Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ
DEGLI STUDI
DI PADOVA

Investigating Neutrino Oscillations with Reactor Antineutrinos in JUNO

XX International Workshop on Neutrino Telescopes

Andrea Serafini
on behalf of the JUNO collaboration

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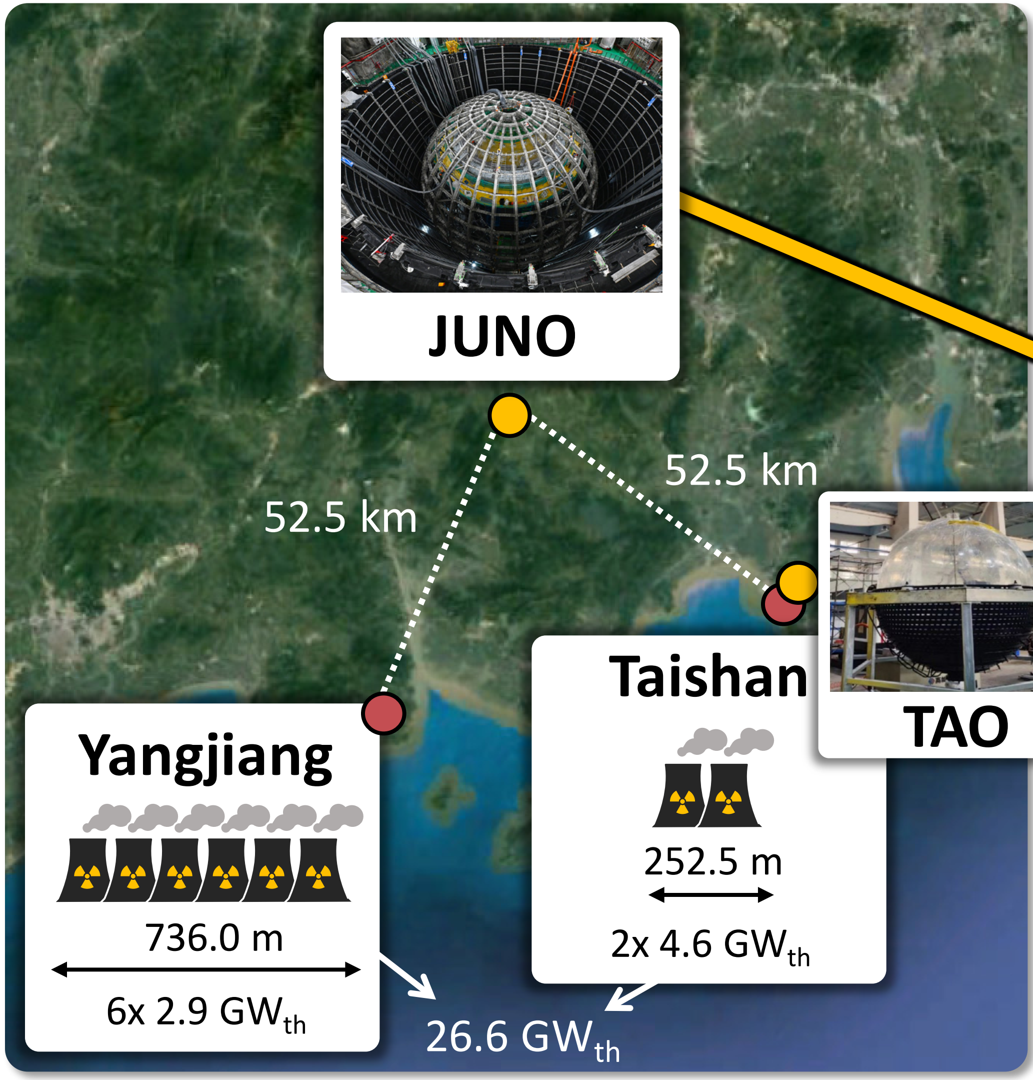
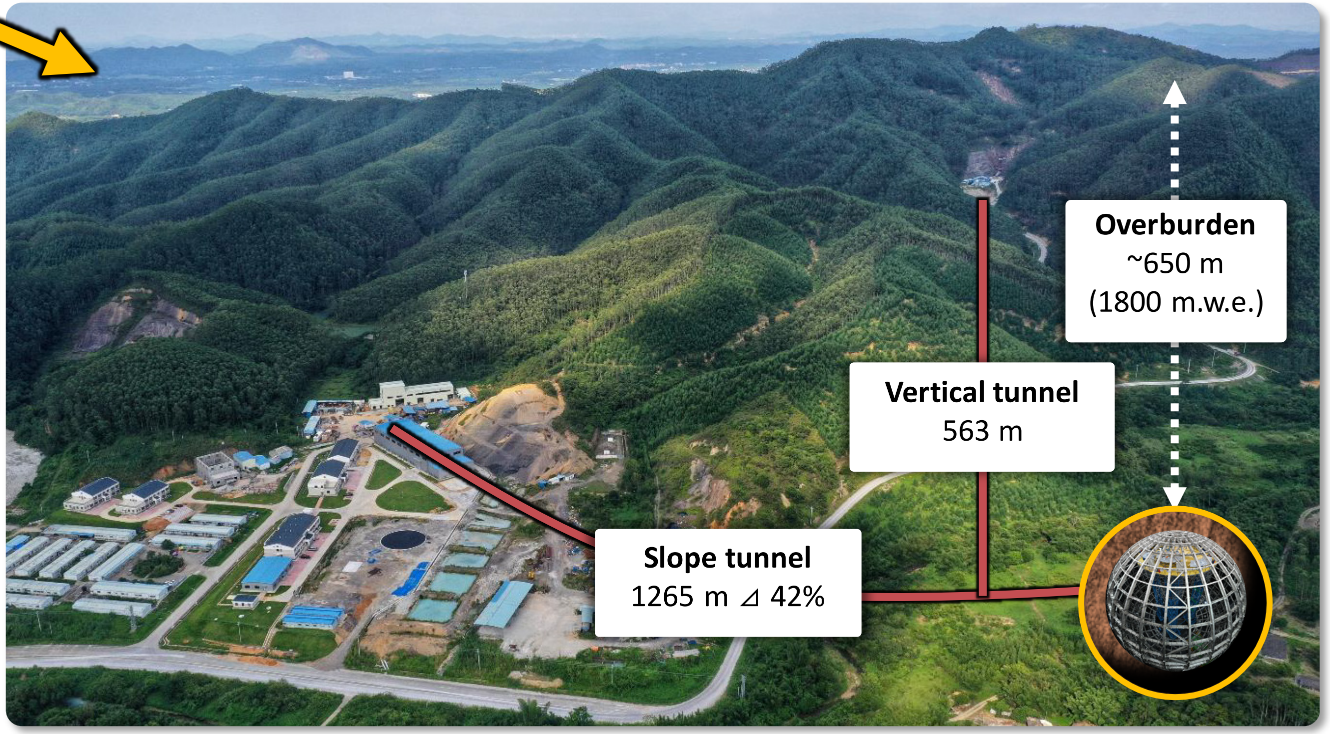
The Jiangmen Underground Neutrino Observatory



JUNO is a **20 kton** multi-purpose underground **liquid scintillator** detector currently under construction.

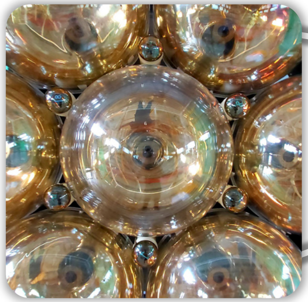
It sits at a baseline of about **52.5 km** from eight **nuclear reactors** in the Guangdong Province of South China.



The JUNO detector

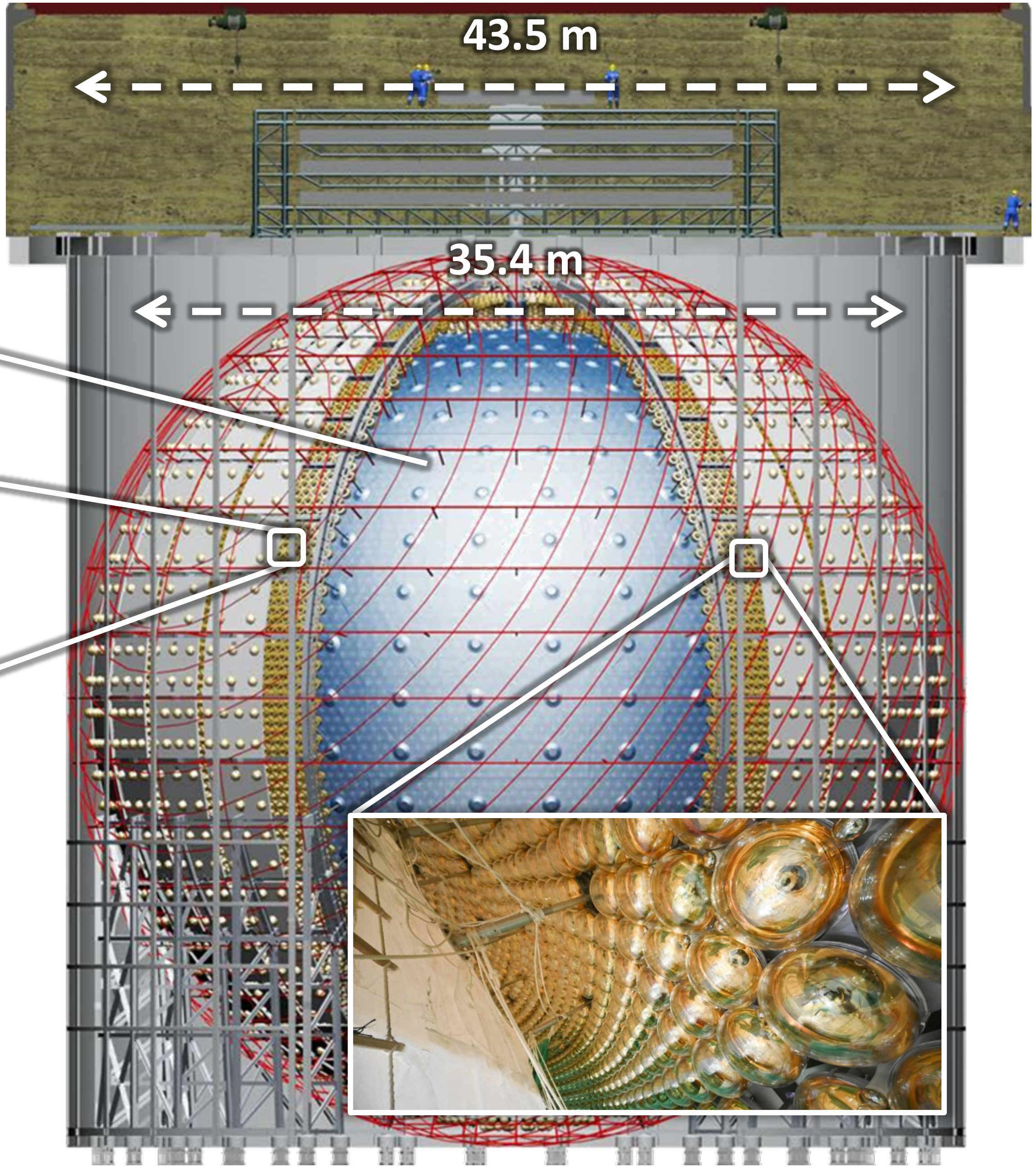
Main requirements:

- **high statistics**
  → 20 kton of liquid scintillator acrylic sphere
- **<3% energy resolution @ 1 MeV**
  → photocoverage ~78%
- **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**	**~1600**

[Prog. Part. Nucl. Phys. 2021.103927]



The JUNO detection process

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

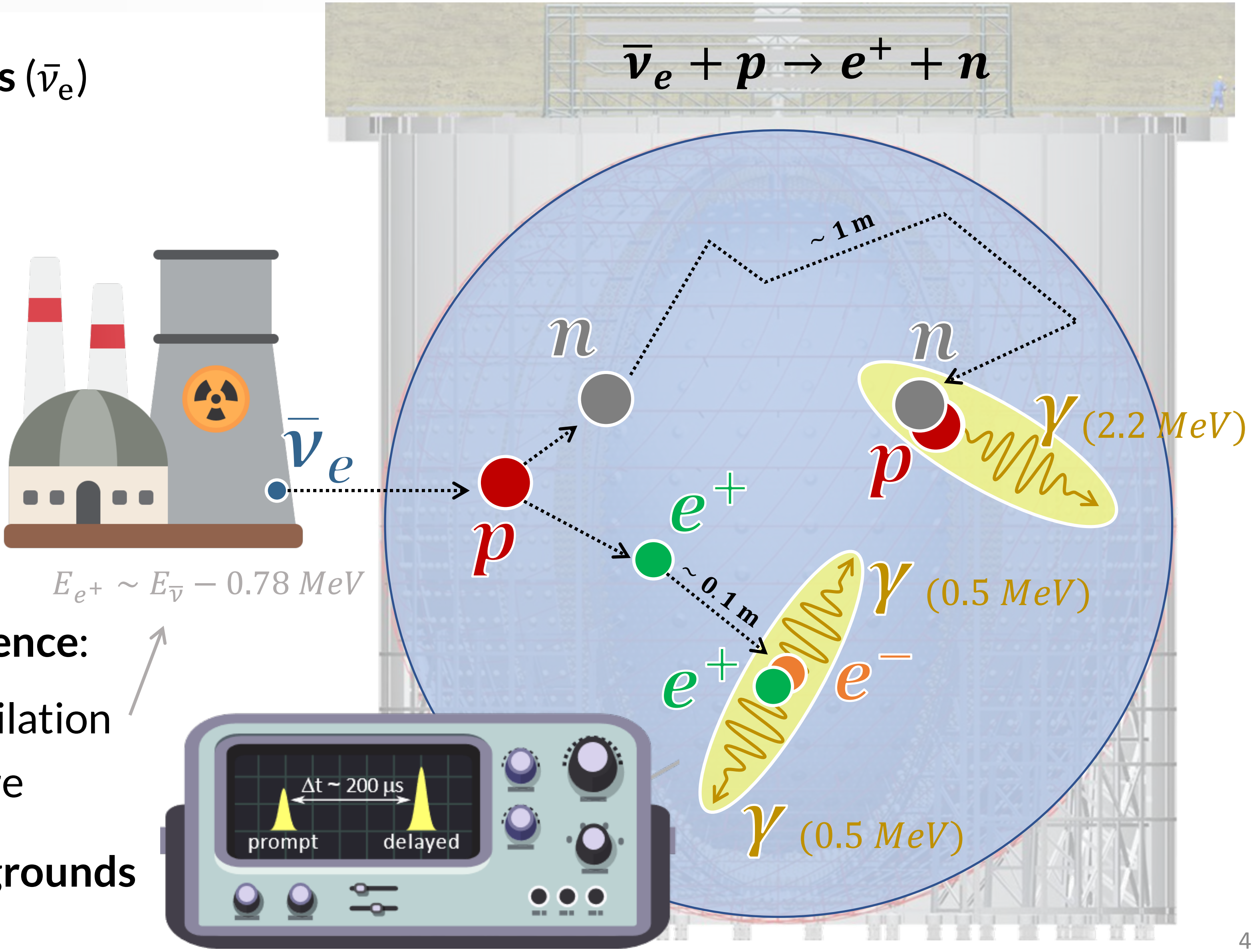
The **detection** is based on a charged current interaction named Inverse Beta Decay (**IBD**) on protons (p)

→ **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:

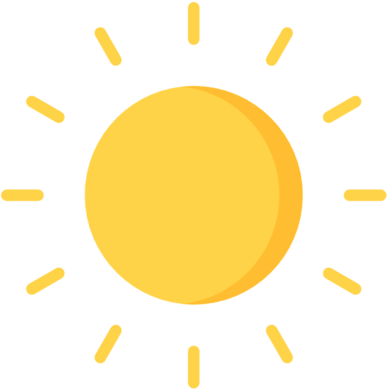
Reactor

~50/day

Atmosphere

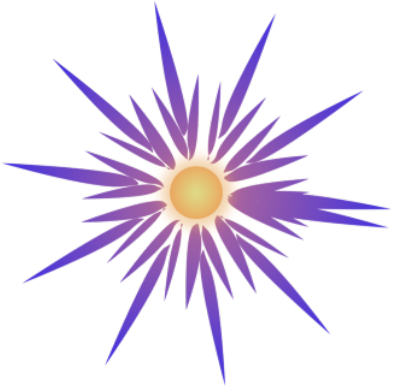
>100/year

Sun



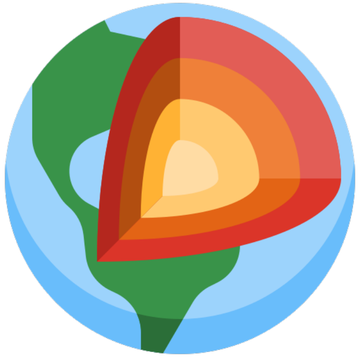
>100/day

Supernovae



~10^4/10 s @ 10kpc

Earth



~400/year

Neutrino oscillation properties

Neutrinos as a probe

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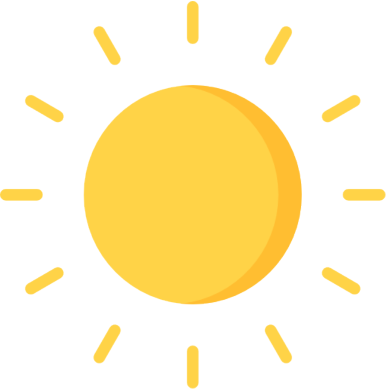

>100/day

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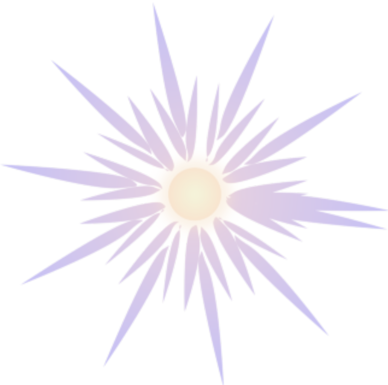

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Covered in this talk

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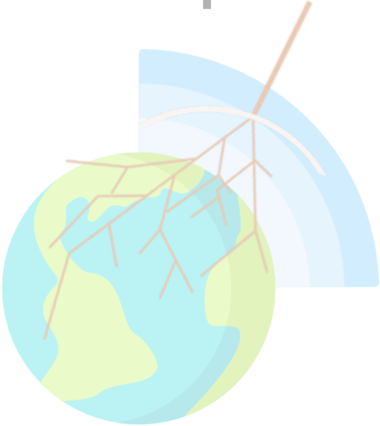
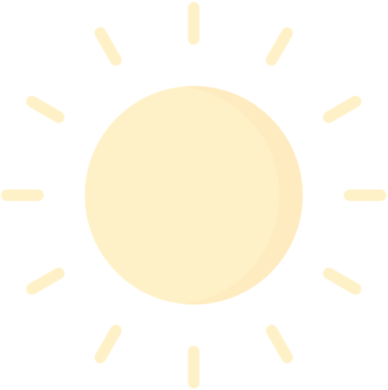


>100/year

Sun



>100/day

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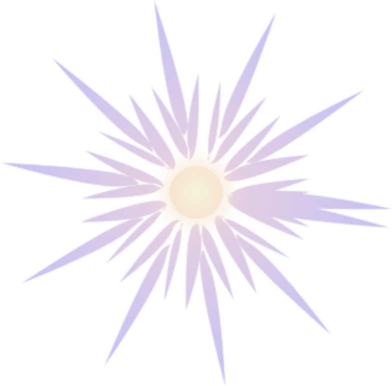

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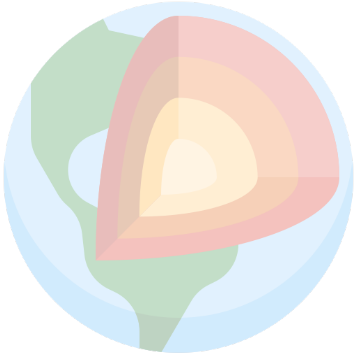


~400/year

Neutrino oscillation properties

Neutrinos as a probe

The rationale behind JUNO

Oscillation parameters

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

Let's write the $\bar{\nu}_e$ survival probability:

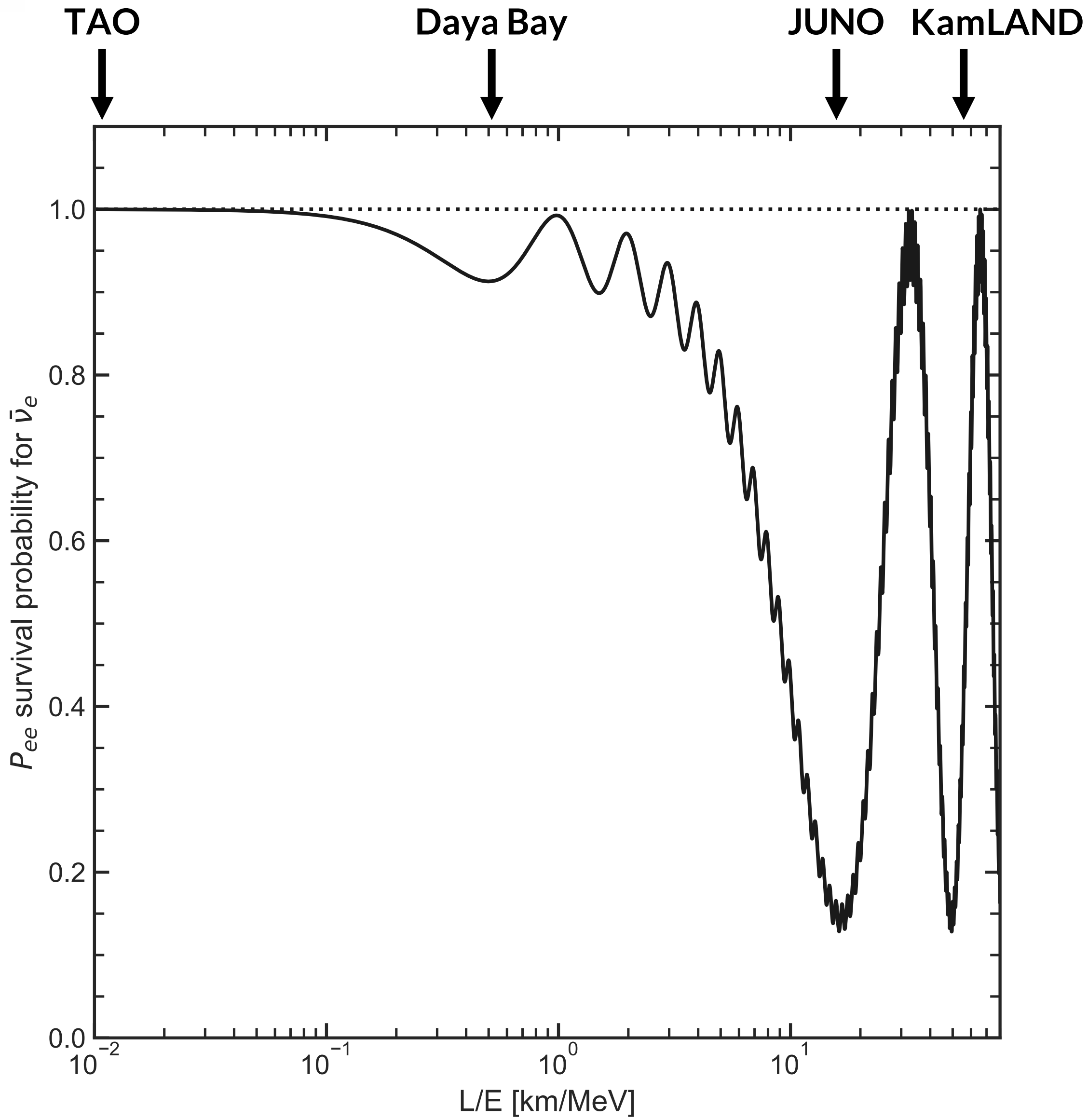
$$\boldsymbol{P_{ee} = 1 - P_{21} - P_{31} - P_{32}}$$

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

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

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

→ probability does **not depend on $\boldsymbol{\delta_{CP}}$ and $\boldsymbol{\theta_{23}}$**



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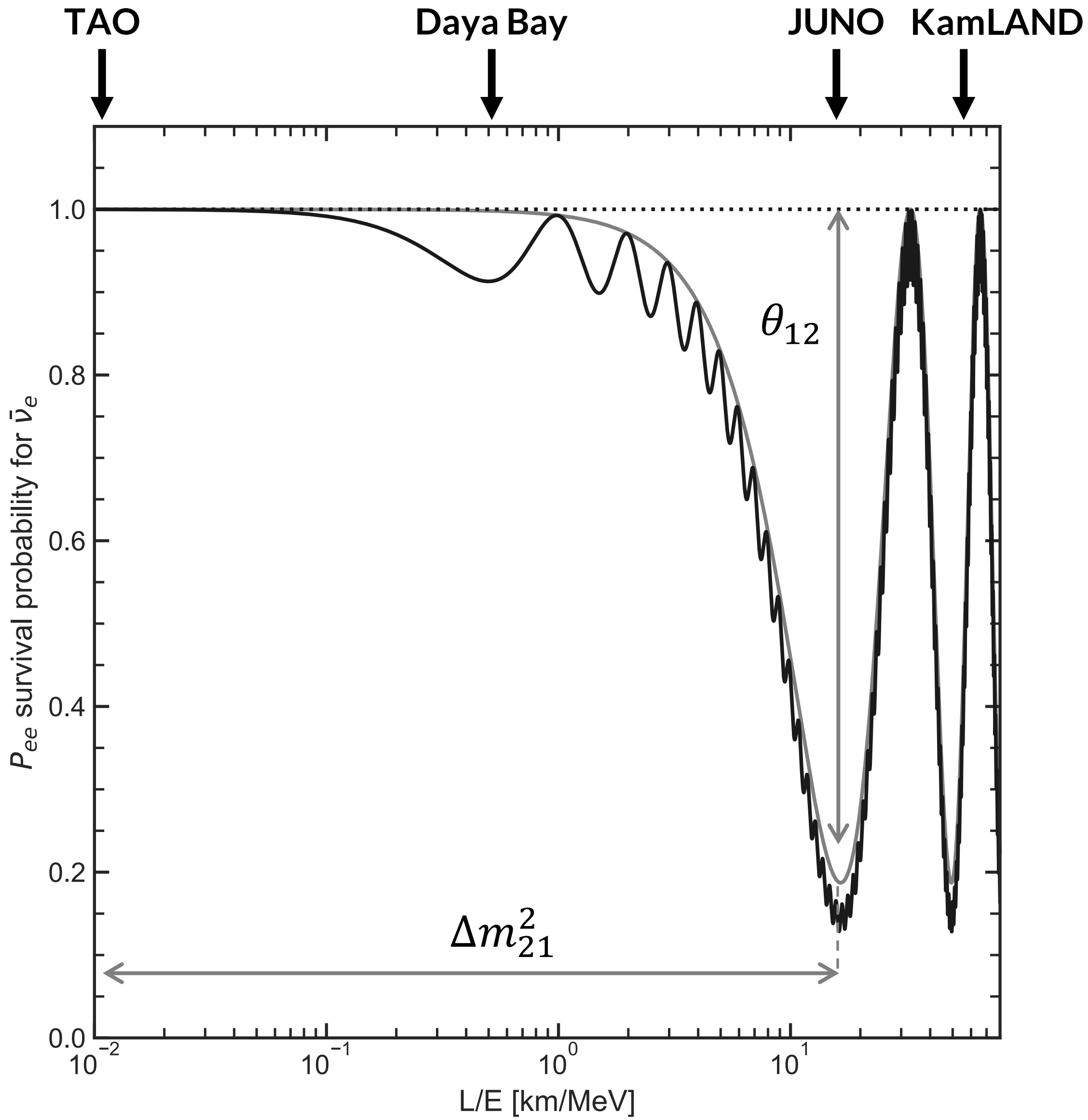

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FAST

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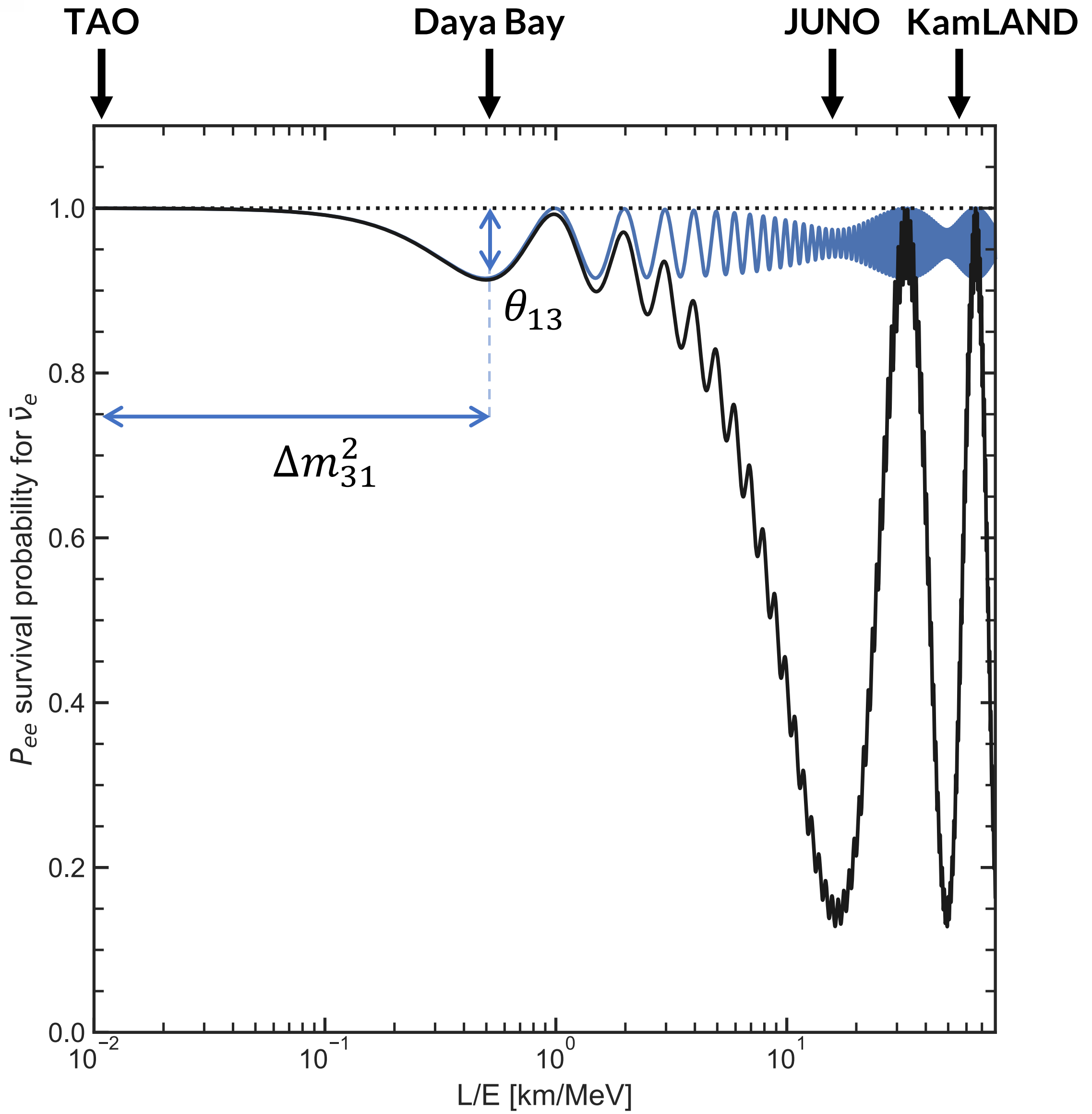

The rationale behind JUNO

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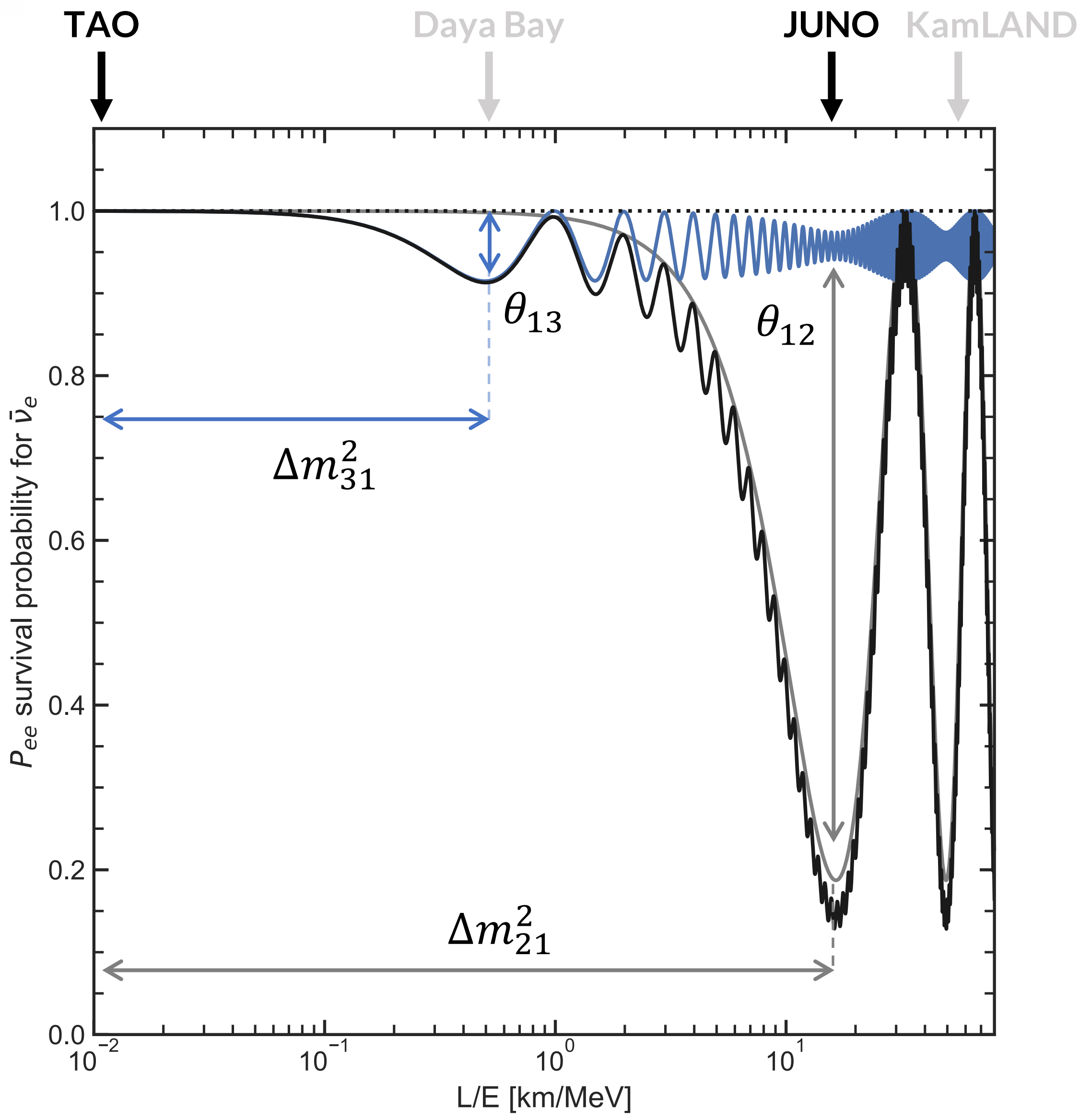
→ **JUNO** is **sensitive to $\boldsymbol{\Delta m^2_{21}}$, $\boldsymbol{\theta_{12}}$, $\boldsymbol{\Delta m^2_{31}}$** and $\boldsymbol{\theta_{13}}$



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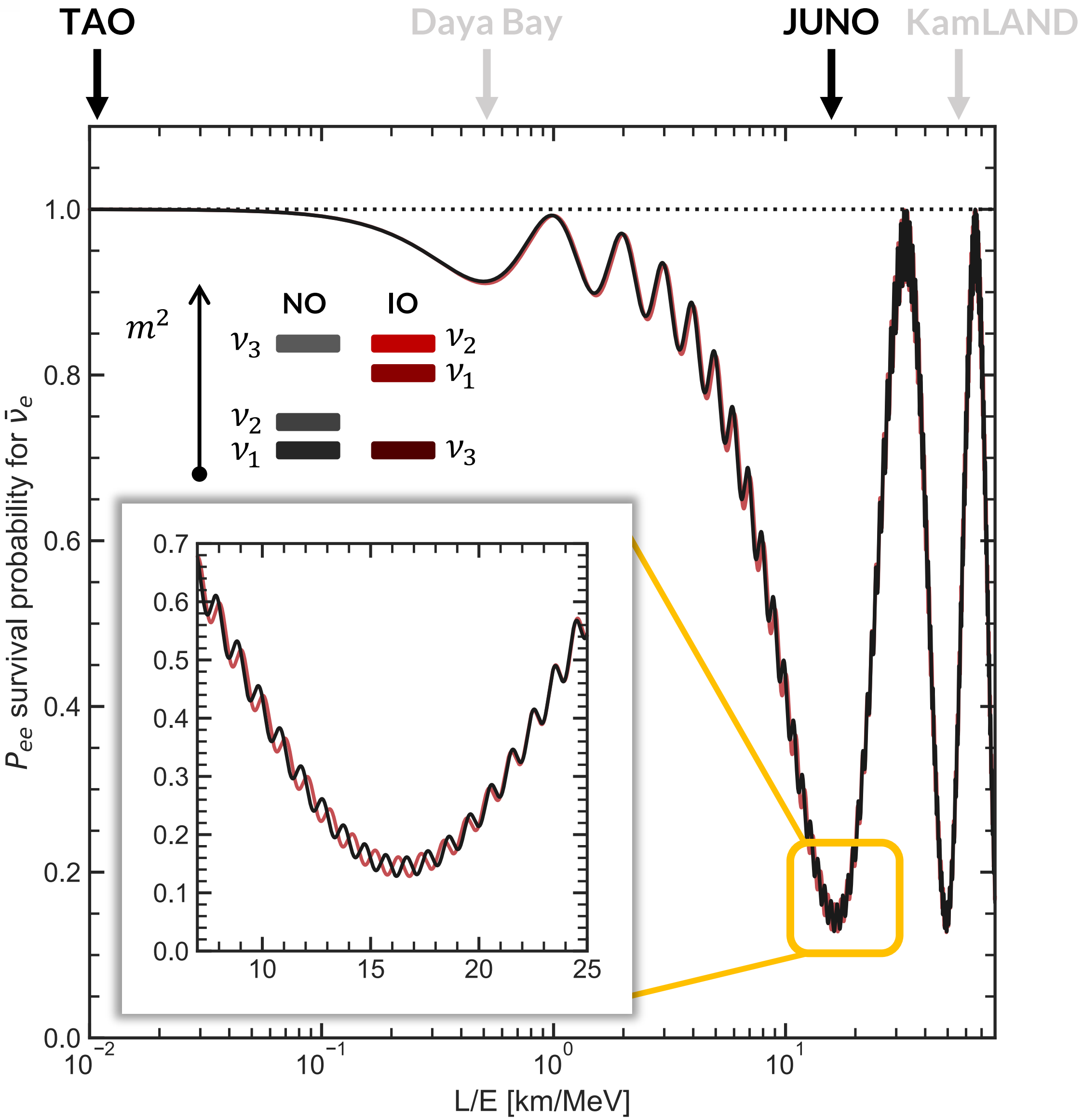
Neutrino Mass Ordering (NMO)

NMO sensitivity manifests as an energy dependent phase

→ **JUNO** sits at the **baseline maximizing NMO sensitivity**



Antineutrino oscillations in JUNO

JUNO rich spectrum contains a lot of information:

- **simultaneously** observe **fast** and **slow oscillations**
- **independently observe** $\boldsymbol{\Delta m^2_{21}}$, $\boldsymbol{\theta_{12}}$, $\boldsymbol{\Delta m^2_{31}}$ and $\boldsymbol{\theta_{13}}$
- **sensitive** to neutrino mass ordering (**NMO**)

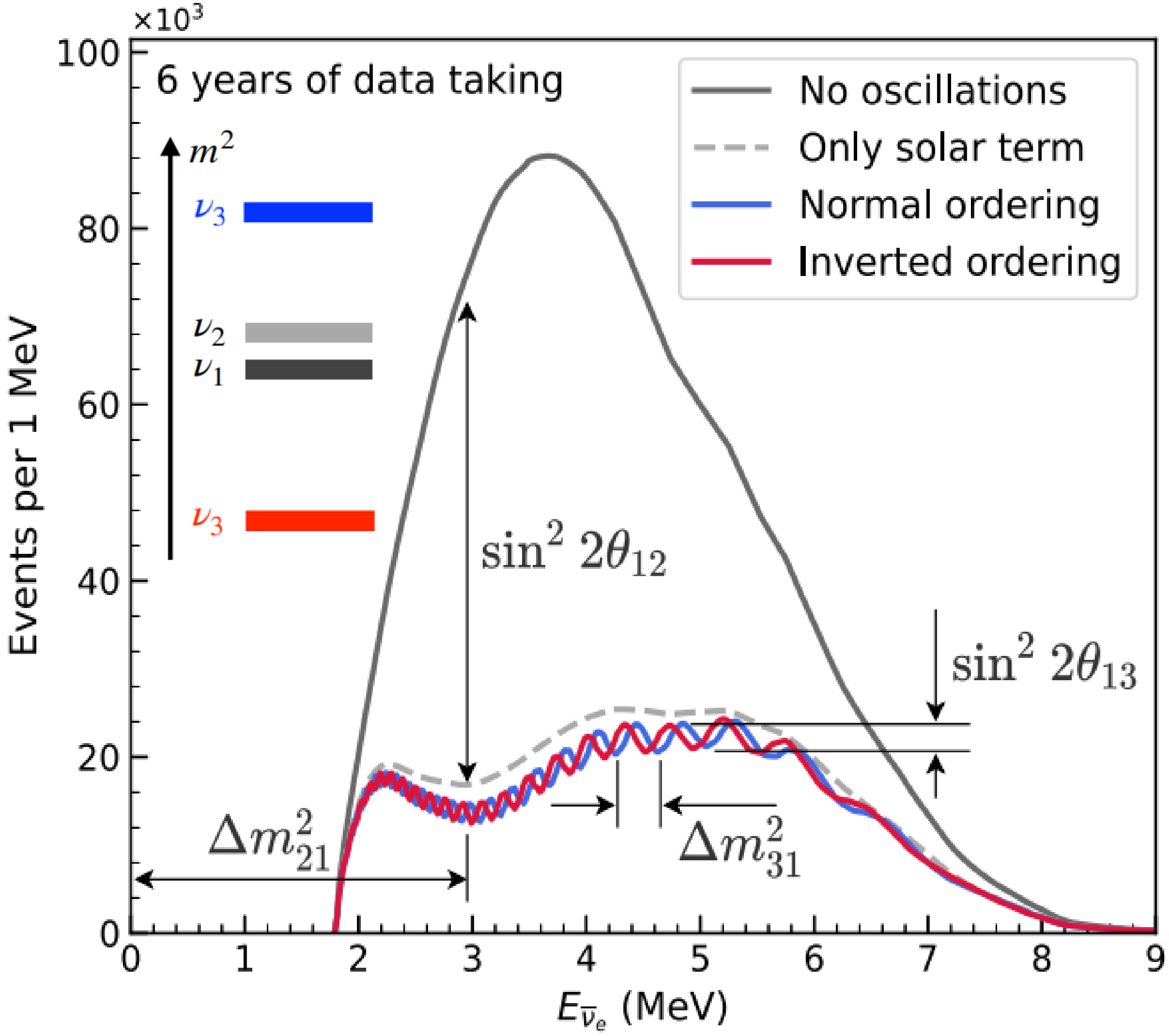
JUNO aims in 6 years at:

→ **determining NMO** @ >3σ

→ place **<1% precision** on $\Delta m^2_{21}, \theta_{12}, \Delta m^2_{31}$

Main systematics:

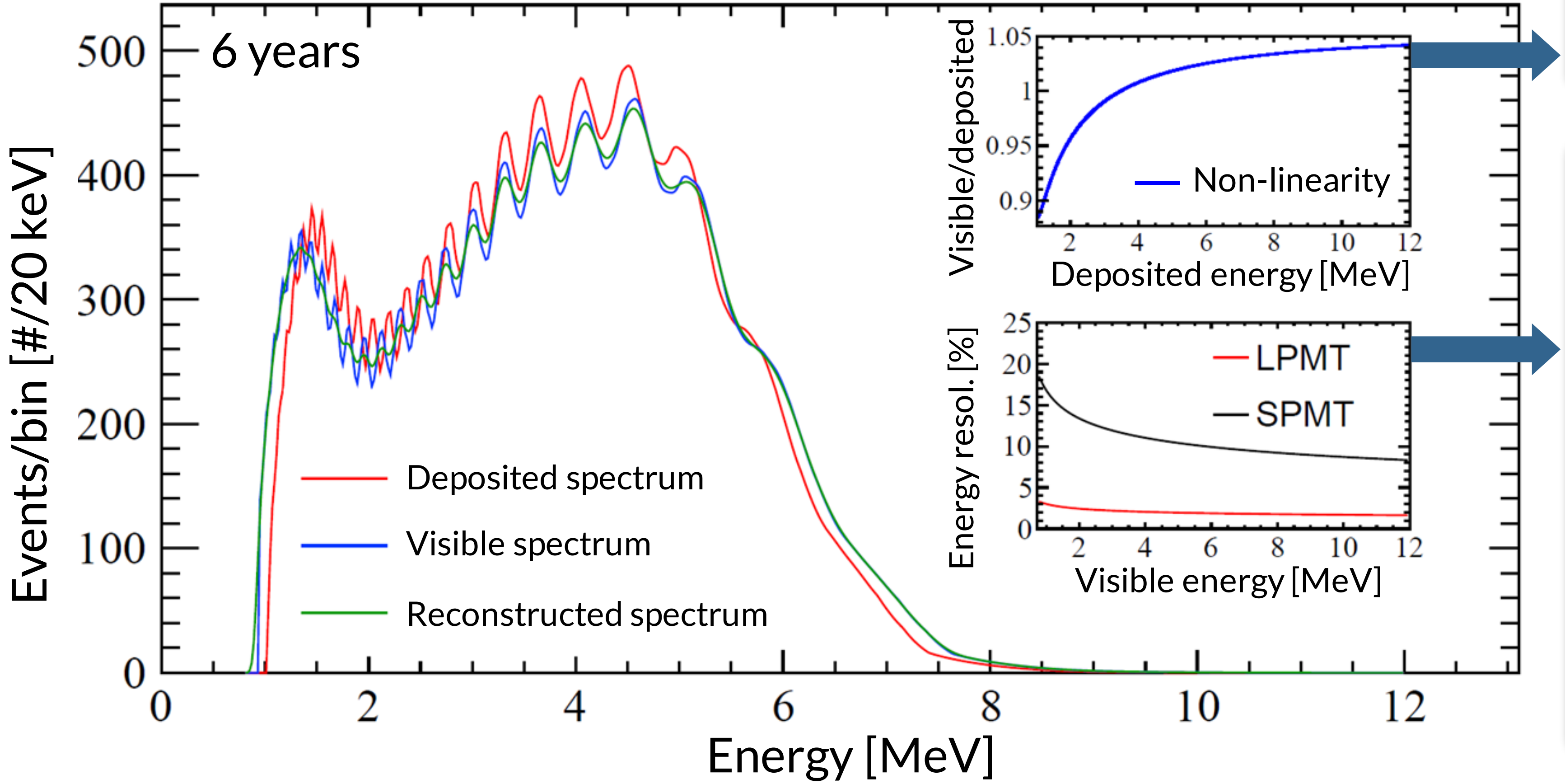
- Detector response
- Backgrounds
- Reference spectrum



Detector response: what JUNO actually sees

$$E_\nu \xrightarrow{\text{interaction}} E_{dep} \xrightarrow{\text{light emission}} E_{vis} \xrightarrow{\text{light detection}} E_{rec}$$

Antineutrino energy — **Deposited energy** — **Visible energy** — **Reconstructed energy**



Calibration campaigns

- **automated** multiple-**position** and multi-**source calibration** (link)
- **periodic calibration** campaigns
- **dual-calorimetry** system (link)

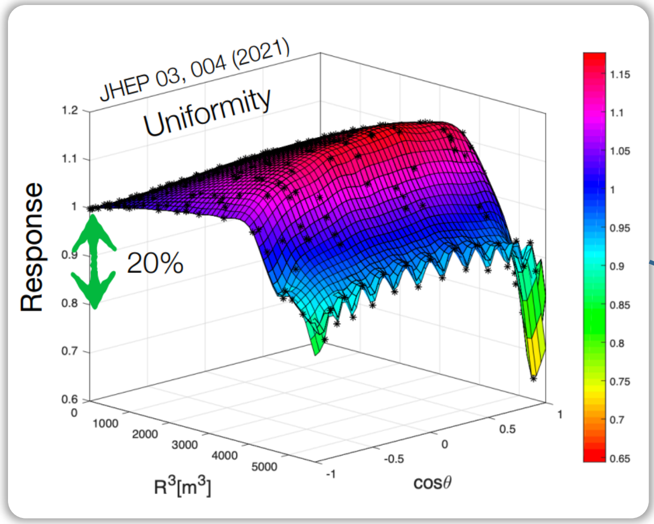
Energy resolution

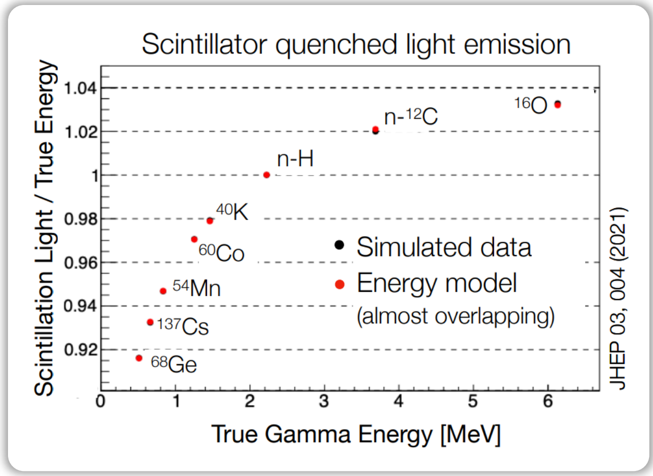
$$\frac{\sigma}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2}$$

a	**Stochastic term**: light yield (from source calibration)
b	Dominated by **non-uniformity** (from multi-source calibration)
c	PMT **dark noise**

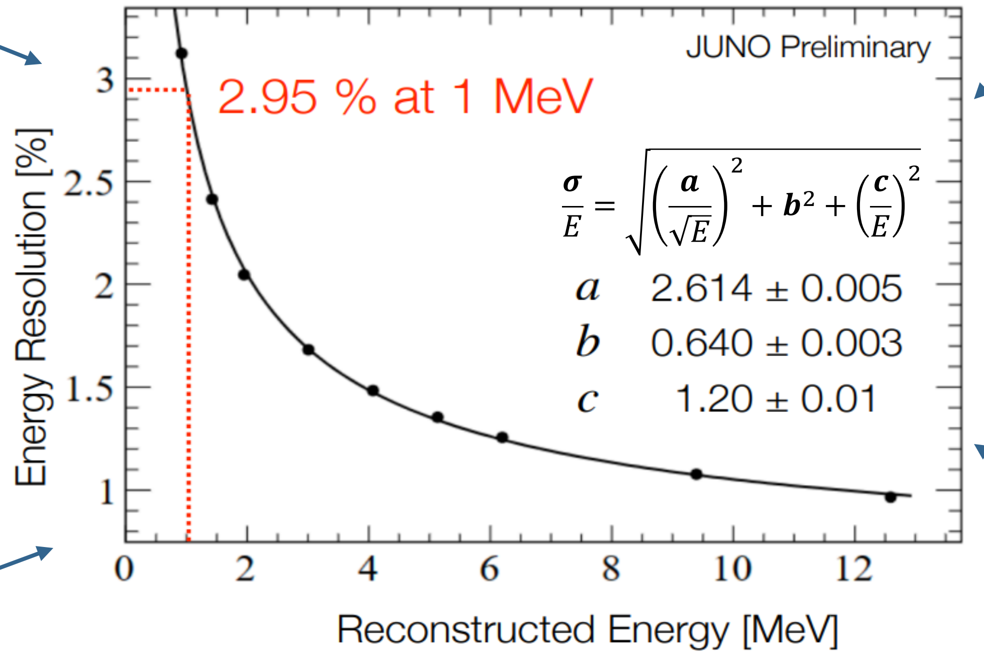
JUNO detector response: state of the art

Realistic MC simulation





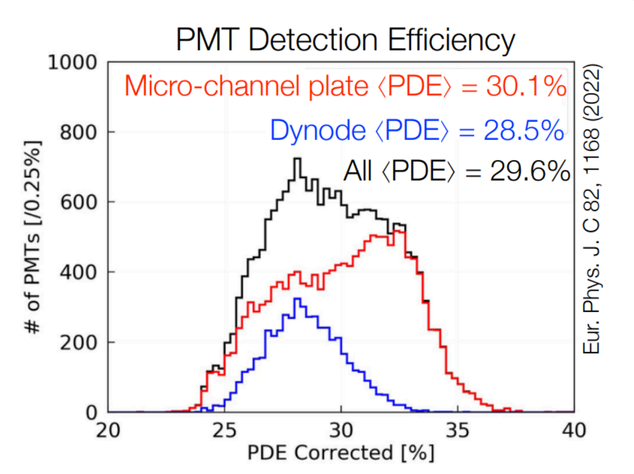
Updated values based on **commissioning data** and **realistic MC simulation**

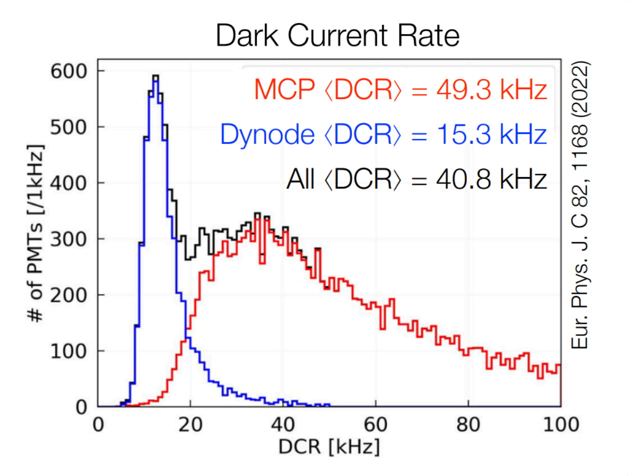


$$\frac{\sigma}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2}$$

a	2.614 ± 0.005
b	0.640 ± 0.003
c	1.20 ± 0.01

Measured data

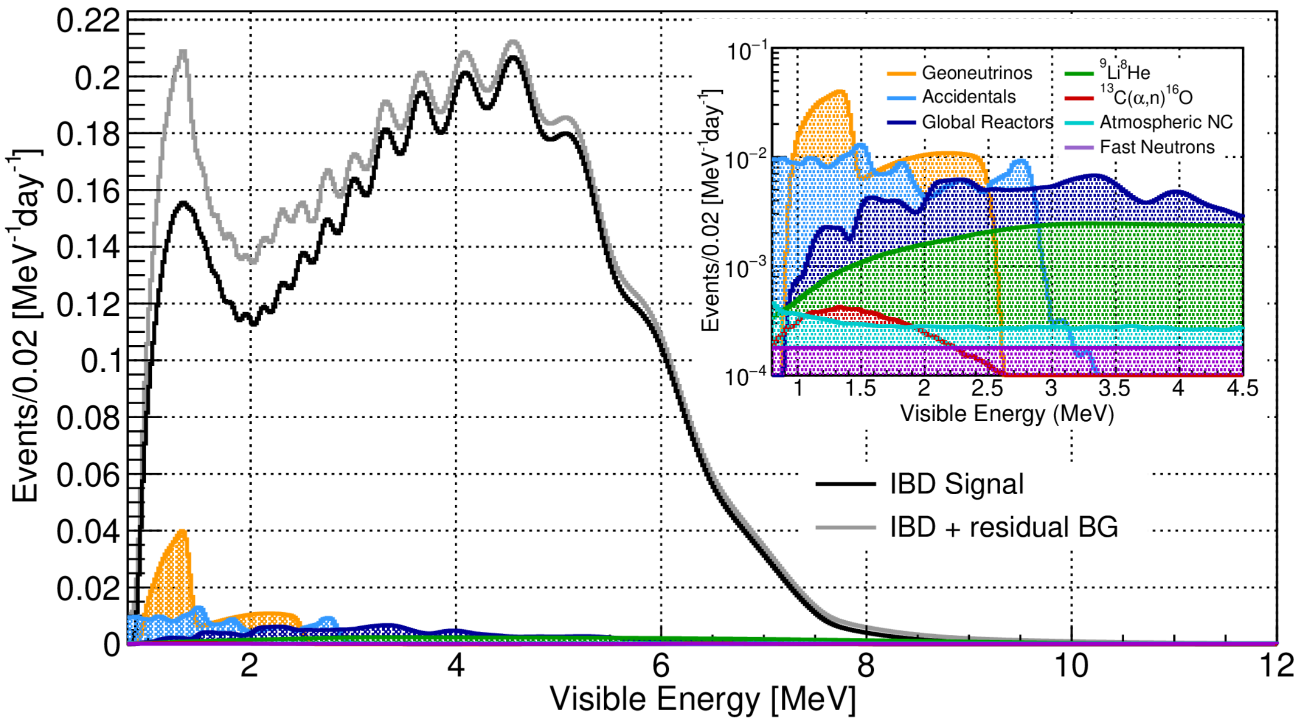




IBD backgrounds in JUNO

JUNO employs various **selection cuts** to retain **high efficiency** and assure **high purity** in the IBD signal:

- **Cosmogenic** backgrounds → **muon veto**
- **Accidental coincidences → fiducial volume + IBD cuts**
- **Irreducible** backgrounds → **negligible** (~1/20 of signal)



IBD selection cuts	Efficiency [%]	IBD rate [day^{-1}]
All IBDs	**100.0**	**57.4**
Fiducial volume	91.5	52.5
IBD selection	98.1	51.1
Energy range	99.8	-
Time correlation ($\Delta T_{p\text{-}d}$)	99.0	-
Spatial correlation ($\Delta R_{p\text{-}d}$)	99.2	-
Muon veto (Time+spatial)	91.6	47.1
Combined selection	**82.2**	**47.1**

Residual backgrounds	Rate [day^{-1}]	Rate unc. [%]	Shape unc. [%]
Geoneutrinos	1.2	30	5
World reactors	1.0	2	5
Accidentals	0.8	1	negligible
^{9}Li/^{8}He	0.8	20	10
Atmospheric neutrinos	0.16	50	50
Fast neutrons	0.1	100	20
^{13}C(α,n)^{16}O	0.05	50	50
Total background	**4.11**	**-**	**-**

TAO: a reference spectrum for JUNO

Accurate and **precise reference spectrum → boost** JUNO **precision** in **parameters** and **NMO**

- Conversion and ab-initio **reactor** spectrum **models** affected by **large uncertainties**
- **Models** and **data** (e.g. Daya Bay) **inconsistent**, current data has **low** energy **resolution**

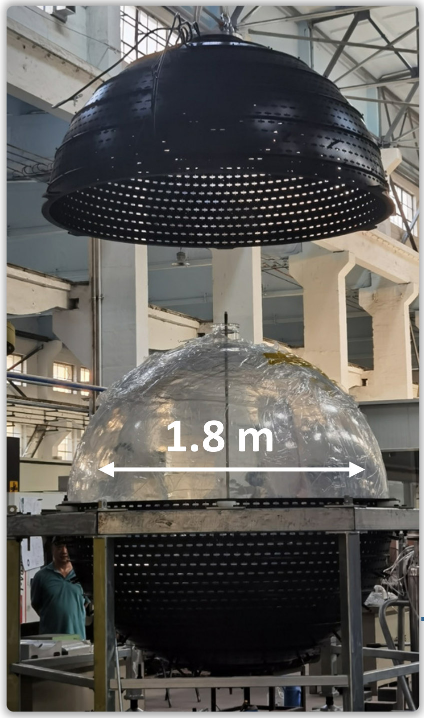
→ **Taishan Antineutrino Observatory** (TAO)

~30 m

Taishan core

TAO main features:

- **2.8 ton** of LS with Gd
- ~**10 m^2 (94%)** of **SiPM**
- working at **-50° C**
- **<2%** / $\sqrt{E\ [MeV]}$
- ~**4000 IBD/day**



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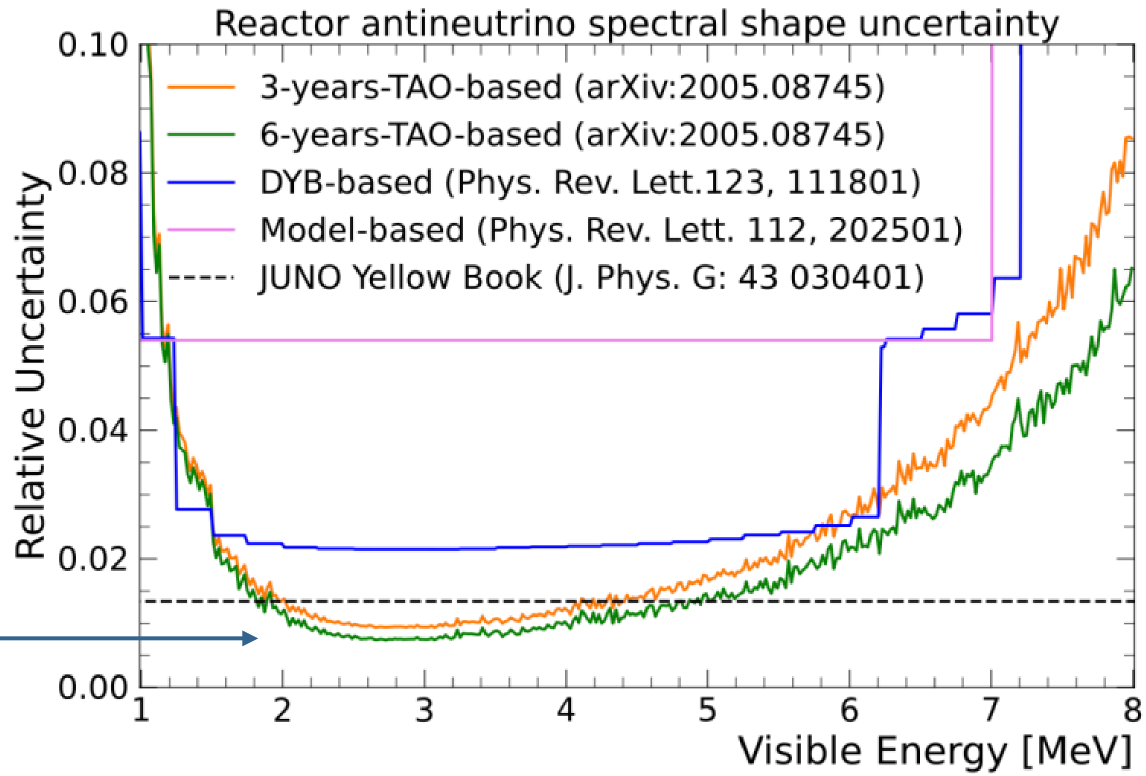
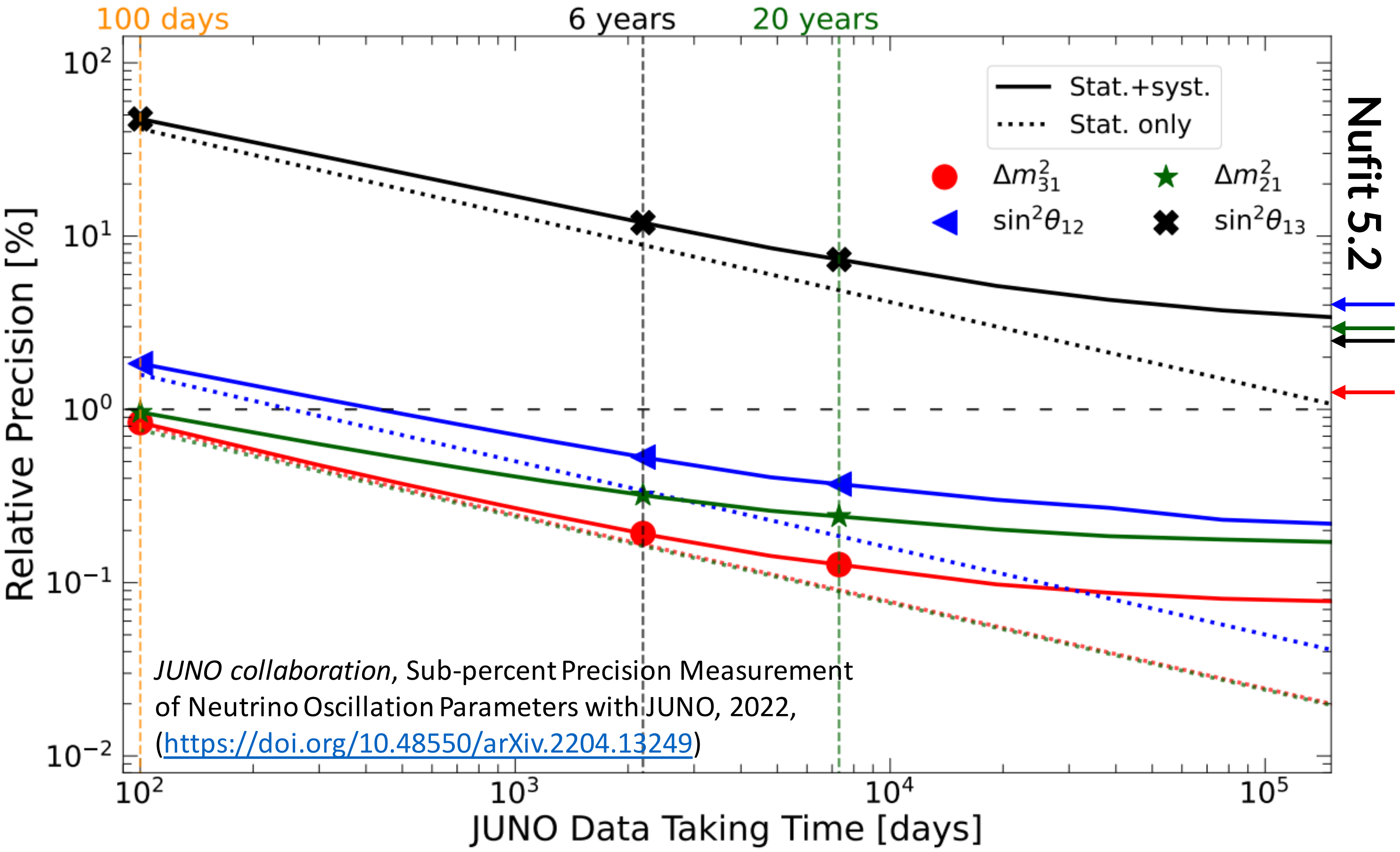


Lower uncertainty

Subpercent precision on oscillation parameters



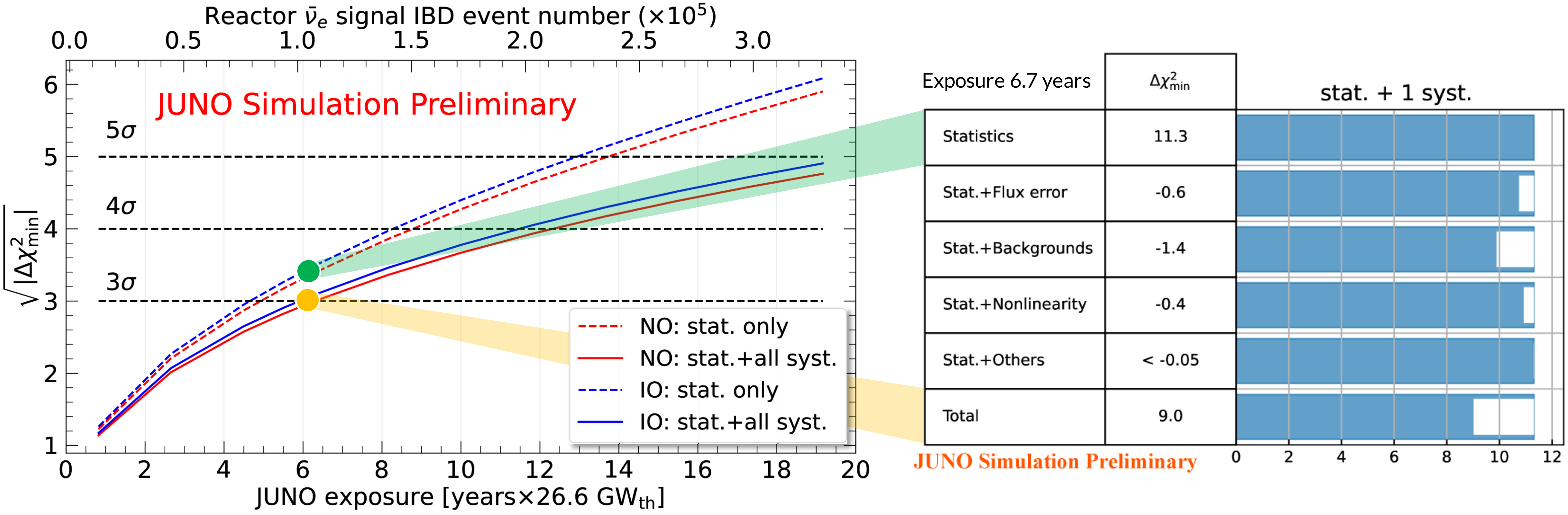
JUNO collaboration, Sub-percent Precision Measurement of Neutrino Oscillation Parameters with JUNO, 2022, (https://doi.org/10.48550/arXiv.2204.13249)

- In **<2 years** $\theta_{12}, \Delta m^2_{21}, \Delta m^2_{31}$ precision → **unprecedented <1%** level
- **In 6 years** $\theta_{12}, \Delta m^2_{21}, \Delta m^2_{31}$ precision → **0.5%, 0.3%** and **0.2%**

	PDG 2020	Nufit 5.2	JUNO 6 years
$\sin^2\theta_{13}$	3.2%	2.6%	12%
$\sin^2\theta_{12}$	4.2%	4.0%	**0.5%**
Δm^2_{21}	2.4%	2.8%	**0.3%**
Δm^2_{31}	1.4%	1.1%	**0.2%**

Determination of Neutrino Mass Ordering (NMO)

JUNO **NMO sensitivity: 3σ** (**reactors only**) in **6.7 y** (with 26.6 GW_{th})

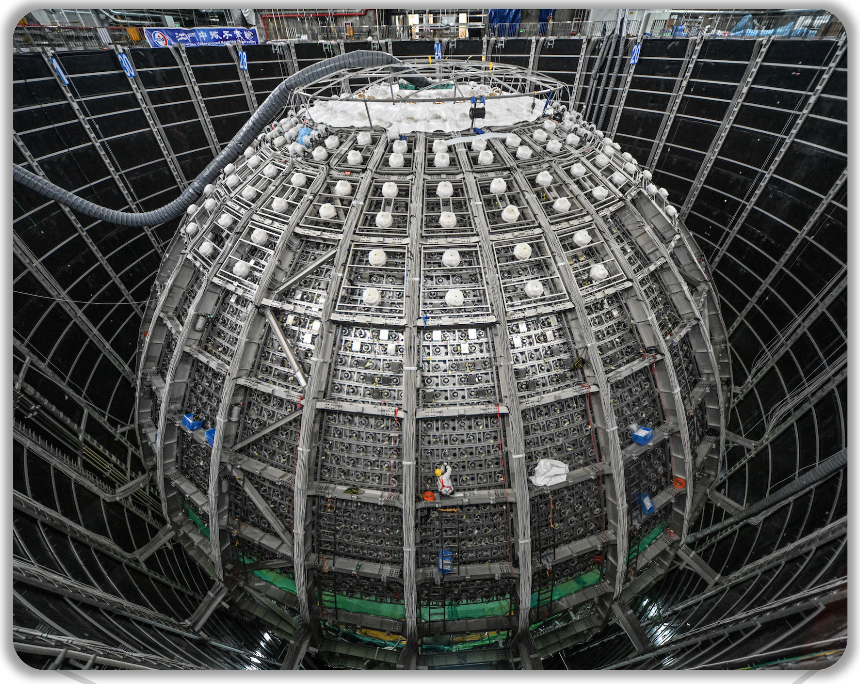


Exposure 6.7 years	$\Delta\chi^2_{min}$
Statistics	11.3
Stat.+Flux error	-0.6
Stat.+Backgrounds	-1.4
Stat.+Nonlinearity	-0.4
Stat.+Others	< -0.05
Total	9.0

JUNO Simulation Preliminary

- Combination **reactor + atmospheric** neutrino analysis **ongoing** → further **improve** NMO sensitivity
- Combination with **external Δm^2_{31}** long baseline experiments constraint → **enhanced NMO sensitivity**

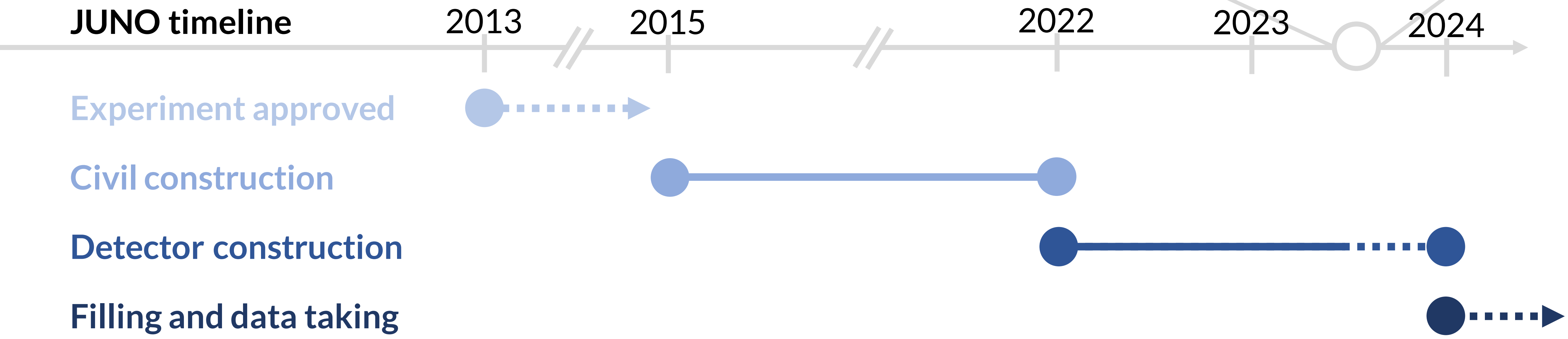
Final remarks



JUNO will inaugurate a **high precision** era in the neutrino oscillation field. In ~6 years:

→ **<1% precision** on $\theta_{12}, \Delta m^2_{21}$ and Δm^2_{31}

→ **neutrino mass ordering** at 3σ with reactor neutrinos only (completely **independent** from $\boldsymbol{\delta_{CP}}$ and $\boldsymbol{\theta_{23}}$)



JUNO timeline

Experiment approved

Civil construction

Detector construction

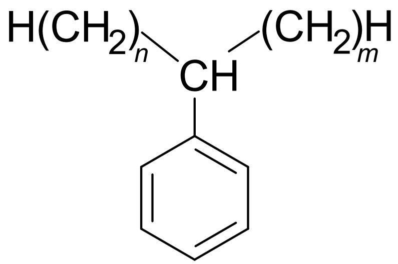
Filling and data taking

Back up

Detection channels in JUNO

Liquid scintillator:
Linear alkylbenzenes

C – 88%
H – 12%



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

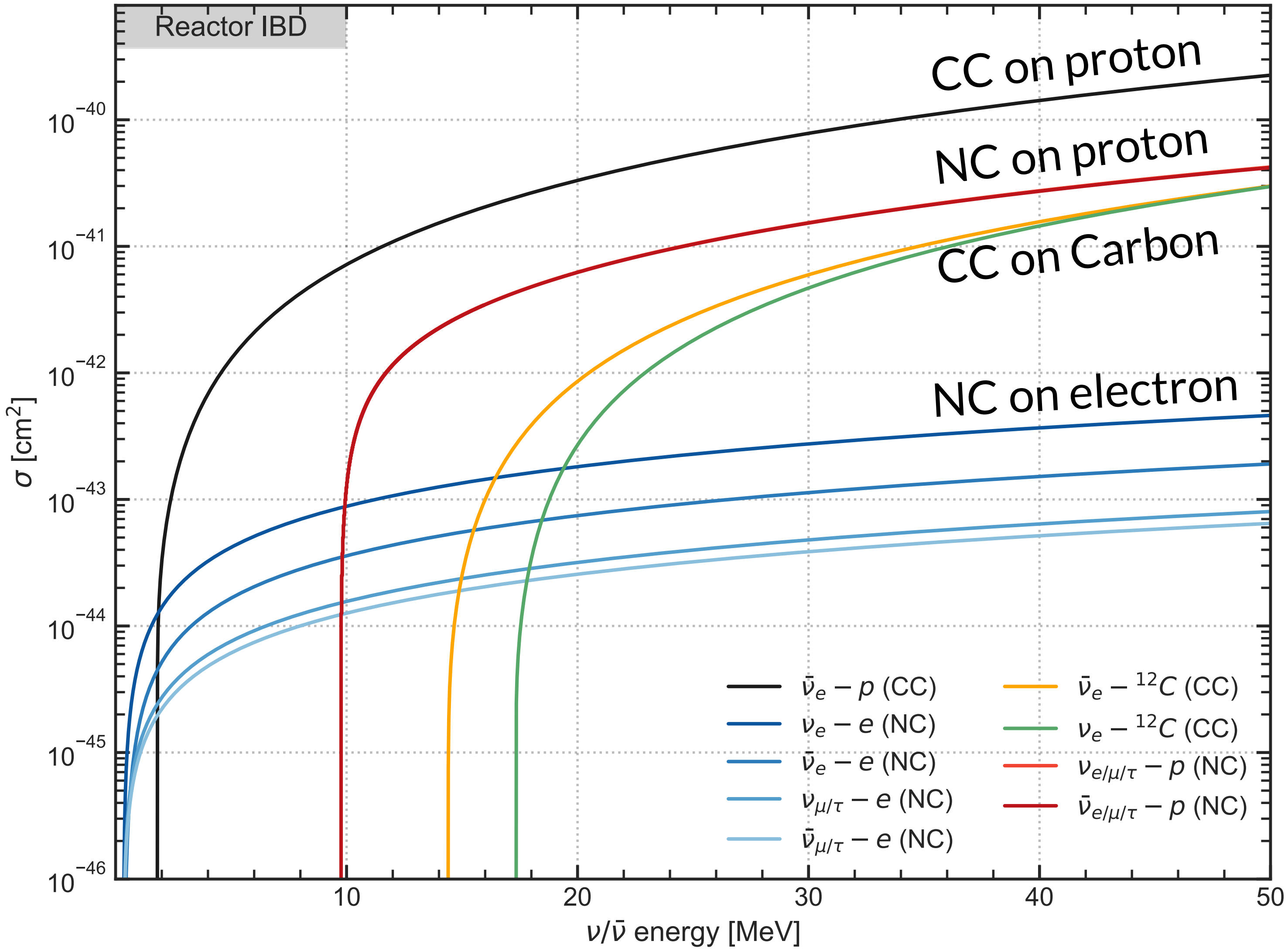
— $\nu + p \rightarrow \nu + p$

— $\nu + e \rightarrow \nu + e$

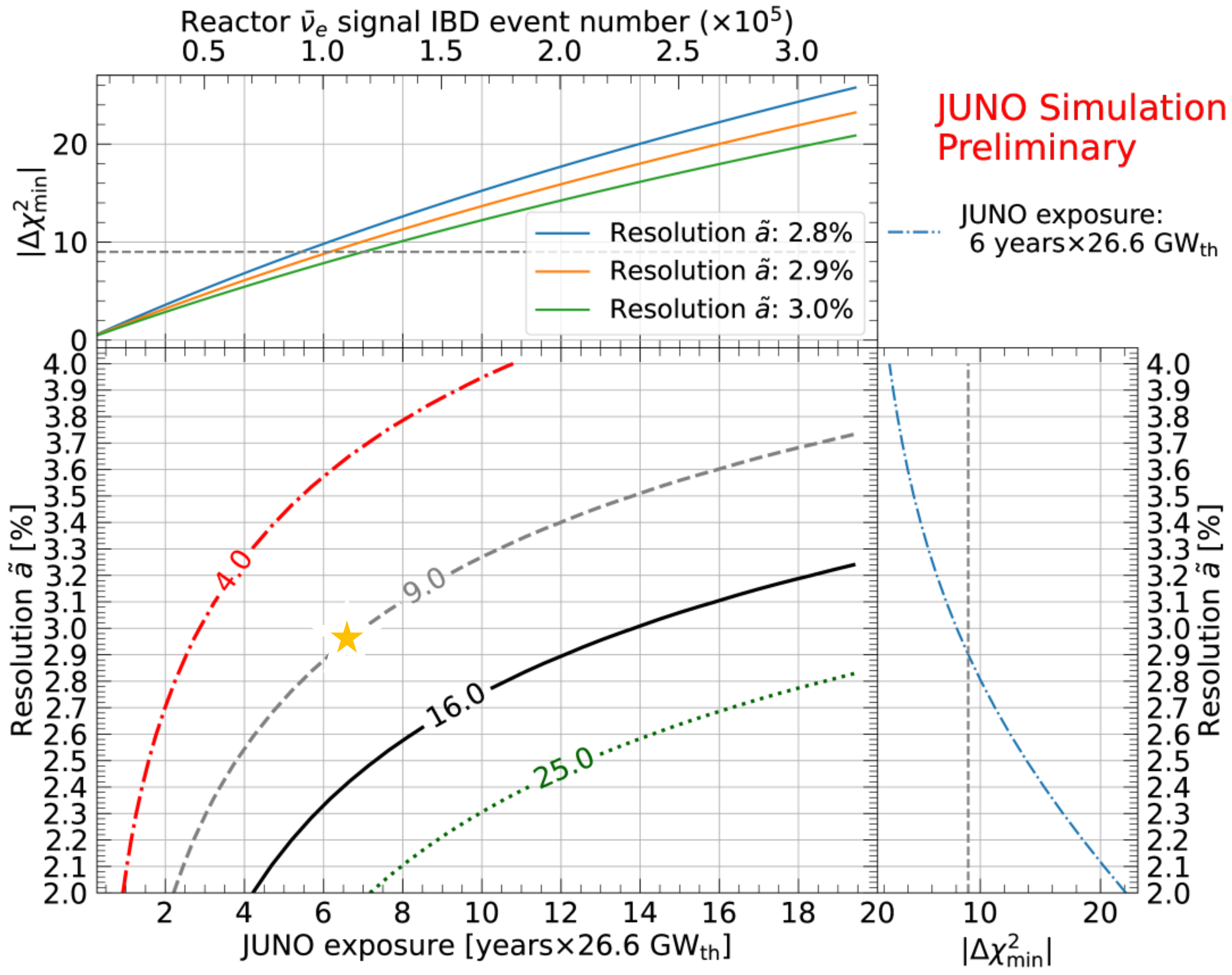
— $\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$

— $\bar{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B$

NC recoil threshold: 200 keV



Changes respect to JPG 43, 030401 (2016)

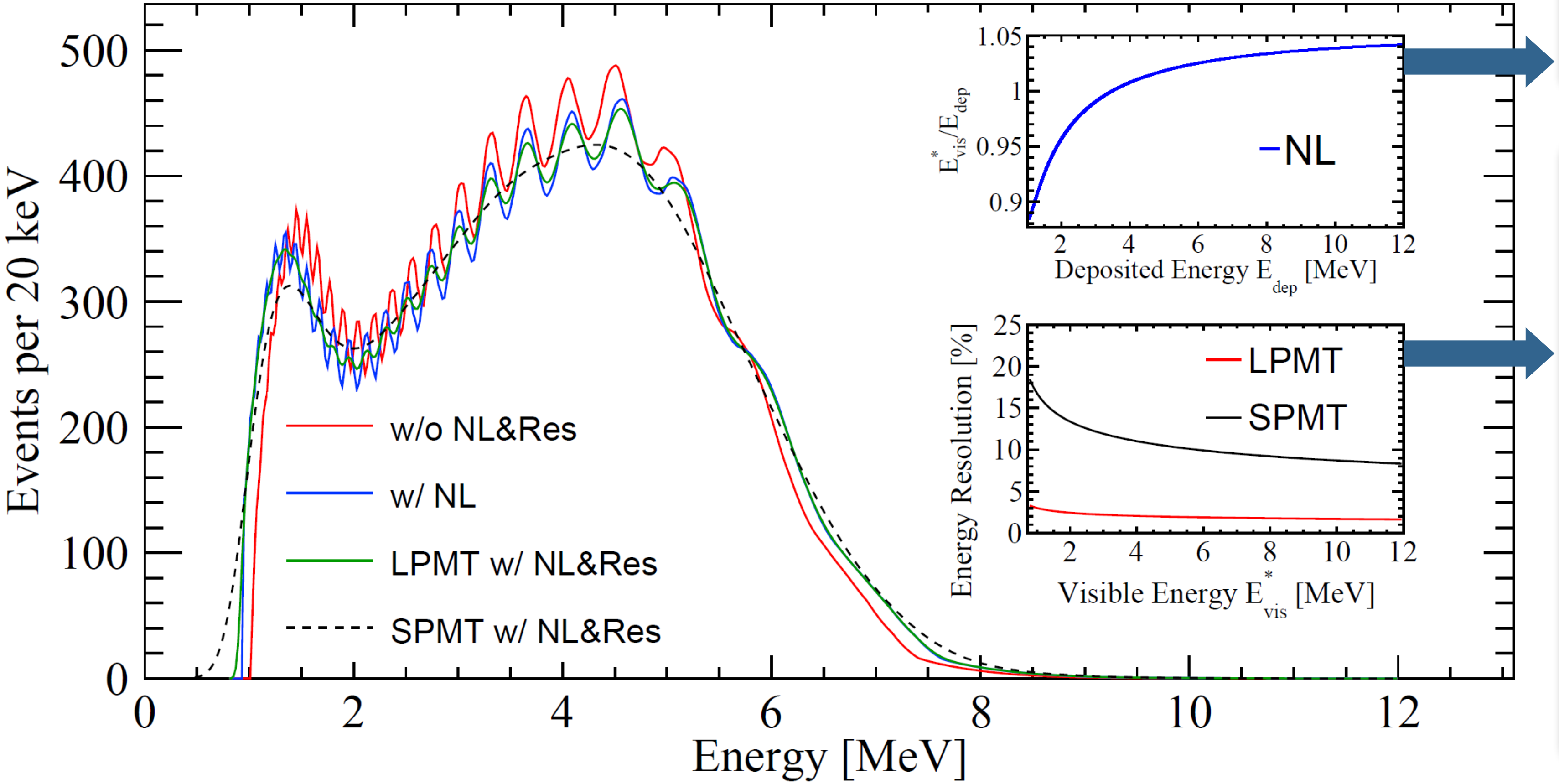


Changes	Design	Now	
Thermal power [$\mathrm{GW_{th}}$]	35.8	26.6	↓
Signal rate [$\mathrm{day^{-1}}$]	60	47.1	↓
Overburden [m]	~700	~650	↓
Muon flux in LS [Hz]	3 Hz	4 Hz	↓
Muon veto efficiency	83%	91.6%	↑
Background rate [$\mathrm{day^{-1}}$]	3.75	4.11	↓
Energy resolution @ 1 MeV	3%	2.95%	↑
Shape uncertainty	1%	JUNO+TAO	↑
3σ NMO exposure	**< 6 yrs**	**~6 yrs**	

Detector response: what JUNO actually sees

$$E_\nu \xrightarrow{\text{interaction}} E_{dep} \xrightarrow{\text{light emission}} E_{vis} \xrightarrow{\text{light detection}} E_{rec}$$

Antineutrino energy **Deposited energy** **Visible energy** **Reconstructed energy**



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$$\frac{\sigma}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2}$$

a	**Stochastic term**: light yield (from source calibration)
b	Dominated by **non-uniformity** (from multi-source calibration)
c	PMT **dark noise**

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:

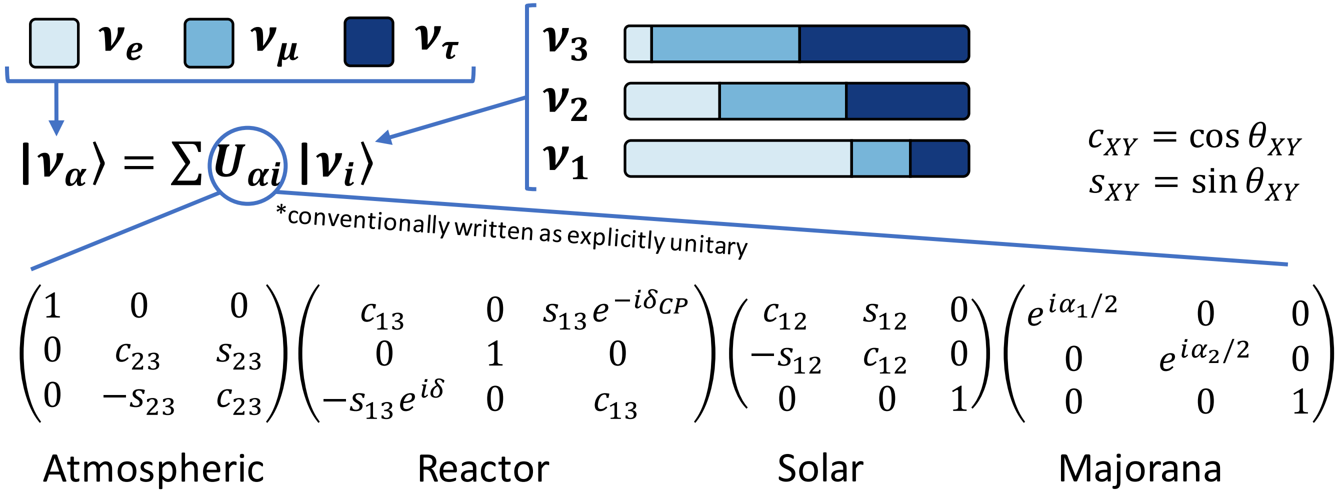
- 3 mixing angles ($\boldsymbol{\theta_{12}}, \boldsymbol{\theta_{13}}, \boldsymbol{\theta_{23}}$)
- 1 CP-violating phase ($\boldsymbol{\delta_{CP}}$)

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).

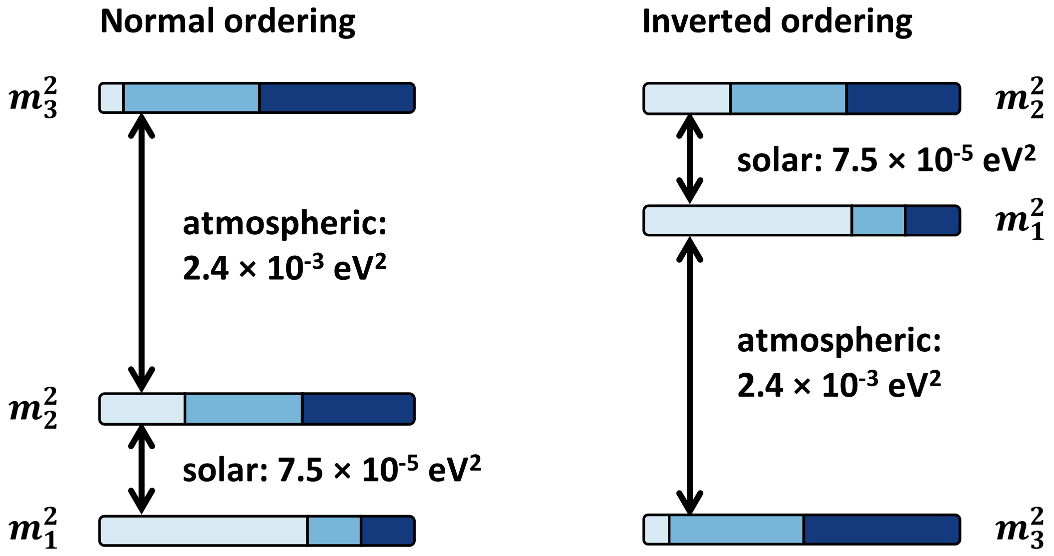


$$|\nu_\alpha\rangle = \sum U_{\alpha i}\,|\nu_i\rangle$$

*conventionally written as explicitly unitary

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

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



Normal ordering

$\boldsymbol{m_3^2}$

atmospheric: 2.4 × 10^{-3} eV^2

$\boldsymbol{m_2^2}$

solar: 7.5 × 10^{-5} eV^2

$\boldsymbol{m_1^2}$

Inverted ordering

$\boldsymbol{m_2^2}$

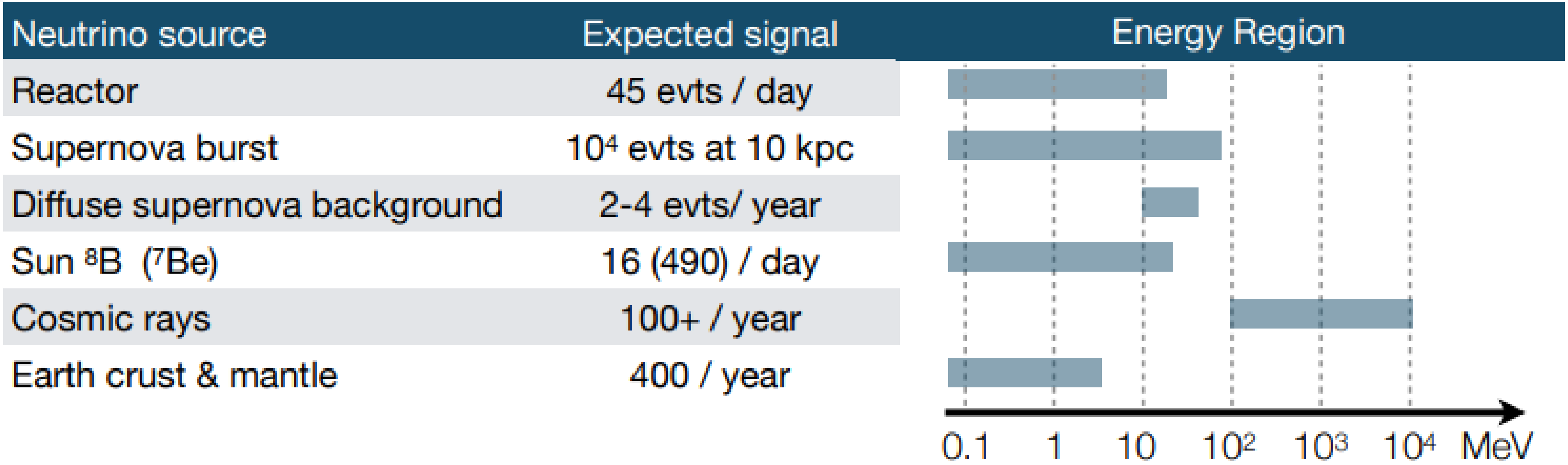
solar: 7.5 × 10^{-5} eV^2

$\boldsymbol{m_1^2}$

atmospheric: 2.4 × 10^{-3} eV^2

$\boldsymbol{m_3^2}$

The JUNO physics program



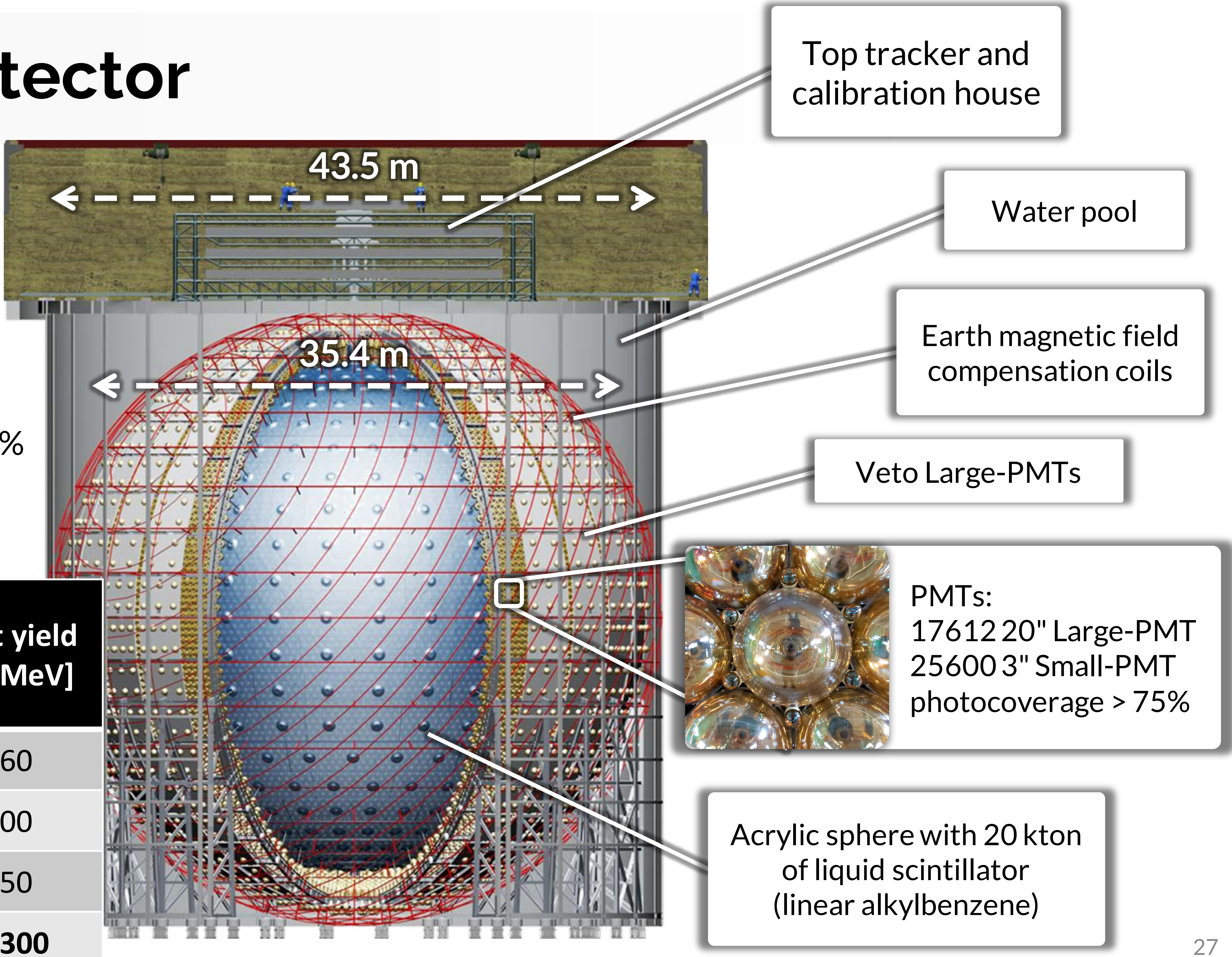
Neutrino source	Expected signal
Reactor	45 evts / day
Supernova burst	10^4 evts at 10 kpc
Diffuse supernova background	2-4 evts/ year
Sun ^{8}B (^{7}Be)	16 (490) / day
Cosmic rays	100+ / year
Earth crust & mantle	400 / year

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)

Photomultiplier Tubes

See Yury Malyshkin's talk

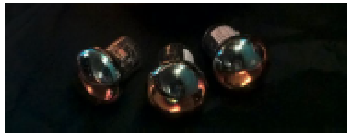
5000 x 20" Hamamatsu R12860

High QE:	28.5%
Fine TTS:	1.3 ns

15012 x 20" NNVT MCP-PMTs

Highest QE:	30.1%
Good TTS:	7.0 ns

High efficiency of photon detection



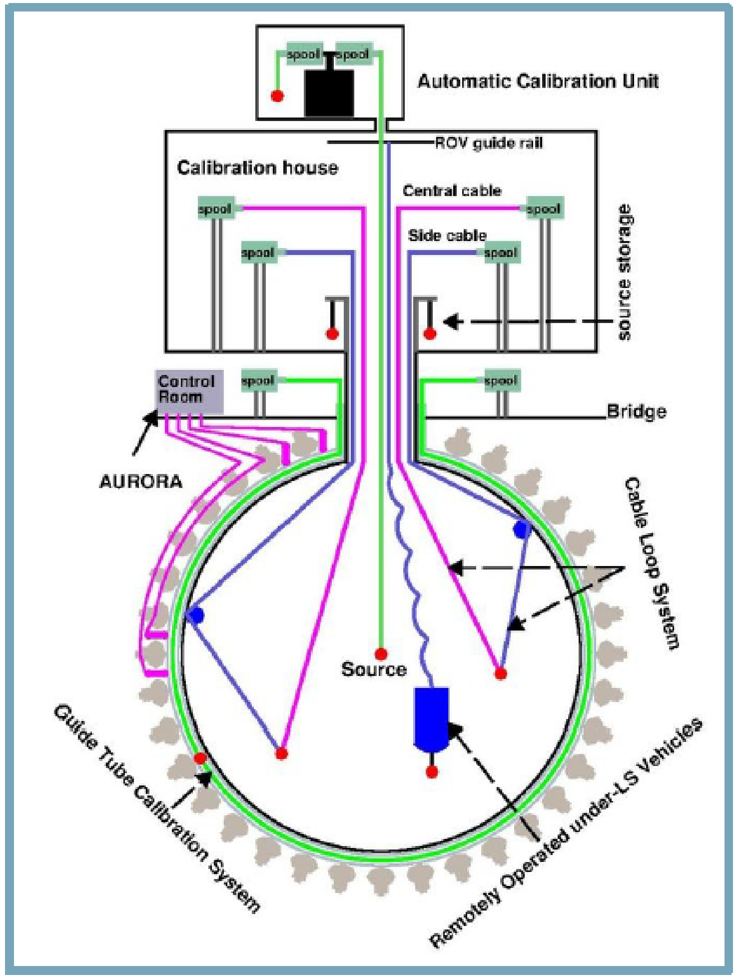
25600 x 3" HZC XP72B22

- Calibration of 20" PMTs' non-linearities
- Extension of dynamic range

More details about multi-calorimetry concept in talk by Yang Han on Thursday

The JUNO detector

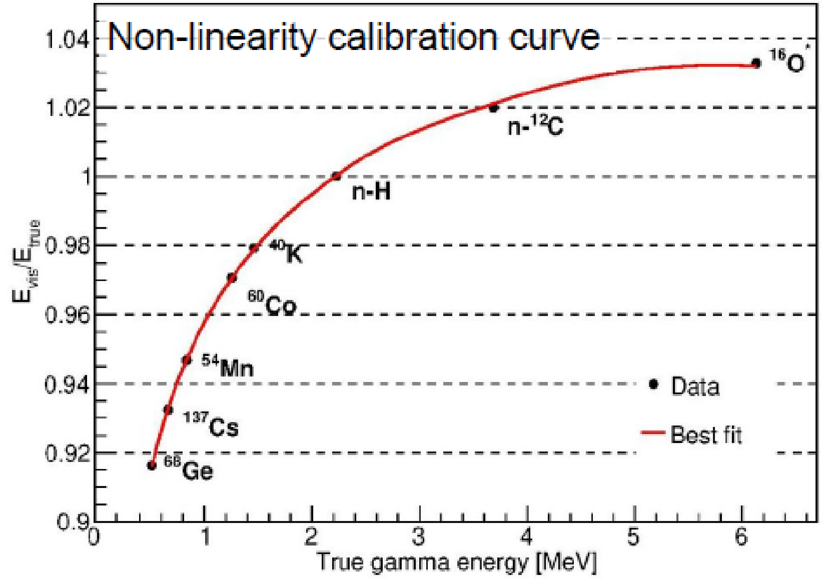
See Yury Malyshkin’s [talk]



[JHEP 2021, 4 (2021)]

Regular insertion of the calibration sources into the detector:

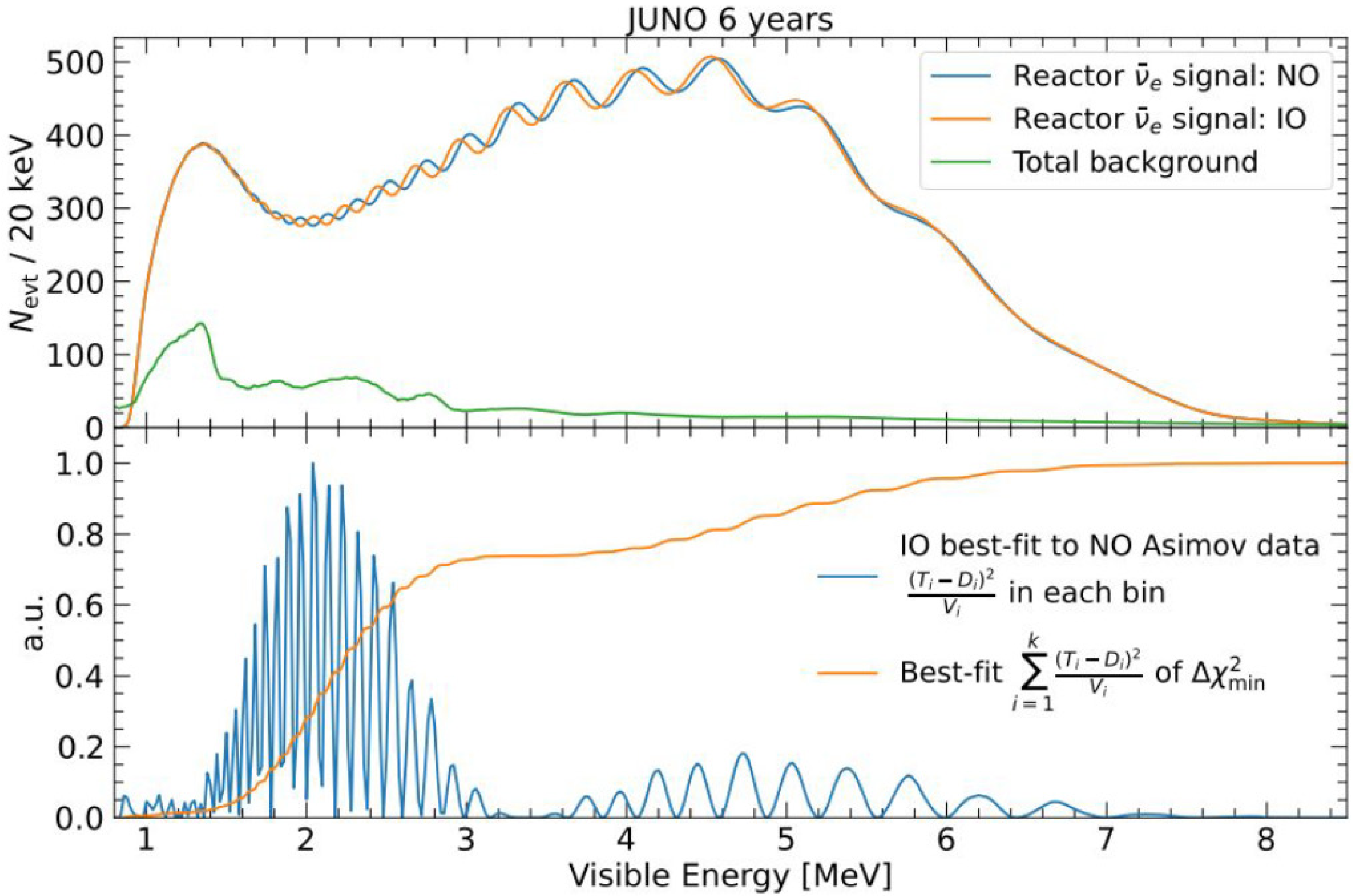
- Understanding of the detector response
- Testing of the reconstruction algorithms
- Calibration of the energy scale non-linearities



< 1% energy scale uncertainty

More details in talk by Jiaqi Hui on Thursday

Contributions to NMO sensitivity

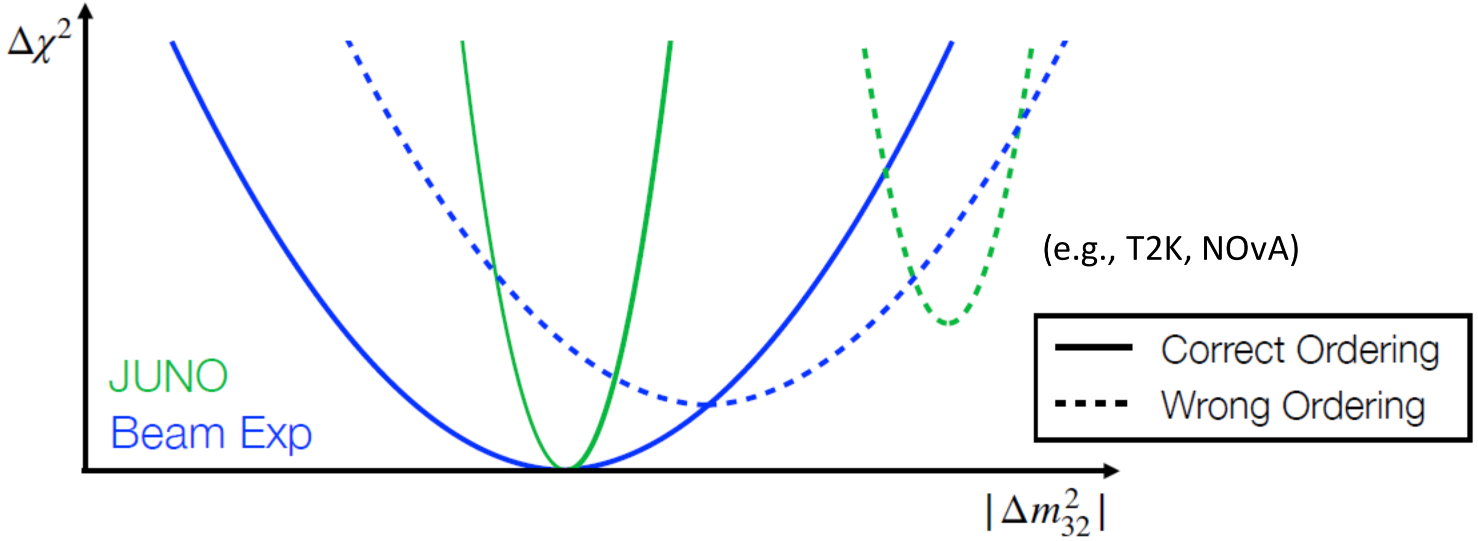


Synergy with long baseline experiments

Disappearance	$\bar{\nu}_e \to \bar{\nu}_e$	Reactor
Appearance	$\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_\mu \to \nu_e$	Beam

Both sensitive to atmospheric mass splitting Δm^2_{32}

Values are expected to agree only when correct ordering is assumed



(e.g., T2K, NOvA)

Combined analysis expected to yield significance $> 4\sigma$