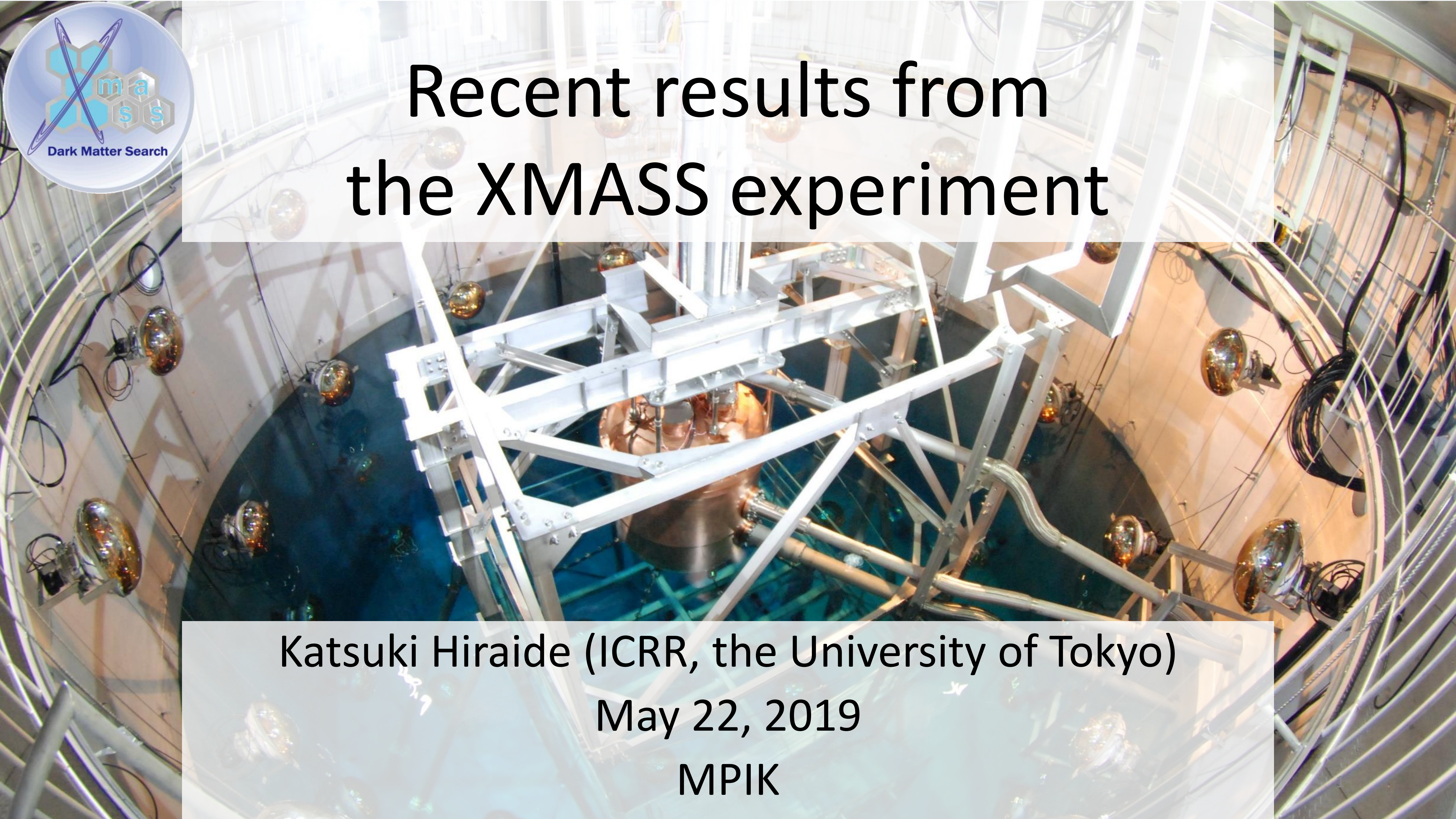

Recent results from the XMASS experiment

Katsuki Hiraide (ICRR, the University of Tokyo)

May 22, 2019

MPIK

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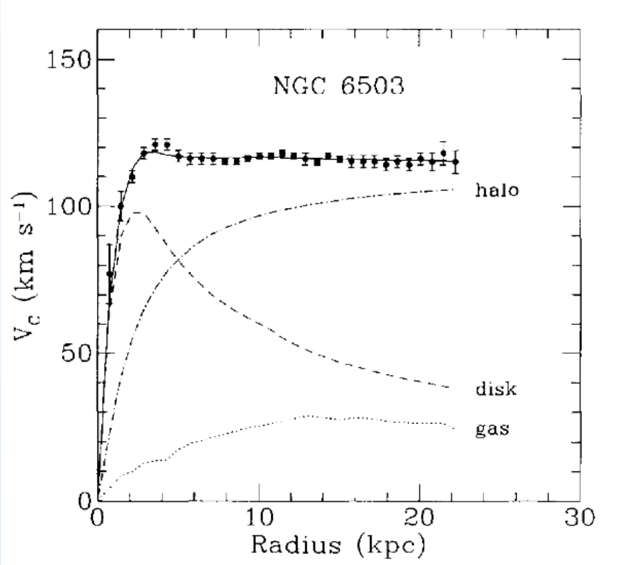
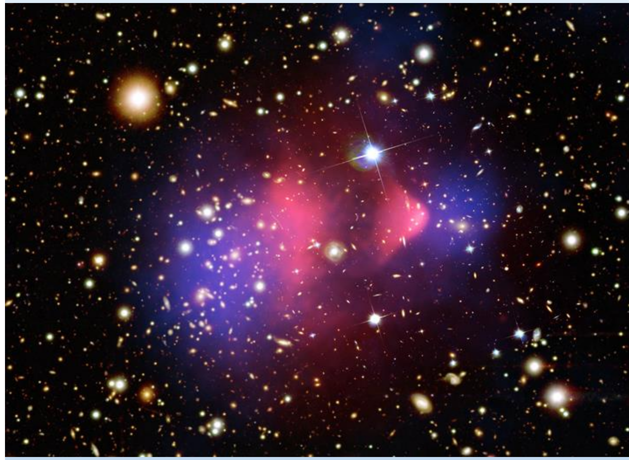
- Introduction
  - Direct dark matter search
  - XMASS experiment
- Recent dark matter search results from XMASS
  - Search for standard (O(100)GeV/c^2) WIMPs
  - Search for annual modulation
  - Search for sub-GeV dark matter
  - Search for hidden photons/axion-like particles
- Diversity of physics targets with XMASS
  - Search for 2ν double electron capture on ^{124}Xe
- Summary

Introduction

Dark matter

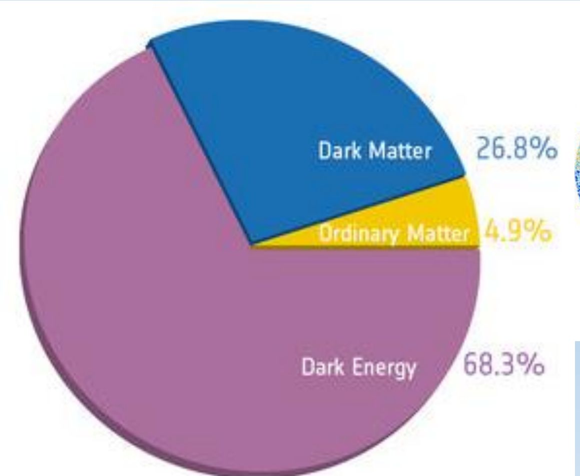
- There are substantial astronomical observation which support the existence of dark matter in the universe.
    - Rotation curve of galaxies
    - Bullet clusters
    - Gravitational lensing
    - Cosmic microwave background
    - etc

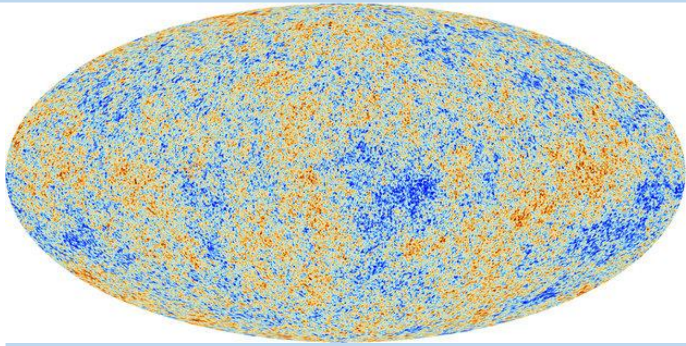




- However, its identity is still unknown.

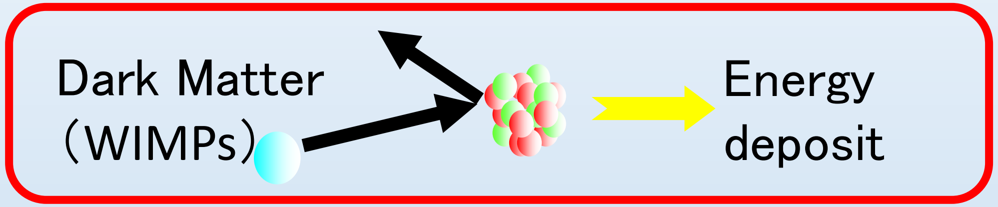
- The most plausible candidate is Weekly Interacting Massive Particles (WIMPs).

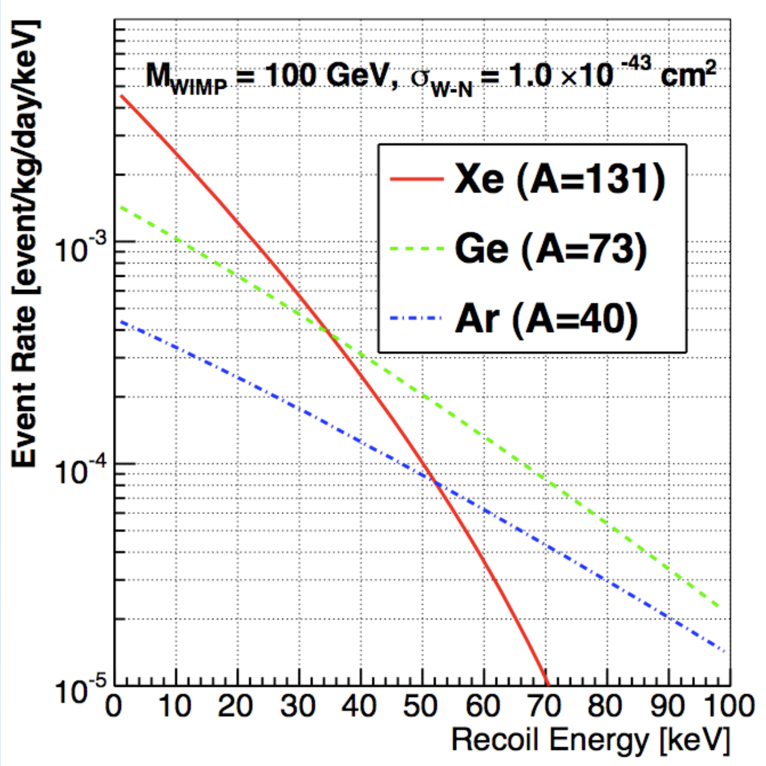


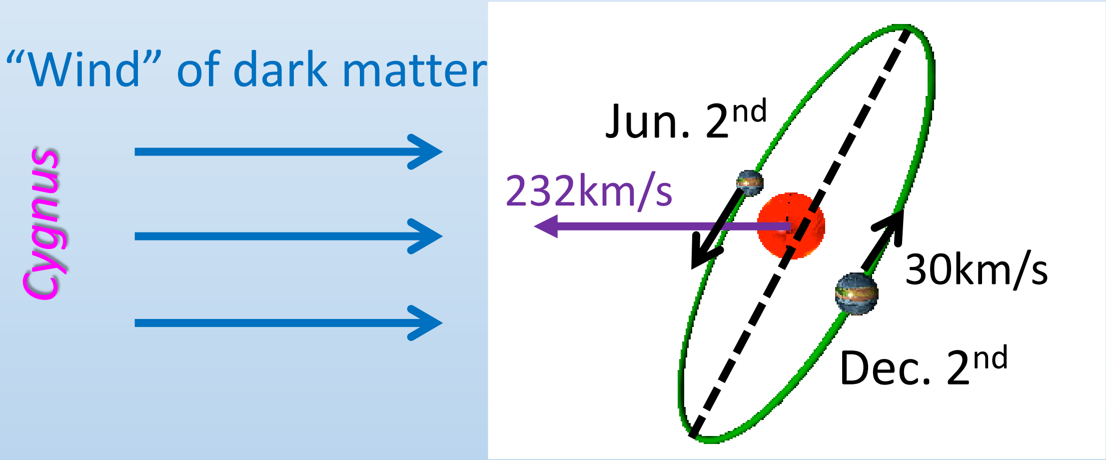


Strategy of direct dark matter searches

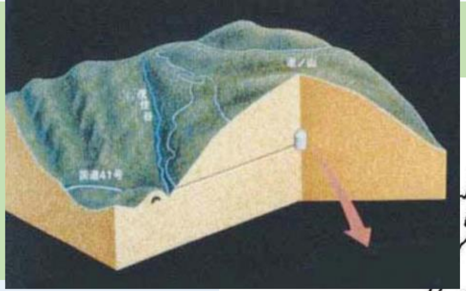
- Look for scattering of dark matter and detector material
  - Energy spectrum (or number of events)
  - Annual modulation of event rate
  - Direction of dark matter "wind"

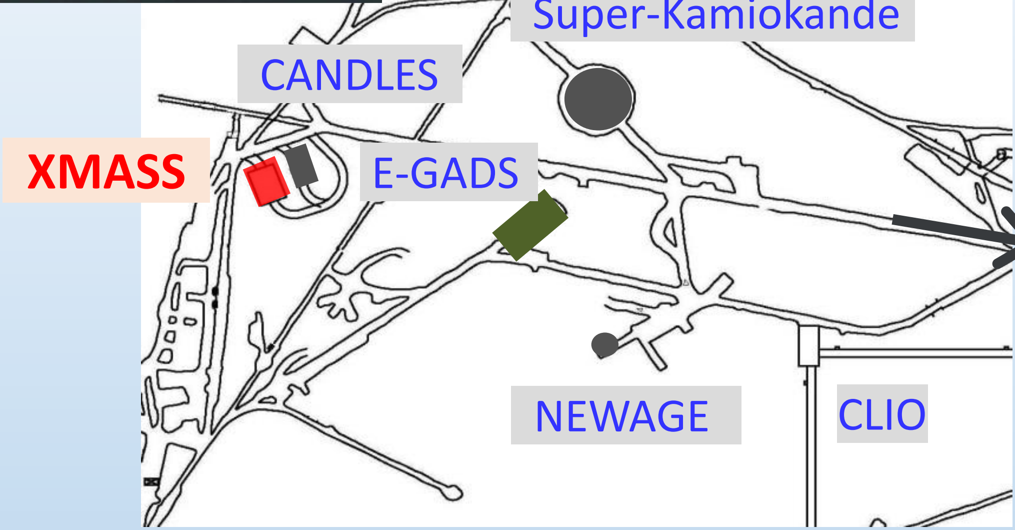




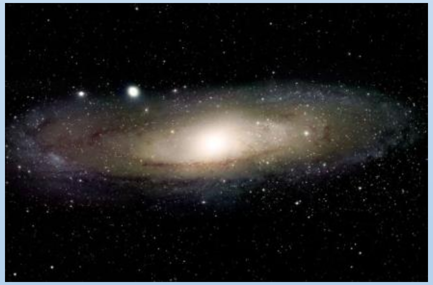


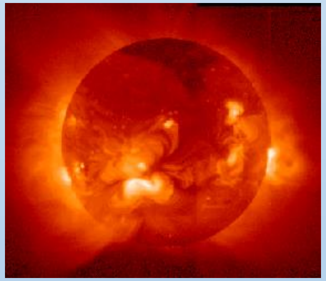
The XMASS project

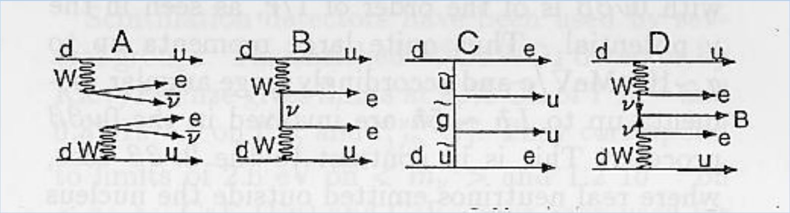




- XMASS: a multi purpose experiment with liquid xenon
- Located 1,000 m underground (2,700 m.w.e.) at the Kamioka Observatory in Japan
- Aiming for
  - Direct detection of dark matter
  - Observation of low energy solar neutrinos (*pp*/^{7}Be)
  - Search for neutrino-less double beta decay
- Features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

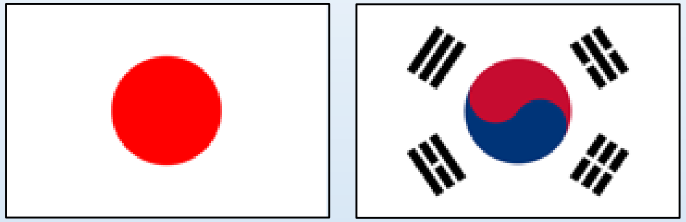






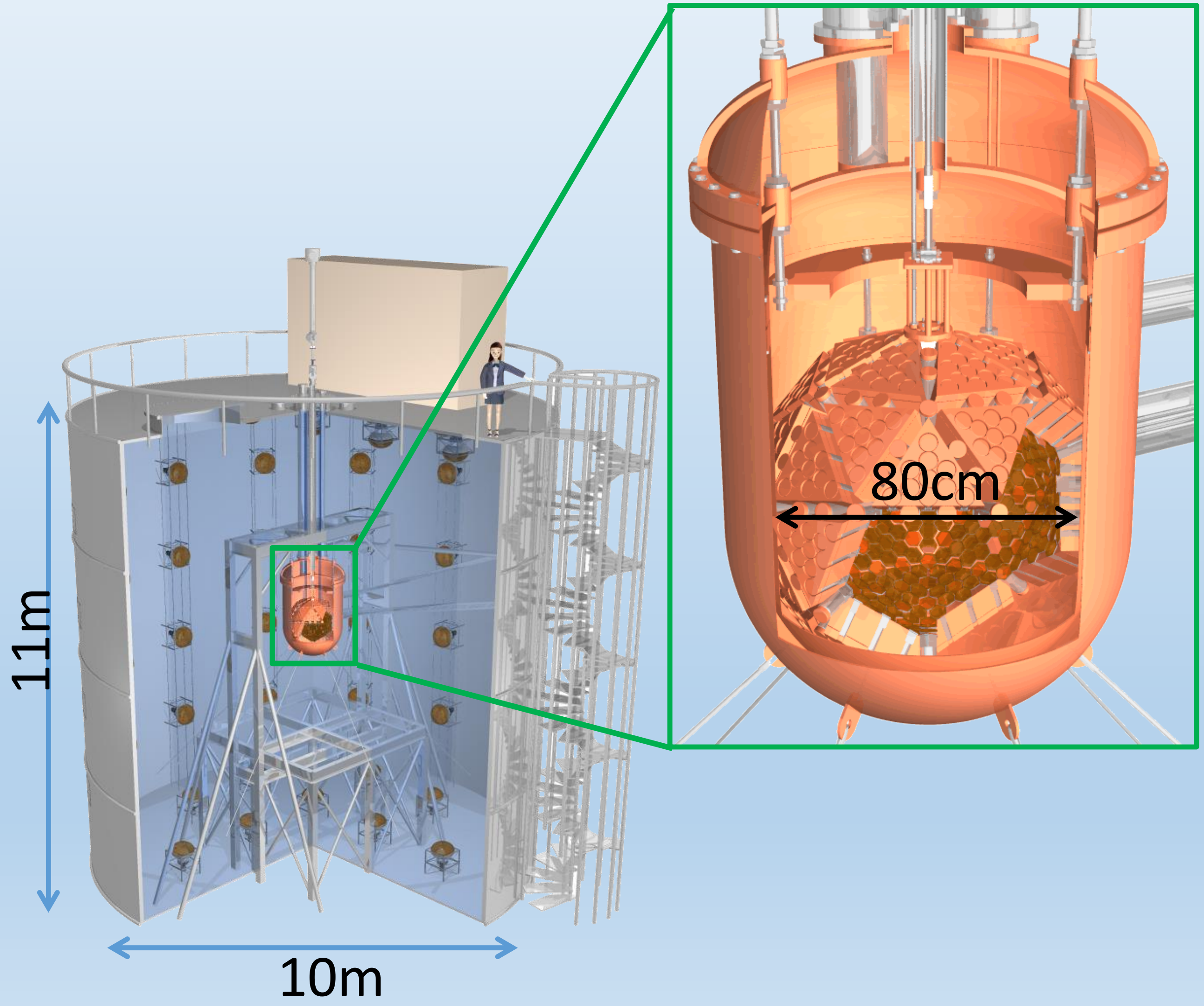
XMASS Collaboration

- 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



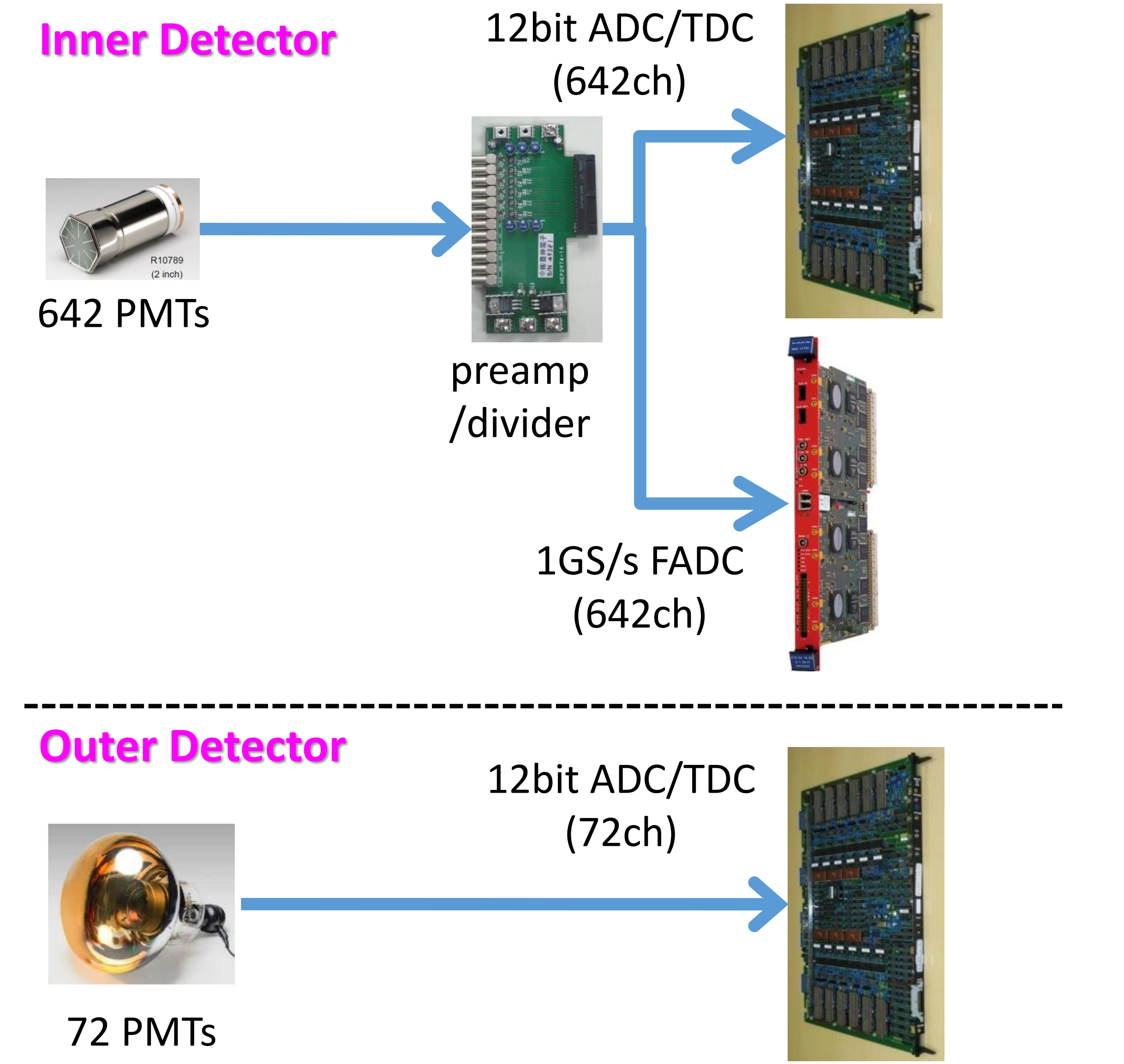
~40 physicists
from 11 institutes

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

Readout electronics/DAQ



- ADC/TDC (ATM)
  - 642ch (ID) + 72ch (OD)
  - 12 bit resolution
  - ADC dynamic range: 0-450pC
  - TDC dynamic range: 1.3 μsec
  - Readout through VME
- Flash-ADC (CAEN V1751)
  - 642ch
  - 10 bit resolution, $1V_{pp}$
  - Readout through optical links

Inner calibration system

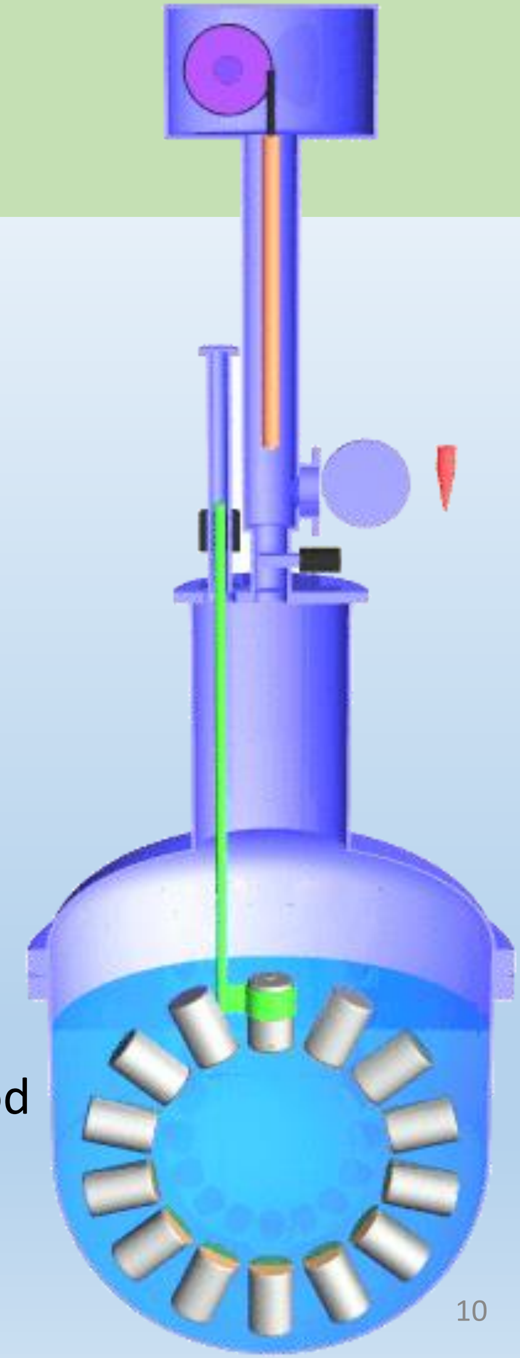
- Various RI sources can be inserted
- Used for light yield monitoring, optical parameter tuning, energy and timing calibrations etc.

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)

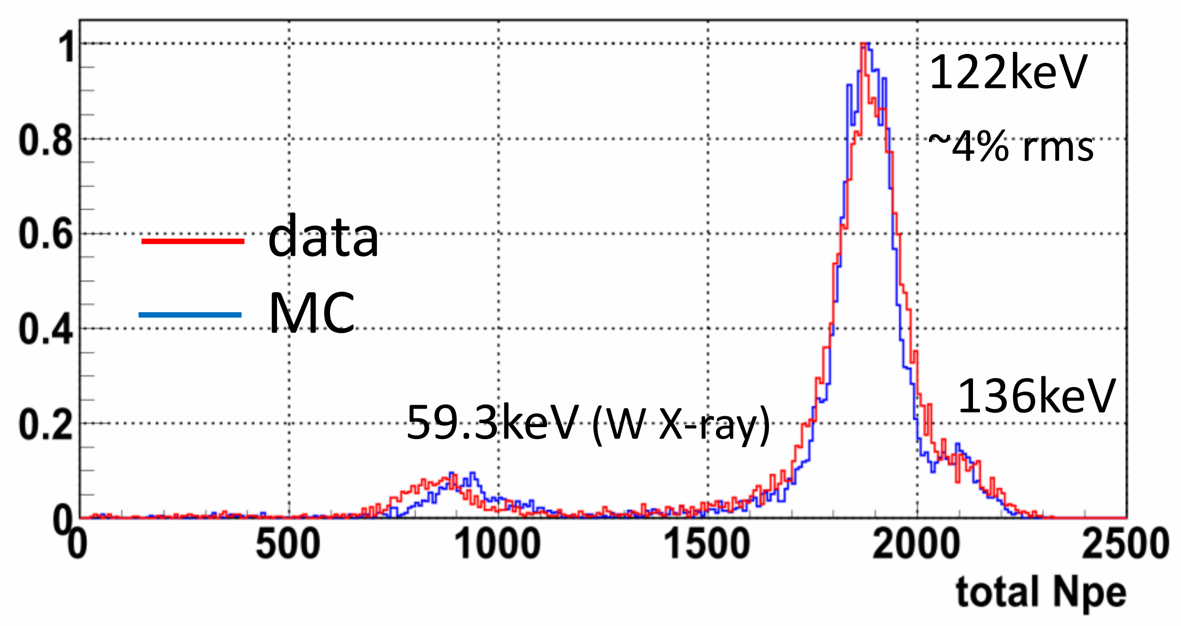
Active region is concentrated on the 1.8 mm edge region



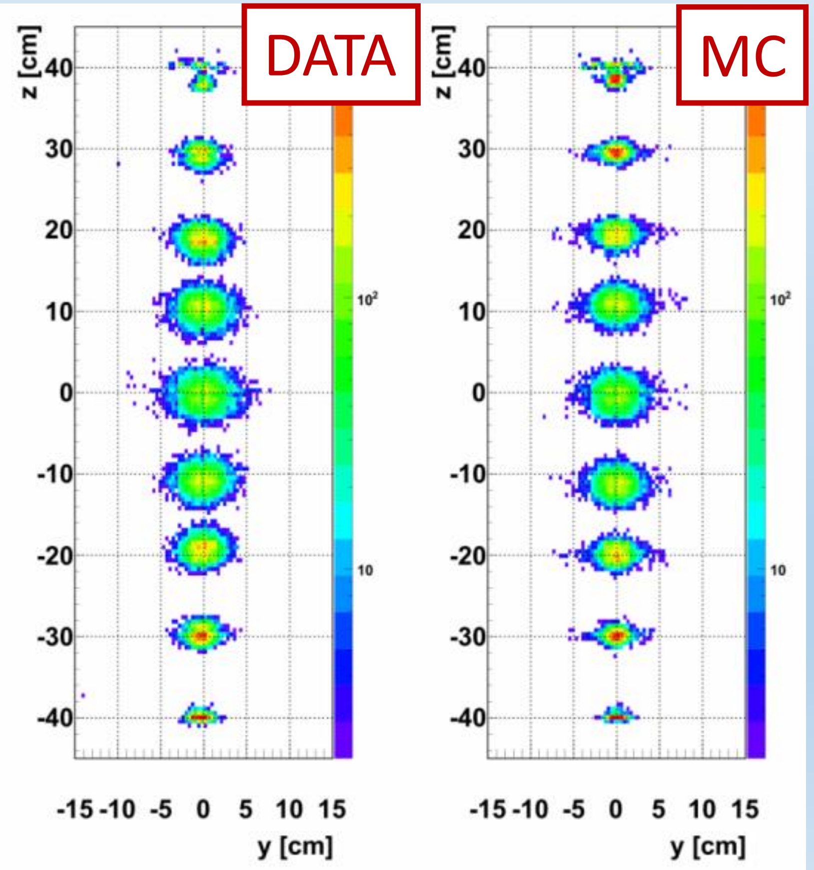
Detector response

- Photoelectron yield is monitored by the ^{57}Co source.
- The distributions are reproduced by simulation well.

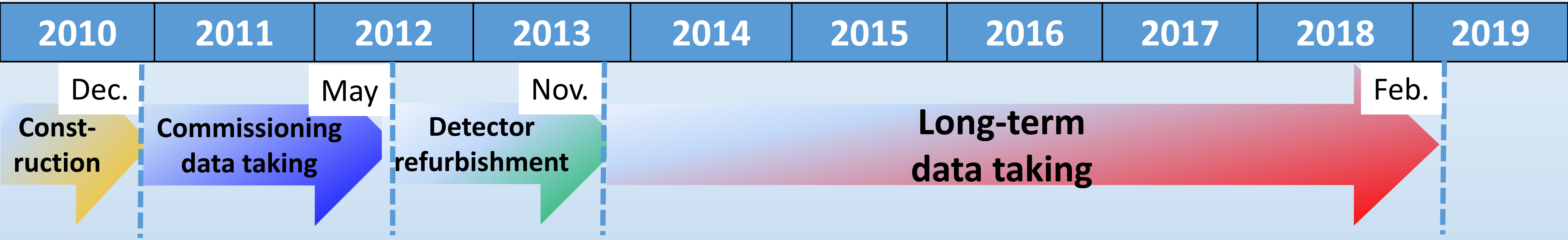
Total number of photoelectrons



Reconstructed vertex



History of XMASS-I data-taking



- Detector construction completed in Dec. 2010
- Commissioning data-taking in 2010-2012
  - Low mass WIMPs, solar axions, bosonic super-WIMPs, etc.
- Detector refurbishment in 2012-2013
- Long-term data-taking in 2013-2019
  - Annual modulation, standard WIMPs, etc.
  - >5 years of data
- Data analyses are still ongoing.

Recent dark matter search results from XMASS

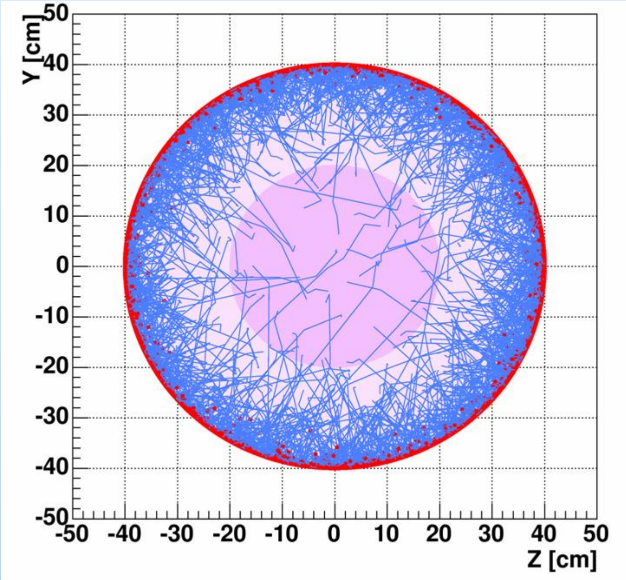
1) WIMP dark matter search by fiducialization

Introduction

^{57}Co 122keV

Reconstructed vertex

Traces of γ-rays from PMTs



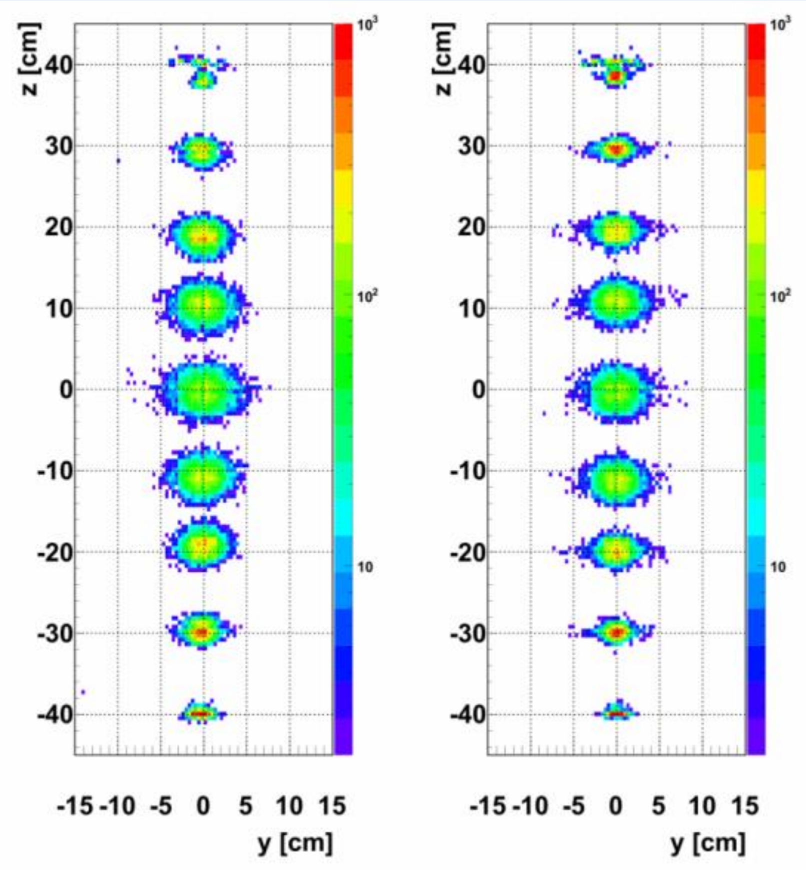
Fiducial volume
R<20cm

- 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

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

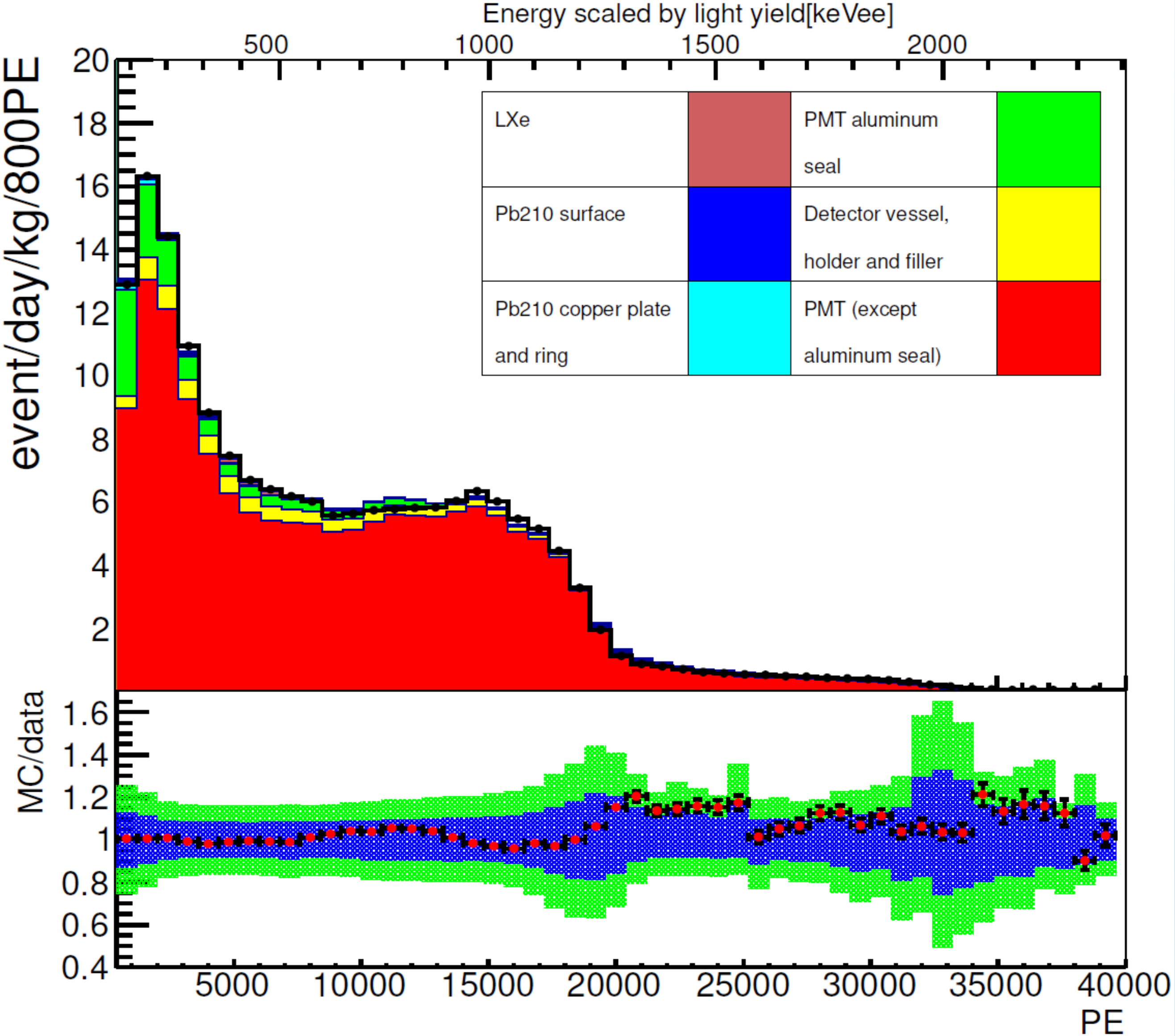
P_i (n) : probability that the i-th PMT detects n PE

DATA MC



1) WIMP dark matter search by fiducialization

Background spectrum in the whole 832kg volume



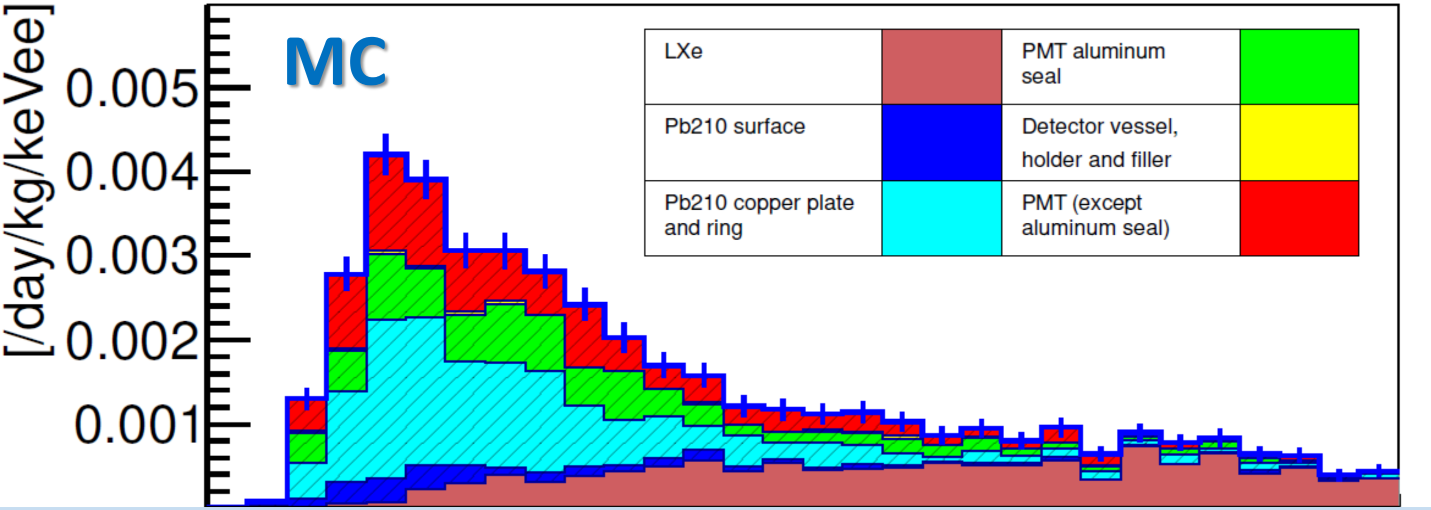
- All the detector material (except for copper and LXe) was screened by the Ge detector before installation.
- Then, the energy spectrum above 30 keV was fitted under these constraints.

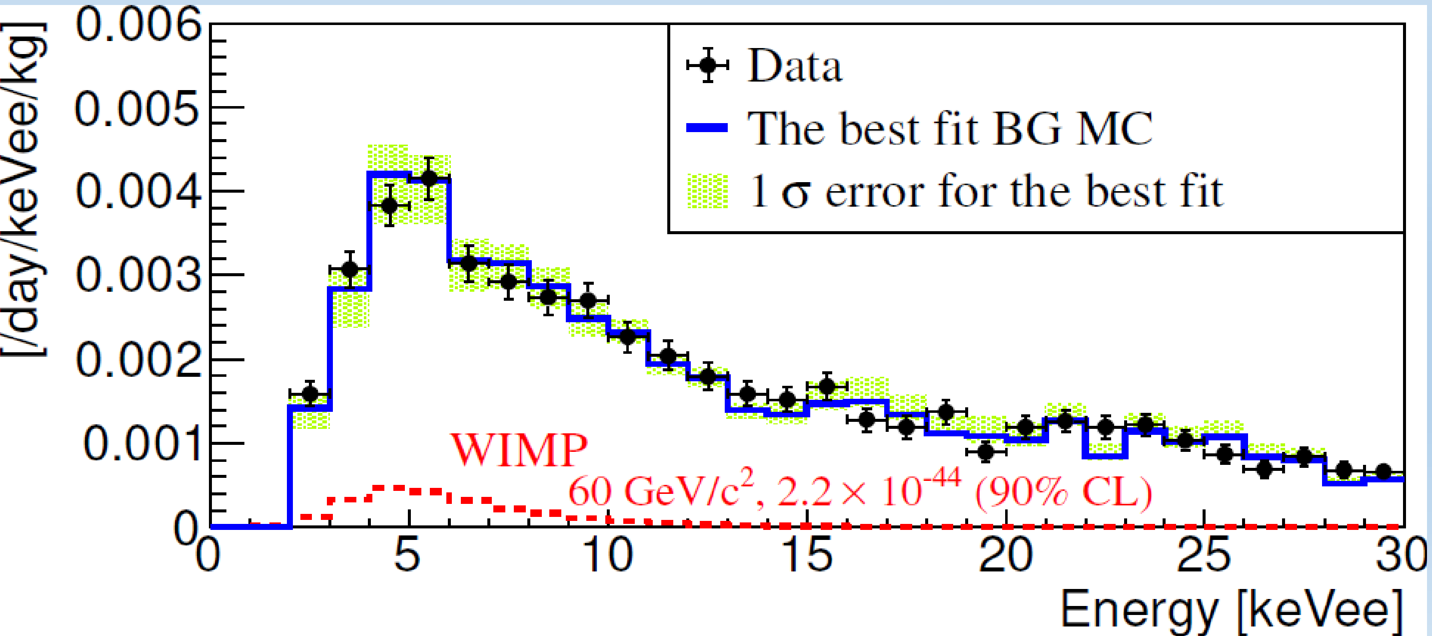
- α-rays are selected using scintillation decay time to constrain PMT/copper surface/bulk ^{210}Pb.
  - Contamination of ^{210}Pb (~20 mBq/kg) in the bulk of the copper was identified by a low-BG alpha-particle counter

- 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)

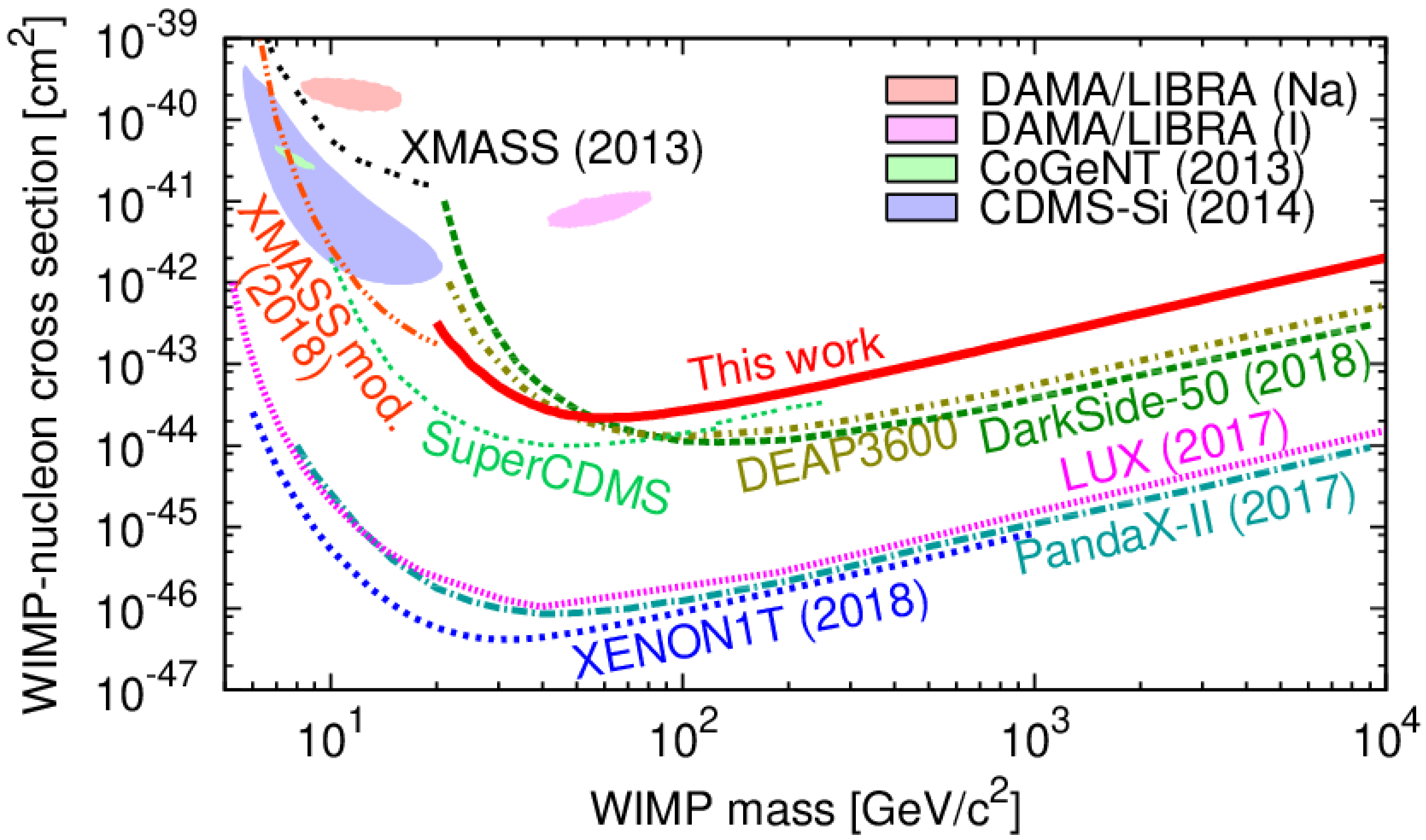
- Main background in the WIMP search region
  - ^{210}Pb in the copper bulk
  - γ-rays from PMTs
  - Neutrons, alpha-rays are negligible

- The energy spectrum at 2-15 keVee is fitted with signal + 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.
  - $\sigma_{SI} < 2.2 \times 10^{-44}$ cm^2 (60 GeV/c^2)
- First stringent constraint by a single-phase LXe detector
- Published in Phys. Lett. B789 (2019) 45.

2) WIMP-^{129}Xe inelastic scattering

Introduction

- Inelastic scattering of WIMP-^{129}Xe with nuclear excitation
  - $\chi + {}^{129}Xe \rightarrow \chi + {}^{129}Xe^*$
    $\quad {}^{129}Xe^* \rightarrow {}^{129}Xe + \gamma$ (39.6keV)
  - Nuclear recoil + 39.6 keV γ-ray
  - Natural abundance of ^{129}Xe: 26.4% (2nd 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
  - 1st 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

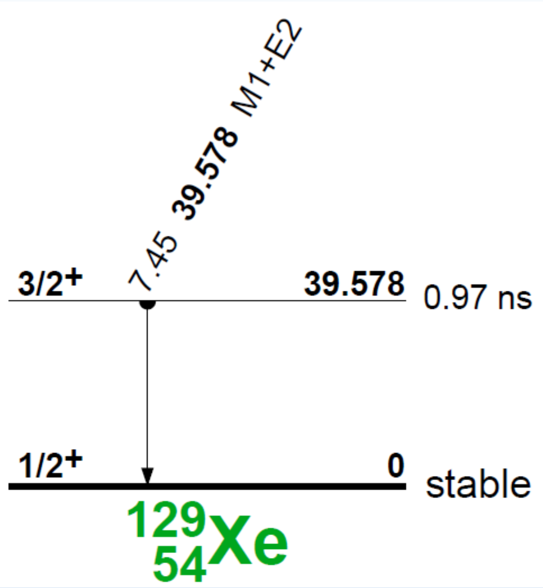
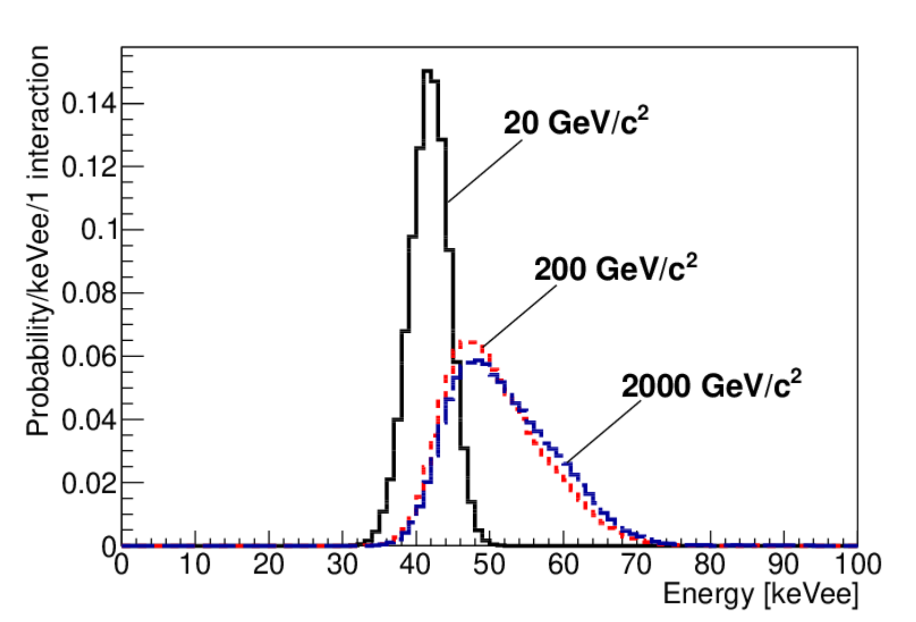
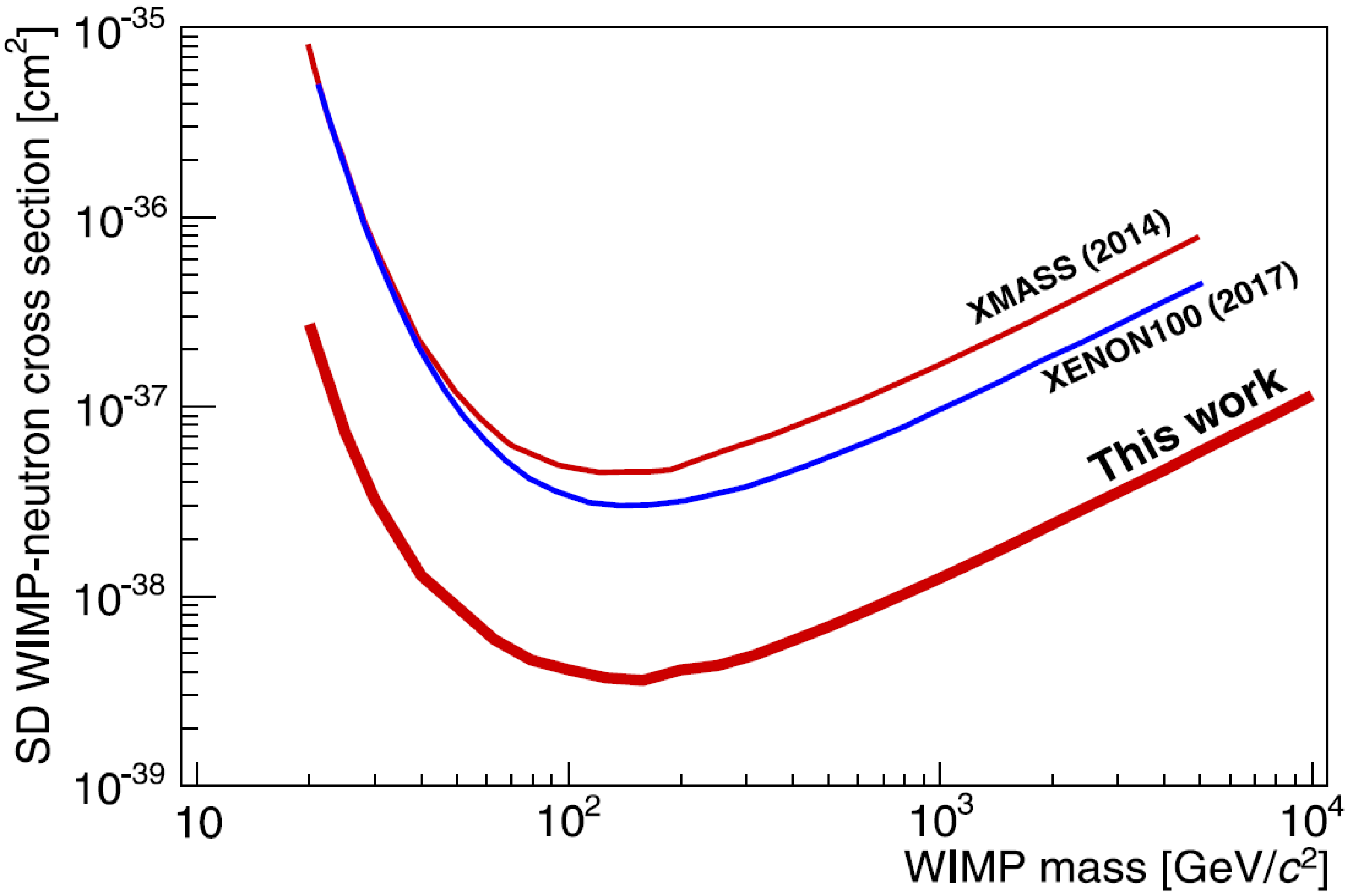


Fig. taken from Table of isotopes

Simulated energy spectra (area normalized)

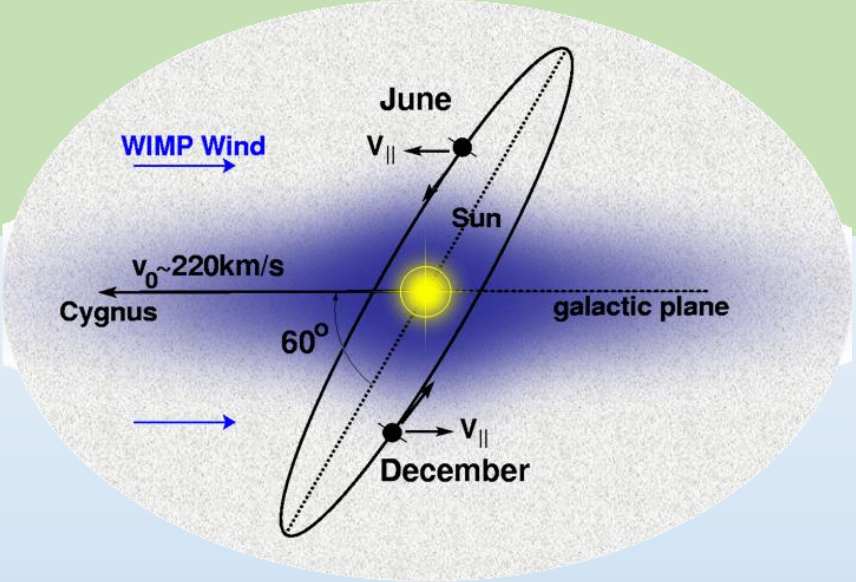


2) WIMP-^{129}Xe inelastic scattering
Results

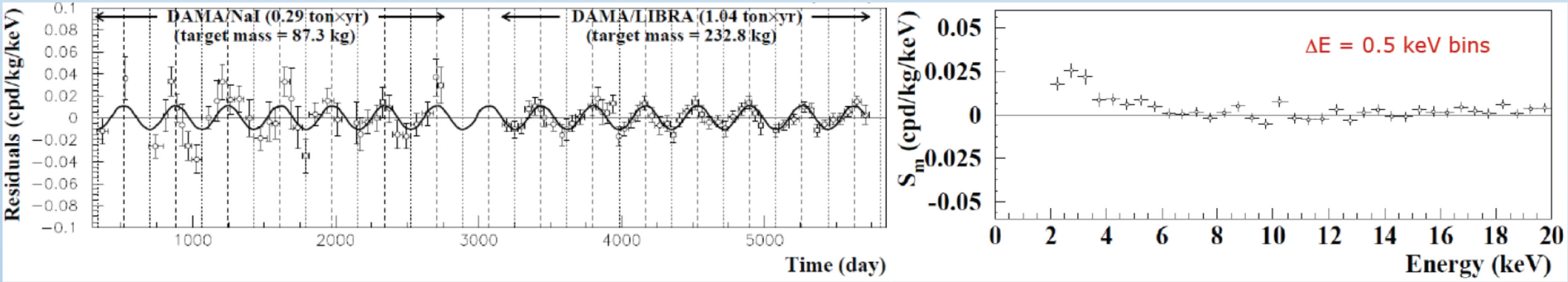


- 800 days x 327 kg exposure
- No significant signal was observed.
- Hence, 90% CL limit on the SD WIMP-neutron cross section was set.
  - $\sigma<4.1\times10^{-39}$ cm^2 for 200 GeV/c^2
- The most stringent limit among searches in the SD inelastic channel
- Published in Astropart. Phys. 110 (2019) 1.

3) Annual modulation search
Introduction



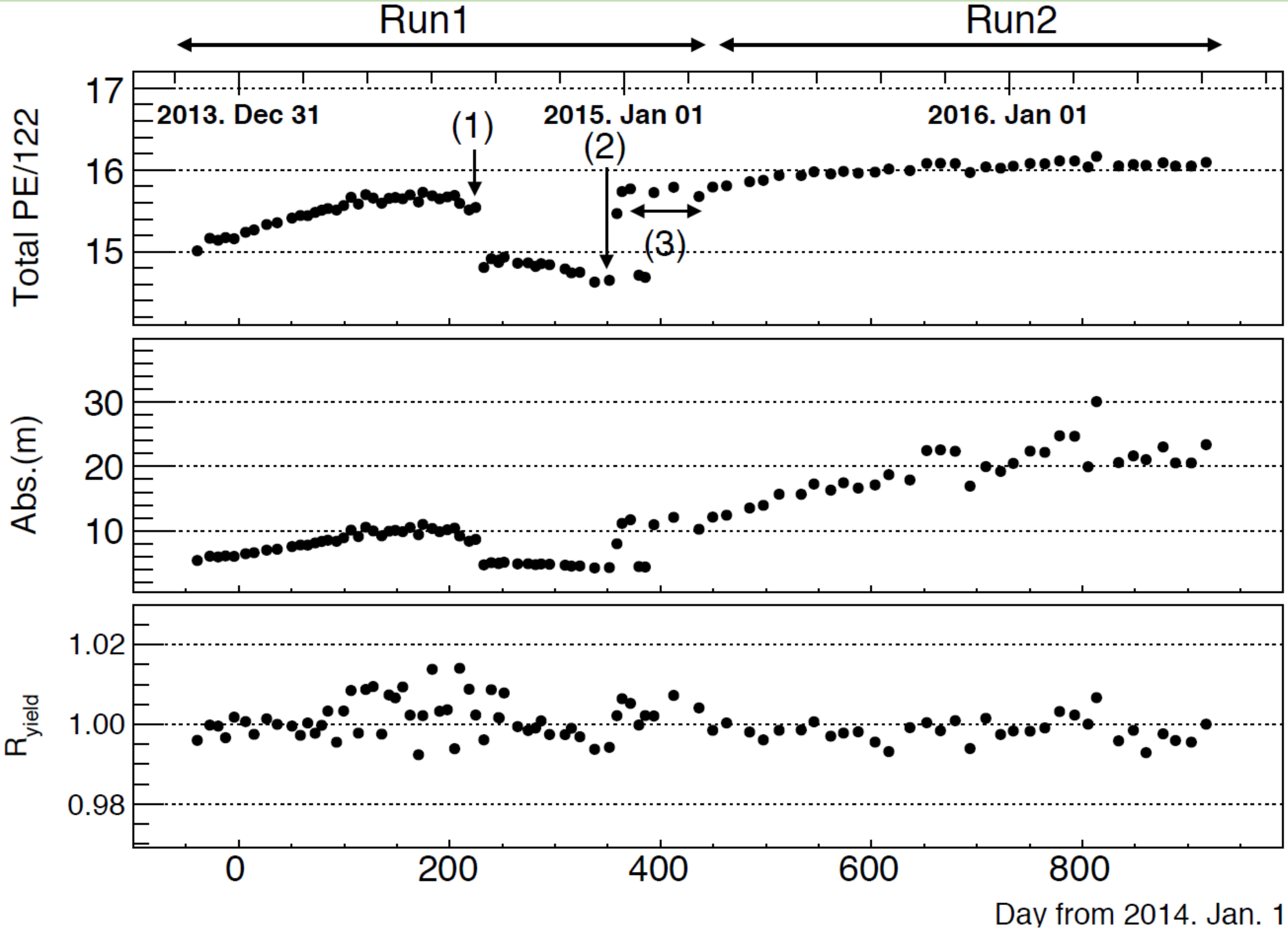
- Expect annual modulation of event rate of dark matter signal due to Earth's rotation around the Sun.
- DAMA/LIBRA claims modulation at 9.3σ
  - ➢ Total exposure of 1.33 ton year (14 cycles)
  - ➢ Modulation amplitude of (0.0112+/-0.0012) cpd/kg/keV for 2-6 keV



- 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

3) Annual modulation search

Detector stability

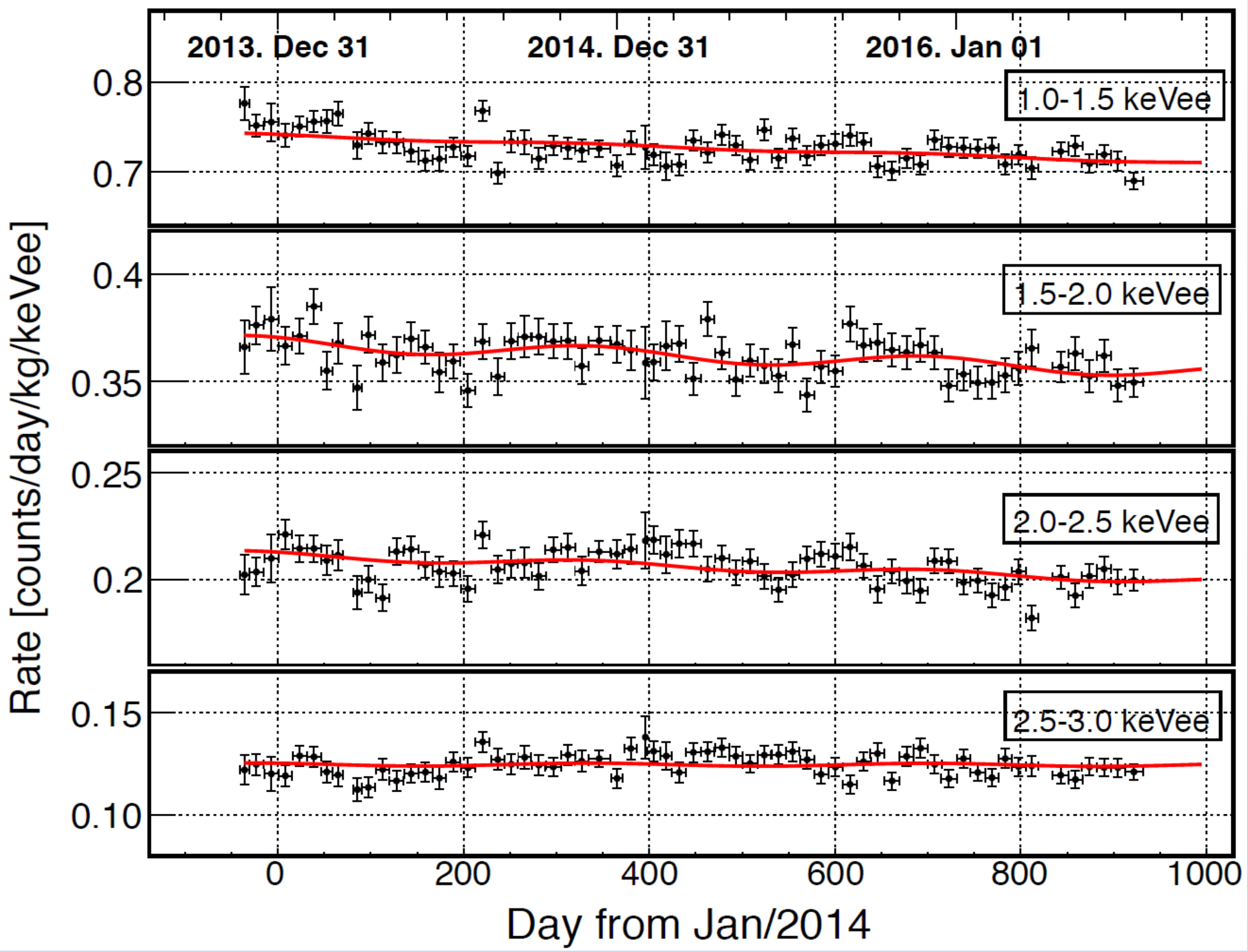


(1) Power cut
(2) Switched to other refrigerator
(3) Purification work

- 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)

3) Annual modulation search

Results: time variation of event rate



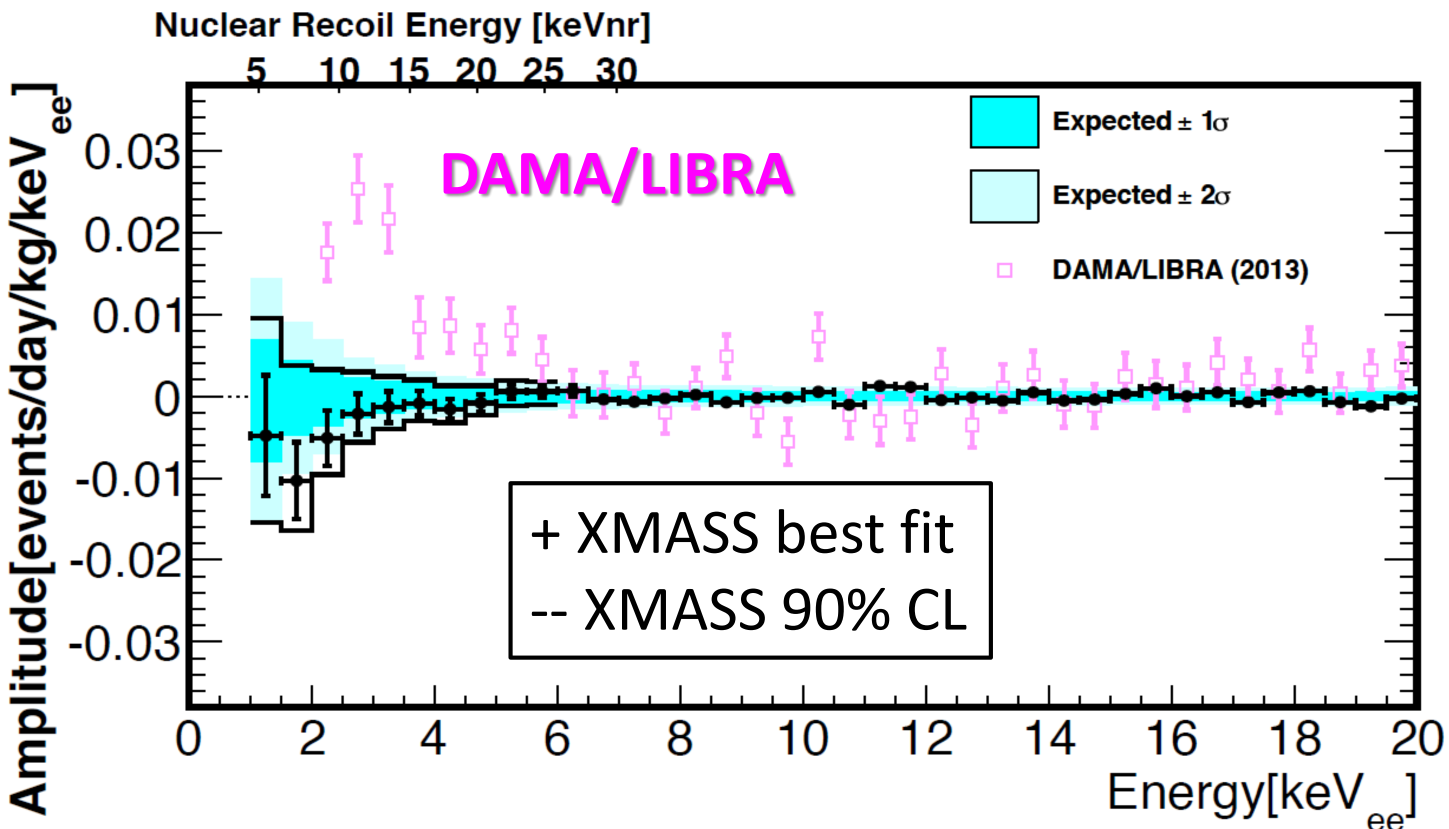
$$R^{ex}_{i,j} = \int_{t_j - \frac{1}{2}\Delta t_j}^{t_j + \frac{1}{2}\Delta t_j} \left(\epsilon^s_{i,j} A^s_i \cos 2\pi \frac{(t-\phi)}{T} + \epsilon^b_{i,j}(\alpha)(B^b_i t + C^b_i) \right) dt$$

- 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

3) 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.

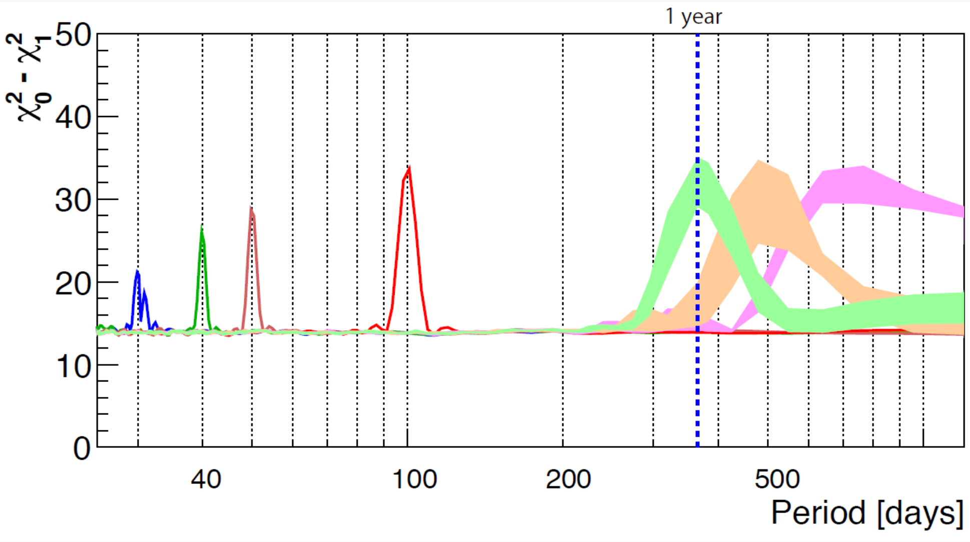
Experiment	Amplitude (/day/kg/keVee)
DAMA/LIBRA	~20x10^{-3} (2-3.5 keV_{ee})
XENON100	(1.67+/-0.73)x10^{-3} (2-5.8 keV_{ee})
XMASS	<(1.3-3.2)x10^{-3} (2-6 keV_{ee})



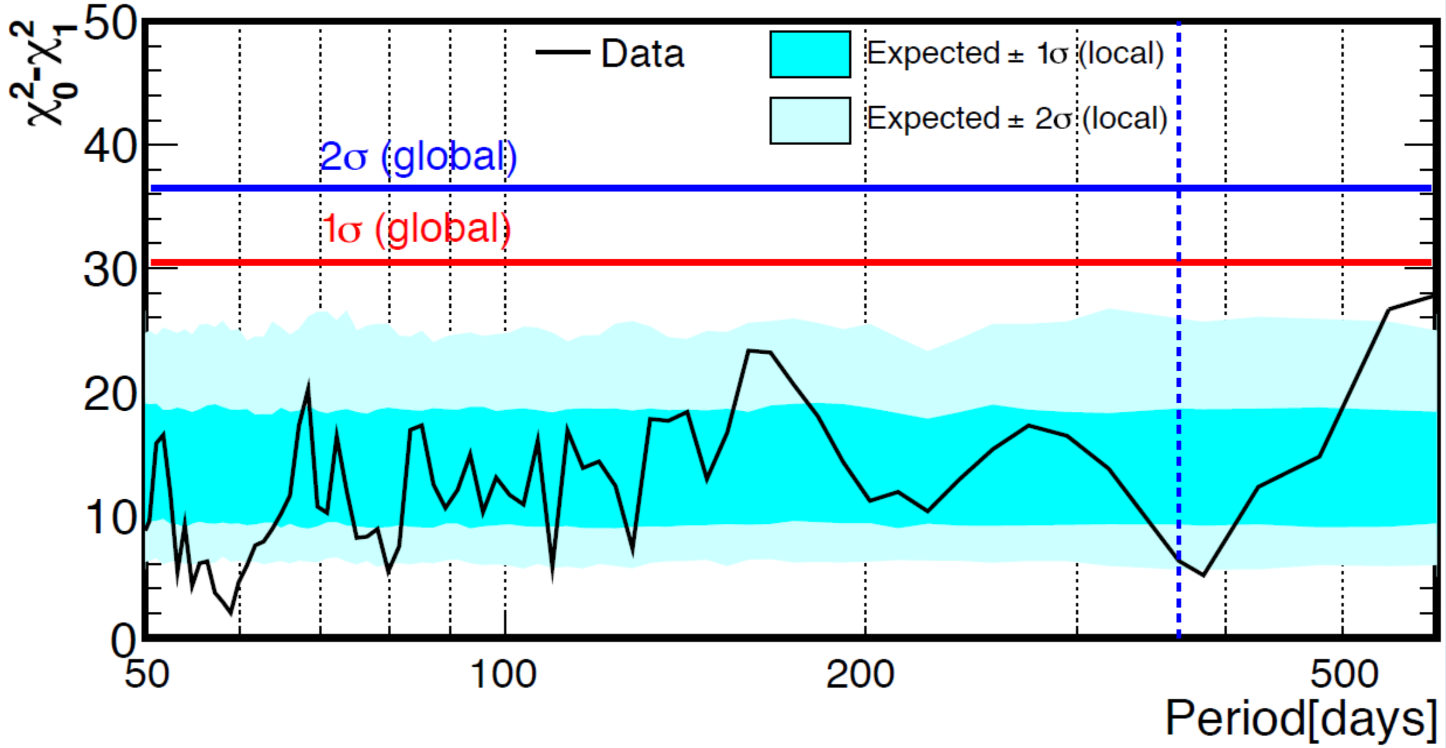
- 1-20 keVee energy range
- Null hypothesis: p-value=0.11 (1.6σ)
  - Less significant than the previous result (2.5σ)
- Most stringent constraints on modulation amplitudes.

3) 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.

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 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)

Focused in this work

- XMASS searches for annual modulation of such signals

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

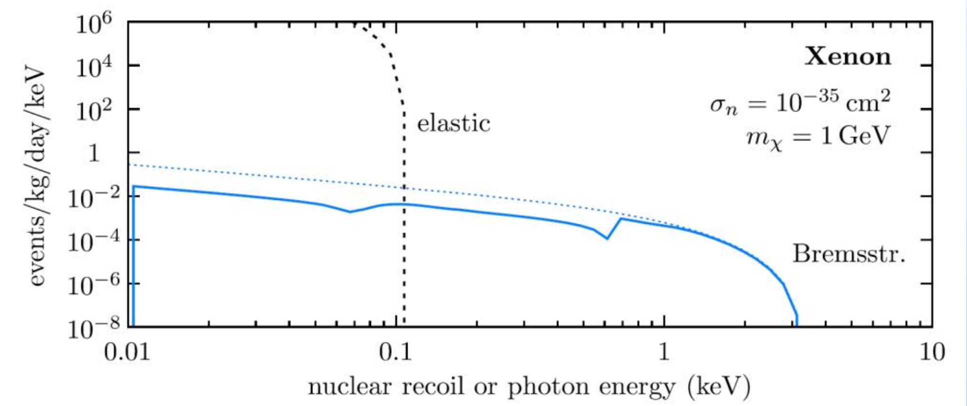
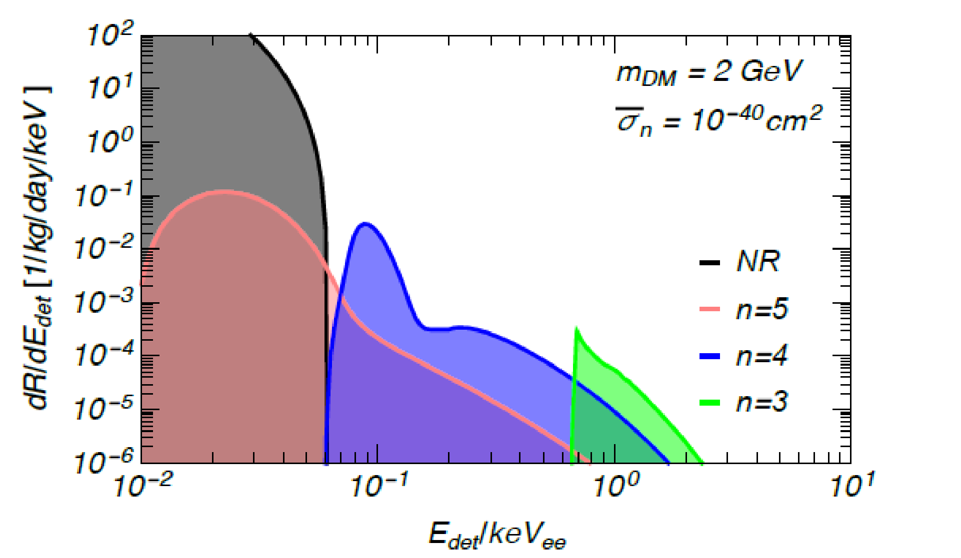


Fig. from M. Ibe et al., JHEP03, 194 (2018)



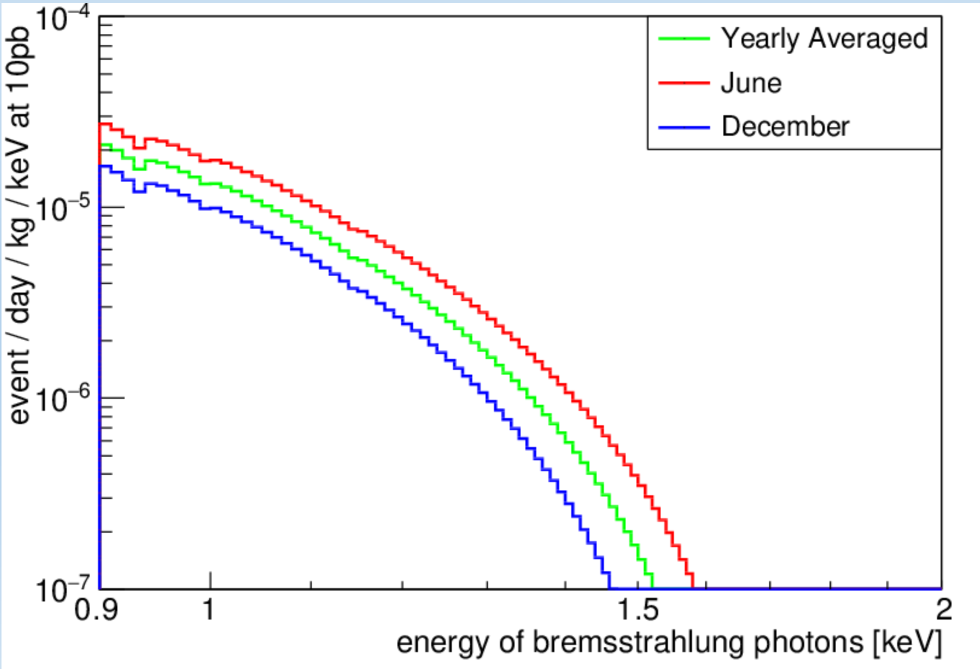
4) sub-GeV and multi-GeV DM search by annual modulation

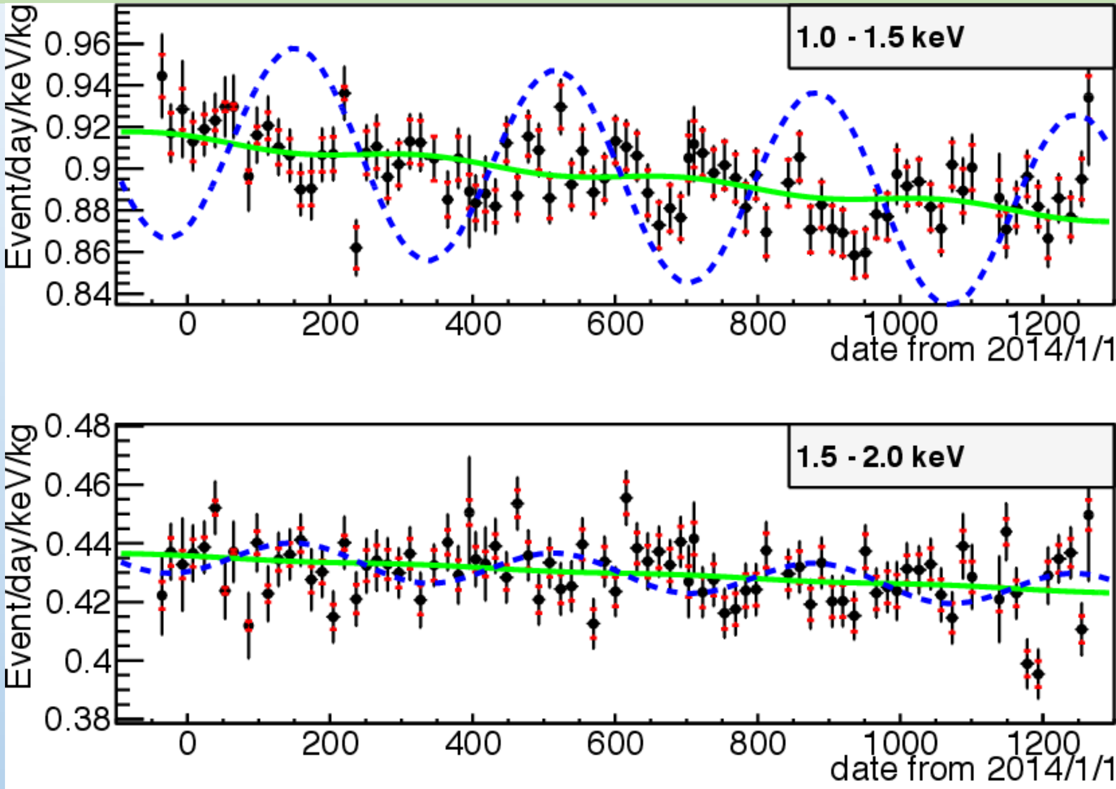
Annual modulation search

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

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

Simulated time variation of energy spectrum

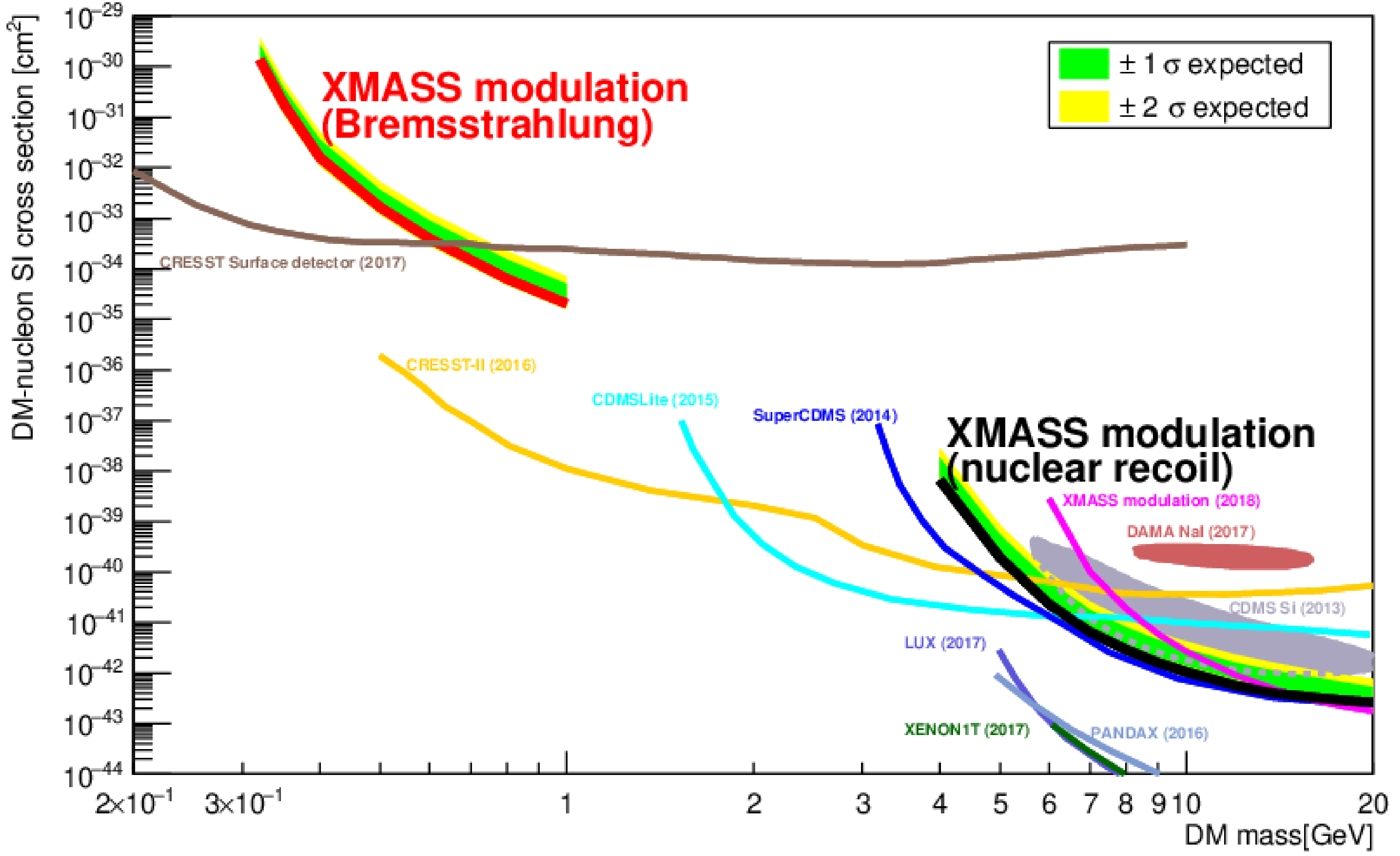




+ Data
-- Best-fit time variation
-- Expected time variation (σ=3x10^{-32} cm^2)

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

Results



- Sub-GeV (0.32-1 GeV/c^2)
  - The first experimental result focused on brems. photon emission and searched by annual modulation
  - $\sigma<1.6\times10^{-39}$ cm^2 (for 0.5 GeV/c^2)
- Multi-GeV (4-20 GeV/c^2)
  - Elastic nuclear recoil searched by modulation
  - $\sigma<2.9\times10^{-42}$ cm^2 (for 8 GeV/c^2)
- arXiv:1808.06177

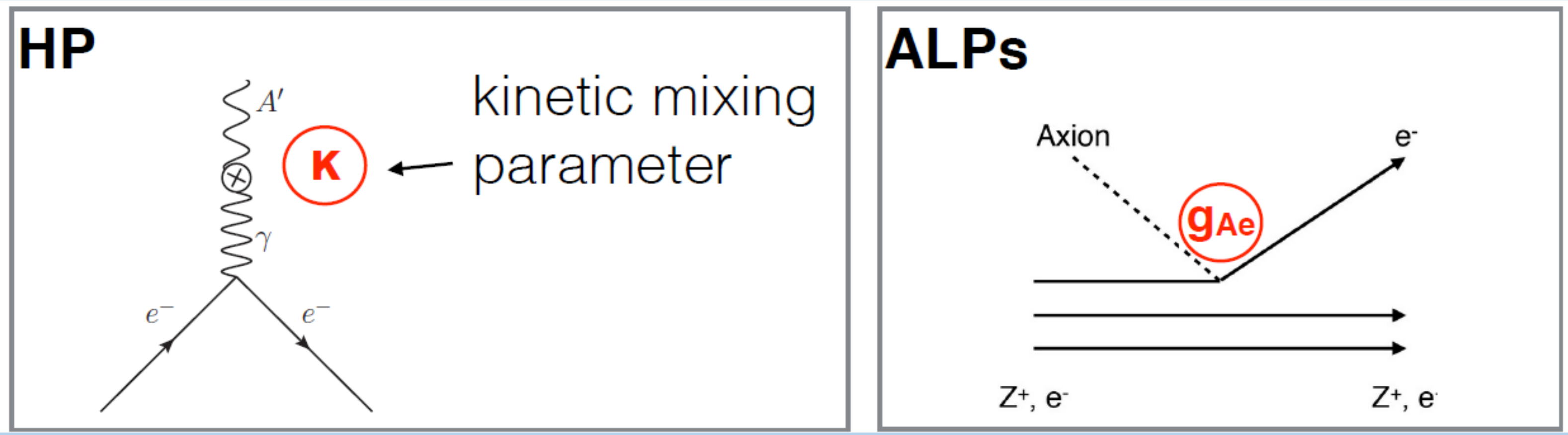
5) Hidden photons & axion-like particles dark matter

Introduction

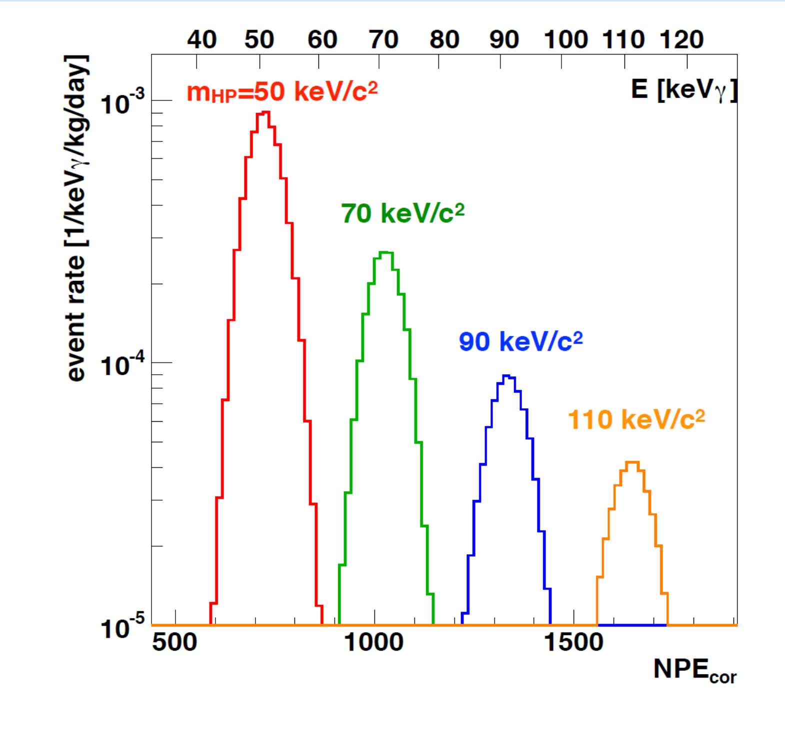
- Hidden photon (HP): gauge boson of hidden U(1)
  Axion-like particles (ALPs): pseudo-Nambu-Goldstone boson

Cold dark matter candidates

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



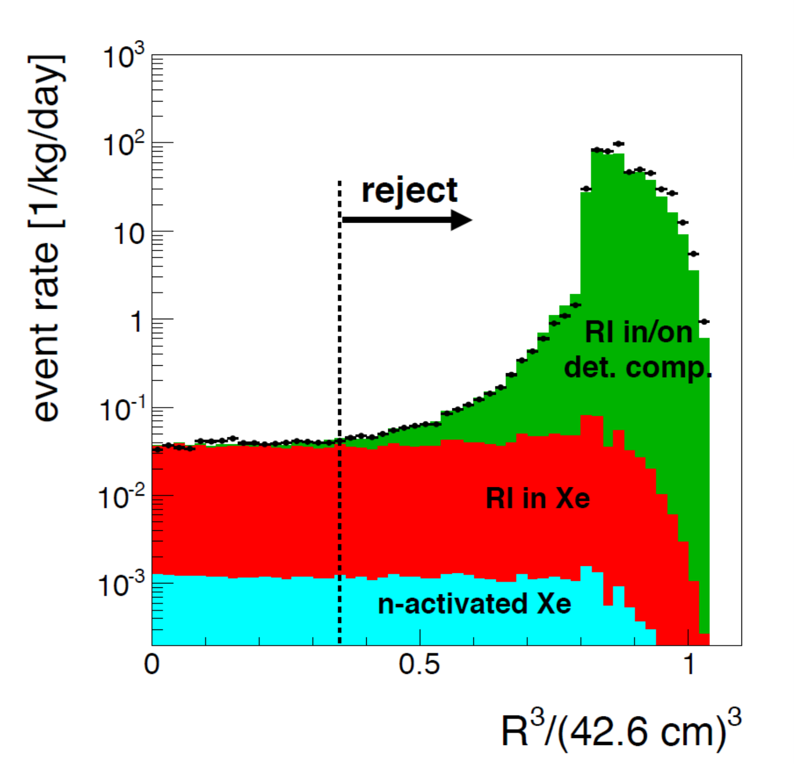
$$\frac{\sigma_{abs} v}{\sigma_{pe}(\omega = m_{HP})c} = \frac{\alpha'}{\alpha} \qquad \frac{\sigma_{abs} v}{\sigma_{pe}(\omega = m_{ALP})c} = \frac{3m_{ALP}^2}{16\pi\alpha m_e^2} \times g_{Ae}^2$$



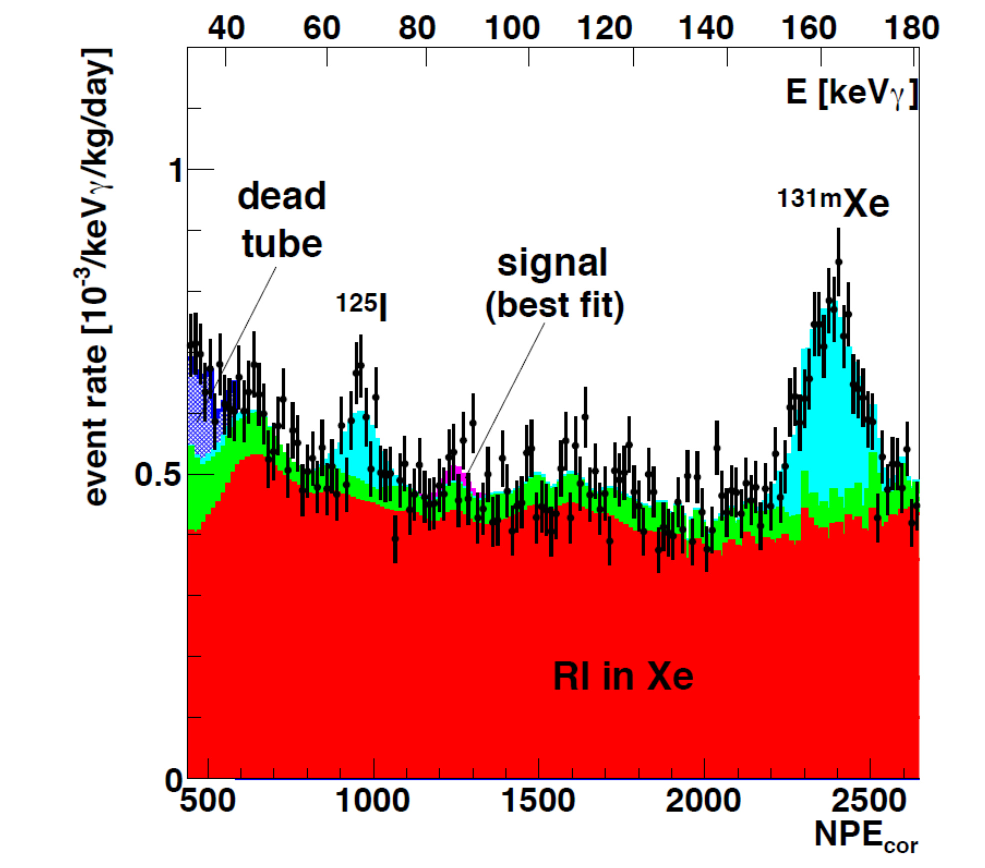
- Event rate ∝ $(a'/a)/m_{HP}$ or $g_{Ae}^2 \times m_{ALP}$

5) 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)

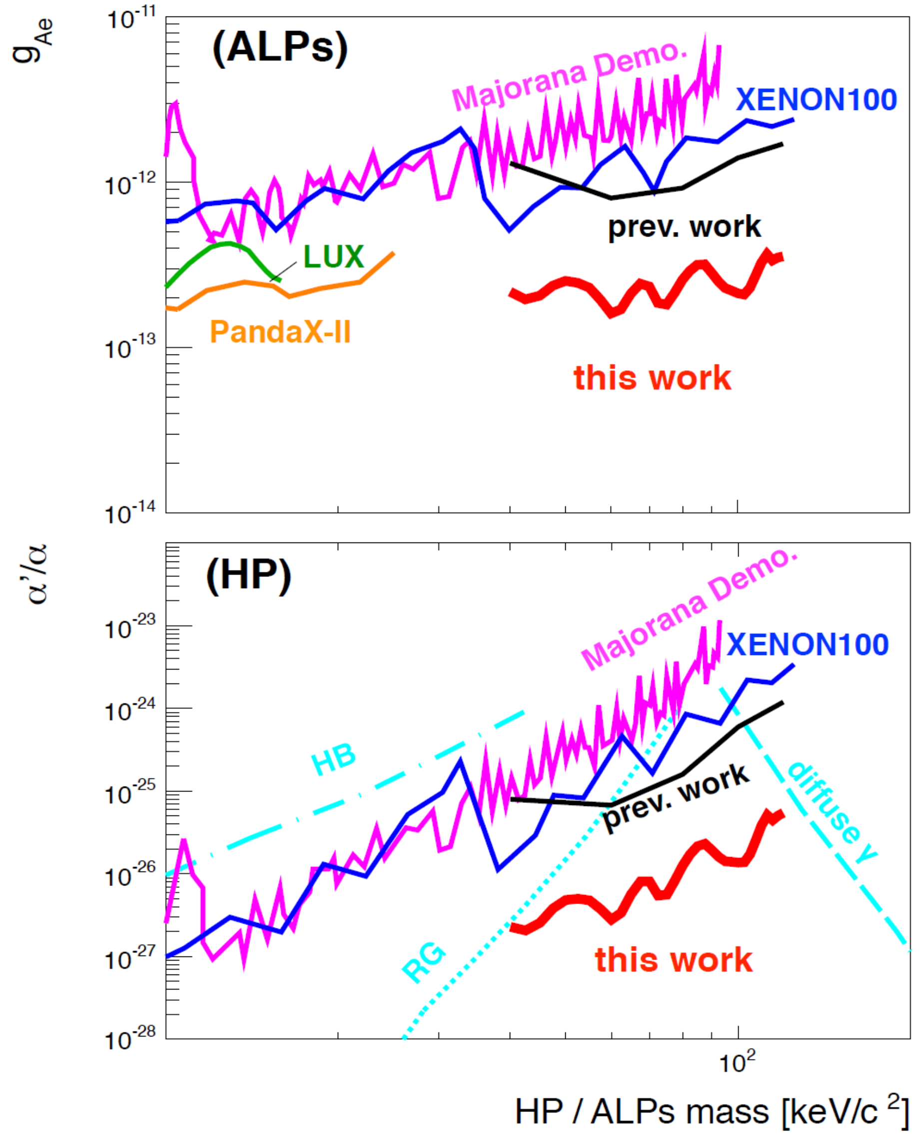


- Peak search by fitting the energy spectrum with the signal + background model.

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

5) Hidden photons & axion-like particles dark matter

Results



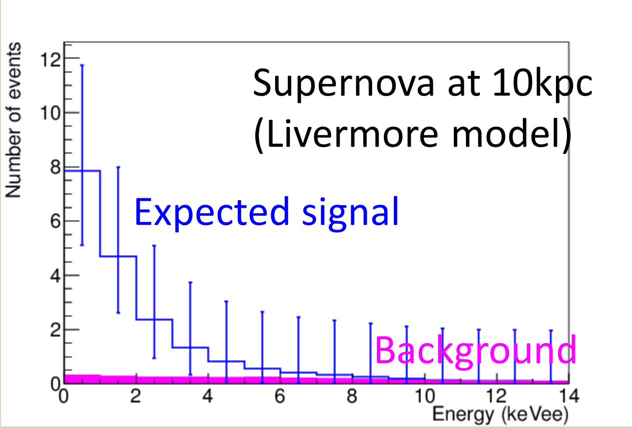
- 800 days x 327 kg exposure
- No significant signal was observed.
- Axion-like particles DM
  - $g_{Ae} < 4\times10^{-13}$ (90% CL) for 40-120 keV/c^2
  - Cover higher mass region than LUX and PandaX-II
- Hidden photon DM
  - $\alpha'/\alpha < 6\times10^{-26}$ (90% CL) for 40-120 keV/c^2
  - Cover a region where indirect searches are weak
- **The best constraint in 40-120 keV/c^2 for both cases.**
- **Published in Phys. Lett. B787 (2018) 153.**

Diversity of physics targets with XMASS

Diversity of physics targets with XMASS

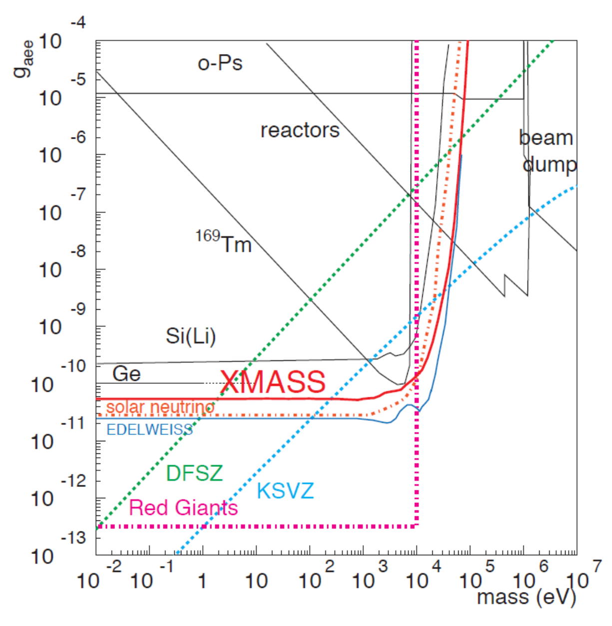
- Possibility of supernova neutrino detection

Astropart. Phys. 89 (2017) 51



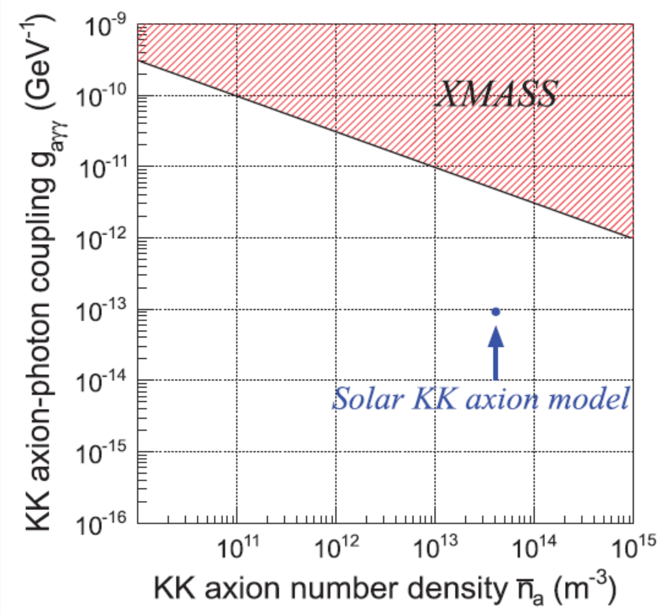
- Solar axion search

Phys. Lett. B724 (2013) 46

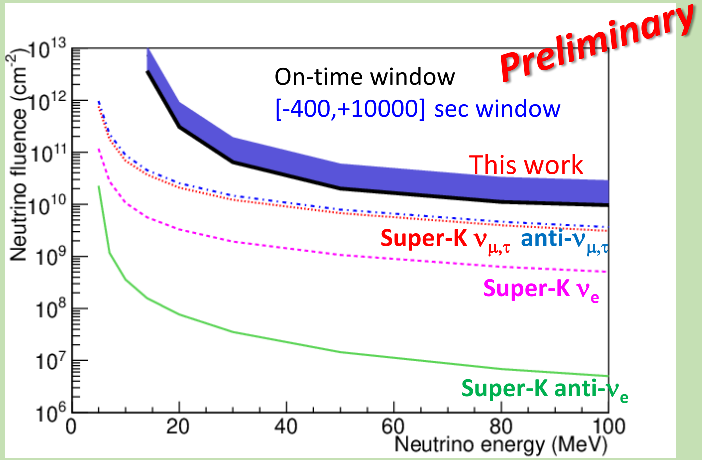


- Solar Kaluza-Klein axion search

PTEP2017 (2017) 103C01



- Search for event burst correlated with GW



6) ^{124}Xe 2ν double electron capture (ECEC)

Introduction

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

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

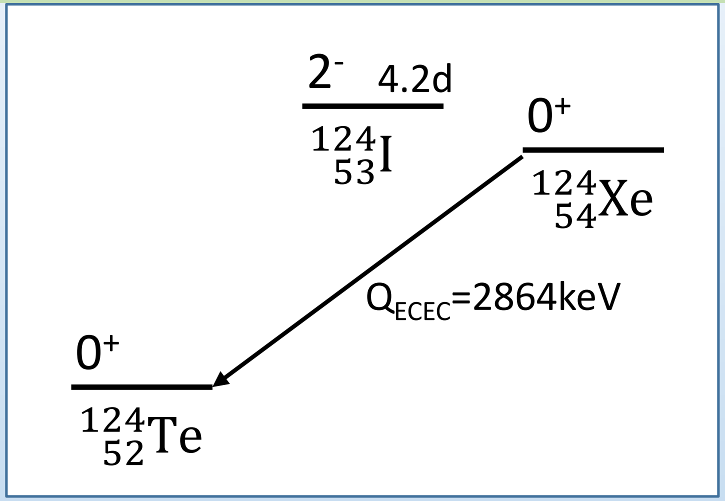
  ECEC, β^+/EC, and $\beta^+\beta^+$ are possible

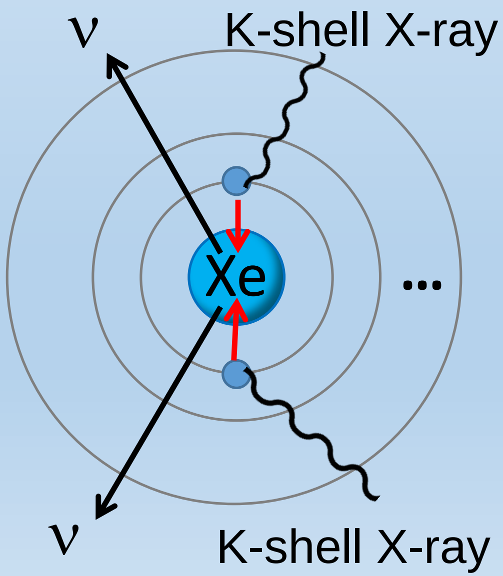
- 0ν mode → Evidence of lepton number violation
  2ν mode → New input for nuclear matrix element calculation

- ^{124}Xe 2ν double electron capture from K-shell (2ν2K)
  - Total deposit energy of **64 keV by X-rays/Auger electrons**
  - Expected half-life is **10^{20}-10^{24} years**

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





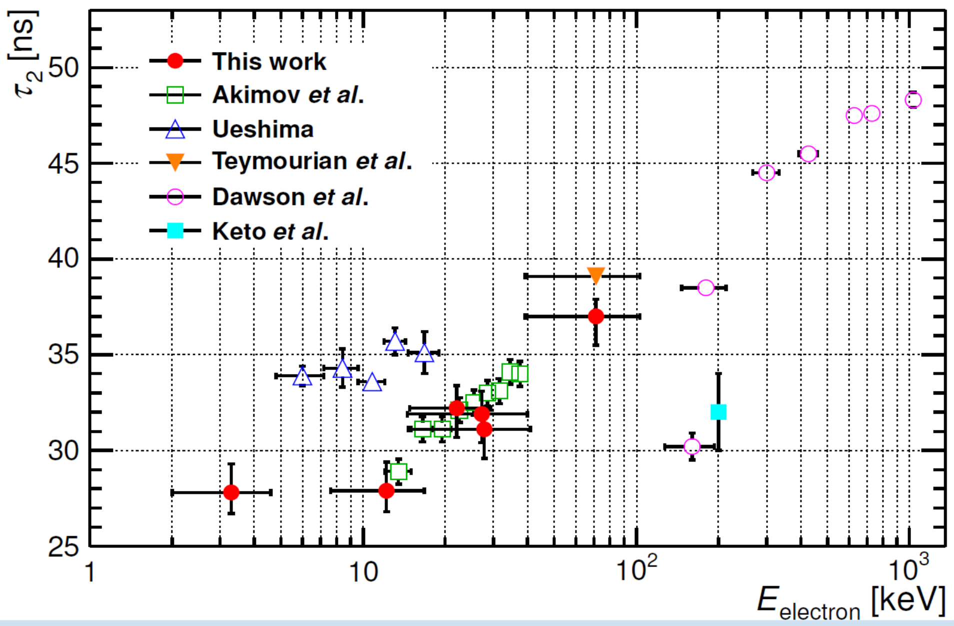
6) ^{124}Xe 2ν double electron capture

Particle ID using scinti. time profile

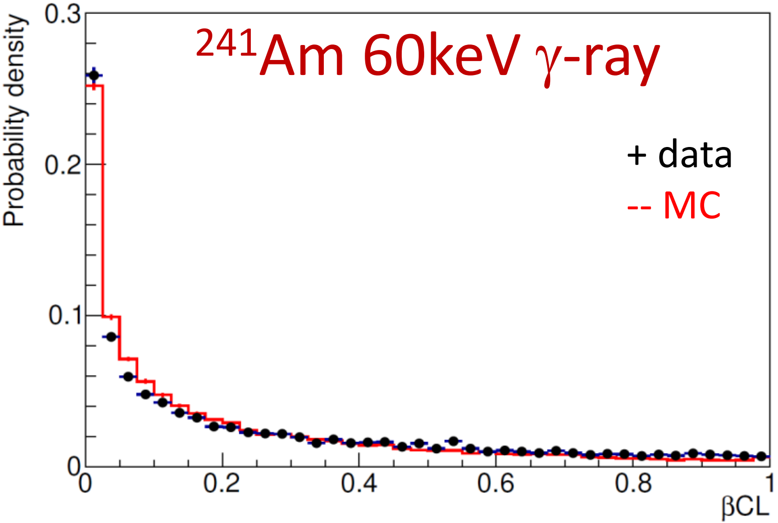
- LXe scintillation decay time depends on electron kinetic energy
- This allows us to separate

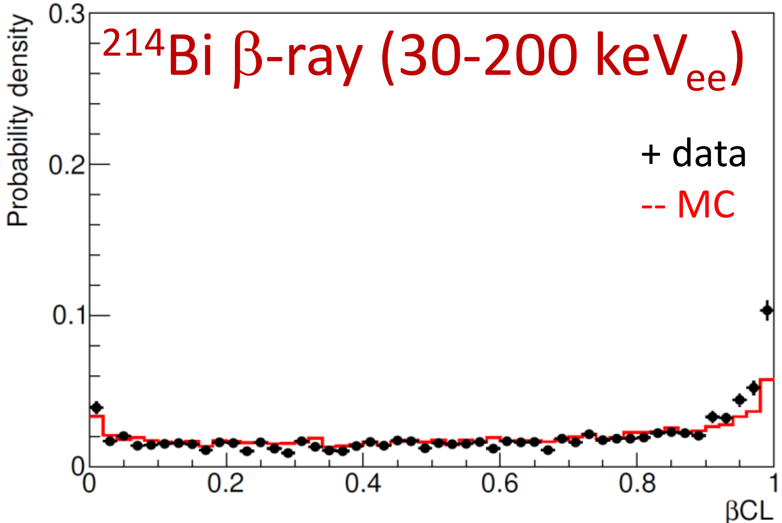
β-ray (single electron track)	vs.	γ-ray/X-ray or 2ν2K (multiple electrons)

- 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





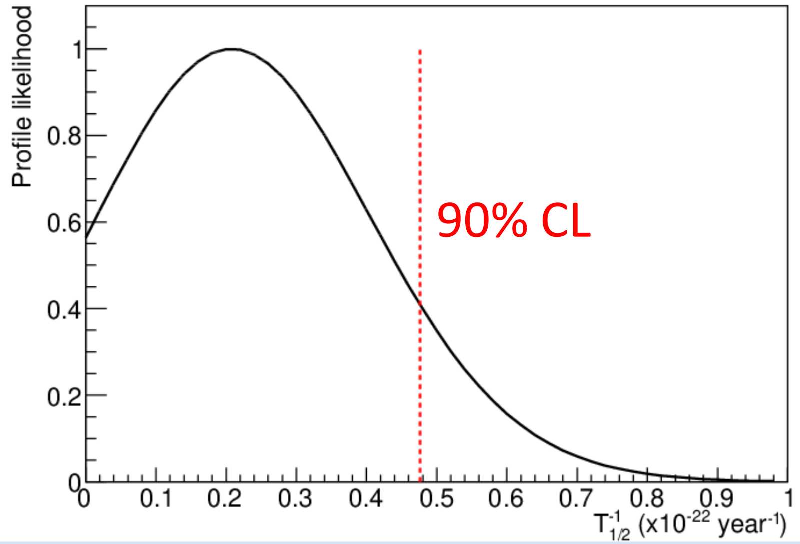
$$\beta\mathrm{CL} = P \times \sum_{i=0}^{n-1} \frac{(-\ln P)^i}{i!} \qquad P = \prod_{i=1}^{n} CL_i$$

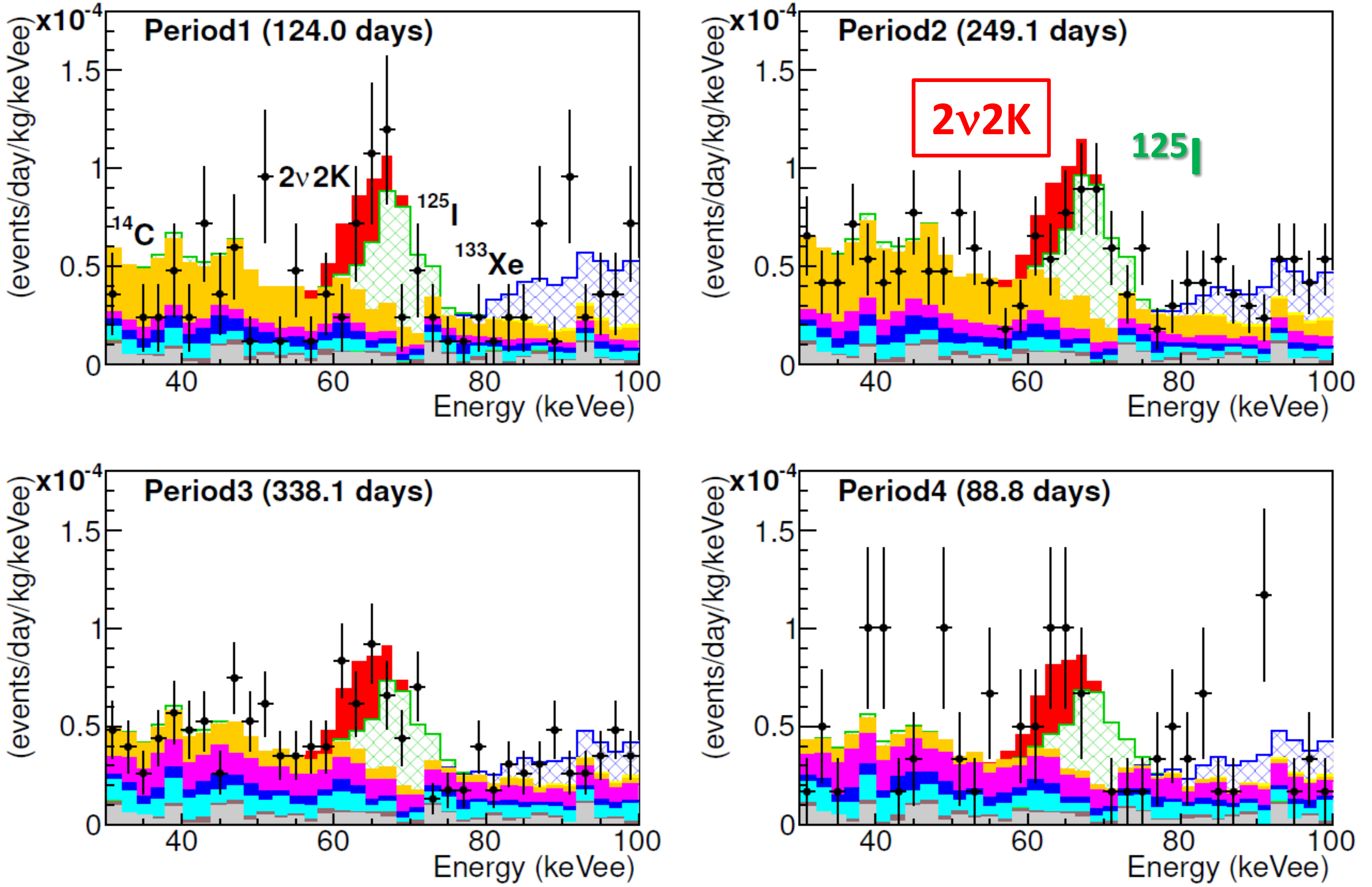
βCL<0.05

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

➔ S/N improves by x5

6) ^{124}Xe 2ν double electron capture
Results: close-up spectrum of ROI

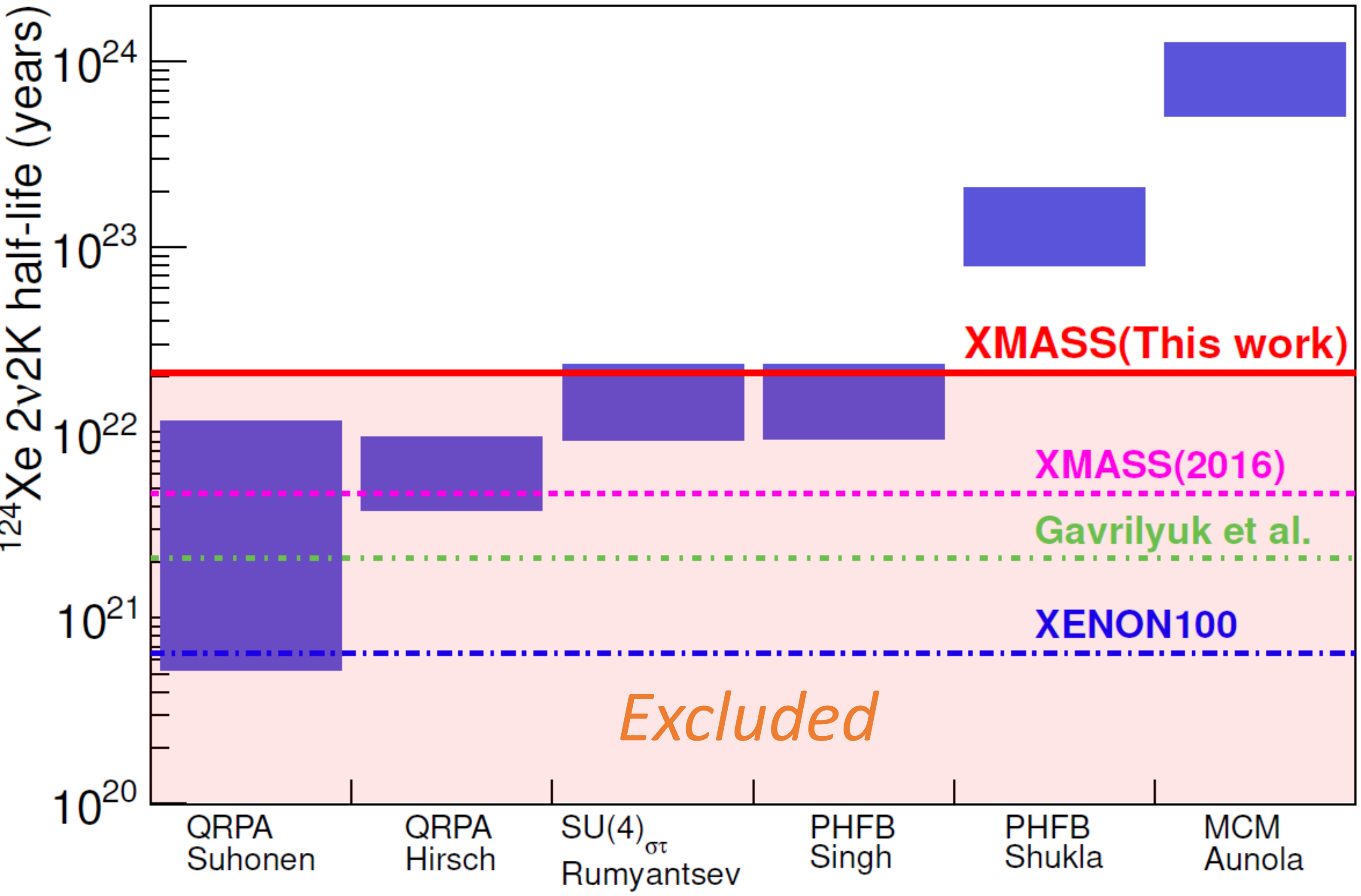




- ^{125}I is created by thermal neutron capture on ^{124}Xe outside the water shield, giving a peak at 67.5 keVee.
- Thermal neutron flux is constrained by independent measurement.
- No significant signal was observed.

6) ^{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***

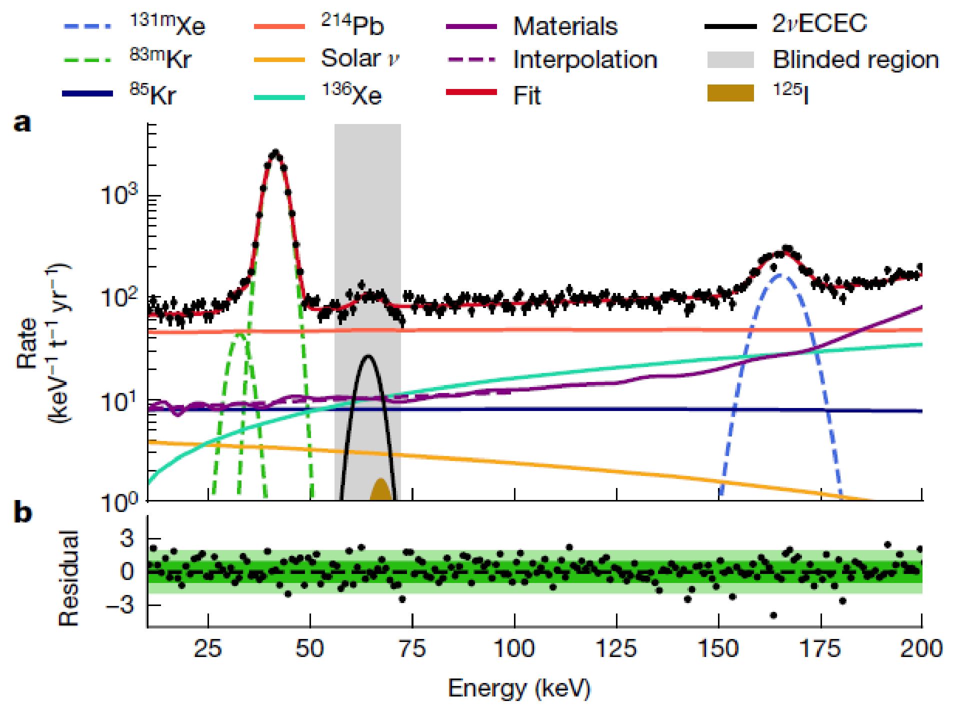
^{124}Xe 2ν double electron capture

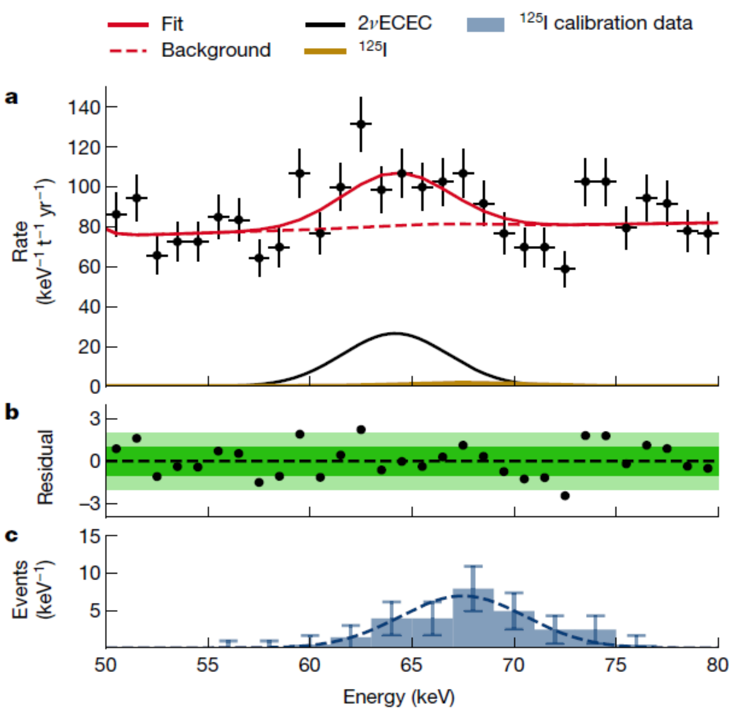
LETTER

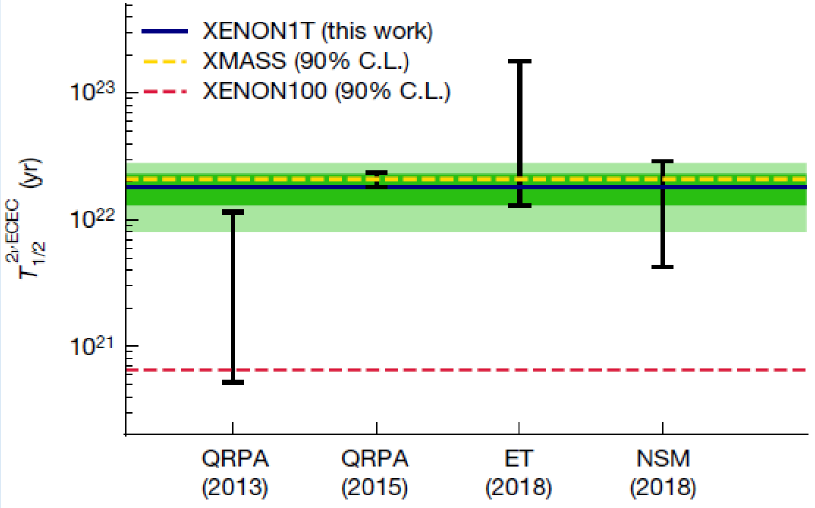
https://doi.org/10.1038/s41586-019-1124-4

Observation of two-neutrino double electron capture in ^{124}Xe with XENON1T

XENON Collaboration*





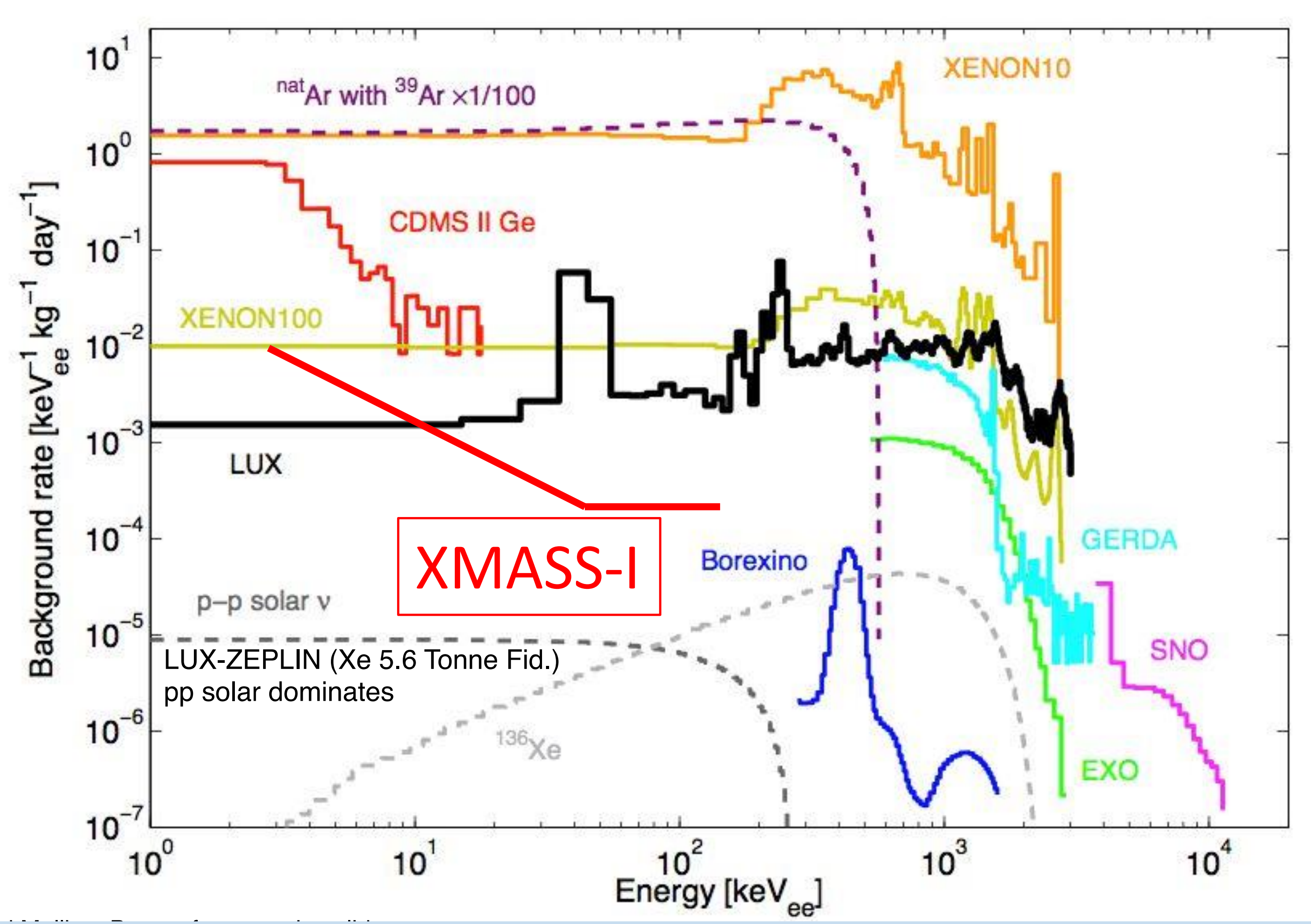


Summary

- XMASS is a multi-purpose experiment using 832 kg of Lxe located at the Kamioka underground laboratory in Japan.
- We have successfully taken data for >5 years.
- We searched for various types of dark matter particles and interactions.
  - ☐ Standard WIMPs *Phys. Lett. B789 (2019) 45*
  - ☐ WIMP-^{129}Xe inelastic scattering *Astropart. Phys. 110 (2019) 1*
  - ☐ Annual modulation *Phys. Rev. D97 (2018) 102006*
  - ☐ Sub-GeV dark matter via nuclear bremsstrahlung *arXiv: 1808.06177*
  - ☐ Hidden photon/axion-likes particles *Phys. Lett. B787 (2018) 153*
- We have also challenged various topics in particle and astroparticle physics.
  - ☐ ^{124}Xe 2ν double electron capture *PTEP2018 (2018) 053D03*

Backup slides

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

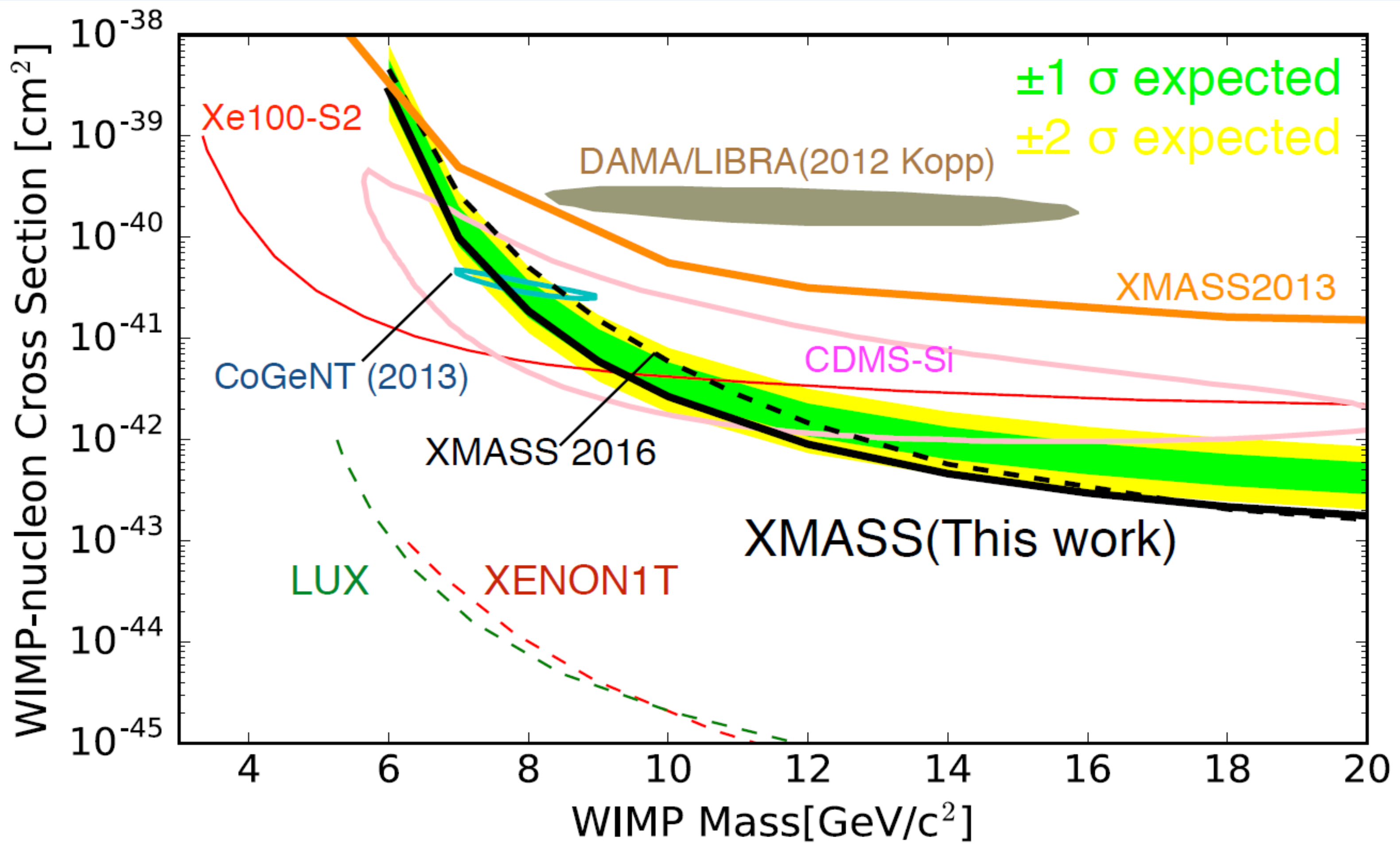


- XMASS achieved low background rate of O(10^{-4}) dru in a few 10s keV including e/γ events
- Low background rate for e/γ events is good for searching for dark matter other than WIMPs.

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

3) Annual modulation search

Results: WIMP analysis

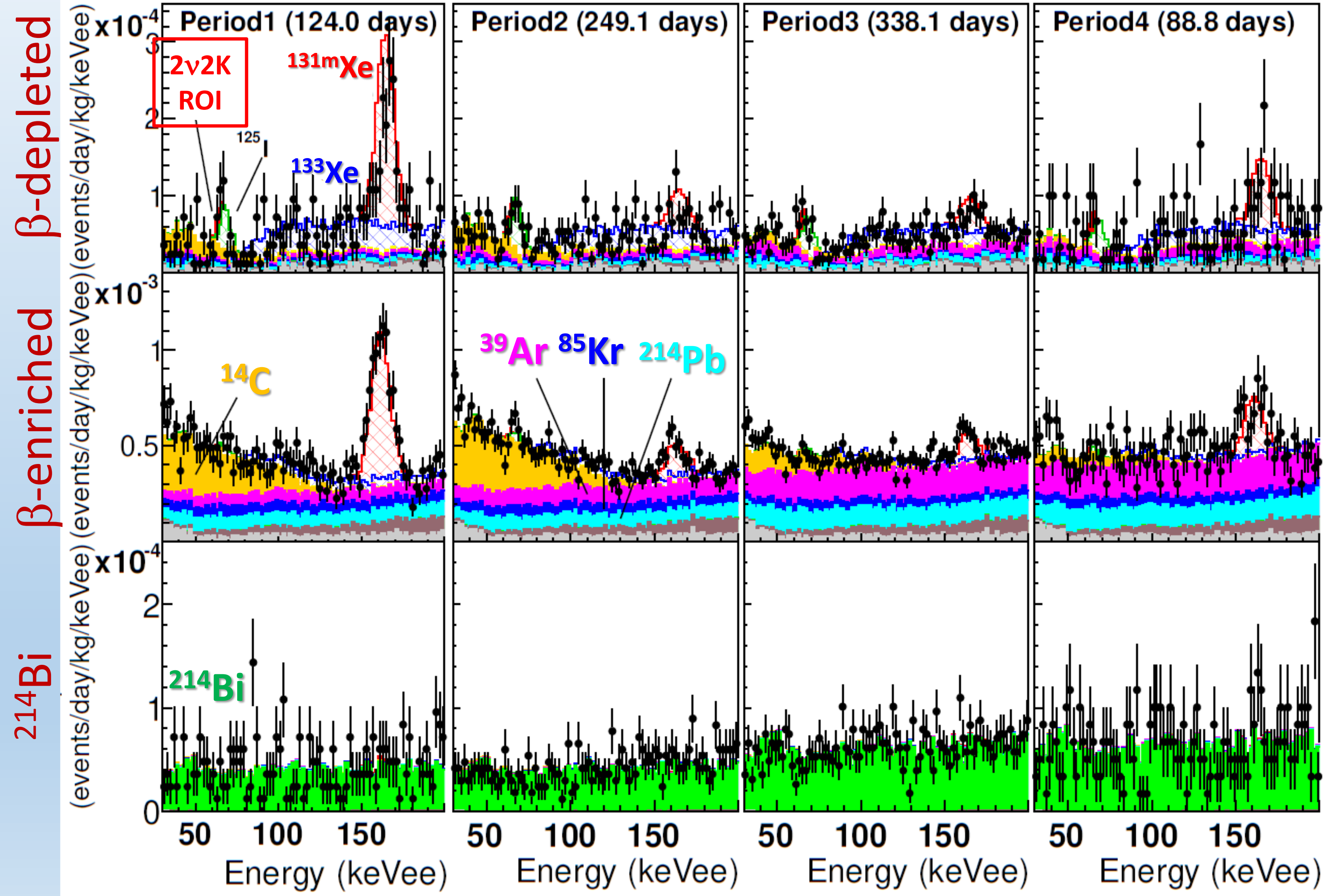


- Assuming WIMP and standard halo model
  - Lewin and Smith (1996, APP)
  - V_0=232 km/s, V_{esc}=544 km/s
  - ρ_{DM}=0.3 GeV/cm^3
  - T= 365.24 days, ϕ=152.5 day

- 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

6) ^{124}Xe 2ν double electron capture

Spectrum fitting in 30-200 keVee

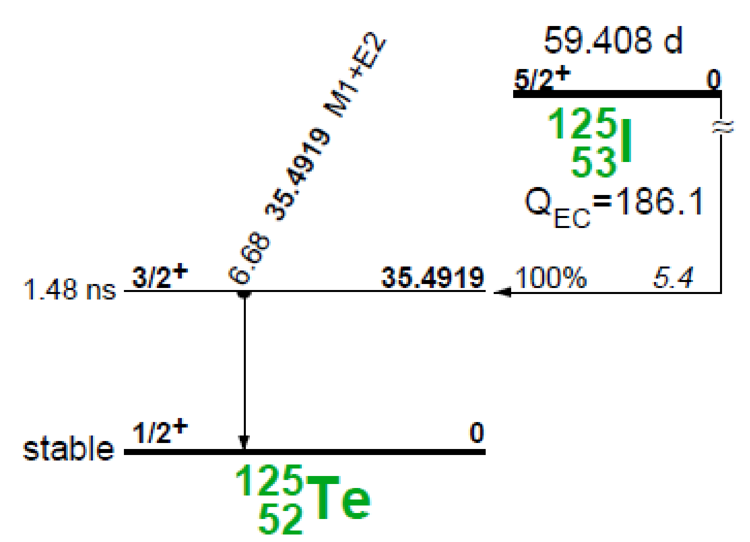


- 4 periods x 3 sub-samples are fitted simultaneously.
- ^{131m}Xe, ^{133}Xe, ^{125}I: xenon activation by neutrons
- ^{214}Pb: ^{222}Rn daughter
- ^{85}Kr: constrained by external β-γ coincidence measurement
- ^{39}Ar: confirmed by gas chromatography measurement
- ^{14}C: decreased after gas circulation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

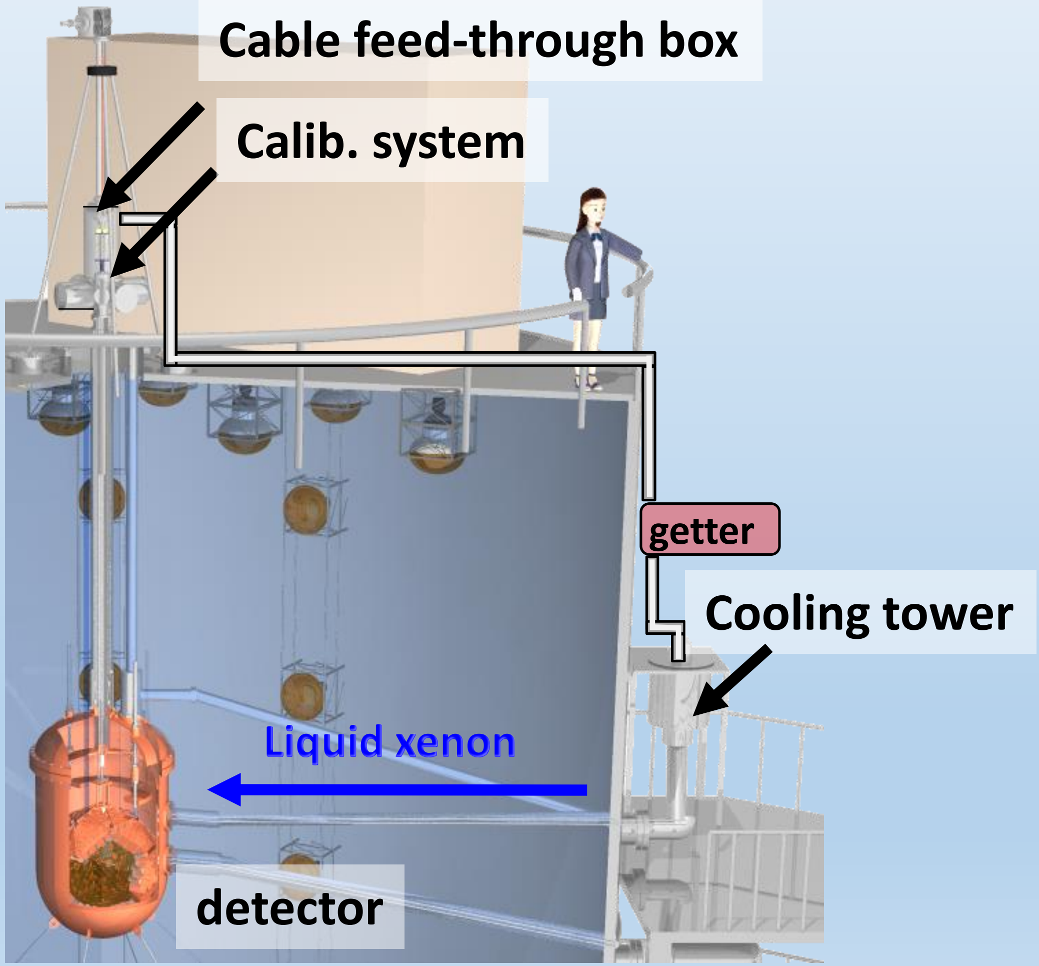
6) ^{124}Xe 2ν double electron capture

^{125}I background

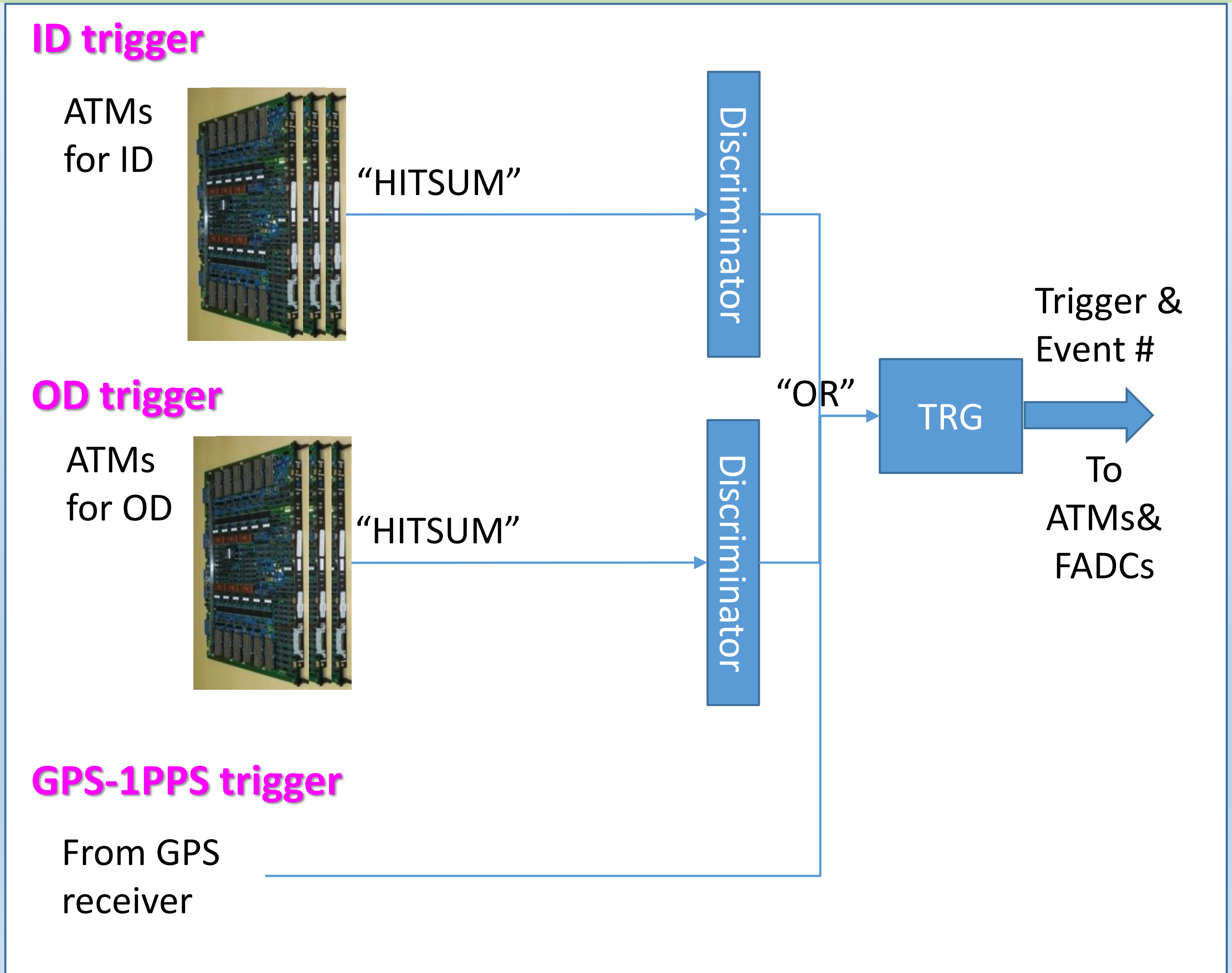
- ^{125}I is created by thermal neutron capture on ^{124}Xe
  - $^{124}Xe(n, \gamma)^{125}Xe$ (σ=137 barn)
  - $^{124}Xe(n, \gamma)^{125m}Xe$ (σ=28 barn)
  - $^{125m}Xe \rightarrow ^{125}Xe$ (IT , $T_{1/2}$=57 sec)
  - $^{125}Xe \rightarrow ^{125}I$ (β^+/EC, $T_{1/2}$=16.9 hours)
- Thermal neutron flux 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)



Trigger system

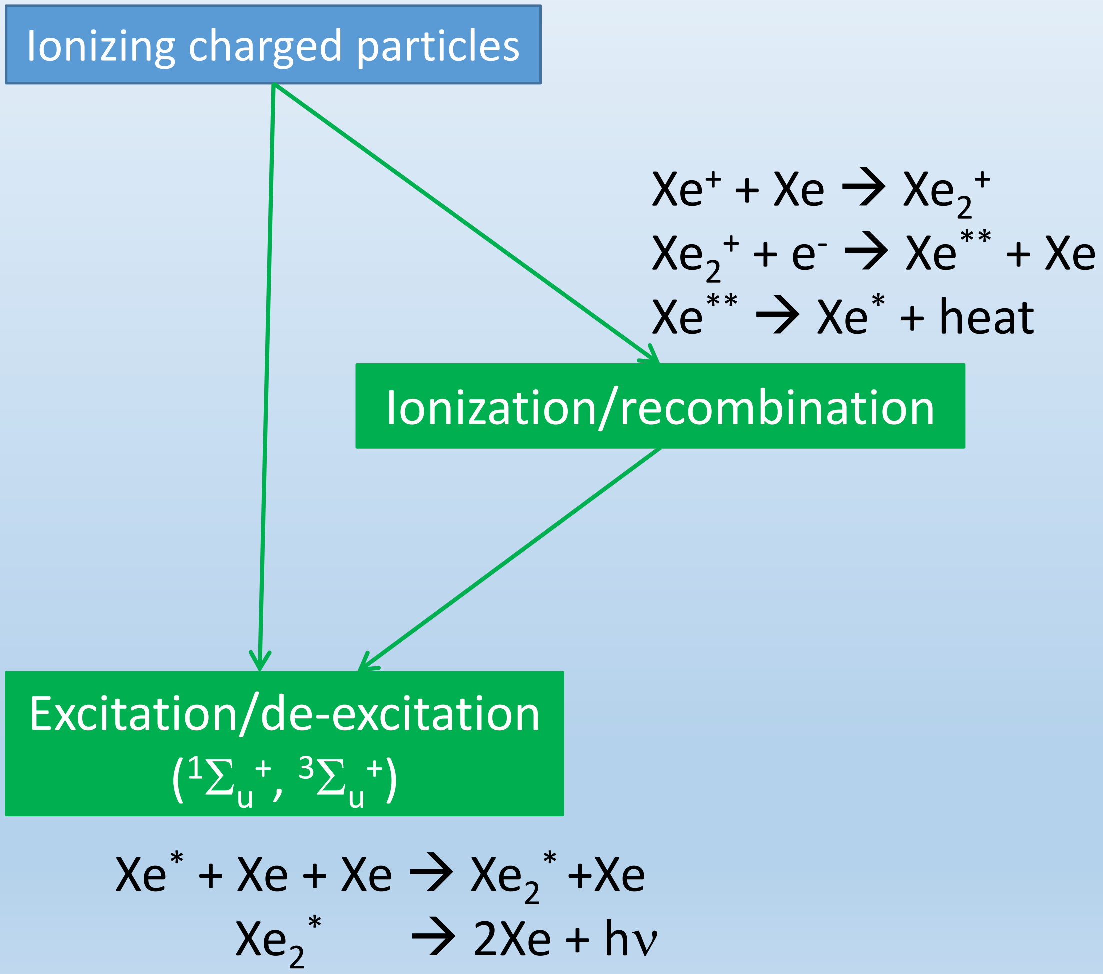


- ID (or OD) trigger
  - ATM outputs the analog signal whose height is proportional to the number of hits within 200 nsec (HITSUM).
- GPS-1PPS trigger
  - To calibrate absolute time.
  - Also used to monitor PMTs' dark rate and gain by flashing LED.
- Trigger module (TRG)
  - 8ch input at maximum.
  - Assign event number.
  - Record type of trigger and trigger time with 20 ns resolution.

Scintillation time profile

- Scintillation time profile is important for
  - Discrimination between nuclear recoil and electron/gamma-ray
  - Vertex reconstruction using hits' timing

- Liquid xenon scintillation processes
  - Direct excitation
    - Singlet ($^1\Sigma_u^+$): τ ~ a few ns
    - Triplet ($^3\Sigma_u^+$): τ ~ 20 ns
  - Recombination: τ >~30 ns



Measurement of LXe scintillation time profile for low energy gamma-ray induced events

- Waveforms are decomposed into "single PE" pulses
- Timing distributions of data and MC are compared to obtain intrinsic decay time parameters.
- MC simulation takes into account optical parameters (absorption, scattering, …), electronics response.