Latest results from the XMASS experiment

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NDM2018@Daejeon, Korea

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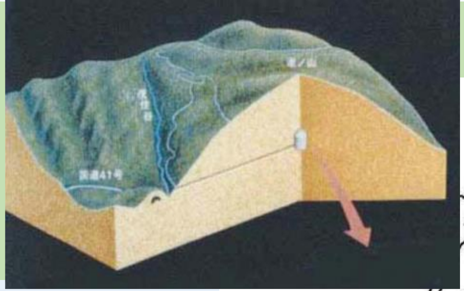
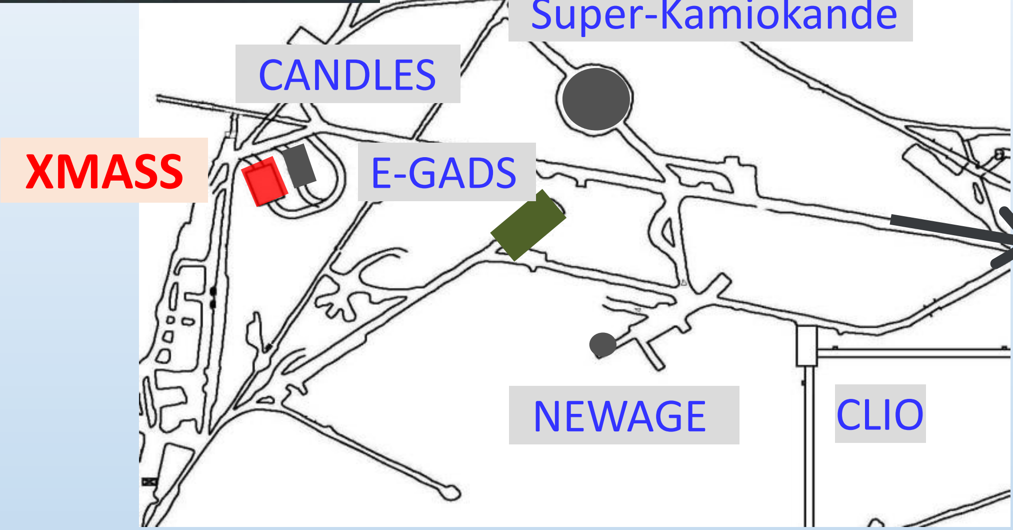
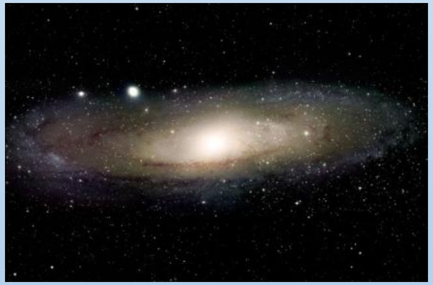
  4. ^{124}Xe 2ν double electron capture search *PTEP2018 (2018) 053D03*
- Summary

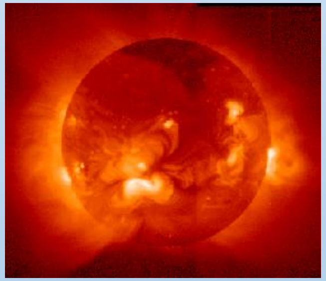
The XMASS project

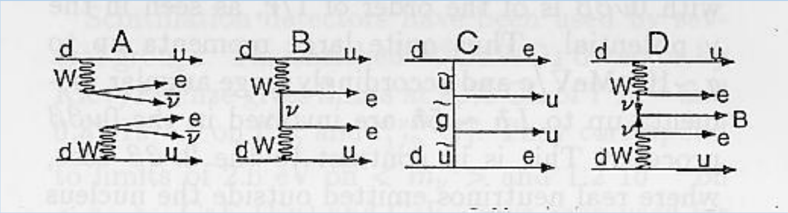




- XMASS: a multi purpose experiment with liquid xenon
- Located 1,000 m underground (2,700 m.w.e.) at the Kamioka Observatory in Japan
- Aiming for
  - Direct detection of dark matter
  - Observation of low energy solar neutrinos (*pp*/^{7}Be)
  - Search for neutrino-less double beta decay
- Features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

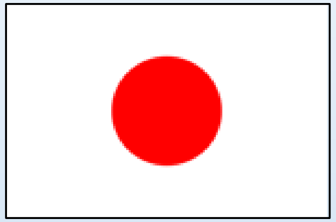






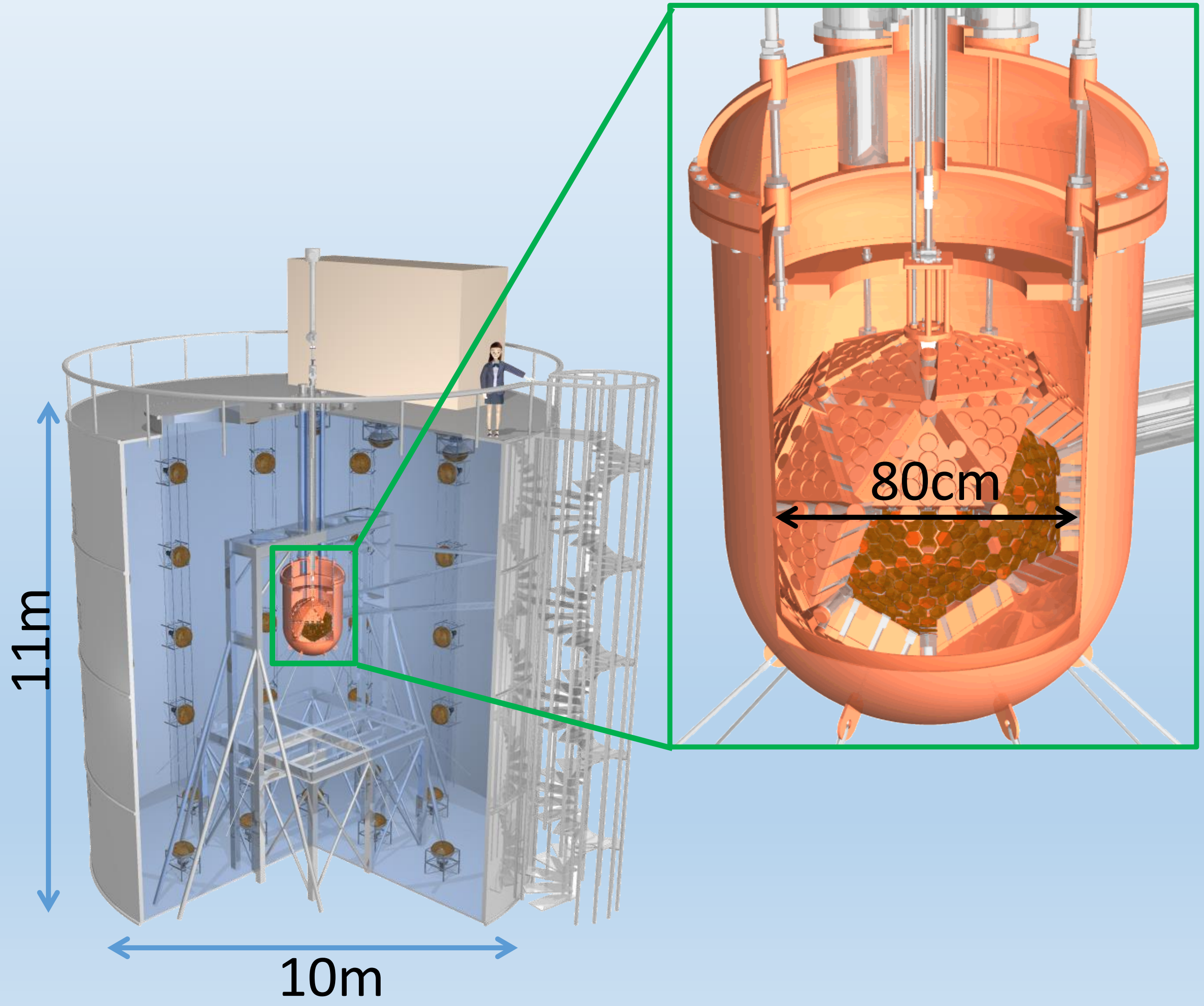
XMASS Collaboration

- 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

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

Inner calibration system

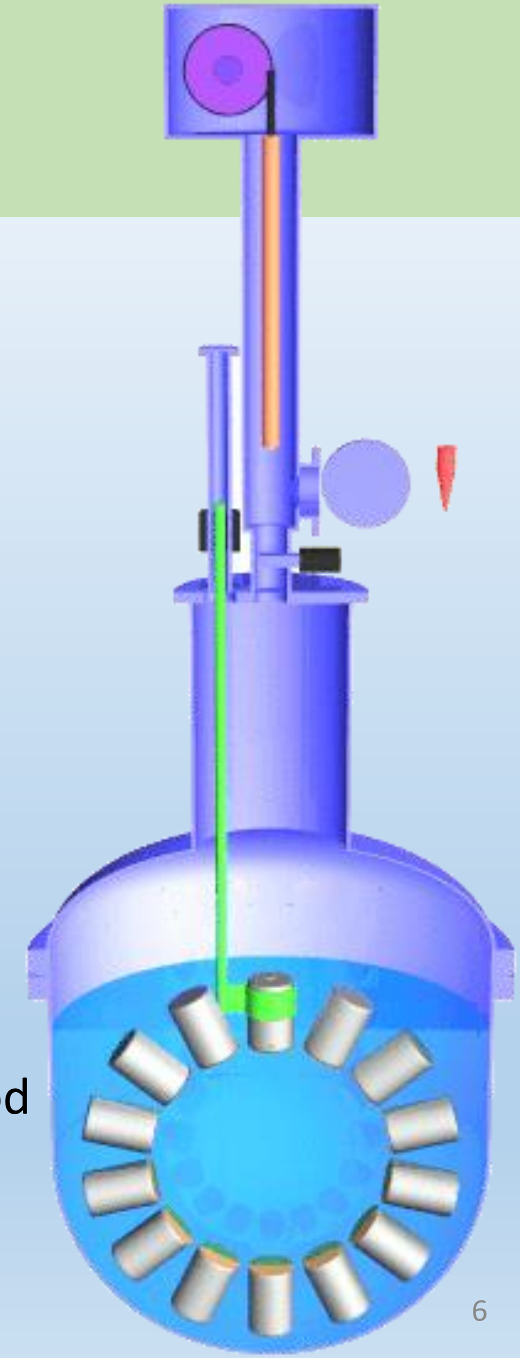
- Various RI sources can be inserted
- Used for light yield monitoring, optical parameter tuning, energy and timing calibrations etc.

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

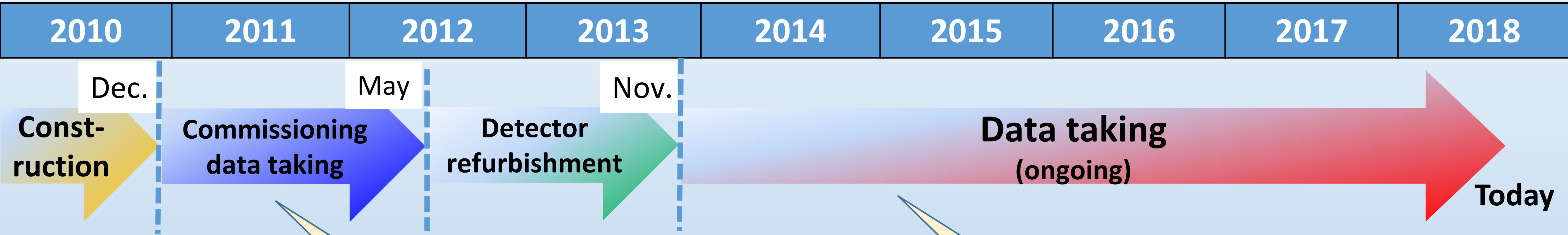
^{57}Co source

Source rod (Ti)

Active region is concentrated on the 1.8 mm edge region



History of XMASS-I data-taking



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

- WIMPs search by fiducialization
- Annual modulation
- Hidden photons/ALPs DM
- ^{124}Xe 2ν double electron capture
- Solar Kaluza-Klein axion

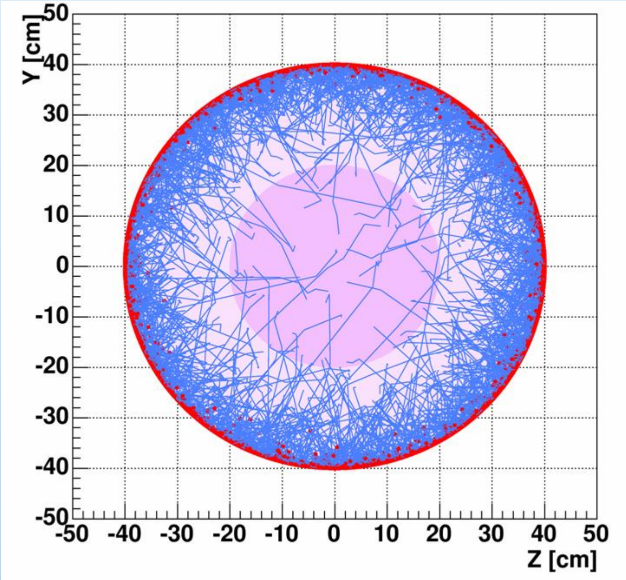
- ***Stably taking data for >4 years since Nov. 2013.***
- ***Will continue data-taking until Dec. 2018.***

Latest results from XMASS

1) WIMP dark matter search by fiducialization

Introduction

Traces of γ-rays from PMTs



Fiducial volume
R<20cm

- Self-shielding of external γ-rays owing to high atomic number (Z=54) and high density (2.9g/cm3)
- Event vertex position and energy are reconstructed using number of PE in each PMT

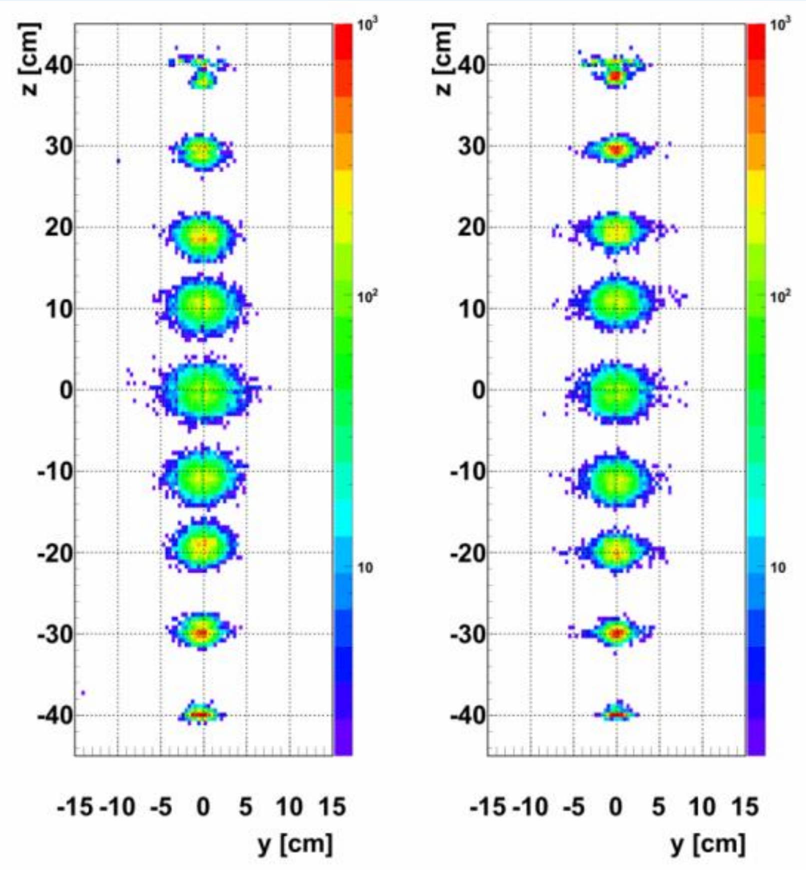
$$L(\mathbf{x}) = \prod_{i=1}^{642} p_i(n_i)$$

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

^{57}Co 122keV

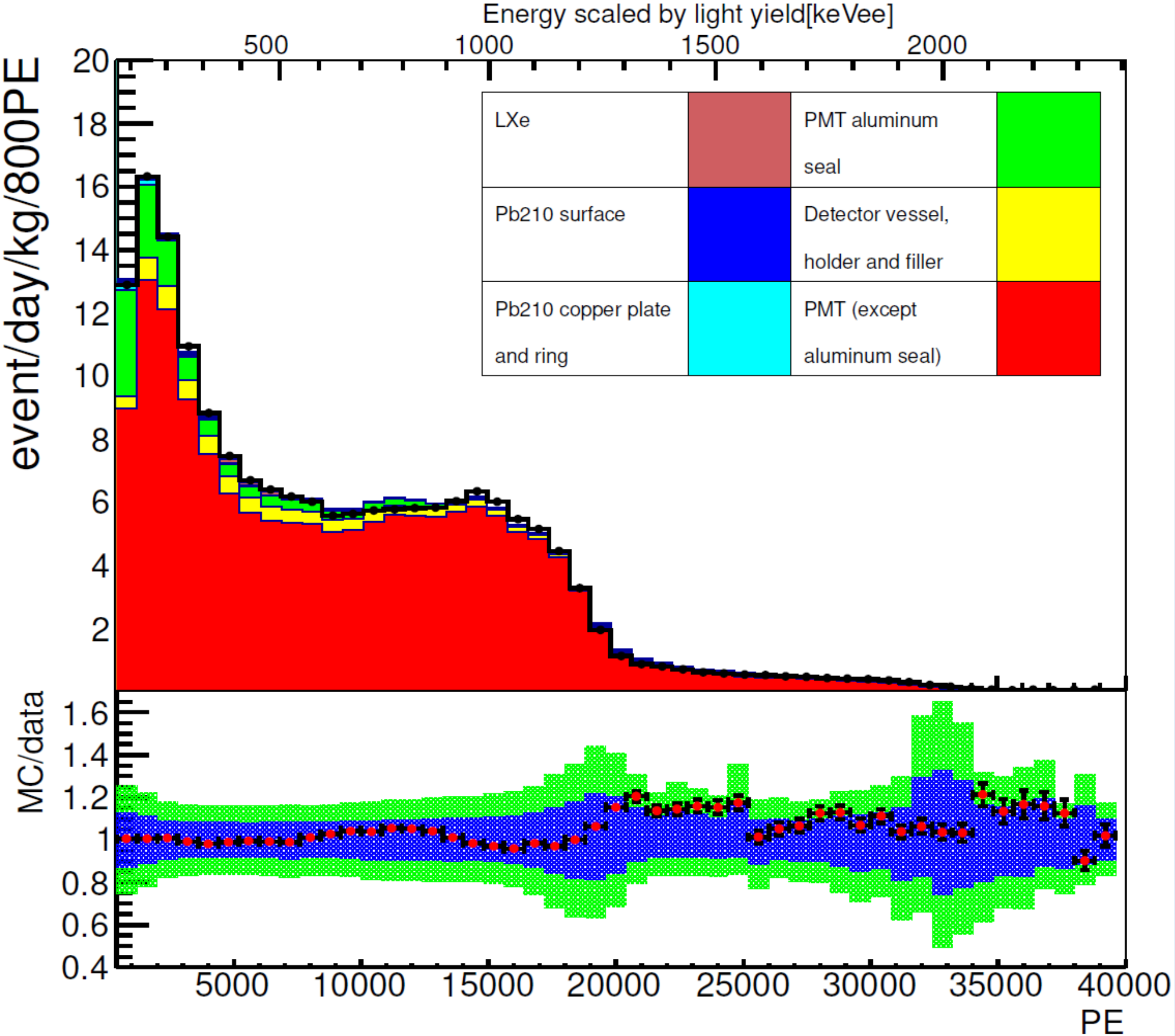
Reconstructed vertex

DATA MC



1) WIMP dark matter search by fiducialization

Background spectrum in the whole 832kg volume



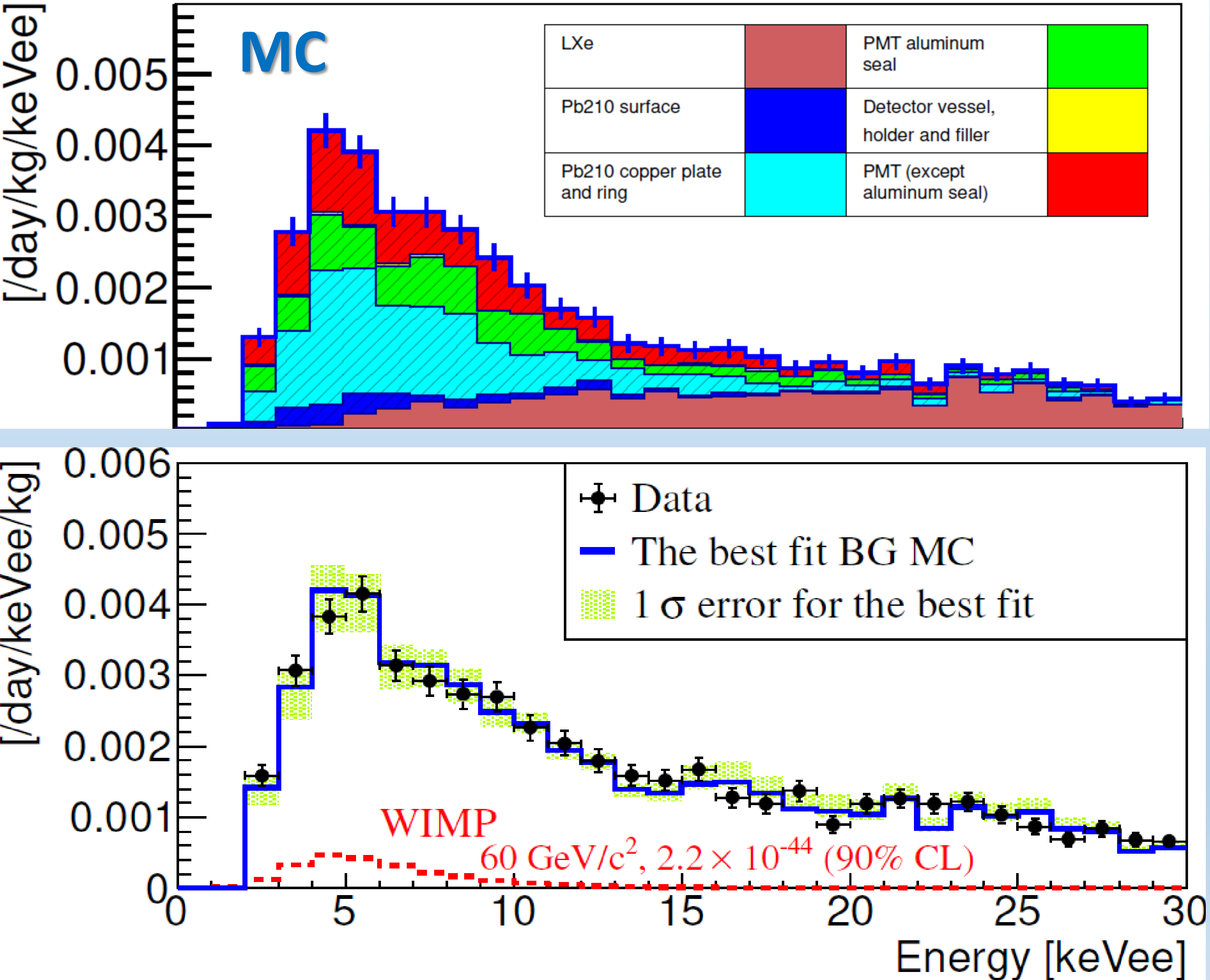
- All the detector material (except for copper and LXe) was screened by the Ge detector before installation.
- Then, the energy spectrum above 30 keV was fitted under these constraints.

- α-rays are selected using scintillation decay time to constrain PMT/copper surface/bulk ^{210}Pb.
  - Contamination of ^{210}Pb (~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}Rn: 10.3+/-0.2 μBq/kg
  - ^{85}Kr: 0.30+/-0.05 μBq/kg
  - ^{39}Ar, ^{14}C: evaluated by spectrum fit in R<30cm and 30—250 keV$_{ee}$

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 BG in the WIMP search region
  - ^{210}Pb in the copper bulk
  - γ-rays from PMTs

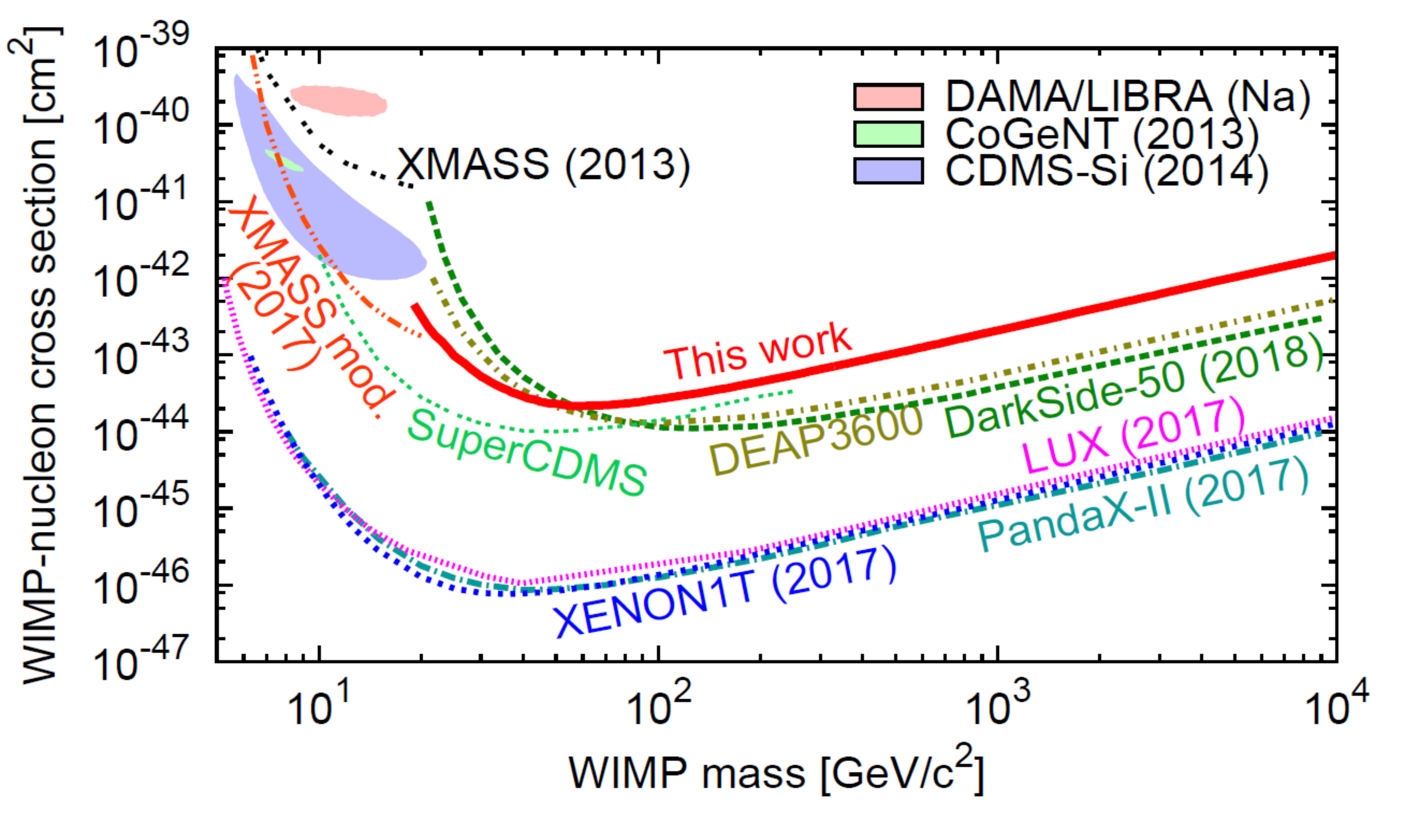
- Neutrons, alpha-rays are negligible

- The energy spectrum at 2-15 keVee is fitted with signal + BG.

- 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

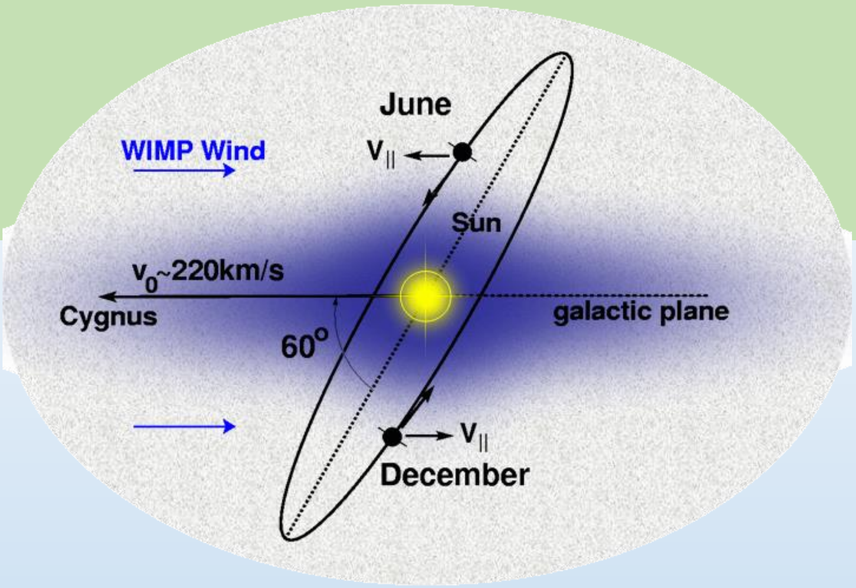
Results: Limits on SI WIMP-nucleon cross section



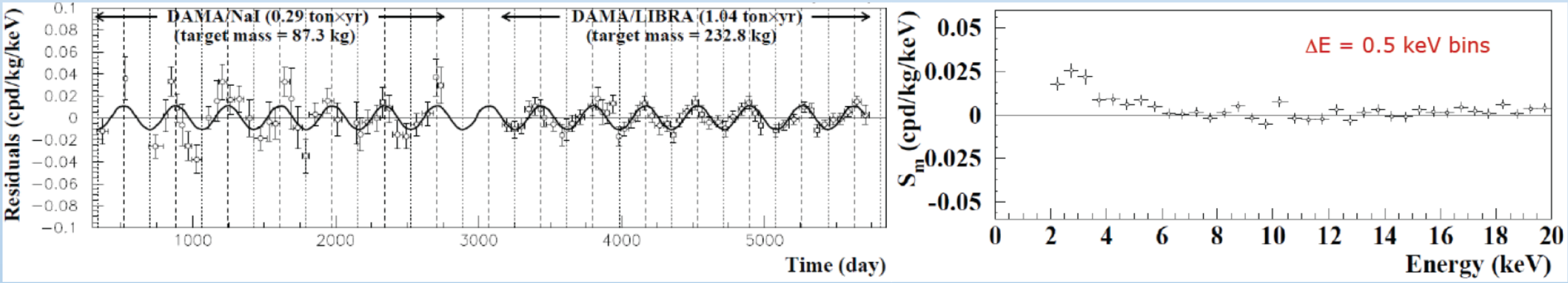
- 97kg x 706 days exposure with a single-phase LXe detector
- 90% CL upper limit on spin-independent WIMP-nucleon cross section was derived.
- $\sigma_{SI}<2.2\times10^{-44}$ cm^2 for 60 GeV/c^2
- arXiv: 1804.02180

2) Annual modulation search

Introduction



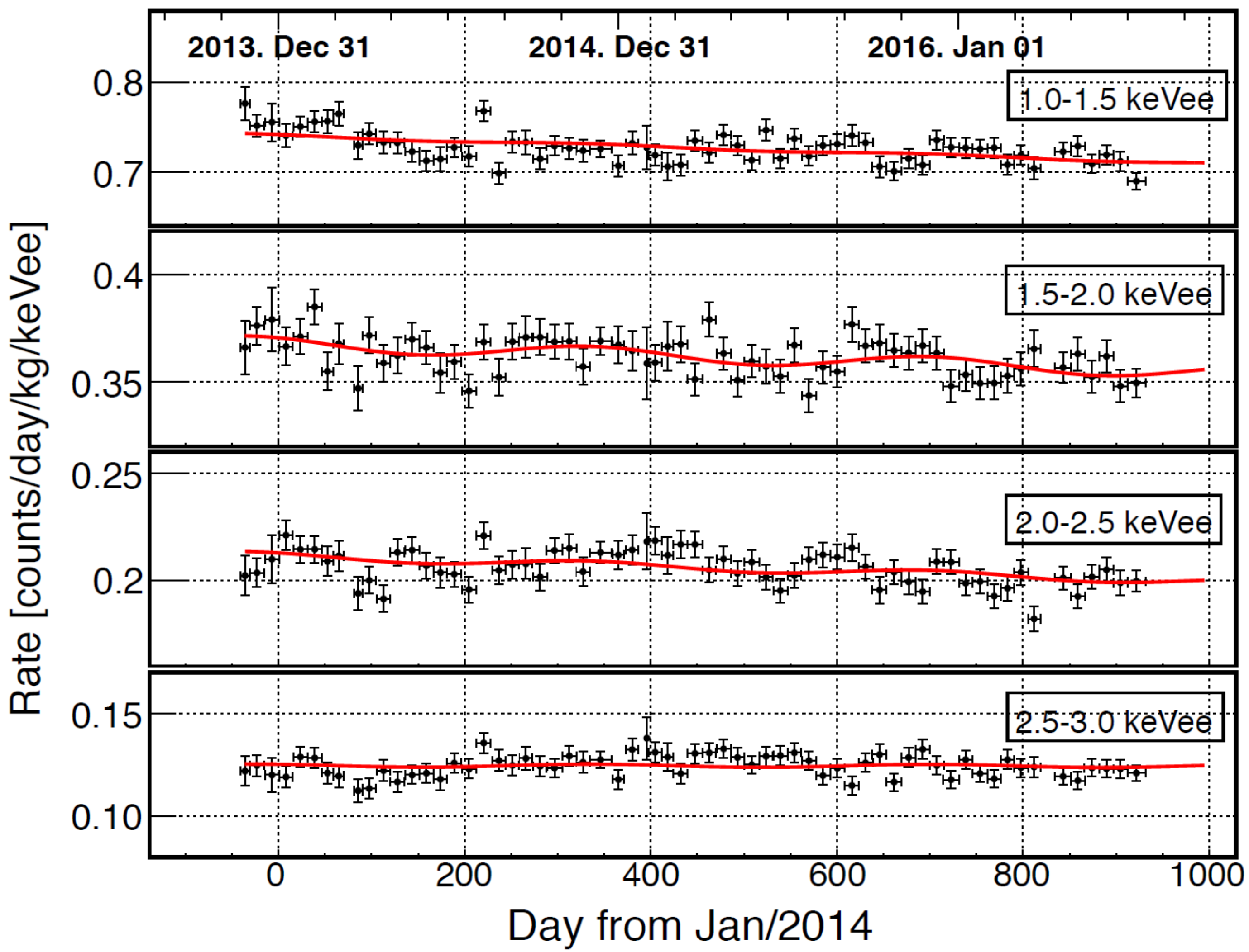
- Expect annual modulation of event rate of dark matter signal due to Earth's rotation around the Sun.
- DAMA/LIBRA claims modulation at 9.3σ
  - Total exposure of 1.33 ton year (14 cycles)
  - Modulation amplitude of (0.0112+/-0.0012) cpd/kg/keV for 2-6 keV



- 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/γ events

2) Annual modulation search

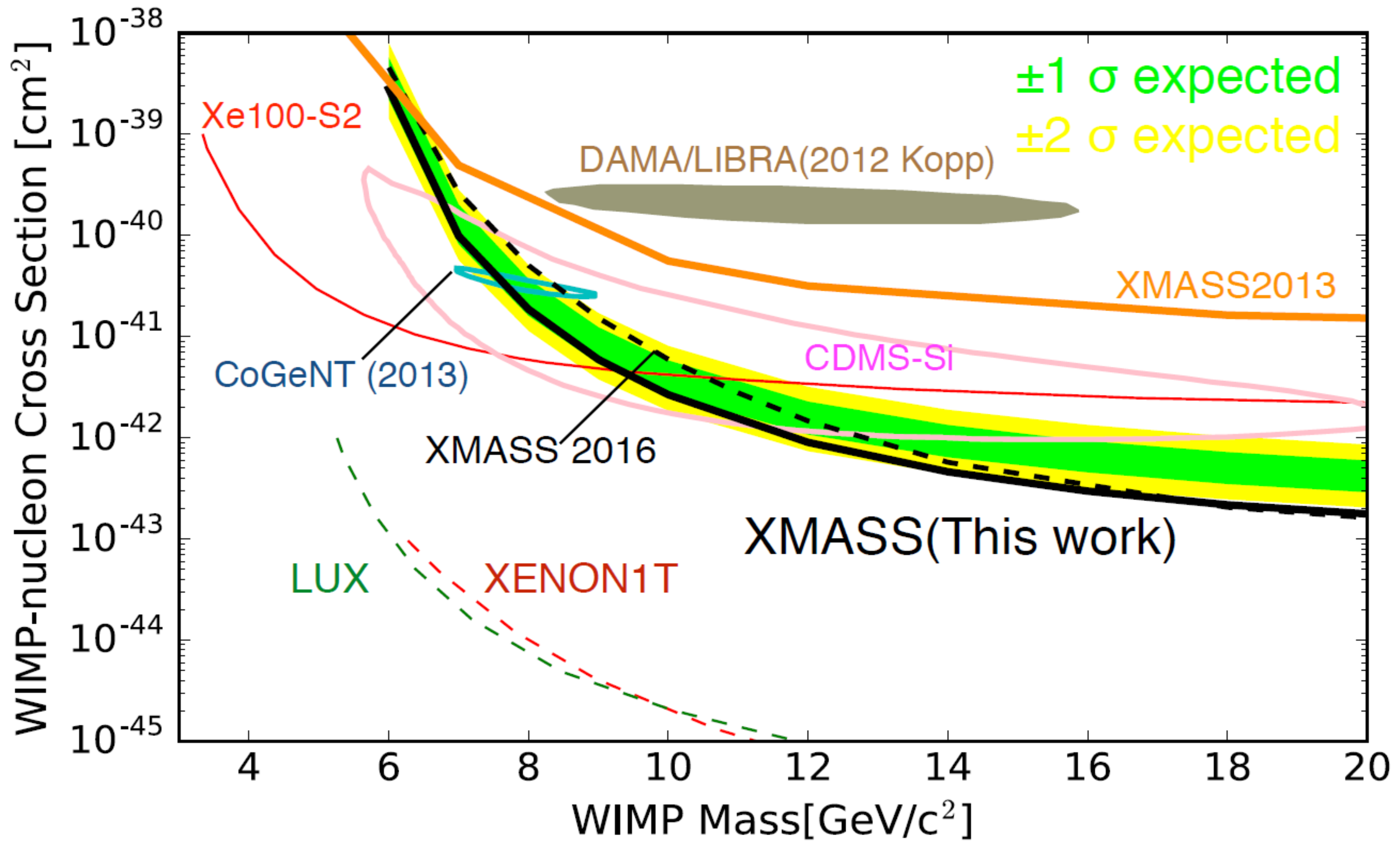
Results: time variation of event rate



$$R^{\mathrm{ex}}_{i,j} = \int_{t_j-\frac{1}{2}\Delta t_j}^{t_j+\frac{1}{2}\Delta t_j} \left(\epsilon^s_{i,j} A^s_i \cos 2\pi \frac{(t-\phi)}{T} + \epsilon^b_{i,j}(\alpha)(B^b_i t + C^b_i) \right) dt$$

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

2) Annual modulation search
Results: WIMP analysis

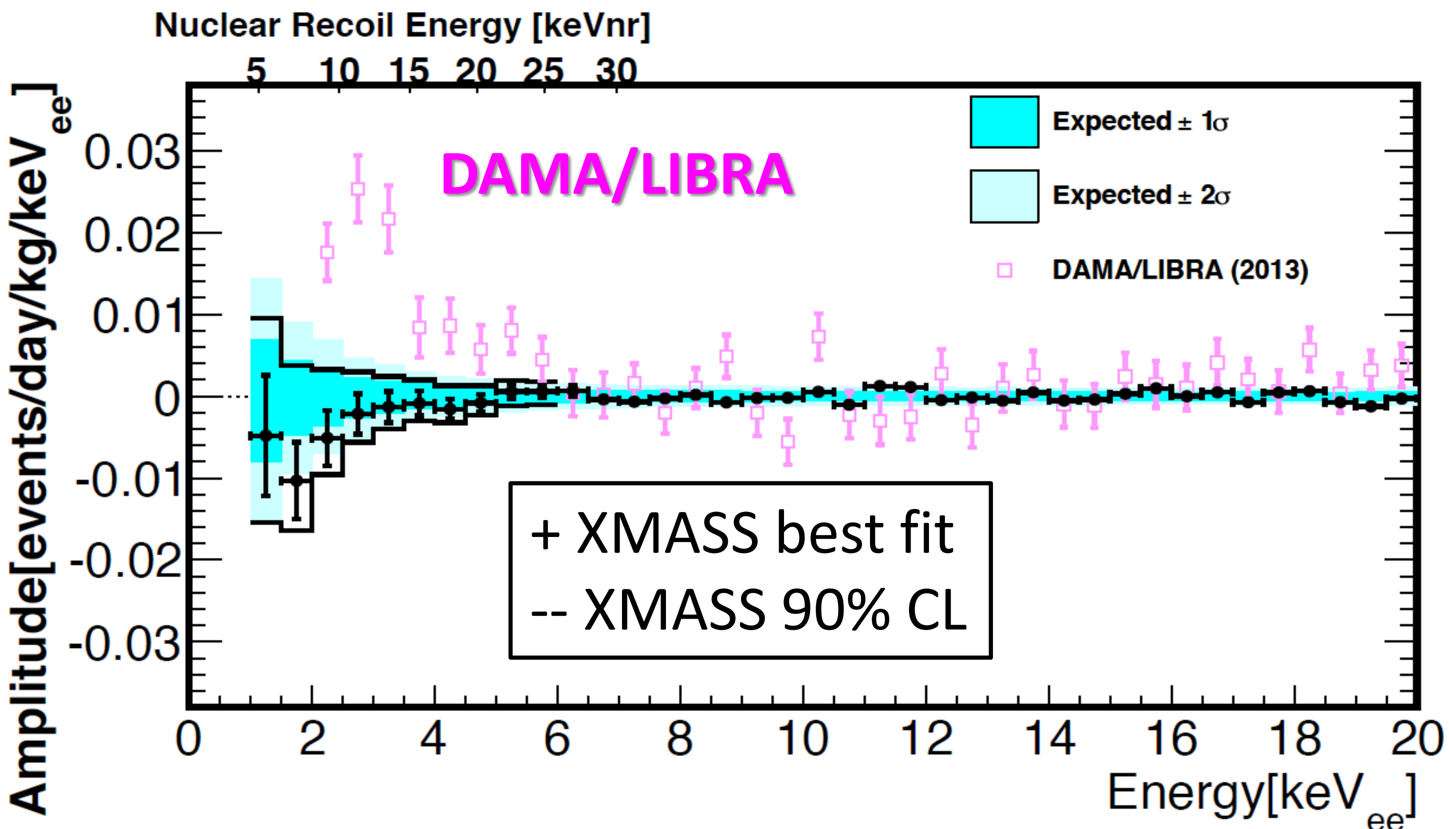


- Assuming WIMP and standard halo model
  - Lewin and Smith (1996, APP)
  - V_0=232 km/s, V_{esc}=544 km/s
  - ρ_{DM}=0.3 GeV/cm^3
  - T= 365.24 days, ϕ=152.5 day
- DAMA/LIBRA allowed region was excluded by annual modulation search.
  - $\sigma_{\chi n}$< 1.9x10^{-41} cm^2 (90%CL) for 8 GeV/c^2

2) Annual modulation search
Results: model independent analysis

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

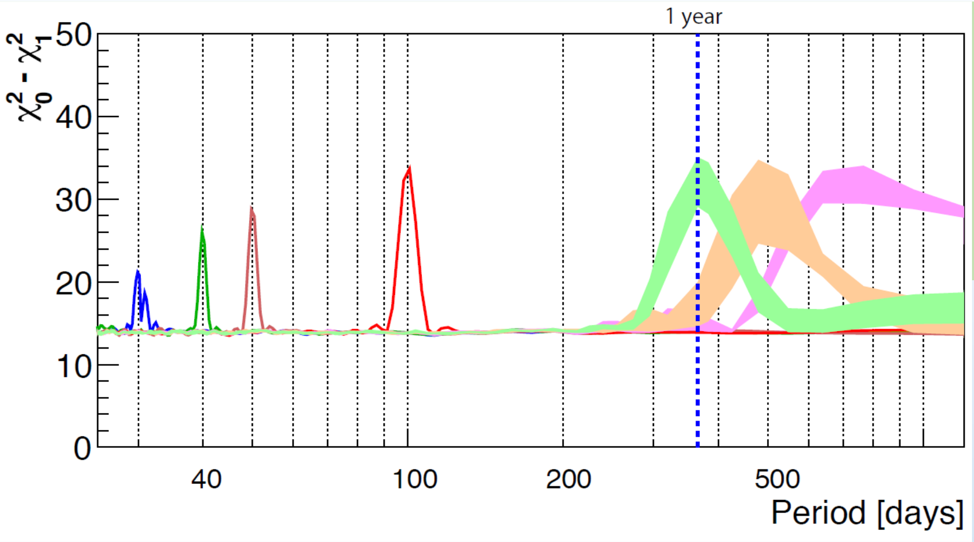
Experiment	Amplitude (/day/kg/keVee)	
DAMA/LIBRA	~20×10^{-3}	(2-3.5 keV_{ee})
XENON100	$(1.67+/-0.73) \times 10^{-3}$	(2-5.8 keV_{ee})
XMASS	<$(1.3\text{-}3.2) \times 10^{-3}$	(2-6 keV_{ee})



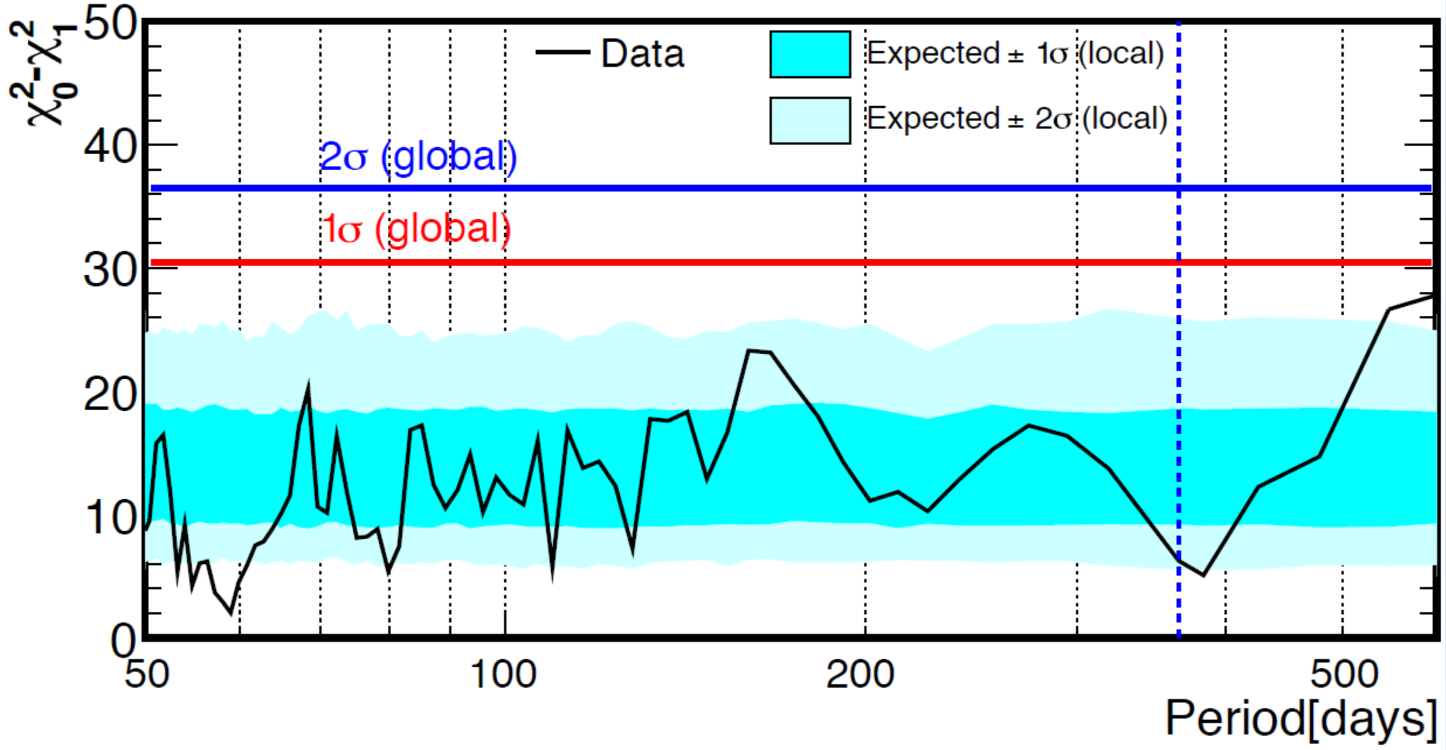
- 1-20 keVee energy range
- Null hypothesis: p-value=0.11 (1.6σ)
  - Less significant than the previous result (2.5σ)
- Most stringent constraints on modulation amplitudes.

2) Annual modulation search
Results: frequency analysis

- Test statistics: $\Delta\chi^2 = \chi^2(\text{null}) - \chi^2(\text{modulation})$
- Use the 1-6 keVee 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>600days (← nearly duration of data-taking)
- Tested only for T=50-600 days for the data
  - No significant periodicity was found.

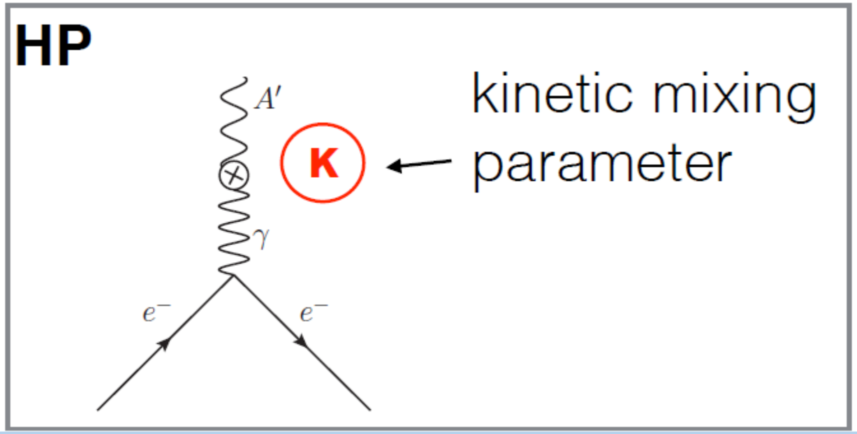
3) Hidden photons & axion-like particles dark matter

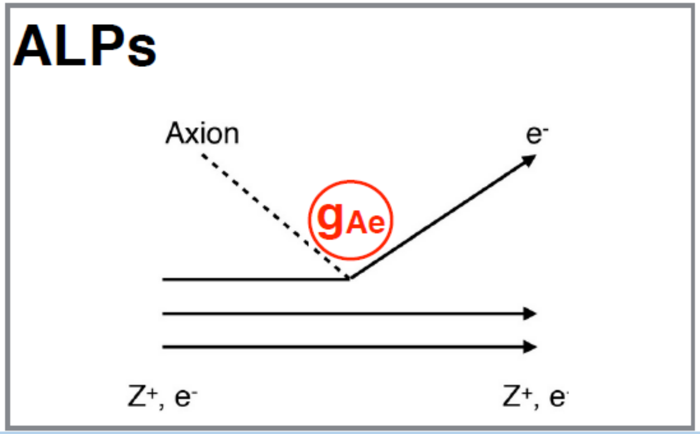
Introduction

- Hidden photon (HP): gauge boson of hidden U(1)
  Axion-like particles (ALPs): pseudo-Nambu-Goldstone boson

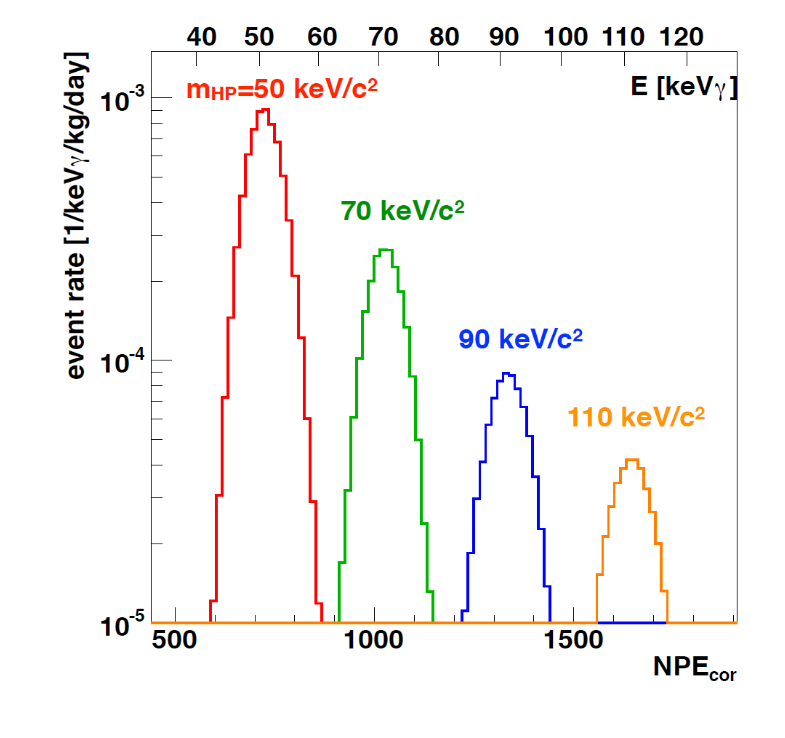
Cold dark matter candidates

- Both bosons can be absorbed in the detector medium with emission of an electron. ➔ analogue to photoelectric effect





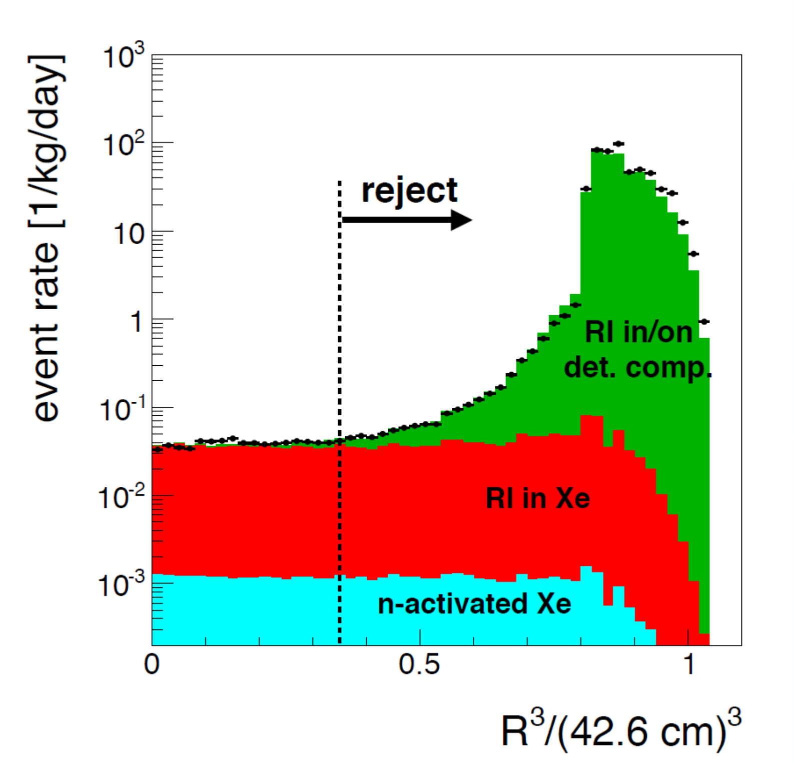
$$\frac{\sigma_{abs} v}{\sigma_{pe}(\omega = m_{HP})c} = \frac{\alpha'}{\alpha} \qquad \frac{\sigma_{abs} v}{\sigma_{pe}(\omega = m_{ALP})c} = \frac{3m_{ALP}^2}{16\pi\alpha m_e^2} \times g_{Ae}^2$$



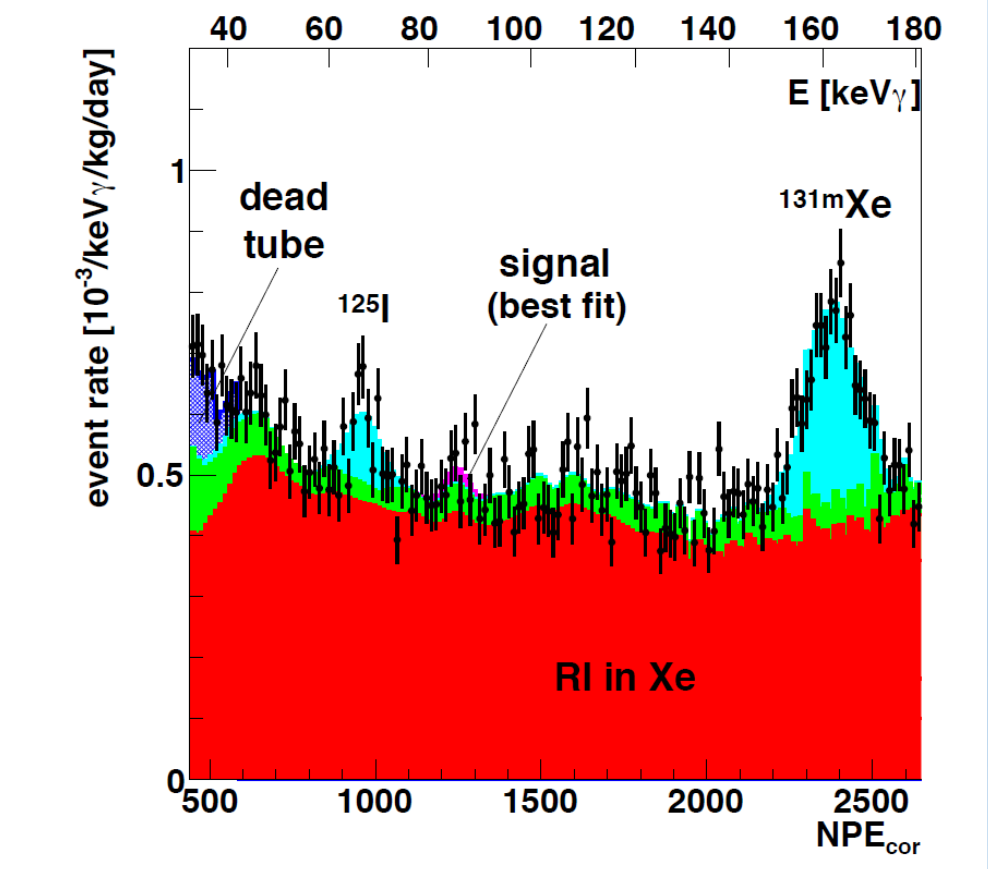
- Event rate ∝ $(a'/a)/m_{HP}$ or $g_{Ae}{}^2 \times m_{ALP}$

3) Hidden photons & axion-like particles dark matter

Results



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

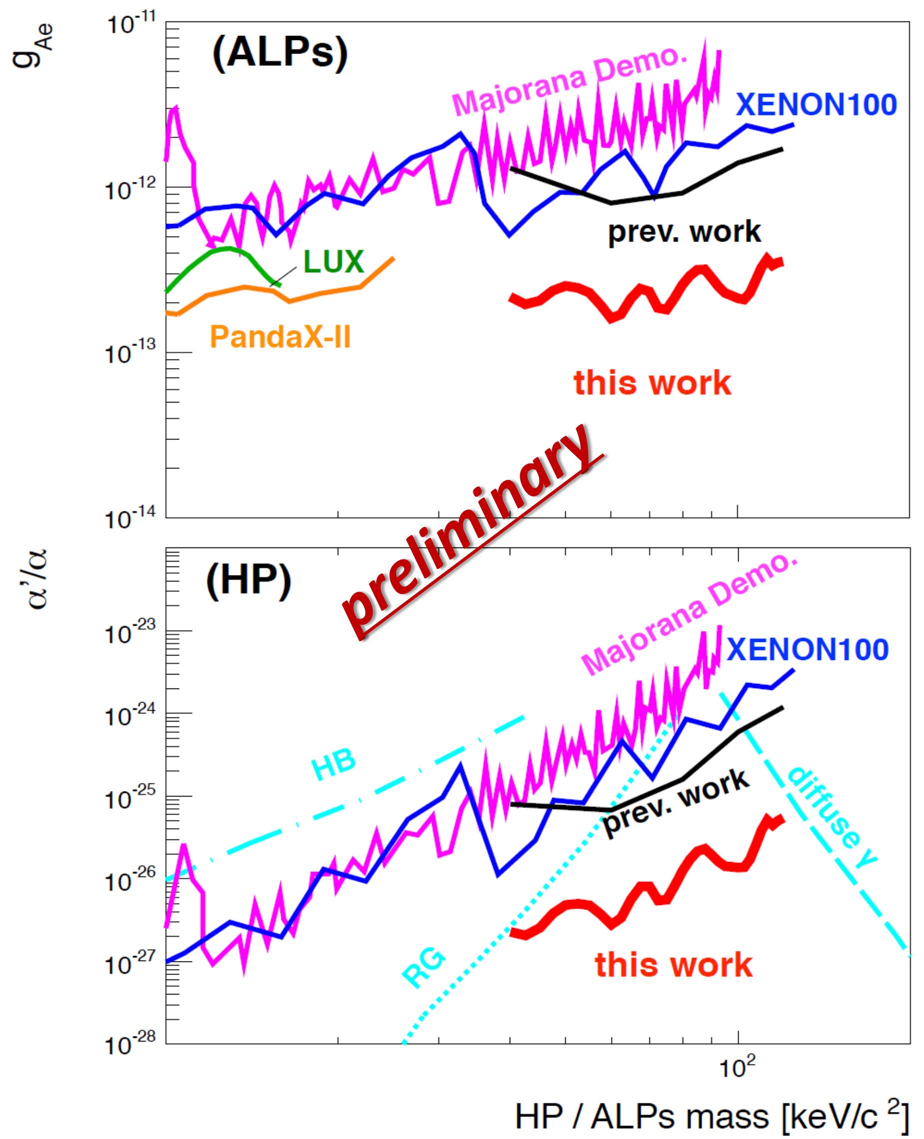


- Peak search by fitting the energy spectrum with the signal + background model.

- Fitting energy range 30-180 keV
- Scanning mass every 2.5 keV/c^2 in 40-120 keV/c^2

3) Hidden photons & axion-like particles dark matter

Results



- Axion-like particles DM
  - g_{Ae}< 4x10^{-13} (90%CL) for 40-120 keV/c^2
  - Cover higher mass region than LUX and PandaX-II
- Hidden photon DM
  - α'/α < 6x10^{-26} (90%CL) for 40-120 keV/c^2
  - Cover a region where indirect searches are weak
- The best constraint in 40-120 keV/c^2 for both cases.

4) ^{124}Xe 2ν double electron capture

Introduction

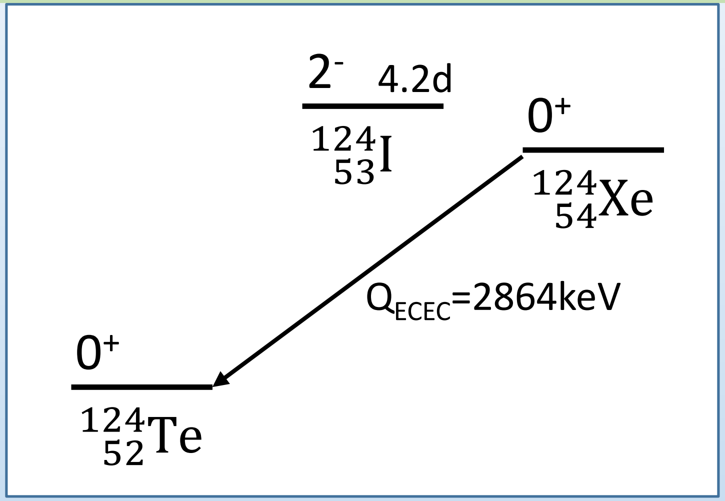
- Natural xenon contains ^{124}Xe (N.A.=0.095%) and ^{126}Xe (N.A.=0.089%) which can undergo double electron capture.
  ^{124}Xe (g.s., 0^+) + $2e^-$ → ^{124}Te (g.s., 0^+) + ($2\nu_e$) + 2864keV

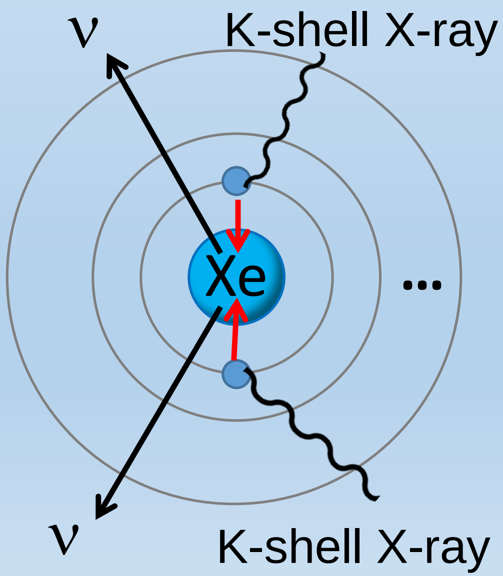
- 0ν mode → Evidence of lepton number violation
  2ν mode → New input for nuclear matrix element calculation

- ^{124}Xe 2ν double electron capture from K-shell (2ν2K)
  - Total deposit energy of **63.6 keV by X-rays/Auger electrons**
  - Expected half-life is **10^{20}-10^{24} years**

- Previously, XMASS set a lower limit **$T_{1/2}^{2\nu 2K}$ > 4.7x10^{21} years (@90%CL)** using 132 live days x 41 kg LXe (39g of ^{124}Xe)
  XMASS Collaboration, PLB759 (2016) 64

- An improved search was conducted using a new data set, 800.0 live day x 327 kg (311g of ^{124}Xe)





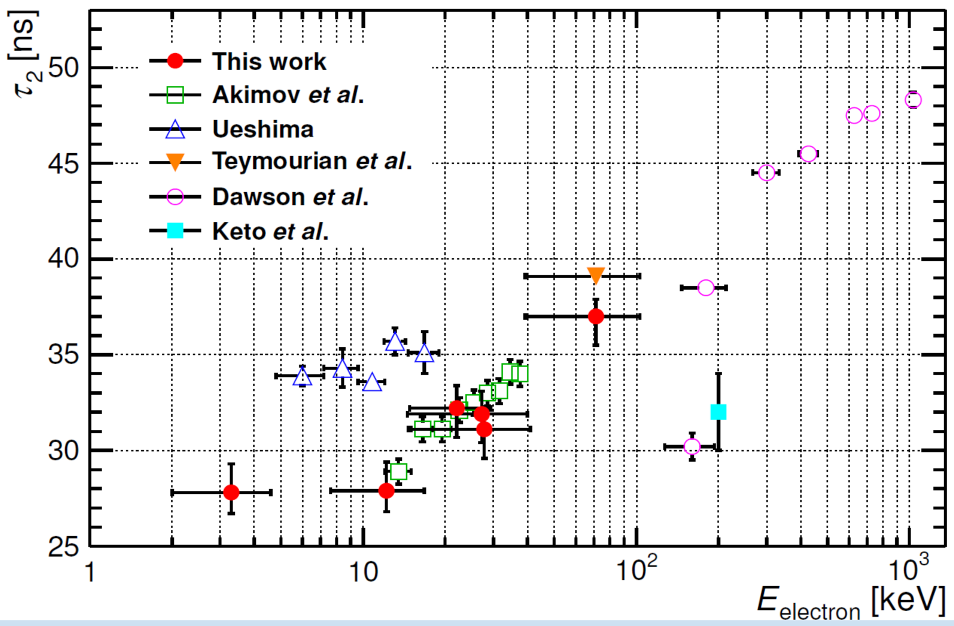
4) ^{124}Xe 2ν double electron capture

Particle ID using scinti. time profile

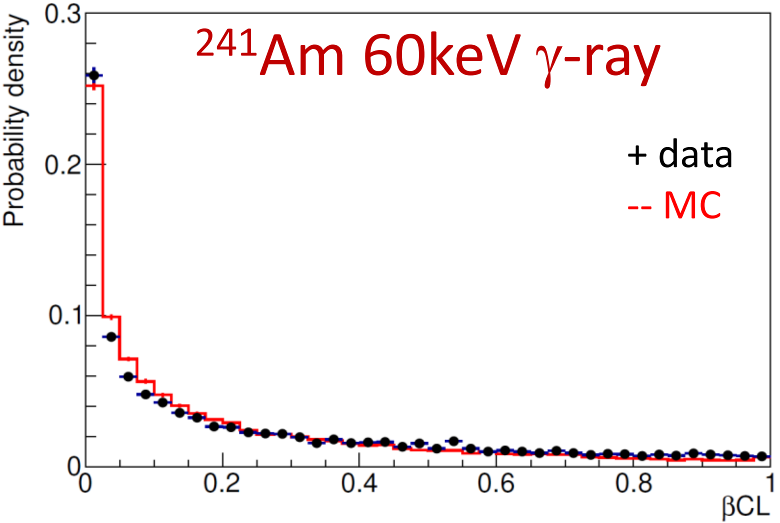
- LXe scintillation decay time depends on electron kinetic energy
- This allows us to separate

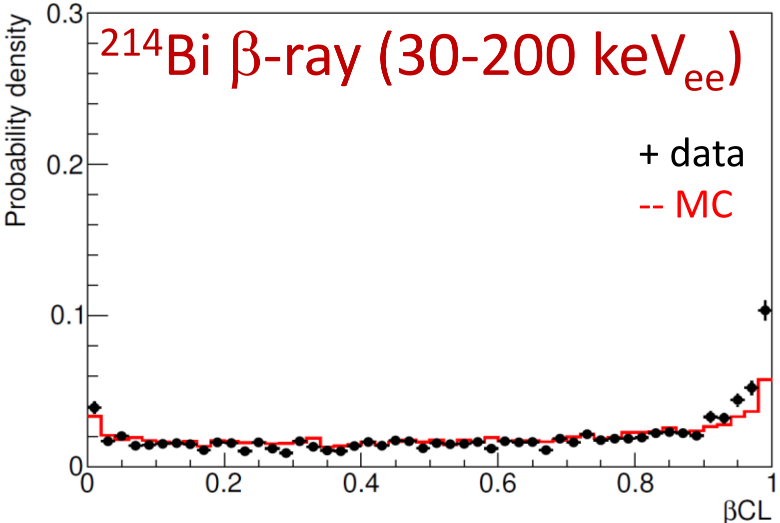
β-ray (single electron track)	vs.	γ-ray/X-ray or 2ν2K (multiple electrons)

- Particle ID parameter (βCL) is constructed from each photoelectron's timing assuming the event is caused by a β-ray.



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





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

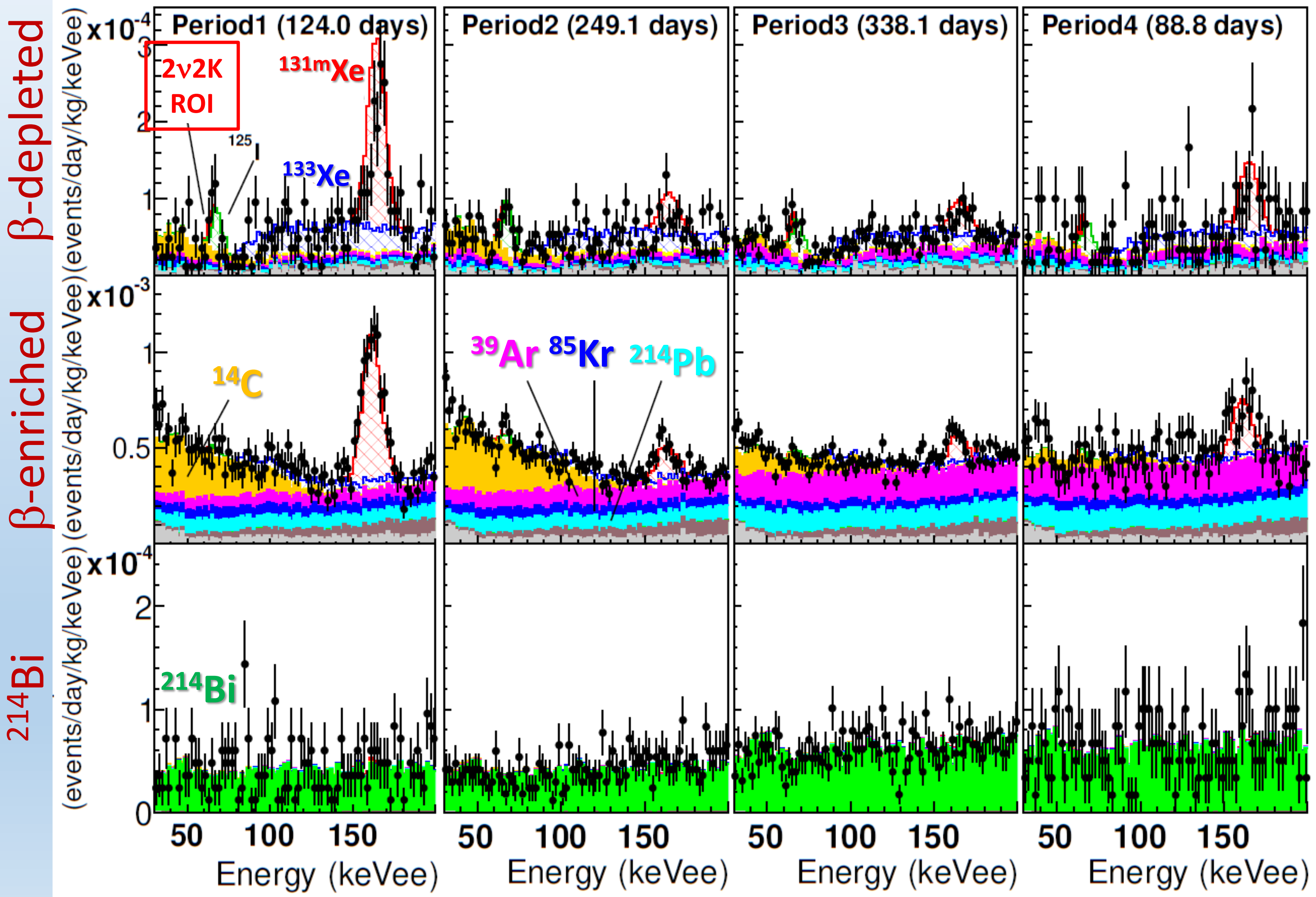
βCL<0.05

- Acceptance for γ-ray ~35%
- Acceptance for β-ray ~7%

➔ S/N improves by x5

4) ^{124}Xe 2ν double electron capture

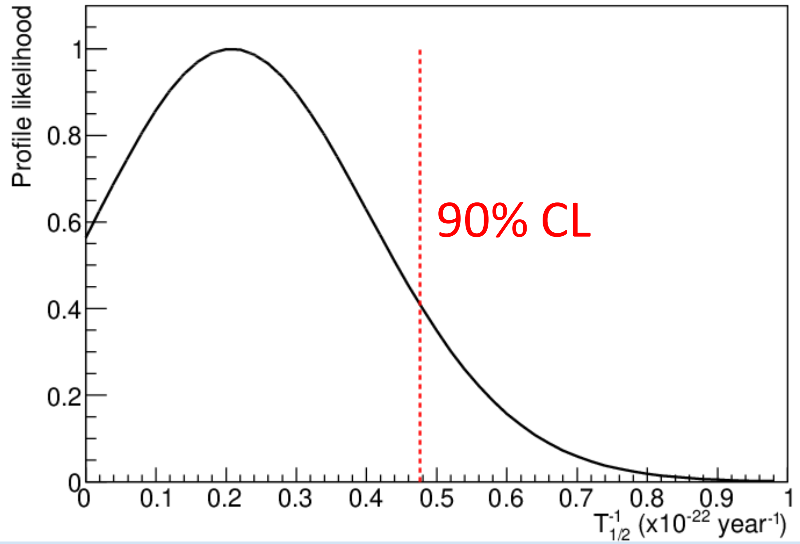
Spectrum fitting in 30-200 keVee

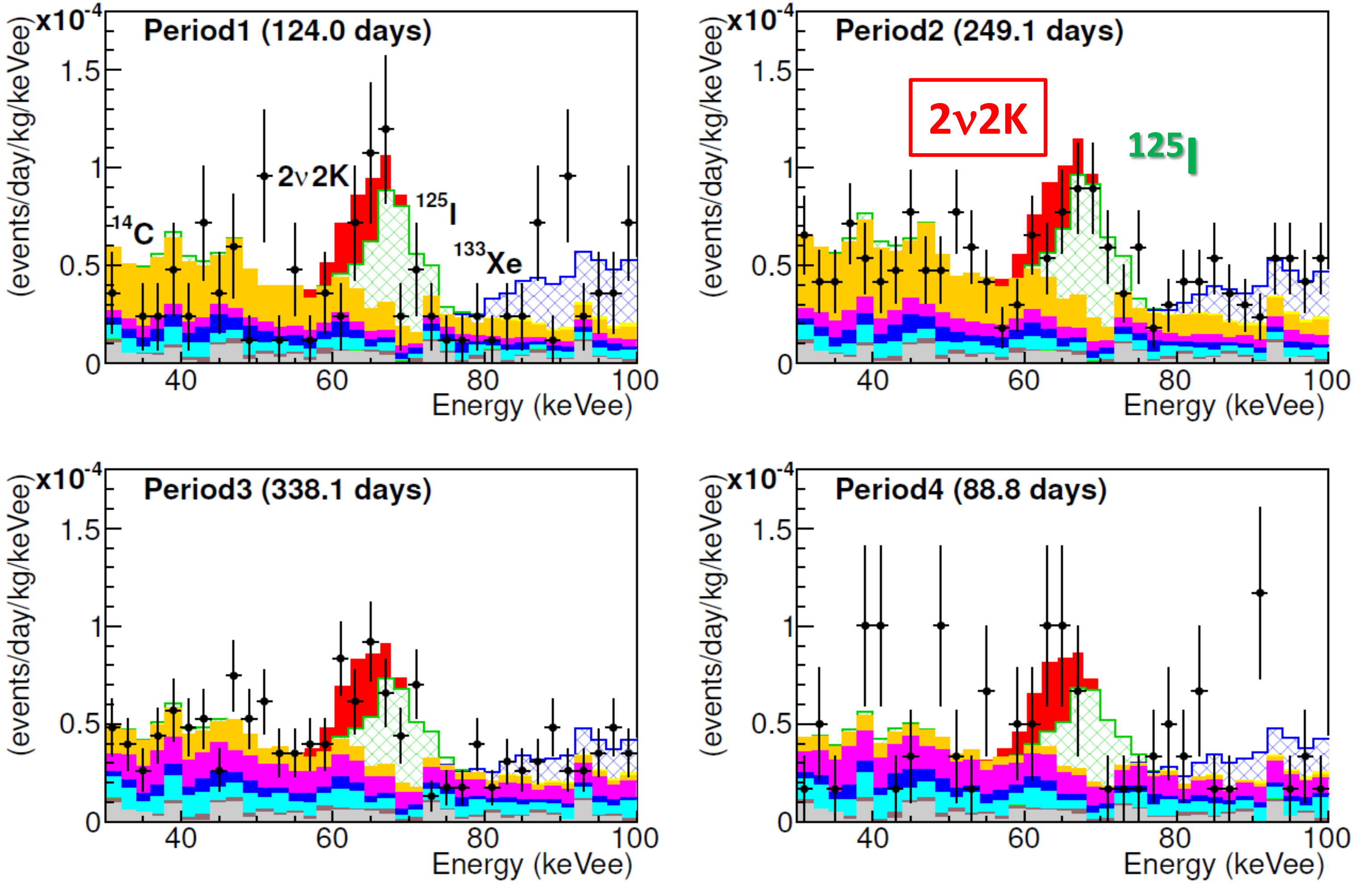


- 4 periods x 3 sub-samples are fitted simultaneously.
- ^{131m}Xe, ^{133}Xe, ^{125}I: xenon activation by neutrons
- ^{214}Pb: ^{222}Rn daughter
- ^{85}Kr: constrained by external β-γ coincidence measurement
- ^{39}Ar: confirmed by gas chromatography measurement
- ^{14}C: decreased after gas circulation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

4) ^{124}Xe 2ν double electron capture

Results: close-up spectrum of ROI

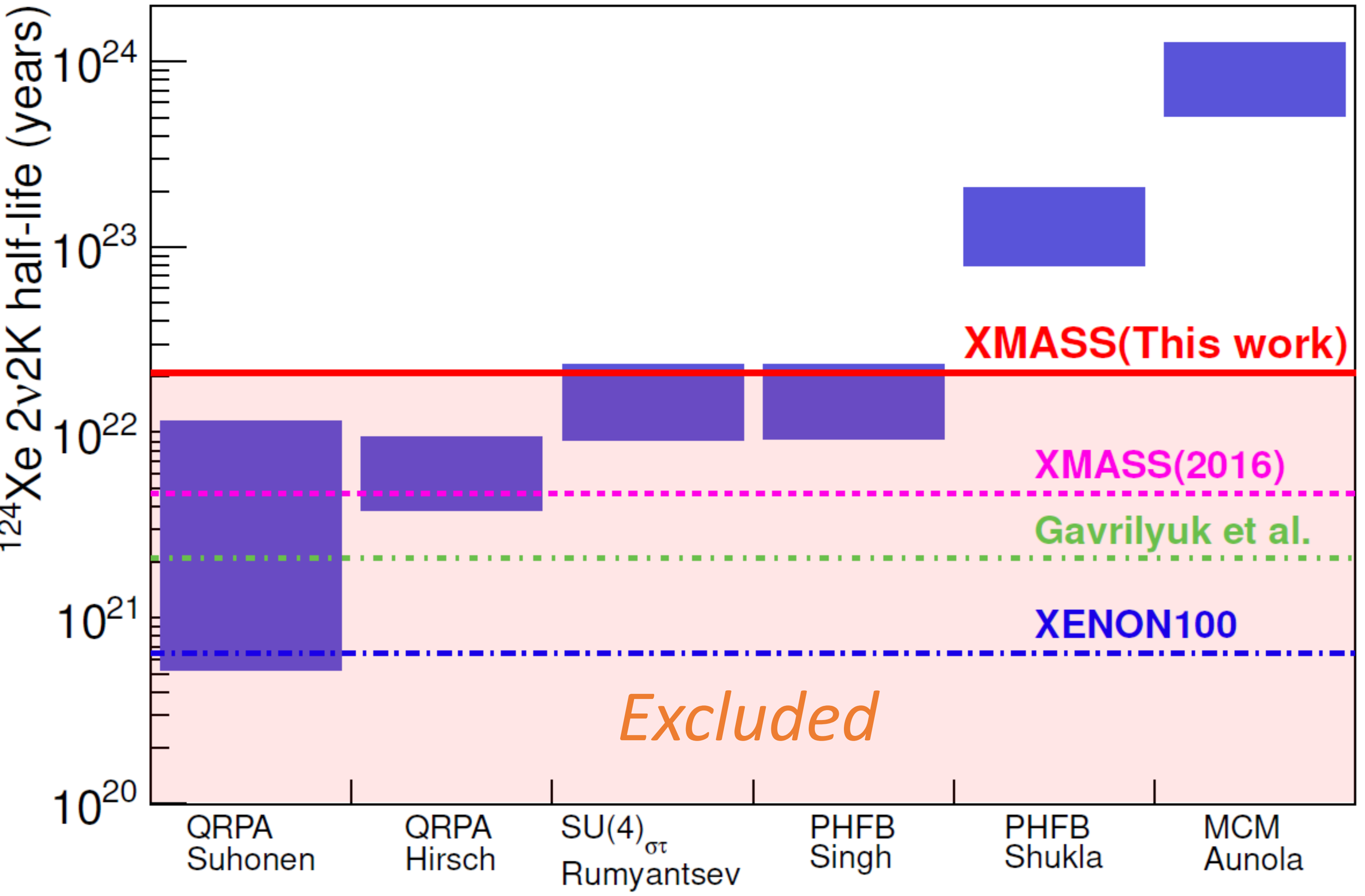




- ^{125}I is created by thermal neutron capture on ^{124}Xe outside the water shield, giving a peak at 67.5 keVee.
- Thermal neutron flux is constrained by independent measurement.
- No significant signal was observed.

4) ^{124}Xe 2ν 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
  - $T_{1/2}^{2\nu 2K}(^{124}Xe)>2.1\times10^{22}$ yrs
  - $T_{1/2}^{2\nu 2K}(^{126}Xe)>1.9\times10^{22}$ yrs

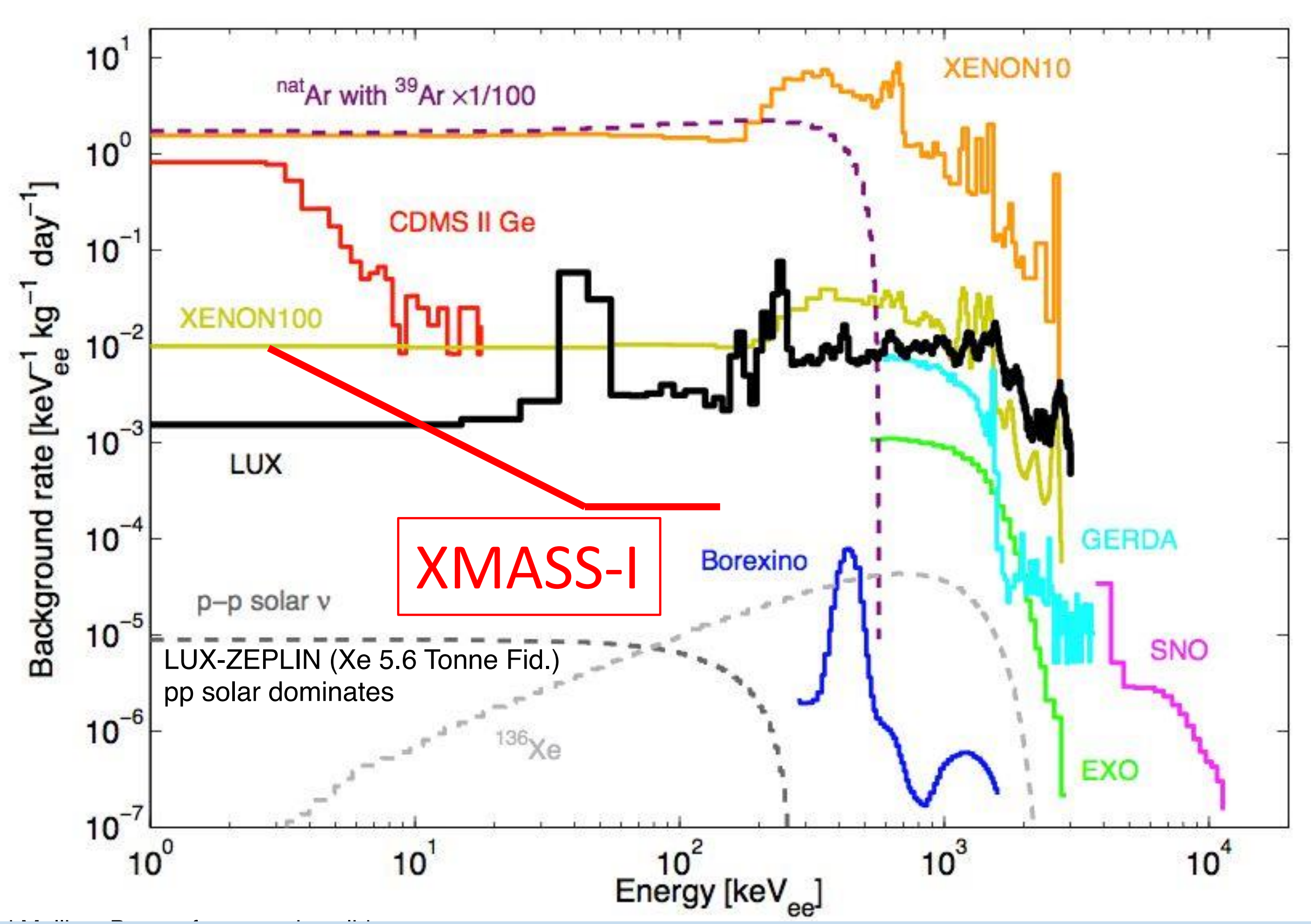
- Published in ***PTEP2018 (2018) 053D03***

Summary

- XMASS
  - a multi-purpose experiment using 832 kg of liquid xenon
  - has been stably taking data for more than 4 years
- Latest results
  - WIMP search by fiducialization:
    - First stringent constraint from the single-phase LXe detector
    - σ_{SI}<2.2x10^{-44} cm^2 for 60 GeV/c^2 ***arXiv: 1804.02180***
  - Annual modulation:
    - Most stringent constraints on amplitudes with 1.82 ton years
    - No periodicity with T=50-600 days ***PRD97 (2018) 102006***
  - Hidden photons/Axion-like particles DM:
    - Best constraint α'/α<6x10^{-26} or g_{Ae}<4x10^{-13} for 40-120 keV/c^2 ***Preliminary results***
  - ^{124}Xe 2ν double electron capture:
    - Most stringent lower limit $T_{1/2}^{2\nu 2K}(^{124}Xe)$>2.1x10^{22} years ***PTEP2018 (2018) 053D03***

Backup slides

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



- XMASS achieved low background rate of O(10^{-4}) dru in a few 10s keV including e/γ events

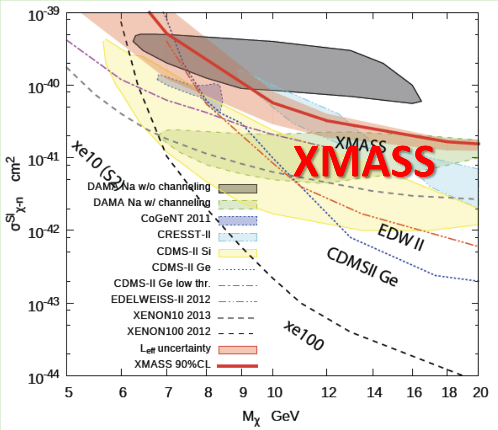
- Low background rate for e/γ events is good for searching for dark matter other than WIMPs.

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

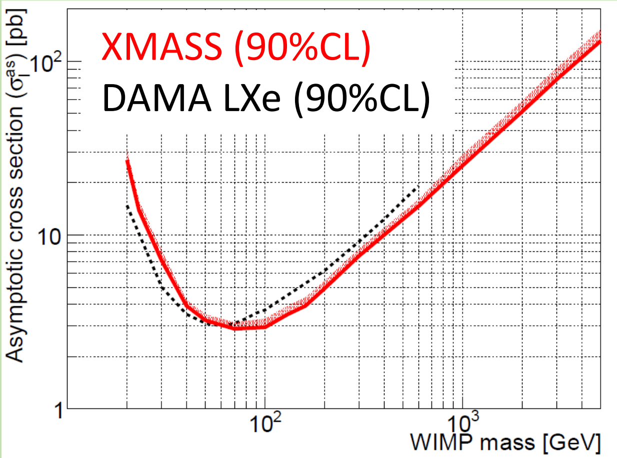
Diversity of physics target with XMASS

Dark matter searches

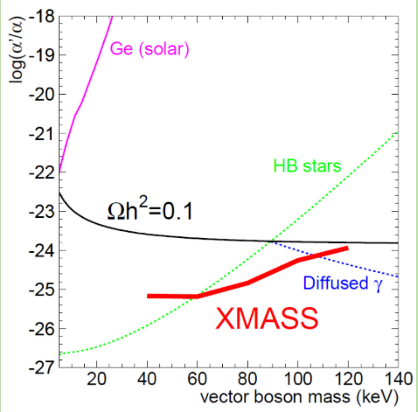
Low mass WIMP search
Phys. Lett. B719 (2013) 78



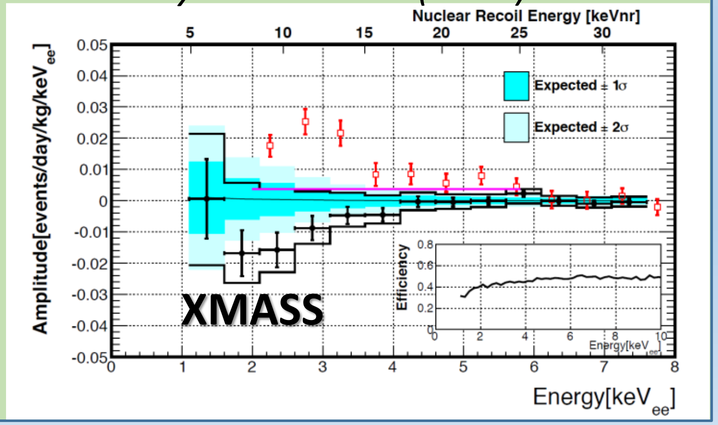
WIMP-^{129}Xe inelastic scattering
PTEP (2014) 063C01



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

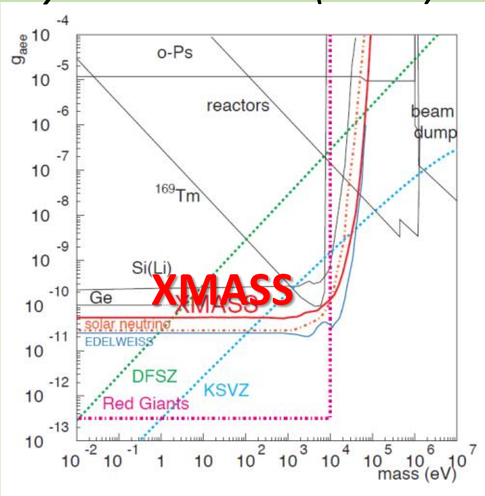


Annual modulation search
Phys. Lett. B759 (2016) 272



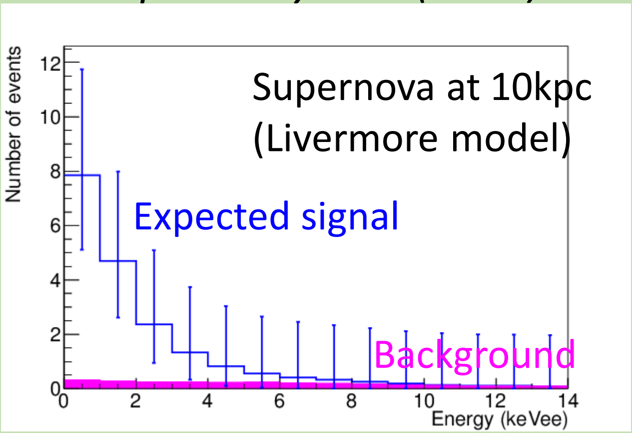
Solar axion search

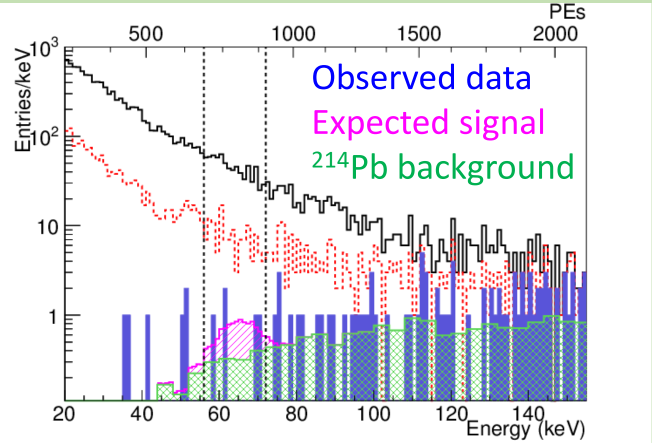
Phys. Lett. B724 (2013) 46



Possibility of supernova neutrino detection

Astropart. Phys. 89 (2017) 51

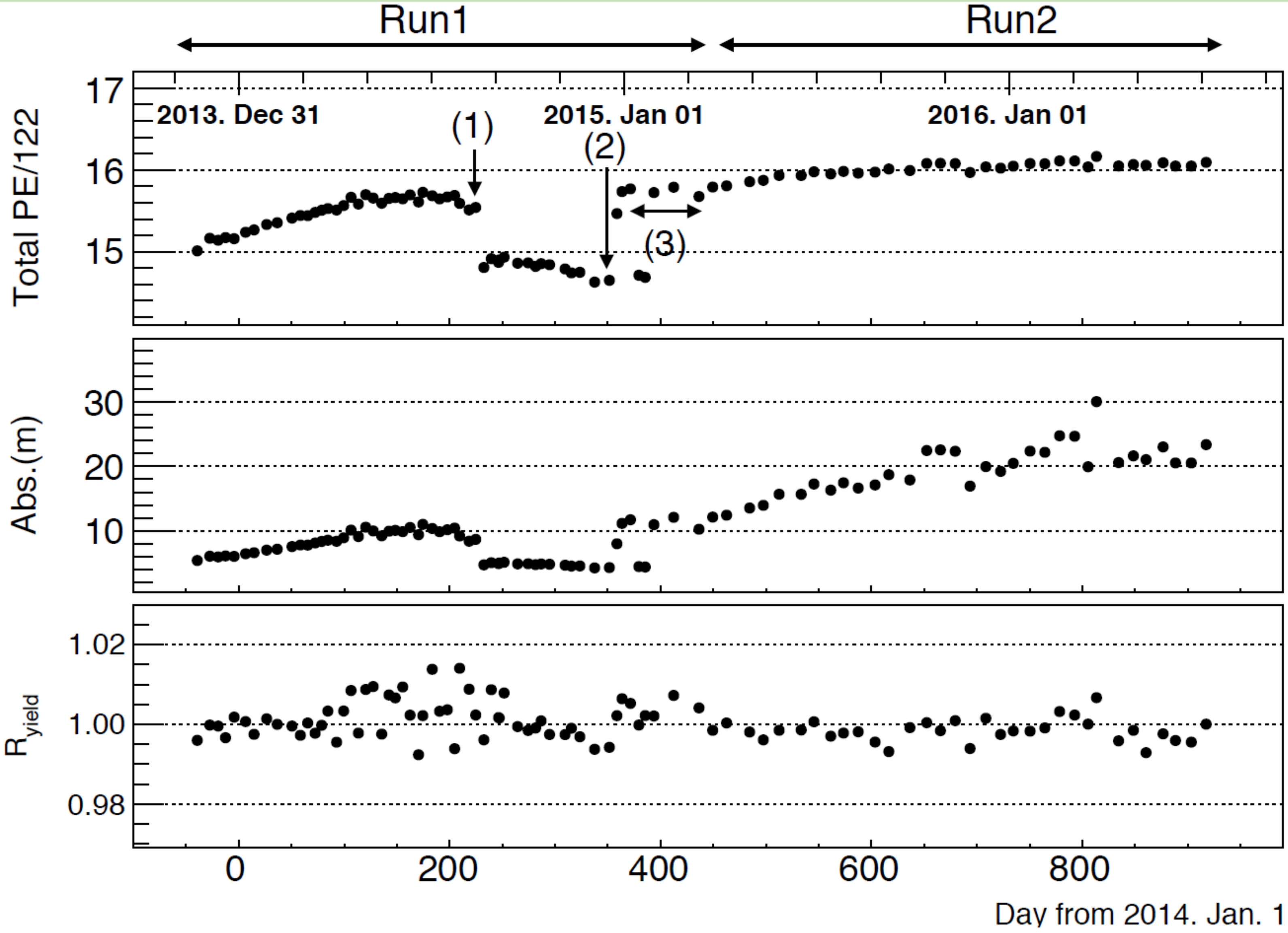




Phys. Lett. B759 (2016) 64

2) Annual modulation search

Detector stability

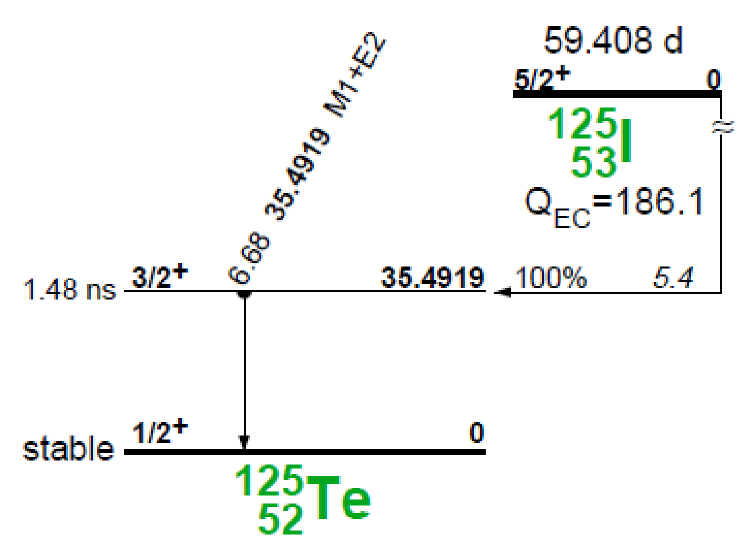


(1) Power cut
(2) Switched to other refrigerator
(3) Purification work

- 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)

4) ^{124}Xe 2ν double electron capture
^{125}I background

- ^{125}I is created by thermal neutron capture on ^{124}Xe
  - ☐ $^{124}Xe(n, \gamma)^{125}Xe$ (σ=137 barn)
  - ☐ $^{124}Xe(n, \gamma)^{125m}Xe$ (σ=28 barn)
  - ☐ $^{125m}Xe \rightarrow {}^{125}Xe$ (IT , $T_{1/2}$=57 sec)
  - ☐ $^{125}Xe \rightarrow {}^{125}I$ (β^+/EC, $T_{1/2}$=16.9 hours)
- Thermal neutron flux in the Kamioka mine (0.8-1.4)x10^{-5} /cm^2/s
- Xenon gas volume outside the water shield 2.6x10^5 cm^3 (STP)



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