Search for neutrinoless quadruple β decay of ^{136}Xe in XMASS-I

2205.05231,
submitted for PLB

Kentaro Miuchi (Kobe University)
for the XMASS collaboration
2022 July 21st

Contents

- Introduction
- Experiment
- Quadruple β decay search
- Summary

Introduction

Introduction: neutrinoless quadruple decay ($0\nu4\beta$)

- Bunch of $0\nu2\beta$ searches.

Plenary Sessions #8:

08:30 - 09:00 (25'+5') **KamLAND-Zen 800**
Hideyoshi Ozaki (Tohoku University, Sendai)

09:00 - 09:30 (25'+5') **The NEXT program for neutrinoless double beta searches**
Francesc Monrabal (Donostia International Physics Center, San Sebastian)

09:30 - 10:00 (25'+5') **Status of the AMoRE experiment**
Seung Cheon Kim (Institute of Basic Science, Daejeon)

10:00 - 10:30 Coffee Break

Plenary Sessions #9:

10:30 - 11:00 (25'+5') **Latest results from the CUORE experiment**
Chiara Capelli (LBNL, Berkeley)

11:00 - 11:30 (25'+5') **The CUPID Project**
Mattia Beretta (University of California Berkeley)

11:30 - 12:00 (25'+5') **Status of the high pressure Xe gas TPC 0νββ experiment AXEL**
Shinichi Akiyama (Tohoku University, Sendai)

09:00 - 09:30 (25'+5') **nEXO, search for 0νββ beyond 10^{28} years**
Julien Masbou (Subatech, Nantes)

09:30 - 10:00 (25'+5') **The LEGEND experiment**
Felix Hagemann (Max-Planck-Institut für Physik, Munich)

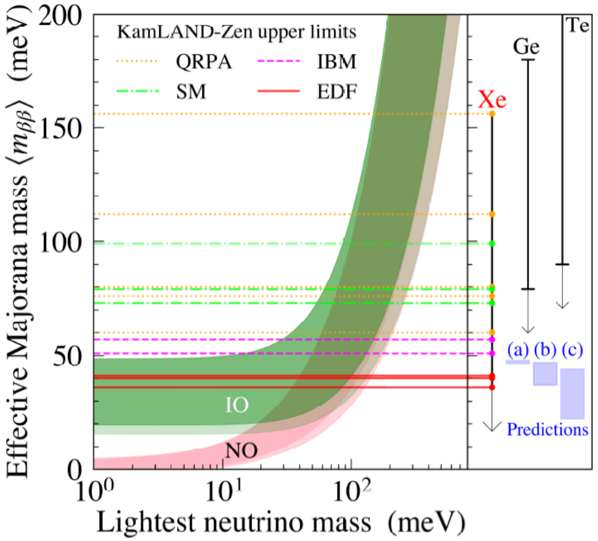
10:00 - 10:30 Coffee Break

Plenary Session #11

10:30 - 11:00 (25'+5') **Commissioning of the SuperNEMO Demonstrator**
Malak Hoballah (IJCLab, Orsay)

11:00 - 11:30 (25'+5') **Revealing the nature of neutrinos with XENON direct dark matter detector and future perspectives**
Maxime Pierre (Subatech, Nantes)

11:30 - 12:00 (25'+5') **Status and perspectives of the DarkSide experimental program**
Claudio Savarese (Princeton University)



KamLAND-Zen paper
2203.02139v1

- Discoveries may be around the corner, in case neutrinos are Majorana particles...

- What is neutrinos are Dirac particles?

- Discoveries may be around the corner,
  in case neutrinos are Majorana particles…

- What is neutrinos are Dirac particles?

lepton flavor violating

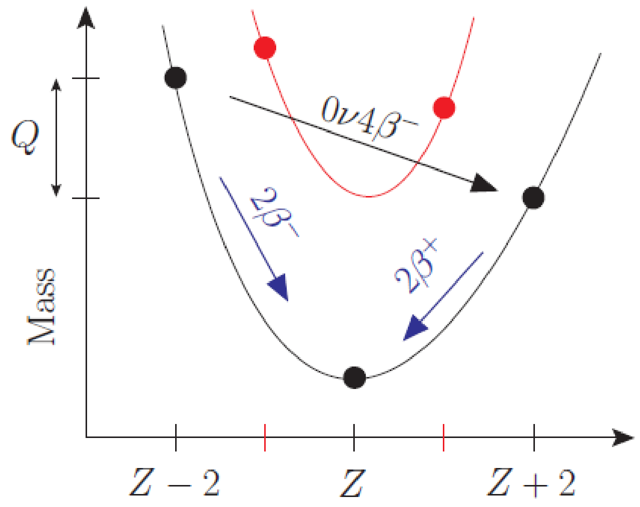
- $0\nu 2\beta$ doesn’t happen, but $0\nu 4\beta$ still can.

Neutrinoless Quadruple Beta Decay
Julian Heeck, Werner Rodejohann
EPL 103 (2013) 32001, 1306.0580

- Discoveries may be around the corner, in case neutrinos are Majorana particles…

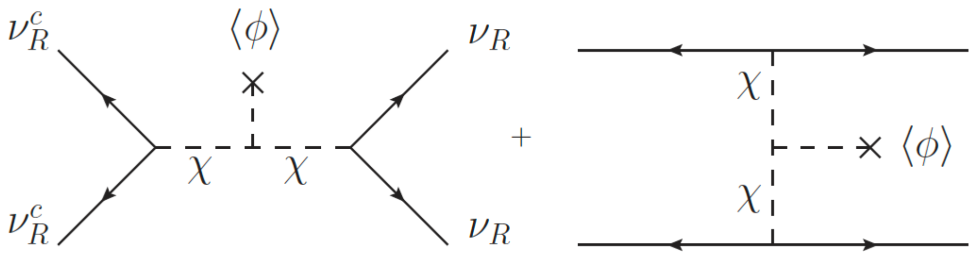
- diagrams, mass levels

energy level example



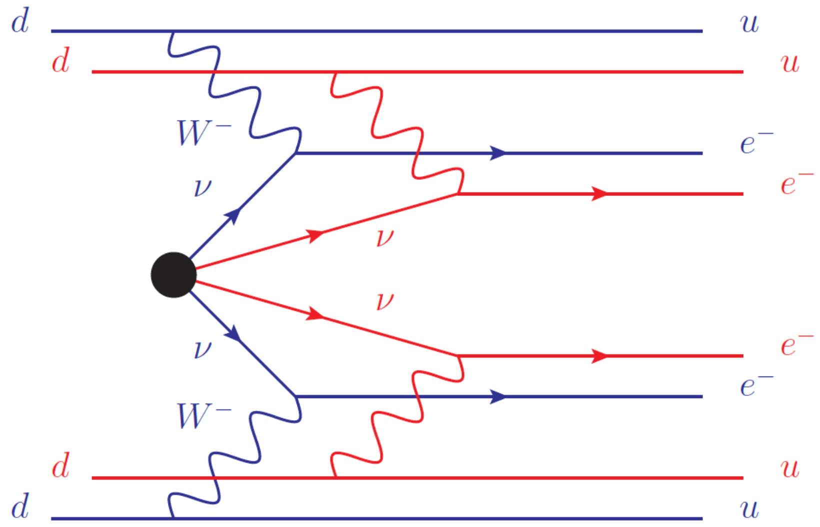
EPL, 103 (2013) 32001

⊿L=4 scattering diagrams



EPL, 103 (2013) 32001

0 ν 4 β decay diagram



EPL, 103 (2013) 32001

- ⊿L = 4 linked to
  - Naturally light Dirac mass terms of neutrinos
    - Chen, Ratz,Staudt,Vaudrevange, Nucl.Phys.B 866 157 (2013)
  - CP violation
    - Chuli,Srivastava,Valle, Phys.Lett.B 761,431 (2016)
  - Dark Matter candidates
    - Chuli,Ma,Srivastava,Valle, Phys.Lett.B 767 209 (2017)
  - Leptogenesis
    - Heeck, Phys.Rev.D 88, 076004 (2013)

- ⊿L=4 candidates

	$Q_{0\nu4\beta}$	Other decays	natural abundance
$^{96}_{40}Zr \to ^{96}_{44}Ru$	0.629	$\tau^{2\nu2\beta}_{1/2} \simeq 2 \times 10^{19}$	2.8
$^{136}_{54}Xe \to ^{136}_{58}Ce$	0.044	$\tau^{2\nu2\beta}_{1/2} \simeq 2 \times 10^{21}$	8.9
$^{150}_{60}Nd \to ^{150}_{64}Gd$	2.079	$\tau^{2\nu2\beta}_{1/2} \simeq 7 \times 10^{18}$	5.6
	$Q_{0\nu4EC}$		
$^{124}_{54}Xe \to ^{124}_{50}Sn$	0.577	—	0.095
$^{130}_{56}Ba \to ^{130}_{52}Te$	0.090	$\tau^{2\nu2EC}_{1/2} \sim 10^{21}$	0.106
$^{148}_{64}Gd \to ^{148}_{60}Nd$	1.138	$\tau^{\alpha}_{1/2} \simeq 75$	—
$^{154}_{66}Dy \to ^{154}_{62}Sm$	2.063	$\tau^{\alpha}_{1/2} \simeq 3 \times 10^{6}$	—
	$Q_{0\nu3EC\beta+}$		
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EPL, 103 (2013) 32001

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	[illegible]		
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150Nd: $T_{1/2}$ > (1.1–3.2) × 10^{21}
by NEMO-3 (PRL 119, 041801 (2017))

EPL, 103 (2013) 32001

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by NEMO-3 (PRL 119, 041801 (2017))

EPL, 103 (2013) 32001

136Xe:
Q value was updated in
Chinese Physics C 41 (3) (2017) 030003, 41 (3)

A	Elt.	Z	S(n)		S(p)		Q(4β⁻)	
136	In	49	2050#	570#	*		39040#	400#
	Sn	50	3340#	300#	16660#	500#	30530#	300#
	Sb	51	2888	6	11164	7	21832	6
	Te	52	4767.8	2.9	12024	3	14461.7	2.3
	I	53	3837	14	9105	14	6490	60
	Xe	54	8087	4	9939.0	2.1	79.2	0.4
	Cs	55	6828.4	2.1	7215	4	−4998	12
	Ba	56	9107.74	0.04	8594.2	1.0	−9688	12
	La	57	7470	50	5480	50	−14870	90
	Ce	58	9964	10	7154	9	−19697	13
	Pr	59	8476	16	4013	15	−25100#	200#
	Nd	60	11057	22	5552	17	−30110#	300#
	Pm	61	9190	100	2250	70	−35040#	510#
	Sm	62	12020	160	4050	80	*	
	Eu	63	10170#	280#	680#	250#	*	
	Gd	64	12770#	500#	2230#	360#	*	
	Tb	65	11380#	640#	−970#	640#	*	

⇒ search for a 79keV peak

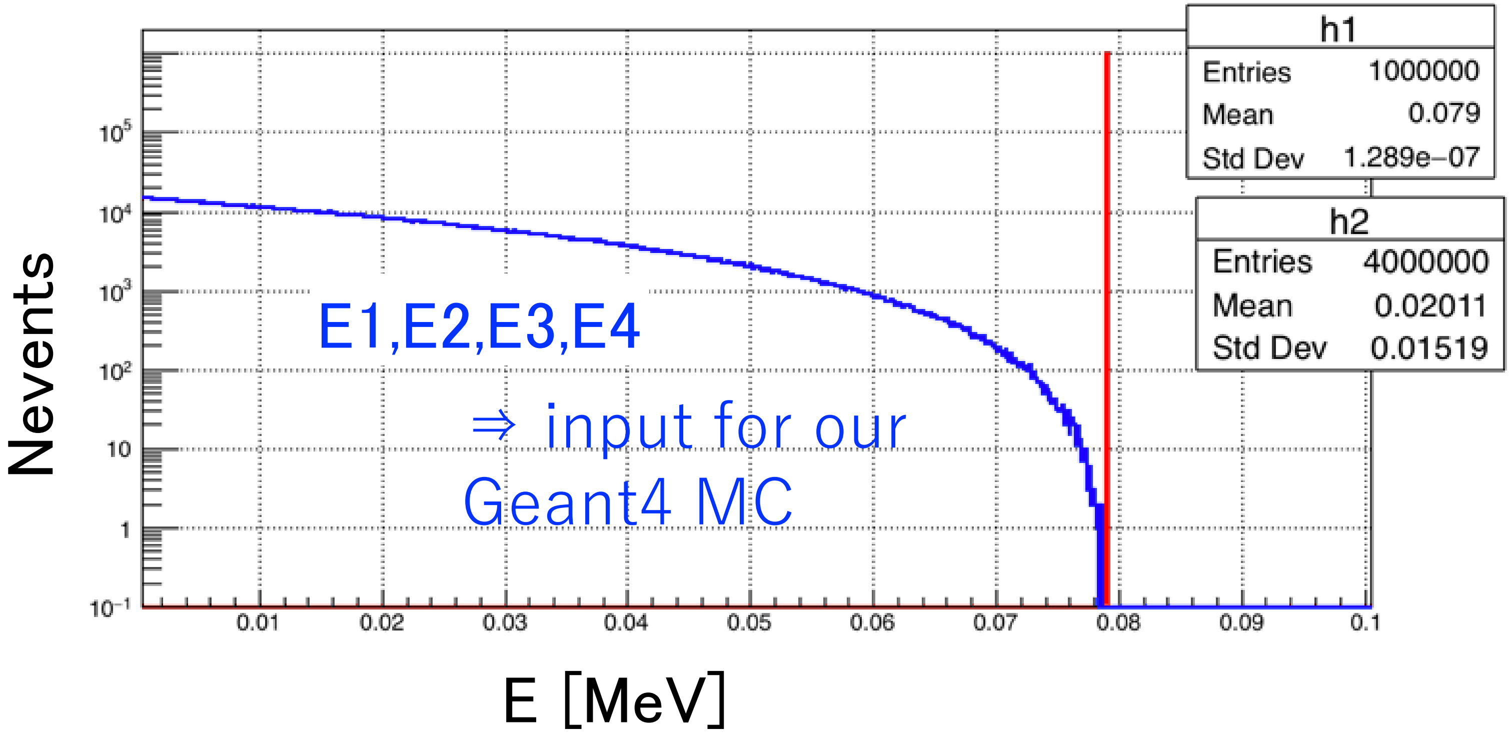
- 136Xe 0ν4β signal
  - Energy of each electron was calculated by Decay0/GENBB for

NEMO note
3.04.2016

New possibilities in the DECAY0/GENBB code:
$4\beta0\nu$ decay and $2\beta2\nu$ decay with Lorentz violation

Vladimir I. Tretyak
Institute for Nuclear Research, MSP 03680 Kyiv, Ukraine

can handle:
96Zr, 136Xe and 150Nd (4β)
124Xe, 130Ba (4EC)

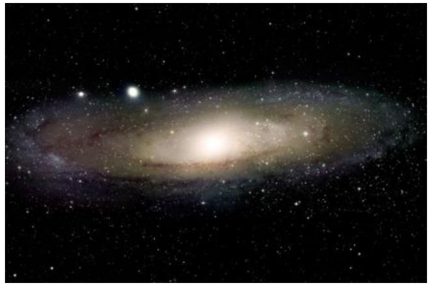


E1+E2+E3+E4(peak@79 keV)

Experiment

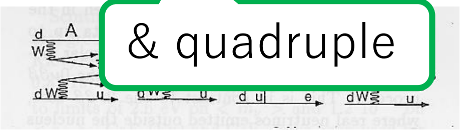
XMASS-I experiment

- Unique experiment
  - Single phase (use scintillation photon only) liquid xenon detector.
  - Long stable observation period, 5 years
    - 2013/11~2019/2
  - large light yield ~14pe/keV and low threshold ~1keVee
- Variety of rare events search with large amount of xenon (~1 ton)
  - Dark matter, modulation, low mass, inelastic, hidden photon
  - solar axion, 2νECEC, GW, exotic neutrino interaction
- Wide variety results are quite important for present dark matter search

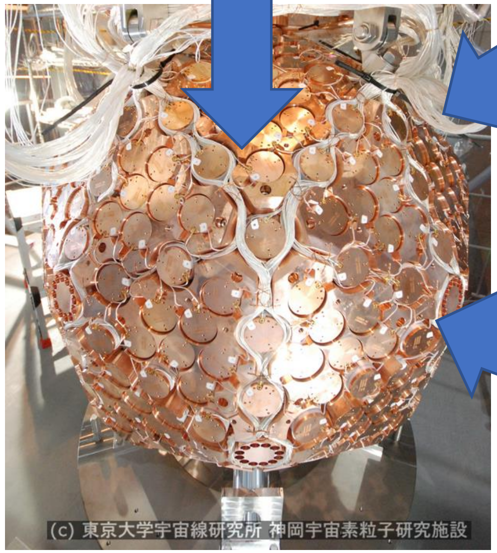


Dark matter

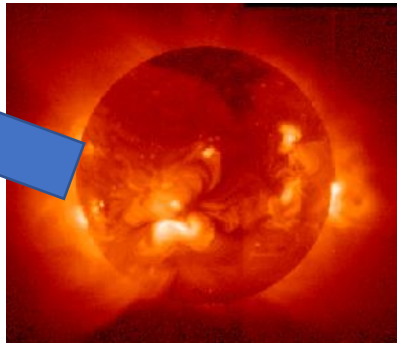
Neutrino-less double beta decay



& quadruple



Solar neutrino



2010	2011	2012	2013	2014	2015	2016	2017	2018	2019

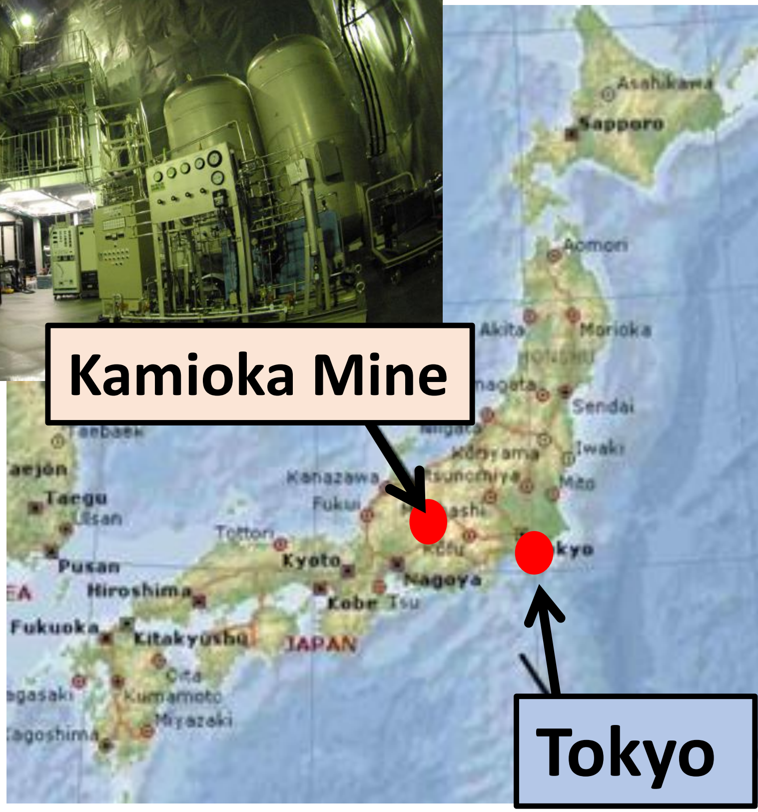
Detector construction → Commissioning run data taking → Detector refurbishment → Data taking (-Feb.2019)

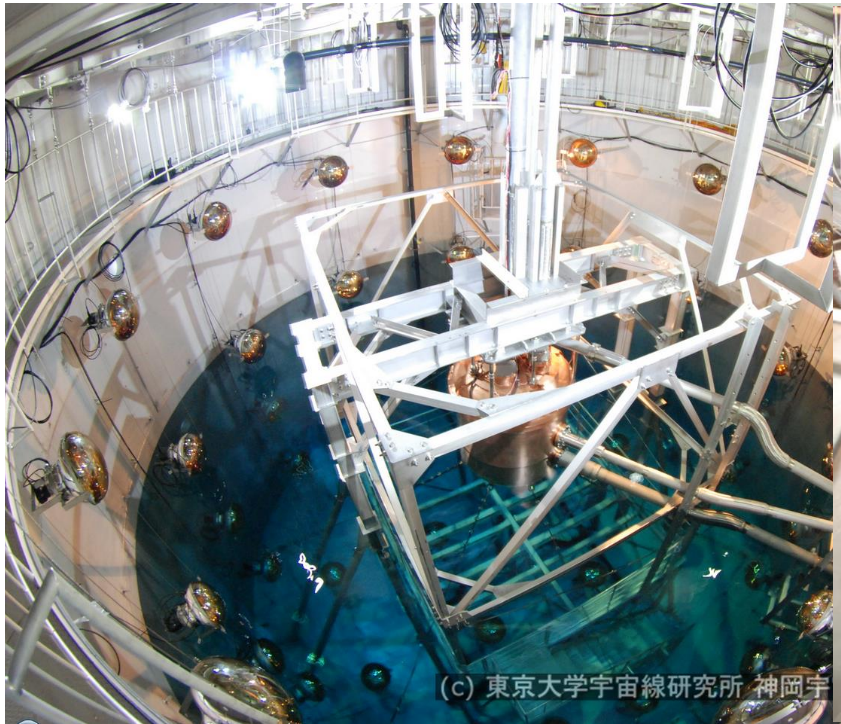
>5yrs continues operation

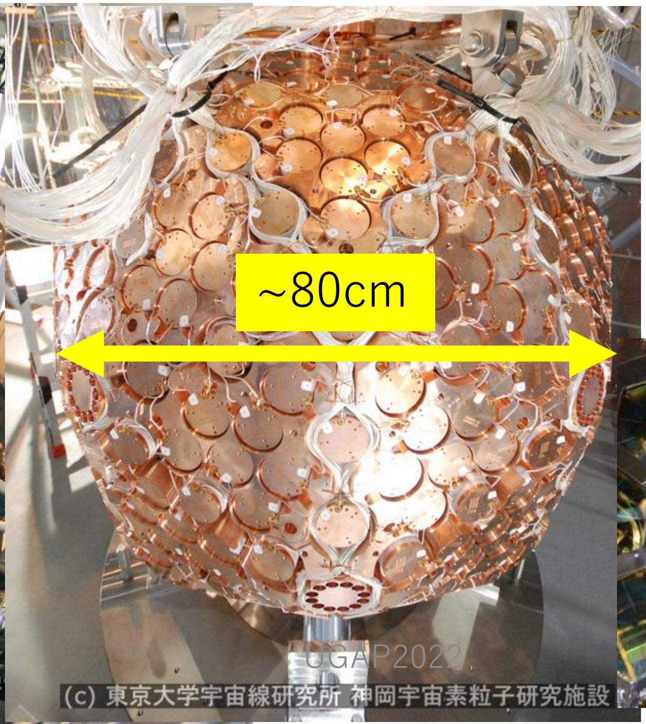
XMASS detector NIM A 716 (2012) 78

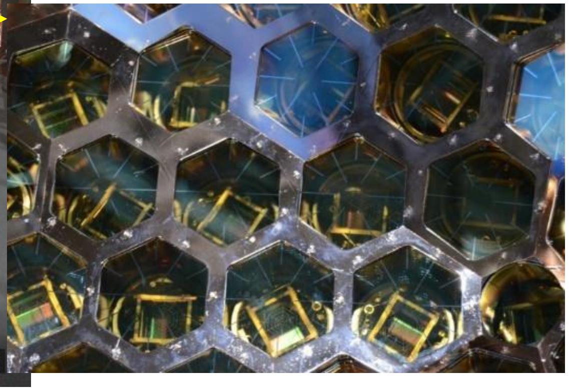
- Kamioka Observatory (~2700m.w.e.), Japan.
- 832kg (Φ~80cm) liquid xenon for active volume.
- ~2inch PMT (hex and round shape) ×642 : 62% photo-coverage
- 10x10m water tank for muon veto with 20 inch PMT×70.

Japan









XMASS pioneered...

- water-tank style veto
- many physics channels

Search for solar Kaluza–Klein axions by annual modulation with the XMASS-I detector

XMASS Collaboration*
N. Oka[7], K. Abe[1,5], K. Hiraide[1,5], K. Ichimura[1,5],

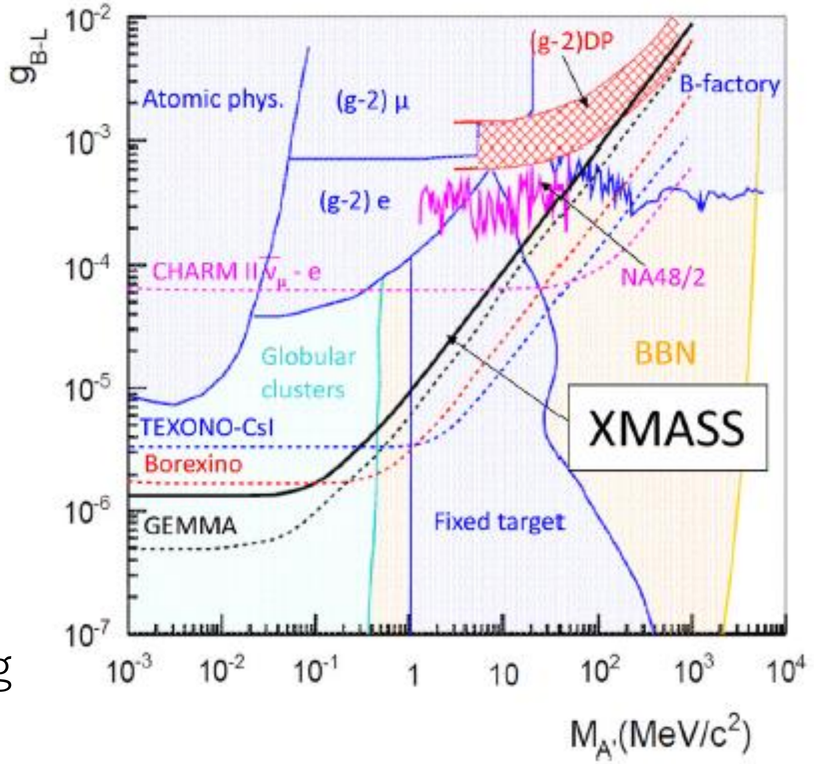
PTEP(2017) 103C01

Search for exotic neutrino-electron interactions using solar neutrinos in XMASS-I

XMASS Collaboration *

PLB 809 (2020) 135741

neutrino magnetic moment < $1.8 \times 10^{-10} \mu_B$



dark photon coupling
(U(1)B-L symmetry)

PTEP(2018) 053D03

PTEP

Prog. Theor. Exp. Phys. **2018**, 053D03 (15 pages)
DOI: 10.1093/ptep/pty053

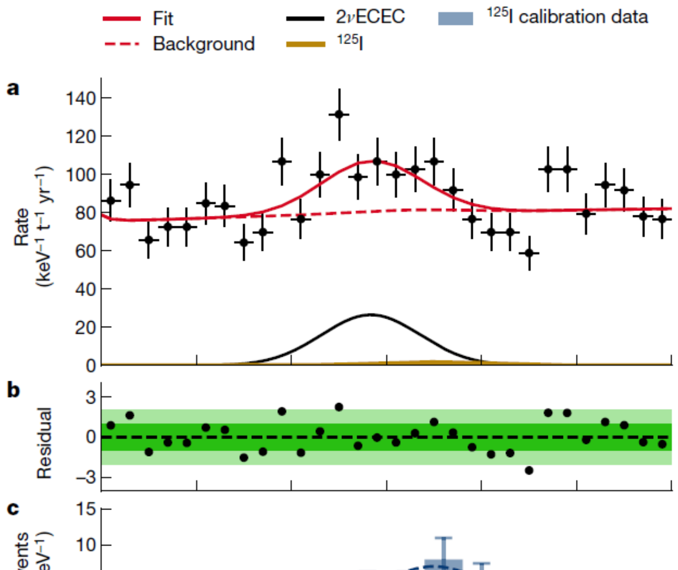
Improved search for two-neutrino double electron capture on ^{124}Xe and ^{126}Xe using particle identification in XMASS-I

$T_{1/2} > 2.1 \times 10^{22}$ years (90%C.L.)

Observation of two-neutrino double electron capture in ^{124}Xe with XENON1T

XENON Collaboration*

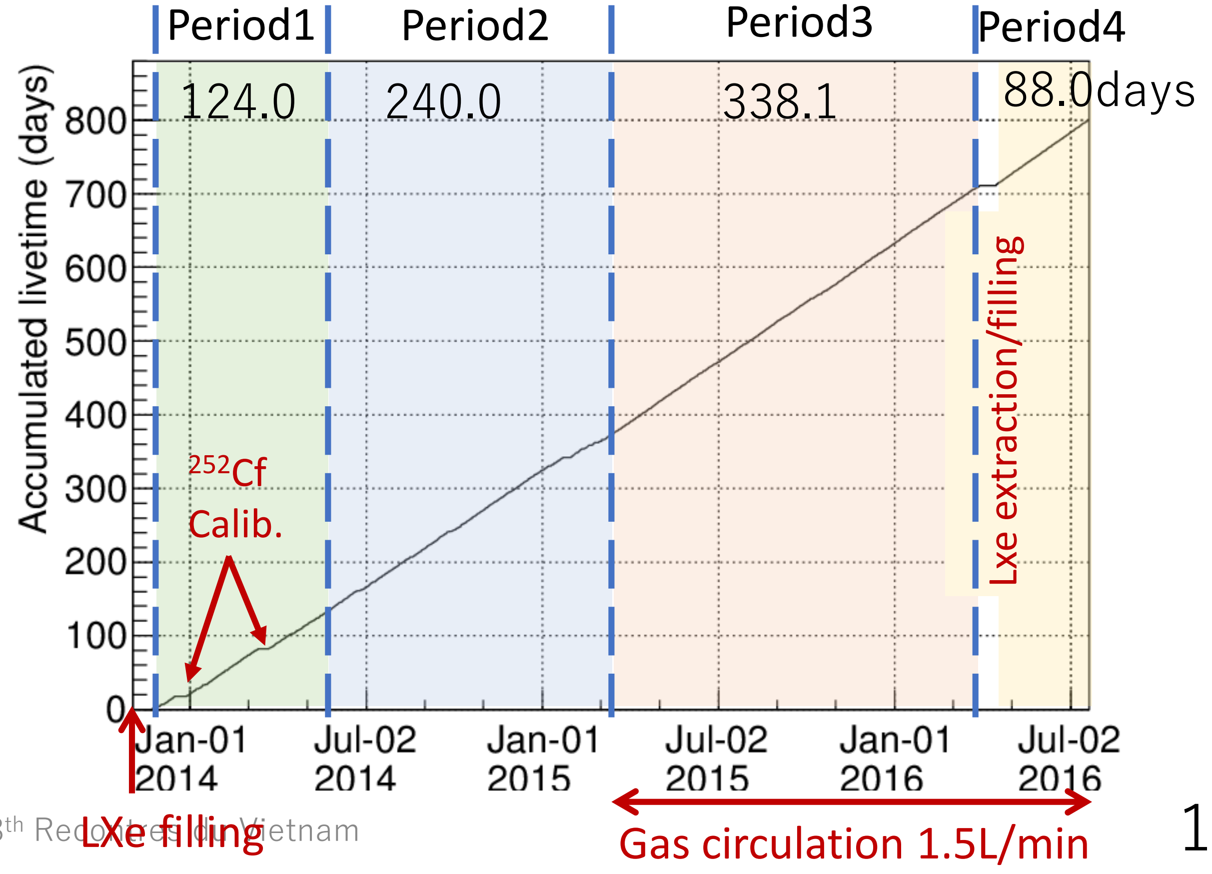
532 | NATURE | VOL 568 | 25 APRIL 2019



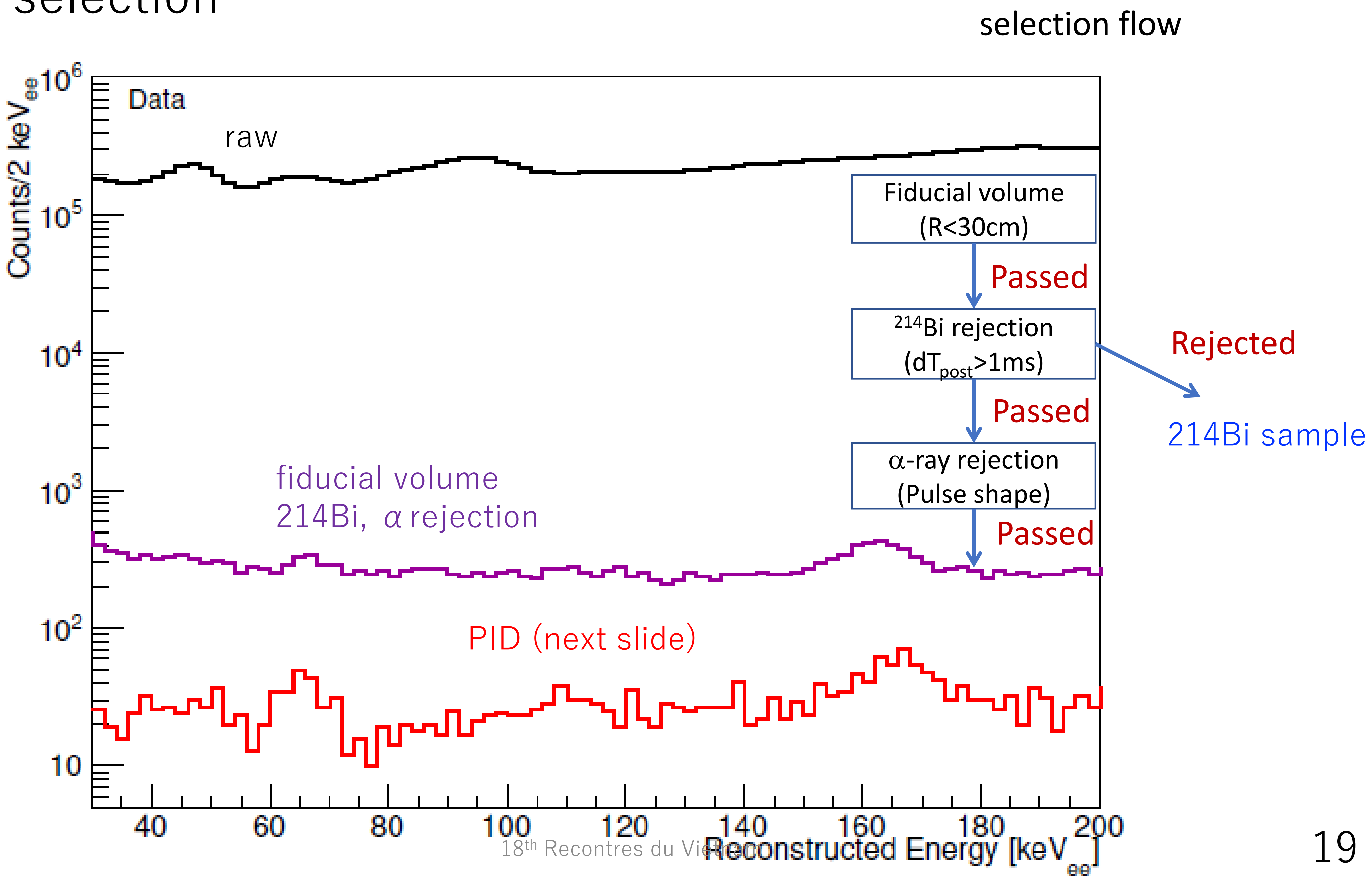
$T_{1/2} = 1.8 \times 10^{22}$ years

Quadruple β decay search

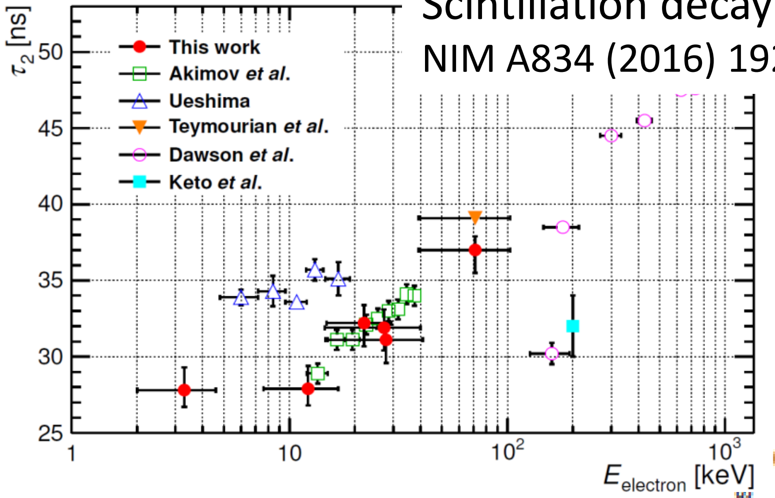
- Data set
  - Data acquisition: November 2013 to July 2016
    - first half of the “full data”
    - 4 periods
  - Fiducial volume: r<30cm
  - Exposure: 327kg(LXe) × 800days (136Xe, 29kg)



- Event selection



- PID (4 β selection by "β CL")
  - Decay time depends on the electron energy
    ⇒ discriminate β (one electron) and γ (multiple electrons of lower energies) by "β CL"



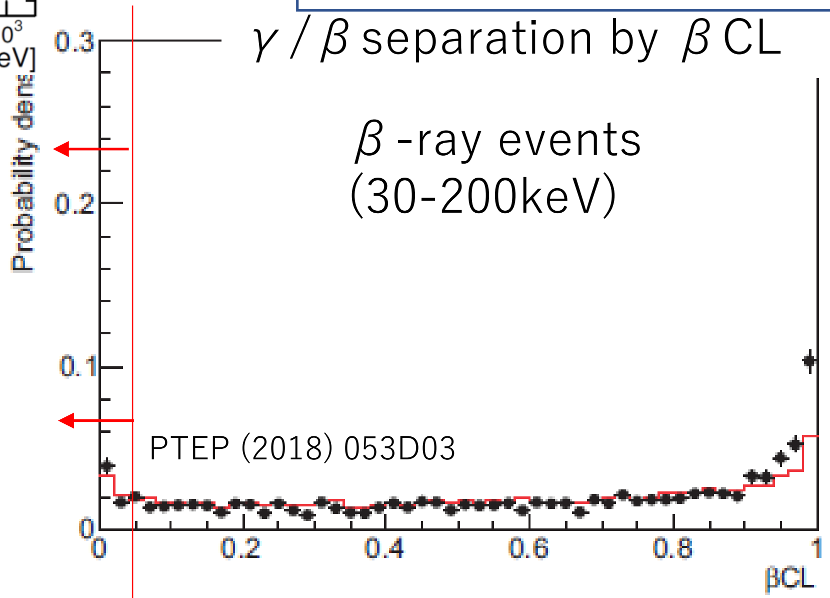
Scintillation decay time
NIM A834 (2016) 192

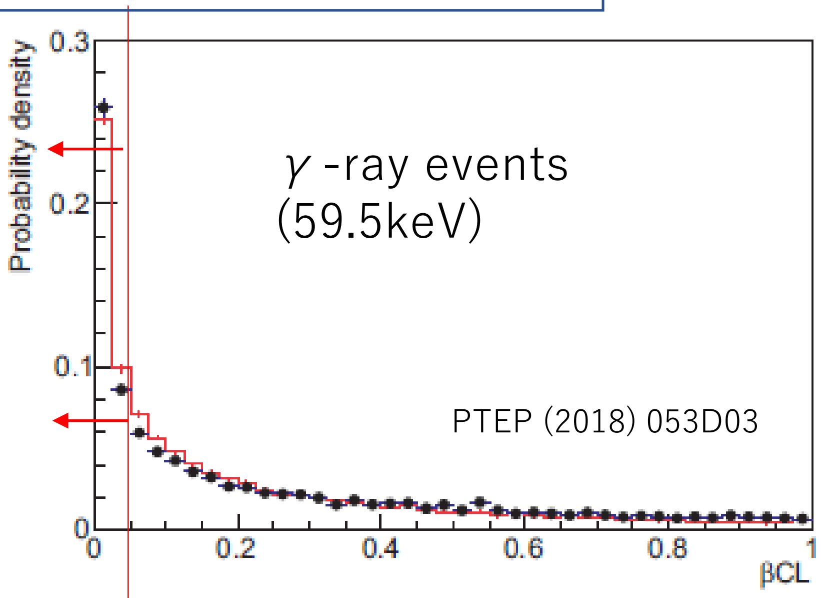
$$\beta\mathrm{CL} = P\sum_{k=0}^{N-1}\frac{(-\ln P)^k}{k!} \quad \left(P = \prod_{k=0}^{N-1}\mathrm{CDF}_\beta(E, t_k)\right) , \qquad (3)$$

N: number of PMTs with pulses
tk: timing of k-th pulse
CDF: cumulative distribution function for a β-ray of energy E to find a pulse at t

single β : uniform in 0-1
others(including 0 ν 4 β) : peak at 0

γ / β separation by β CL

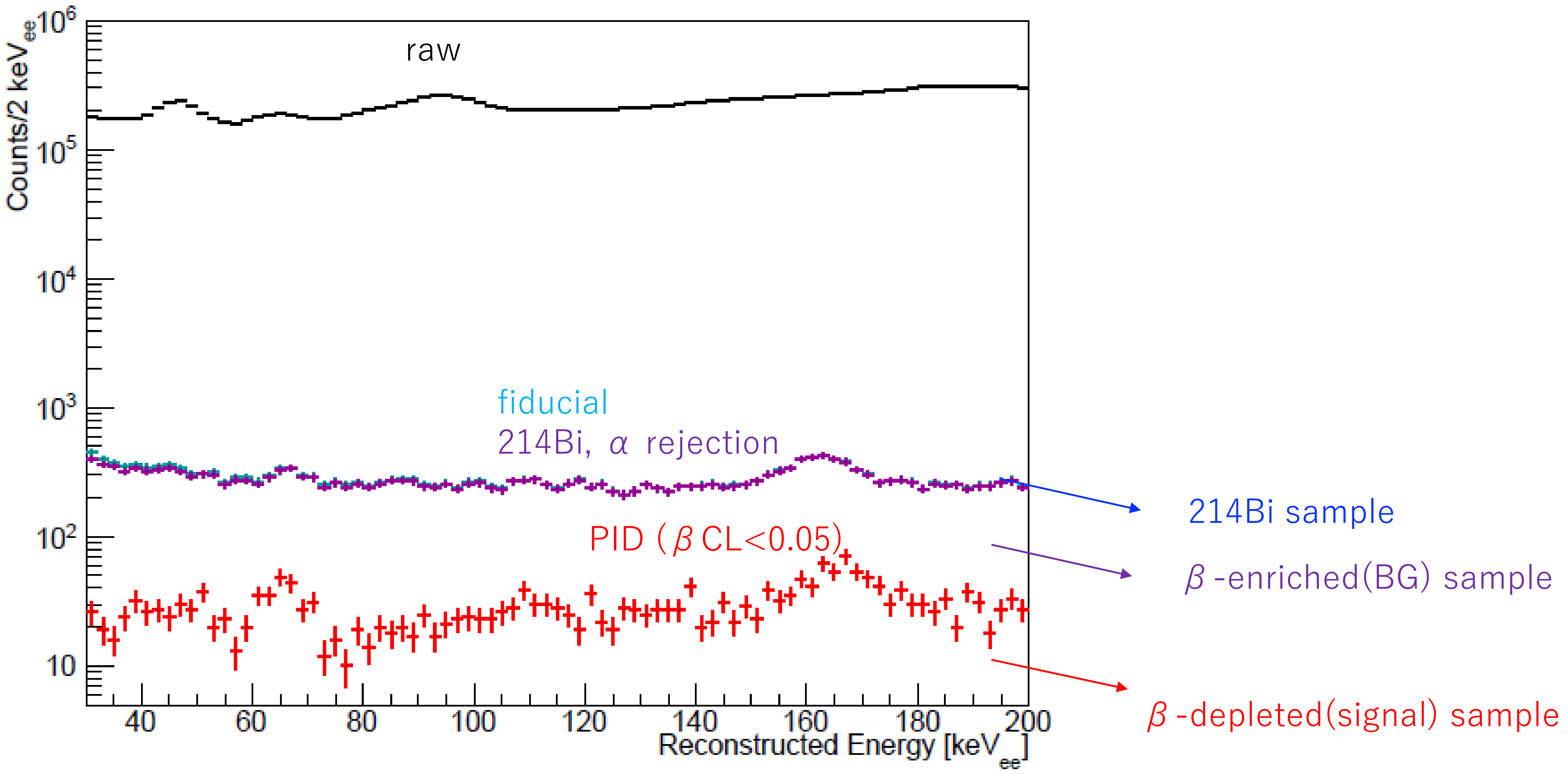




β CL>0.05:
β -enriched (BG) sample

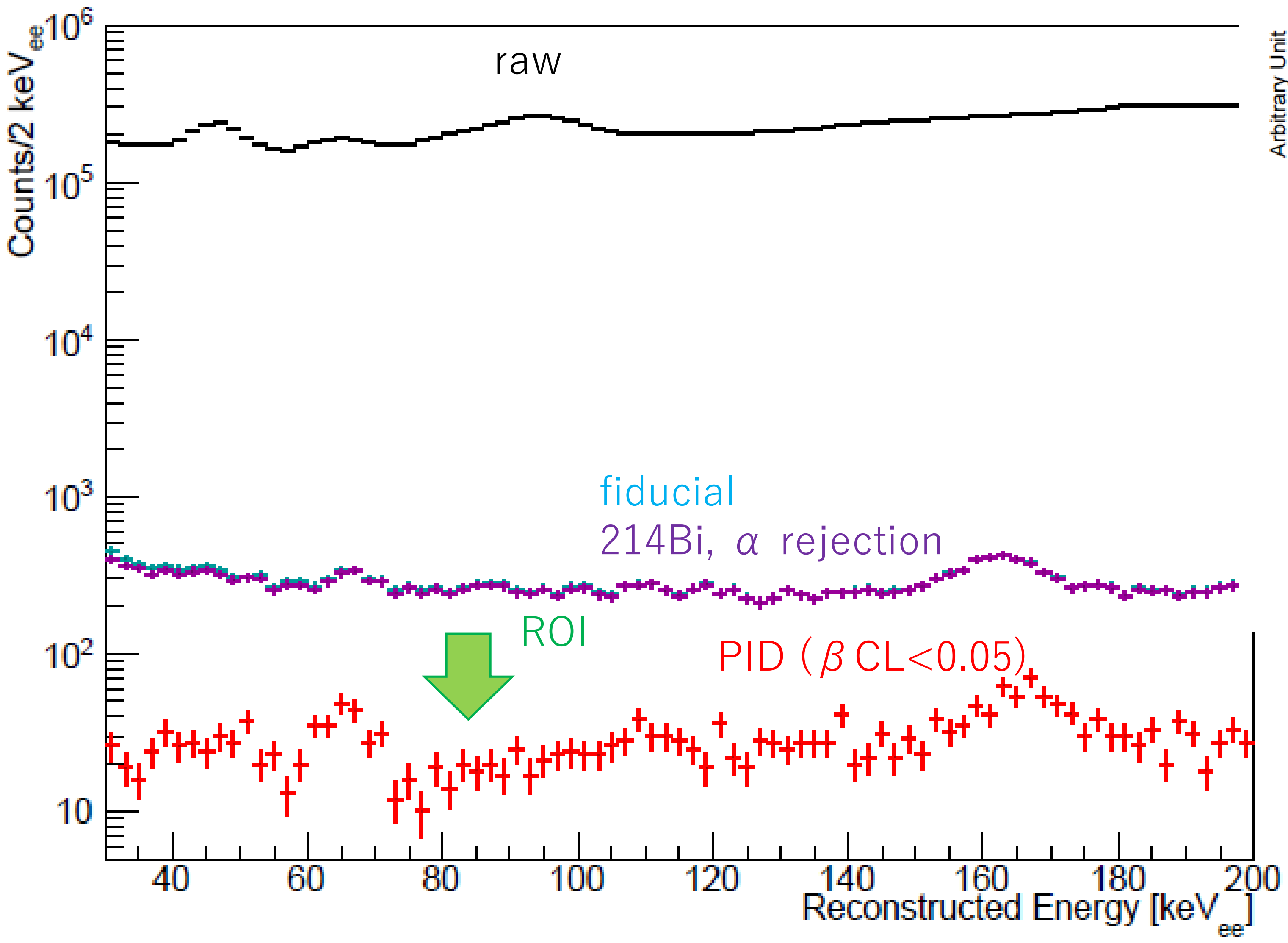
β CL<0.05 :
β -depleted (signal) sample

- “Samples“

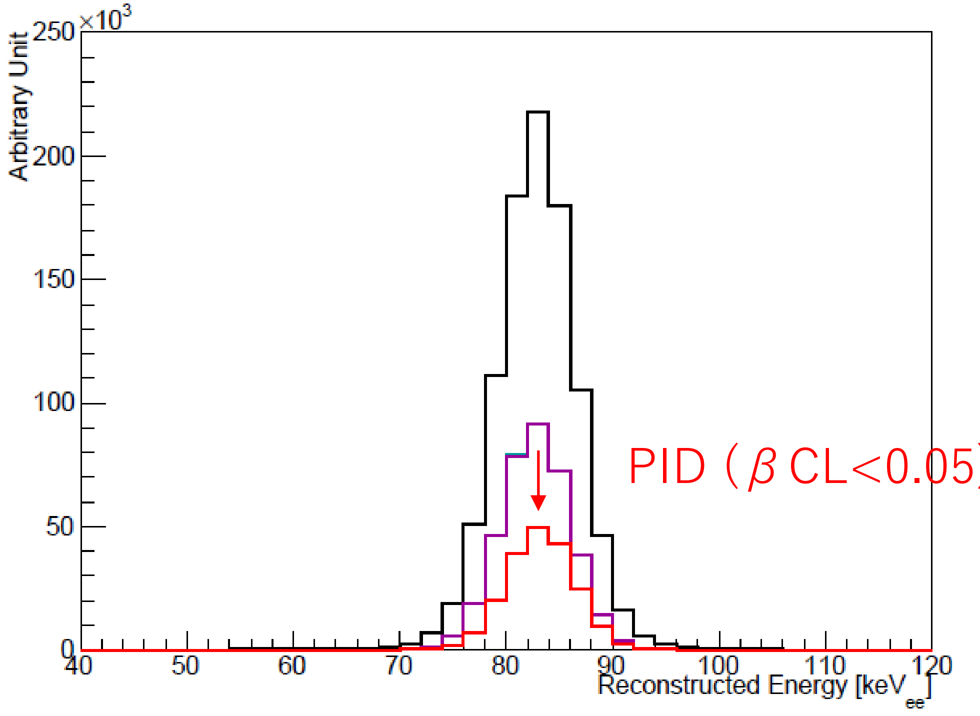


raw
fiducial
214Bi, α rejection
PID (β CL<0.05)
214Bi sample
β -enriched(BG) sample
β -depleted(signal) sample
Counts/2 keV$_{ee}$
10^6
10^5
10^4
10^3
10^2
10
40
60
80
100
120
140
160
180
200
Reconstructed Energy [keV$_{ee}$]

- Selected events and signal shape



expected signal (MC)

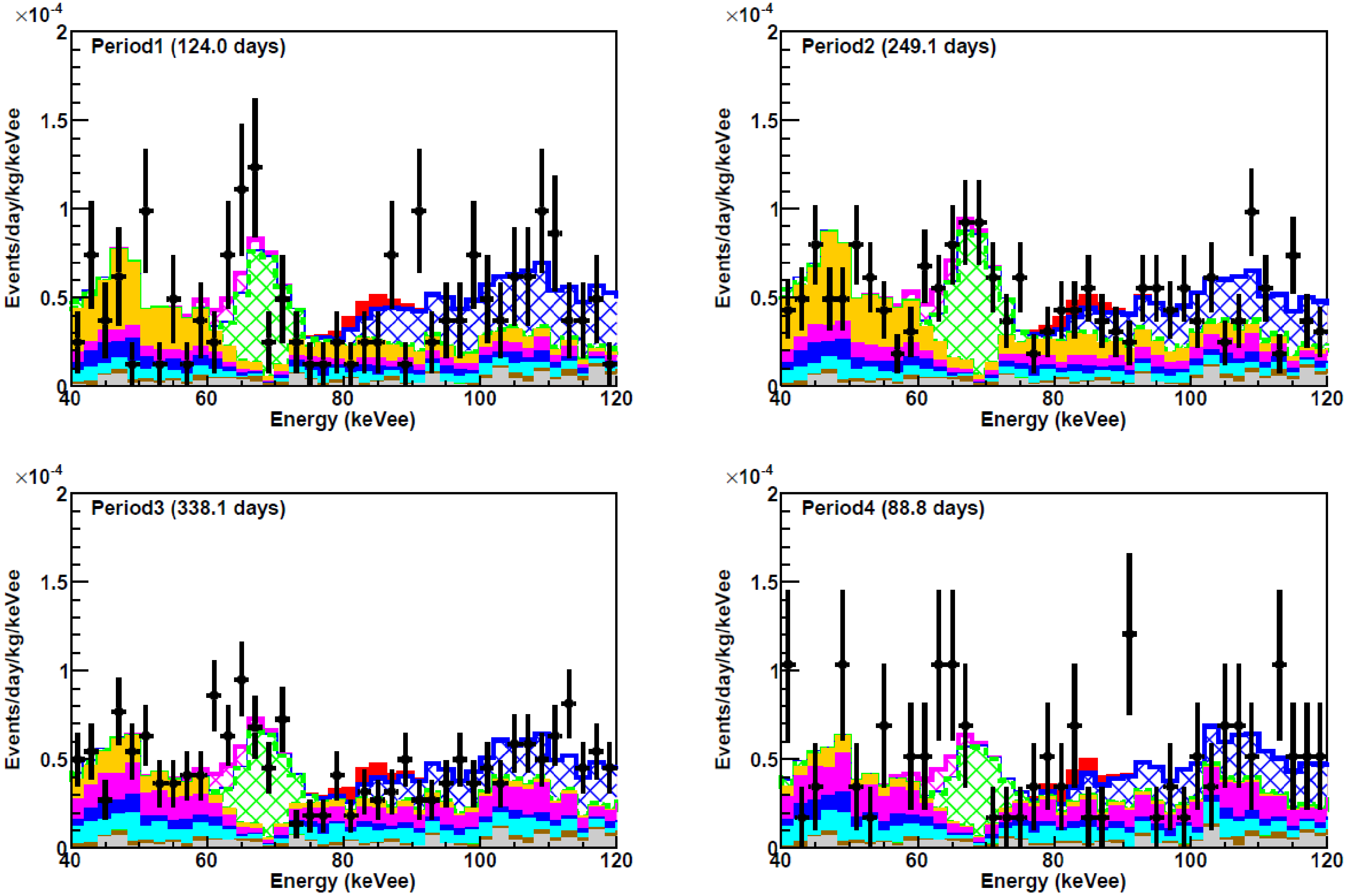


efficiencies:

$0\nu4\beta$	53±16 %	remain
β (214Bi)	94±2 %	rejection

S/N enhancement ~9

- results
  - data(black): count rate ~10^{-4} counts/day/kg/keVee
  - BG(color): will be discussed in the following slides.



data
136Xe 0ν4β
(90% C.L. upper limit)

126Xe 2e capture (hatched)
125I
133Xe (hatched)
14C
39Ar
85Kr (filled)
214Pb
136Xe 2νββ
external gamma

- signal+BG fitting

$$\chi^2 = -2\ln L$$
$$= 2\sum_{i=1}^{N_{\rm sample}}\sum_{j=1}^{N_{\rm subset}}\sum_{k=1}^{N_{\rm bin}}\left[n_{ijk}^{\rm MC}(\{p_l^{\rm const}\},\{p_m^{\rm free}\}) - n_{ijk}^{\rm data} + n_{ijk}^{\rm data}\ln\frac{n_{ijk}^{\rm MC}(\{p_l^{\rm const}\},\{p_m^{\rm free}\})}{n_{ijk}^{\rm data}}\right] + \sum_{l=1}^{N_{\rm sys}}\frac{(1-p_l^{\rm const})^2}{\sigma_l^2}, \quad (4)$$

expected

constrained and free parameters

measured

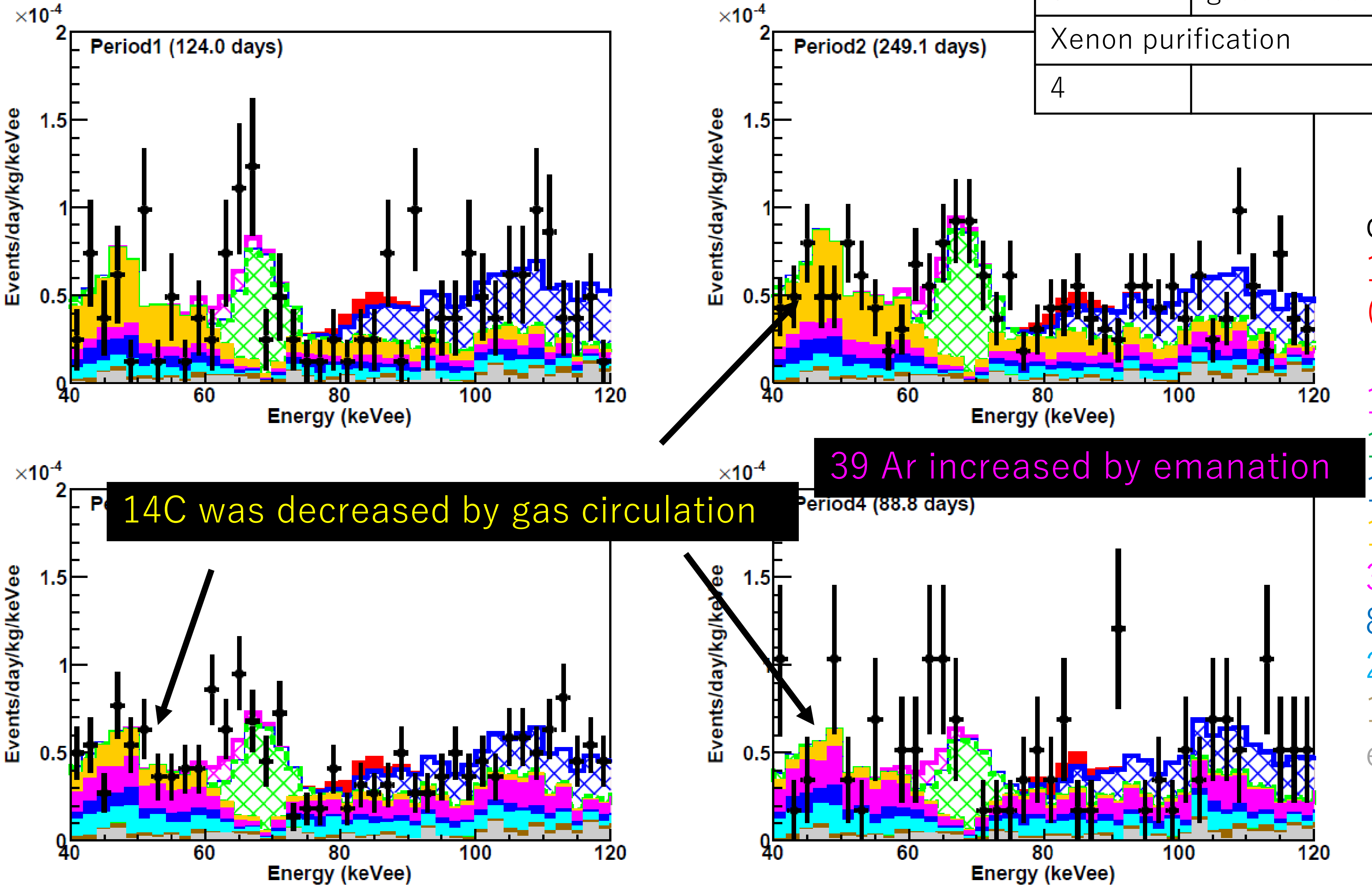
parameter uncertainties

i :sample ID (β -depleted, β -enriched, 214Bi)
j: period (1-4)
k: energy bin (1-85)

Item	Fractional uncertainty for each item
^{238}U γ-rays BG from PMTs	±9.4%
^{232}Th γ-rays BG from PMTs	±24%
^{60}Co γ-rays BG from PMTs	±11%
^{40}K γ-rays BG from PMTs	±17%
^{85}Kr abundance in LXe	±23%
Thermal neutron flux	±27%
Isotopic abundance of ^{136}Xe	±1.3%
Fiducial volume	±4.5%
Energy scale for β-depleted sample	±2.0%
Energy scale for β-enriched sample	±2.0%
γ acceptance	±30%
Event increase due to dead PMT	
for $30 \leq E \leq 35$ keV$_{ee}$	(7 ± 14 %)
for $35 \leq E \leq 40$ keV$_{ee}$	(19 ± 16 %)
β mis-ID	Energy dependent as shown in Fig.2

- BG interpretation with gas conditions

Period	
1	252Cf calibrations
2	started 60 days after the 252Cf calibration
3	gas circulation (w/ hot getter) started
Xenon purification	
4	



- BG interpretation with activations

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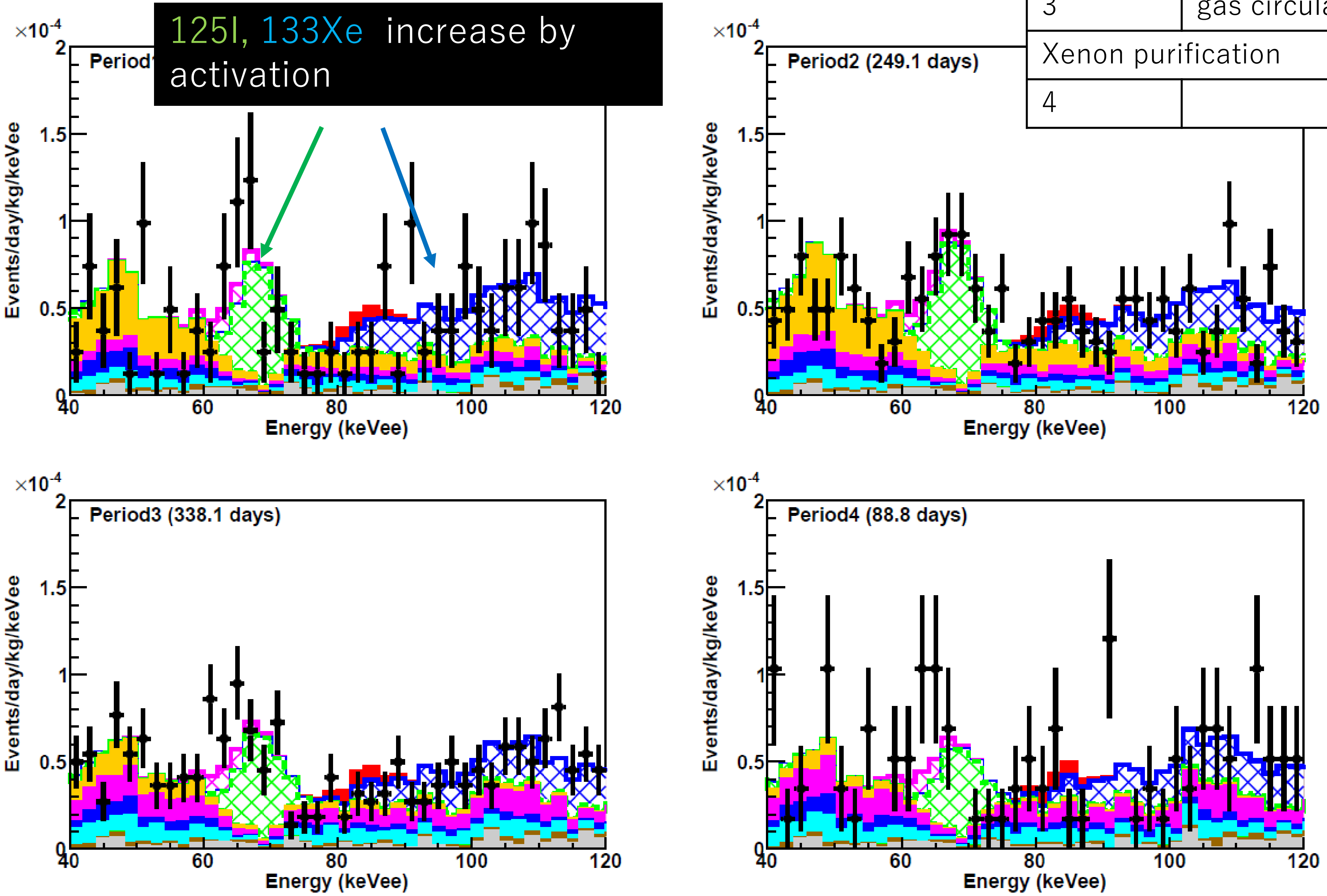

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(90% C.L. upper limit)

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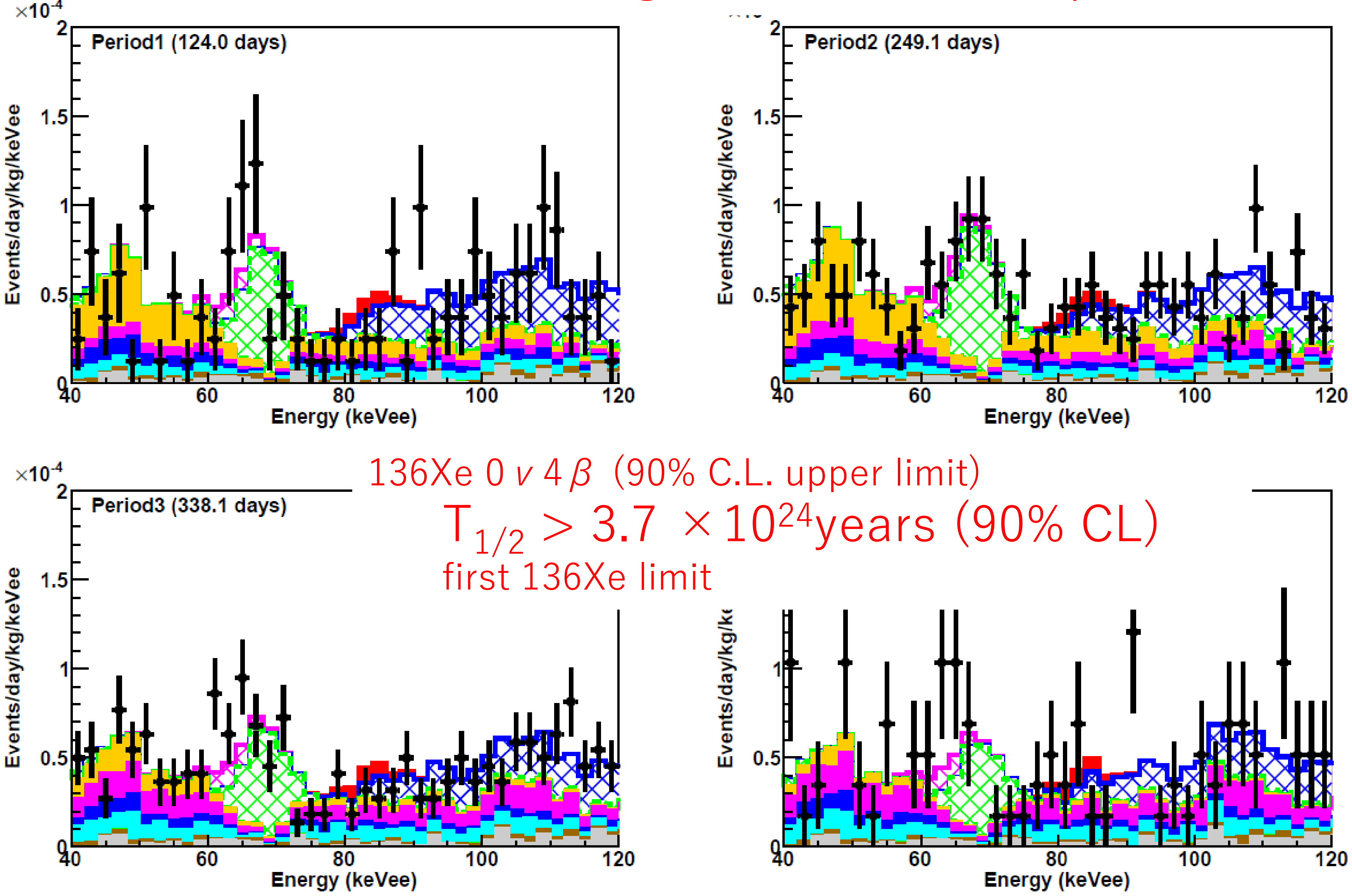
14C
39Ar
85Kr (filled)
214Pb
136Xe 2νββ
external gamma

- results

best fit for null signal of 136Xe 0ν4β



136Xe 0ν4β (90% C.L. upper limit)

$T_{1/2} > 3.7 \times 10^{24}$ years (90% CL)

first 136Xe limit

data
136Xe 0ν4β
(90% C.L. upper limit)

126Xe 2e capture (hatched)
125I
133Xe (hatched)
14C
39Ar
85Kr (filled)
214Pb
136Xe 2νββ
external gamma

- Summary
  - First experimental search for $4\nu 0\beta$ of 136Xe
  - 327kg × 800days XMASS data
  - consistent with null signal
  - $T_{1/2} > 3.7 \times 10^{24}$ years (90% CL) first 136Xe limit
  - submitted for PLB (arXiv: 2205.05231)

Thank you, and see you in Japan…