Prospects of neutrino oscillation physics with JUNO

Beatrice Jelmini

International PhD Summer School on Neutrinos:

Here, There & Everywhere

Copenhagen, DK, 12/07/2022

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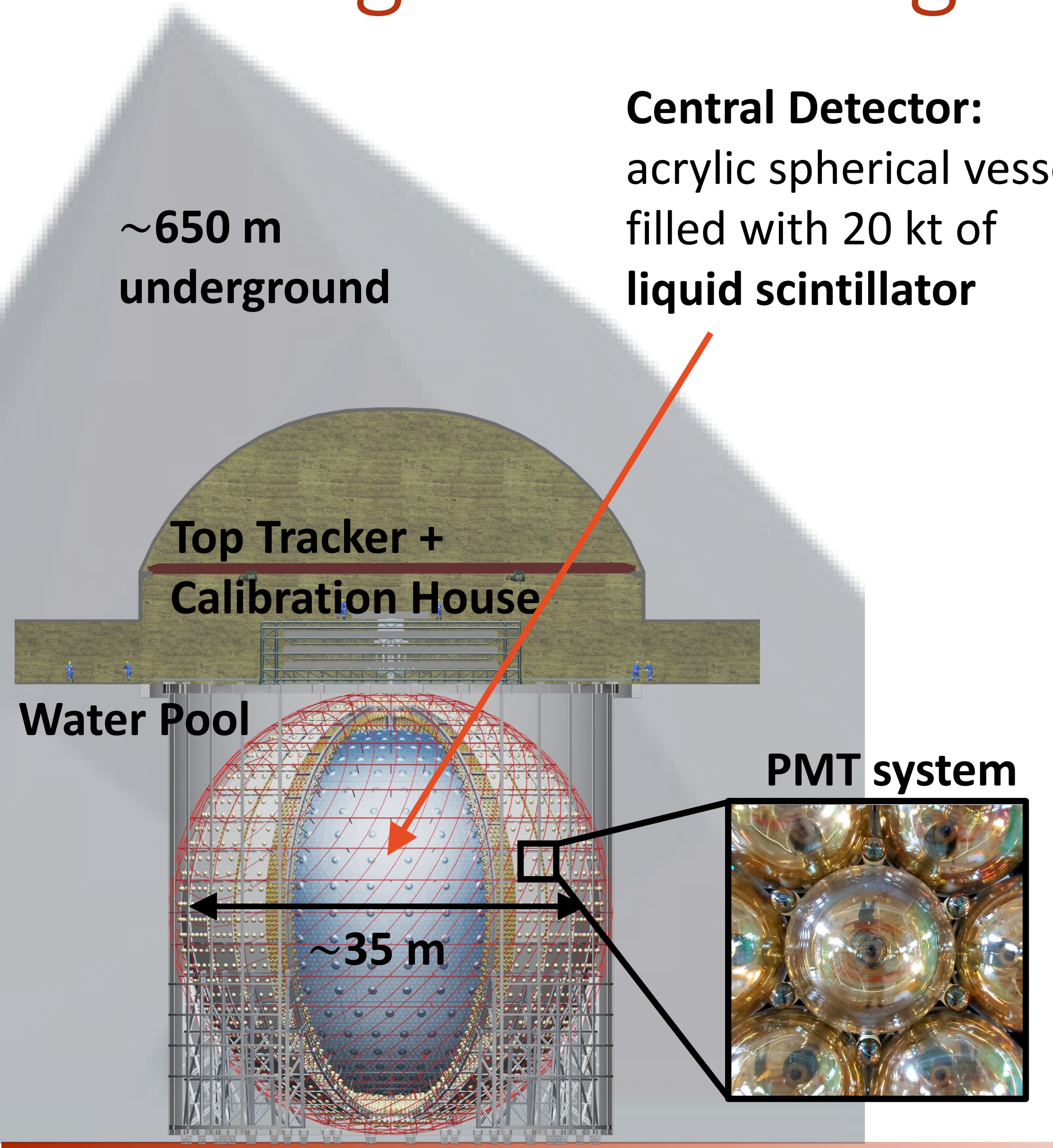
Jiangmen Underground Neutrino Observatory



	Target mass [ton]	Energy resolution	Light yield [PE/MeV]
Daya Bay	20 (x8)	$8\%/\sqrt{E}$	160
Borexino	300	$5\%/\sqrt{E}$	500
KamLAND	1000	$6\%/\sqrt{E}$	250
JUNO*	20 000	$3\%/\sqrt{E}$ (requested)	>1300

*values from Prog. Part. Nucl. Phys. 123 (2022) 103927

Extensive neutrino physics & astrophysics program

- Reactor $\bar{\nu}_e$: 60 IBD/day
- Solar ν: O(100)/year
- Atmospheric ν: O(100)/year
- Geo-ν: ~400/year
- DSNB: 2-4 IBD/year
- SN burst: 5000 IBD + 2300 ES in 10 s (@ 10 kpc)
- …

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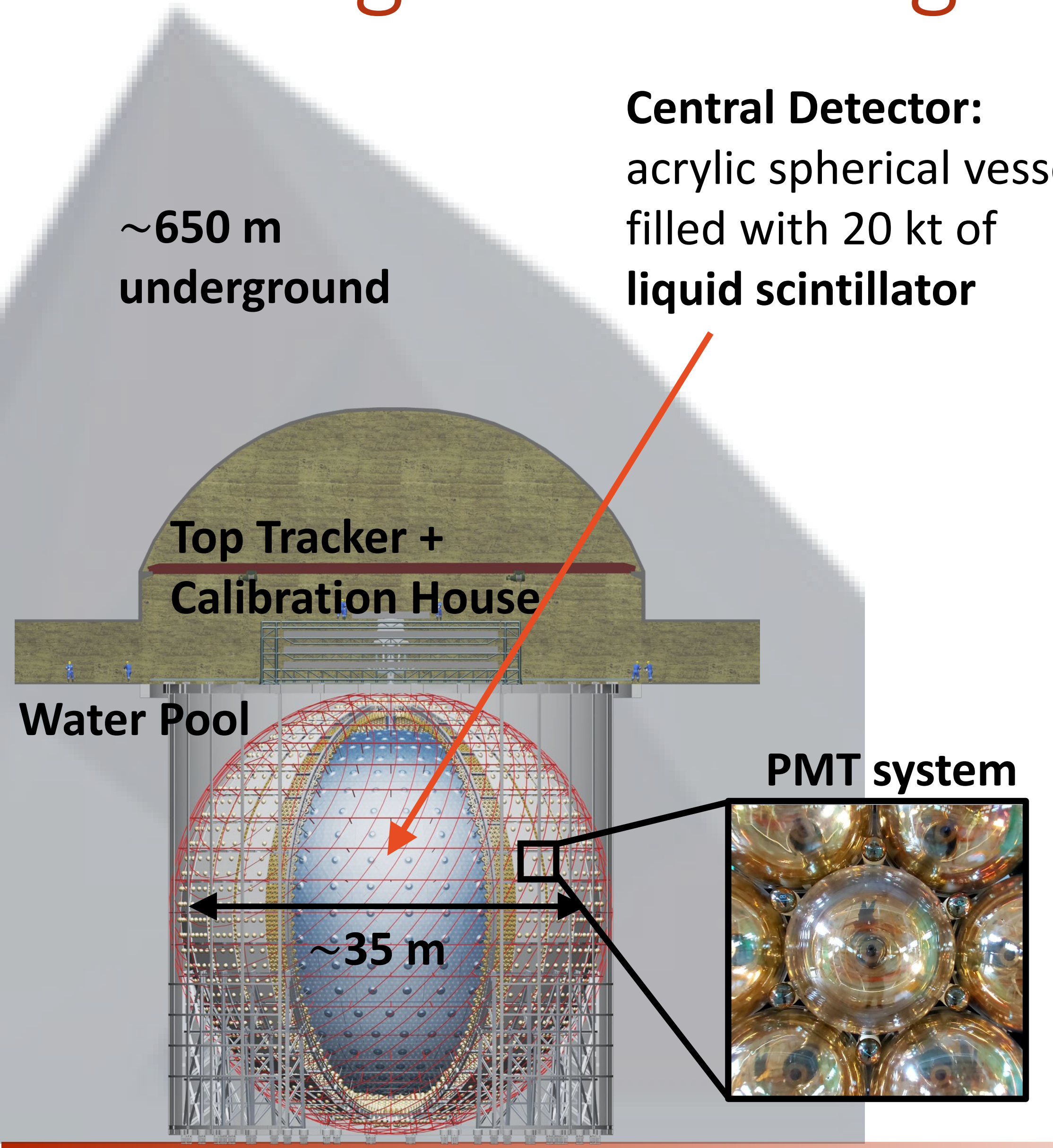

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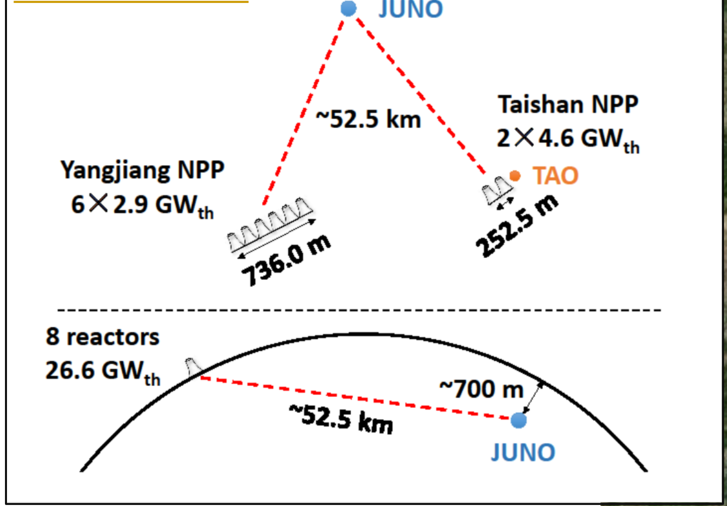
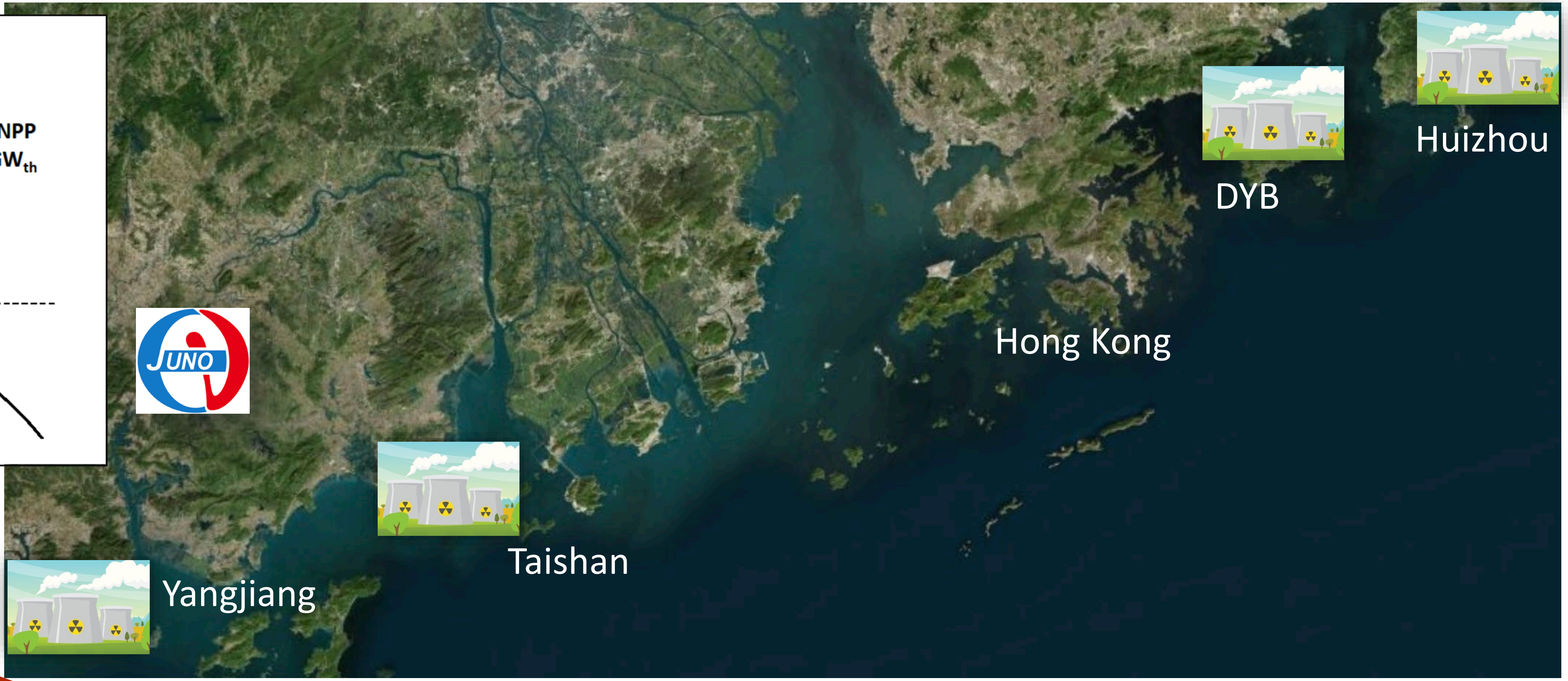
The JUNO site

JUNO is currently under construction in southern China
Data taking is expected to begin in 2023

Kaiping, Jiangmen, Guangdong, southern China

arXiv :2204.13249





Total thermal power:
26.6 GW

$$N_{events} \propto \frac{\text{power}}{\text{baseline}^2}$$

Core	YJ-1	YJ-2	YJ-3	YJ-4	YJ-5	YJ-6	TS-1	TS-2	DYB	HZ
Power [GW]	2.9	2.9	2.9	2.9.	2.9	2.9	4.6	4.6	17.4	17.4
Baseline [km]	52.74	52.82	52.41	52.49	52.11	52.19	52.77	52.64	215	265

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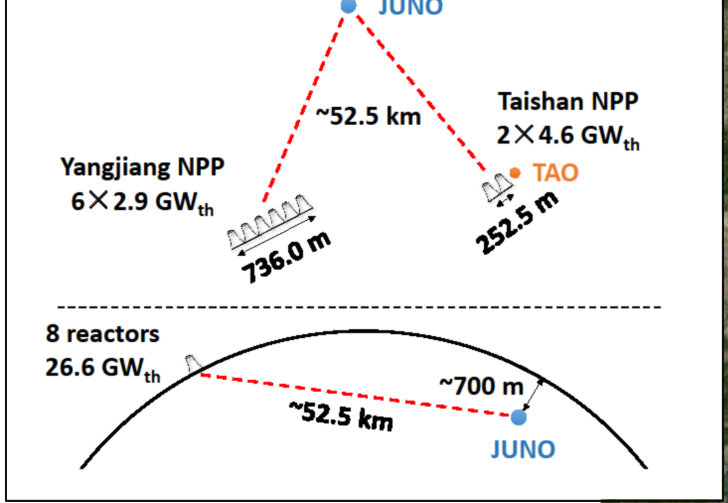

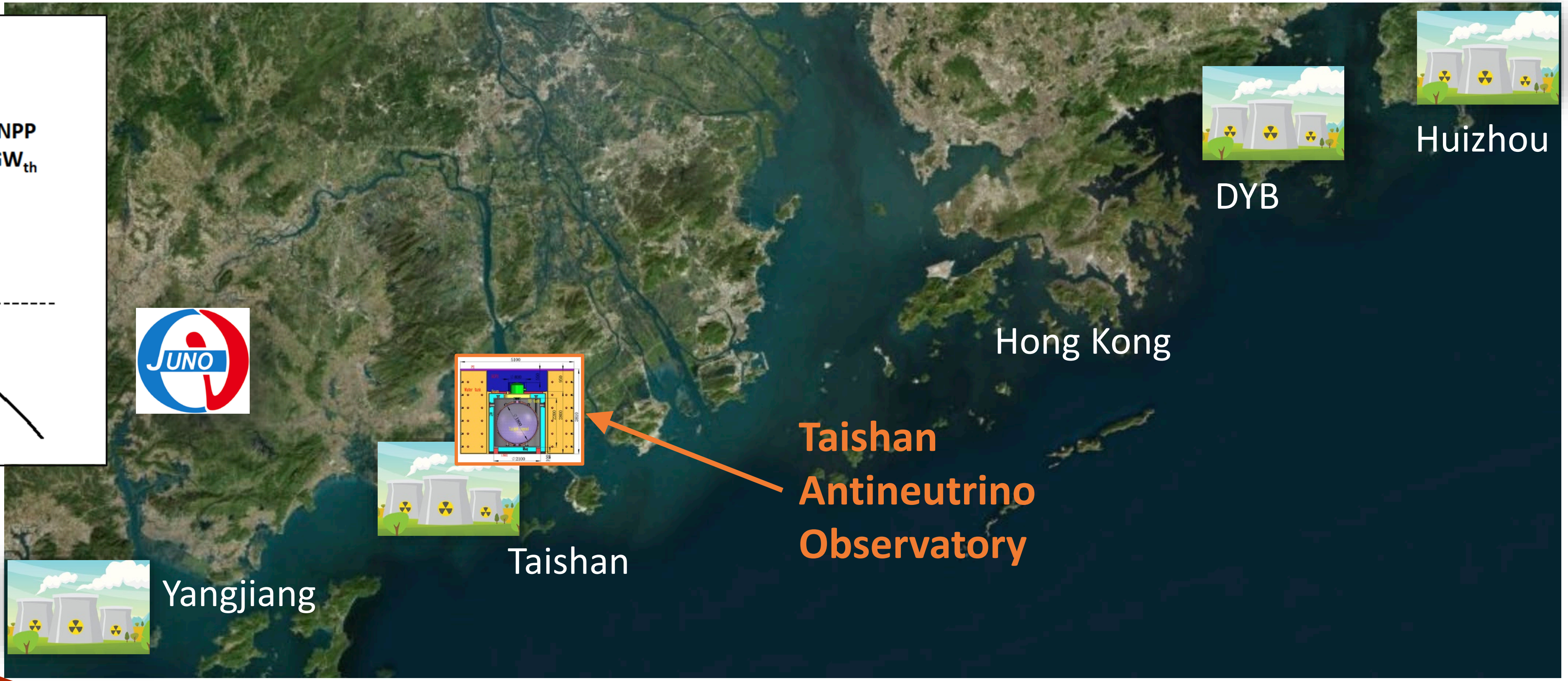

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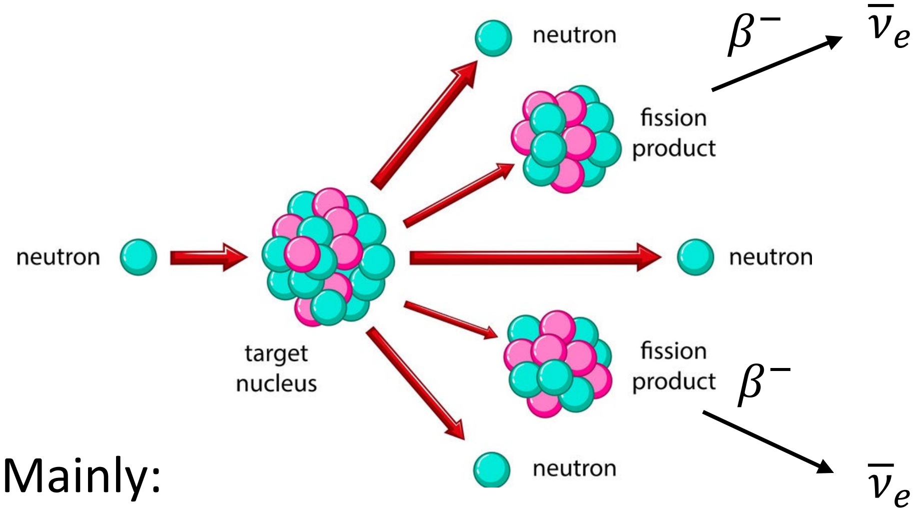
Reactor spectrum: isotopic spectra

Electron antineutrinos are produced from
beta decays of fission products



Mainly:
^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

Fission fraction of isotope i, f_i: # of fissions from *i-th* isotope / total # of fissions

$f_{235}: f_{238}: f_{239}: f_{241} = 0.58: 0.07: 0.30: 0.05$ (for JUNO)

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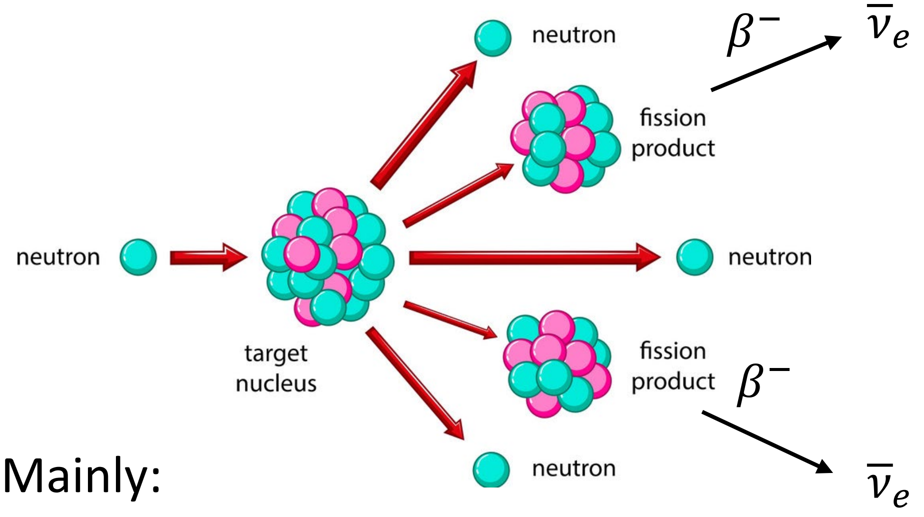

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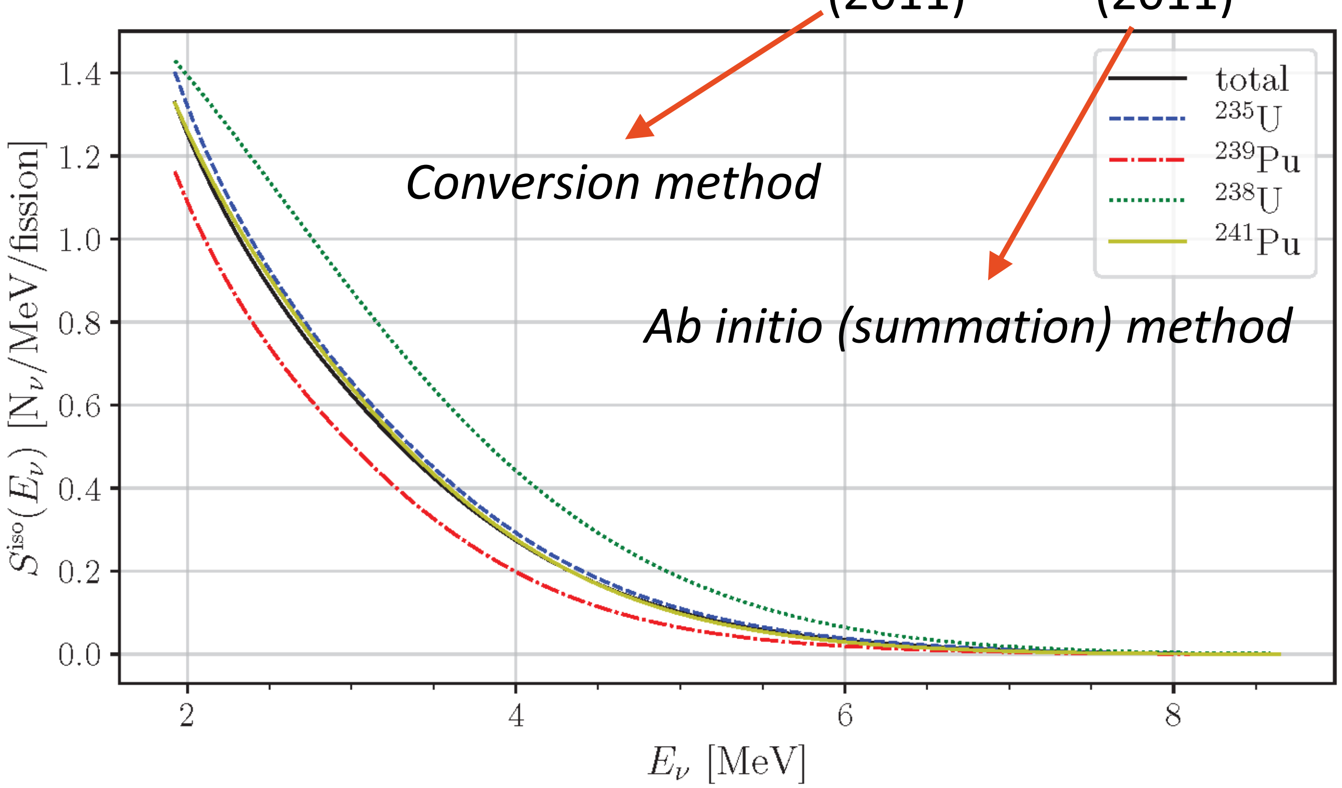
Standard approach: use spectra from Huber*) and Mueller**)
(2011) (2011)



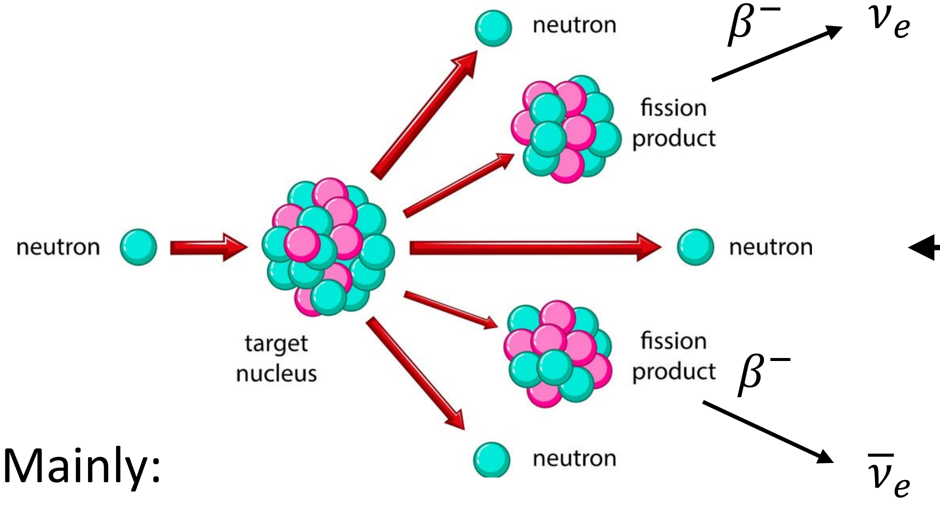
$$S^{total}(E_\nu) = \sum_i f_i \cdot S_i^{iso}(E_\nu)$$

S_i^{iso} can be parametrized with the exponential of a polynomial of 5th order

*) arXiv:1106.0687; **) arXiv:1101.2663v3

Reactor spectrum: isotopic spectra – TAO

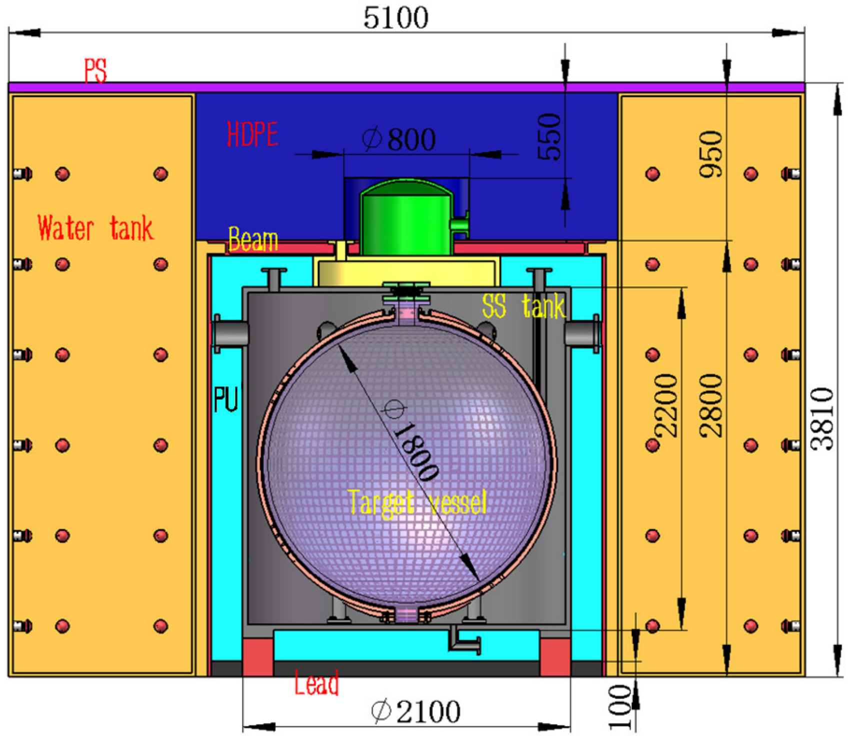
Electron antineutrinos are produced from **beta decays of fission products**



Mainly:
^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

~ 30 meter

TAO CDR: arXiv:2005.08745



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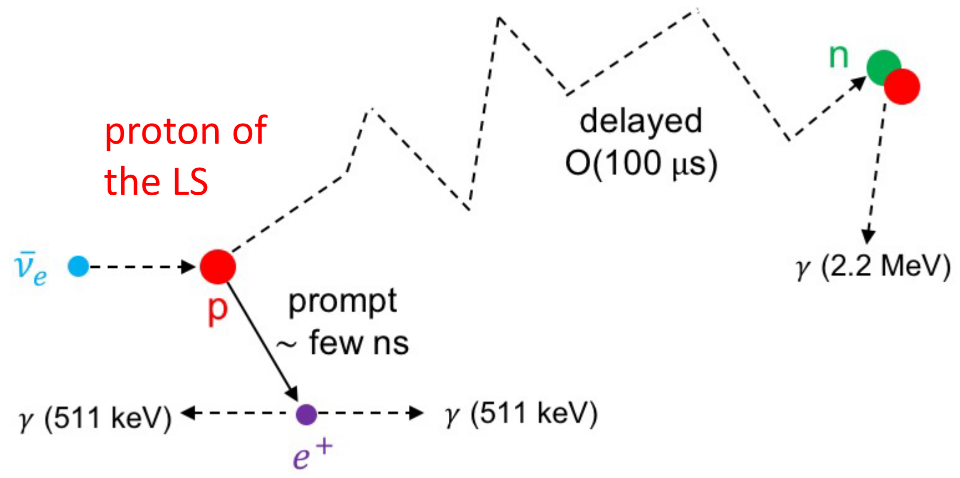
2.8 ton gadolinium-doped liquid scintillator
4500 PEs/MeV & energy resolution < 2% @ 1 MeV
~ 30 meter from a reactor core
Goals: provide JUNO with a reference spectrum + sterile neutrinos physics
Data taking starts in 2023

Inverse Beta Decay (IBD)

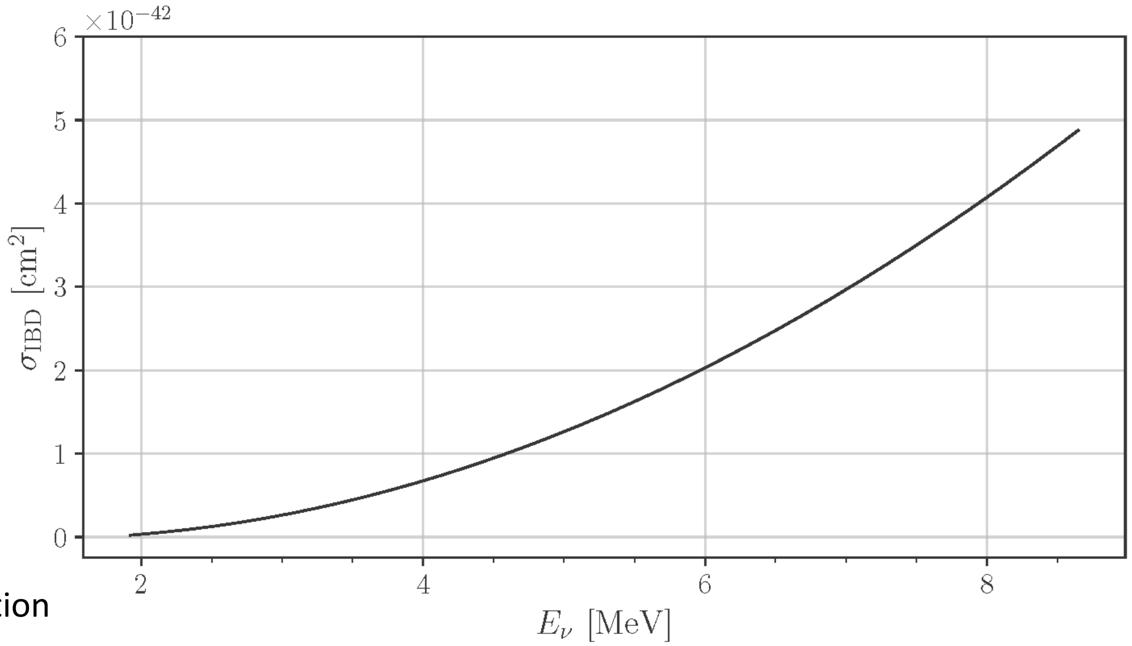
Electron antineutrinos detected via Inverse Beta Decay (IBD)

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

IBD threshold: $E_\nu > 1.806\ \mathrm{MeV}$



IBD cross section



Strumia & Vissani's approximated equation
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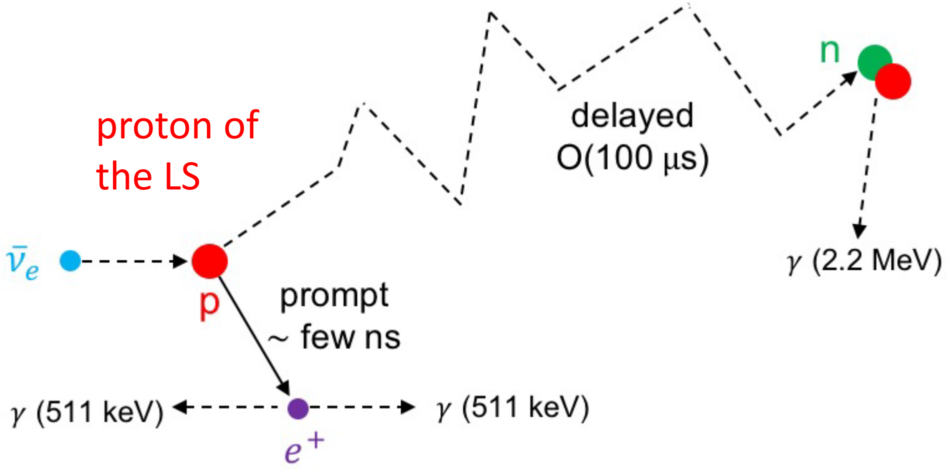
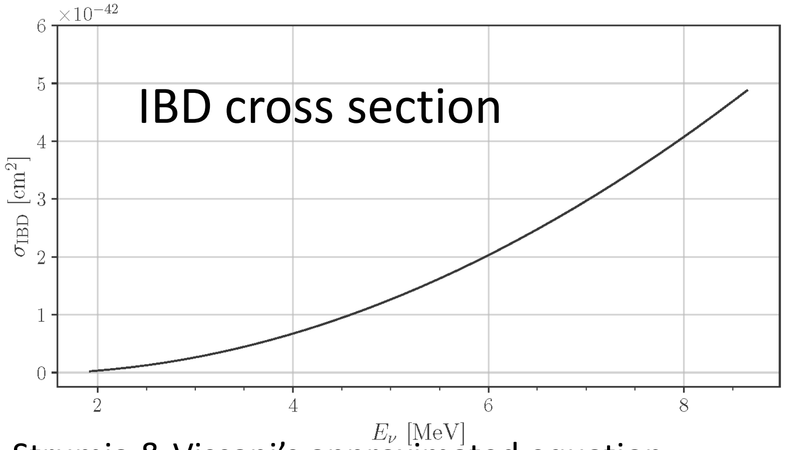
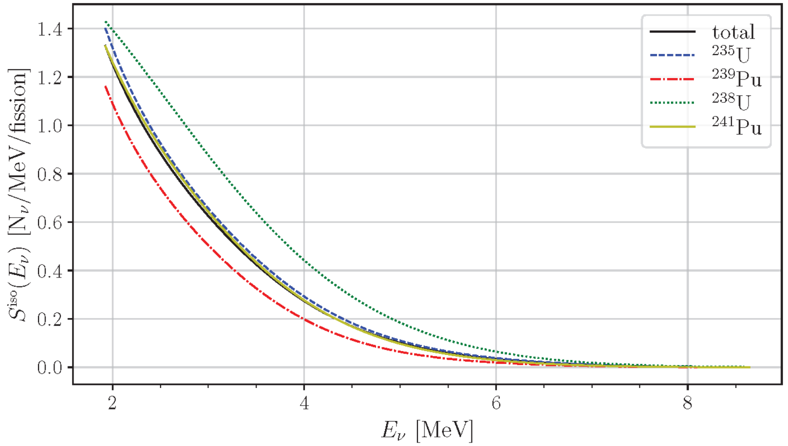


IBD cross section x isotopic spectrum = reactor spectrum



x



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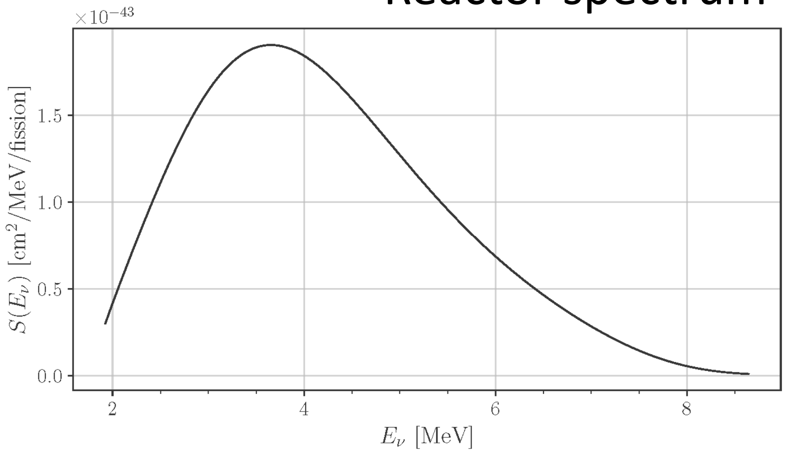
Reactor spectrum



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Neutrino oscillations @ JUNO

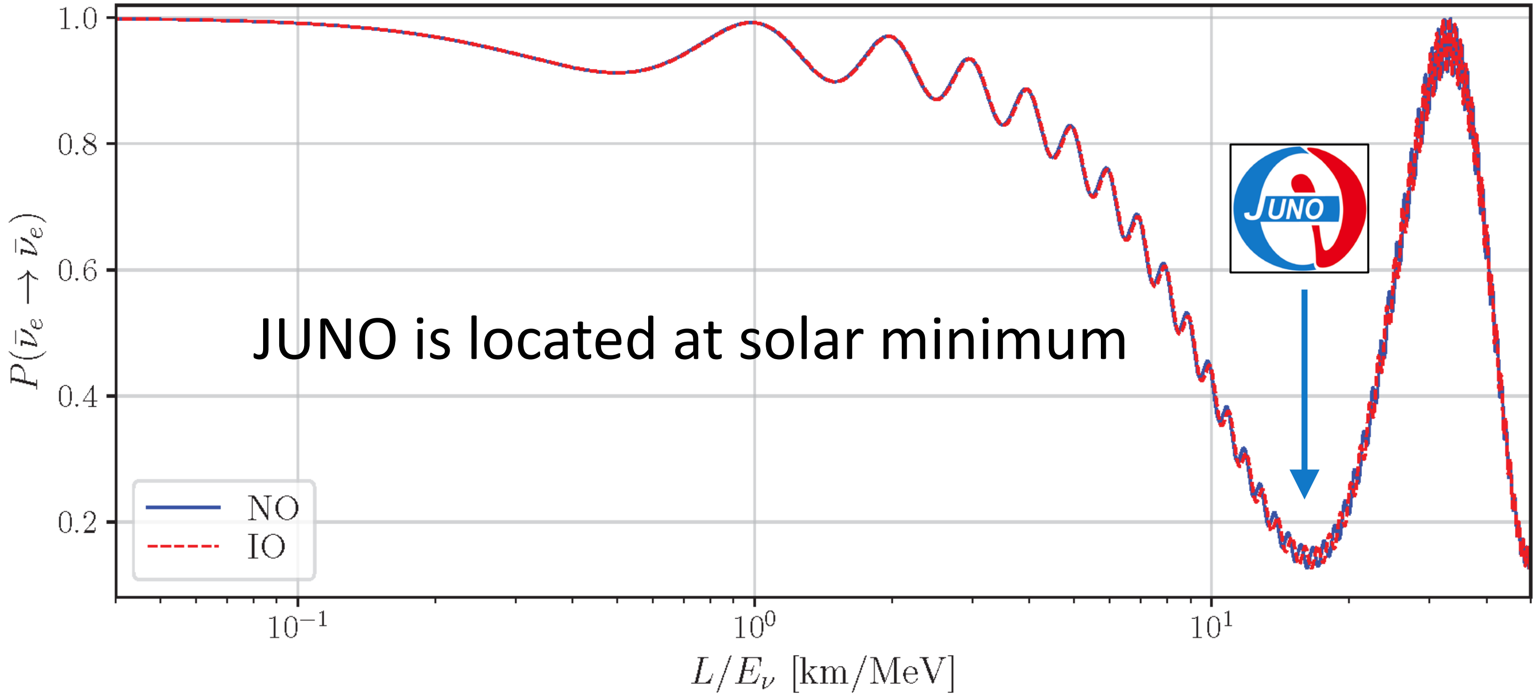
Electron antineutrino survival probability:

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2 2\theta_{13}(\sin^2\theta_{12}\sin^2\Delta_{32} + \cos^2\theta_{12}\sin^2\Delta_{31}) - \sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2\Delta_{21}$$

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

"fast" or atmospheric oscillations — "slow" or solar oscillations

<u>JUNO will be the first to see both oscillation modes simultaneously</u>



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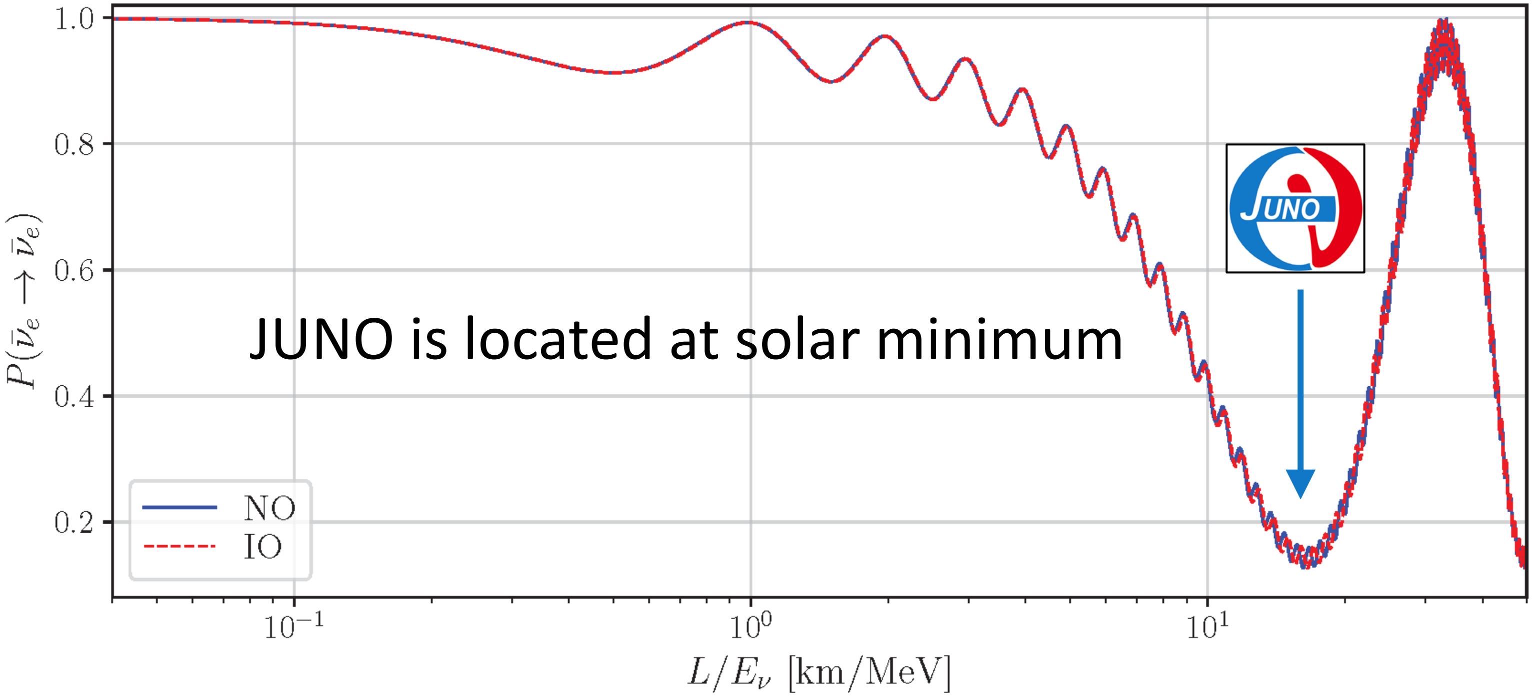
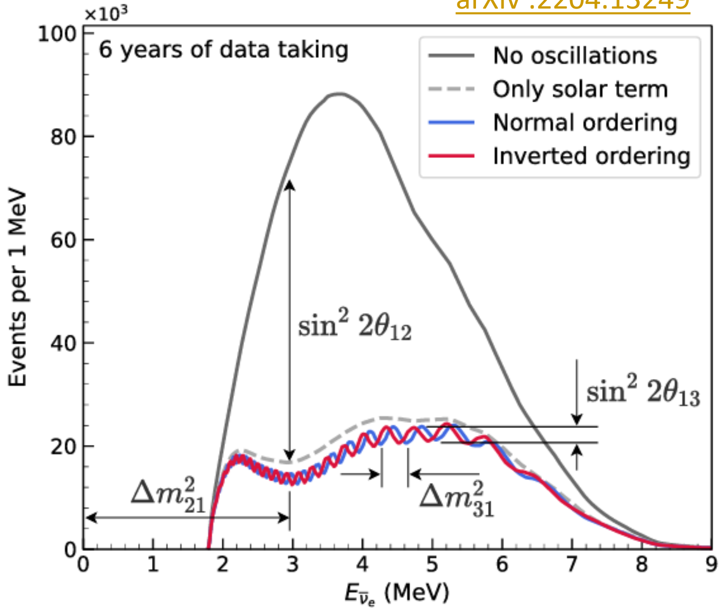


arXiv :2204.13249



Mass ordering sensitivity

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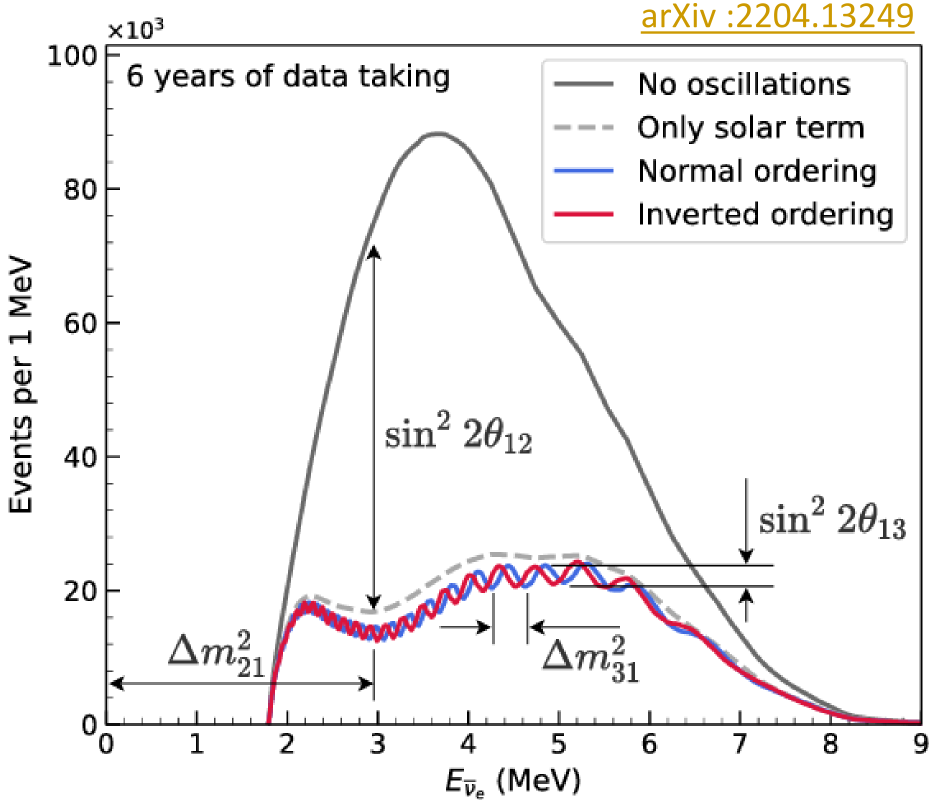
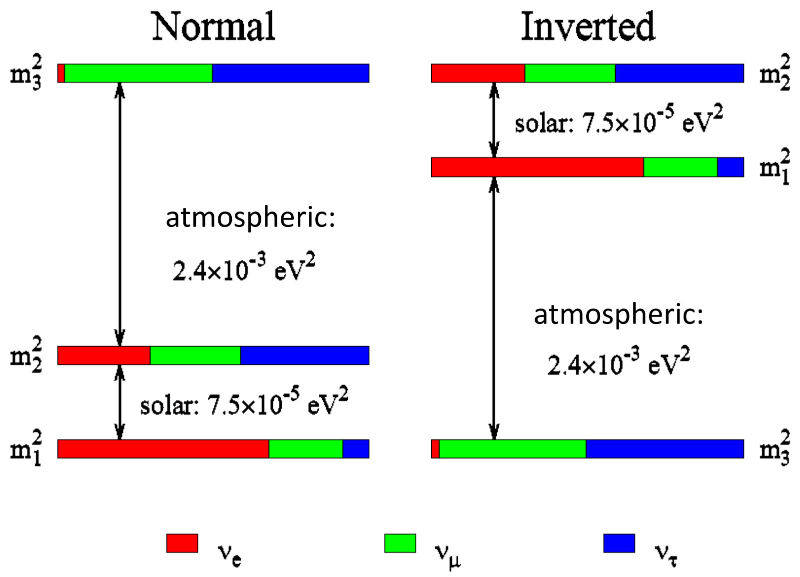


$$\Delta m^2_{21} > 0$$
$$\Delta m^2_{31} > 0 \text{ or } < 0?$$

Two mass orderings are out of phase

Shape analysis to distinguish between the two orderings



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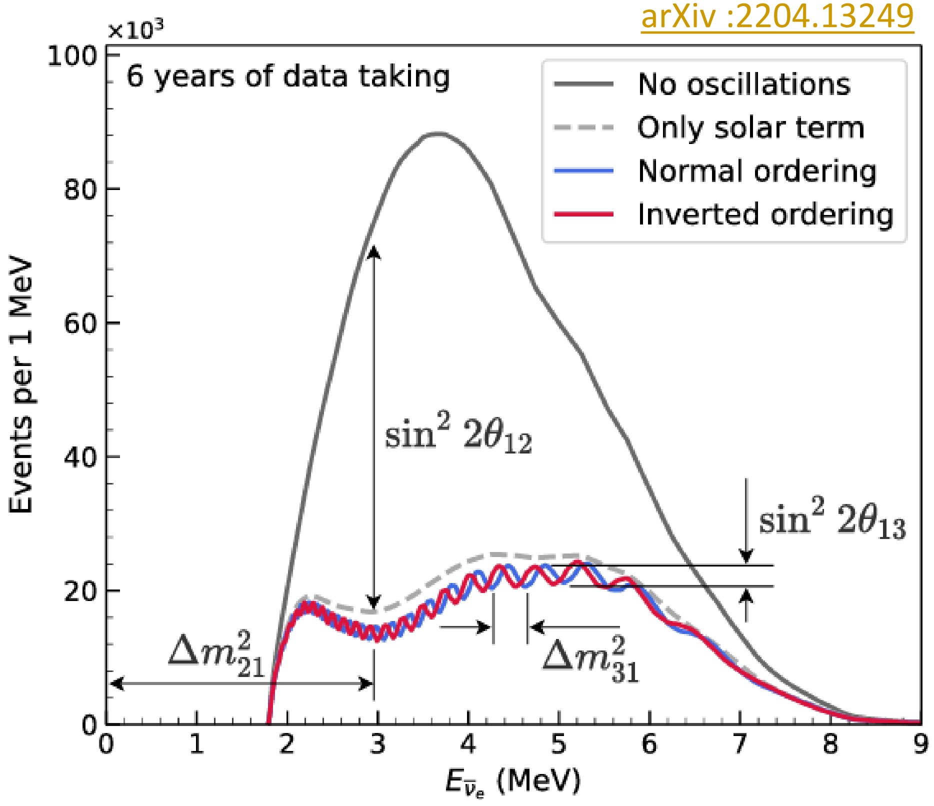

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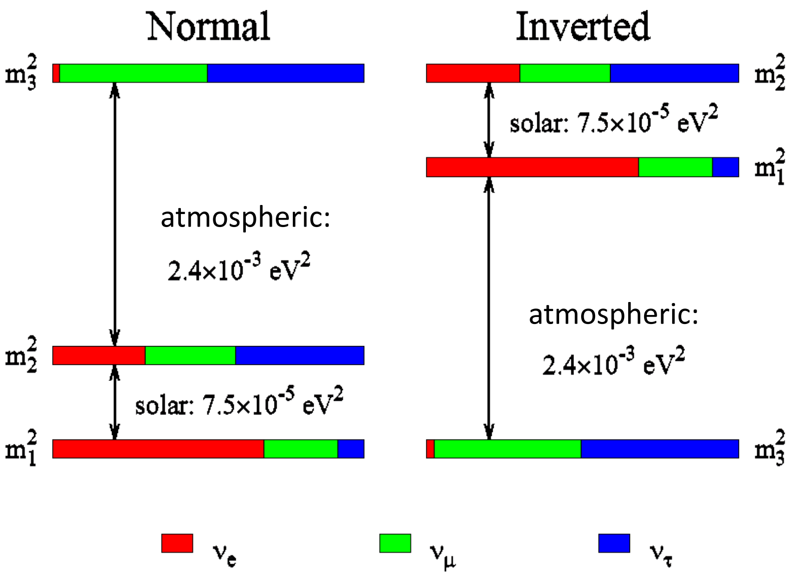

Mass ordering determination expected at 3σ in approximately 6 years

Precision measurement of oscillation parameters

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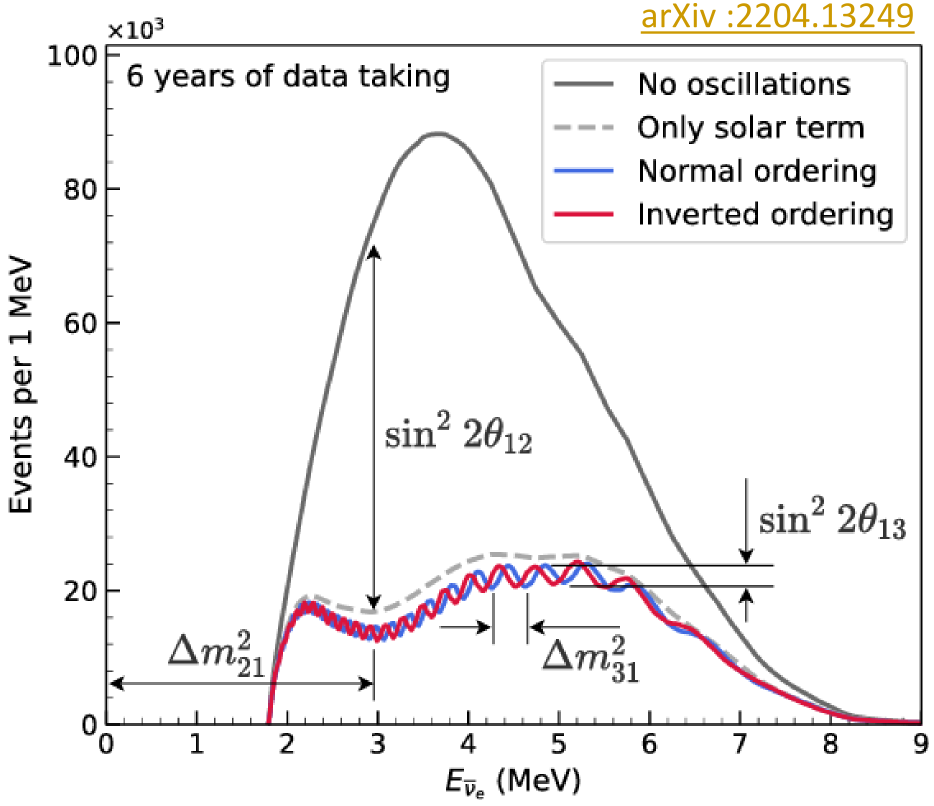
Parameters:

- Mass splittings: Δm^2_{31}, Δm^2_{21}
- Mixing angles: θ_{13}, θ_{12}
- Independent of θ_{23}, δ_{CP}

arXiv :2204.13249



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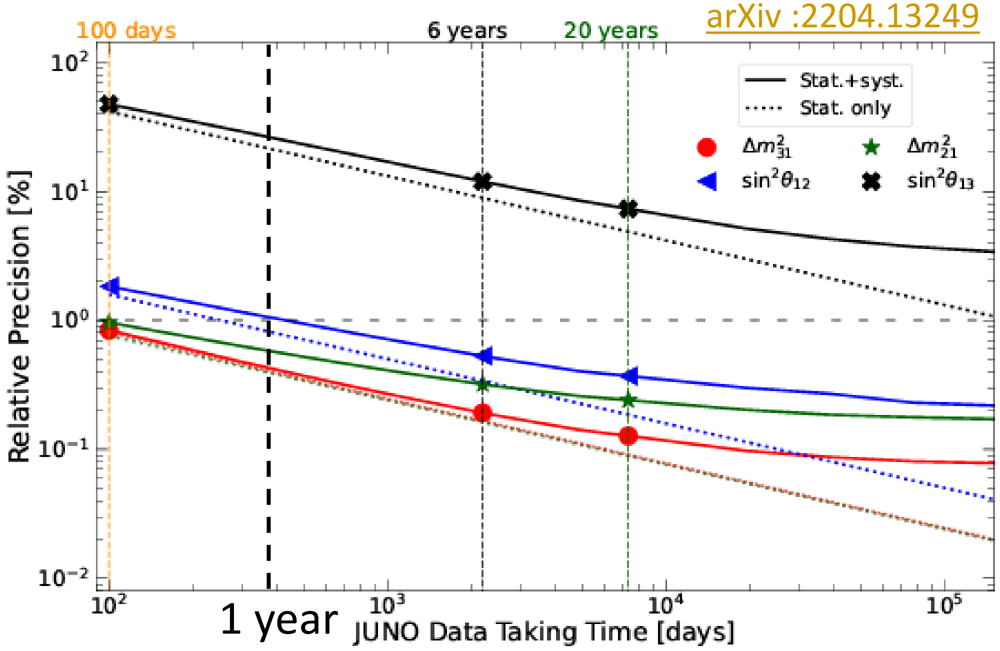

TAO uncertainties propagated to JUNO

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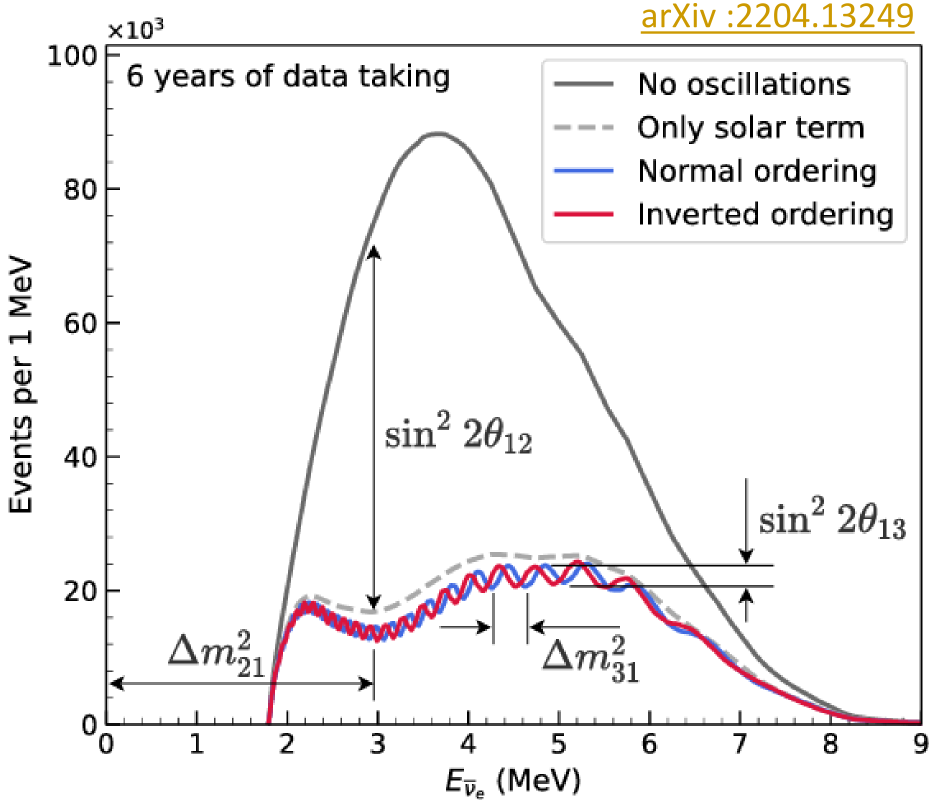

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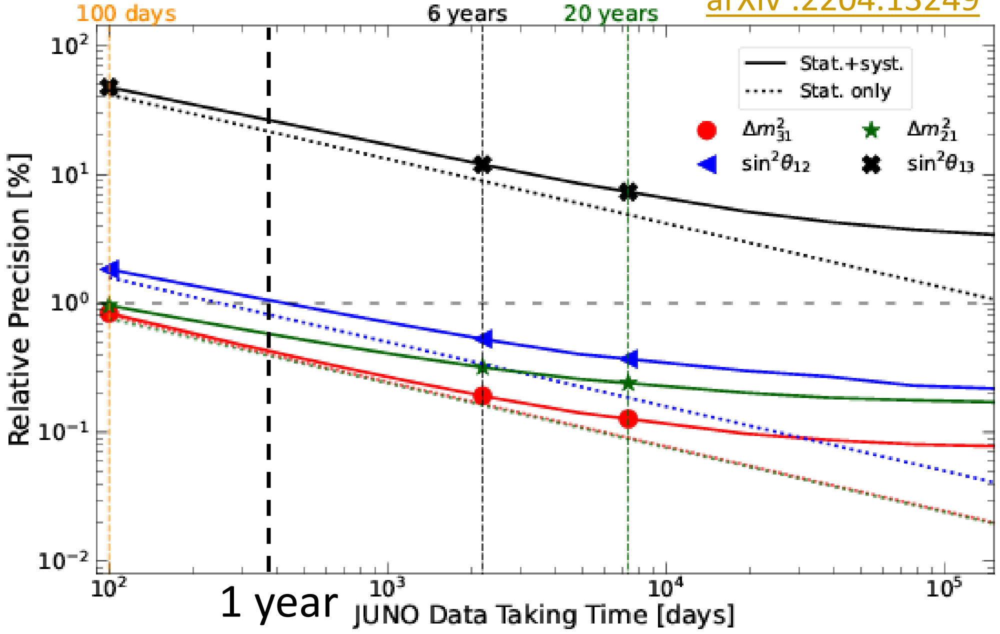


TAO uncertainties propagated to JUNO

sub-percent precision in ~ 1 years

Conclusions

- JUNO will be the first experiment to simultaneously see both fast and slow oscillation modes
- 3 oscillation parameters measured with sub-percent precision in $\sim$1 year
- Mass ordering determination at 3σ in approximately 6 years
- Data taking starts in 2023, stay tuned!

Thank you!

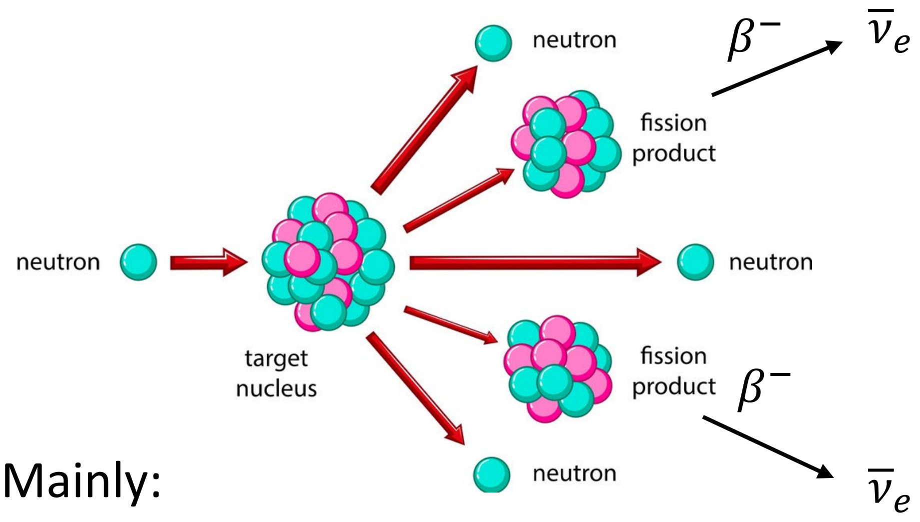
The 15th JUNO Collaboration Meeting

January 13-17, 2020, Guangxi University, Nanning

Backup

Reactor spectrum: isotopic spectra

Electron antineutrinos are produced from **beta decays of fission products**



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$f_{235}: f_{238}: f_{239}: f_{241} = 0.58: 0.07: 0.30: 0.05$ (for JUNO)

Standard approach: use spectra from Huber*) and Mueller**)

Conversion method:
Measured beta spectra from the 1980s @ ILL, fitted, then converted to antineutrino spectra
^{235}U, ^{239}Pu, ^{241}Pu only
No ^{238}U

Ab initio (summation) method:
Theoretical calculation of antineutrino spectra, relies on nuclear databases
^{238}U only

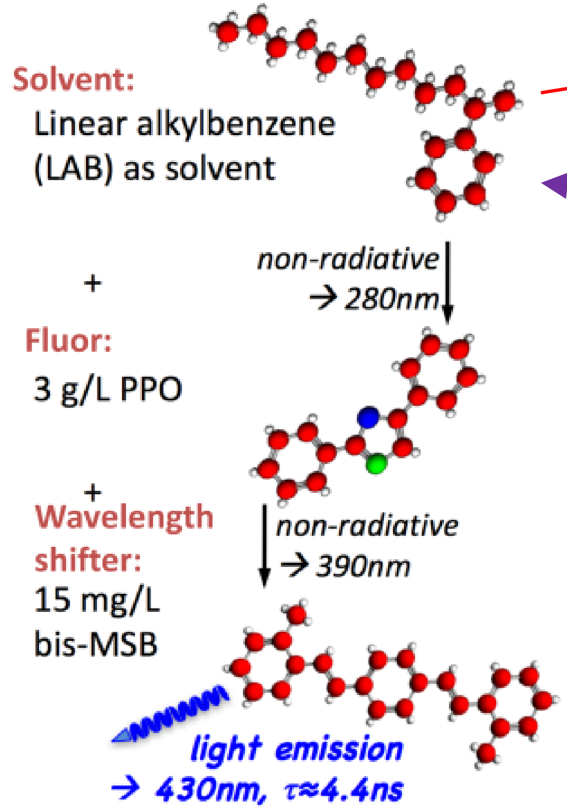
*) arXiv:1106.0687; **) arXiv:1101.2663v3

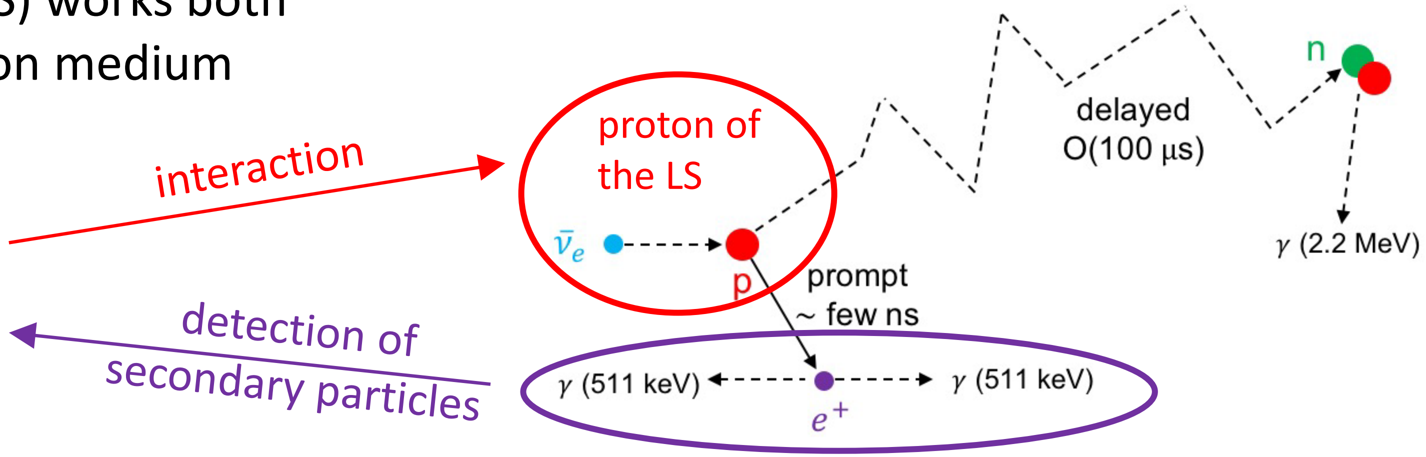
Inverse Beta Decay (IBD)

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

Electron antineutrinos interact via Inverse Beta Decay (IBD)

JUNO Liquid Scintillator (LS) works both as interaction and detection medium





IBD threshold:
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Strumia & Vissani's approximated equation
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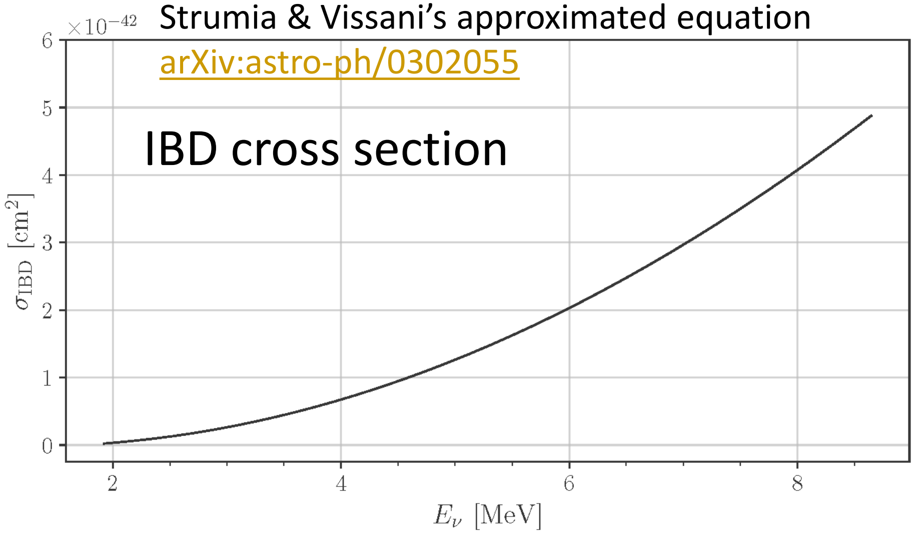
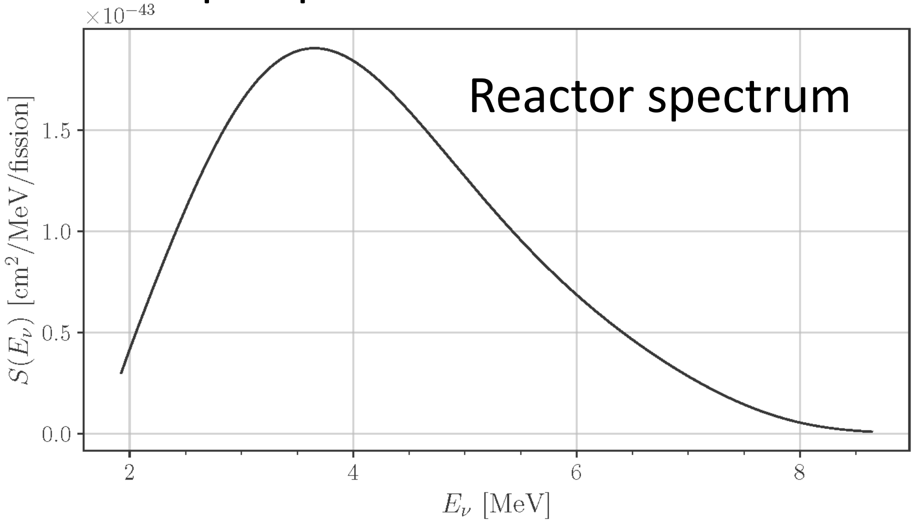
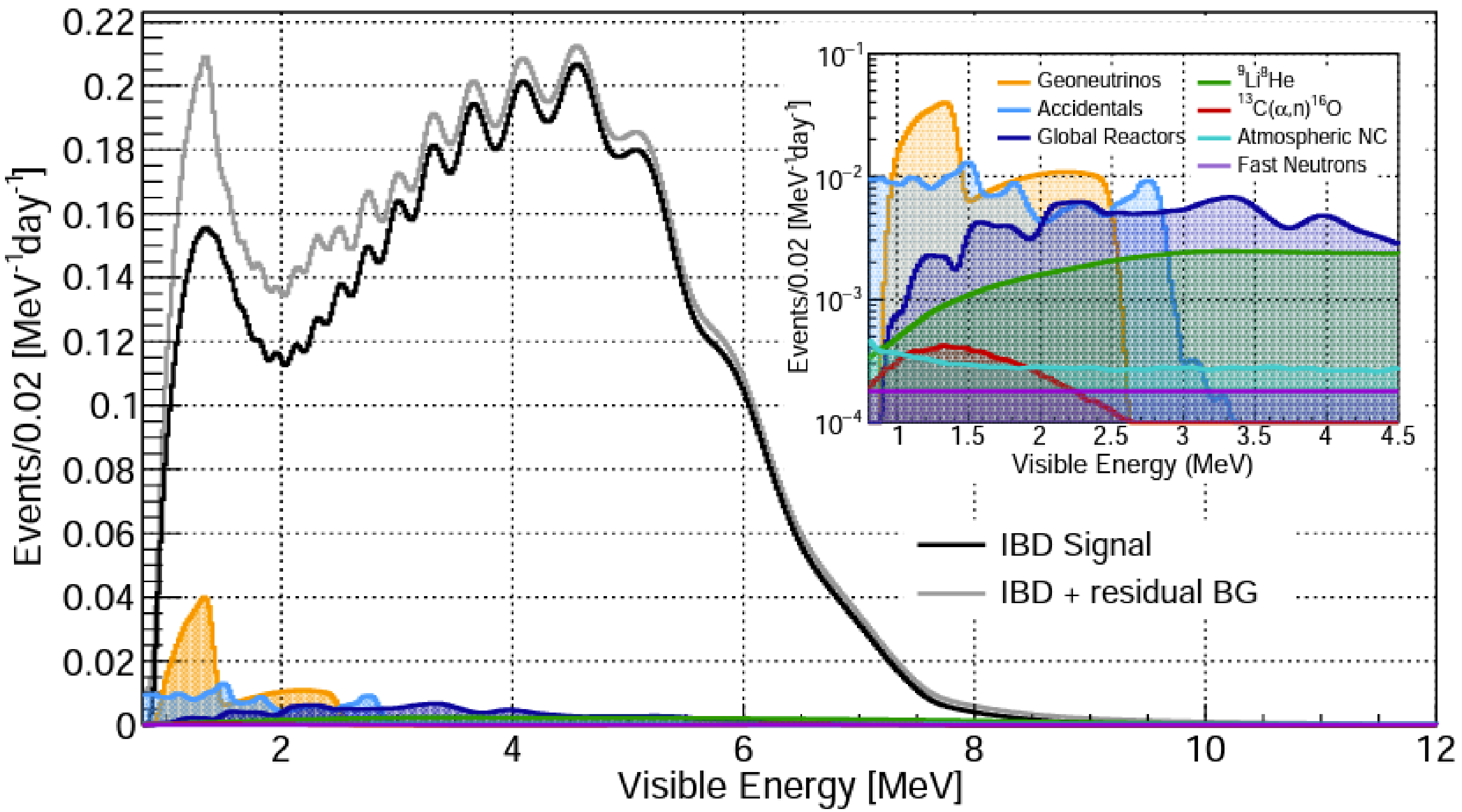


isotopic spectrum x IBD cross section



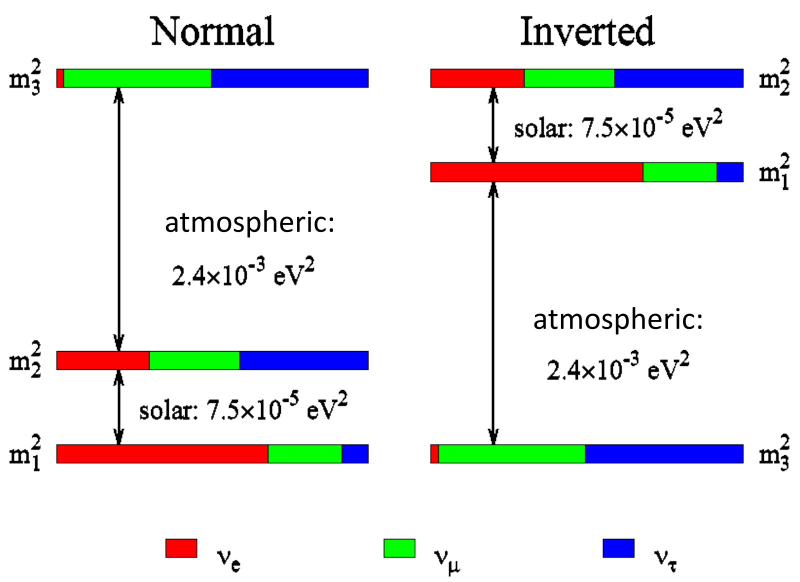
Backgrounds

Background	Rate (day^{-1})	Rate Uncertainty (%)	Shape Uncertainty (%)
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
$^{13}C(\alpha,n)^{16}O$	0.05	50	50



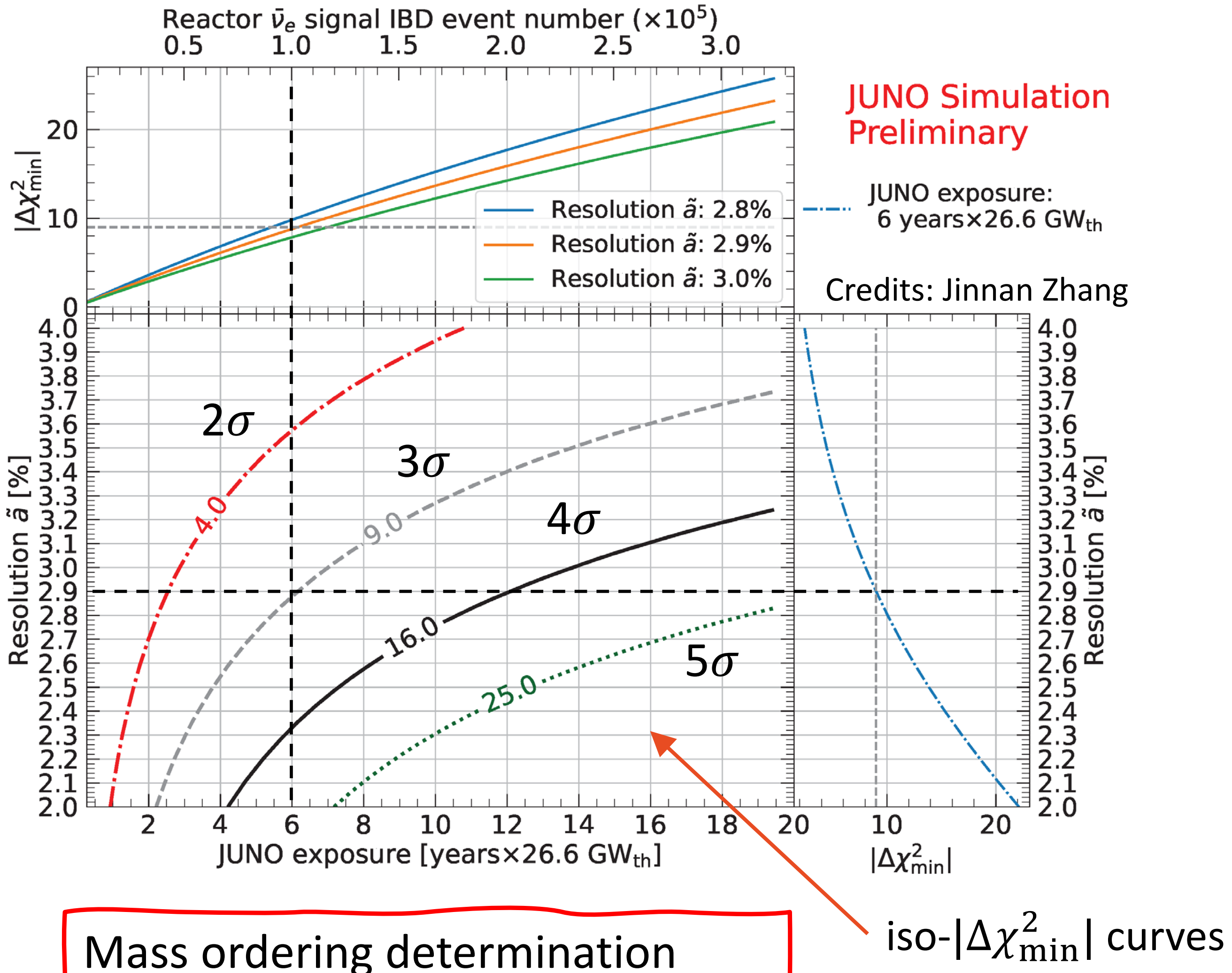
Mass Ordering sensitivity

Two possible Mass Orderings:



$|\Delta\chi^2_{\min}|$ is the test statistic used to discriminate between the two orderings: $\sqrt{|\Delta\chi^2_{\min}|} = \#\sigma$

<u>JUNO + TAO combined analysis</u>



Mass ordering determination expected at 3σ in approx 6 years

Energy resolution

Common parametrization with 3 terms:

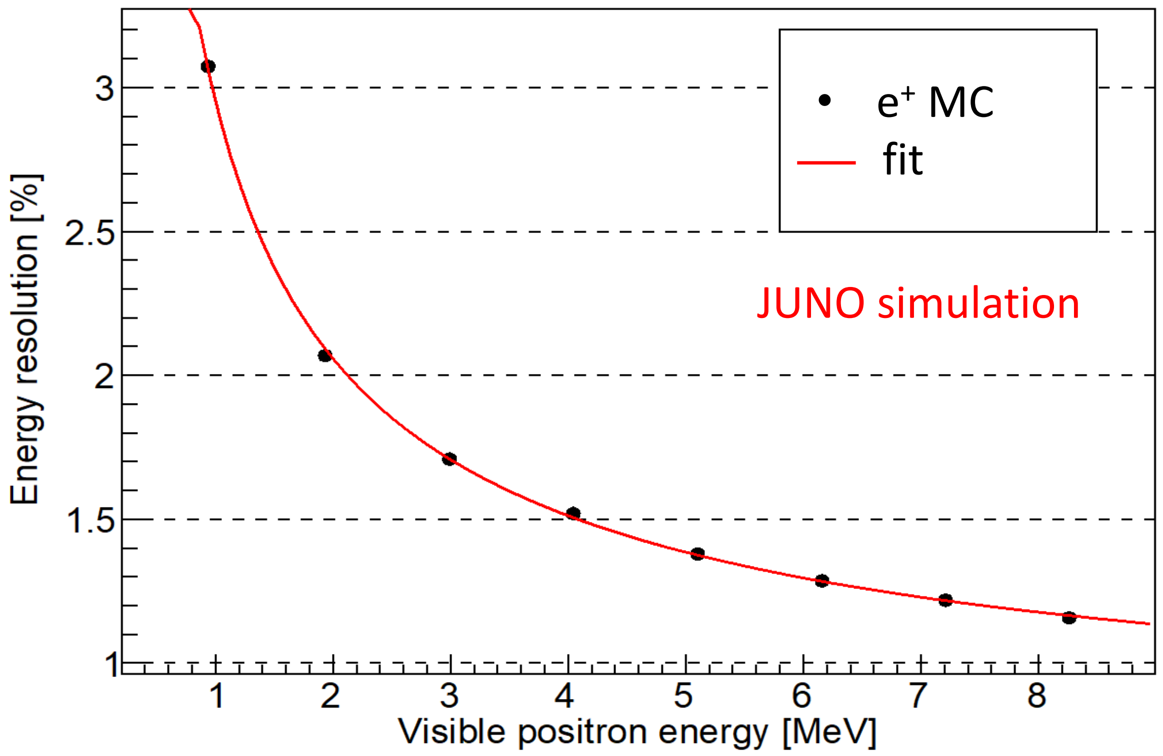
$$\frac{\sigma_E}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2}$$

stochastic term: light yield (from multiple-source calibration)

dominated by position non-uniformity, controlled with multiple-positional calibration

PMT dark noise

JHEP 03, 004 (2021)



Effective energy resolution: $\tilde{a} = \sqrt{(a)^2 + (1.6 \cdot b)^2 + \left(\frac{c}{1.6}\right)^2} = 2.9\% < 3\%$

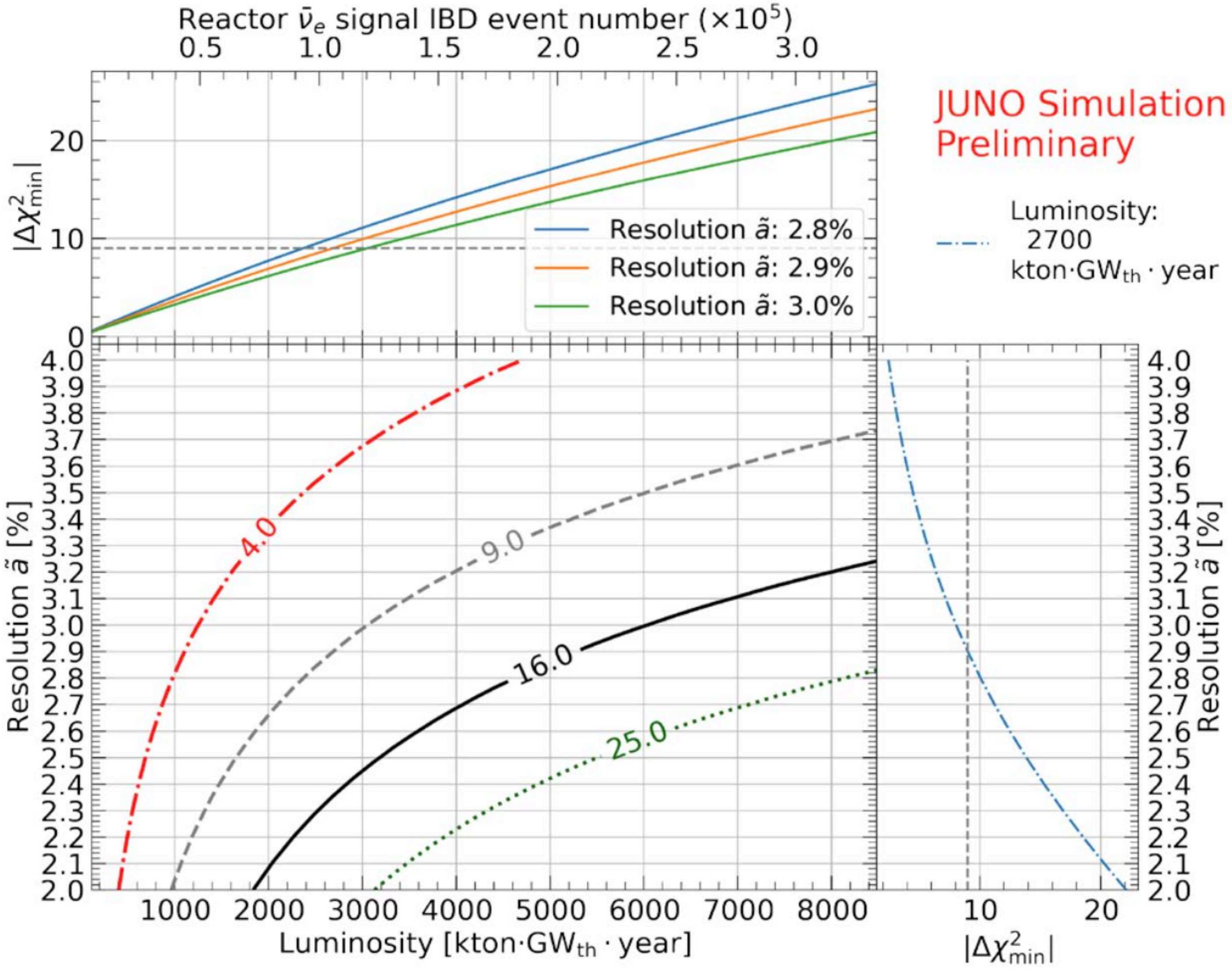
Effective energy resolution

$$\tilde{a} = \sqrt{(a)^2 + (1.6 \cdot b)^2 + \left(\frac{c}{1.6}\right)^2}$$

Introduced to easily display the relation between the sensitivity to the mass ordering and energy resolution

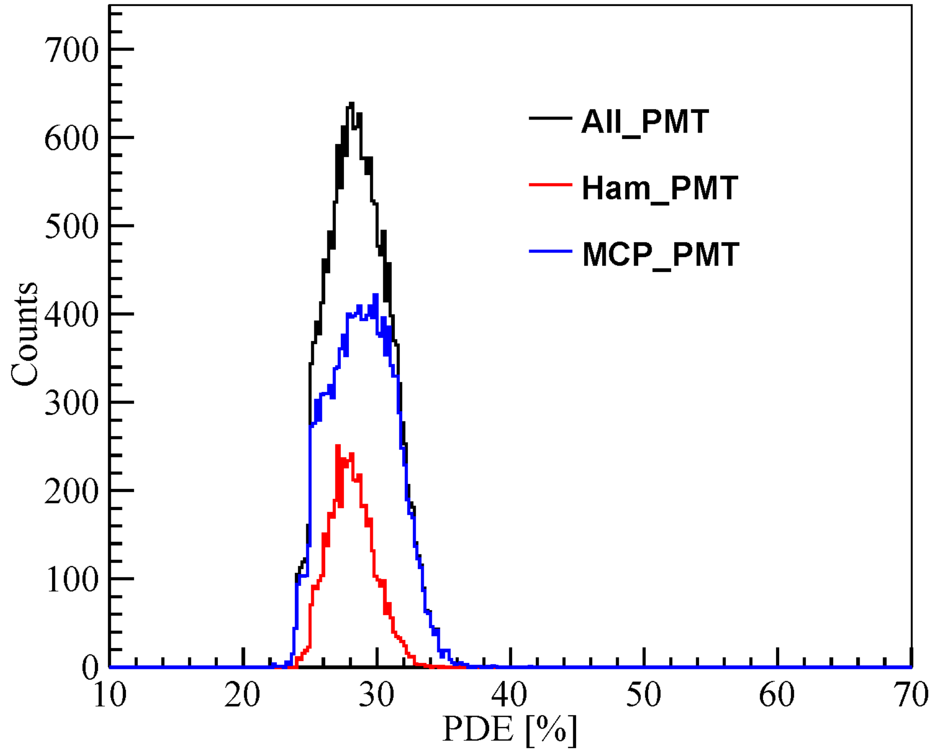
$|\Delta\chi^2_{\min}|$ is the test static used to discriminate between the two orderings

$$|\Delta\chi^2_{\min}| = |\chi^2_{\min}(\text{NO}) - \chi^2_{\min}(\text{IO})|$$



Light yield

- High phocathode coverage: 78%
- High PMT Photon Detection Efficiency (PDE): ~ 30%
  - PDE = quantum efficiency x collection efficiency
- High liquid scintillator transparency: absorption length > 20 m
- 1345 PE/MeV
- Increased by about 22% from recent simulations



20-inch Large-PMT (LPMT) system

Primary calorimetric system:
17612 20-inch PMTs

Photocathode coverage: 75.2%

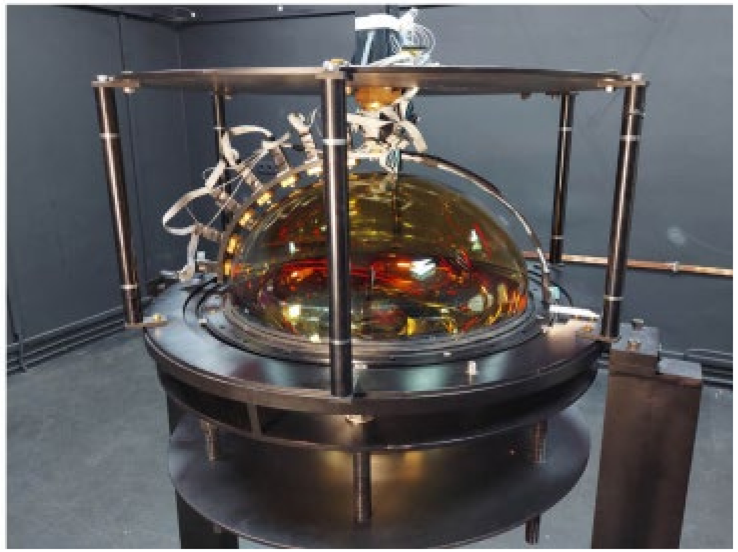
High photon detection efficiency

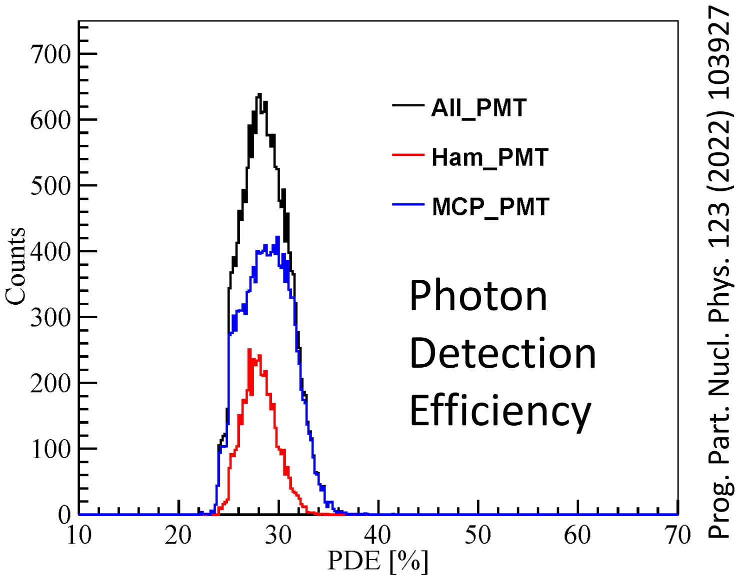
- Hamamatsu dynode PMTs: 28.1%
- NNTV MCP* PMTs: 28.9%

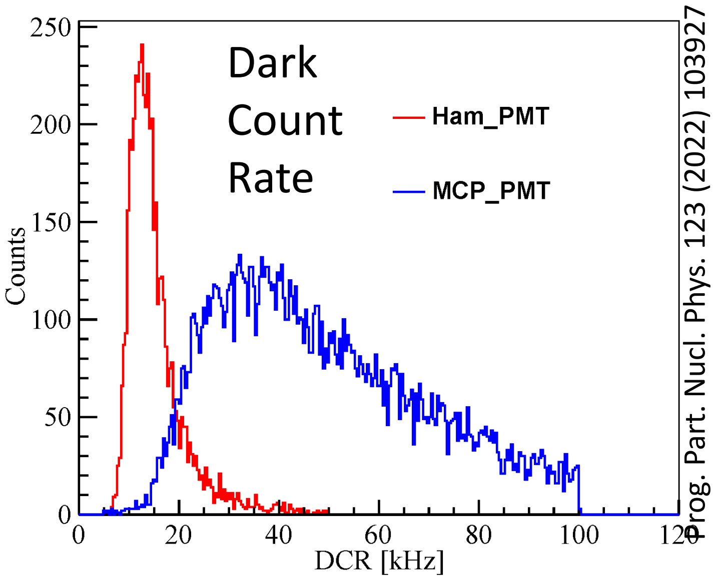
Low dark count rate (DCR)

Dynamic range: 0 - 100 PE

Waveform acquisition and charge reconstruction







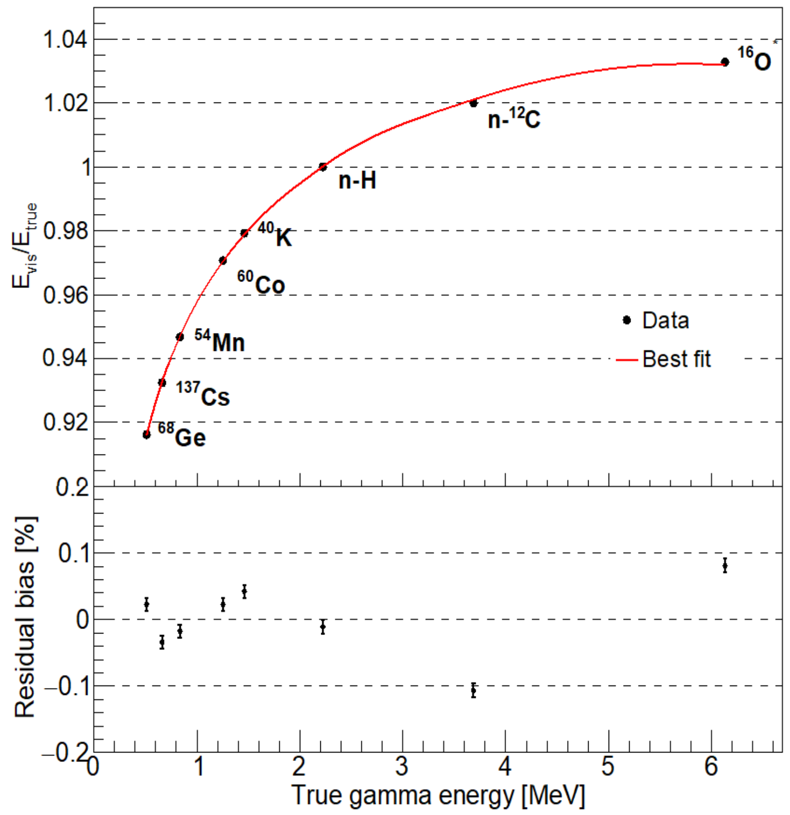
*Micro-channel plate PMTs

JUNO calibration strategy

Calibration of liquid scintillator nonlinearity

Multiple-source campaign: up to ~6 MeV
+ cosmogenic background ^{12}B: up to 12 MeV

Source	Type	Radiation
^{137}Cs	γ	0.662 MeV
^{54}Mn	γ	0.835 MeV
^{60}Co	γ	1.173 + 1.333 MeV
^{40}K	γ	1.461 MeV
^{68}Ge	e^+	annihilation 0.511 + 0.511 MeV
^{241}Am-Be	n, γ	neutron + 4.43 MeV ($^{12}C^*$)
^{241}Am-^{13}C	n, γ	neutron + 6.13 MeV ($^{16}O^*$)
(n,γ)p	γ	2.22 MeV
(n,γ)^{12}C	γ	4.94 MeV or 3.68 + 1.26 MeV



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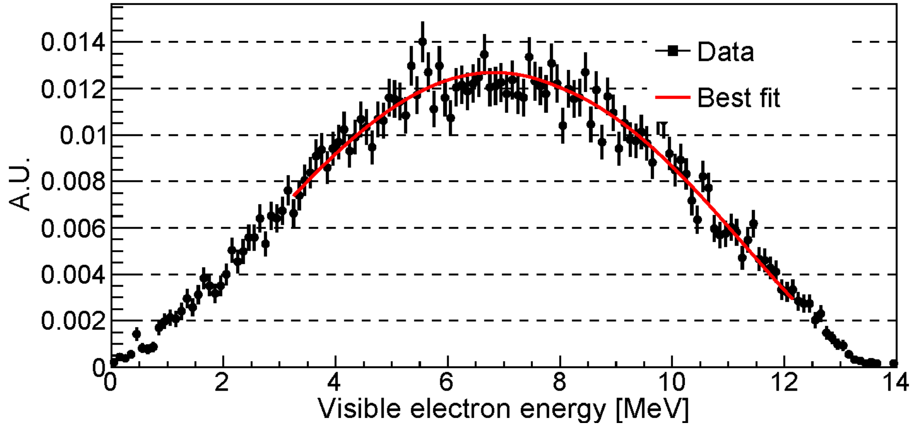
^{12}B spectrum



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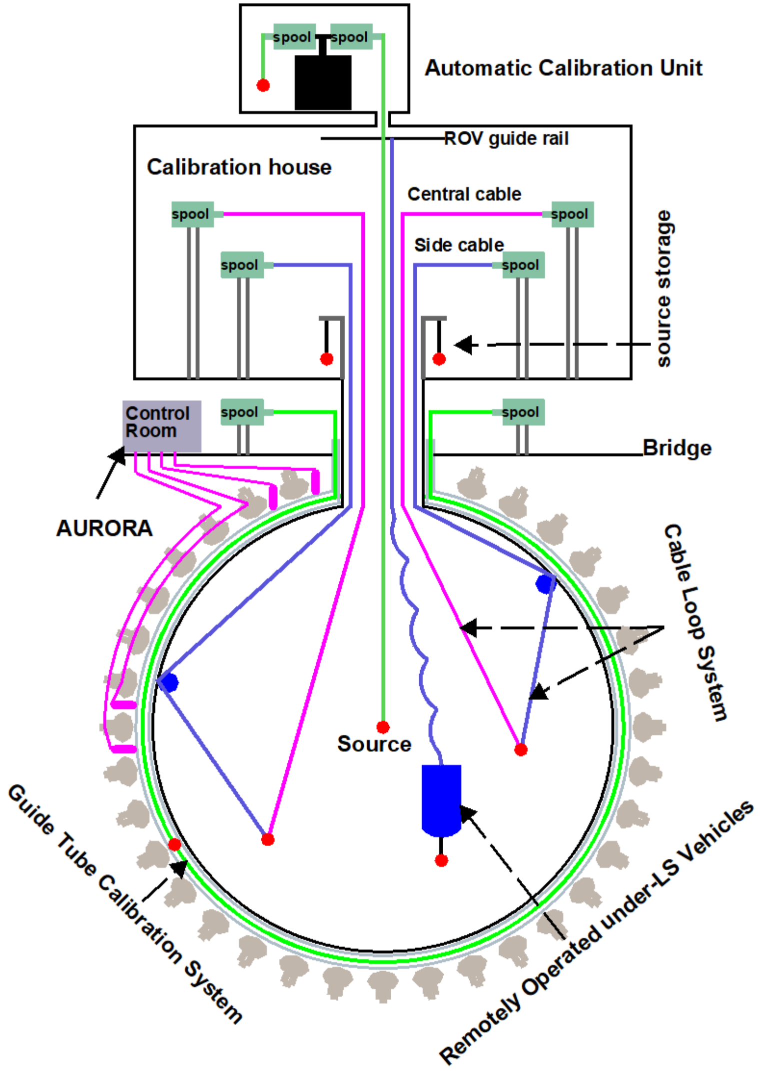
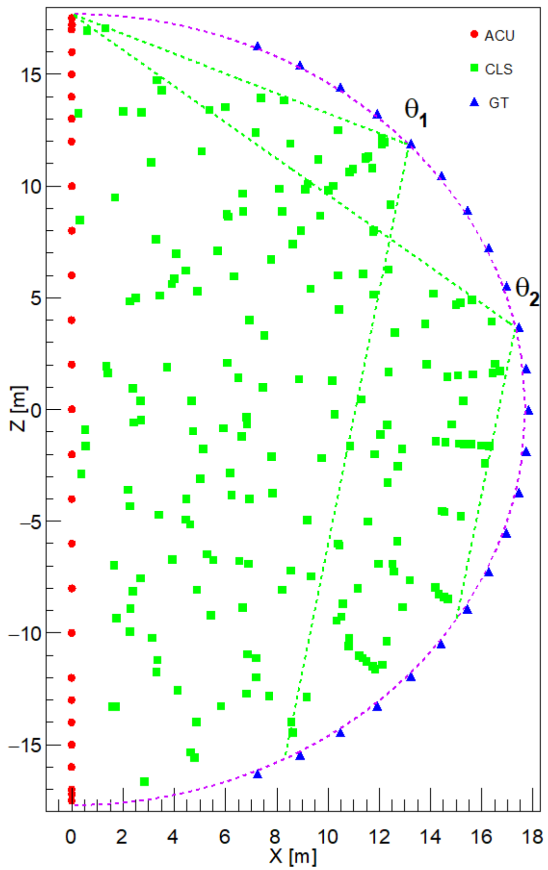
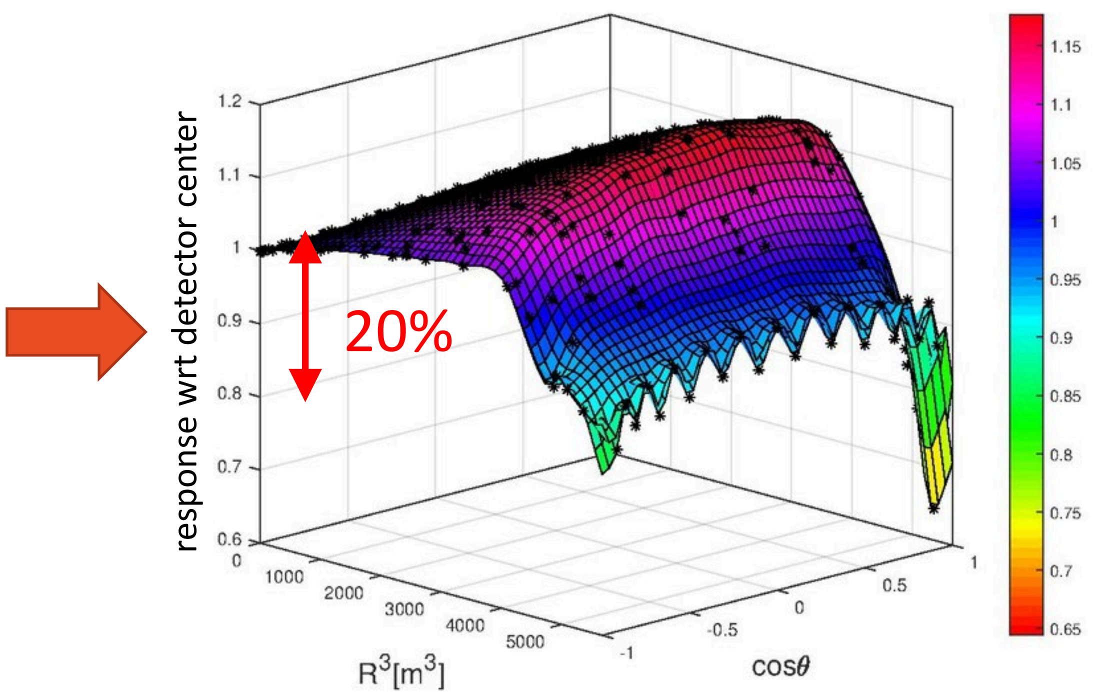
Non-Uniformity: Multiple-positional calibration



250 calibration points



Non-Uniformity in one vertical plane



JUNO simulation

azimuthal symmetry is assumed

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