Search for double electron capture in XMASS

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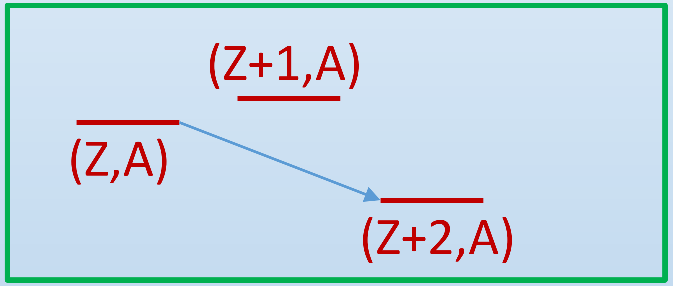
Outline

- Introduction
  - Double electron capture on ^{124}Xe
  - Why is ^{124}Xe interesting?
- Search for 2ν double electron capture on ^{124}Xe in XMASS
  - Results from commissioning data ***[Phys. Lett. B 759 (2016) 64]***
- Future prospects
- Summary

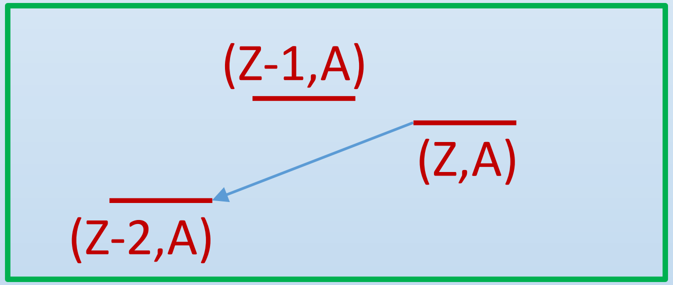
Introduction

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)

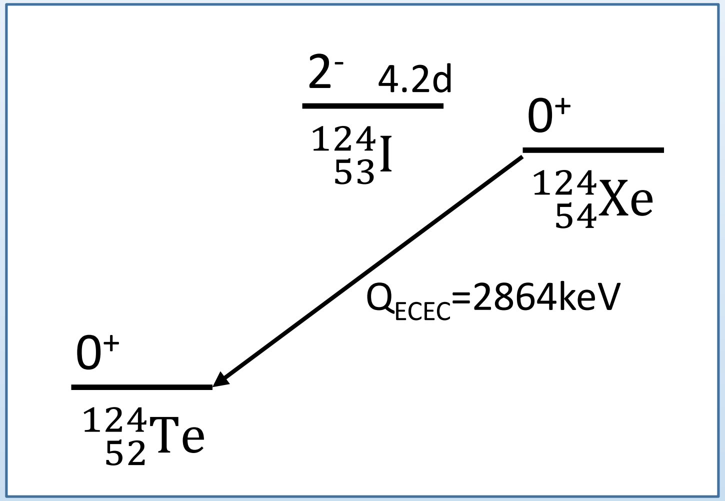
Double electron capture (ECEC)
$(Z,A) + 2e^- \rightarrow (Z-2,A) + (2\nu_e)$



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

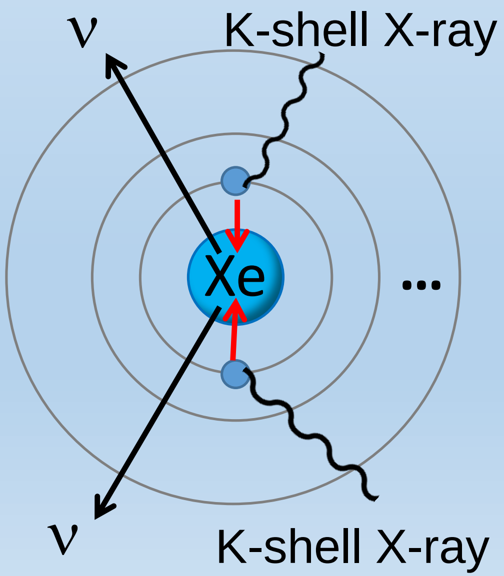
2ν double electron capture on ^{124}Xe



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

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

- 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).

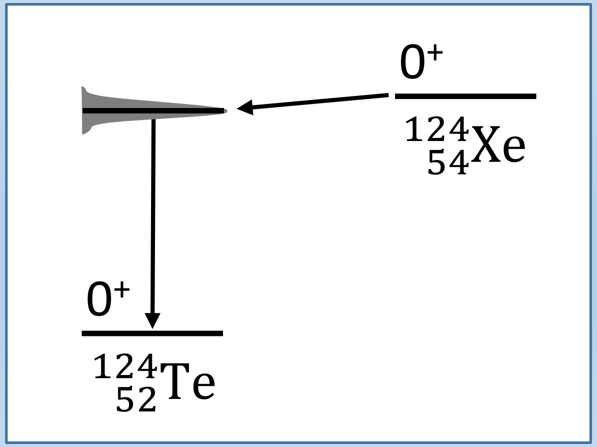
Why is ^{124}Xe interesting?

- ^{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: $(Z,A) + e^- \rightarrow (Z-2,A) + e^+ (+2\nu_e)$
  - $\beta^+\beta^+$: $(Z,A) \rightarrow (Z-2,A) + 2e^+ (+2\nu_e)$

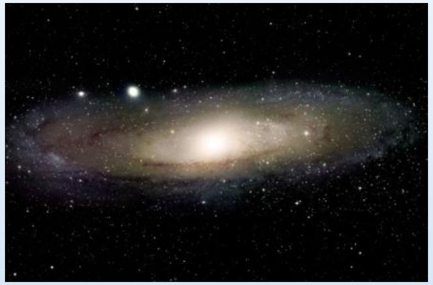
- The $0\nu\beta^+$EC mode has an enhanced sensitivity to right-handed weak current.
  - It can help to disentangle the contributions of different mechanisms if observed.

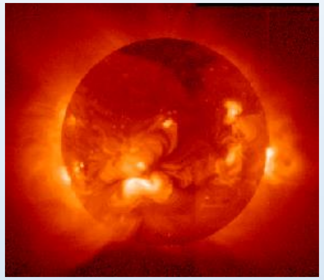
- The 0νECEC process may be resonantly enhanced
  if there exists an excited state with $\Delta = Q_{ECEC} - 2E_x - E_\gamma \sim 0$.

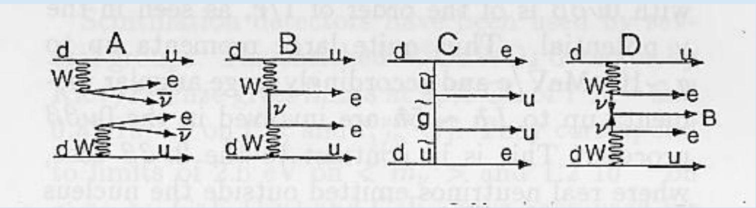
- And… any measurement of 2νECEC will provide a new
  reference for the calculation of nuclear matrix elements.



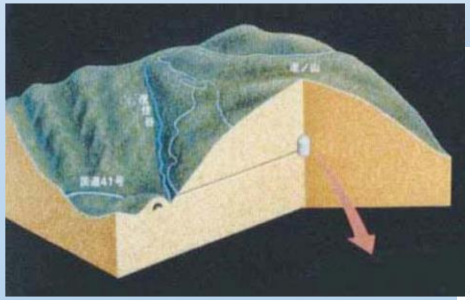
The XMASS experiment

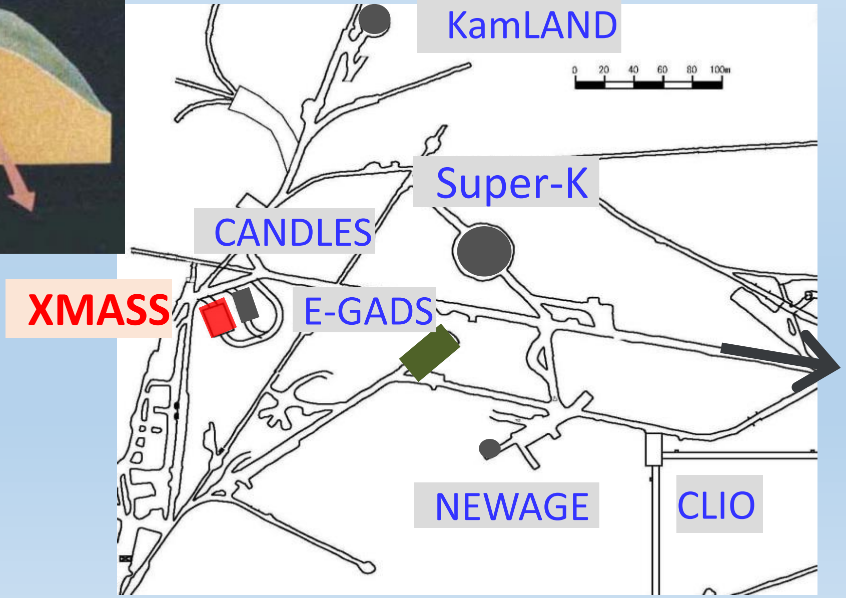






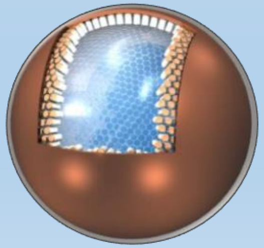
- **A multi-purpose experiment using liquid xenon in the Kamioka mine (2,700 m.w.e.) in Japan.**
  - Direct detection of dark matter
  - Observation of pp/^{7}Be solar neutrinos
  - Search for neutrinoless double beta decay



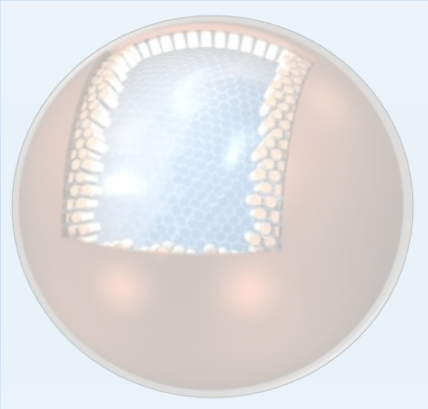


Operating

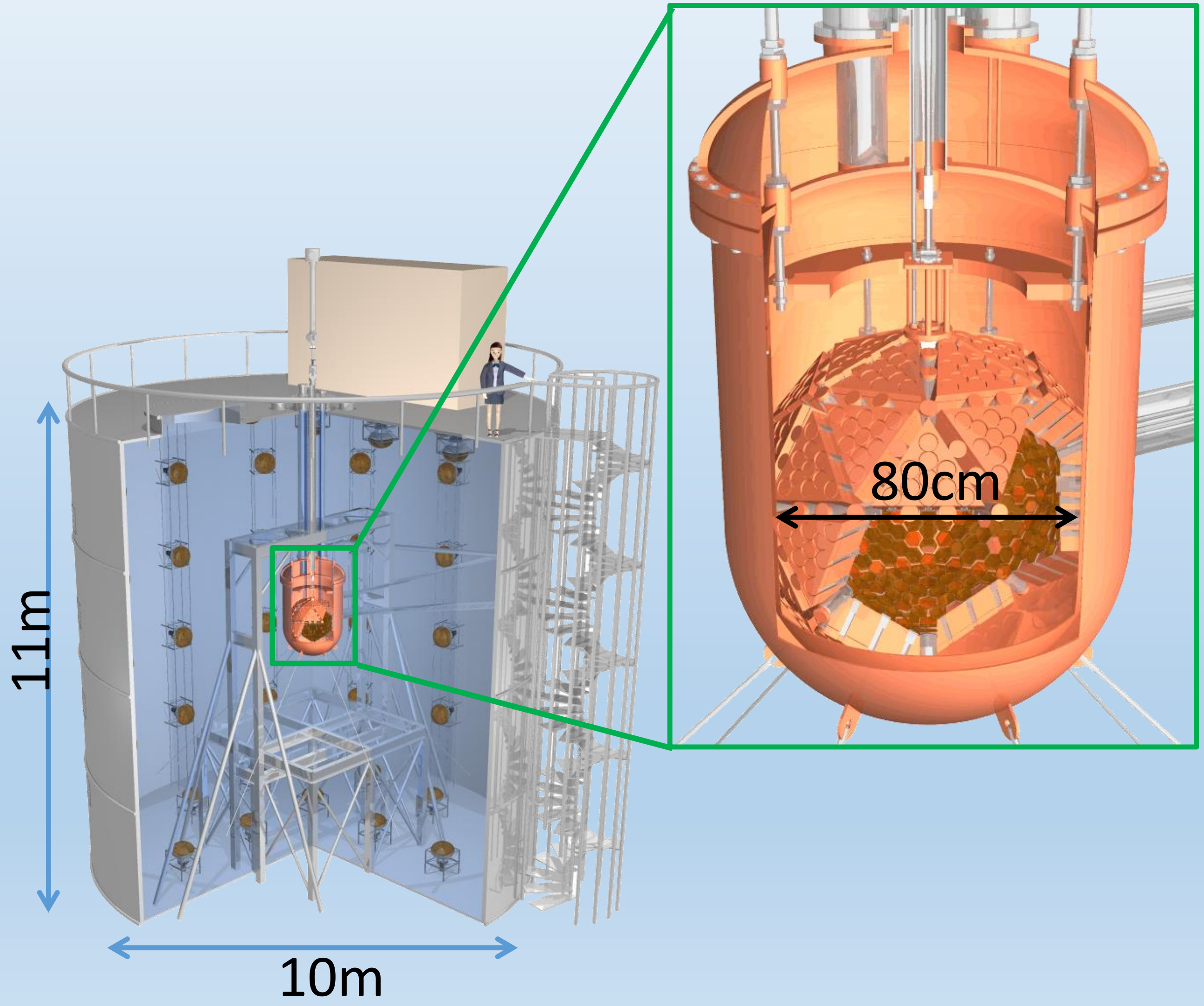
XMASS-1.5
(total ~6tons)



XMASS-2
(total ~24tons)

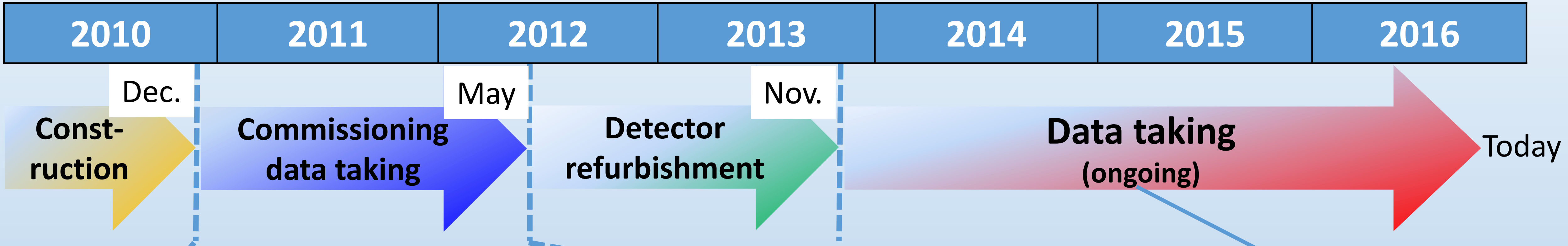


The XMASS-I detector



- Single-phase liquid xenon detector
  - ~830 kg of liquid xenon (-100 ^{o}C)
  - 642 2-inch PMTs (Photocathode coverage >62%)
  - ~14 photoelectrons/keV
- Water Cherenkov detector
  - 10m diameter, 11m high
  - 72 20-inch PMTs
  - Active shield for cosmic-ray muons
  - Passive shield for n/γ

History of XMASS-I

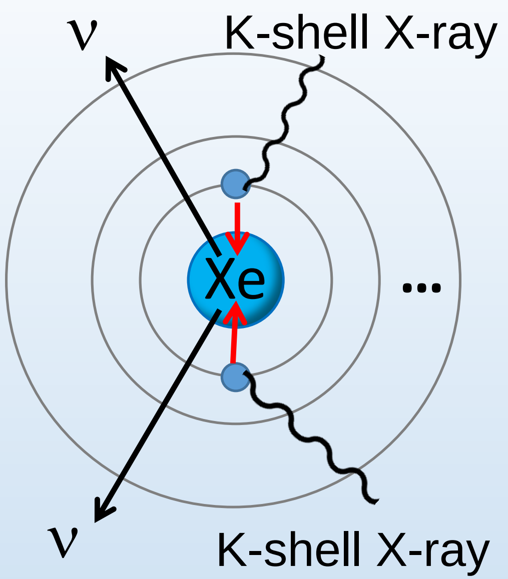


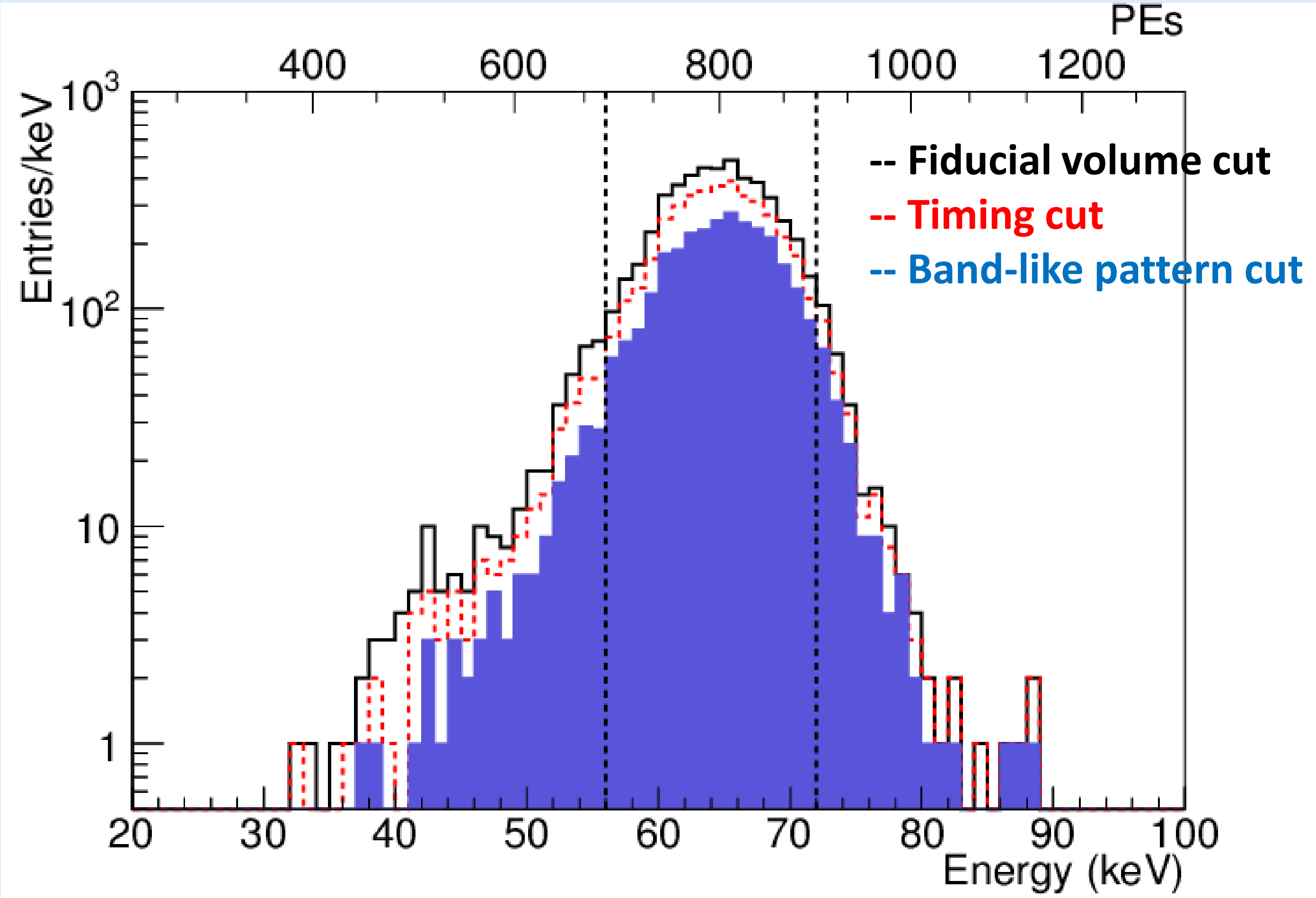
- Search for Low mass WIMPs [PLB 719 (2013) 78]
- Search for solar axion [PLB 724 (2013) 46]
- Search for WIMP-^{129}Xe inelastic scattering [PTEP (2014) 063C01]
- Search for bosonic super-WIMPs [PRL 113 (2014) 121301]
- This talk → **Search for 2ν ECEC on ^{124}Xe [PLB 759 (2016) 64]**

- Search for annual modulation [PLB 759 (2016) 272]

Dark matter results will be presented by K. Sato in the dark matter session on Nov. 10th.

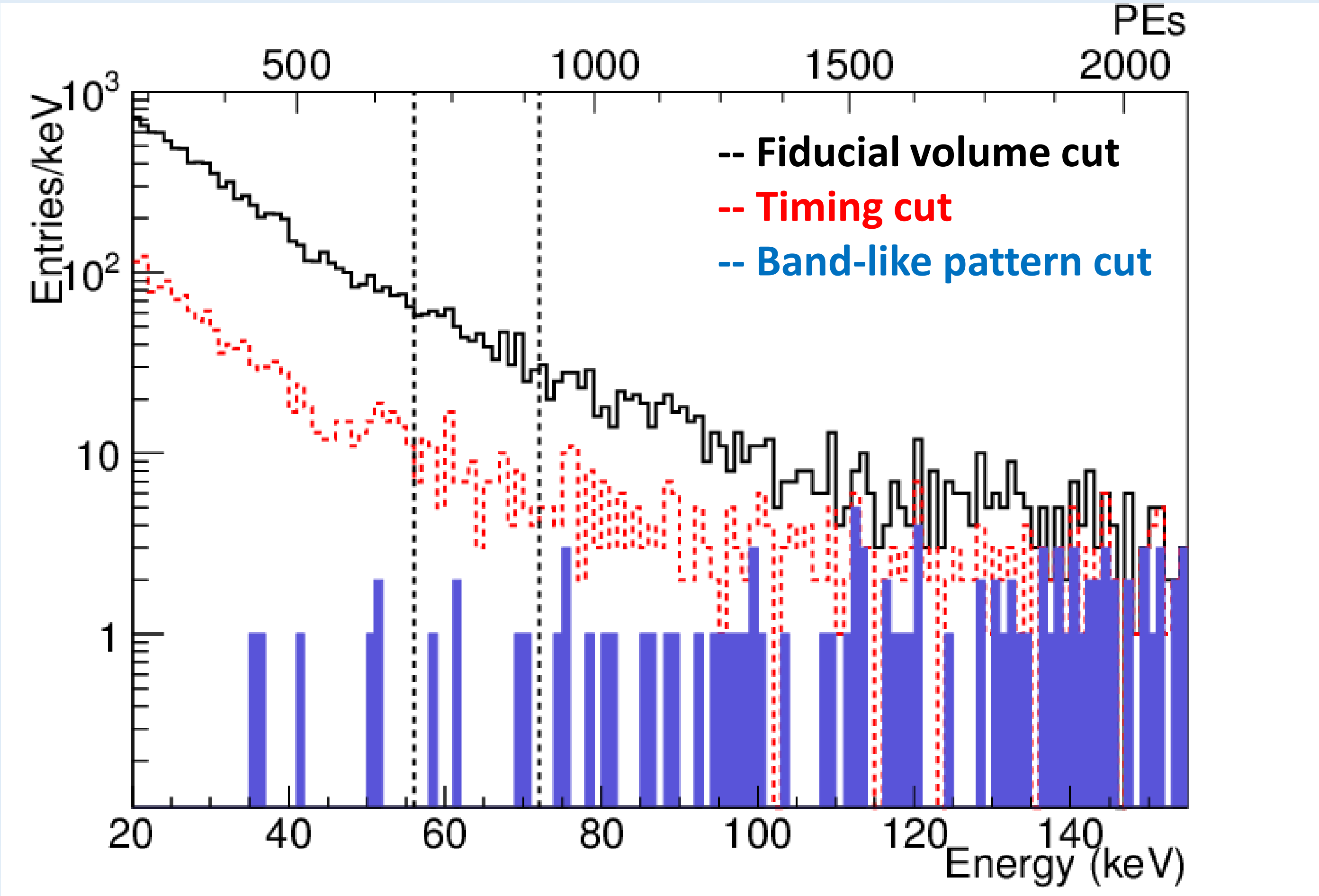
Expected ^{124}Xe 2ν 2K-capture signal





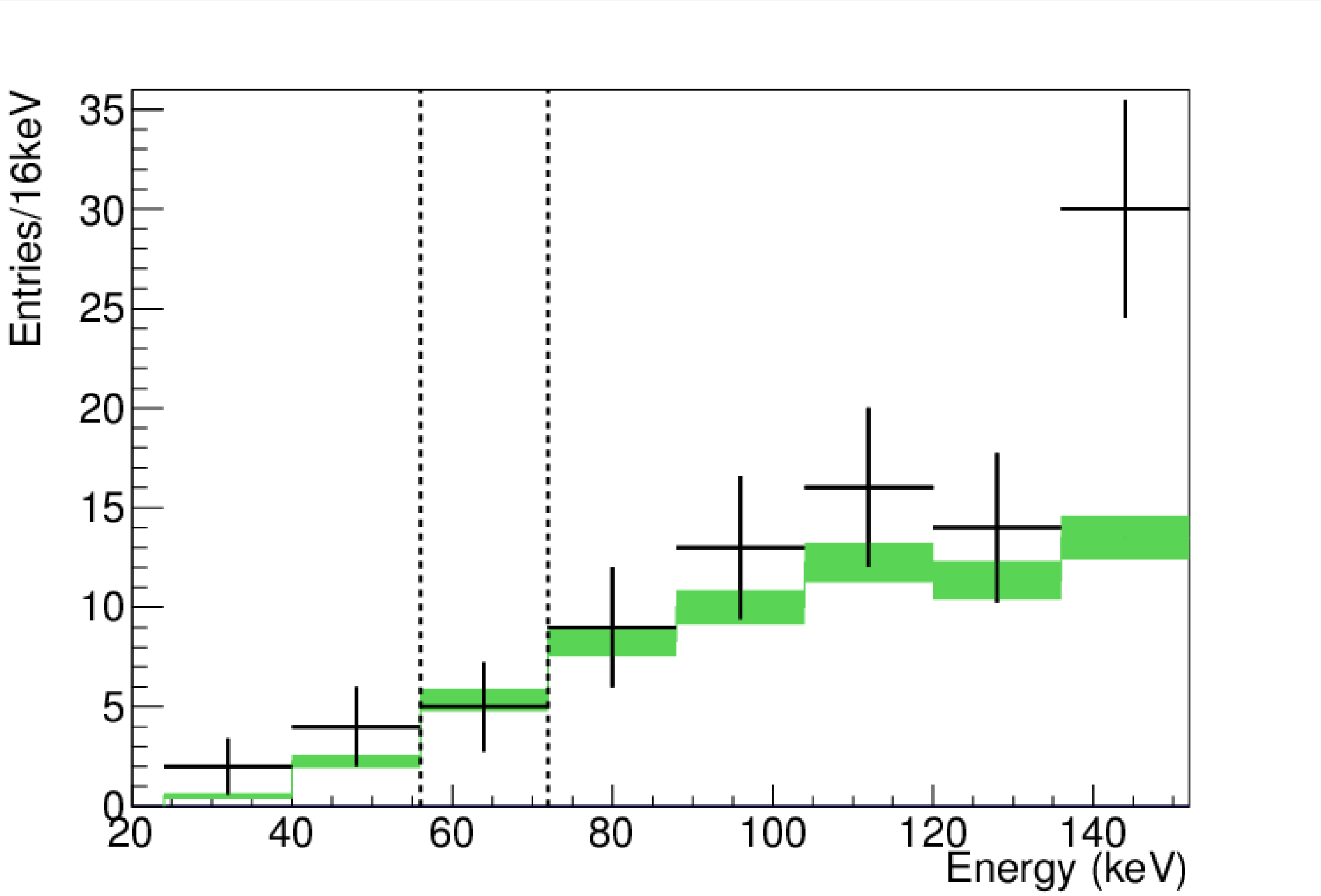
- X-rays and Auger electrons after 2ν 2K-capture are simulated.
- The energy window (56-72keV) is determined so that it contains 90% of the simulated signal.
- Efficiency for signal is 59.7%.

Observed data



- Data taken between Dec. 2010 and May 2012 (132.0 live days)
- Fiducial mass is 41kg (It contains 39g of ^{124}Xe)
- 5 events remained in the signal region

Comparison with background prediction

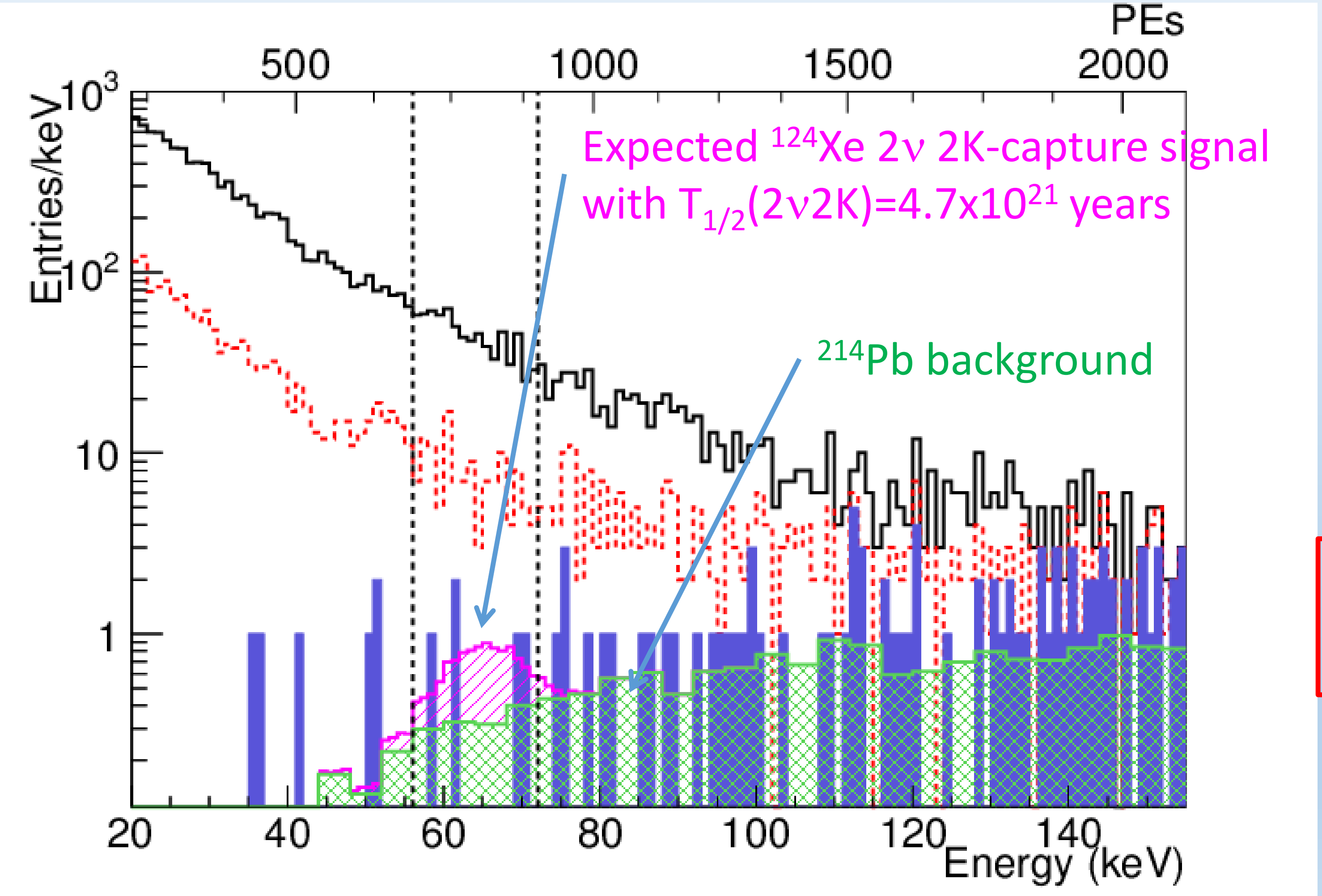


+ Data

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

- Main background 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 above background.

Limits on 2ν 2K-capture half-lives



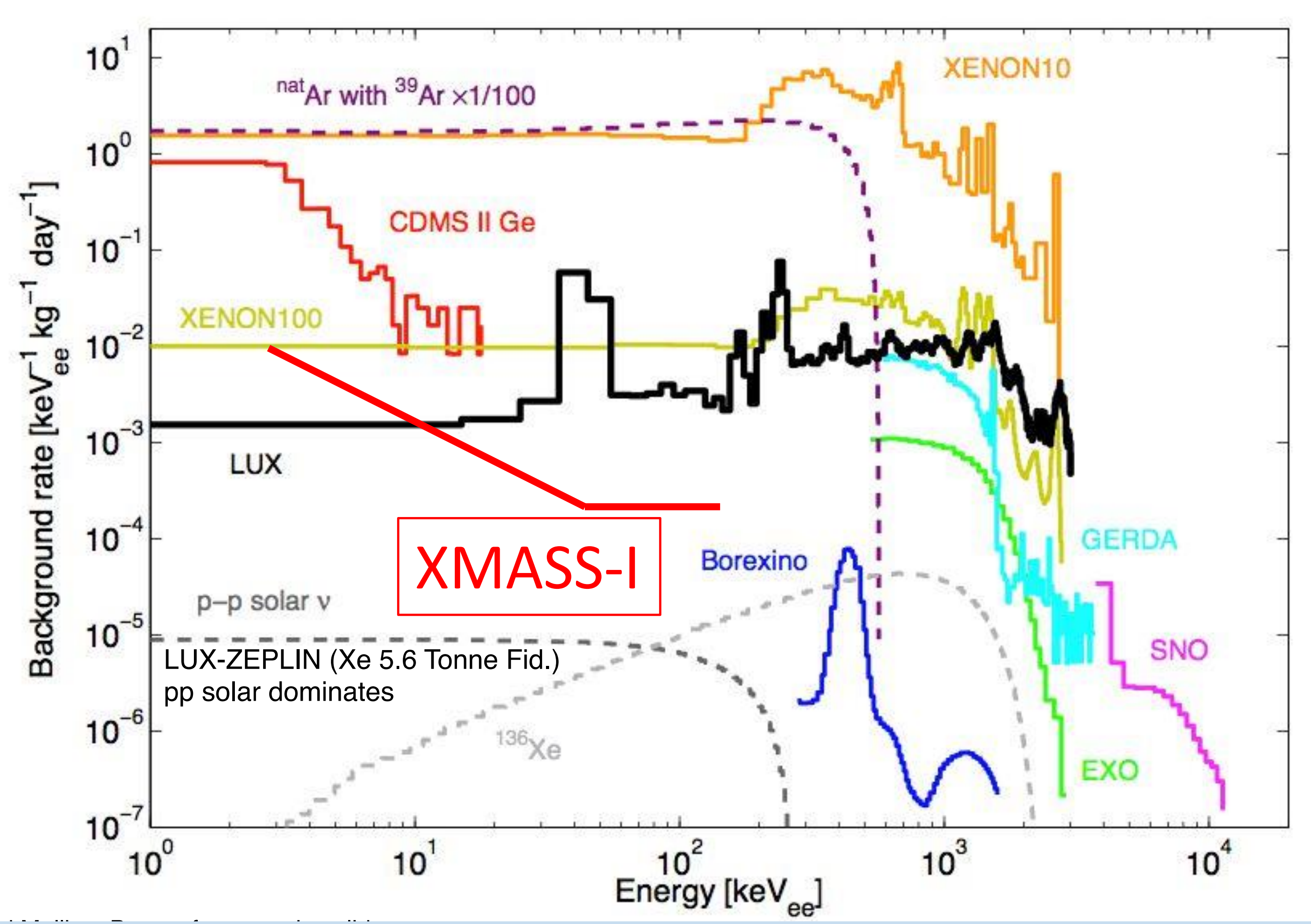
- We derived the 90% CL lower limit on ^{124}Xe 2νECEC half-life using the Bayesian approach.
- Since we do not see signal, we set limit on ^{126}Xe 2νECEC half-life as well.

$T_{1/2}^{2\nu2K}(^{124}Xe)>4.7\times10^{21}$ yrs
$T_{1/2}^{2\nu2K}(^{126}Xe)>4.3\times10^{21}$ yrs
(90%CL)

The world best limits to date !!

Published in Phys. Lett. B759 (2016) 64.

Comparison of background rate in fiducial volume including both nuclear recoil and e/γ events

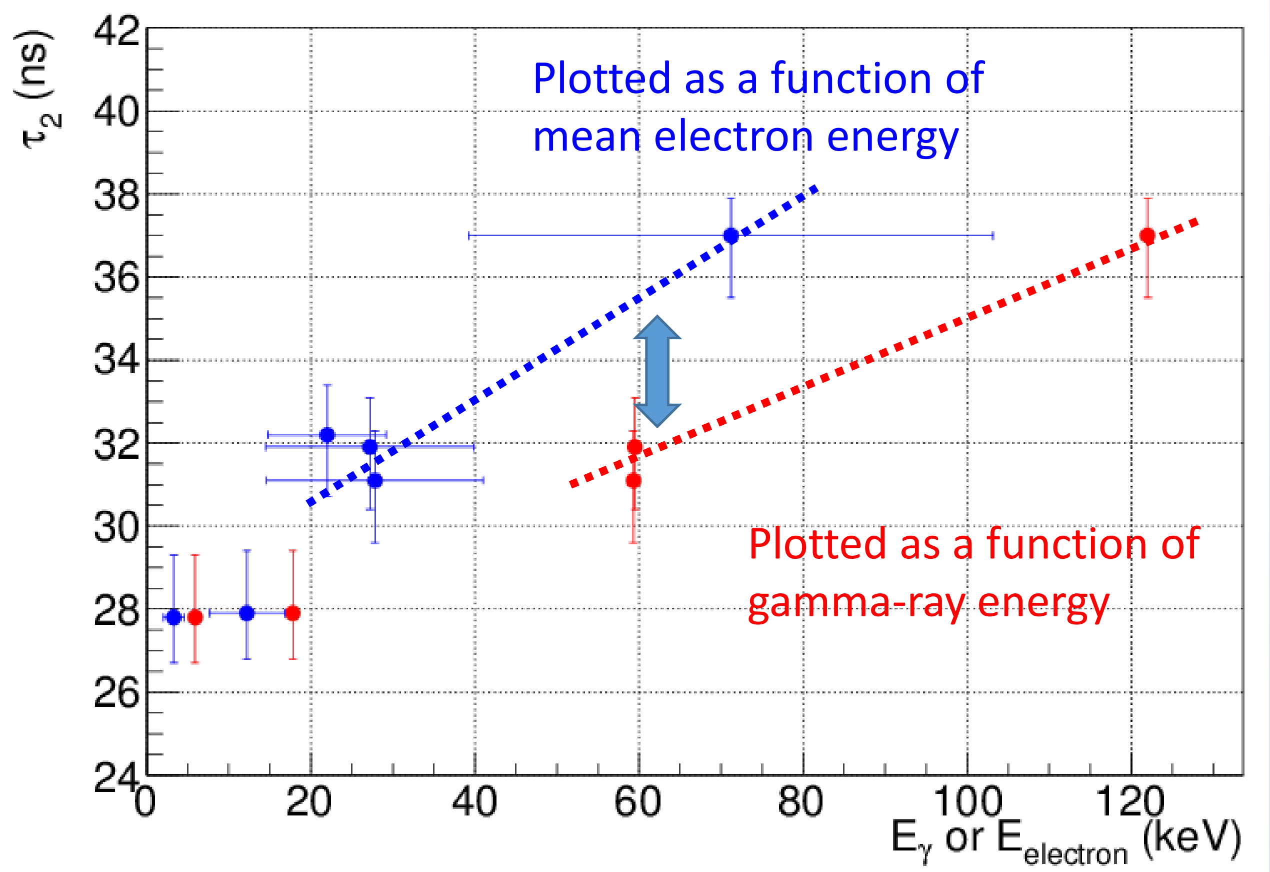


- XMASS achieved low background rate of O(10^{-4}) event/day/kg/keV in a few 10s keV including e/γ events
- Low background rate for e/γ events is good for searching for dark matter other than WIMPs.

Original figure taken from
D. C. Mailing, Ph.D (2014) Fig 1.5

Future prospects (1)

- Reduction of β-ray background by PSD
  - 2νECEC: 2 X-ray/Auger electrons with ~30 keV each
  - β-ray BG: single electron
- Measured LXe scintillation time profile using gamma-ray sources (^{55}Fe, ^{241}Am, ^{57}Co).
  Takiya et al. (XMASS Collaboration), NIM A834 (2016) 192.
- In the case of gamma-rays with Eγ<~200 keV, they are converted into multiple electrons.
  e.g.) 122 keV gamma-ray from ^{57}Co
  ➔ ~90 keV photo-electric electron + ~30 keV Auger electron + …
- If we compare β/γ with the same energy, γ events have a few ns shorter decay time.



Future prospects (2)

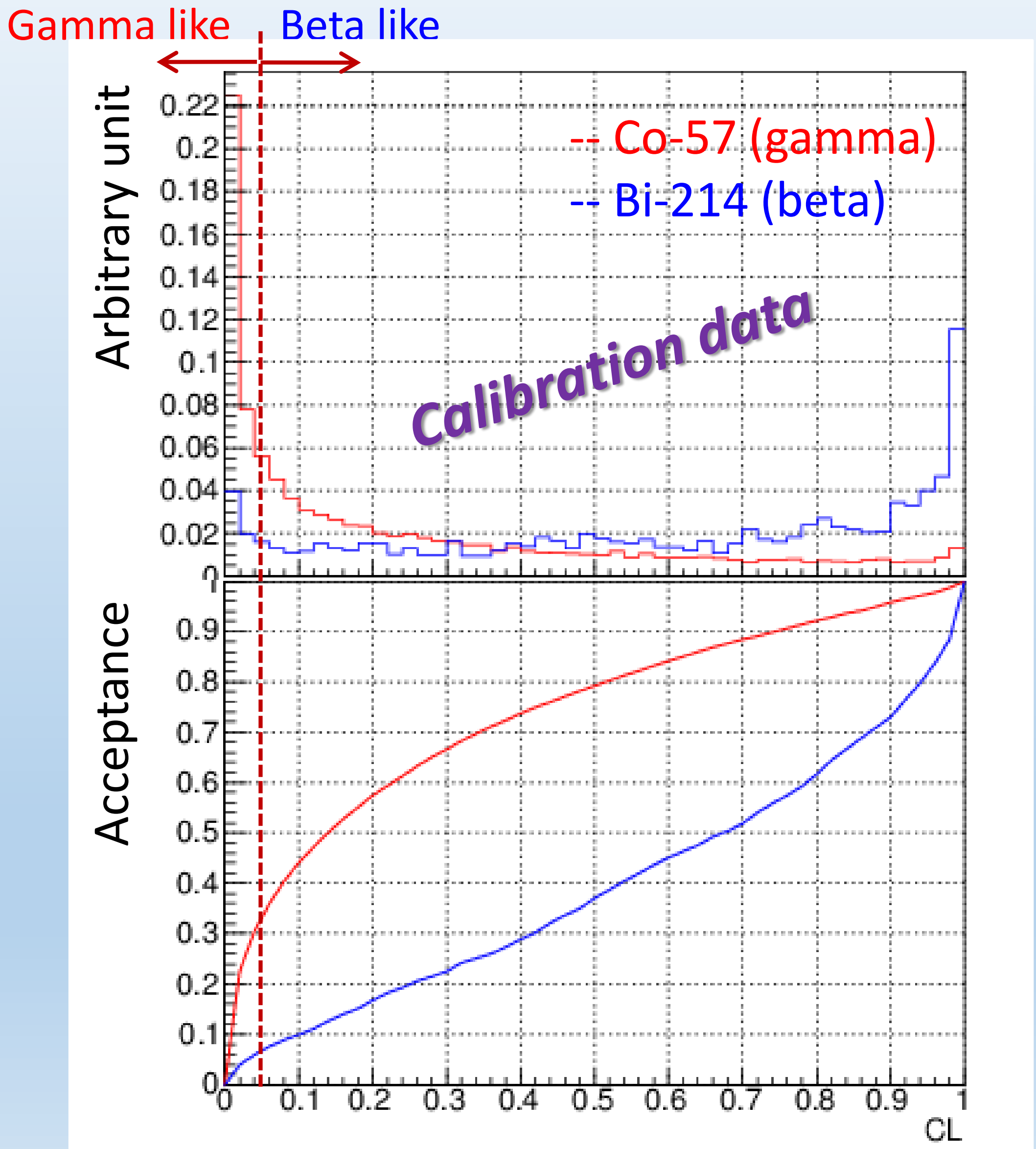
- We constructed a particle ID parameter from the observed photoelectron timing distribution in each event.

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

where CLi is the confidence level of each PE's timing assuming beta-ray.

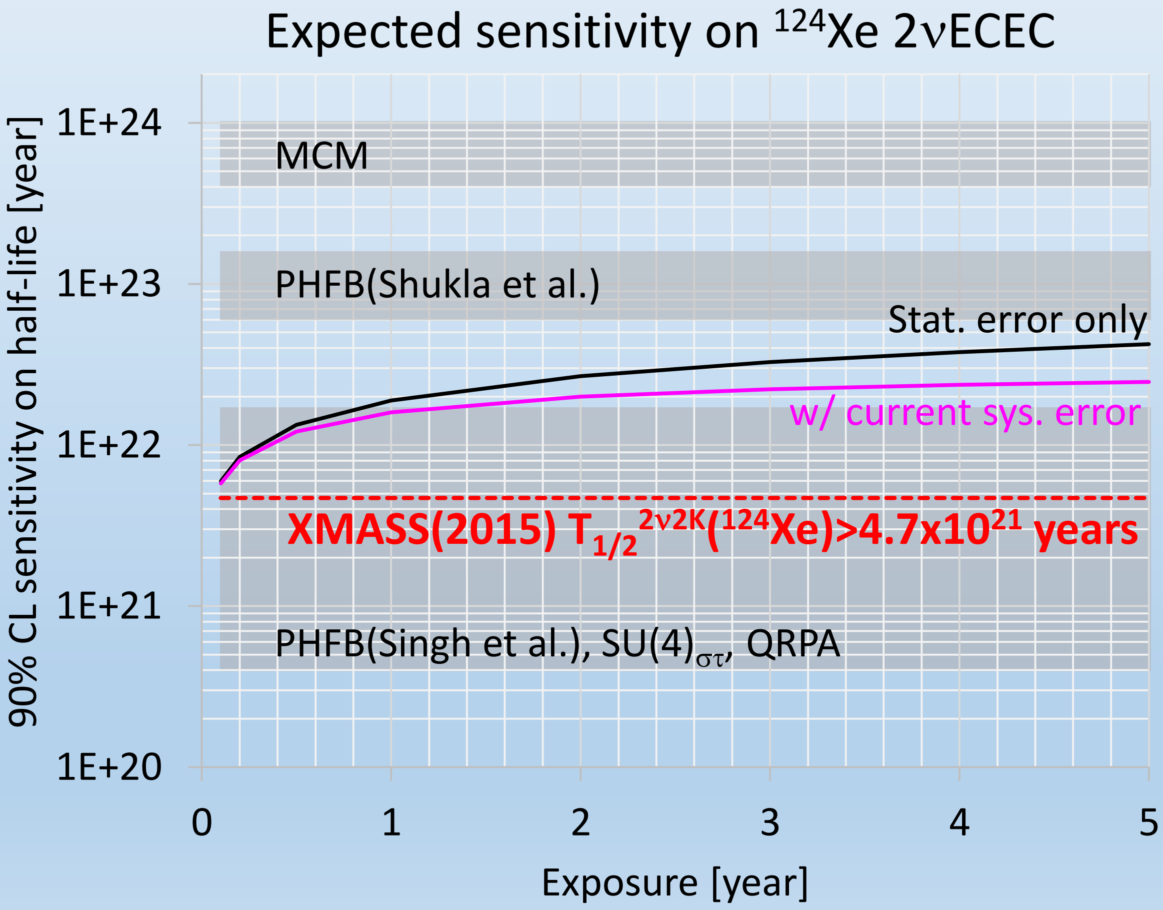
- If events with βCL<0.05 are selected as gamma-like,
  - Acceptance for gamma-ray ~35%.
  - Acceptance for beta-ray is ~7%.
  - ➔ S/N will improve by a factor ~5.

PID parameter distribution



Future prospects (3)

- We have already accumulated more than 2 years of data after refurbishment.
- Assuming 100 kg fiducial mass (95g ^{124}Xe) and BG level of 10^{-4} event/day/kg/keV, the 90%CL sensitivity will reach $T_{1/2}$ = (2-3)x10^{22} years.
- XMASS-1.5 (total 6 tons) will cover whole the expected range of 2νECEC.



Summary

- ^{124}Xe is an interesting nucleus to study double electron capture (and β^+EC, $\beta^+\beta^+$).
- We performed a search for 2ν double electron capture using 132 days of commissioning data collected with the XMASS-I detector.
  - No significant excess above background was found.
  - Set lower limits $T_{1/2}^{2\nu 2K}(^{124}Xe)>4.7\times10^{21}$ years and $T_{1/2}^{2\nu 2K}(^{126}Xe)>4.3\times10^{21}$ years (90% CL)
- We have already accumulated more than 2 years of data after refurbishment.
- XMASS-1.5 will cover whole the expected range of ^{124}Xe 2ν ECEC.

Backup slides

Theoretical calculation for ^{124}Xe 2ν ECEC

Model	$T_{1/2}$ (2νECEC) (yr)	Reference
QRPA	$(0.4\text{-}8.8)\text{x}10^{21}$	Suhonen (2013)
QRPA	$(2.9\text{-}7.3)\text{x}10^{21}$	Hirsch et al. (1994)
$SU(4)_{\sigma\tau}$	$(7\text{-}17.7)\text{x}10^{21}$	Rumyantsev et al. (1998)
PHFB	$(7.1\text{-}18.0)\text{x}10^{21}$	Singh et al. (2007)
PHFB	$(61.4\text{-}155.1)\text{x}10^{21}$	Shukla et al. (2007)
MCM	$(390\text{-}986.1)\text{x}10^{21}$	Aunola et al. (1996)

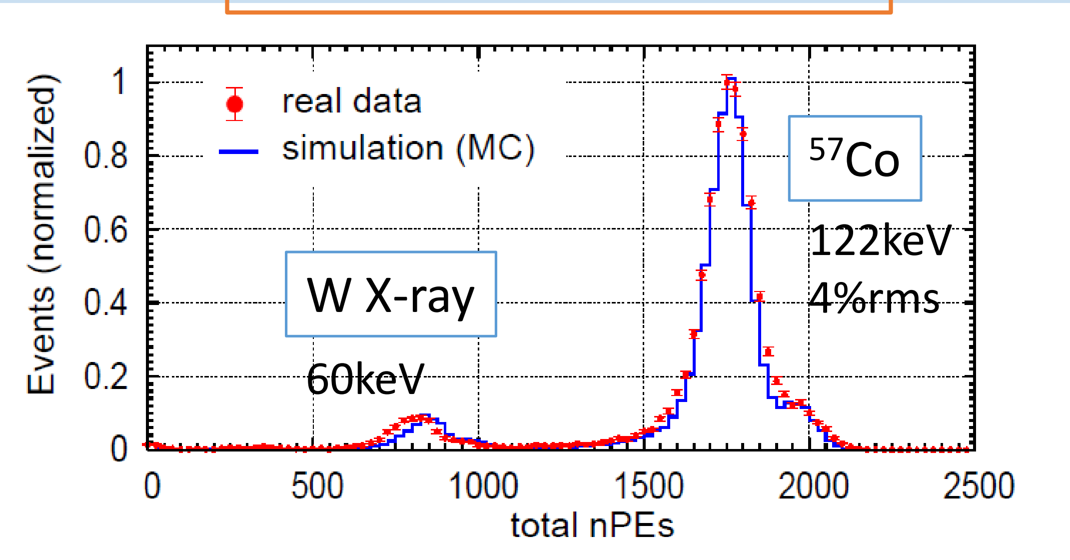
Experimental results on ^{124}Xe 2nECEC

Experiment	$T_{1/2}$ (10^{21} yr)	^{124}Xe mass	Livetime	Reference
Abe et al. (XMASS)	>4.7	39 g	132 days	This work
Gavrilyuk et al.	>2.0	59 g	134 days	arXiv:1507.04520
Mei et al.	>1.66	34 g	225 days	Phys. Rev. C89 (2014) 014608
Aprile et al. (XENON100)	>0.65	29 g	225 days	arXiv:1609.03354

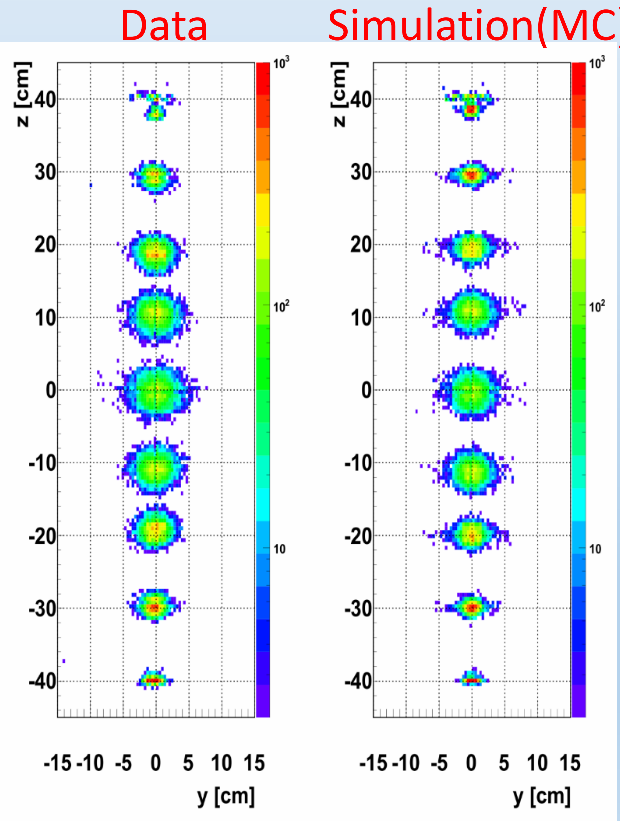
Detector calibration

- 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



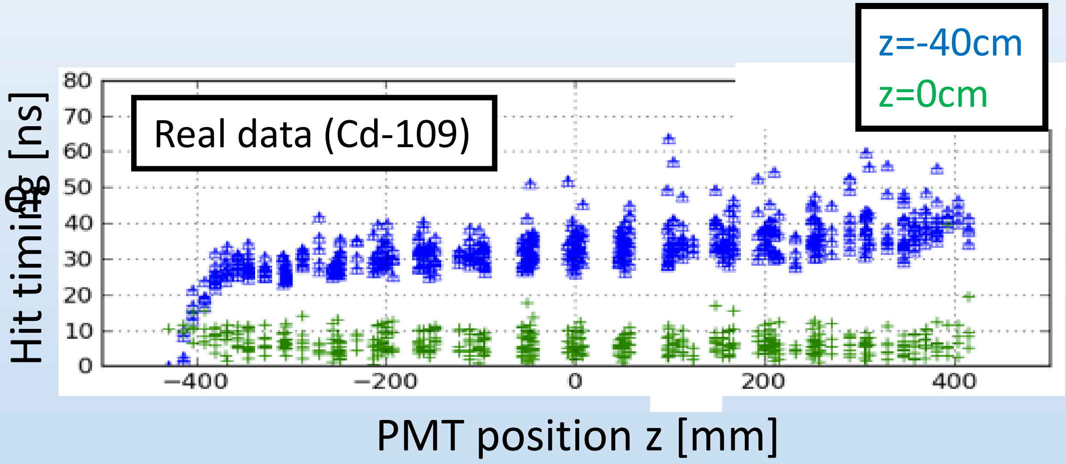
Data set and event selection (1/2)

- 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.

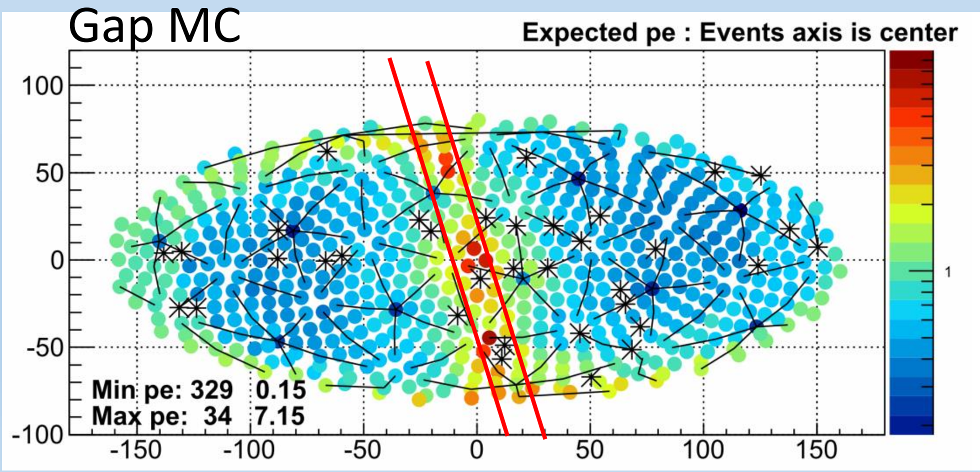
$$\delta T_m = t_{\text{mean of 2nd half of hits}} - t_{\text{1st hit}}$$



  - 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.

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

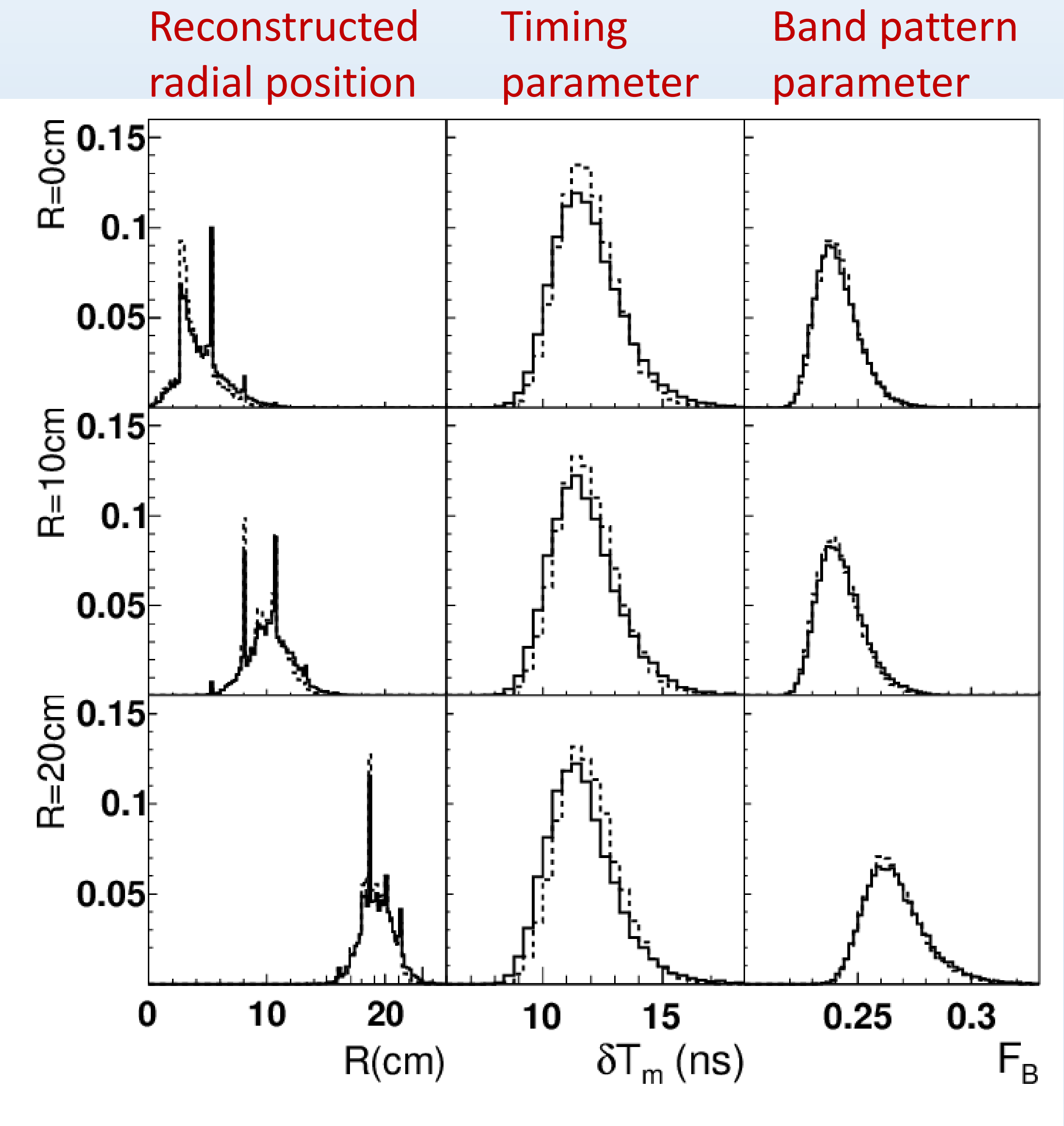
λ: exposure
ε: signal efficiency (uncorrelated with BG)
ε_{corr}: correlated efficiency
$b\varepsilon_{corr}$: number of BG events in the signal region

- 90% confidence level limit

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

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

Data/MC comparison for 241Am calibration data



(Solid) Data
(Dashed) MC

Contributions from right-handed current

$$H_{eff} = \frac{G_F}{\sqrt{2}}\left(J_L J_L^\dagger + \eta J_R J_L^\dagger + \lambda J_R J_R^\dagger\right) + h.c.$$

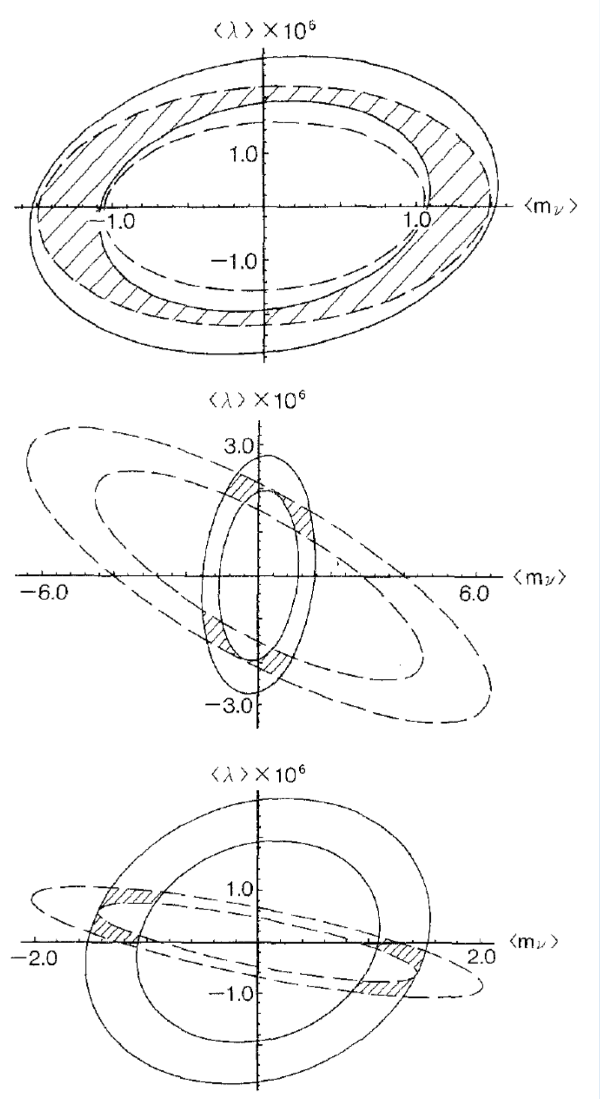
$$T_{1/2}^{-1} = C_{mm}\left(\frac{\langle m_\nu\rangle}{m_e}\right)^2 + C_{\eta\eta}\langle\eta\rangle^2 + C_{\lambda\lambda}\langle\lambda\rangle^2$$
$$+C_{m\eta}\frac{\langle m_\nu\rangle}{m_e}\langle\eta\rangle + C_{m\lambda}\frac{\langle m_\nu\rangle}{m_e}\langle\lambda\rangle + C_{\eta\lambda}\langle\eta\rangle\langle\lambda\rangle$$

$$\langle\eta\rangle = \sum \eta U_{ej}V_{ej}\ ,\ \langle\lambda\rangle = \sum \lambda U_{ej}V_{ej}$$

(a)
^{76}Ge: $T_{1/2}$=(1.5+/-0.5)x10^{24} yr (solid)
^{136}Xe: $T_{1/2}$=(1.5+/-0.5)x10^{24} yr (dash)

(b)
^{76}Ge: $T_{1/2}$=(1.5+/-0.5)x10^{24} yr (solid)
^{124}Xe: $T_{1/2}$=(1.5+/-0.5)x10^{25} yr (dash)

(c)
^{76}Ge: $T_{1/2}$=(1.5+/-0.5)x10^{24} yr (solid)
^{124}Xe: $T_{1/2}$=(1.5+/-0.5)x10^{26} yr (dash)



M. Hirsch et al., Z. Phys. A347 (1994) 151