



# Latest results from XMASS

Katsuki Hiraide (ICRR, the University of Tokyo)

October 22, 2018

DBD18@Hawaii, USA

# Contents

- XMASS detector and data taking
- Latest results from XMASS

*Dark  
Matter  
related*

1. WIMP dark matter search by fiducialization
2. Hidden photons & axion-like particles DM search
3. WIMP- $^{129}\text{Xe}$  inelastic scattering search
4. Sub-GeV/multi-GeV DM search by annual modulation
5.  $^{124}\text{Xe}$   $2\nu$  double electron capture search

*arXiv: 1804.02180 (accepted to PLB)*

*arXiv: 1807.08516*

*arXiv: 1809.05358*

*arXiv: 1808.06177*

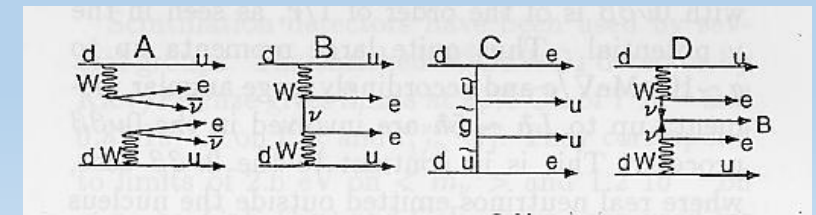
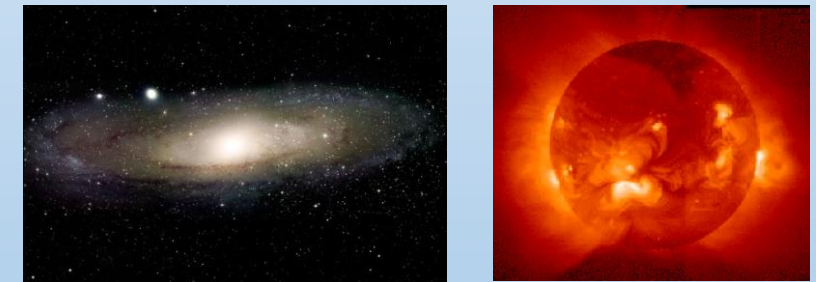
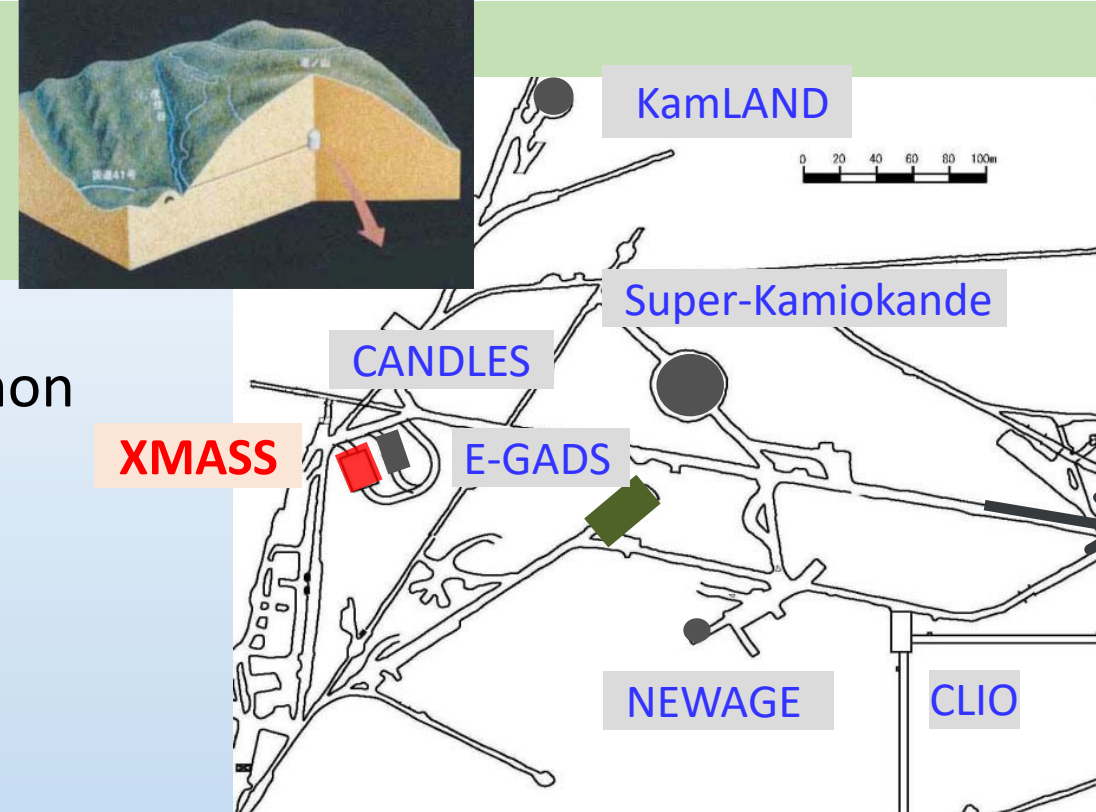
*PTEP2018 (2018) 053D03*

*DBD  
related*

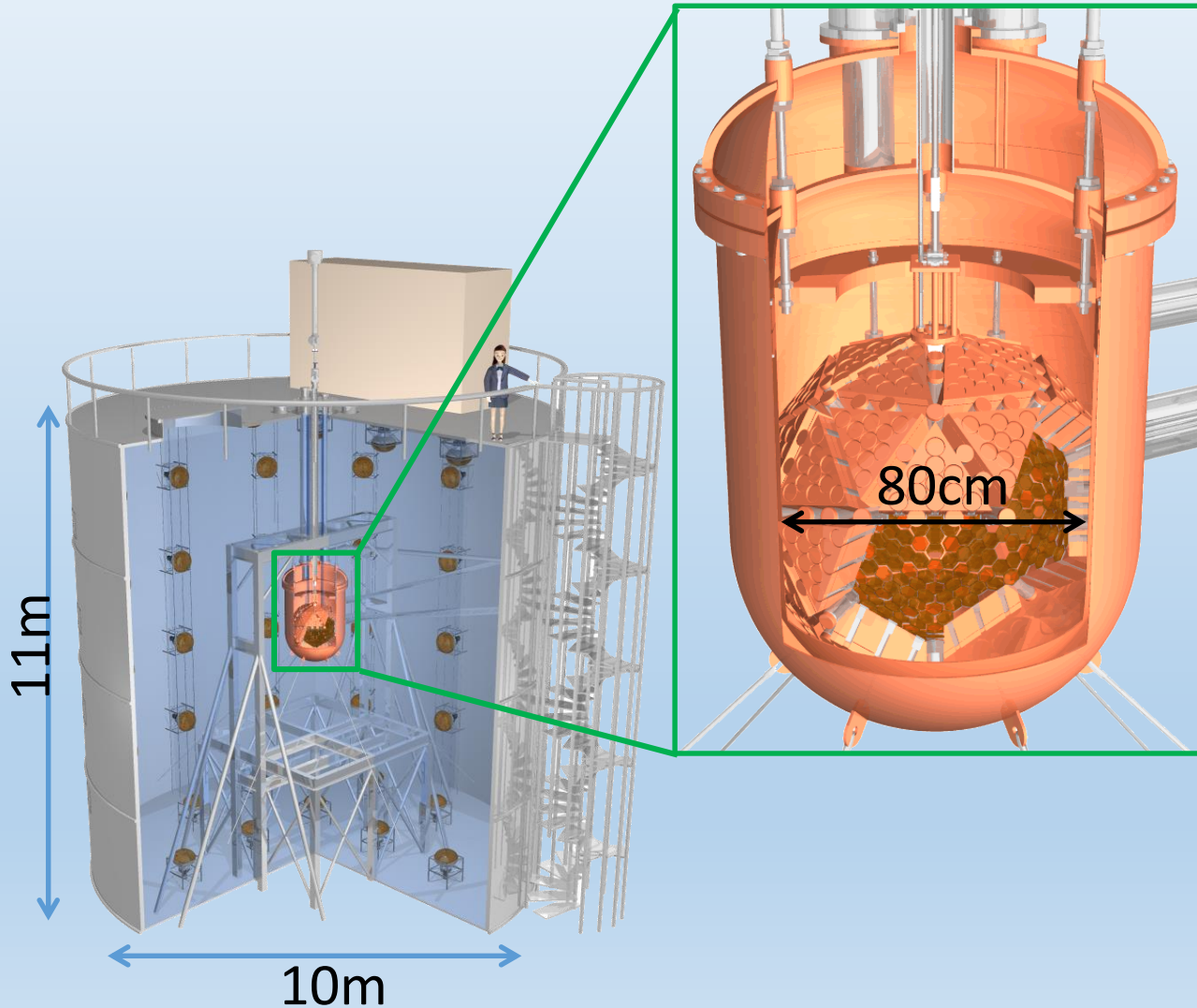
- Summary

# 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 ( $pp/{}^7\text{Be}$ )**
  - ❑ Search for **neutrino-less double beta decay**
- Features
  - ❑ Low energy threshold ( $\sim 0.5\text{keVee}$ )
  - ❑ Sensitive to  $e/\gamma$  events as well as nuclear recoil
  - ❑ Large target mass and its scalability



# Single-phase liquid Xenon detector: XMASS-I



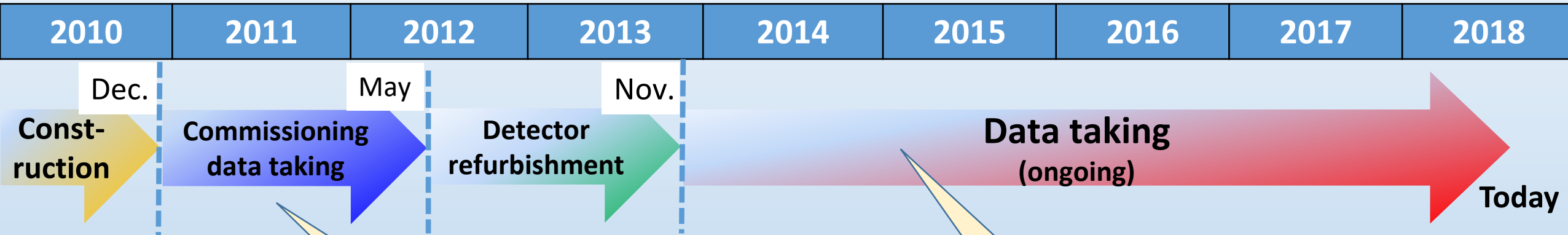
- **Liquid xenon detector**

- 832 kg of liquid xenon (-100 °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  $n/\gamma$

# History of XMASS-I data-taking



- Light WIMPs
- WIMP- $^{129}\text{Xe}$  inelastic scattering
- Bosonic super-WIMPs
- Solar axion
- $^{124}\text{Xe}$  2 $\nu$  double electron capture

- WIMPs search by fiducialization
- WIMP- $^{129}\text{Xe}$  inelastic scattering
- Hidden photons/ALPs DM
- Sub-GeV and multi-GeV DM
- Model independent modulation
- $^{124}\text{Xe}$  2 $\nu$  double electron capture
- Solar Kaluza-Klein axion



- *Stably taking data for >4 years since Nov. 2013.*
- *Will continue data-taking until Dec. 2018.*

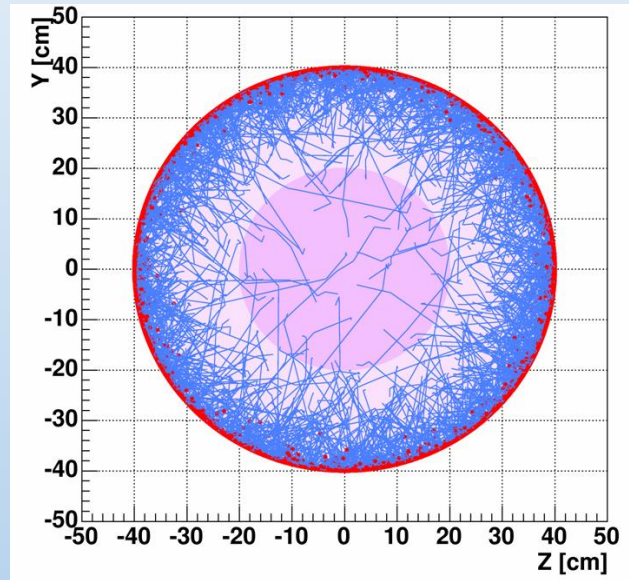
# Latest results from XMASS

# 1) WIMP dark matter search by fiducialization

## Introduction

$^{57}\text{Co}$  122keV

Traces of  $\gamma$ -rays from PMTs



Fiducial volume  
 $R < 20\text{cm}$

- Self-shielding of external  $\gamma$ -rays owing to high atomic number ( $Z=54$ ) and high density ( $2.9\text{g/cm}^3$ )
- Event vertex position and energy are reconstructed using number of PE in each PMT

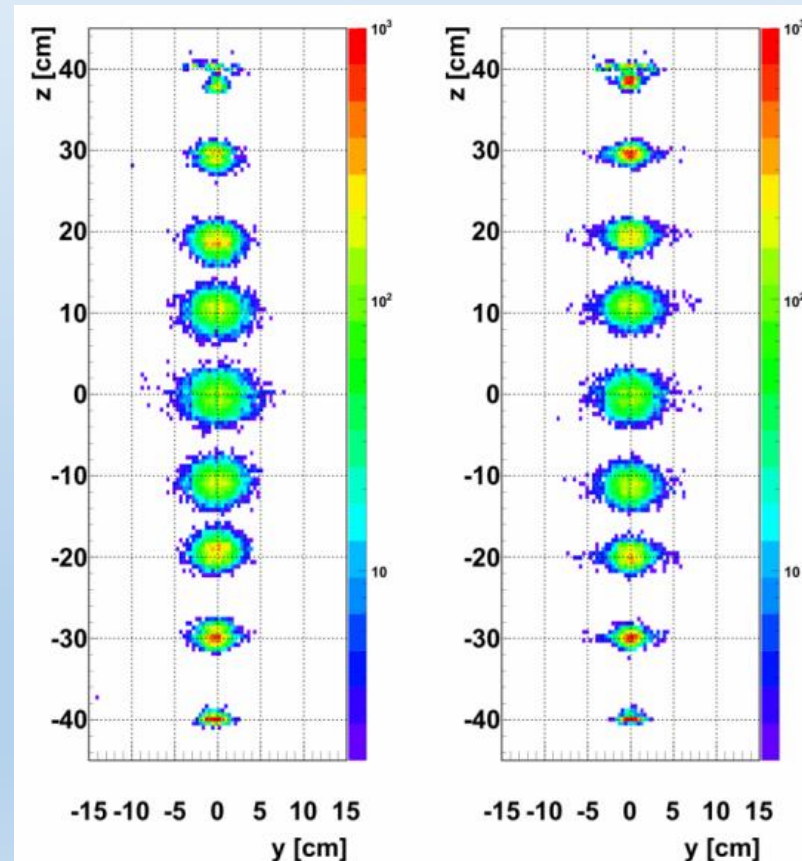
$$L(\mathbf{x}) = \prod_{i=1}^{642} p_i(n_i)$$

$P_i(n)$  : probability that the  $i$ -th PMT detects  $n$  PE

Reconstructed vertex

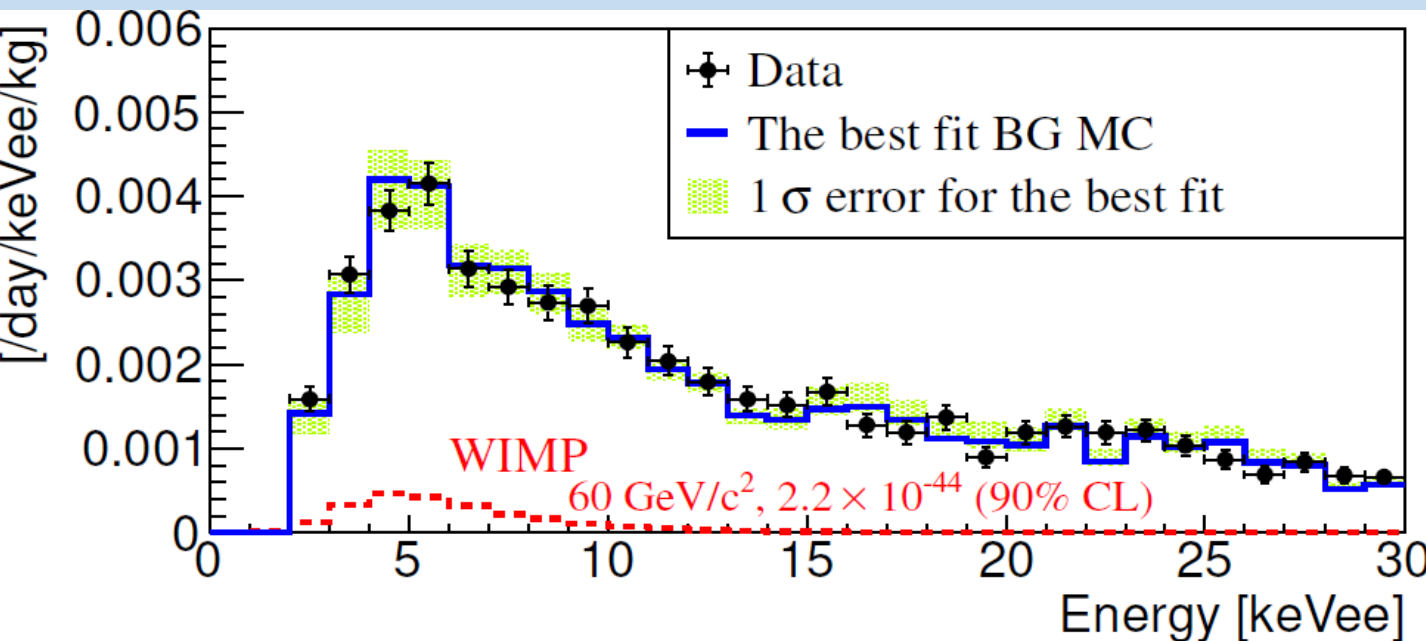
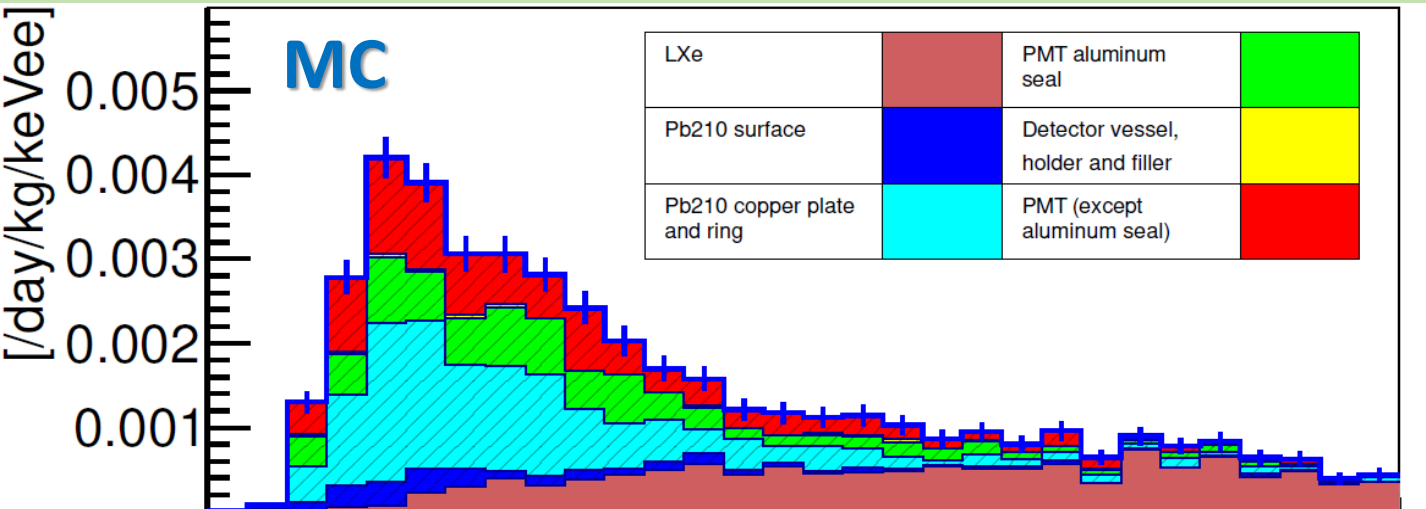
DATA

MC



# 1) WIMP dark matter search by fiducialization

## Results: energy spectrum in the fiducial volume

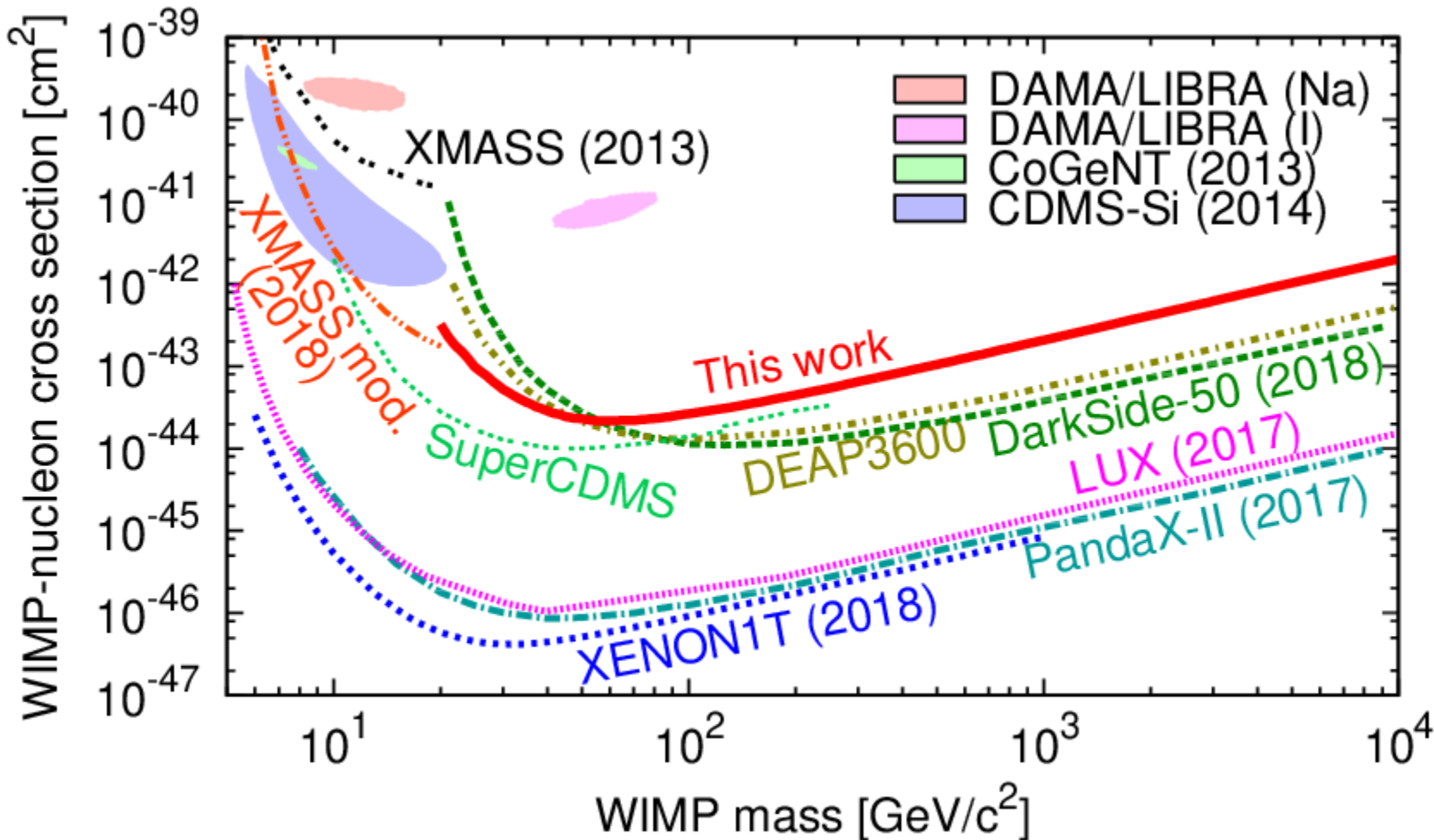


- 706 live days taken in Nov. 2013 – Mar. 2016
- Fiducial mass 97kg (R<20cm)
- Main background in the WIMP search region
  - $^{210}\text{Pb}$  in the copper bulk
  - $\gamma$ -rays from PMTs
  - Neutrons, alpha-rays are negligible
- The energy spectrum at 2-15 keVee is fitted with signal + background.
- Systematic uncertainties are taken into account as nuisance parameters in the fit.
  - Detector surface conditions (gap, roughness) are dominant.



# 1) WIMP dark matter search by fiducialization

## Results: Limits on SI WIMP-nucleon cross section



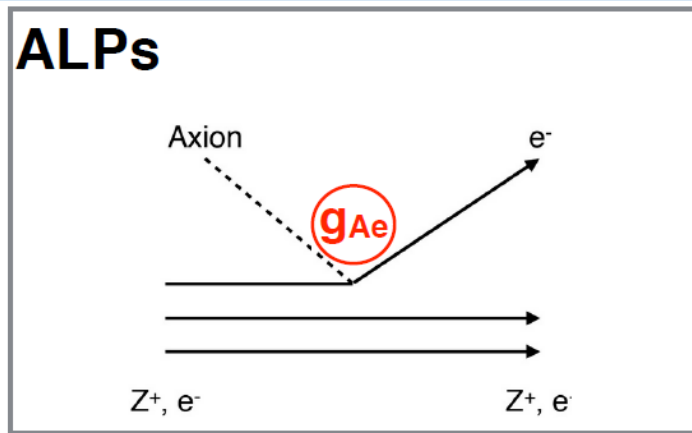
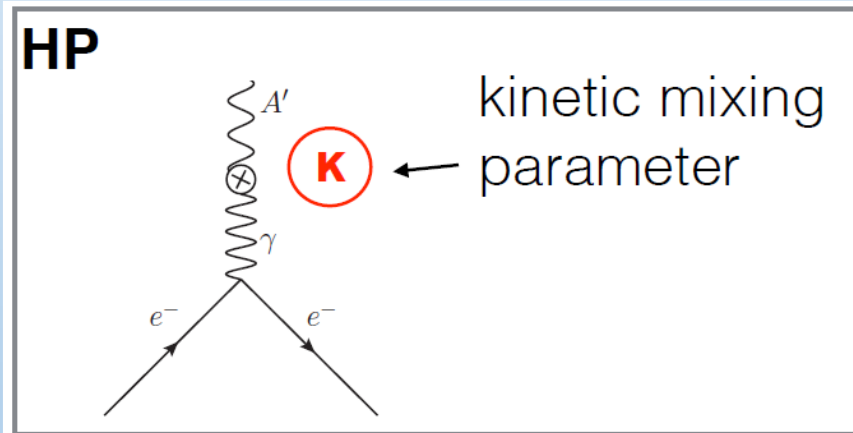
- 97kg x 706 days exposure
- 90% CL upper limit on spin-independent WIMP-nucleon cross section was derived.
  - $\sigma_{SI} < 2.2 \times 10^{-44} \text{ cm}^2$  ( $60 \text{ GeV}/c^2$ )
- First stringent constraint by a single-phase LXe detector
- arXiv: 1804.02180 (accepted to Phys. Lett. B)

# 2) Hidden photons & axion-like particles dark matter

## Introduction

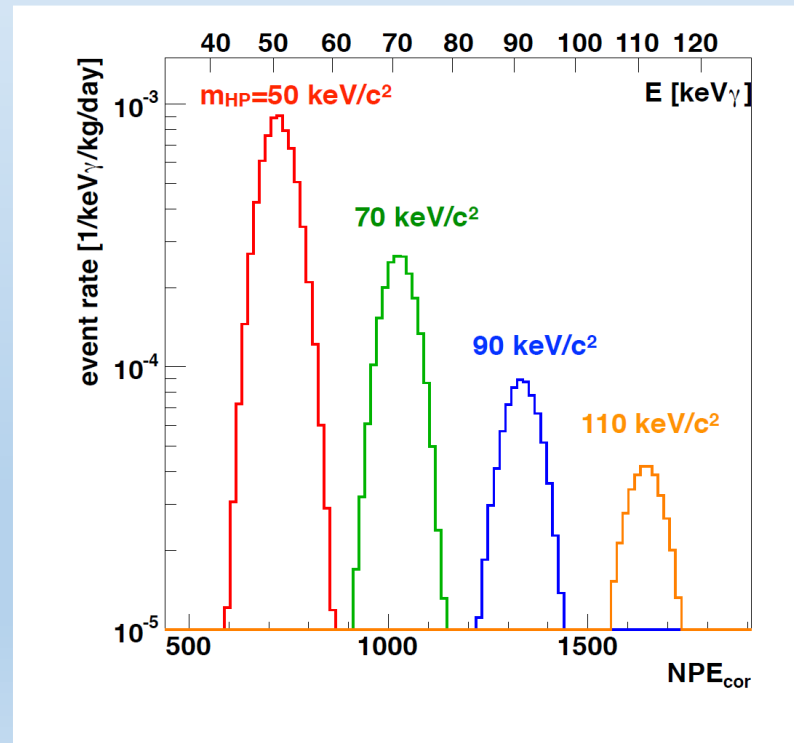
- Hidden photon (HP): gauge boson of hidden U(1)  
Axion-like particles (ALPs): pseudo-Nambu-Goldstone boson
- Both bosons can be absorbed in the detector medium with emission of an electron. → analogue to photoelectric effect

Cold dark matter candidates



$$\frac{\sigma_{abs} v}{\sigma_{pe}(\omega = m_{HP})c} = \frac{\alpha'}{\alpha}$$

$$\frac{\sigma_{abs} v}{\sigma_{pe}(\omega = m_{ALP})c} = \frac{3m_{ALP}^2}{16\pi\alpha m_e^2} \times g_{Ae}^2$$

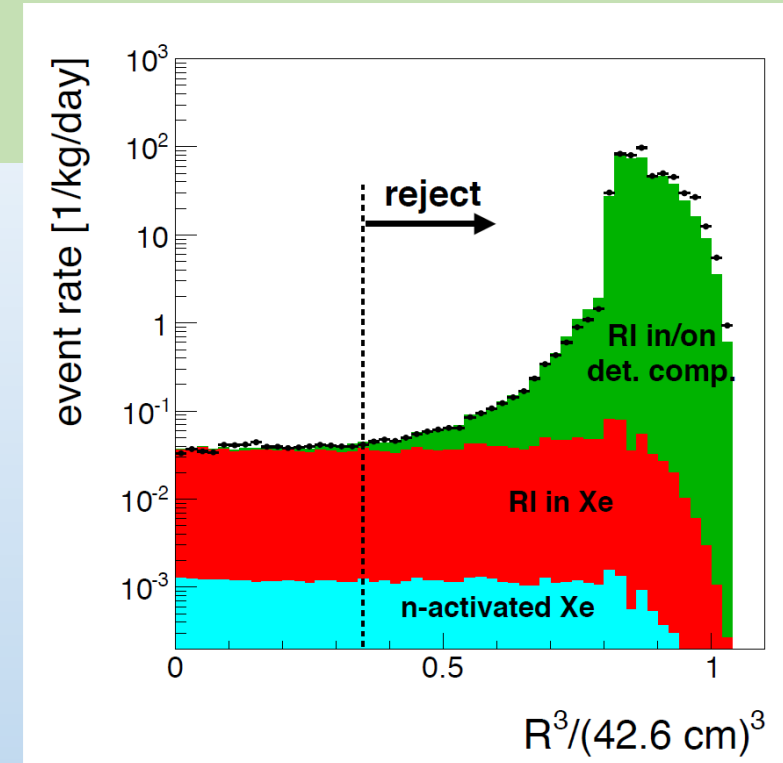
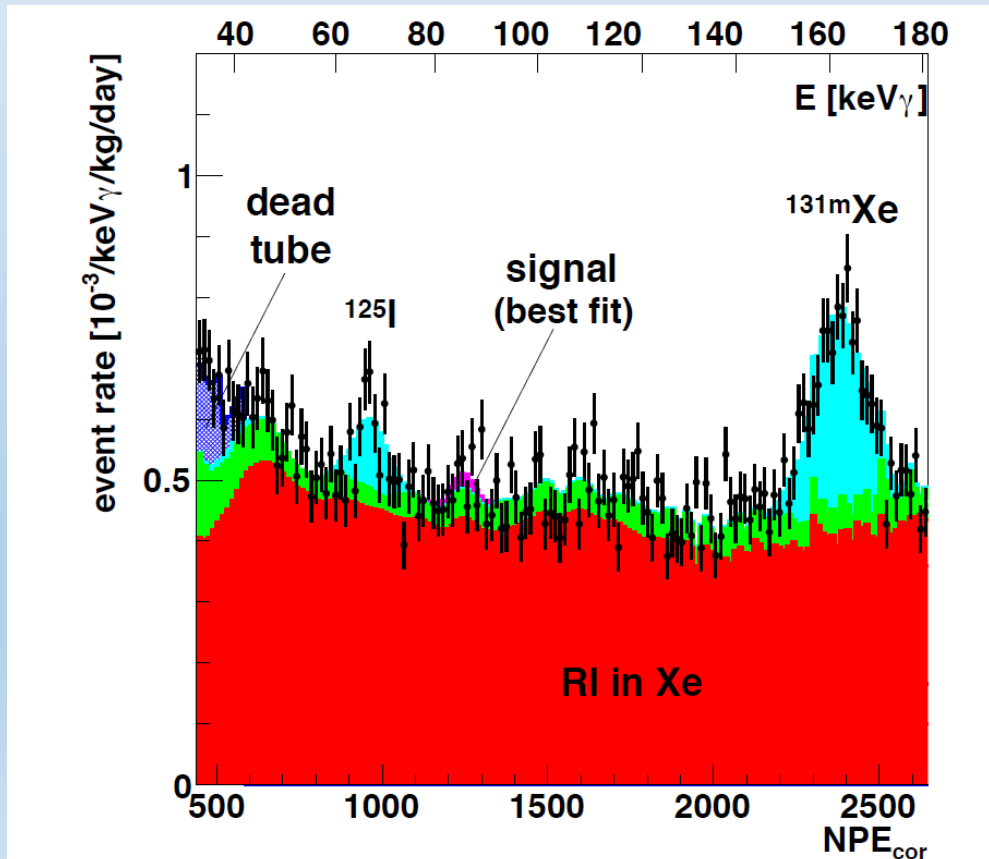


- Event rate  $\propto (a'/a)/m_{HP}$  or  $g_{Ae}^2 \times m_{ALP}$

# 2) Hidden photons & axion-like particles dark matter

## Results

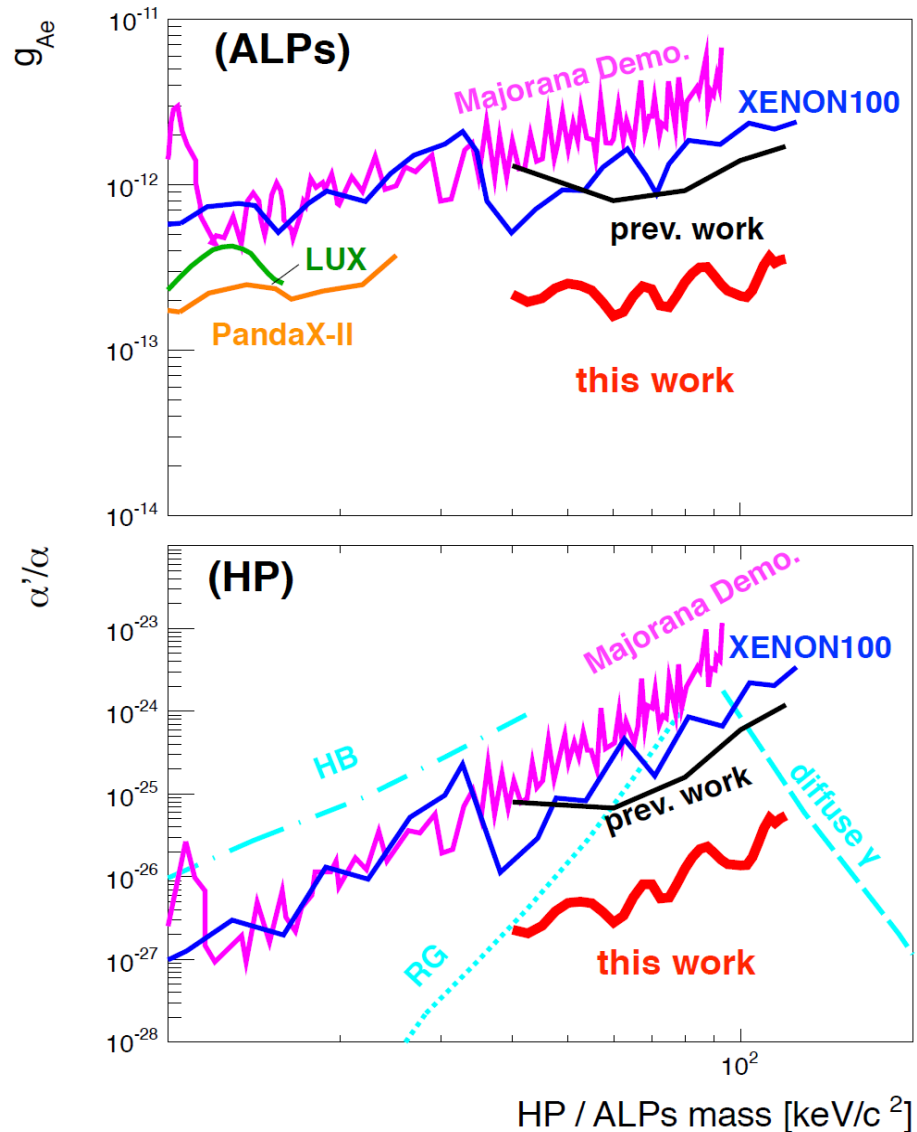
- 800 live days of data (Nov. 2013 – Jul. 2016)
- Fiducial volume was extended to  $R < 30\text{cm}$  (327 kg of LXe)



- Peak search by fitting the energy spectrum with the signal + background model.
- Fitting energy range 30-180 keV
- Scanning mass every  $2.5\text{ keV}/c^2$  in  $40\text{-}120\text{ keV}/c^2$

# 2) Hidden photons & axion-like particles dark matter

## Results

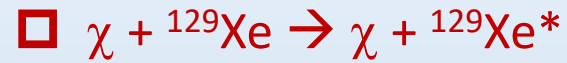


- 800 days x 327 kg exposure
- No significant signal was observed.
- Axion-like particles DM
  - $g_{Ae} < 4 \times 10^{-13}$  (90% CL) for 40-120 keV/c<sup>2</sup>
  - Cover higher mass region than LUX and PandaX-II
- Hidden photon DM
  - $\alpha'/\alpha < 6 \times 10^{-26}$  (90% CL) for 40-120 keV/c<sup>2</sup>
  - Cover a region where indirect searches are weak
- **The best constraint in 40-120 keV/c<sup>2</sup> for both cases.**
- **arXiv:1807.08516**

# 3) WIMP- $^{129}\text{Xe}$ inelastic scattering

## Introduction

- Inelastic scattering of WIMP- $^{129}\text{Xe}$  with nuclear excitation



- Nuclear recoil + 39.6 keV  $\gamma$ -ray

- Natural abundance of  $^{129}\text{Xe}$ : 26.4% (2<sup>nd</sup> highest in xenon)

- Observation of the inelastic channel would imply

- WIMP has a spin

- Spin-dependent (SD) interaction exists

- XMASS has intensively searched for this process

- 1<sup>st</sup> analysis [*PTEP2014, 063C01 (2014)*]

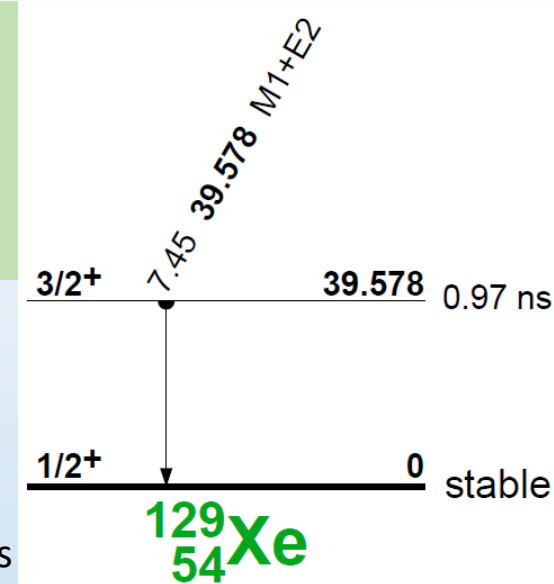
- ✓ 132 days x 41 kg

- ✓ Conservative limit w/o background subtraction

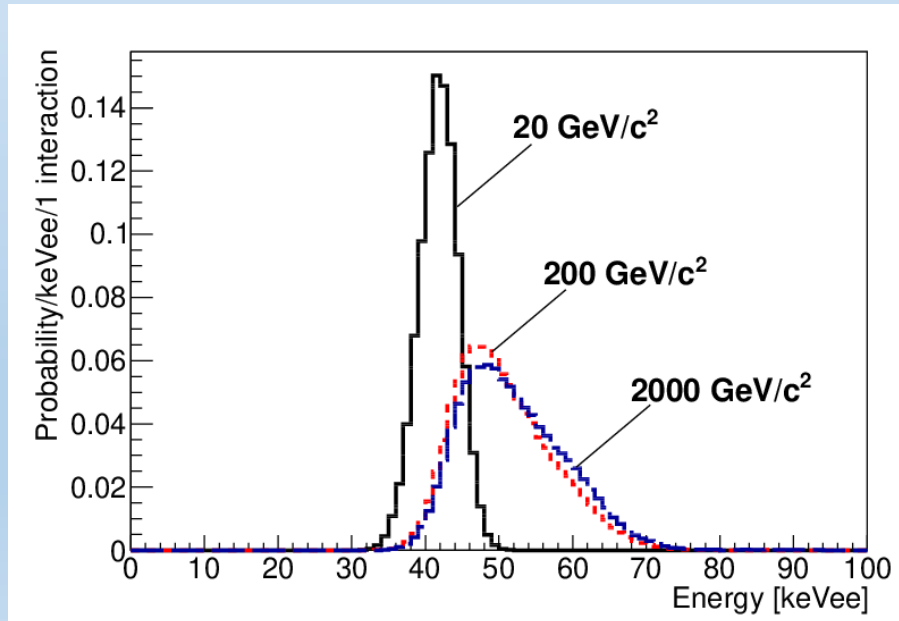
- New analysis:

- ✓ 800 days x 327 kg (x48 larger exposure)

- ✓ Spectrum fitting with signal + background model

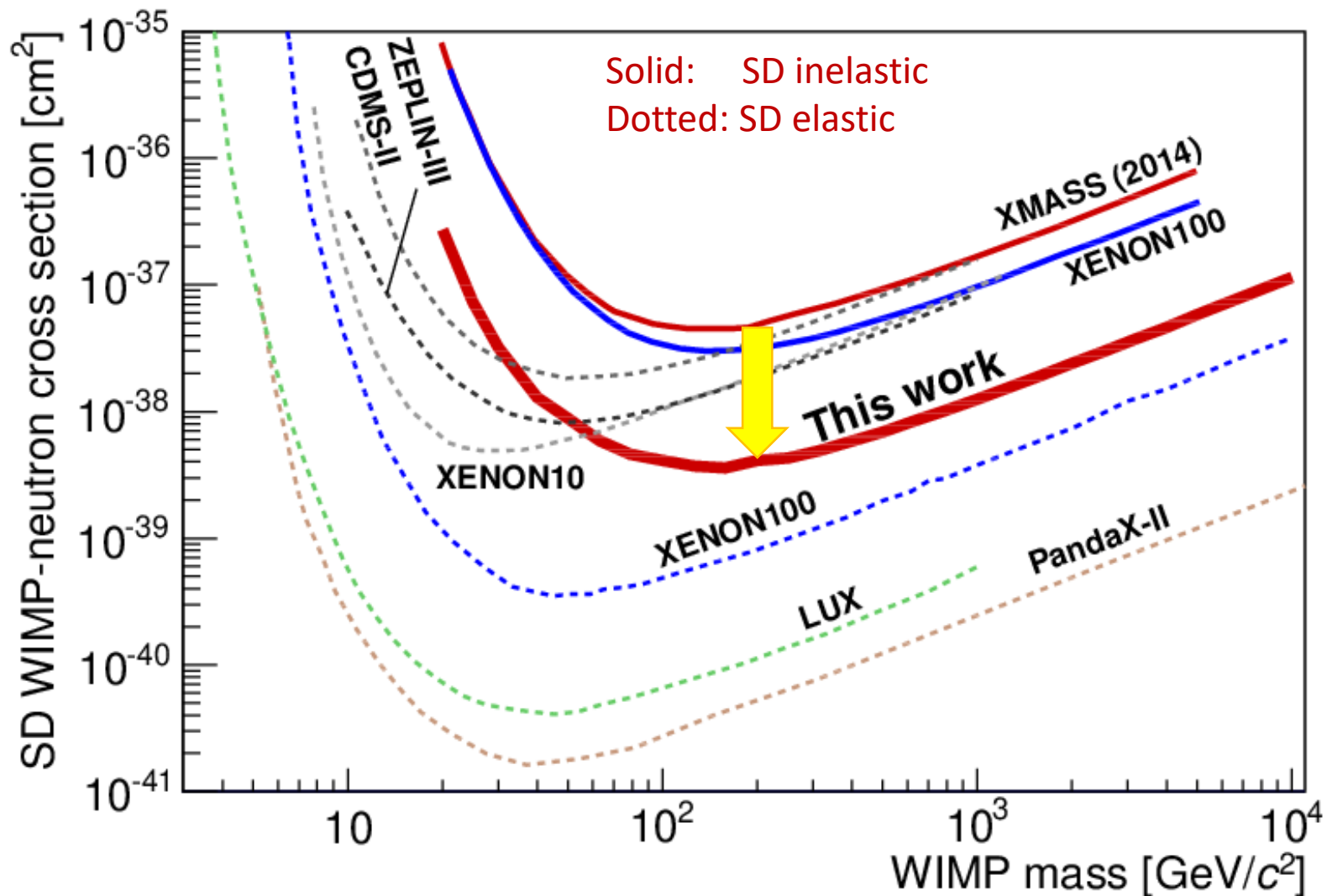


Simulated energy spectra (area normalized)



# 3) WIMP- $^{129}\text{Xe}$ inelastic scattering

## Results



- 800 days x 327 kg exposure
- No significant signal was observed.
- Hence, 90% CL limit on the SD WIMP-neutron cross section was set.
  - $\sigma < 4.1 \times 10^{-39} \text{ cm}^2$  for  $200 \text{ GeV}/c^2$
- The most stringent limit among searches in the SD inelastic channel
- [arXiv: 1809.05358](https://arxiv.org/abs/1809.05358)

# 4) sub-GeV and multi-GeV DM search by annual modulation

## Introduction

- Conventional searches for WIMPs dark matter

- ▣ Via DM-nucleus elastic scattering
- ▣ Difficult to search for  $M_\chi < 4 \text{ GeV}/c^2$

- New approach to sub-GeV dark matter

- ▣ There are irreducible DM-nucleus inelastic scattering

- ▣ Bremsstrahlung photon emission

- ✓ Photon emission from the nucleus in the DM-nucleus scattering

- ✓ C. Kouvaris and J. Pradler, PRL 118, 031803 (2017)

- ▣ Electron emission by Migdal effect

- ✓ Ionization and excitation of the atom after nuclear recoil in the DM-nucleus scattering

- ✓ M. Ibe et al., JHEP03, 194 (2018)

- XMASS searches for annual modulation of such signals

Fig. from C. Kouvaris & J. Pradler, PRL 118, 031803 (2017)

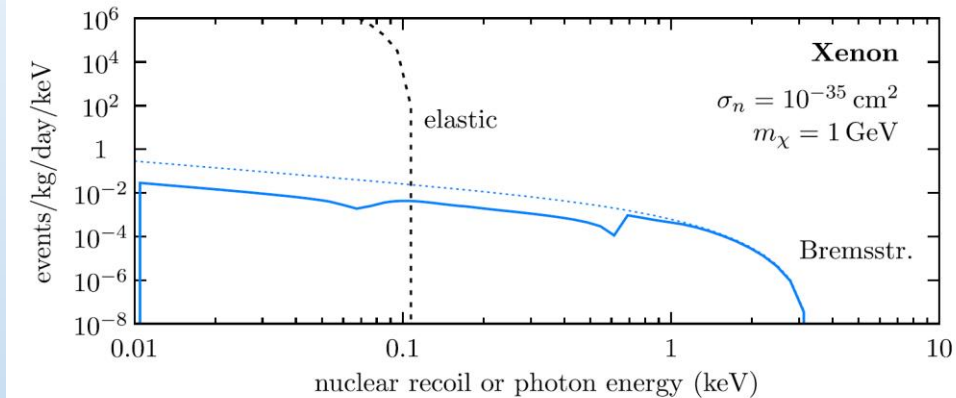
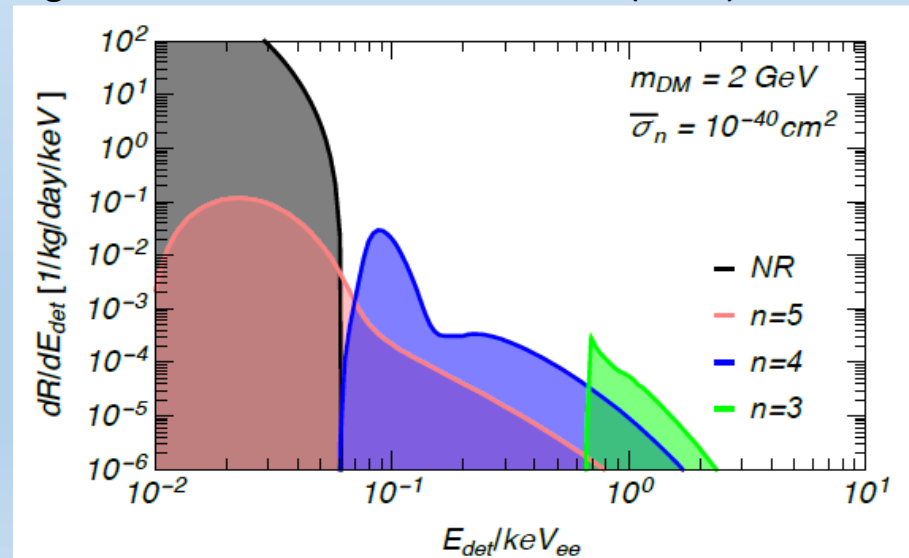


Fig. from M. Ibe et al., JHEP03, 194 (2018)



Focused  
in this work

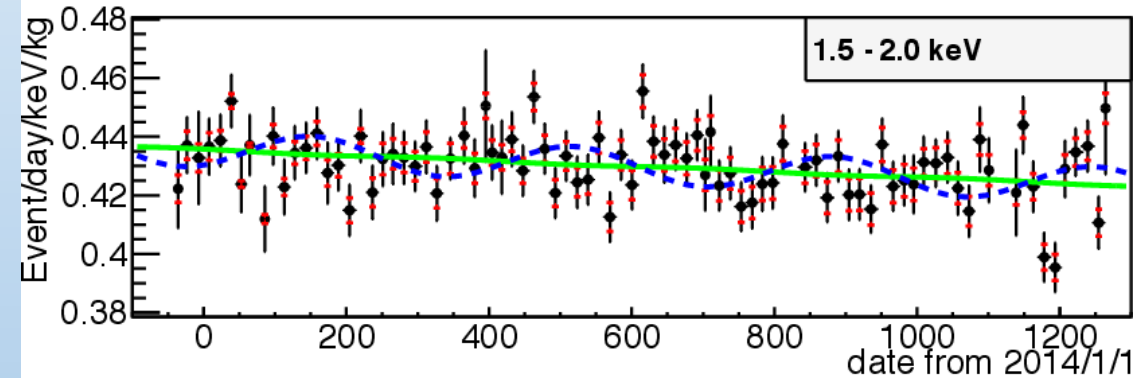
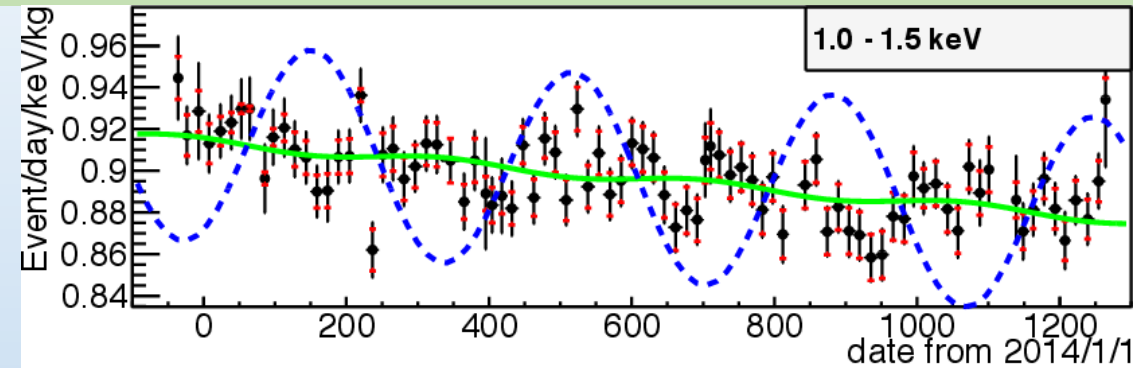
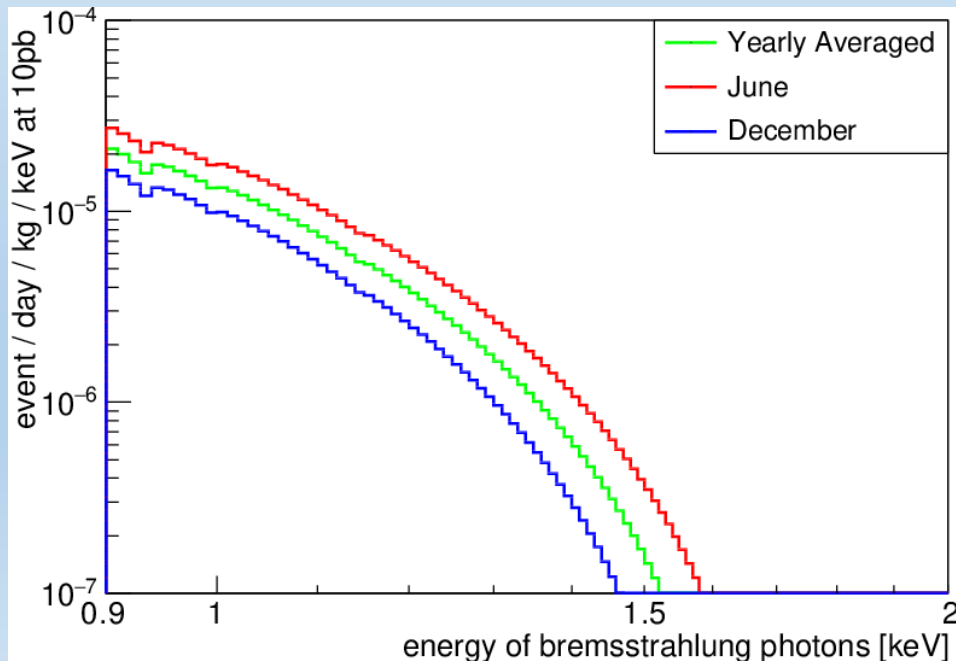
# 4) sub-GeV and multi-GeV DM search by annual modulation

## Annual modulation search

- Total live time of 2.8 year (in 3.5 calendar year)  
= Total exposure of 2.38 ton-years
- Energy threshold of  $1 \text{ keV}_{ee}$  for brems. search

$$R_{exp} = \int_{t_j - \delta t_j}^{t_j + \delta t_j} dt \left[ \underbrace{E_{bg} \cdot (C_{bg} + S_{bg} \cdot t)}_{BG} + \underbrace{\sigma \cdot E_{sig} \left\{ C_{sig} + A_{sig} \cos 2\pi \frac{t - t_0}{T} \right\}}_{signal} \right]$$

Simulated  
time variation of  
energy spectrum



+ Data

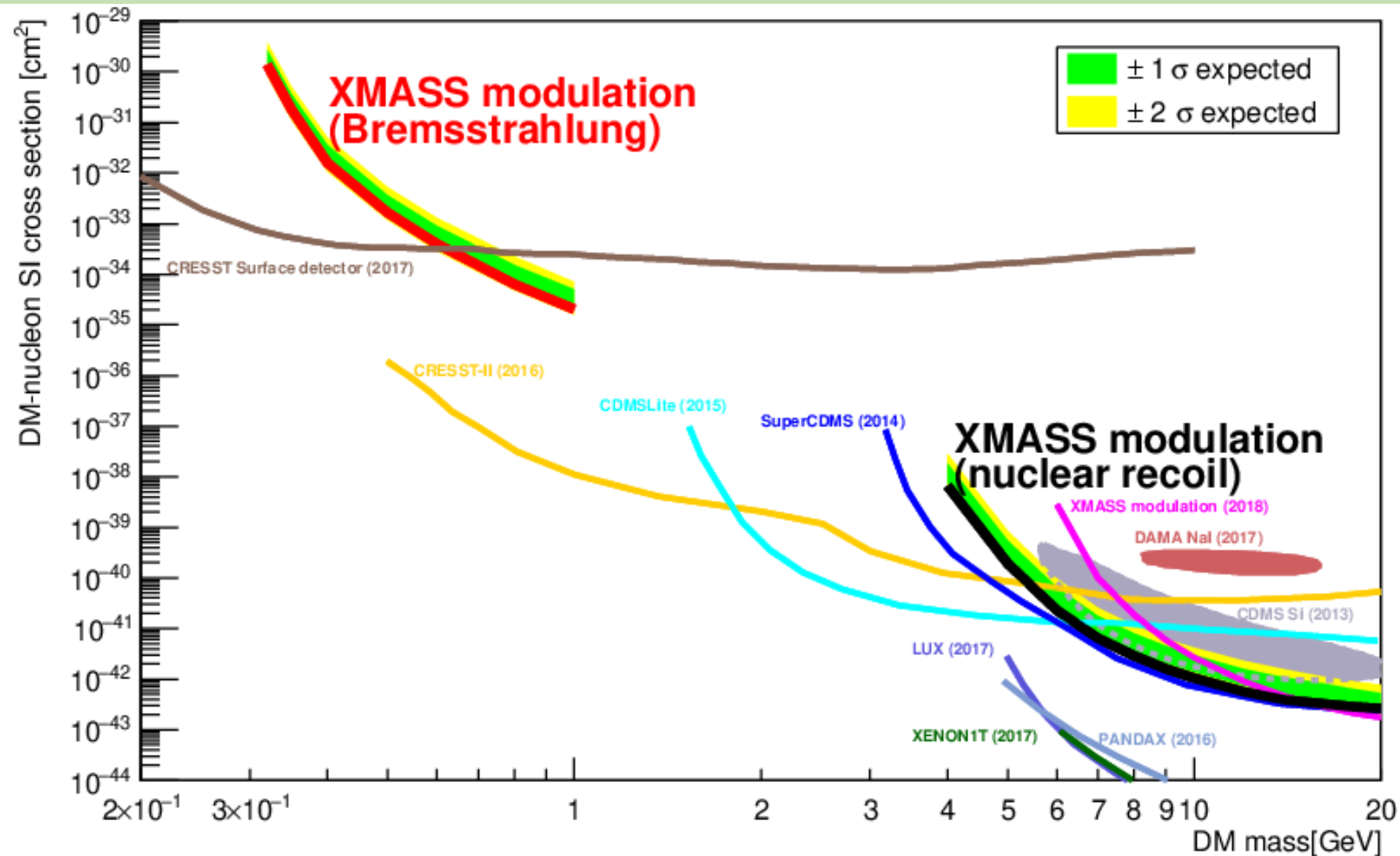
-- Best-fit time variation

-- Expected time variation ( $\sigma=3 \times 10^{-32} \text{ cm}^2$ )



# 4) sub-GeV and multi-GeV DM search by annual modulation

## Results



- Sub-GeV ( $0.32\text{-}1 \text{ GeV}/c^2$ )
  - The first experimental result focused on brems. photon emission and searched by annual modulation
  - $\sigma < 1.6 \times 10^{-39} \text{ cm}^2$  (for  $0.5 \text{ GeV}/c^2$ )
- Multi-GeV ( $4\text{-}20 \text{ GeV}/c^2$ )
  - Elastic nuclear recoil searched by modulation
  - $\sigma < 2.9 \times 10^{-42} \text{ cm}^2$  (for  $8 \text{ GeV}/c^2$ )
- [arXiv:1808.06177](https://arxiv.org/abs/1808.06177)

# 5) $^{124}\text{Xe}$ $2\nu$ double electron capture (ECEC)

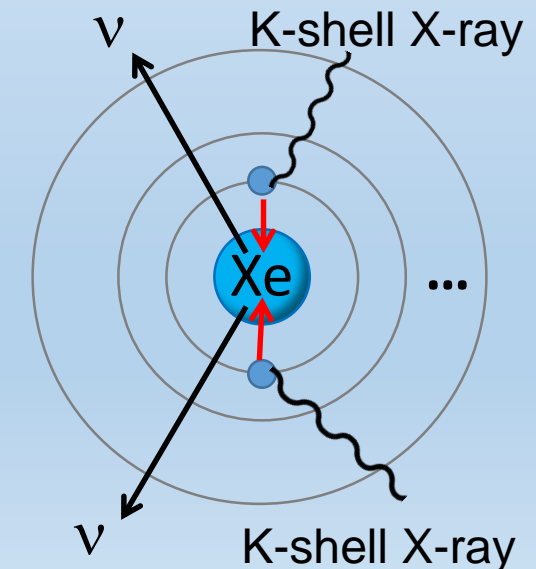
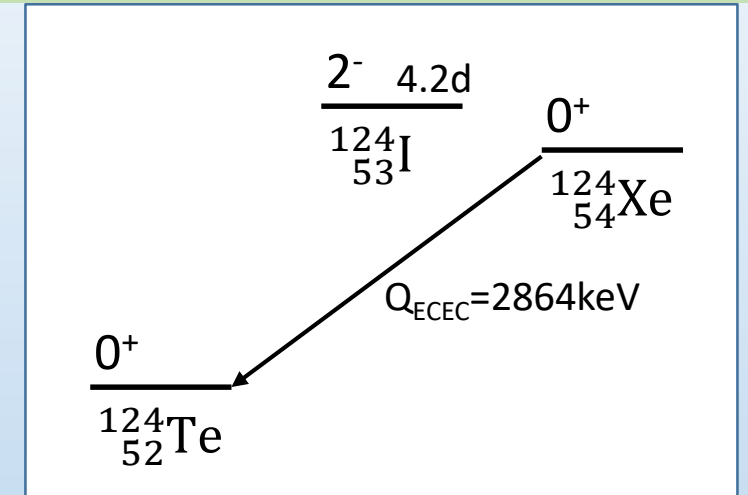
## Introduction

- Natural xenon contains  $^{124}\text{Xe}$  (N.A.=0.095%) and  $^{126}\text{Xe}$  (N.A.=0.089%) which can undergo double electron capture.



ECEC,  $\beta^+/\text{EC}$ , and  $\beta^+\beta^+$  are possible

- $0\nu$  mode  $\rightarrow$  Evidence of lepton number violation
- $2\nu$  mode  $\rightarrow$  New input for nuclear matrix element calculation
- $^{124}\text{Xe}$   $2\nu$  double electron capture from K-shell ( $2\nu 2\text{K}$ )
  - Total deposit energy of **64 keV by X-rays/Auger electrons**
  - Expected half-life is  **$10^{20}$ - $10^{24}$  years**
- Previously, XMASS set a lower limit  $T_{1/2}^{2\nu 2\text{K}} > 4.7 \times 10^{21}$  years (@90%CL) using 132 live days x 41 kg LXe (39g of  $^{124}\text{Xe}$ ) *Phys. Lett. B759 (2016) 64*
- An improved search was conducted using a new data set, 800.0 live day x 327 kg (311g of  $^{124}\text{Xe}$ )



# 5) $^{124}\text{Xe}$ $2\nu$ double electron capture

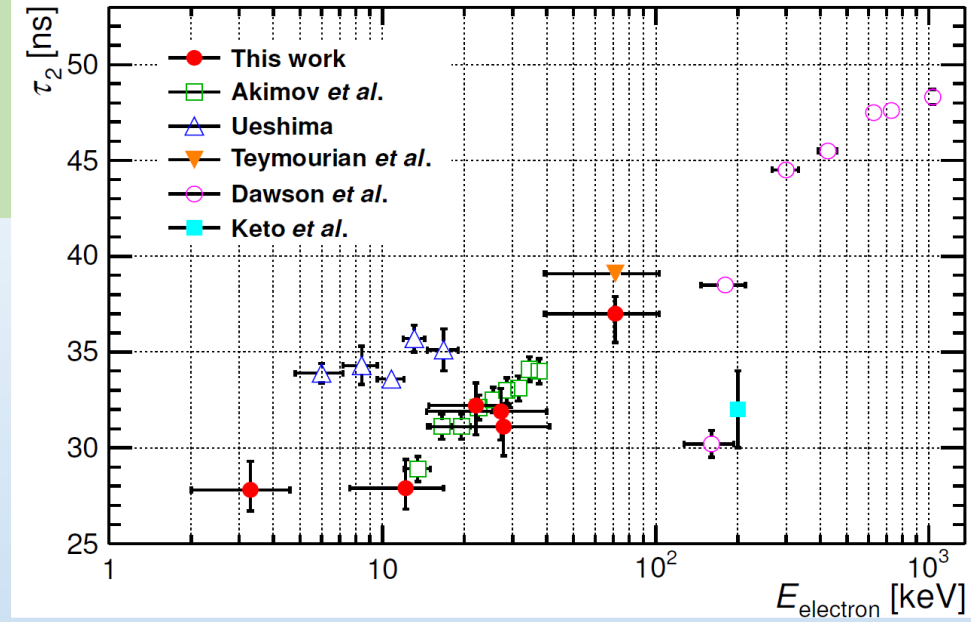
## Particle ID using scinti. time profile

- LXe scintillation decay time depends on electron kinetic energy
- This allows us to separate
 

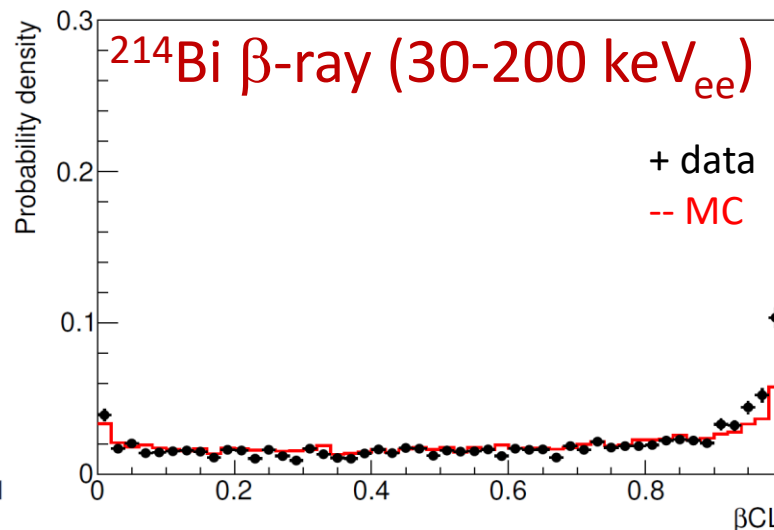
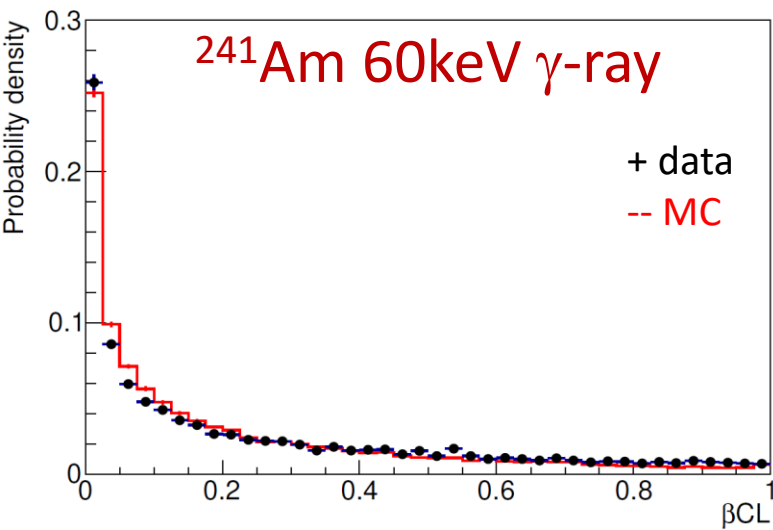
$\beta$ -ray  
(single electron track)

vs.

$\gamma$ -ray/X-ray or  $2\nu 2K$   
(multiple electrons)
- Particle ID parameter ( $\beta\text{CL}$ ) is constructed from each photoelectron's timing assuming the event is caused by a  $\beta$ -ray.



Scintillation decay time for electronic events  
*XMASS Collaboration, NIM A834 (2016) 192*



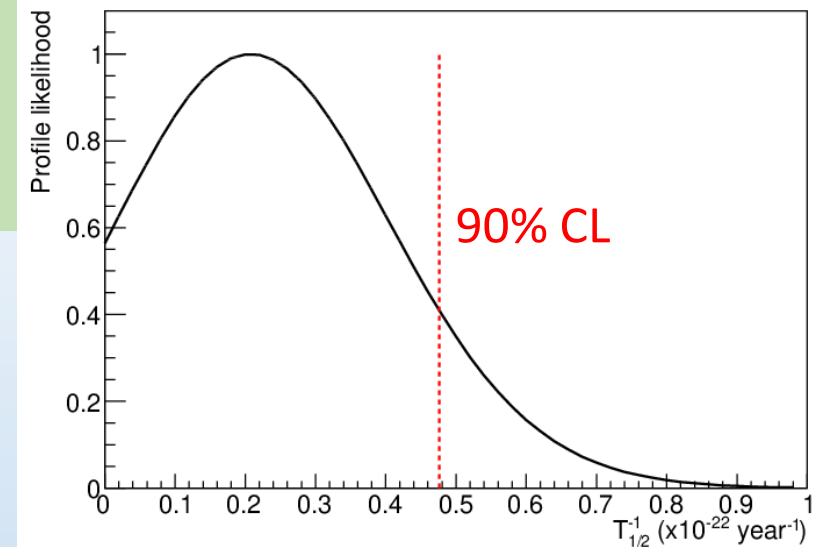
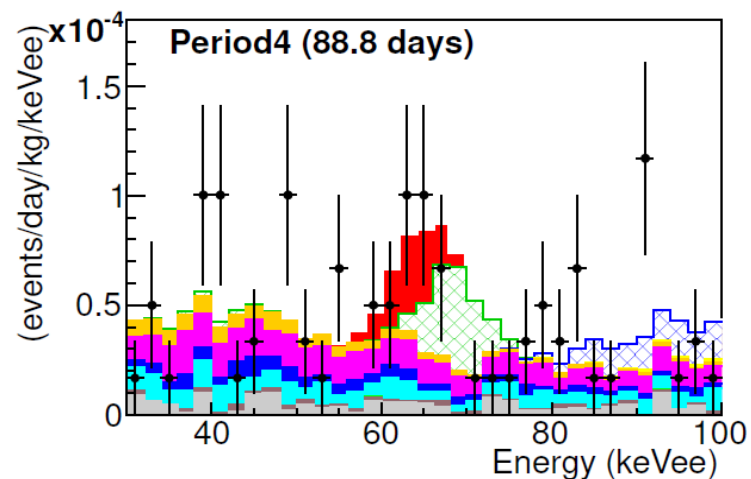
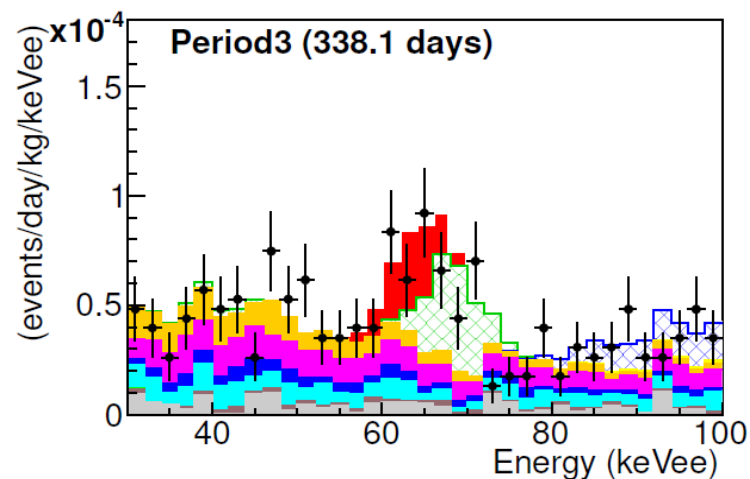
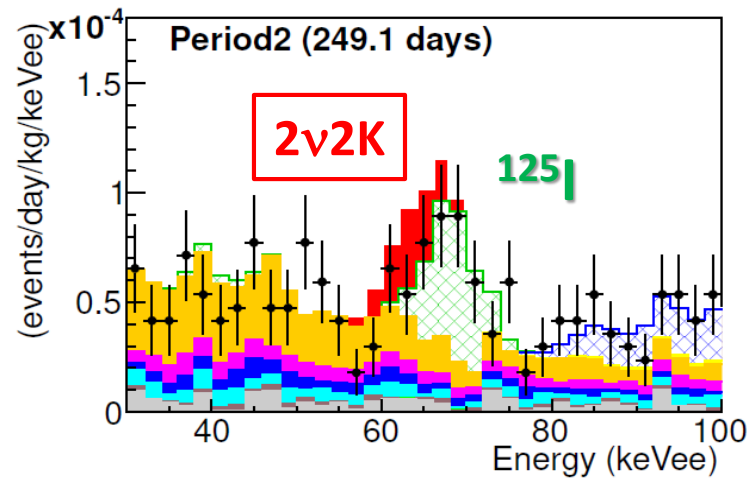
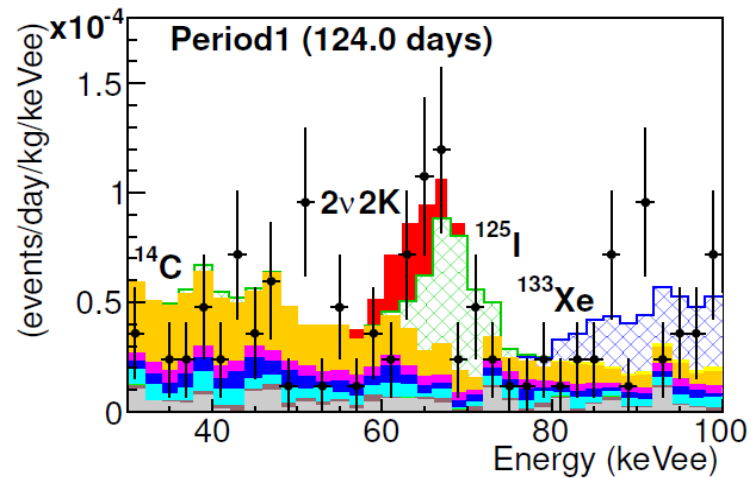
$$\beta\text{CL} = P \times \sum_{i=0}^{n-1} \frac{(-\ln P)^i}{i!} \quad P = \prod_{i=1}^n \text{CL}_i$$

$\beta\text{CL} < 0.05$

- Acceptance for  $\gamma$ -ray  $\sim 35\%$
- Acceptance for  $\beta$ -ray  $\sim 7\%$
- $\rightarrow$  S/N improves by x5

# 5) $^{124}\text{Xe}$ $2\nu$ double electron capture

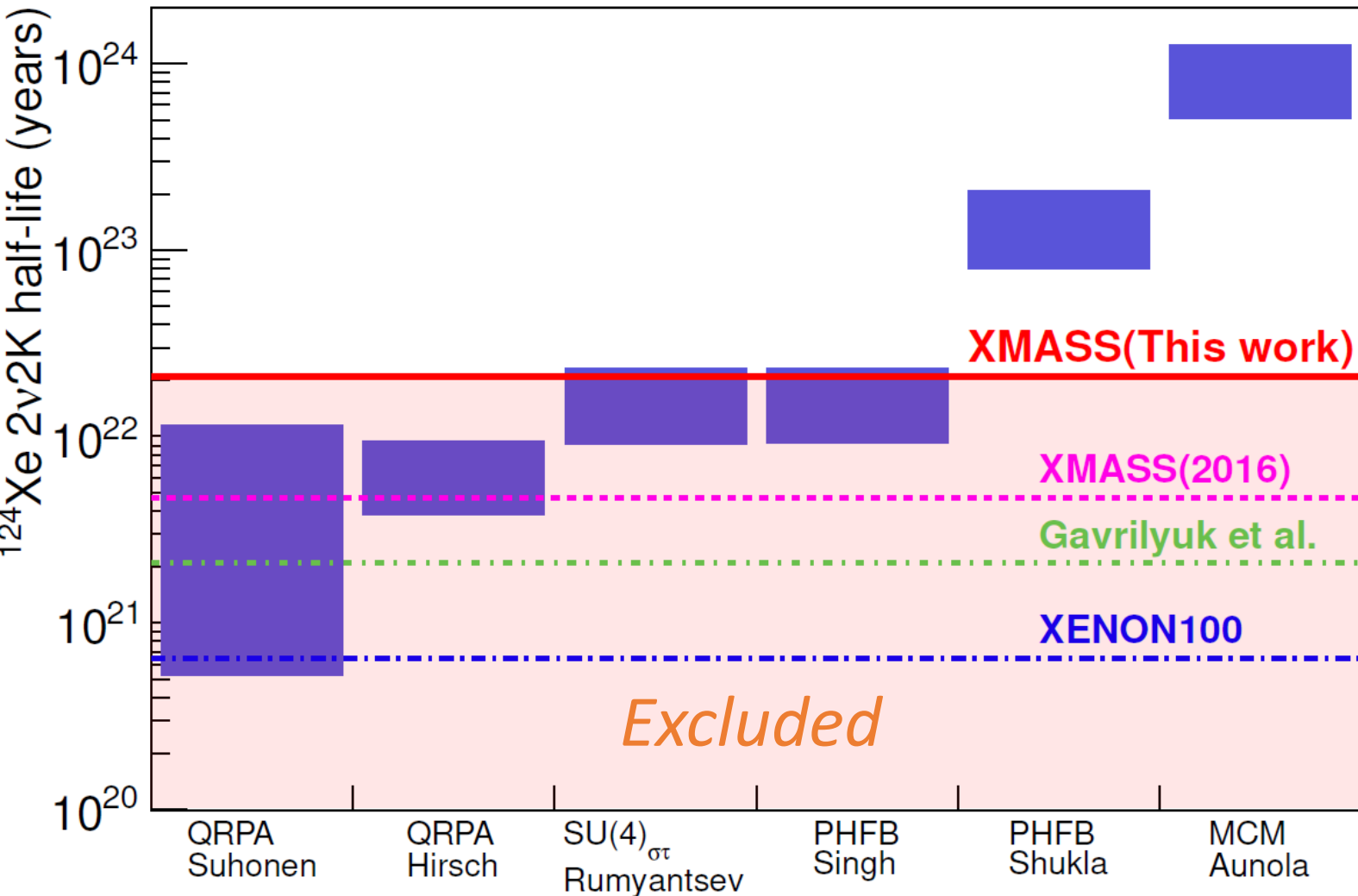
## Results: close-up spectrum of ROI



- $^{125}\text{I}$  is created by thermal neutron capture on  $^{124}\text{Xe}$  outside the water shield, giving a peak at 67.5 keVee.
- Thermal neutron flux is constrained by independent measurement.
- No significant signal was observed.

# 5) $^{124}\text{Xe}$ $2\nu$ double electron capture

## Results: comparison with other exp. and predictions



Note on theoretical predictions:

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

- The most stringent lower limits to date

$$\square T_{1/2}^{2\nu 2K}(^{124}\text{Xe}) > 2.1 \times 10^{22} \text{ yrs}$$

$$\square T_{1/2}^{2\nu 2K}(^{126}\text{Xe}) > 1.9 \times 10^{22} \text{ yrs}$$

- Published in ***PTEP2018 (2018) 053D03***

# Summary

- XMASS is a multi-purpose experiment using 832kg LXe and is stably taking data for more than 4 years
- Latest results
  - **WIMP search by fiducialization**
    - ✓ First stringent constraint from the single-phase LXe detector
    - ✓  $\sigma_{SI} < 2.2 \times 10^{-44} \text{ cm}^2$  for 60 GeV/c<sup>2</sup>
  - **Hidden photons/Axion-like particles DM search**
    - ✓ Best constraint  $\alpha'/\alpha < 6 \times 10^{-26}$  or  $g_{Ae} < 4 \times 10^{-13}$  for 40-120 keV/c<sup>2</sup>
  - **WIMP-129Xe inelastic scattering search**
    - ✓ Most stringent limit among searches in the inelastic channel
  - **Sub-GeV/multi-GeV DM search by annual modulation**
    - ✓ First experimental result focused on brems. photon emission
  - **<sup>124</sup>Xe 2ν double electron capture search**
    - ✓ Most stringent lower limit  $T_{1/2}^{2\nu 2K}(^{124}\text{Xe}) > 2.1 \times 10^{22}$  years

*arXiv: 1804.02180 (accepted to PLB)*

*arXiv: 1807.08516*

*arXiv: 1809.05358*

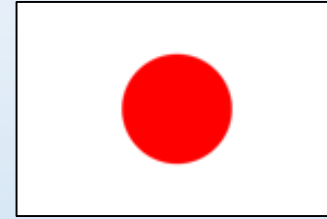
*arXiv: 1808.06177*

*PTEP2018 (2018) 053D03*

**Backup slides**

# XMASS Collaboration

- Kamioka Observatory, the University of Tokyo
- Institute for Basic Science
- Nagoya University
- Kavli IPMU, the University of Tokyo
- Kobe University
- Korea Research Institute of Standards and Science
- Miyagi University of Education
- Nihon University
- Tokai University
- Tokushima University
- Yokohama National University



~40 physicists  
from 11 institutes





# Inner calibration system

- Various RI sources can be inserted
- Used for light yield monitoring, optical parameter tuning, energy and timing calibrations etc.

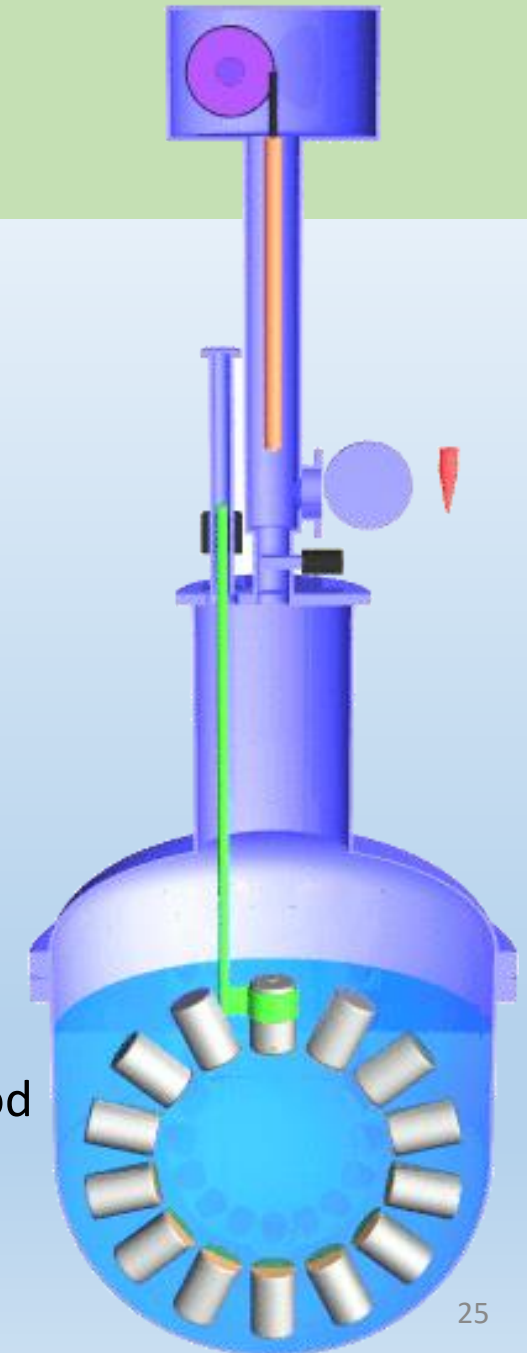
RI	Energy [keV]	Diameter [mm]	Geometry
$^{55}\text{Fe}$	5.9	10	2pi source
$^{109}\text{Cd}$	8, 22, 25, 88	5	2pi source
$^{241}\text{Am}$	17.8, 59.5	0.17	2pi/4pi source
$^{57}\text{Co}$	59.3 (W X-ray), 122	0.21	4pi source
$^{137}\text{Cs}$	662	5	cylindrical

$^{57}\text{Co}$  source

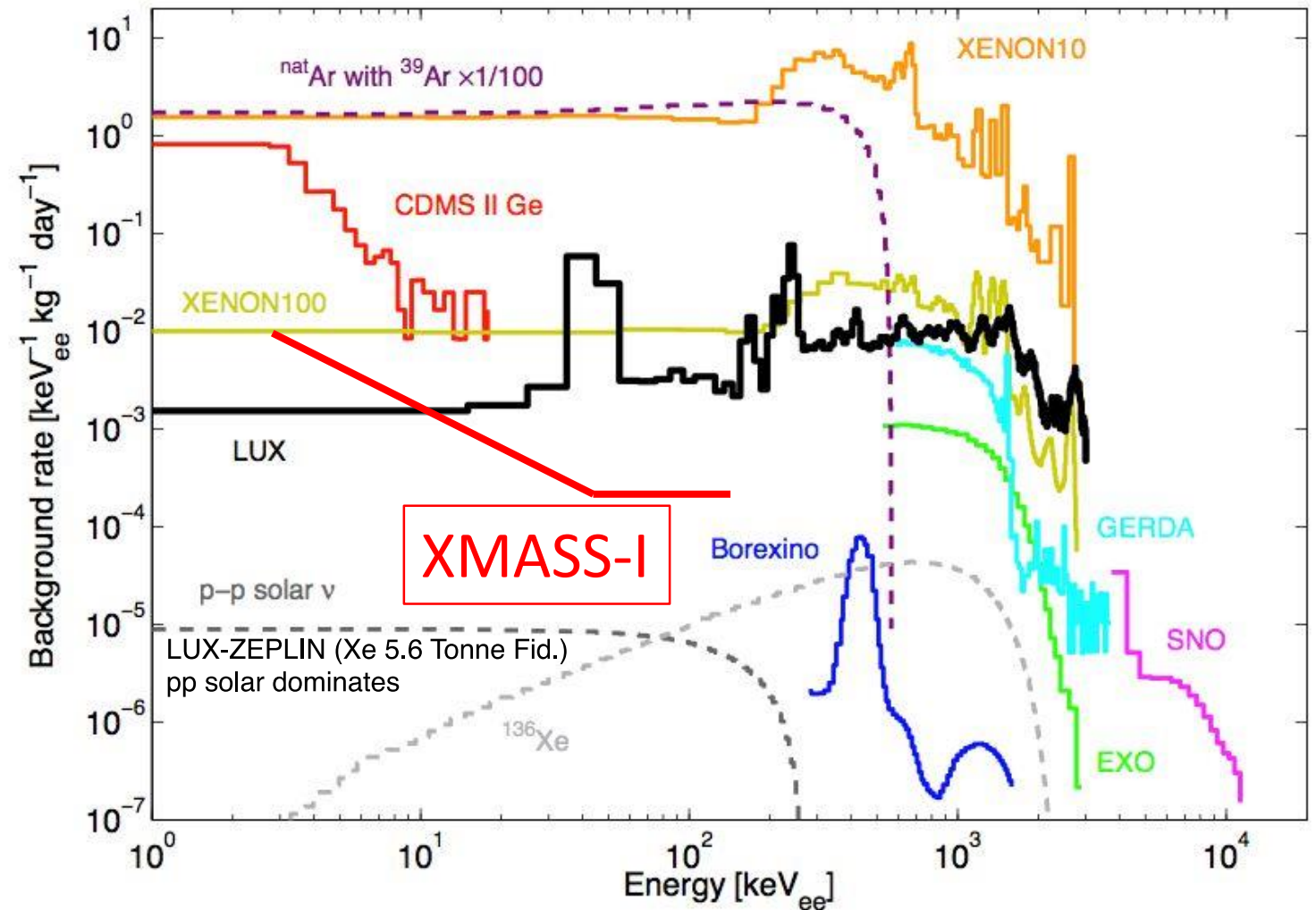


Active region is concentrated on the 1.8 mm edge region

Source rod  
(Ti)



# Comparison of background rate in fiducial volume including both nuclear recoil and e/ $\gamma$ events



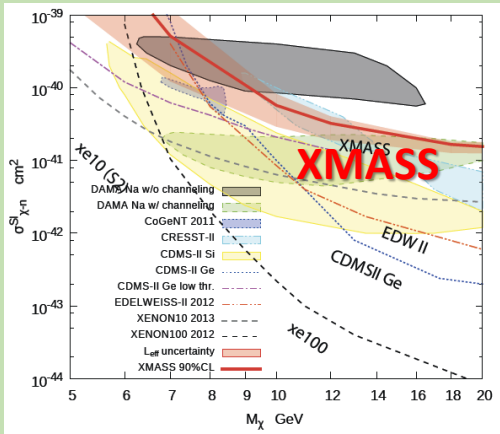
- XMASS achieved low background rate of  $O(10^{-4})$  dru in a few 10s keV including e/ $\gamma$  events
- Low background rate for e/ $\gamma$  events is good for searching for dark matter other than WIMPs.

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

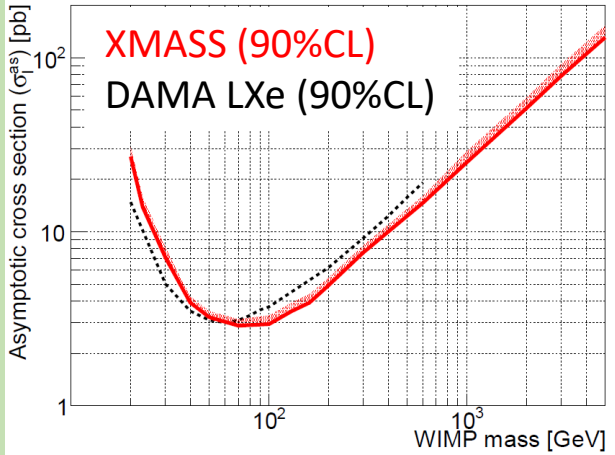
# Diversity of physics target with XMASS

■ Dark matter searches

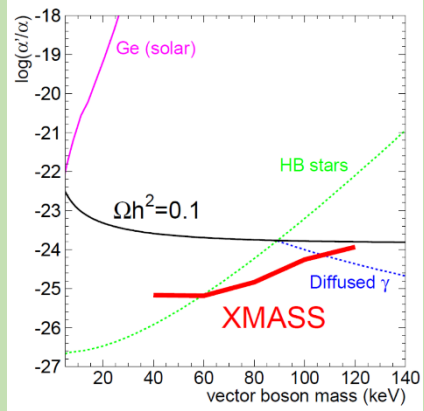
Low mass WIMP search  
*Phys. Lett. B719 (2013) 78*



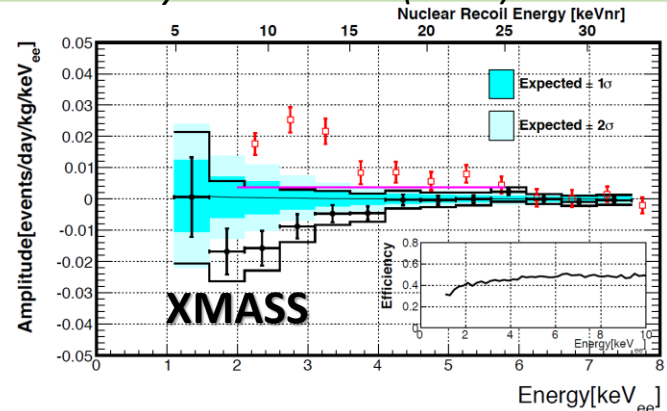
WIMP- $^{129}\text{Xe}$  inelastic scattering  
*PTEP (2014) 063C01*



Bosonic super-WIMPs search  
*Phys. Rev. Lett. 113 (2014) 121301*

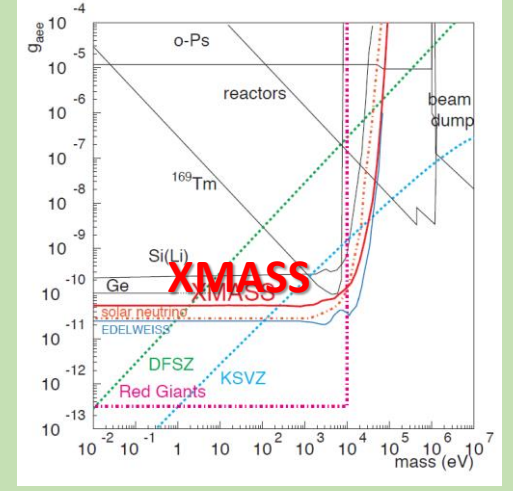


Annual modulation search  
*Phys. Lett. B759 (2016) 272*



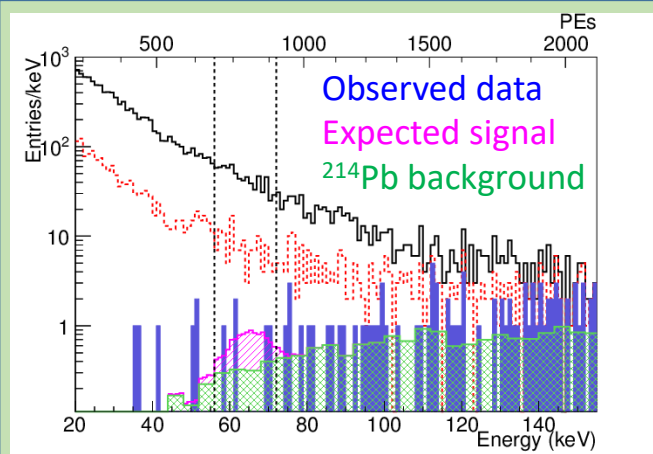
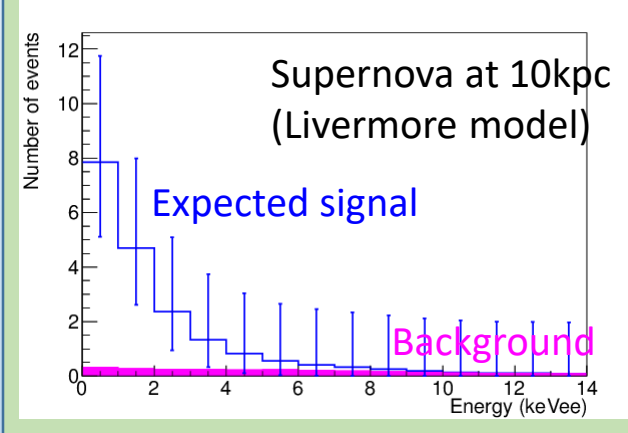
■ Solar axion search

*Phys. Lett. B724 (2013) 46*



■ Possibility of supernova neutrino detection

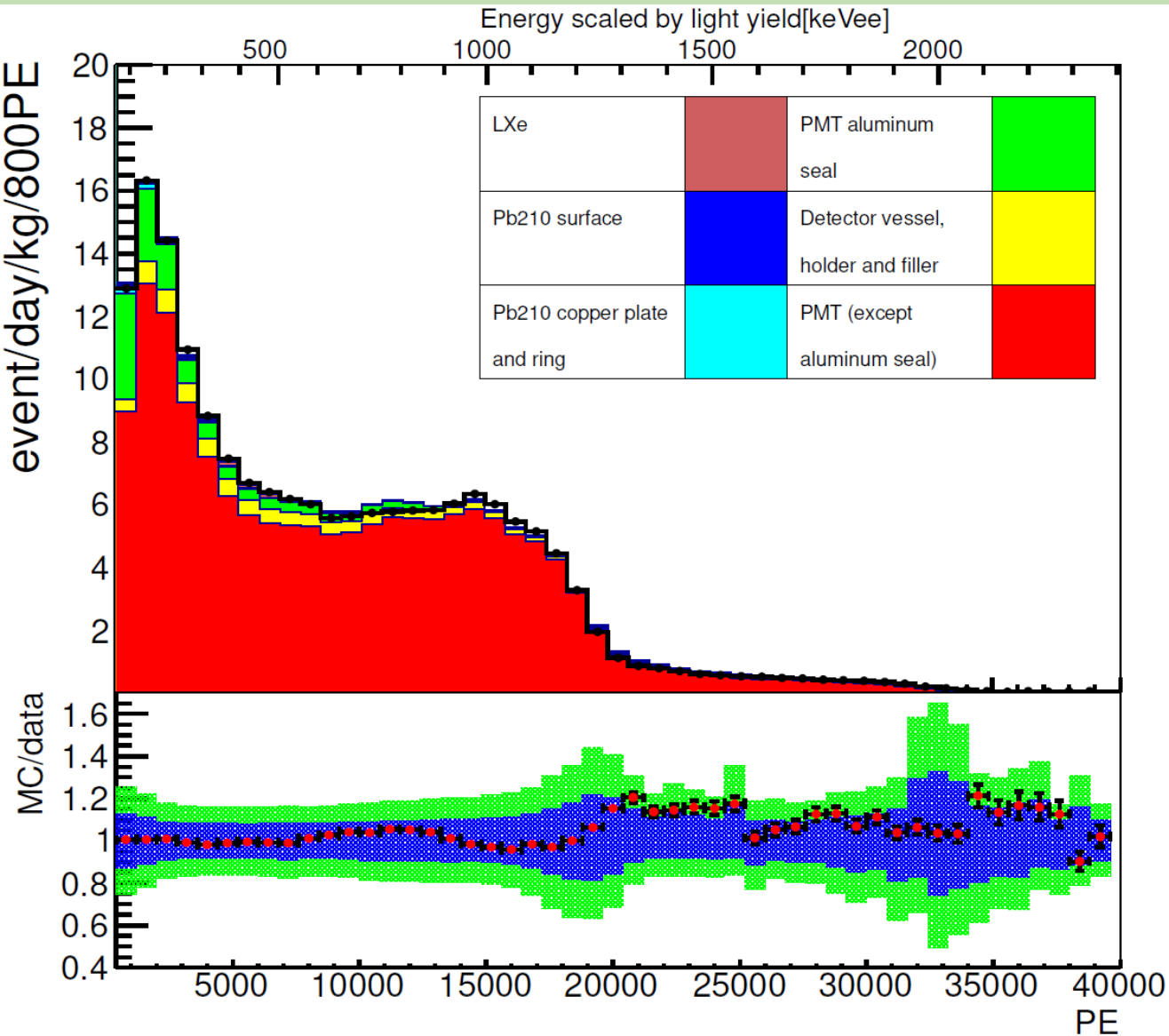
*Astropart. Phys. 89 (2017) 51*



*Phys. Lett. B759 (2016) 64*

# 1) WIMP dark matter search by fiducialization

## Background spectrum in the whole 832kg volume

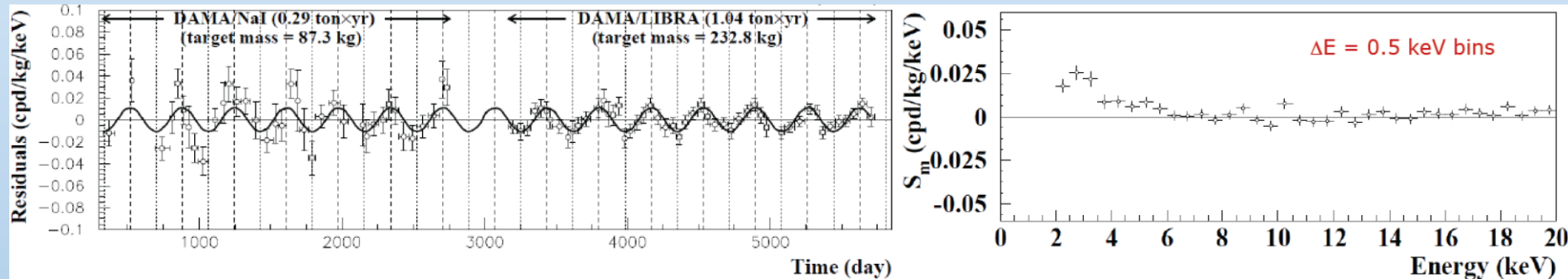
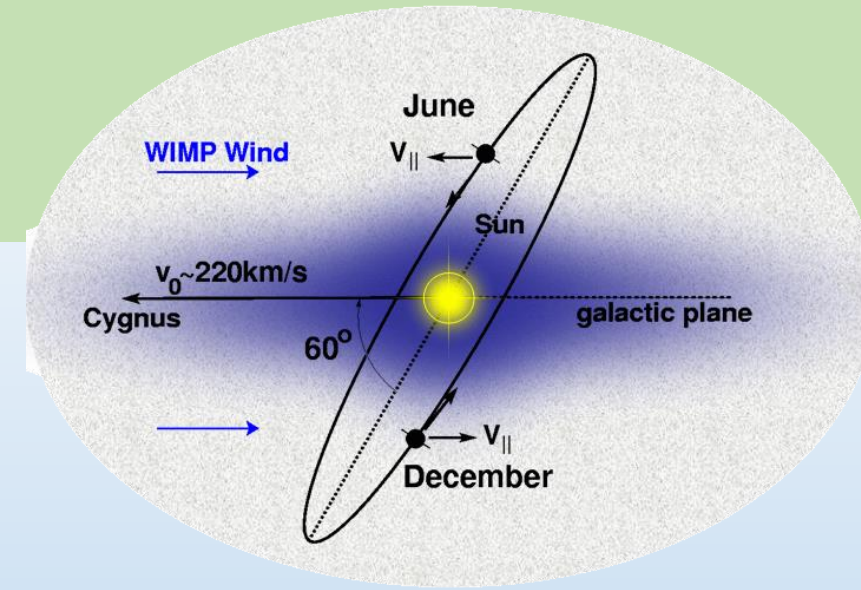


- All the detector material (except for copper and LXe) was screened by the Ge detector before installation.
- Then, the energy spectrum above 30 keV was fitted under these constraints.
- $\alpha$ -rays are selected using scintillation decay time to constrain PMT/copper surface/bulk  $^{210}\text{Pb}$ .
  - Contamination of  $^{210}\text{Pb}$  ( $\sim 20$  mBq/kg) in the bulk of the copper was identified by a low-BG alpha-particle counter
- Internal background (RIs in LXe)
  - Negligible in this figure
  - $^{222}\text{Rn}$ :  $10.3 \pm 0.2$   $\mu\text{Bq/kg}$
  - $^{85}\text{Kr}$ :  $0.30 \pm 0.05$   $\mu\text{Bq/kg}$
  - $^{39}\text{Ar}$ ,  $^{14}\text{C}$ : evaluated by spectrum fit in  $R < 30\text{cm}$  and  $30 - 250$  keV<sub>ee</sub>

# 4) Annual modulation search

## Introduction

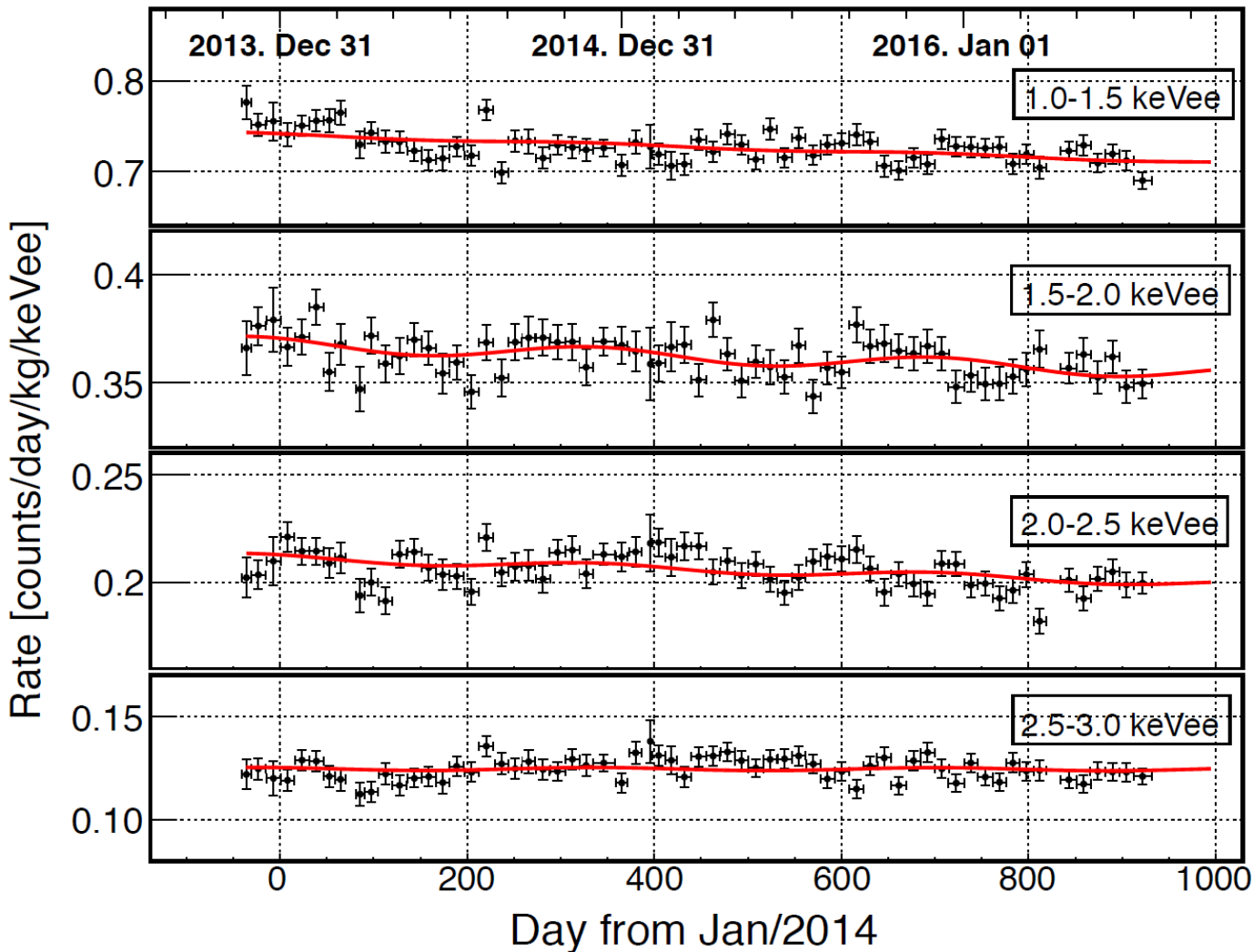
- Expect annual modulation of event rate of dark matter signal due to Earth's rotation around the Sun.
- DAMA/LIBRA claims modulation at  $9.3\sigma$ 
  - Total exposure of 1.33 ton year (14 cycles)
  - Modulation amplitude of  $(0.0112 \pm 0.0012)$  cpd/kg/keV for 2-6 keV



- Annual modulation search in XMASS
  - 800.0 live days x 832 kg (=1.82 ton year)
  - Analysis threshold 1 keVee (=4.8 keVnr)
  - Look for event rate modulation not only for nuclear recoil but also for  $e/\gamma$  events

# 4) Annual modulation search

## Results: time variation of event rate

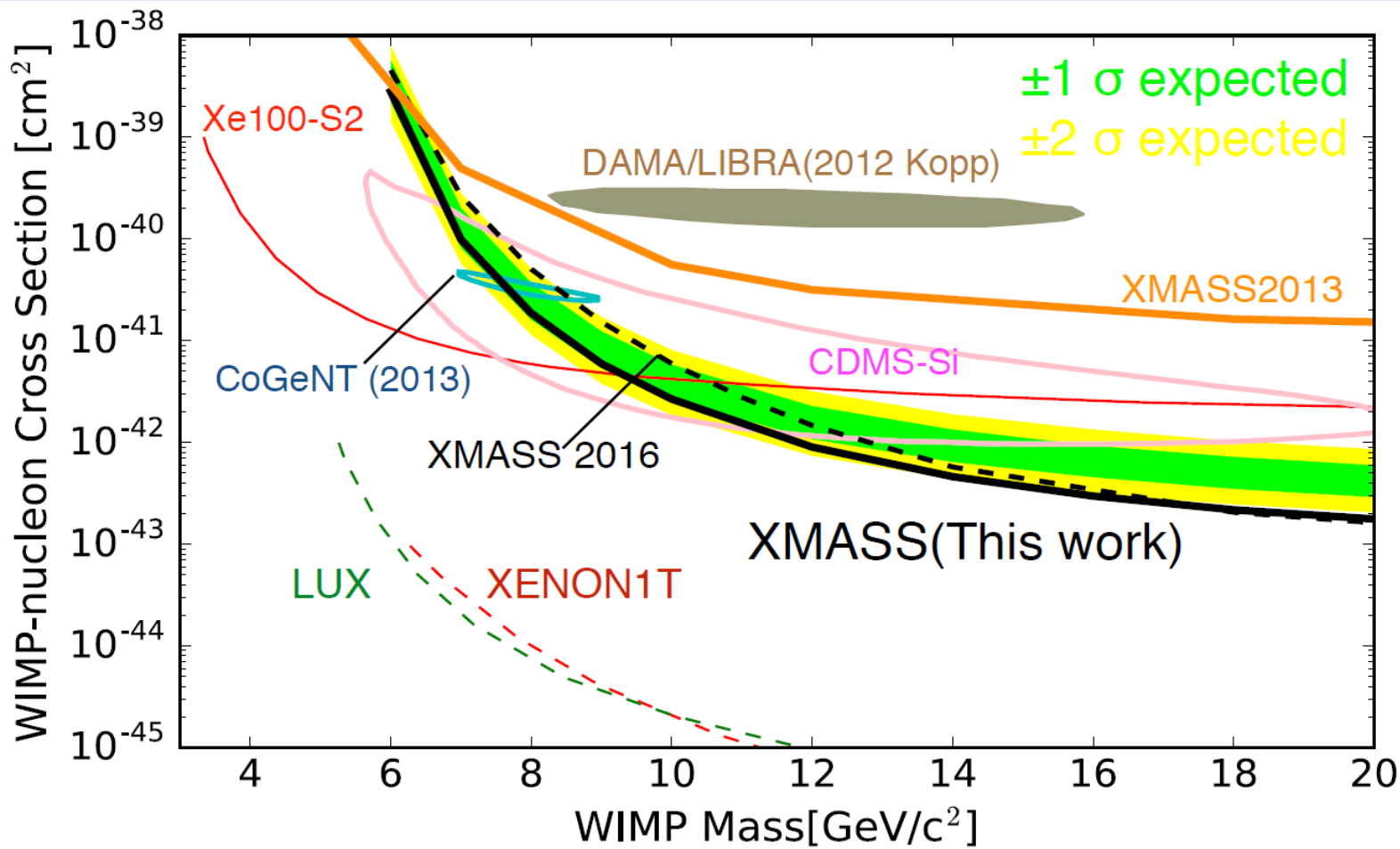


$$R_{i,j}^{\text{ex}} = \int_{t_j - \frac{1}{2}\Delta t_j}^{t_j + \frac{1}{2}\Delta t_j} \left( \epsilon_{i,j}^s A_i^s \cos 2\pi \frac{(t - \phi)}{T} + \epsilon_{i,j}^b(\alpha) (B_i^b t + C_i^b) \right) dt$$

- Background was modeled using a simple linear function to take into account long-lived isotopes (e.g.  $^{60}\text{Co}$  and  $^{210}\text{Pb}$ )
- Energy resolution ( $\sigma/E$ ) is estimated to be 36% (19%) at 1 keVee (5keVee) based on gamma-ray calibrations

# 4) Annual modulation search

## Results: WIMP analysis

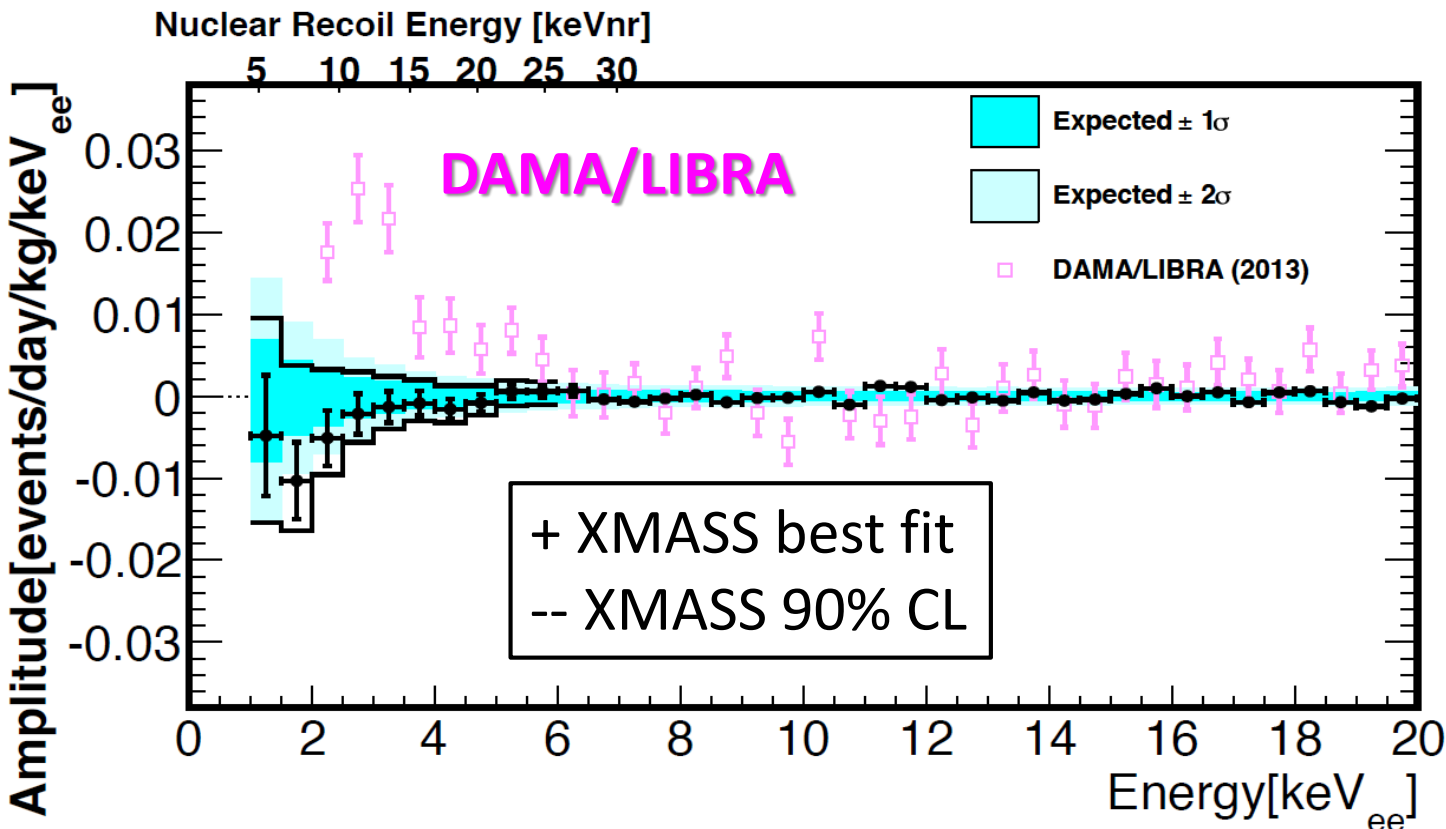


- Assuming WIMP and standard halo model
  - Lewin and Smith (1996, APP)
  - $V_0=232$  km/s,  $V_{esc}=544$  km/s
  - $\rho_{DM}=0.3$  GeV/cm<sup>3</sup>
  - $T=365.24$  days,  $\phi=152.5$  day
- DAMA/LIBRA allowed region was excluded by annual modulation search.
  - $\sigma_{\chi n} < 1.9 \times 10^{-41}$  cm<sup>2</sup> (90%CL) for 8 GeV/c<sup>2</sup>

# 4) Annual modulation search

## Results: model independent analysis

- Without assuming any specific dark matter model.
- $T=365.24$  days and  $\phi=152.5$  day are fixed.
- Important to look for various candidates.



Experiment	Amplitude (/day/kg/keV <sub>ee</sub> )
DAMA/LIBRA	$\sim 20 \times 10^{-3}$ (2-3.5 keV <sub>ee</sub> )
XENON100	$(1.67 \pm 0.73) \times 10^{-3}$ (2-5.8 keV <sub>ee</sub> )
XMASS	$< (1.3-3.2) \times 10^{-3}$ (2-6 keV <sub>ee</sub> )

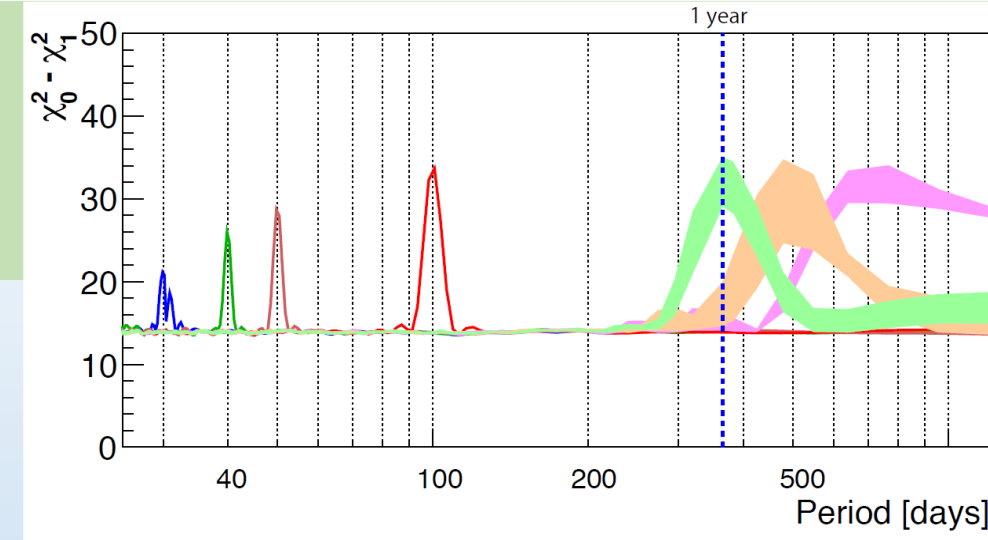
- 1-20 keV<sub>ee</sub> energy range
- Null hypothesis: p-value=0.11 (1.6σ)
  - Less significant than the previous result (2.5σ)
- Most stringent constraints on modulation amplitudes.



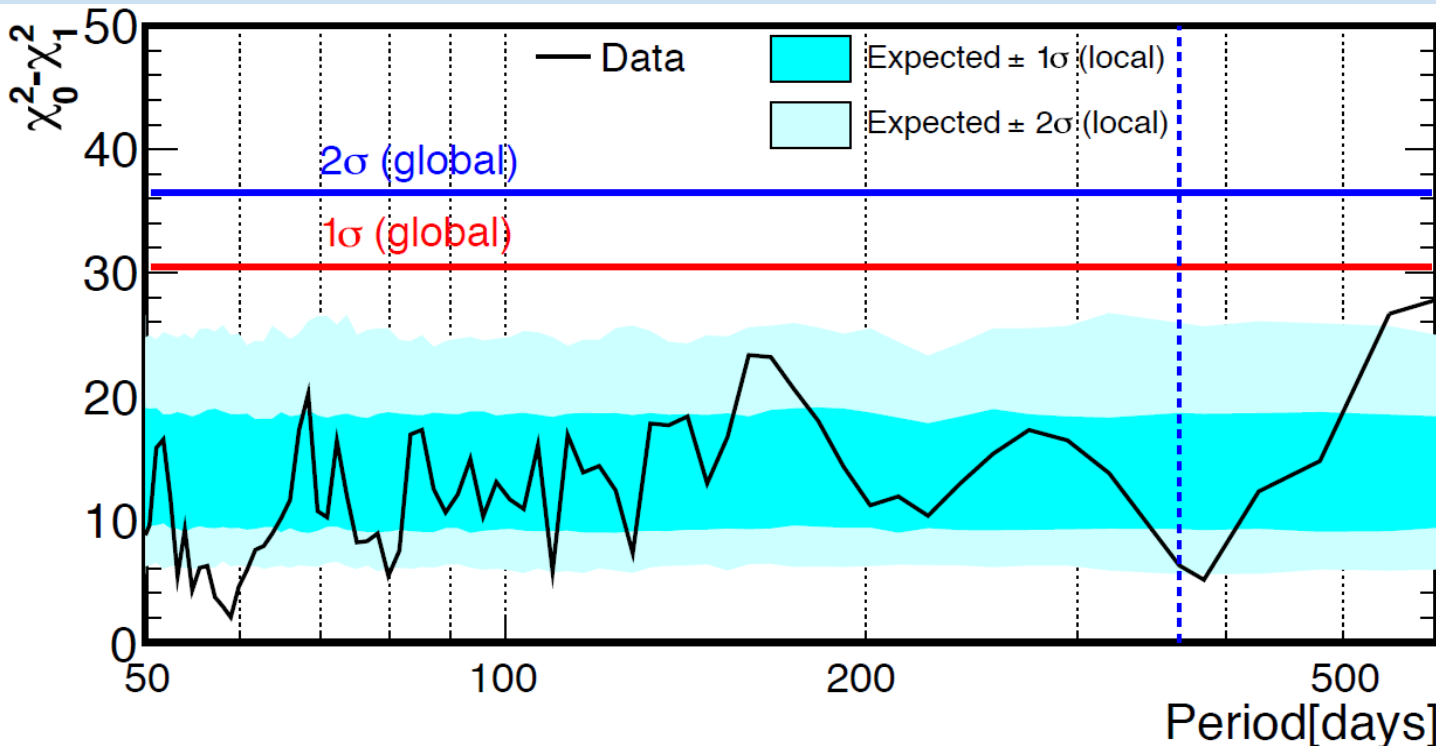
# 4) Annual modulation search

## Results: frequency analysis

- Test statistics:  $\Delta\chi^2 = \chi^2(\text{null}) - \chi^2(\text{modulation})$
- Use the 1-6 keV energy range
- Phase is a free parameter
- Checked global significance to take into account “look elsewhere effect”



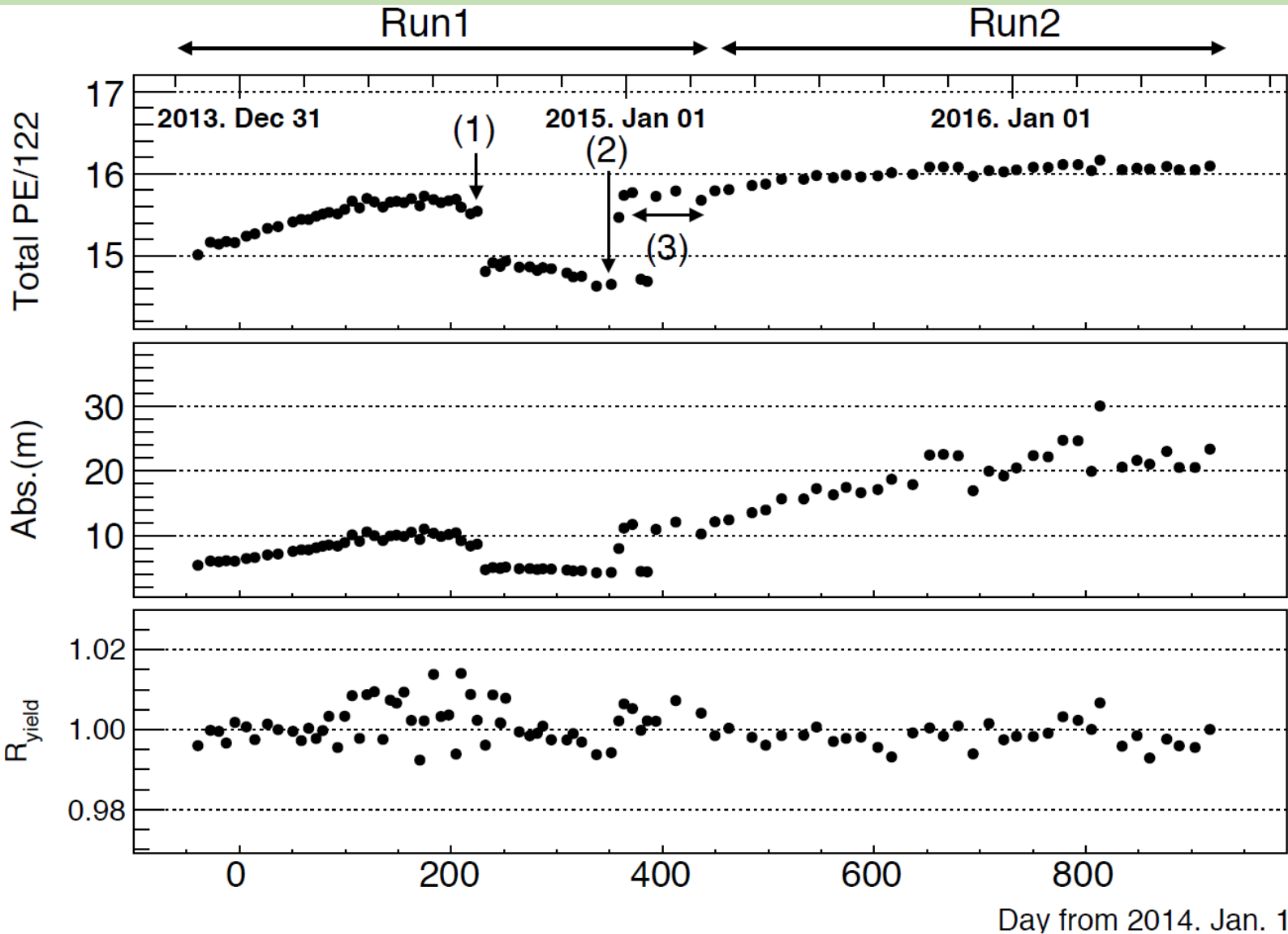
Dummy samples with artificial periodicity



- Sensitivity study
  - Lose significance in  $T < 50$  days (← using 15-day time-bins)
  - Worse resolution for  $T > 600$  days (← nearly duration of data-taking)
- Tested only for  $T = 50 - 600$  days for the data
  - No significant periodicity was found.

# 4) Annual modulation search

## Detector stability

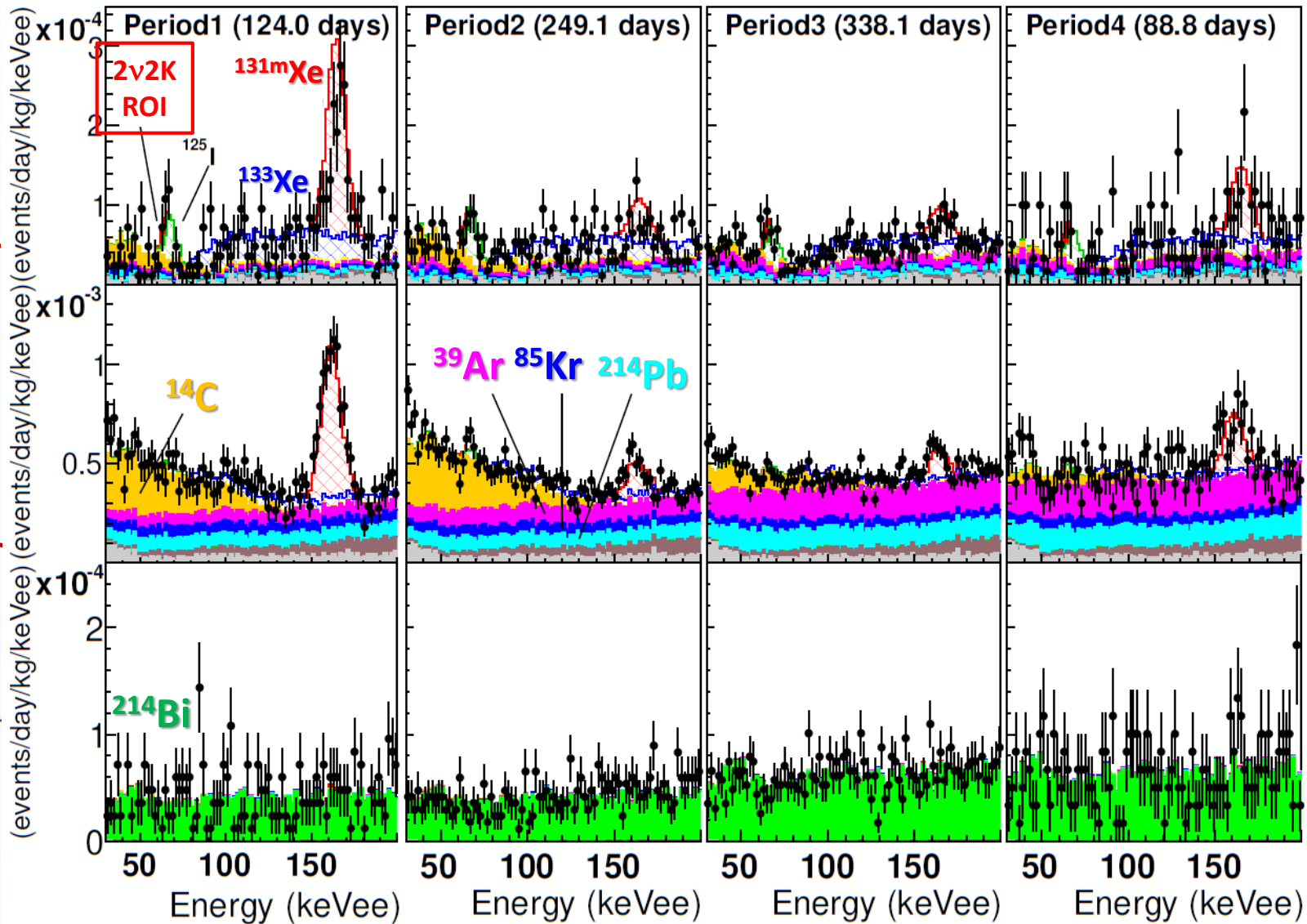


- (1) Power cut
- (2) Switched to other refrigerator
- (3) Purification work

- Large photoelectron yield  
~15 PE/keV
- Evaluated absorption length  
4-30 m, scattering length ~52cm
- Stable intrinsic light yield  
Std: 2.4% (Run1), 0.5% (Run2)

# 5) $^{124}\text{Xe}$ $2\nu$ double electron capture Spectrum fitting in 30-200 keVee

$^{214}\text{Bi}$   
 $\beta$ -enriched  
 $\beta$ -depleted

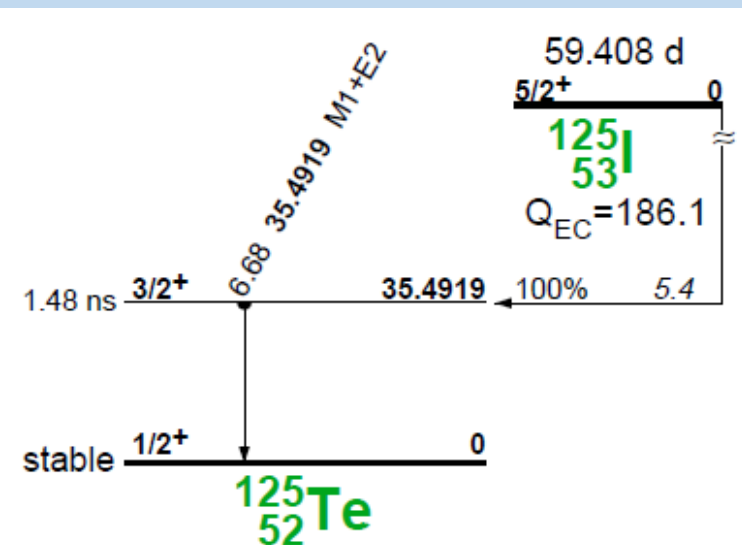


- 4 periods x 3 sub-samples are fitted simultaneously.
- $^{131\text{m}}\text{Xe}$ ,  $^{133}\text{Xe}$ ,  $^{125}\text{I}$ : xenon activation by neutrons
- $^{214}\text{Pb}$ :  $^{222}\text{Rn}$  daughter
- $^{85}\text{Kr}$ : constrained by external  $\beta$ - $\gamma$  coincidence measurement
- $^{39}\text{Ar}$ : confirmed by gas chromatography measurement
- $^{14}\text{C}$ : decreased after gas circulation
- $^{214}\text{Bi}$ :  $^{222}\text{Rn}$  daughter, increased after gas circulation

# 5) $^{124}\text{Xe}$ $2\nu$ double electron capture

## $^{125}\text{I}$ background

- $^{125}\text{I}$  is created by thermal neutron capture on  $^{124}\text{Xe}$ 
  - $^{124}\text{Xe}(n, \gamma)^{125}\text{Xe}$  ( $\sigma=137$  barn)
  - $^{124}\text{Xe}(n, \gamma)^{125m}\text{Xe}$  ( $\sigma=28$  barn)
  - $^{125m}\text{Xe} \rightarrow ^{125}\text{Xe}$  (IT,  $T_{1/2}=57$  sec)
  - $^{125}\text{Xe} \rightarrow ^{125}\text{I}$  ( $\beta^+/\text{EC}$ ,  $T_{1/2}=16.9$  hours)
- Thermal neutron flux in the Kamioka mine  $(0.8-1.4) \times 10^{-5}$  / $\text{cm}^2/\text{s}$
- Xenon gas volume outside the water shield  $2.6 \times 10^5$   $\text{cm}^3$  (STP)



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

