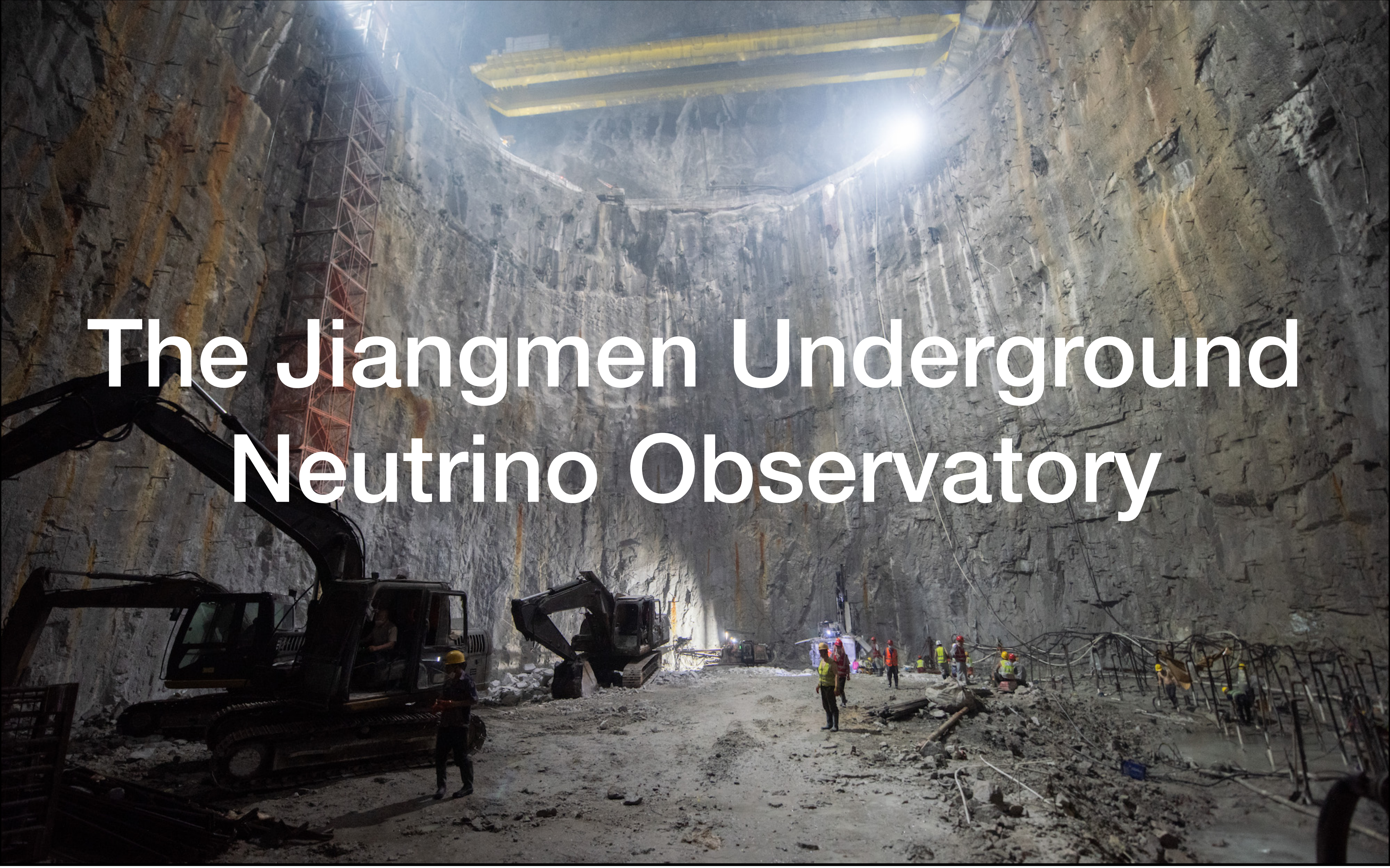
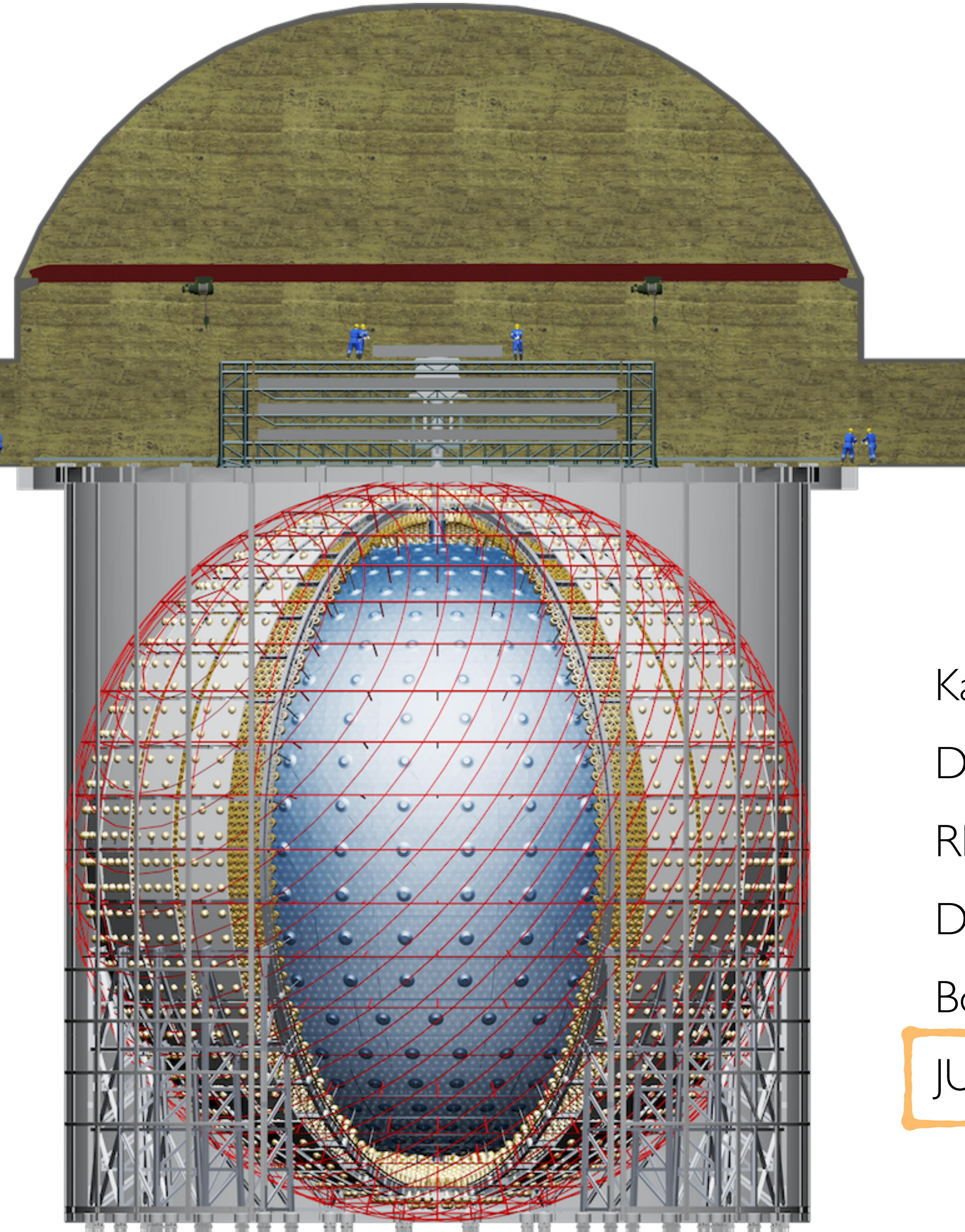


The Jiangmen Underground Neutrino Observatory

Marco Grassi (U. Padova & INFN)
on behalf of the JUNO collaboration

What is JUNO?



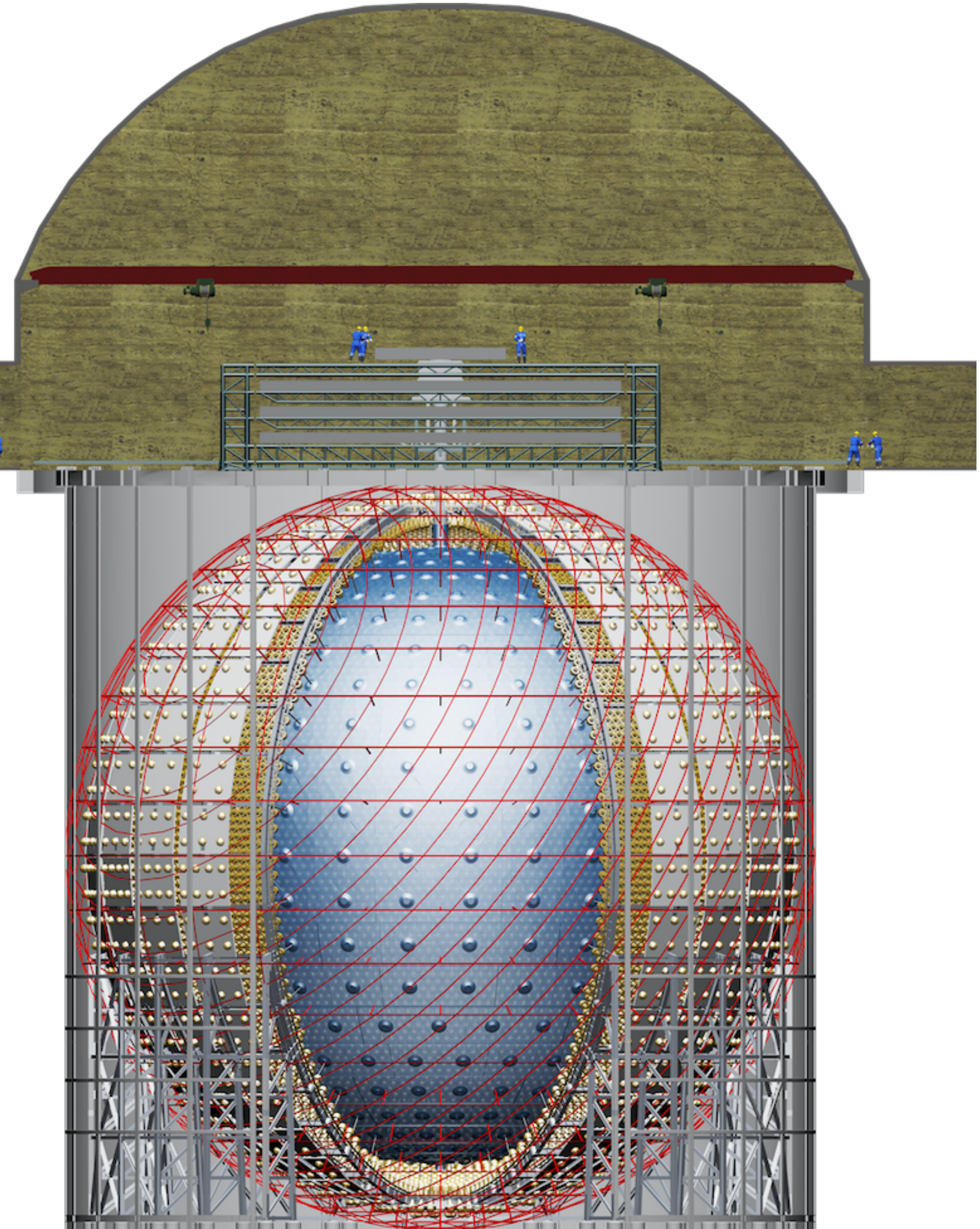
a huge liquid scintillator detector

2 key parameters:

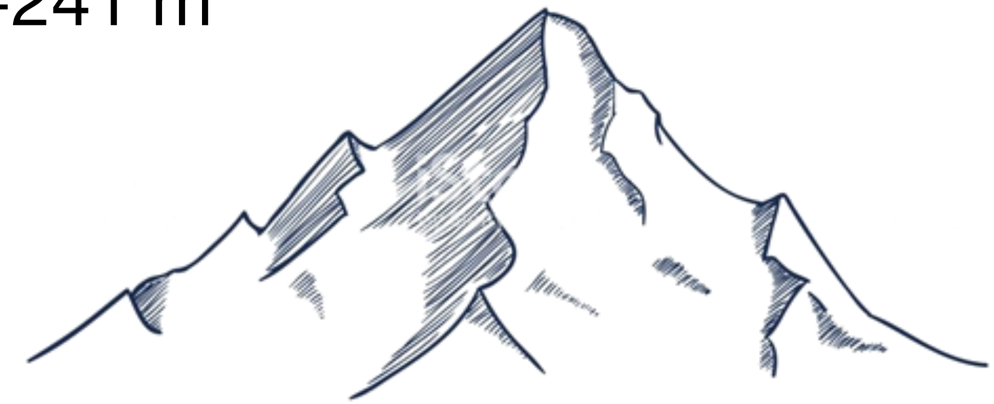
LARGE & PRECISE

	DETECTOR TARGET MASS	RESOLUTION
KamLAND	1000 t	6%/√E
Double Chooz	8 t	8%/√E
RENO	16 t	8%/√E
Daya Bay	20 t	8%/√E
Borexino	300 t	5%/√E
JUNO	**20000 t**	**3%/√E**

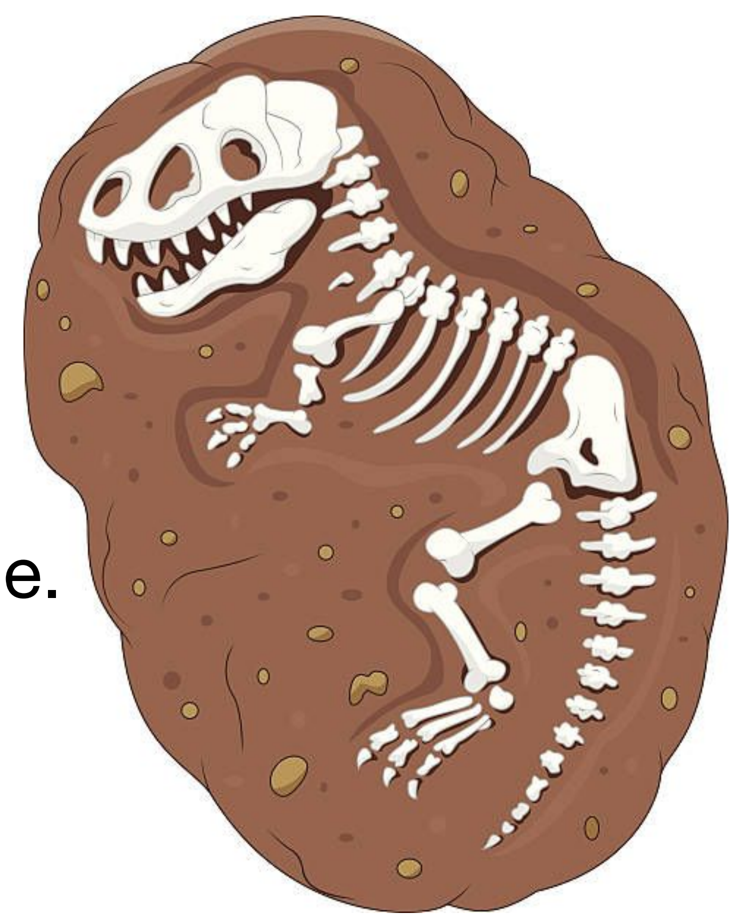
JUNO is Underground



+241 m



-430 m

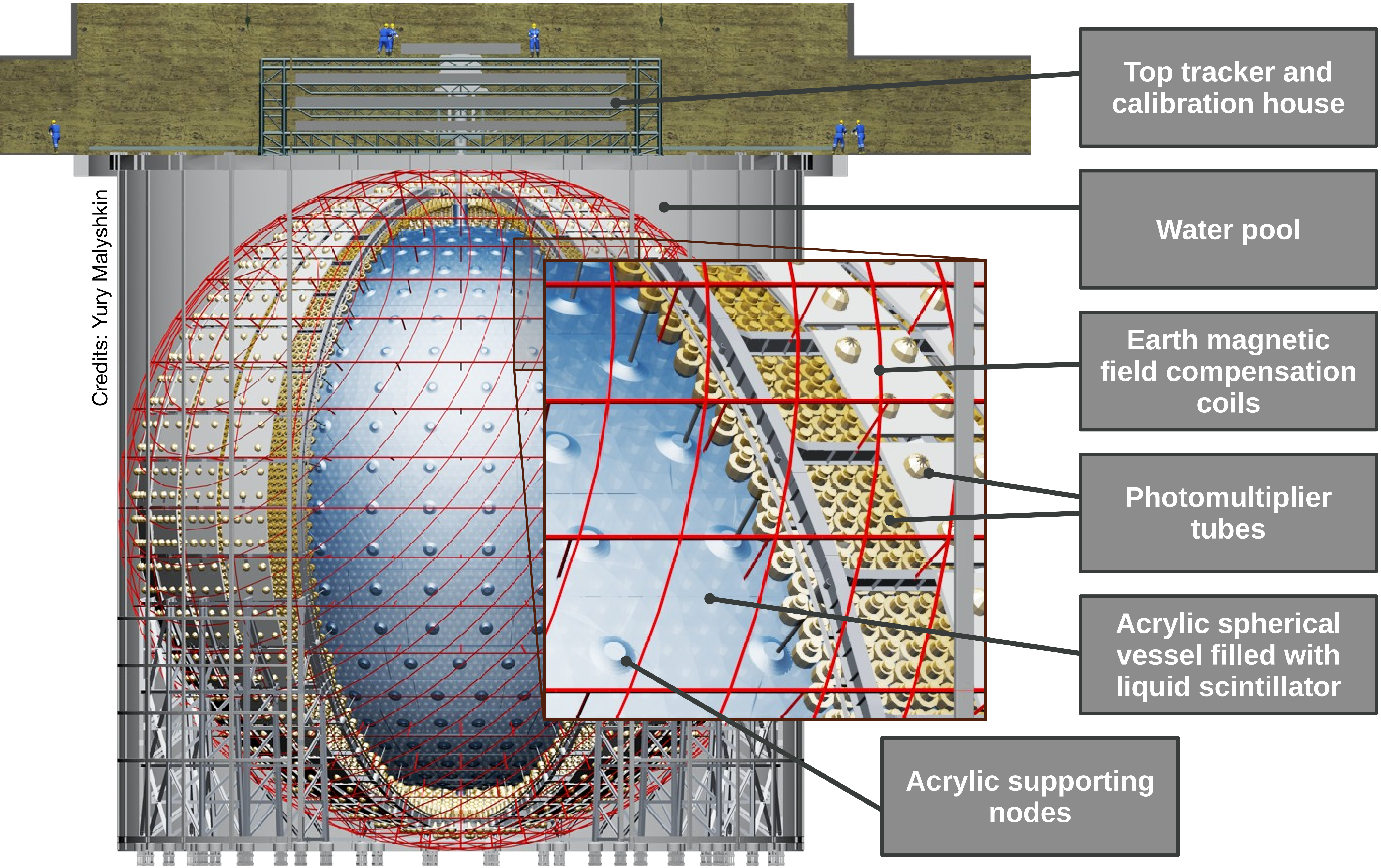


-453 m

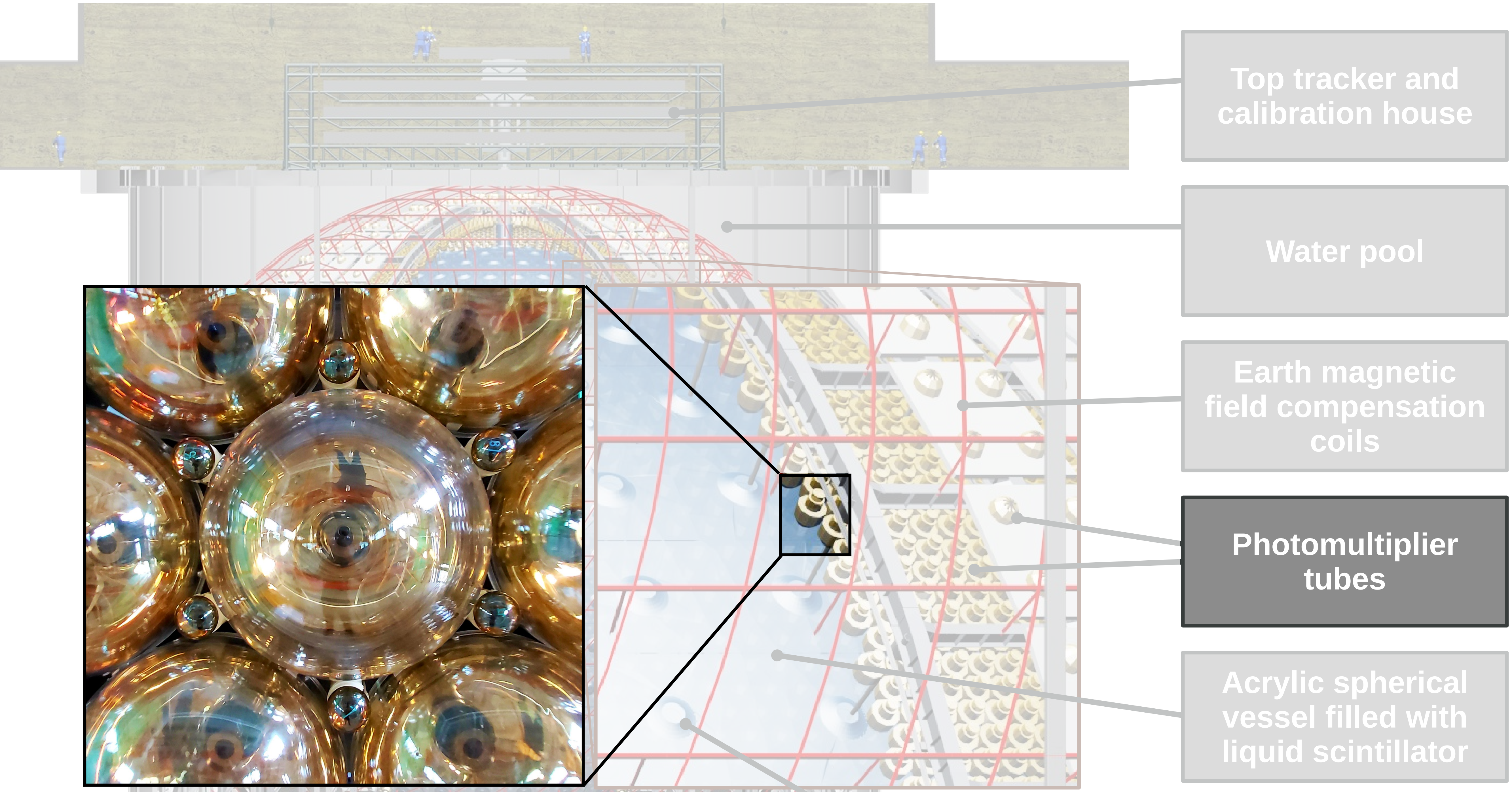
1800 m.w.e.

$\rho_{rock} \sim 2.6\ g/cm^3$

JUNO is a Neutrino Detector



JUNO is a Neutrino Detector



Largest PMT coverage to date: 78% active surface

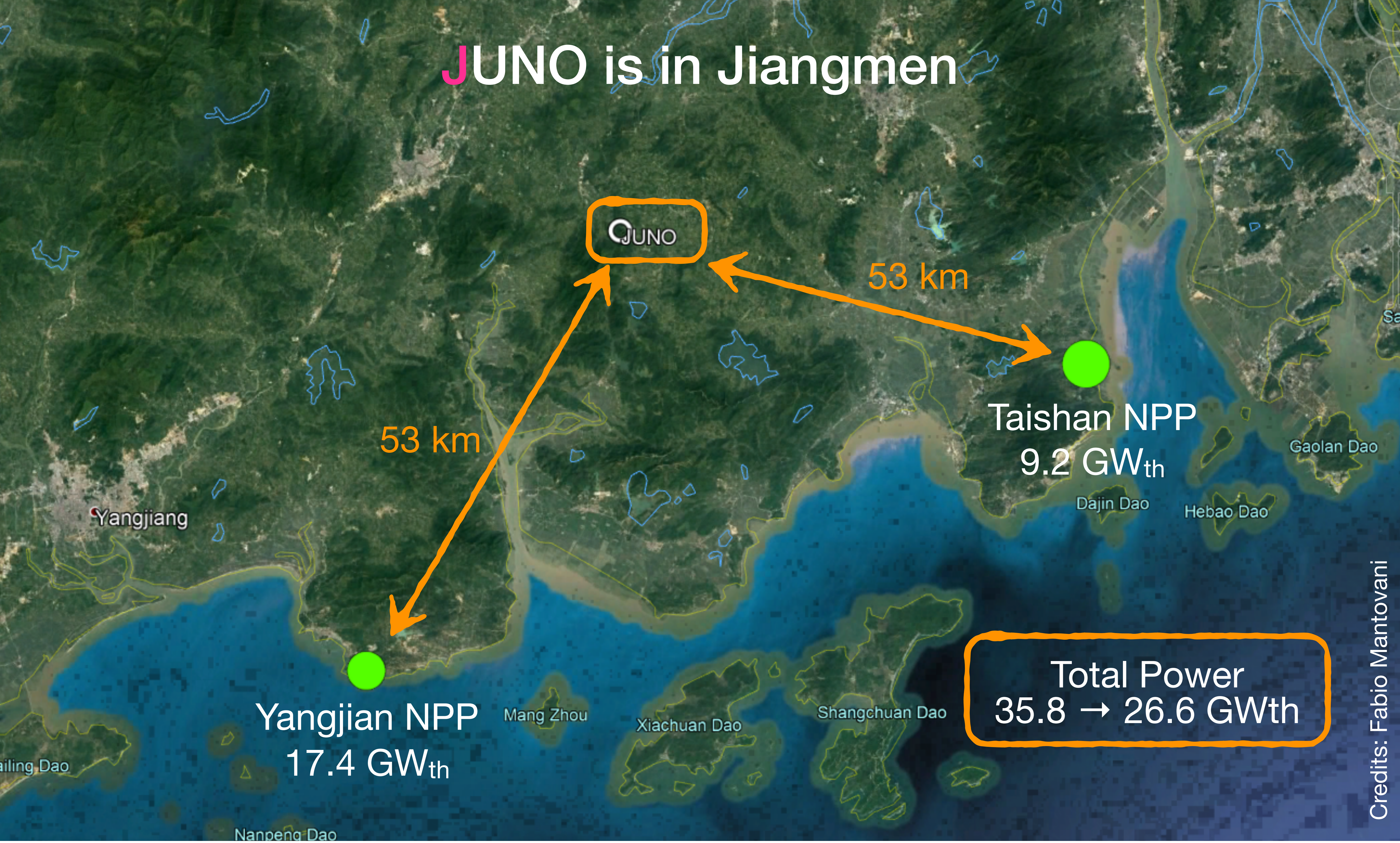
Unprecedented light level for a PMT-based detector: ~1300 pe/MeV (expected)

(Daya Bay 160 pe/MeV - Borexino 500 pe/MeV - KamLAND 250 pe/MeV)

JUNO is an Observatory

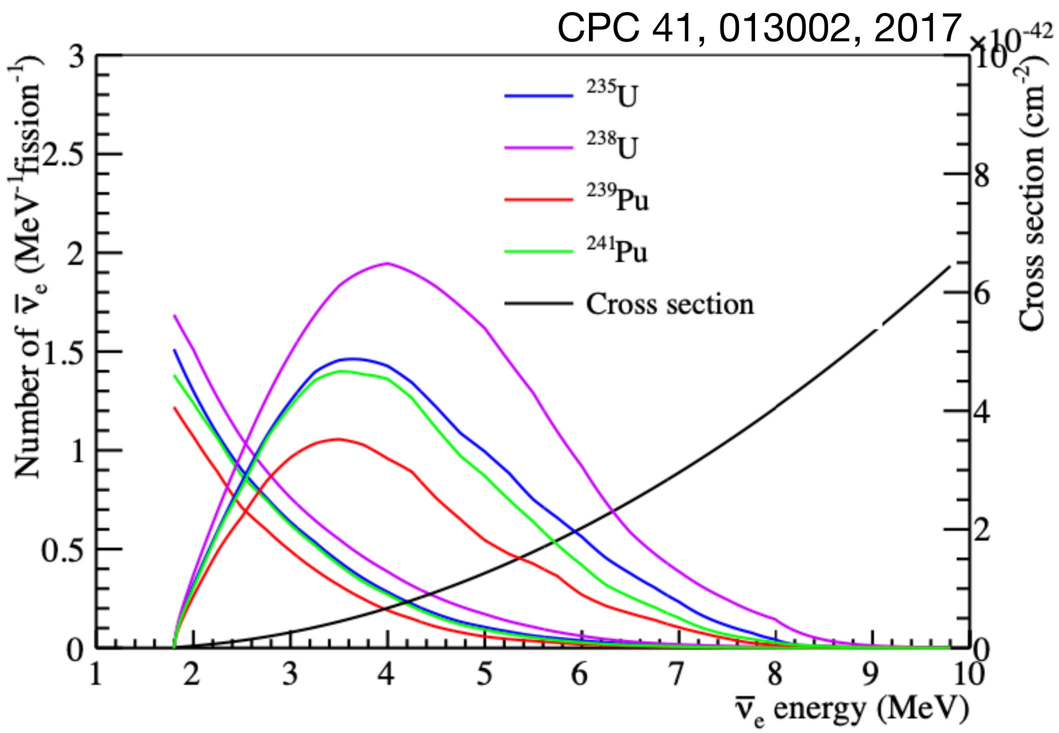
Research	Expected signal	Energy region	Major backgrounds
Reactor antineutrino	45 IBDs/day	0–12 MeV	Radioactivity, cosmic muon
Supernova burst	5000 IBDs at 10 kpc 2300 elastic scattering	0–80 MeV	Negligible
DSNB (w/o PSD)	2–4 IBDs/year	10–40 MeV	Atmospheric ν
Solar neutrino	hundreds per year for ^{8}B	0–16 MeV	Radioactivity
Atmospheric neutrino	hundreds per year	0.1–100 GeV	Negligible
Geoneutrino	$\sim$ 400 per year	0–3 MeV	Reactor ν

JUNO is in Jiangmen



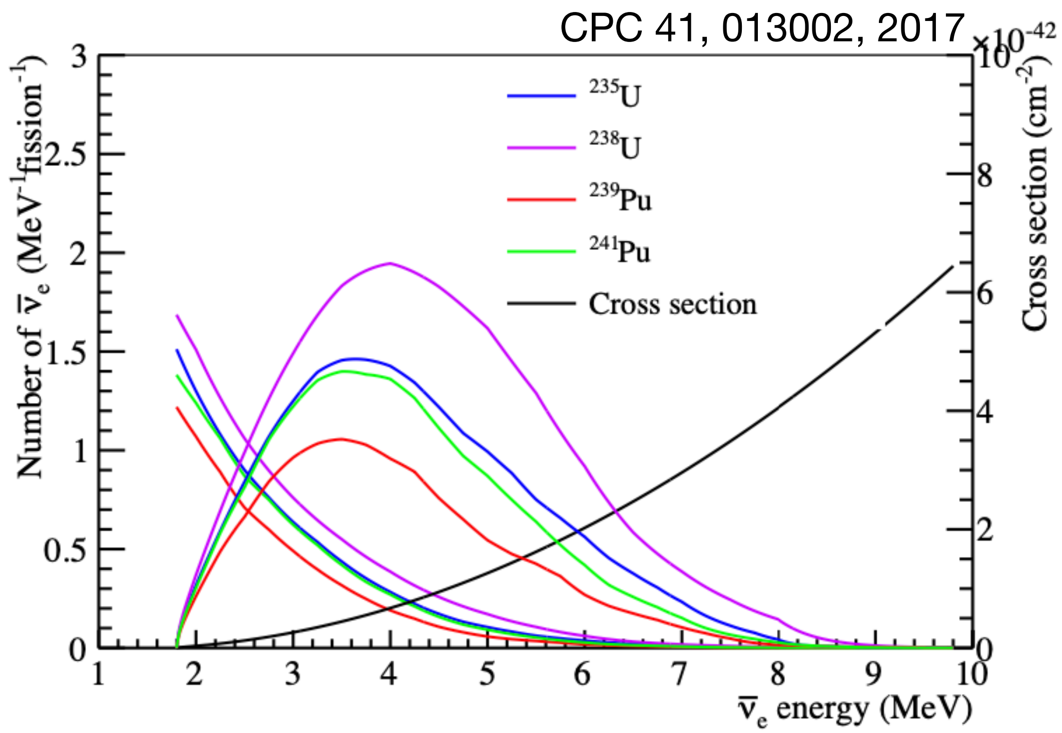
Cores	YJ-1	YJ-2	YJ-3	YJ-4	YJ-5	YJ-6	TS-1	TS-2	DYB	HZ
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9	4.6	4.6	17.4	17.4
Baseline(km)	52.74	52.82	52.41	52.49	52.11	52.19	52.77	52.64	215	265

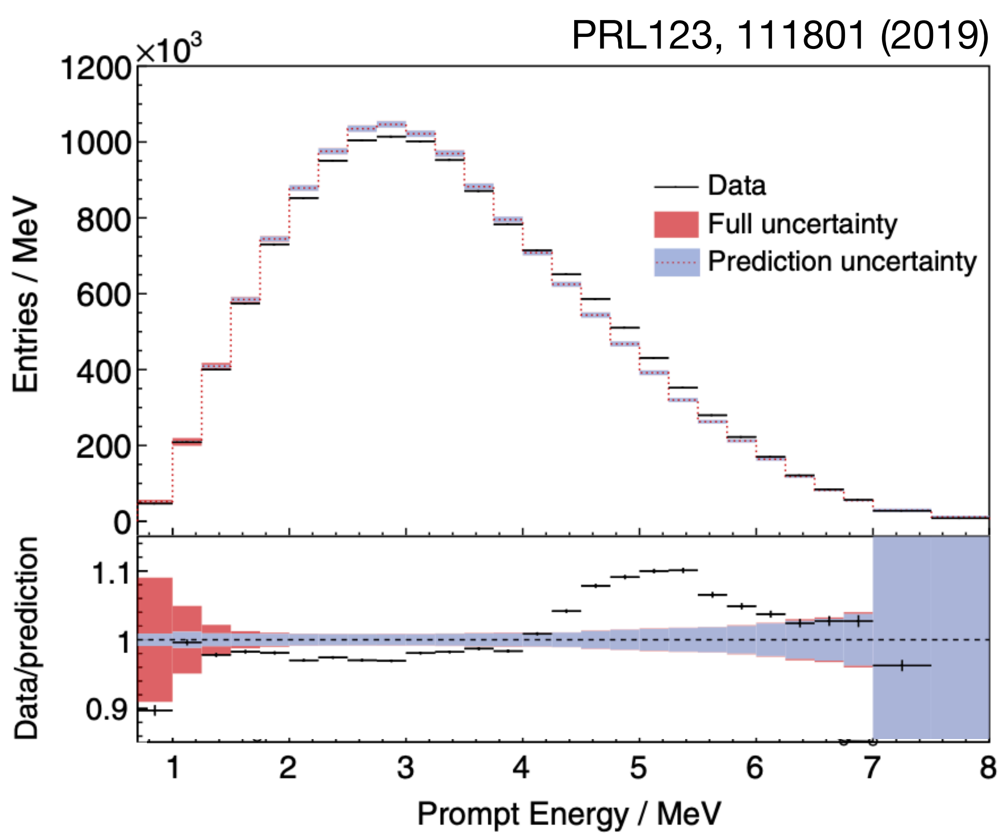
Antineutrino Yield at Nuclear Reactors



Four isotopes are responsible for most of the $\bar{\nu}_e$ flux

Antineutrino Yield at Nuclear Reactors

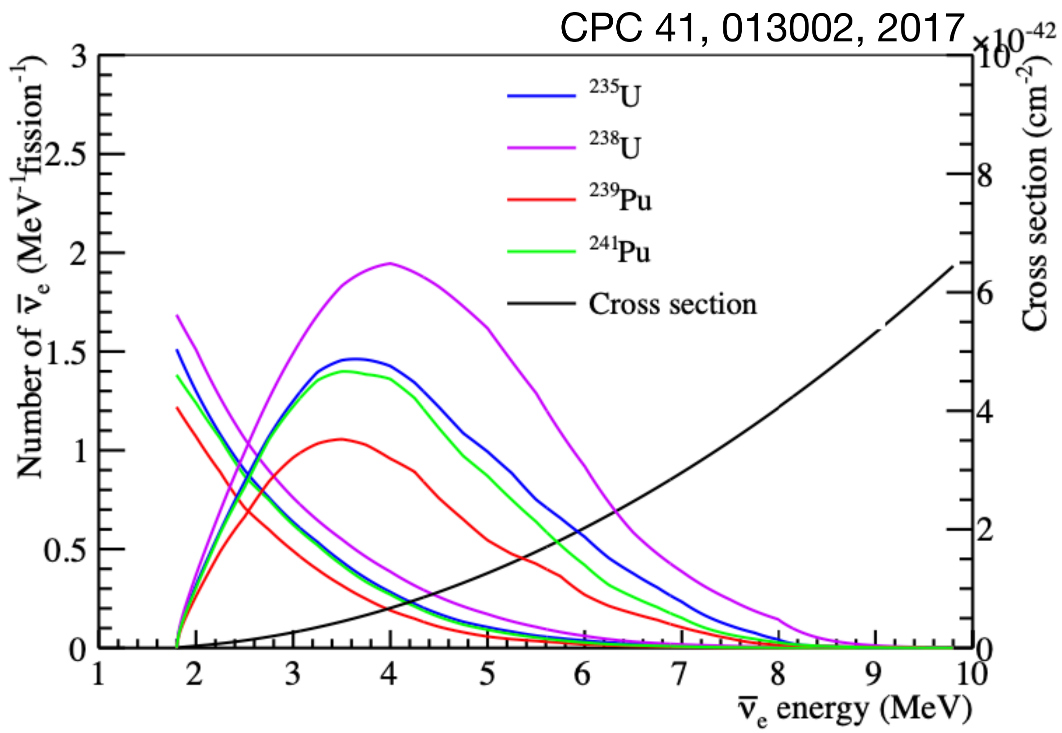




Four isotopes are responsible for most of the $\bar{\nu}_e$ flux

Any feature in $\bar{\nu}_e$ energy spectrum needs to be properly taken into account

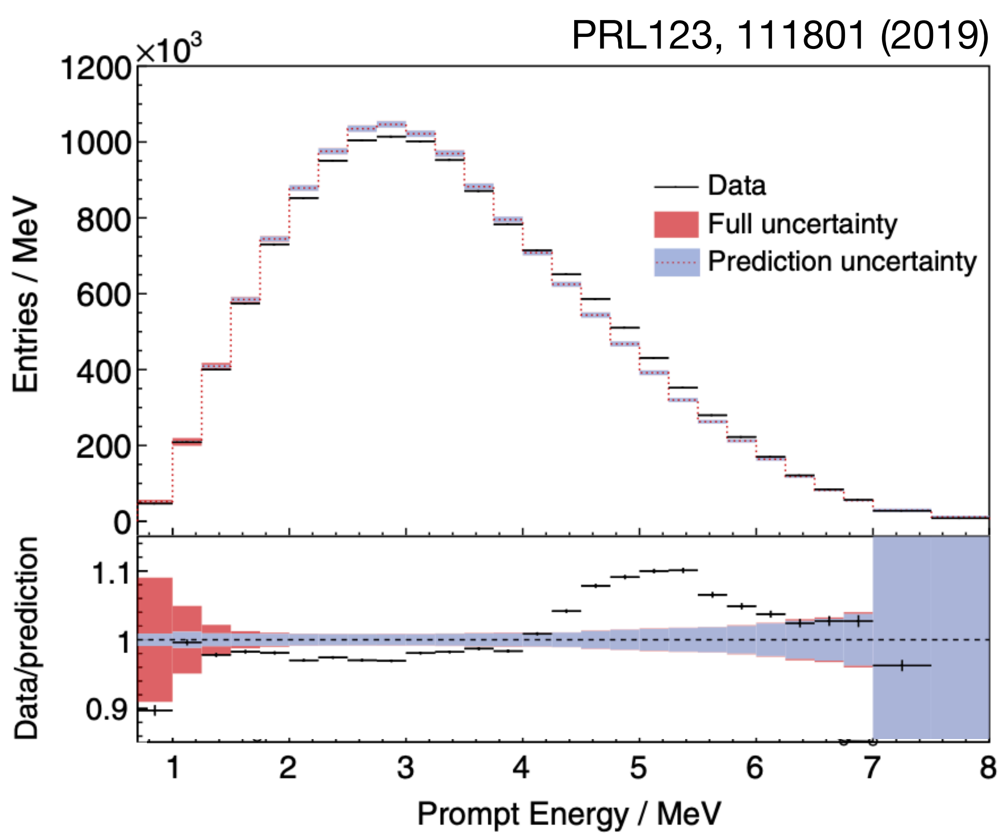
Antineutrino Yield at Nuclear Reactors

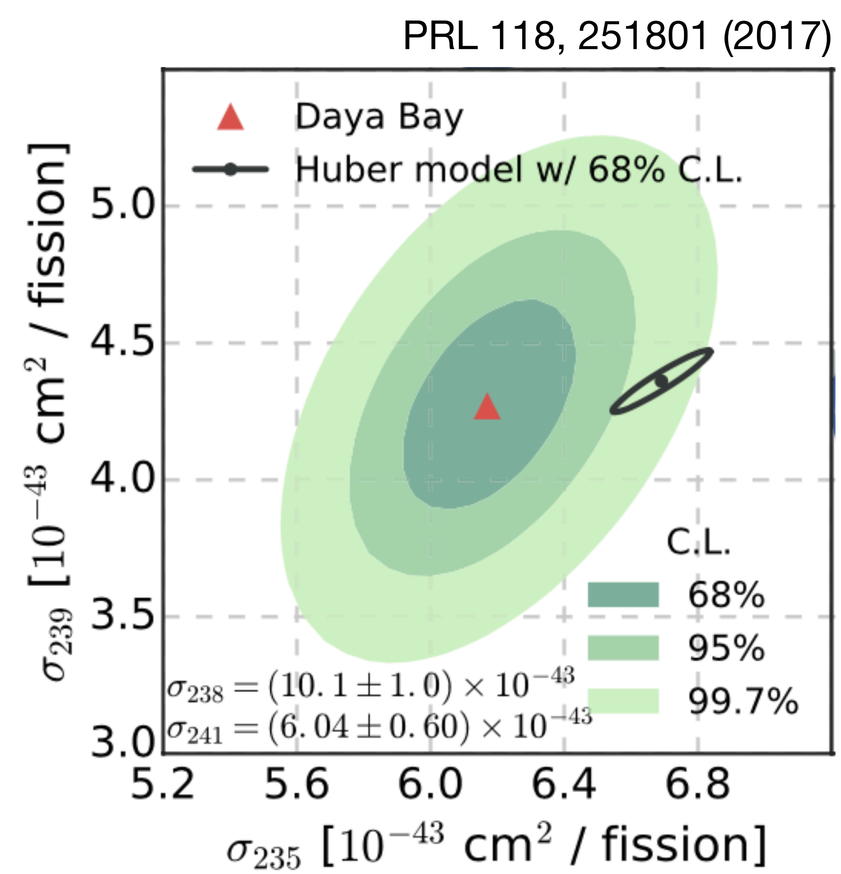


Four isotopes are responsible for most of the $\bar{\nu}_e$ flux

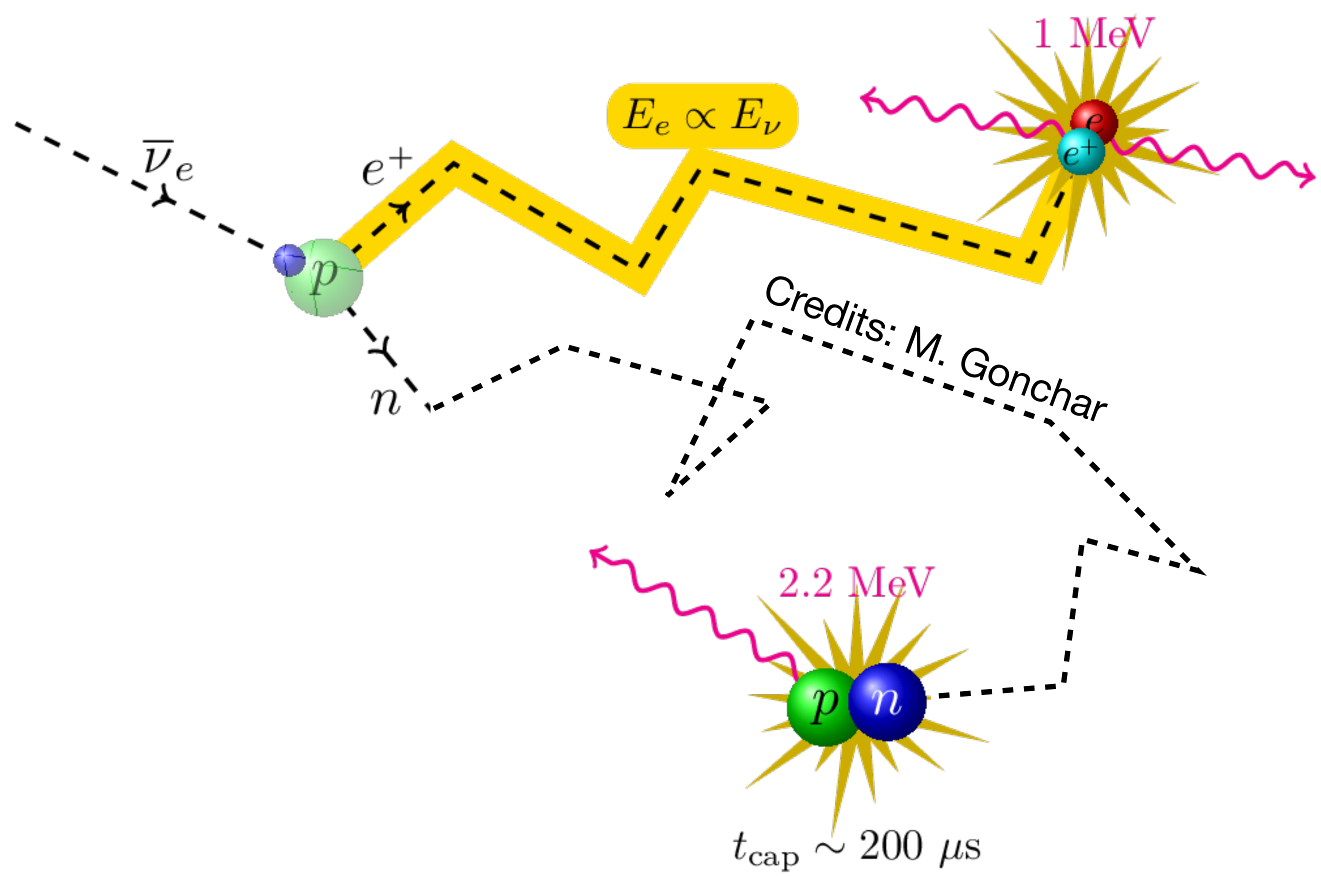
Any feature in $\bar{\nu}_e$ energy spectrum needs to be properly taken into account

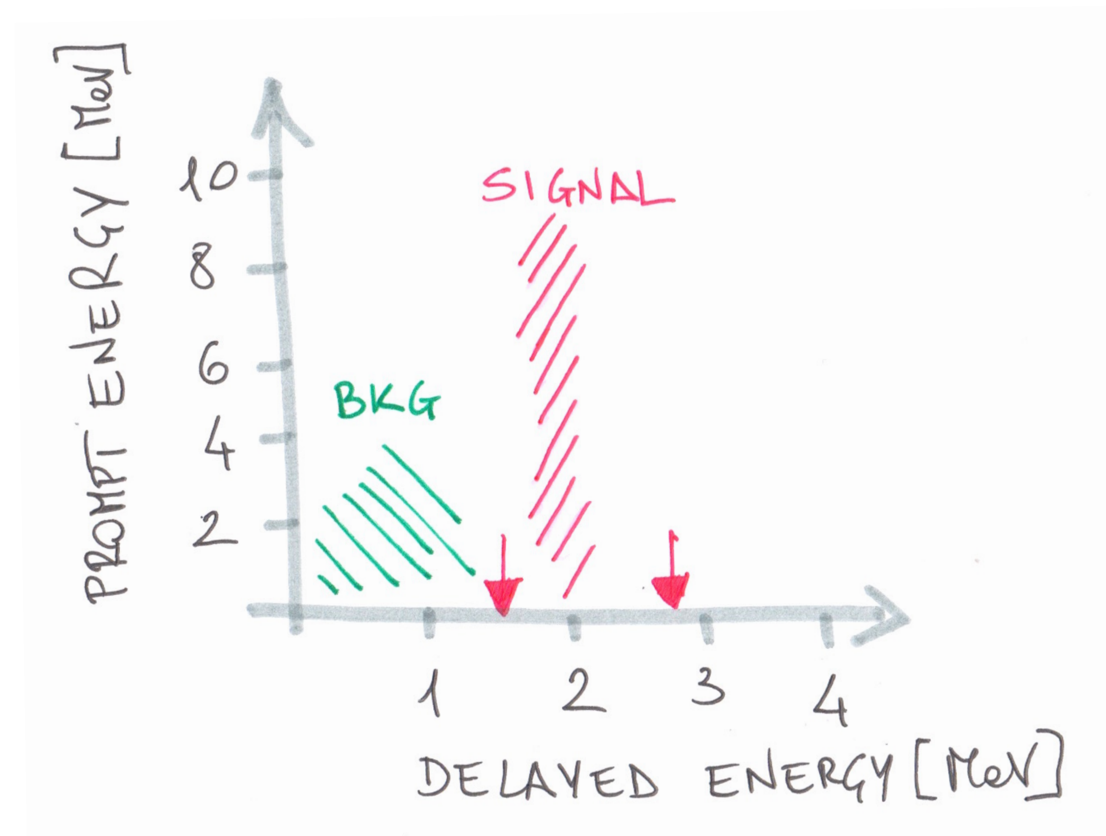
Issues in the overall flux are less important





Antineutrino Detection and Selection





Modified from JPG 43, 030401 (2016)

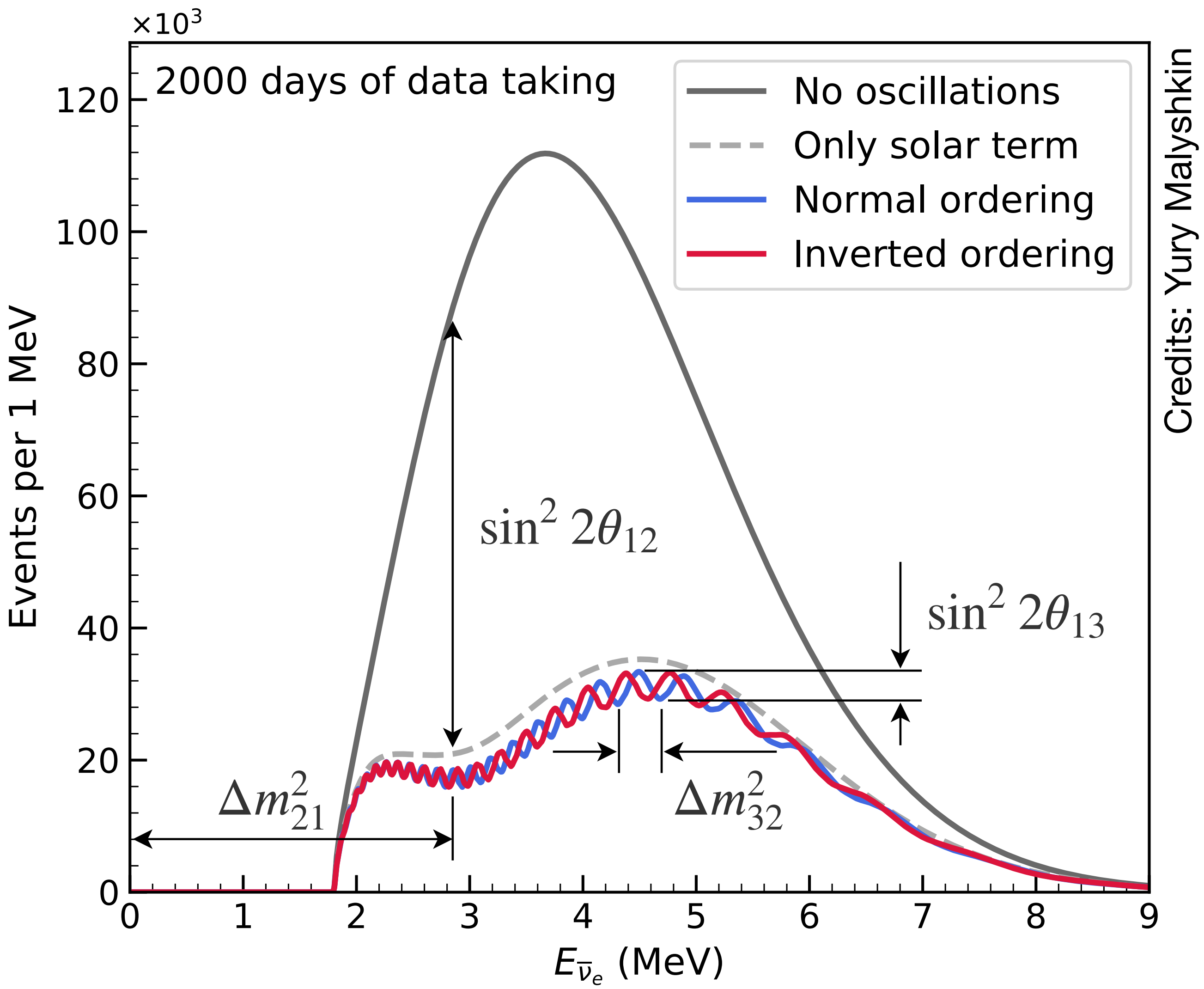
Selection	IBD efficiency	IBD	Geo-νs	Accidental	^{9}Li/^{8}He	Fast n	(α, n)
-	-	62	1.5	-	84	-	-
Fiducial volume	91.8%	57	1.4	410	77	0.1	0.05
Energy cut	97.8%	55	1.3		71		
Time cut	99.1%						
Vertex cut	98.7%			1.1			
Muon veto	83%	45	1.1	0.9	1.6		
Combined	73%	45	3.75				

Same signal signature

Neutrino Oscillation Parameters

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \left(\sin^2\theta_{12} \sin^2 \frac{\Delta m^2_{32}}{4E} + \cos^2\theta_{12} \sin^2 \frac{\Delta m^2_{31}}{4E} \right)$$

$$- \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2 \frac{\Delta m^2_{21}}{4E}$$



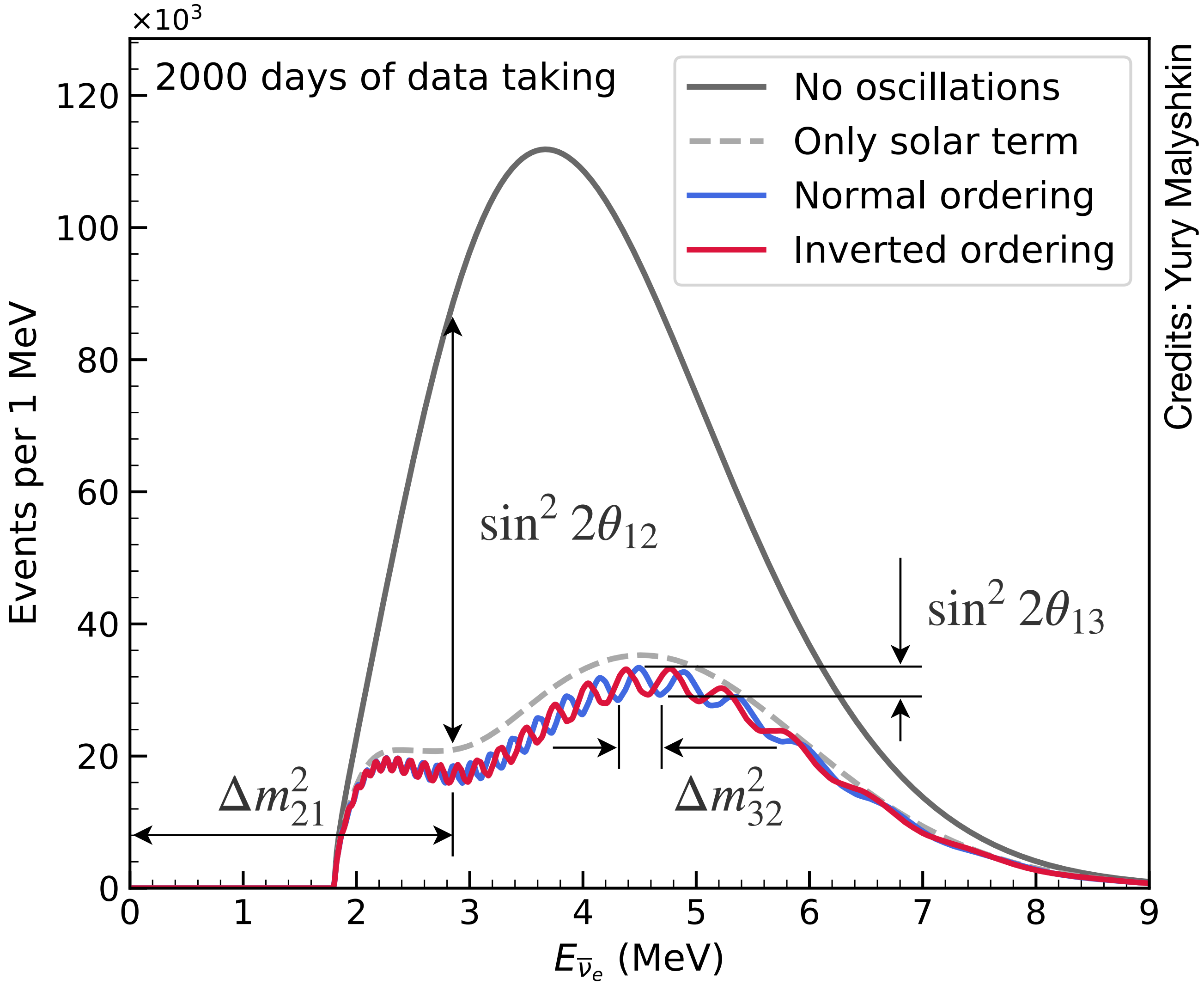
Detect for the first time solar and atmospheric modes simultaneously

Sensitivity driven by shape analysis

Uncertainty in absolute number of events has negligible impact

JUNO will measure $\sin^2\theta_{12}$, Δm^2_{31} and Δm^2_{12} with a precision better than 1% in few years

Neutrino Mass Ordering



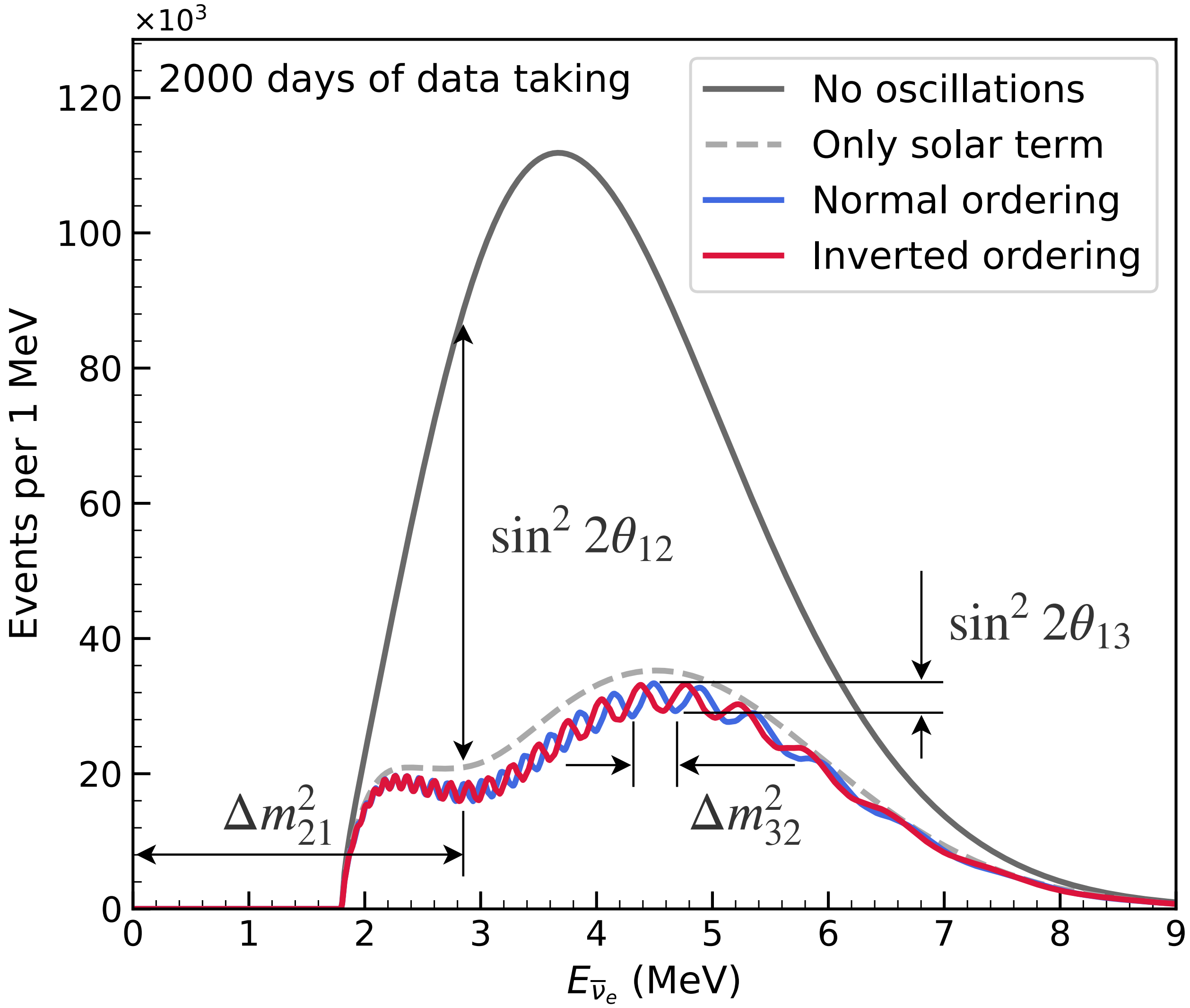
Test Statistic

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

Expected $\Delta\chi^2 \sim 10$

Significance $\sim 3\sigma$

Neutrino Mass Ordering



Credits: Yury Malyshkin

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Expected $\Delta\chi^2 \sim 10$

Significance $\sim 3\sigma$

Updates w.r.t JPG 43, 030401 (2016)

2 reactor cores won't be built ↓

Experimental hall up by 60 m
30% larger muon flux ↓

Measured PMT quantum efficiency better than specs: 27% → 29% ↑

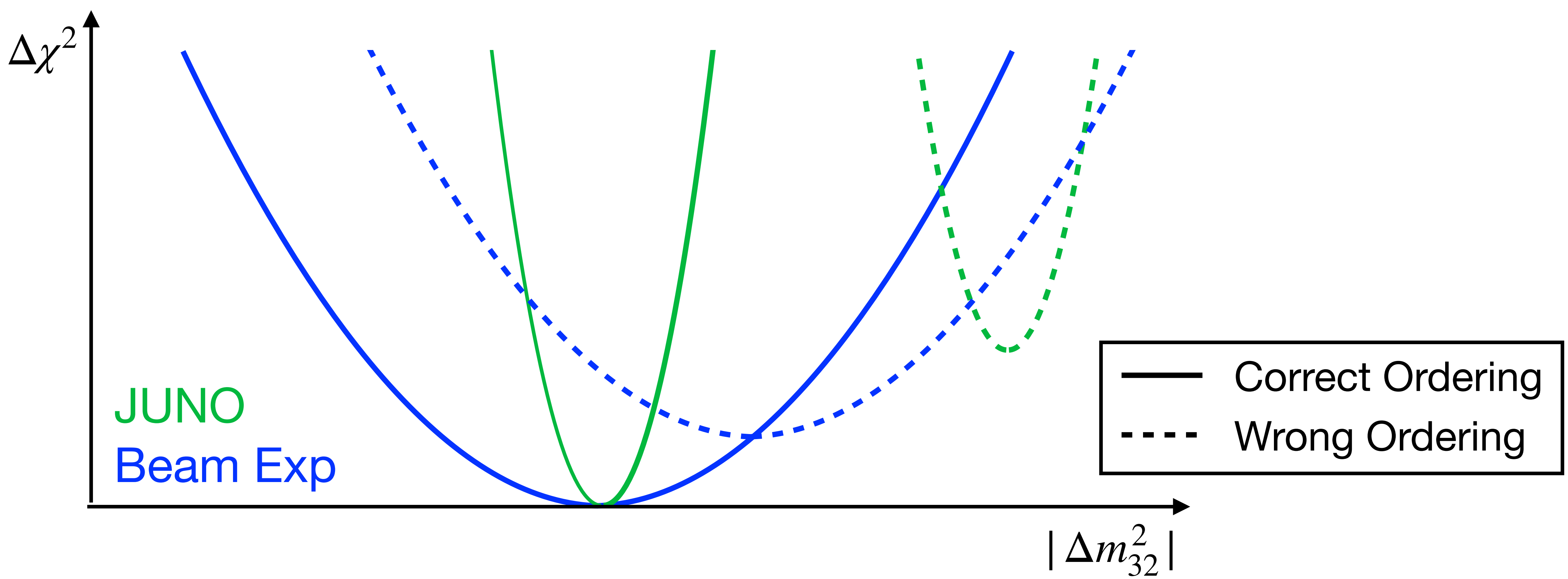
More light from LS cocktail based on experimental measurements ↑

Unoscillated reactor spectrum better constrained thanks to TAO (see later) ↑

Synergy in Determining the Mass Ordering

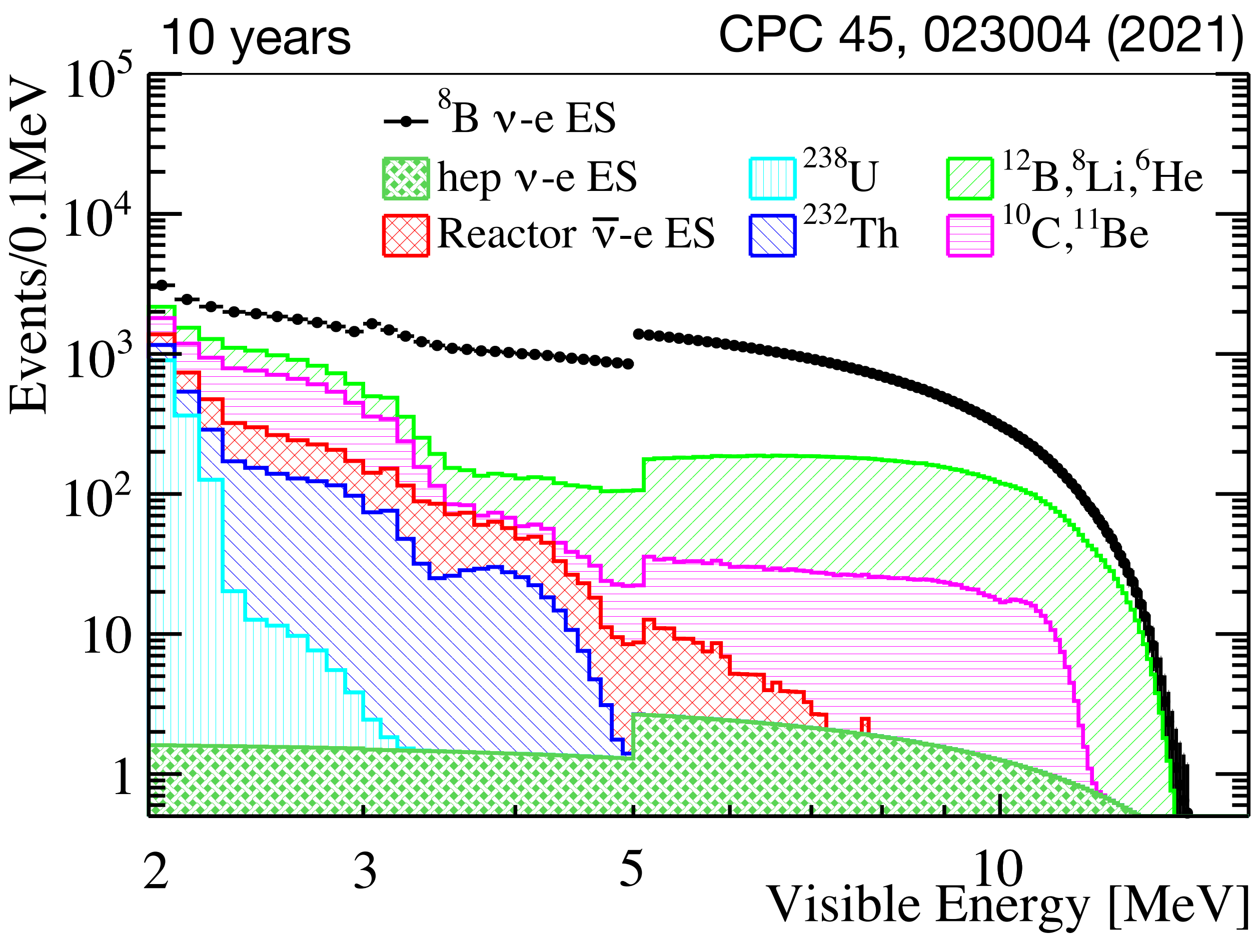
Disappearance	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	Reactor	Both sensitive to atmospheric mass splitting Δm^2_{32}
Appearance	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_\mu \rightarrow \nu_e$	Beam	

Values are expected to agree only when correct ordering is assumed



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

Neutrinos from the ^{8}B decay in the Sun



Detection: ν_e elastic scattering off e^-

Main backgrounds:

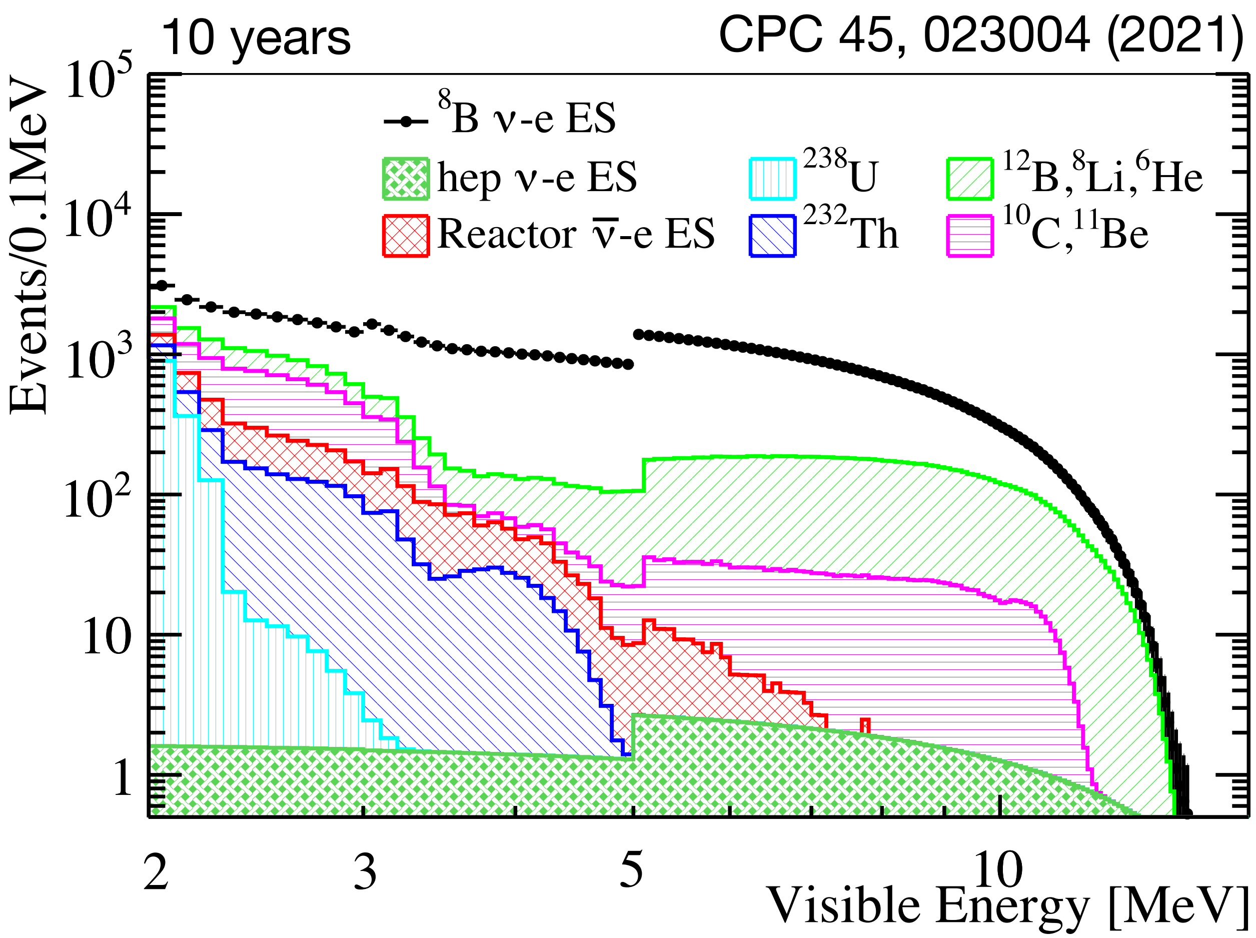
LS intrinsic radioactivity (10^{-17}g/g)

Fiducial volume & 2 MeV threshold

Decay of cosmogenic isotopes

Test of the transition from vacuum to matter-dominated ν_e survival probability

Neutrinos from the ^{8}B decay in the Sun



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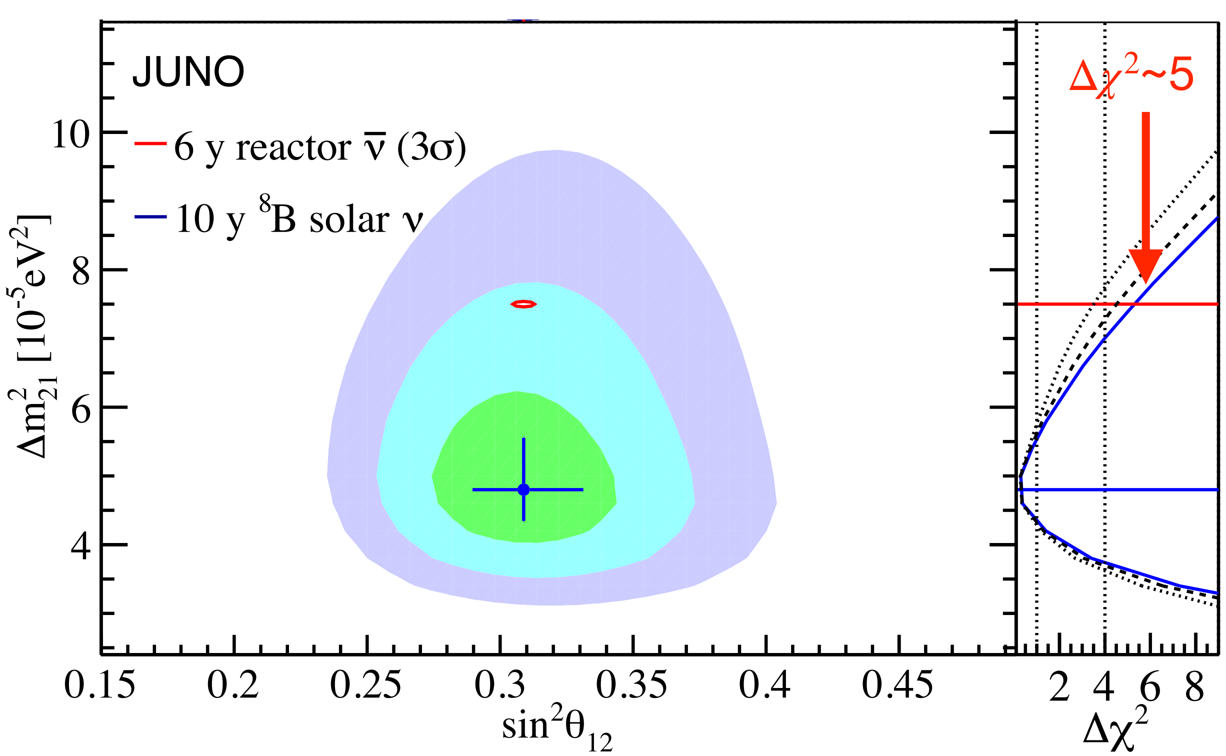


Joint fit of

elastic scattering reaction rate

P_{ee} spectral distortion

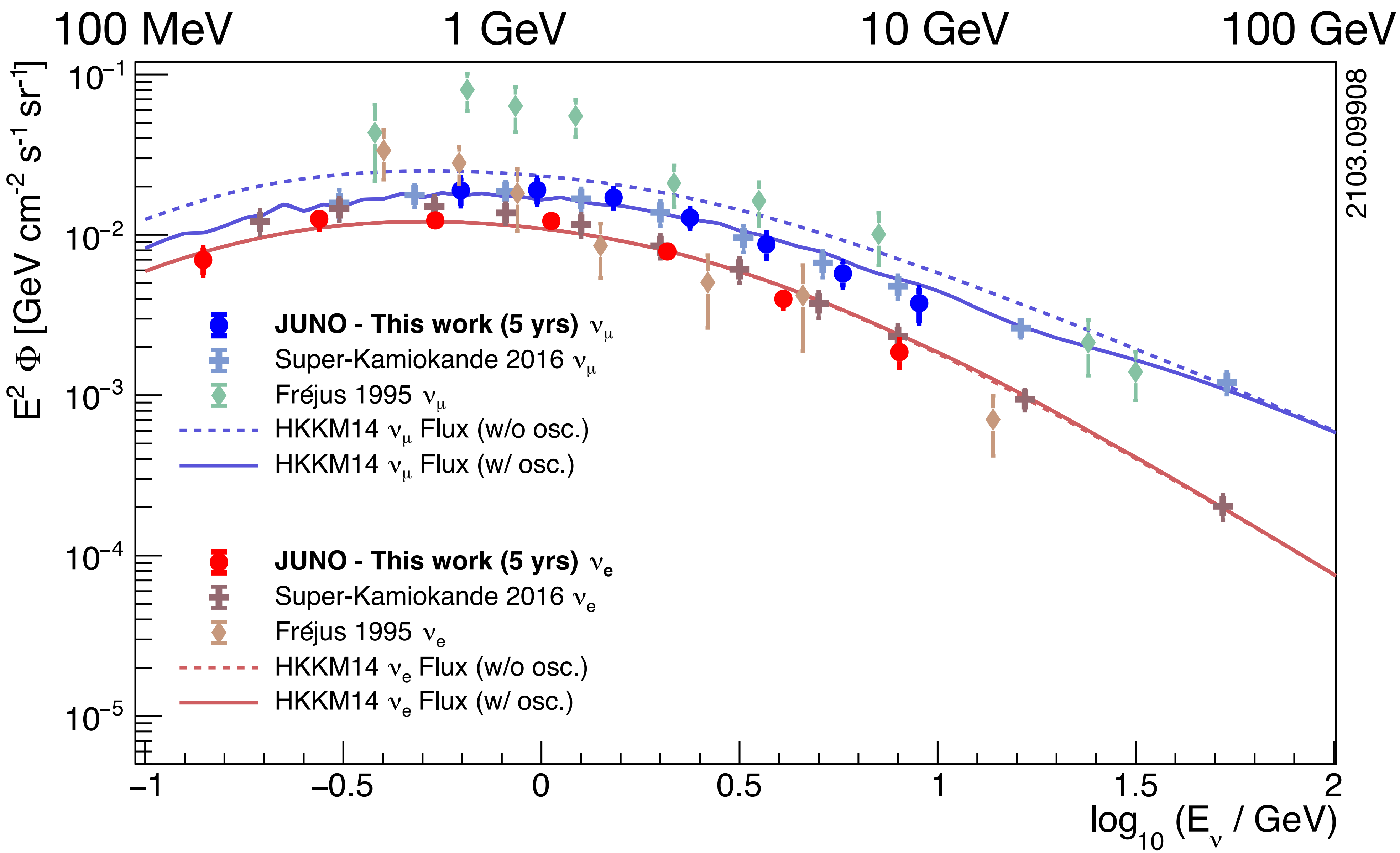
day-night asymmetry

Simultaneous determination of

$\sin^2\theta_{12}$ — limited by SNO NC

Δm^2_{12} — limited by D/N & upturn

Atmospheric Neutrinos



Based on full simulation and reconstruction chains

ν_e vs ν_μ discrimination thanks to hit time pattern

Complementary measurement of the Neutrino Mass Ordering (~1 σ in 10 years)

Proton Decay

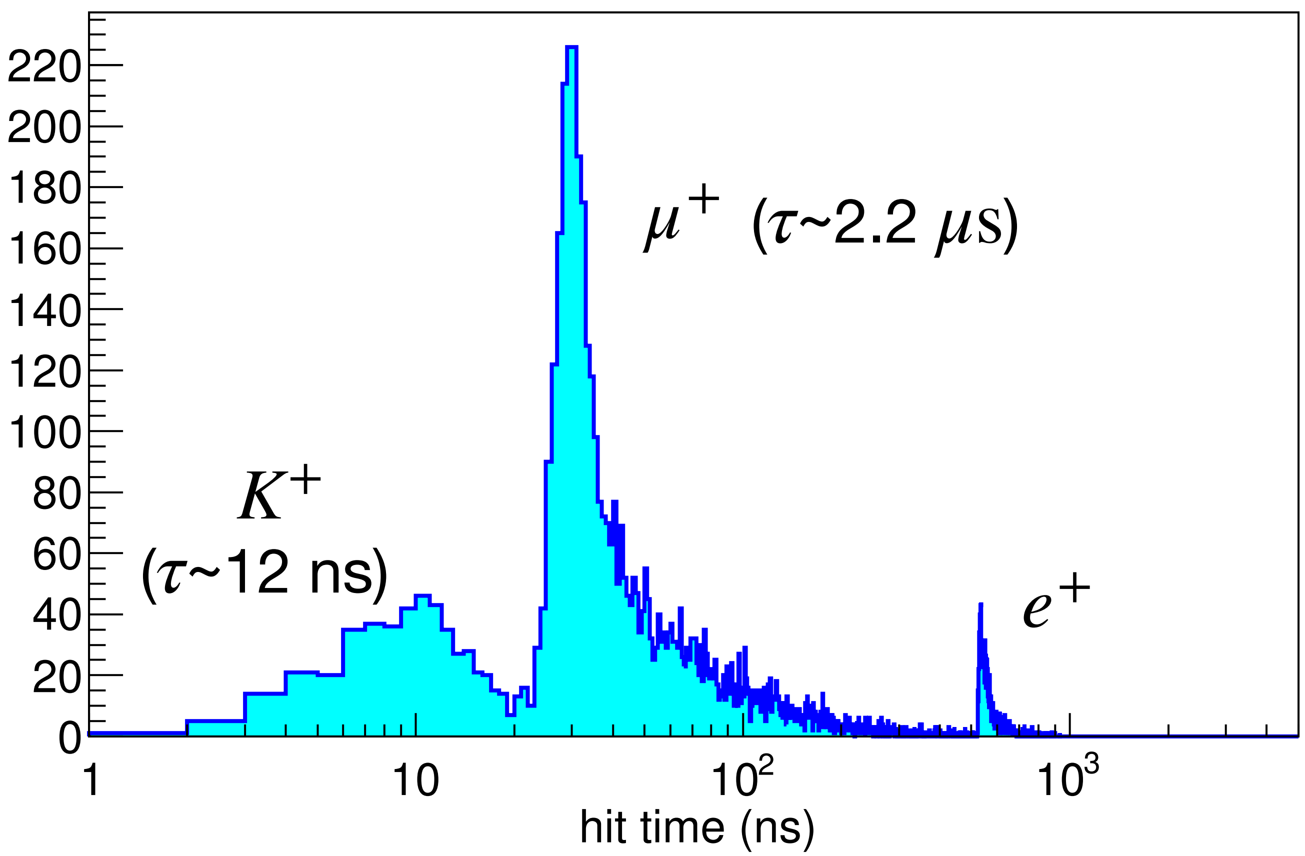
20 kton liquid scintillator: great sensitivity to $p \to \bar{\nu} K^+$

Signature: three-fold time coincidence

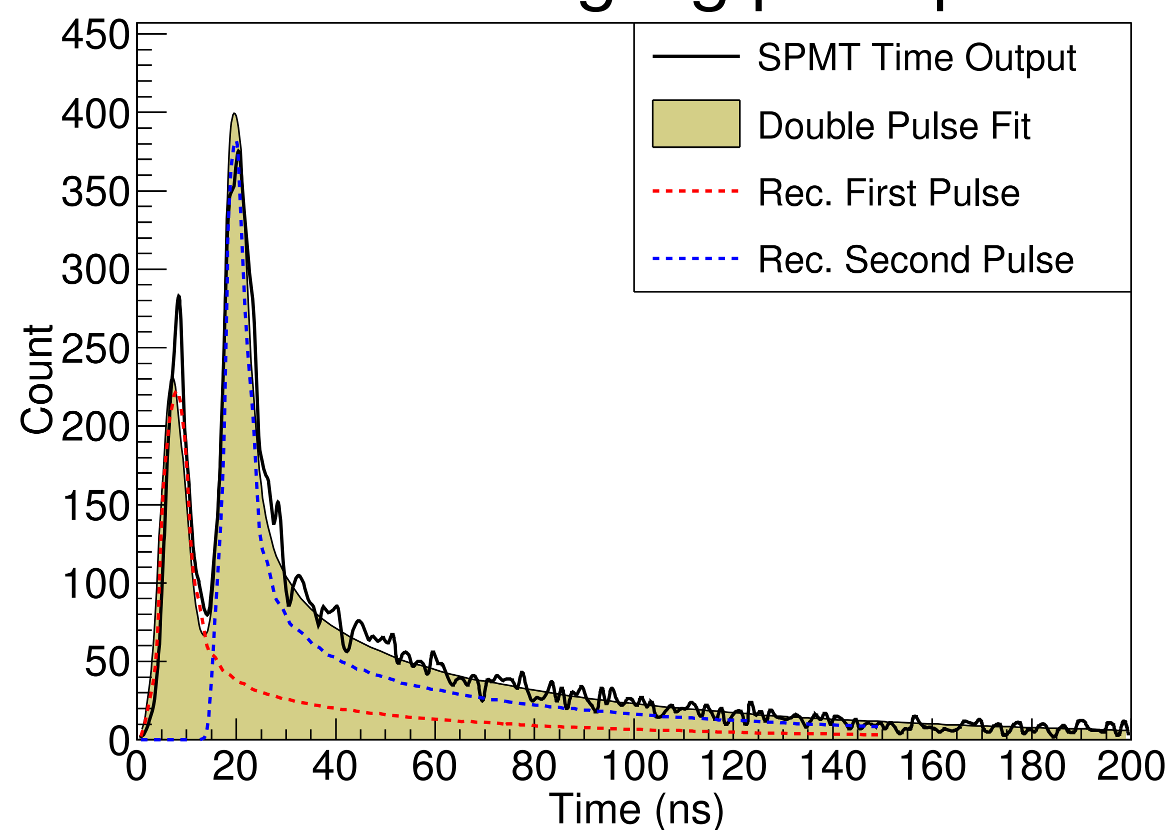
K^+ ionization $\to$ μ^+ ionization from K^+ decay $\to$ e^+ from μ^+ decay

Able to reject atmospheric ν background

Time-of-flight-corrected Hit Time



Disentangling pile-up



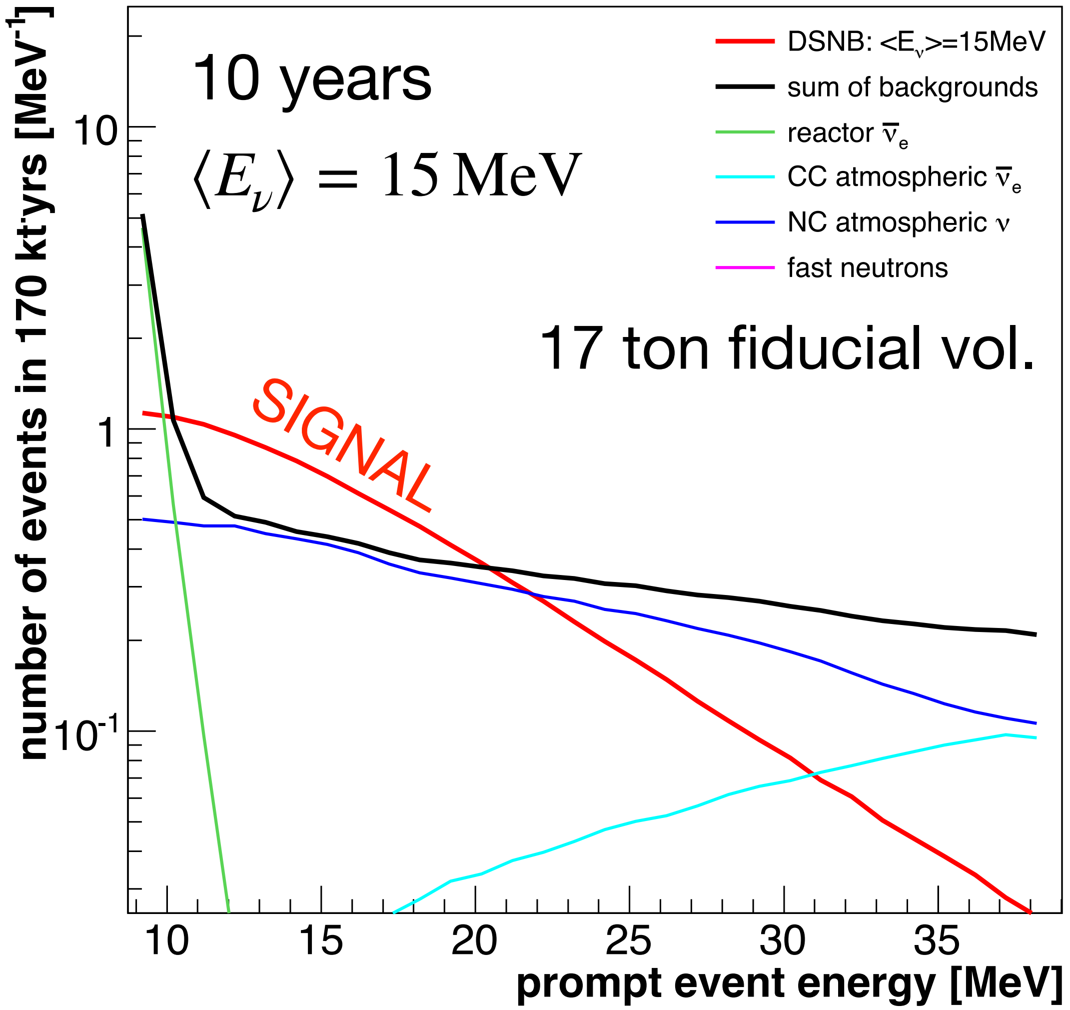
Expected sensitivity: $8.34 \cdot 10^{33}$ years (90% CL) in 10 years data-taking

Neutrinos From Supernovae

Detect the $\bar{\nu}_e$ component of the Diffuse Supernova Neutrino Background

2-4 IBD events / year with energy above reactor $\bar{\nu}_e$ expected

Pulse shape discrimination allows to reject NC interactions of atmospheric ν on ^{12}C



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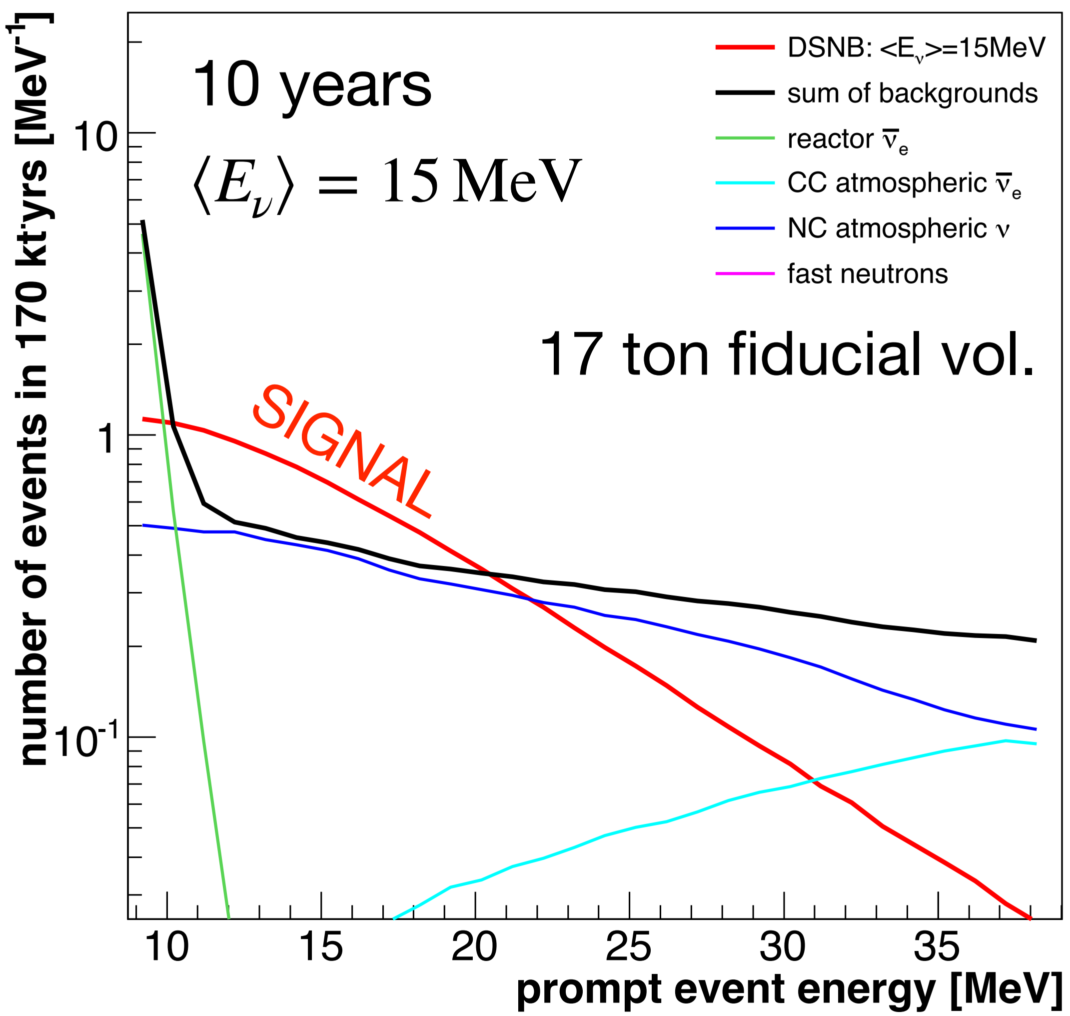
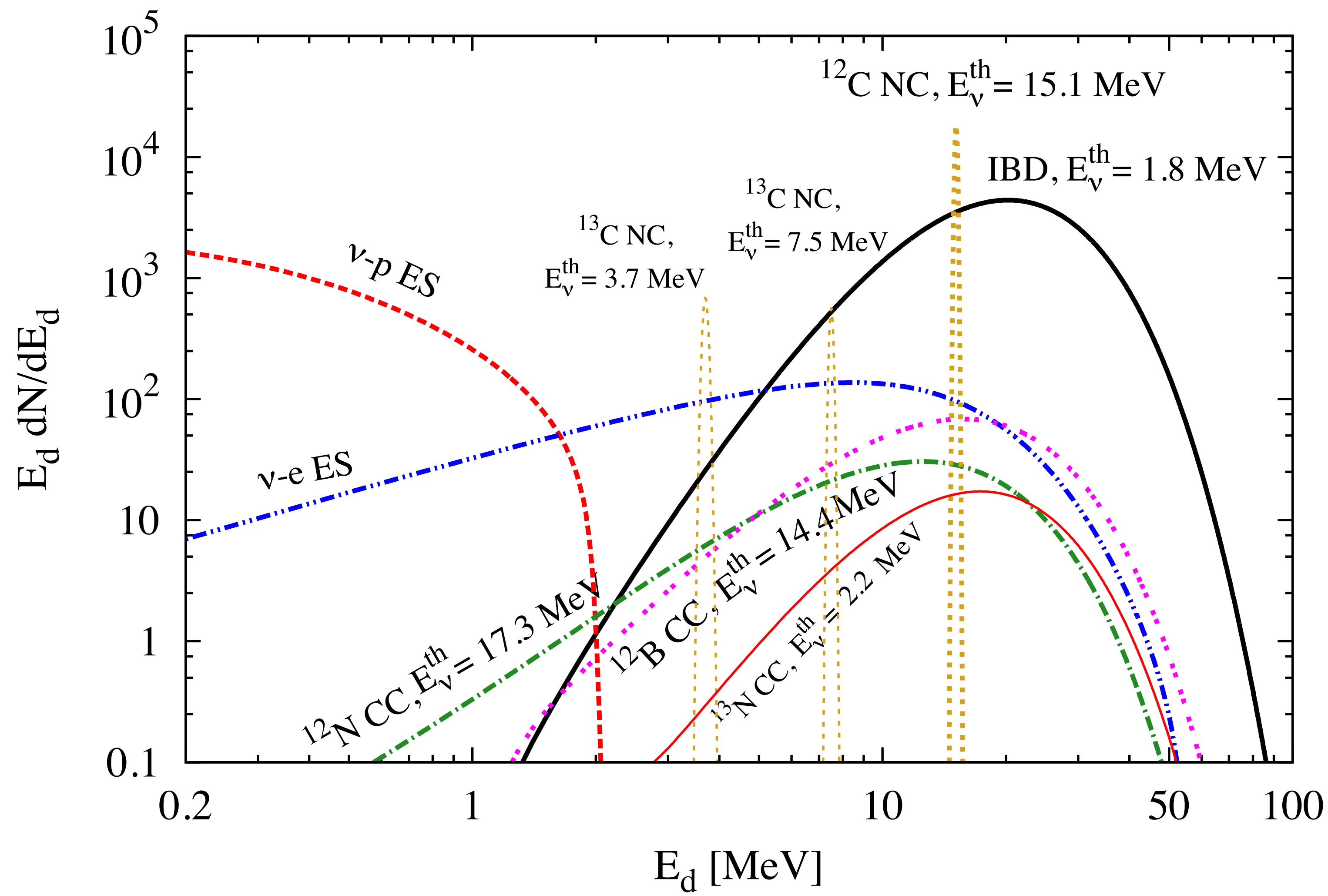
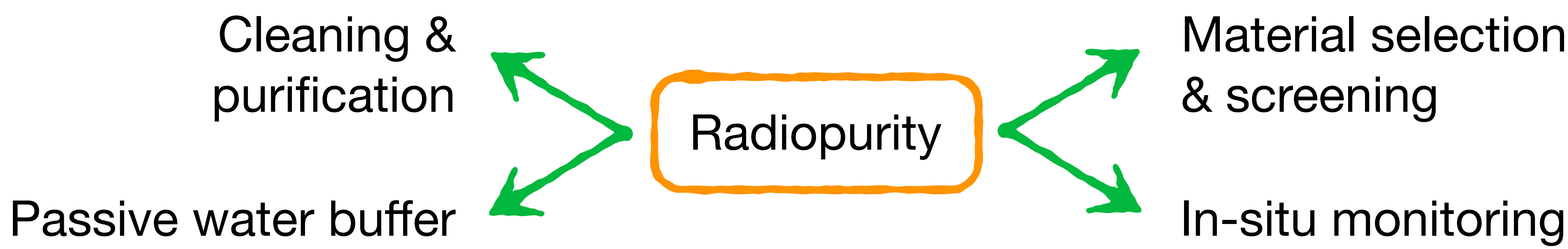




Core-collapse SNe: JUNO will detect O(10MeV) postshock ν of all flavors

Typical SN at 10 kpc: ~5000 IBD, ~300 eES, ~2000 pES, ~300 NC-^{12}C

Radiogenic Backgrounds



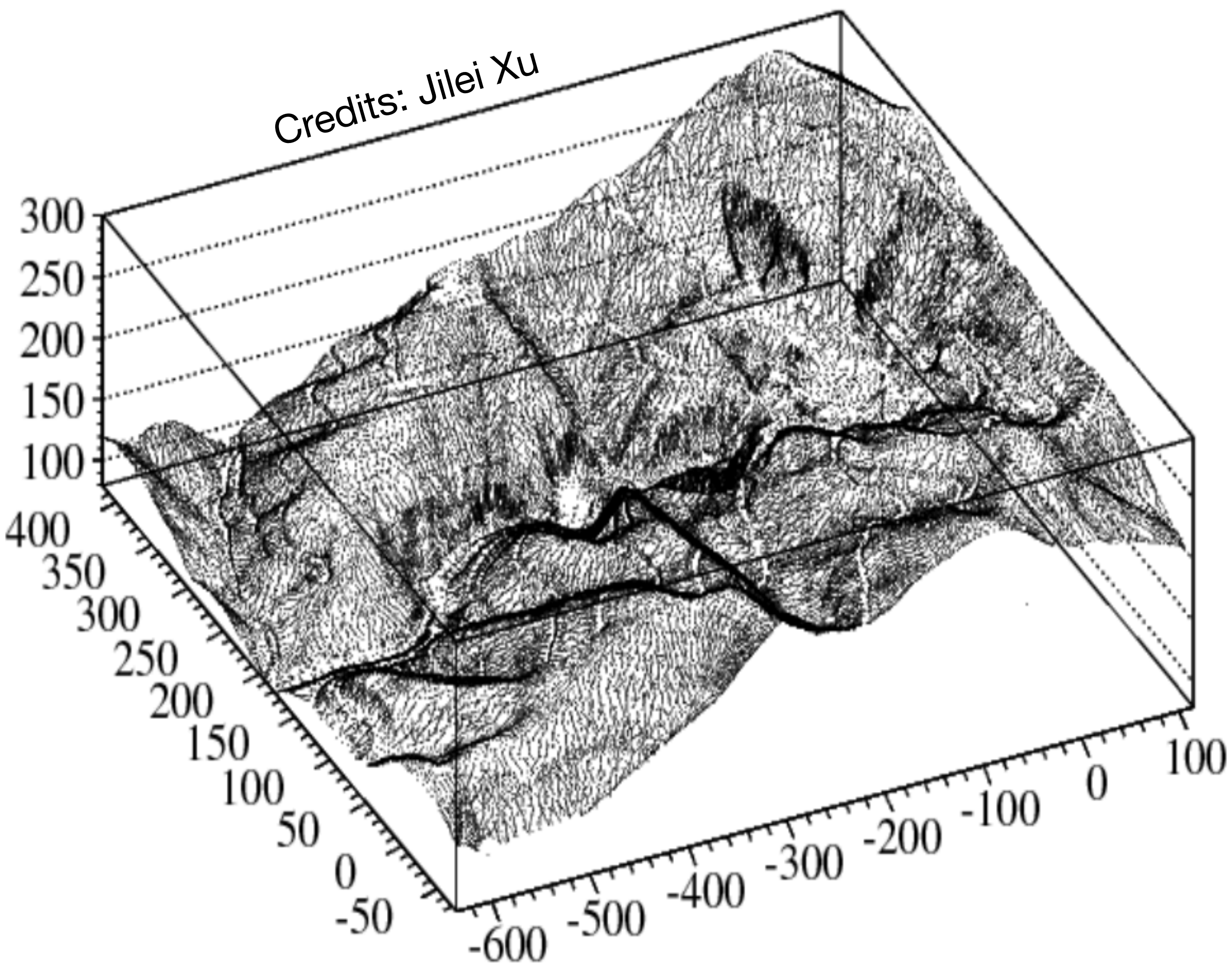
Material	Mass [t]	Target impurity concentration ^{238}U [ppb]	^{232}Th [ppb]	^{40}K [ppb]	^{210}Pb/^{222}Rn	^{60}Co [mBq/kg]	Singles in ROI ALL [Hz]	FV [Hz]
LS	20 k	10^{-6}	10^{-6}	10^{-7}	10^{-13} ppb		2.5	2.2
Acrylic	610	10^{-3}	10^{-3}	10^{-3}			8.4	0.4
SS truss and nodes	1 k	0.2	0.6	0.02		1.5	15.8	1.1
dynode-LPMT glass	33.5	400	400	40				
MCP-LPMT glass	100.5	200	120	4			26.2	2.8
dynode-SPMT glass	2.6	400	400	200				
Water	35 k				10 mBq/m^3		1.0	0.06
Other							5	0.6
Sum							59	7.2

2104.02565

Reduce count rate of single energy depositions (bkg to solar analysis) and "accidental" coincidences (bkg to inverse beta decay detection)

Cosmogenic Background

Reactor $\bar{\nu}_e$ detected via inverse beta decay → final state: $e^+ + n$



^{8}He and ^{9}Li: unstable isotopes produced by μ spallation on ^{12}C and decaying β-n

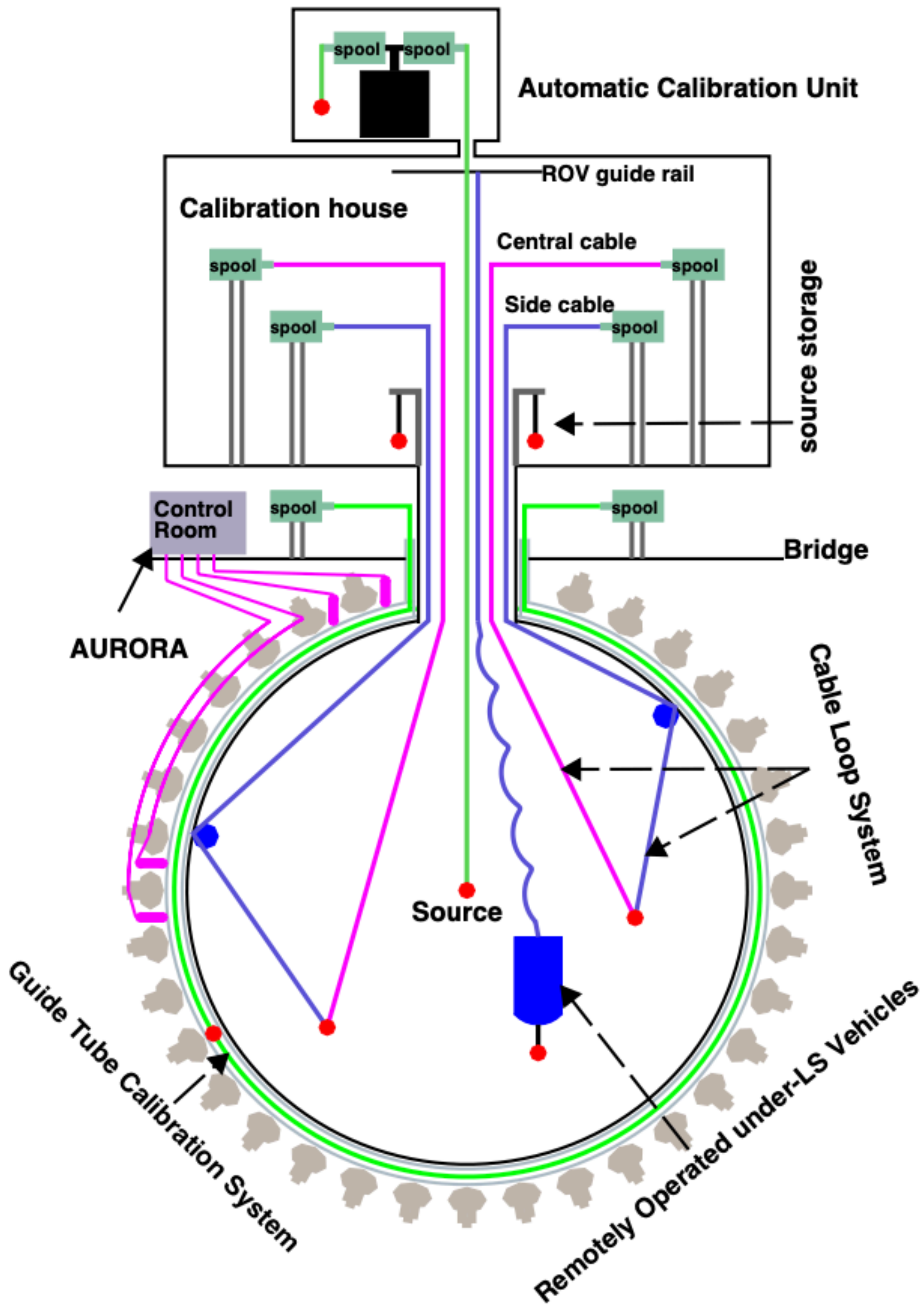
Untagged μ yield irreducible background

Expected μ rate: 4 Hz
Mean μ energy: 207 GeV

Old veto strategy → Tagging ε: 83% → Residual ^{8}He ^{9}Li event rate: 1.6/day

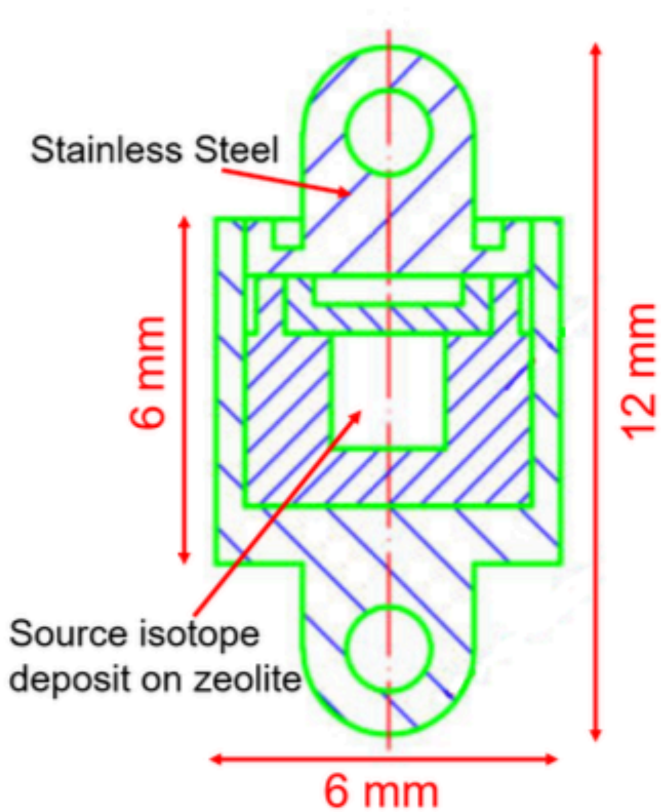
New veto strategy → Tagging ε: 91.6% → Residual ^{8}He ^{9}Li event rate: 1.4/day

Calibration Strategy

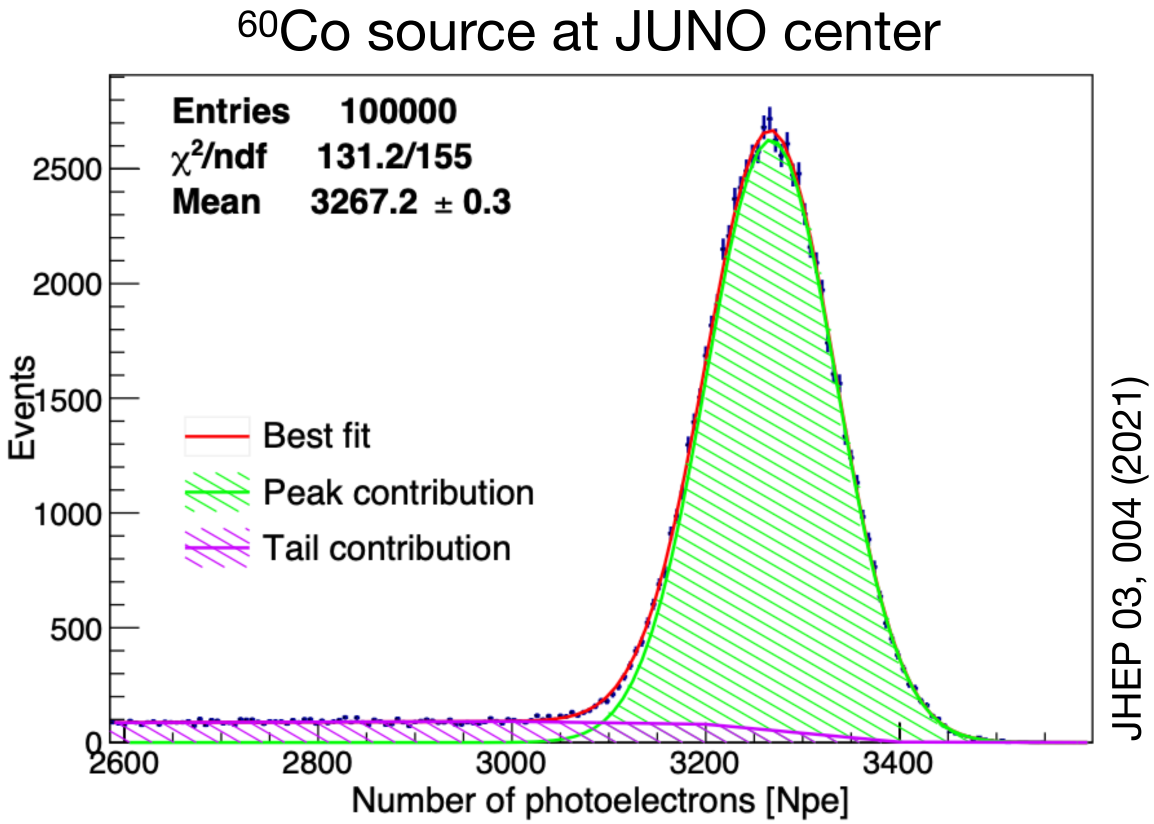


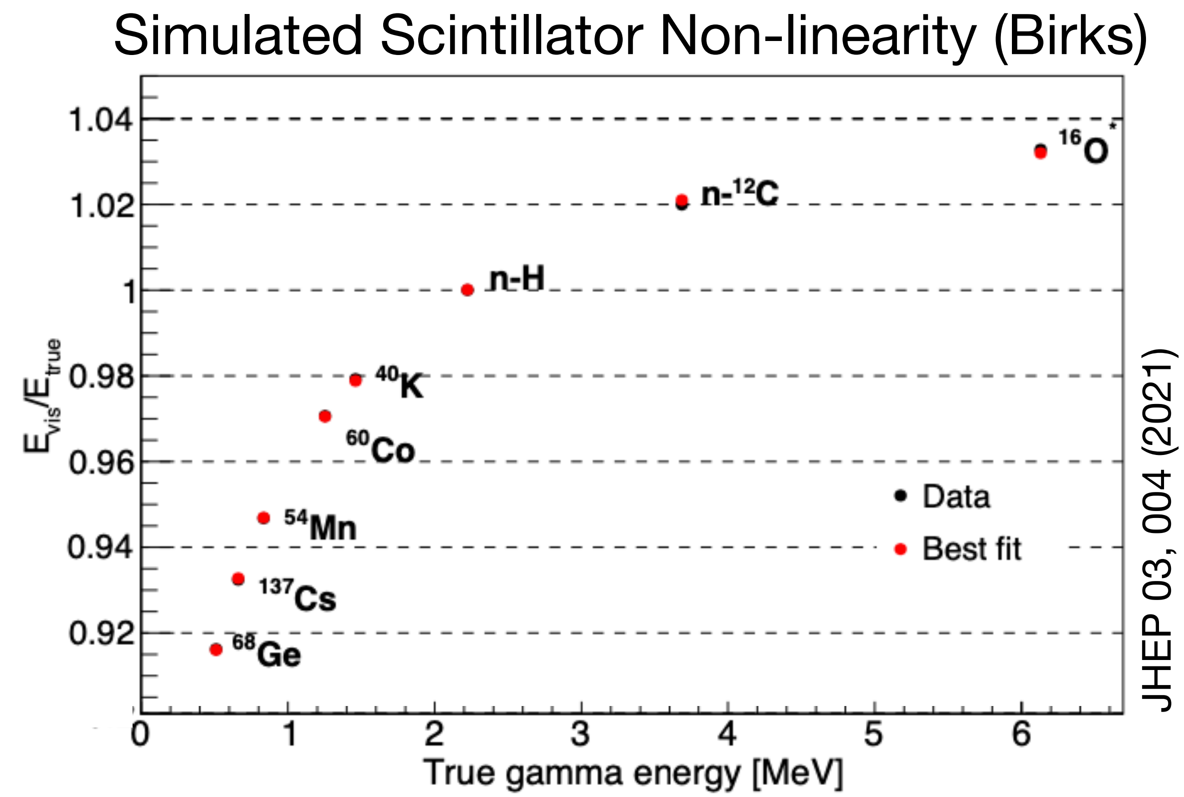
JHEP 03, 004 (2021)

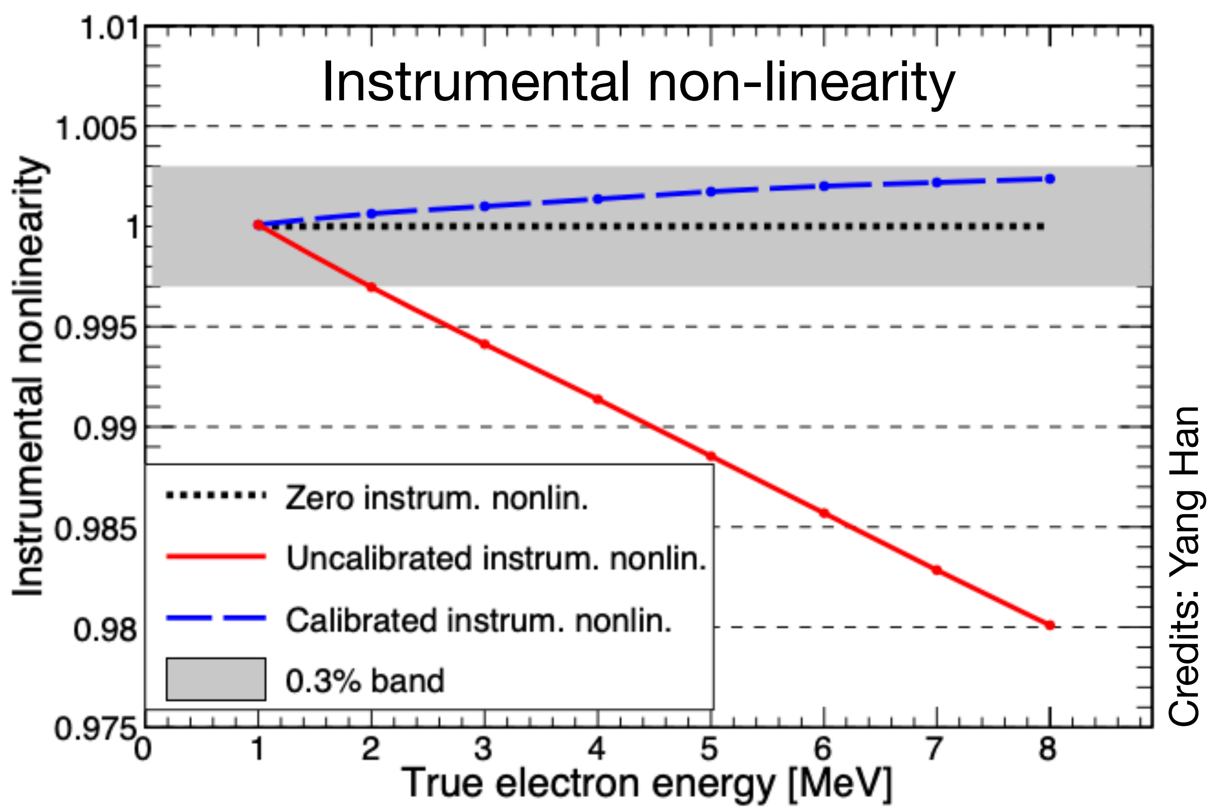
Sources/Processes	Type	Radiation
^{137}Cs	γ	0.662 MeV
^{54}Mn	γ	0.835 MeV
^{60}Co	γ	1.173 + 1.333 MeV
^{40}K	γ	1.461 MeV
^{68}Ge	e^+	annihilation 0.511 + 0.511 MeV
^{241}Am-Be	n, γ	neutron + 4.43 MeV (^{12}C*)
^{241}Am-^{13}C	n, γ	neutron + 6.13 MeV (^{16}O*)
(n,γ)p	γ	2.22 MeV
(n,γ)^{12}C	γ	4.94 MeV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

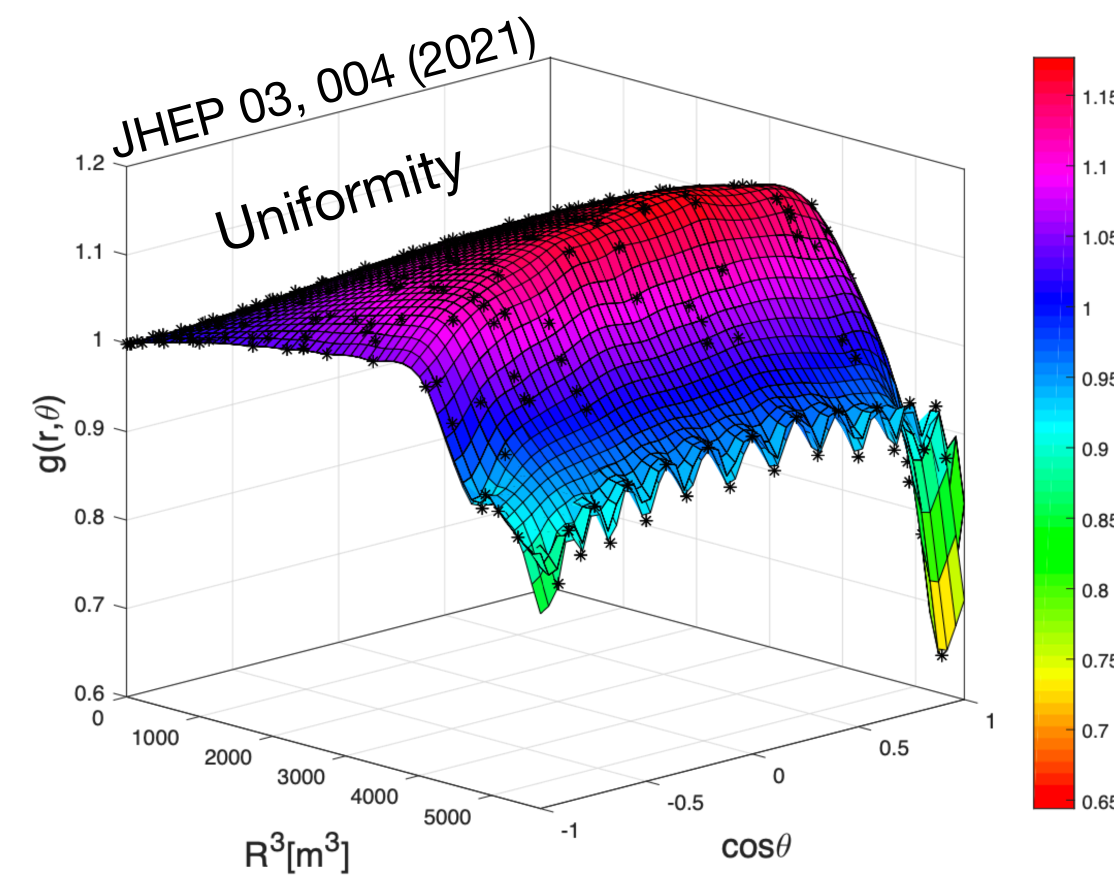


Expected Calibration Performance





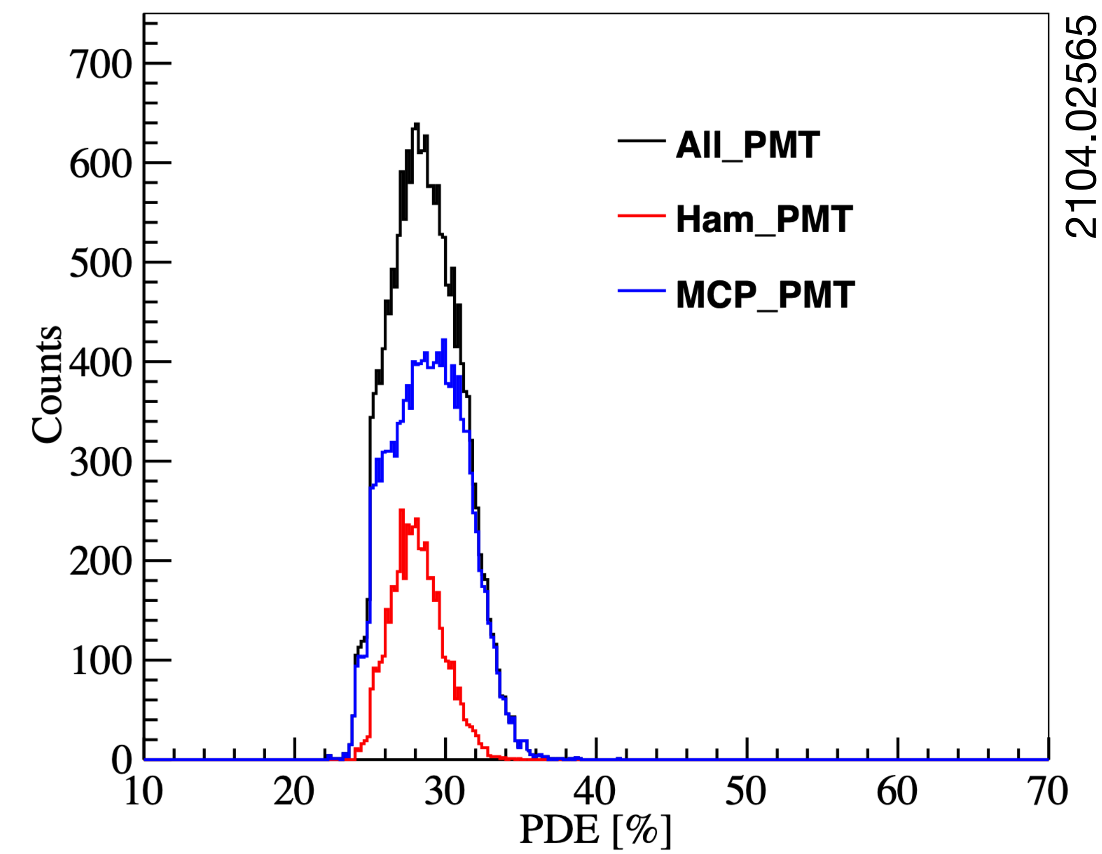




Main Photodetection: The 20-inch PMT System

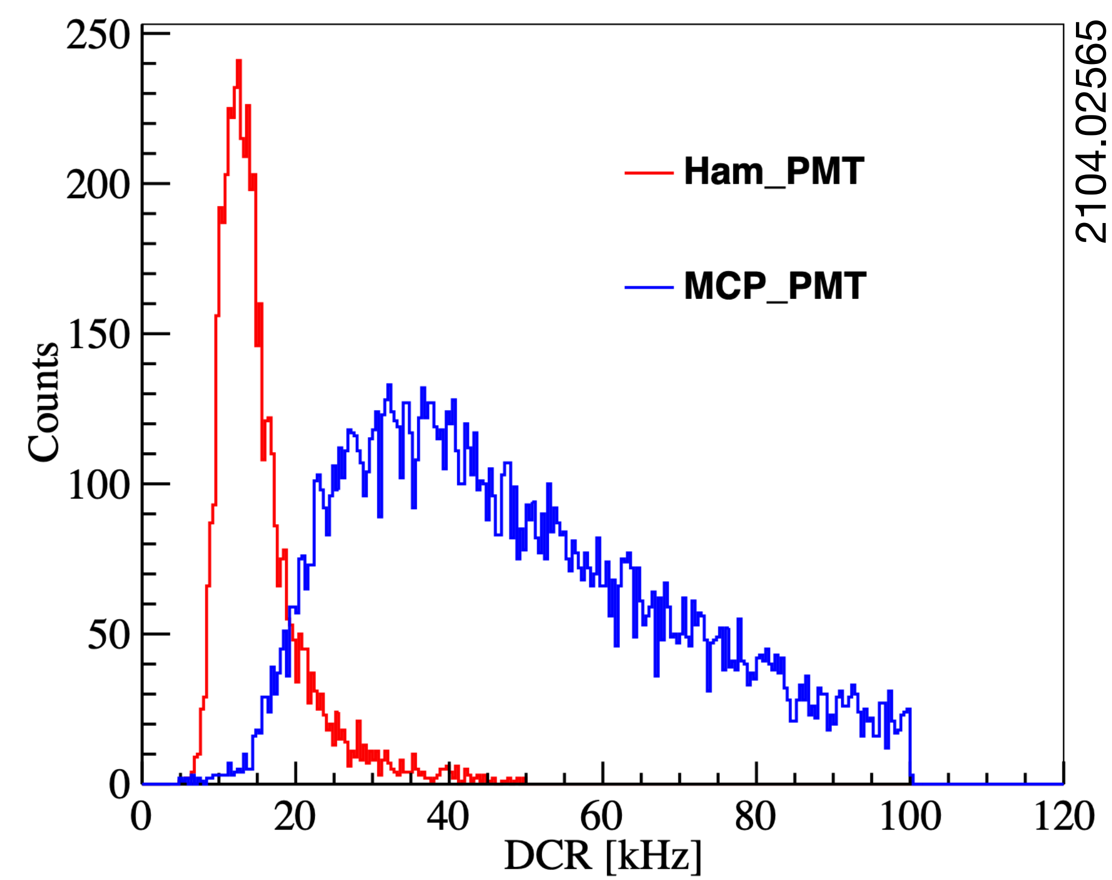
5000 Dynode PMTs
Hamamatsu

TTS σ 1.2 ns
FWHM 2.8 ns



15 000 MCP PMTs
NNVT (China)

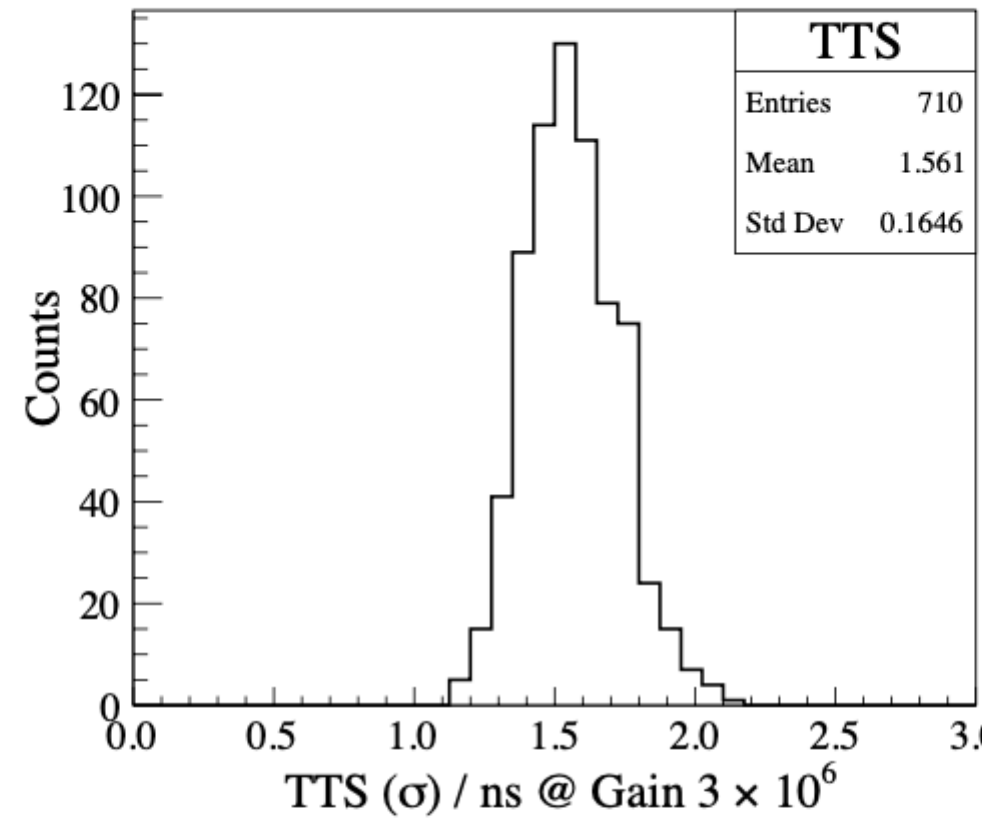
TTS σ 9.1 ns
FWHM 21.5 ns



Bolstering Calorimetry: The 3-inch PMT System

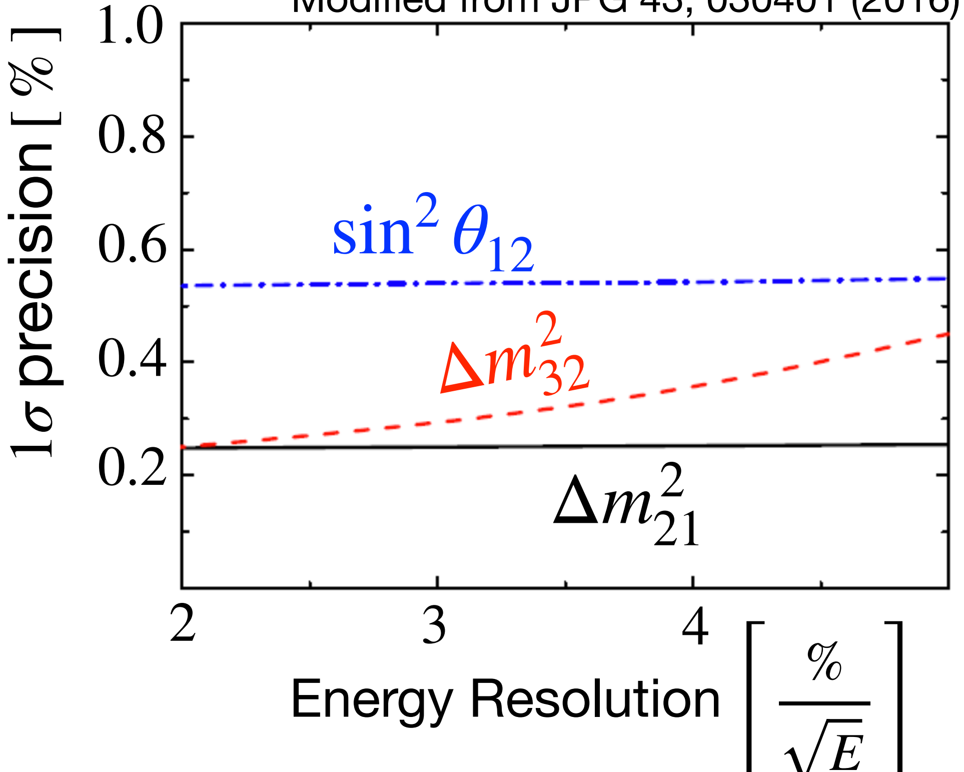
Credits: C Cerna

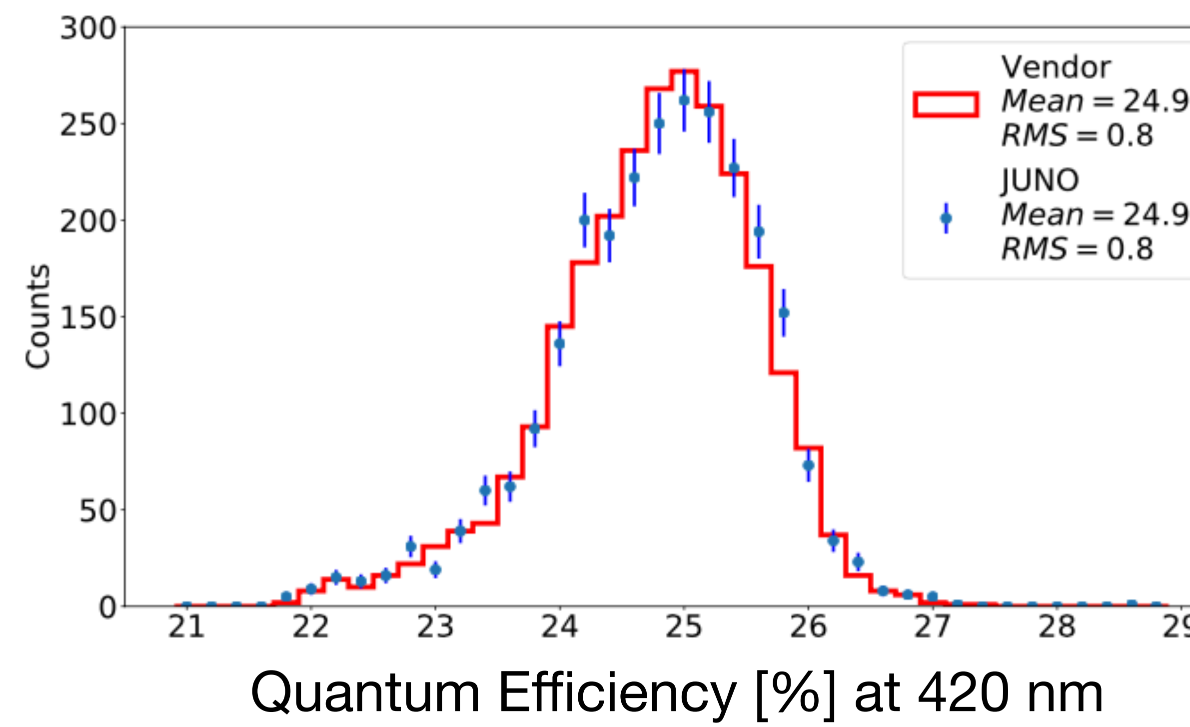
- More light (more coverage)
- Excellent timing (→ vertex)
- Reduced dynamic range (calibration)
- Oscillation analysis validation



NIMA 1005, 165347 (2021)

Modified from JPG 43, 030401 (2016)

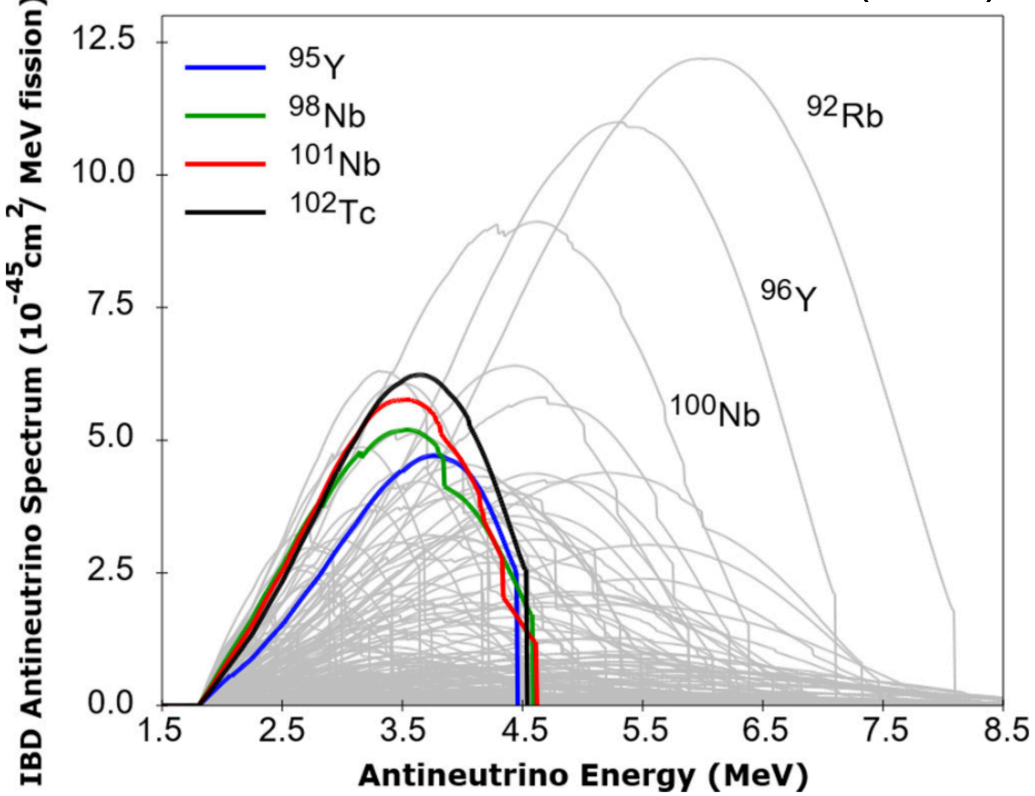




NIMA 1005, 165347 (2021)

Addressing The Reactor Spectral Uncertainties: TAO

PRC 98, 014323 (2018)



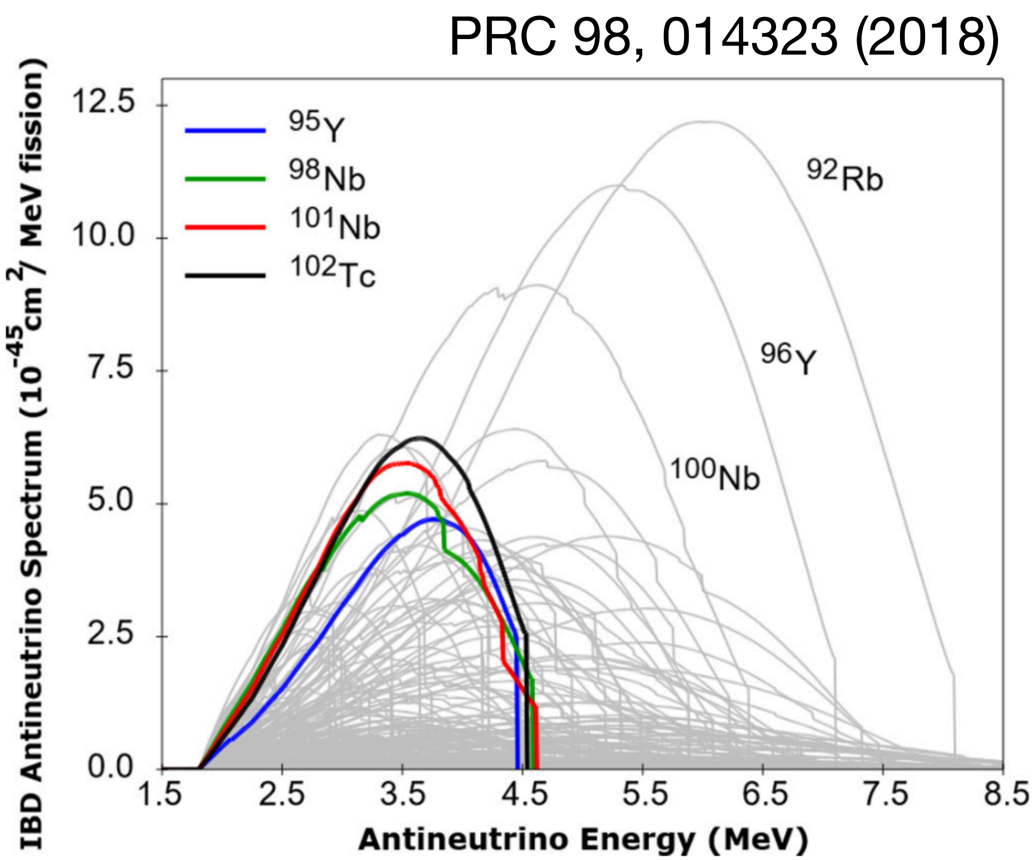
Many beta decays contribute to $\bar{\nu}_e$ yield at nuclear reactors

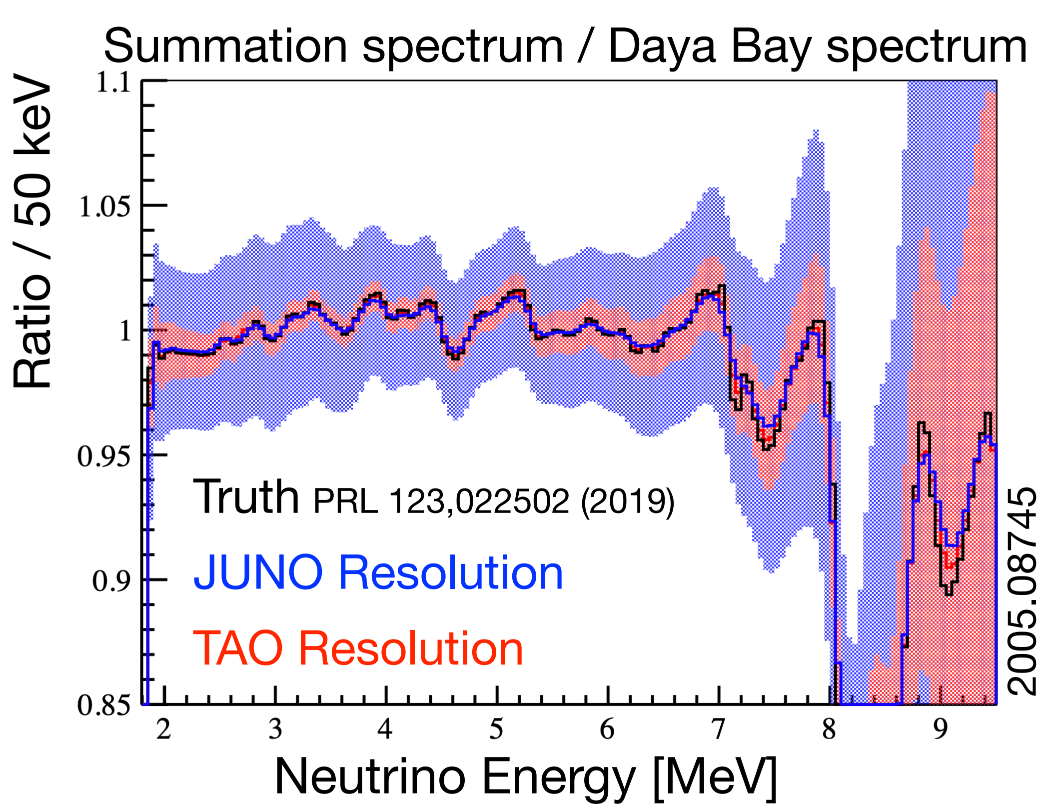
Wide consensus on models being affected by larger-than-predicted uncertainties

Reactor spectrum distortion (a.k.a. “bump”) summation *vs* conversion

JUNO relies on good knowledge of the unoscillated spectrum

Addressing The Reactor Spectral Uncertainties: TAO





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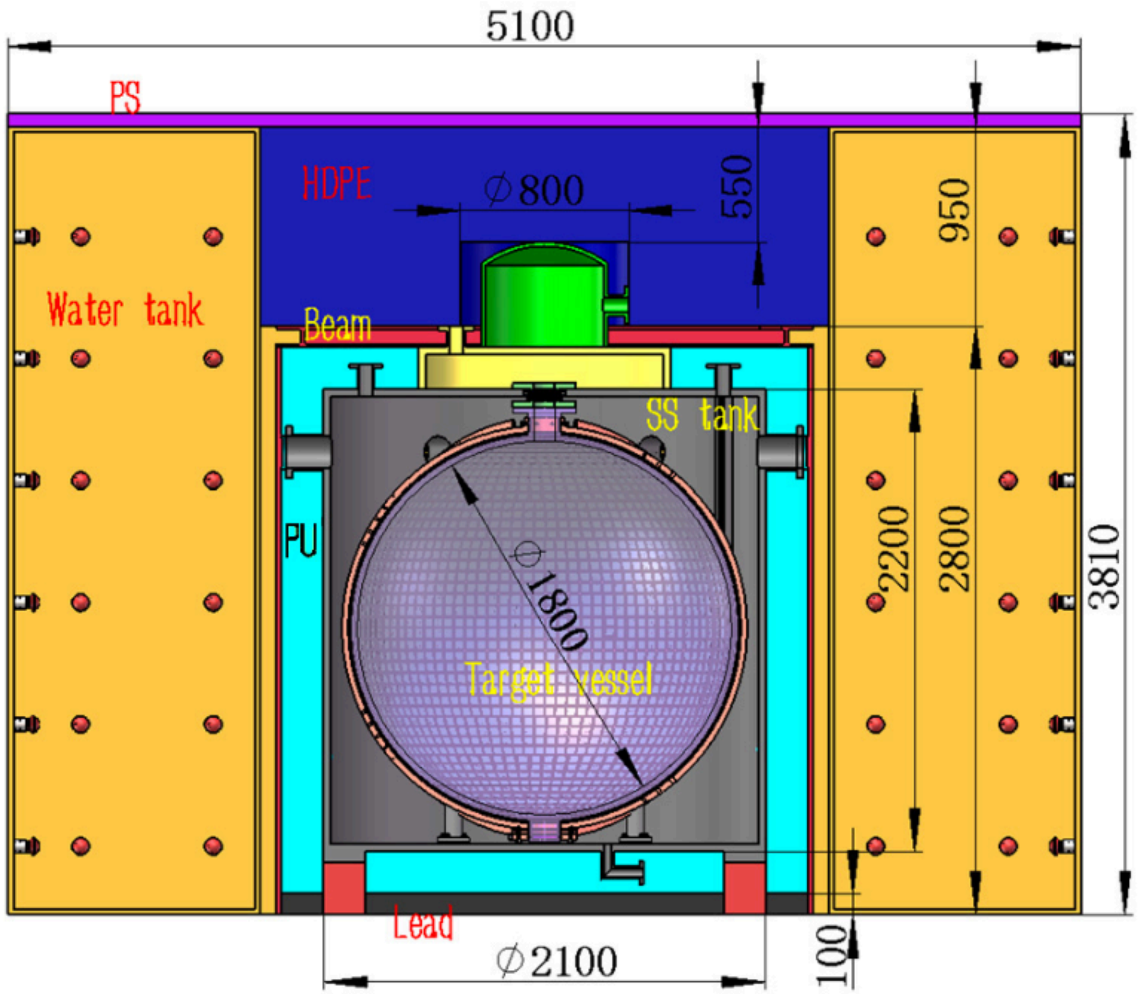
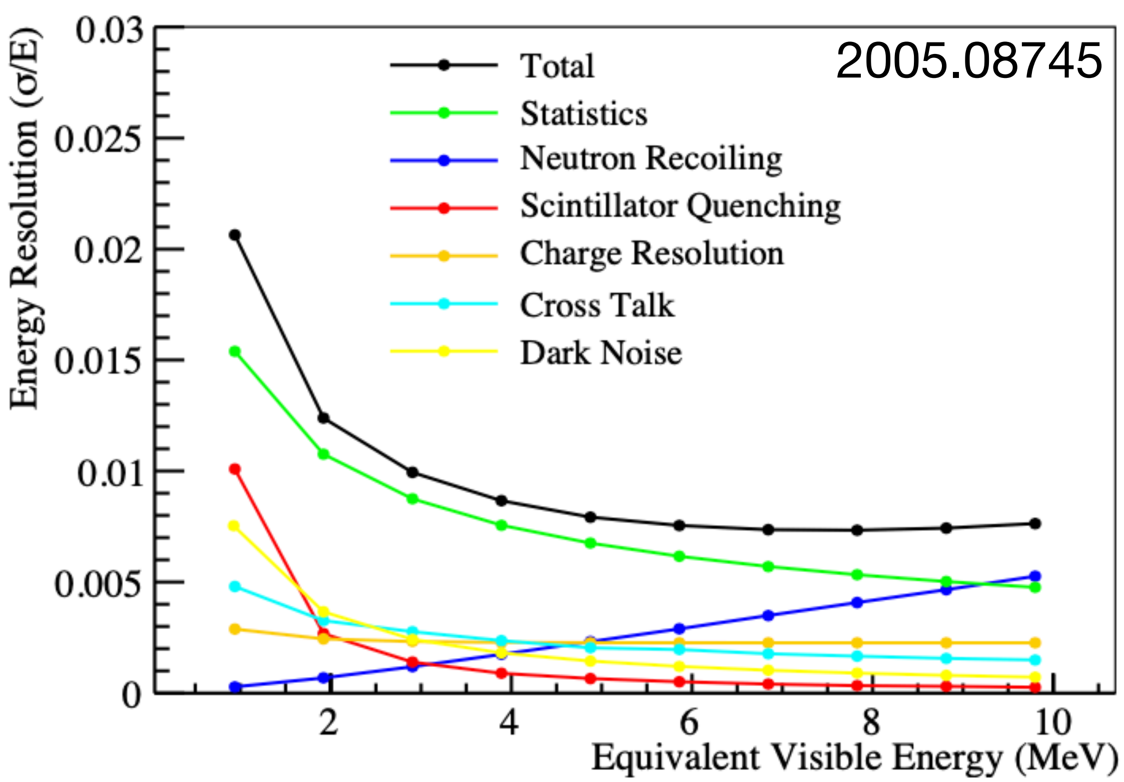
JUNO relies on good knowledge of the unoscillated spectrum

Taishan Antineutrino Observatory (TAO)

Ancillary detector to study unoscillated spectrum with resolution better than JUNO

The TAO Detector





2.8 ton Gd-doped liquid scintillator

Light detection: 10 m^2 SiPM

Operated at -50°C (reduce SiPM DCR)

30 m from reactor core

Light level: 4500 pe/MeV

$2 \cdot 10^6\ \bar{\nu}_e$ events in 3 years (2000+/day)

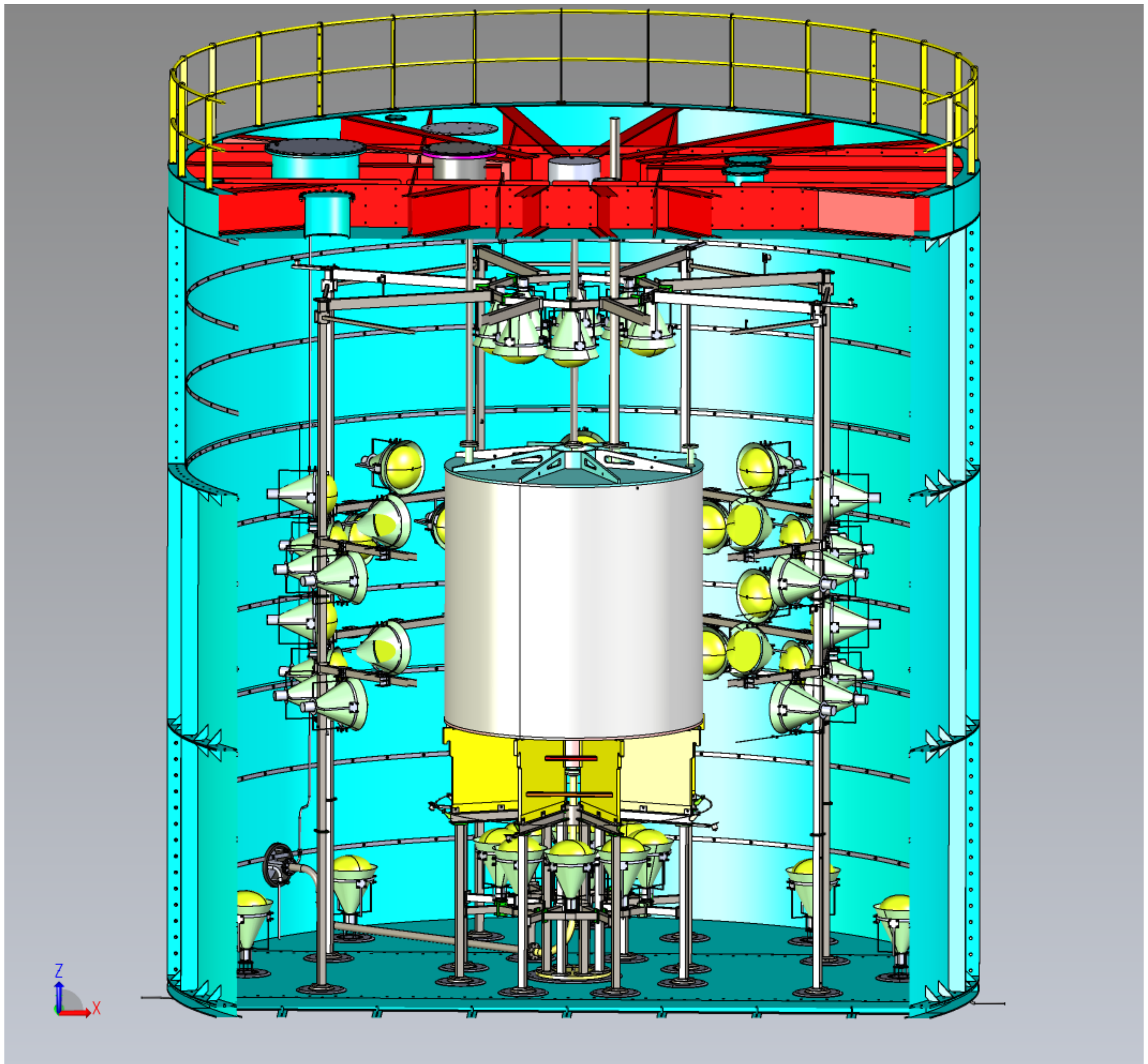
Statistical unc. < 1% in [2.5;6] MeV

Fast n background rate < 200 evts/day

^8He+^9Li background rate ~54 evts/day

Ensuring Scintillator Radiopurity: OSIRIS

The Online Scintillator Internal Radioactivity Investigation System



20 m^3 volume ~ 17 ton LS

Monitor liquid scintillator while detector is being filled

Quality control of LS purification

Measure ^{238}U and ^{232}Th through fast decay coincidences

- ^{214}Bi-^{214}Po (τ~164 μs)
- ^{212}Bi-^{212}Po (τ~0.43 μs)

Few coincidence events/day

10^{-15}g/g in few days data taking

10^{-16}g/g in 2-3 weeks

Summary

Vast program in particle physics & astrophysics

Probing the neutrino oscillation mechanism at unprecedented precision

Ready to detect neutrinos from SN burst

Competitive solar neutrino program

Detector construction to be completed next year (2022)