Recent Results from KamLAND-Zen, a Neutrinoless Double-beta Decay Search Experiment using ^{136}Xe

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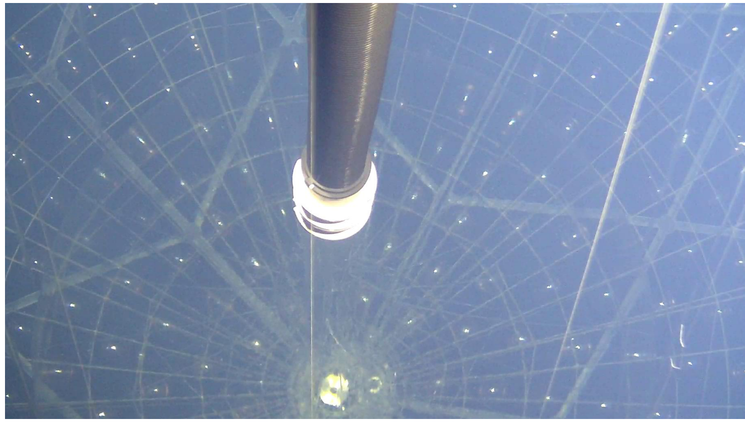
XeSAT2023



KamLAND(-Zen) Collaboration

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~60 phisicists from 10+ institutes

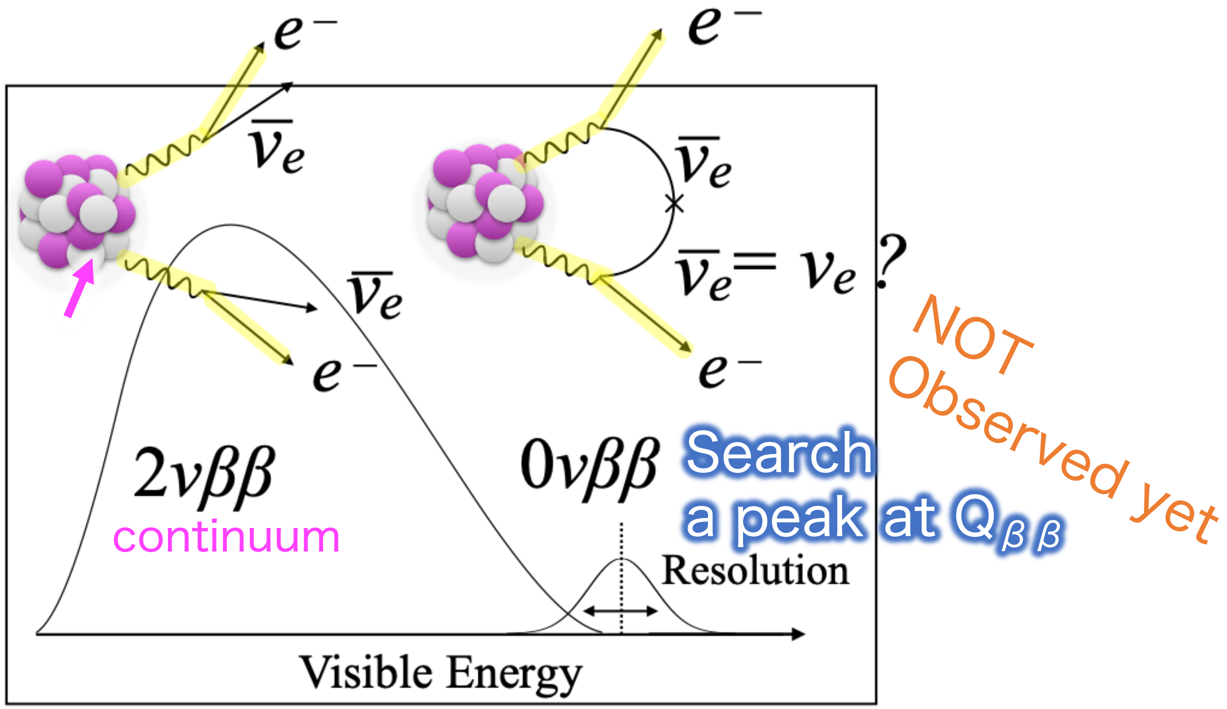
Majorana neutrino and Neutrino-less double-beta decay ($0\nu\beta\beta$)

$\nu=\bar{\nu}$?

Majorana neutrino is a key to
- ✓ Tiny neutrino mass
  - See-saw mechanism*
- ✓ Matter/anti-matter asym.
  - Leptogenesis**

$0\nu\beta\beta$ decay

- Only happen if ν is majorana
- Lepton# violation



~Summed e⁻ kinetic energy

Requirement for exp.
- O(100–1000) kg isotope
- BG reduction at $Q_{\beta\beta}$
- Better energy resolution

*M. Gell-Mann, P. Ramond, R. Slansky ('79), T. Yanagida ('79), R. N. Mohapatra, G. Senjanovic ('80), **M. Fukugita, T. Yanagida ('86)

Effective Majorana mass

Convert half life
to effective Majorana mass

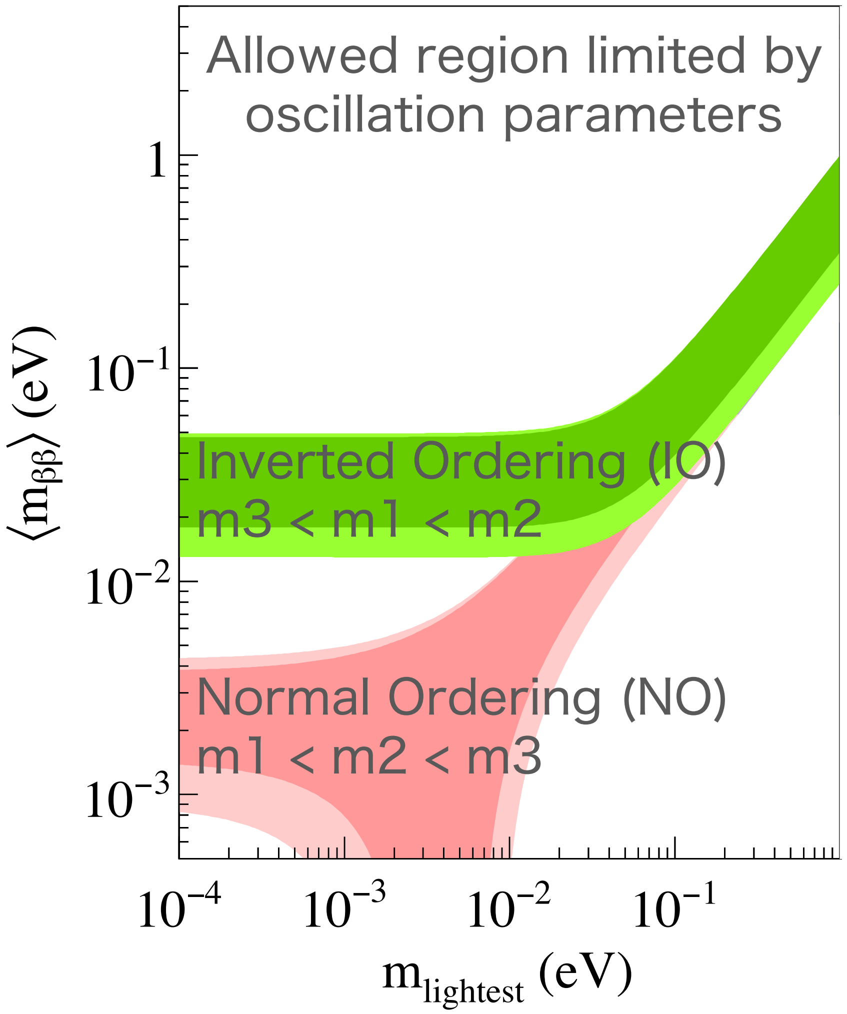
$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

G : Phase space factor
M : Nuclear matrix element

$$\langle m_{\beta\beta}\rangle \equiv \left|\sum_i U_{ei}^2\, m_i\right|$$

U : PMNS matrix
m_i : neutrino mass eigenvalue

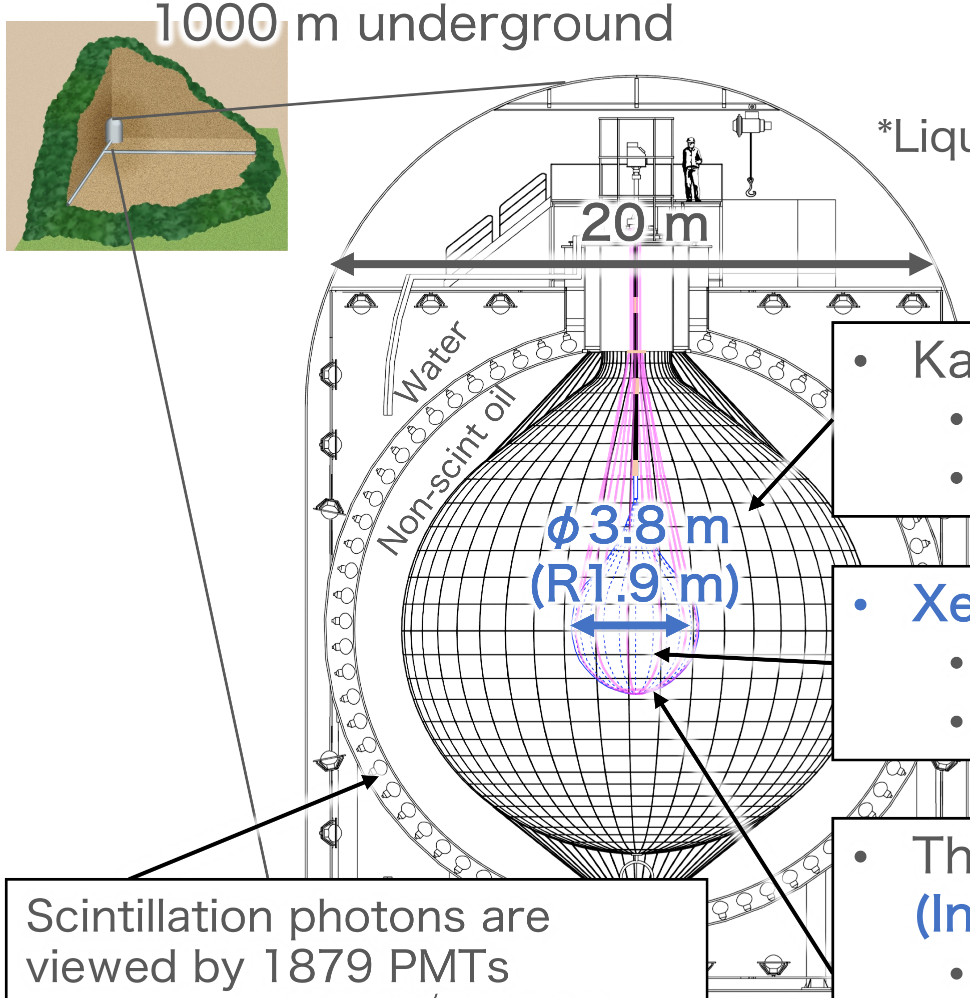
Hint for absolute mass scale



KamLAND-Zen

Kamioka Liquid scintillator Anti-Neutrino Detector
Zero-neutrino double-beta decay search

@Kamioka, Gifu, Japan
1000 m underground



*Liquid Scintillator ≡ LS

- KamLAND (Outer) LS
  - 1 kton
  - U, Th $\lesssim 10^{-17}$ g/g

- **Xe loaded LS (XeLS)**
  - Xe 745 kg, 3wt%
  - ^{136}Xe 91%

- Thin(25 um) nylon film vessel **(Inner Balloon: IB)**
  - U, Th $O(10^{-12})$ g/g (before construction)
  - *JINST* **16** P08023 (2021)

Scintillation photons are viewed by 1879 PMTs
- $\sigma_{energy} = 6.9\%/\sqrt{E}$ [MeV]
- $\sigma_{vertex} = 13.7$ cm$/\sqrt{E}$ [MeV]

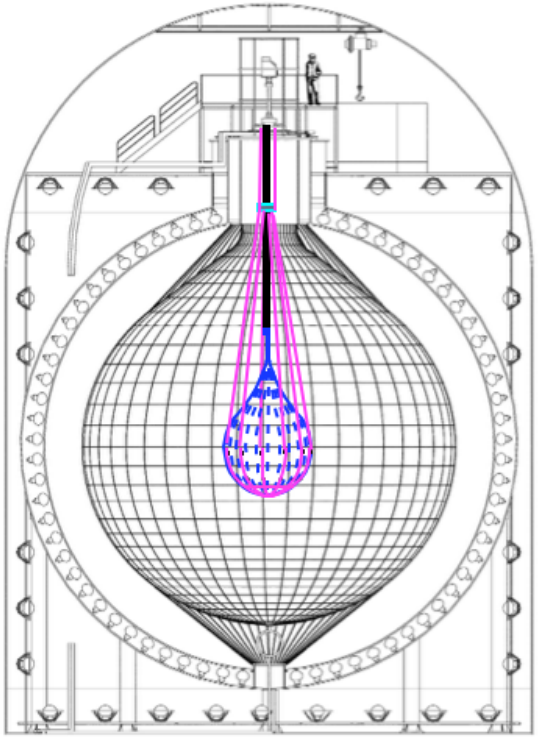
Isotope: ^{136}Xe
- Dissolve into LS (3 w%).
- On/off measurement.
- Easy to purify.

$$^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba} + 2e^-$$
$$\mathrm{Q} = 2.46\ \mathrm{MeV}$$

Pros of using KamLAND
- Already running, quick start.
- Huge & Scalable
- Low BG
- Active veto with Outer-LS

Detector upgrades

2011—2015

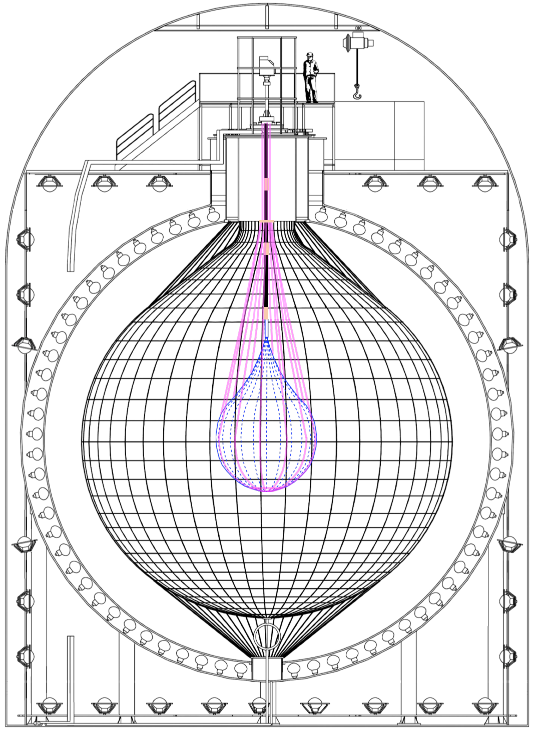


KamLAND-Zen 400

- 380 kg_{Xe}
- World top limit
  - $\langle m_{\beta\beta} \rangle <$ 61—165 meV

Phys. Rev. Lett. **117**, 082503 (2016)

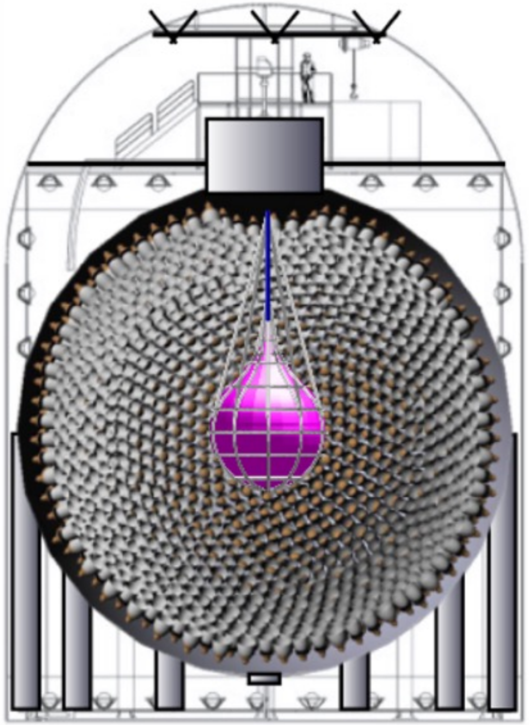
2019—Now



KamLAND-Zen 800

- 750 kg_{Xe}
- Demonstration of Scalability
- Cleaner IB

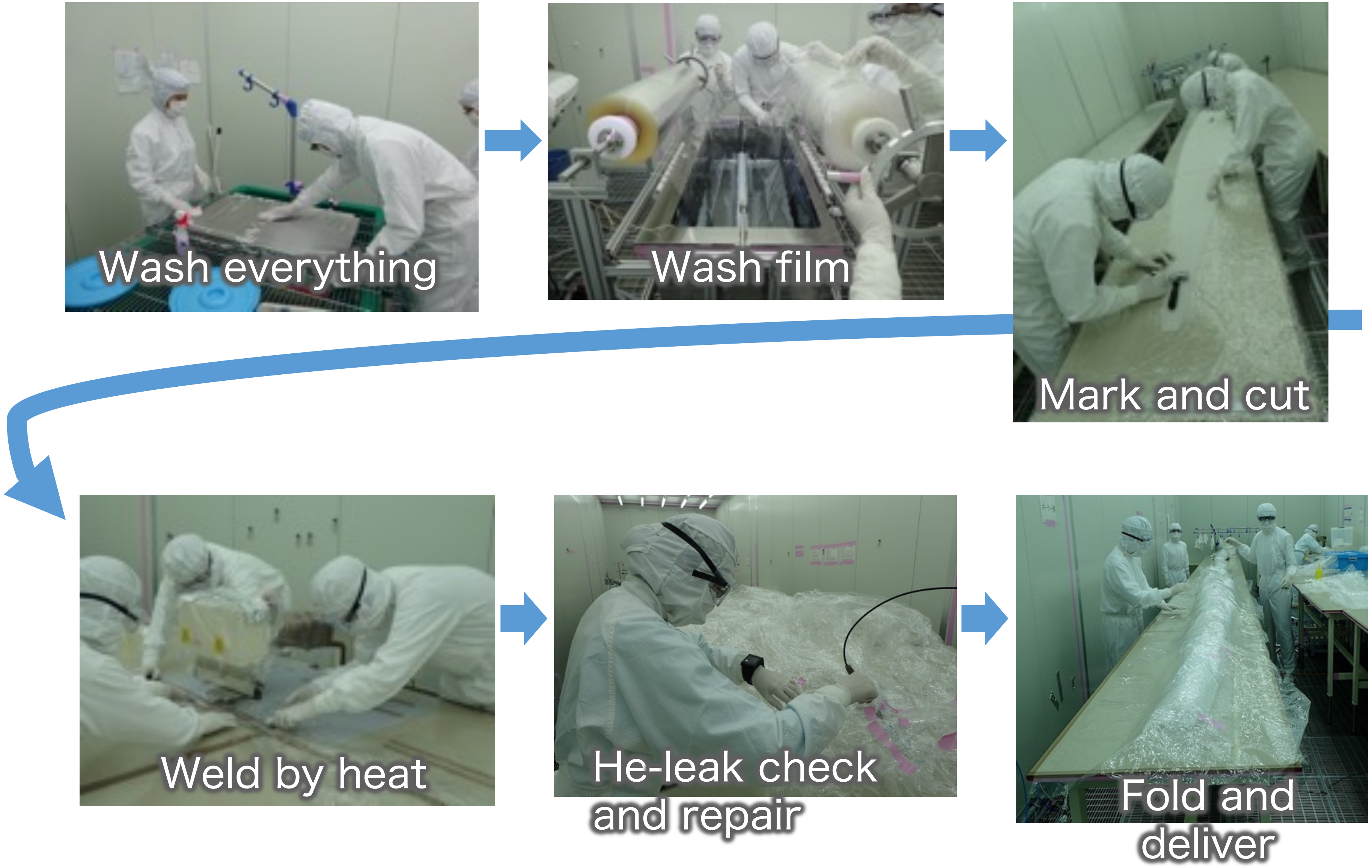
Future

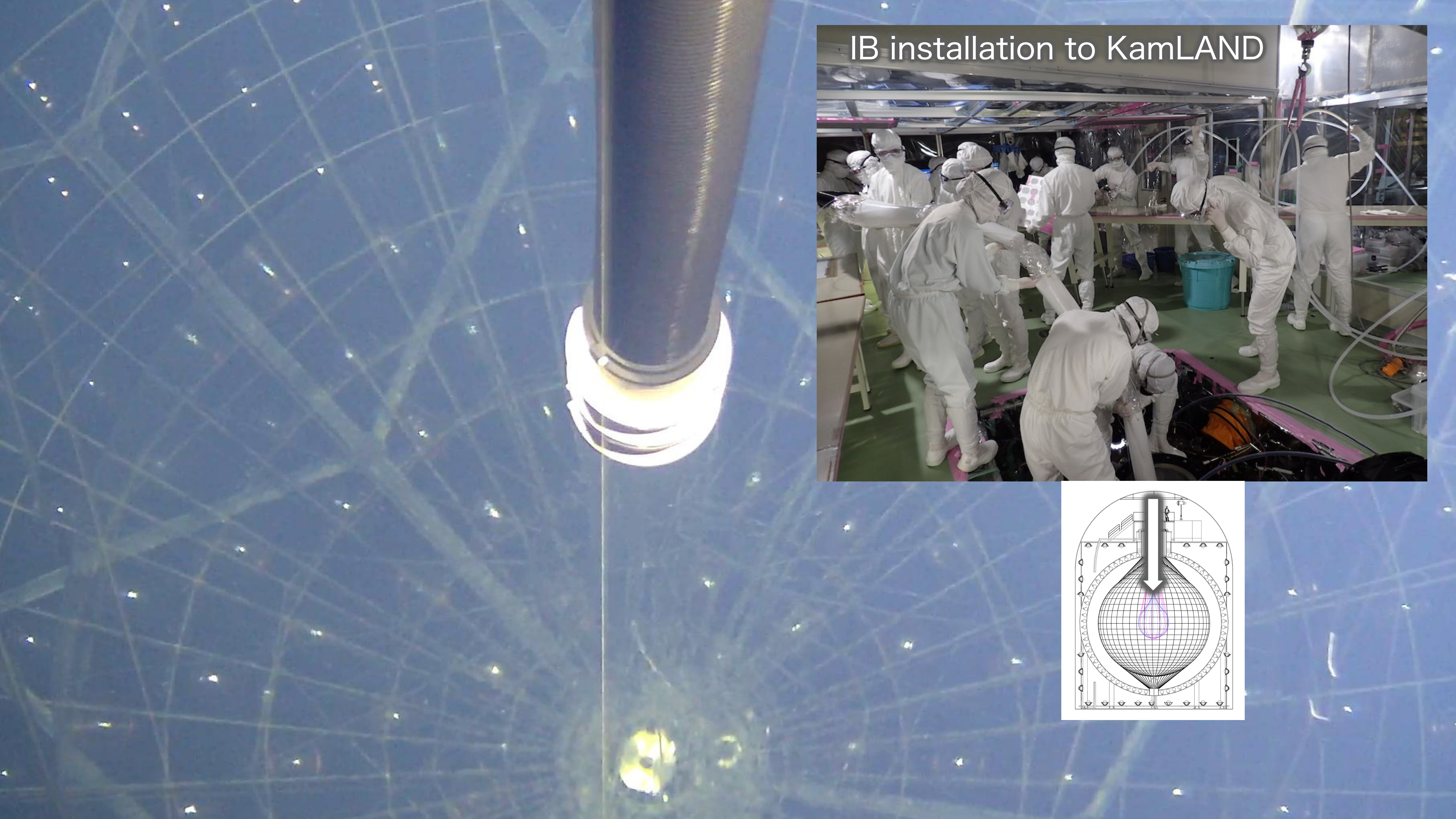


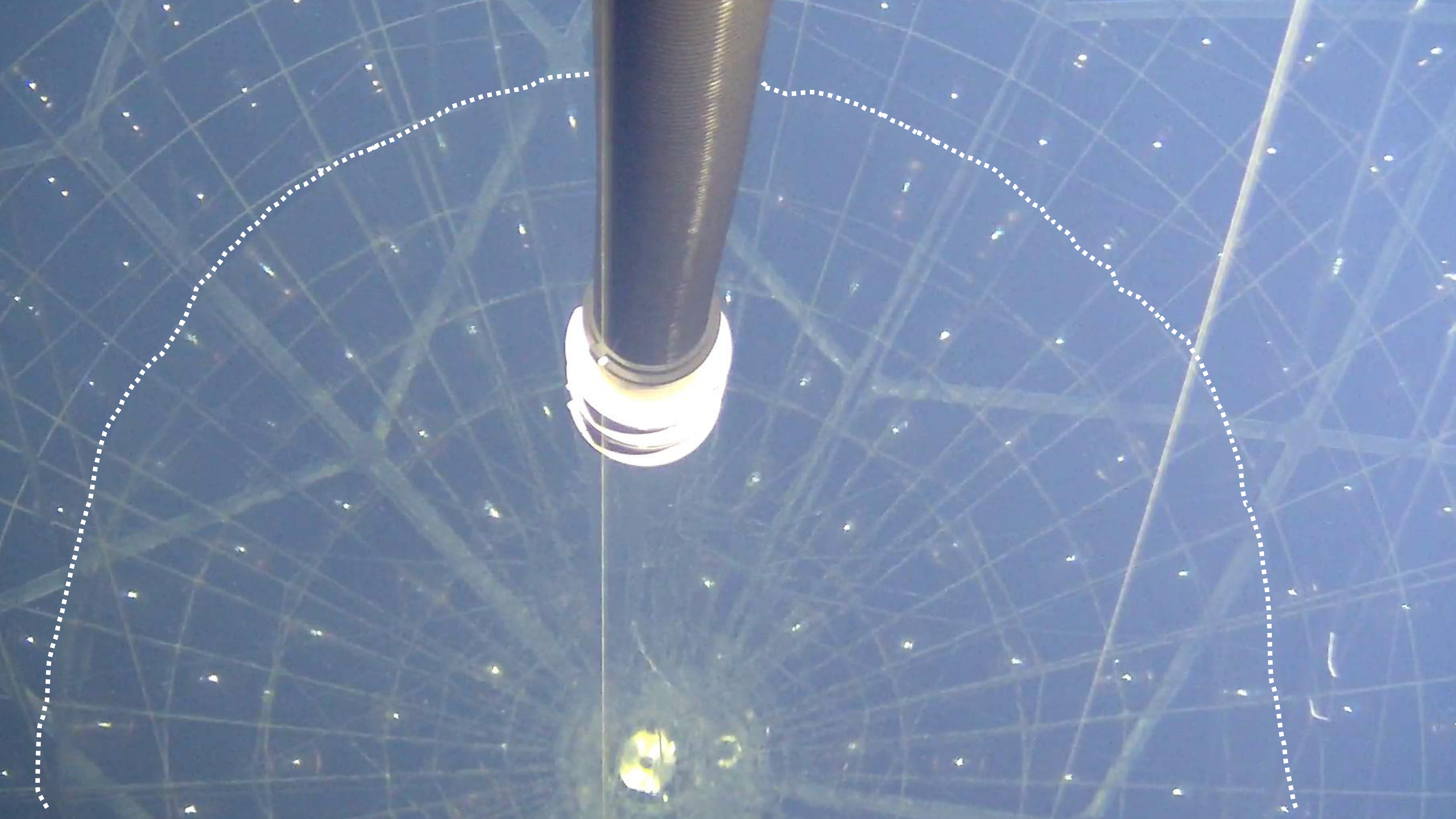
KamLAND2-Zen

- 1000 kg_{Xe}
- Higher light yield
- Many performance upgrades

IB production



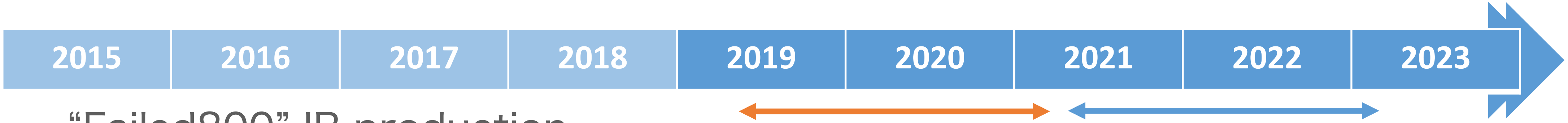

IB installation to KamLAND



KamLAND-Zen 800

- 0nbb search: Phys. Rev. Lett. **130**, 051801 (2023)
- Xe spallation products: Phys. Rev. C **107**, 054612 (2023)

Zen800 time flow



- “Failed800” IB production
- Zen400 IB withdrawal

- “Failed800” IB installation
- Cleaner IB confirmed
- Leakage detection before the Xe loading
- “Failed800” IB withdrawal

- Zen800 IB production

- Zen800 IB installation
- LS purification
- Xe loading

- Phys. run started (2019 Jan.)

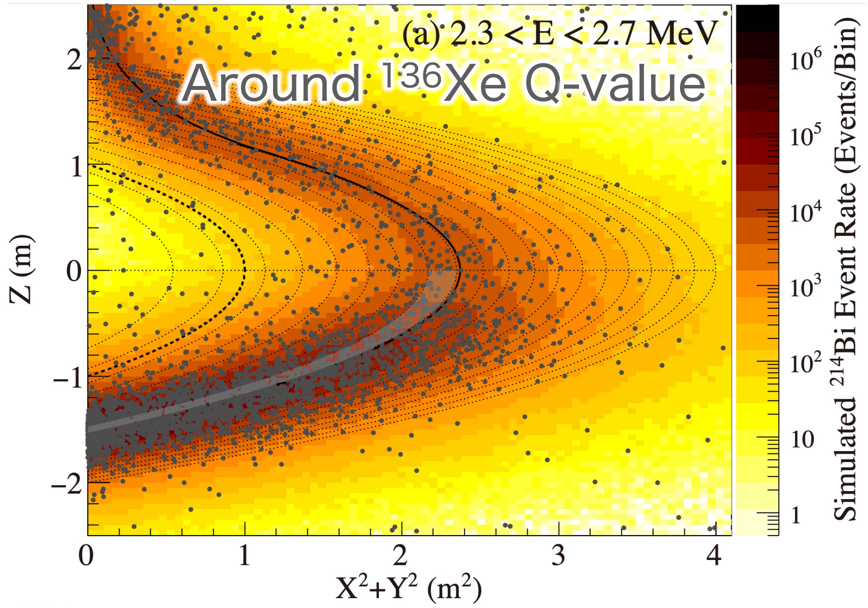
- 1st result data-set 2019 Feb.—2021 May (Livetime 1.4 yr)

- +2.5 yr data now being analyzed

- Now running

Problem of Zen400

Comparison btw. Zen400 2^{nd} phase data and ^{214}Bi(MC) vertex distribution



PRL **117**, 082503 (2016)

RI in/on film

	^{238}U (10^{-12}g/g_{film})	^{232}Th (10^{-12}g/g_{film})
Initial	2	6
Zen 400 1st	14+-1	79+-3
Zen 400 2nd	46.1+-4	336+-2

x7

Pump failure

- **IB was contaminated.**
- Fiducial volume ratio at 2^{nd} phase ~43%* (150 kg_{Xe})

*S. Matsuda, Tohoku univ., Ph. D thesis (2016). Whole volume was binned and simultaneously analyzed at final result of 2^{nd} phase.

Cleaner IB production

- **Clean wears**

Clean inners adopted

Change-room shared with other labs (changing done only here at Zen400)

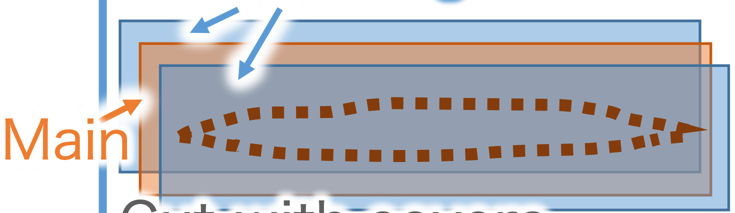
Change again in change-room in clean room

Goggle

Wash hands frequently

Suits go to laundry after one-time-use

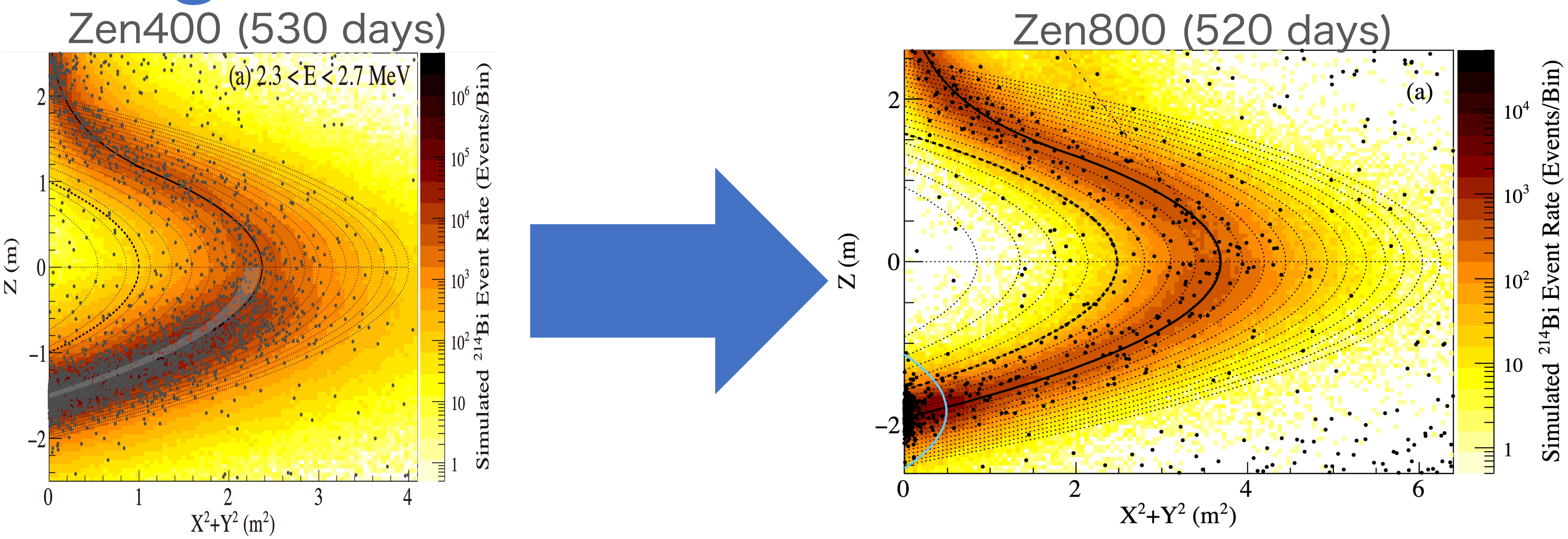
- **Covering film**



Cut with covers.
Strip edge when welding.

Misc.
- Clean clean-room
- Clean tools
- More neutralizers
- **Semi-auto welding**

IB background reduction



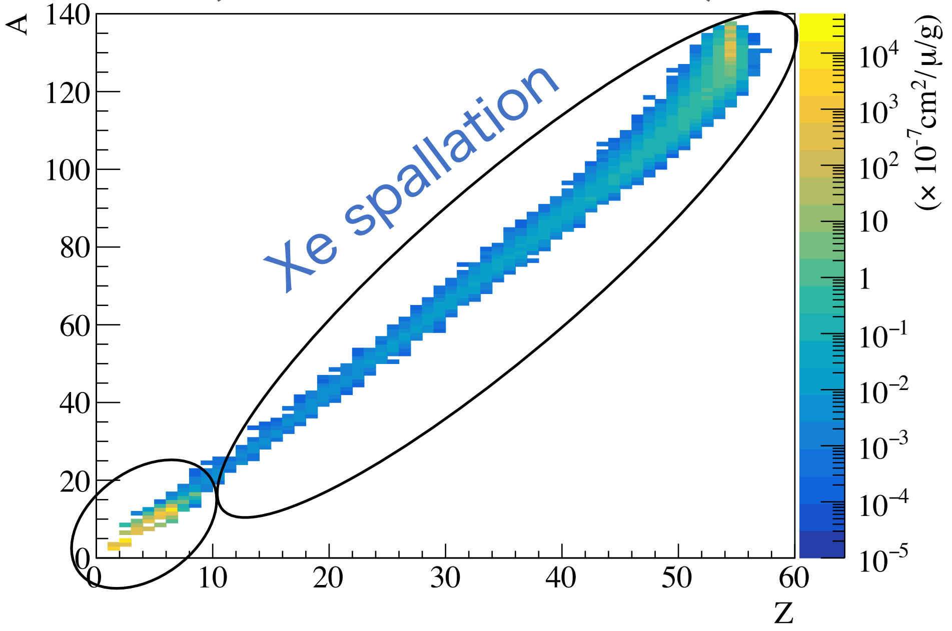
	Zen400	Zen800
^{238}U (10^{-12}g/g$_{film}$)	46 ± 4	3 ± 1
^{232}Th (10^{-12}g/g$_{film}$)	336 ± 2	38 ± 2
Sensitive volume	Z > 0 && R < 1.2 m Z < 0 && R < 1.0 m ~150 kg$_{Xe}$	R < 1.57 m ~380 kg$_{Xe}$

- x10 BG reduction
- >x2 sensitive volume
- Lower BG core

Cosmic-ray muon spallation products

*muon rate: 0.3 Hz per KamLAND

Spallation products in XeLS
(FLUKA simulation)

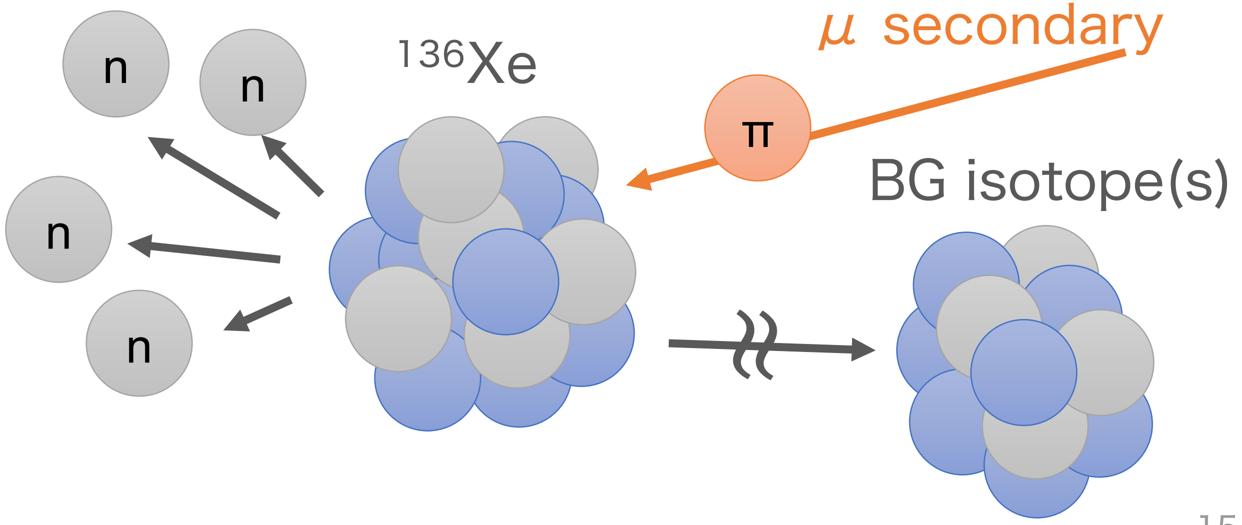


Carbon spallation

- Short lives (τ < 30 s, excl. ^{11}C)
- Sufficient reduction by:
  - 3-fold coincidence (μ, neutron, the decay)
  - Correlation with μ (track & charge)

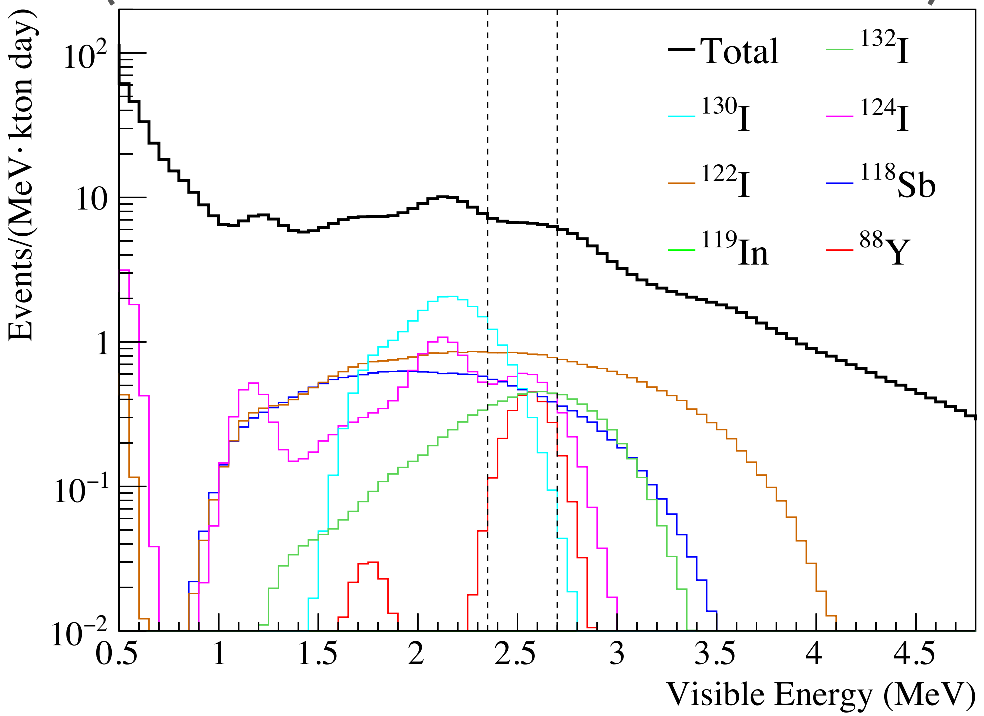
- **^{137}Xe (τ = 5.5 min) from ^{136}Xe + n**
  - Cross section measured by Zen800: 236 ± 145 mb in consistent with prior researches
  - 75% vetoed by 3-fold coinc.

- **Long-lived (LL) isotopes**
  - τ ~ O(hours)
  - Dominant 0nbb BG after all cuts



Long-lived spallation products

Energy spectrum of LL isotopes
(some dominant ones selected)



- Main contributions from 30+ isotopes
- Many decay in $\beta^+\gamma$ mode
- Rate in ROI: 2.6 events/day/kton$_{XeLS}$

- Accompanied by many neutrons at the spallation
- Effective Number of Neutrons

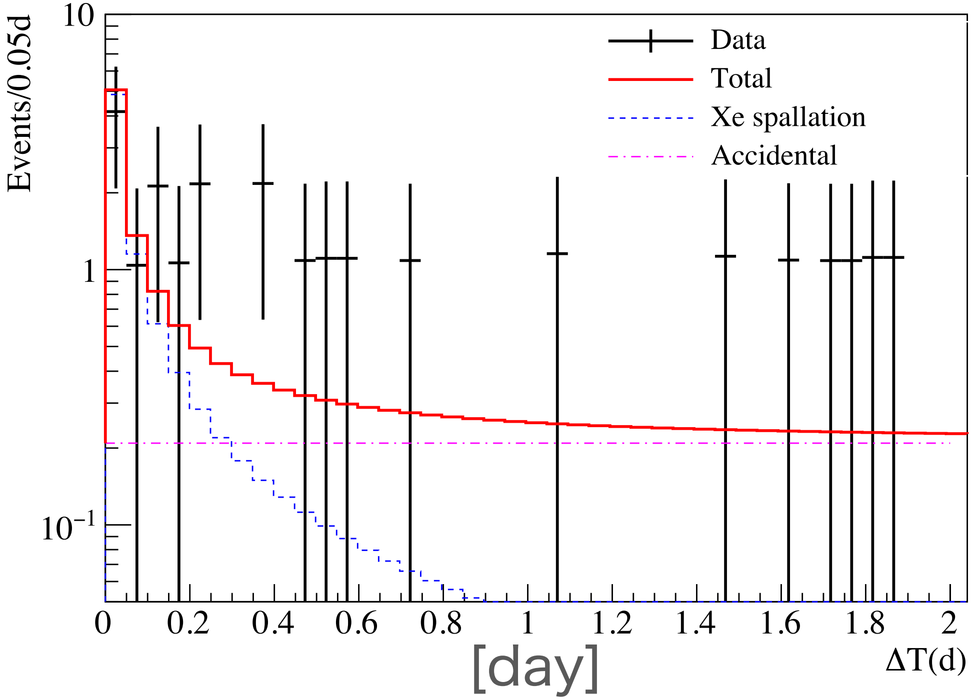
$$N_{\mathrm{eff}} = \sum_i \frac{P_{\mathrm{spallation}}(dR_i)}{P_{\mathrm{spallation}}(dR_i) + P_{\mathrm{accidental}}(dR_i)}$$

where dR: distance btw. a neutron and the isotope

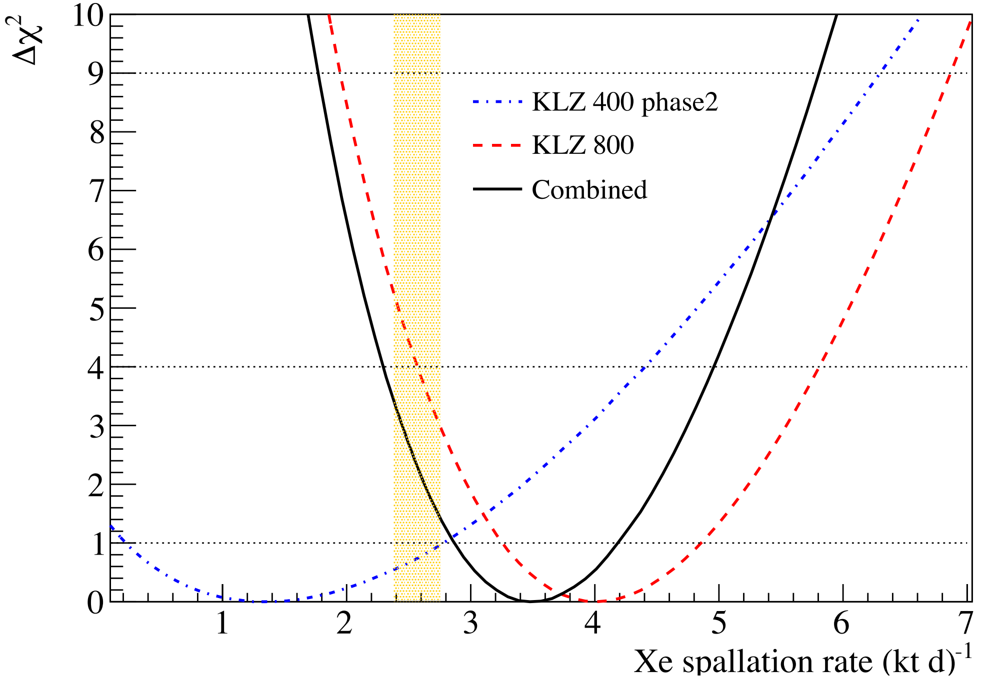
- Likelihood (N$_{\mathrm{eff}}$, dR$_{\mathrm{nearest}}$, dT) cut
  - (42.0 ± 8.8)% rejection efficiency
  - 8.6% 0nbb signal sacrifice

Confirmation of the existence

Time diff. from muons ($N_{eff} \geq 6$)



Rate scan from 0nbb search

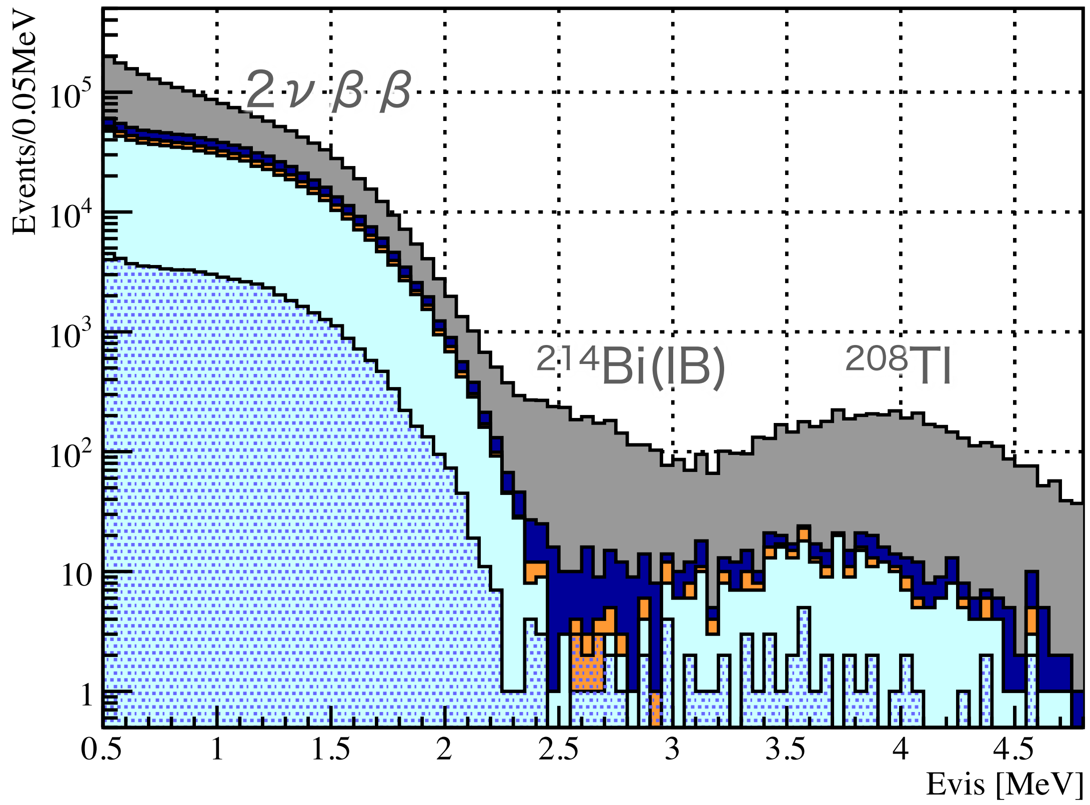


- "Accidental-only" rejected at 4.8σ level

- Rate in ROI: 3.5 ± 0.6 /day/$kton_{XeLS}$
- Consistent with FLUKA prediction (2.6 ± 0.2 /day/$kton_{XeLS}$)

$0\nu 2\beta$ analysis

Event selection

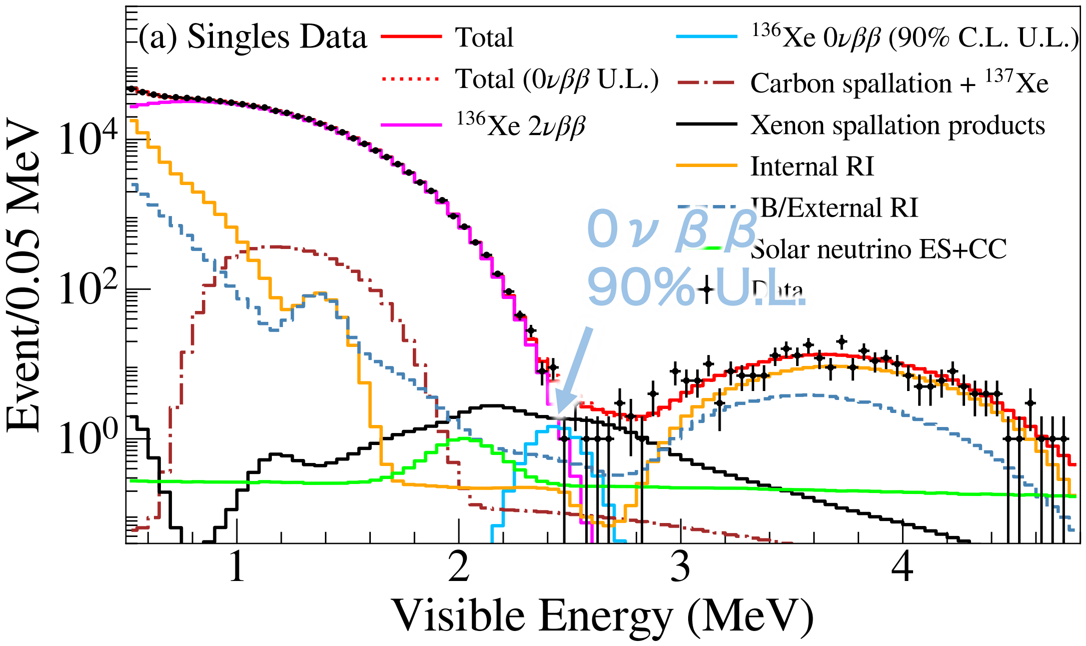


2019 Feb. 5—2021 May 8 (823 days)
R < 2.5 m
↓
Rn veto & R < 1.57 m
↓
Short-lived spallation cut
↓ ↓
LL-untagged (singles) 523.4 days
LL-tagged 49.3 days

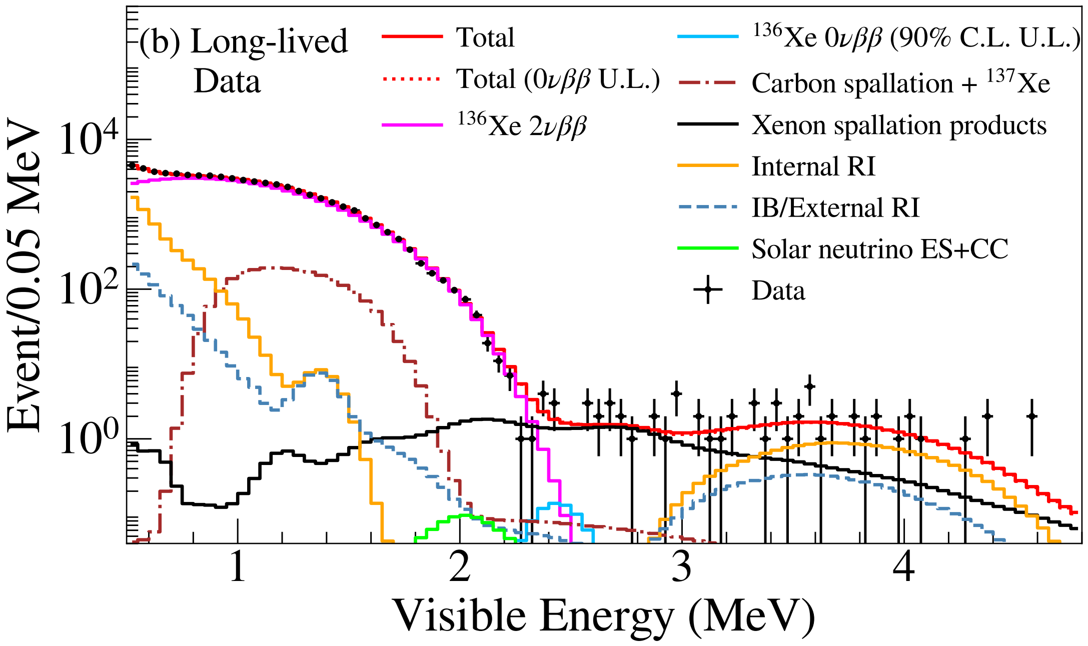
- Multi dimensional simultaneous fitting
  - Energy: 86 bins
  - Volume: 40 bins (Radius 20 x U/L)
  - Time: 3 bins (for PMTs' condition etc.)
  - LL tagged or not: 2 bins

Best-fit energy spectra (r < 1.57 m)

Singles

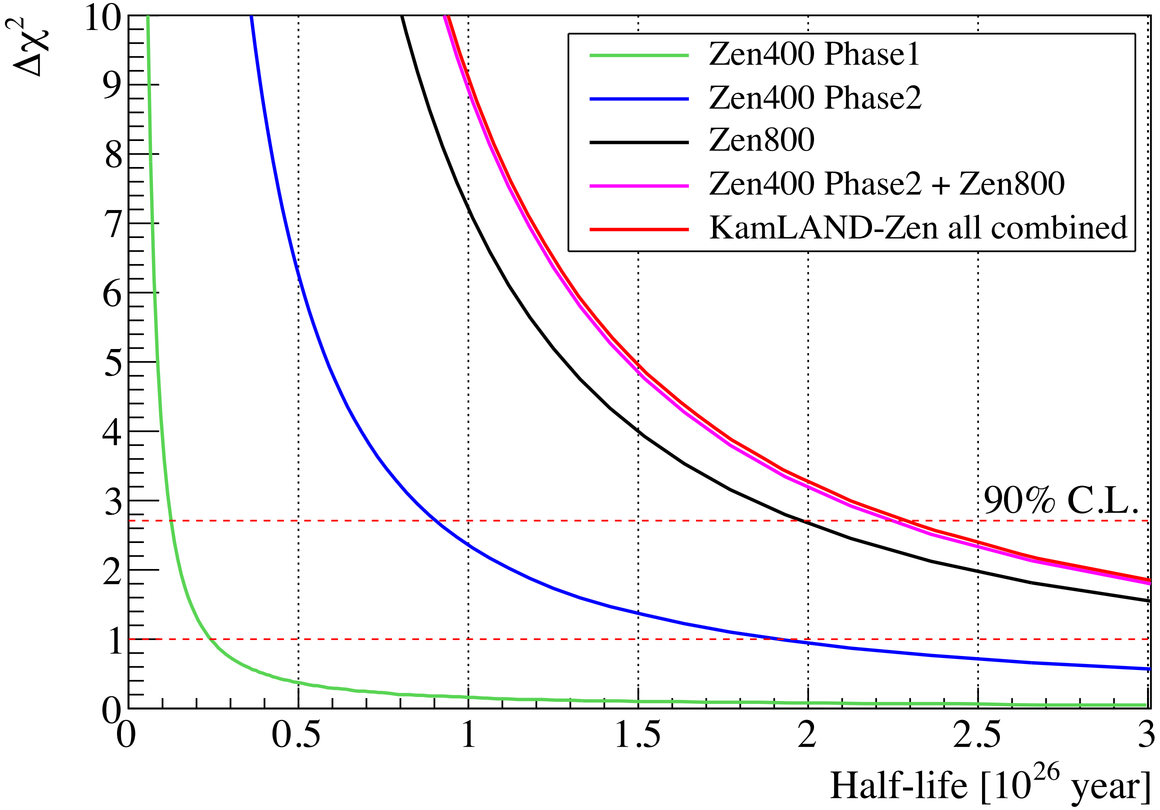


LL-tagged



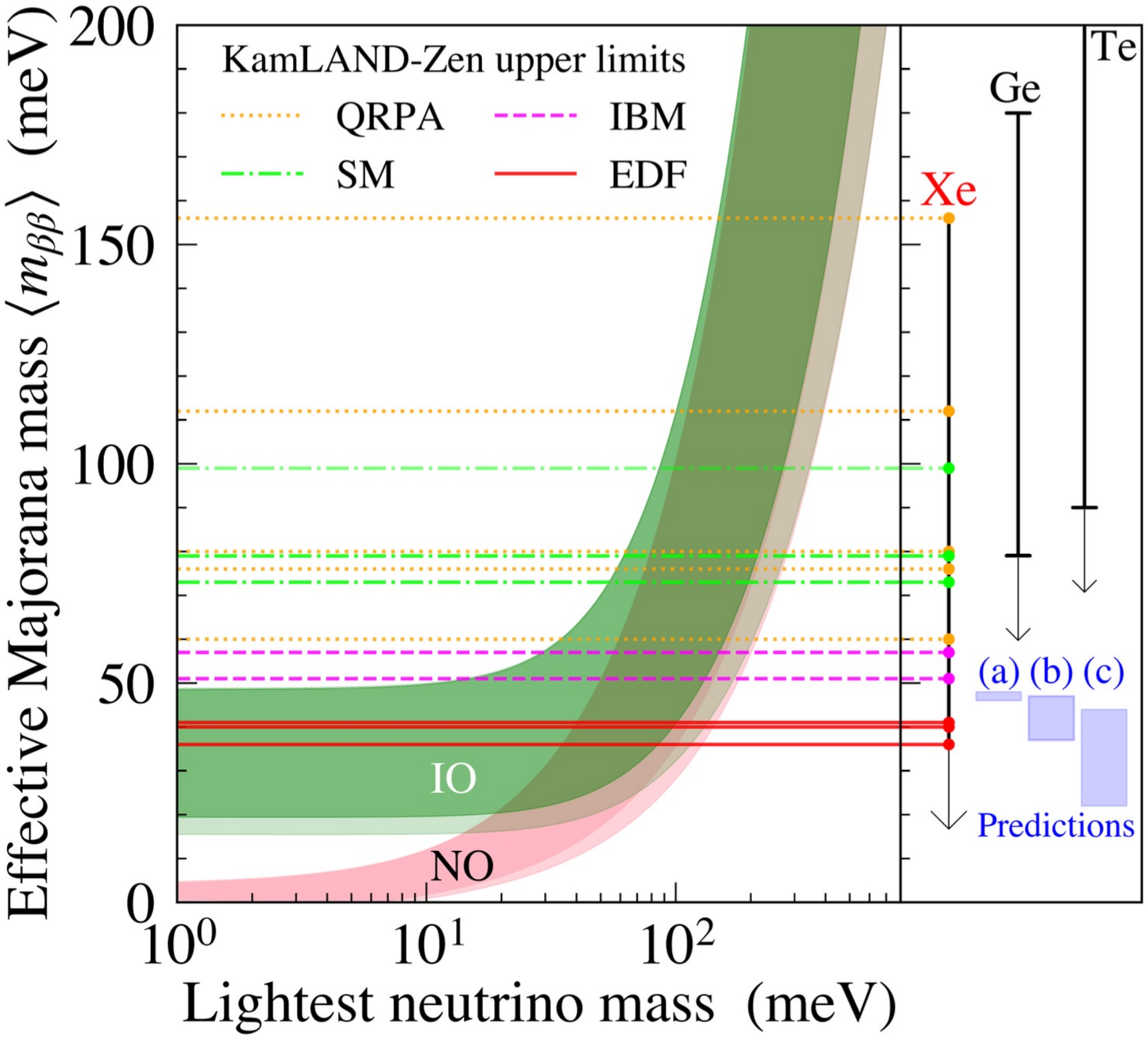
- $0\nu\beta\beta$
  - Best-fit: 0 event
  - Upper limit: < 7.9 events (90% C.L.)
- Dominant BG: $2\nu\beta\beta$ & LL spallation products

Limits on 0νββ half-life



- Re-analyzed Zen400 data with updated cuts and BG models
- 0νββ half-life limits (90% C.L.)
  - Zen400: > 0.9 x 10^{26} yr
  - Zen800: > 2.0 x 10^{26} yr
  - Combined: > 2.3 x 10^{26} yr
- Twice better results by Zen800

Limit on effective Majorana mass



$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

G : Phase space factor
M : Nuclear matrix element

World leading limit:

$\langle m_{\beta\beta}\rangle$ < 36—156 meV (90% C.L.)

*g_A~1.27 assumed

Entering IO region with some NMEs

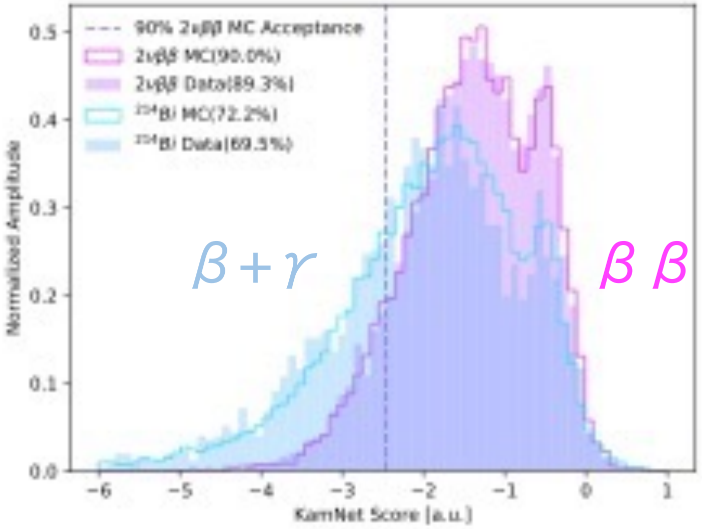
Expected improvements in Zen800

BG summary in ROI

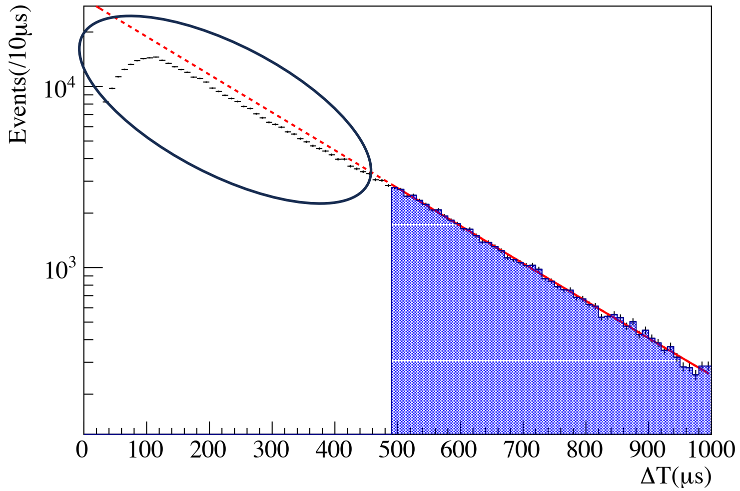
BG	Events
(a) $2\nu\beta\beta$	12.0
(b) LL spallation	12.5
(c) IB	3.0

- **PID with Machine Learning: (b), (c)**
  - $0\nu\beta\beta$ (point-like) vs γ BGs (spread)
  - KamNET: Phys. Rev. C **107**, 014323 (2023)
    - already achieved 27% veto eff. while keeping 90% signal eff.
- **Electronics upgrade (MoGURA2): (b)**
  - Improve the neutron detection efficiency after muons

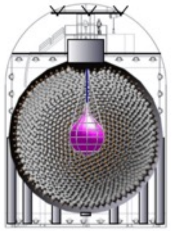
KamNet's PID Performance



μ—n time difference (current electronics)



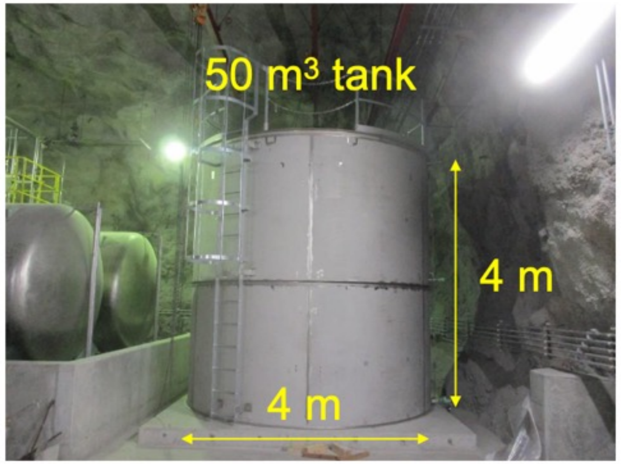
KamLAND2-Zen



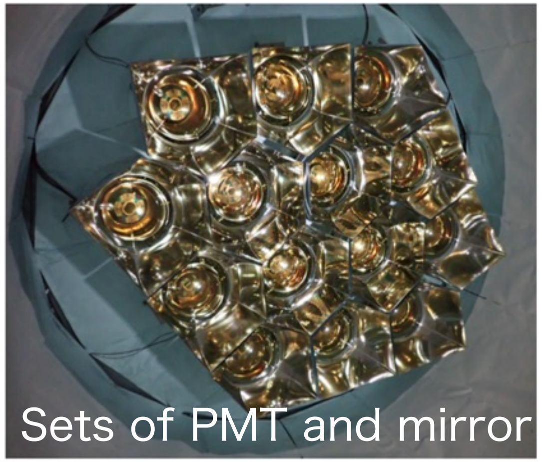
- 1/100 $2\nu\beta\beta$ reduction by higher light yield
  - x5 L.Y. to be achieved by:
    - Light collecting mirror: x1.8
    - High Q.E. PMT: x1.9
    - New LS: x1.4
  - σ_{energy} at Q-value = 2%
- New electronics (MoGURA2)
  - Improve the neutron detection efficiency after muons
- Target $\langle m_{\beta\beta} \rangle$ ~20 meV (5 yr)

Ongoing R&D

KamLAND2 prototype



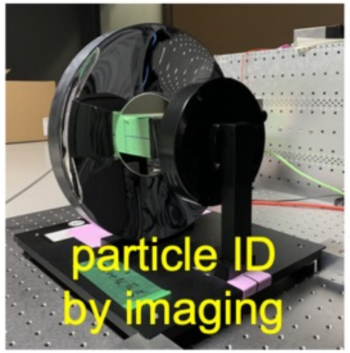
inside view



Options

Scintillating IB:
100% fiducial vol.

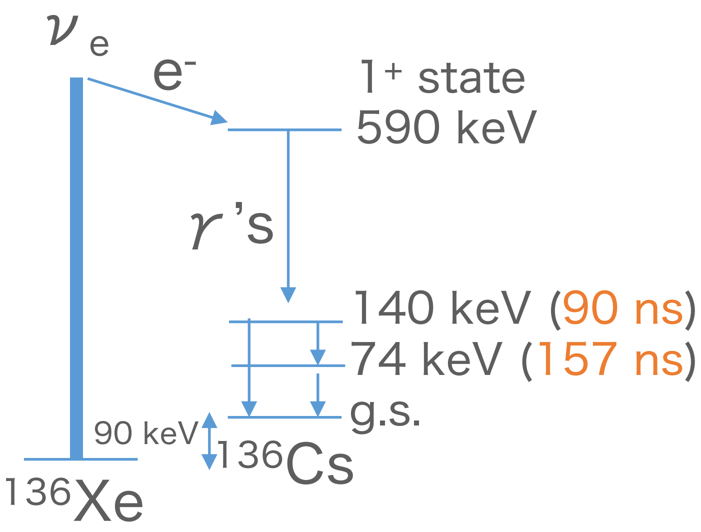
Imaging device



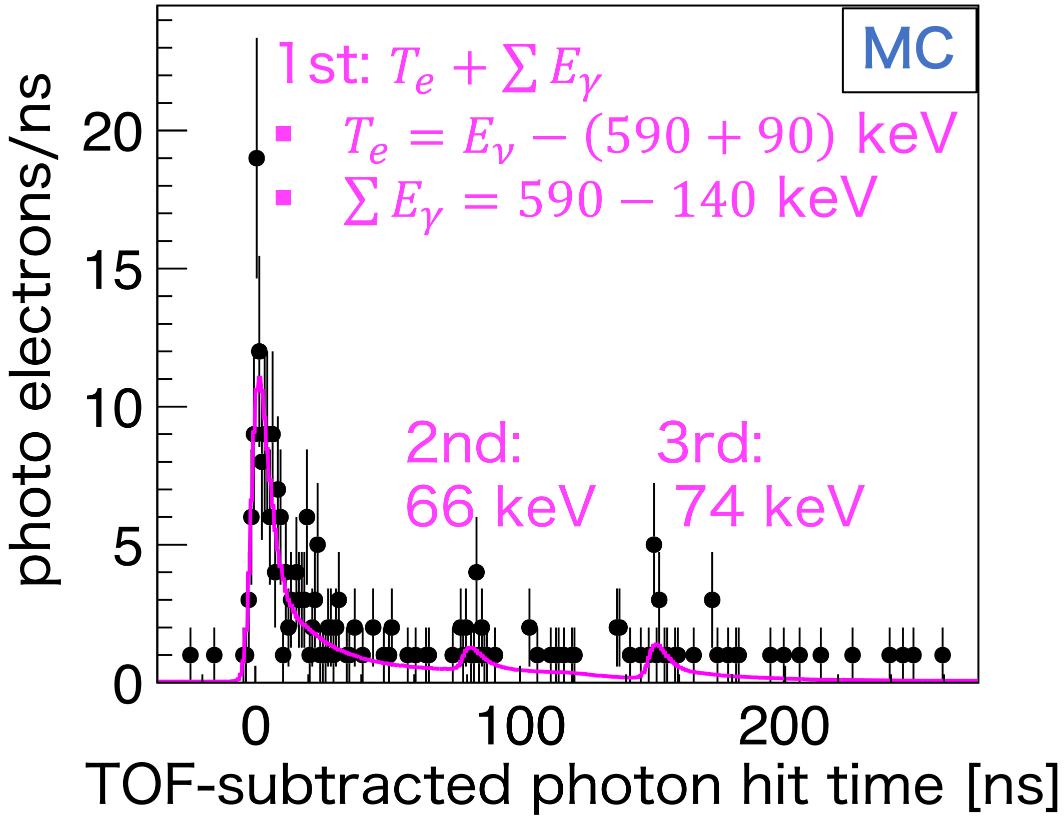

One more slide…
apple.com

$\nu_e + ^{136}Xe \rightarrow e^- + ^{136}Cs^*$

"Observation of low-lying isomeric states in Cs-136"
S.J. Haselschwardt *et al.*, arXiv:2301.11893



(KamLAND-Zen MC)
^{7}Be solar-ν (860 keV) event



- Taggable with delayed coincidence (BG free?)
- $E_{\nu e}$ reconstruction (detect e^- & all γ's)
- Usable for solar-ν measurements (and DM search)
- Case for KamLAND-Zen
  - Accidental BG: 2nbb + ^{14}C
  - Correlated BG: ^{212}Bi—Po (from IB)
  - now being studied

^{7}Be solar-ν expected rate:
5.9 evt/(ton$_{Xe\text{-}136}$ * yr)

Summary

- Results from KamLAND-Zen
  - ($^{136}Xe + n \rightarrow {}^{137}Xe + \gamma$) cross section: 236 ± 145 mb
  - Confirmation of Xe spallation products in 2 ways
    - Time correlation: 4.8σ level
    - $0\nu\beta\beta$ search fitting: 3.5 ± 0.6 /day/kton$_{XeLS}$ (in ROI)
  - ^{136}Xe $0\nu\beta\beta$ half-life > 2.3 x 10^{26} yr (90% C.L.)
  - $\langle m_{\beta\beta} \rangle$ < 36—156 meV (90% C.L.) (Entering IO region!!)

- R&D's for improvement of current KamLAND-Zen 800 and future upgrade KamLAND2-Zen are ongoing.

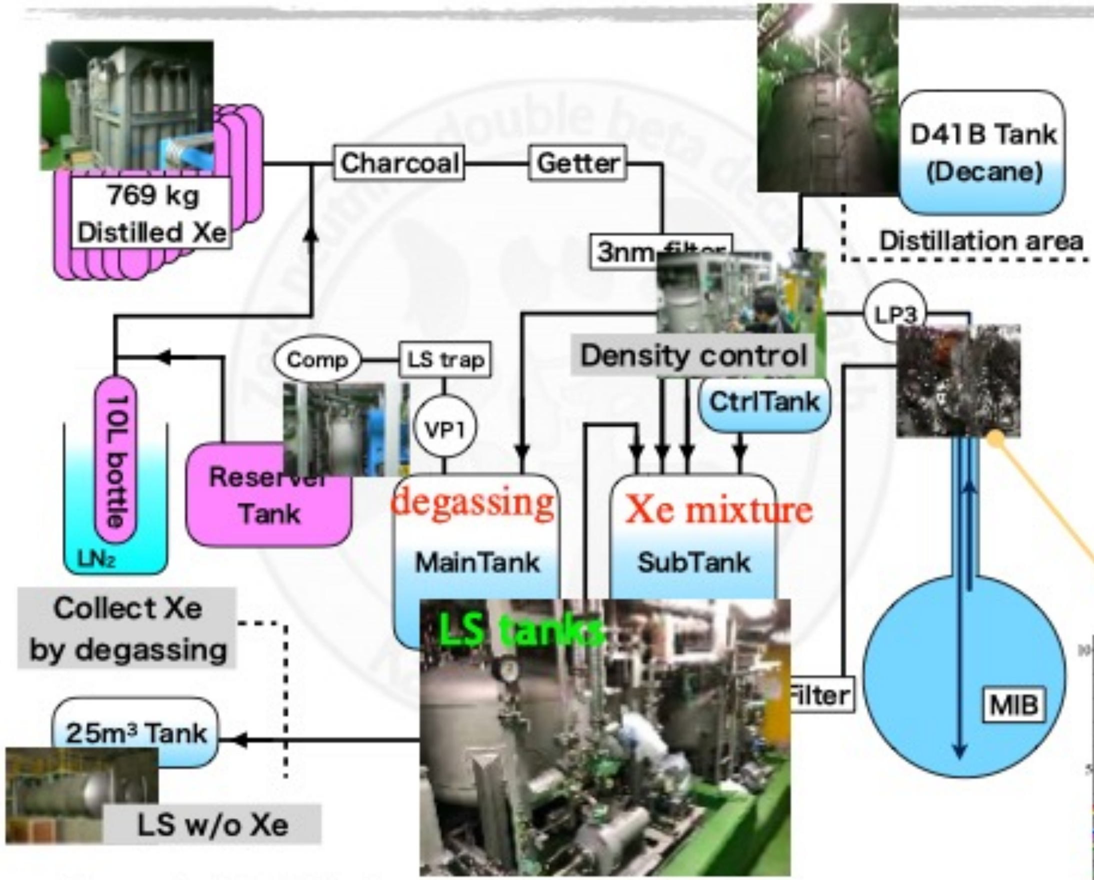
Publications

- 0nbb search: Phys. Rev. Lett. **130**, 051801 (2023)
- Xe spallation products: Phys. Rev. C **107**, 054612 (2023)

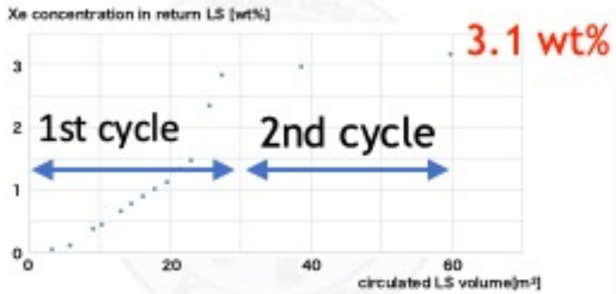
Back up

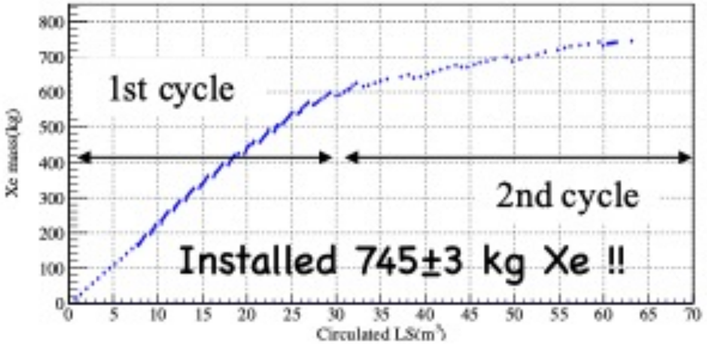
slide by H. Ozaki

Xenon-loaded LS installation

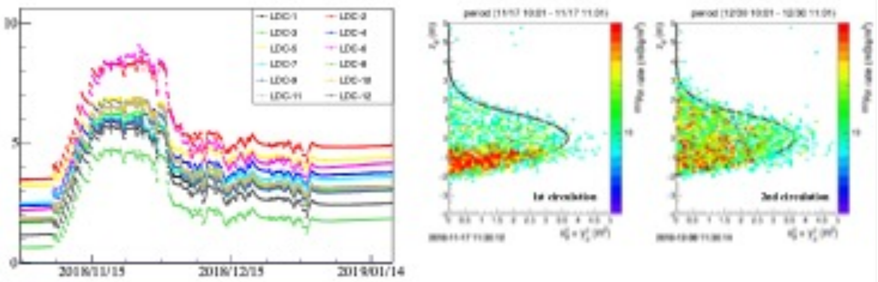


Controlled XeLS density 0.7774 g/l and temperature ~10.5 °C.
(KamLS: 0.77728 g/l, 12.0°C)



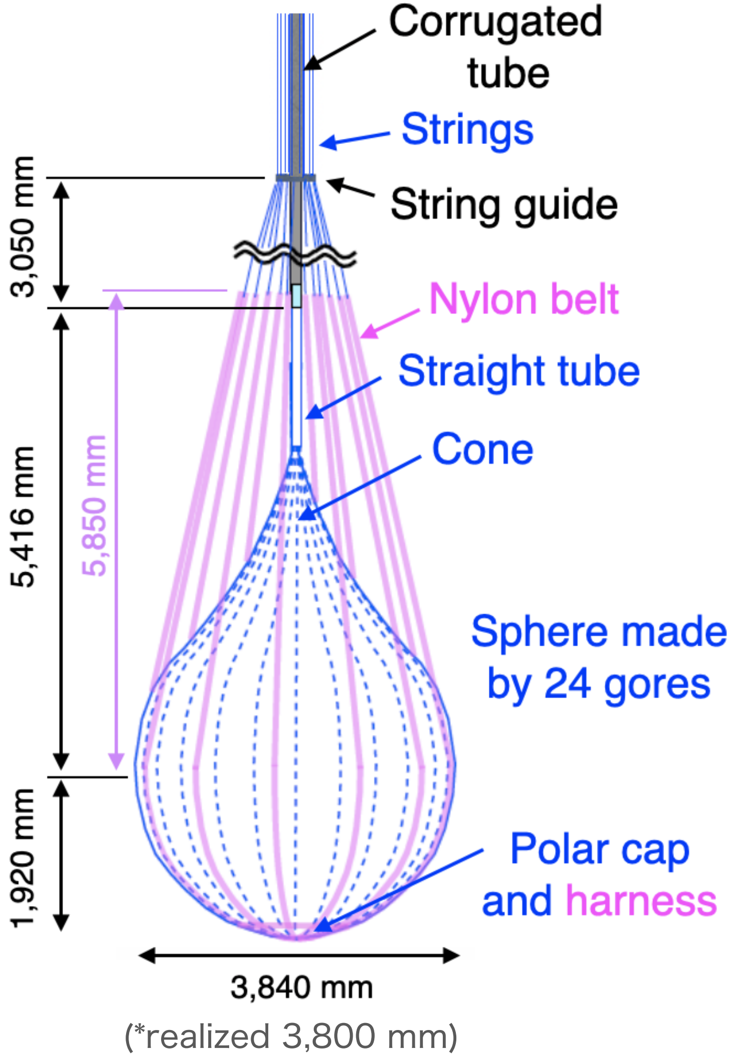


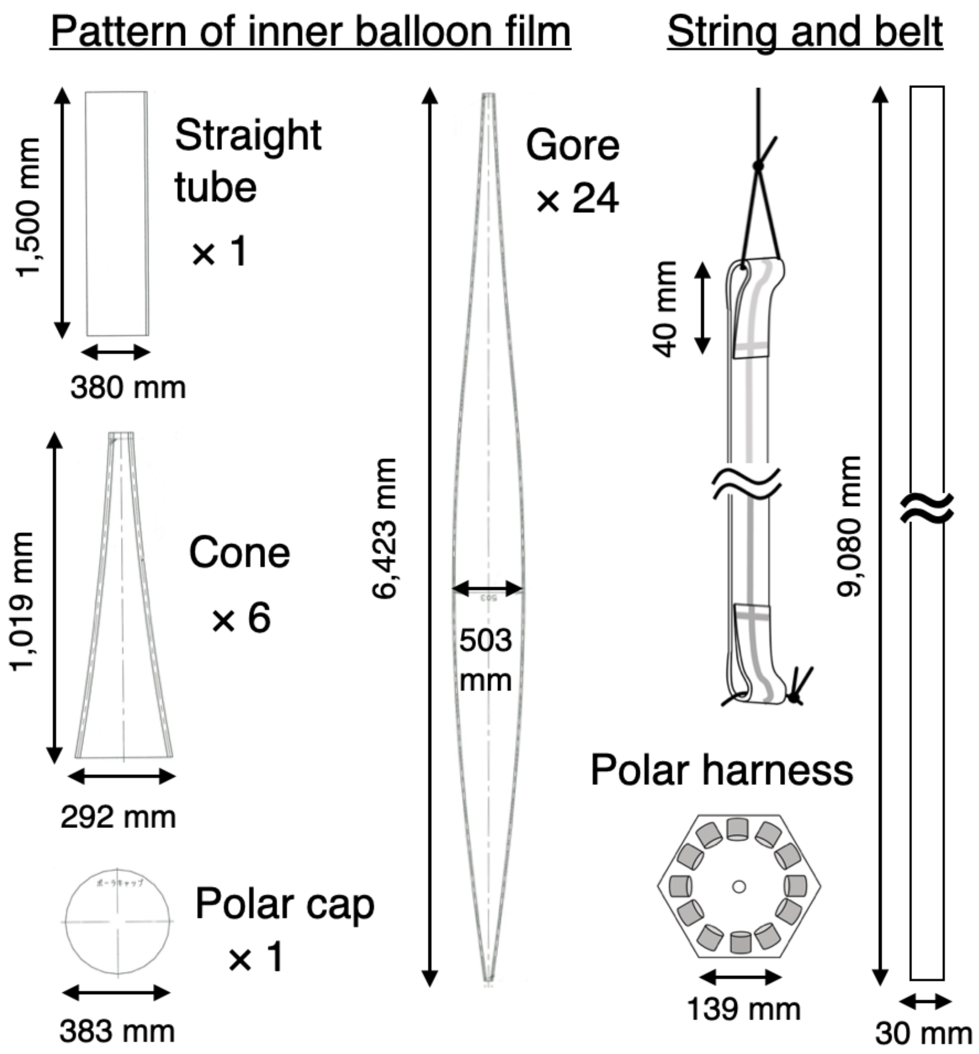
Monitored by Bi-Po from Rn



12 load cell values (MIB weights) were monitored so as not to stress the mini-balloon.

Inner Balloon: IB

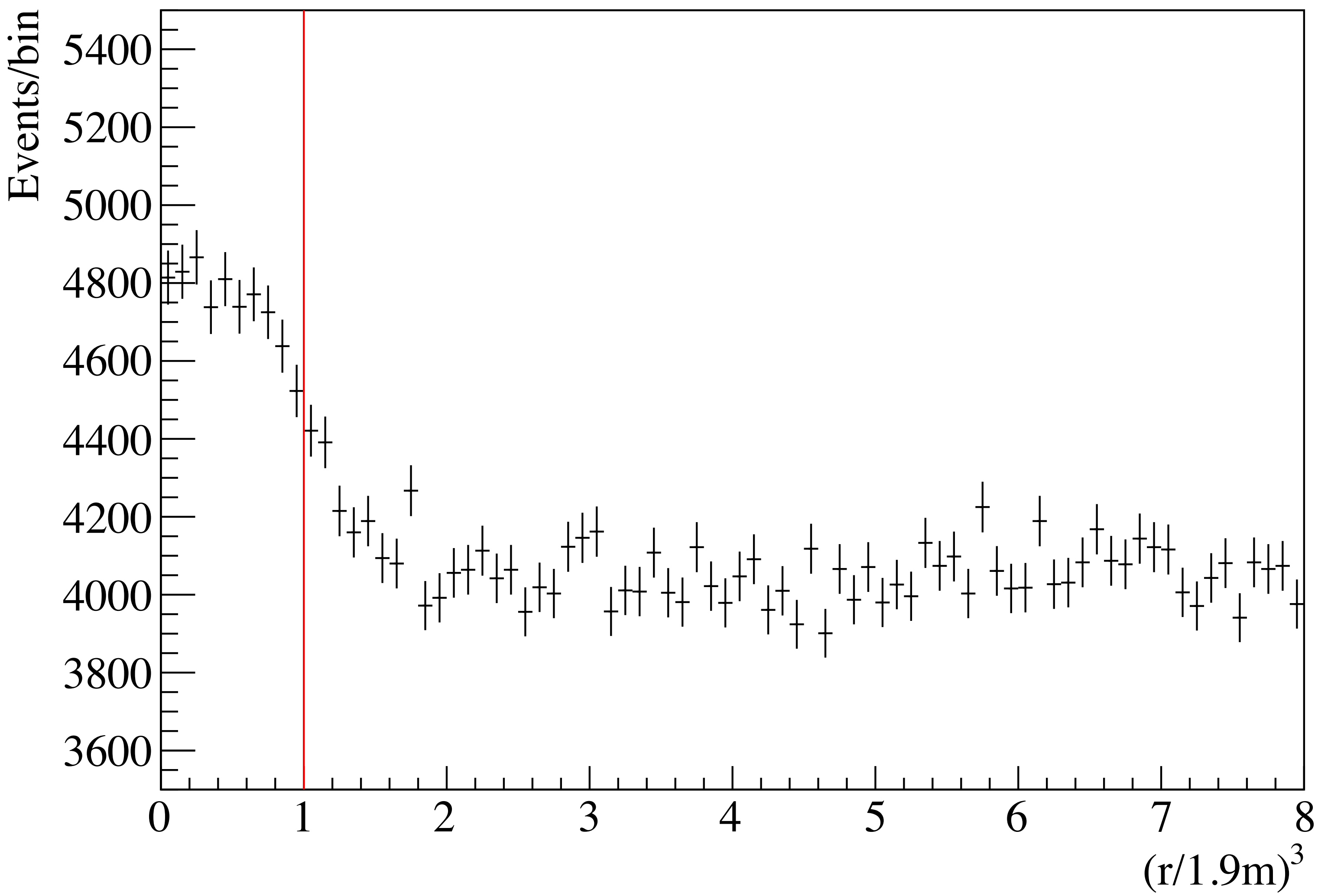


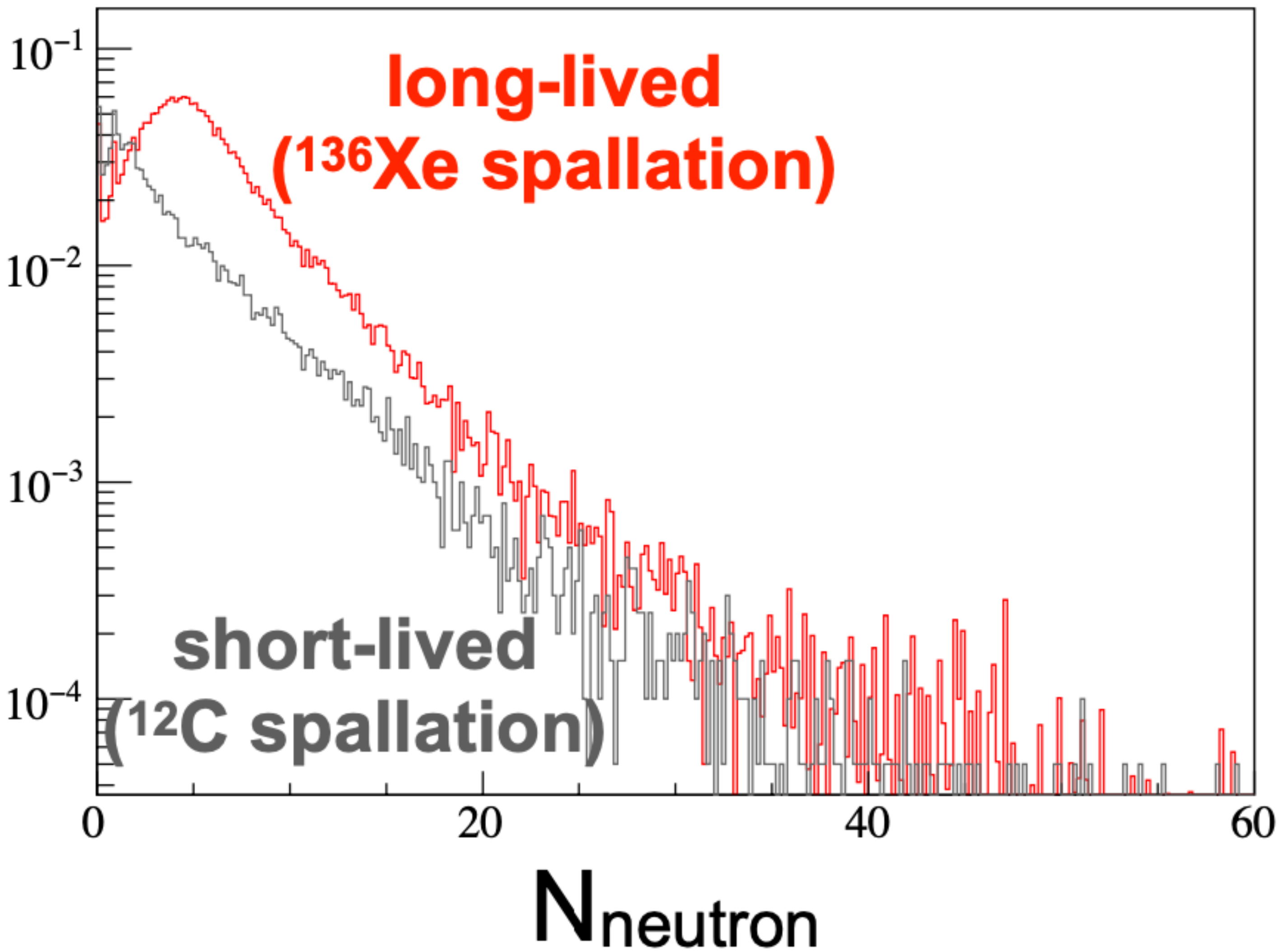


Most of parts were heat-welded

see *JINST* **16** P08023 (2021) for more details

neutron candidates

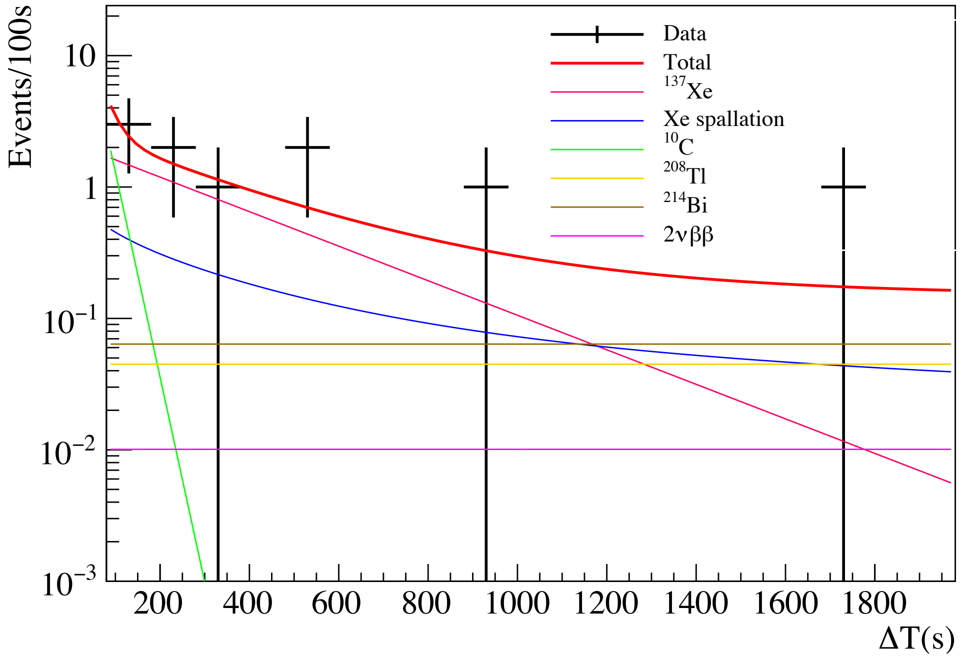




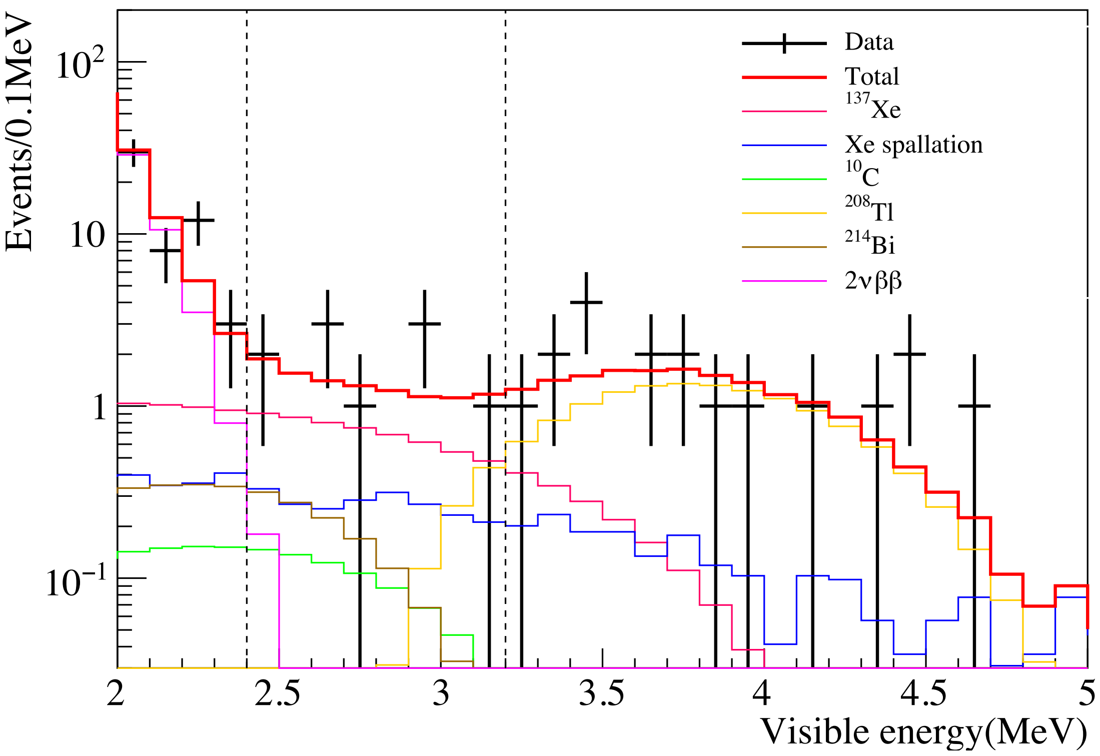
long-lived
(136Xe spallation)
short-lived
(12C spallation)
10−1
10−2
10−3
10−4
0
20
40
60
Nneutron

I. Shimizu

^{137}Xe



Events/100s
ΔT(s)
Data
Total
^{137}Xe
Xe spallation
^{10}C
^{208}Tl
^{214}Bi
2νββ



Events/0.1MeV
Visible energy(MeV)
Data
Total
^{137}Xe
Xe spallation
^{10}C
^{208}Tl
^{214}Bi
2νββ

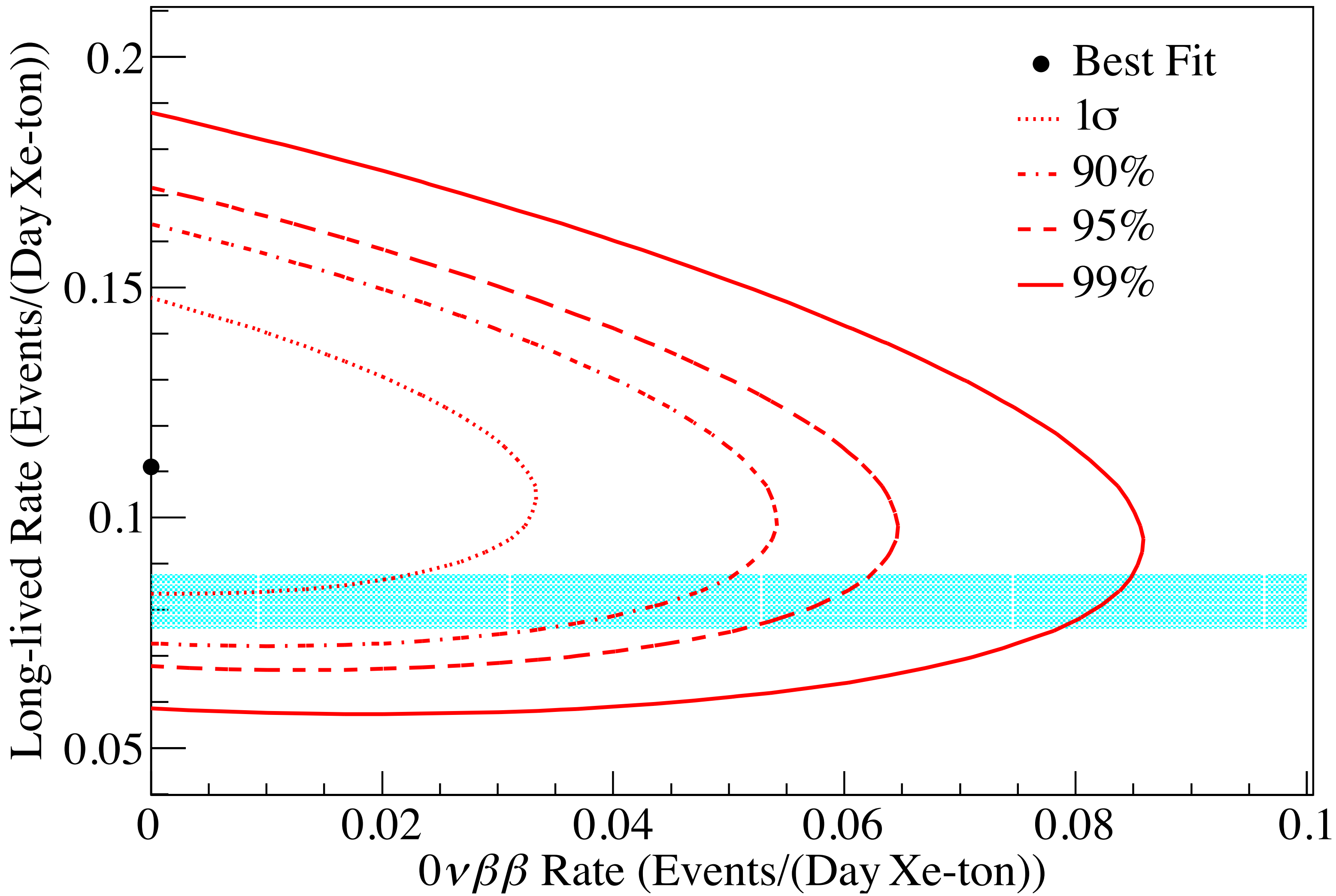
TABLE IX. Simulated production rate of dominant isotopes in $2.35 \leq E \leq 2.70$ MeV in Xe-LS.

	$\tau_{1/2}$ (s)	Q (MeV)	$(\mathrm{kton\,day})^{-1}$ ROI	Total
^{88}Y	9.212×10^{6}	3.62 (EC/$\beta^{+}\gamma$)	0.110	0.136
^{90m1}Zr	8.092×10^{-1}	2.31 (IT)	0.012	0.093
^{90}Nb	5.256×10^{4}	6.11 (EC/$\beta^{+}\gamma$)	0.024	0.095
^{96}Tc	3.698×10^{5}	2.97 (EC/$\beta^{+}\gamma$)	0.012	0.059
^{98}Rh	5.232×10^{2}	5.06 (EC/$\beta^{+}\gamma$)	0.011	0.076
^{100}Rh	7.488×10^{4}	3.63 (EC/$\beta^{+}\gamma$)	0.088	0.234
^{104}Ag	4.152×10^{3}	4.28 (EC/$\beta^{+}\gamma$)	0.012	0.160
^{104m1}Ag	2.010×10^{3}	4.28 (EC/$\beta^{+}\gamma$)	0.018	0.111
^{107}In	1.944×10^{3}	3.43 (EC/$\beta^{+}\gamma$)	0.019	0.135
^{108}In	3.480×10^{3}	5.16 (EC/$\beta^{+}\gamma$)	0.089	0.194
^{110}In	1.771×10^{4}	3.89 (EC/$\beta^{+}\gamma$)	0.053	0.236
^{110m1}In	4.146×10^{3}	3.89 (EC/$\beta^{+}\gamma$)	0.066	0.351
^{109}Sn	1.080×10^{3}	3.85 (EC/$\beta^{+}\gamma$)	0.027	0.122
^{113}Sb	4.002×10^{2}	3.92 (EC/$\beta^{+}\gamma$)	0.036	0.231
^{114}Sb	2.094×10^{2}	5.88 (EC/$\beta^{+}\gamma$)	0.020	0.297
^{115}Sb	1.926×10^{3}	3.03 (EC/$\beta^{+}\gamma$)	0.031	0.839
^{116}Sb	9.480×10^{2}	4.71 (EC/$\beta^{+}\gamma$)	0.071	0.939
^{118}Sb	2.160×10^{2}	3.66 (EC/$\beta^{+}\gamma$)	0.165	1.288
^{124}Sb	5.201×10^{6}	2.90 (EC/$\beta^{-}\gamma$)	0.016	0.054
^{115}Te	3.480×10^{2}	4.64 (EC/$\beta^{+}\gamma$)	0.012	0.124
^{117}Te	3.720×10^{3}	3.54 (EC/$\beta^{+}\gamma$)	0.052	0.594
^{119}I	1.146×10^{3}	3.51 (EC/$\beta^{+}\gamma$)	0.053	0.533
^{120}I	4.896×10^{3}	5.62 (EC/$\beta^{+}\gamma$)	0.091	0.953
^{122}I	2.178×10^{2}	4.23 (EC/$\beta^{+}\gamma$)	0.289	1.965
^{124}I	3.608×10^{5}	3.16 (EC/$\beta^{+}\gamma$)	0.190	1.654
^{130}I	4.450×10^{4}	2.95 ($\beta^{-}\gamma$)	0.195	1.188
^{132}I	8.262×10^{3}	3.58 ($\beta^{-}\gamma$)	0.148	0.427
^{134}I	3.150×10^{3}	4.18 ($\beta^{-}\gamma$)	0.043	0.183
^{121}Xe	2.406×10^{3}	3.75 (EC/$\beta^{+}\gamma$)	0.100	0.540
^{125}Cs	2.802×10^{3}	3.09 (EC/$\beta^{+}\gamma$)	0.012	0.266
^{126}Cs	9.840×10^{1}	4.82 (EC/$\beta^{+}\gamma$)	0.011	0.080
^{128}Cs	2.196×10^{2}	3.93 (EC/$\beta^{+}\gamma$)	0.031	0.229

Table 5.1: Summary of the deadtime

Event selection	Deadtime ratio [%]
Spallation veto	14.64
MoGURA neutron veto	4.91
^{137}Xe veto	1.33
Shower veto	7.37
^{12}B veto	3.11
Xe spallation veto	8.56
Detector deadtime veto (post PPS, after muons and missing waveforms)	9.47
Hardware related	0.0078
Delayed coincidence Rn veto	0.0013
Delayed coincidence Reactor veto	0.0010
Total	29.52

A. Takeuchi, Ph.D thesis


Best Fit
1σ
90%
95%
99%
0.2
0.15
0.1
0.05
0
0.02
0.04
0.06
0.08
0.1
Long-lived Rate (Events/(Day Xe-ton))
0νββ Rate (Events/(Day Xe-ton))

Observation of low-lying isomeric states in ^{136}Cs: a new avenue for dark matter and solar neutrino detection in xenon detectors

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(Dated: January 30, 2023)

We report on new measurements establishing the existence of low-lying isomeric states in ^{136}Cs using γ rays produced in ^{136}Xe(p,n)^{136}Cs reactions. Two states with $\mathcal{O}(100)$ ns lifetimes are placed in the decay sequence of the ^{136}Cs levels that are populated in charged-current interactions of solar neutrinos and fermionic dark matter with ^{136}Xe. Xenon-based experiments can therefore exploit a delayed-coincidence tag of these interactions, greatly suppressing backgrounds to enable spectroscopic studies of solar neutrinos and dark matter.

arXiv:2301.11893

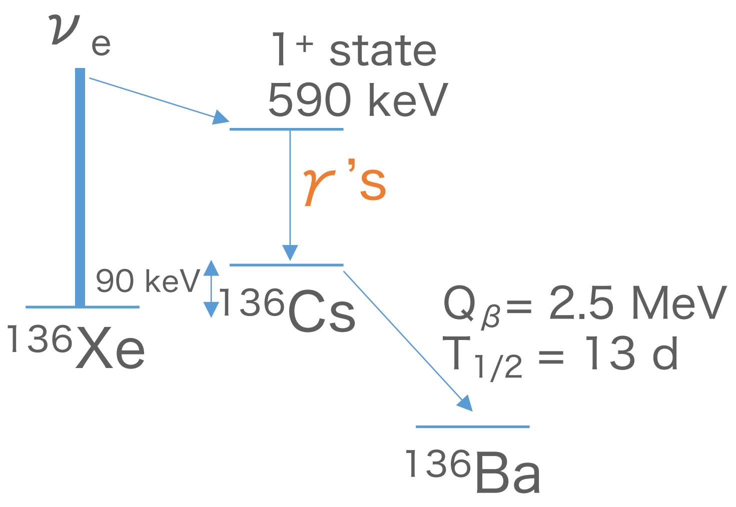
$\nu_e + {}^{136}Xe \rightarrow {}^{136}Cs^* + e^-$

- Ref.
  - PRC 89, 055501 (2014)
  - PRD 102, 072009 (2020)

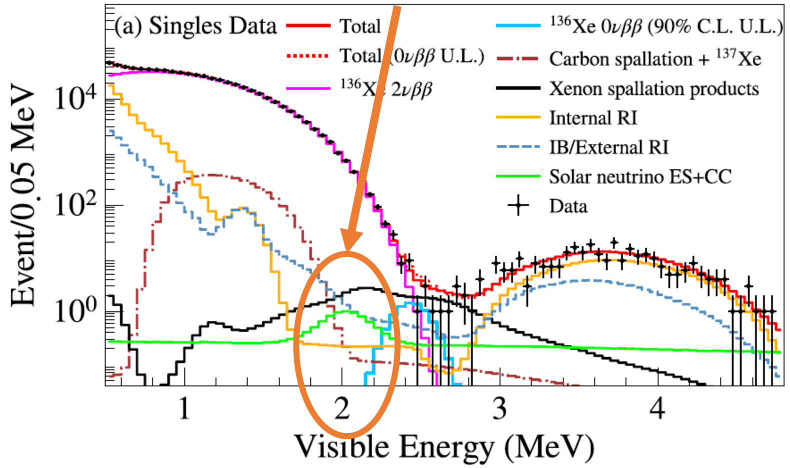
- 1^+ has the highest cross section.
- 5^+ (g.s.) is highly suppressed.

- Solar nue rates [evt/ton$_{Xe136}$/yr]
  - ^{7}Be: 5.9
  - CNO: 0.7
  - pep: 0.57
  - ^{8}B: 0.35

- ^{136}Cs(g.s.)→^{136}Ba is in 0nbb analysis



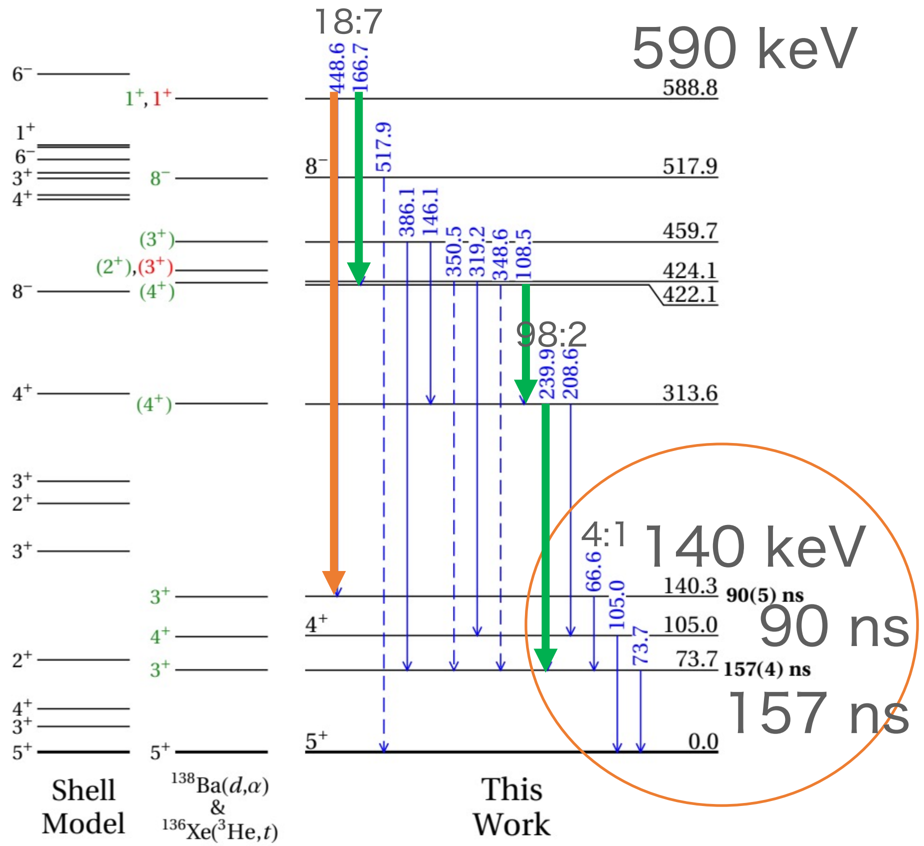
(Mainly) ^{7}Be solar nu origin
^{136}Cs(g.s.)→^{136}Ba



“Observation of low-lying isometric states in ^{136}Cs”

arxiv:2301.11893

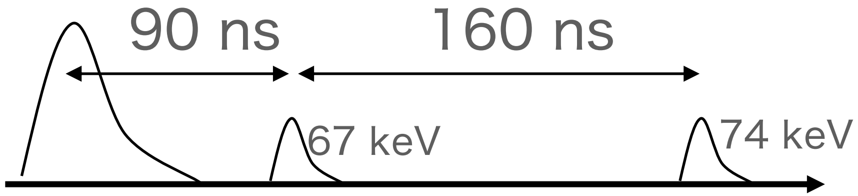
- O(100 ns) states were observed very recently (Jan. 30th).
- 590→140
  - →74→g.s (Mode1: 58%, 90+157 ns)
  - →105→g.s (Mode2: 14%, 90 ns)
- 590→422
  - →314→74→g.s (Mode3: 27%, 157 ns)
- 70 or 140 keV γ’s
  - Less than KamLAND’s trigger threshold
  - More than dark hits
  - Multi-pulses in an event window (~200 ns) can be tagged!!



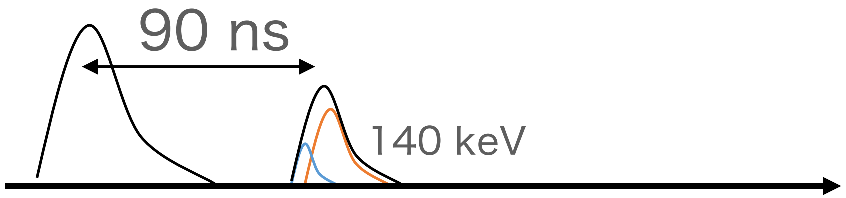
How the signal looks like? (^{7}Be solar ν 860 keV example)

- $E_{1st} = E_{e\text{-kinetic}} + E_{\gamma\text{'s}}$
  $= (860 - 90.2 - 590) + 450$ keV
  $= 630$ keV (~550 keV in Evis)

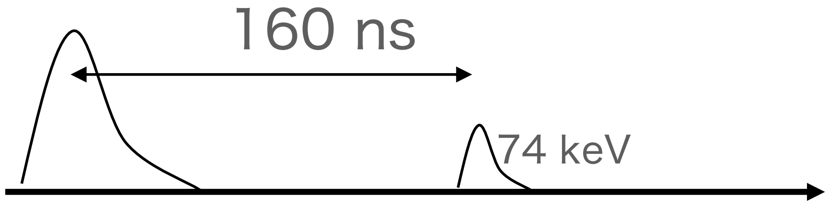
- Mode1: 58%
  - 2nd: 67 keV (90 ns)
  - 3rd: 74 keV (160 ns)



- Mode2: 14%
  - 2nd: (35+105) keV (90 ns)



- Mode3: 27% (E_{1st}+= 67 keV)
  - 2nd: 74 keV (160 ns)



- γ's in Evis
  - 67, 74 keV→ ~50 keV ~12 hits
  - 140 keV→ ~100 keV ~24 hits

*Energies in following slides will be Evis.

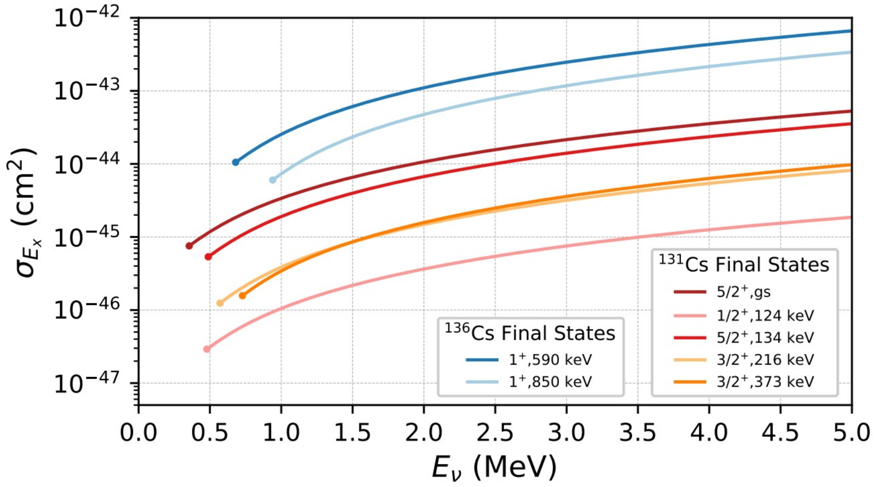
Input parameters

- Solar neutrino fluxes
  - Model: BP16GS98 (so called “highZ”) https://arxiv.org/abs/1611.09867
    - CNO
      - N-13: 2.78e8 /cm^2/s
      - O-15: 2.05e8 /cm^2/s
      - F-17: 5.29e6 /cm^2/s
    - Be-7: 4.93e9 /cm^2/s
    - pep: 1.44e8 /cm^2/s

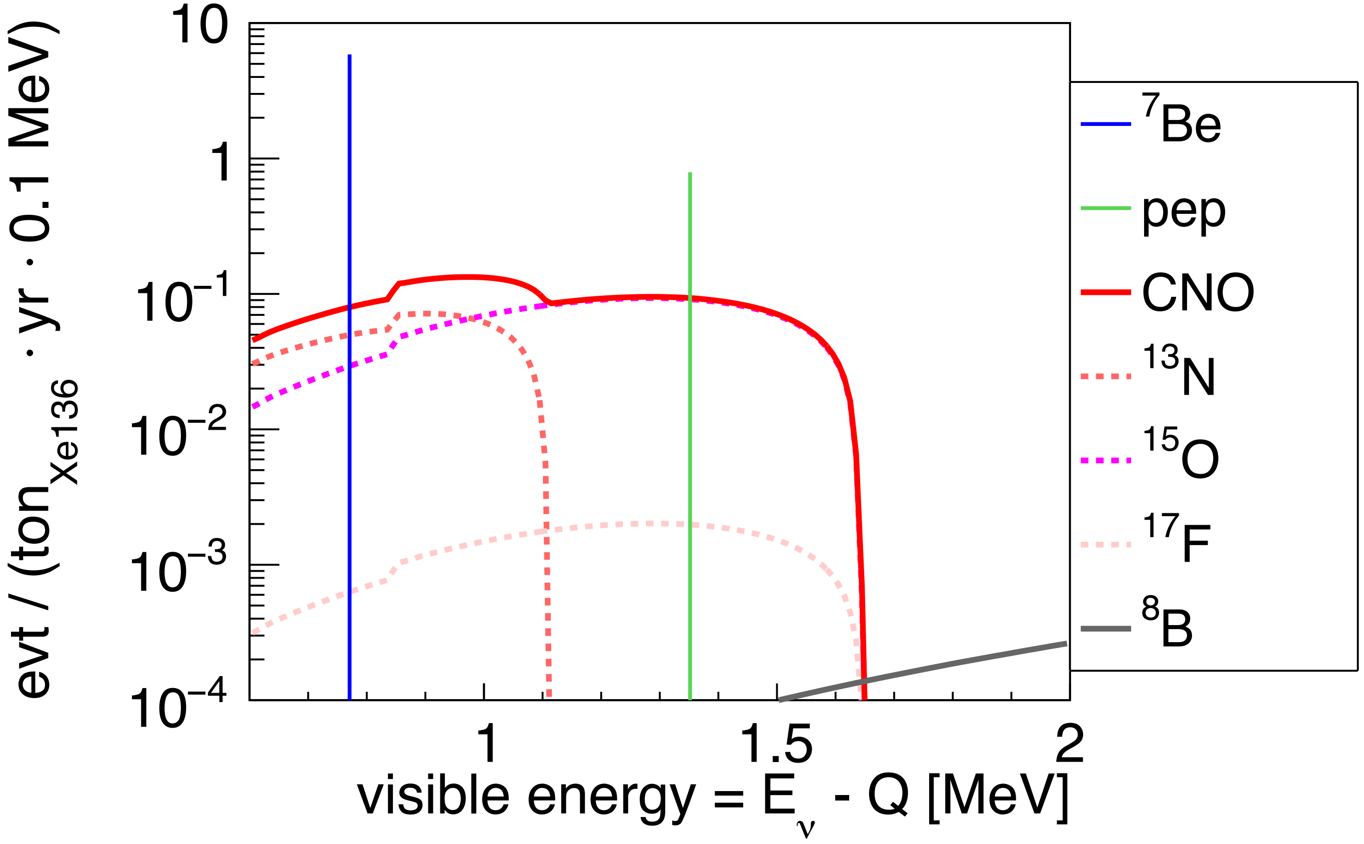
- Oscillation
  - Day-time (osc. in the Sun only)
  - dm^2_21 = 7.51e-5 eV^2
  - sin^2(θ_12) = 0.306
  - sin^2(θ_13) = 0.0219

*Neutrino2020 SK result

- Cross section
  - https://arxiv.org/abs/2009.00535
  - 1+ (590 keV + 850 keV)



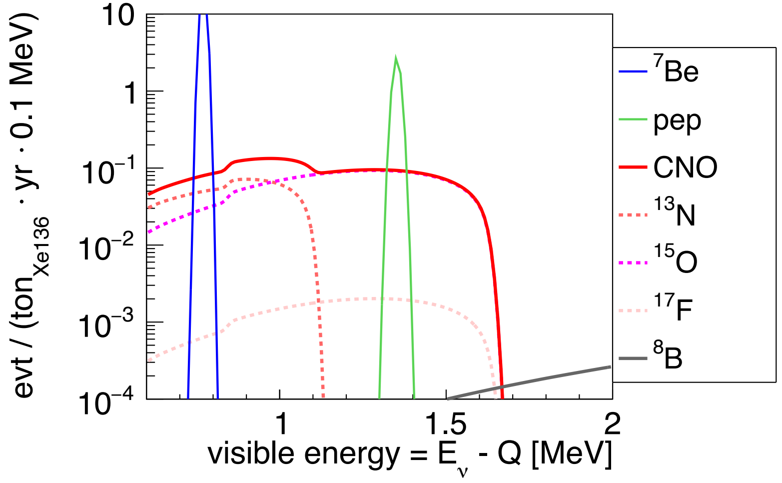
Event rate (wo resolution)



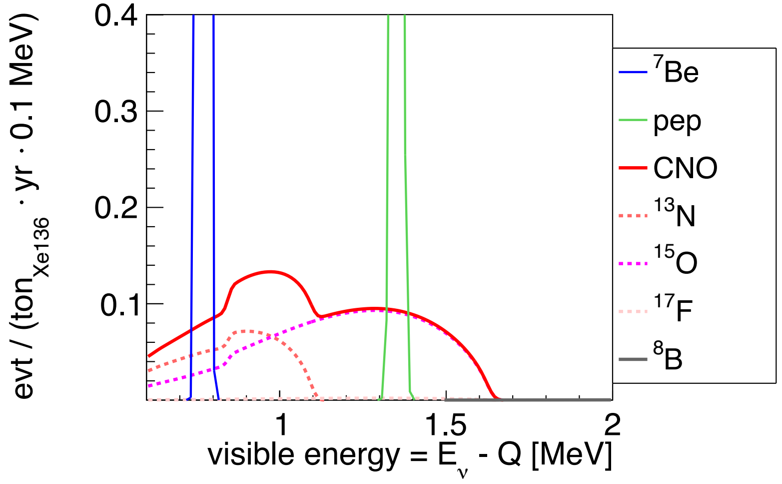
- CNO: 0.917 /yr/ton
- Be-7: 5.87 /yr/ton
- pep: 0.792 /yr/ton

Event rate (sigma = 1%/sqrt(E [MeV]))

Log

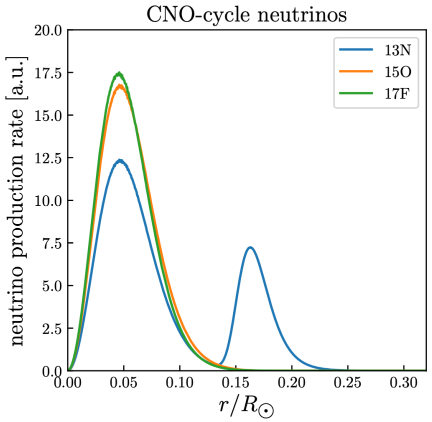


Linear



CNO usable range and rates

- [0.50, 0.73] MeV: 0.090 /yr/ton
- [0.81, 1.31] MeV: 0.553 /yr/ton
- [1.39, 1.80] MeV: 0.152 /yr/ton
- usable total: 0.800 /yr/ton (87%)



arXiv:2209.14832

Ultimately we can measure N-13 and O-15 separately?

Their production position dist. are different.