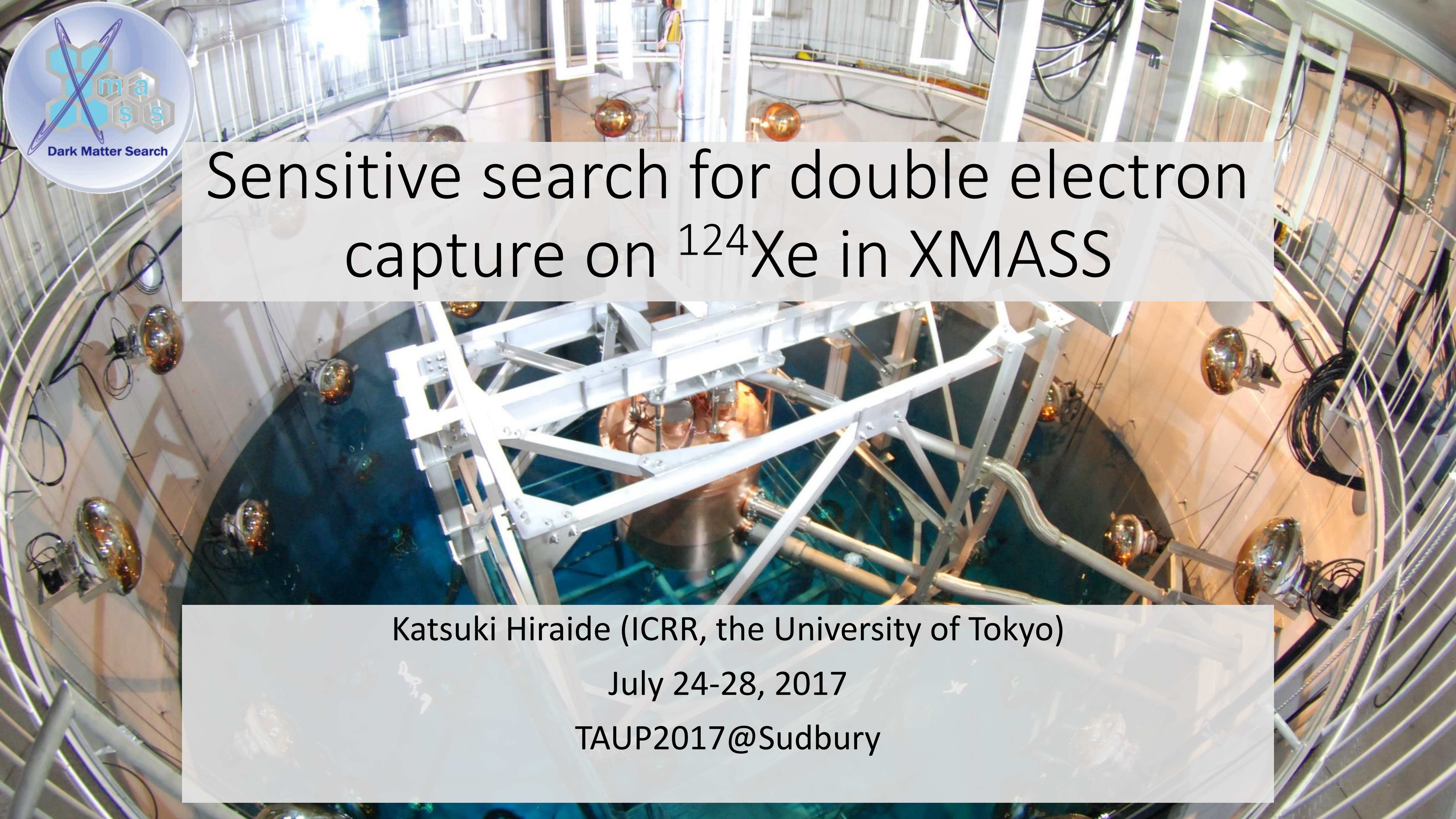


Sensitive search for double electron capture on ^{124}Xe in XMASS

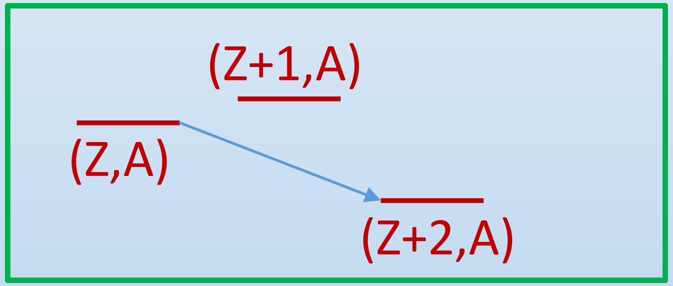
Katsuki Hiraide (ICRR, the University of Tokyo)

July 24-28, 2017

TAUP2017@Sudbury

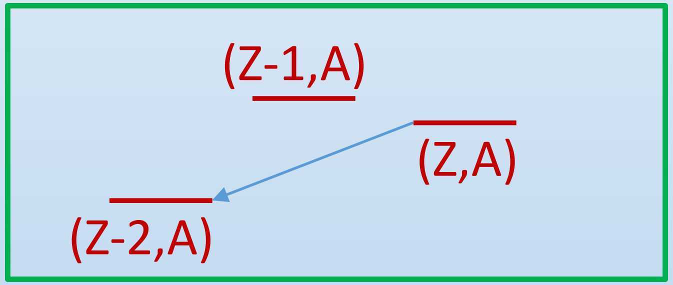
Introduction to double electron capture

Double beta decay ($\beta^-\beta^-$)
$(Z,A) \rightarrow (Z+2,A) + 2e^- + (2\overline{\nu}_e)$



- Two β^- decays occur simultaneously.
- 2ν modes have been observed in 11 nuclei with half-life of 10^{18}-10^{24} years.
  (^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd, ^{238}U)

Double electron capture (ECEC)
$(Z,A) + 2e^- \rightarrow (Z-2,A) + (2\nu_e)$



- Two orbital electrons are captured simultaneously.
- There are only two positive results on 2ν modes
  ^{78}Kr : $T_{1/2} = (9.2^{+5.5}_{-2.6}(\text{stat}) \pm 1.3(\text{sys})) \times 10^{21}$ years
  ^{130}Ba : $T_{1/2} = (2.2 \pm 0.5) \times 10^{21}$ years

In both cases, if 0ν modes are observed,
they would be evidence of lepton number violation and Majorana neutrino.

2ν double electron capture on ^{124}Xe

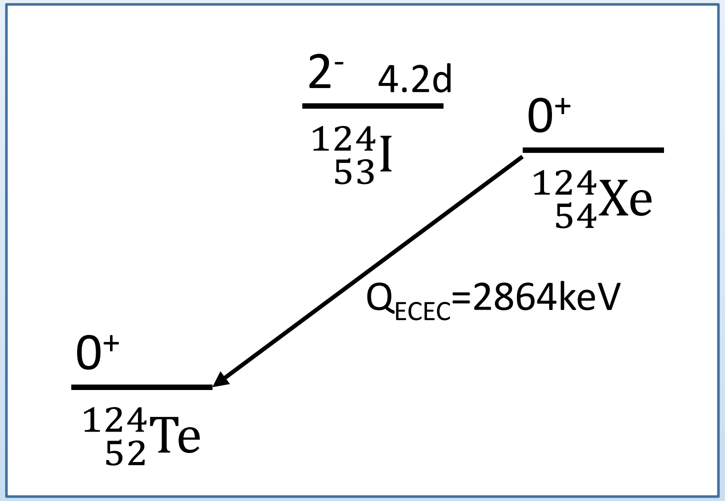
- Natural xenon contains ^{124}Xe (N.A.=0.095%) which can undergo 2νECEC.

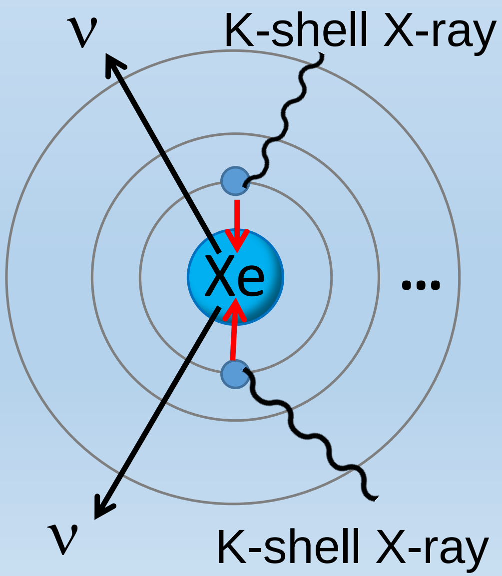
  $^{124}\mathrm{Xe}\ (\mathrm{g.s.}, 0^+) + 2e^- \rightarrow {}^{124}\mathrm{Te}\ (\mathrm{g.s.}, 0^+) + 2\nu_e + 2864\mathrm{keV}$

- In the case of 2 K-shell electrons are captured,
  - Only X-rays and Auger electrons are observable
  - Total energy deposit is 2 x E_B =63.6 keV

- Expected half-life is 10^{20}-10^{24} years.

- ^{126}Xe (N.A.=0.089%) can also undergo 2νECEC, but it is much slower due to smaller Q-value (896keV).





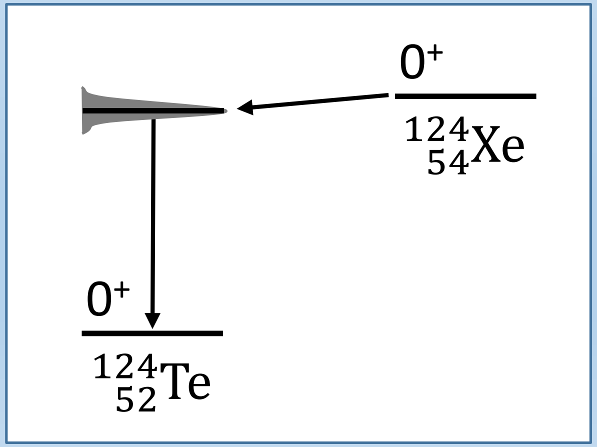
Why is ^{124}Xe interesting?

- ^{124}Xe has the largest Q-value among all the 35 ECEC candidates.
  It is large enough so that β^+EC and $\beta^+\beta^+$ channels are also allowed.
  - β^+EC: $(Z,A) + e^- \rightarrow (Z-2,A) + e^+ (+2\nu_e)$
  - $\beta^+\beta^+$: $(Z,A) \rightarrow (Z-2,A) + 2e^+ (+2\nu_e)$

- The $0\nu\beta^+$EC mode has an enhanced sensitivity to right-handed weak current.
  - It can help to disentangle the contributions of different mechanisms if observed.

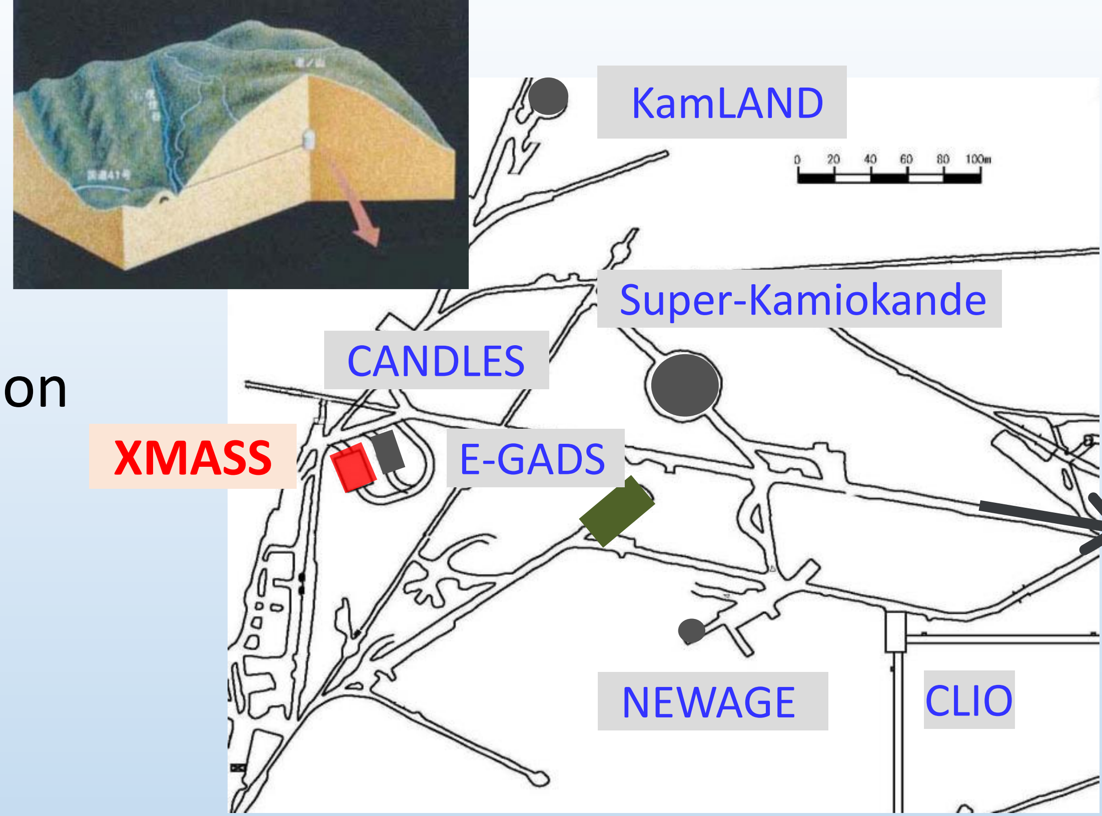
- The 0νECEC process may be resonantly enhanced
  if there exists an excited state with $\Delta=Q_{ECEC}-2E_x-E_\gamma\sim0$.

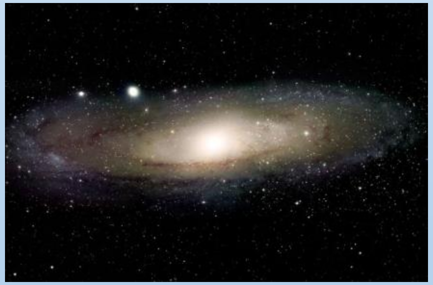
- And… any measurement of 2νECEC will provide a new
  reference for the calculation of nuclear matrix elements.

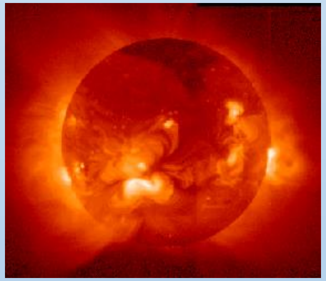


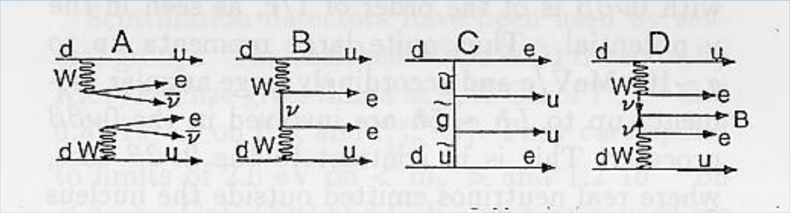
The XMASS project

- XMASS: a multi purpose experiment with liquid xenon
- Located 1,000 m underground (2,700 m.w.e.)
  at the Kamioka Observatory in Japan
- Aiming for
  - Direct detection of dark matter
  - Observation of low energy solar neutrinos (*pp*/^{7}Be)
  - Search for neutrino-less double beta decay
- Features
  - ➢ Low energy threshold (~0.5keVee)
  - ➢ Sensitive to e/γ events as well as nuclear recoil
  - ➢ Large target mass and its scalability

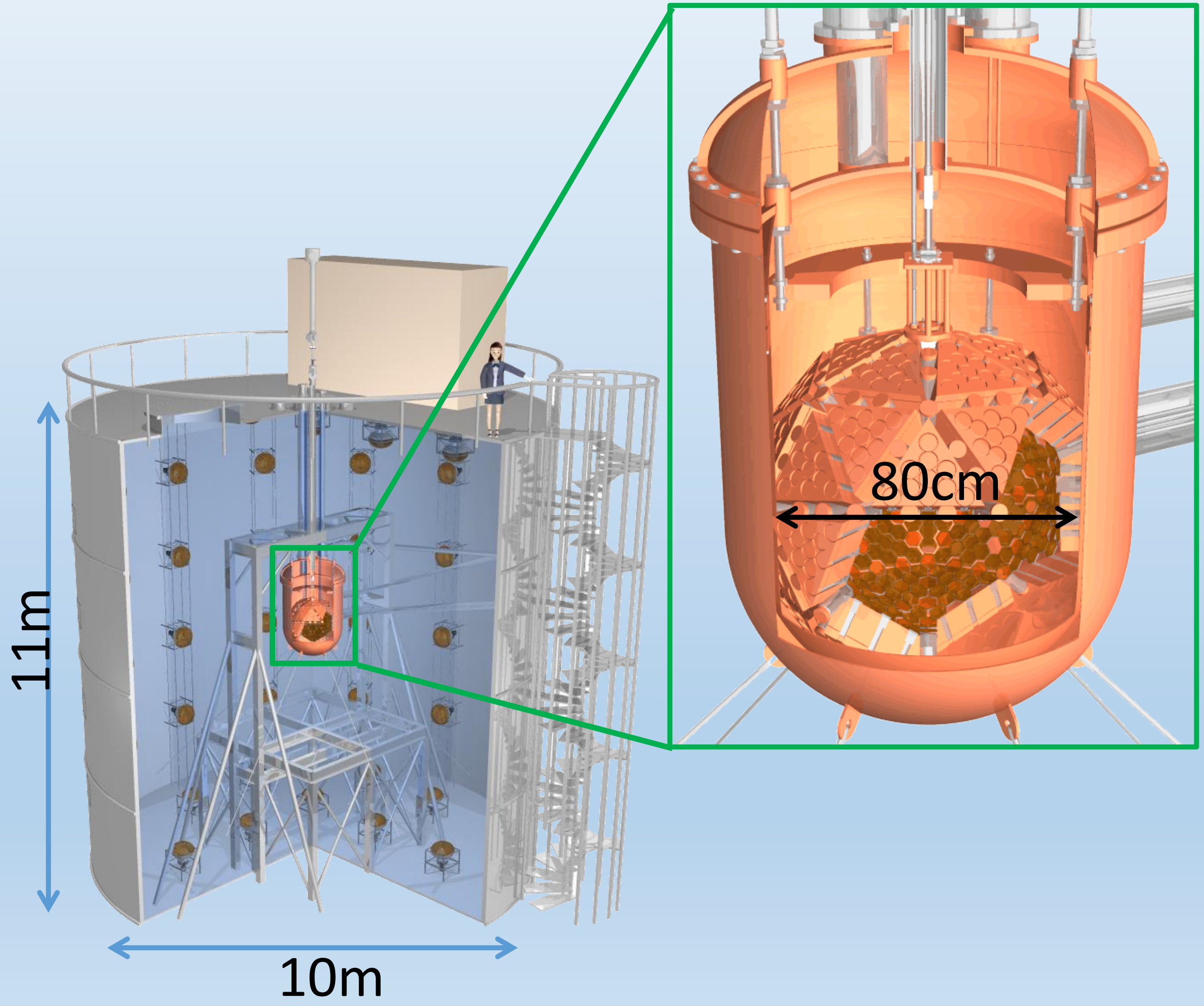








Single-phase liquid Xenon detector: XMASS-I



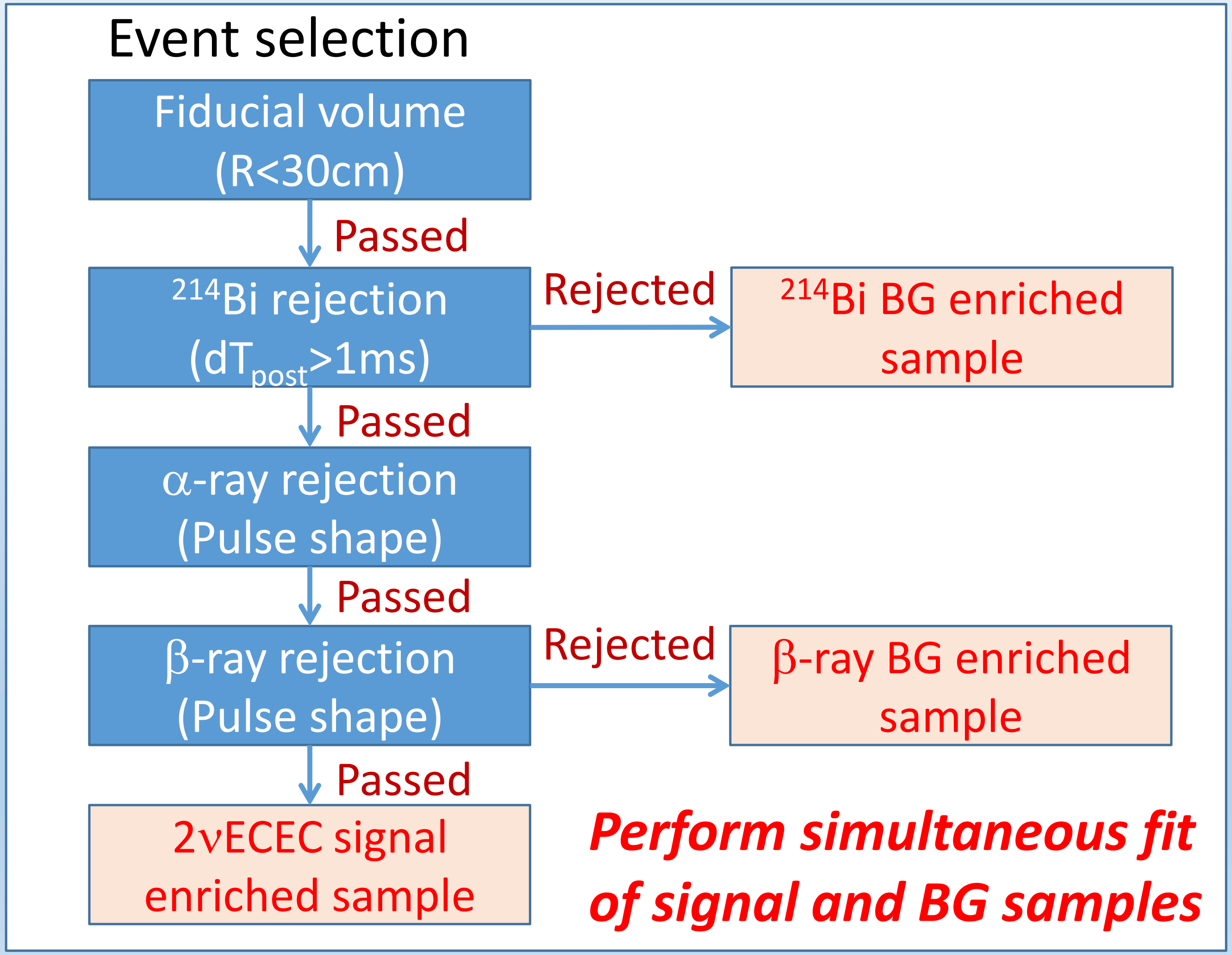
- Liquid xenon detector
  - 832 kg of liquid xenon (-100 ^{o}C)
  - 642 2-inch PMTs (Photocathode coverage >62%)
  - Each PMT signal is recorded by 10-bit 1GS/s waveform digitizers
- Water Cherenkov detector
  - 10m diameter, 11m high
  - 72 20-inch PMTs
  - Active shield for cosmic-ray muons
  - Passive shield for n/γ

Data set and event selection

- **<u>Previous analysis</u>**: *Phys. Lett. B759 (2016) 64*
  - Data taken during commissioning (Dec. 2010 - May 2012)
  - 132.0 live days
  - 41 kg nat. Xe in fiducial volume

$T_{1/2}^{2\nu 2K}(^{124}Xe) > 4.7\times10^{21}$ years
$T_{1/2}^{2\nu 2K}(^{126}Xe) > 4.3\times10^{21}$ years

- **<u>This analysis</u>**
  - Data taken after detector refurbishment (Nov. 2013 - Jul. 2016)
  - 800.0 live days → x6 longer
  - 327 kg nat. Xe in fiducial volume → x8 larger
  - Introduced waveform digitizers
    → Enabled scintillation pulse shape analysis

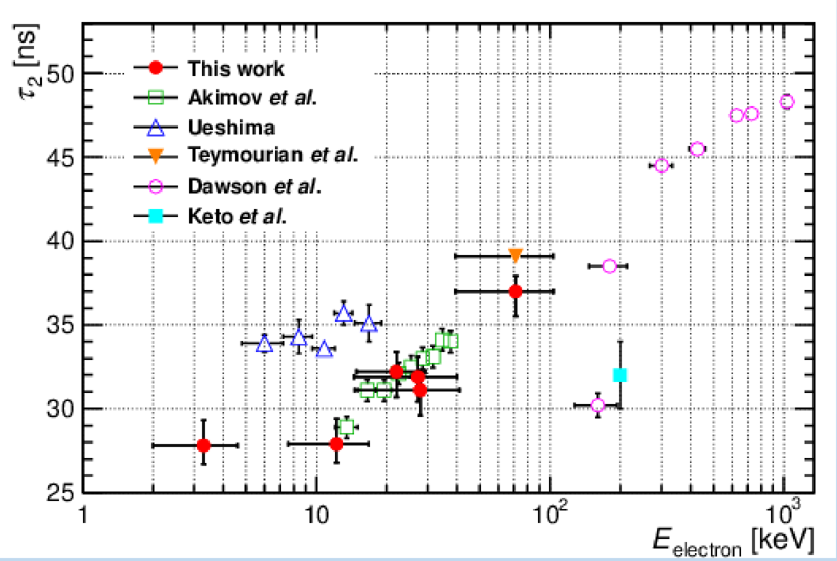


β-ray rejection using scintillation time profile

- LXe scintillation decay time depends on electron kinetic energy
- This allows us to separate
  β-ray (single electron track)
  vs.
  X-ray/γ-ray (multiple electrons)
  or 2ν2K (two X-rays)
- PSD parameter (βCL) is constructed from each photoelectron's timing under the hypothesis that the event is caused by a β-ray.

$$\beta\mathrm{CL} = P \times \sum_{i=0}^{n-1} \frac{(-\ln P)^i}{i!} \qquad P = \prod_{i=1}^{n} CL_i$$

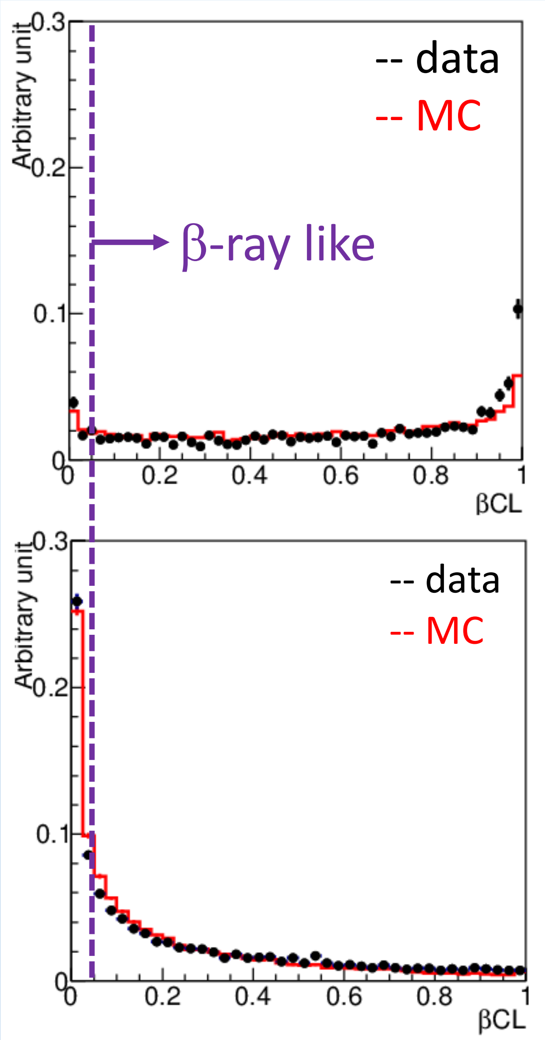
Scintillation decay time measurement
XMASS Collaboration, NIM A834 (2016) 192



PSD parameter: βCL

^{214}Bi
β-ray

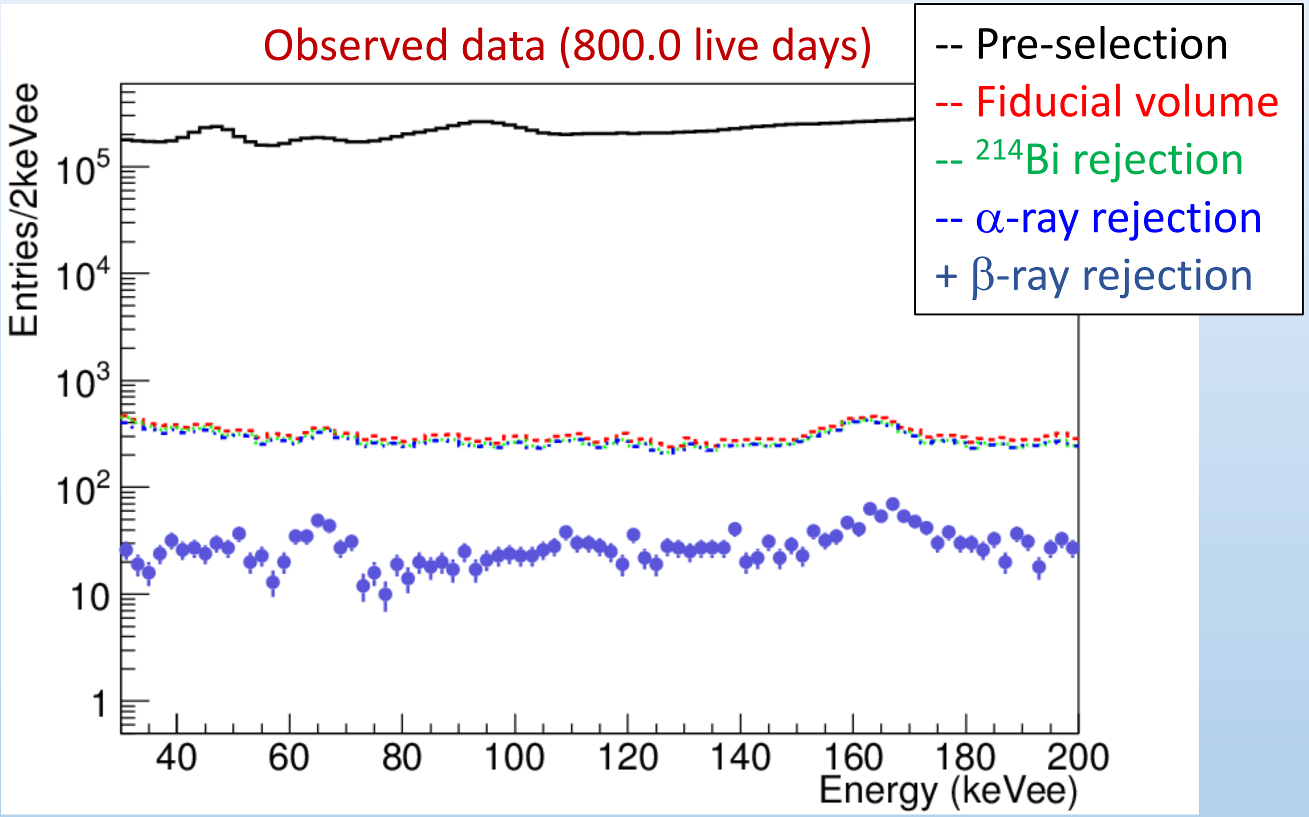
^{241}Am
60keV
γ-ray

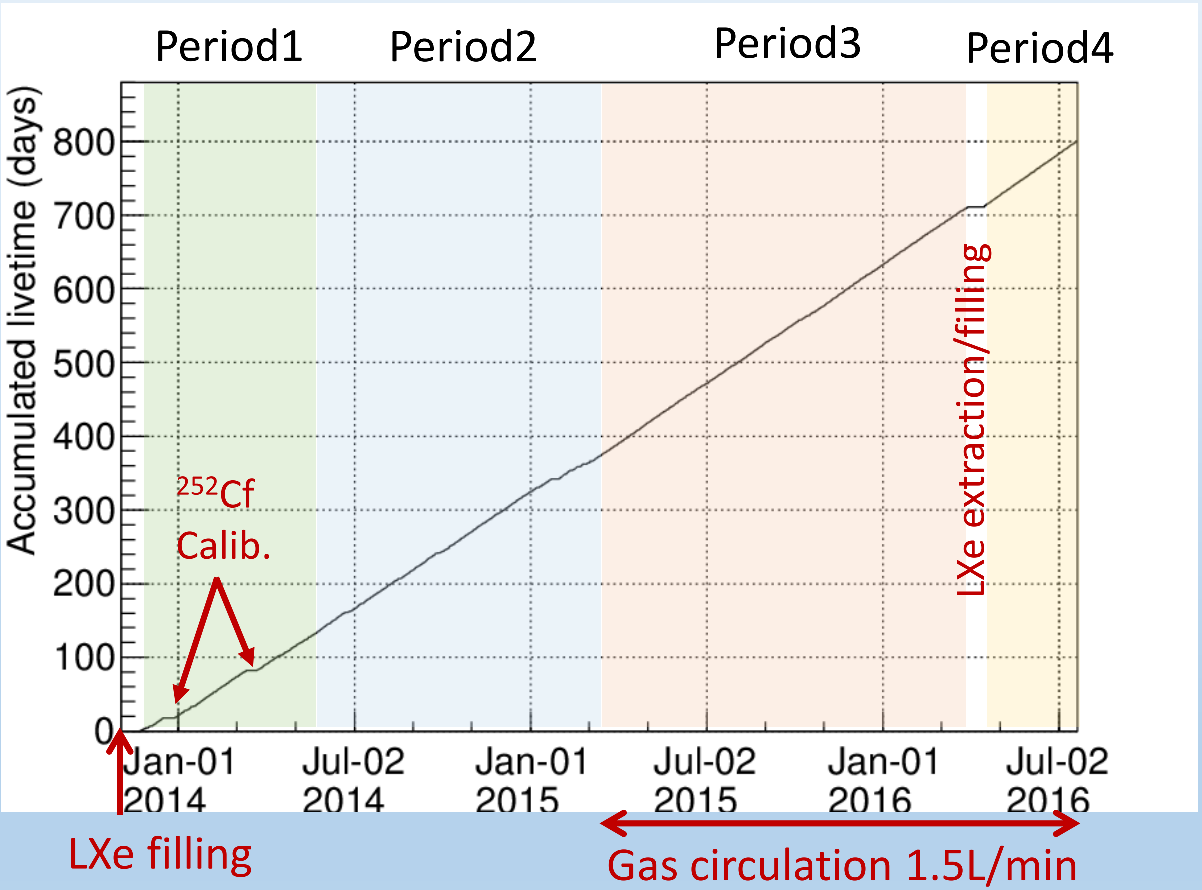


βCL<0.05
- Acceptance for γ-ray ~35%
- Acceptance for β-ray ~7%

➔ S/N improves by x5

Data set and period





- Data in 30-200 keVee are analyzed.
- The data set is divided into 4 periods depending on the detector condition.

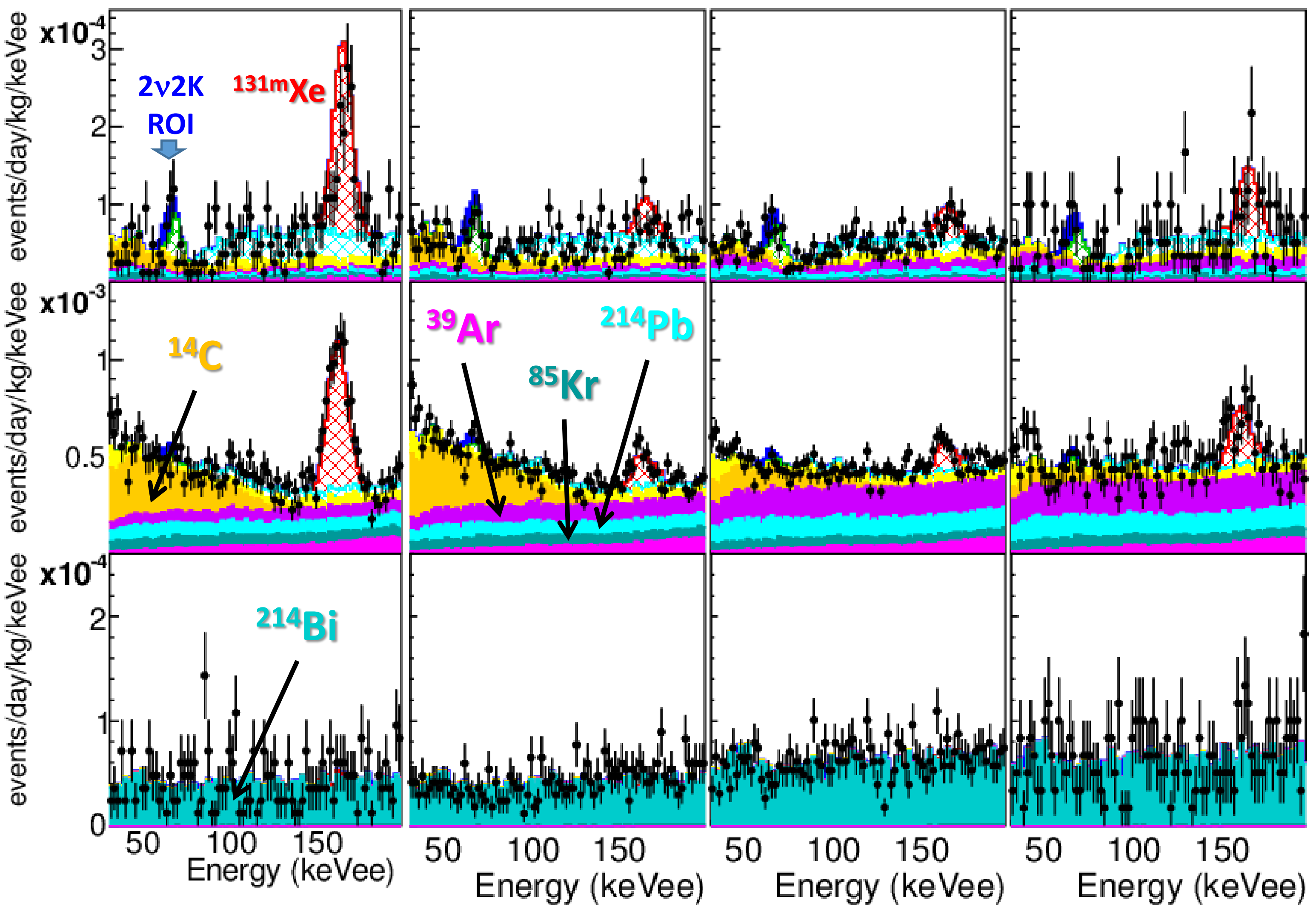
Energy spectra in 30-200 keVee (after fitting)

Period1 Period2 Period3 Period4

2νECEC signal enriched sample

β-ray BG enriched sample

^{214}Bi BG enriched sample



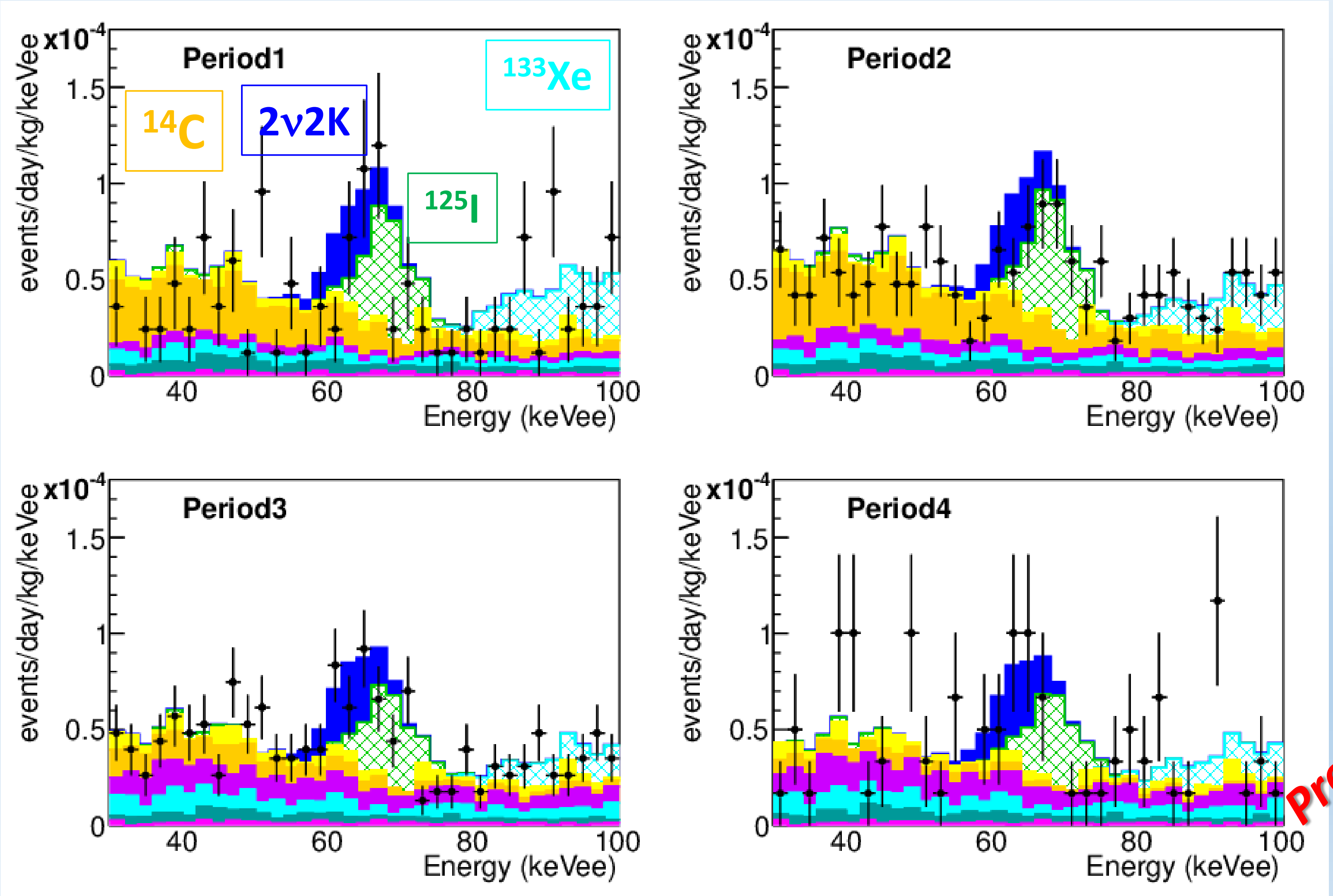
- Chi-square fitting is performed.
- 4 periods x 3 sub-samples are fitted simultaneously.

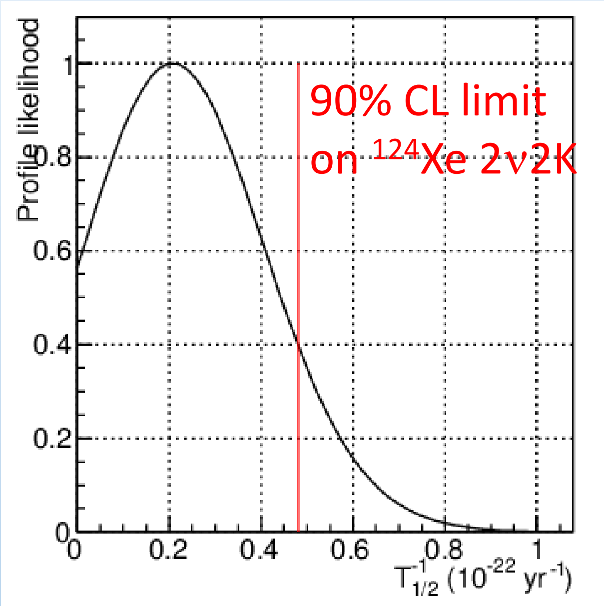
- ^{131m}Xe, ^{133}Xe, ^{125}I: xenon activation by neutrons

- ^{214}Pb: ^{222}Rn daughter
- ^{85}Kr: constrained by external β-γ coincidence measurement
- ^{39}Ar: confirmed by gas chromatography measurement
- ^{14}C: decreased after gas circulation

- ^{214}Bi: ^{222}Rn daughter, increased after gas circulation

Close-up of region of interest (30-100 keVee)





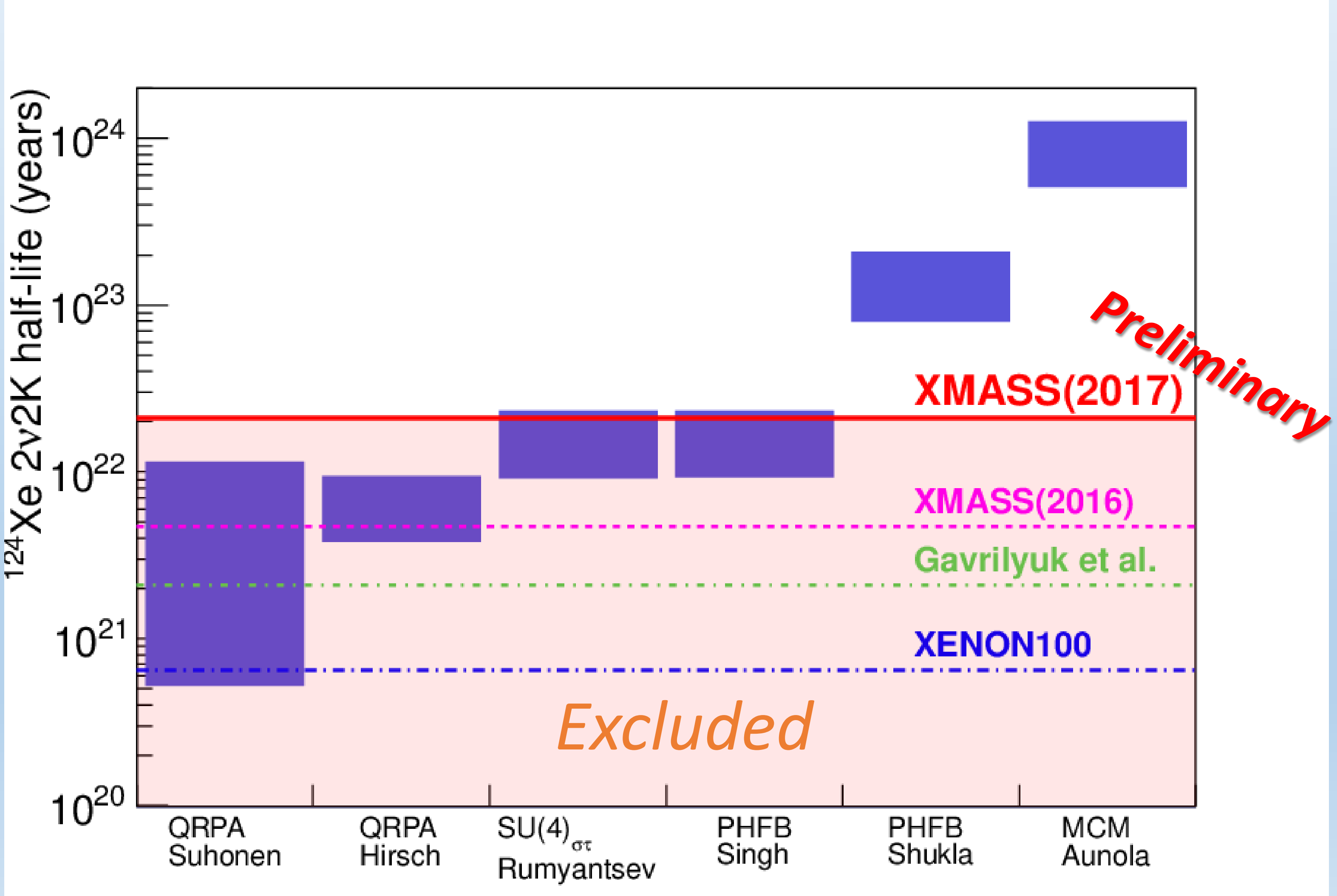
- No significant signal was observed.
- 90% CL lower limit on half-lives:

Preliminary

$T_{1/2}^{2\nu 2K}(^{124}Xe) > 2.1 \times 10^{22}$ years
$T_{1/2}^{2\nu 2K}(^{126}Xe) > 1.9 \times 10^{22}$ years

x4.5 improvement from the previous result

Exclusion limits on ^{124}Xe 2ν2K half-life and its theoretical predictions



Note on theoretical predictions:

- g_A= 1.26(lower) – 1(upper)
- Probability of 2K-capture = 0.767

We set the most stringent lower limits on the ^{124}Xe 2ν2K half-life

Summary

- We have conducted an improved search for two-neutrino double electron capture on ^{124}Xe and ^{126}Xe in XMASS.
  - 800.0 live days (Nov. 2013 – Jul. 2016)
  - 327 kg natural xenon in fiducial volume (contains 311 g of ^{124}Xe, 291 g of ^{126}Xe)

- No significant signal above BG was observed and we set the most stringent lower limits on half-lives.
  - $T_{1/2}^{2\nu 2K}$ (^{124}Xe) > 2.1×10^{22} years @90%CL
  - $T_{1/2}^{2\nu 2K}$ (^{126}Xe) > 1.9×10^{22} years @90%CL
  - x4.5 improvement from the previous result (XMASS(2016))

Preliminary

Backup slides

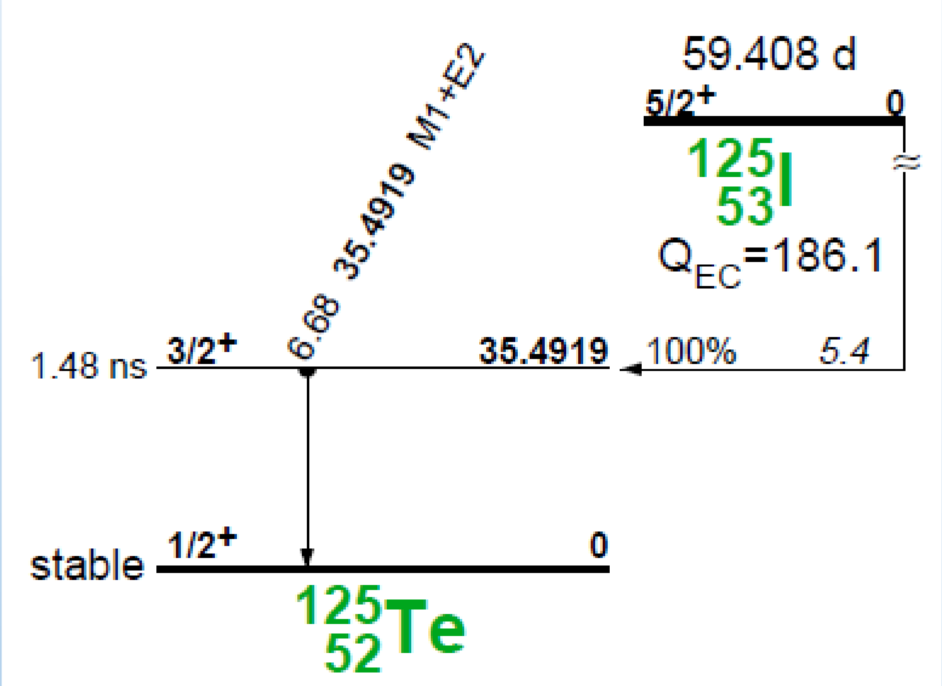
^{125}I background

- ^{125}I is created from decay of ^{125}Xe or ^{125m}Xe, which is created by thermal neutron capture on ^{124}Xe.
  - ☐ ^{124}Xe(n, γ)^{125}Xe (σ=137 barn)
  - ☐ ^{124}Xe(n, γ)^{125m}Xe (σ=28 barn)
  - ☐ ^{125m}Xe → ^{125}Xe (IT , $T_{1/2}$=57 sec)
  - ☐ ^{125}Xe → ^{125}I (β^+/EC, $T_{1/2}$=16.9 hours)

- ^{125}I decays to the excited state of ^{125}Te. (EC, $T_{1/2}$=59.4 days)
  - ☐ X-ray/Auger electron + 35.5 keV γ-ray

- Potential background to search for ^{124}Xe 2ν2K
  - ☐ Total deposit energy is similar (ΔE~4 keV)
  - ☐ Emits two X-rays (or γ-ray)
  - ☐ Originated from ^{124}Xe

^{125}I decay scheme (Table of isotope)



Xenon activation by thermal neutron capture

- Xenon is activated by thermal neutron capture
  $^{A}Xe(n, \gamma)^{A+1}Xe$
  in the gas xenon volume outside the water shield

- Xenon RIs have shorter half-lives ($T_{1/2}$< O(10) days), and they reach decay equilibrium.

- Total gas xenon volume: 2.6×10^{5} cm^{3}
  - Cable feed-through box 89%
  - Calibration system 9%
  - Refrigerator 1.2%
  - Piping 0.6%

- Thermal neutron flux in the Kamioka mine
  - $(8.3 +/- 0.58) \times 10^{-6}$ /sec/cm^{2} Minamino (2004)
  - 1.4×10^{-5} /sec/cm^{2} Ootani (1994)