Search for double electron capture on ^{124}Xe with the XMASS-I detector

KATSUKI HIRAIDE (ICRR, THE UNIVERSITY OF TOKYO)

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^{124}Xe 2ν double electron capture

- Natural xenon contains double electron capture nuclei as well as double beta decay nuclei

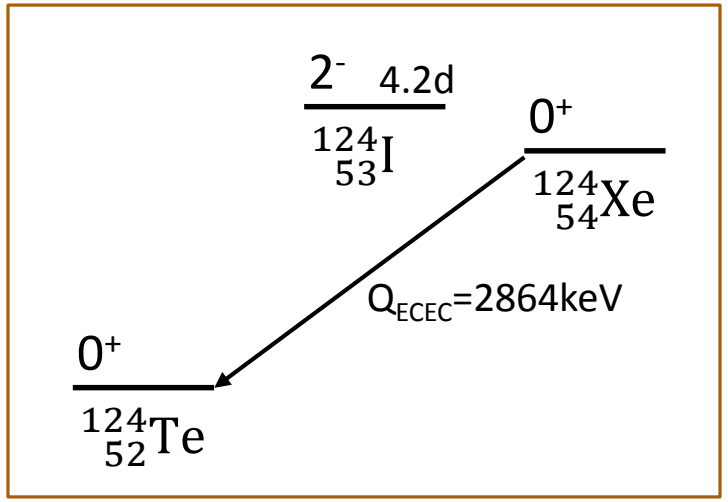
Isotope Natural abundance	^{124}Xe 0.095%	^{126}Xe 0.089%	^{128}Xe 1.9%	^{129}Xe 26.4%	^{130}Xe 4.1%	^{131}Xe 21.2%	^{132}Xe 26.9%	^{134}Xe 10.4%	^{136}Xe 8.9%

- ^{124}Xe 2ν double electron capture (ECEC)

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

  - In the case of 2K-capture, signal is total energy deposition of 63.6keV from atomic X-rays and Auger electrons.

- ^{126}Xe can also undergo 2ν ECEC,
  but this reaction is much slower. (Q=896keV)



^{124}Xe 2ν double electron capture (cont'd)

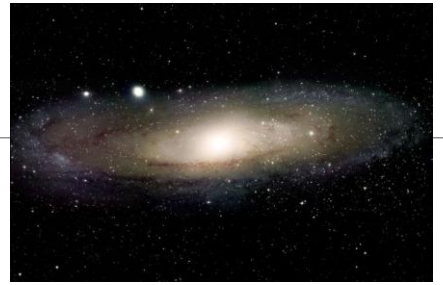
- Predictions for ^{124}Xe 2ν ECEC half-life
  - Wide spread between 10^{20} and 10^{24} years

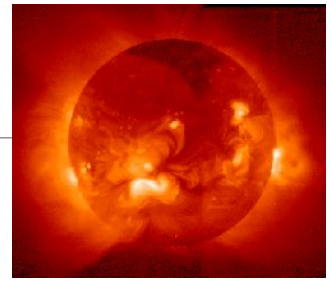
Model	$T_{1/2}$ (2νECEC) (yr)	Reference
QRPA	$(0.4\text{-}8.8)\times10^{21}$	Suhonen (2013)
QRPA	$(2.9\text{-}7.3)\times10^{21}$	Hirsch et al. (1994)
$SU(4)_{\sigma\tau}$	$(7\text{-}17.7)\times10^{21}$	Rumyantsev et al. (1998)
PHFB	$(7.1\text{-}18.0)\times10^{21}$	Singh et al. (2007)
PHFB	$(61.4\text{-}155.1)\times10^{21}$	Shukla et al. (2007)
MCM	$(390\text{-}986.1)\times10^{21}$	Aunola et al. (1996)

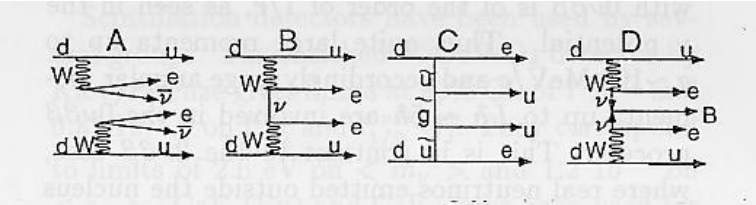
- Experimental result on ^{124}Xe 2ν ECEC
  - Y.M.Gavrilyuk et al., arXiv:1507.04520
    - Enriched 58.6g of ^{124}Xe; proportional counter
    - $T_{1/2}(2\nu2K)>2.0\times10^{21}$ years (90% CL)

- Large volume dark matter detectors have potential to measure ^{124}Xe 2ν ECEC
  - D.-M.Mei et al. (2014): sensitivity test using XENON100 data → $T_{1/2}(2\nu2K)>1.66\times10^{21}$ years
  - N.Barros et al. (2014): sensitivity study for future detectors

The XMASS experiment







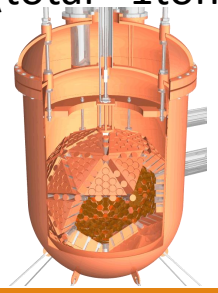
- Proposed as a multi purpose experiment with liquid Xenon
  - **X**enon detector for Weakly Interacting **MASS**ive Particles (**dark matter**)
  - **X**enon **MASS**ive detector for solar neutrino (**pp/^{7}Be solar neutrino**)
  - **X**enon neutrino **MASS** detector (**neutrinoless double beta decay**)

- Low energy threshold
- Sensitive to e/γ events as well as nuclear recoil

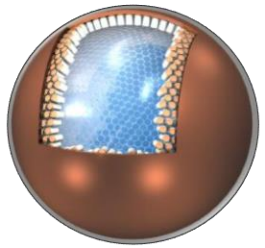
  WIMPs (by elastic and ^{129}Xe inelastic scattering),
  Solar axions, Bosonic super-WIMPs,
  Supernova neutrino burst, double electron capture, …

- Large target mass and its scalability

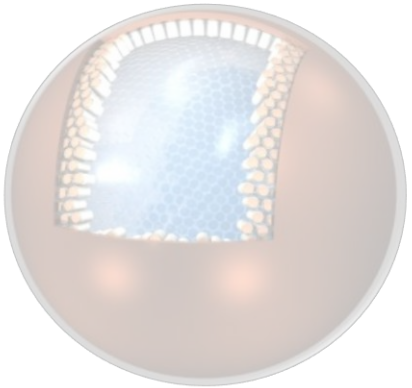
XMASS-1
(total ~1ton)



XMASS-1.5
(total ~5tons)

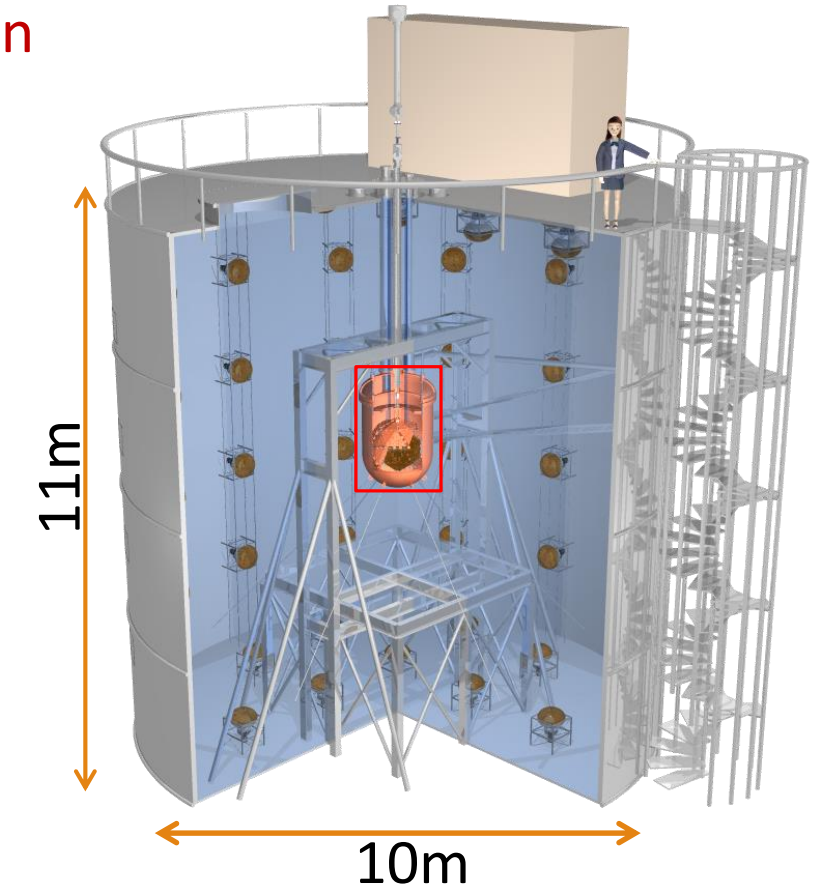


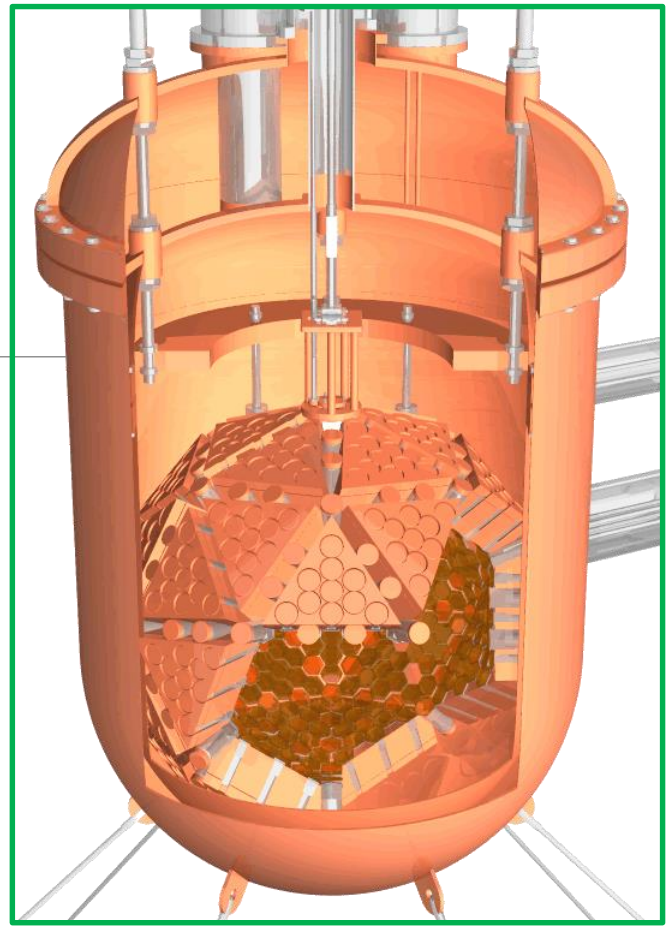
XMASS-2
(total ~24tons)



The XMASS-1 detector

- Located in the Kamioka mine in Japan (~2,700m water equivalent)
- A single-phase detector employing ~830kg of liquid xenon
- Equipped with 642 PMTs
- Active water shield

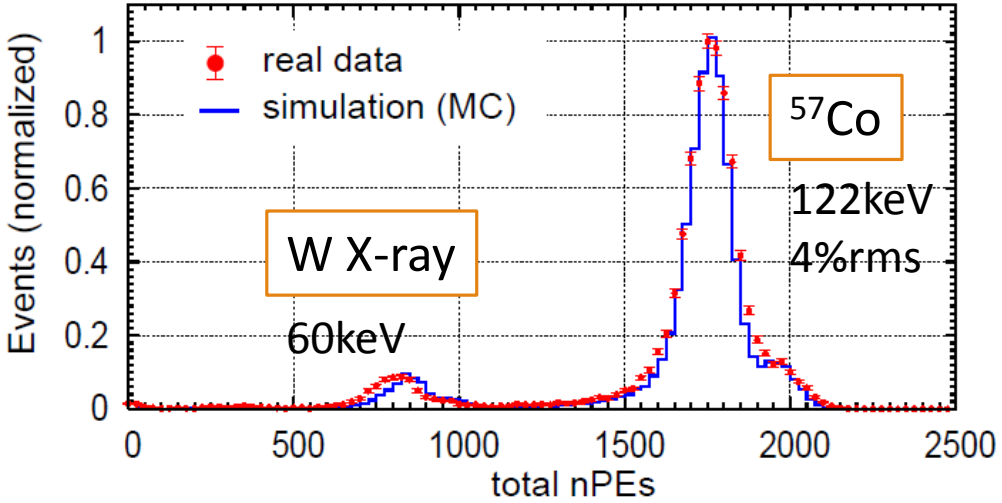




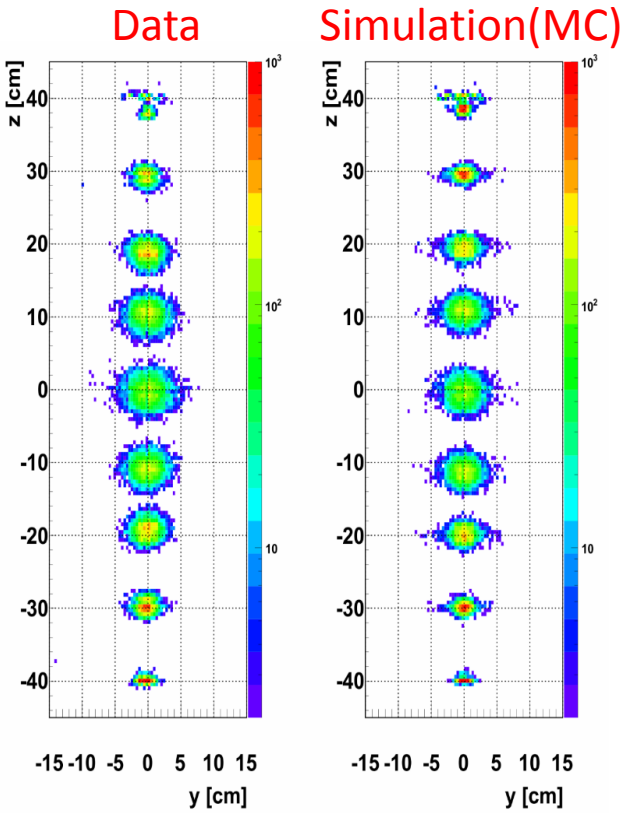
Detector calibration

- Various calibration sources:
  ^{55}Fe, ^{109}Cd, ^{241}Am, ^{57}Co, ^{137}Cs
- Light yield, optical parameters, position reconstruction

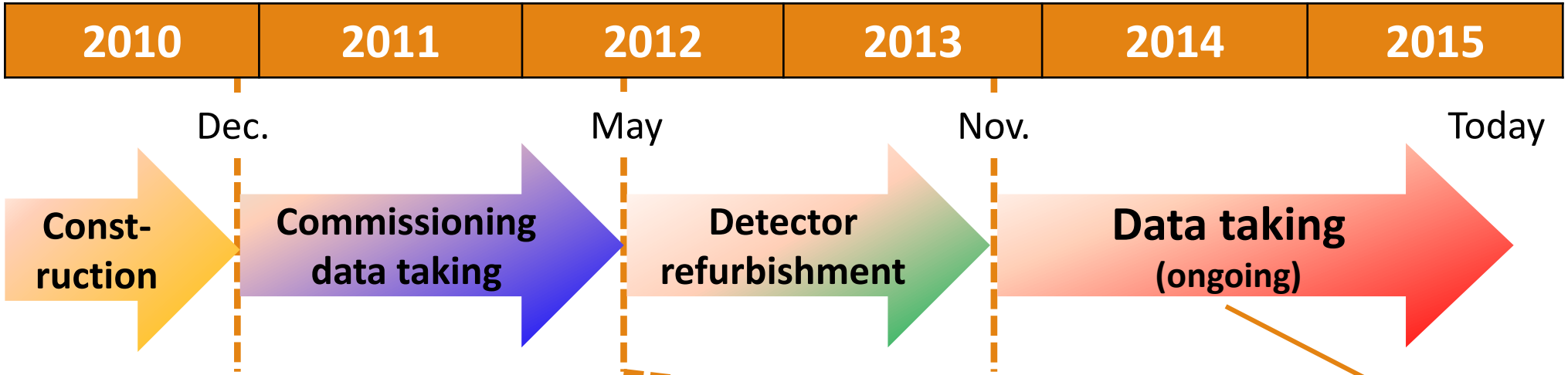
Total photoelectron distribution



Reconstructed vertex distribution



History of XMASS-1



- Low mass WIMP search [PLB 719 (2013) 78]
- Solar axion search [PLB 724 (2013) 46]
- WIMP-^{129}Xe inelastic scattering search [PTEP (2014) 063C01]
- Bosonic super-WIMP search [PRL 113 (2014) 121301]
- **^{124}Xe double electron capture search: This talk (New result)**

Dark matter search by seasonal modulation *[Talk by K. Kobayashi in Dark Matter A session on Sep. 8]* **(New result)**

Data set and event selection (1/2)

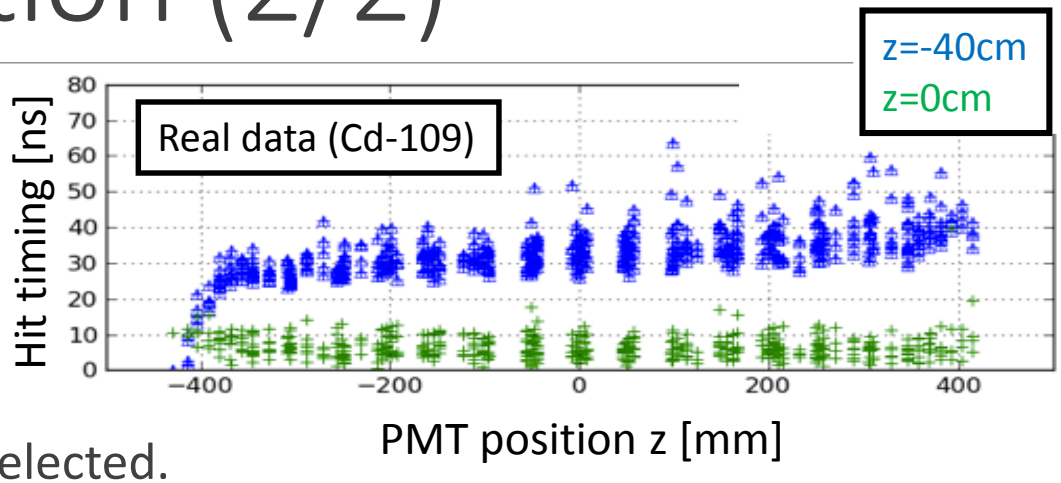
- Data set
  - Dec 24, 2010 ~ May 10, 2012 (Total livetime of 165.9 days)
- Pre-selection
  - No outer detector trigger is associated with the event.
  - The event is separated from the nearest event by at least 10 msec.
  - RMS spread of hit timings of the event is less than 100 nsec.
  - Dead time due to pre-selection reduces the total effective livetime to 132.0 days.
- Fiducial volume cut (Radius cut)
  - Event vertex is reconstructed based on the observed light distribution in the detector.
  - Select events with the reconstructed position is within 15 cm from the center.
  - Fiducial mass of natural xenon is 41kg (It contains 39g of ^{124}Xe)

Data set and event selection (2/2)

- Timing cut
  - Hits' timing is used to reject events from the detector inner surface that are wrongly reconstructed.

$$\delta T_m = t_{\text{mean of 2nd half of hits}} - t_{\text{1st hit}}$$

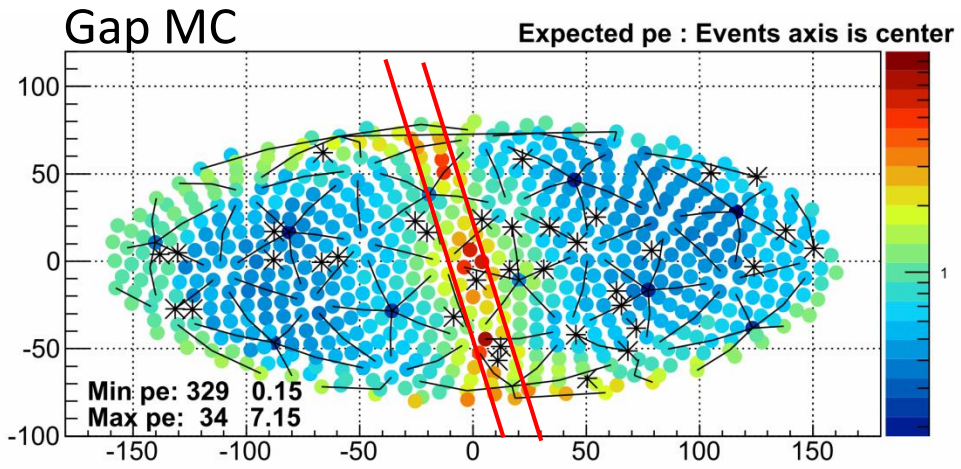
  - Events with smaller δTm are less likely to be surface BG and selected.



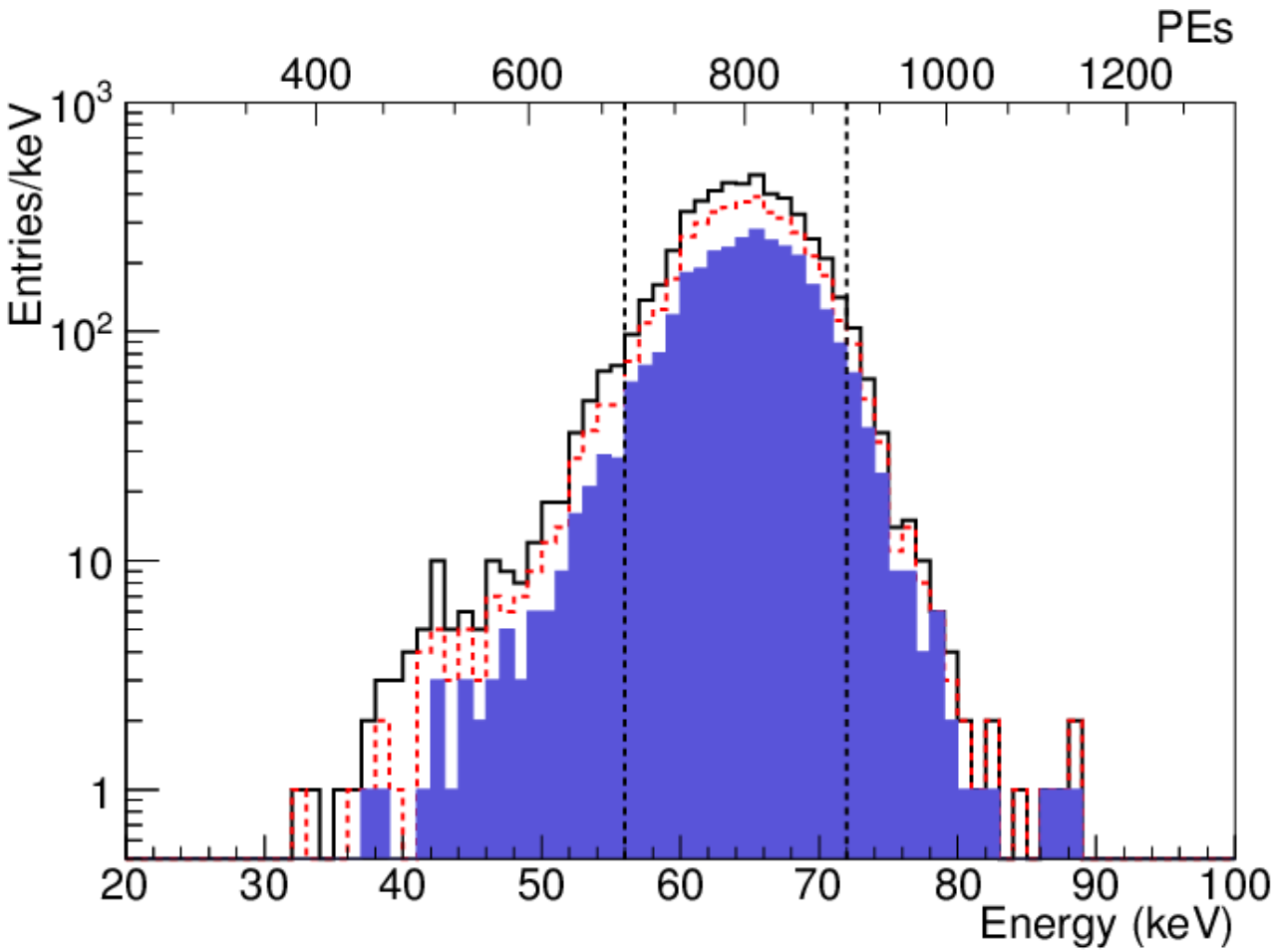
- Band-like pattern cut
  - BG events occurred in groves in the inner detector surface make band-like pattern.

$$F_B = \frac{\text{Max. PE in a band of width 15cm}}{\text{Total PE in the event}}$$

  - Events with larger F_B are likely to be those BG and rejected.



Expected ^{124}Xe 2ν 2K-capture signal



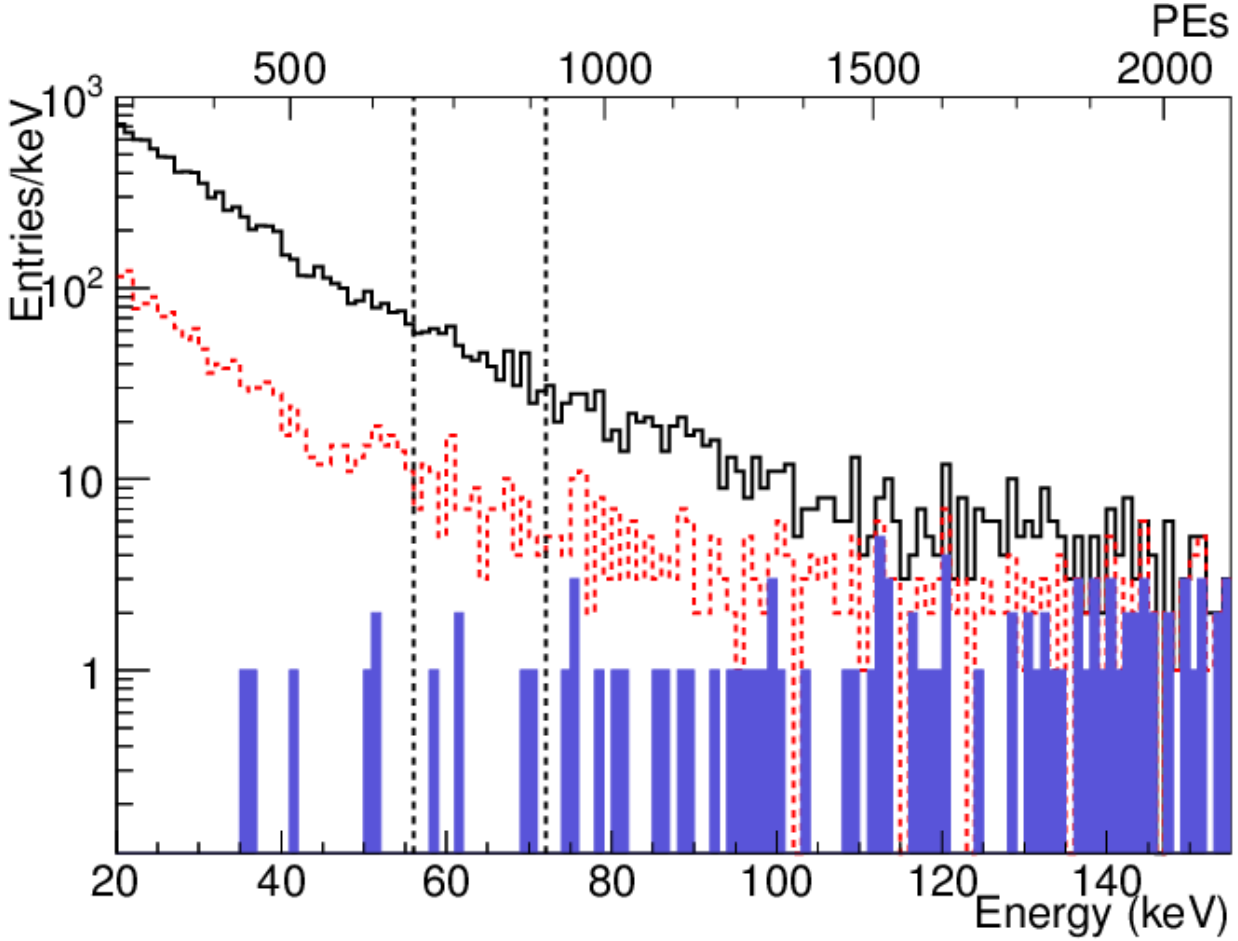
-- Fiducial volume cut

-- Timing cut

-- Band-like pattern cut

- X-rays and Auger electrons after 2ν 2K-capture are simulated.
- The energy window (56-72keV) is determined so that it contains 90% of the simulated signal.
- Efficiency for signal is 59.7%.

Observed data



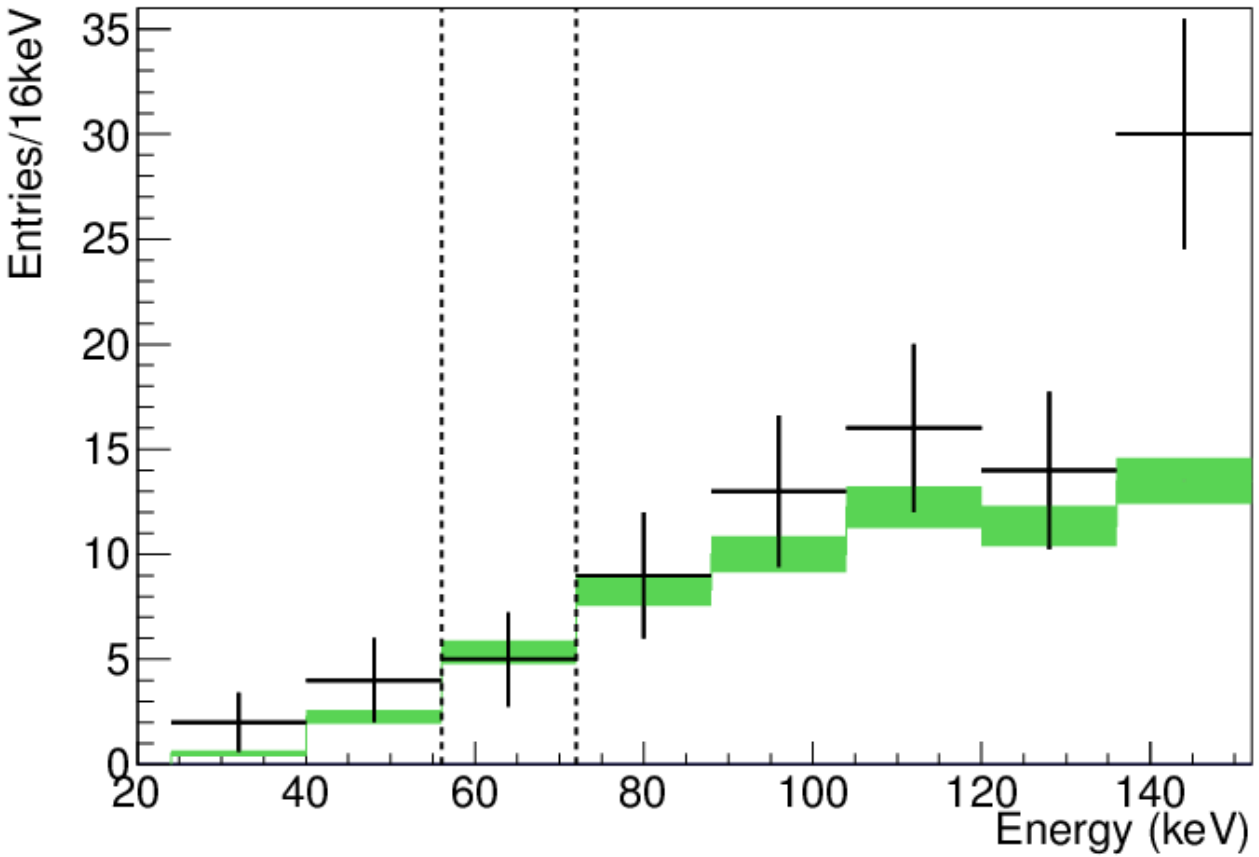
-- Fiducial volume cut

-- Timing cut

-- Band-like pattern cut

- Effective live time of 132.0 days
- Fiducial mass of natural xenon is 41kg (It contains 39g of ^{124}Xe)
- 5 events remained in the signal region

Comparison with background prediction



+ Data

-- Pb-214 background MC (w/ sys. error)

- Main background in this energy region is ^{214}Pb (daughter of ^{222}Rn) in the detector.
- The amount of ^{222}Rn was estimated from the observed rate of ^{214}Bi-^{214}Po decay.
- Expected number of ^{214}Pb BG events in the signal region: 5.3+/-0.5 events
- No significant excess in the signal region

Systematic uncertainty in signal prediction

Item	Fractional uncertainty
Abundance of ^{124}Xe	+/-8.5%
Liquid xenon density	+/-0.5%
Energy scale	+0%, -8.6%
Energy resolution	+0%, -5.3%
Scintillation decay time	+0%, -7.1%
Radius cut (R<15cm)	+0%, -6.7%
Timing cut (T<12.54ns)	+3%, -0%
Band cut (B<0.248)	+/-5%
Total	**+10.3%, -17.2%**

- A sample was taken from our detector and its isotope composition was measured.
- Systematic uncertainty in signal efficiency was estimated from comparisons between data and MC simulation for ^{241}Am (60keV γ) calibration data at various positions.

Limit on ^{124}Xe 2ν 2K-capture half-life

- We derive a lower limit using a Bayesian method

- Conditional probability density function for the decay rate Γ

$$P(\Gamma|n_{obs}) = \iiint \frac{e^{-\mu}\mu^{n_{obs}}}{n_{obs}!} \times P(\Gamma)P(\lambda)P(\varepsilon)P(\varepsilon_{corr})P(b)d\lambda d\varepsilon d\varepsilon_{corr} db$$

where $\mu = (\Gamma\lambda\varepsilon + b)\varepsilon_{corr}$

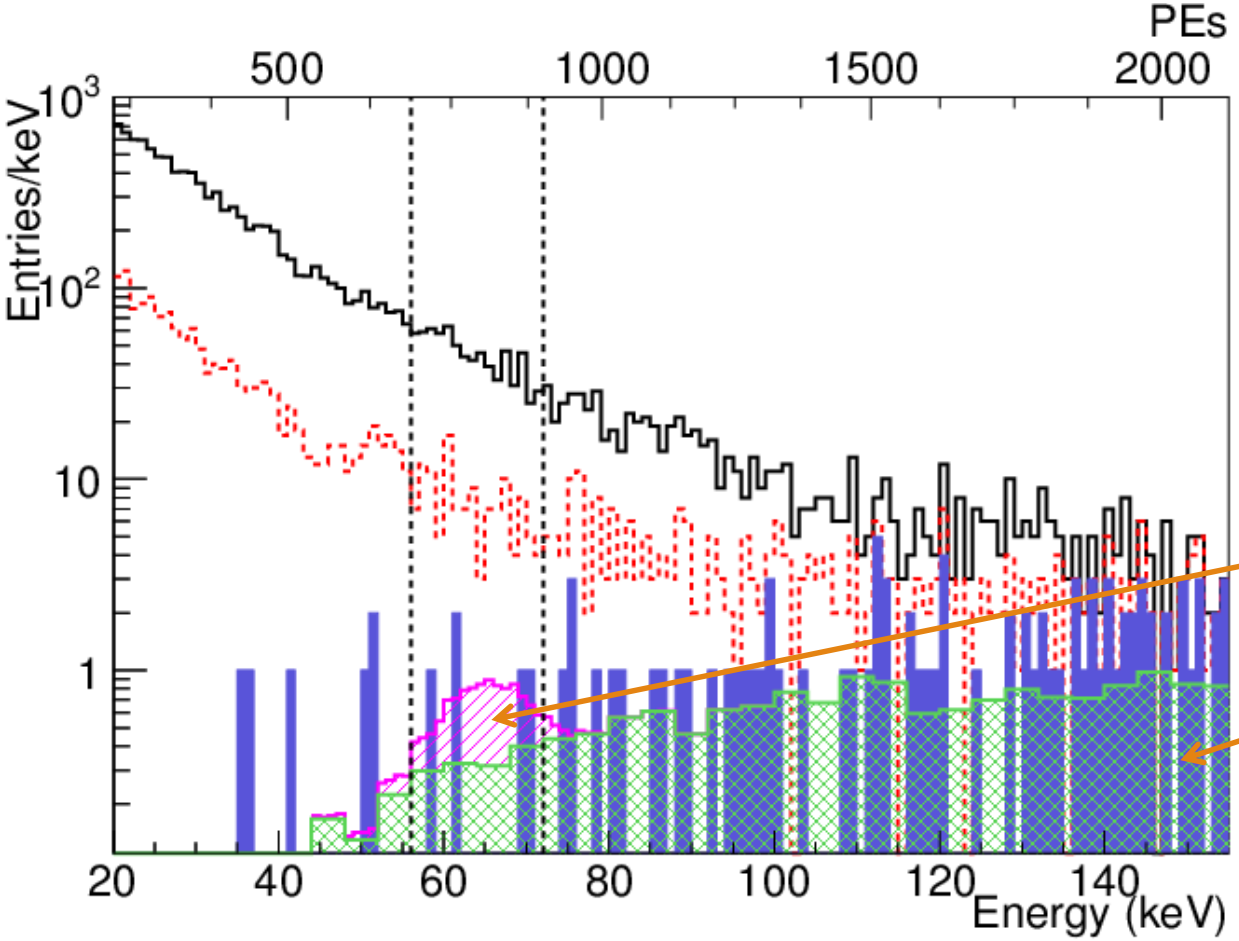
λ: exposure
ε: signal efficiency (uncorrelated with BG)
ε_{corr}: correlated efficiency
$b\varepsilon_{corr}$: number of BG events in the signal region

- 90% confidence level limit

$$\frac{\int_0^{\Gamma_{limit}} P(\Gamma|n_{obs})d\Gamma}{\int_0^{\infty} P(\Gamma|n_{obs})\, d\Gamma} = 0.9$$

$$T_{1/2}(2\nu 2K) > \frac{\ln 2}{\Gamma_{limit}} = 4.7 \times 10^{21} \text{ years (90\%CL)}$$

Limit on ^{124}Xe 2ν 2K-capture half-life



$T_{1/2}$>4.7x10^{21} years (90%CL)

Cf. Other experimental result
$T_{1/2}$(2ν2K)>2.0x10^{21} years (90% CL)
by Y.M.Gavrilyuk et al., arXiv:1507.04520

Expected ^{124}Xe 2ν 2K-capture signal with $T_{1/2}$(2ν2K)=4.7x10^{21} years

^{214}Pb background

Conclusions

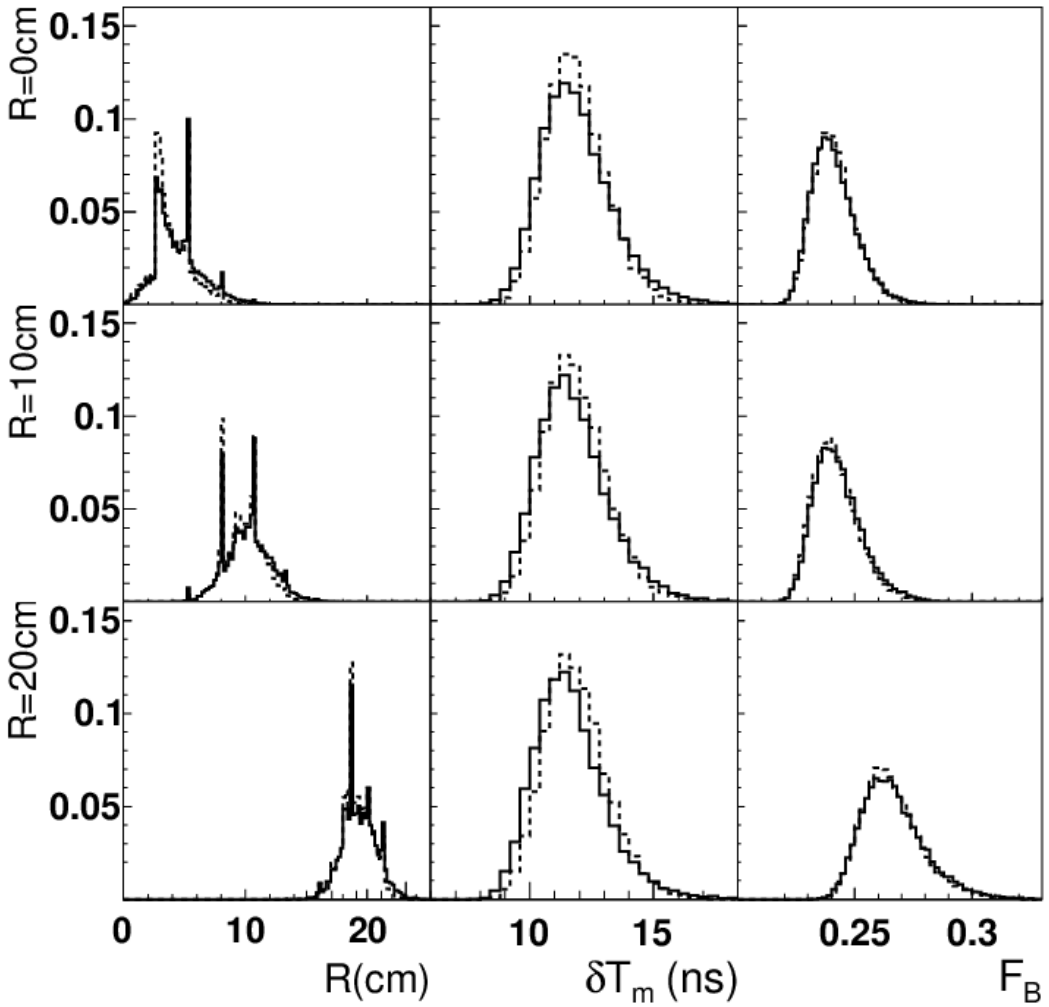
- XMASS is a multi-purpose experiment using liquid xenon at Kamioka in Japan.
  - Direct detection of dark matter
  - Neutrino-less double beta decay
  - ^{7}Be/*pp* solar neutrinos

- We performed a search for 2ν double electron capture on ^{124}Xe using data collected with the XMASS-I detector.
  - Effective livetime of 132.0 days, 39g of ^{124}Xe in fiducial volume.
  - No significant excess above background was observed.
  - We set a lower limit $T_{1/2}(2\nu 2K)>4.7\times10^{21}$ years (90% CL)

Backup slides

Data/MC comparison for 241Am calibration data

Reconstructed radial position | Timing parameter | Band pattern parameter



(Solid) Data
(Dashed) MC