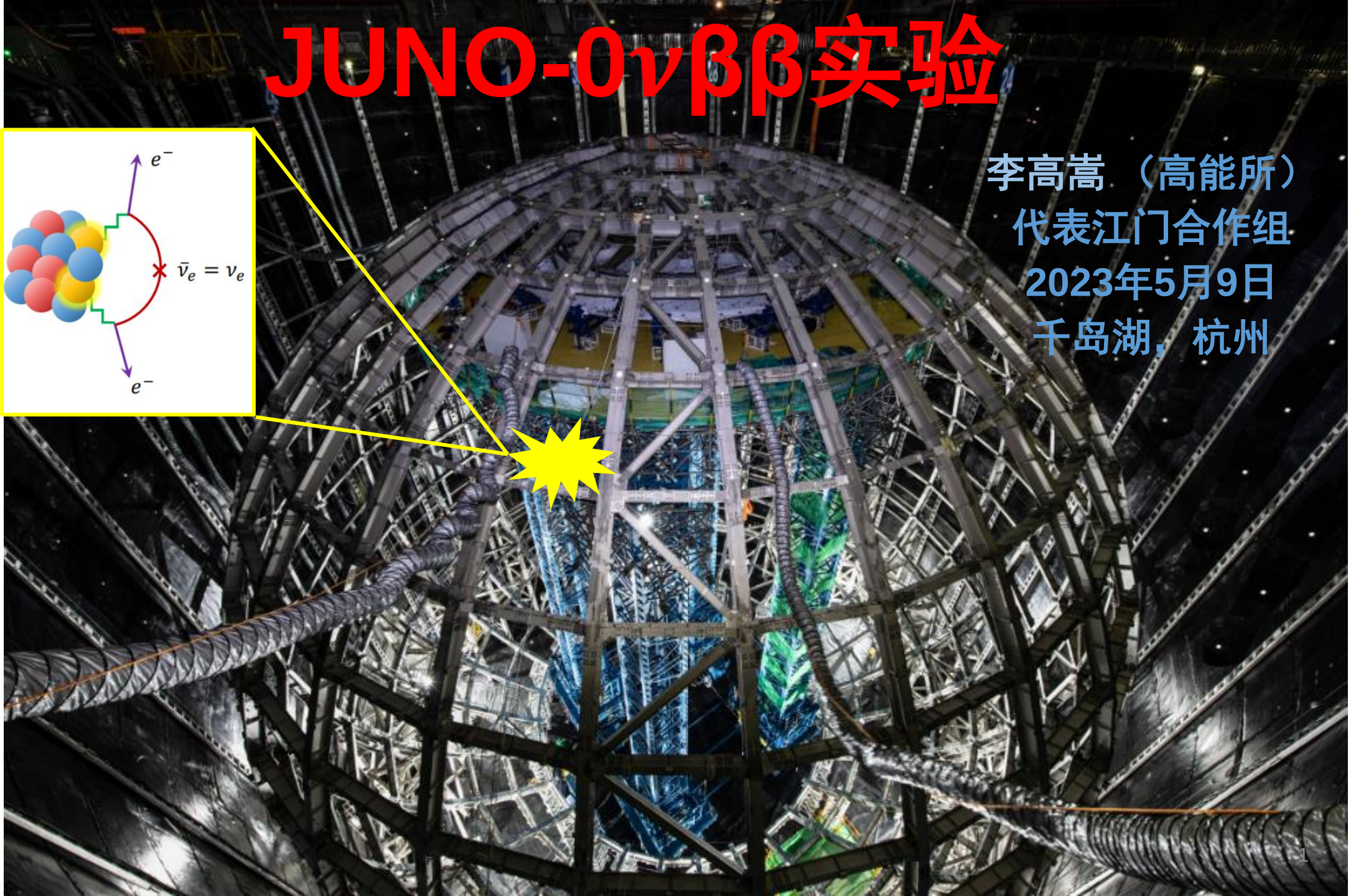
JUNO-0νββ实验



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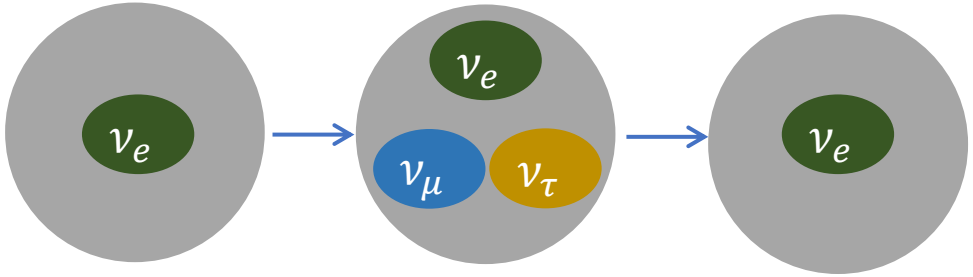
代表江门合作组

2023年5月9日
千岛湖，杭州

Neutrino oscillation



Massive neutrinos!

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

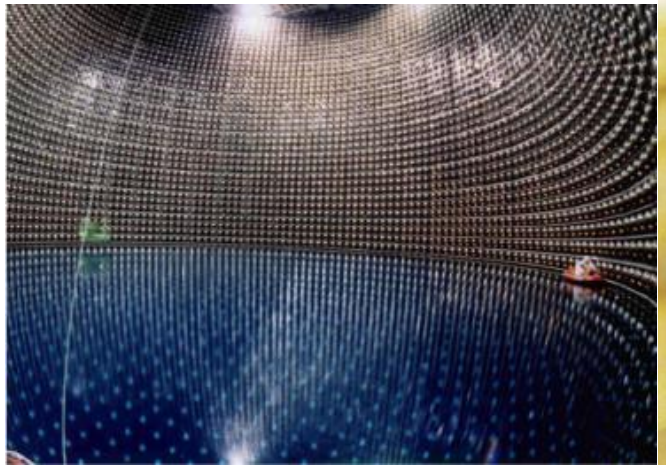
$\theta_{23} \approx 45^\circ$	$\theta_{13} \approx 10^\circ$	$\theta_{12} \approx 35^\circ$
Accelerator + Atmospheric	Reactor + Accelerator	Solar + Reactor

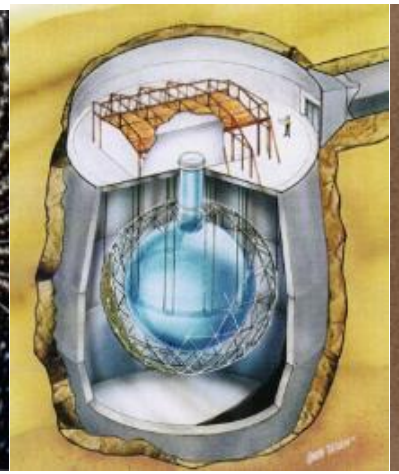
The Nobel Prize in Physics 2015

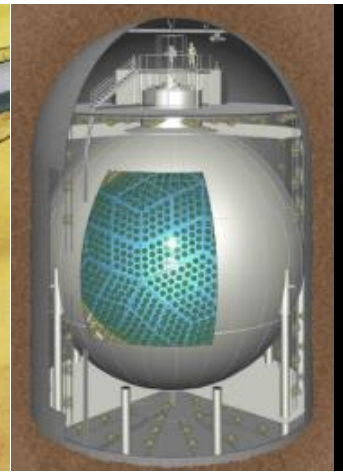
Photo: A. Mahmoud
Takaaki Kajita
Prize share: 1/2

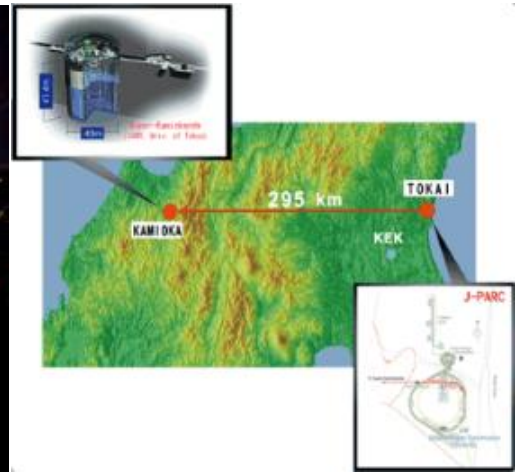
Photo: A. Mahmoud
Arthur B. McDonald
Prize share: 1/2

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"*



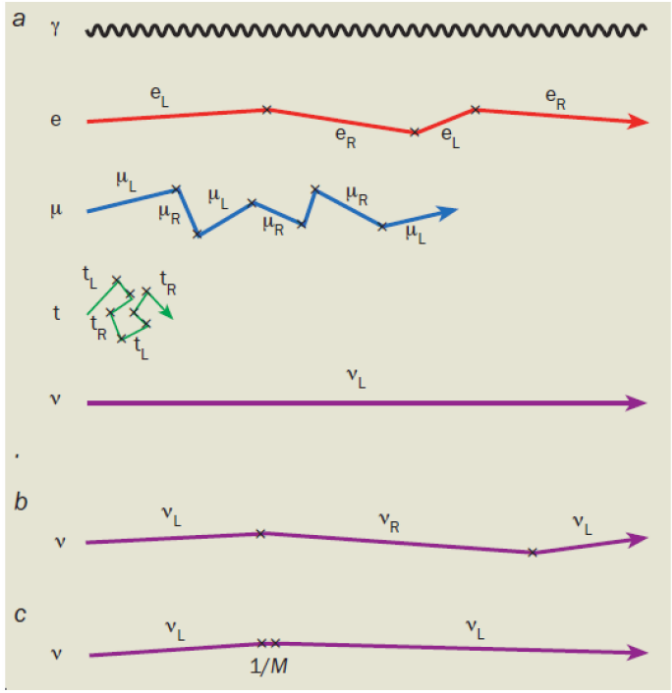


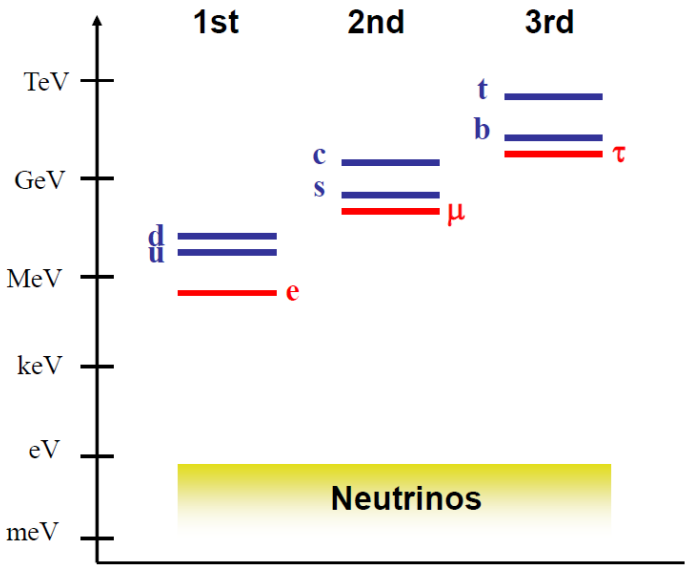




Neutrino mass generation mechanism

- 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

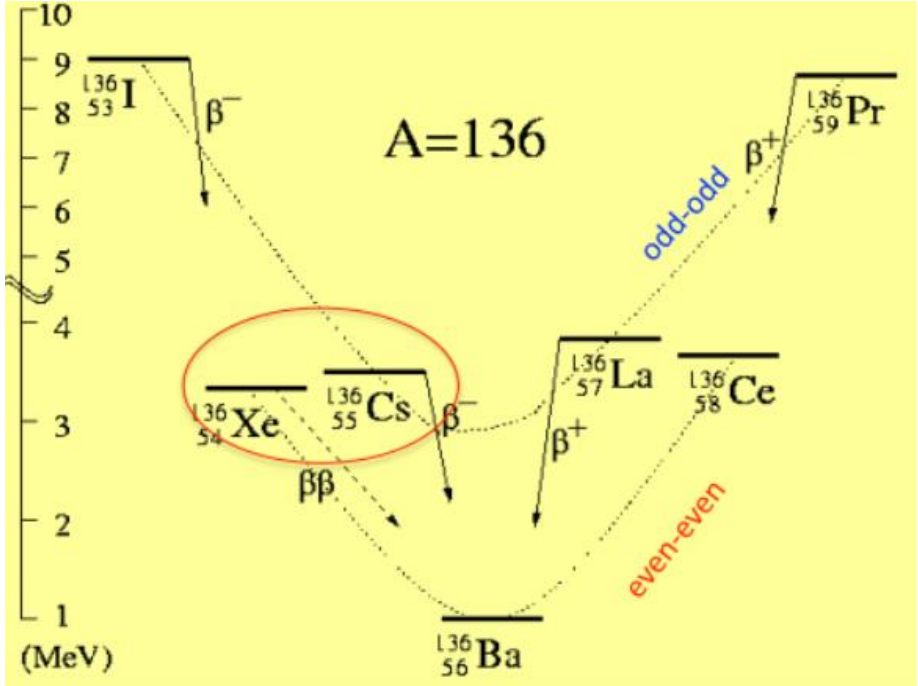




The search for $0\nu\beta\beta$ is the most sensitive probe of Majorana nature of neutrinos.

Double beta decay

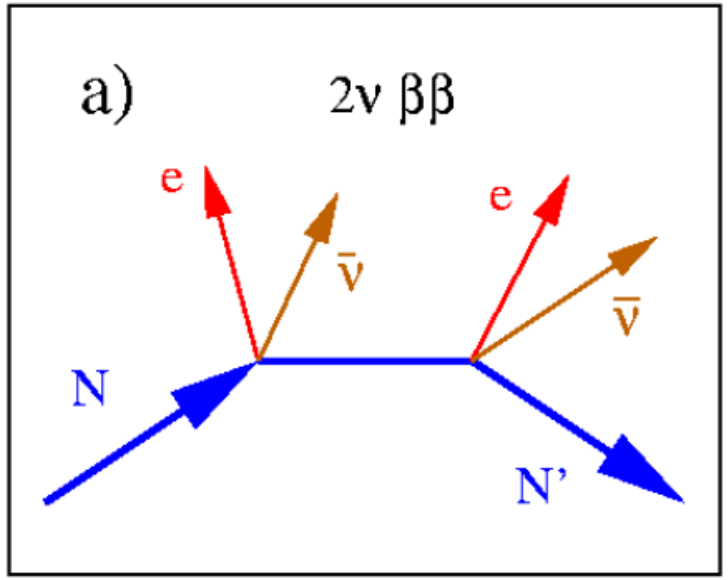
- Double beta decay is a second order process
- Only observable if first order beta decay is energetically forbidden

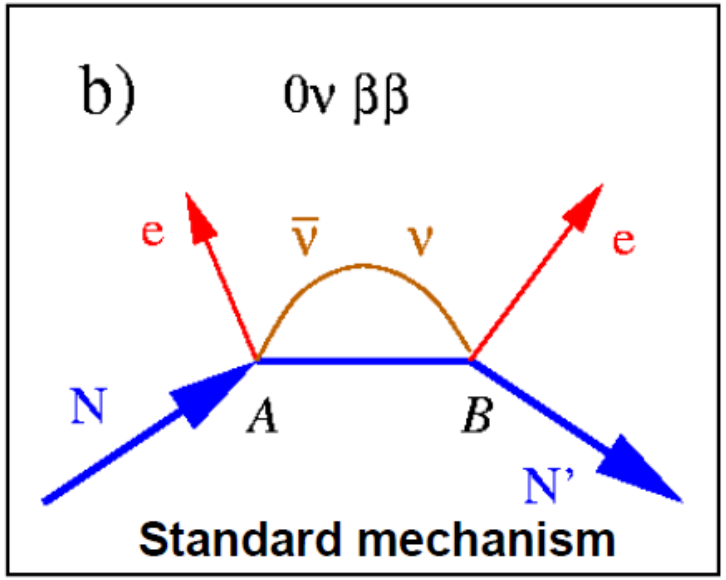


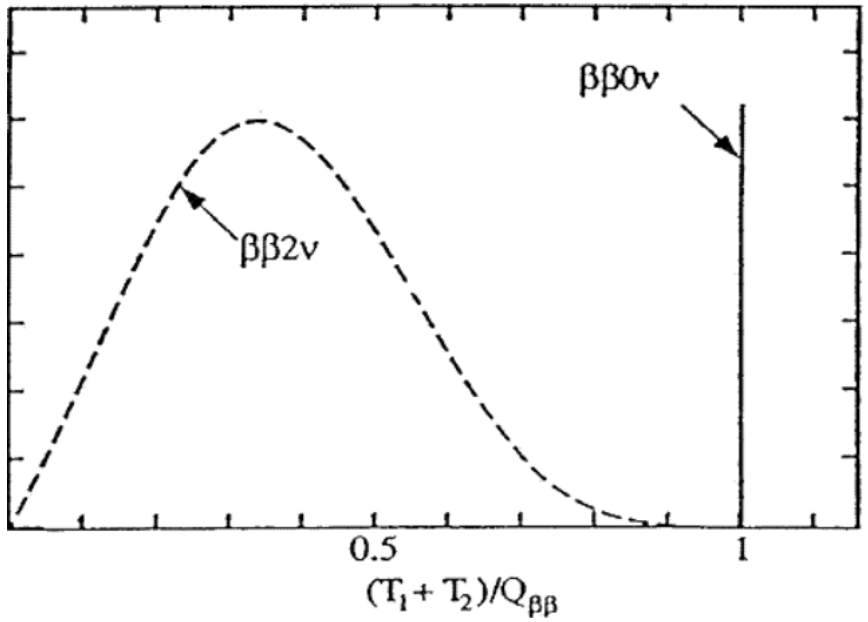
Candidate with Q>2 MeV

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

Neutrinoless double beta decay ($0\nu\beta\beta$)







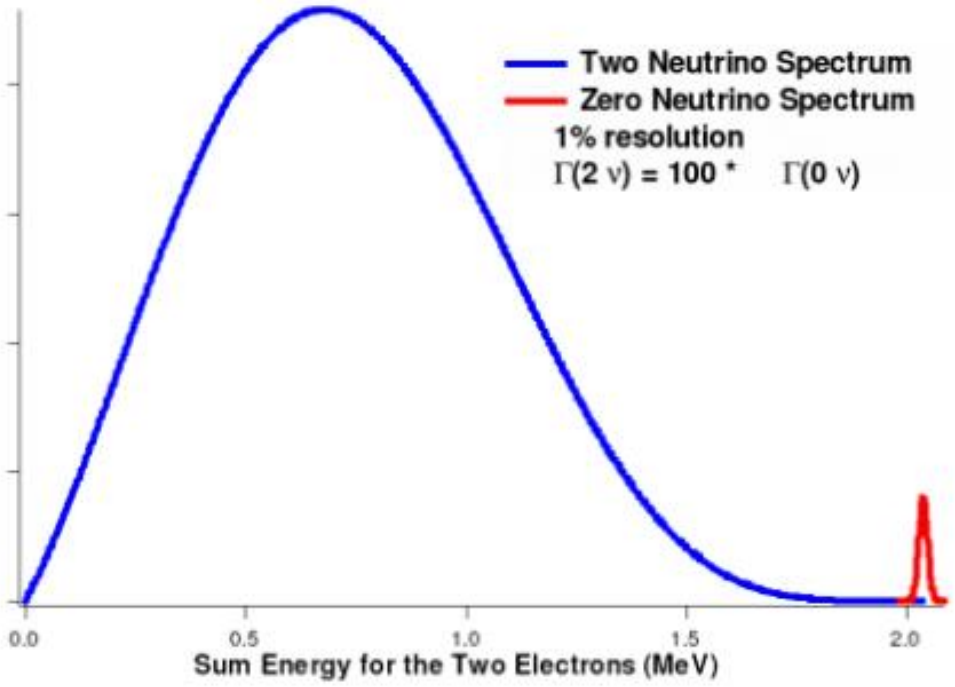
$2\nu\beta\beta$ decay
- Conventional process

$0\nu\beta\beta$ has huge physics implications:
- **Majorana neutrino**
- **Lepton number violation**
- **Absolute neutrino mass scale**

- 2ν VS 0ν spectrum: continuuum vs peak
- Good energy resolution required to separate 0ν from 2ν

Experimental sensitivity

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

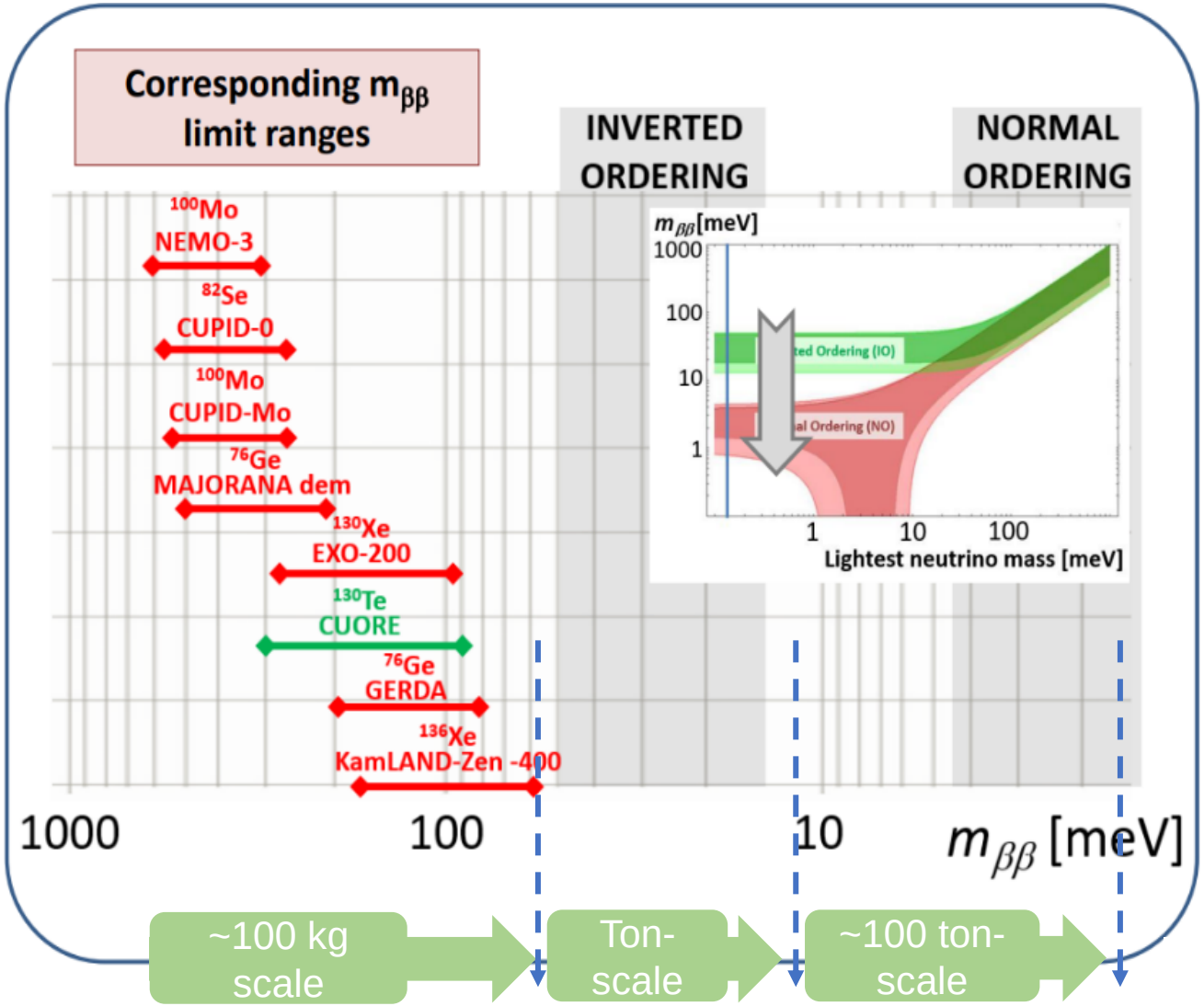


- **Low background level**
  - low radioactivity detector
  - powerful background rejectior
- Good energy resolution
- Large detector mass

Experimental results

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

GERDA *Phys. Rev. Lett. 125, 252502 (2020)*	$T_{1/2} > 1.8\times10^{26}$ y
KamLAND-Zen 400 *Phys. Rev. Lett. 117, 082503 (2016)*	$T_{1/2} > 1.07\times10^{26}$ y
EXO-200 *Phys. Rev. Lett. 123, 161802 (2019)*	$T_{1/2} > 3.5\times10^{25}$ y
MAJORANA dem. *Phys. Rev. C 100, 025501*	$T_{1/2} > 2.7\times10^{25}$ y
CUORE *arXiv:1907.09376*	$T_{1/2} > 2.2\times10^{25}$ y
CUPID-0 *L. Pagnanini, TAUP 2021*	$T_{1/2} > 4.7\times10^{24}$ y
CUPID-Mo *B. Welliver, TAUP 2021*	$T_{1/2} > 1.8\times10^{24}$ y
NEMO-3 *Phys. Rev. D 92, 072011 (2015)*	$T_{1/2} > 1.1\times10^{24}$ y



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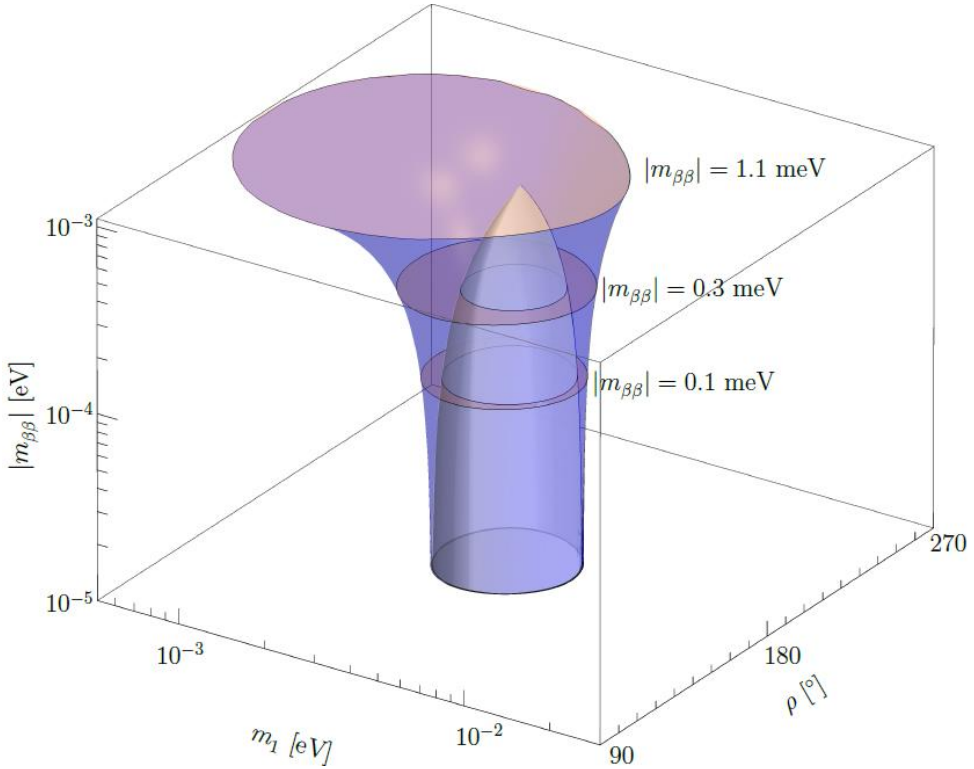
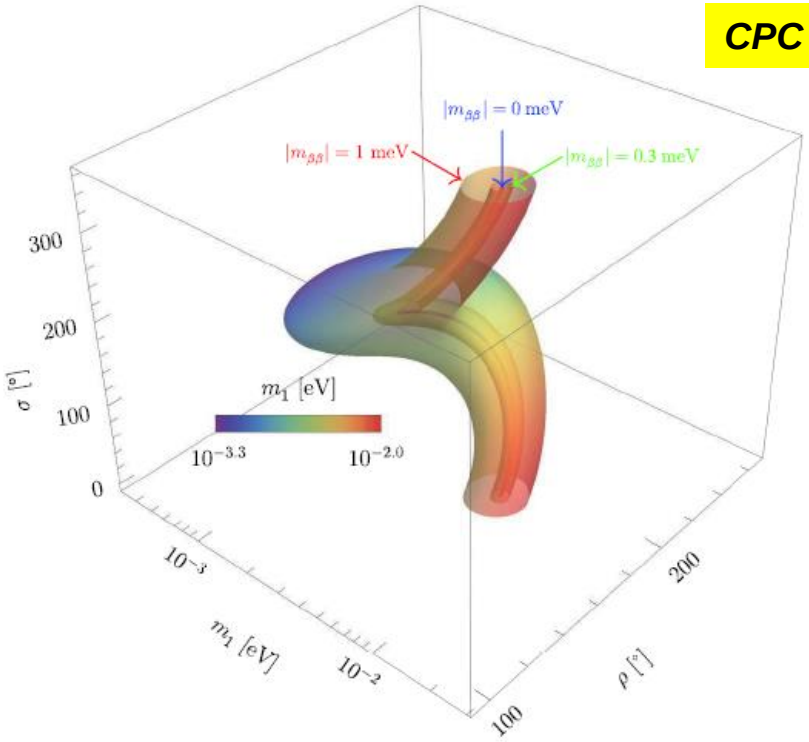




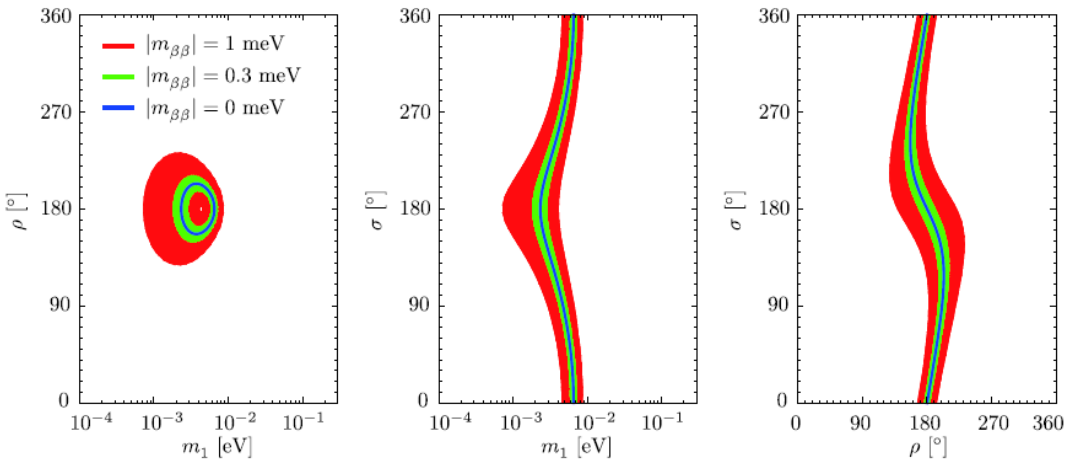
$$|m_{\beta\beta}| \equiv \left|m_1 \cos^2\theta_{13}\cos^2\theta_{12}e^{i\rho} + m_2\cos^2\theta_{13}\sin^2\theta_{12} + m_3\sin^2\theta_{13}e^{i\sigma}\right|$$

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

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

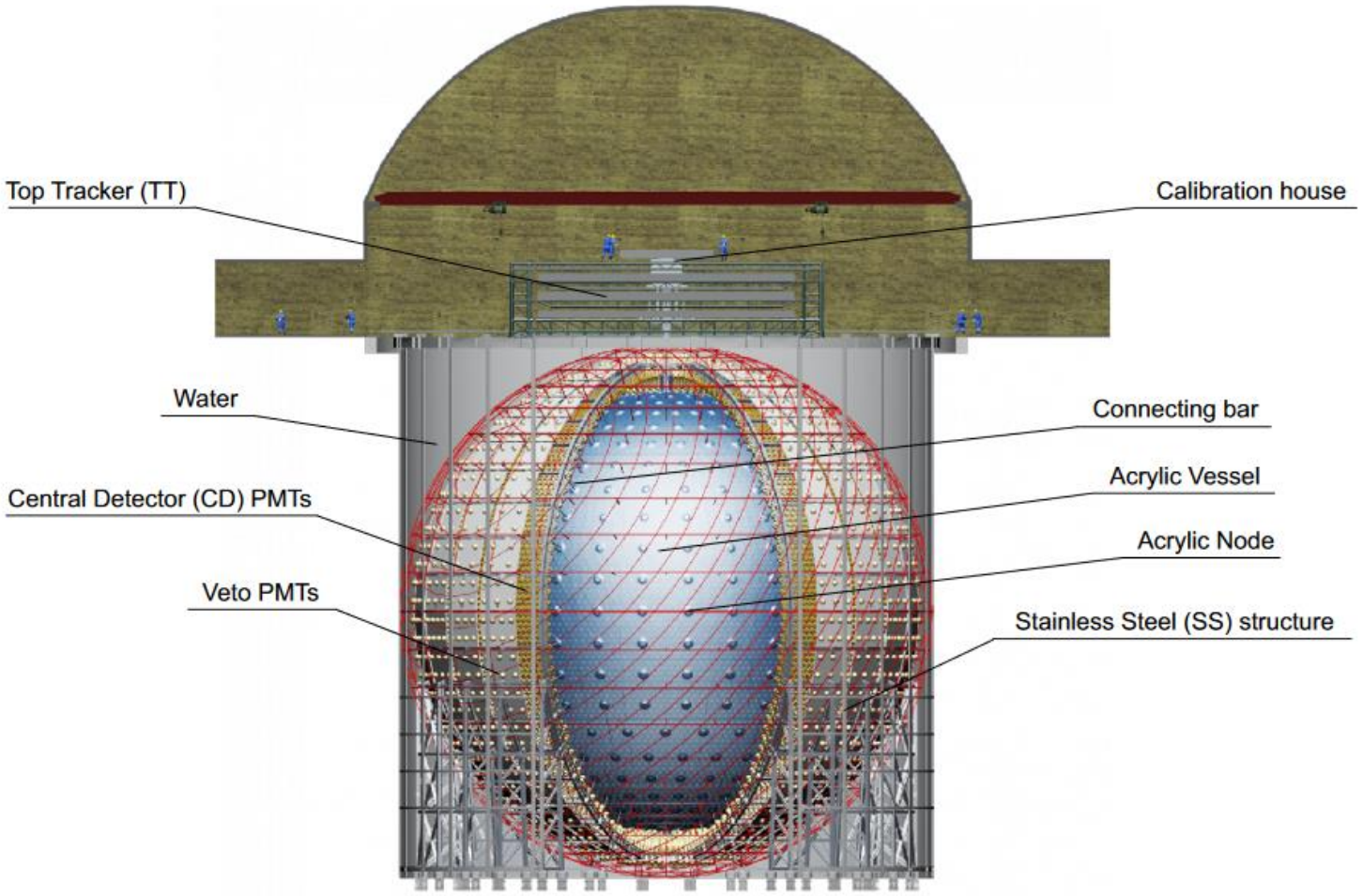
$$m_1 \in [0.7, 8] \text{ meV}$$

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



JUNO

- 20 kton multi-purpose neutrino detector with the primary goal
  - 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

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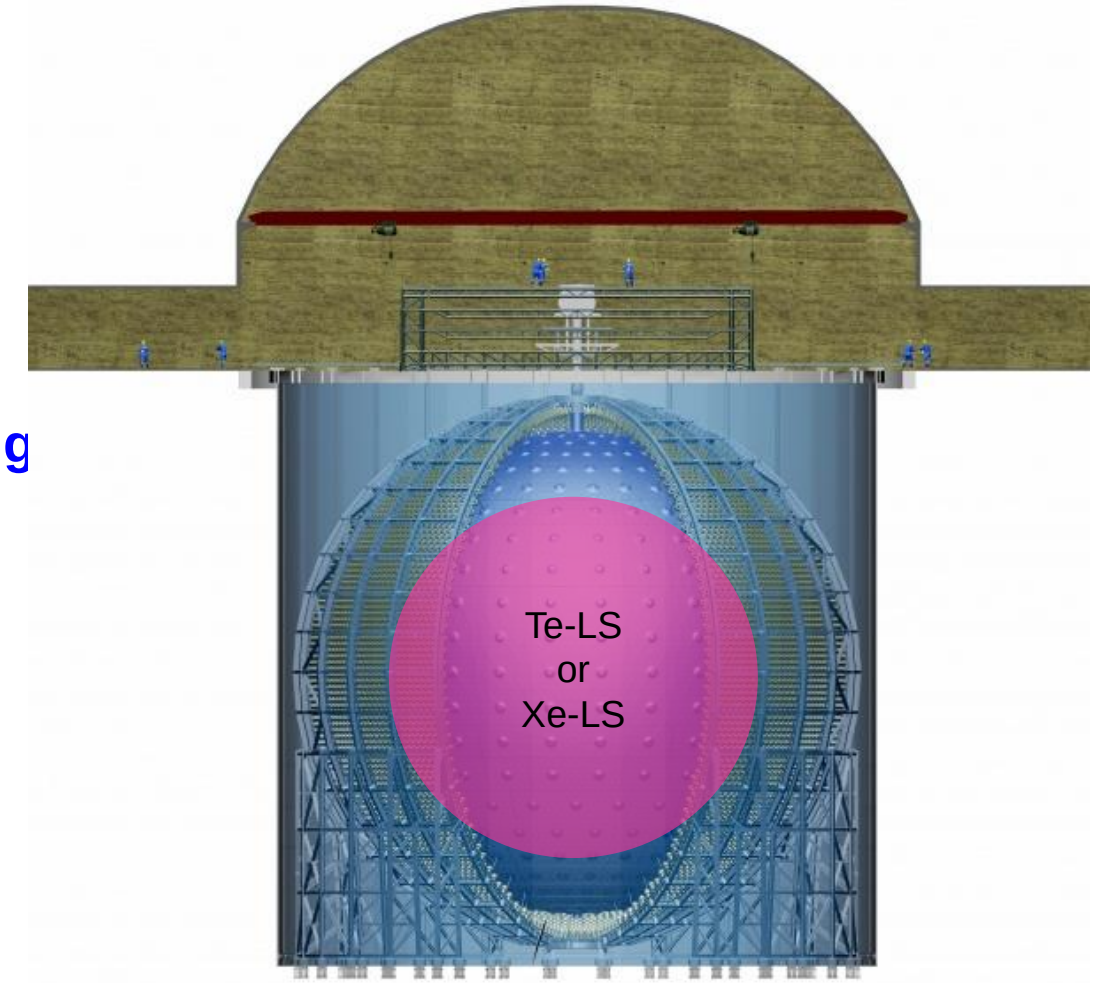
Impact of JUNO's physics outcome on 0νββ searches, by 2030

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

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

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



Concept of the experiment

Searching for 0νββ decays in JUNO, Snowmass2021 LOI
Snowmass2021 Topical group report for NF05, arXiv 2209.03340

Background budget

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 ($Z\leqslant6$)	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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- Full background evaluation
  - ^{136}Xe loading as an example in 2016
  - ^{130}Te loading estimate ongoing
- Advantage of large LS based detector → negligible external background
- Background dominated by
  - ^{8}B solar ν-e scattering
  - $2\nu\beta\beta$
  - Cosmogenic isotope
  - Internal LS radiopurity

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

Very small bkg contribution after rejection

	^{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)

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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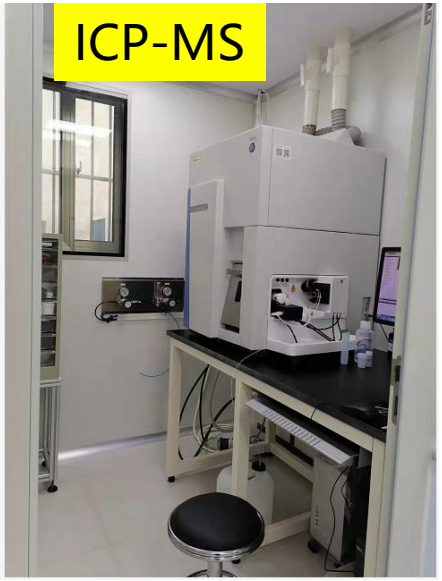
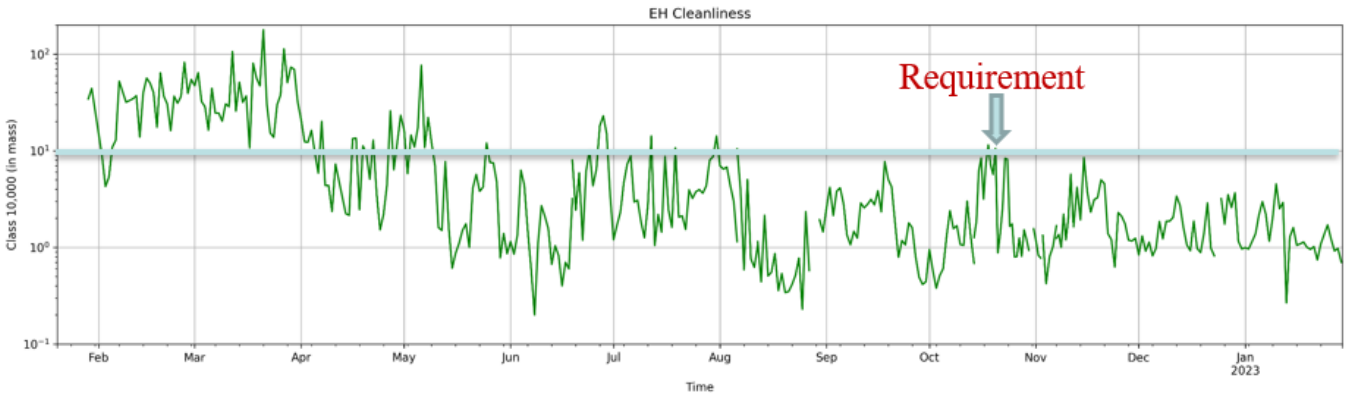
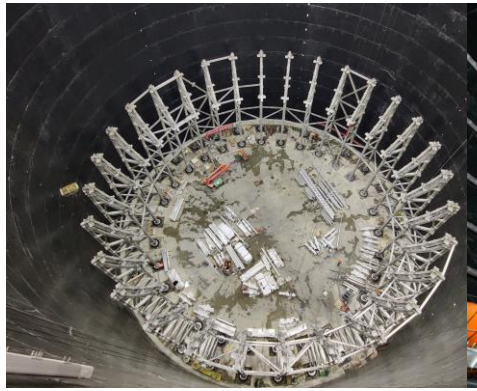


	U/Th sens. [10^{-12} g/g]	Ref
OFHC	~0.1	*NIM A, 941 (2019) 162335*
Acrylic	<0.1	*NIM A*, 1004 (2021) 165377
PPO (LS solute)	~0.1	-
Kapton, Si	~< 1	-

Background control for JUNO detector

- During assembly
  - dust and radon control
- Dust/contamination control
  - Clean-room assembly environment
  - Surface cleaning procedures
- Radon (& progenies) control
  - Improve underground ventilation
  - Control air exposure to detector/pipe surfaces





Cosmogenic background on ^{12}C

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

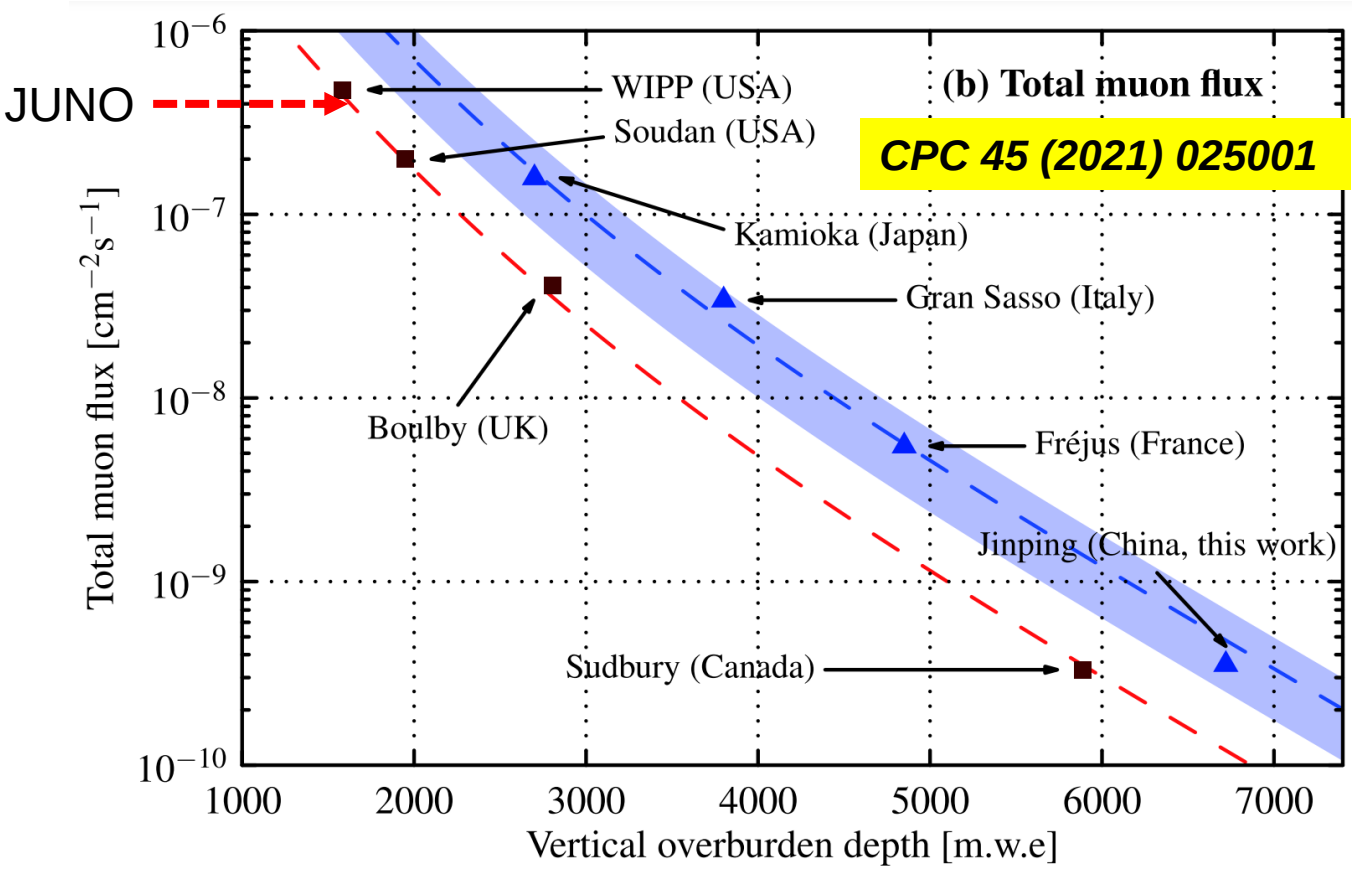
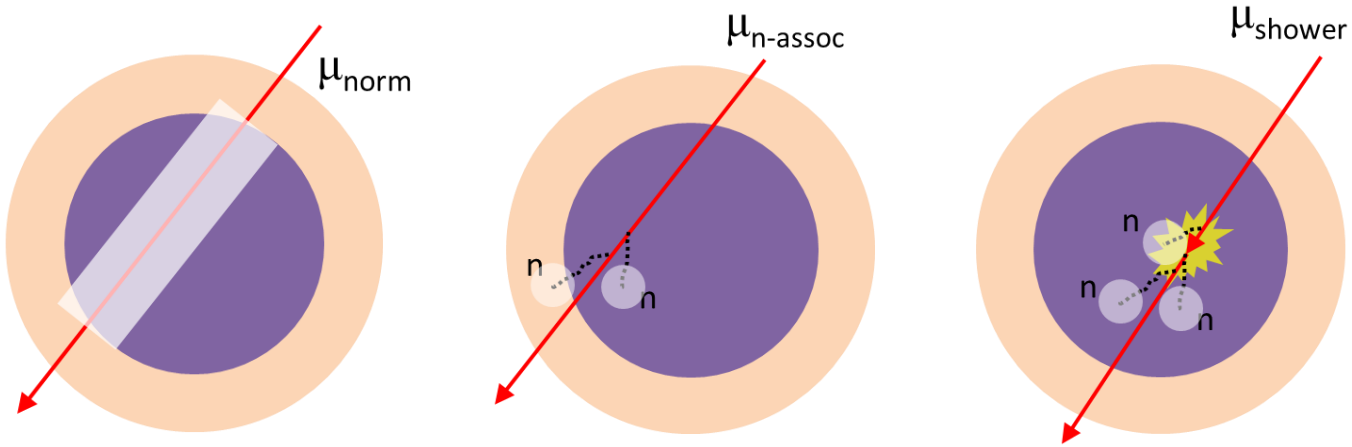


Table A9. The estimated rates for cosmogenic isotopes in JUNO LS by FLUKA simulation, in which the oxygen isotopes are neglected. The decay modes and Q value are from TUNL Nuclear Data Group [475].

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

** Long-lived muon-induced xenon spallation products reported by KamLAND-Zen recently is taken into account

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

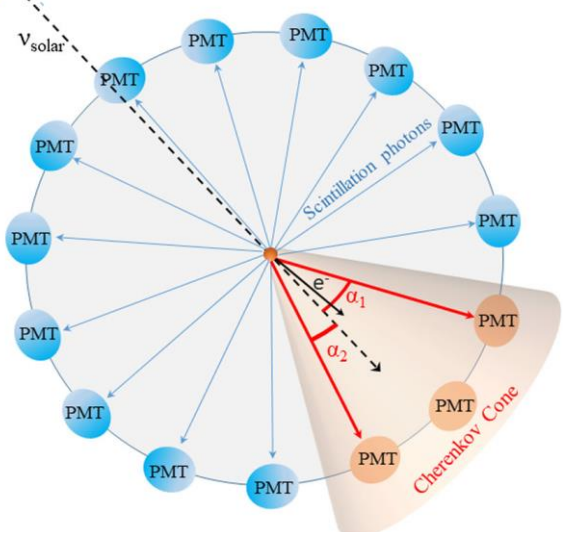
B8 solar neutrino

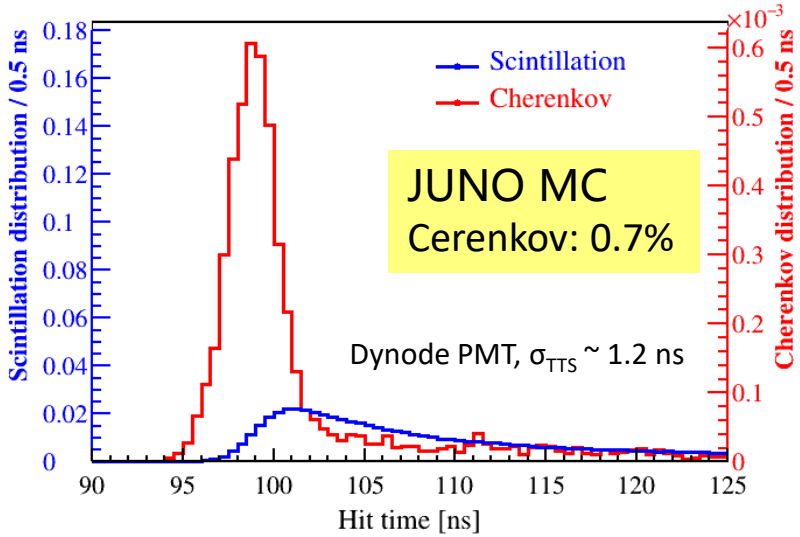
- ^{8}B solar ν-e scattering events has special directionality w.r.t the sun

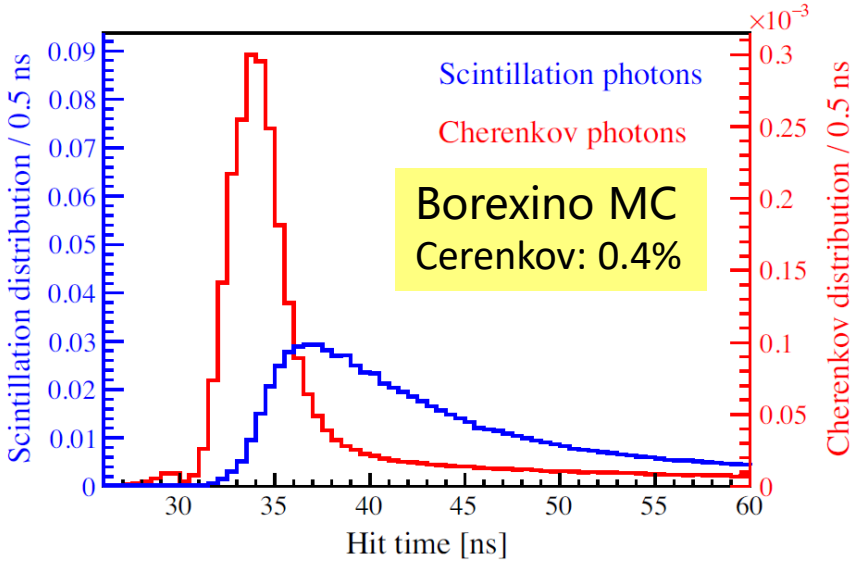
- Directional Cerenkov light in JUNO LS detector helps to disentangle 0νββ decay and ^{8}B solar ν-e
  - Higher energy ROI
  - Higher Cerenkov fraction

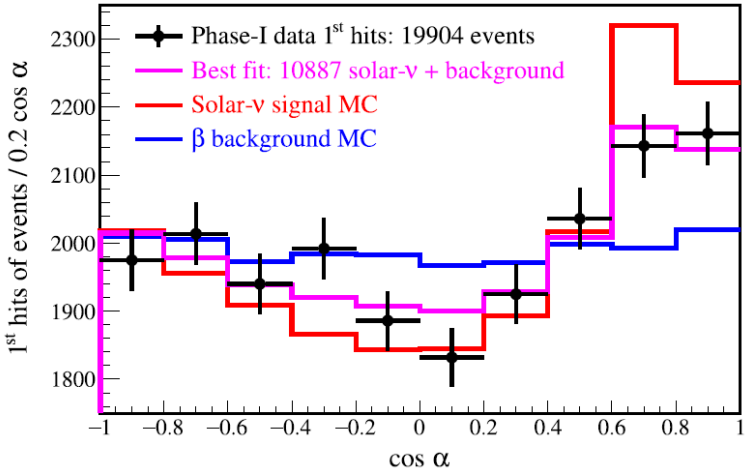
  Ongoing work. Expectation: a factor of 2 suppression

Borexino Collaboration, Phys. Rev. Lett. 128 (2022) 091803





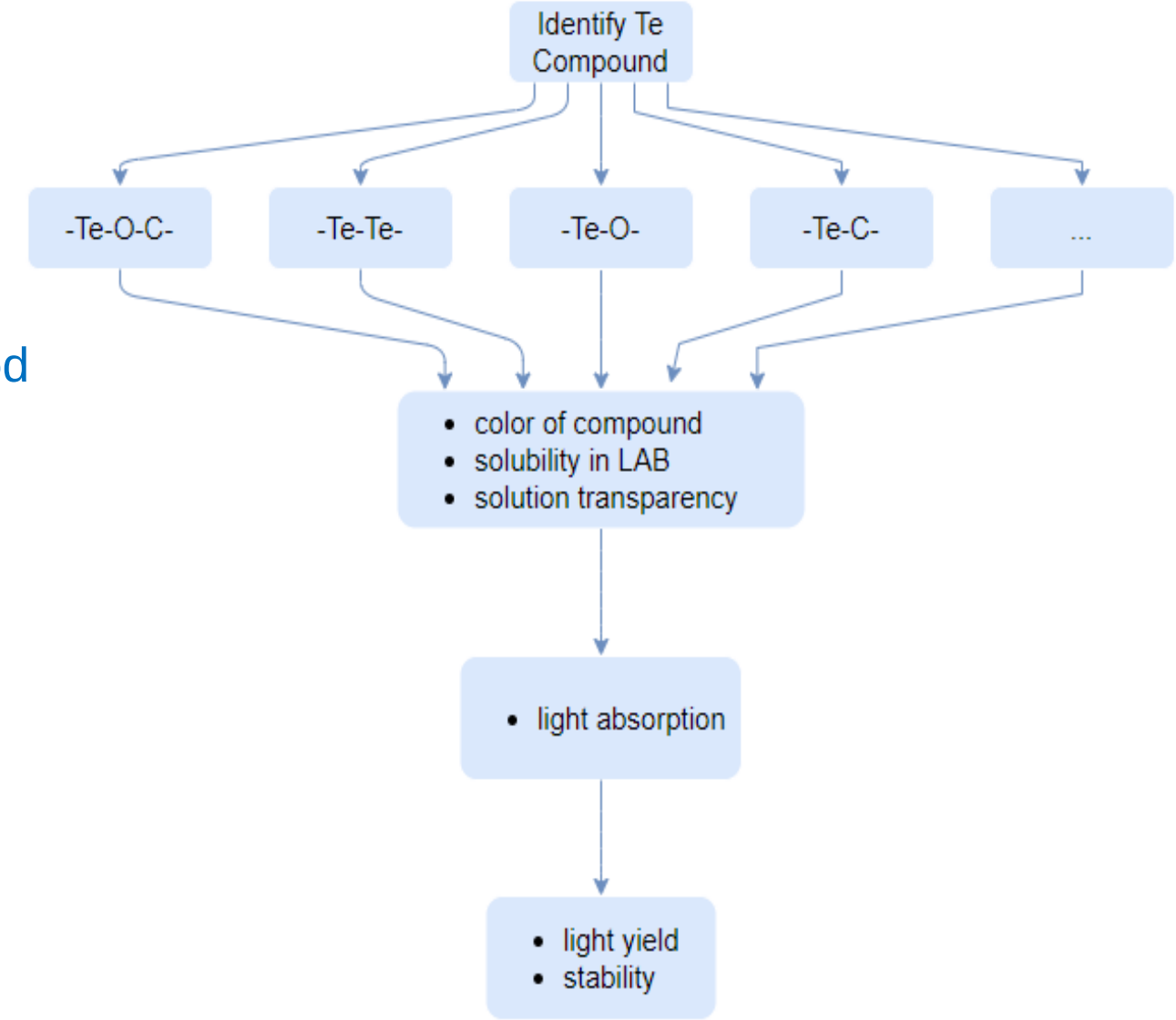




(0.54, 0.74) MeV region

TeLS development

- Critical R&D: Te loading
- Desired features for Te molecule
  - High Te mass fraction
  - Easy and cost effective synthetic method
- Strategy
  - Try as many compounds
  - Quick screening criteria
    - Solubility in LAB
    - Colorless or white
  - Light yield measurement
  - Iteration and optimization



TeLS development

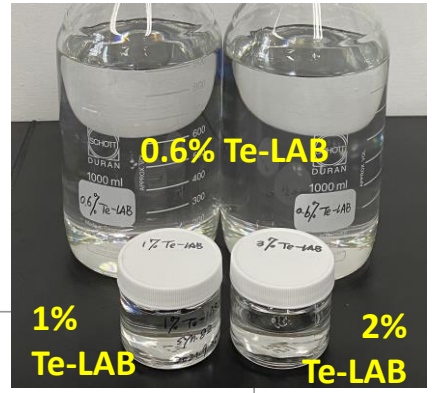
A promising recipe under R&D

$Te(OH)_6$

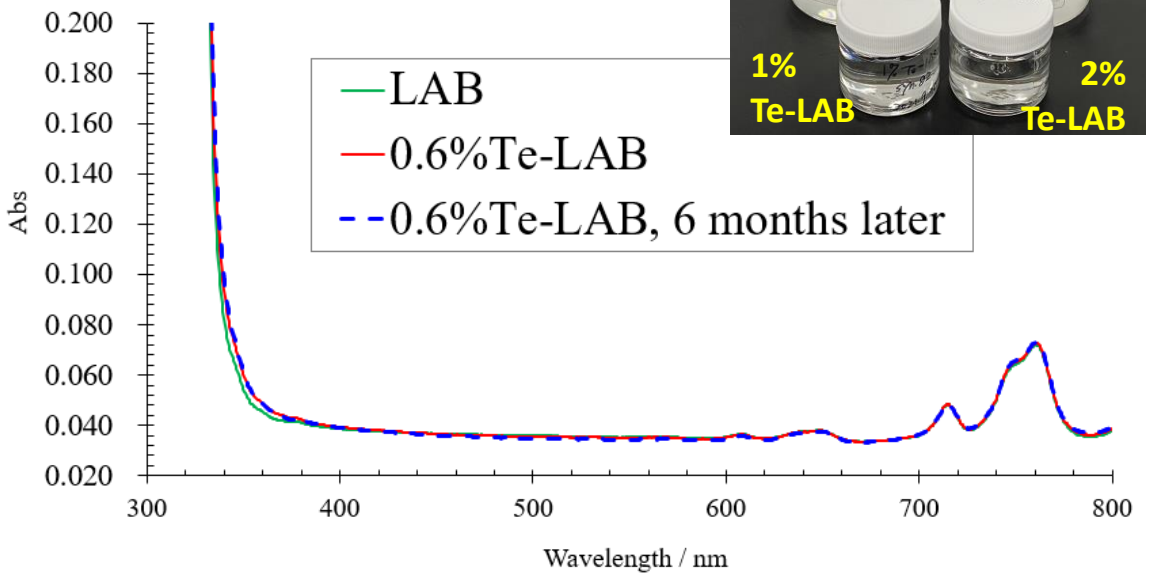
$R_3CH(OH)\text{-}CR_1(OH)R_2$

One-step synthetic method → Te-organic compounds → Direct dissolve into LAB + PPO, bis-MSB → Te-LS

- Promising one-step synthetic method, capability of Te loading in LAB: > 3%
  - Good stability, transparency and solubility of Te-compounds
  - Quick, convenient and applicable for most diols

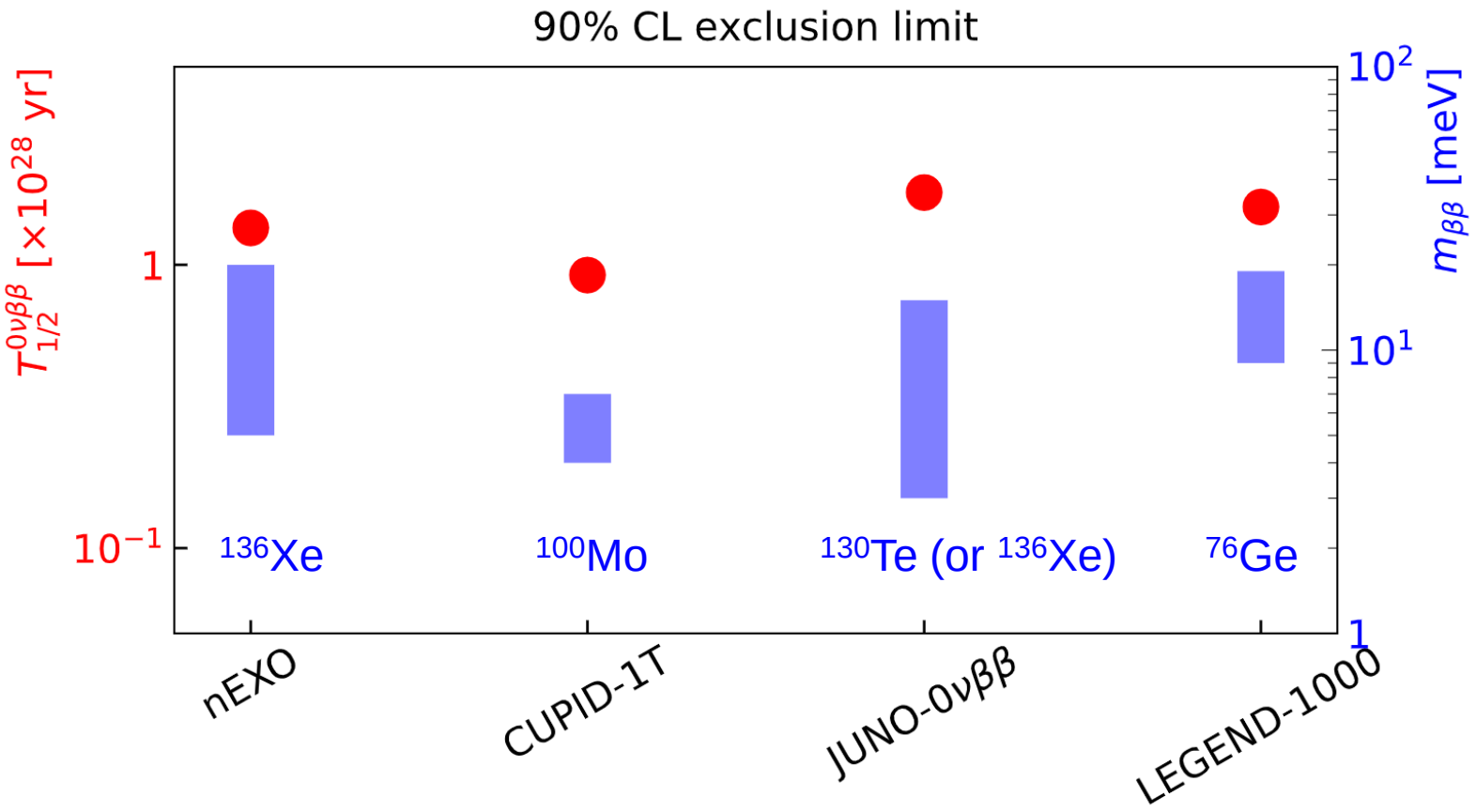


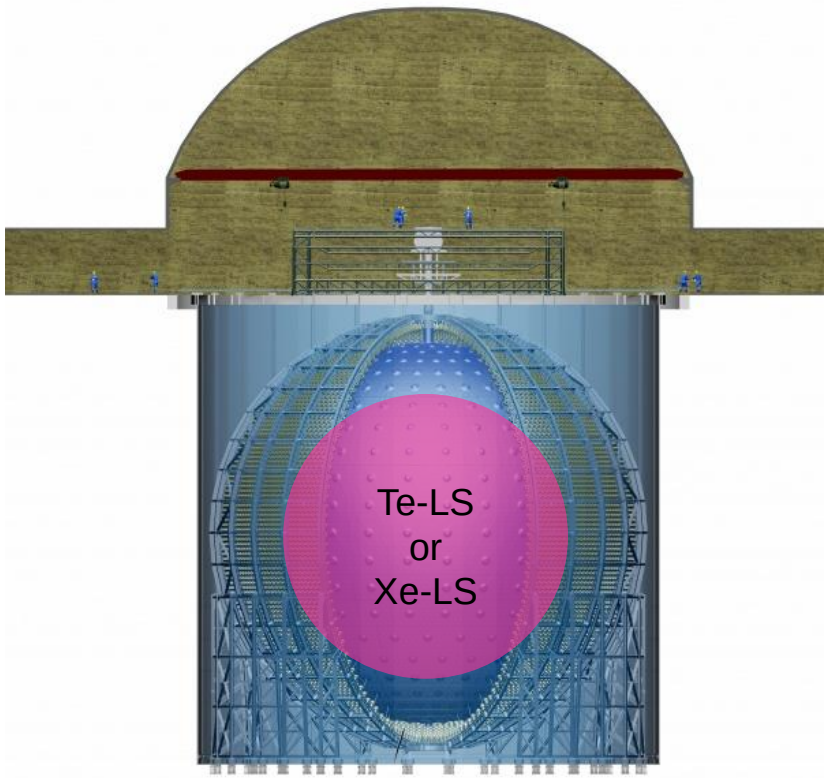
- Current characteristics w/ 0.6% Te-loading
  - Good UV-Vis spectra for Te-LAB
    - NO visible difference (Δ_{ABS}<0.002 for λ>370 nm) compared to the purified LAB (A.L. > 20m)
    - NO degradation after 6 months
  - Light yield to-be-improved: 60%~70% w.r.t un-loaded LS



NIM A 1049 (2023) 168111

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 0νββ 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 $\boldsymbol{T_{1/2}^{0\nu\beta\beta}}$
- By 2030, the current LS experiments (KamLAND, SNO+) may reach 10^{27} yrs, next generation projects (LEGEND, nEXO, CUPID) may start running
- JUNO has the potential to explore the $|m_{\beta\beta}|$~meV region w/ >100 tons of 0νββ isotope
  - Clear route for technologies R&D
  - By 2025, resolve the Te-loading technique, background control/suppression strategy
  - By 2030, design & build Te loading and purification systems