R&D program for neutrinoless double beta decay search at JUNO

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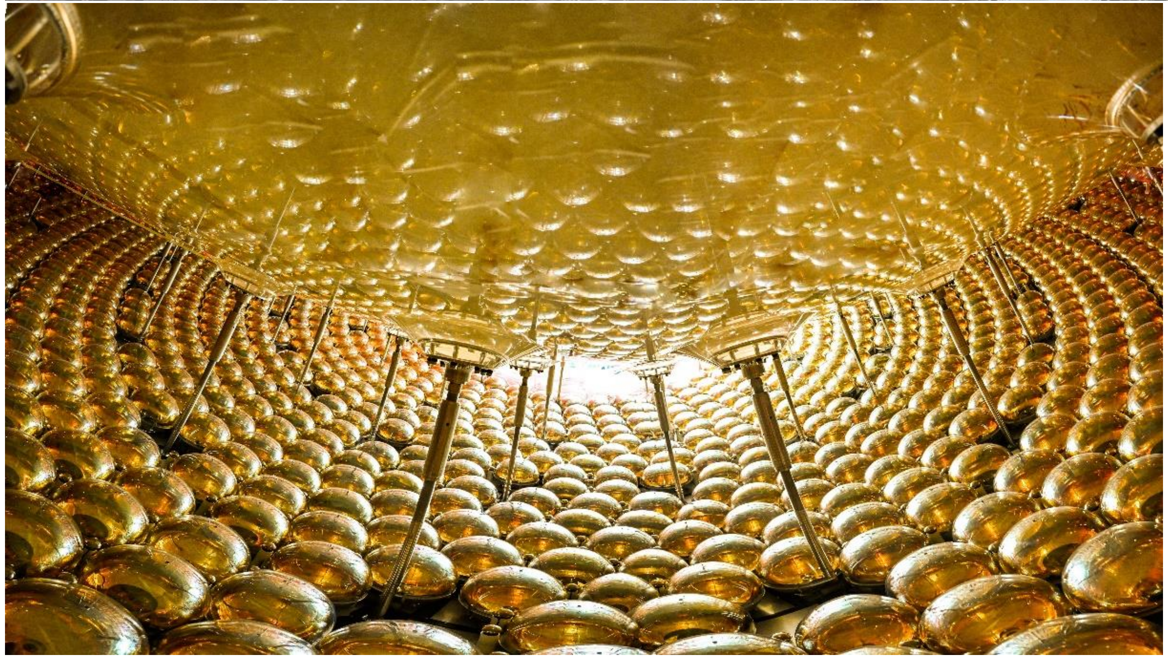
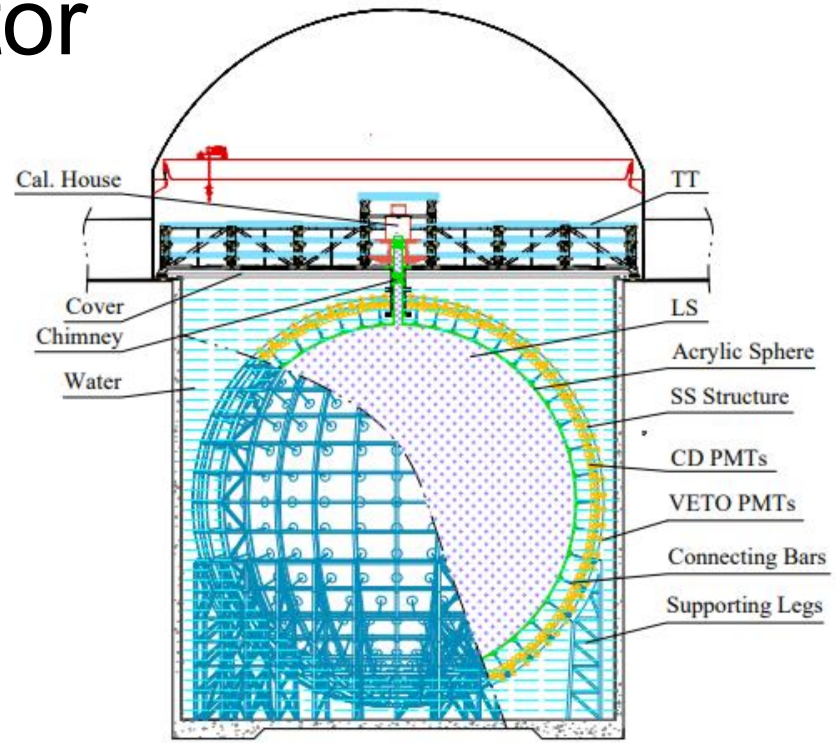
on behalf of the JUNO collaboration

Aug 25, 2025 @ TAUP, Xichang

JUNO Detector

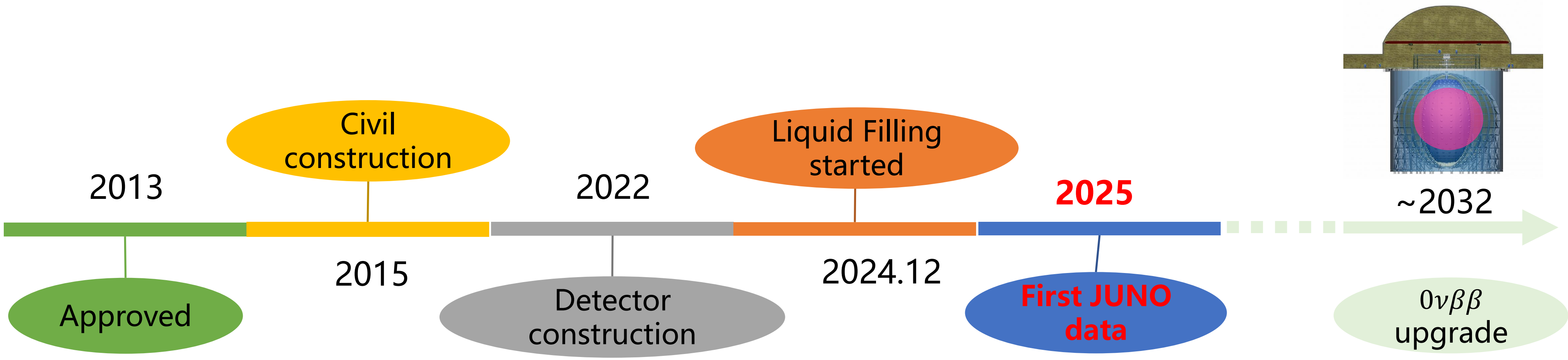


- Largest LS detector ever (20 kton), designed for NMO determination with reactor $\overline{\nu_e}$
- 650m rock overburden underground
- 35.4m acrylic vessel covered by 20”+3” PMTs (75%+3% photocoverage)

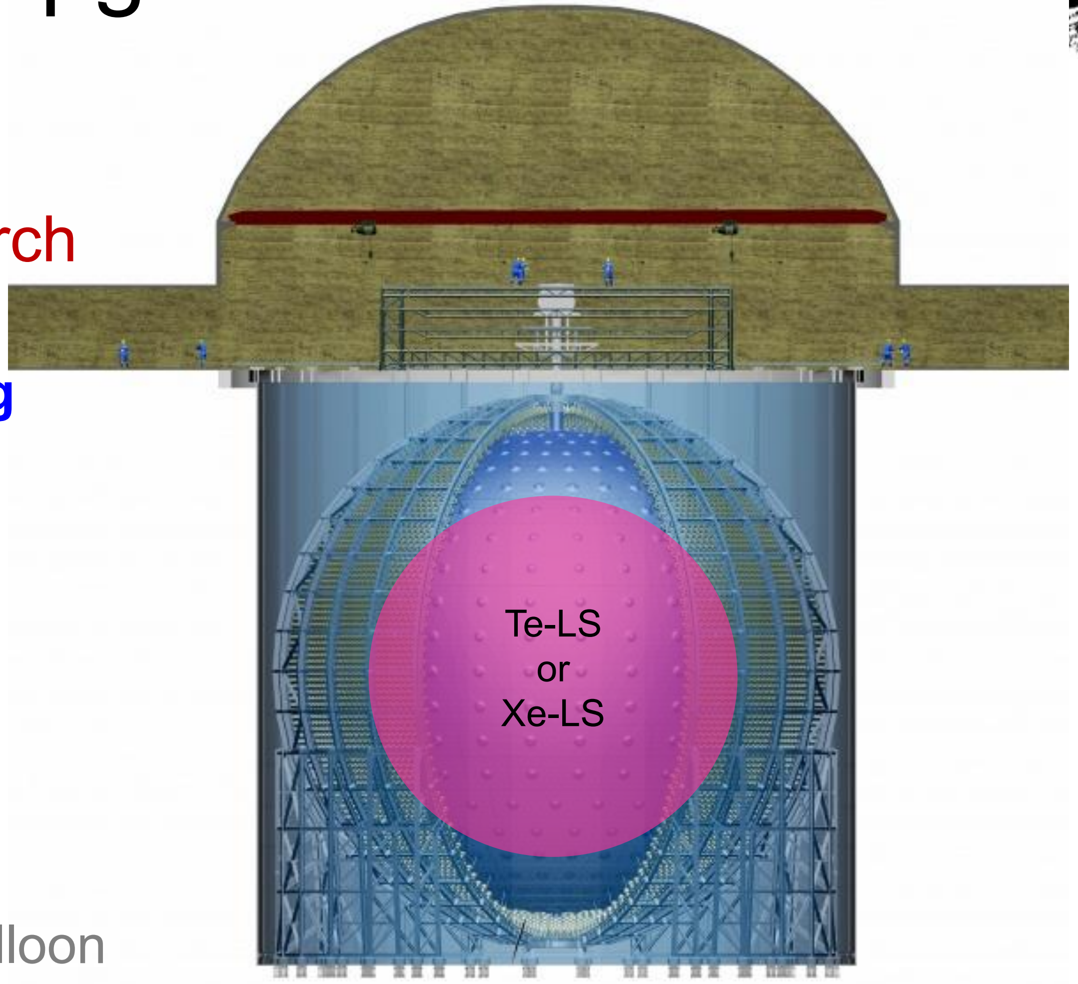
JUNO Status

- 10 years endeavor of construction of the experiment
- Ready to start physics data taking in August
- Determine NMO with 6.5 years of data
- Upgrade for 0vbb decay search after NMO determination



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**
- Critical R&D
  - Te route: Isotope loading technology
  - Xe route: cost effective enrichment & clean balloon
  - Background control



Concept of the experiment

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

TeLS R&D program

2020: Azeotropic distillation approach developed → >5% Te mass loading
2021: Absorbance at 430 nm unchanged for 0.6% Te loading
2022~2023: R.T. synthesis approach established to decrease safety risks
2024: Synthesis and purification protocol established for Te-LS production

Exploratory stage — 2017 - 2019

Technical Breakthrough — 2020 - 2024

Application-oriented — 2025 -

2017: inorganic Te + surfactant
2018: liquid-liquid extraction
2019: organic Te-diol compounds

2025: 100 kg production demonstration
Lab studies: L.Y. optimization, stability test (>3 years), Te-LS transparency characterized by A.L., develop methods for radioactive impurities removal

Te-LS @IHEP

Te-LS for 0νββ:
An internationally recognized challenge

- Excep. high Te-doping conc.(3~5%)
- No Impact on LS Optical Perf.
- Ultra-low rad. Background
- Stability >10 years

× Liquid-Liquid Extraction

✓ Organic Te-compound

×surfactant

× Inorganic Te nanoparticles

TA + 1,2-hexanediol

×Benzene-C-Te- compound

×...

Technical Route 1: Azeotropic distillation approach

Innovation Highlights: water-free reaction → enhanced solubility and stability

Advantages： Te>>5%， Uniform Transparent, and Stable

Patent： *ZL 202011370855.5*

Publication： *NIM A 1049 (2023) 168111*

Technical Route 2: Room temp. Syn. approach

Innovation Highlights:

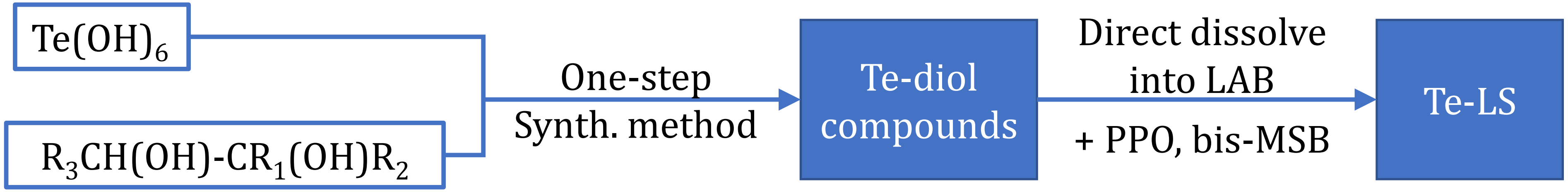
No heating required, R.T. Synthesis

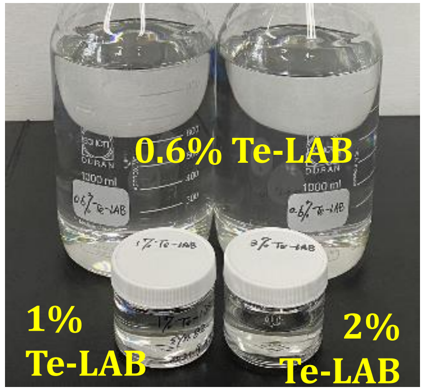
Advantages ： Performance unchanged, greener & more scalable

Patent： *applied*

Publication： *in preparation*

Route 1: Azeotropic distillation approach



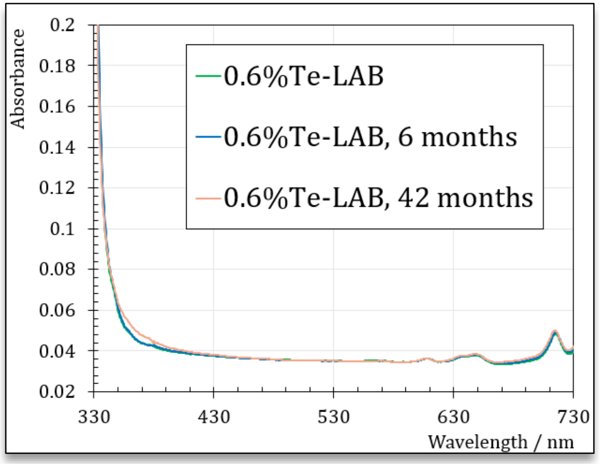


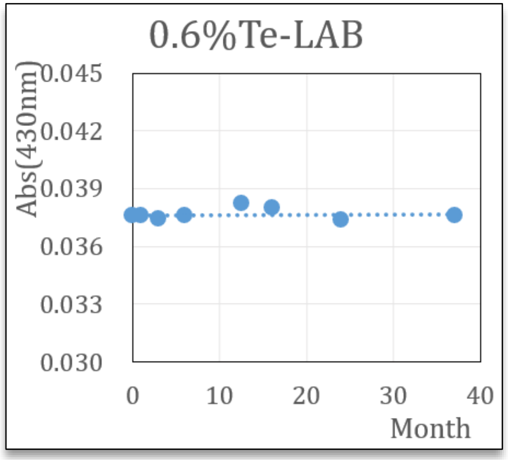
- Water-free environment for the synthesis
- No extra water introduced into the reaction system
  - Solid state telluric acid used directly instead of being dissolved in the water
- Water generated removed continuously by azeotropic distillation
  - Azeotropic solvent → Acetonitrile, for its relatively lower boiling point (81.6 ◦C) and higher water content (16%) in azeotrope

Y. Ding, et al., NIM A 1049 (2023)

Route 1: performance

- Ultrahigh Te Solubility
  - miscible with LAB, capability of Te loading in JUNO LS: > 5%
- Exceptionally High Transparency & Long-Term Stability
  - limited influence on the absorbance of scintillation solvent and stable for 3.5 years
- A one-step synthesis
  - simple, the product can be used for preparing Te-LS directly without post-processing, easily Scalable for mass production
- Broad applicability to diverse diols
  - a serials of diols with more sophisticated structures can be used since the reaction is greatly facilitated by the removal of water





Route 2: Room temperature Synthesis approach

- **Disadvantage** of Azeo. Dist. Approach: safety risks associated with large-scale heating and distillation of low-boiling-point solvents (acetonitrile, 81.6 ◦C)
- Developed a **Room-Temperature Synthesis approach**
  - one-step synthesis **at room temperature**
- Excellent properties of Te-samples:
  - Exceptional optical transparency (ΔAbs(430nm)/%Te ≤ 0.0003)
  - Long-term spectral stability exceeding or approaching 1 year till now for both **1% and 3% Te** formulations
  - Outperform even those produced by the Azeo. Dist. Method
- A green, efficient alternative for large-scale Te-LS production for next-generation neutrinoless double-beta decay experiments

Patent applied, Manuscript to be submitted

Accomplished

Screening of Preparation Routes

Accomplished

Development of Novel Technical Routes

Achieved

Exceptional optical transparency, Long-term spectral stability (Max. 3.5-year duration), Mod. Light Yield

Past：Lab-scale preparation

High Difficulty

3~4 Orders of Mag.

Now：100-kg production with higher quality

Moderate diff.

~2 Orders of Mag.

Near Future: 20ton-scale production

Moderate diff.

~2 Orders of Mag.

Ultimate kton-scale production

Challenges

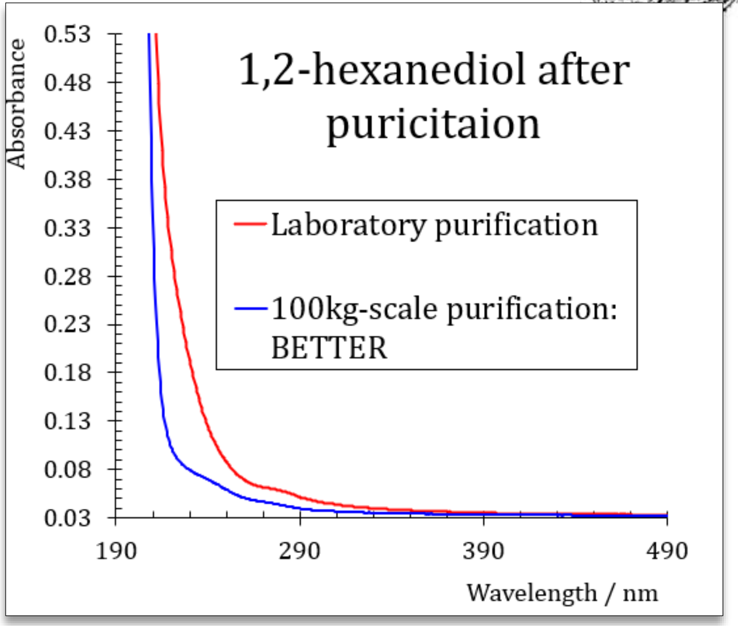
- Feasibility of Purification Method Scale-Up Efficiency & Cost
- Synth. Tech. Scale-Up: How to control Stability, Repeatability & Reliability?
- Max. 3% Te-loading in 100-kg production

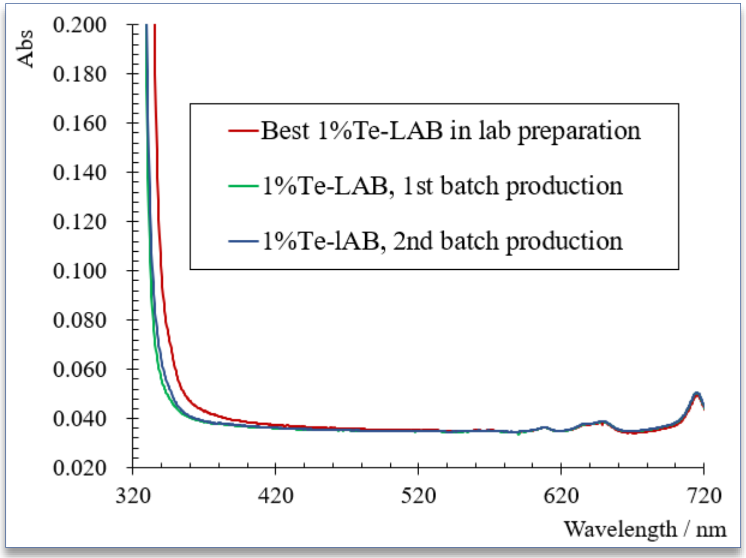
Goals

- Obtain higher-purity tellurium products
- Achieve higher transparency and enhanced stability in Te-LS
- Synthesis Conditions-Structures-Performance Study

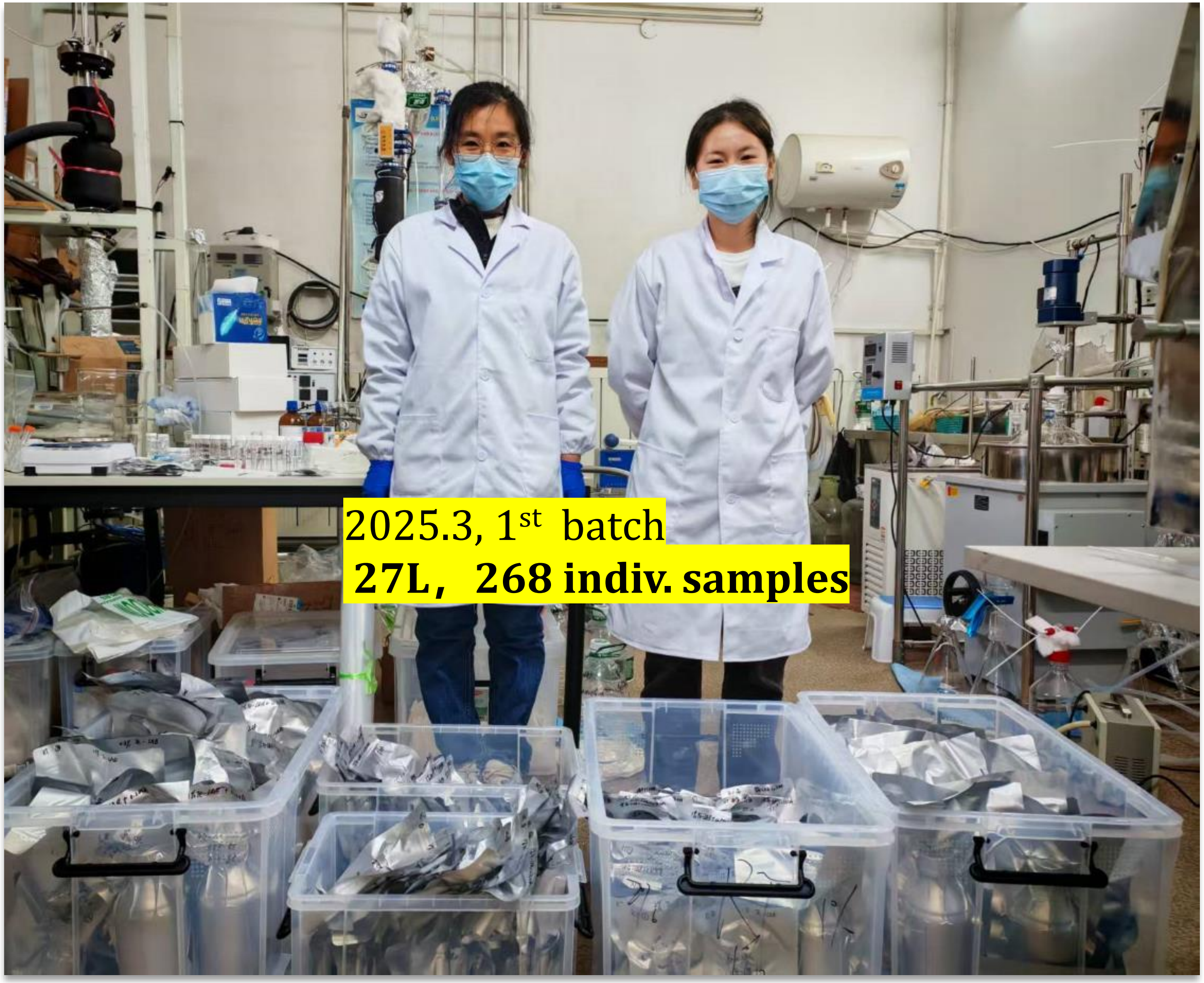
Progress of 100-kg production

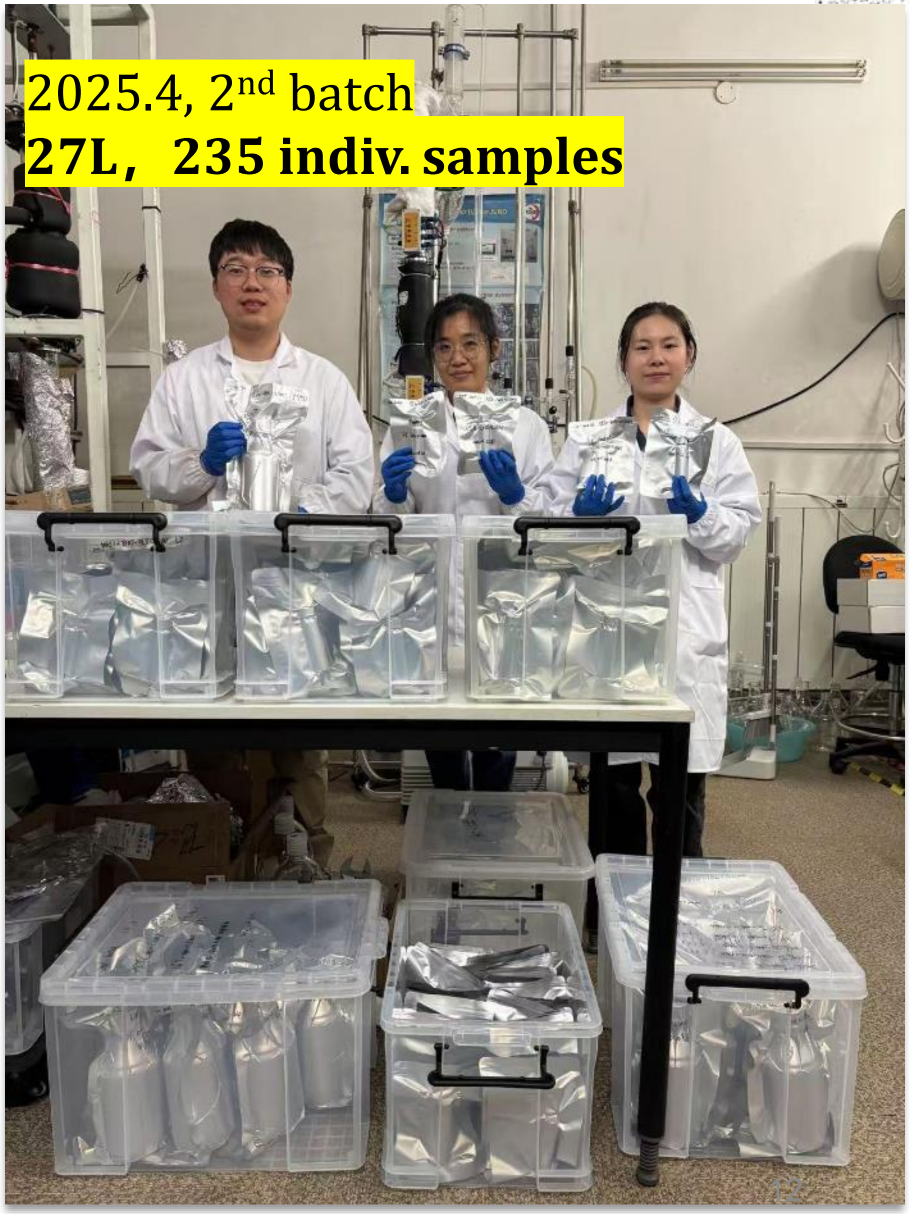
- Bulk purification methods for raw materials with corresponding QC standards and protocols developed
  - Extensive research on optical purification method
  - A combined purification approach for both purification efficiency and cost
  - Dramatic cost reduction with superior purity compared to expensive lab purification
- Dual-Temperature (Room Temp./High Temp.) Reactor was designed and customized
- 100kg-scale production in 10 batches in progress
  - Higher-transparency Te-LAB samples were obtained, >50 kg
  - Te-LAB samples from 1st and 2nd production exhibit absorption spectra far superior to the best lab samples.
  - Attenuation length of Te-LAB (0.5% doping) reaches **20m @ 430nm**
  - L.Y. measurement is ongoing





Te samples w/ diff. formulations were prep. for mult. research purposes





Backgrounds

- 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 contributions:
  - Cosmogenic isotope
    - Updates on spallation background on Te/Xe
  - ^{8}B solar ν-e scattering
  - $2\nu\beta\beta$
  - Internal LS background

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 [ROI·(ton ^{136}Xe)·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

CPC 41 (2017) 053001

Cosmogenic background on ^{12}C

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

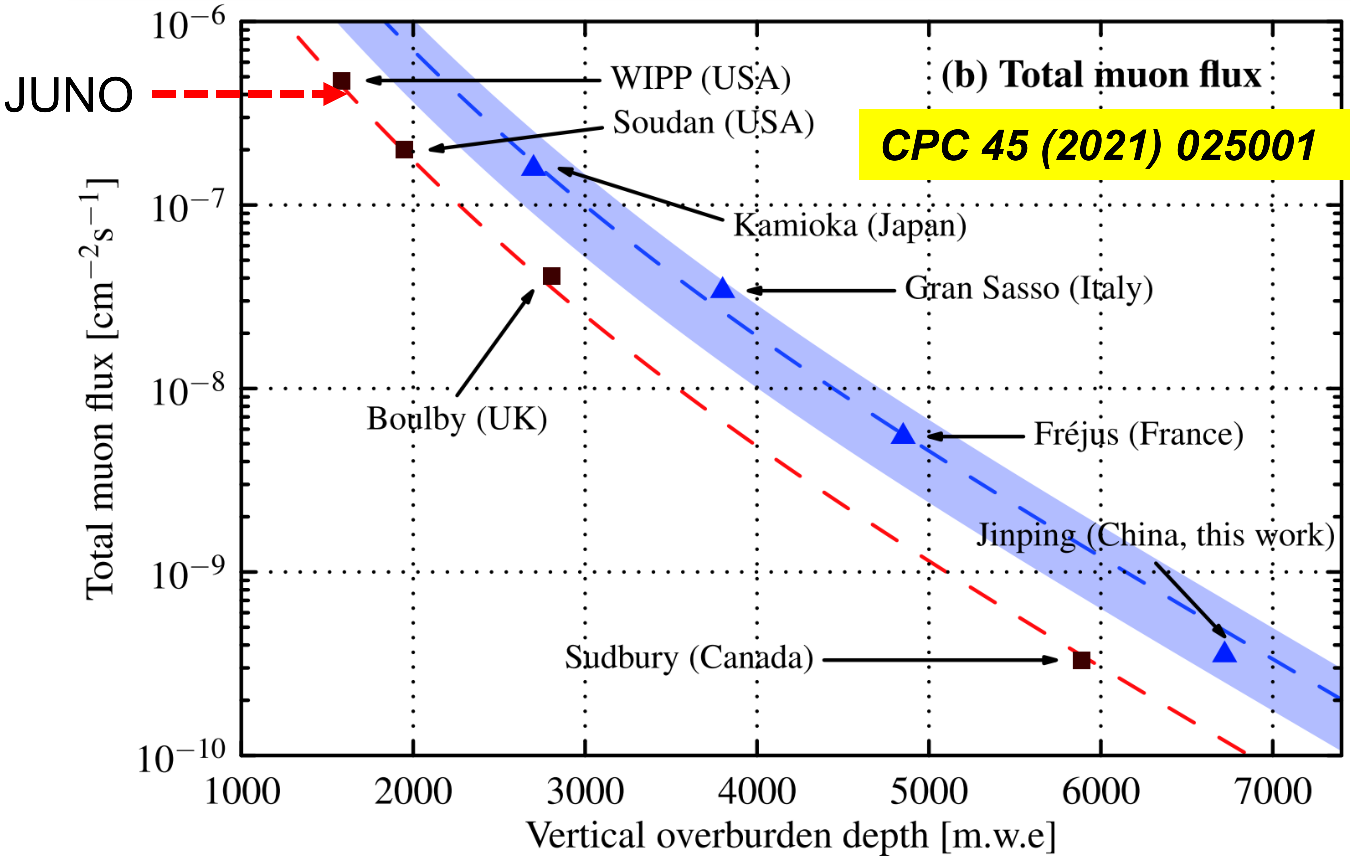
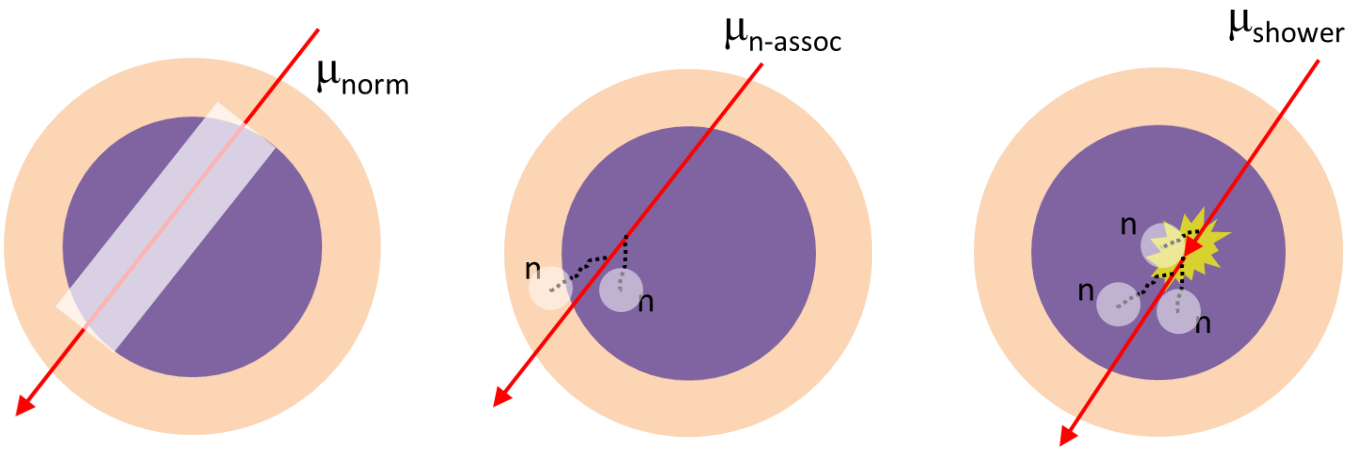


Table A9. The estimated rates for cosmogenic isotopes in JUNO LS by FLUK simulation, in which the oxygen isotopes are neglected. The decay modes and Q value are from TUNL Nuclear Data Group [475].

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_γ = 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 on ^{12}C after Veto

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

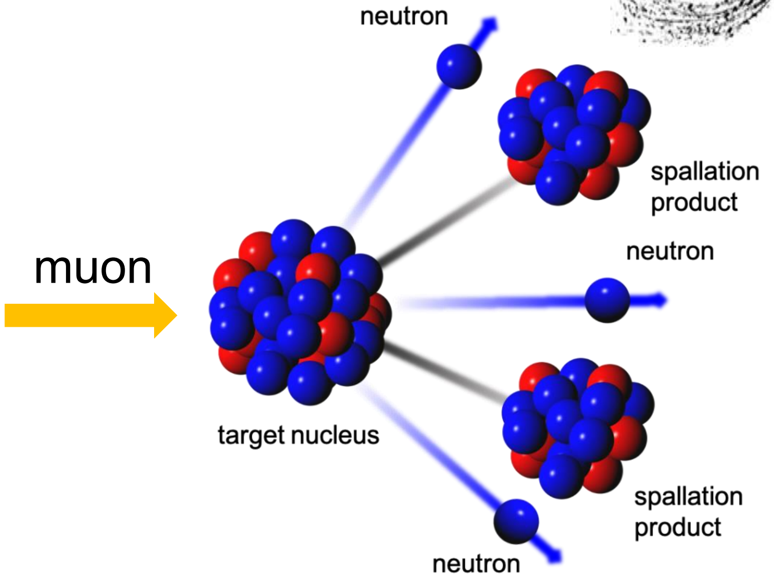


Refs: arXiv:2006.11760, Chin. Phys. C 45 (2021) 023004
arXiv:1610.07143, Chin. Phys. C 41 (2017) 053001

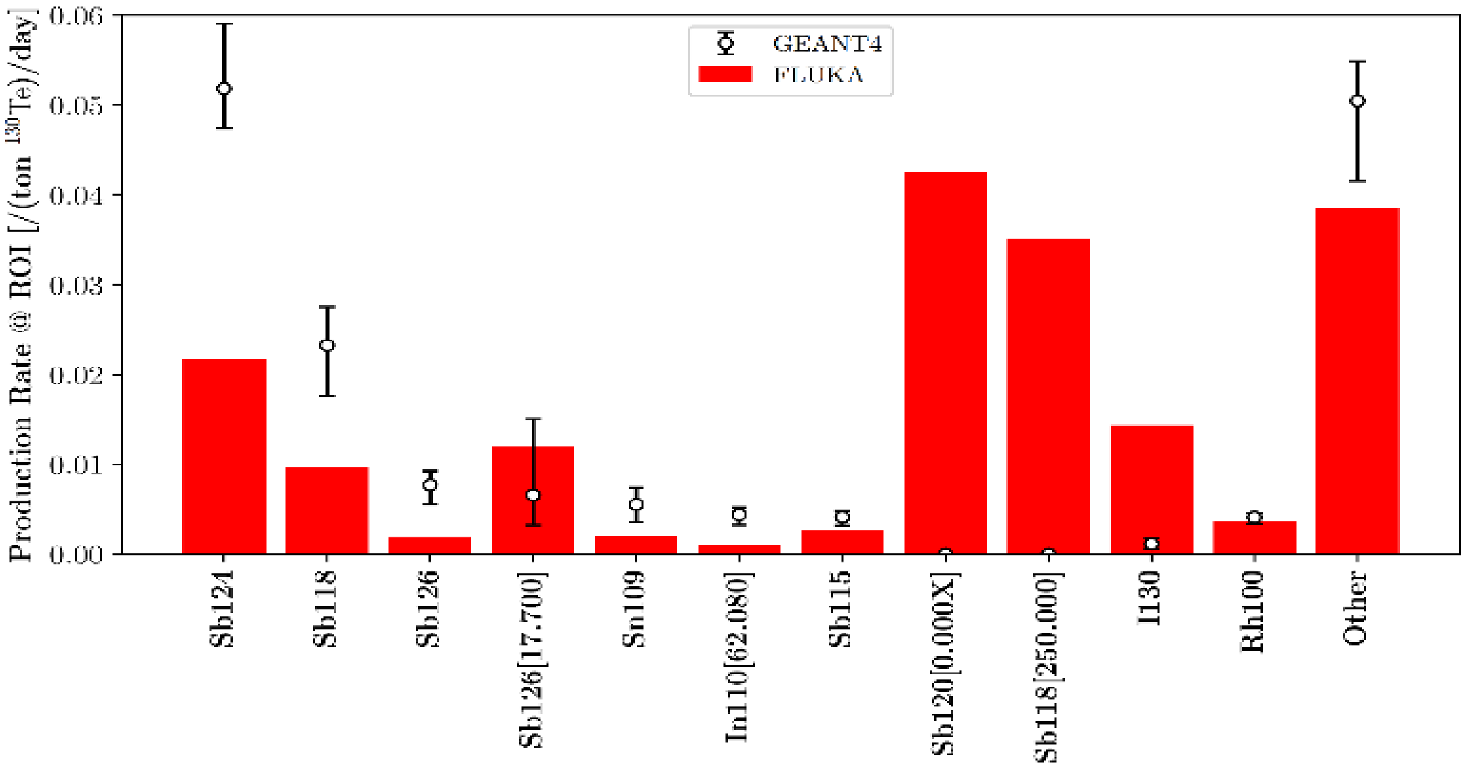
Cosmogenic Isotopes	Background Index unit: ROI^{-1} (ton 136Xe)$^{-1}$ yr^{-1}	
	No veto	w/ veto
^{10}C	16.4	0.053
^{6}He	4.9	0.063
^{8}Li	1.5	0.016
^{12}B	1.9	3.8e-4
^{137}Xe	2.3	0.07
Others (Z≤6)	0.51	0.01
Total		0.2

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

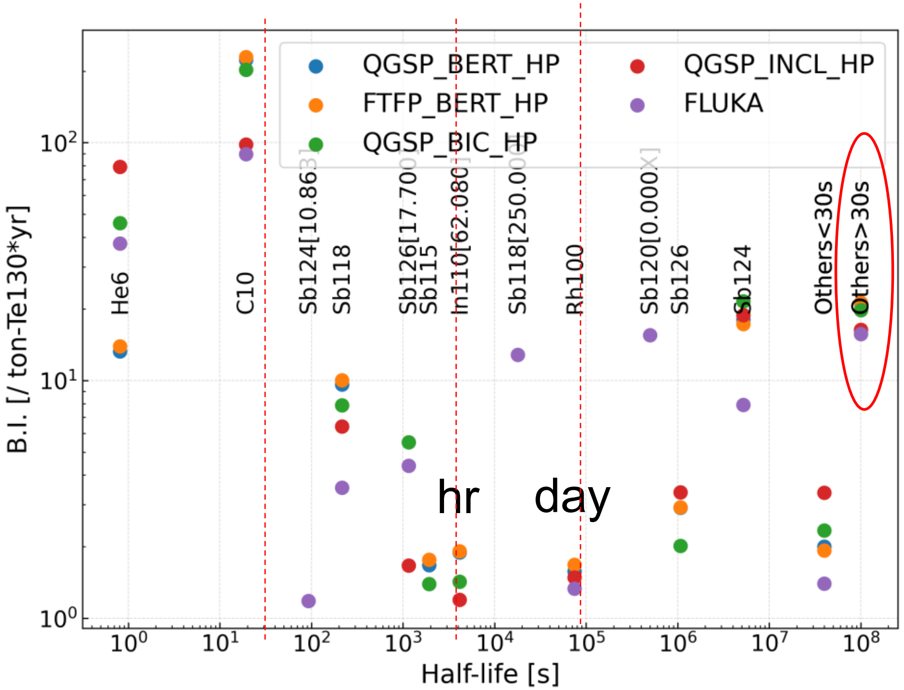


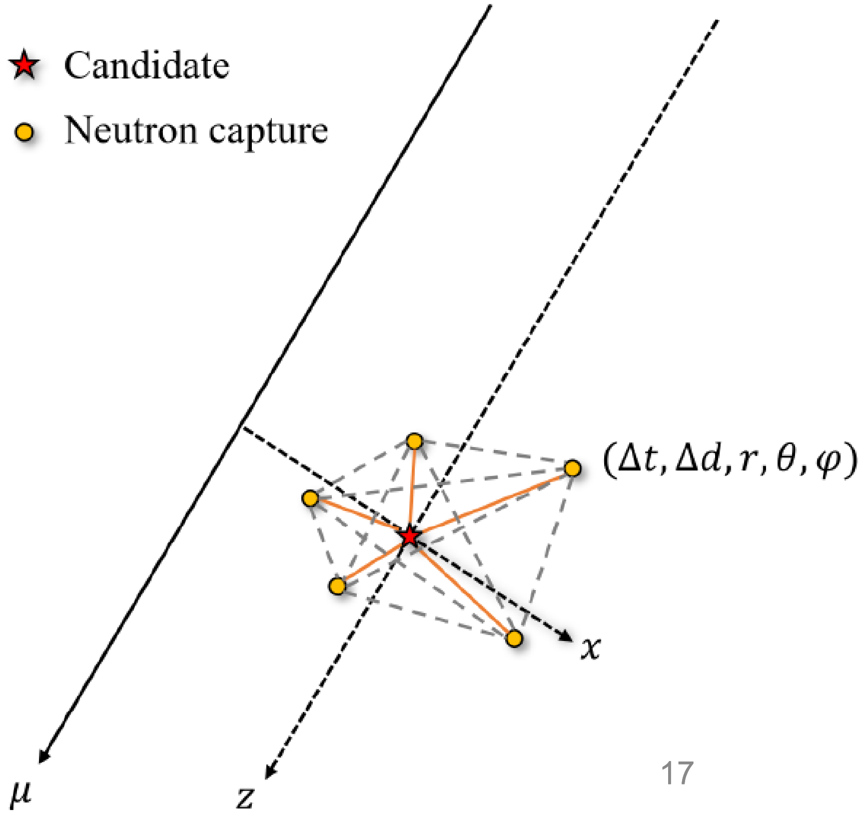
Isotopes with $\tau > 30s$



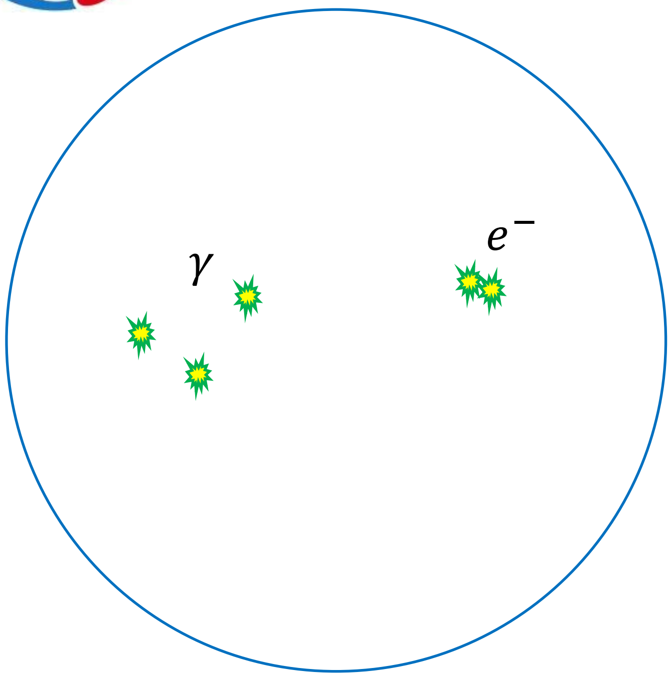
Development of Rejection method

- 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

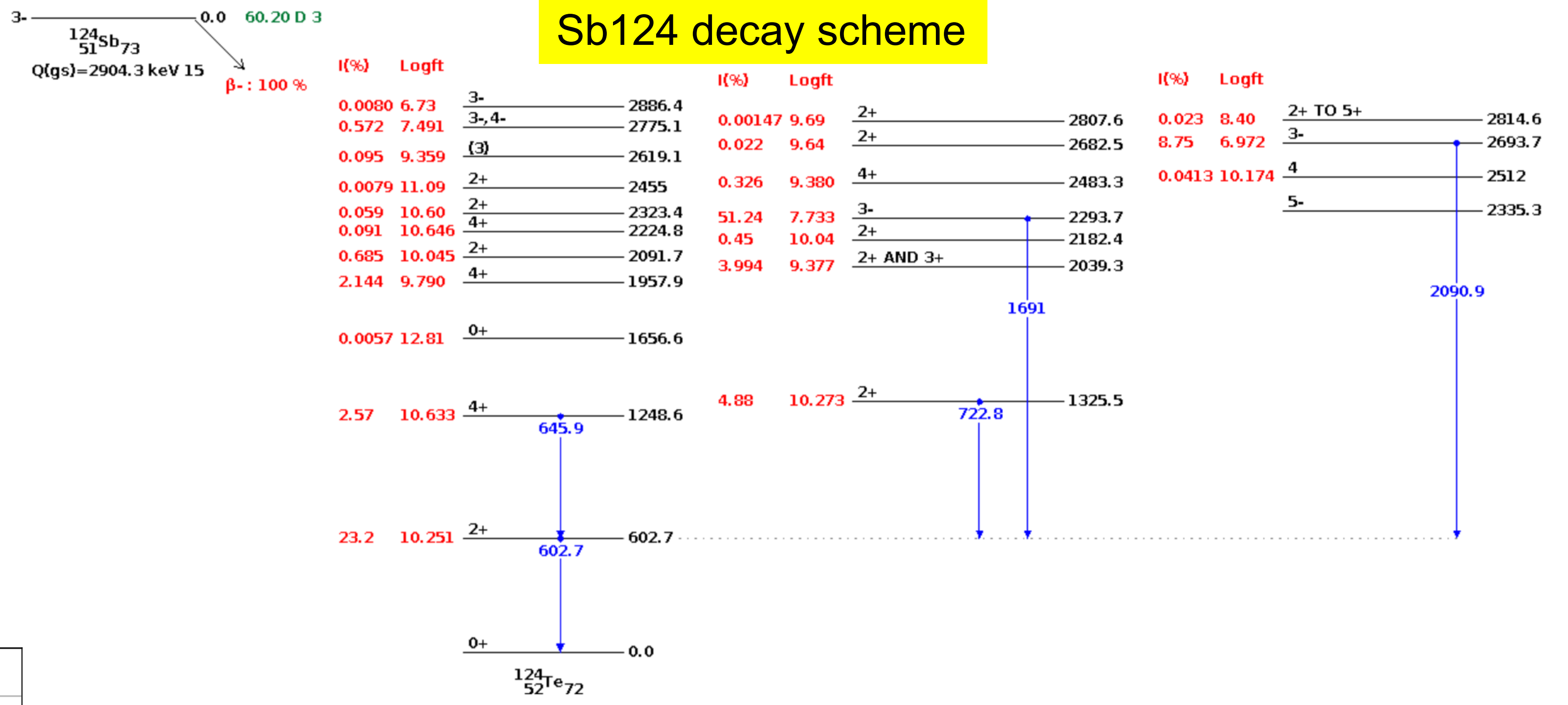


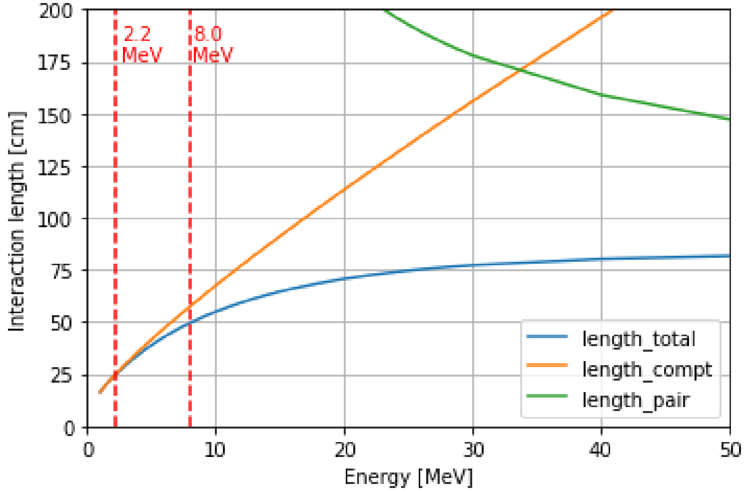


Multi-site discrimination



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
- Analysis ongoing

Summary

- After years of efforts, promising TeLS technical routes have been established
  - High loading concentration (>5% Te), excellent optical performance (20m A.L. 0.5% Te) and stability (>3 years 0.6% Te) achieved
  - Core technologies on enhancing transparency and stability mastered
  - Light yield optimization is our next goal
- We made comprehensive FLUKA/GEANT study on cosmogenic spallation isotope background and developed efficient rejection strategy
- We are updating the sensitivity evaluation with more realistic and up-to-date JUNO detector information
- JUNO has great potential to explore the $|m_{\beta\beta}|$~meV region w/ >100 tons of $0\nu\beta\beta$ isotope with clear route for technologies R&D
- Stay tuned!