$0\nu\beta\beta$ R&D for future JUNO upgrade

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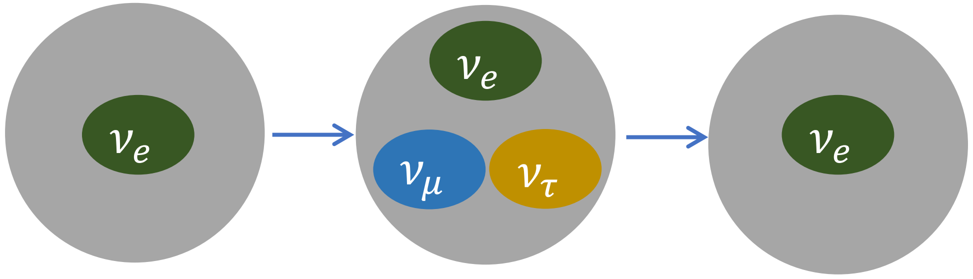
Jul 23, 2025

@νNN2025, Lanzhou

Neutrino oscillation



Massive neutrinos!

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos\theta_{23} & sin\theta_{23} \\ 0 & -sin\theta_{23} & cos\theta_{23} \end{pmatrix} \begin{pmatrix} cos\theta_{13} & 0 & e^{-i\delta} sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} sin\theta_{13} & 0 & cos\theta_{13} \end{pmatrix} \begin{pmatrix} cos\theta_{12} & sin\theta_{12} & 0 \\ -sin\theta_{12} & cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

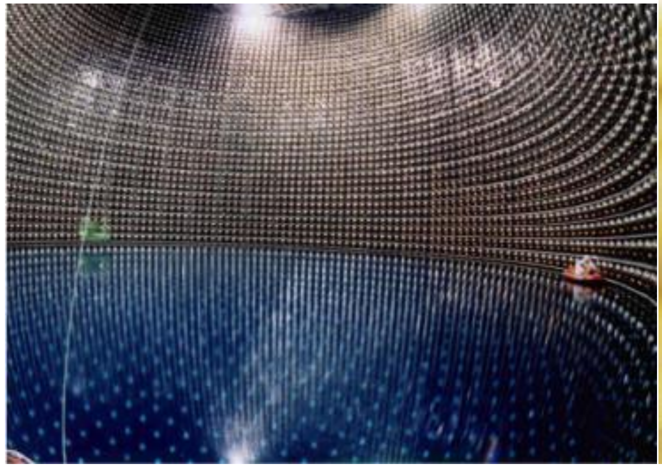
$\theta_{23} \approx 45^\circ$	$\theta_{13} \approx 10^\circ$	$\theta_{12} \approx 35^\circ$
Accelerator + Atmospheric	Reactor + Accelerator	Solar + Reactor

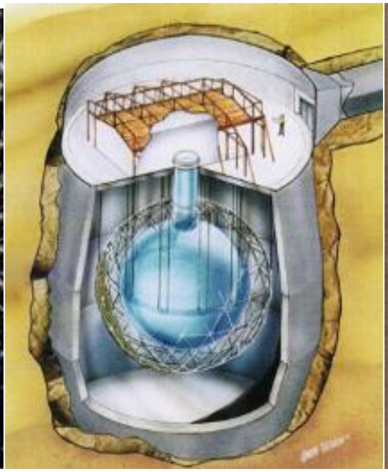
The Nobel Prize in Physics 2015

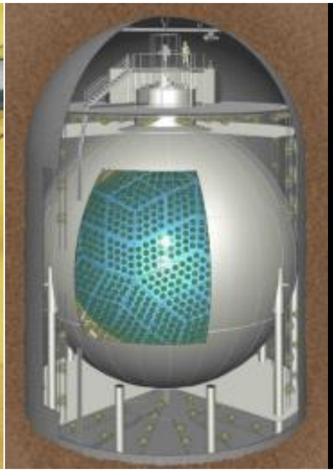
Photo: A. Mahmoud
Takaaki Kajita
Prize share: 1/2

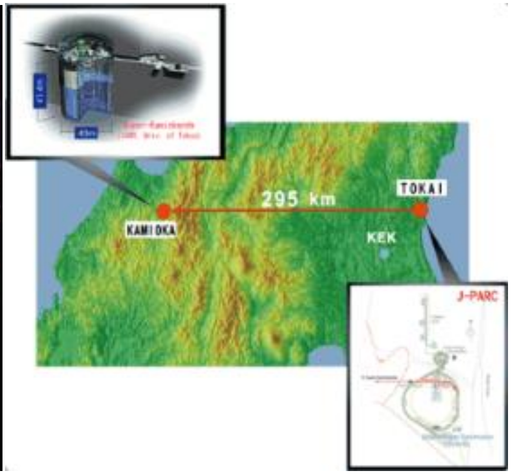
Photo: A. Mahmoud
Arthur B. McDonald
Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

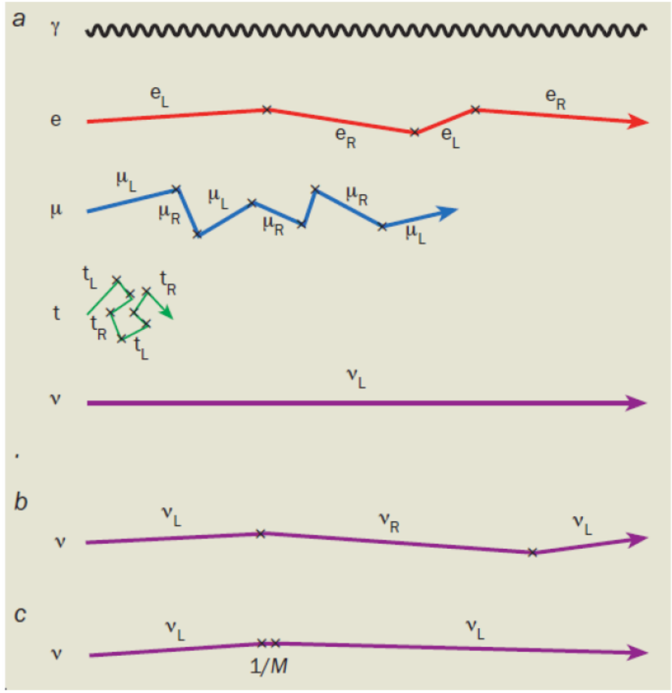




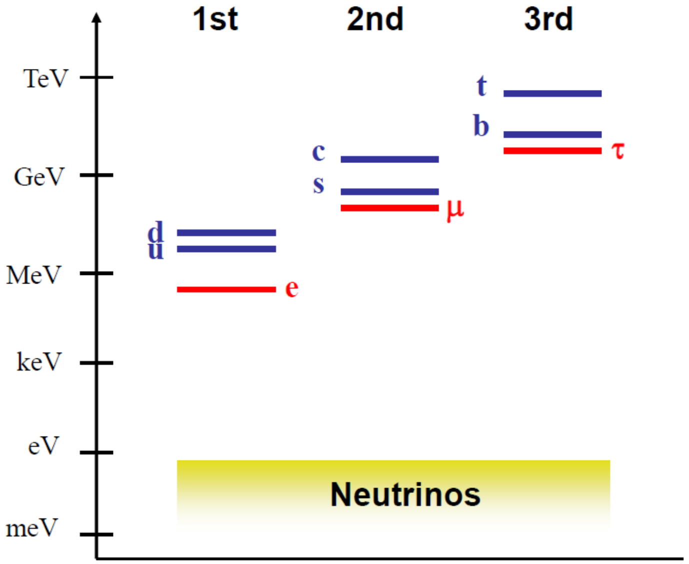




Neutrino mass generation mechanism



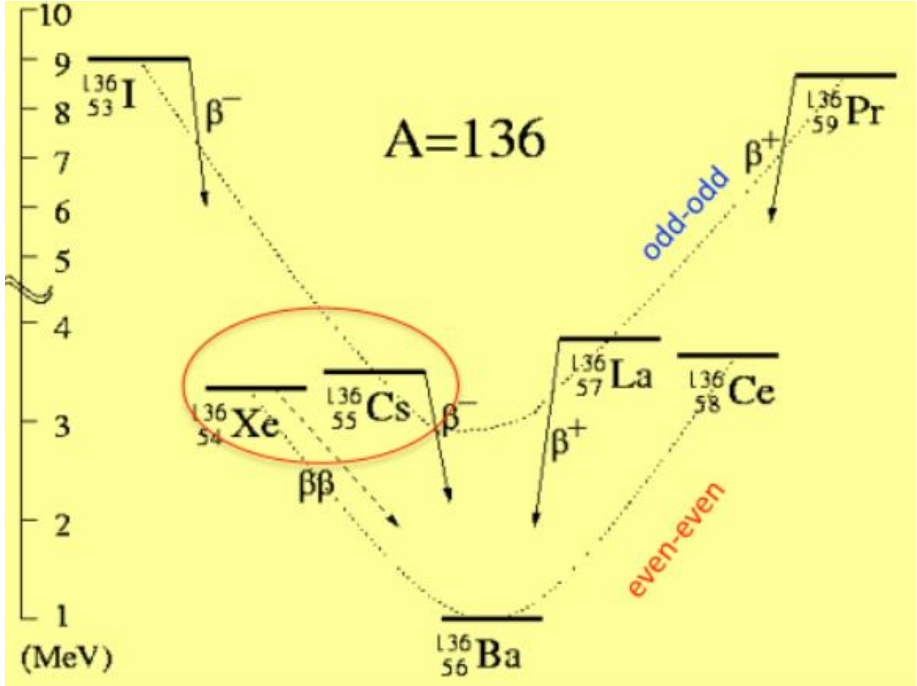
- Neutrino oscillation experiments demonstrate neutrinos have non-zero mass
- Neutrino mass is significantly smaller than other fermions
- **Majorana nature** of neutrinos allows a natural way to explain the small neutrino mass by see-saw mechanism



The search for $0\nu\beta\beta$ is the most sensitive probe of Majorana nature of neutrinos.

Double beta decay

- Double beta decay is a second order process
- Only observable if first order beta decay is energetically forbidden



Candidate with Q>2 MeV

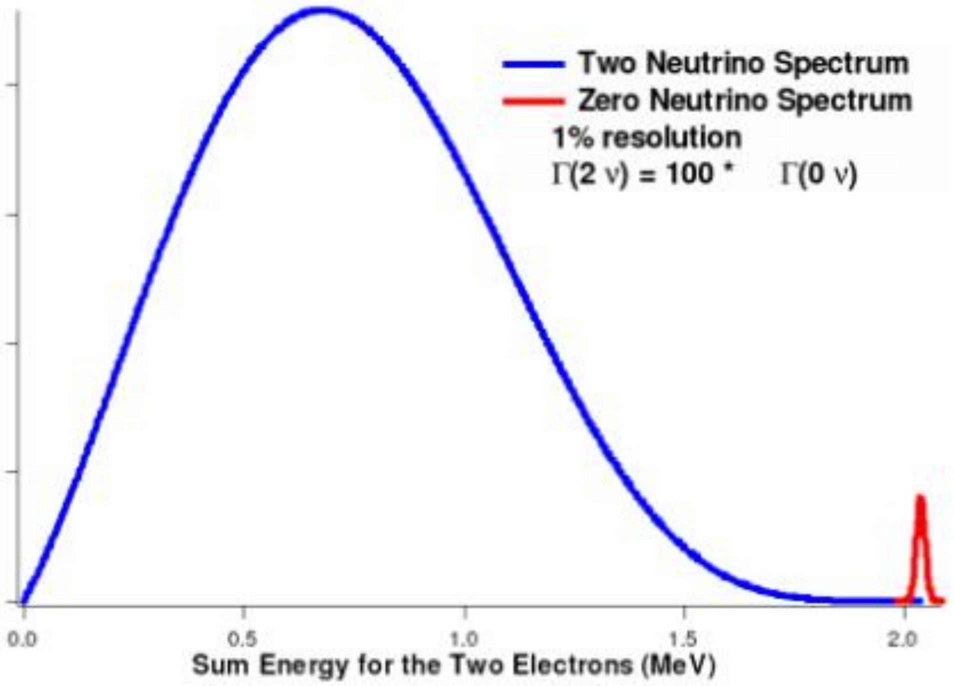
Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow {}^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow {}^{76}Se$	2.040	7.8
$^{82}Se \rightarrow {}^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow {}^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow {}^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow {}^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow {}^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow {}^{124}Te$	2.228	5.64
$^{130}Te \rightarrow {}^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow {}^{136}Ba$	2.458	8.9
$^{150}Nd \rightarrow {}^{150}Sm$	3.367	5.6

Experimental sensitivity

Non "bkg-free" regime

$$t_{1/2} \sim \sqrt{\frac{MT}{B \times \Delta E}}$$

- **Low background level**
  - low radioactivity detector
  - powerful background rejection
- Good energy resolution
- Large detector mass



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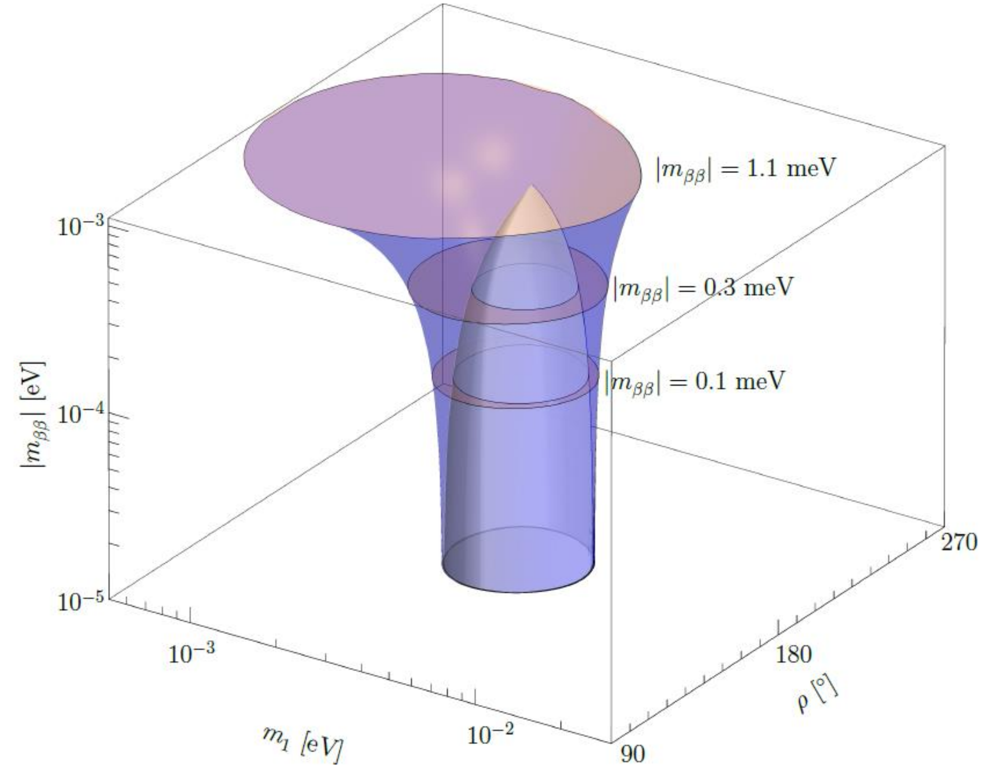
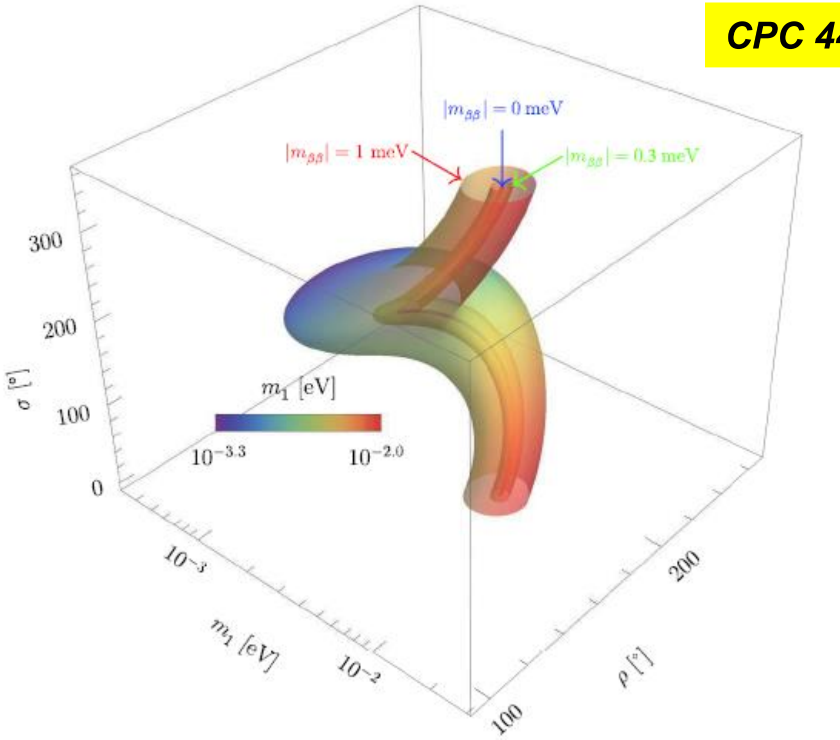




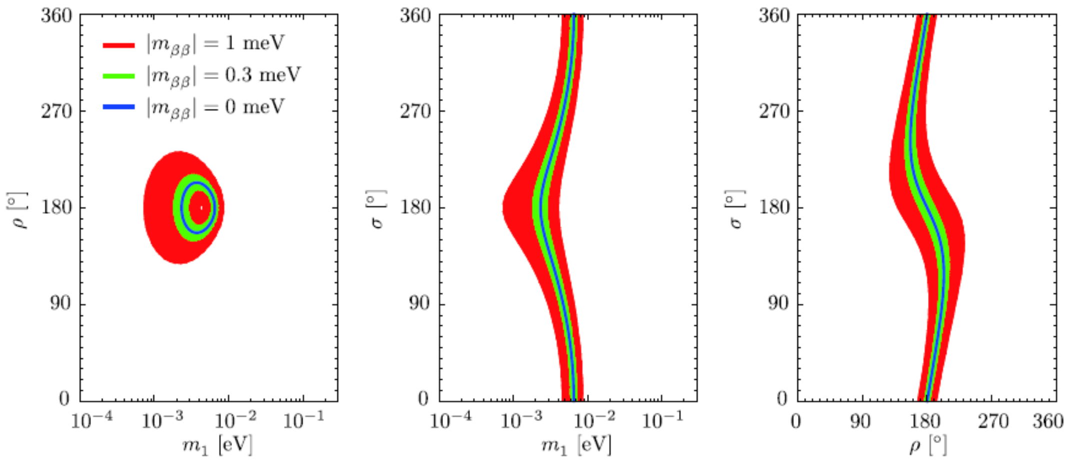
$$|m_{\beta\beta}| \equiv \left|m_1 \cos^2\theta_{13}\cos^2\theta_{12}e^{i\rho} + m_2\cos^2\theta_{13}\sin^2\theta_{12} + m_3\sin^2\theta_{13}e^{i\sigma}\right|$$

Towards $|m_{\beta\beta}|$~meV

- **Precise determination of the lightest neutrino mass**

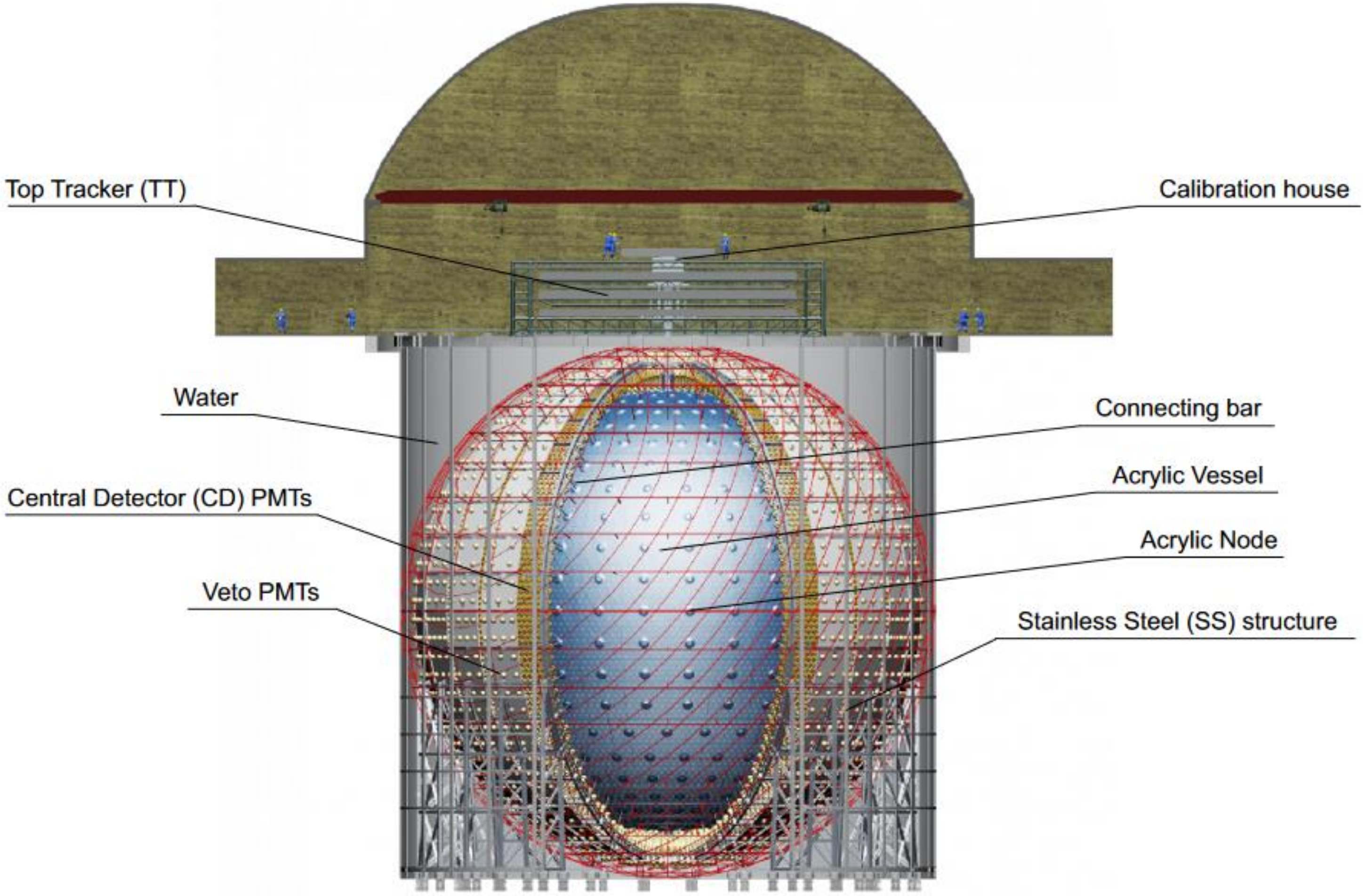
$$m_1 \in [0.7, 8]\ \text{meV}$$

- **Constrain (m_1, ρ, σ) to a very small parameter space**



JUNO

- 20 kton multi-purpose neutrino detector with the primary goals
  - Determine Neutrino mass ordering
  - Precision measurement of neutrino oscillation



	Precision by 2030	Expt.
Δm^2_{21}	0.3%	JUNO
$\Delta m^2_{31}/\Delta m^2_{32}$	0.2%	JUNO
$\sin^2\theta_{12}$	0.5%	JUNO
$\sin^2 2\theta_{13}$	2.8%	Daya Bay

CPC 46 (2022) 12, 123001

Impact of JUNO's physics outcome on 0νββ searches, by 2030

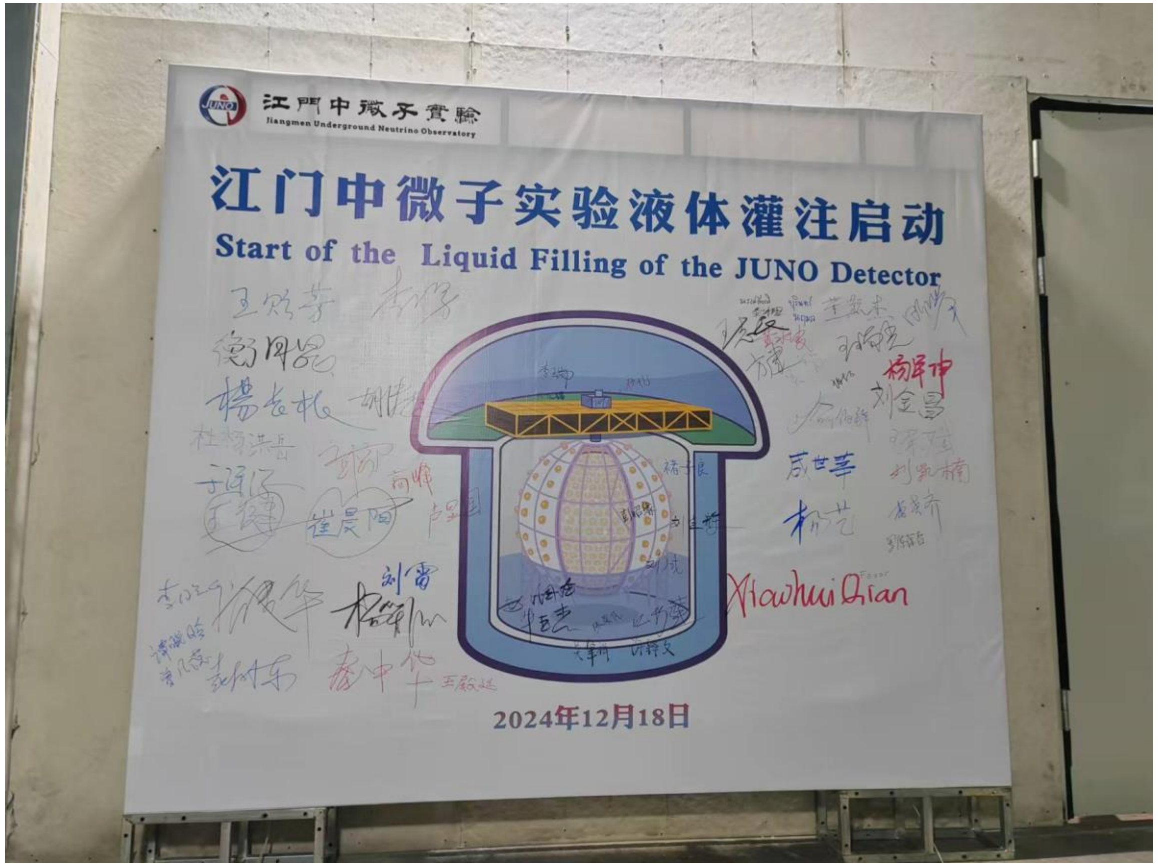
- Precision measurement → reduce the uncertainty of $m_{\beta\beta}$
- Determine neutrino mass ordering @ 6 years:
  ~3σ (reactor), ~4σ (reactor + atmospheric)

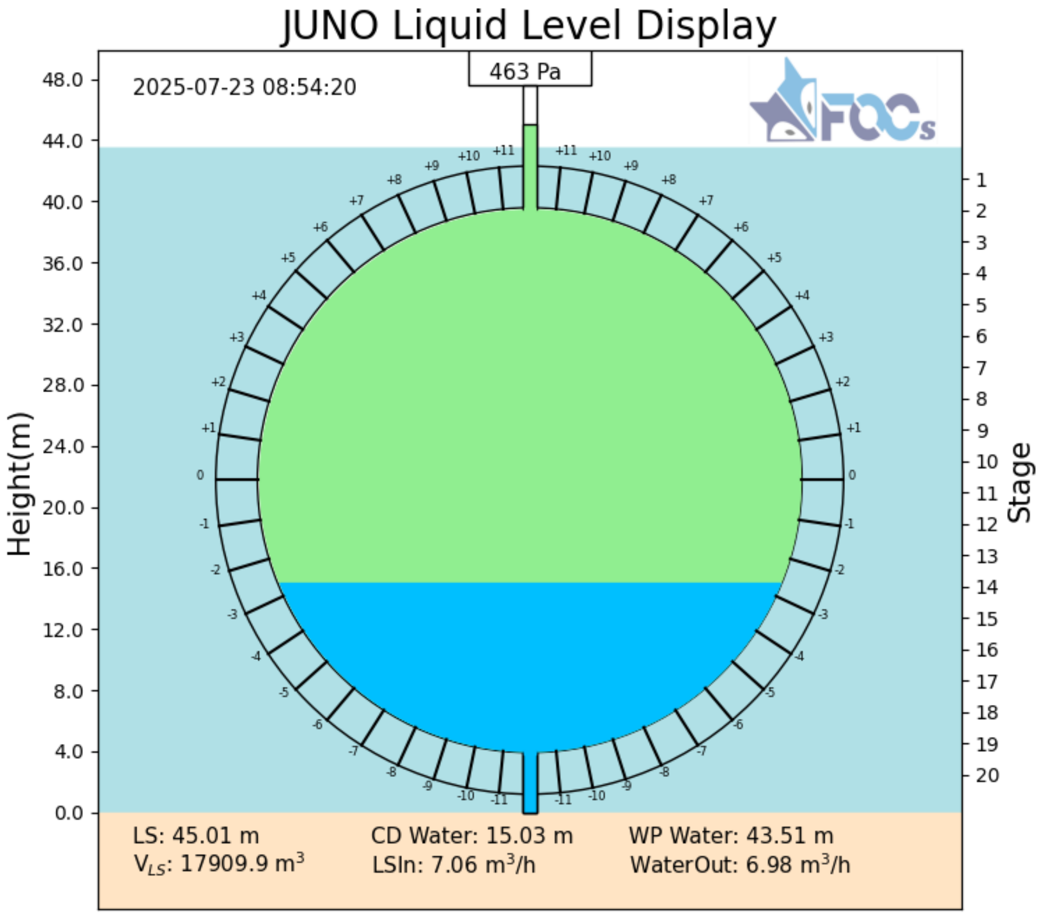
JUNO detector

Closure of acrylic vessel

Final removal of protection paper film

JUNO liquid filling started on Dec 18, 2024

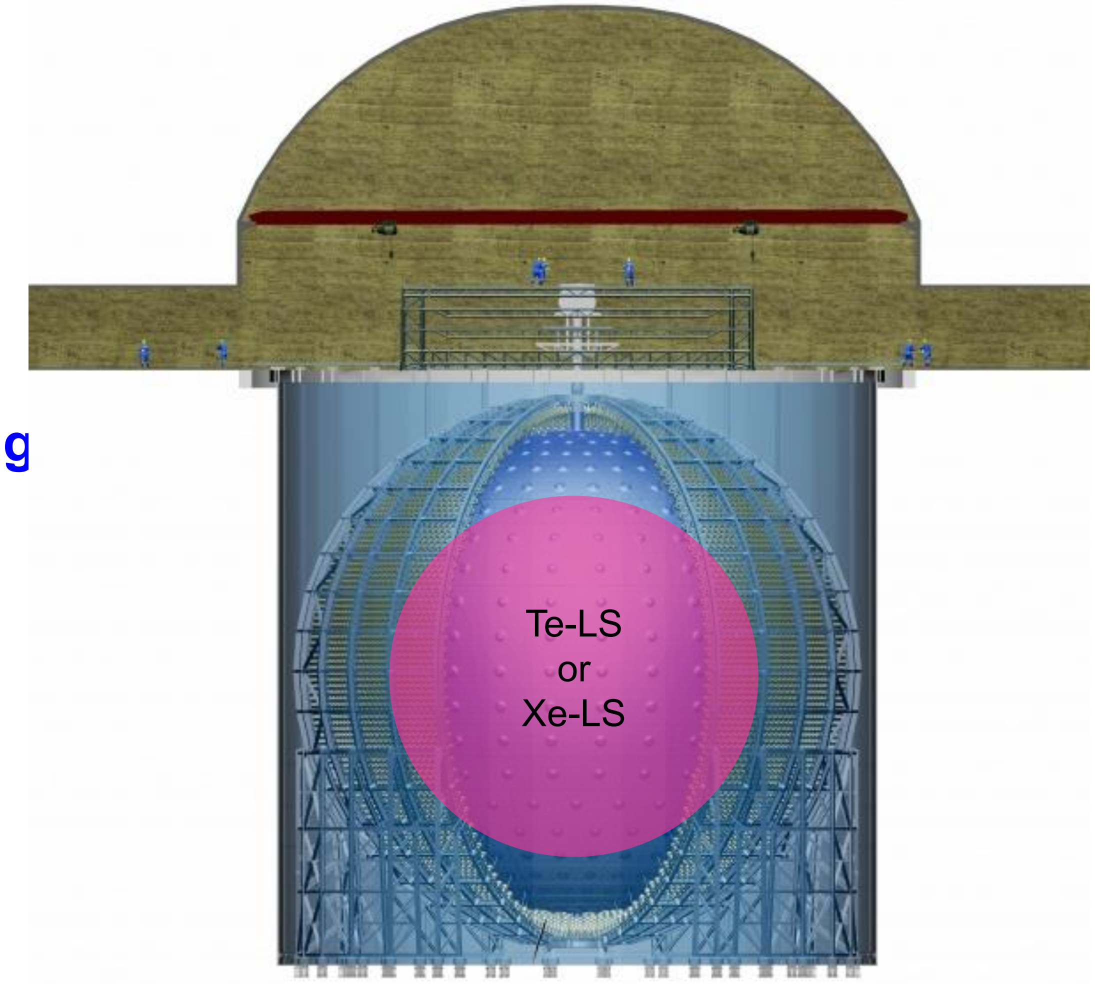




- Water filling started Dec 2024
- LS filling started Feb 2025, 75% filled!
- Detector commissioning in parallel

JUNO-$0\nu\beta\beta$ upgrade

- JUNO offers an unique opportunity to search for $0\nu\beta\beta$
  - 20 kton LS → **100-ton scale isotope loading** (e.g., Tellurium OR Xenon)
  - Low background
  - Energy resolution < 3% @ 1 MeV → **2.4x better than KamLAND-Zen**



Concept of the experiment

Searching for $0\nu\beta\beta$ decays in JUNO, Snowmass2021 LOI
Snowmass2021 Topical group report for NF05, arXiv 2209.03340

Background budget

- Full background evaluation
  - ^{136}Xe loading as an example in 2016
  - ^{130}Te loading estimate ongoing
- Advantage of large LS based detector → negligible external material background
- Background dominated by
  - Cosmogenic isotope
  - ^{8}B solar ν-e scattering
  - $2\nu\beta\beta$
  - Internal LS radiopurity

Table 5. Summary of the projected backgrounds in the $0\nu\beta\beta$ ROI. For light cosmogenic isotopes, the values are from GEANT4 MC, while for FLUKA MC the total residual background would increase 0.07/ROI/(ton ^{136}Xe)/yr.

summary of backgrounds in $0\nu\beta\beta$ ROI	$[\mathrm{ROI}\cdot(\mathrm{ton}\ ^{136}\mathrm{Xe})\cdot\mathrm{yr}]^{-1}$
$2\nu\beta\beta$	0.2
^{8}B solar ν	0.7
cosmogenic background	
^{10}C	0.053
^{6}He	0.063
^{8}Li	0.016
^{12}B	3.8×10^{-4}
others ($Z \leqslant 6$)	0.01
^{137}Xe	0.07
internal LS radio-purity (10^{-17} g/g)	
^{214}Bi (^{238}U chain)	0.003
^{208}Tl (^{232}Th chain)	—
^{212}Bi (^{232}Th chain)	0.03
external contamination	
^{214}Bi (Rn daughter)	0.2
total	1.35

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Background control for JUNO detector

- Before assembly
  - Massive material screening
- Low bkg assay approaches
  - HPGe, NAA, ICPMS
  - Rn detector
- Develop pre-treatment methods for different materials

	sens.	Note
HPGe	10 ppb – 10 ppt	sample ~1-10 kg
NAA	0.1-1 ppt	sample ~1 g
ICP-MS	~< 0.1 ppt	sample ~1 g
Rn assay facility	<10 uBq/m^3-N_2	w/i enrichment
	~50 uBq/m^3-H_2O	w/i enrichment

1 ppt=10^{-12}, 1 ppb=10^{-9}

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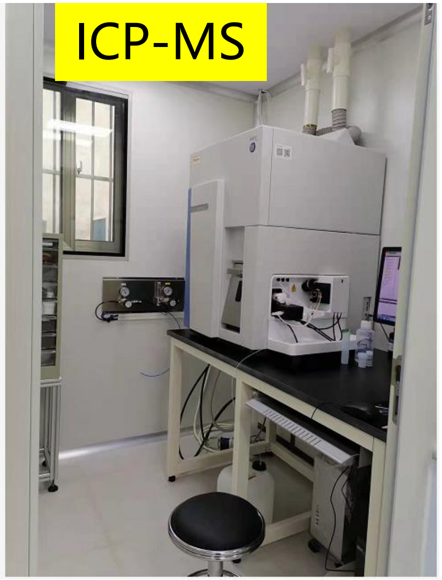
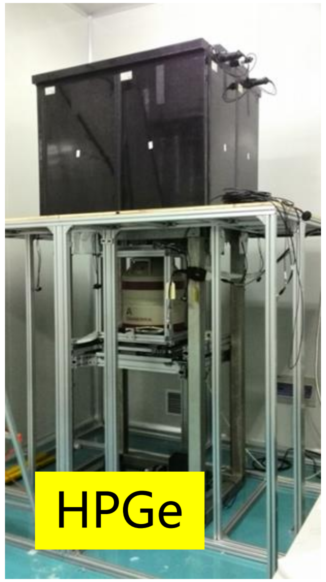
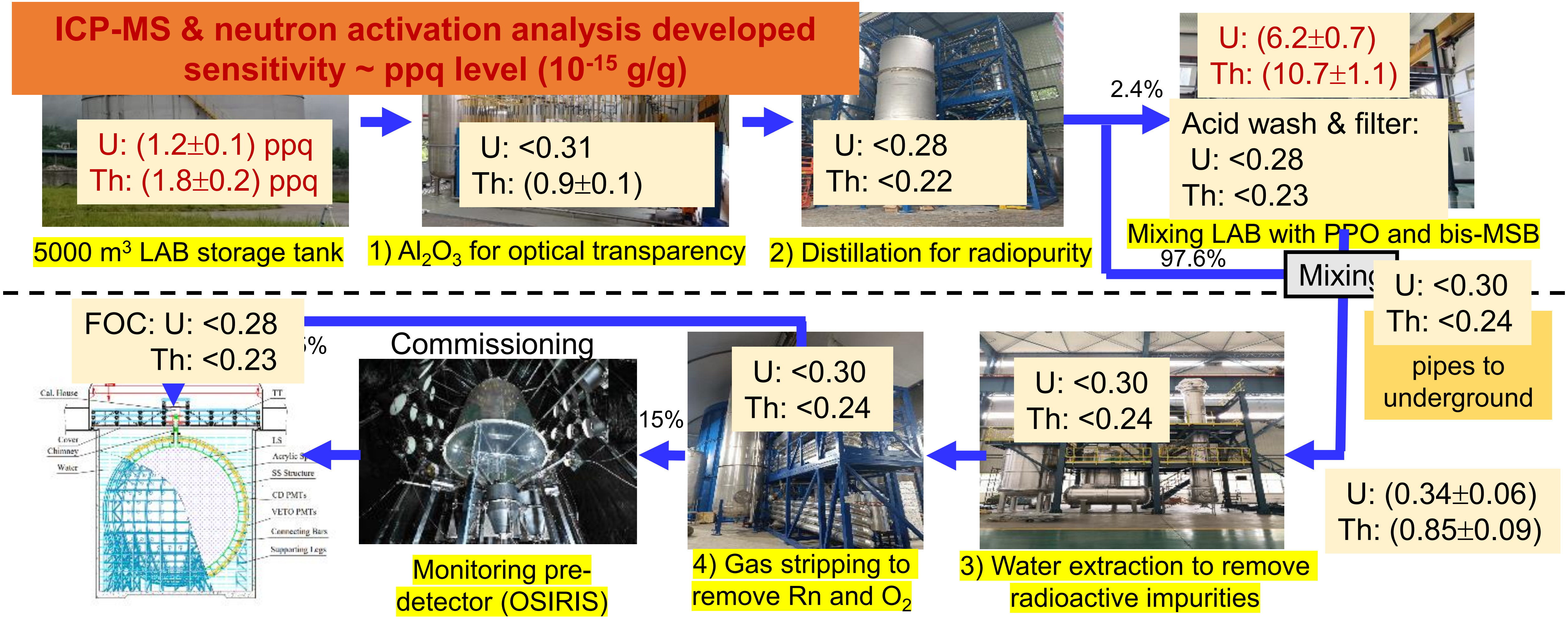




	U/Th sens. [10^{-12} g/g]	Ref
OFHC	~0.1	*NIM A, 941 (2019) 162335*
Acrylic	<0.1	*NIM A,* 1004 (2021) 165377
PPO (LS solute)	~0.1	-
Kapton, Si	~< 1	-
LAB	**~10^{-4}**	**w/i enrichment**

JUNO LS radiopurity



LS radiopurity (U/Th) after purification is cleaner than ~3×10^{-16} (upper limit of the ICPMS method)

Cosmogenic background on ^{12}C

- JUNO: 650 m rock overburden
- Long-lived μ-spallation isotope could become background

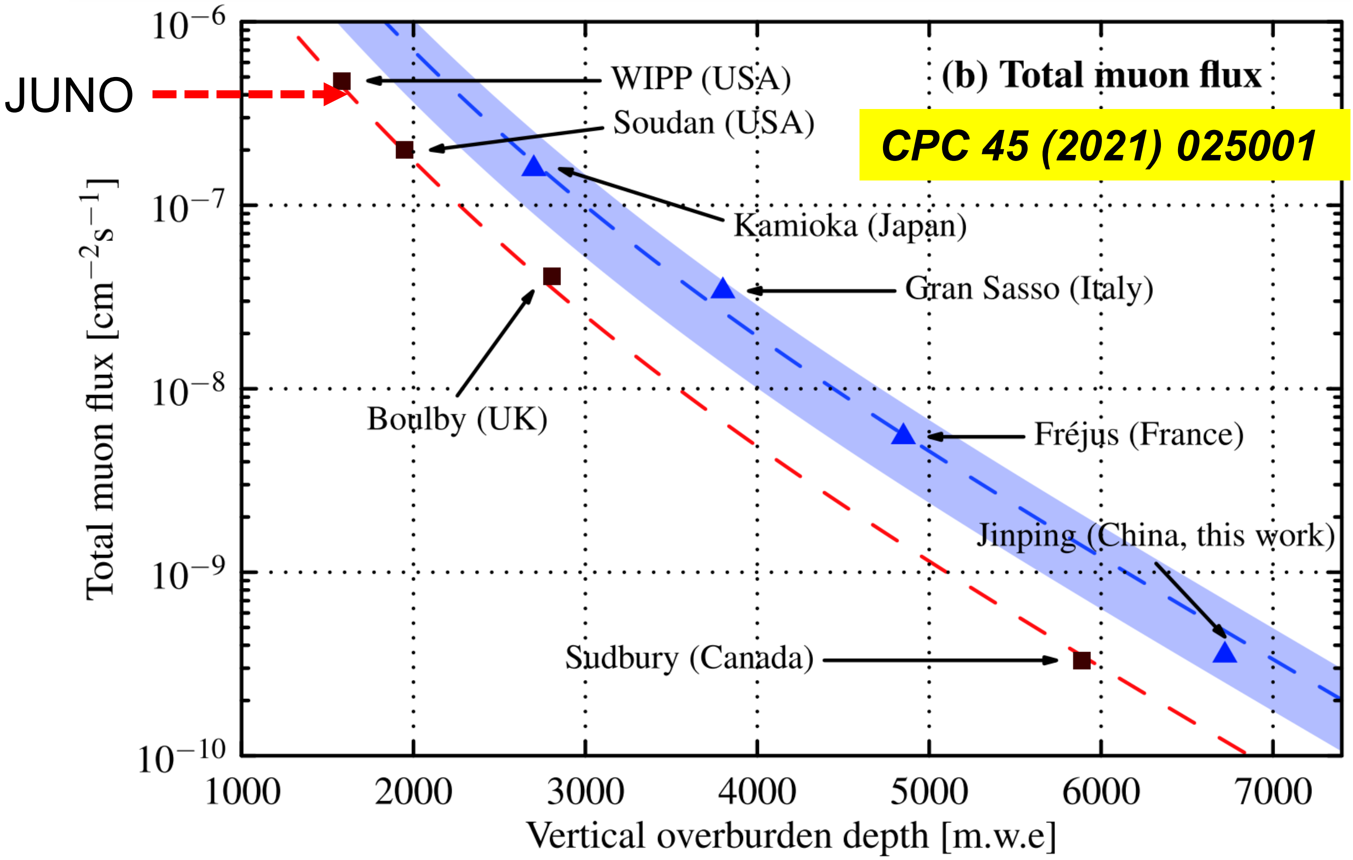
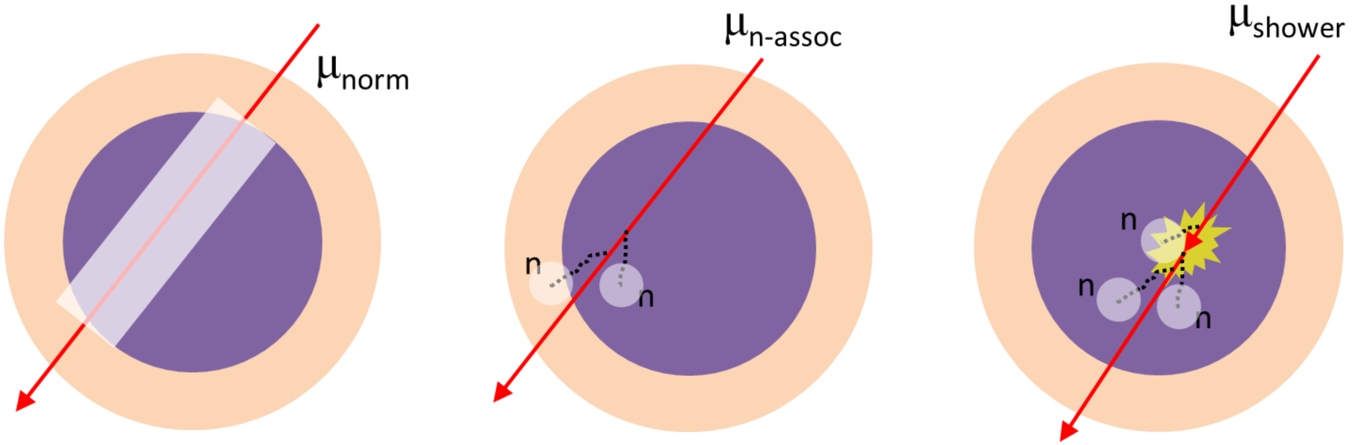


Table A9. The estimated rates for cosmogenic isotopes in JUNO LS by FLUKA simulation, in which the oxygen isotopes are neglected. The decay modes and Q value are from TUNL Nuclear Data Group [475].

Isotopes	Q (MeV)	$T_{1/2}$	Rate (per day)
^{3}H	0.0186 (β^-)	12.31 year	1.14×10^4
^{6}He	3.508 (β^-)	0.807 s	544
^{7}Be	$Q_{EC} = 0.862$ (10.4% γ, $E_\gamma = 0.478$)	53.22 d	5438
^{8}He	10.66 ($\beta^-\gamma$: 84%), 8.63 (β^-n: 16%)	0.119 s	11
^{8}Li	16.0 (β^-)	0.839 s	938
^{8}B	16.6 (β^+)	0.770 s	225
^{9}Li	13.6 (β^-: 49%), 11.94 (β^-n: 51%)	0.178 s	94
^{9}C	15.47 (β^+p: 61.6%, $\beta^+\alpha$: 38.4%)	0.126 s	31
^{10}Be	0.556 (β^-)	1.51e6 year	1419
^{10}C	2.626 ($\beta^+\gamma$)	19.29 s	482
^{11}Li	20.55 (β^-n: 83%, β^-2n: 4.1%)	0.00875 s	0.06
^{11}Be	11.51 ($\beta^-\gamma$: 96.9%), 2.85 ($\beta^-\alpha$: 3.1%)	13.76 s	24
^{11}C	0.960 (β^+)	20.36 min	1.62×10^4
^{12}Be	11.708 ($\beta^-\gamma$, β^-n: 0.5%)	0.0215 s	0.45
^{12}B	13.37 ($\beta^-\gamma$)	0.0202 s	966
^{12}N	16.316 ($\beta^+\gamma$)	0.0110 s	17
^{13}B	13.437 ($\beta^-\gamma$)	0.0174 s	12
^{13}N	1.198 (β^+)	9.965 min	19
^{14}B	20.644 ($\beta^-\gamma$, β^-n: 6.1%)	0.0126 s	0.021
^{14}C	0.156 (β^-)	5730 year	132
^{15}C	9.772 (β^-)	2.449 s	0.6
^{16}C	8.010 (β^-n: 99%)	0.747 s	0.012
^{16}N	10.42 ($\beta^-\gamma$)	7.130 s	13
^{17}N	8.680 ($\beta^-\gamma$: 5%), 4.536 (β^-n: 95%)	4.173 s	0.42
^{18}N	13.896 ($\beta^-\gamma$: 93%), 5.851 (β^-n: 7%)	0.620 s	0.009
Neutron			155 000

Background Veto

- Excellent μ tagging and tracking capability
- Dedicated veto strategies for different types of muons
- Major isotopes can be efficiently rejected



Refs: arXiv:2006.11760, Chin. Phys. C 45 (2021) 023004
arXiv:1610.07143, Chin. Phys. C 41 (2017) 053001

Cosmogenic Isotopes	Background Index unit: ROI^{-1} (ton 136Xe)$^{-1}$ yr^{-1}	
	No veto	w/ veto
^{10}C	16.4	0.053
^{6}He	4.9	0.063
^{8}Li	1.5	0.016
^{12}B	1.9	3.8e-4
^{137}Xe	2.3	0.07
Xe spallation **	--	2.5*
Others (Z≤6)	0.51	0.01
Total		2.7

Cosmogenic background on Te/Xe

- Long-lived, high-Q isotopes
- Activation above the ground
  - Minimize exposure
  - Underground cooling down
- In-situ activation underground
  - Rate/spectra evaluation with Geant4/FLUKA ongoing
  - Develop veto strategy
- Guide development of transfer and storage strategy for Te raw materials

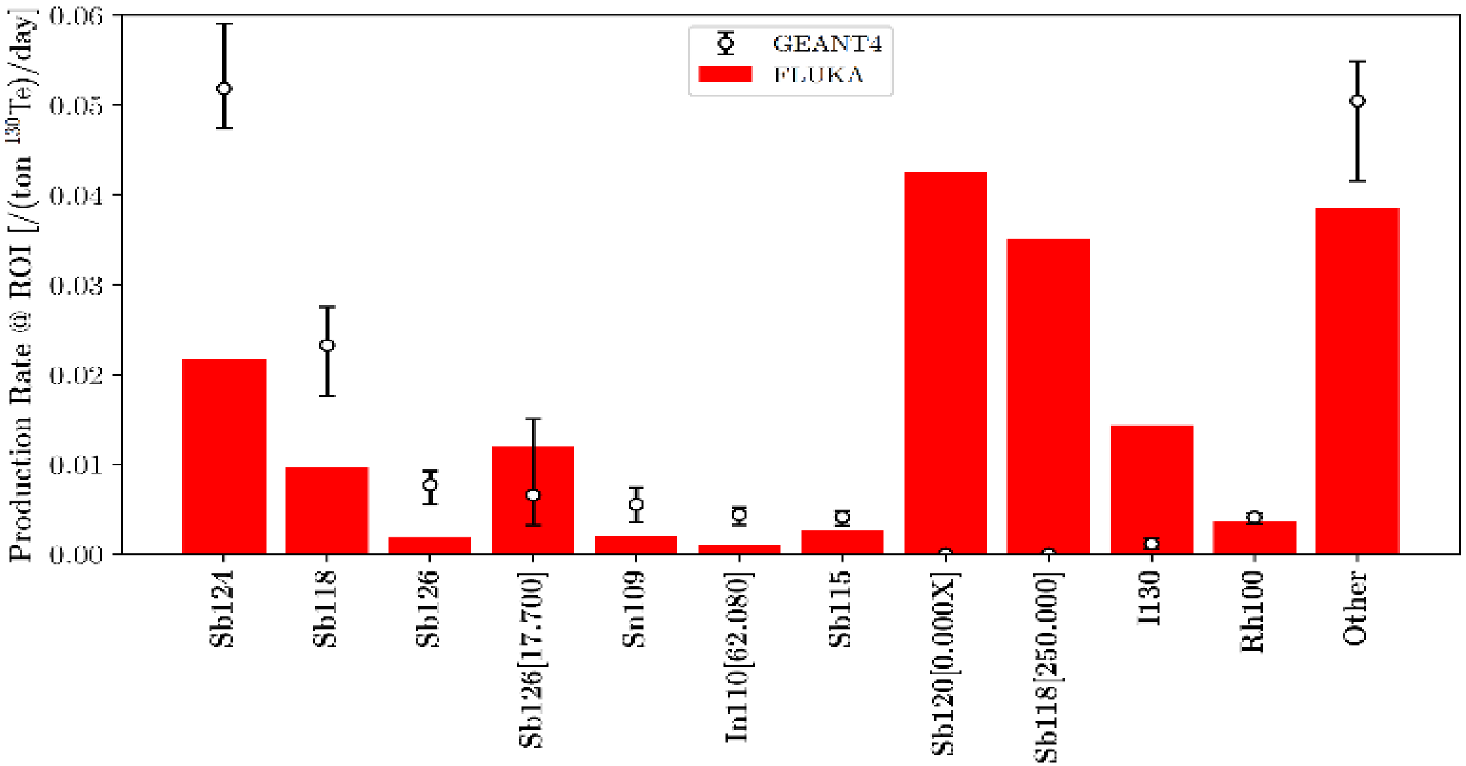
Isotope	$T_{1/2}$ [d]	Q-value [MeV]	Decay mode (BR) (%)
^{22}Na	950.6	2.84	EC,β^+
^{26}Al	2.62E+8	4.00	β^+
^{42}K (^{42}Ar)	0.51 (1.20E+4)	3.53	β^-
^{44}Sc (^{44}Ti)	0.17 (2.16E+4)	3.65	EC,β^+
^{46}Sc	83.79	2.37	β^-
^{56}Co	77.2	4.57	EC,β^+
^{58}Co	70.9	2.31	EC,β^+
^{60}Co (^{60}Fe)	1925.27 (5.48E+8)	2.82	β^-
^{68}Ga (^{68}Ge)	4.70E-2 (271)	2.92	EC,β^+
^{82}Rb (^{82}Sr)	8.75E-4 (25.35)	4.40	EC,β^+
^{84}Rb	32.8	2.69	EC,β^+ (96.1)
^{88}Y (^{88}Zr)	106.63 (83.4)	3.62	EC,β^+
^{90}Y (^{90}Sr)	2.67 (1.05E+4)	2.28	β^-
^{102}Rh (^{102m}Rh)	207.3	2.32	EC,β^+ (78)
^{102m}Rh	1366.77	2.46	EC (99.77)
^{106}Rh (^{106}Ru)	3.47E-4 (371.8)	3.54	β^-
^{110m}Ag	249.83	3.01	β^- (98.67)
^{110}Ag (^{110m}Ag)	2.85E-4	2.89	β^- (99.70)
^{124}Sb	60.2	2.90	β^-
^{126m}Sb (^{126}Sn)	0.01 (8.40E+7)	3.69	β^- (86)
^{126}Sb (^{126m}Sb)	12.35 (0.01)	3.67	β^-

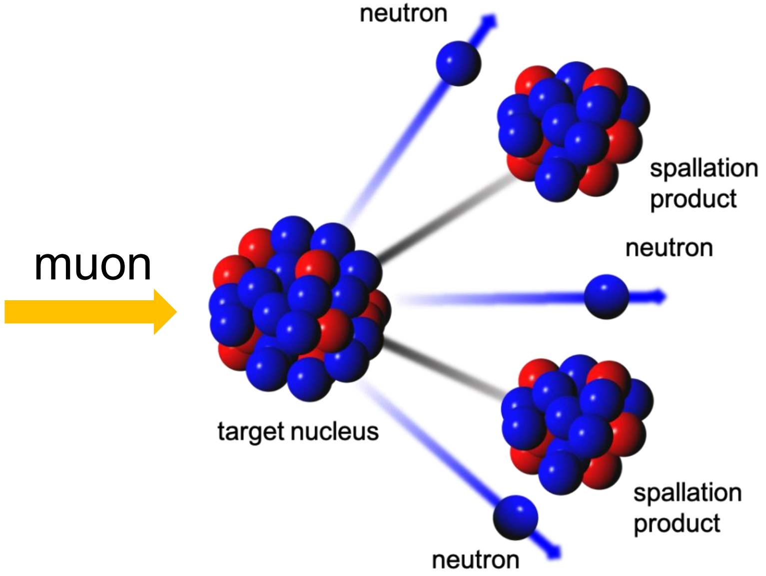
Astropart. Phys. 61 (2015) 62-71

Te spallation isotopes yield calculation

- Muon induced spallation isotopes from Te
- Isotope yield calculation with FLUKA and GEANT
  - Variations among models
  - Identification of major long lived isotopes

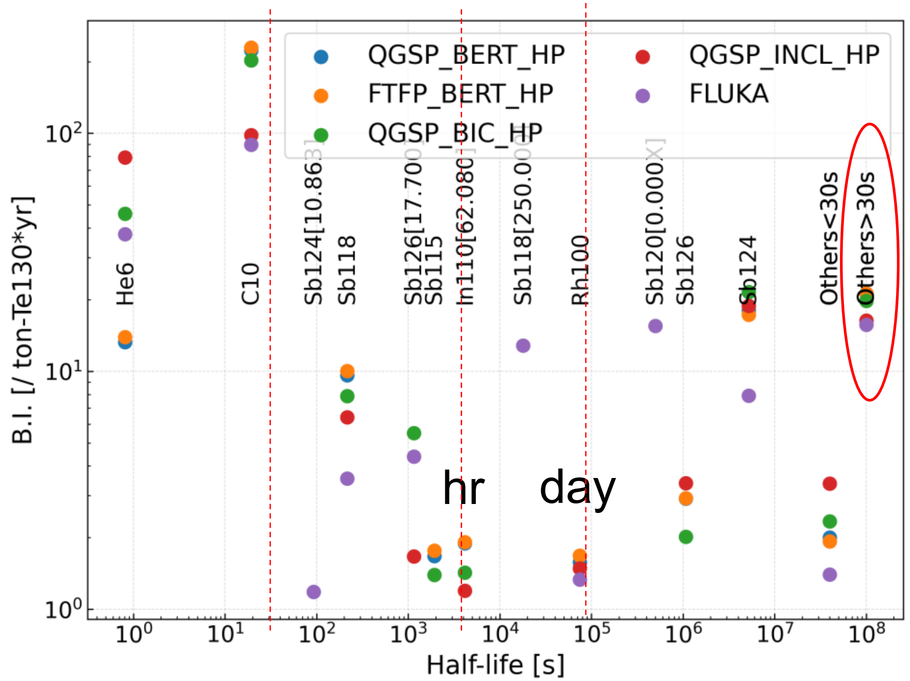
Isotopes with $\tau > 30s$

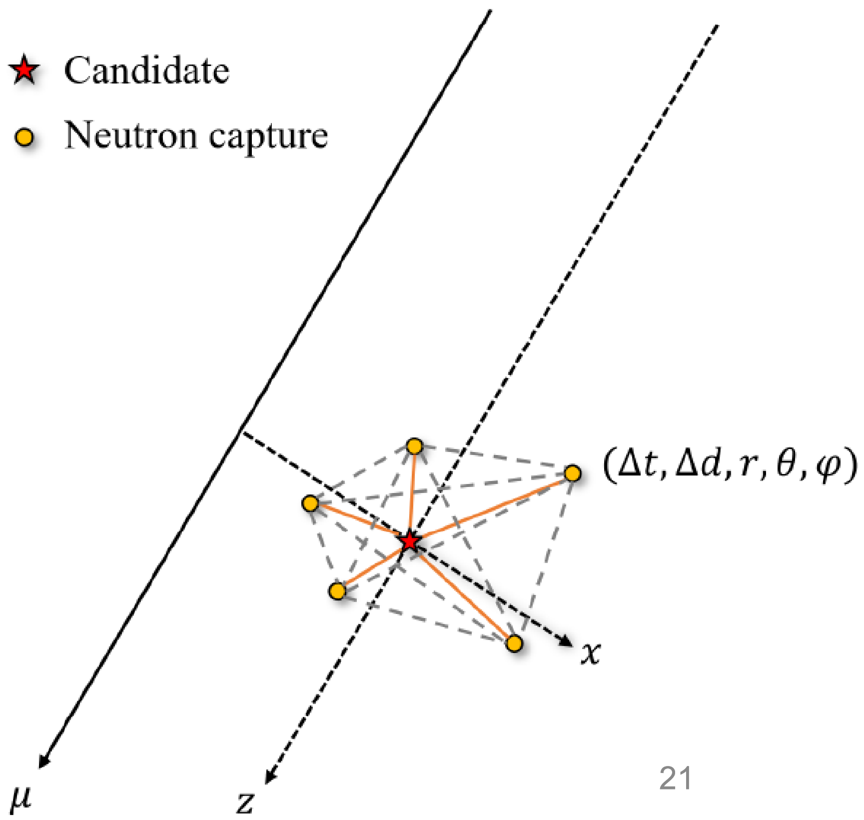




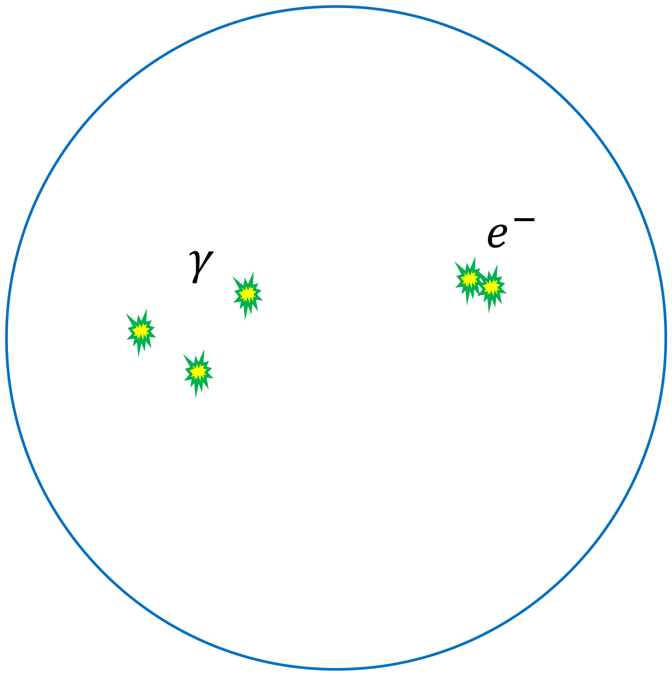
Development of Rejection method

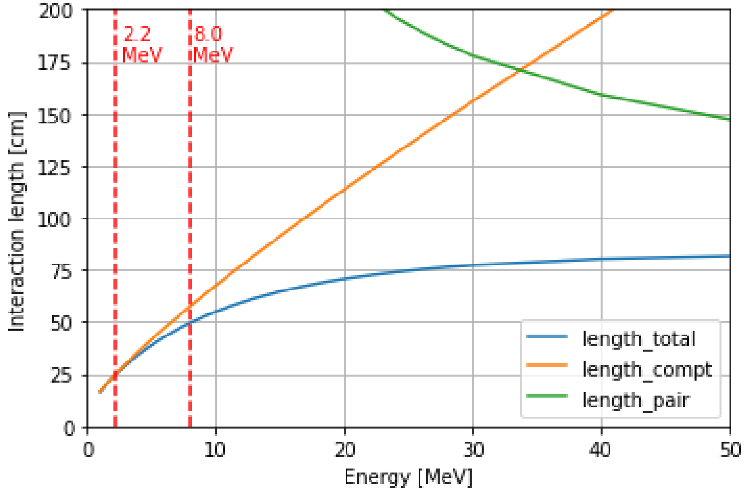
- Understanding of shower and attempts to reject background
  - Using accompanying neutrons information
  - Powerful rejection achieved for short lived isotopes
    - 98% bkg. rej. @ ~80% sig eff. with BDT
    - Advanced ML like GNN and transformer expected to improve further
  - Long lived isotopes are more difficult for event-by-event rejection
    - Large number of preceding muons, convection et al
    - Multi-site discrimination will help



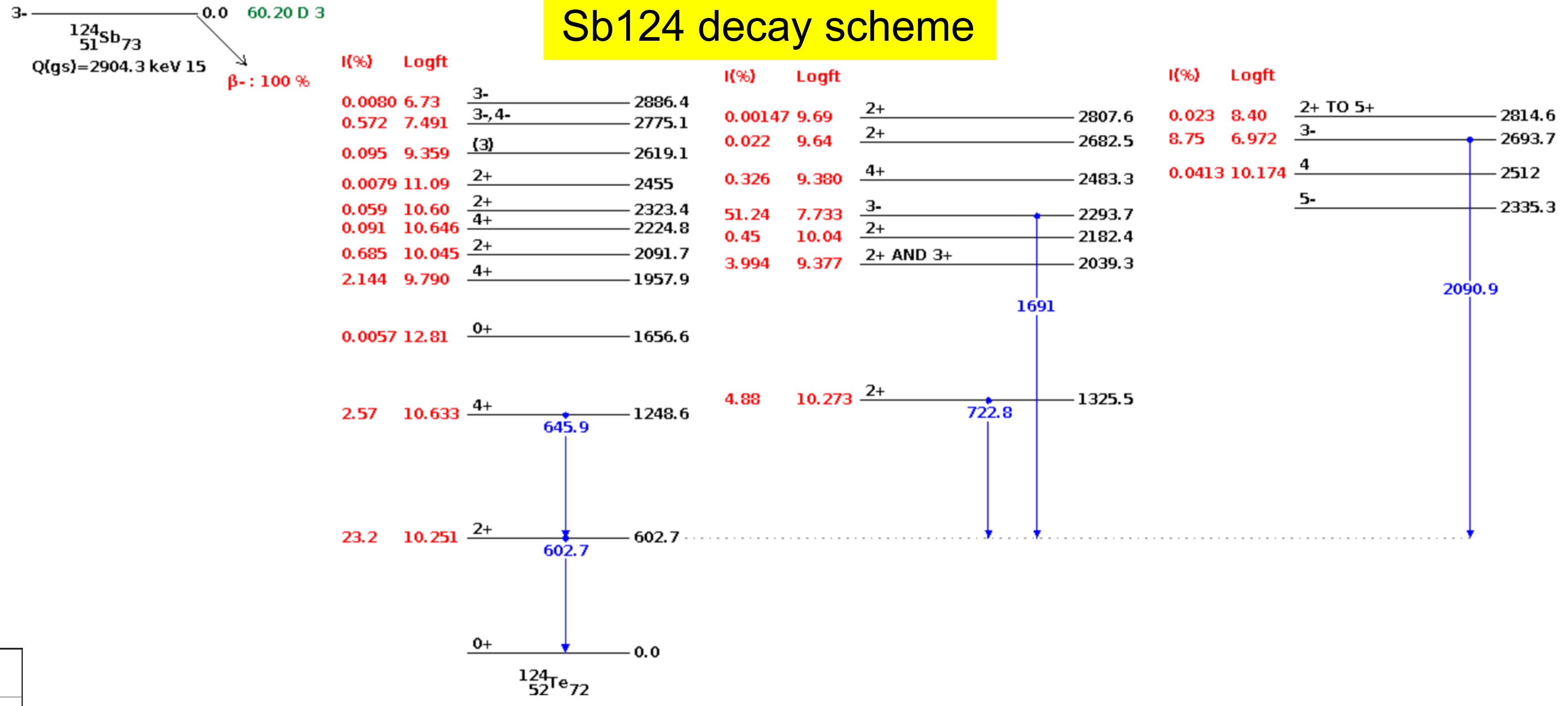


Multi-site discrimination





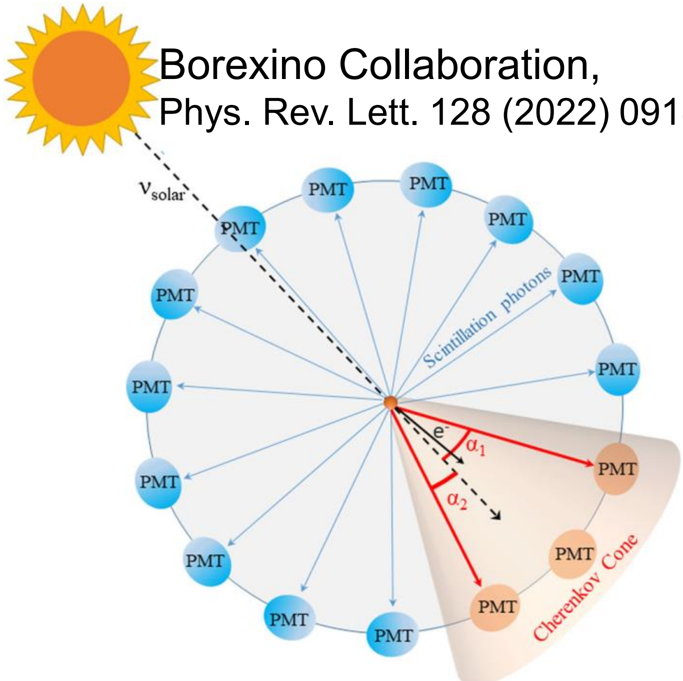
Sb124 decay scheme



- Interaction length of ~1-2 MeV gammas in LAB 10-30 cm
  → 0.5-1.5 ns time of flight
- Timing resolution: ~1ns (Dynode PMTs)
- Further suppression of ultra-long-lived isotope is promising

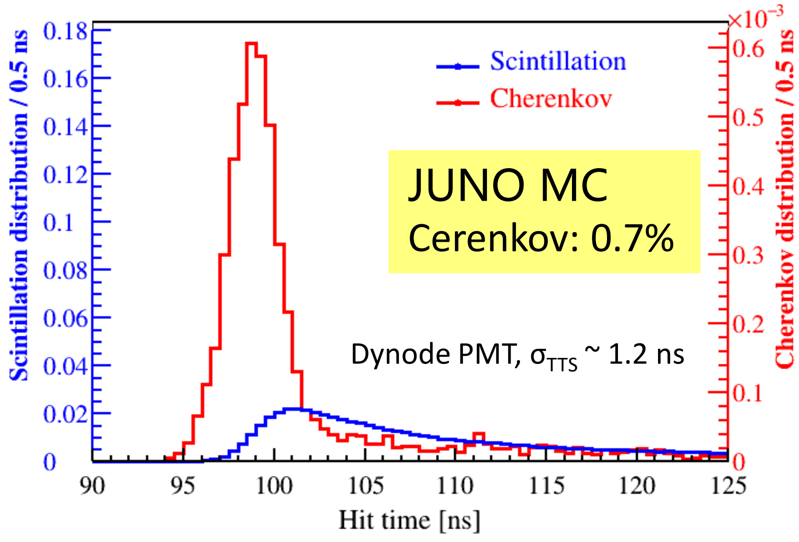
B8 solar neutrino

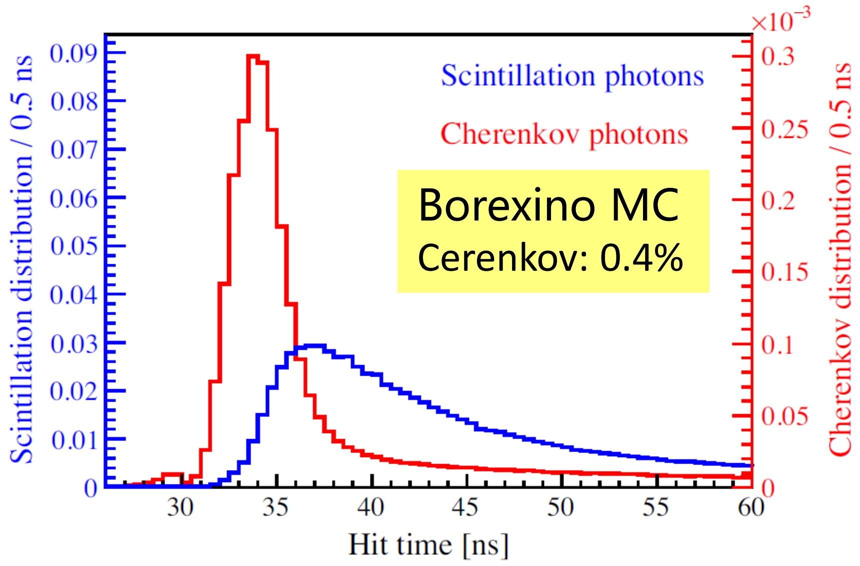
- ^{8}B solar ν-e scattering events has special directionality w.r.t the sun

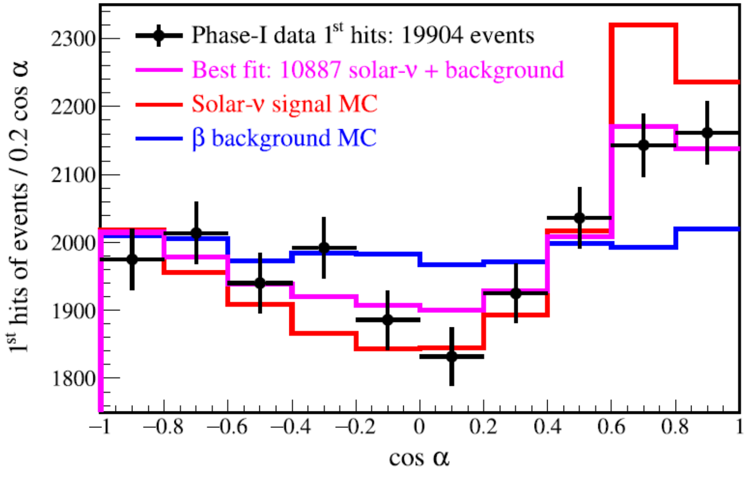


- Directional Cerenkov light in JUNO LS detector helps to disentangle 0νββ decay and ^{8}B solar ν-e
  - Higher energy ROI
  - Higher Cerenkov fraction

Expectation: a factor of 2 suppression







(0.54, 0.74) MeV region

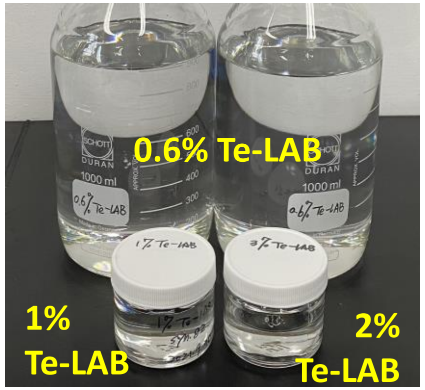
Te loading R&D

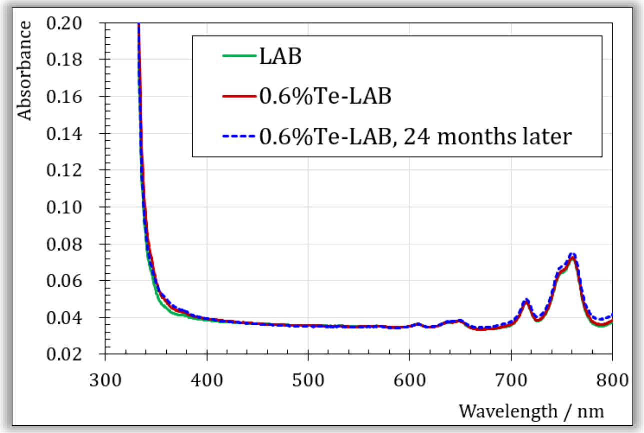
See Yayun's talk

- Challenge
  - high doping (>3%), good optical performance, stability (>10 yr), low background
- Te-compound search
  - Tellurium acid + diol → screening
  - Identified hexanediol as best diol

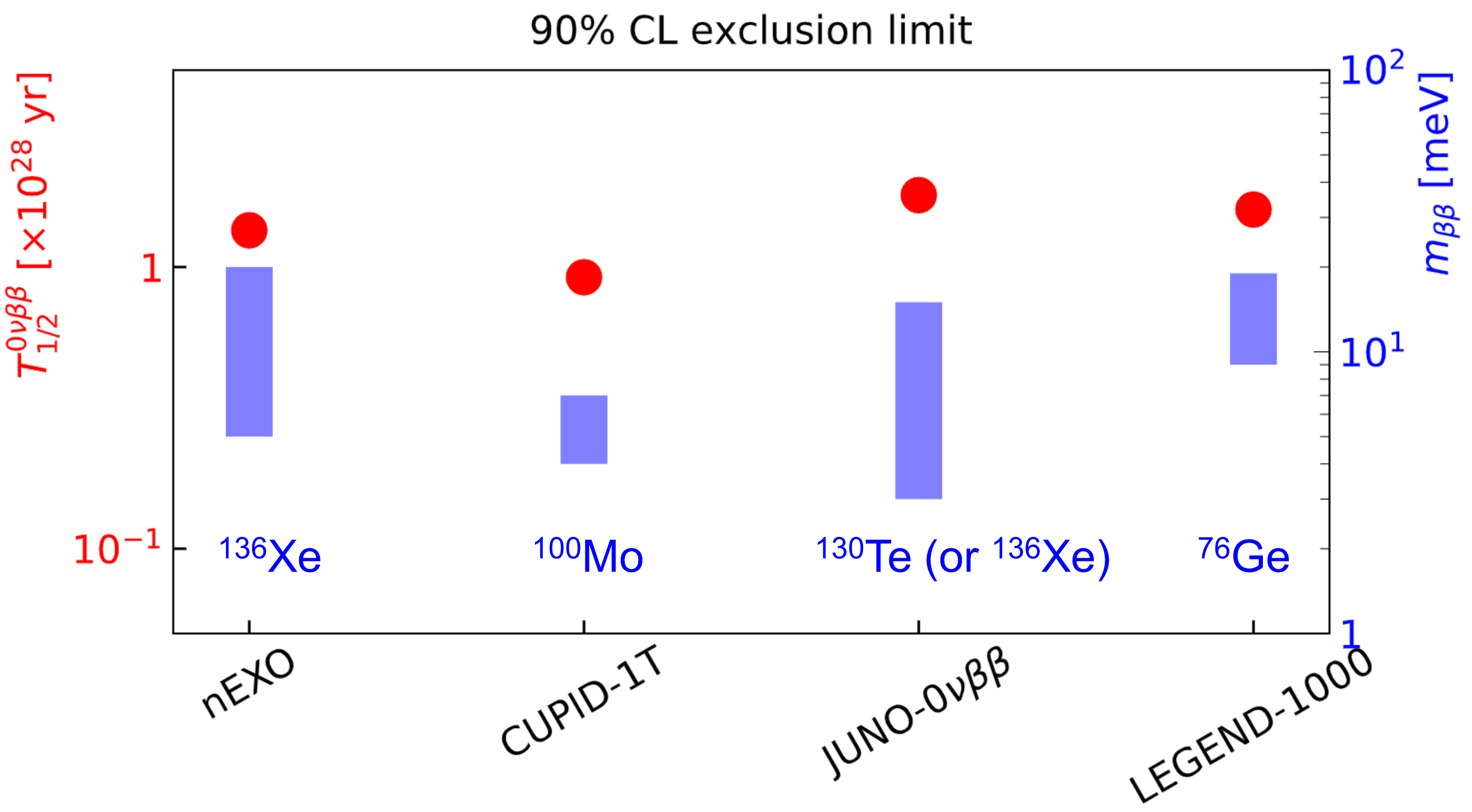
NIM A 1049 (2023) 168111

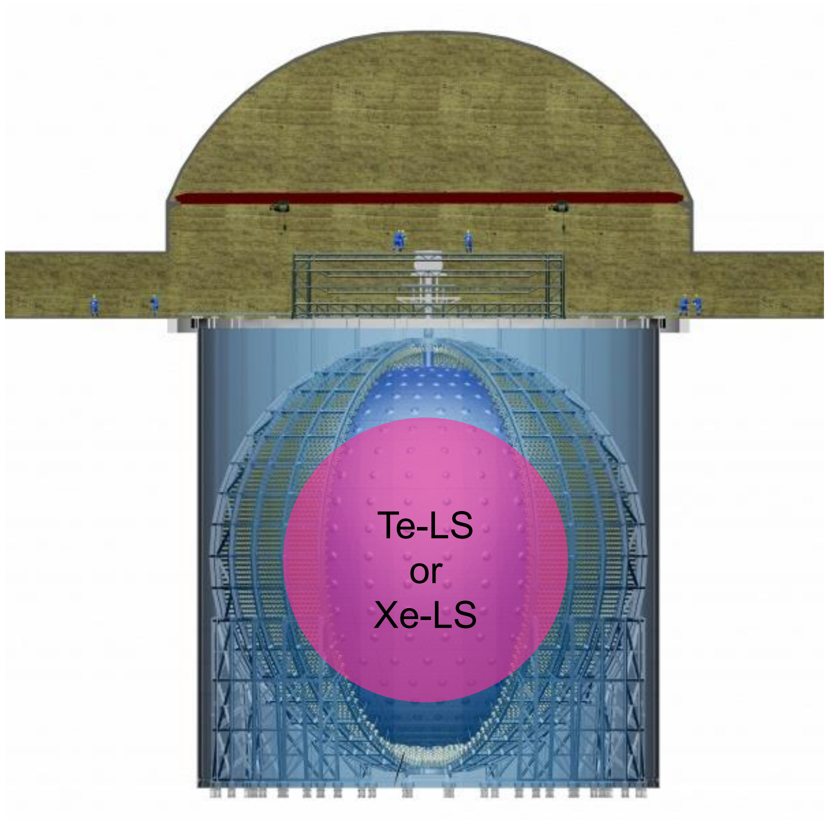
- Two different synthesis methods developed:
  - Azeotropic distillation: water-free env → stable product
  - RT approach: energy effective → good for mass production
- Achieved sample performance
  - Te loading > 3%
  - Good stability monitored for > 2 years
  - Light yield ~60% @ 0.5% Te-loading → First attempt to improve light yield to ~80%
- Scale up (100kg) production ongoing
  - Optical purification
  - Stability of synthesis methods





Sensitivity





Concept of the experiment

* Numbers are quoted from results shown in Neutrino2022 Conf. and the North America – Europe workshop on future 0νββ experiments in 2021.

Summary

- Searching for 0vββ decay is the most sensitive to probe the nature of neutrino mass and absolute neutrino masses
- Liquid scintillator is a competitive technology to go beyond 10^{28} yrs of $T_{1/2}^{0\nu\beta\beta}$
- By 2030, the current LS experiments (KamLAND-Zen, SNO+) may reach 10^{27} yrs, next generation projects (LEGEND-1T, nEXO, CUPID) may start running
- JUNO has the potential to explore the $|m_{\beta\beta}|$~meV region w/ >100 tons of 0vββ isotope
  - Clear route for technologies R&D
  - By 2028, resolve the Te-loading technique, background control/suppression strategy
  - By 2030, design & build Te loading and purification systems

Backup

Internal LS radio-inpurity

- Four purification plants to remove radio-impurities in LS
  - Alumina column, distillation, water extraction, gas stripping
- Strict control measures for LS pipes/plants to limit contaminations during filling
  - Detailed cleaning protocols
  - Limit radon exposure
- Rejection in the analysis
  - β-α cascade
  - Pulse shape discrimination for different particle type

	^{238}U (g/g)	^{232}Th (g/g)
KamLAND (2002 osci. RPL)	$(3.5\pm0.5) \times 10^{-18}$	$(5.2\pm0.8) \times 10^{-17}$
KamLAND (2015 solar)	$(5\pm0.2) \times 10^{-18}$	$(1.3\pm0.1) \times 10^{-17}$
KamLAND-Zen (2013 PRL)	$(1.3\pm0.2) \times 10^{-16}$	$(1.8\pm0.1) \times 10^{-15}$
KamLAND-Zen (2022)	$(1.5\pm0.4) \times 10^{-17}$	$(3.0\pm0.4) \times 10^{-16}$
SNO+ (2020)	10^{-15}	10^{-16}
Borexino (w/o water extraction)	$(5.3\pm0.5) \times 10^{-18}$	$(3.8\pm0.8) \times 10^{-18}$
Borexino (w/i water extraction)	$< 9.4 \times 10^{-20}$	$< 5.7 \times 10^{-19}$
JUNO (target)	**10^{-17}**	**10^{-17}**

References: Phys. Rev. C. 85.045504, Phys. Rev. C 92, 055808 (2015), Phys. Rev. Lett.90.021802, Phys. Rev. Lett. 117.082503, Phys. Rev. C.84.035804, PRL 110, 062502 (2013), Eur. Phys. J. C (2020) 80:41, talks at NEUTRINO2020, Phys. Rev. D 89, 112007 (2014)

Radioactive impurities	Background Index unit: ROI^{-1} (ton $^{136}Xe)^{-1}$ yr^{-1}	
	No rejection	After rejection
^{214}Bi-^{214}Po (^{238}U series)	**8.3**	**0.003** (0.03% residual)
^{212}Bi-^{212}Po (^{232}Th series)	**1.25**	**0.03** (2.5% residual)
^{222}Rn external leakage	--	**0.2** (0.03% residual)

Very small bkg contribution after rejection

Experimental landscape

$T_{1/2} > 10^{24}$ y 90% C.I. restricted club

GERDA — $T_{1/2} > 1.8\times10^{26}$ y
Phys. Rev. Lett. 125, 252502 (2020)

KamLAND-Zen 400 — $T_{1/2} > 1.07\times10^{26}$ y
Phys. Rev. Lett. 117, 082503 (2016)

EXO-200 — $T_{1/2} > 3.5\times10^{25}$ y
Phys. Rev. Lett. 123, 161802 (2019)

MAJORANA dem. — $T_{1/2} > 2.7\times10^{25}$ y
Phys. Rev. C 100, 025501

CUORE — $T_{1/2} > 2.2\times10^{25}$ y
arXiv:1907.09376

CUPID-0 — $T_{1/2} > 4.7\times10^{24}$ y
L. Pagnanini, TAUP 2021

CUPID-Mo — $T_{1/2} > 1.8\times10^{24}$ y
B. Welliver, TAUP 2021

NEMO-3 — $T_{1/2} > 1.1\times10^{24}$ y
Phys. Rev. D 92, 072011 (2015)