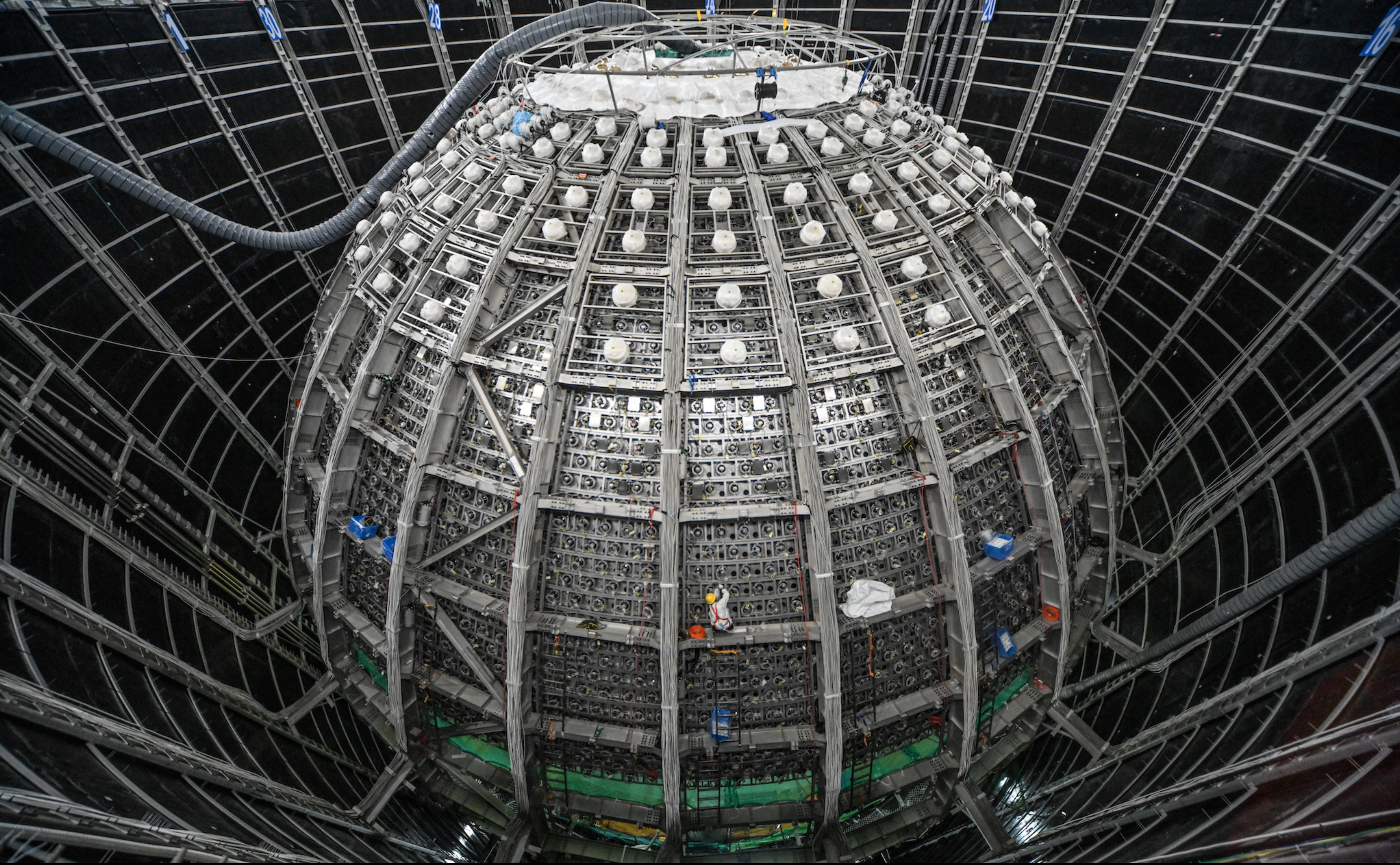
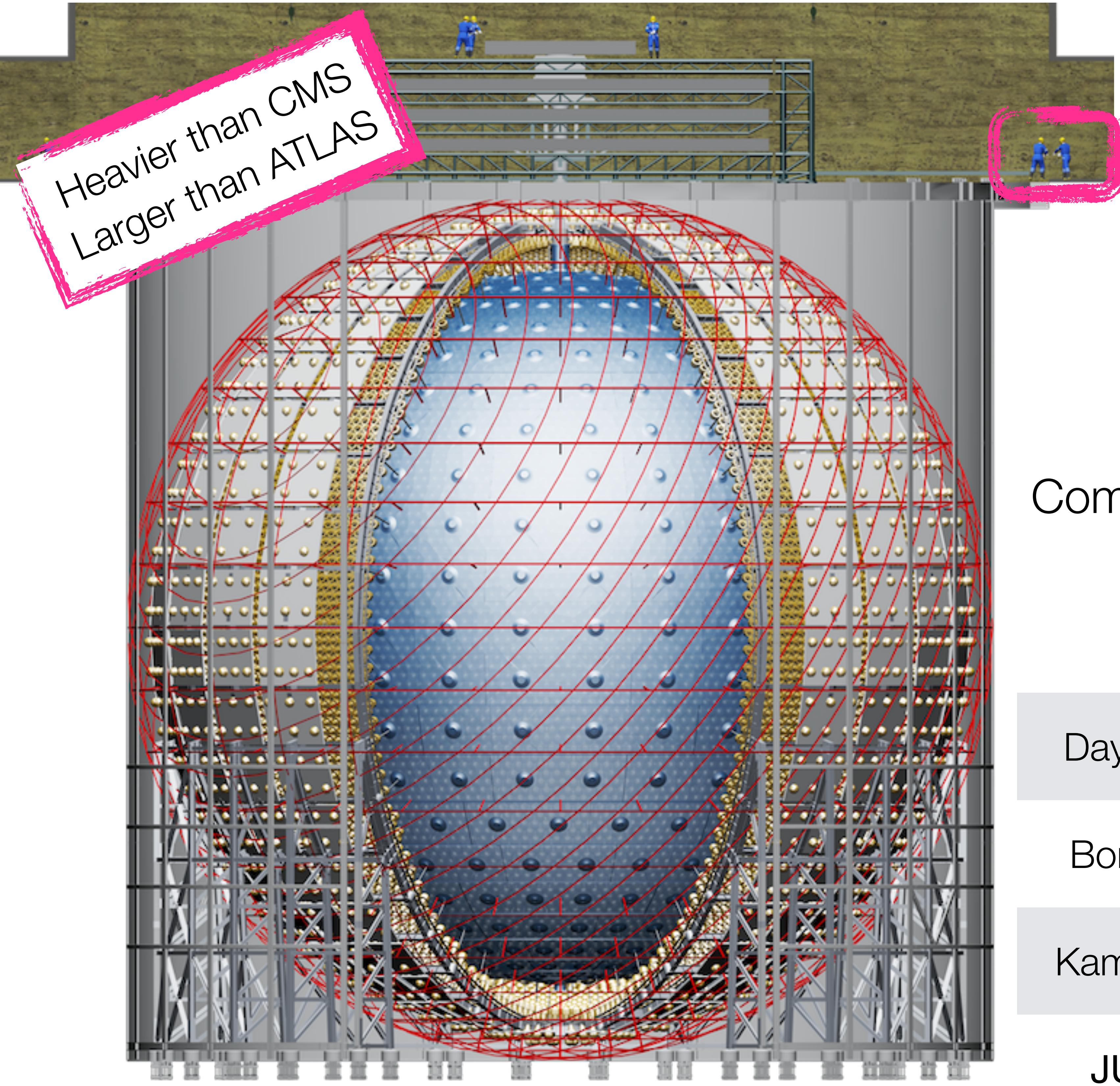


JUNO Status and Prospects

Marco Grassi (U. Padova & INFN)

JUNO is a huge liquid scintillator detector



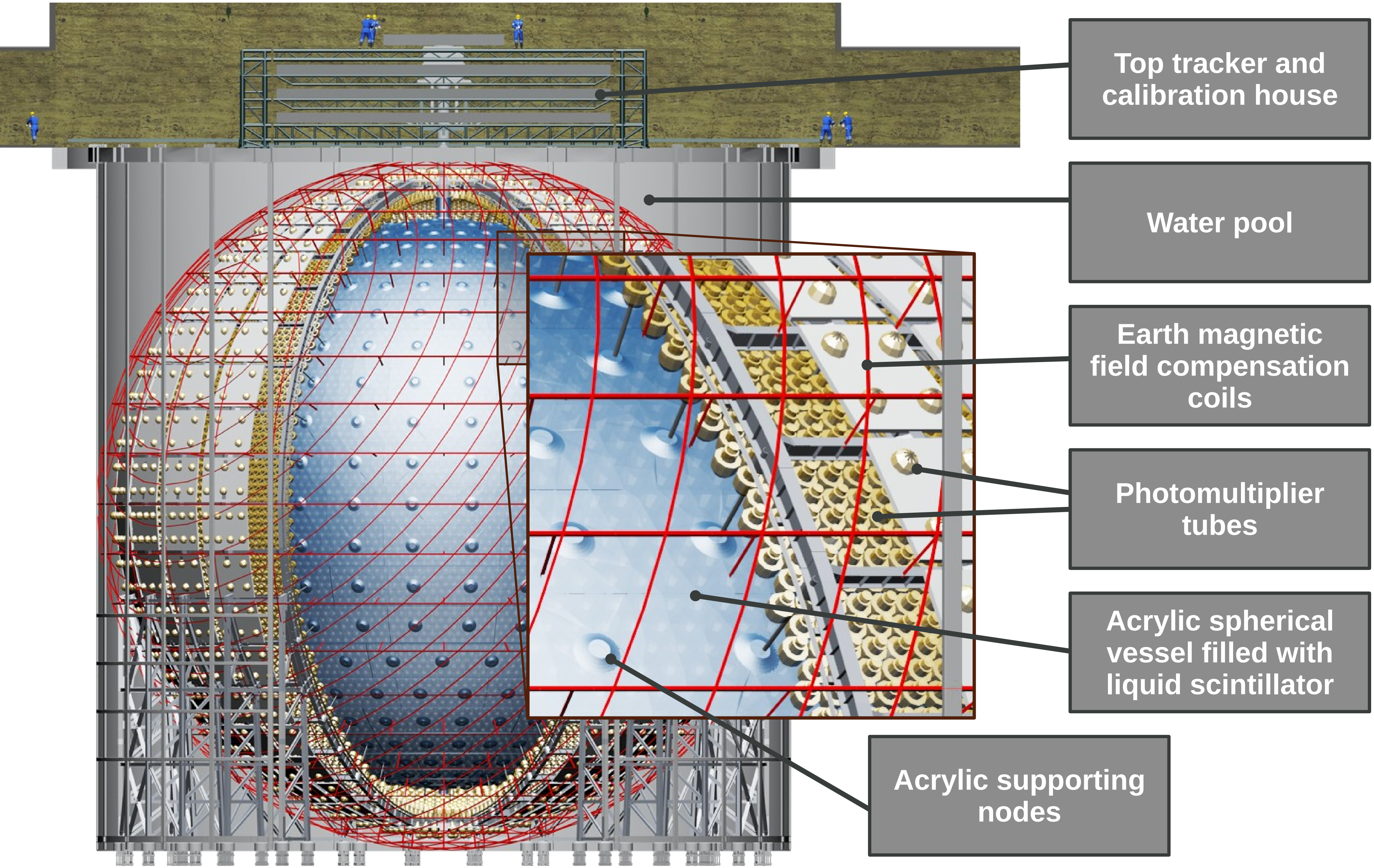
People (to give you the scale)

A large & precise homogeneous calorimeter

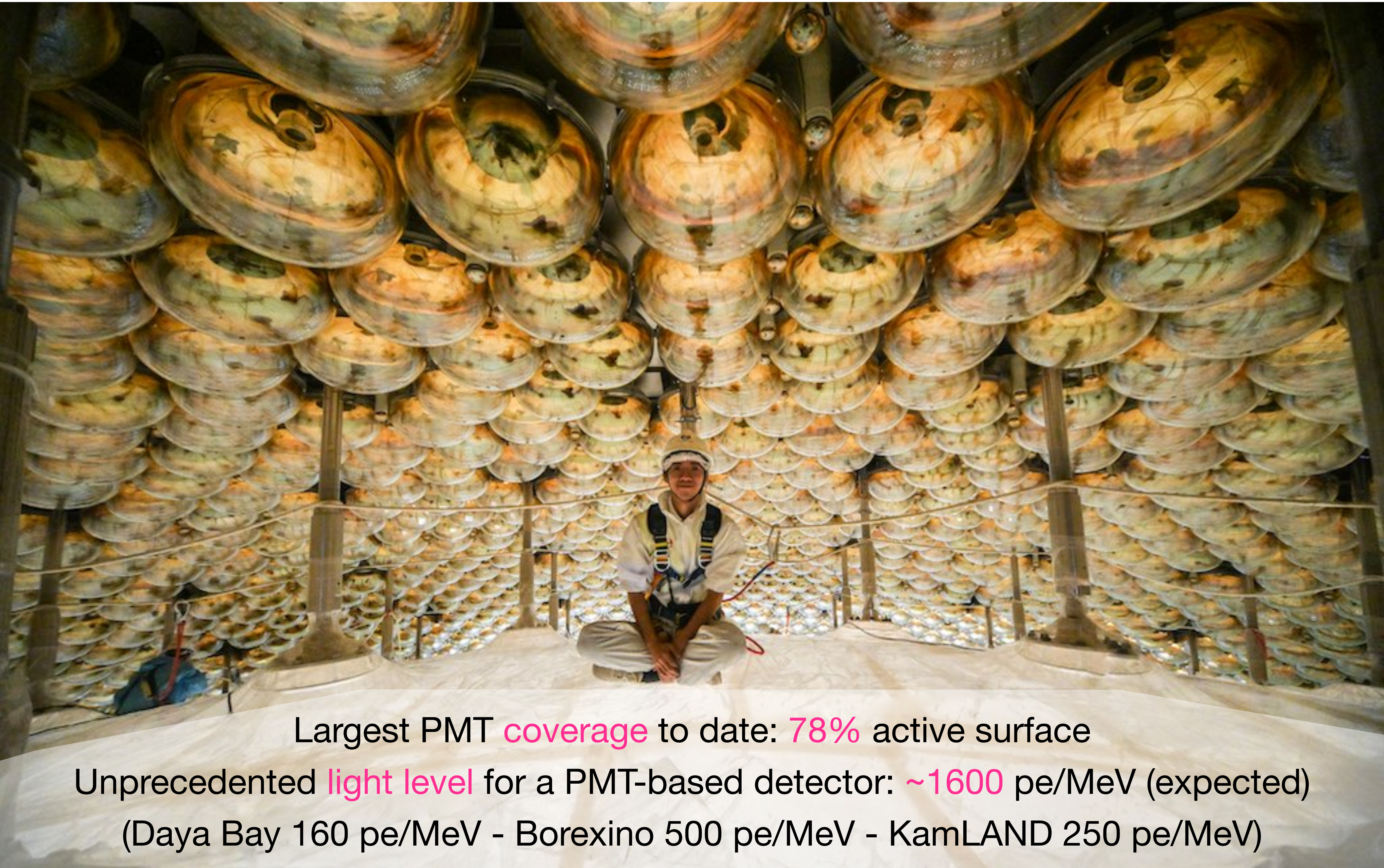
Comparing to previous experiments

	Target mass	Energy resolution (σ)
Daya Bay	20 ton	$8\%/\sqrt{E}$
Borexino	300 ton	$5\%/\sqrt{E}$
KamLAND	1000 ton	$6\%/\sqrt{E}$
JUNO	20 000 ton	$3\%/\sqrt{E}$

JUNO is a huge liquid scintillator detector



JUNO is a huge liquid scintillator detector



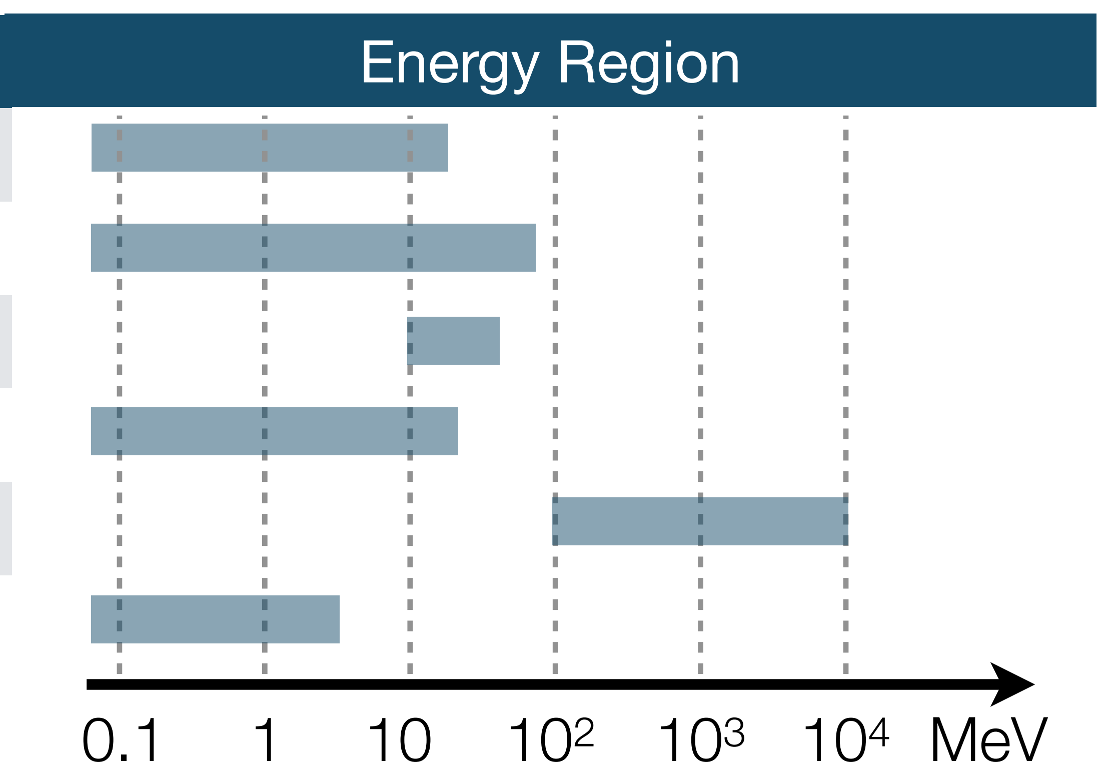
Largest PMT coverage to date: 78% active surface

Unprecedented light level for a PMT-based detector: ~1600 pe/MeV (expected)

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

JUNO is an observatory for rare events

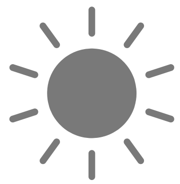
Neutrino source	Expected signal
Reactor	45 evts / day
Supernova burst	10^4 evts at 10 kpc
Diffuse supernova background	2-4 evts/ year
Sun ^8B (^7Be)	16 (490) / day
Cosmic rays	100+ / year
Earth crust & mantle	400 / year



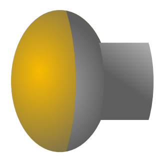
Outline

Status: the detector

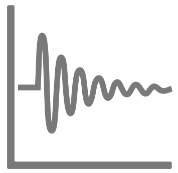
Light Emission



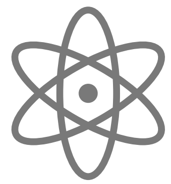
Light Detection



Charge Readout



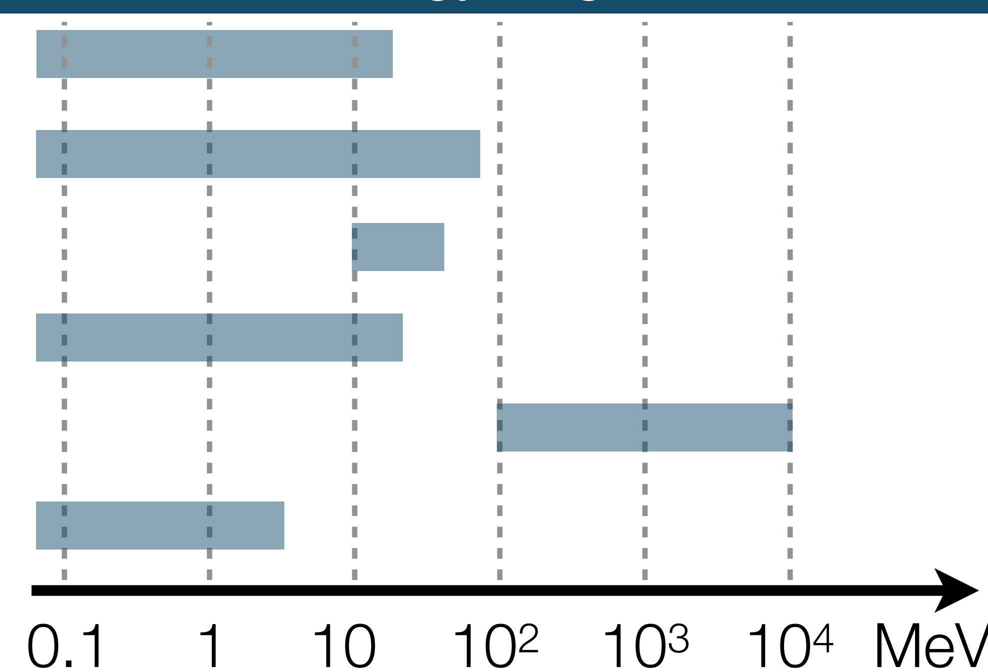
Source Diagnostic



Prospects: physics goals

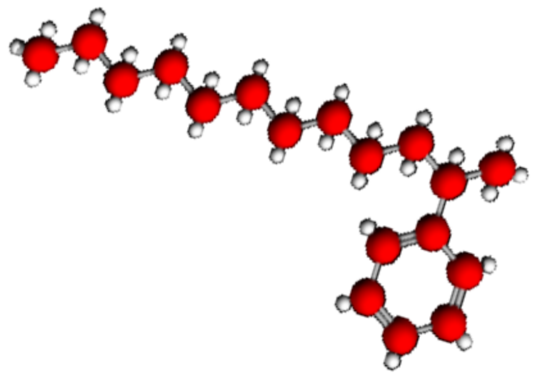
Neutrino source	Expected signal
Reactor	45 evts / day
Supernova burst	10^4 evts at 10 kpc
Diffuse supernova background	2-4 evts/ year
Sun ^8B (^7Be)	16 (490) / day
Cosmic rays	100+ / year
Earth crust & mantle	400 / year

Energy Region



20 kton liquid scintillator target mass

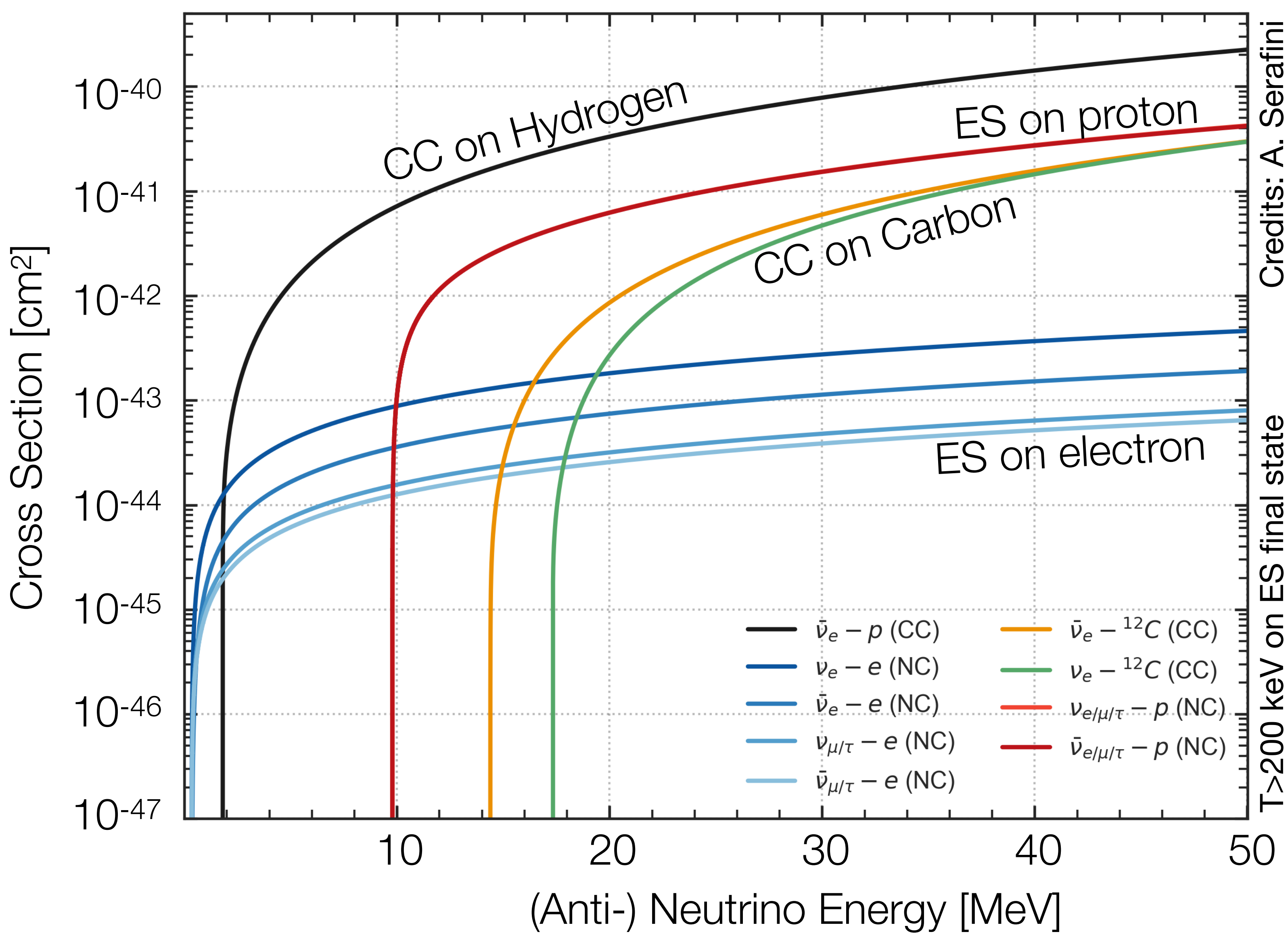
Organic liquid scintillator = interaction medium + detection medium



Solvent:
Linear Alkyl-Benzene
LAB

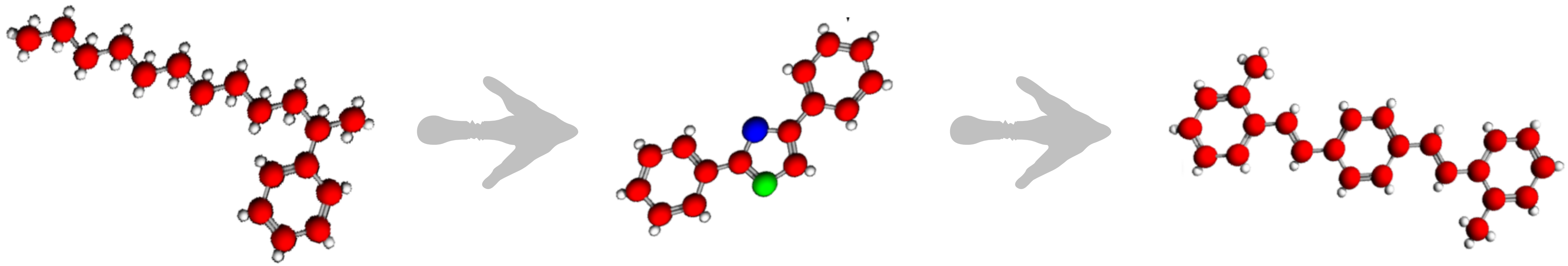
88% C + 12% H

- $\bar{\nu}_e + p \rightarrow e^+ + n$
- $\nu + p \rightarrow \nu + p$
- $\nu + e \rightarrow \nu + e$
- $\nu_e + ^{12}C \rightarrow e^- + ^{12}N$
- $\bar{\nu}_e + ^{12}C \rightarrow e^+ + ^{12}B$



20 kton liquid scintillator target mass

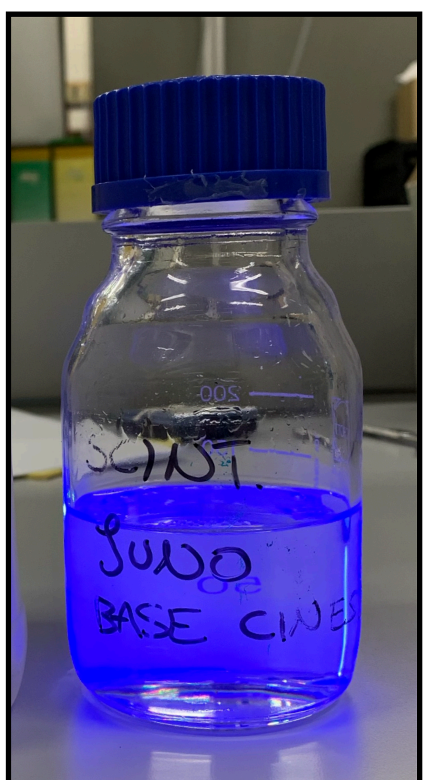
Organic liquid scintillator = interaction medium + detection medium

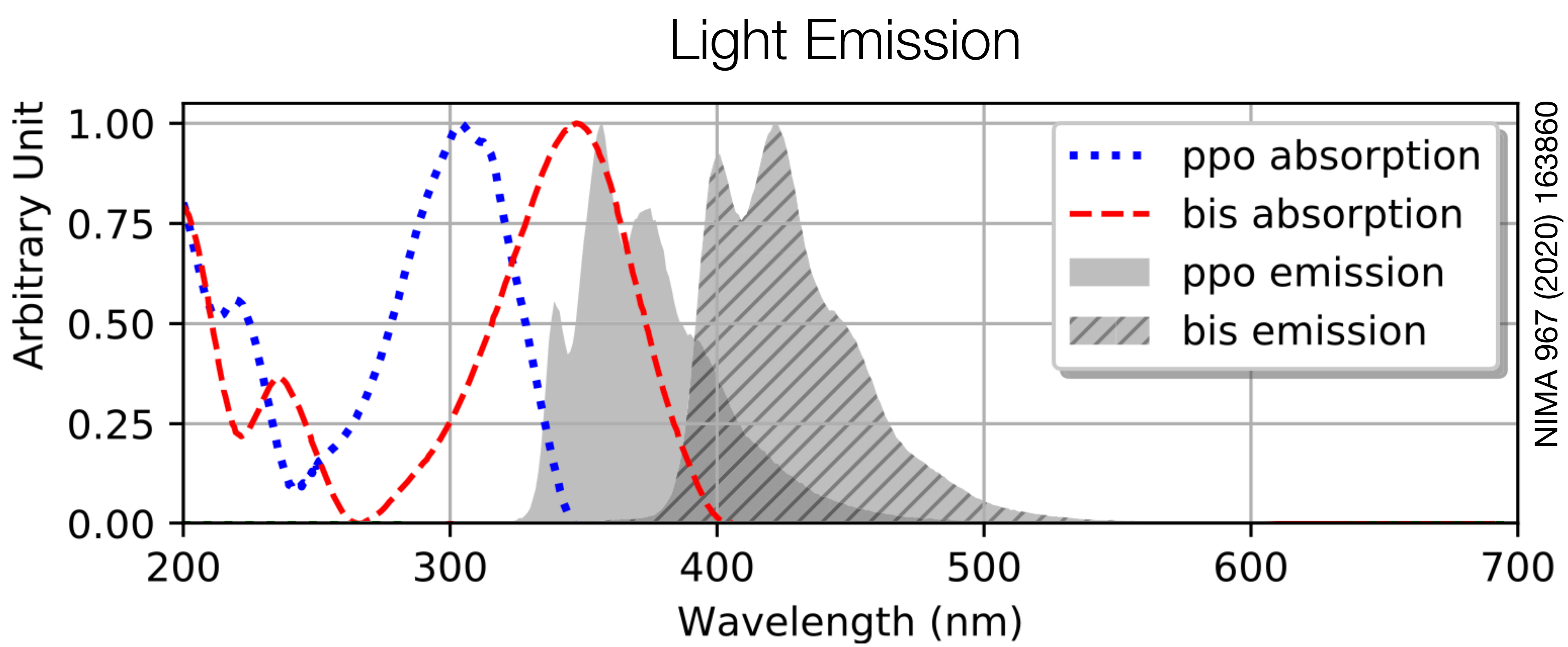


Solvent:
Linear Alkyl-Benzene
LAB

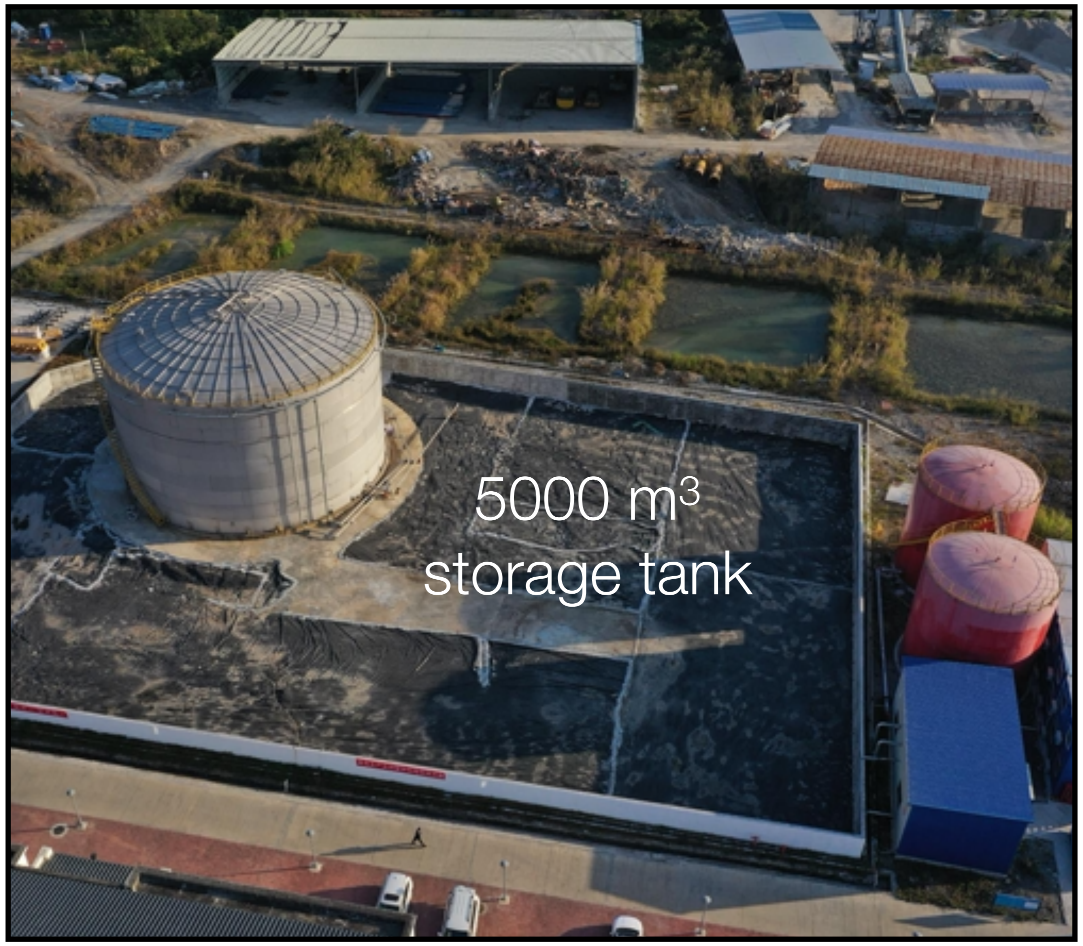
Fluor: 2.5 g/L PPO

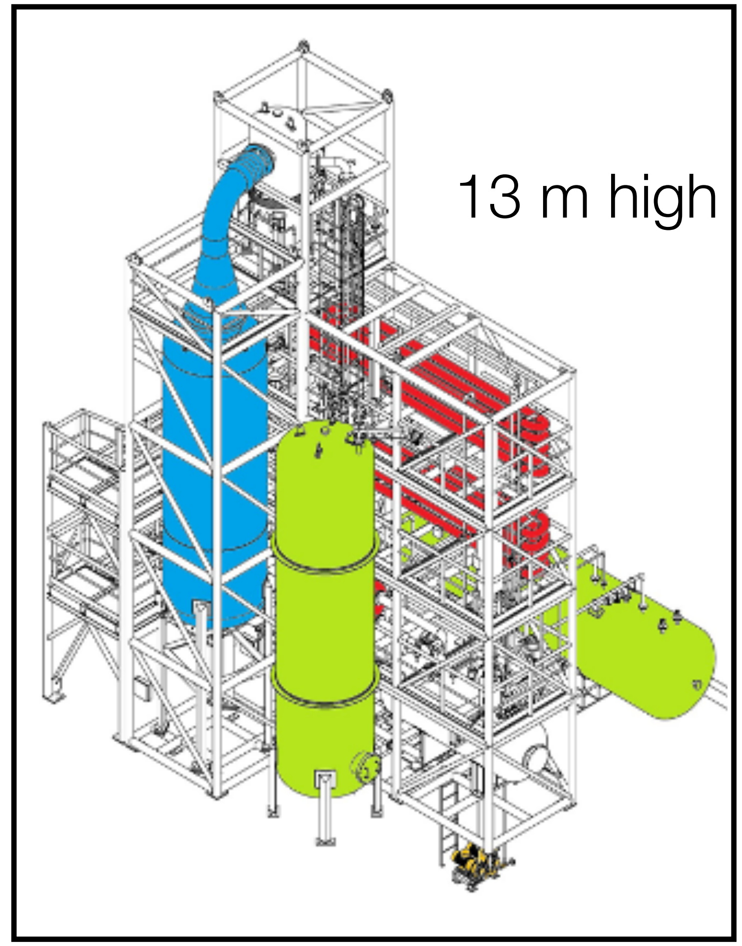
Wavelength shifter:
3 mg/L bis-MSB





Ensuring purity before filling the detector





Optical impurities reduce transparency →

Radioactive contaminants yield background events →

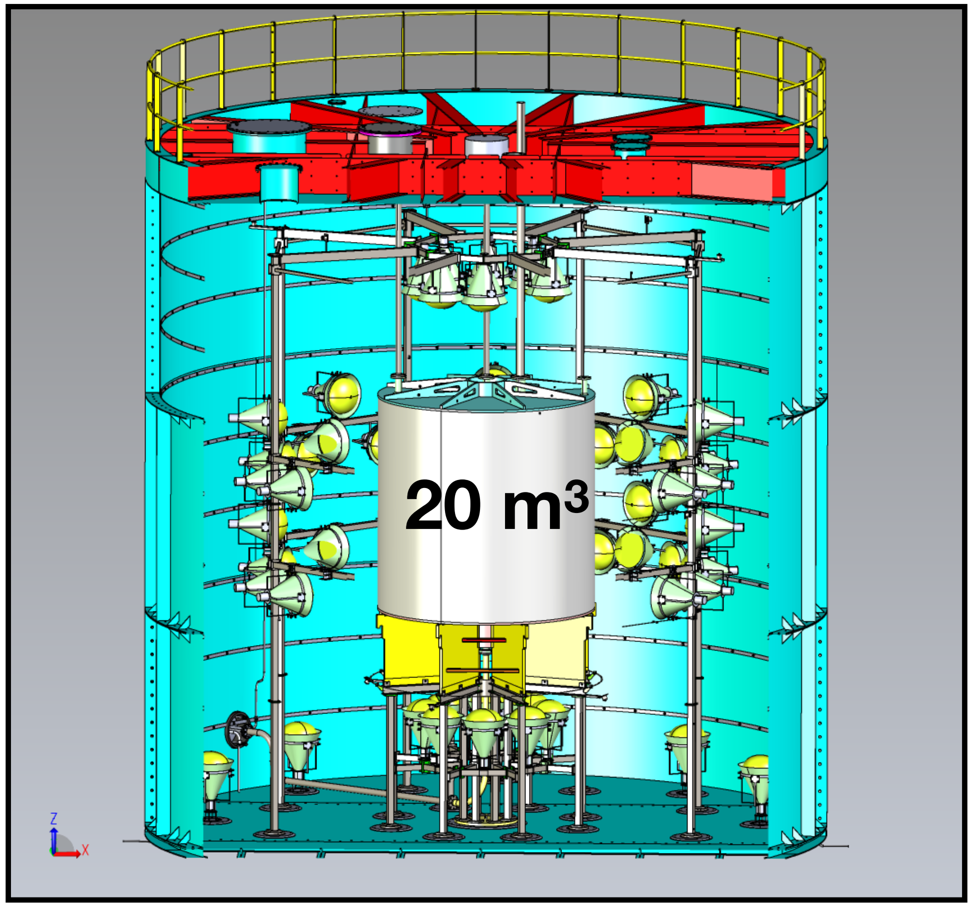
Purification

JHEP 11 (2021) 102

Requirements	^{238}U	^{232}Th	^{226}Ra	^{40}K	^{210}Pb(^{222}Rn)	^{85}Kr / ^{39}Ar
Reactor physics	10^{-15} g/g	10^{-15} g/g		10^{-16} g/g	10^{-22} g/g	
Solar physics	10^{-17} g/g	10^{-17} g/g	$5\cdot10^{-24}$ g/g	10^{-18} g/g	10^{-24} g/g	1μBq/m³

Ensuring radio purity during filling

During JUNO filling, batches of LS get monitored by 20 m^3 ancillary detector



Measure ^{238}U and ^{232}Th

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

Few coincidences (events) per day

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

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

Light Emission

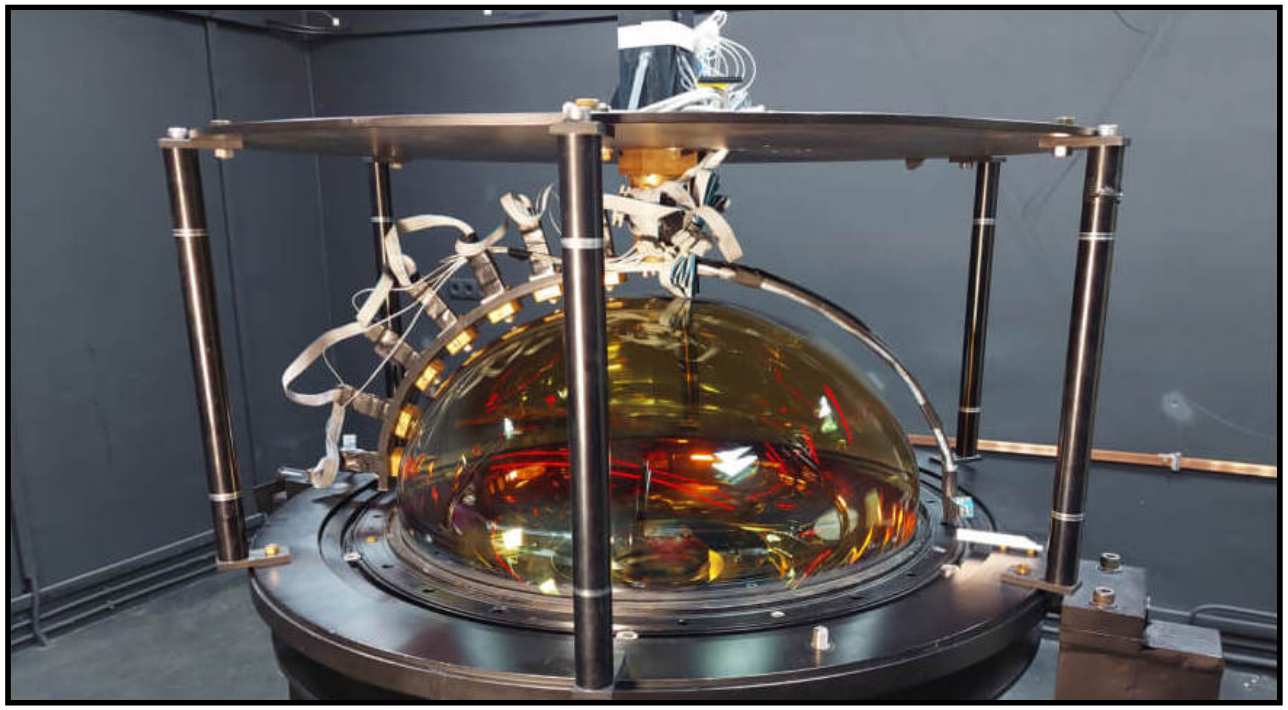
Light Detection

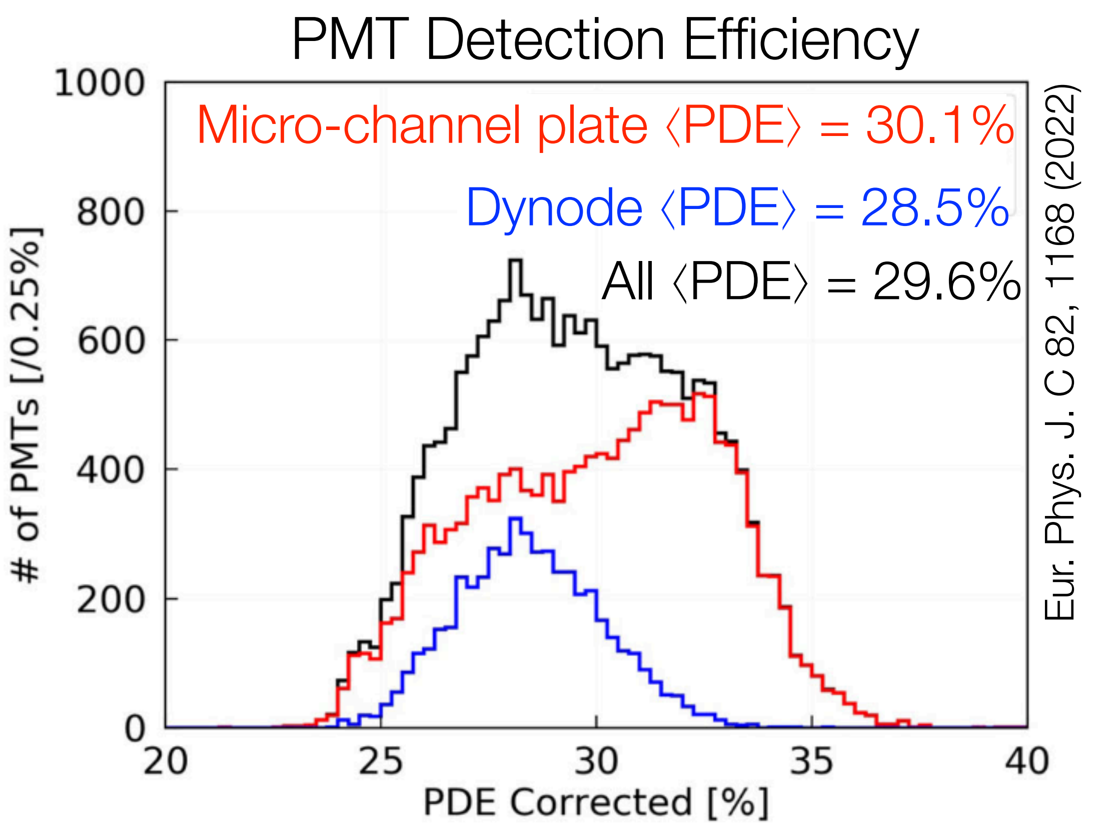
Charge Readout

Source Diagnostic

Energy resolution through photo-statistics

20-inch (large) photomultiplier tubes (PMTs)

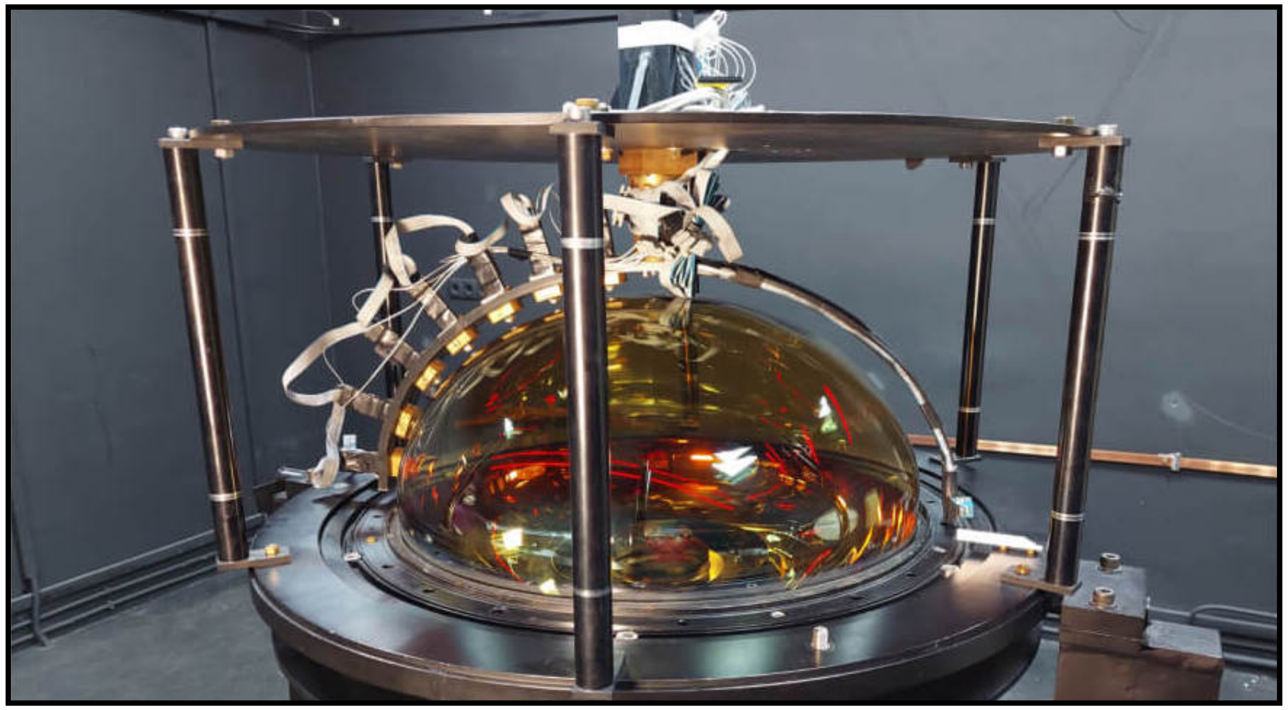




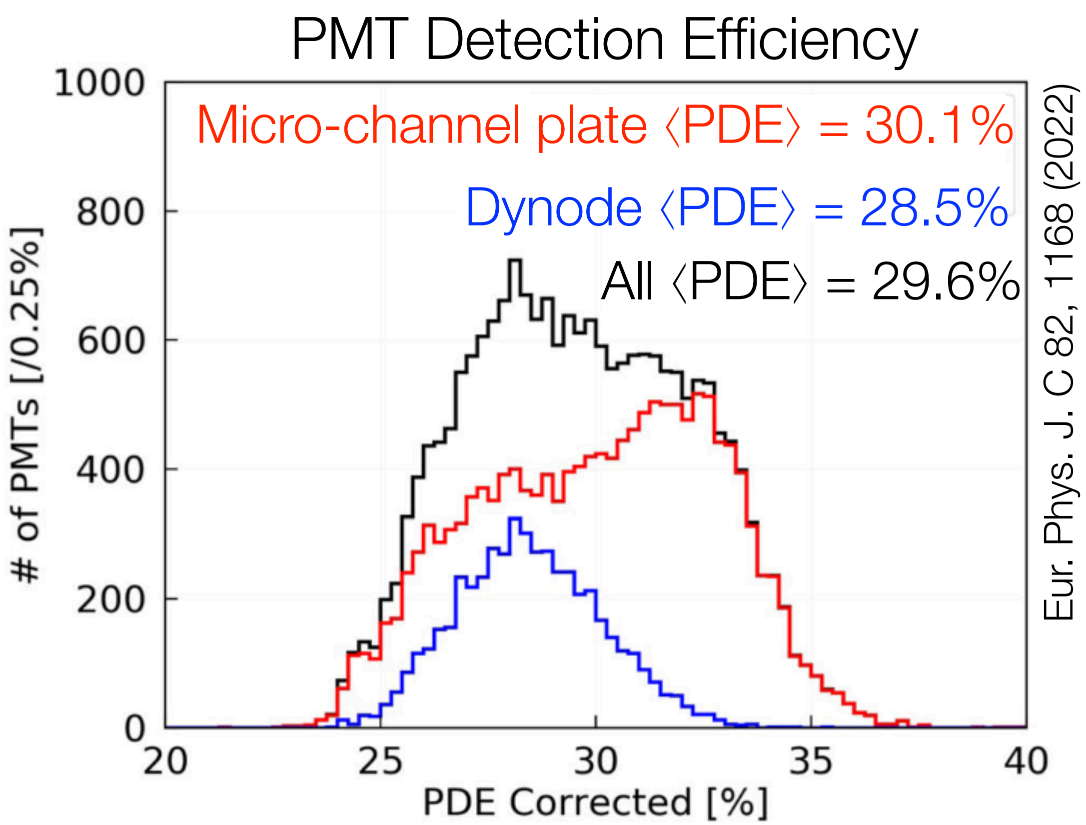
Quantity	5000	15000
Manufacturer	Hamamatsu (JP)	NNVT (CN)
Charge Collection	Dynode	Micro-channel plate
Transit Time Spread	σ 1.3 ns	σ 7.0 ns

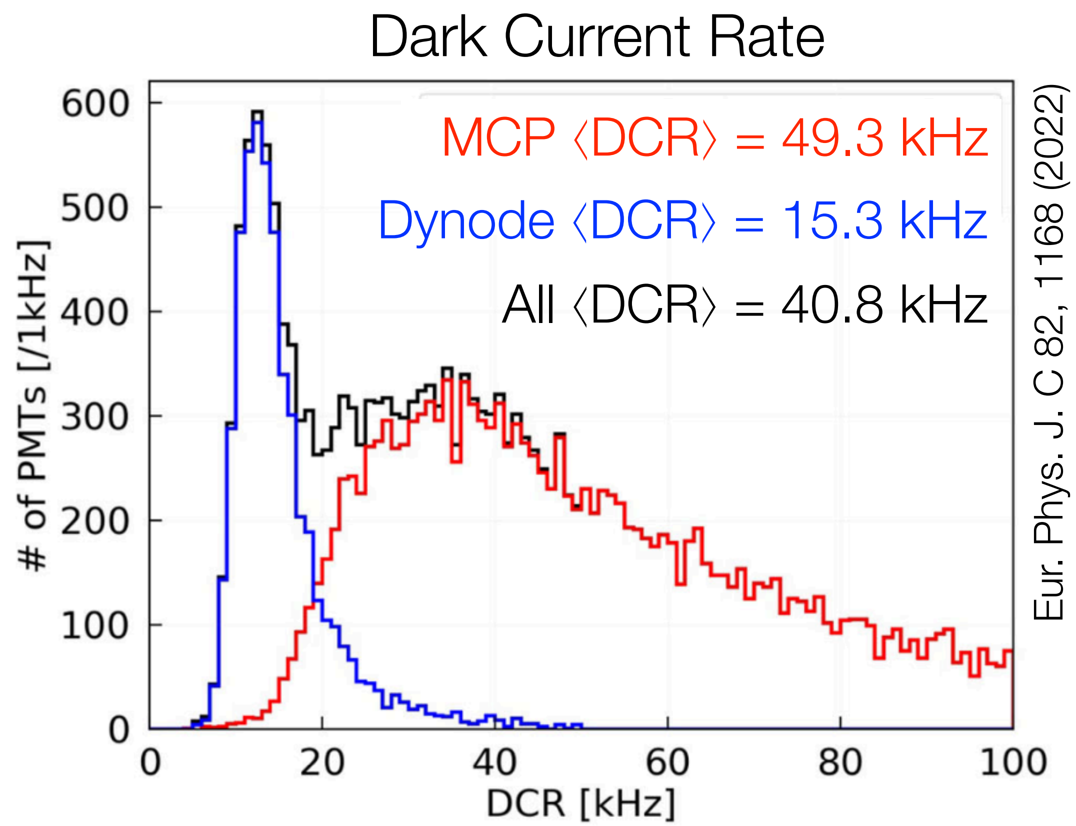
Energy resolution through photo-statistics

20-inch (large) photomultiplier tubes (PMTs)

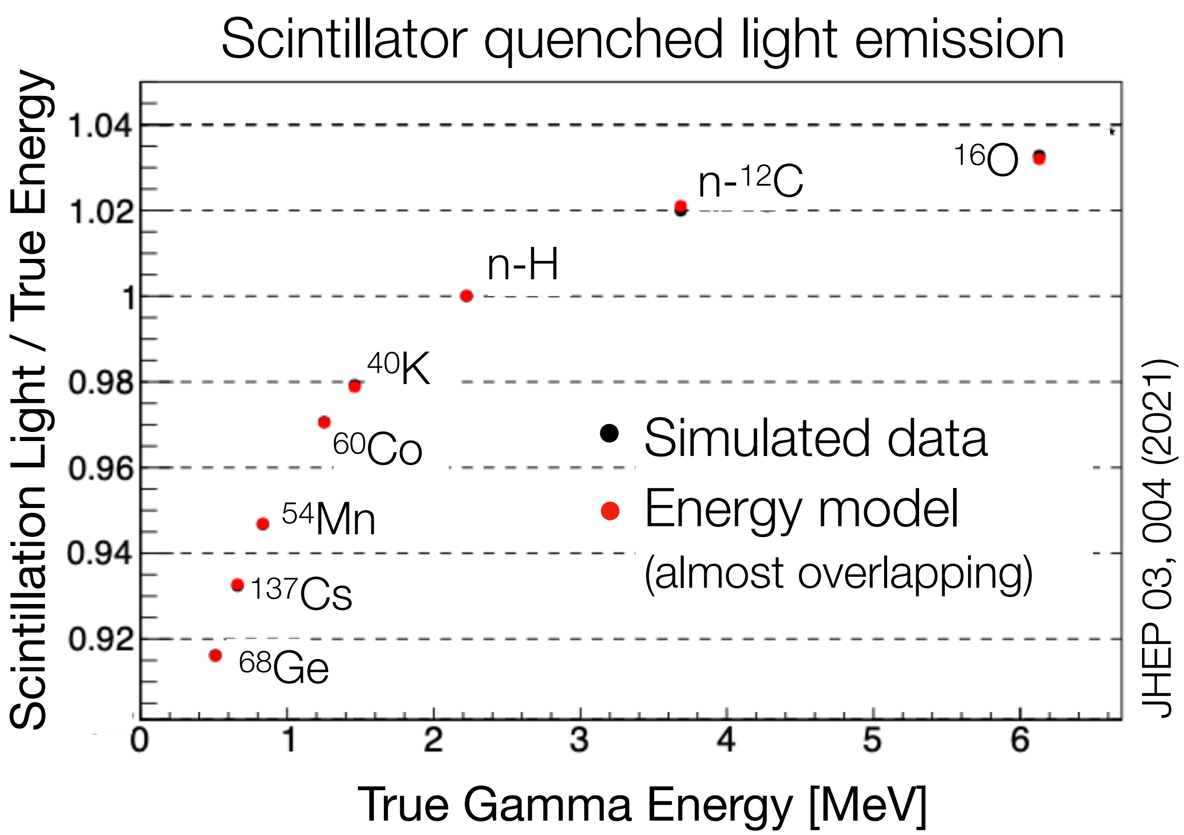


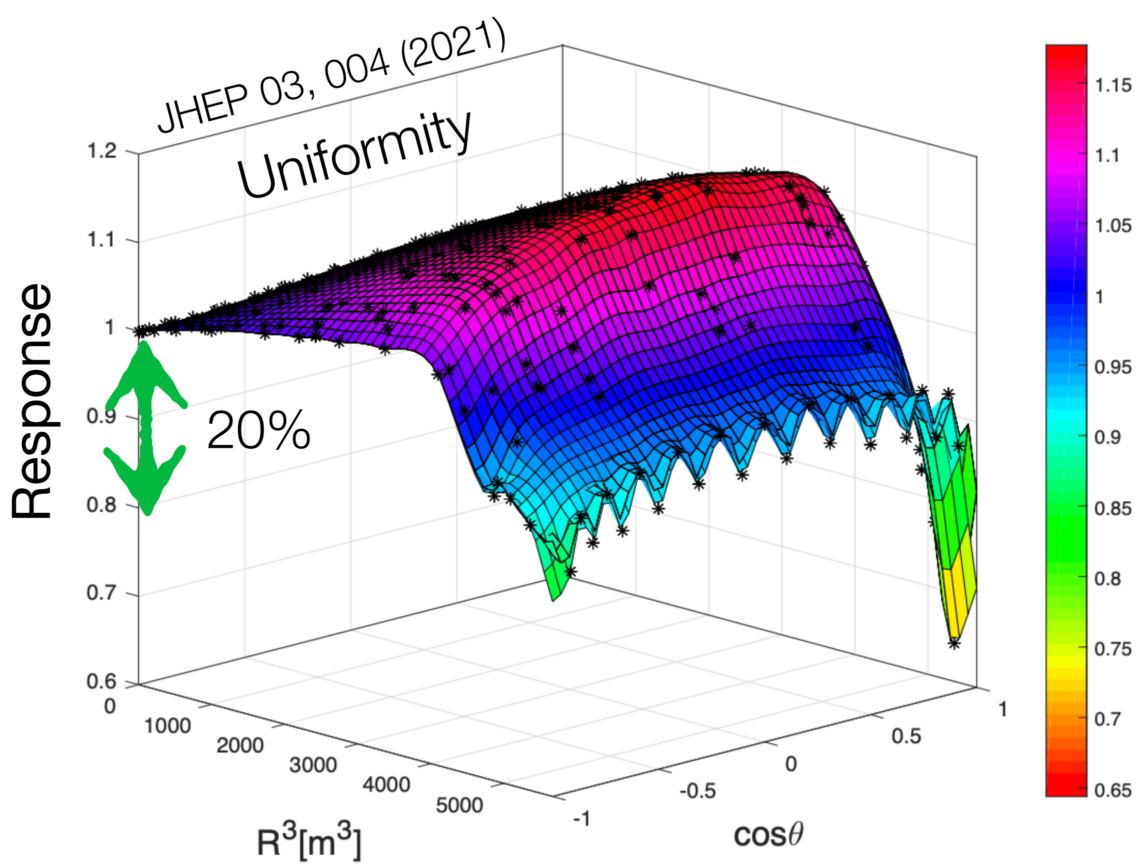
Quantity	5000	15000
Manufacturer	Hamamatsu (JP)	NNVT (CN)
Charge Collection	Dynode	Micro-channel plate
Transit Time Spread	σ 1.3 ns	σ 7.0 ns



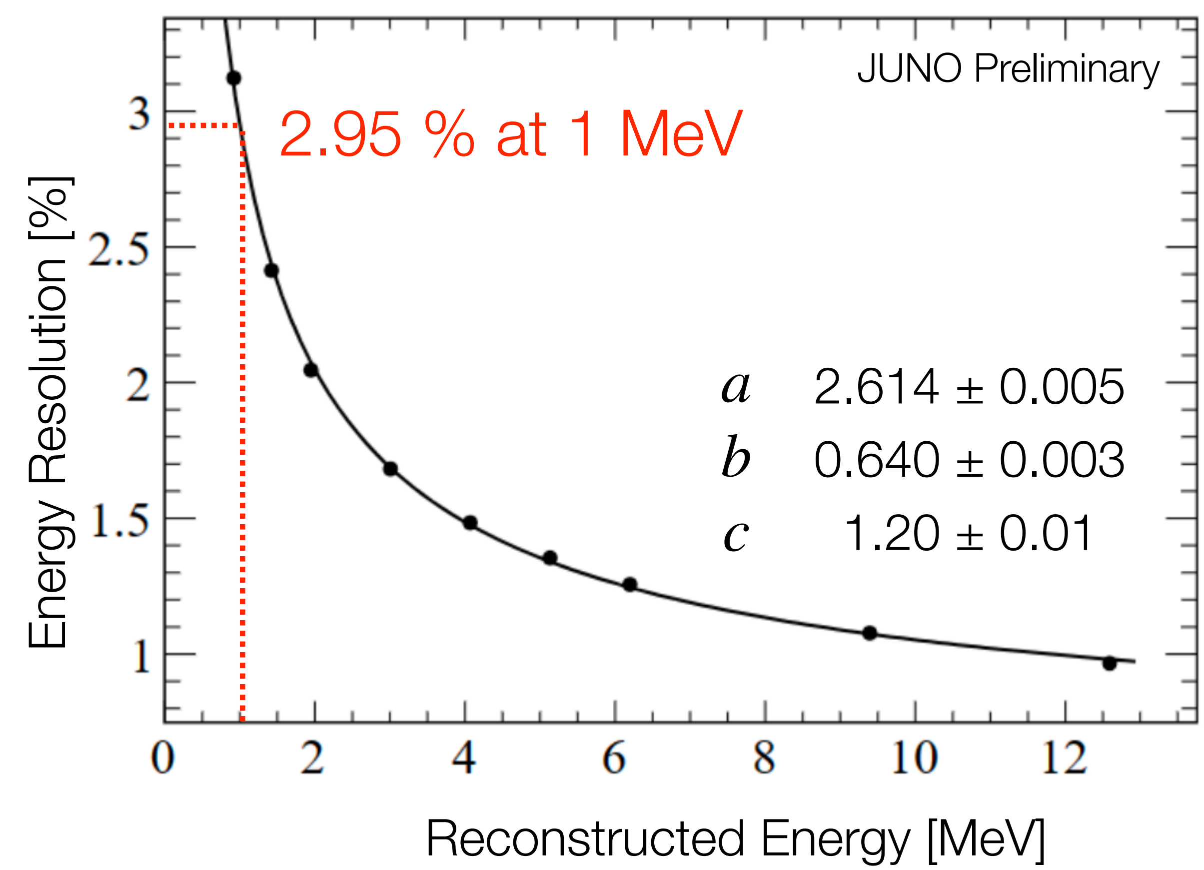


Energy resolution & scale through calibration

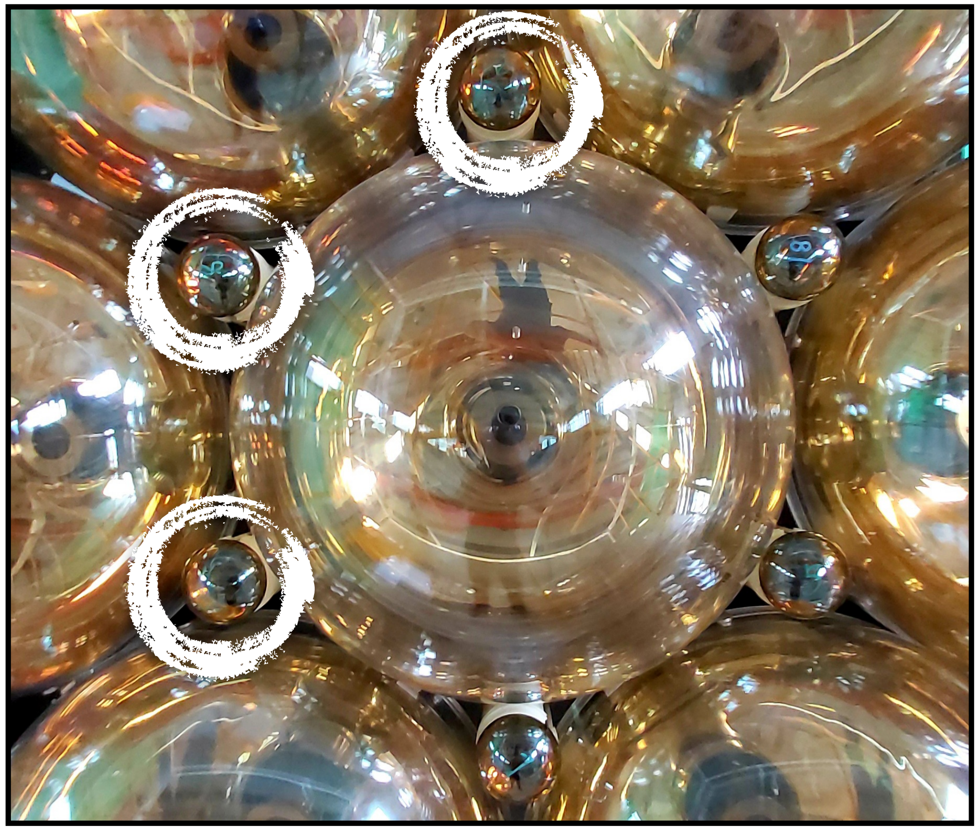




$$\frac{\sigma(E)}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2}$$



Understanding energy- & charge-related systematics

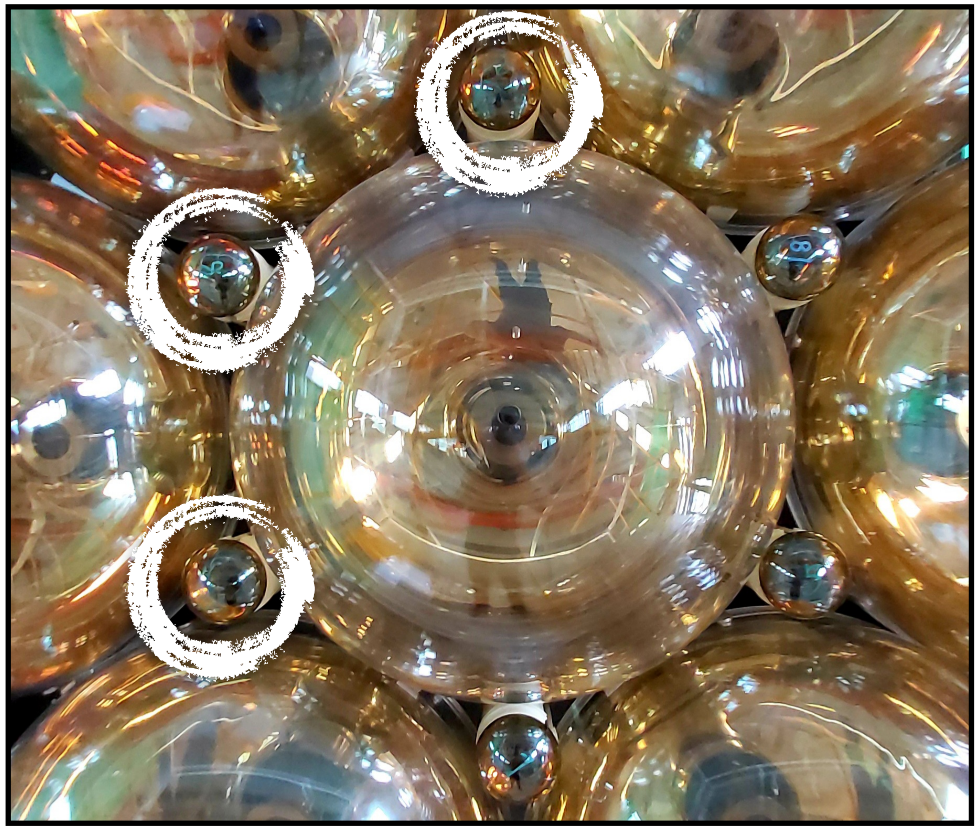


25600 3-inch PMTs (dynode-based) by HZC

Custom-designed shape - 25% Quantum eff.

Additional 3% coverage → more light detected

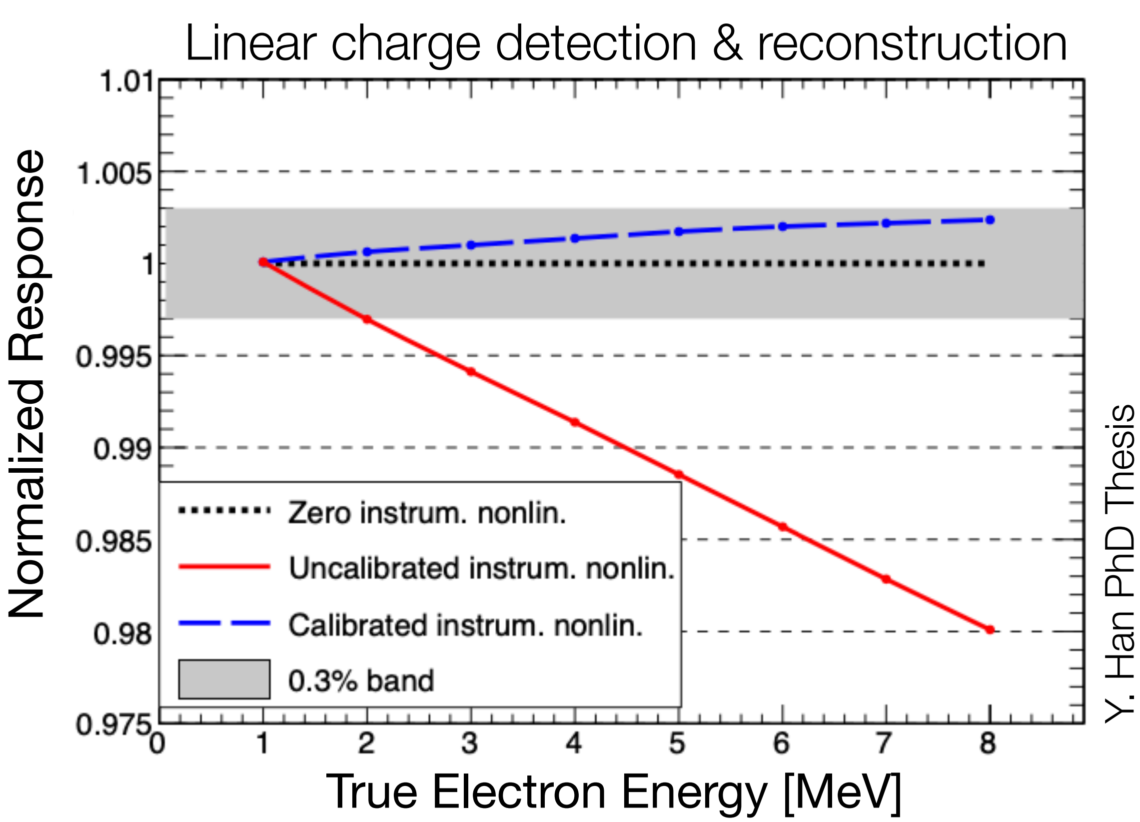
Understanding energy- & charge-related systematics



25600 3-inch PMTs (dynode-based) by HZC

Custom-designed shape - 25% Quantum eff.

Additional 3% coverage → more light detected



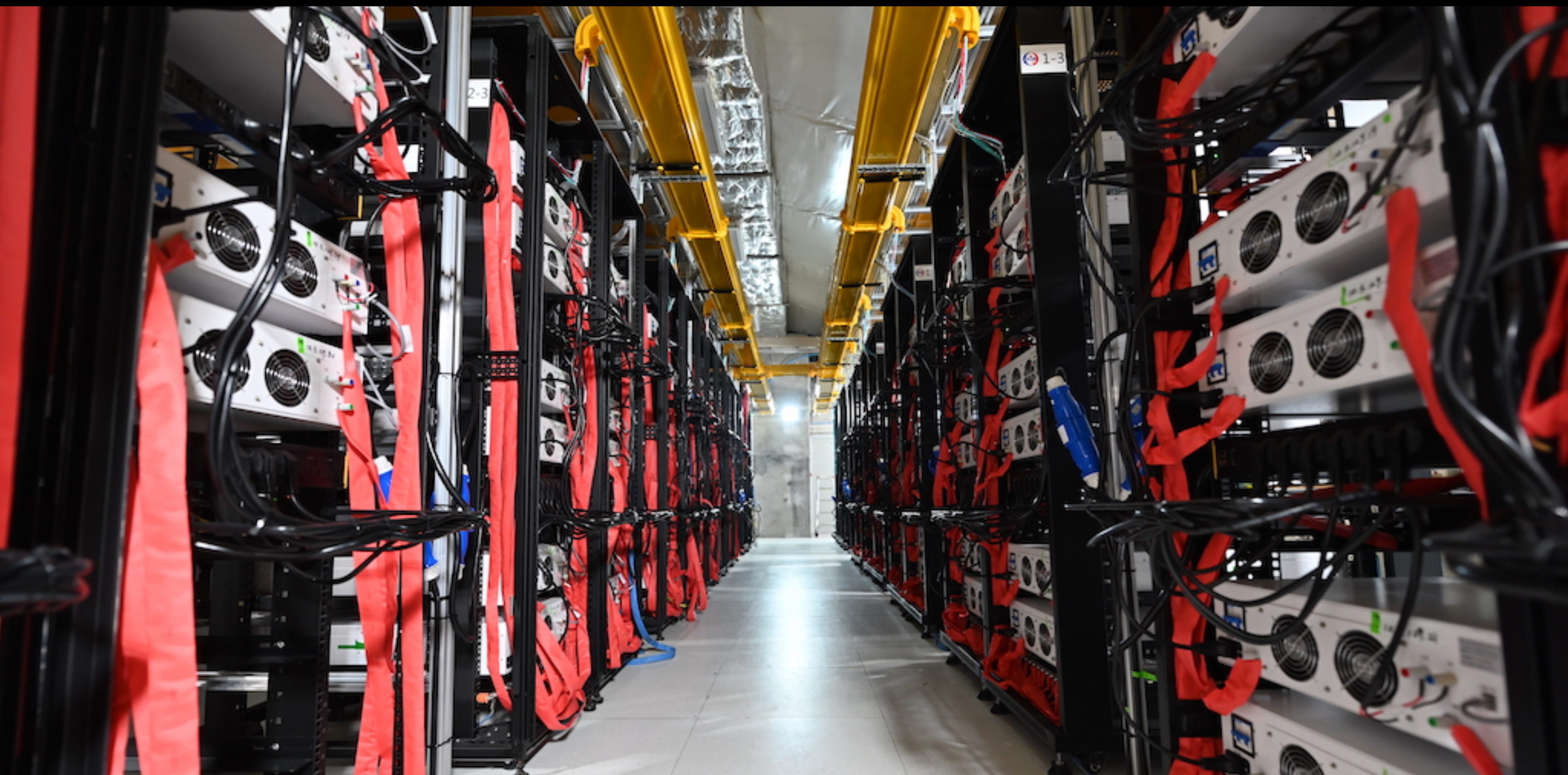
- 20” PMT “reactor” dynamic range: [0,100] PEs
  - Challenge: ensure sub-% energy systematics
- 3” PMT “reactor” dynamic range: [0,2] PEs
  - Well understood regime
- Powerful synergy to ensure charge linearity

Light Emission

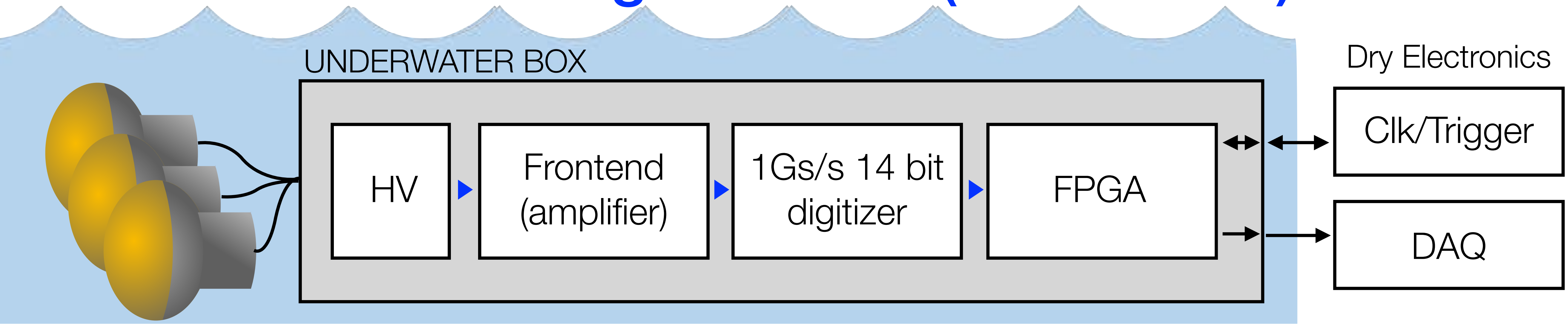
Light Detection

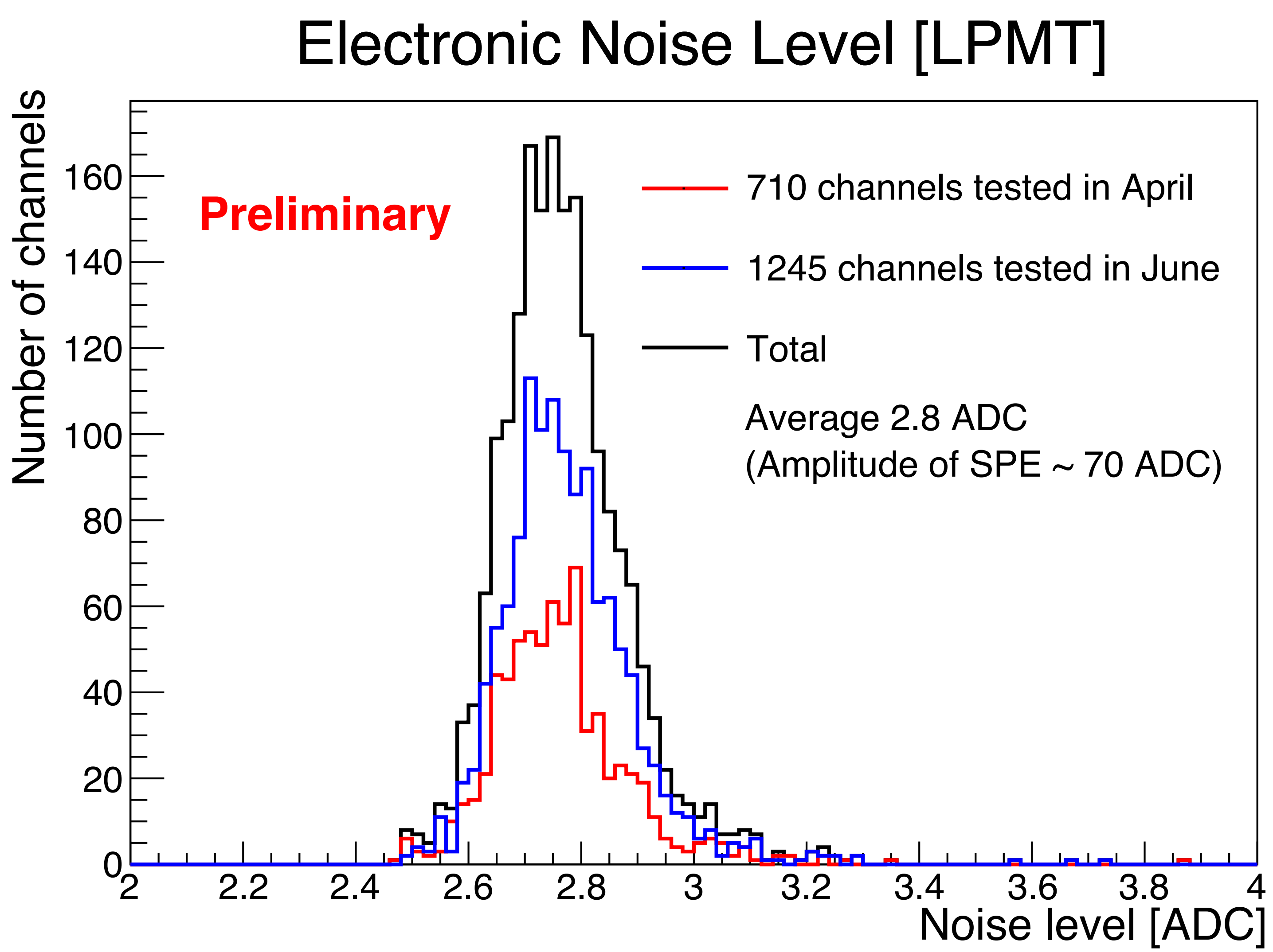
Charge Readout

Source Diagnostic



PMT charge readout (Electronics)

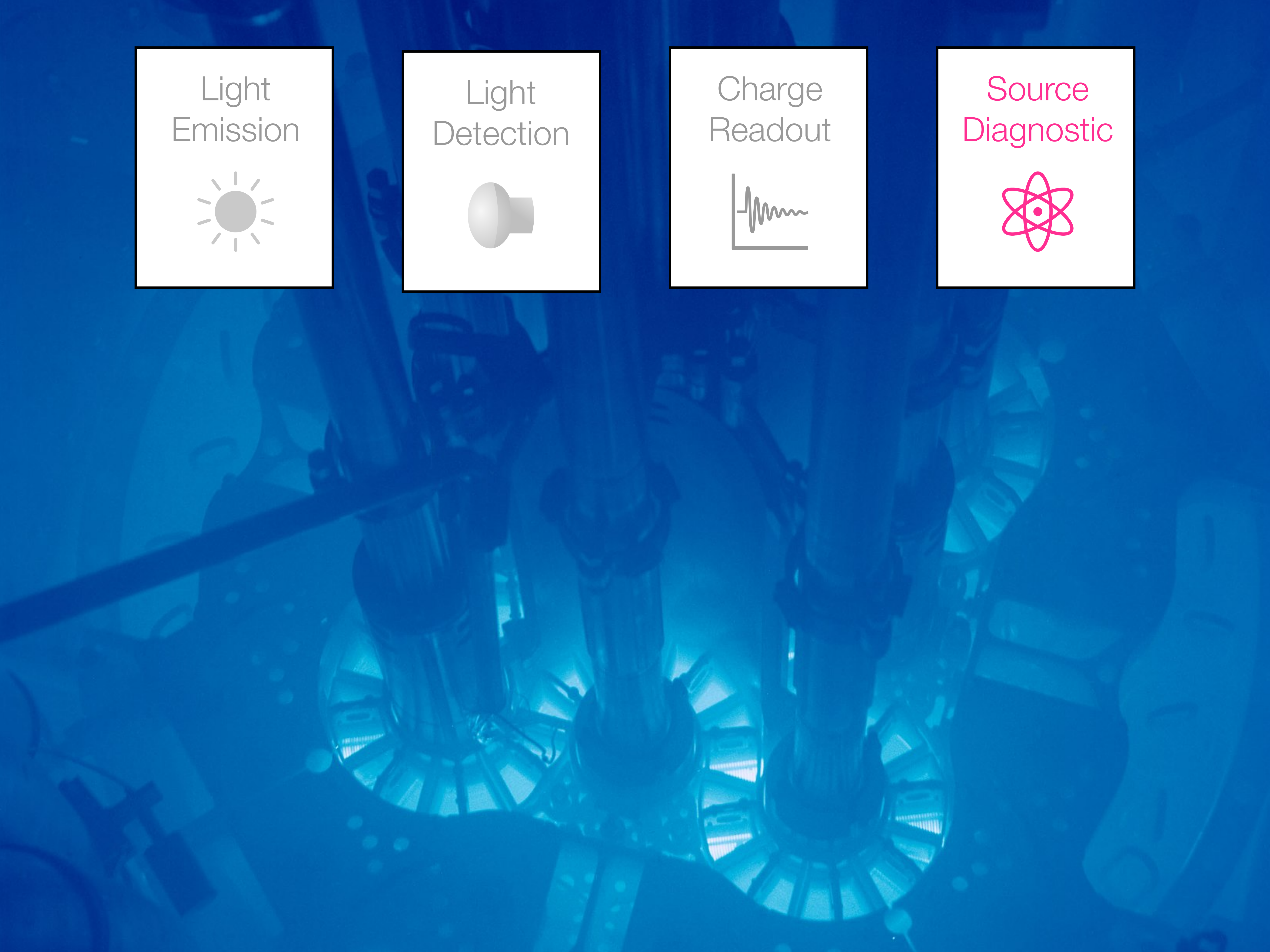




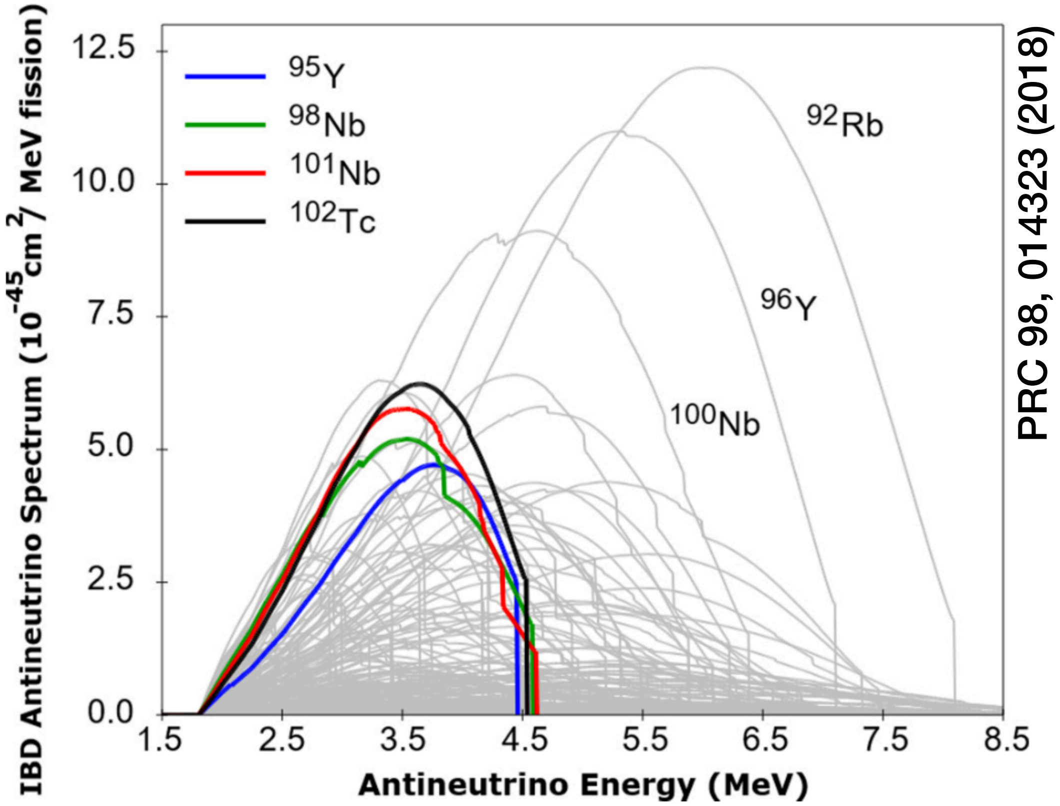
6862 boards produced and tested before installation

Ongoing test campaign during installation

Careful design & excellent grounding: noise level: 4% at 1 photoelectron better than specs: 10% at 1 p.e.


Light Emission
Light Detection
Charge Readout
Source Diagnostic

Understanding reactor neutrino source (TAO)

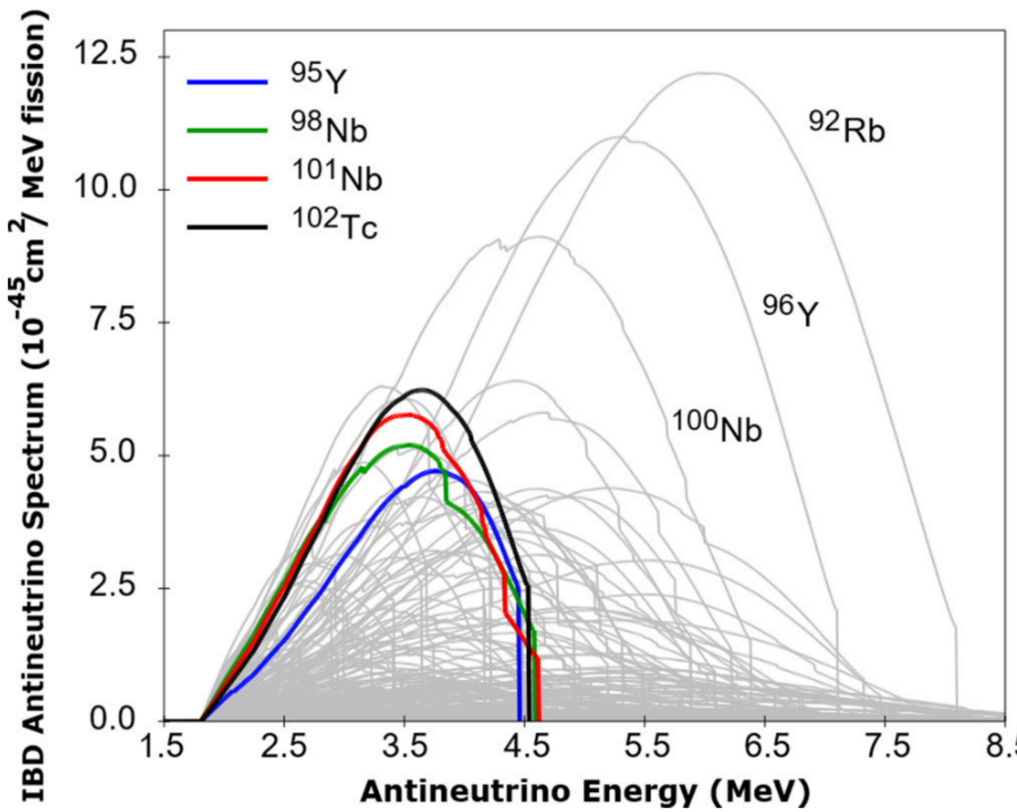


PRC 98, 014323 (2018)

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

Reactor models being affected by larger-than-predicted uncertainties

Understanding reactor neutrino source (TAO)



PRC 98, 014323 (2018)

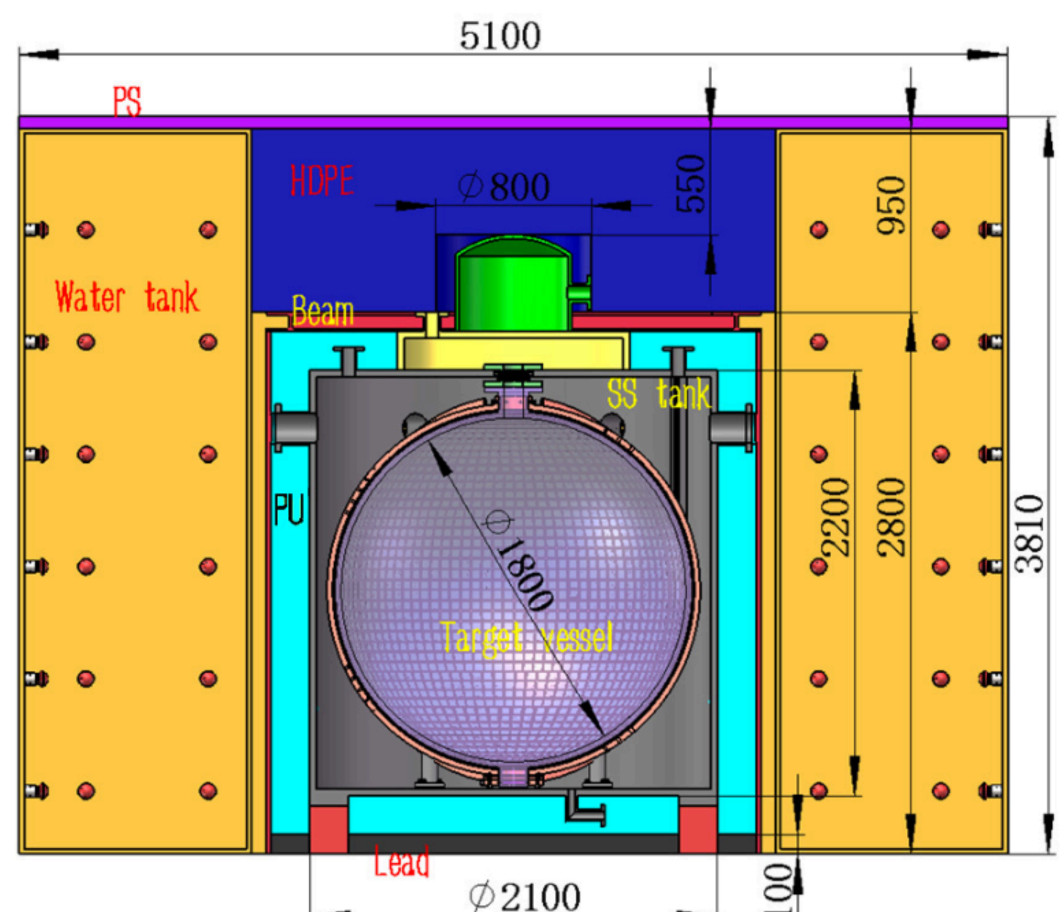
Many beta decays contribute to $\bar{\nu}_e$ yield at nuclear reactors

Reactor models being affected by larger-than-predicted uncertainties

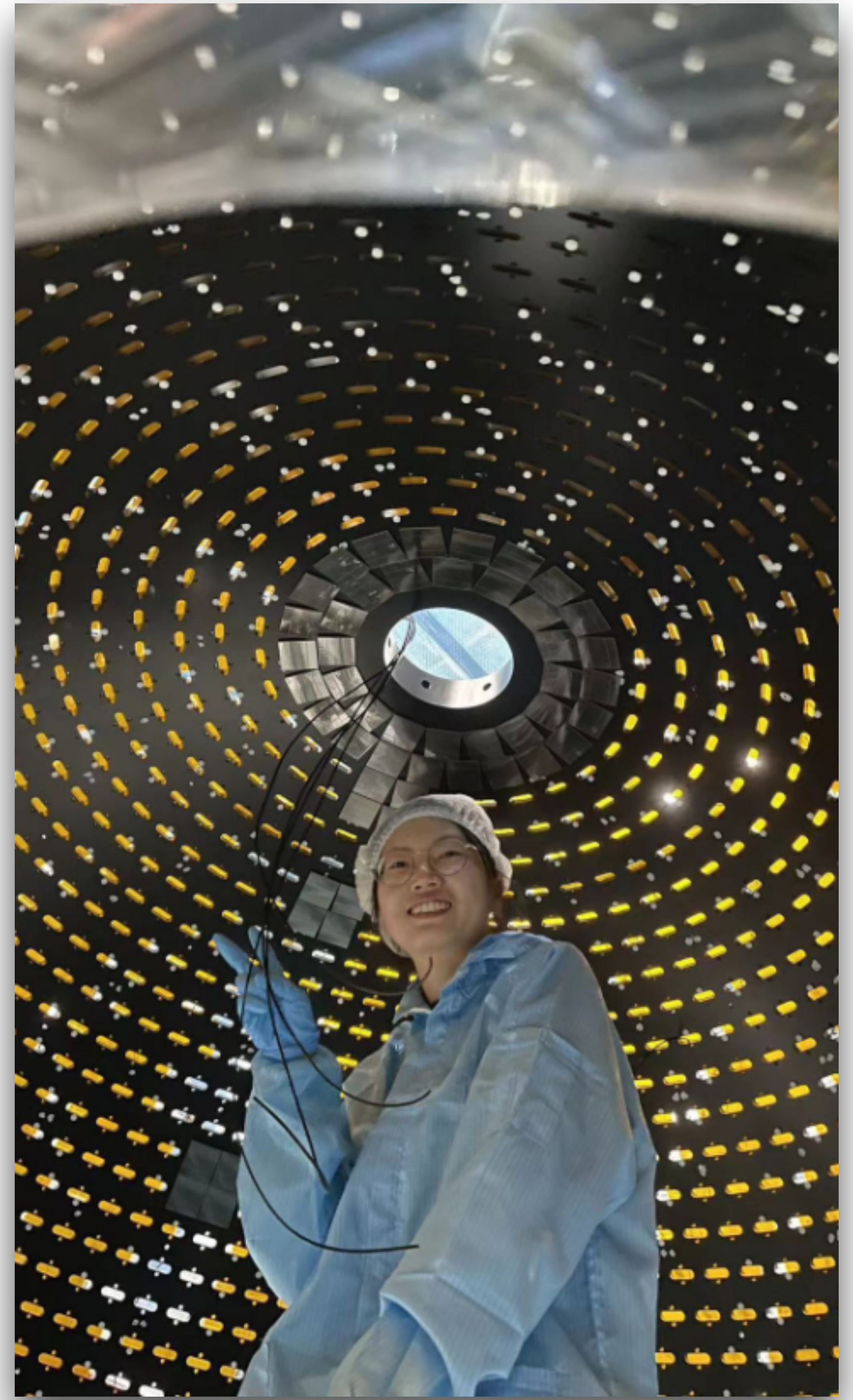
2.8 ton detector at ~44 m from reactor

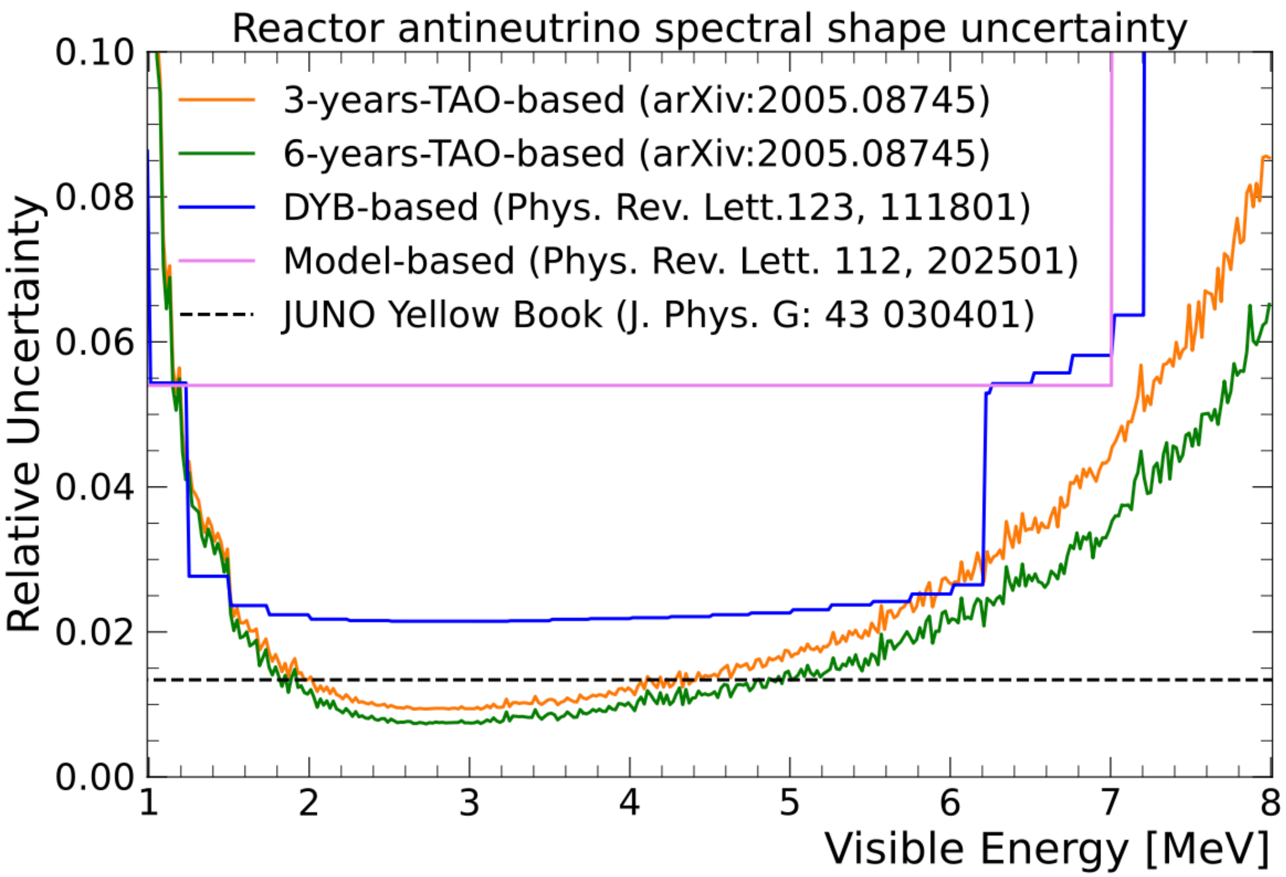
Energy resolution: < 2% at 1 MeV (4500 PE/MeV)

Detector at -50°C (reduce SiPM dark rate)



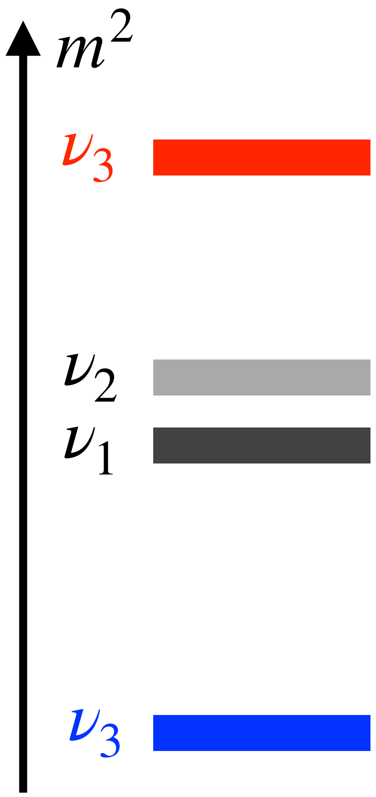
TAO construction and expected performance





Physics

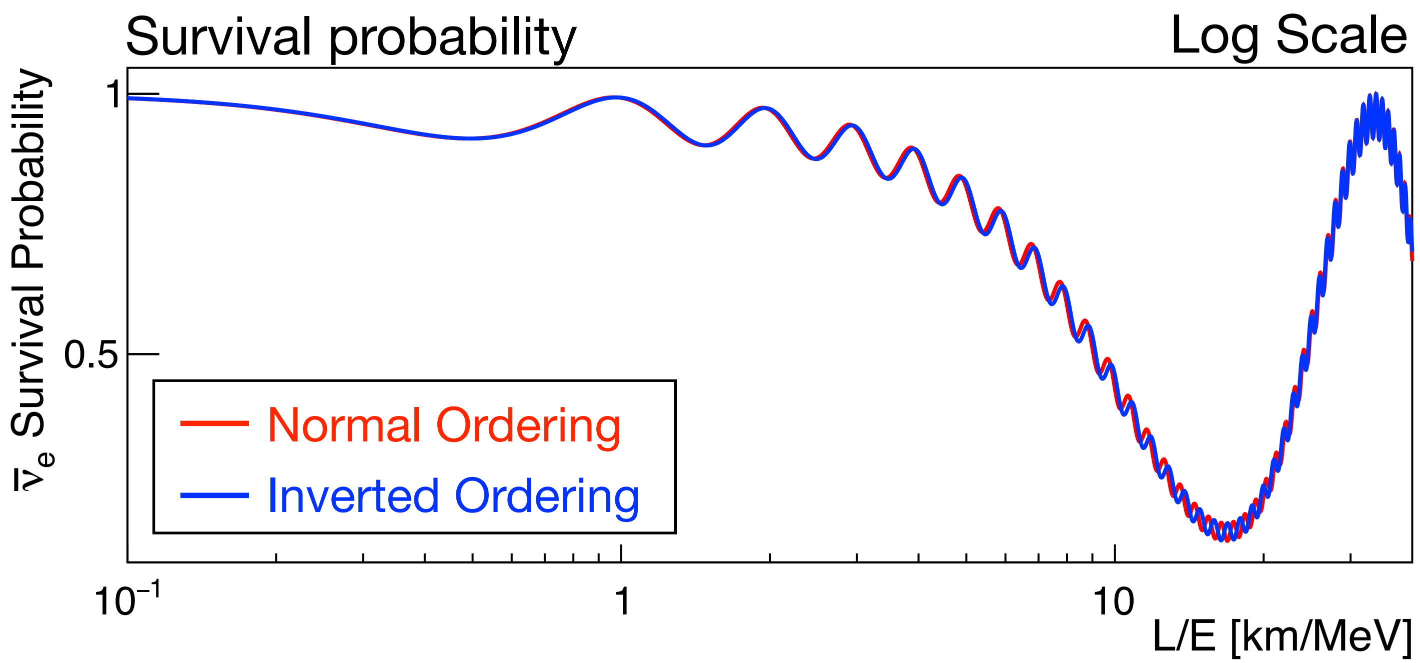
Rationale behind the JUNO design



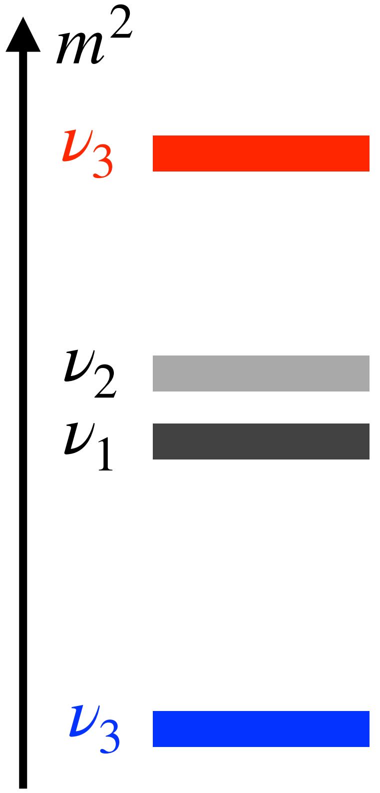
$m_2^2 > m_1^2$, but $\mathrm{sign}(\Delta m_{32}^2)$ not conclusively known

Is m_3^2 the heaviest (normal ordering) or the lightest (inverted ordering)?

$\bar{\nu}_e$ survival probability has this information embedded



Rationale behind the JUNO design



$m_2^2 > m_1^2$, but $\mathrm{sign}(\Delta m_{32}^2)$ not conclusively known

Is m_3^2 the heaviest (normal ordering) or the lightest (inverted ordering)?

$\bar{\nu}_e$ survival probability has this information embedded

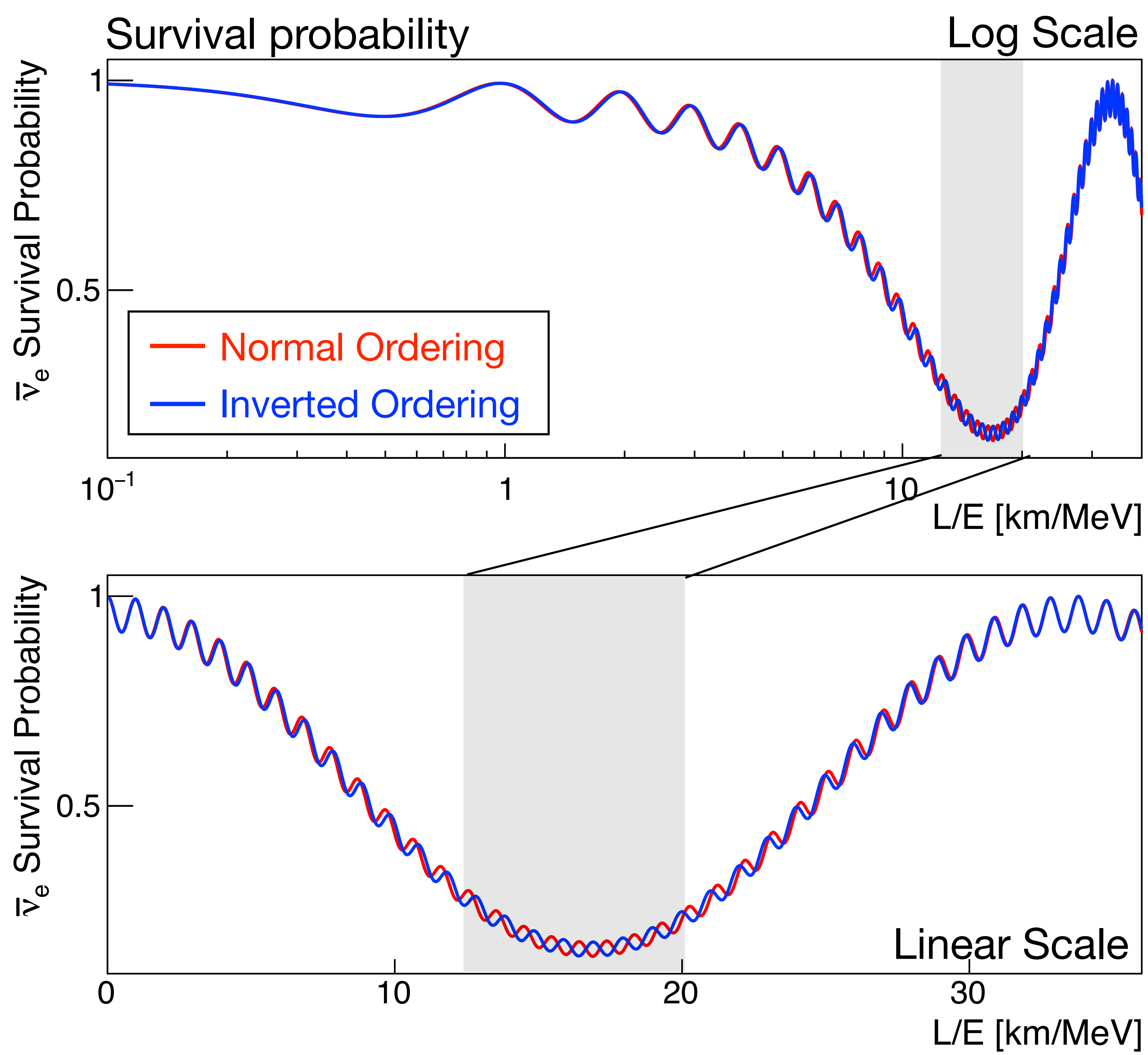
Two orderings get out of phase

$\frac{\sigma(E)}{E} \sim 3\%$ to disentangle them

Reactor $\bar{\nu}_e$ energy: [0,8] MeV

→ Baseline = 52.5 km

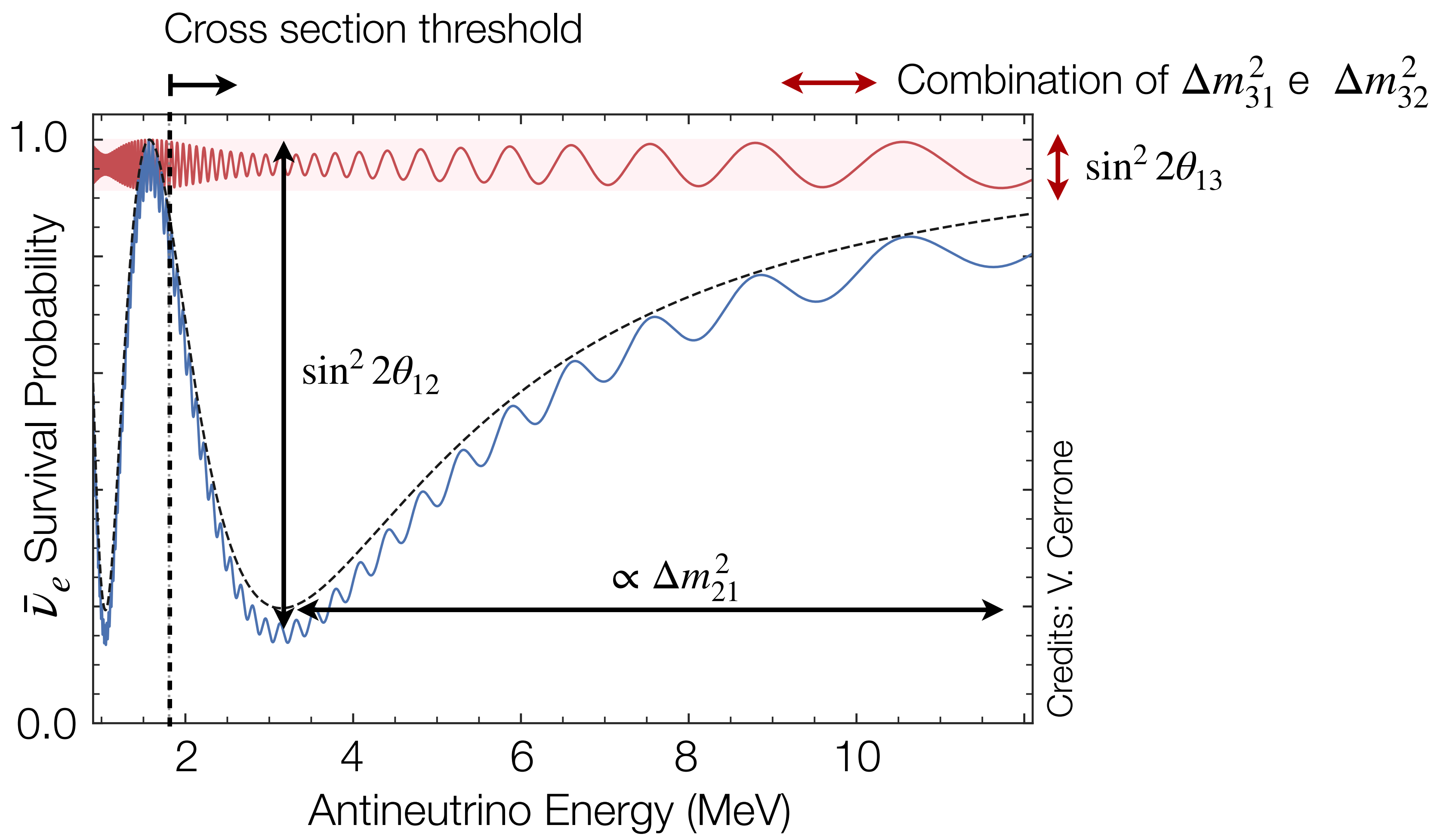
→ 20 kton to compensate 1/R²



Neutrino oscillation parameters

Detect for the first time solar and atmospheric oscillation modes simultaneously

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{12}\, c_{13}^4 \sin^2 \Delta_{21} - \sin^2 2\theta_{13} \left(c_{12}^2 \sin^2 \Delta_{31} + s_{12}^2 \sin^2 \Delta_{32} \right)$$

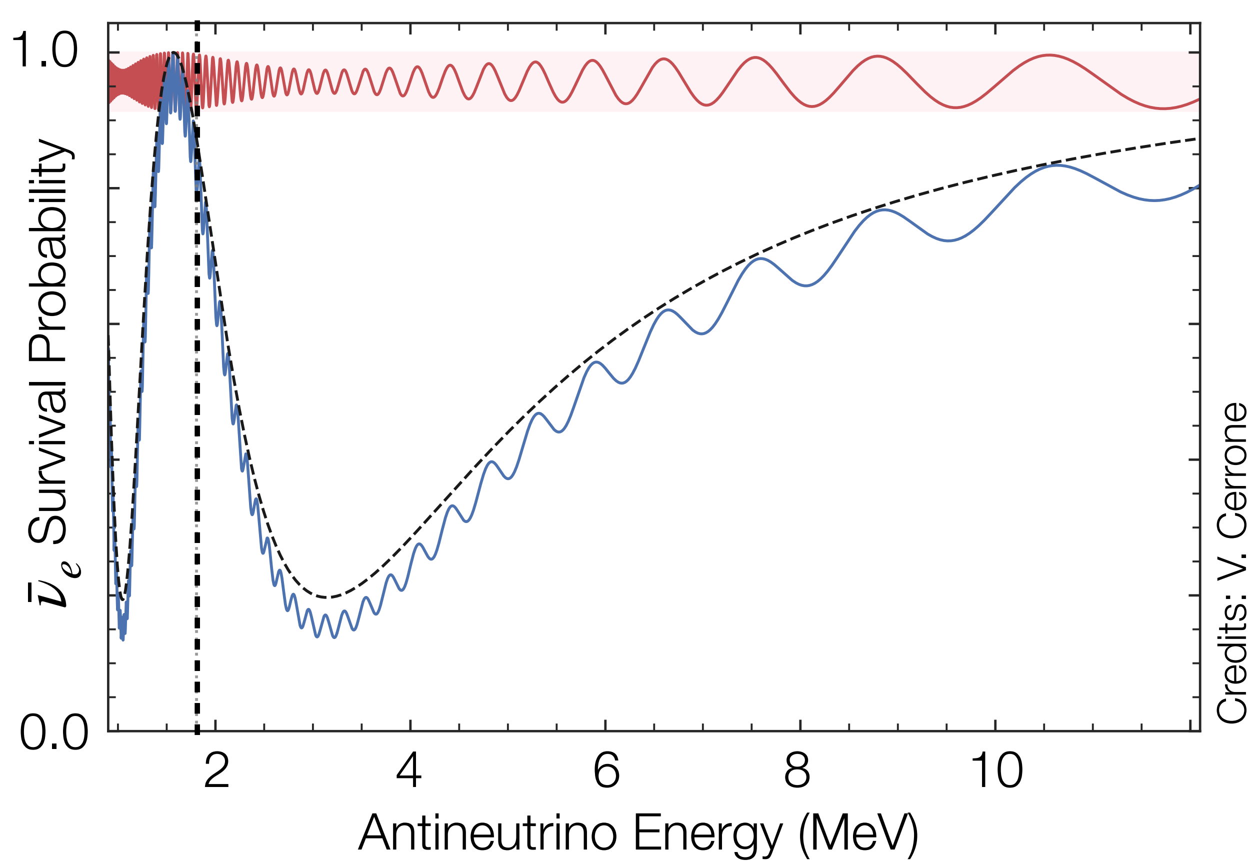


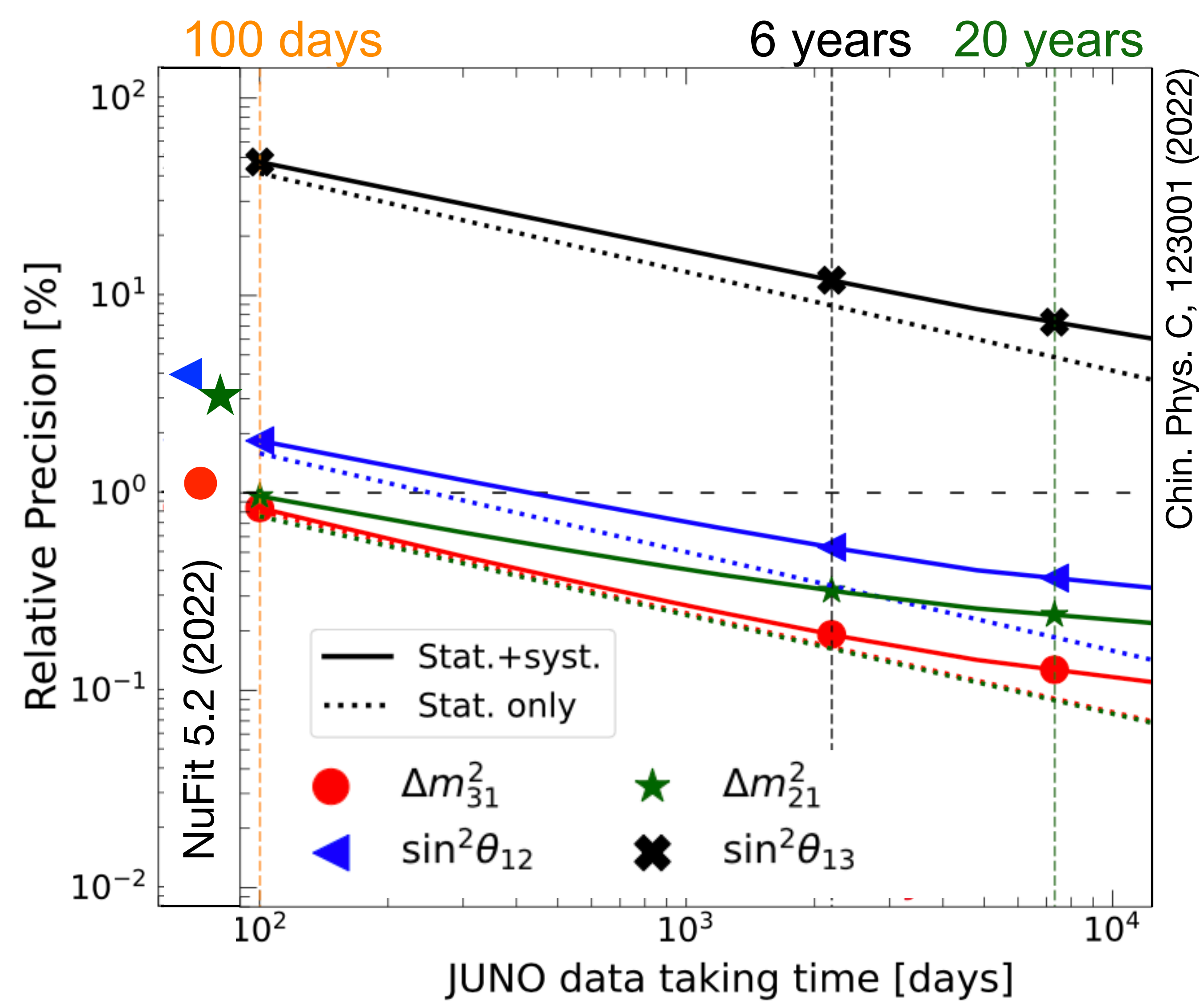
Neutrino oscillation parameters

Detect for the first time solar and atmospheric oscillation modes simultaneously

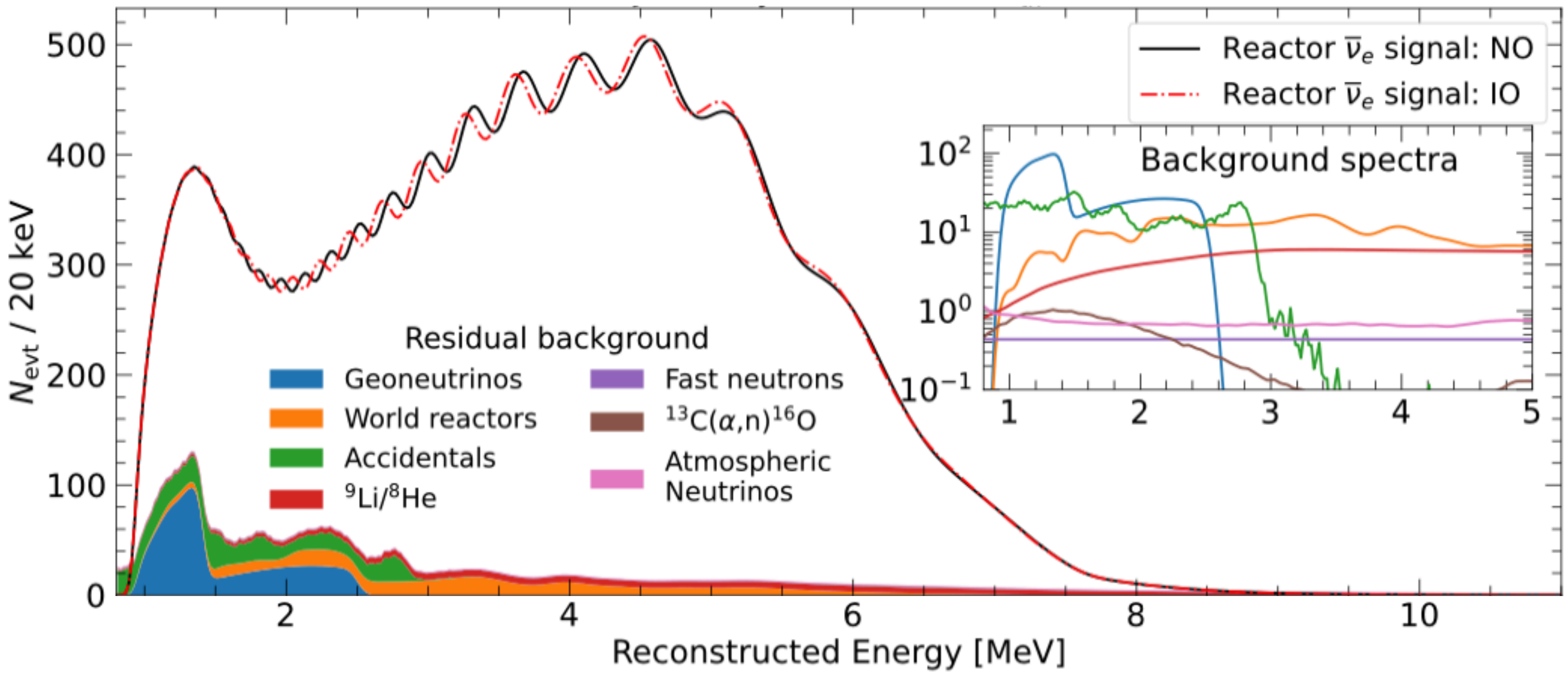
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{12}\, c_{13}^4 \sin^2 \Delta_{21} - \sin^2 2\theta_{13} \left(c_{12}^2 \sin^2 \Delta_{31} + s_{12}^2 \sin^2 \Delta_{32}\right)$$

JUNO will measure $\sin^2\theta_{12}$ and the two mass splittings with a sub-percent precision in a few years





Ordering of the neutrino mass eigenstates



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

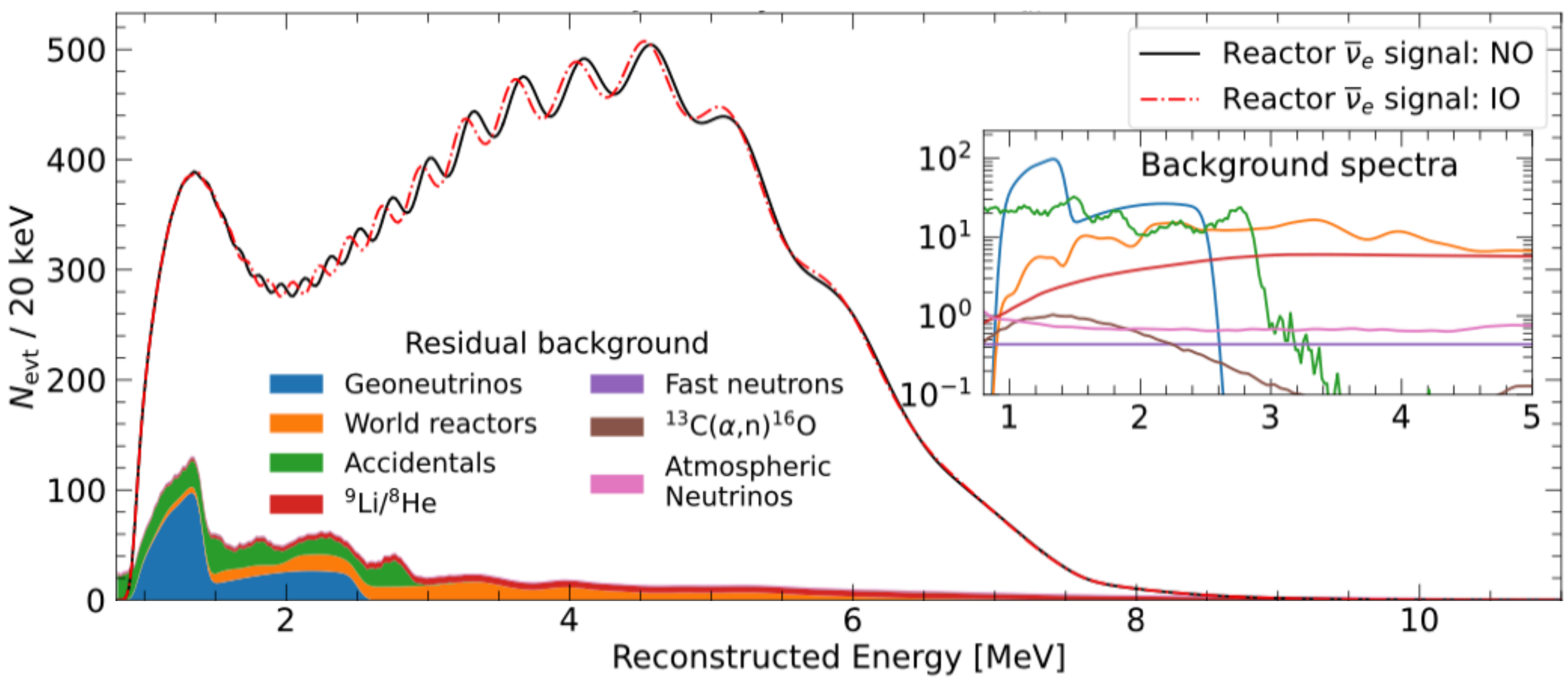
2 reactor cores won't be built ↓

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

PMT detection efficiency
better than specs: 27% → 29% ↑

Unoscillated reactor spectrum
better constrained by TAO ↑

Ordering of the neutrino mass eigenstates



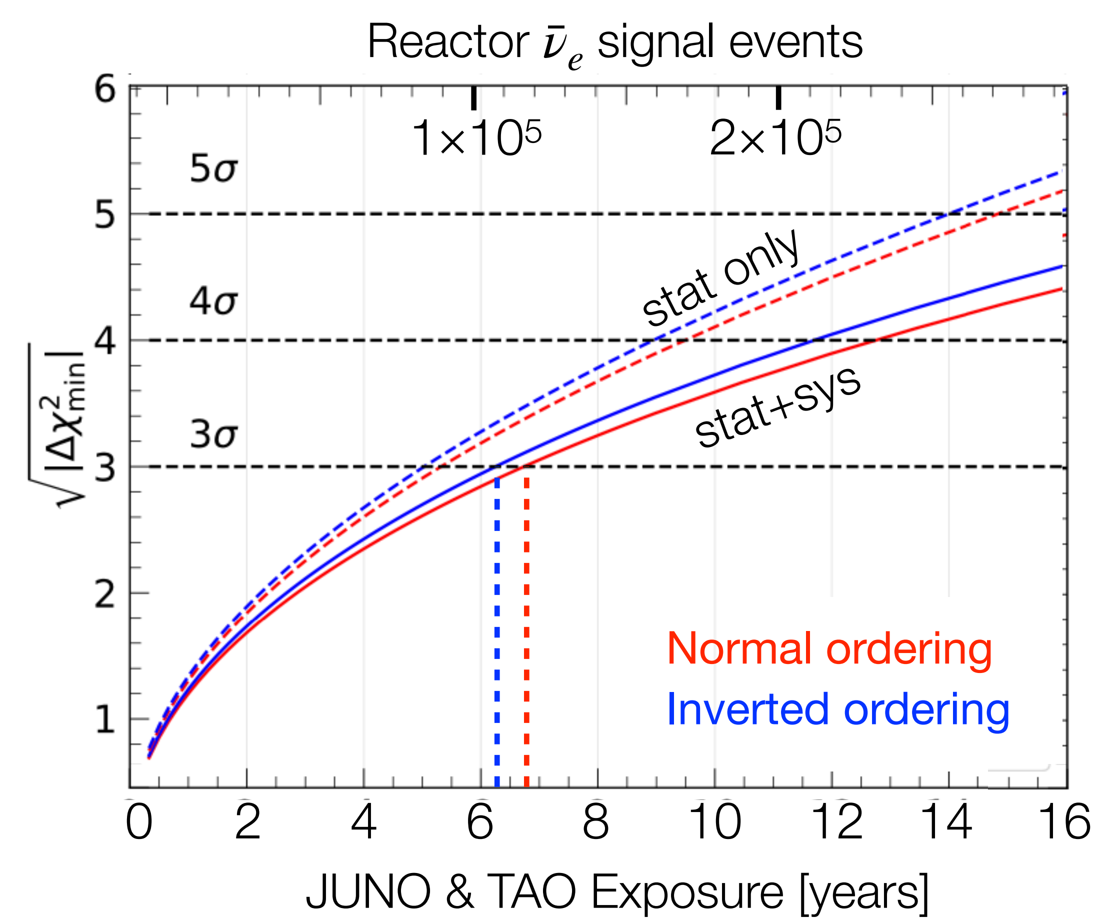
Major Updates w.r.t JPG 43, 030401 (2016)

2 reactor cores won't be built ↓

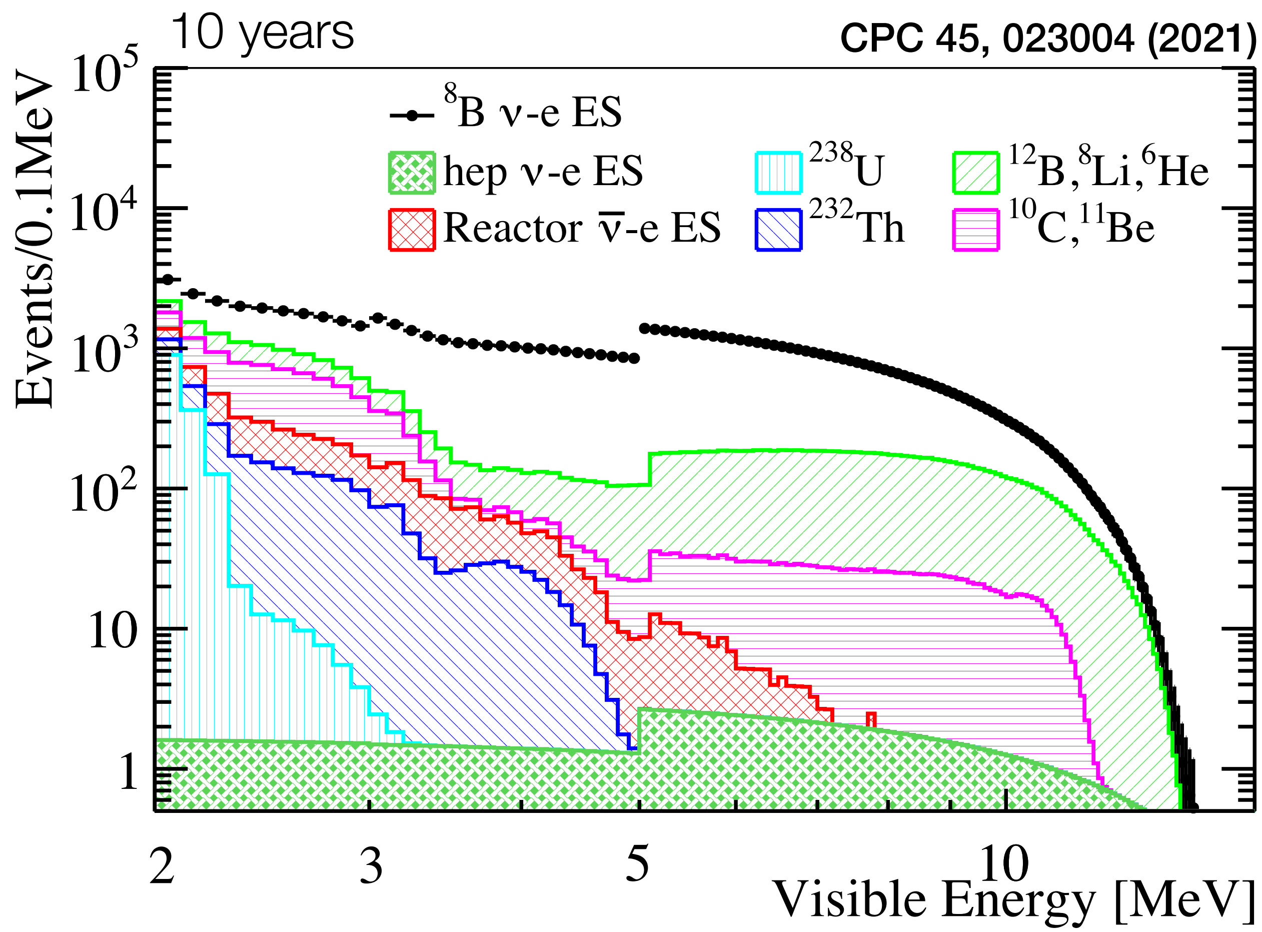
Experimental hall up by 60 m:
30% larger muon flux ↓

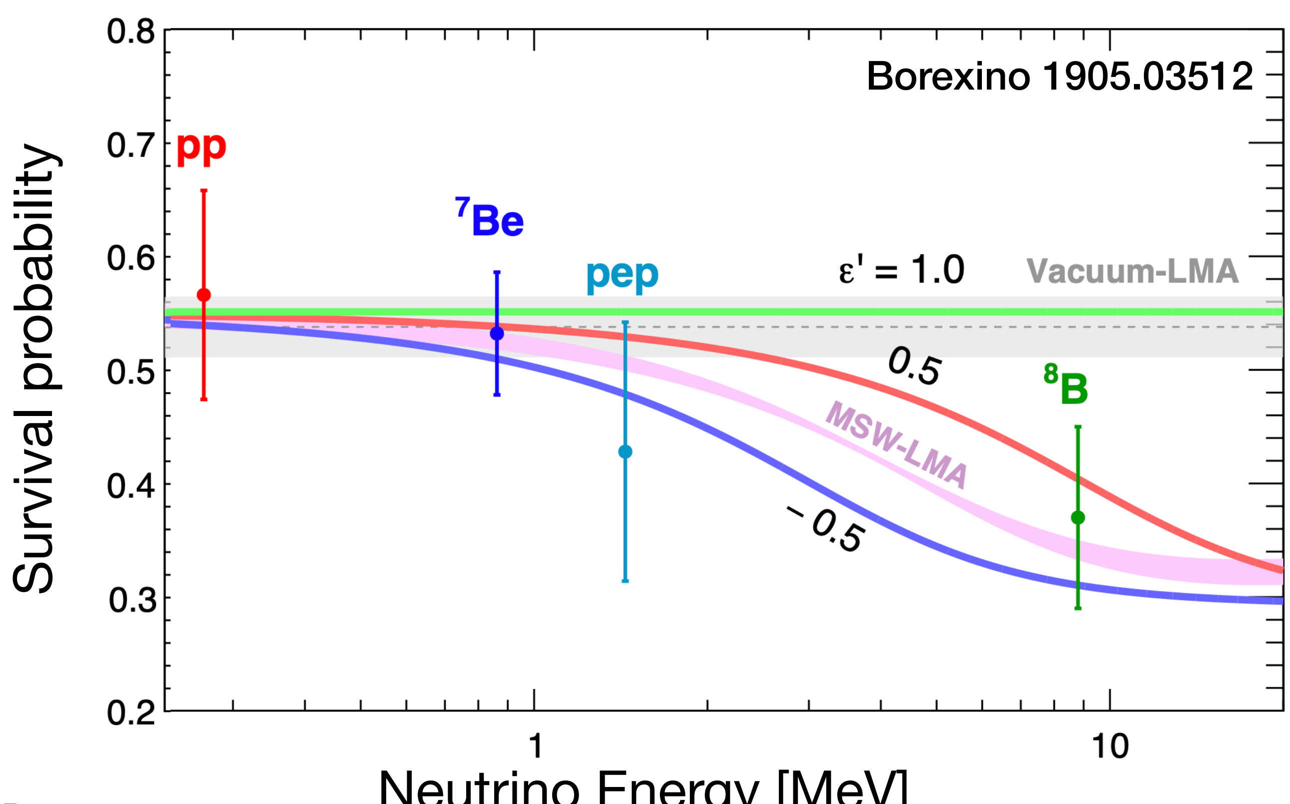
PMT detection efficiency
better than specs: 27% → 29% ↑

Unoscillated reactor spectrum
better constrained by TAO ↑



High-energy solar neutrinos from ^8B





Detection: ν_e elastic scattering off e^-

Main backgrounds:

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

▼

Fiducial volume & 2 MeV threshold

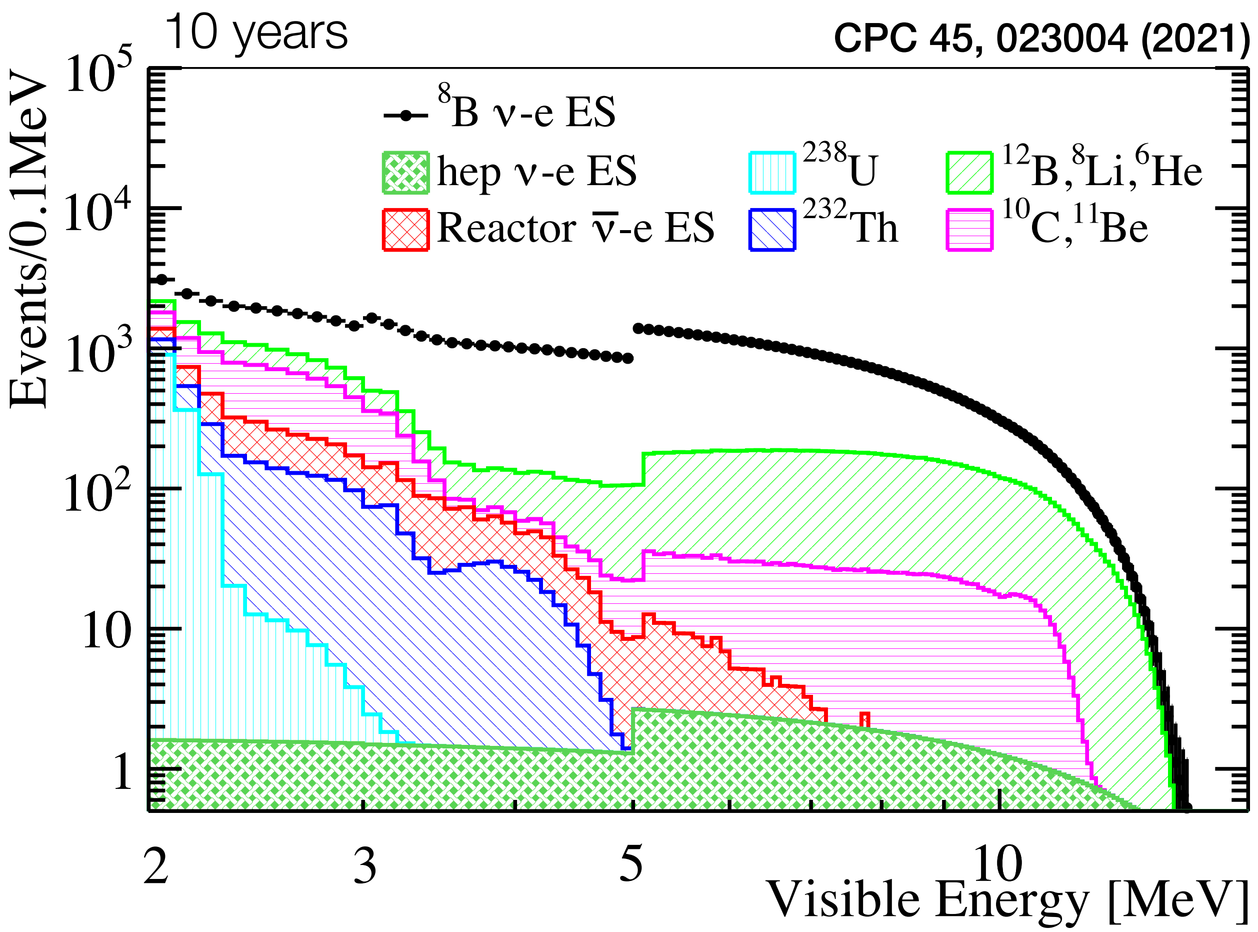
Decay of cosmogenic isotopes

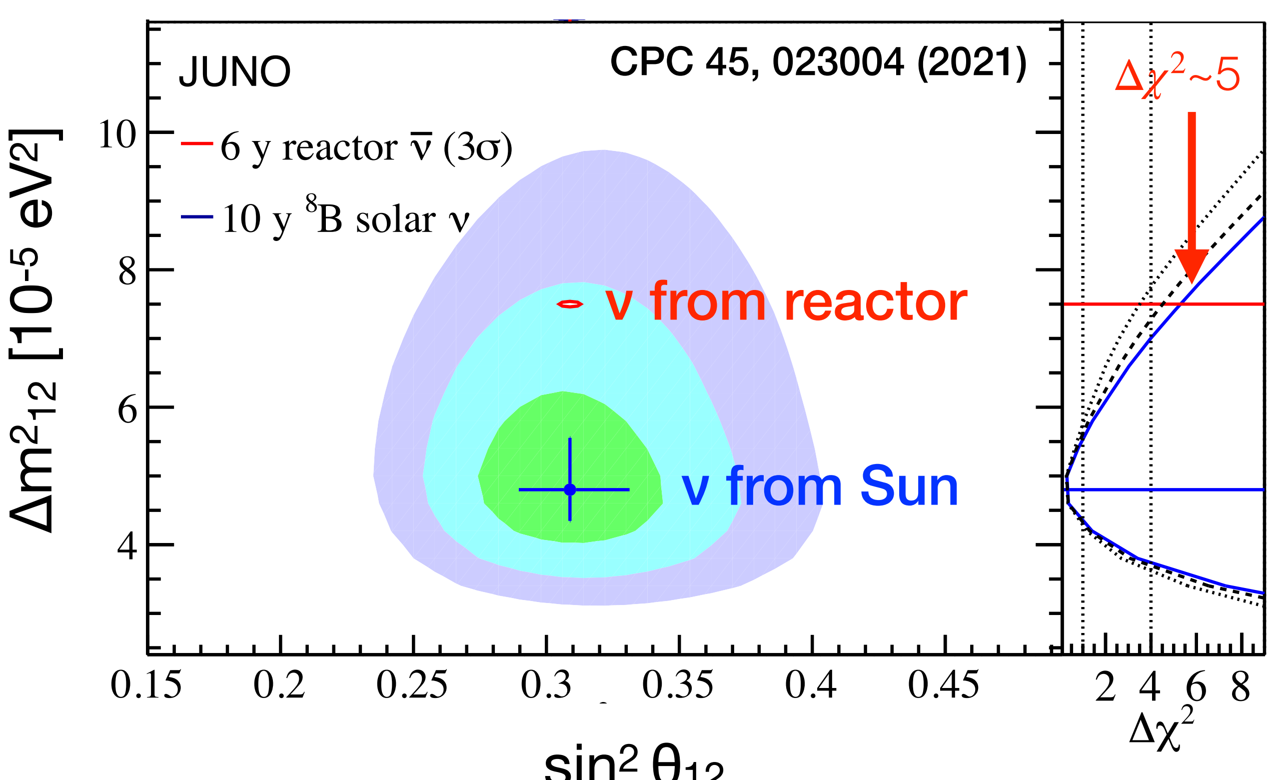
▼

Muon tagging

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

High-energy solar neutrinos from ^8B





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

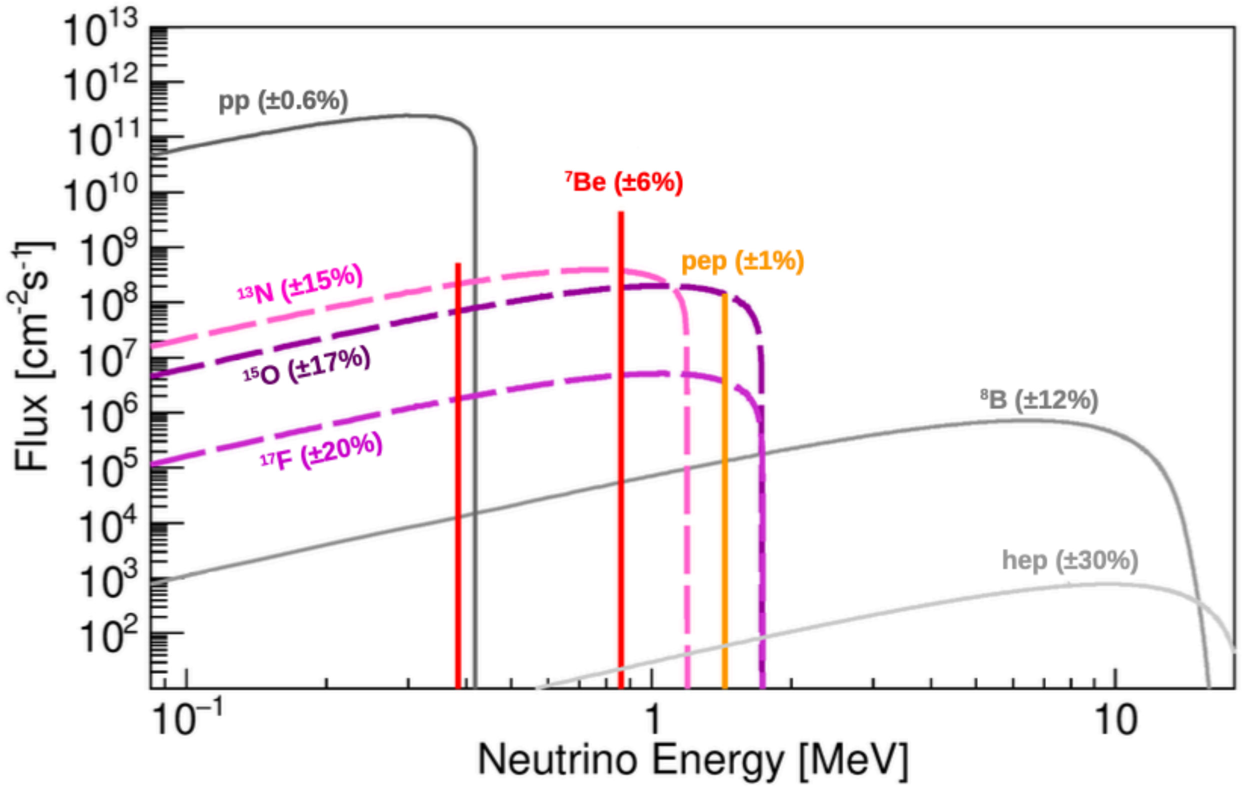
▽

Muon tagging

Simultaneous determination of

$\sin^2\theta_{12}$	Δm^2_{12}
limited by SNO NC	limited by D/N & upturn

Intermediate-energy solar neutrinos

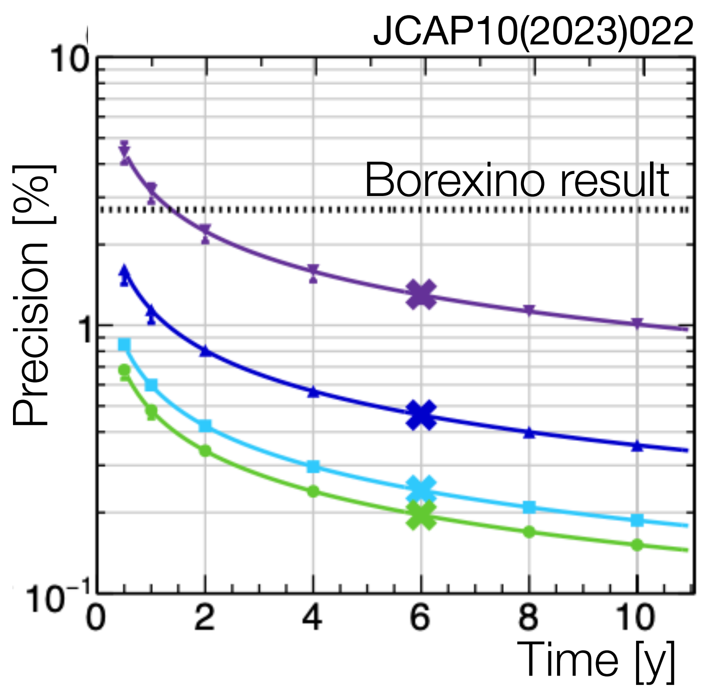


Improve the understanding of neutrino-emitting solar processes

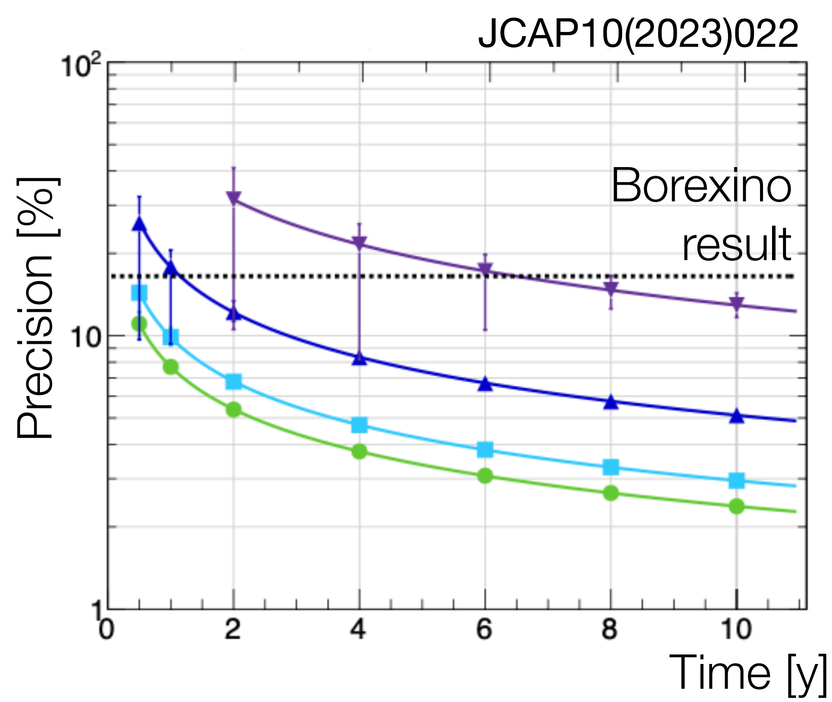
First CNO measurement without external constraints

Radiopurity is the key

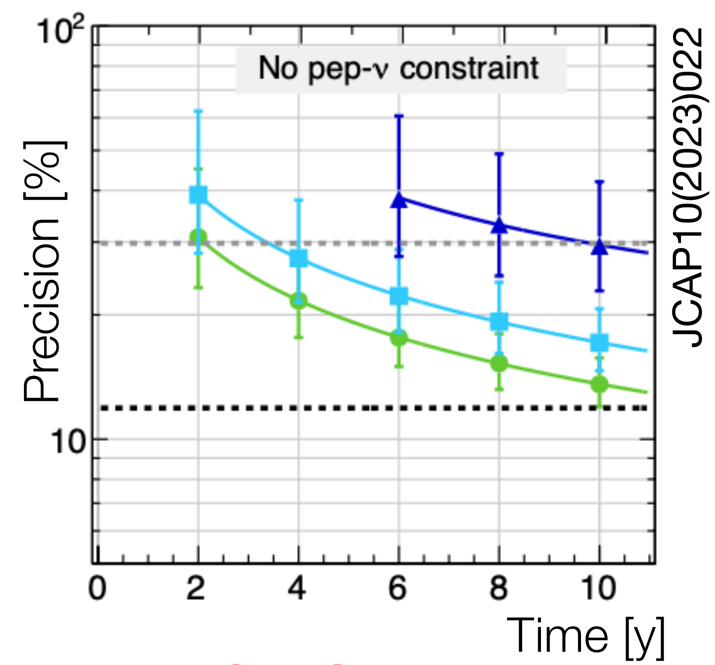
	^{238}U, ^{232}Th
Borexino-like	10^{-19} g/g
Ideal	10^{-17} g/g
Baseline	10^{-16} g/g
Reactor	10^{-15} g/g



^{7}Be Rate



pep Rate



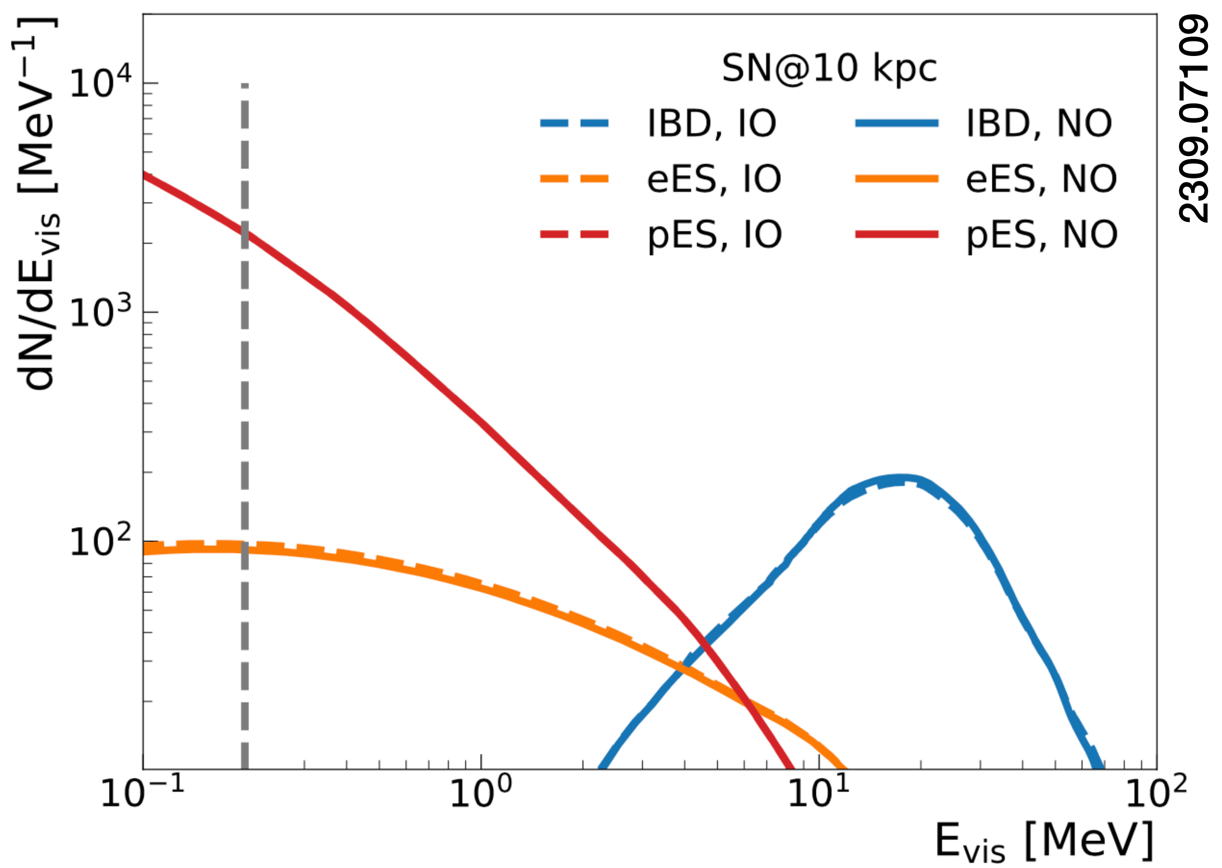
CNO Rate

Neutrinos from supernovae

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

Early warning (10-30 ms) up to 240-400 kpc (depending on mass) @ 50% prob



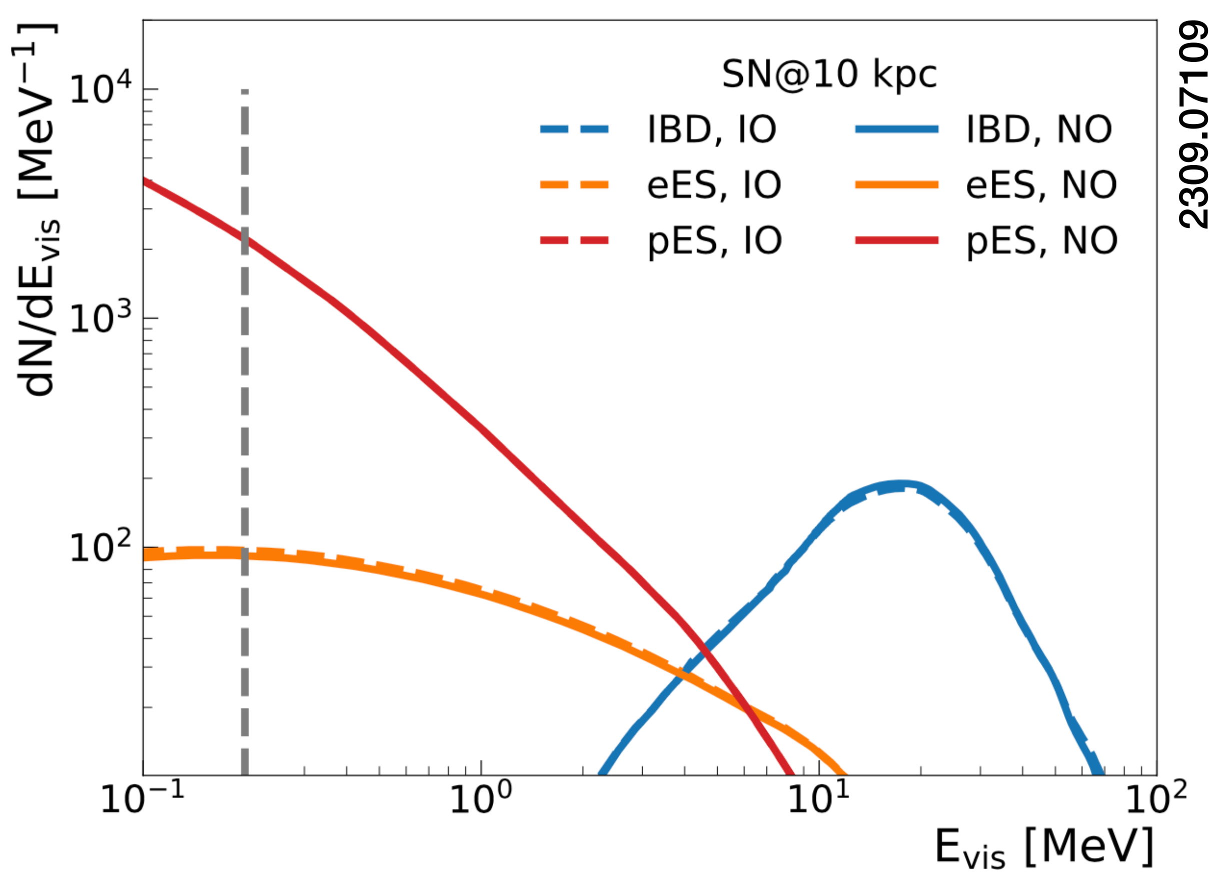
Core-collapse supernova ν
30 $M_\odot$ at 10 kpc

Neutrinos from supernovae

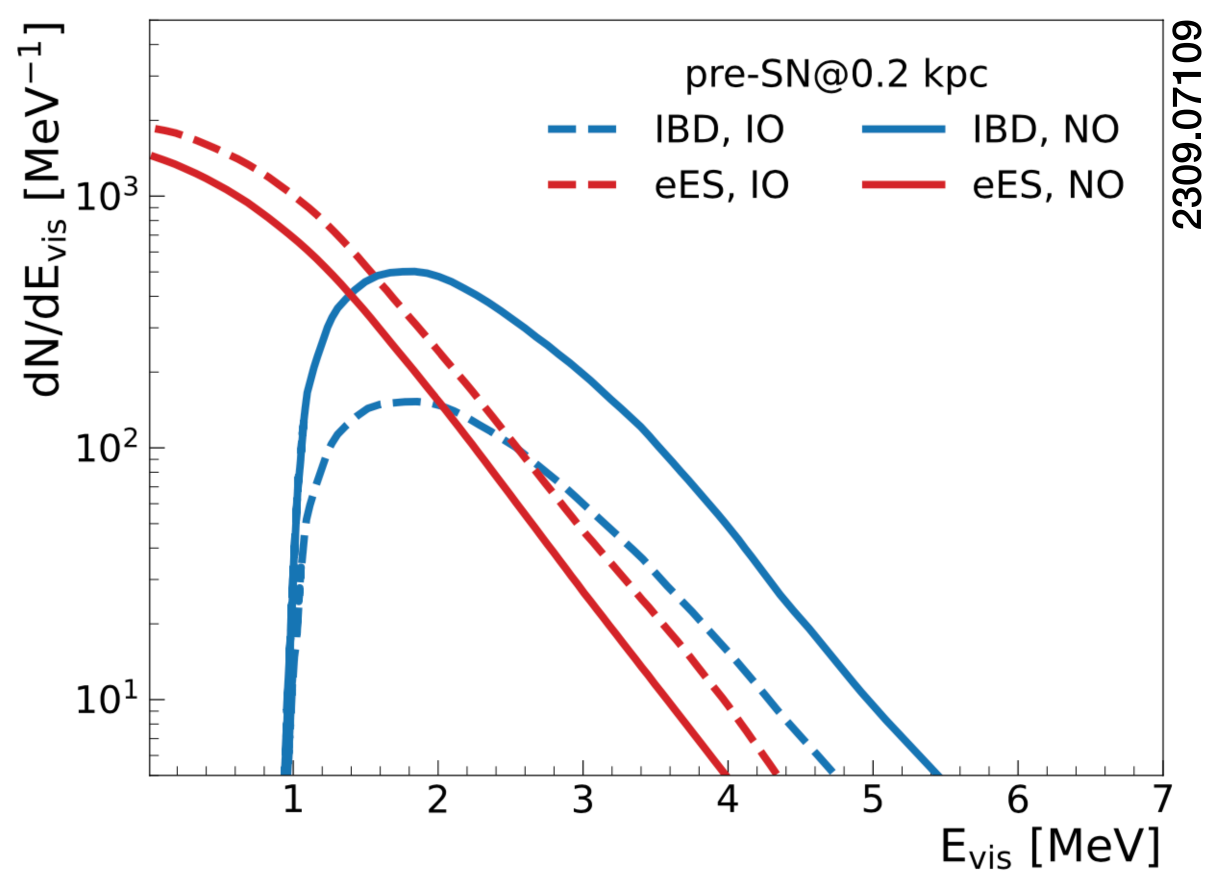
Core-collapse SNe: JUNO will detect O(10MeV) postshock ν of all flavors

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

Early warning (10-30 ms) up to 240-400 kpc (depending on mass) @ 50% prob



Core-collapse supernova ν
30 M☉ at 10 kpc



Pre-Supernova ν:
30 M☉ at 0.2 kpc Integrated of 5 days

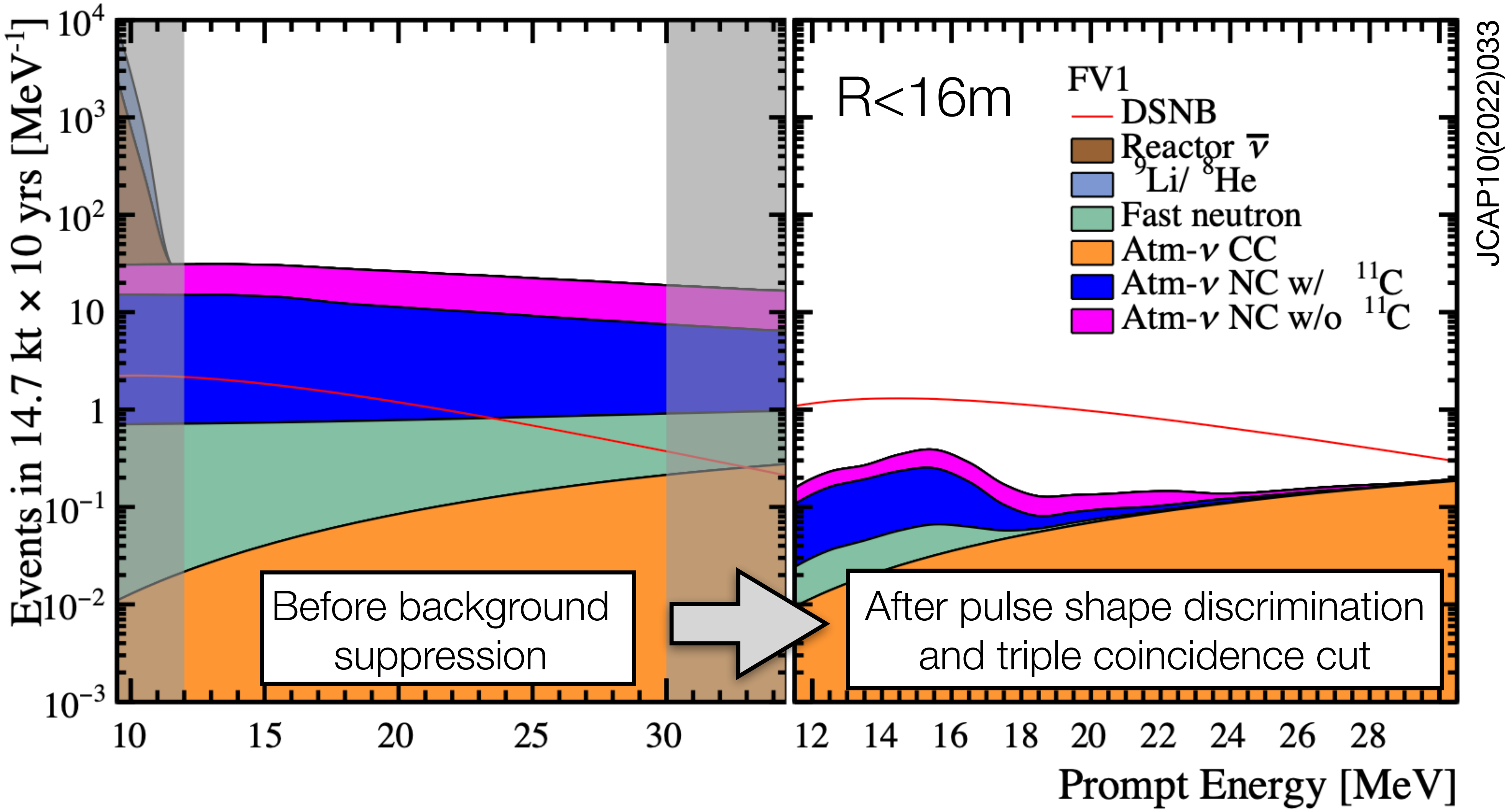
(30 M☉ at 0.2 kpc: old values for the red supergiant Betelgeuse values to ease comparison with other experiments)

Diffuse supernova neutrino background

Integrated neutrino signal from all the SN explosions in the Universe

Signal: Inverse Beta Decay (2~4/year) → Expected significance: 3σ in 3 years

If no observation: best limit + rule out large region parameter space



Proxy for average core-collapse SN neutrino spectrum, cosmic star-formation rate, fraction of failed black-hole forming SNe

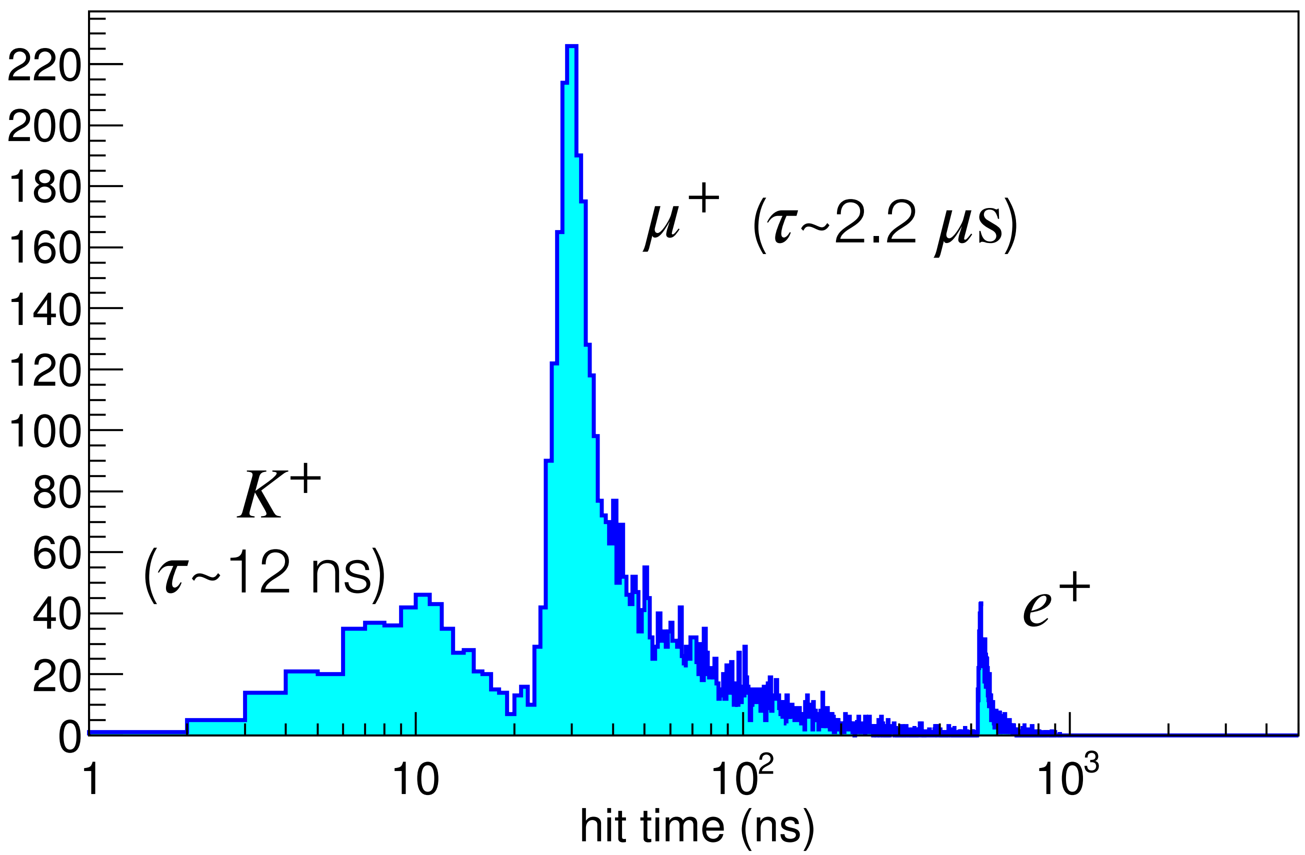
Proton Decay

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

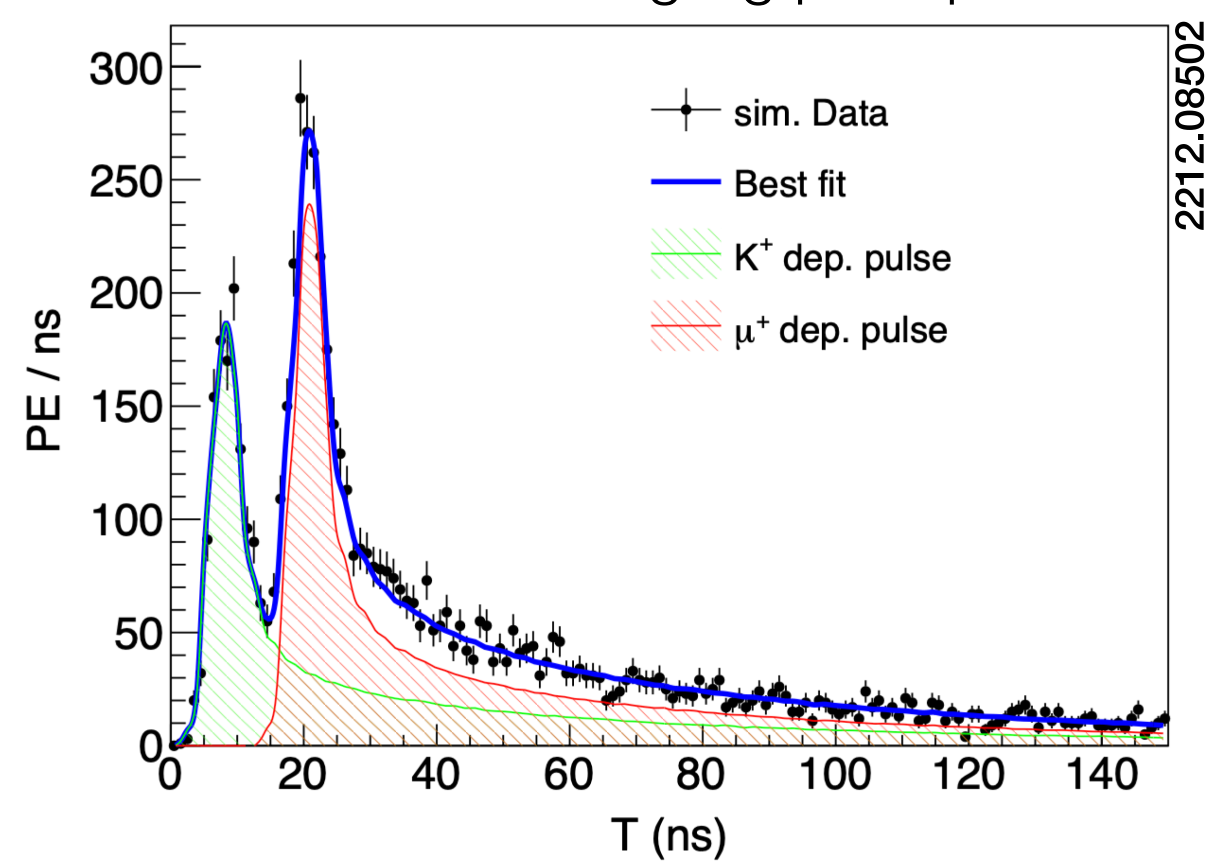
Signature: three-fold time coincidence ($K^+ \to \mu^+ \to e^+$)

Able to reject atmospheric ν background

Time-of-flight-corrected Hit Time



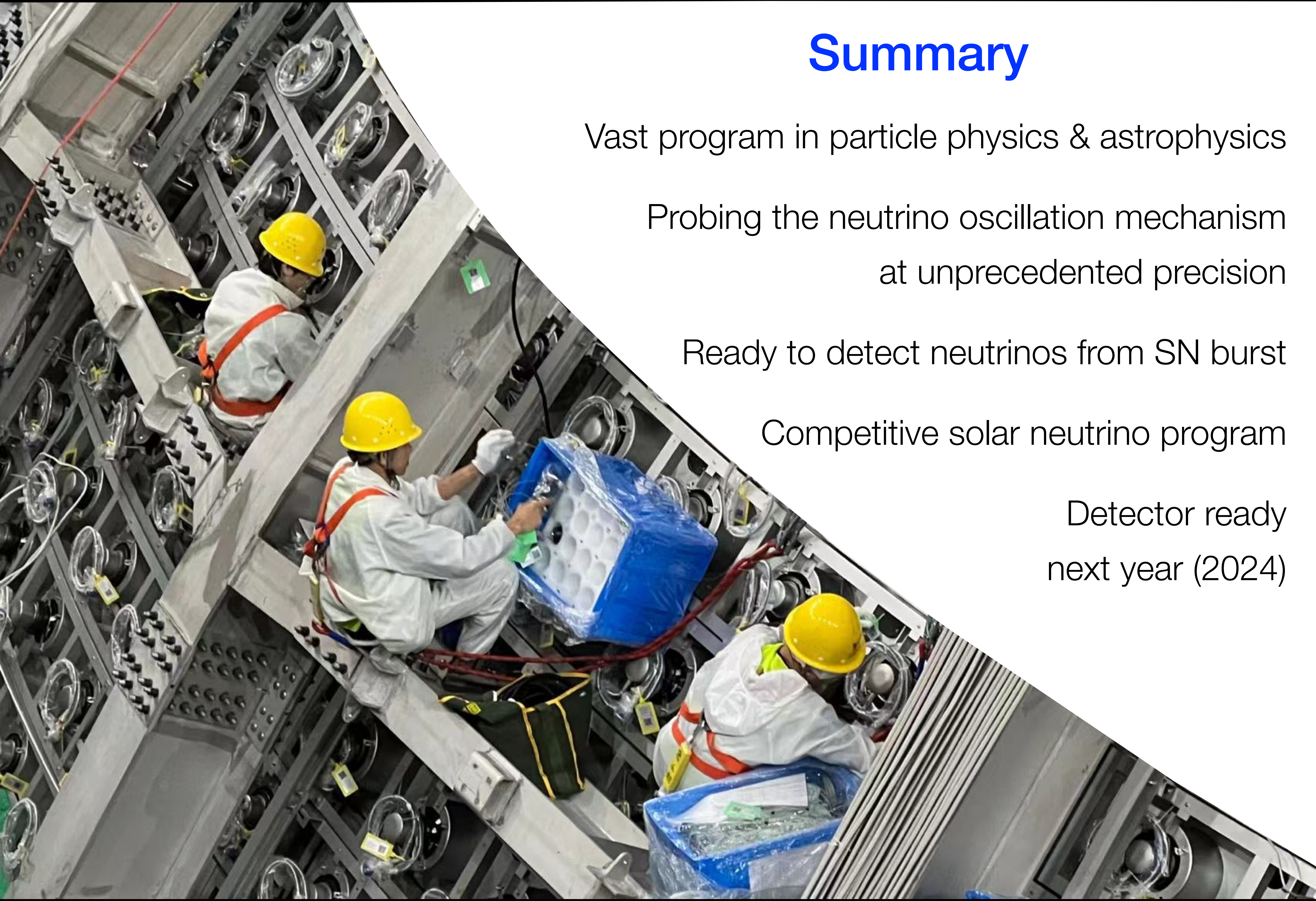
Disentangling pile-up



Expected sensitivity: 9.6 $\cdot 10^{33}$ years at 90% CL in 10 years data-taking (200 kton·yr)

SuperKamiokande (2014) > 5.9 $\cdot 10^{33}$ year with 260 kton · yrs

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

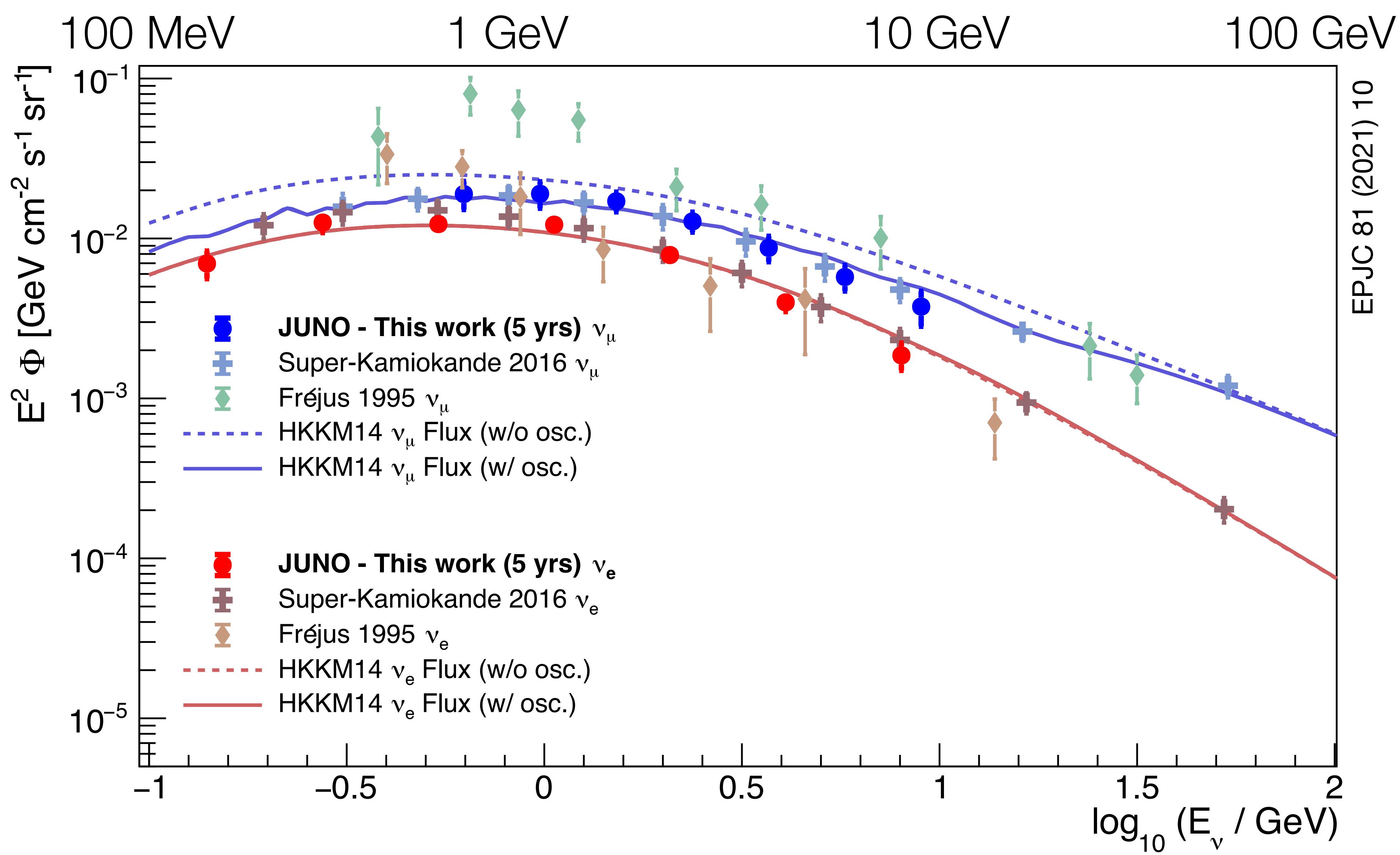
Detector ready next year (2024)

Backup

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

Atmospheric neutrinos from cosmic rays



Based on full simulation and reconstruction chains

ν_e vs ν_μ discrimination thanks to hit time pattern

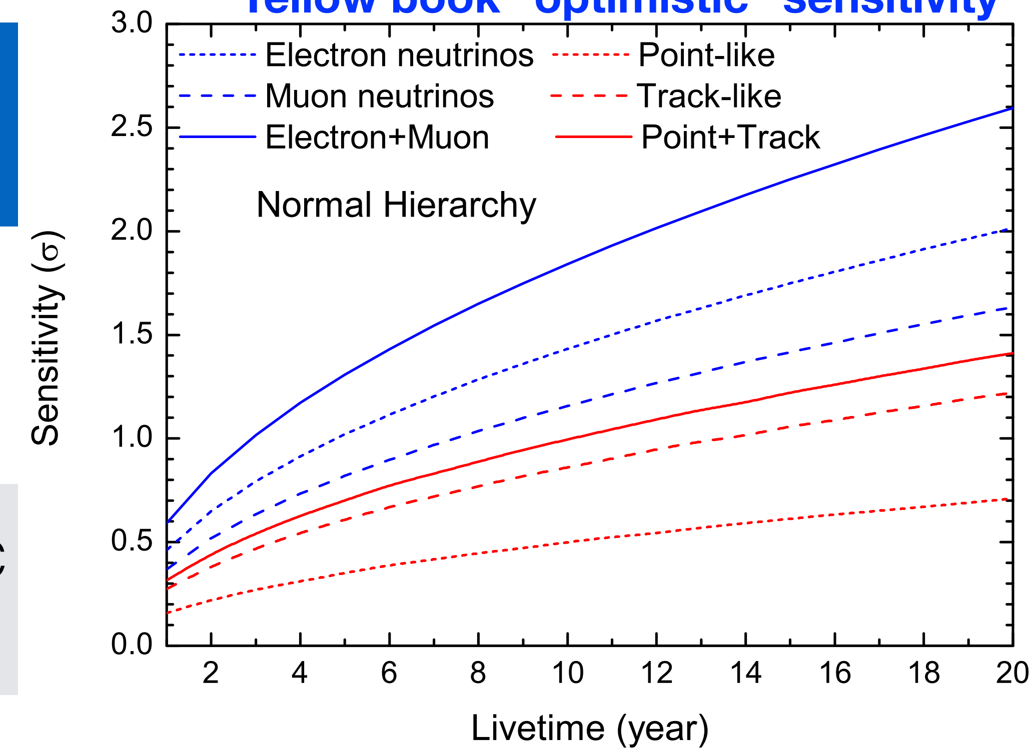
Complementary measurement of the Neutrino Mass Ordering (~1 σ in 10 years)

Updated atmospheric neutrino analysis

	Yellow Book “Optimistic case”	Recent Improvements
Directionality	$\sigma_{\theta\mu} = 1^\circ$ $\sigma_{\theta\nu} = 10^\circ$	$\sigma_{\theta\nu} < 10^\circ$ (E_ν>3GeV)
Energy	Visible energy	Neurino energy for FC events
e-like Event Selection	E_{vis} > 1GeV, $Y_{vis}=E_h/E_{vis}$ < 0.5	ML-based selection allowing for more stats
Classification	Simple classification with Michel e, Y_{vis} cuts	ν vs $\bar{\nu}$: 60%~80% eff.
Sensitivity	1.8 σ in 10 years	**To be updated**

Neutrino physics with JUNO
J. Phys. G 43, 030401 (2016)

Yellow book “optimistic” sensitivity

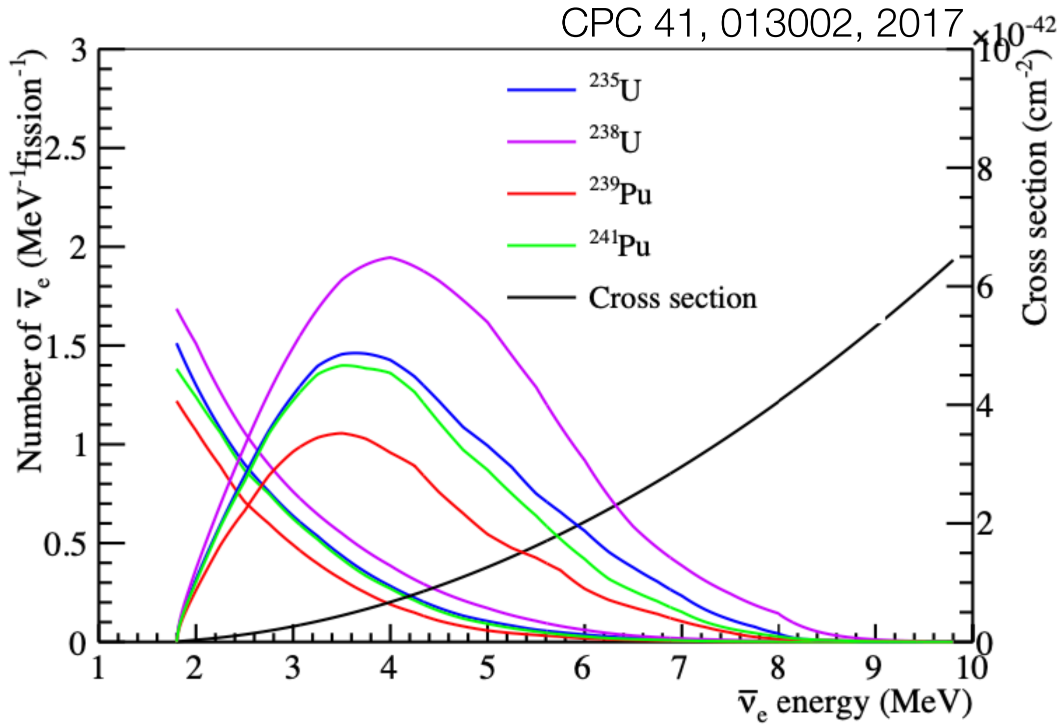


- A lot of recent progress in reconstruction and event identification.
- Aiming to release an updated NMO sensitivity soon.

FC = Fully contained

Credits: H. Duyang at NuFact 23

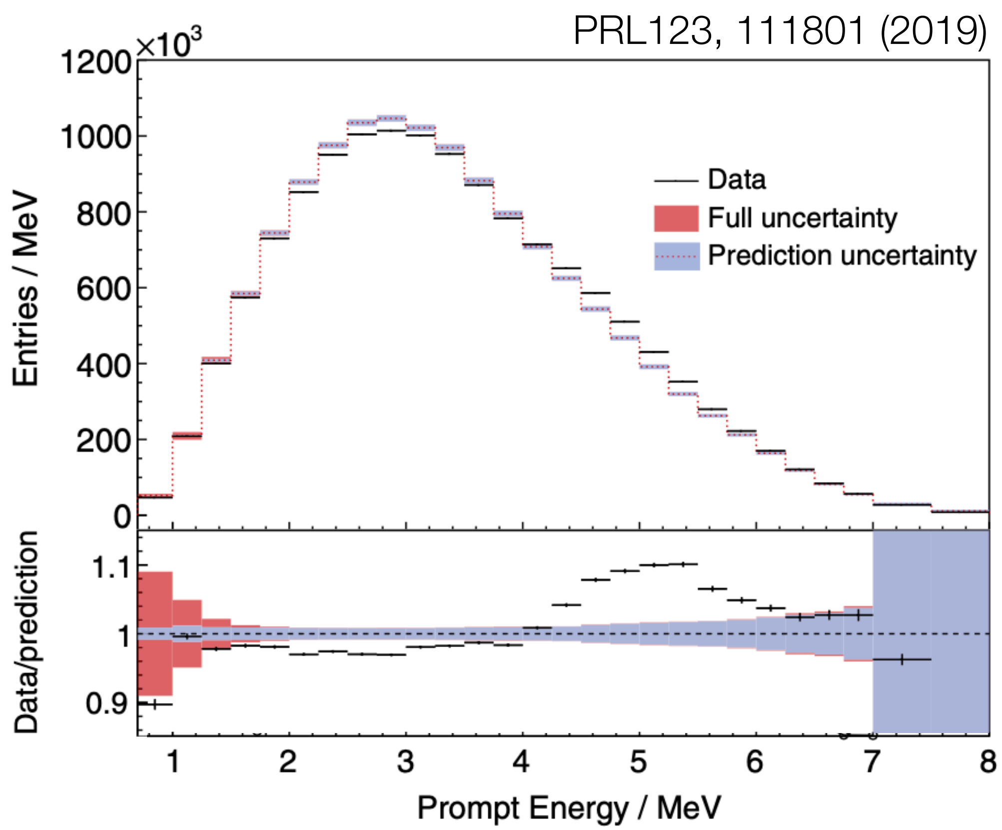
Antineutrino Yield at Nuclear Reactors

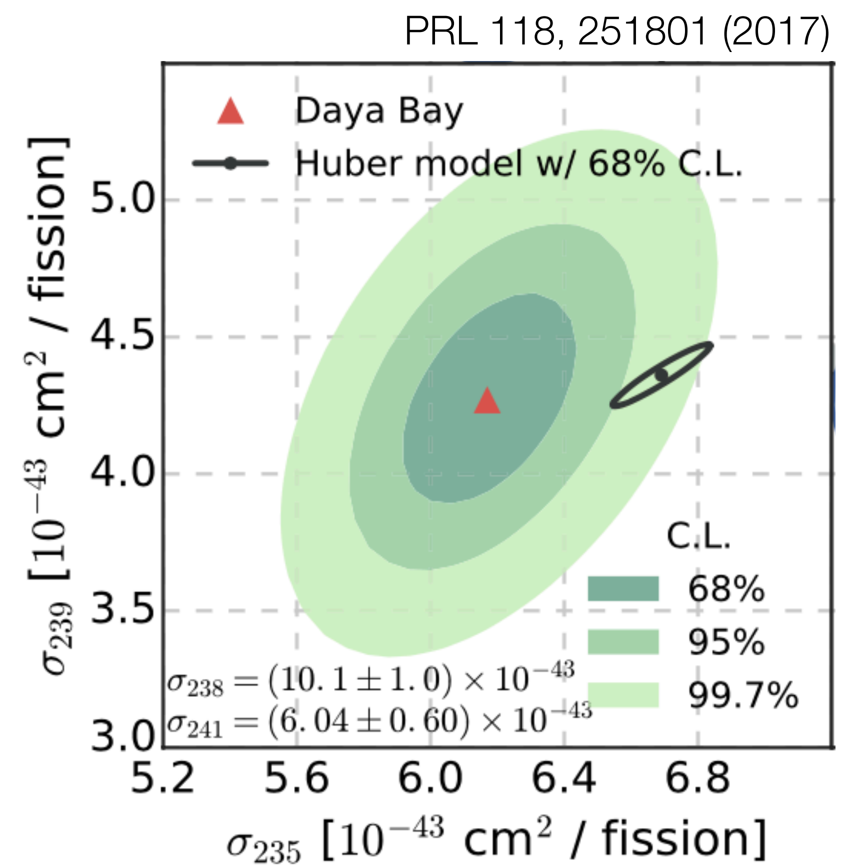


Four isotopes are responsible for most of the $\bar{\nu}_e$ flux

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

Issues in the overall flux are less important





$\bar{\nu}_e \rightarrow \bar{\nu}_\mu, \bar{\nu}_\tau$ undetectable via charged current: not enough energy to yield μ or τ

Detect surviving $\bar{\nu}_e$

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}\left(\sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}}{4}\frac{L}{E} + \cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}}{4}\frac{L}{E}\right) - \sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2\frac{\Delta m^2_{21}}{4}\frac{L}{E}$$

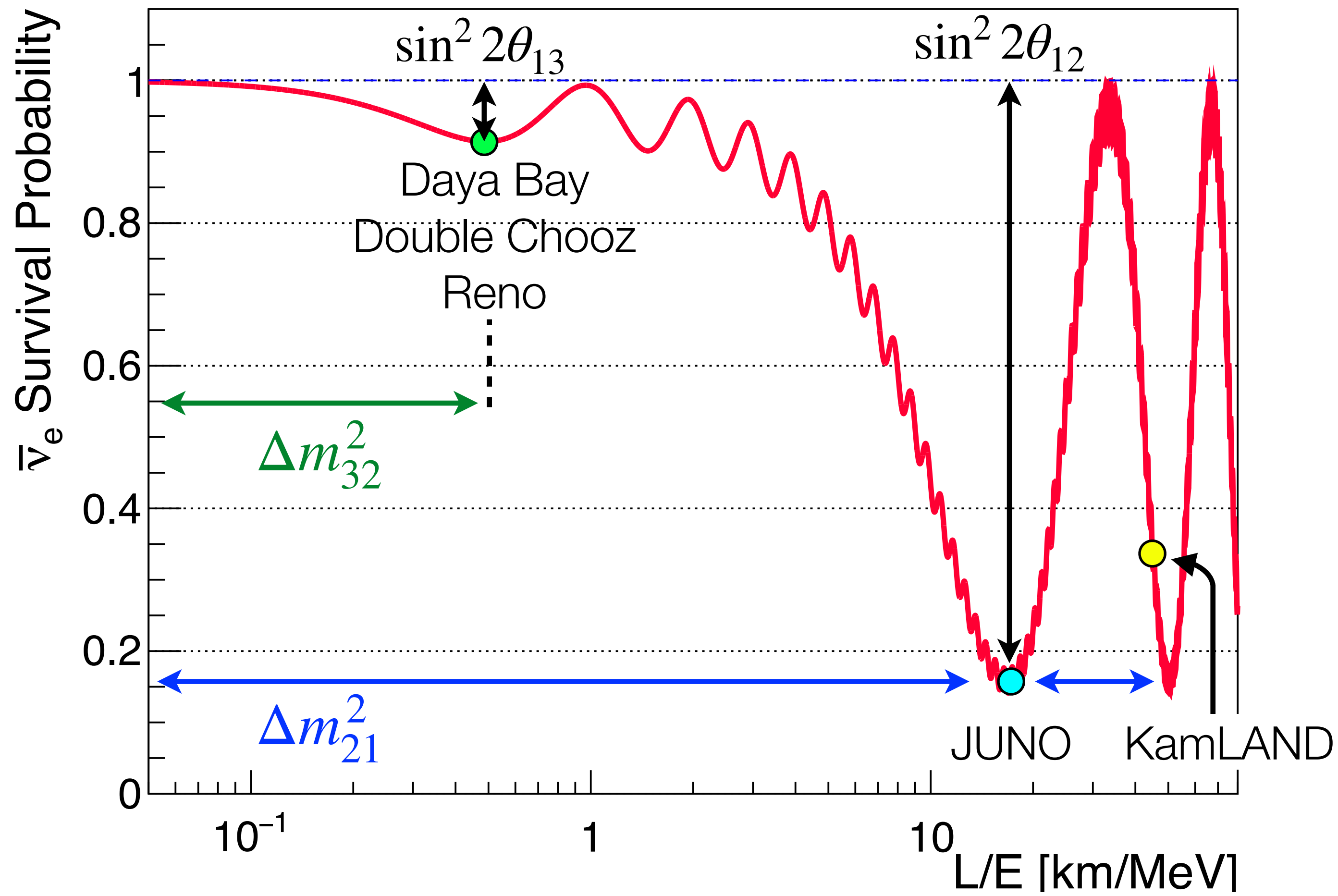
Two mixing parameters

Three mass splittings

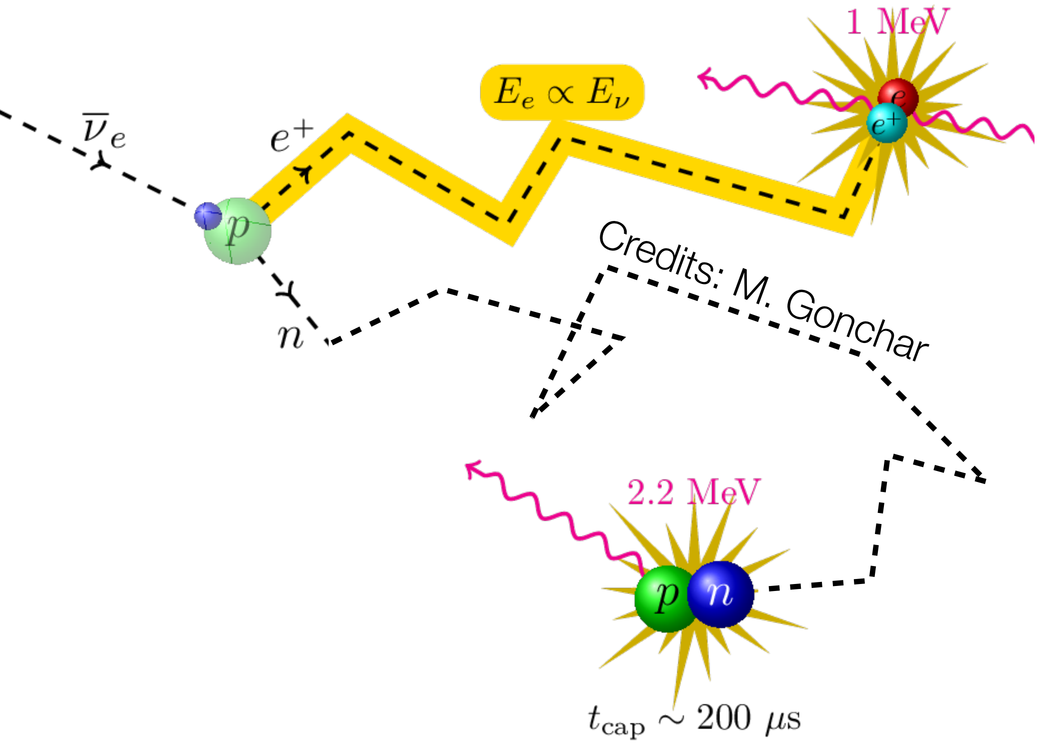
Baseline choice allows to enhance one oscillation regime

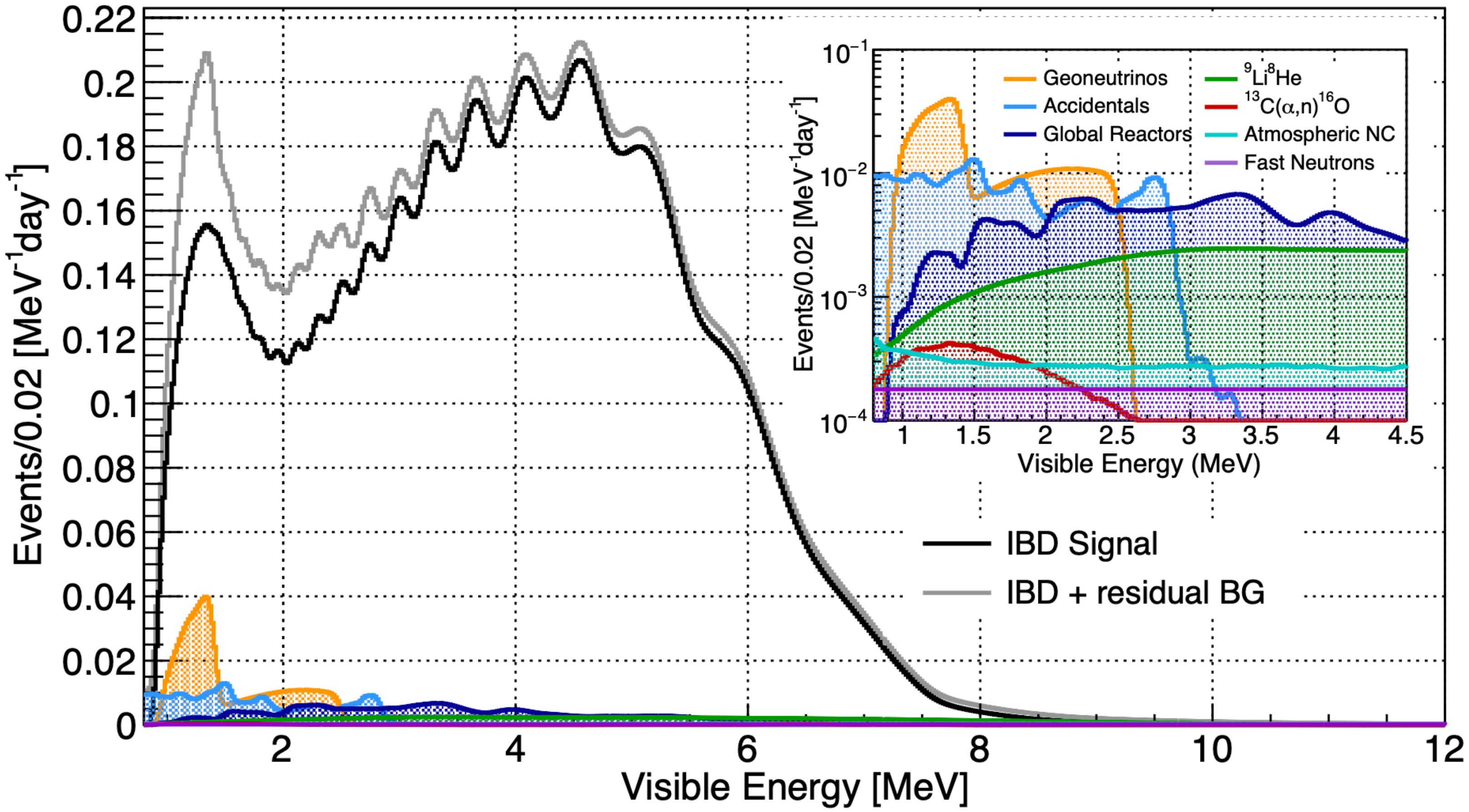
JUNO will be the first to see both of them simultaneously

No dependence on δ_{CP} and θ_{23}



Antineutrino Detection and Selection





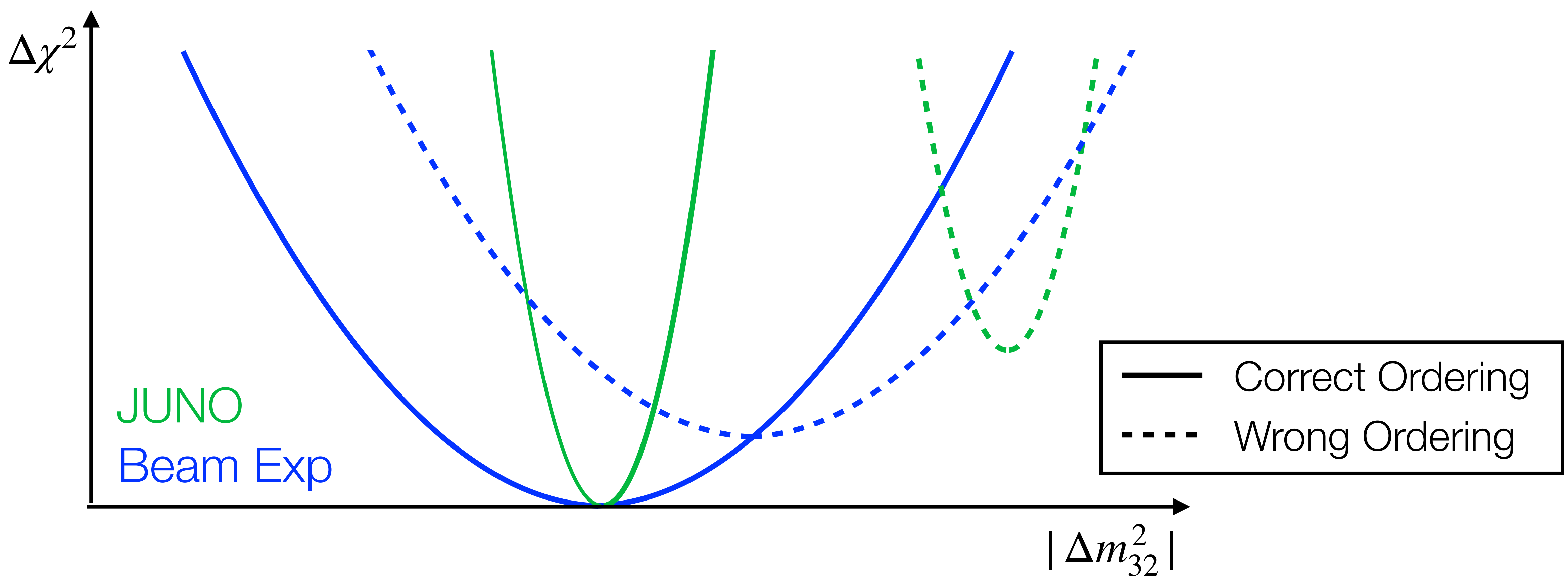
Selection Criterion	Efficiency (%)	IBD Rate (day^{-1})
All IBDs	100.0	57.4
Fiducial Volume	91.5	52.5
IBD Selection	98.1	51.5
Energy Range	99.8	-
Time Correlation (ΔT_{p-d})	99.0	-
Spatial Correlation (ΔR_{p-d})	99.2	-
Muon Veto (Temporal⊕Spatial)	91.6	47.1
Combined Selection	82.2	47.1

Background	Rate (day^{-1})
Geoneutrinos	1.2
World reactors	1.0
Accidentals	0.8
^{9}Li/^{8}He	0.8
Atmospheric ν's	0.16
Fast neutrons	0.1
^{13}C(α,n)^{16}O	0.05

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 $> 4\sigma$

Radiogenic Backgrounds

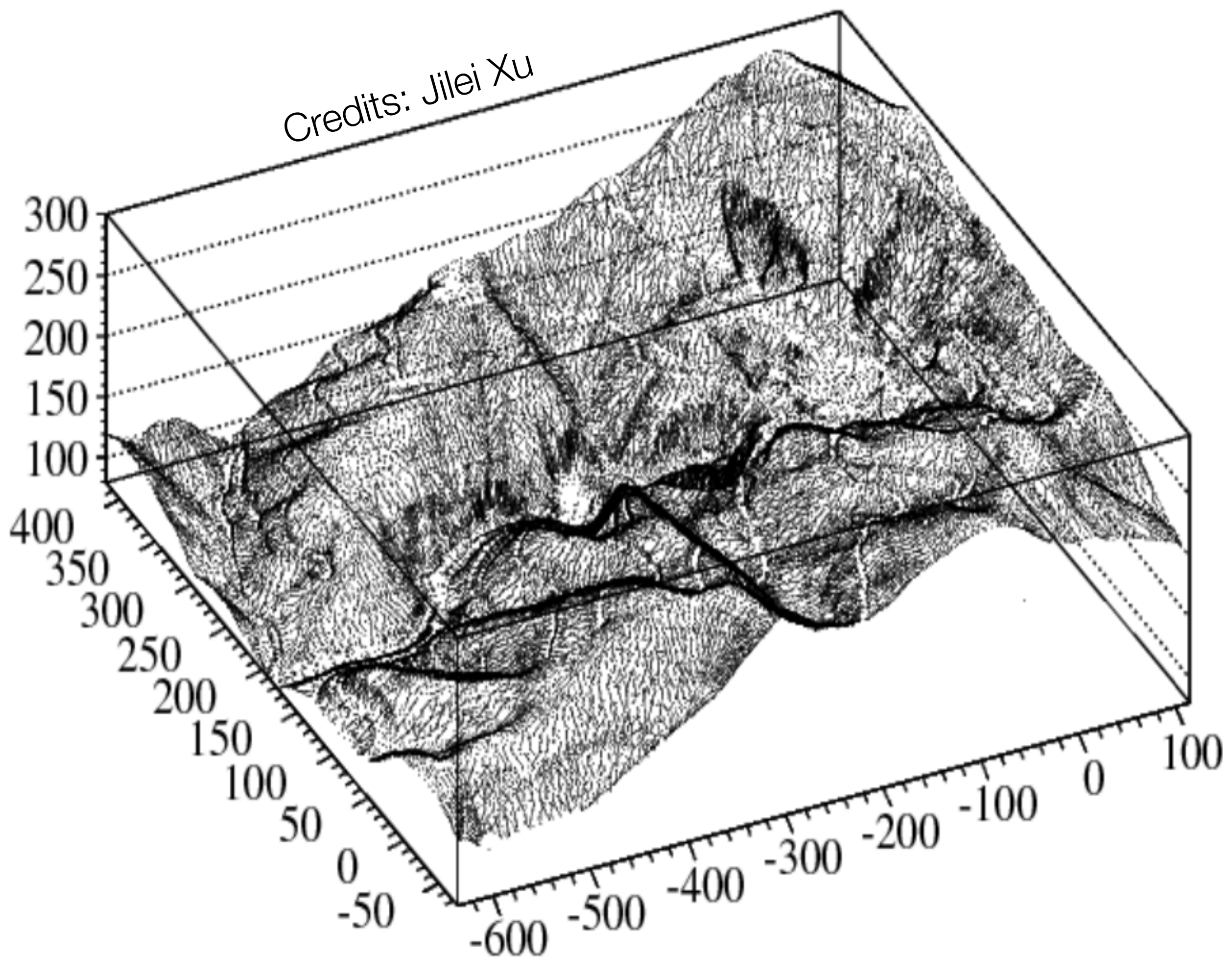
Material	Mass	Target impurity concentration					Singles in ROI	
	[t]	^{238}U [ppb]	^{232}Th [ppb]	^{40}K [ppb]	^{210}Pb/^{222}Rn	^{60}Co [mBq/kg]	ALL [Hz]	FV [Hz]
LS	20 k	10^{-6}	10^{-6}	10^{-7}	10^{-13} ppb		2.5	2.2
Acrylic	610	10^{-3}	10^{-3}	10^{-3}			8.4	0.4
SS truss and nodes	1 k	0.2	0.6	0.02		1.5	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

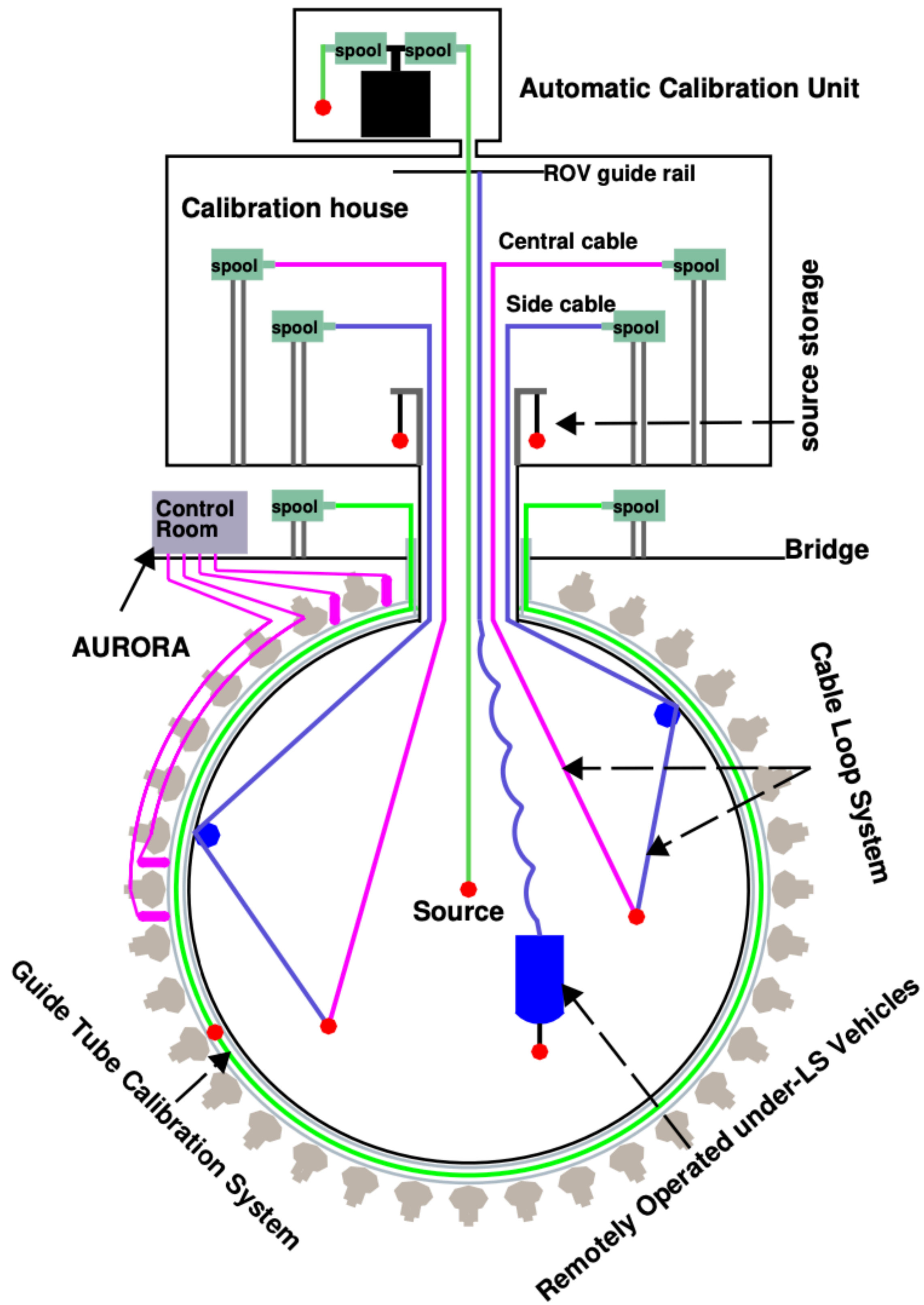
Untagged μ yield irreducible background

Expected μ rate: 4 Hz

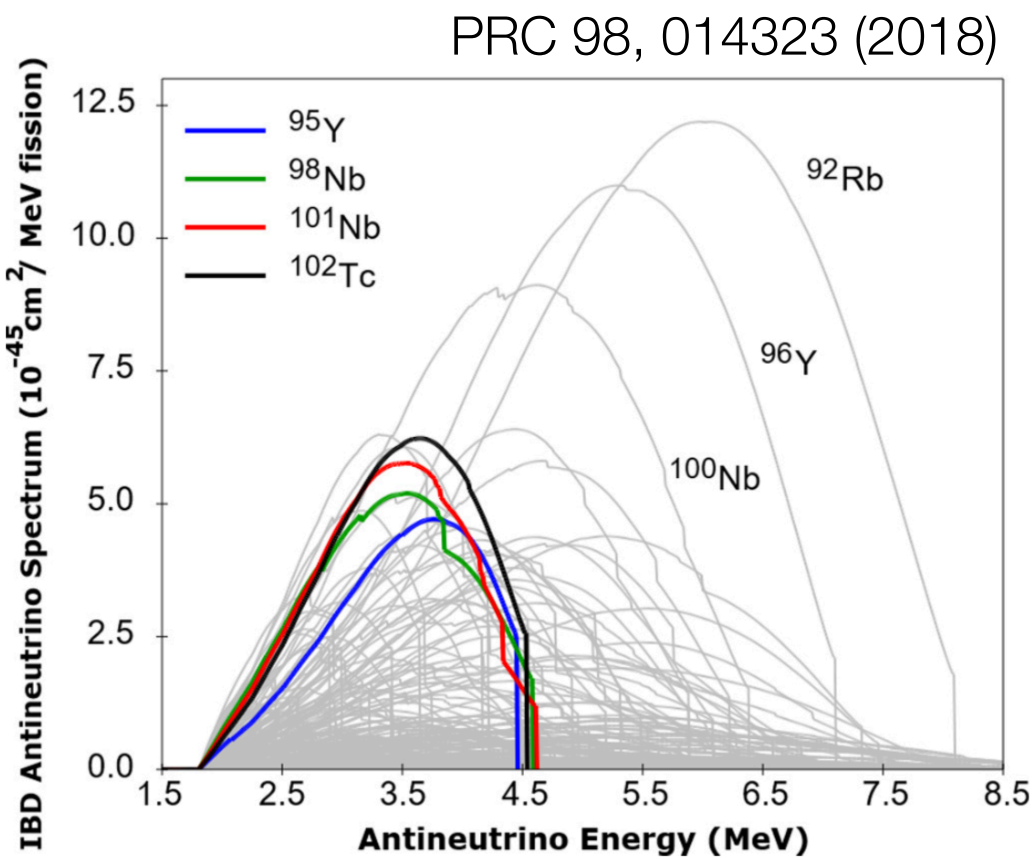
Mean μ energy: 207 GeV

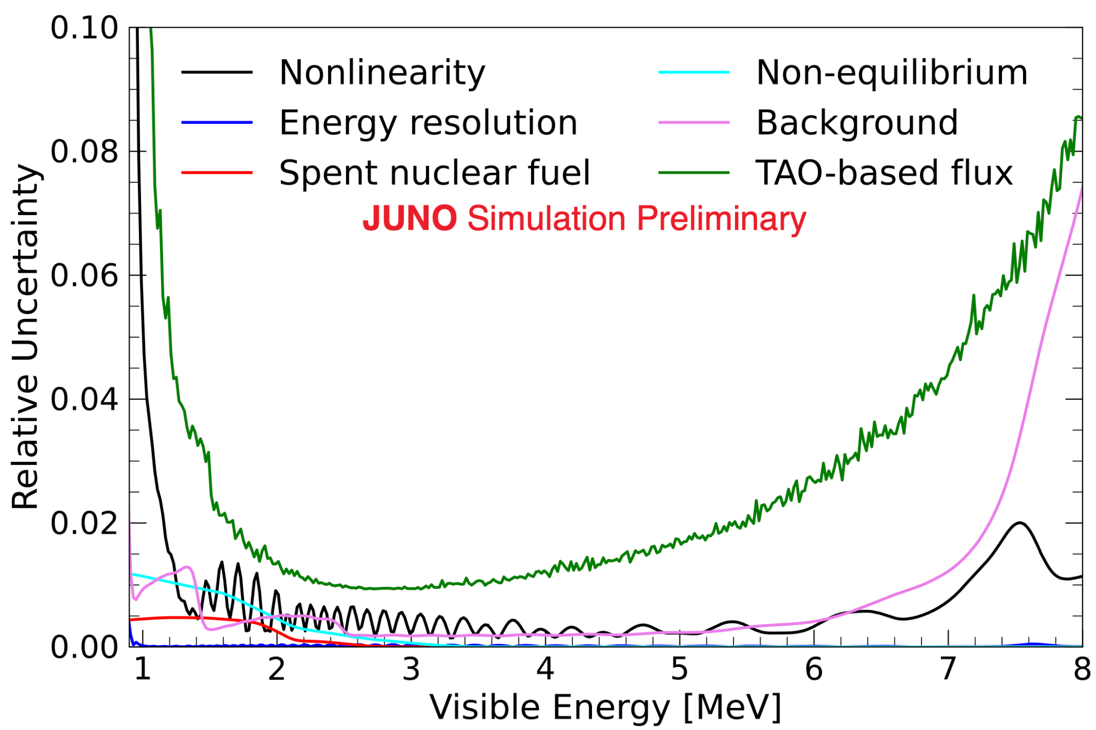
New veto strategy → Tagging ε: 91.6% → Residual ^{8}He ^{9}Li event rate: 0.8/day

Calibration Hardware



Addressing The Reactor Spectral Uncertainties: TAO





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

Taishan Antineutrino Observatory (TAO)

Ancillary detector to study unoscillated spectrum with resolution better than JUNO

Supernova interactions

All interaction channels (excluding CEvNS)

No trigger threshold assumed