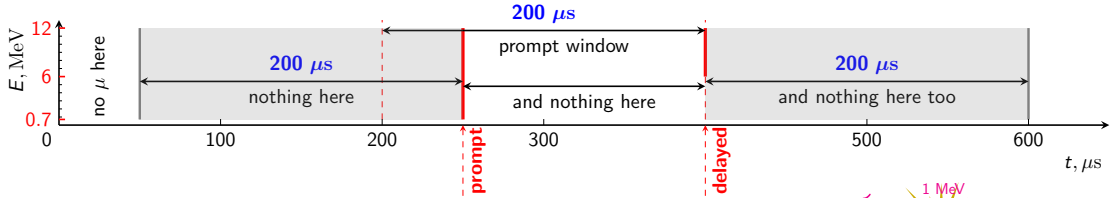
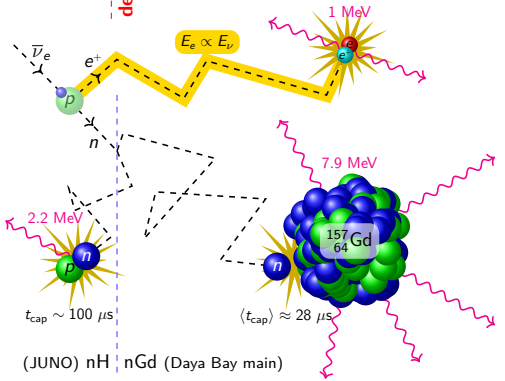


Cut	Daya Bay nGd	JUNO nH
Instrumental	Flashers	
Fiducial volume	natural	$R < 17$ m
Time	200 μs	1 ms
Prompt E, MeV	$0.7 - 12$	
Delayed E, MeV	$6 - 12$	$1.9 - 2.5$
Distance, m	no	1.5
Muon veto	0.6 ms – 1 s	TBD
Multiplicity veto, us	±200	TBD



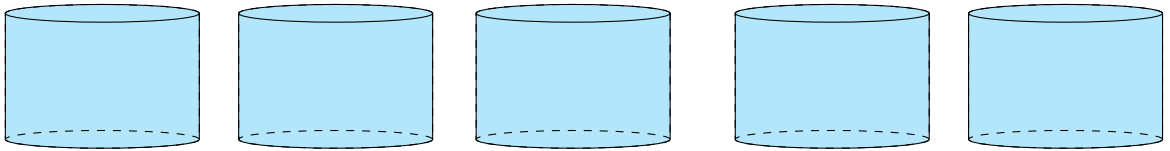
Plot: Daya Bay

Cherenkov: < 5%

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	

Accidentals β-n isotopes Fast neutrons ACU $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$



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	

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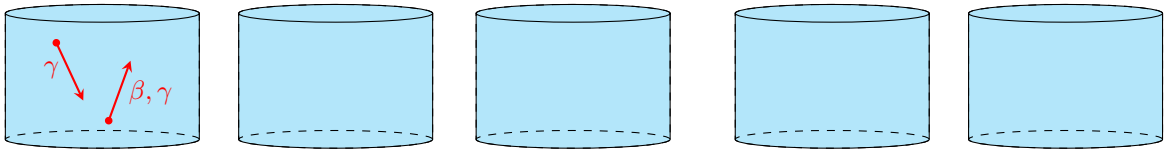

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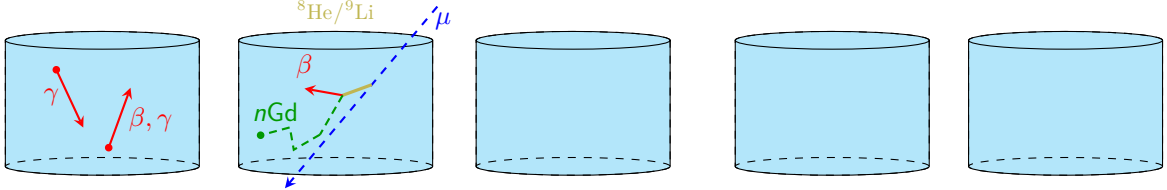

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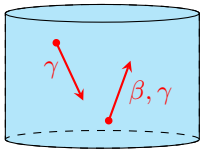
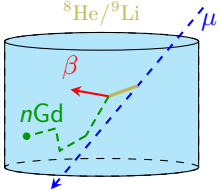
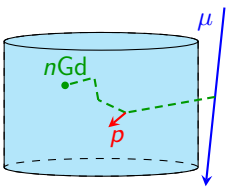
Accidentals



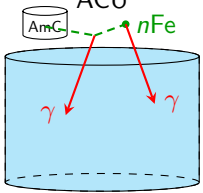
β-n isotopes



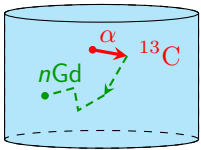
Fast neutrons



ACU



$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$



Daya Bay, JUNO and TAO location

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

	Yangjian	Taishan
Thermal power, GW	2.9×6	4.6×~~4~~2
Total, GW	~~35.8~~	26.6

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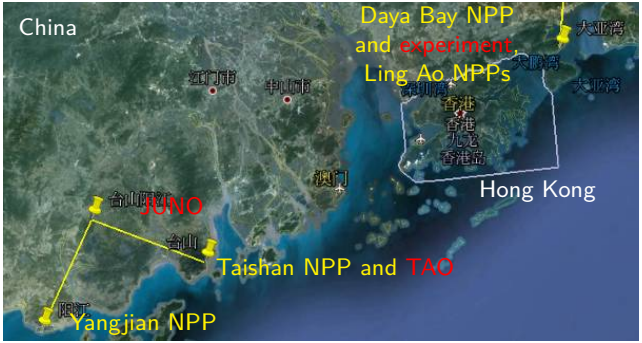

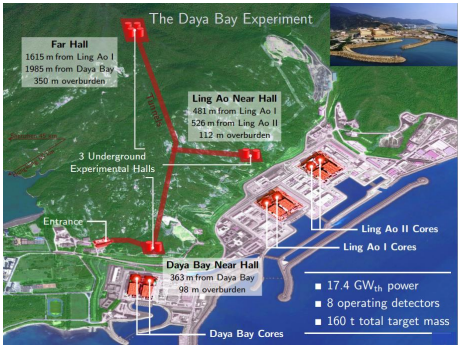

	Yangjian	Taishan	Daya Bay	Ling Ao	Ling Ao II
Thermal power, GW	2.9×6	4.6×~~4~~2	2.9×2	2.9×2	2.9×2
Total, GW	~~35.8~~	26.6		17.4	

Daya Bay, JUNO and TAO location

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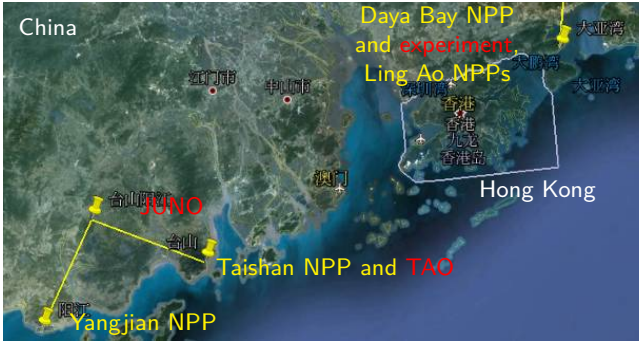
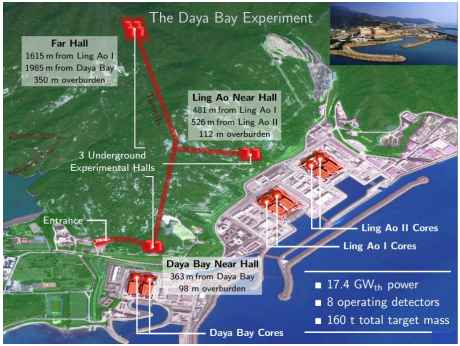
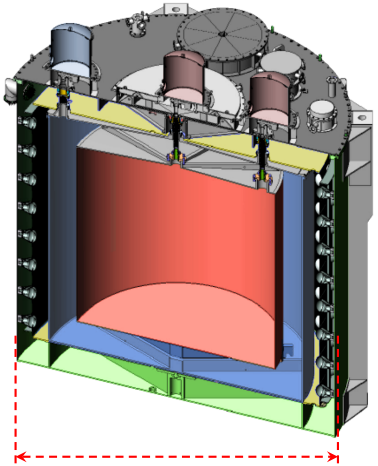
- TAO — Taishan Antineutrino Observatory





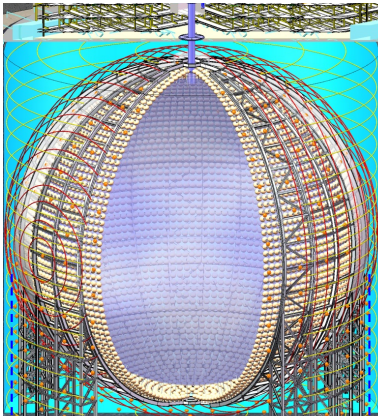
	Yangjian	Taishan	Daya Bay	Ling Ao	Ling Ao II	Huizhou
Thermal power, GW	2.9×6	4.6×~~4~~2	2.9×2	2.9×2	2.9×2	2.9×6
Total, GW	~~35.8~~ 26.6			17.4		17.4 ?

Antineutrino Detectors (AD)



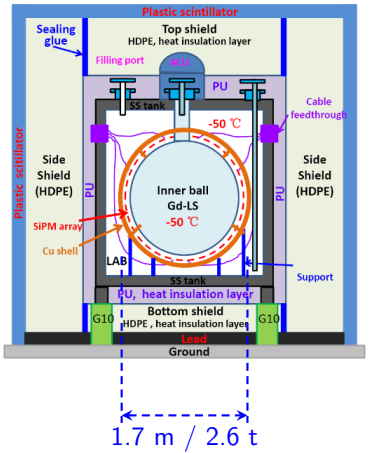
	Daya Bay
Attention	**Uncorr. ε unc.**
Method	**Identical ADs** **3 zones**
Scintillator	**GdLS/LS**
PMTs	**192 8”**
Coverage, %	**12**
Light col. p.e./MeV	**160**
E res. at 1 MeV, %	**8.7**
Detectors	**4/4** far / near
Thermal power, GW	**17.4**
Baseline	**0.5 km–2 km**
IBD/day/AD	**75/635** far / near

Antineutrino Detectors (AD)

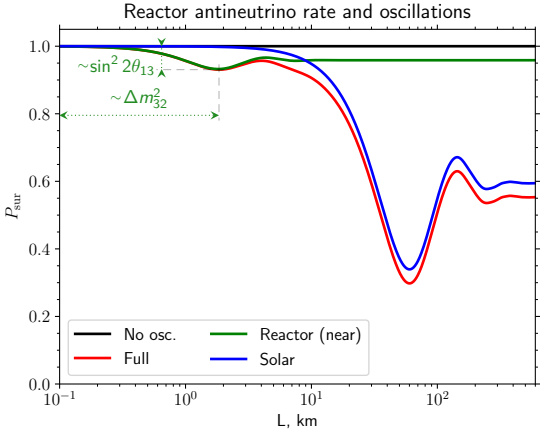


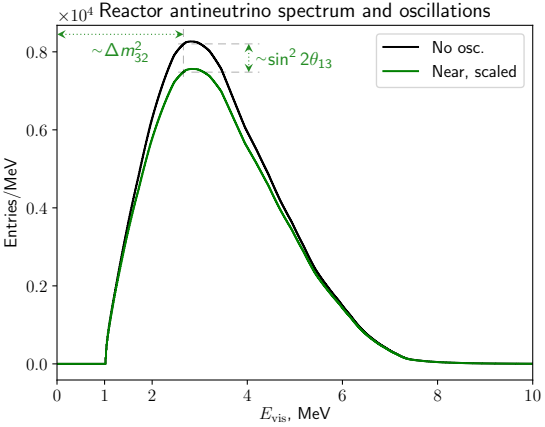
	Daya Bay	JUNO
Attention	Uncorr. ε unc.	**Energy resolution**
Method	Identical ADs 3 zones	**Light collection**
Scintillator	GdLS/LS	**LS**
PMTs	192 8"	**18k 20"** **+26k 3"**
Coverage, %	12	**78**
Light col. p.e./MeV	160	~~1200~~ **1350**
E res. at 1 MeV, %	8.7	**3**
Detectors	4/4 far/near	**1**
Thermal power, GW	17.4	~~35.8~~ **26.6**
Baseline	0.5 km−2 km	**52 km**
IBD/day/AD	75/635 far/near	**60**

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





deficit value

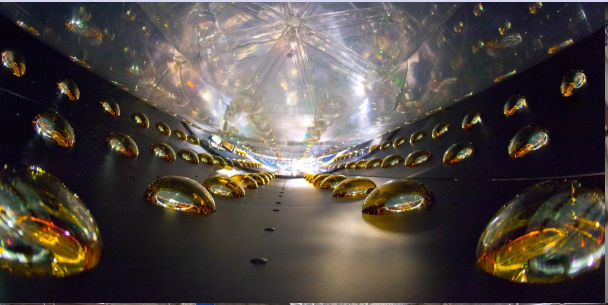
minimum location

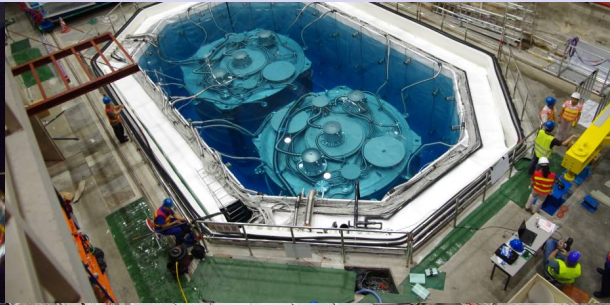
$$1 - P_{\nu_e \to \nu_e} = \sin^2 2\theta_{13} \underbrace{\left(\sin^2\theta_{12} \sin^2 \frac{\Delta m^2_{32} L}{4E} + \cos^2\theta_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E} \right)}_{\stackrel{\text{def}}{=} \sin^2 \Delta m^2_{ee} L/(4E)} + \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2 \frac{\Delta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

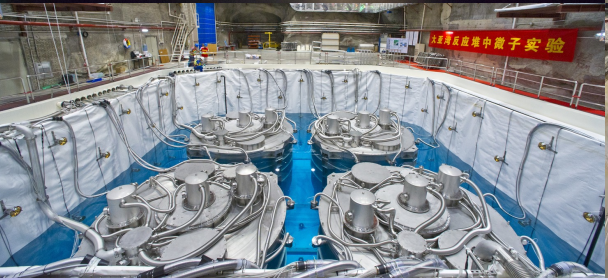
~~δ_{CP}, θ_{23}~~

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

Daya Bay detectors







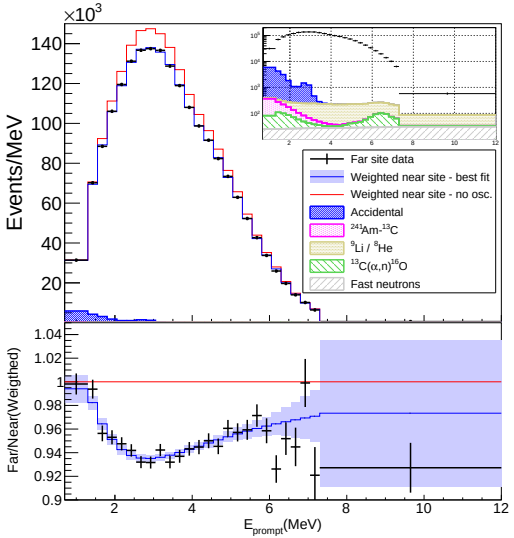
Data set: 1958 DAQ days

	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)

Daya Bay oscillation result: 500K/4M events



1958 days, arXiv:1809.02261, PRL

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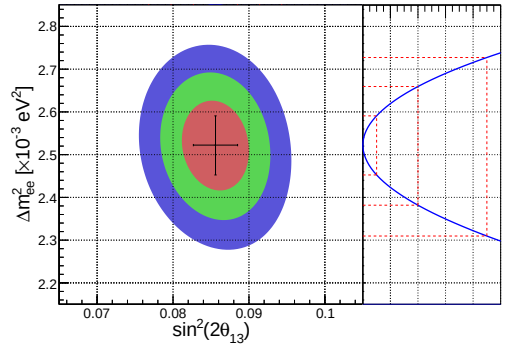
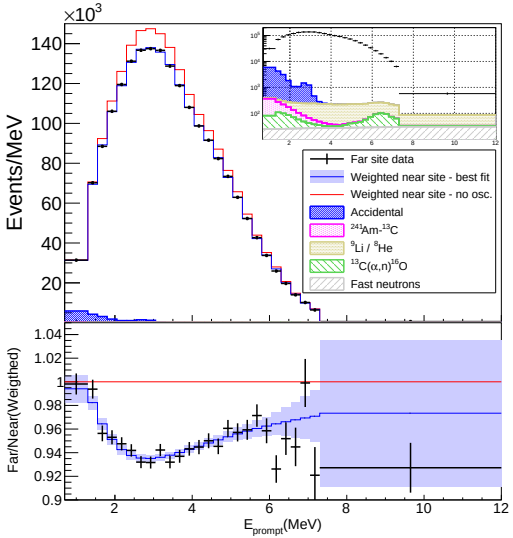


$\sin^2 2\theta_{13} = 8.56 \pm 0.29 \quad \times 10^{-2} \quad 3.4\%$

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

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

✓ Consistent with 3ν oscillations

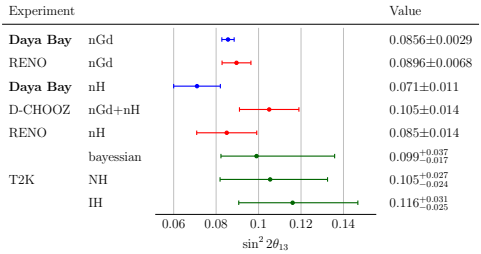


1958 days, arXiv:1809.02261, PRL

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

Daya Bay oscillation result

nH, 621 days, arXiv:1603.03549, PRD

nGd, 1958 days, arXiv:1809.02261, PRL

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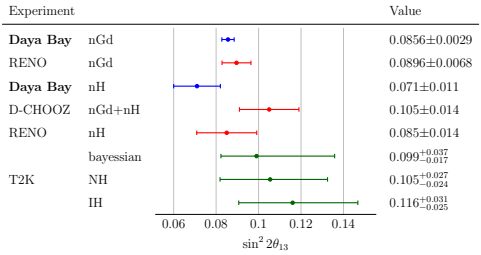
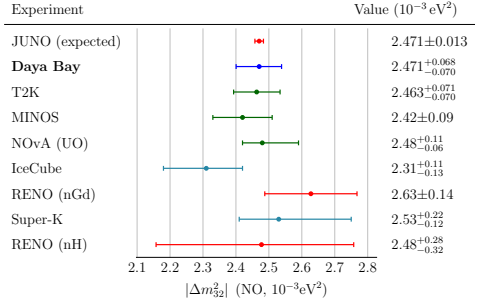
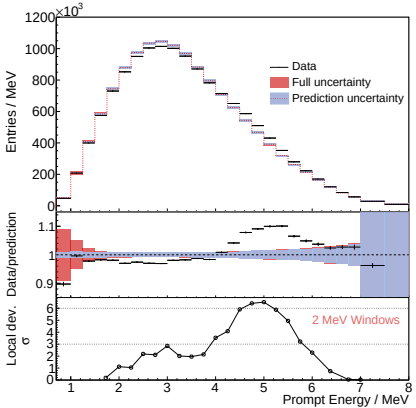




Comparison updated: 2019.09.11

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

Observed positron spectrum



- Disagreement with Huber+Mueller:

  5.3σ global/6.3σ local.

1958 days, arXiv:1904.07812, PRL

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

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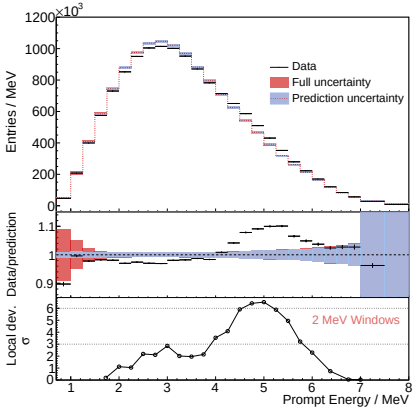
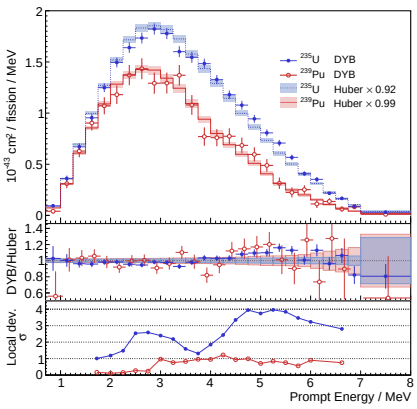


Extracted antineutrino spectra



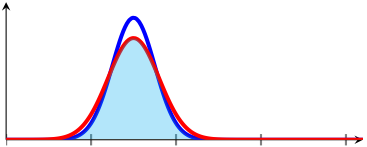
- Disagreement with Huber+Mueller: 5.3σ global/6.3σ local.
- $4-6$ MeV excess: 7% ^{235}U/9% ^{239}Pu.
- ^{235}U shape discrepancy: 4σ.

1958 days, arXiv:1904.07812, PRL

Wave packet effects

$$\sigma_p = \frac{1}{2\sigma_x}$$

Maximal coherence:
oscillations

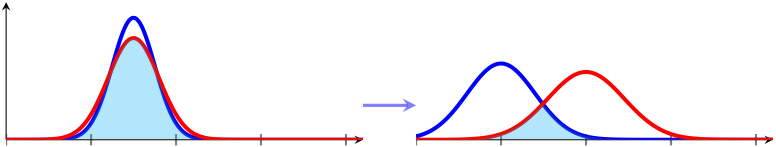


- Plane-wave (PW) model of neutrino oscillations is not self-consistent.
- A wave-packet (WP) model modifies the oscillation probability formula.
- New parameter σ_p — effective dispersion of neutrino wave-packet.
- Predicts suppression of oscillations:
  - at distances exceeding the **coherence length** $L^{\text{coh}} = \dfrac{L^{\text{osc}}}{\sqrt{2}\pi\sigma_{\text{rel}}}$, where $\sigma_{\text{rel}} = \sigma_p/p$.
  - if $\sigma_x \gg L^{\text{osc}}$, where $\sigma_x = 1/(2\sigma_p)$.
- No experimental bounds.

Wave packet effects

Maximal coherence: oscillations

Partial coherence: oscillations suppressed



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  - if $\sigma_x \gg L^{\text{osc}}$, where $\sigma_x = 1/(2\sigma_p)$.
- No experimental bounds.

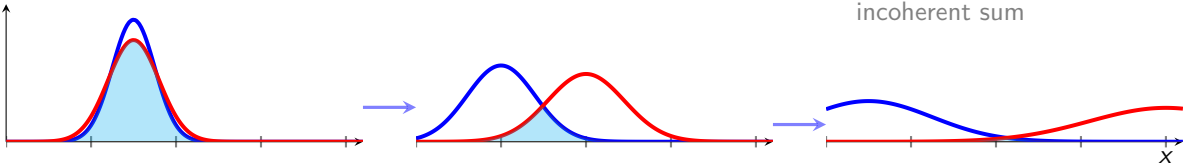
Wave packet effects

Maximal coherence: oscillations

Partial coherence: oscillations suppressed

∼No coherence: no oscillations
incoherent sum

$$\sigma_p = \frac{1}{2\sigma_x}$$



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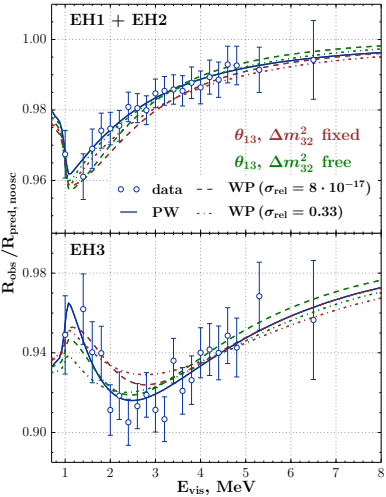
- New parameter σ_p — effective dispersion of neutrino wave-packet.
- Predicts suppression of oscillations:
  - at distances exceeding the **coherence length** $L^{\text{coh}} = \dfrac{L^{\text{osc}}}{\sqrt{2}\pi\sigma_{\text{rel}}}$, where $\sigma_{\text{rel}} = \sigma_p/p$.
  - if $\sigma_x \gg L^{\text{osc}}$, where $\sigma_x = 1/(2\sigma_p)$.
- No experimental bounds.

Wave packet effects in Daya Bay



621 days, arXiv:1608.01661, EPJC

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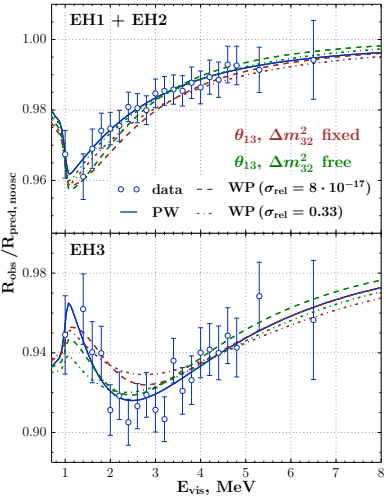
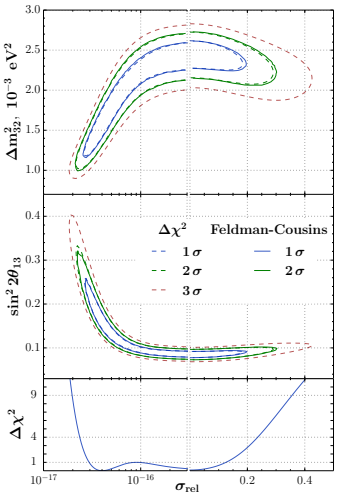


- The obtained limits read
$$2.38 \cdot 10^{-17} < \sigma_{\rm rel} < 0.23,$$
- taking into account the reactor/detector sizes:
$$\boxed{10^{-11}\ \text{cm} \lesssim \sigma_x} \lesssim 2m.$$
at 95% C.L.
- These results ensure unbiased measurement of $\sin^2 2\theta_{13}$ and Δm^2_{32} within the PW model.



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Daya Bay status and prospects

DAQ status

✓ Stable operation.

- December 2020: shutdown ceremony.

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

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Highlights

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

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

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

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

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Daya Bay status and prospects

DAQ status

✓ Stable operation.

- December 2020: shutdown ceremony.

Prospects

- Combined analysis with PROSPECT (^{235}U): 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

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

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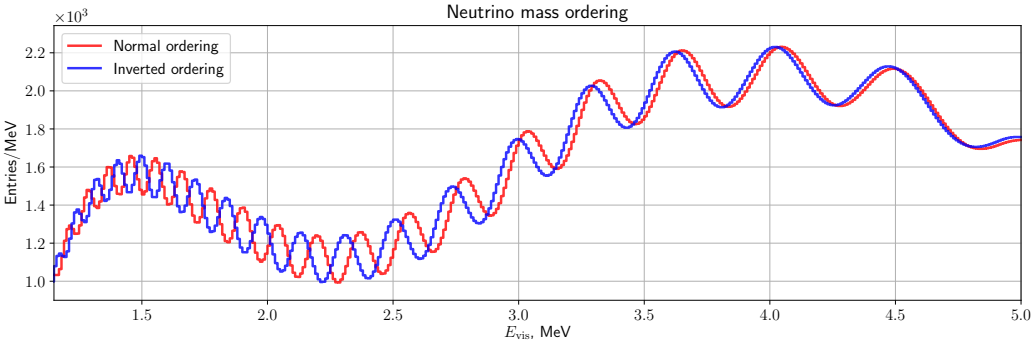


(same Δm^2_{ee})

Challenges:

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

Daya Bay

total flux, spectrum shape

$\lesssim 0.2\%$ uncorrelated

JUNO

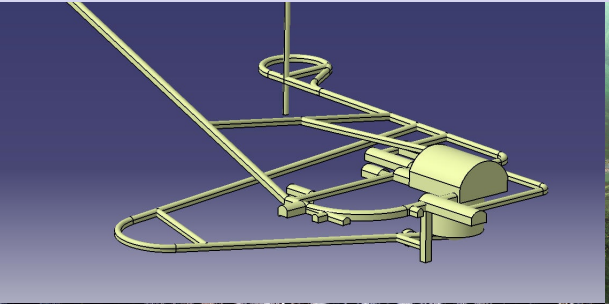
fine structure?

$<1\%$

$<3\%$ at 1 MeV

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

Civil construction



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.

JUNO, IceCUBE, PINGU, arXiv:1911.06745

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  - Expected precision for $\Delta m^2_{32/21}$ and $\sin^2 2\theta_{12} < 0.7\%$.
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- Atmospheric neutrinos ▶
  - Measure θ_{23} with 6° precision.
  - Complimentary NMO sensitivity.

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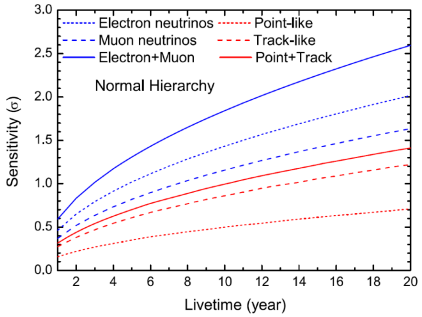

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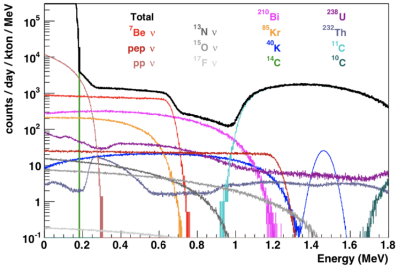
Neutrino physics at JUNO II

- Solar neutrino ▶
  - 10 ^{7}Be and 1000 ^{8}B neutrino interactions per day.



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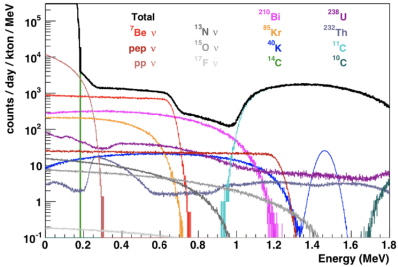
  - 3σ sensitivity in 10 years or strongest constraint.



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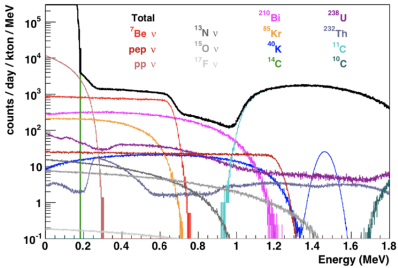

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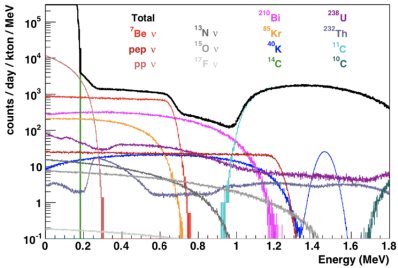
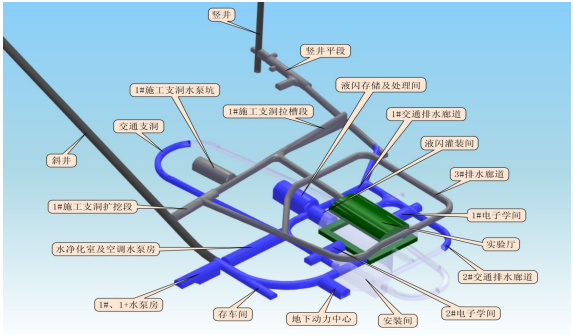
  - Competitive sensitivity via $p \to \overline{\nu} + K^{+}$.
  - Triple coincidence signal.



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 the end of 2020.



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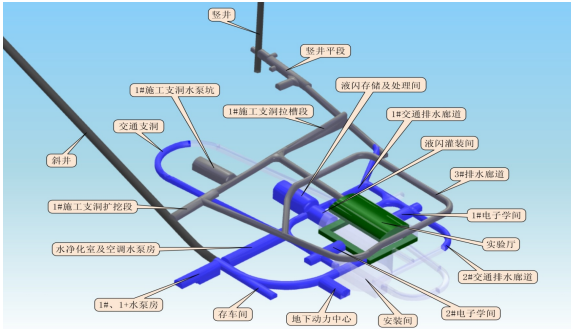
Experiment preparation

- 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.
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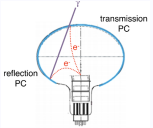
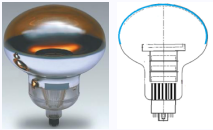
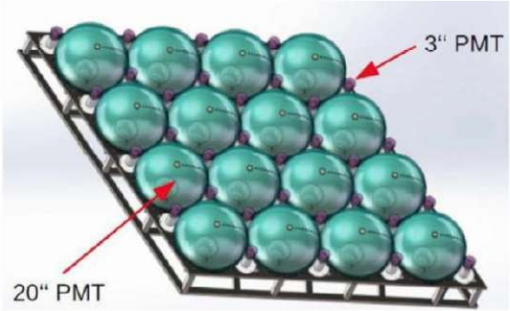
NNVT MCP

Photograph of MCP-PMT



Hamamatsu Dynode





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✓ Complementary PMT system:

- Increase dynamic range.
- Control systematics.

- 26'000 PMTs by HZC: produced.

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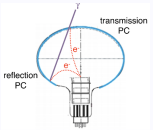

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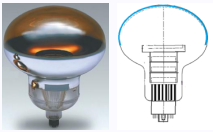

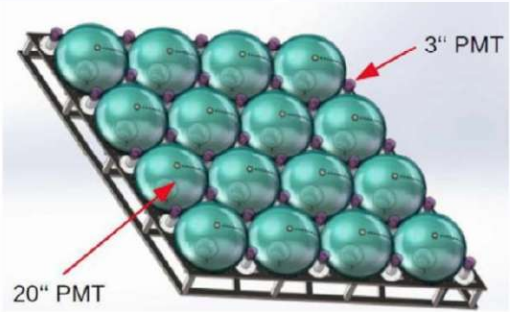

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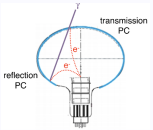
	NNVT	Hamamatsu	HZC
PDE, %	28.3	28.1	24
TTS, ns	12	2.7	1.5

NNVT MCP

Photograph of MCP-PMT



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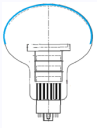
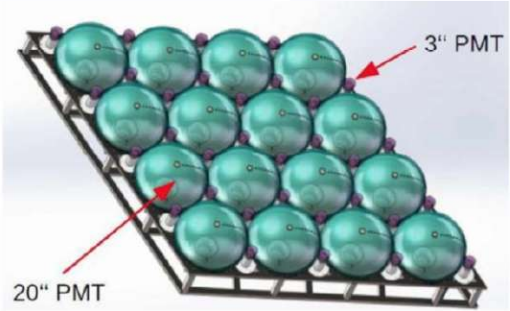
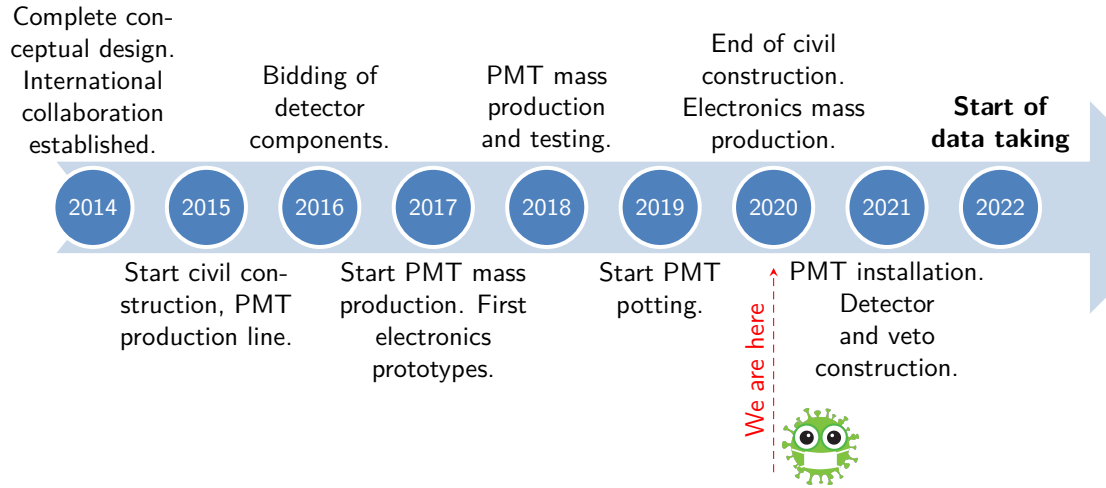




JUNO SCHEDULE



JINR GROUP ACTIVITIES

JUNO and TAO: hardware

- PMT:
  - characterization
  - mass testing
  - HV for JUNO
- SiPM for TAO
  - acceptance studies
  - mass characterization
  - HV for TAO
- Top Tracker Support
- EMF shielding
- Computing

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- Vertex, energy, track reco.
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Daya Bay (recent)

- Oscillation analysis
- Wave packets
- IBD selection
- Sterile neutrino
- Neutrino directionality

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Analysis frameworks

- GNA

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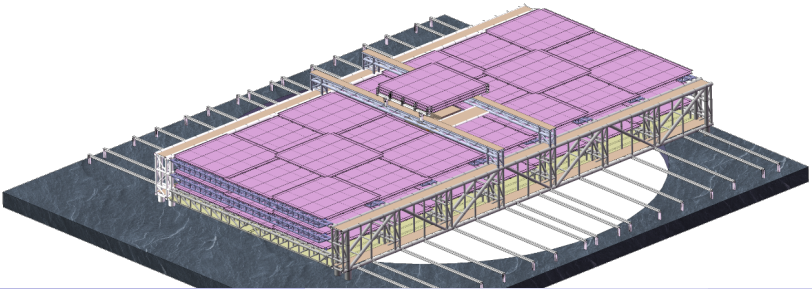
Veto: Top muon Tracker (TT)

Motivation

- Precision muon tracking: 0.2°/0.5°
- Layered plastic scintillator detector
- Partial coverage: ∼63%
- 3 layers x 21 "walls" x 8 modules
- Wall: 7x7 m^2, 1 t / Layer: ∼1000 m^2



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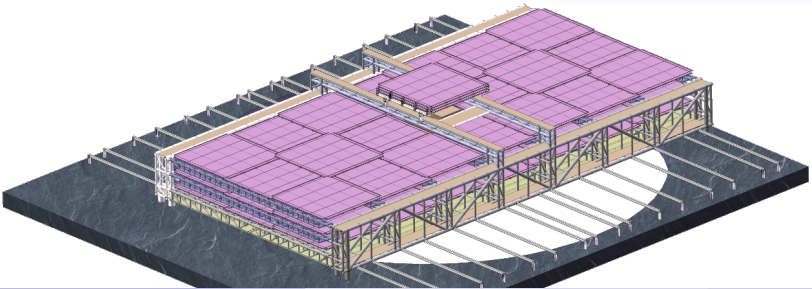
Status: JINR

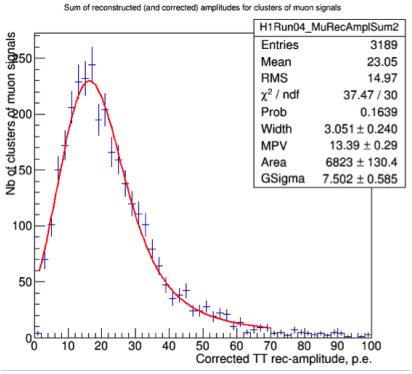
- Mechanical support structure R&D, prototyping and validation: done
- Assembly procedure, tools: done, reviewed
- Bidding: done
- Manufacturing (140 t): 2021
- Assembly on site: 2021.09→2022.03

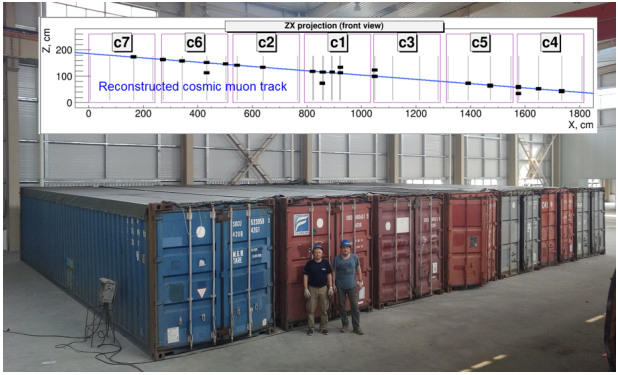


TT: PLASTIC SCINTILLATOR MONITORING

Plastic scintillator for TT

- Re-used OPERA Target Tracker
- ✓ Delivered on-site and stored in 7 containers
- ✓ Active DAQ to study aging





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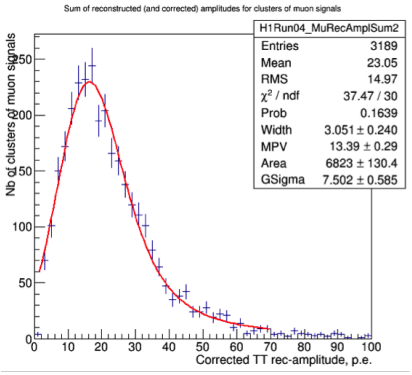
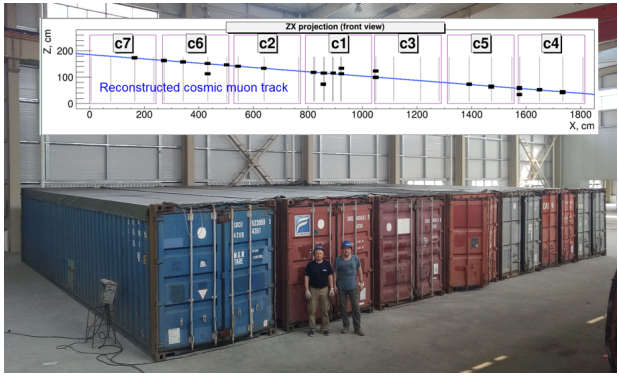
JINR

- ✓ Mobile DAQ and software (storage): operating
- DAQ software for TT: in progress



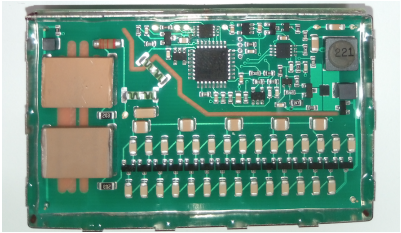


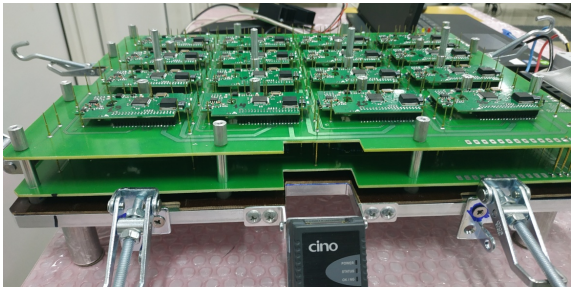
HV units

High Voltage supply provided by JINR

- ∼18'000 large PMTs — central detector
- ∼ 2'000 large PMTs — veto
- ∼25'600 small PMTs — central detector
- **∼25'000** underwater HV units — required

  1 unit per 8 sPMTs





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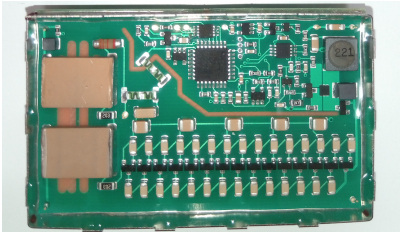
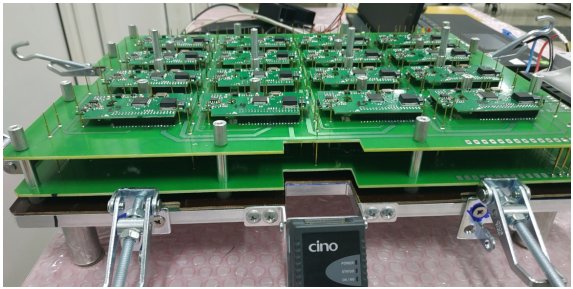


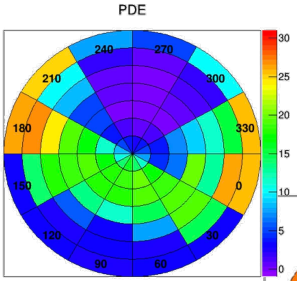
Status

- ✓ R&D, prototyping
- ✓ Testing: materials, ageing, thermo cycling
- ✓ Factory setup, procedures: Shenzhen
- ✓ Test batch: 500 items
- Production via single batch: → 2020

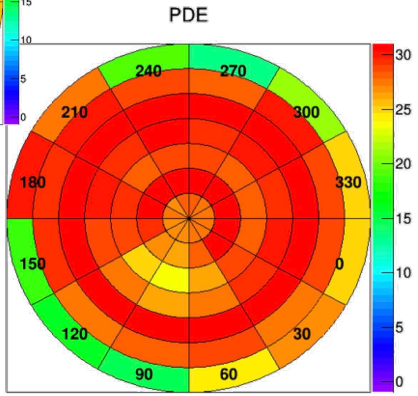


PMT Scanning

- ✓ 3 Scanning stations produced @JINR:
  - 1 in DLNP / 2 in China
  - All in individual dark rooms
  - Dedicated software
- ✓ Scanning: 3-4 PMTs/day
- ✓ $\sim$ 2500 PMTs scanned
- ✓ Maintain database, web accessible
- ✓ Study Earth Magnetic Field impact ▶
- • Complementary to mass testing

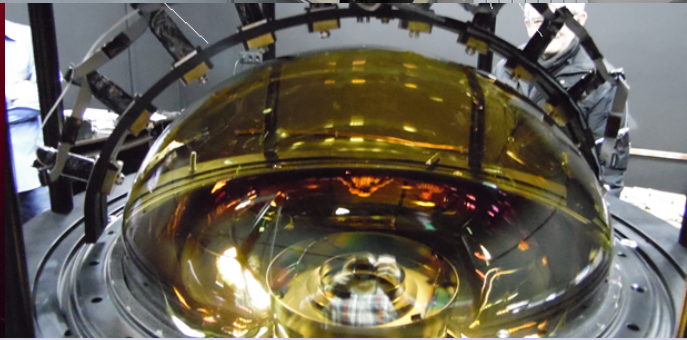


◀ Magnetic field: 42 μT



Magnetic field: compensated ▶

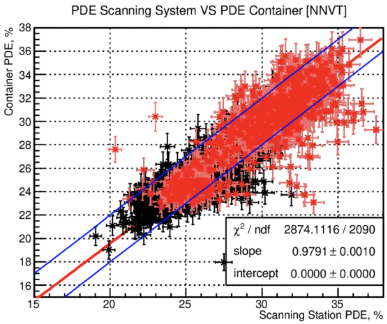
JINR PMT testing laboratory



Mass PMT Testing

Scanning and mass testing

- ✓ Almost 17k PMTs tested
- ✗ ∼3% rejected
- ✓ 3'110 PMTs tested after potting
- ✓ Complementary and consistent performance



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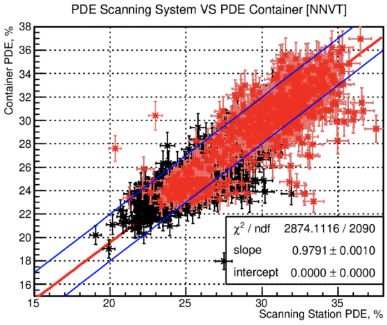
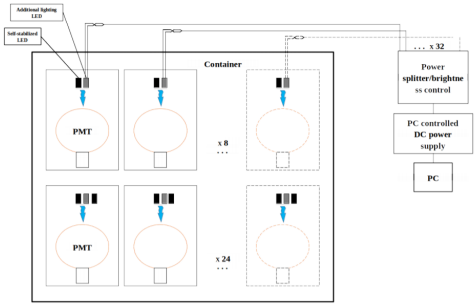
Long term stability

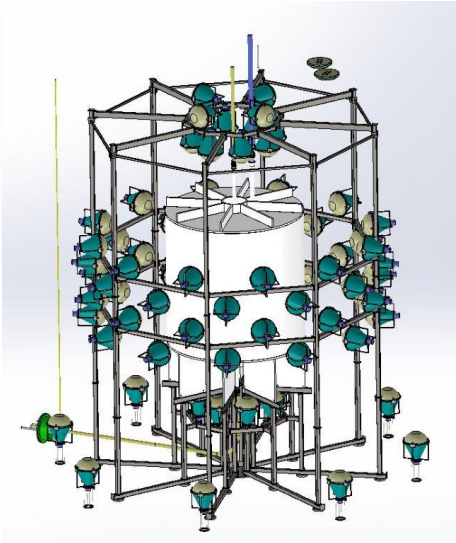
- ✓ 1 container equipped by JINR
- ✓ Operating since February 2020
- • 32 PMTs for 1 year
- ✓ DAQ software by JINR group





OSIRIS: PMT protection vs. Earth Magnetic Field

- Online Scintillator Internal Radioactivity Investigation System
- 76 20" PMTs: 64 detector + 12 veto
- Individual EMF protection: Metglas+Al cones:
  - detector: carbon fiber composite
  - veto: fiberglass composite
- EMF reduction factor: x2 $\parallel$ and x10 $\perp$



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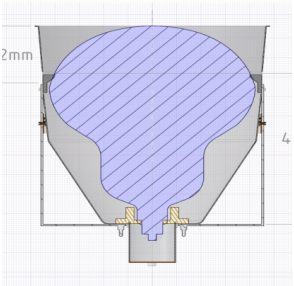

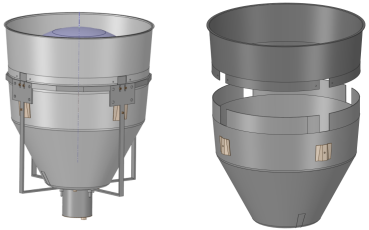

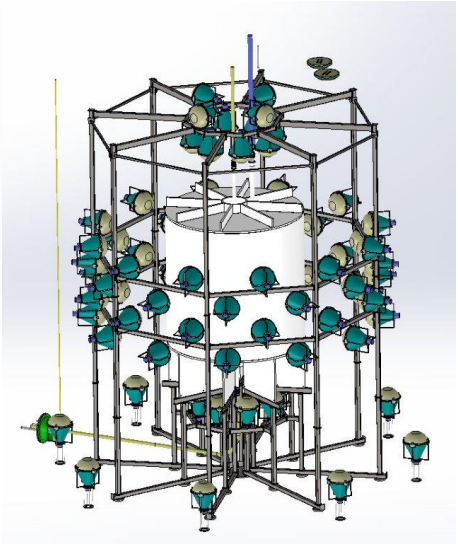

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- Table: carbon fiber option
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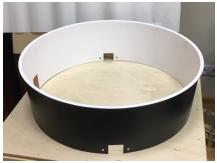

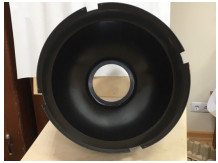

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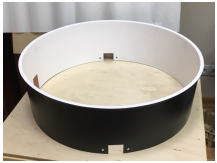

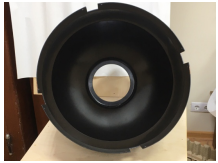

Material	Fraction U, pp**b**	Fraction Th, pp**b**	K, pp**m**	Mass, µg U	Mass, µg Th	Mass, µg ^{40}K
AMAG-170 (0.2 mm)	3	<5	0.84	4.7	<7.8	0.154
Epoxy	<0.1	0.9	0.78	<0.12	0.11	0.1
Carbon fiber	1	<6	15	0.25	<4.9	1.4
Gelcoat white	7	7	4.33	2.5	2.5	0.2
Cu foil	<0.3	<0.2	<0.127	<0.024	0.016	<0.001
Al foil	170	26	<0.96	15.3	2.4	<0.01
Total				22.8	<18	1.9
PMT glass	400	400	60	3600	3600	63

TAO — Taishan Antineutrino Observatory

Objective

- Precision antineutrino spectrum measurement
- High statistics, no oscillations
- Unprecedented precision: $\sim 2\%$ at 1 MeV

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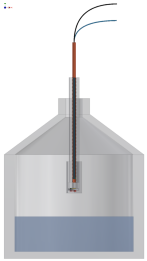

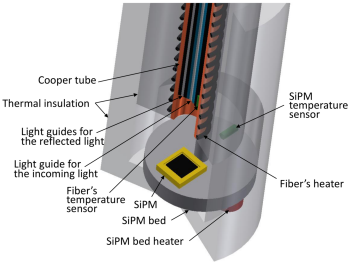

JINR contribution

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- ✓ TAO CDR preparation
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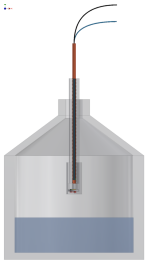
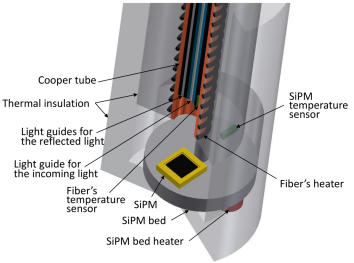
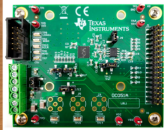




JINR contribution

- ✓ SiPM acceptance studies at $-50\,^{\circ}\mathrm{C}$
- ✓ TAO CDR preparation
- SiPM mass characterization
- SiPM high voltage supply
- 50% SiPM purchase funding: 1M$


a) - Custom made HV unit by JINR


b) - DAC81416EVM by TI

Computing: LIT&DLNP

Total requirements before 2040 (JINR)

- 4000 cores / 4 PB disk / 40 PB tape + 4 PB disk cache
- To store complete copy of JUNO data

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CPU and storage

✓ Current: 300 cores / 25 TB (dCache) + 500 TB (EOS)

- New: HP servers with 2880 cores with increased RAM 16 GB ▸
  - ✓ purchased and delivered in 2019, installed recently
  - ▸ to be powered
  - ▸ Part of Neutrino Computing Platform: shared, quota

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Network and GRID

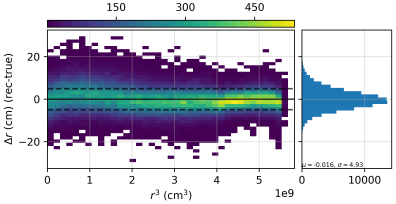
✓ GRID: CVMFS repository / Secondary VOMS server: deployed

✓ Network [Gbps]: 2x100 (local) / 3x100 (wide) / 2x10 (↔ China)

JUNO Reconstruction at JINR: progress

Neural Networks: vertex/energy reco ▸

- ✓ Exceptional performance, industry support
- ✓ Consistent with traditional methods
- ✗ Long training, proper calibration
- • Sphere projection? Graph Neural Networks



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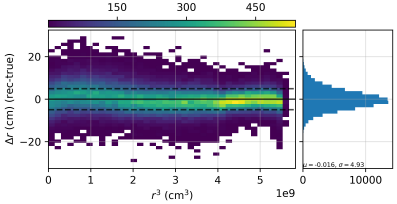
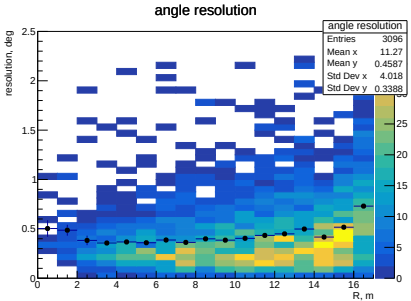
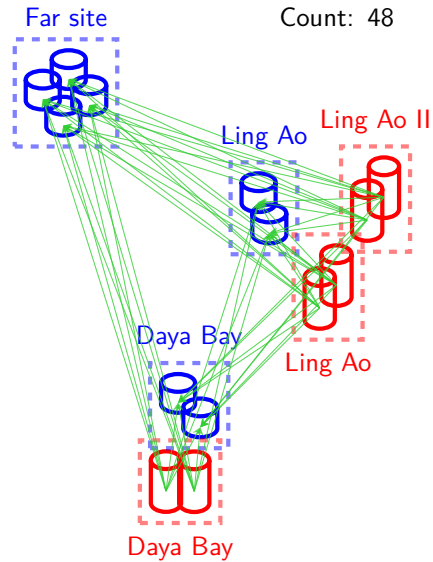
Muon track reconstruction ▸

- • For background rejection: $^{8}\mathrm{He}/^{9}\mathrm{Li}$, fast-$n$
- ✓ Decomposition into spherical functions
- ✓ Single tracks, muon bundles
- ✓ Precision: 0.5° and 10 cm





Why GNA: Day Bay experiment



$$\vec{N}^d = \vec{B}^d + \left(\prod_m C_m\right) \times$$

$$\times \sum_t \cdots \sum_r \cdots \int \vec{\int} \cdots \sum_i \cdots \sum_c P_c(L_r^d, \dots) \cdots$$

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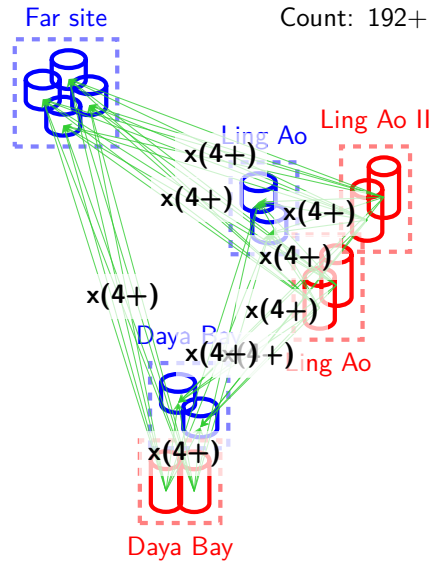

Requirements

- Efficient scalable models, lots of parameters
  - Laziness, caching
  - Flexibility
  - Portability (GPU)
- Long term support and compatibility
  - Readability, hand-over-ability
  - Minimize boilerplate code

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GNA: JUNO/Daya Bay implementation

- GNA framework — scalable high performance fitting.

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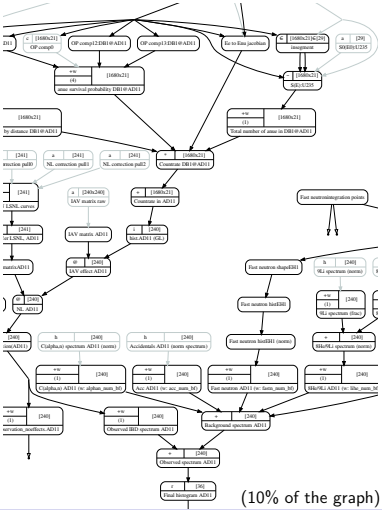

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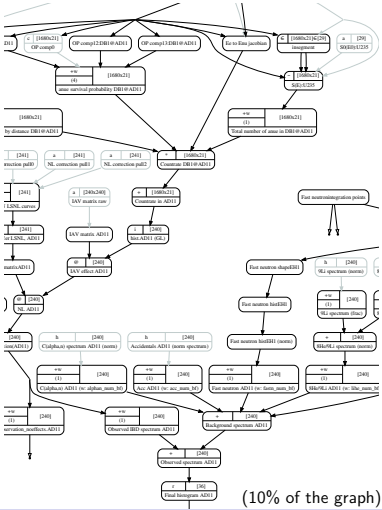

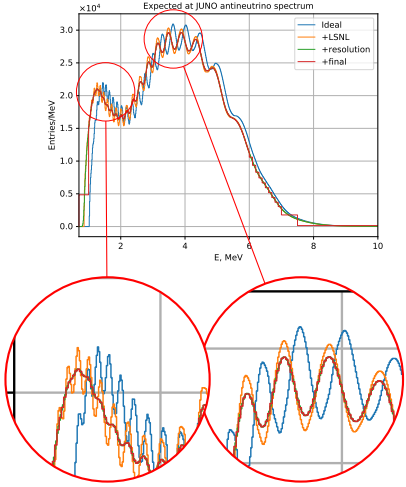

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Plans

- GPU support
- TensorFlow support?
- Documentation, tutorial, etc.

JUNO Expenditures 2018-2020

	HV Units	TOP Tracker	PMT Scanning	JUNO Computing	TAO	Total
JINR contribution	**2M USD**	0.8M USD (in-kind) + 0.2M USD (in progress)	2 stations +personnel on site	**2M USD**	**1M USD** (present)	6M USD
Payment status	100%	80%	Secured	50%	100%	**80%**
In progress		20%		50%		(1.2M) **20%**

Summary

- JUNO and Daya Bay: precision measurement of 4 oscillation parameters:

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- TAO: precision reactor antineutrino spectrum. Resolution: $\sim 2\%$ at 1 MeV.
- Timescale: Daya Bay $\rightarrow$ 2020; JUNO 2022 $\rightarrow$
- JINR: significant contribution to both hardware and analysis in JUNO.

Thank you for your attention!

Spare slides:

Open neutrino questions and tasks

- Neutrino oscillation parameters measurement
  - Precision measurement of oscillation parameters
  - Neutrino mass hierarchy determination
  - CP-violation observation and δ_{CP} measurement
  - θ_{23} octant determination
  - Testing the unitarity of neutrino mixing matrix
- Exotic searches
  - Sterile neutrinos
  - Non-standard interactions
  - Lorenz invariance violation
- Neutrino mass
  - Direct neutrino mass measurement
  - Observation of 0νββ decay
- Astrophysics and geophysics
  - Solar neutrinos flux measurement
  - Observation of solar CNO neutrinos
  - Geo-neutrino flux measurement
  - Observation of SuperNova neutrinos
  - Observation of diffuse SuperNova neutrinos
  - Observation of relic neutrinos
  - Observation of ultra high-energy neutrinos and their sources
- Other questions:
  - Reactor antineutrino spectrum measurement

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

Light sterile neutrino search

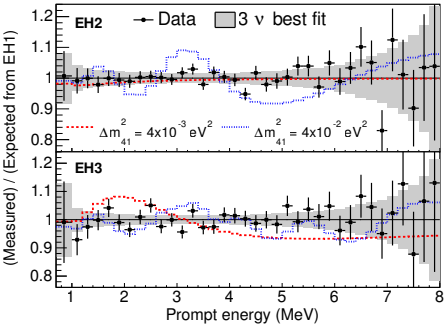
621 days, arXiv:1607.01174, PRL

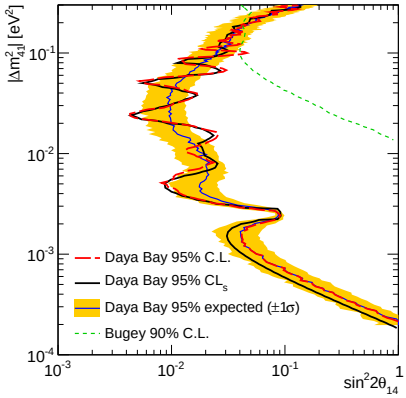
- Sterile neutrino cause spectral distortions, different at the near and far sites.

✓ Relative measurement.

✓ independent of reactor related systematics.

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





Light sterile neutrino search update

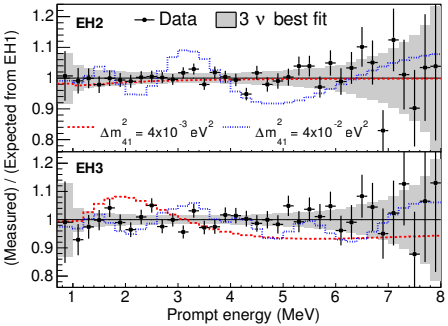
1230 days+MINOS, arXiv:2002.00301

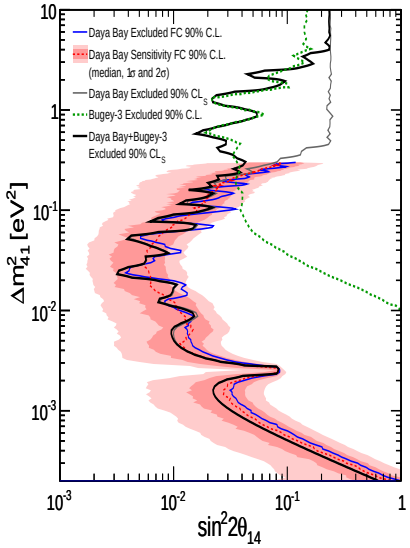
- Sterile neutrino cause spectral distortions, different at the near and far sites.

✓ Relative measurement.

✓ independent of reactor related systematics.

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





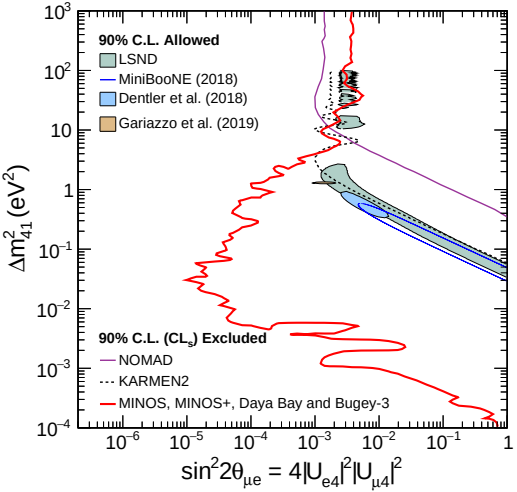
Y-scaled for consistency

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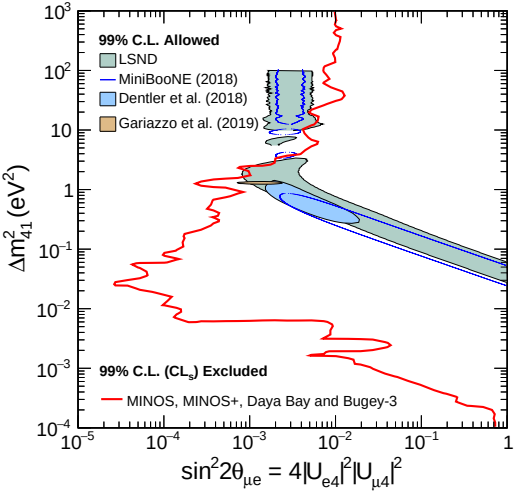
✓ LSND and MiniBooNE parameters space is excluded at the 90% C.L.

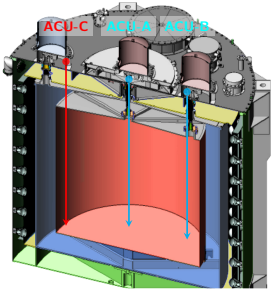
✓ LSND and MiniBooNE parameters space is excluded at the 99% C.L. for $\Delta m^2_{41} < 1.2\,\mathrm{eV}^2$.



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.

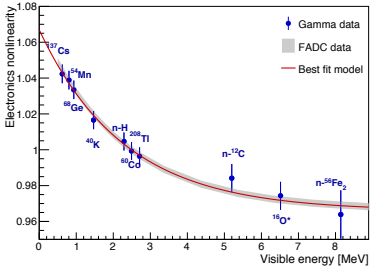
Updates

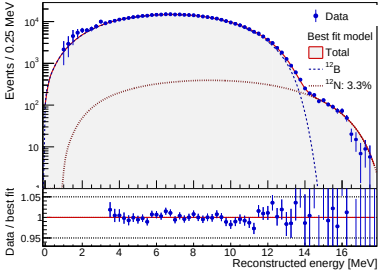
✓ ADC/FADC simultaneous readout in a EH1-AD1 since 2016
↪ measurement of electronics nonlinearity.

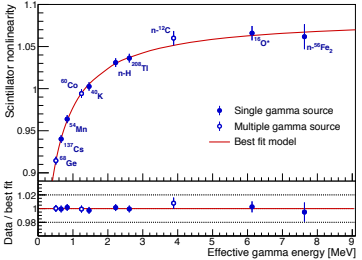
✓ Deployment of ^{60}Co calibration sources with different coating material (early 2017)
↪ measurement of shadowing effects.

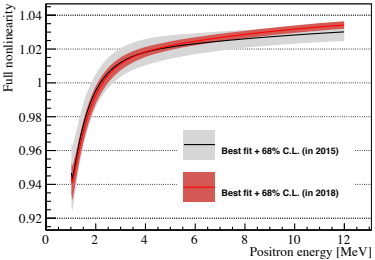
✓ MC simulation of energy loss in ^{60}Co coating material.

Energy response calibration









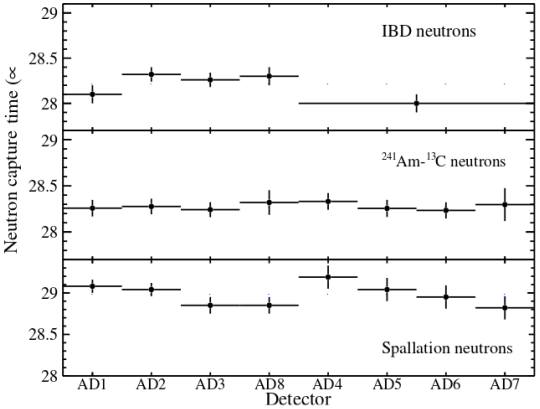
arXiv:1902.08241, NIMA

- ✓ Decoupled electronics and scintillator nonlinearity
- ✓ Continuous ^{12}B spectrum
- ✓ Combined positron energy nonlinearity uncertainty:

  $1\% \rightarrow 0.5\%$

Relative efficiency and relative energy scale

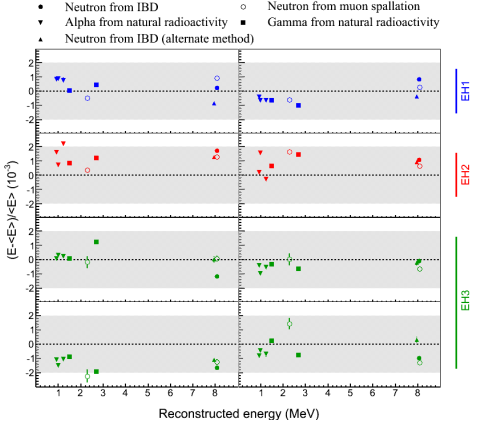
- Relative efficiency $\rightarrow \sin^2 2\theta_{13}$ uncertainty.



✓ 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%**.

Background events

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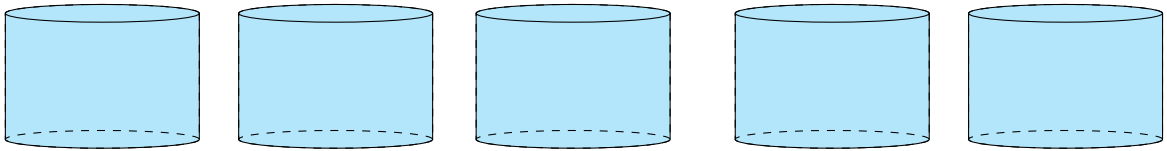
• Accidentals	%	1.3	1.6	1	1.5	negligible
• $^{8}\mathrm{He}/^{9}\mathrm{Li}$	%	**0.3**	**0.2**	**30**	2.7	20
• Fast neutrons	%	0.08	0.07	17	0.2	100
• $^{241}\mathrm{Am}$-$^{13}\mathrm{C}$	%	0.03	0.07	45	no	no
• $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$	%	0.01	0.07	50	0.1	50
• Total bkg	%	1.72	2.01		6.5	

Accidentals β-n isotopes Fast neutrons ACU $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$



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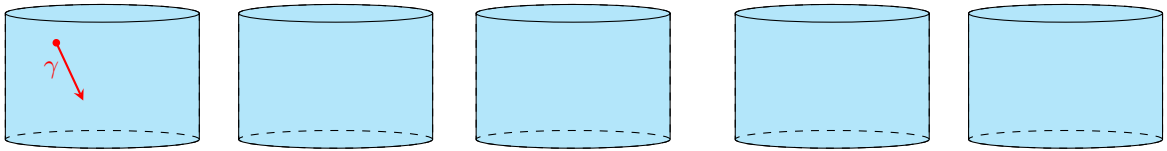

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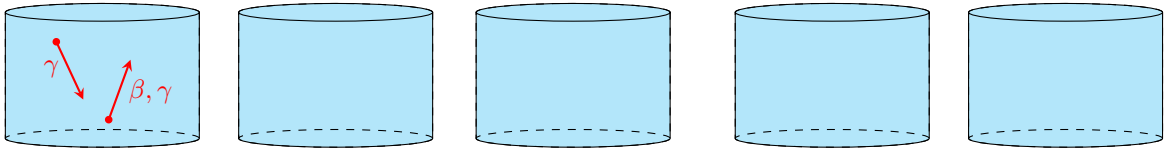

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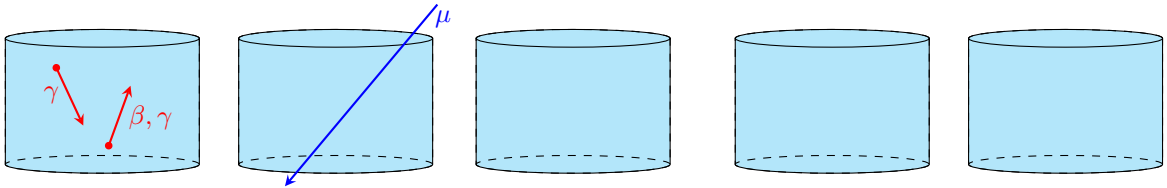

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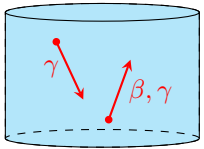

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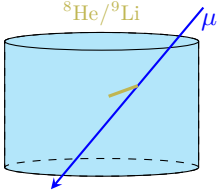

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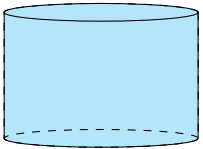
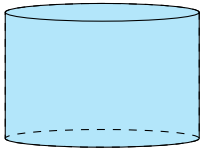


ACU



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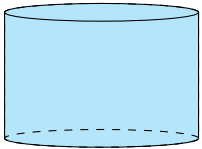

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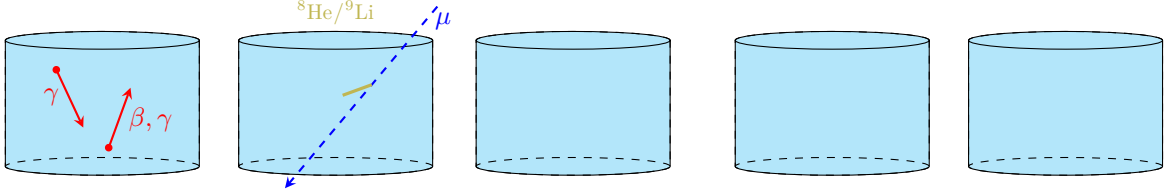

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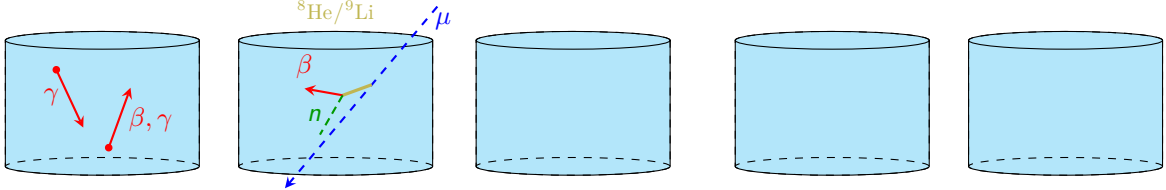

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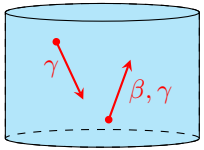

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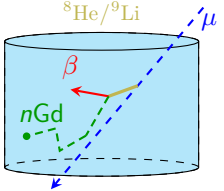

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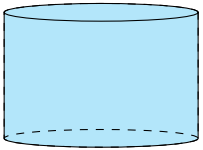
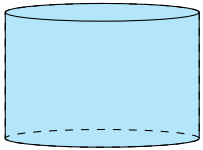
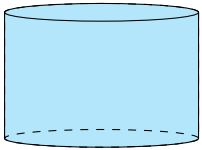


ACU



$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$



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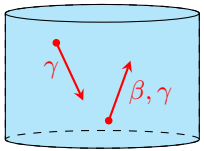
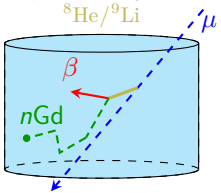


β-n isotopes



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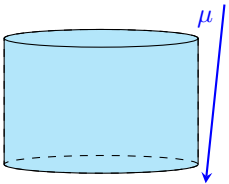
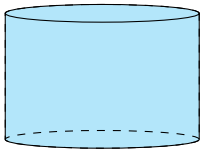
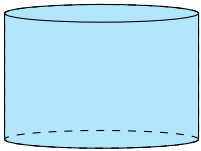


ACU



$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$



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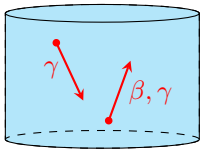
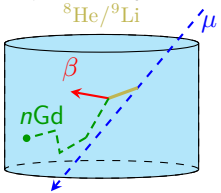
• Total bkg	%	1.72	2.01		6.5	

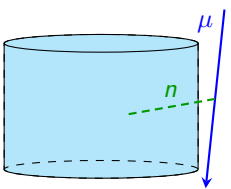
Accidentals



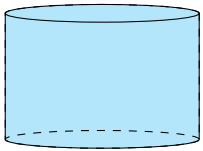
β-n isotopes



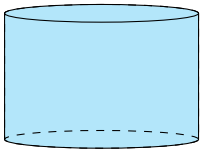
Fast neutrons



ACU



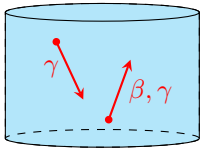
$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$



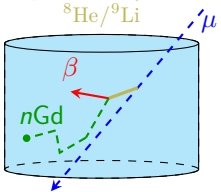
Background events

		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	

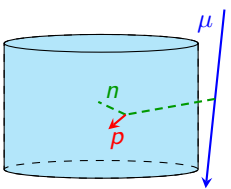
Accidentals



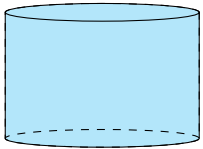
β-n isotopes



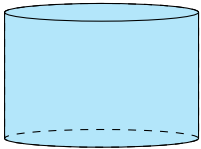
Fast neutrons



ACU



$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$



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
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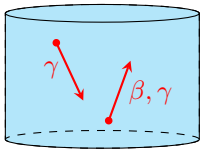
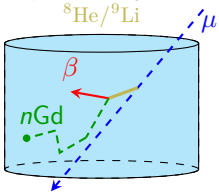
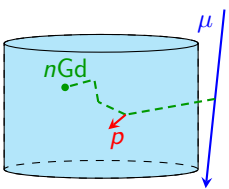


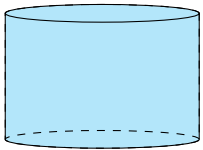
β-n isotopes



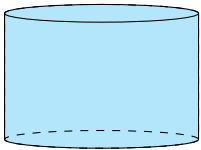
Fast neutrons



ACU



$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$



Background events

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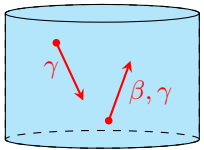
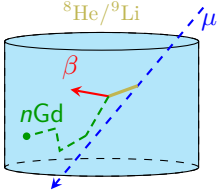
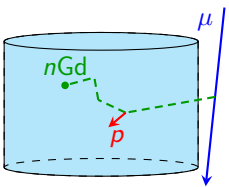


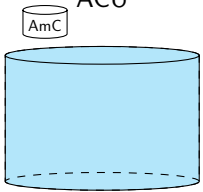
β-n isotopes



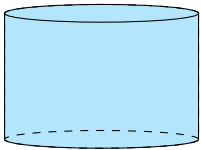
Fast neutrons



ACU



$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$



Background events

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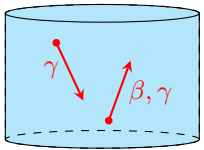
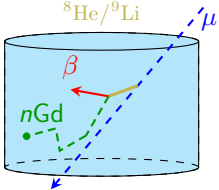
Accidentals

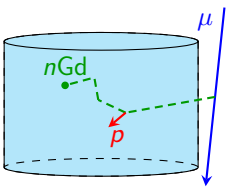


β-n isotopes

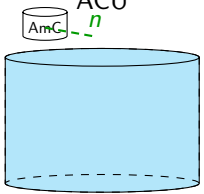
$^{8}\mathrm{He}/^{9}\mathrm{Li}$



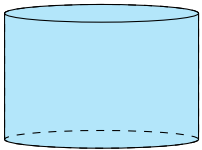
Fast neutrons



ACU



$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$



Background events

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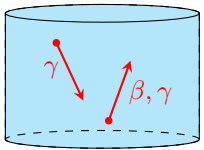
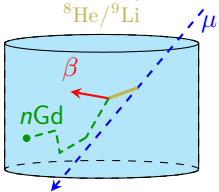
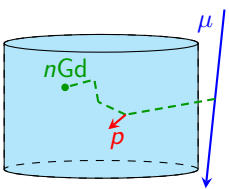
Accidentals



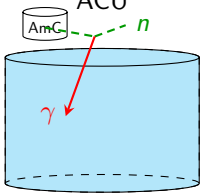
β-n isotopes



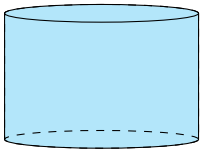
Fast neutrons



ACU



$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$



Background events

		DB Near S/N	DB Far S/N	Unc.	JUNO S/N	Unc.
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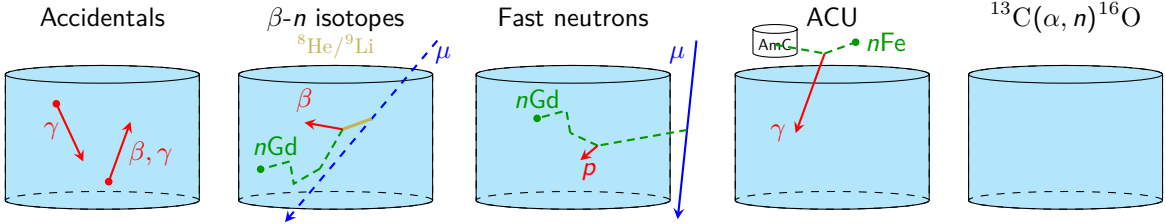

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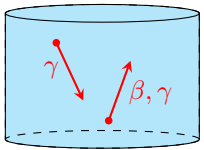
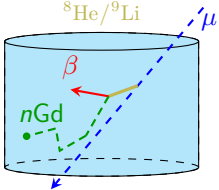
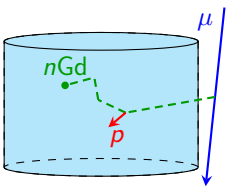


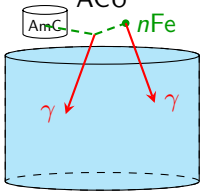
β-n isotopes



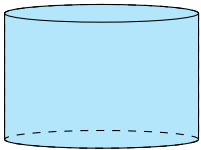
Fast neutrons



ACU



$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$



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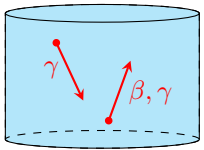
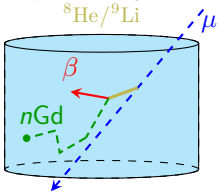
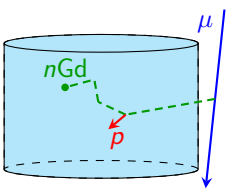


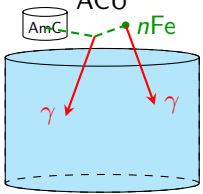
β-n isotopes



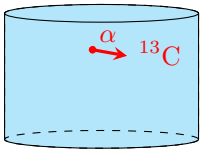
Fast neutrons



ACU



$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$



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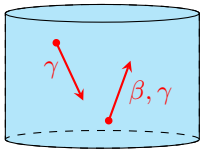
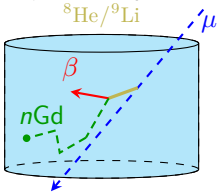
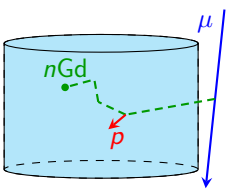


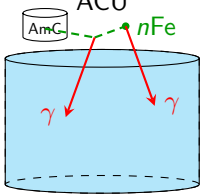
β-n isotopes



Fast neutrons



ACU



$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$