The role of JUNO in leptonic unitarity testing

Inaugurating a new high precision era in the neutrino oscillation field

27 June 2022

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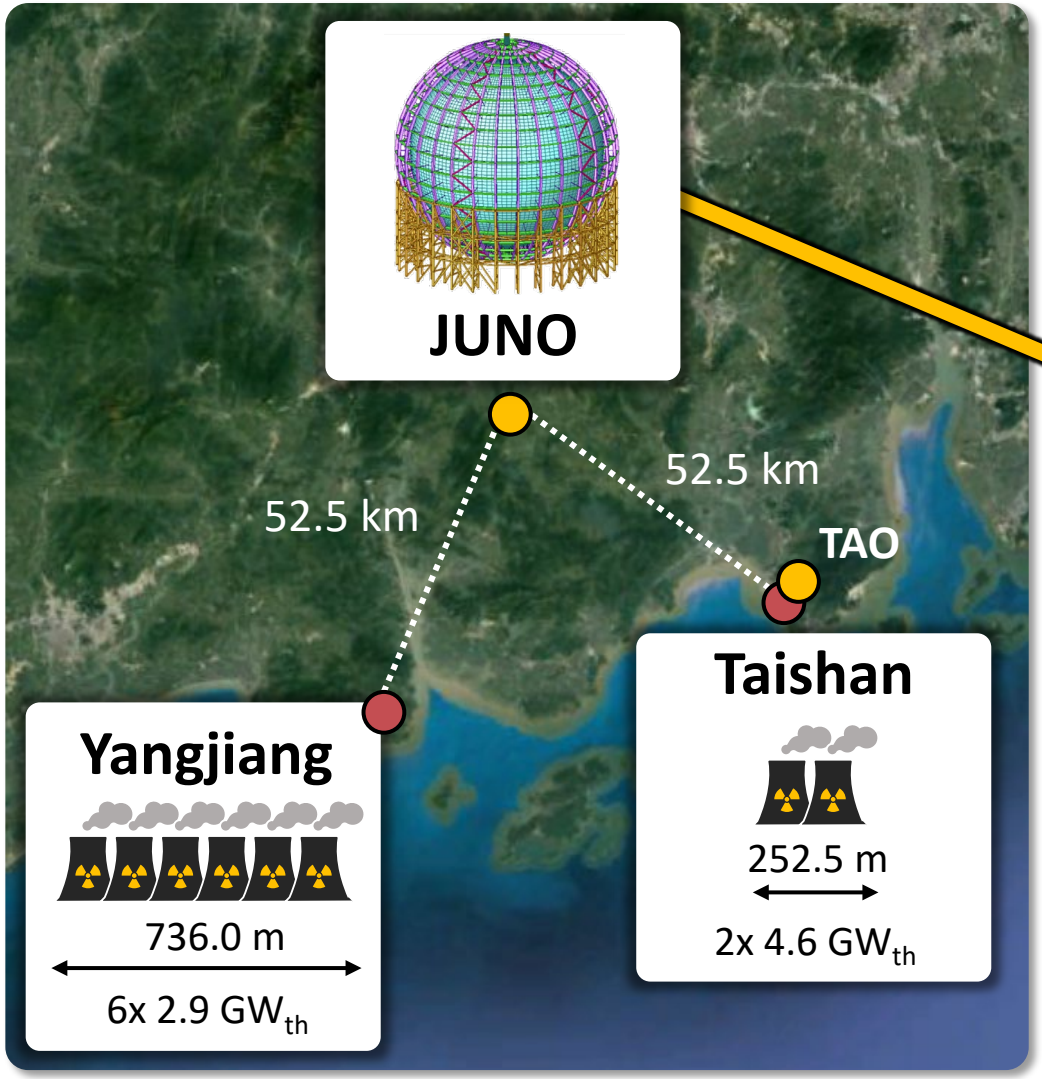
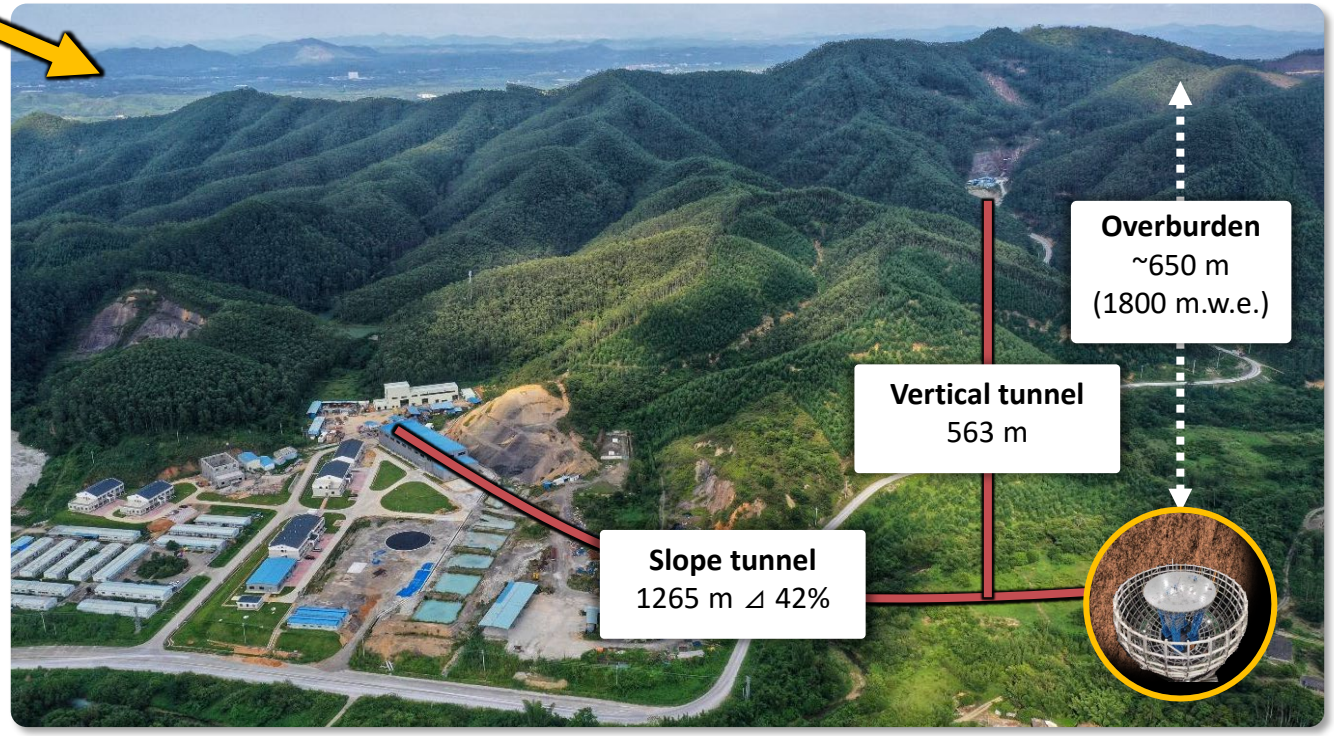
The Jiangmen Underground Neutrino Observatory



JUNO is a **20 kton** multi-purpose underground **liquid scintillator** detector currently under construction at a baseline of about **52.5 km** from eight **nuclear reactors** in the Guangdong Province of South China.

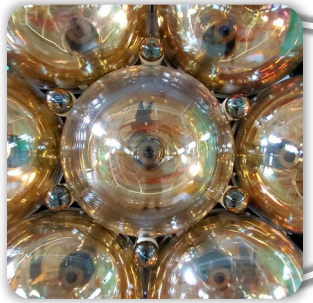


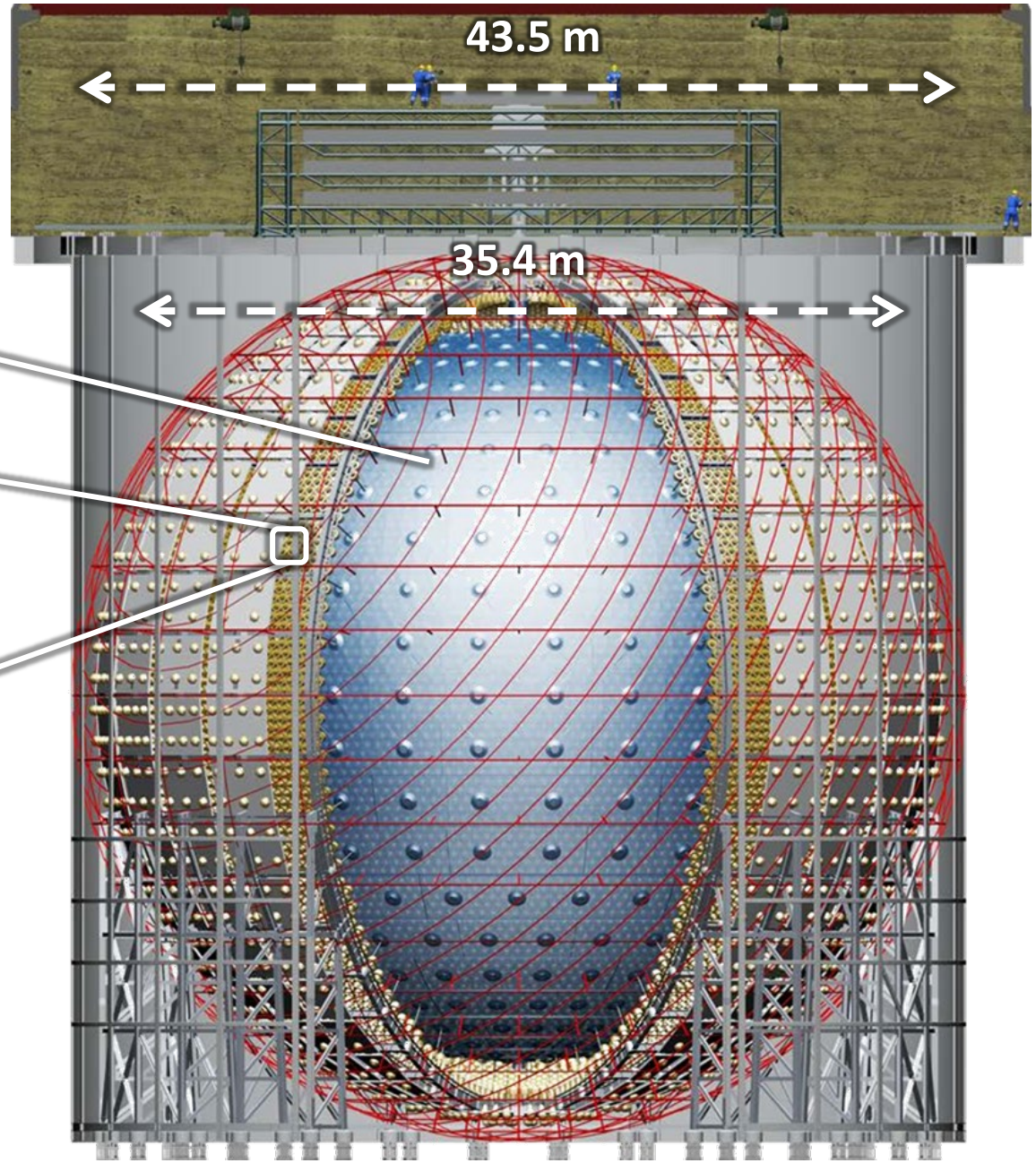
[Prog. Part. Nucl. Phys. 2021.103927]

The JUNO detector

Main requirements:

- **high statistics**
  → 20 kton of liquid scintillator acrylic sphere
- **<3% energy resolution @ 1 MeV**
  → photocoverage > 75%
- **energy-scale systematics below 1%**
  → 17612 20" Large-PMT
  → 25600 3" Small-PMT





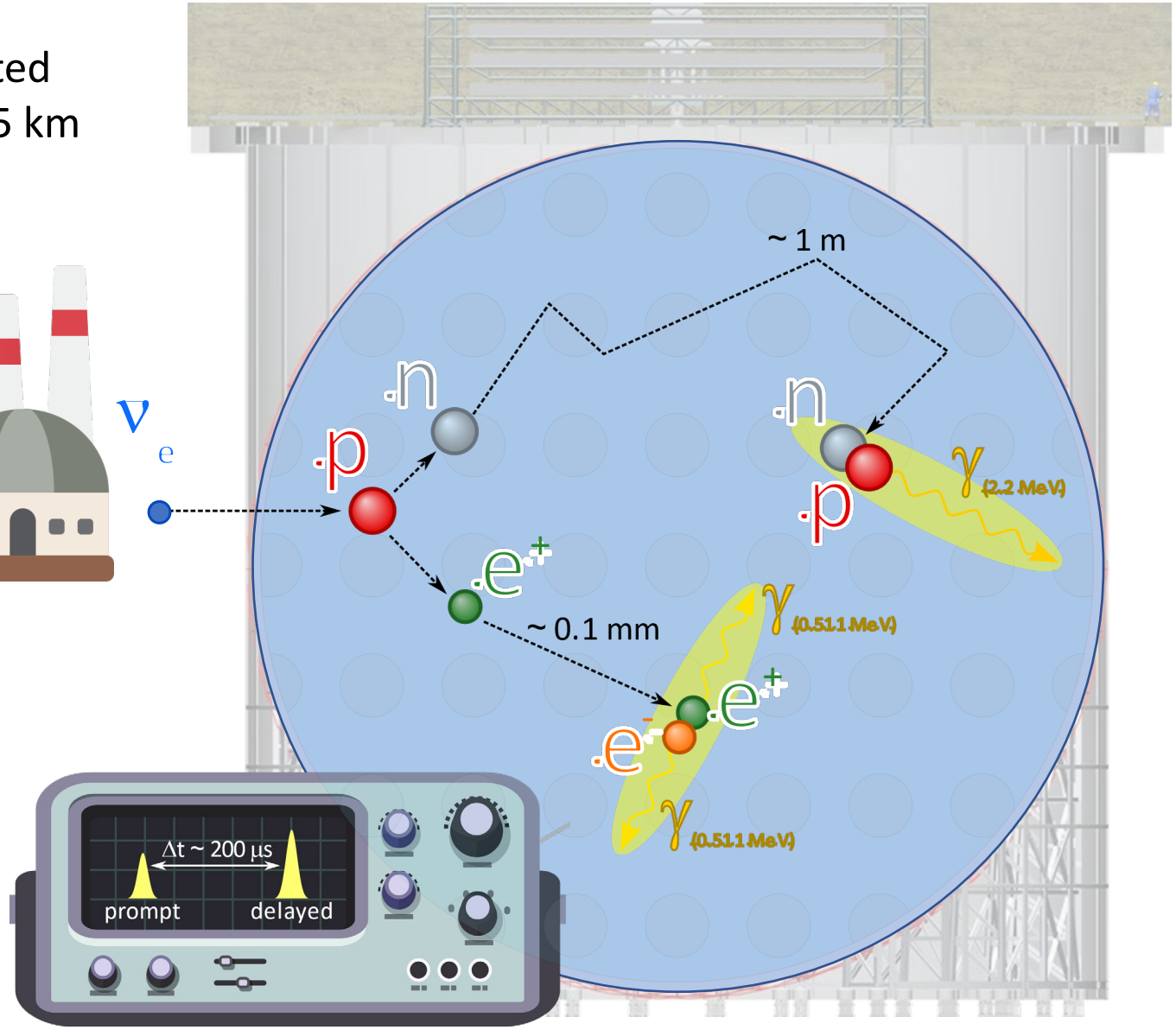
	Target mass [kton]	Energy resolution	Light yield [PE/MeV]
Daya Bay	0.02	8%/√E	160
Borexino	0.3	5%/√E	500
KamLAND	1	6%/√E	250
JUNO	**20**	**3%/√E**	**>1300**

The JUNO detection process

JUNO will measure the **antineutrinos** ($\bar{\nu}$) generated in the fissions occurring in 8 nuclear cores at 52.5 km

The **detection** is based on a charged current interaction named Inverse Beta Decay (**IBD**) on protons (p)

→ **sensitive only to electron $\bar{\nu}_e$**



Detection relies on a **double coincidence**:

- **prompt** signal: positron (e^+) annihilation
- **delayed** signal: neutron (n) capture

→ **strong handle against most backgrounds**

The JUNO physics program

JUNO can detect neutrinos and antineutrinos coming from several sources:

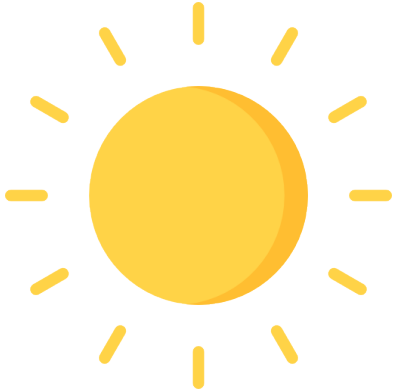
Reactor

~45/day

Atmosphere

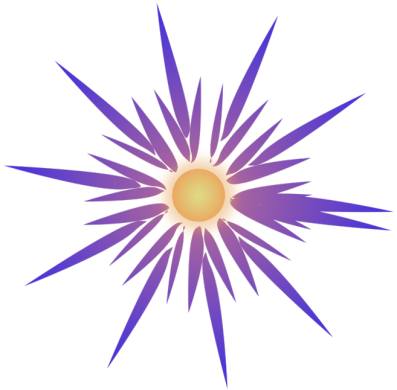
>100/year

Sun



>100/day

Supernovae



~10^4/10 s @ 10kpc

Earth

~400/year

Neutrino oscillation properties

Neutrinos as a probe

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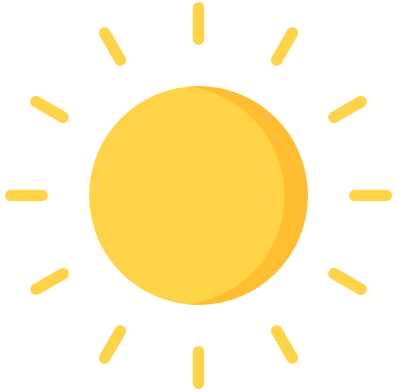

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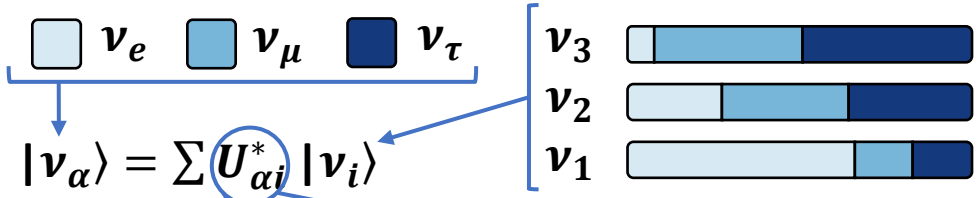
Neutrinos as a probe

A recap of neutrino oscillations

mass eigenstates (ν_i) ≠ flavor (ν_α) eigenstates

→ flavor **"oscillates" during propagation!**

→ **phase depends on** the **splitting** between mass states



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

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

The matrix connecting mass and flavor states is the Pontecorvo-Maki-Nakagawa-Sakata **(PMNS) mixing matrix**.

→ presumably unitary (?)

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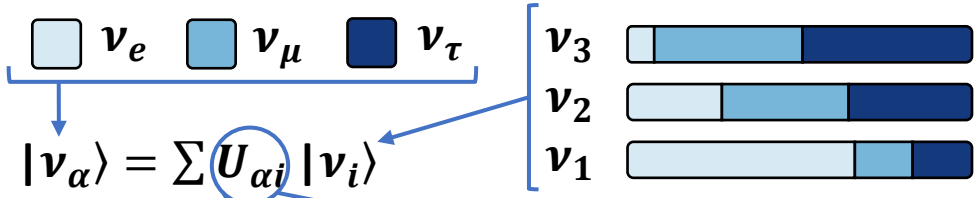

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Unitarity can be **tested directly** via the electron neutrino/antineutrino channel by testing the **Electron Row Unitarity (ERU)**

$$|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 = 1$$

3 unknowns → 3 constraints required

Testing 3x3 PMNS unitarity

The precision measurement of neutrino mixing parameters is a very powerful tool to test the standard 3-flavor neutrino model via ERU: **3 unknowns → 3 independent constraints required**

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Constrained at:

1) Solar → $|U_{e2}|^2 \cdot (|U_{e1}|^2 + |U_{e2}|^2) + |U_{e3}|^4$ $(\sin^2\theta_{12}\cos^4\theta_{13} + \sin^4\theta_{13})$ $\sim$5% [10.5281/zenodo.4134680]

(SNO + Super-K)

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2) Daya Bay →	$\frac{4\lvert U_{e3}\rvert^2(\lvert U_{e1}\rvert^2 + \lvert U_{e2}\rvert^2)}{(\lvert U_{e1}\rvert^2 + \lvert U_{e2}\rvert^2 + \lvert U_{e3}\rvert^2)^2}$	$(\sin^2 2\theta_{13})$	$\sim$3% [Phys. Rev. Lett. 121.241805]

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3) JUNO →	$\boldsymbol{\frac{4\lvert U_{e1}\rvert^2\lvert U_{e2}\rvert^2}{(\lvert U_{e1}\rvert^2 + \lvert U_{e2}\rvert^2 + \lvert U_{e3}\rvert^2)^2}}$	$\boldsymbol{(\sin^2 2\theta_{12}}\cos^4\theta_{13}\boldsymbol{)}$	**<1%** [arXiv:2204.13249]

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Indeed, in the Minimal Unitarity Violation (MNU) scheme, the $\bar{\nu}_e$ survival probability:

$$P^{MNU}_{\bar{e}\bar{e}} = (\lvert U_{e1}\rvert^2 + \lvert U_{e2}\rvert^2 + \lvert U_{e3}\rvert^2) \cdot P_{\bar{e}\bar{e}} =$$
$$= (\lvert U_{e1}\rvert^2 + \lvert U_{e2}\rvert^2 + \lvert U_{e3}\rvert^2)^2 \cdot \left(1 - \frac{4\lvert U_{e1}\rvert^2\lvert U_{e2}\rvert^2}{(\lvert U_{e1}\rvert^2+\lvert U_{e2}\rvert^2+\lvert U_{e3}\rvert^2)^2}\sin^2\Delta_{21} - \frac{4\lvert U_{e3}\rvert^2\left(\lvert U_{e1}\rvert^2\sin^2\Delta_{31}+\lvert U_{e2}\rvert^2\sin^2\Delta_{32}\right)}{(\lvert U_{e1}\rvert^2+\lvert U_{e2}\rvert^2+\lvert U_{e3}\rvert^2)^2}\right)$$

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Oscillation physics with JUNO

JUNO aims at determining the neutrino mass ordering @ >3σ in 6 years, and will be the first experiment to:

- **simultaneously** observe **fast** and **slow oscillations** (Δm^2_{21}, θ_{12}, Δm^2_{31} and θ_{13})
- place **<1% precision** on Δm^2_{21}, θ_{12}, Δm^2_{31}

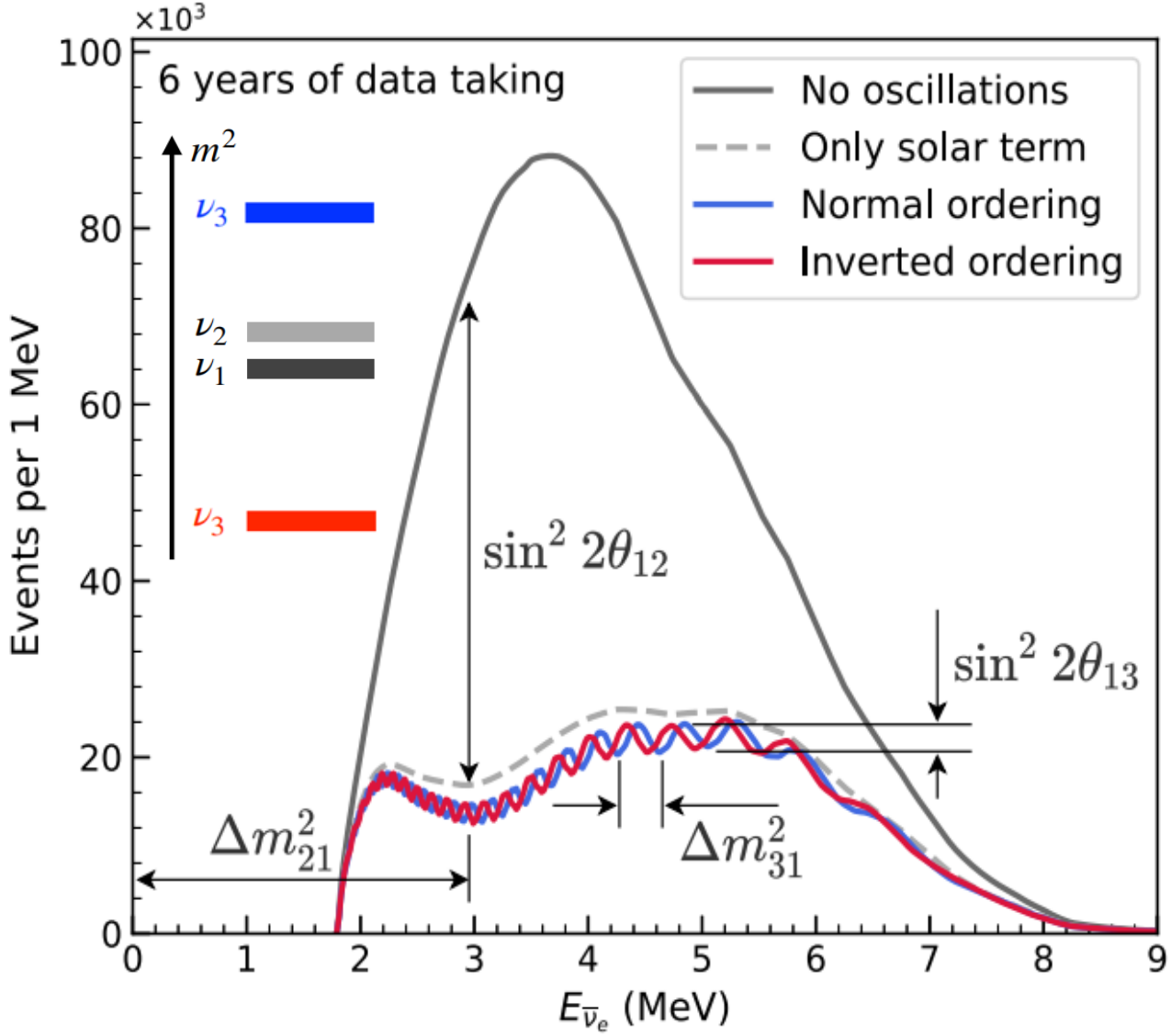
$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$

$$\boldsymbol{P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}}$$

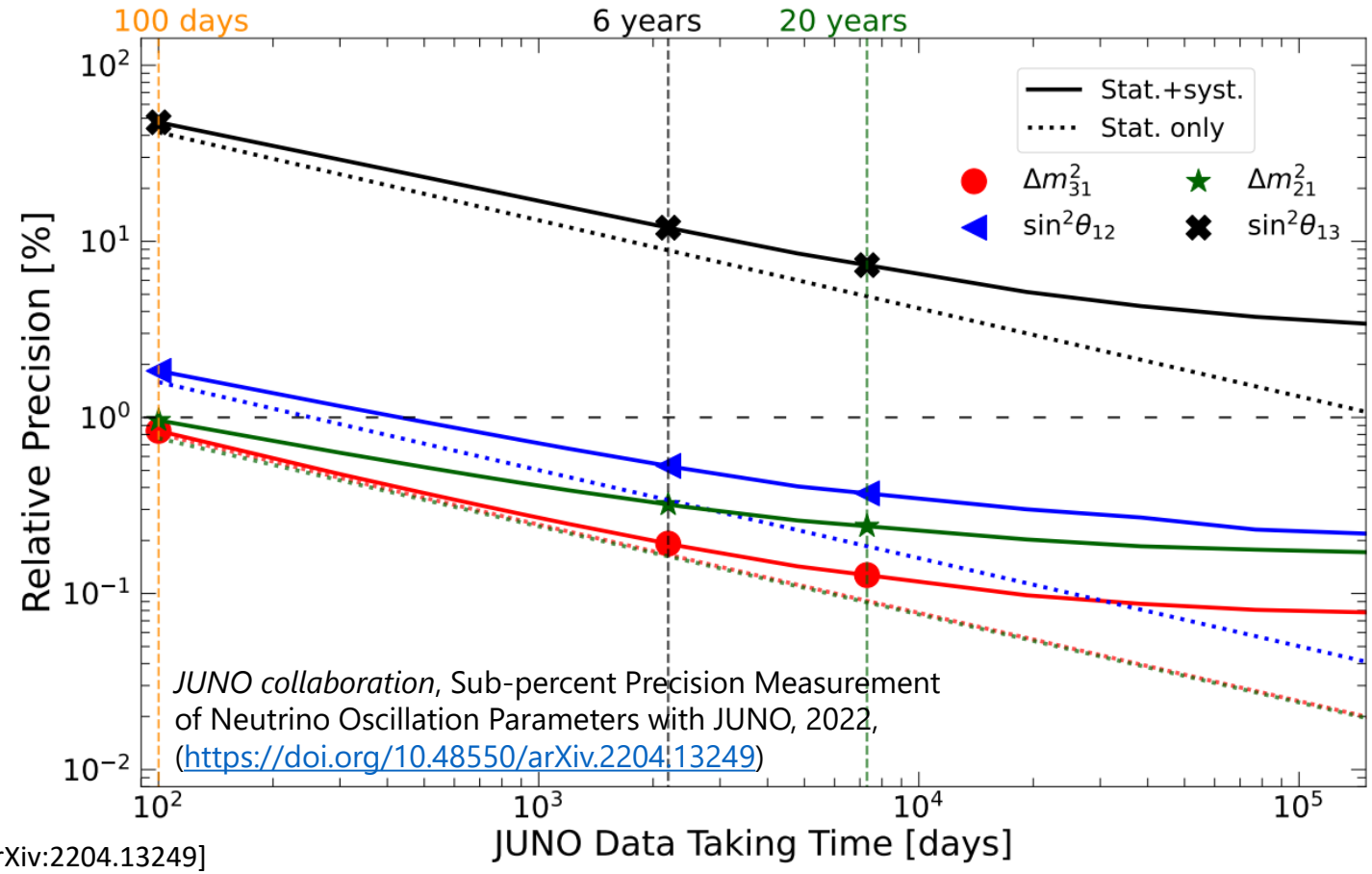
SLOW $P_{21} = \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$

FAST
$$P_{31} = \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{31}$$
$$P_{32} = \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{32}$$

→ **probability does not depend on δ_{CP} and θ_{23}**



Subpercent measurement of oscillation parameters



[arXiv:2204.13249]

	$\sin^2\theta_{12}$	Δm^2_{21}	$\sin^2\theta_{13}$	Δm^2_{31}
PDG2020	4.2%	2.4%	3.2%	1.4%
Nufit5.1	4.0%	2.8%	2.8%	1.1%
JUNO 6 years	**0.5%**	**0.3%**	12%	**0.2%**

In <2 years, JUNO will improve the precision on Δm^2_{21}, θ_{12}, Δm^2_{31}

→ unprecedented <1% level.

In 6 years, the precision on θ_{12}, Δm^2_{21} and Δm^2_{31} will reach 0.5%, 0.3% and 0.2%

rough estimate
[J. Phys. G 43 030401]

- constrain PMNS unitarity @ 2.5% level (limited by SNO solar constraint)
- narrow down the parameter space of 0νββ effective mass
- constrain the neutrino mass sum rule $\Delta m^2_{13} + \Delta m^2_{21} + \Delta m^2_{32} = 0$

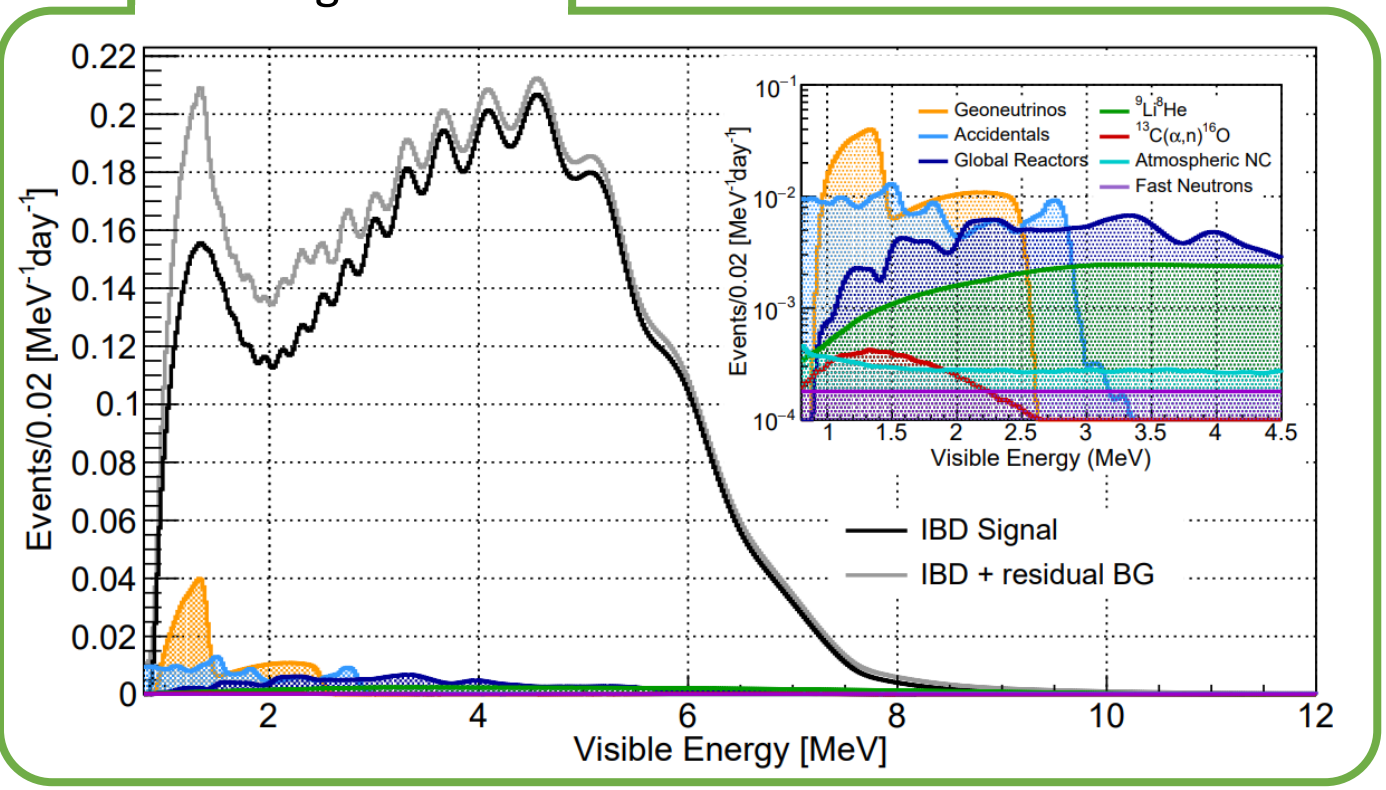
Challenges to θ_{12} measurement

Main systematic uncertainties:

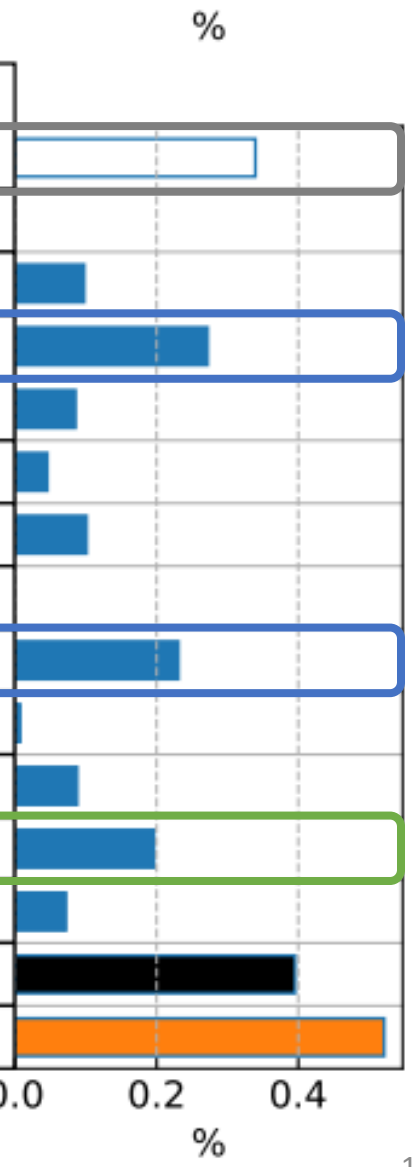
→ rate/normalization:

- reactor flux normalization
- detector efficiency

→ backgrounds



$\sin^2\theta_{12}$	6 years 1σ (%)
Statistics	0.34
Reactor:	
- Uncorrelated	0.10
- Correlated	0.27
- Reference spectrum	0.09
- Spent Nuclear Fuel	0.05
- Non-equilibrium	0.10
Detection:	
- Efficiency	0.23
- Energy resolution	0.01
- Nonlinearity	0.09
- Backgrounds	0.20
Matter density	0.07
All systematics	0.40
Total	0.52

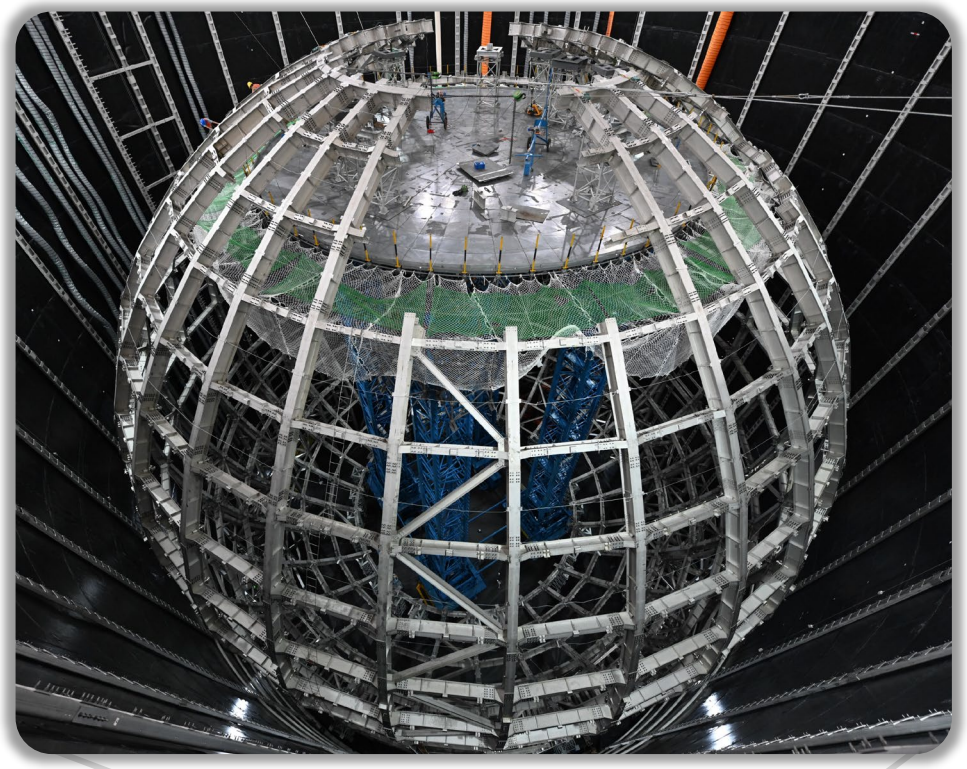


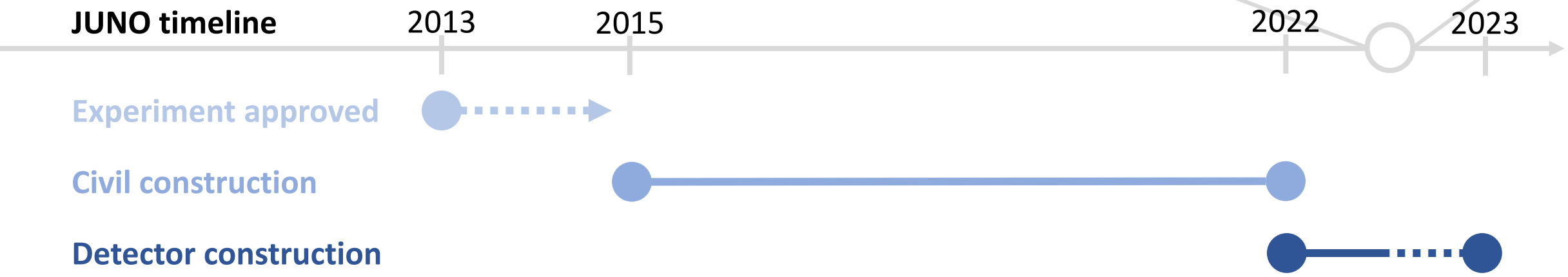
[arXiv:2204.13249]

Final remarks

- **JUNO** will inaugurate a **high precision** era in the neutrino oscillation field. In 6 years:
  - → **neutrino mass hierarchy** at >3σ
  - → **<1% precision** on $\boldsymbol{\theta_{12}}$, Δm^2_{21} and Δm^2_{31}

- The 0.5% precision on θ_{12} will provide a constrain to **directly test leptonic unitarity** via ERU at 2.5% (together with solar and reactor constraints)





Thank you!

Back up

PMNS terms

Table 1. Quantities to which each experiment is sensitive: using the PMNS parameterization when unitarity is assumed (center column), using the MP parametrization when unitarity is not assumed (right column).

Experiment	PMNS Quantity	LMM Quantity
Solar Neutral Current	1	$(\lvert U_{e1}\rvert^2 + \lvert U_{e2}\rvert^2)N_2^2 + \lvert U_{e3}\rvert^2 N_3^2$
Solar Charged Current	$\sin^2\theta_{12}\cos^4\theta_{13} + \sin^4\theta_{13}$	$\lvert U_{e2}\rvert^2(\lvert U_{e1}\rvert^2 + \lvert U_{e2}\rvert^2) + \lvert U_{e3}\rvert^4$
KamLAND	$\cos^4\theta_{13}\sin^2(2\theta_{12})$	$4\lvert U_{e1}\rvert^2\lvert U_{e2}\rvert^2$
Daya Bay	$\sin^2(2\theta_{13})$	$4\lvert U_{e3}\rvert^2(\lvert U_{e1}\rvert^2 + \lvert U_{e2}\rvert^2)/N_e^2$
Sterile Neutrino $P_{\alpha\beta}$ $(\alpha \neq \beta)$	0	$\lvert t_{\alpha\beta}\rvert^2$
OPERA	$\cos^4\theta_{13}\sin^2(2\theta_{23})$	$4\lvert U_{\mu3}\rvert^2\lvert U_{\tau3}\rvert^2/N_\mu^2$
Long-baseline $P_{\mu e}$ (T2K, NOvA, DUNE, T2HK)	$\sin^2\theta_{23}\sin^2(2\theta_{13})$	$4\lvert U_{e3}\rvert^2\lvert U_{\mu3}\rvert^2/N_\mu^2$
Long-baseline $P_{\mu\mu}$ (T2K, NOvA, DUNE, T2HK)	$4\cos^2\theta_{13}\sin^2\theta_{23}\left(1-\cos^2\theta_{13}\sin^2\theta_{23}\right)$	$4\lvert U_{\mu3}\rvert^2(\lvert U_{\mu1}\rvert^2 + \lvert U_{\mu2}\rvert^2)/N_\mu^2$

State of the art and prospects

	knowledge as of 2020		**expected knowledge beyond 2020**		
	dominant	precision (%)	precision (%)	dominant	technique
θ_{12}	SNO	2.3	≤ 1.0	JUNO	*reactor*
θ_{23}	NOvA	2.0	~ 1.0	DUNE+HK	*beam*
θ_{13}	DYB	3.3	3.3	DC+DYB+RENO	*reactor*
δm^2	KL	2.3	≤ 1.0	JUNO	*reactor*
$\lvert\Delta m^2\rvert$	DYB+T2K	1.3	≤ 1.0	JUNO+DUNE+HK	*reactor+beam*
$\pm\Delta m^2$	SK	unknown	measured??	JUNO+DUNE+HK	*reactor+beam*
δ_{CP}	T2K	unknown	measured??	DUNE+HK	*beam*

A recap of neutrino oscillations

For neutrinos, mass (ν_i) and flavor (ν_α) eigenstates do not correspond.

The Pontecorvo-Maki-Nakagawa-Sakata **(PMNS) mixing matrix** can be **parametrized** by:

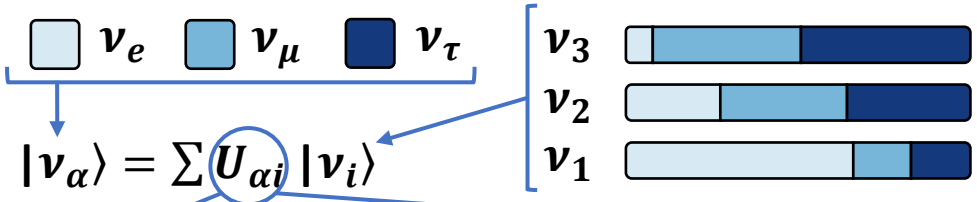
- 3 mixing angles ($\boldsymbol{\theta_{12}}, \boldsymbol{\theta_{13}}, \boldsymbol{\theta_{23}}$)
- 1 CP-violating phase ($\boldsymbol{\delta_{CP}}$)

The non-correspondence between mass and flavor eigenstates causes the flavor to **"oscillate" during propagation**.

The **phase** of this oscillation **depends on** the **splitting** between the mass states:

- $\boldsymbol{\Delta m^2_{21}}$
- $\boldsymbol{\Delta m^2_{31}}$

With Δm^2_{21}>0 and Δm^2_{31} and Δm^2_{32} possibly positive (normal ordering) or negative (inverted).



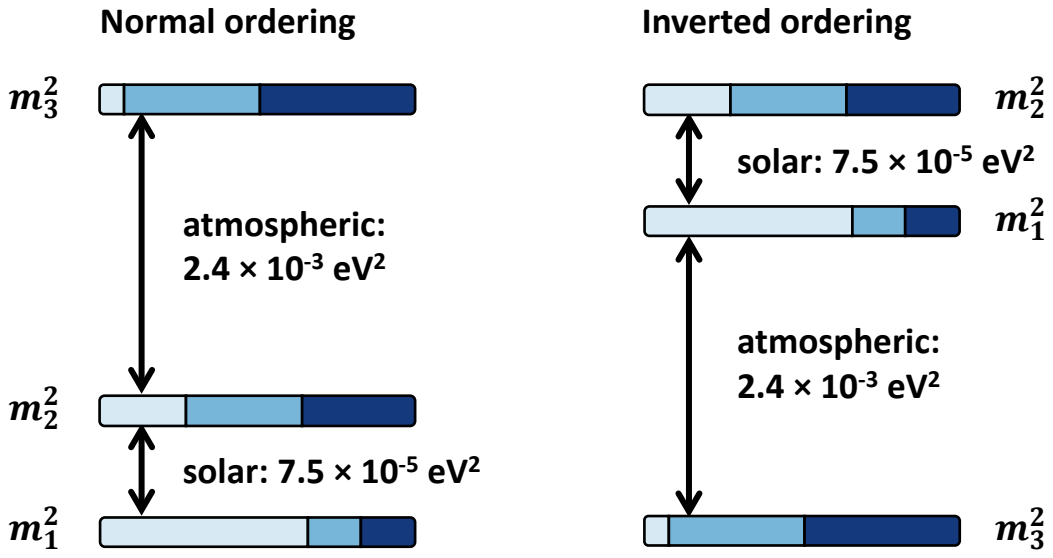
$$|\nu_\alpha\rangle = \sum U_{\alpha i} |\nu_i\rangle$$

*conventionally written as explicitly unitary

$$c_{XY} = \cos\theta_{XY}$$
$$s_{XY} = \sin\theta_{XY}$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric Reactor Solar Majorana



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The precision measurement of neutrino mixing parameters is a very powerful tool to test the standard 3-flavor neutrino model. In particular, PMNS unitarity can be tested directly via **Electron Row Unitarity (ERU)**:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \boxed{U_{e1} \quad U_{e2} \quad U_{e3}} \\ U_{\mu 1} \quad U_{\mu 2} \quad U_{\mu 3} \\ U_{\tau 1} \quad U_{\tau 2} \quad U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Rightarrow |U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 = 1$$

3 unknowns → 3 constraints required

In the Minimal Unitarity Violation (MNU) scheme:

$$P_{\bar{e}\bar{e}}^{MNU} = (|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2) \cdot P_{\bar{e}\bar{e}} =$$
$$= (|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2)^2 \cdot \left(1 - \boxed{\frac{4|U_{e1}|^2|U_{e2}|^2}{(|U_{e1}|^2+|U_{e2}|^2+|U_{e3}|^2)^2} \sin^2 \Delta_{21}} - \boxed{\frac{4|U_{e3}|^2\left(|U_{e1}|^2 \sin^2 \Delta_{31} + |U_{e2}|^2 \sin^2 \Delta_{32}\right)}{(|U_{e1}|^2+|U_{e2}|^2+|U_{e3}|^2)^2}}\right)$$

$\sim \sin^2 2\theta_{12} \cdot \sin^2 \Delta_{21}$

Measurable by **JUNO with <1% precision**

$\sim \sin^2 2\theta_{13} \cdot \sin^2 \Delta_{3(1,2)}$

Measurable by JUNO @ ~10% and **constrained by Daya Bay @ <5%**
[Phys.Rev.D 93 7, 072011]

Additional constraint from solar neutrino experiments (SNO):

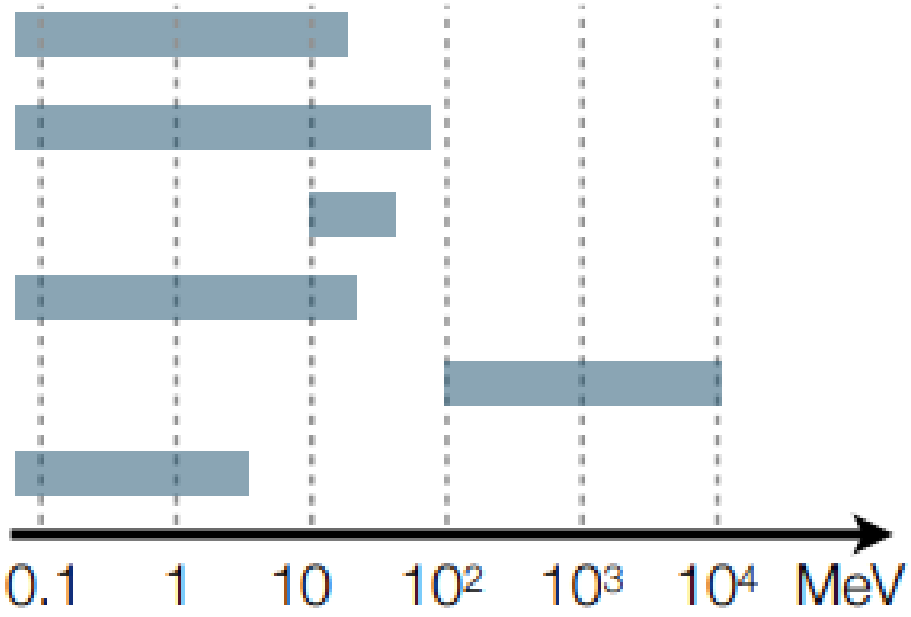
$$\boxed{|U_{e2}|^2 \cdot (|U_{e1}|^2 + |U_{e2}|^2) + |U_{e3}|^4}$$

Constrained by SNO at ~12% [Phys. Rev. C 72, 055502]

The JUNO physics program

Neutrino source	Expected signal
Reactor	45 evts / day
Supernova burst	10^4 evts at 10 kpc
Diffuse supernova background	2-4 evts/ year
Sun ^{8}B (^{7}Be)	16 (490) / day
Cosmic rays	100+ / year
Earth crust & mantle	400 / year

Energy Region

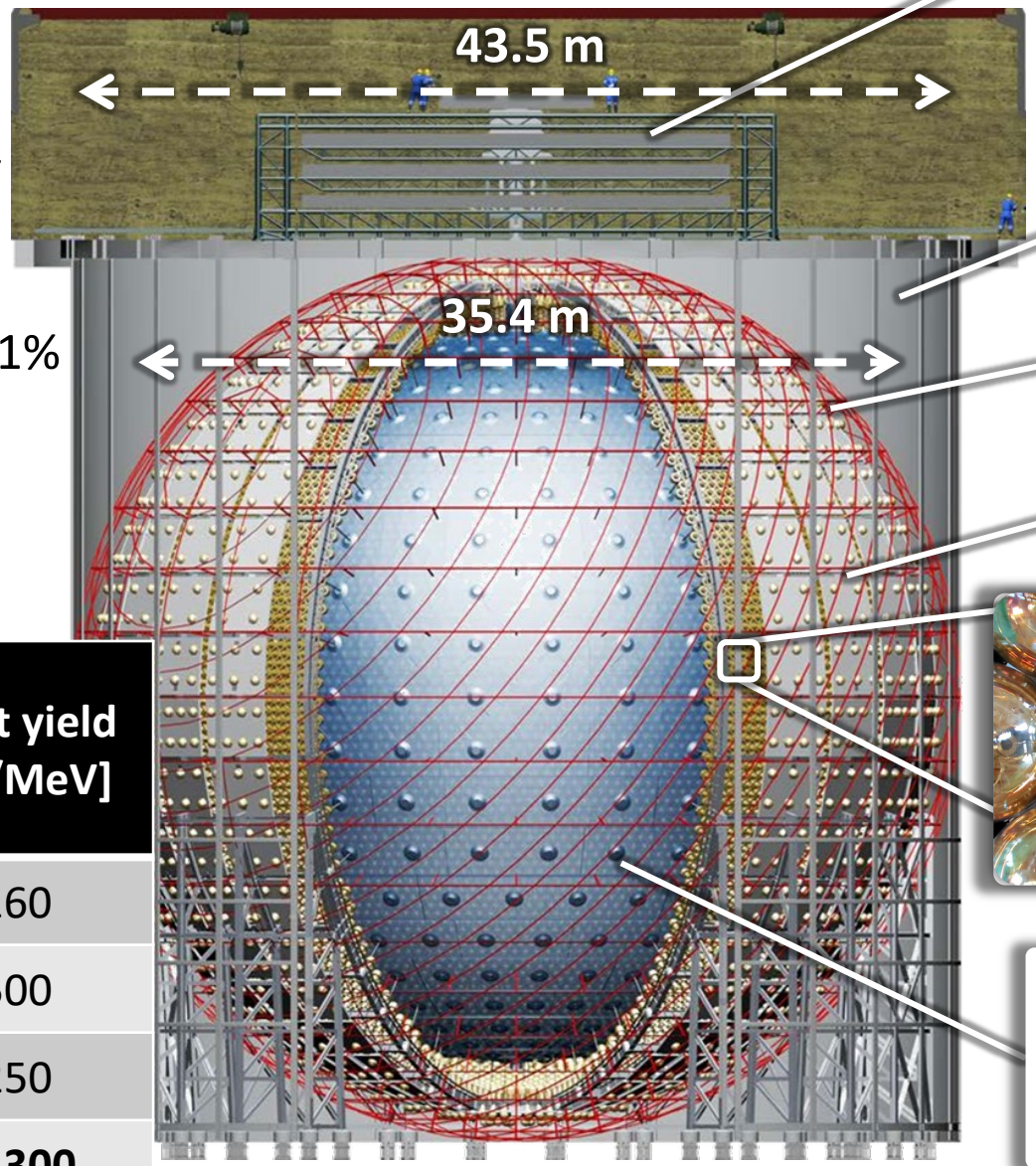


The JUNO detector

Main requirements:

- <3% energy resolution @ 1 MeV
- energy-scale systematics below 1%
- high statistics

	Target mass [kton]	Energy resolution	Light yield [PE/MeV]
Daya Bay	0.02	8%/√E	160
Borexino	0.3	5%/√E	500
KamLAND	1	6%/√E	250
JUNO	**20**	**3%/√E**	**>1300**

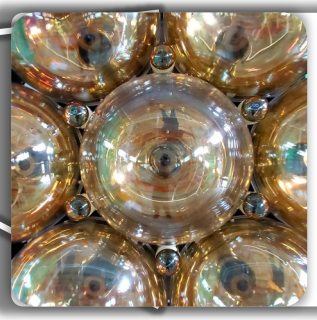


Top tracker and calibration house

Water pool

Earth magnetic field compensation coils

Veto Large-PMTs



PMTs:
17612 20" Large-PMT
25600 3" Small-PMT
photocoverage > 75%

Acrylic sphere with 20 kton of liquid scintillator (linear alkylbenzene)