Direct dark matter search with XMASS

K. Abe for the XMASS collaboration

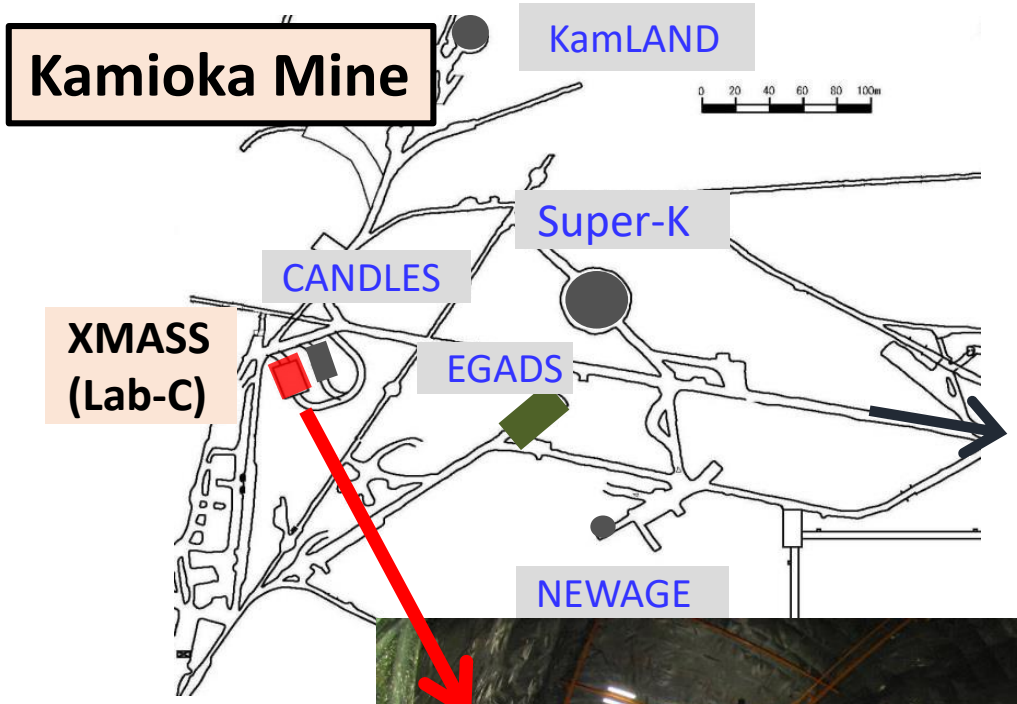
Outline

- XMASS experiment.
  - Single phase liquid xenon detector
- Many targets were searched with XMASS.
  - WIMP search
    - fiducialized volume.
    - Modulation signal search
    - Inelastic scattering by WIMP
  - Solar axion
  - Bosonic super WIMP
  - Solar KK axion

The XMASS collaboration:

- *Institute for Cosmic Ray Research, the University of Tokyo*
- *Kavli Institute for the Physics and Mathematics of the Universe, the University of Tokyo*
- *Kobe University*
- *Tokai University*
- *Yokohama National University*
- *Miyagi Educational University*
- *STE lab., Nagoya University*
- *Tokushima University*
- *Center for Underground Physics, Institute for Basic Science*
- *KRISS*

Site

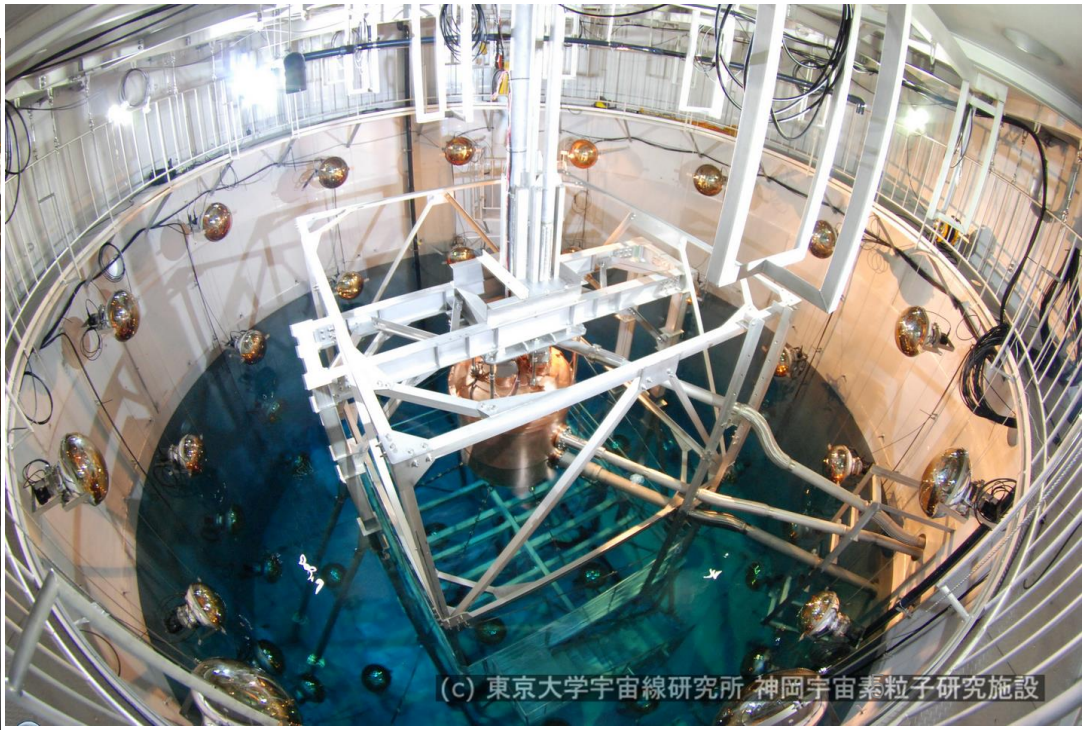


Kamioka mine
Lab-C

~1000m underneath
Mt. Ikenoyama.
(2700 m.w.e.)

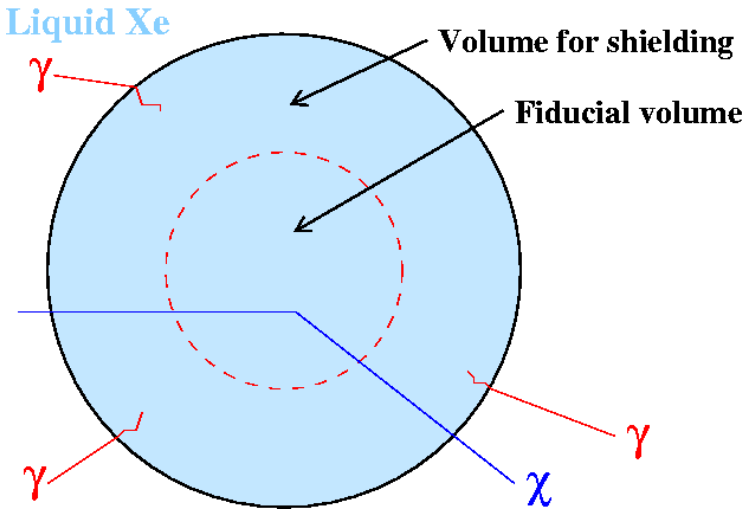
XMASS I detector

- Single phase liquid xenon detector with 835kg of liquid xenon, 80 cm diameter.
- 642 low RI PMTs.
- 62% inner surface is covered with photocathode area
  - High light yield (14.7 pe/keV)
  - Low threshold (0.3keVee)
- Detector is inside 10m x 10m water tank with 70 PMTs (20 inch) for muon veto and shield for neutron/gamma from the outside.
- Stable data taking is ongoing from end of 2013.

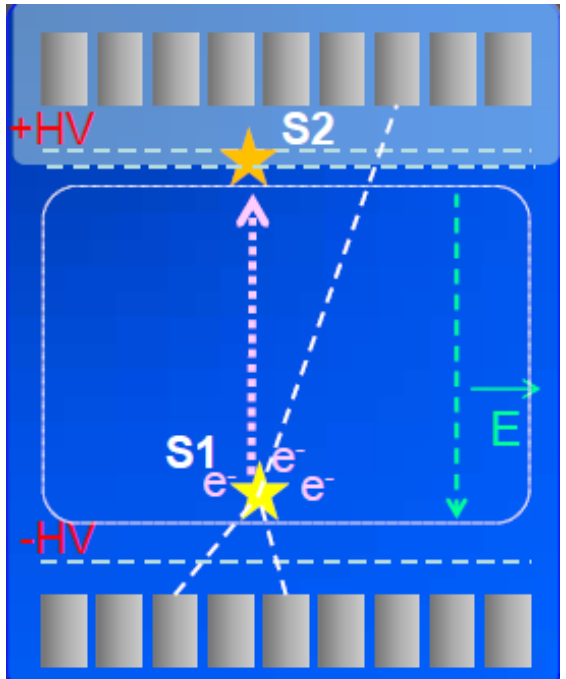


XMASS single phase liquid xenon detector for Dark matter seach

- Single phase :
  - Only liquid phase, only scintillation signal.
  - DM signal (uniformly distributed) are identified by fiducial volume analysis.
    - BG events are stopped outside volume.
  - Also PSD can reduce background.
    - Scintillation decay time difference between nuclear recoil (WIMP indueced) and electron recoil can be used.



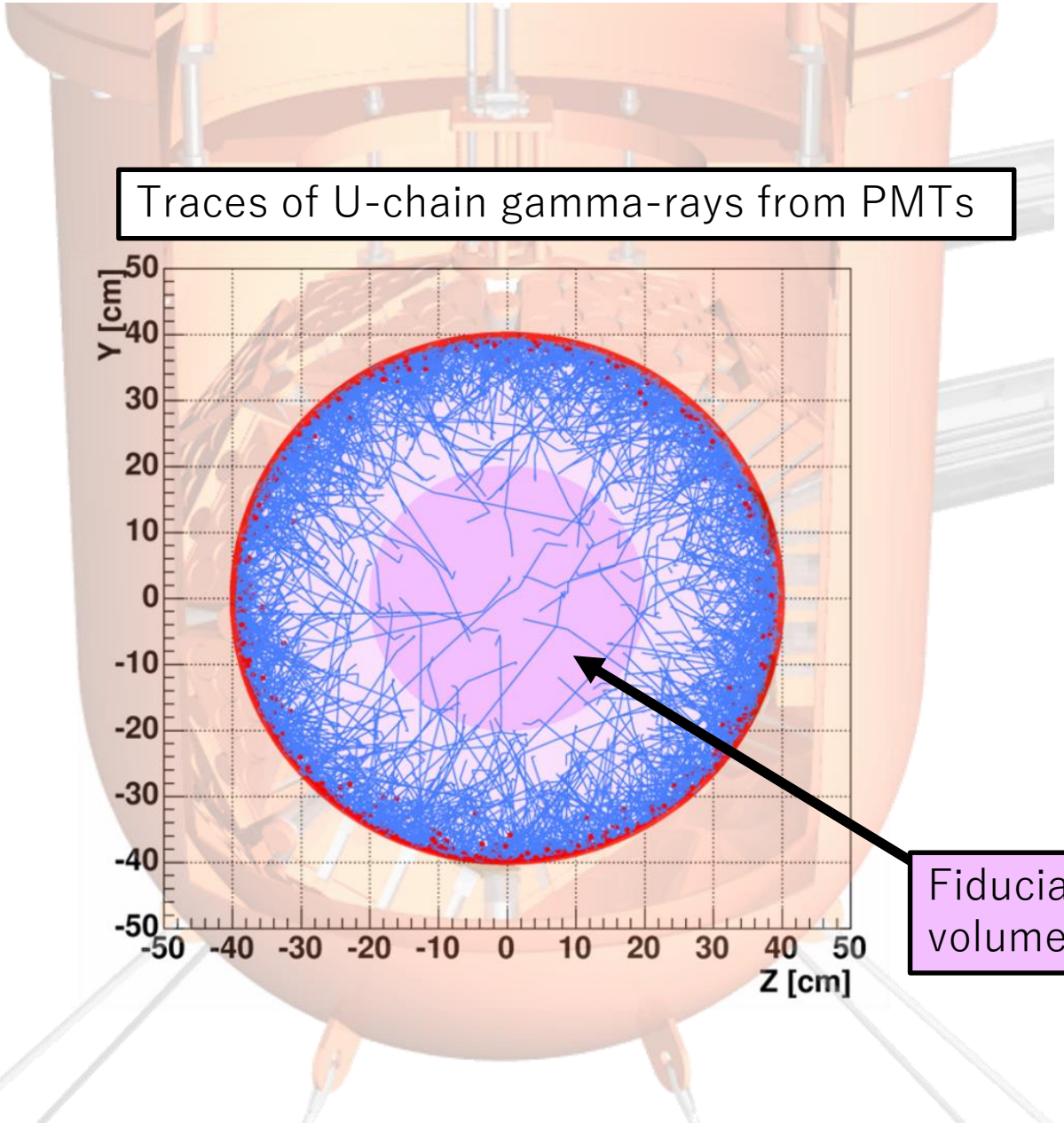
- Two phase :
  - Liquid phase and gas phase, scintillation signal(S1) and ioinization signal(s2).
  - DM signal (nuclear recoil) are identified by S2/S1 ratio and fiducial volume.



Dark matter search by XMASS

1. WIMP
    1. Search in fiducialized volume
    2. Modulation
    3. Inelastic
2. Solar axion
3. Bosonic super WIMP
4. KK solar axion

WIMP search by fiducialized volume



- Self-shielding of γ-ray background
- Owing to high atomic number (Z=54),
  external gamma-ray background (mainly coming from PMTs) can be shielded by liquid xenon itself.

- By selecting events occurred in the restricted inner volume (fiducial volume)
  low background can be achieved.

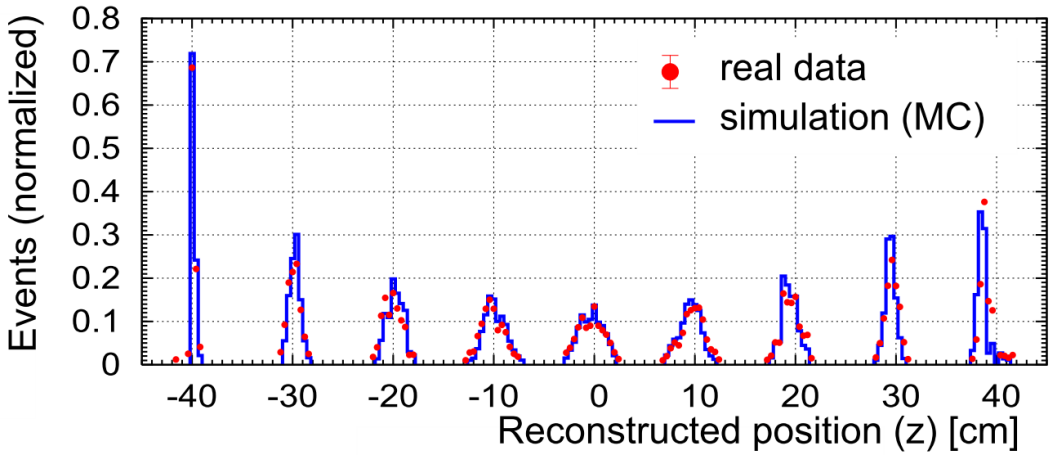
Vertex reconstruction (based on photo electron, R(PE))

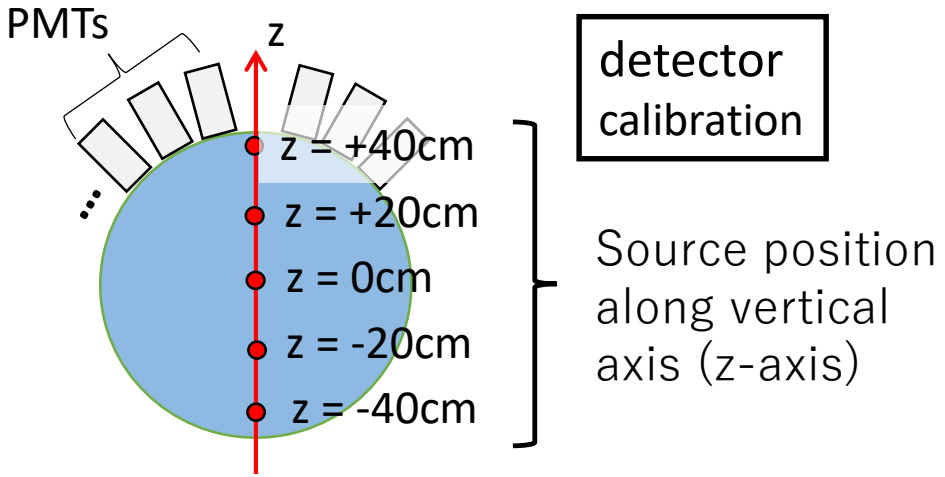
- Position reconstruction
  - (1) Making acceptance map: Many grid points are defined inside whole detector volume including detector surface. Events are generated at each grid point and photo-electrons (pe) expected in each PMT are calculated by our MC.
  - (2) From measured pe and scaled acceptance map (μ) in (1), position is calculated where following likelihood is maximum.

$$\log(\mathrm{L}) = -\sum_{\mathrm{PMT}} \log\left(\frac{\exp(-\mu)\mu^{\mathrm{pe}}}{\Gamma(\mathrm{pe}+1)}\right)$$

Γ(x): Gamma function
(Γ(n) = (n-1)!, n>0)

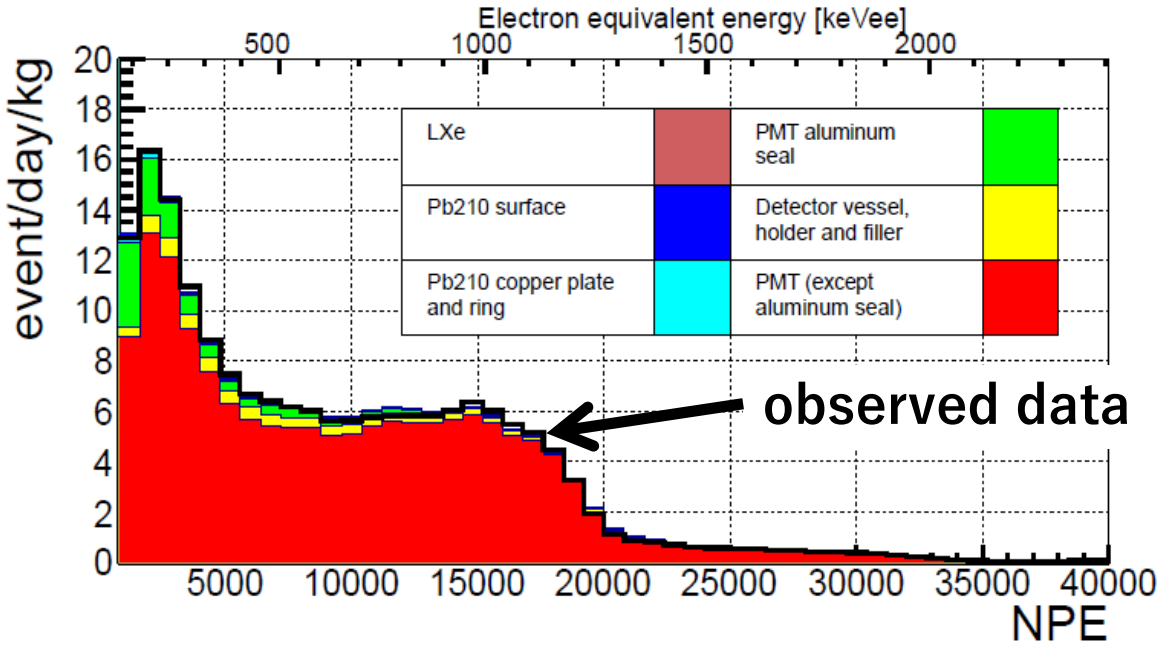
Reconstructed position distribution of ^{57}Co events (122 keV)





Background understanding without fiducialization

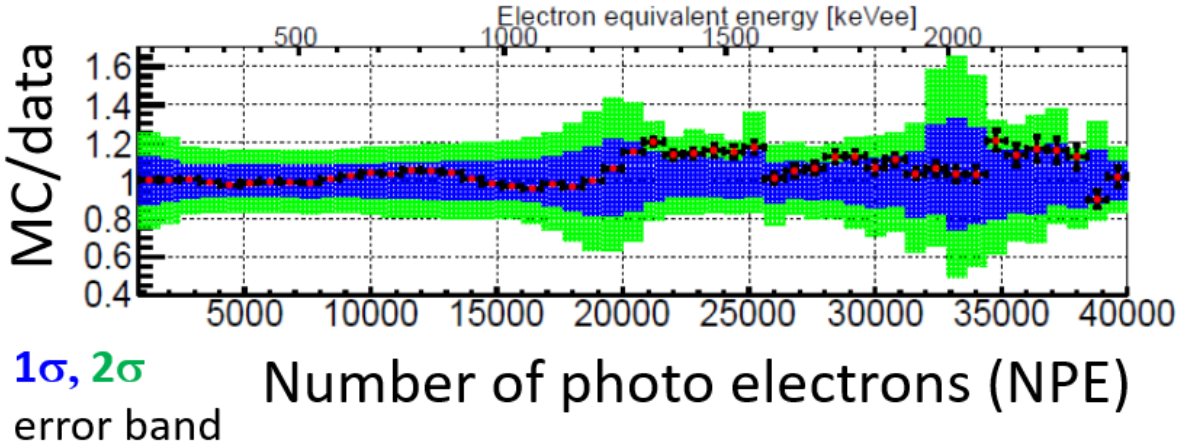
- RI from the detector material is the BG source.
- The each RI activity was evaluated by the observed spectrum fitting for > 400 pe (~30 keV) by the MC expectations with constraints from the screening results by HPGe.



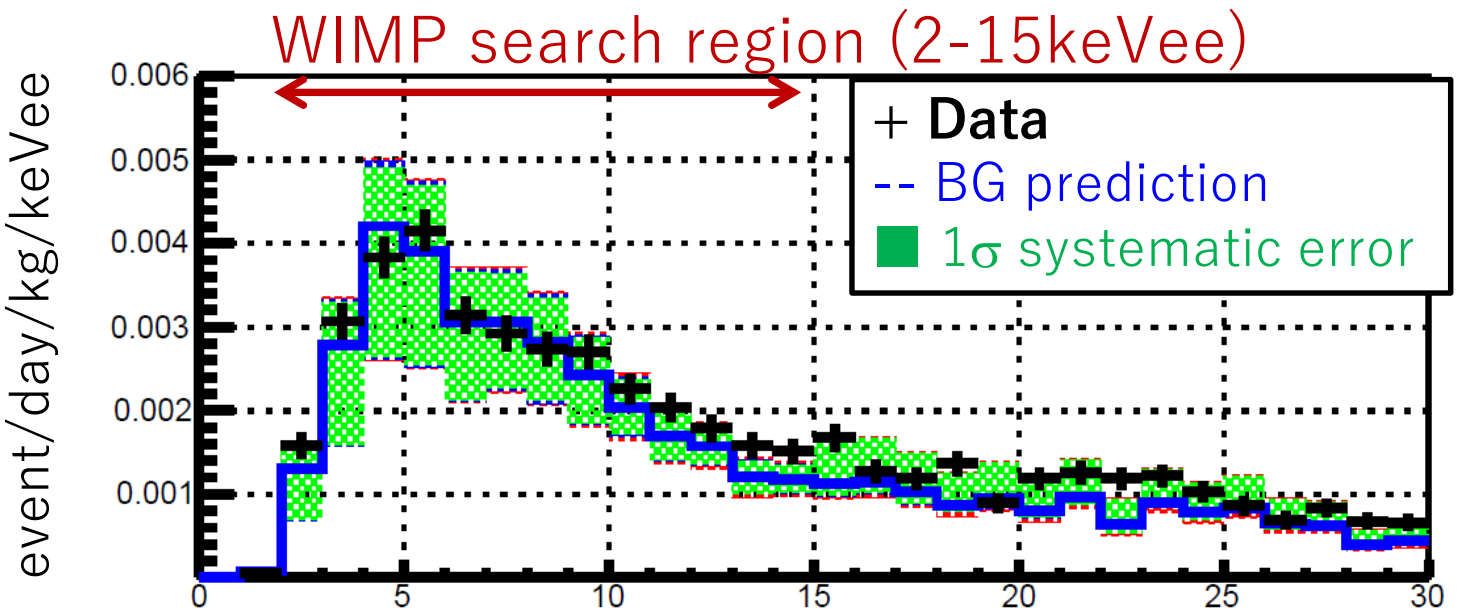
ex. RI screening results for PMT with HPGe detector.

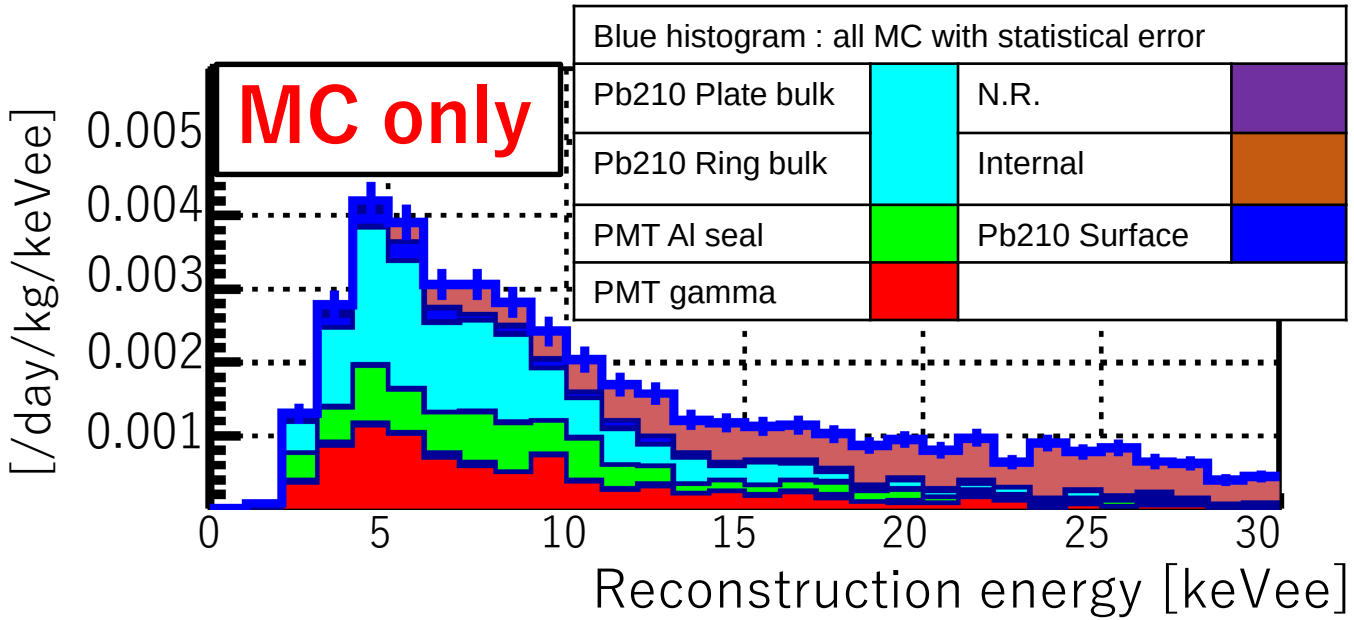
- PMT + base (whole measurement)

	mBq/PMT
^{232}Th	1.80 ± 0.31
^{238}U	2.26 ± 0.28
^{210}Pb	200 ± 100
^{60}Co	2.92 ± 0.16
^{40}K	9.10 ± 2.15



Energy spectrum after fiducialization





- 706 live days taken in Nov. 2013 – Mar. 2016
- Fiducial mass 97kg (R<20cm)

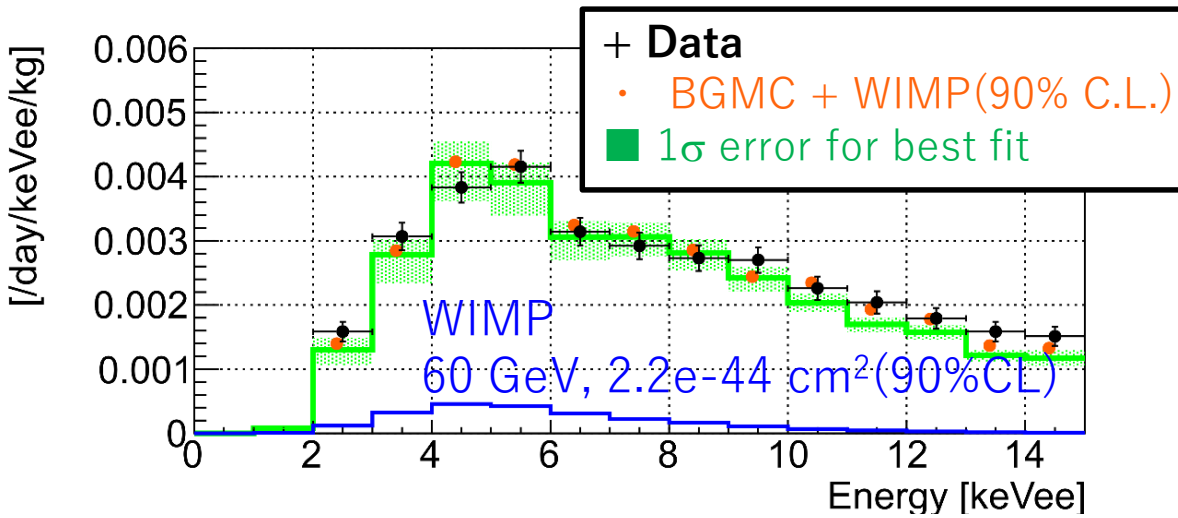
- Main BG in the WIMP search region
  - Not internal but detector surface events (miss-reconstructed events).
- Internal RIs dominate above 15keVee

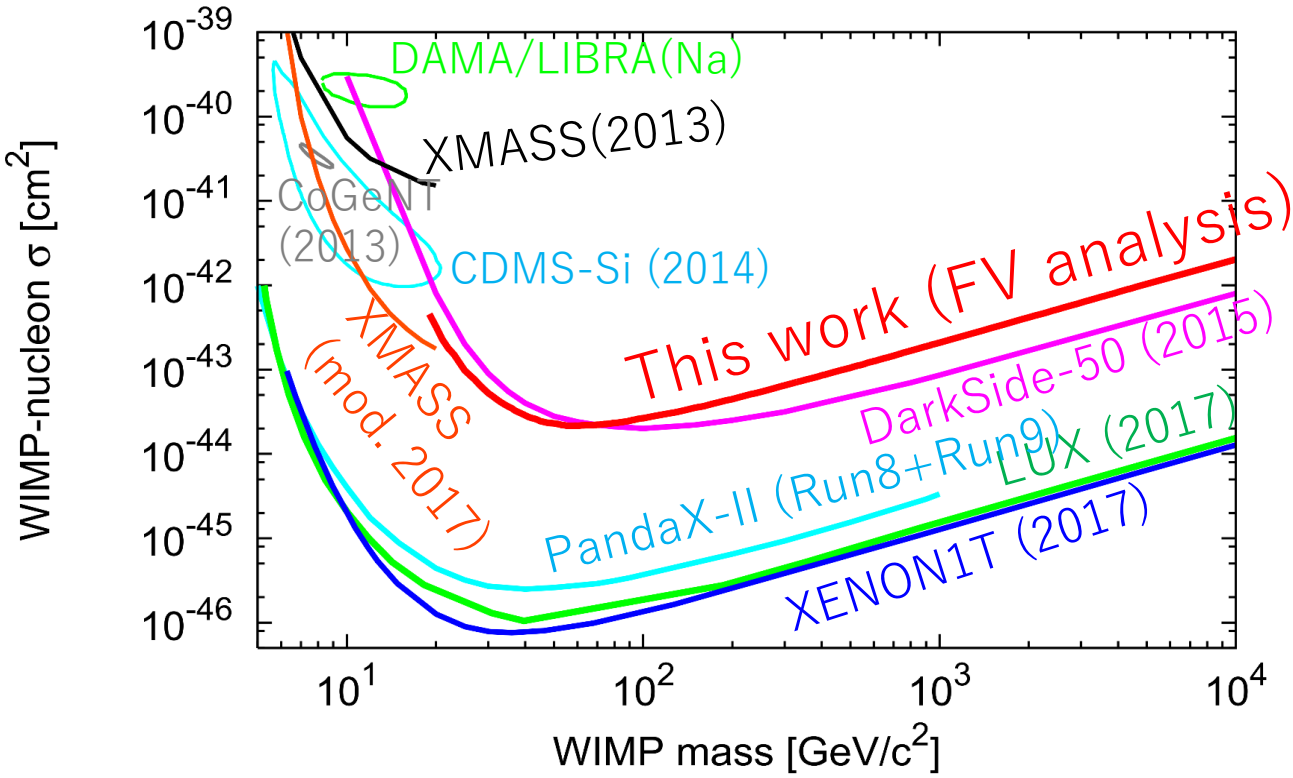
- Neutrons, alpha-rays are negligible

- Dominant systematic uncertainty is condition of detector inner surface (gap size, surface roughness)

WIMP search results

- 706 live days data
- Energy spectrum of data was fitted with background MC and WIMP signal MC in the energy range of 2–15 keVee considering systematic error in both background and WIMP MC.
- Best fit result is consistent with no WIMP case, then 90% C.L. upper limit on the WIMP-nucleon cross section was derived.
- Our preliminary limit is 2.2×10^{-44} cm^2 for 60 GeV WIMP mass.

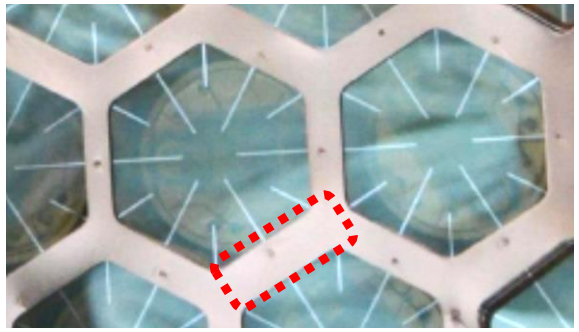


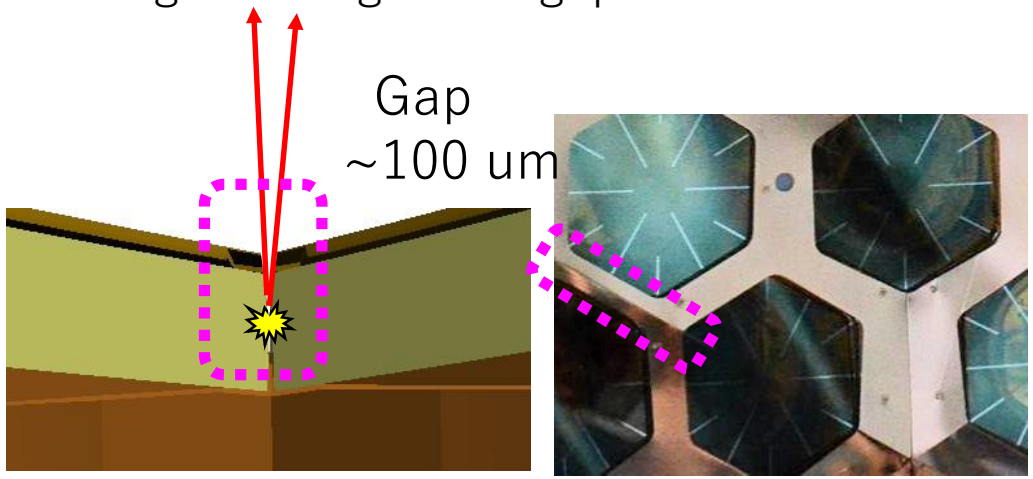


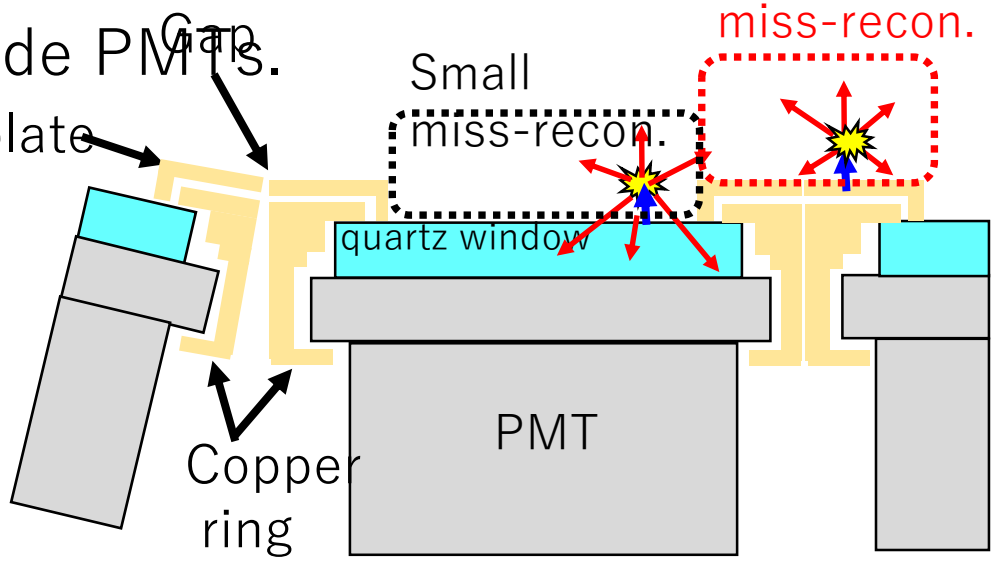
Miss-reconstructed surface events

- Majority of remaining BG
- Certain amount of surface events are wrongly reconstructed as the event inside fiducial volume.
  - Surface of copper plate
  - Light leakage from the gap around boundary of surface structures.
  - It is difficult to observe photon by the near side PMTs.

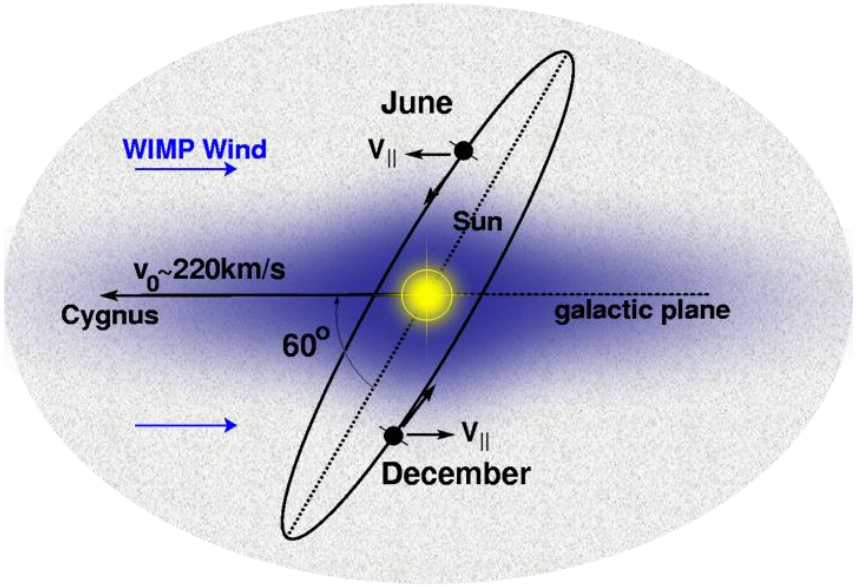
Structure around PMT



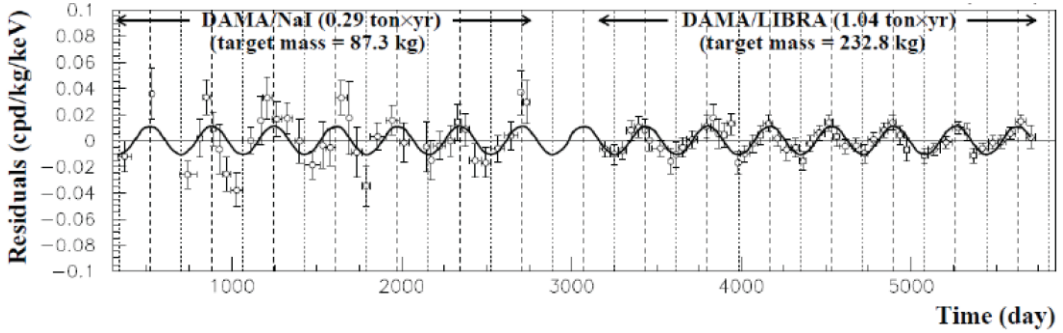


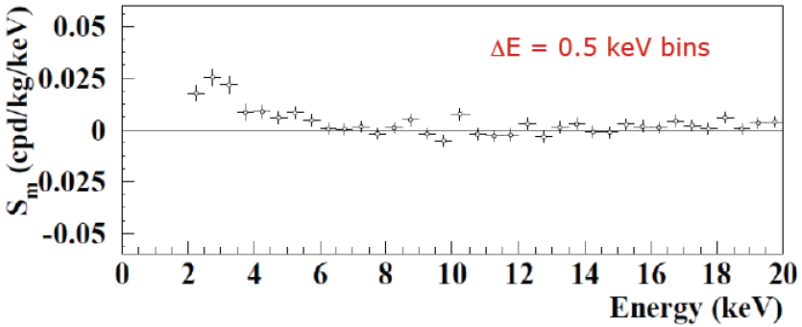


Search for annual modulation



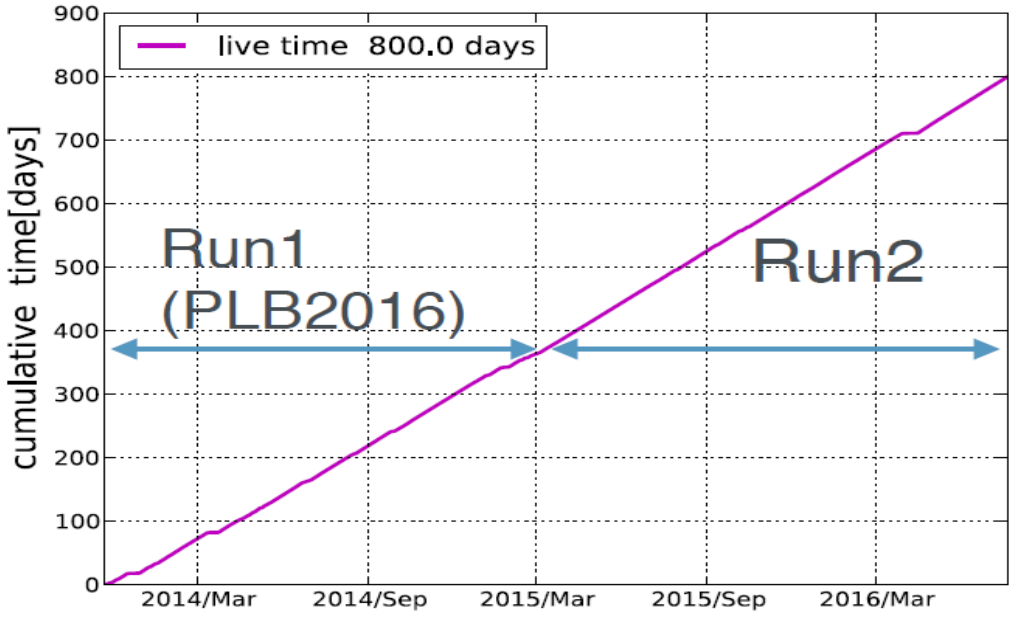
- Due to Earth's rotation around the Sun, annual modulation of event rate of dark matter signal is expected.
- DAMA/LIBRA claims modulation at 9.3σ
  - Total exposure of 1.33 ton year (14 cycles)
  - Modulation amplitude of (0.0112+/-0.0012) cpd/kg/keV for 2-6 keV

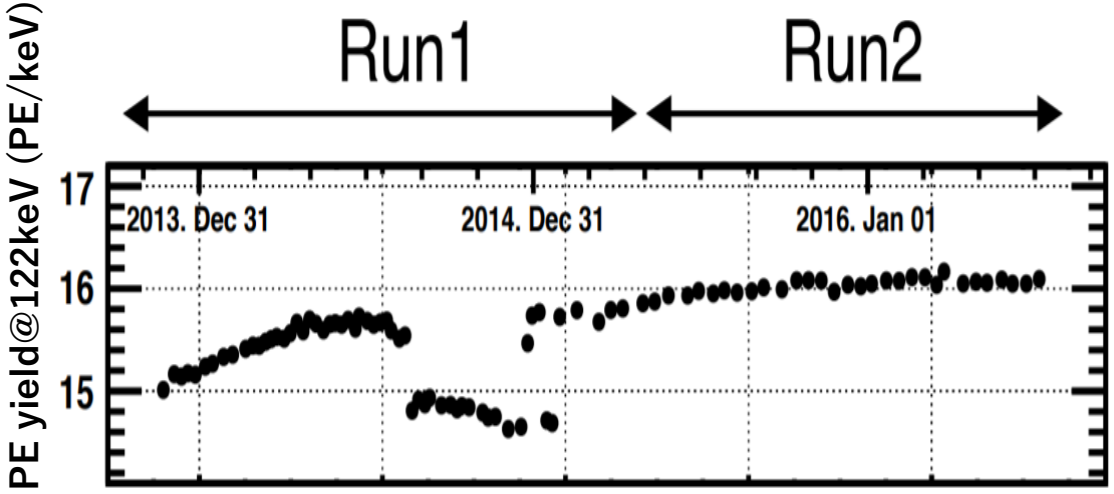




- Annual modulation search in XMASS
  - 800 live days x 832 kg (=1.8 ton year), not fiducialized.
  - Look for event rate modulation not only for nuclear recoil but also for e/γ events

Modulation search with 2.7 years data



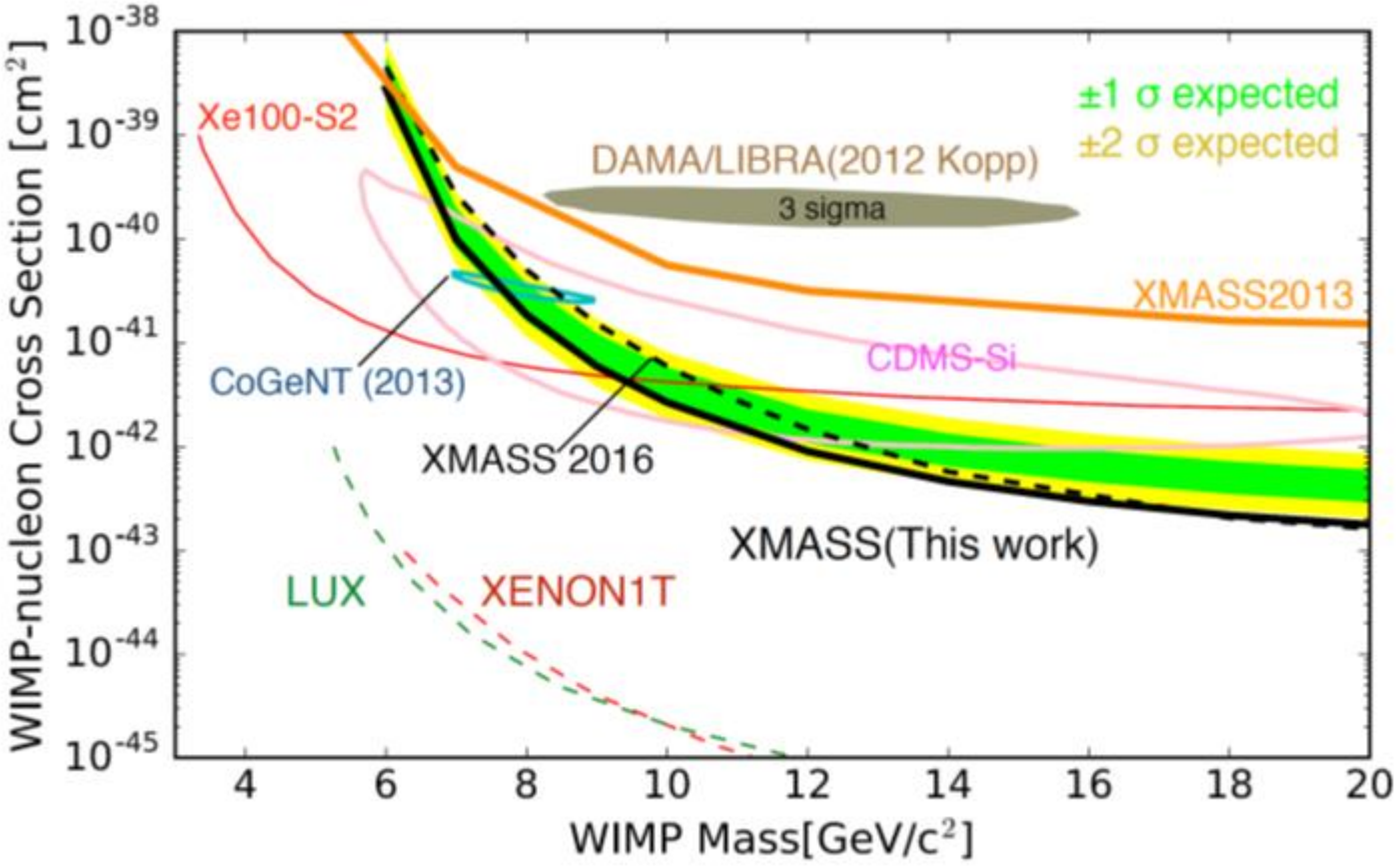


- Large mass (832 kg)
- Data set 2013/11/20 - 2016/07/20 (800.0 live days)
- XMASS (1.82 ton x year) ⇔ DAMA/LIBRA (1.33 ton x year)
  =>Current statistics is larger than that of DAMA/LIBRA (2013)

- Stable detector operation especially during run2.
  run1 +/-2.4%, run2 +/-0.5%

- Low energy threshold: 1.0 keVee (4.8 keVnr) (15PE/keV)
- Likelihood analysis

Modulation analysis: WIMP results

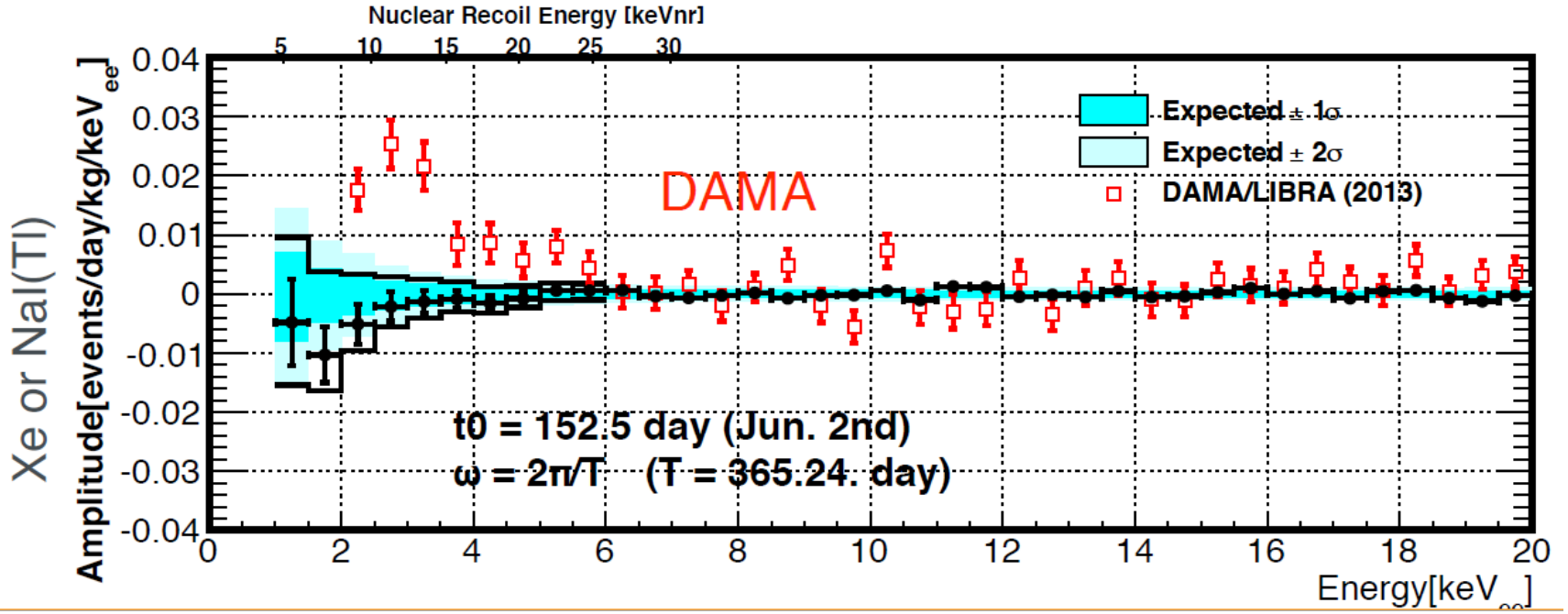


- Assuming WIMP (standard halo model)
  - T= 1year, t_0=152.5 day (fixed)
  - v_0=232km/s, v_{esc}=544km/s
  - ρ_{DM}=0.3GeV/cm^3
- WIMP mass range 6 to 20 GeV/c^2
- Exclude DAMA/LIBRA allowed region by modulation search
  <1.9 x 10-41cm2 (90% CL) @ 8GeV

Model independent case

- Without assuming any specific model except for T=1 year, t_0=152.5 day
- Includes both NR and e/γ signals
- Null hypothesis p-value is 0.11 (1.6 σ)
- Most stringent amplitude for modulation search.
- When models assumed, the relation btw NaI and Xe will be changed.

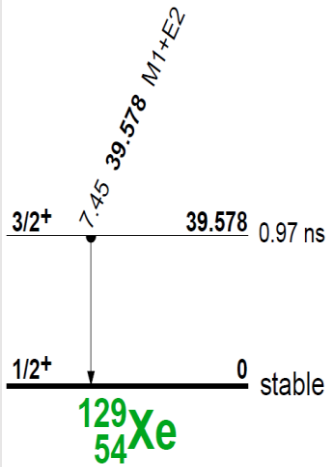
Experiment	Amplitude 10^{-3} (counts/day/kg/keVee)
DAMA/LIBRA(2013)	25@2.75 keVee
XENON100(2017)	1.67±0.73 (2.0-5.8 keVee), <3.1 90CL
XMASS-I (2017)	**< 1.3-3.2 (2-6 keVee) 90CL**



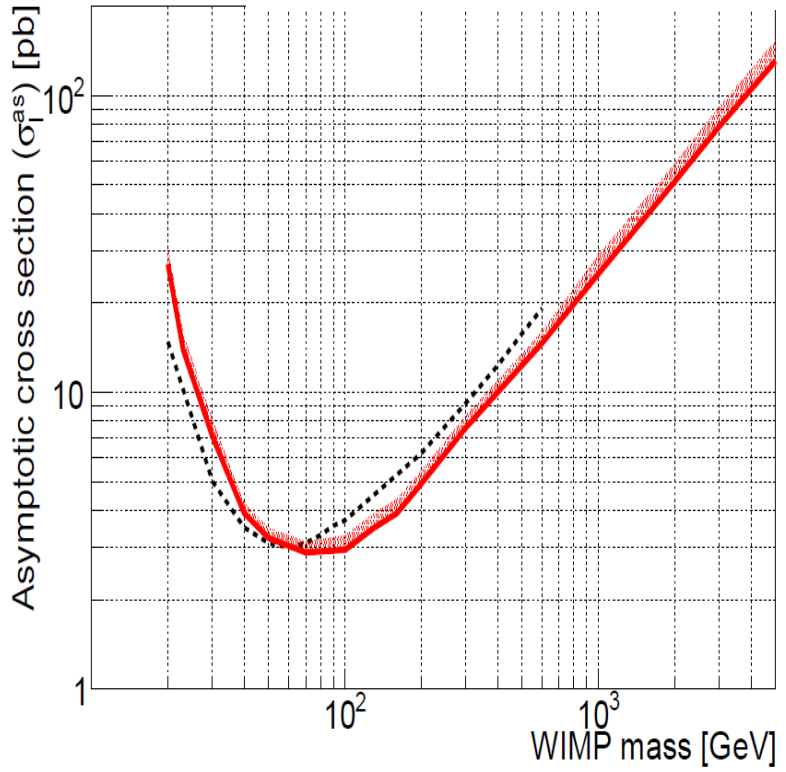
Search for ^{129}Xe inelastic scattering by WIMPs

- By inelastic scattering ^{129}Xe can be excited then emit gamma.
- $\chi + {}^{129}\mathrm{Xe} \rightarrow \chi + {}^{129}\mathrm{Xe}^*$
  $^{129}\mathrm{Xe}^* \rightarrow {}^{129}\mathrm{Xe} + \gamma$ (39.6keV)

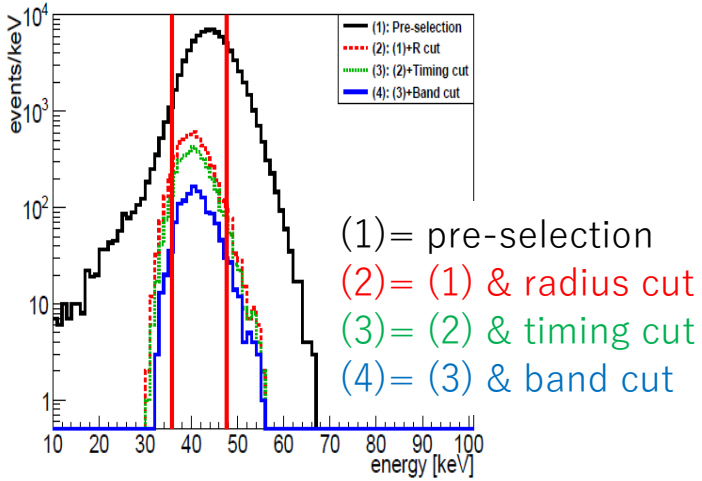
- Search peak signal.
- Natural abundance of ^{129}Xe: 26.4%
- Updated results will be published soon.



Red: XMASS (90% C.L. stat. only)
Pink band: XMASS (w/ sys. error)
Black: DAMA LXe 2000 (90% C.L.)

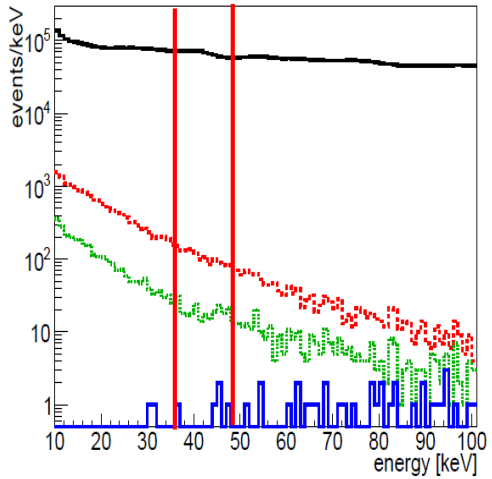


Signal MC for 50GeV WIMP



(1)= pre-selection
(2)= (1) & radius cut
(3)= (2) & timing cut
(4)= (3) & band cut

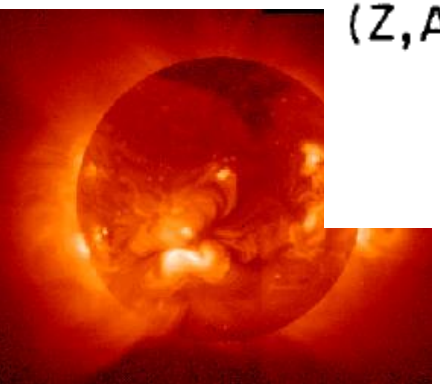
Observed data (165.9 days)



Published in PTEP 063C01 (2014)

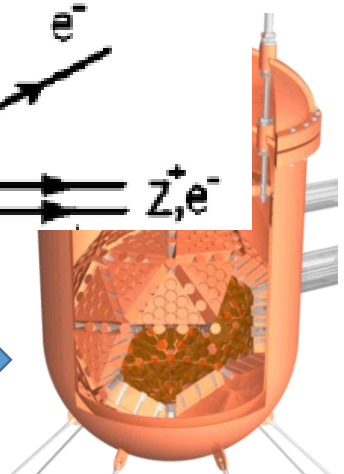
Search for solar axion

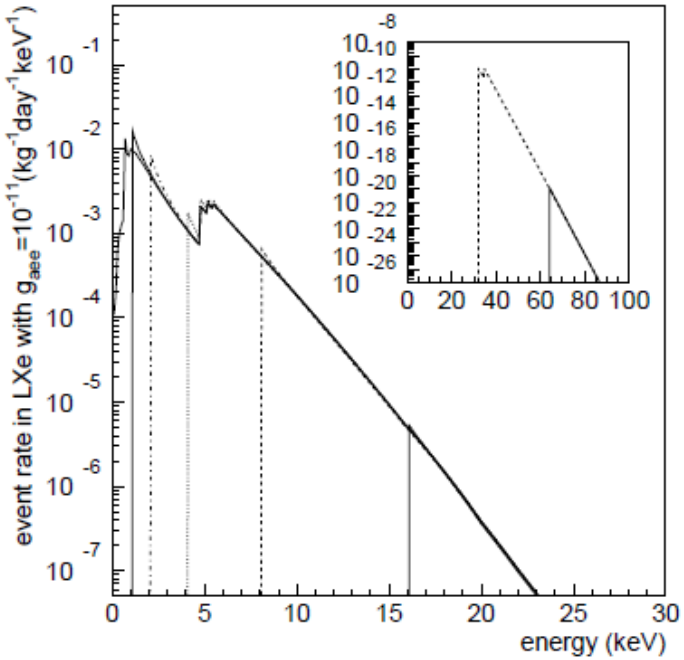
- Axion can be generated by Primakoff effect(γ+Z→a+Z), Compton scattering(e+γ→e+a) and bremsstrahlung (e+Z→e+a+Z).
- In XMASS, electron signal which can be caused by axio-electric effect (a+Z→e+Z) was searched. g_{aee}



Bremsstrahlung and Compton effect

Axio-electric effect



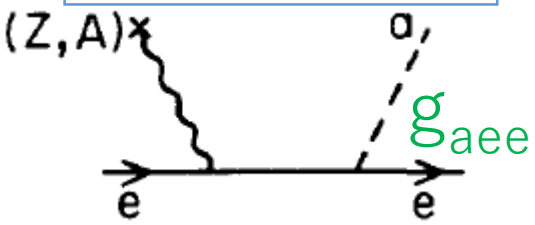


Expected energy spectrum of solar axion (ma=0, 1, 2, 4, 8, 16 keV/c^2)

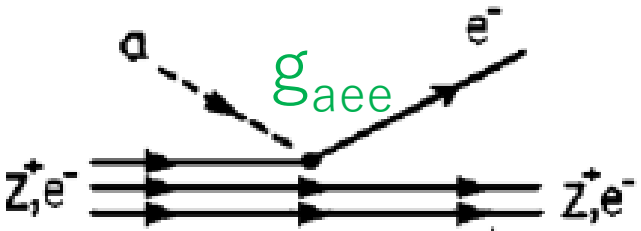
Search for solar axions

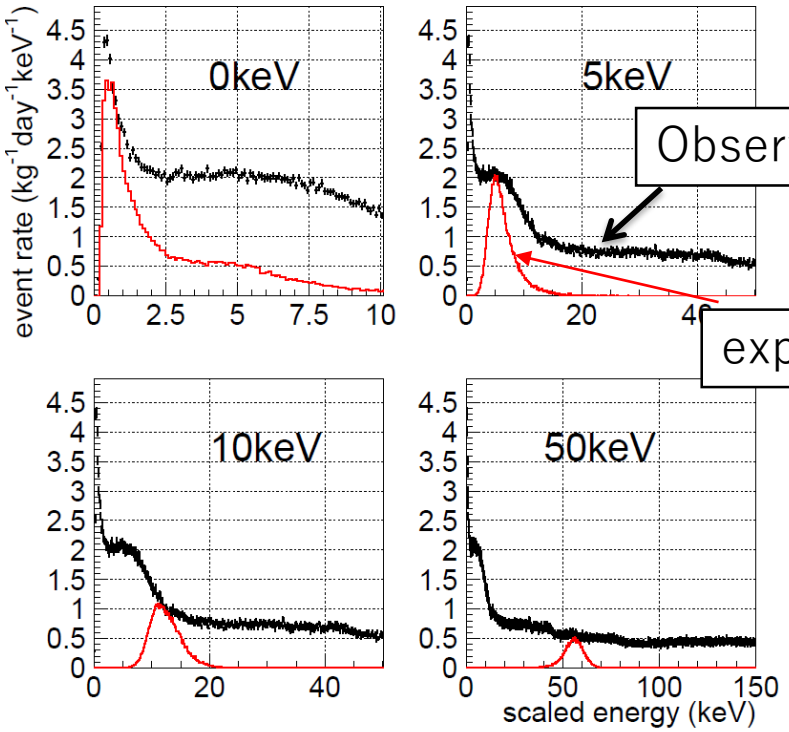
- 6.7 days data taken at 2012 was used.
- 90% confidence level limit were set as expected signal dose not exceed observed data

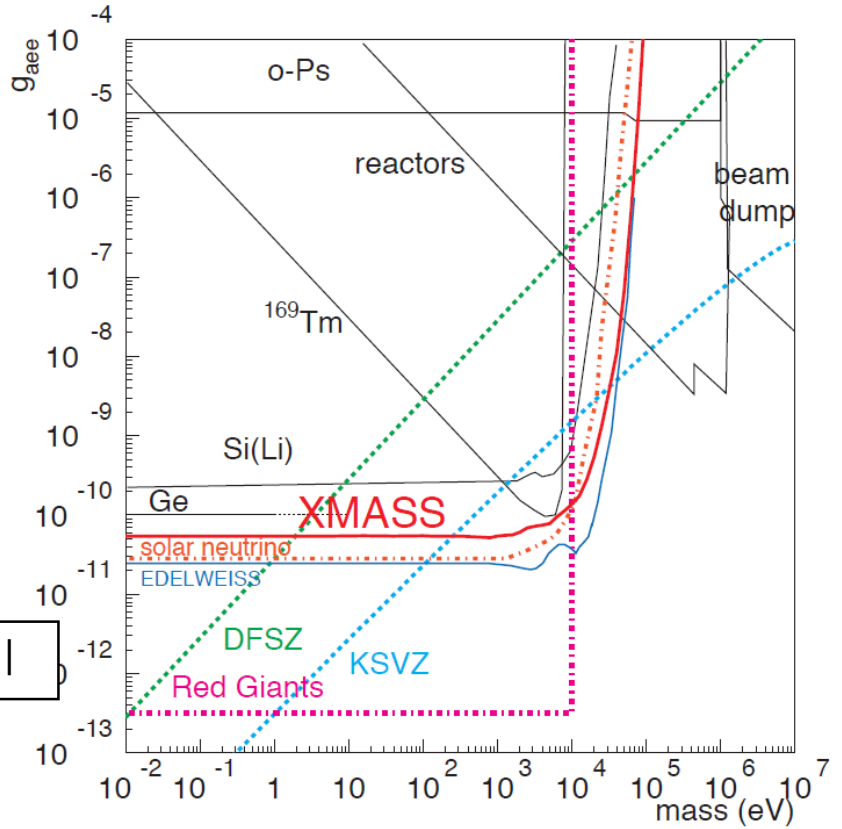
Bremsstrahlung and Compton effect



Axio-electric effect





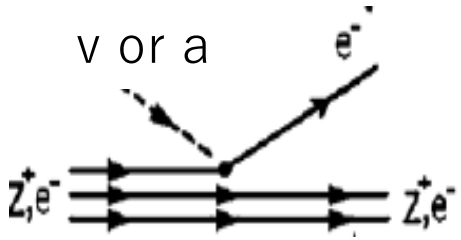


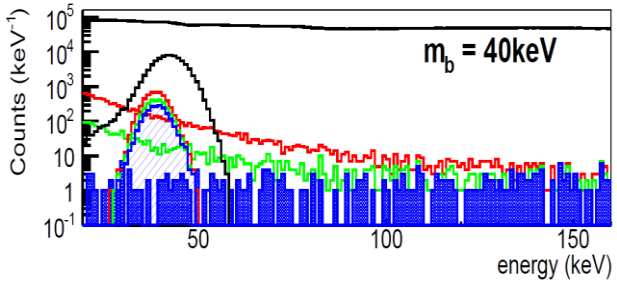
Published in Phys. Lett. B 724 46 (2013)

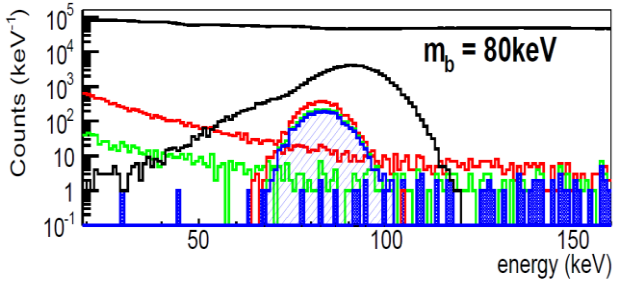
Search for bosonic super-WIMPs (1/2)

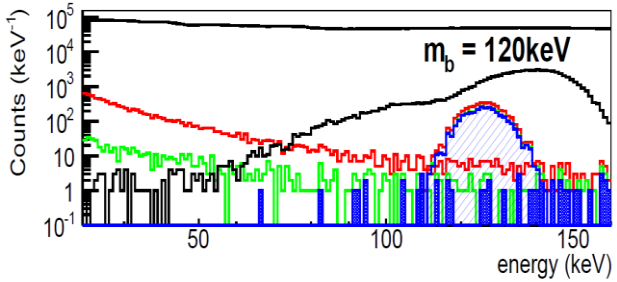
- Lighter and more weekly interacting than WIMPs
- Candidate for warm dark matter
- It can be pseudoscaler(ALP) or vector boson(Hidden photon).
- For vector boson, this analysis was the first experimental constraint.

- It can be detected by absorption of the particle, which is similar to the photoelectric effect.
- Search for mono-energetic peak at the mass of the particle





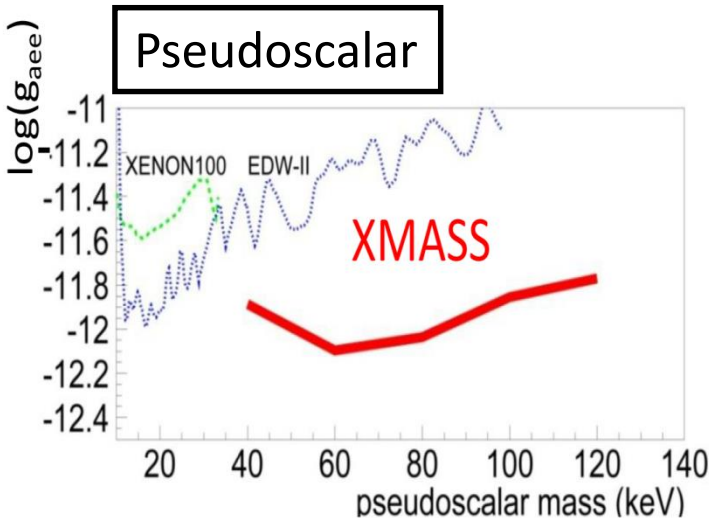


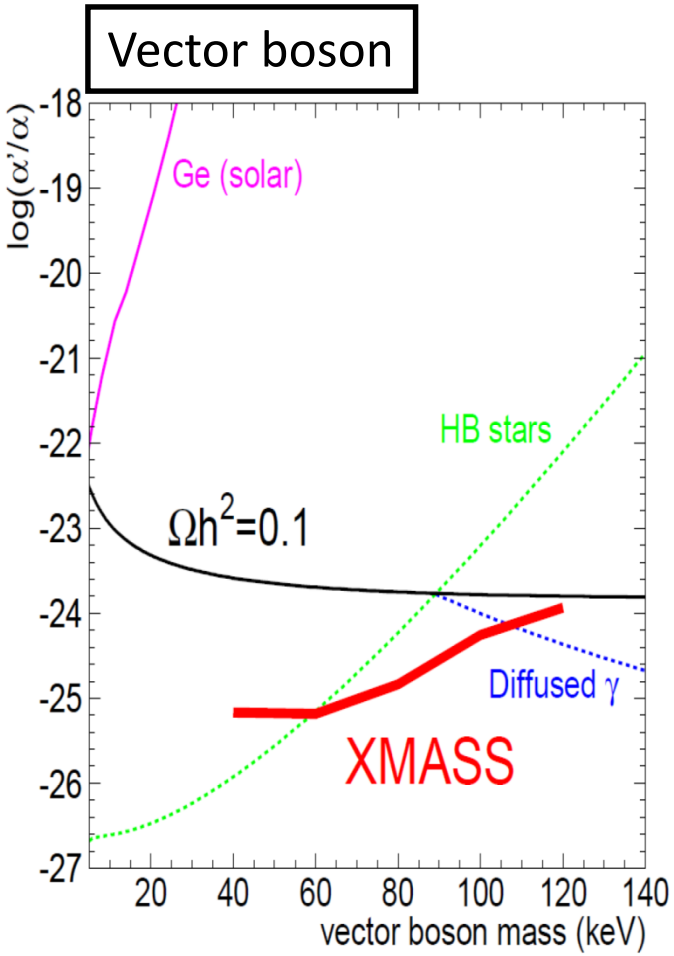


Published in Phys. Rev. Lett. 113, 121301 (2014)

Search for bosonic super-WIMPs (2/2)

- For vector boson case (Hidden photon)
  - The first direct search in the 40–120 keV range.
  - The limit excludes the possibility that such particles constitute all of dark matter.
- For pseudoscaler case (ALP)
  - The most stringent direct constraint on g_{aee}.
- Updated results will be published soon.



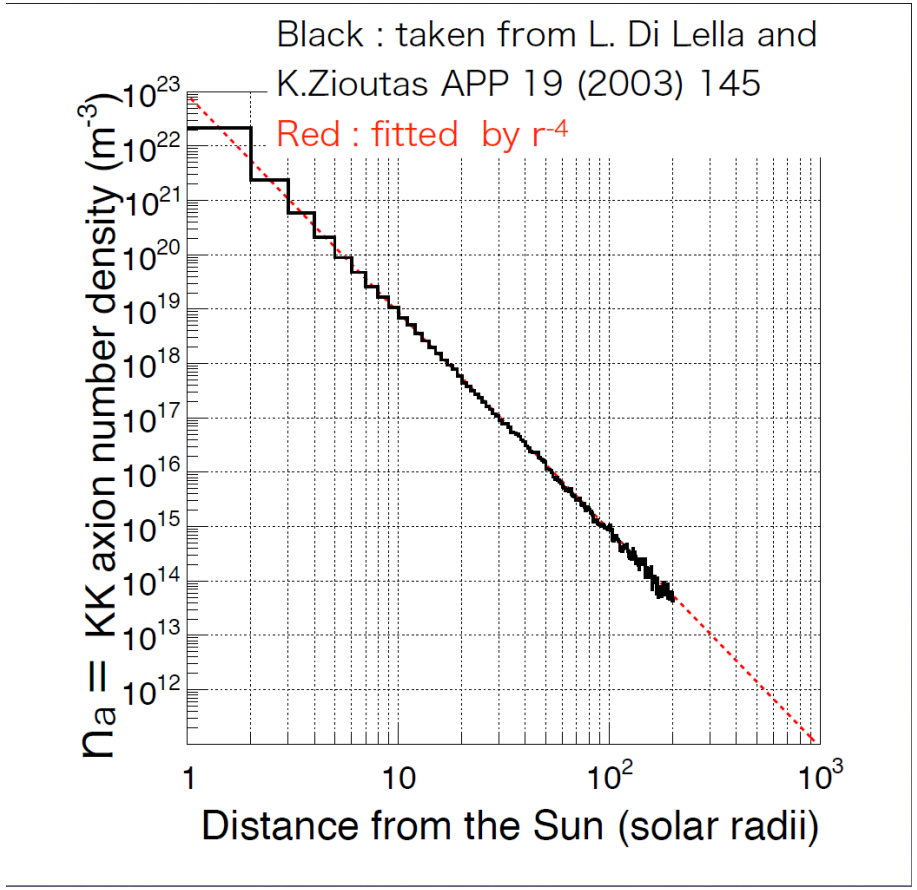


Solar KK axion search

- In the large extra dimension model, motions of a particle can be seen as mass state of Kaluza-Klein (KK) excitations.
- Axions may be able to propagate and acquire KK excitations, acquires an infinite tower of KK modes where the lowest KK state is the normal PQ axions.

- KK axion would be produced in the Sun via the Primakoff effect (γ Z→aZ) and a photon coalescence mechanism (γ γ →a).
- A small fraction is trapped by the gravity of the Sun.
- Such solar/stellar KK axion can explain the solar corona problem by massive axion decay. High temperature of the solar corona ~10^6 K.
- Search KK axion decay into two photons inside the detector.

Expected KK axion number of density vs distance from sun.



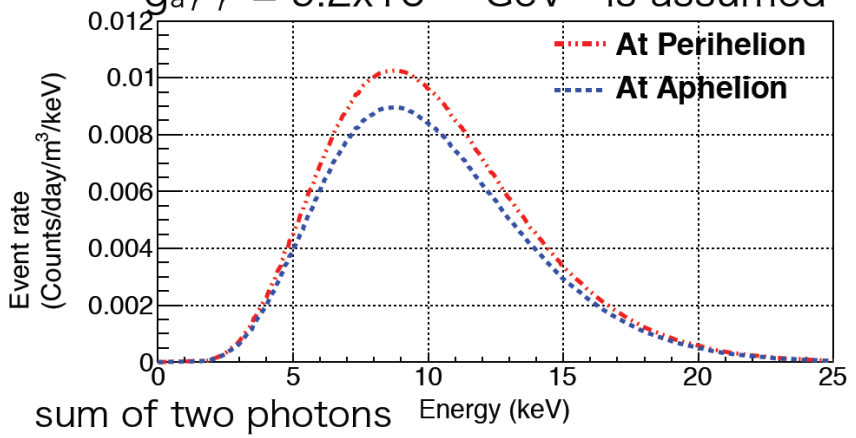
Solar KK axion search

- Caused by the change of distance from the Sun, signal modulation is expected.
- Searched modulation signal.
- First experimental constraint for KK solar axion.
- Published in PTEP

  Volume 2017, Issue 10,

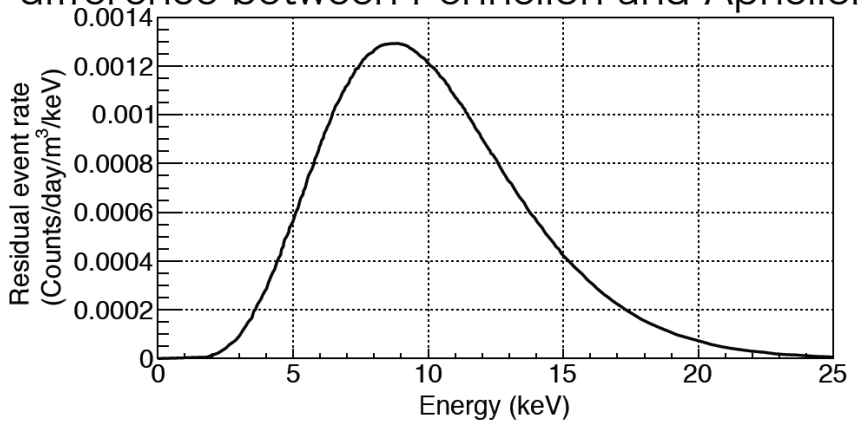
  1 October 2017, 103C01,

$g_{a\gamma\gamma}$ = 9.2x10^{-14} GeV^{-1} is assumed

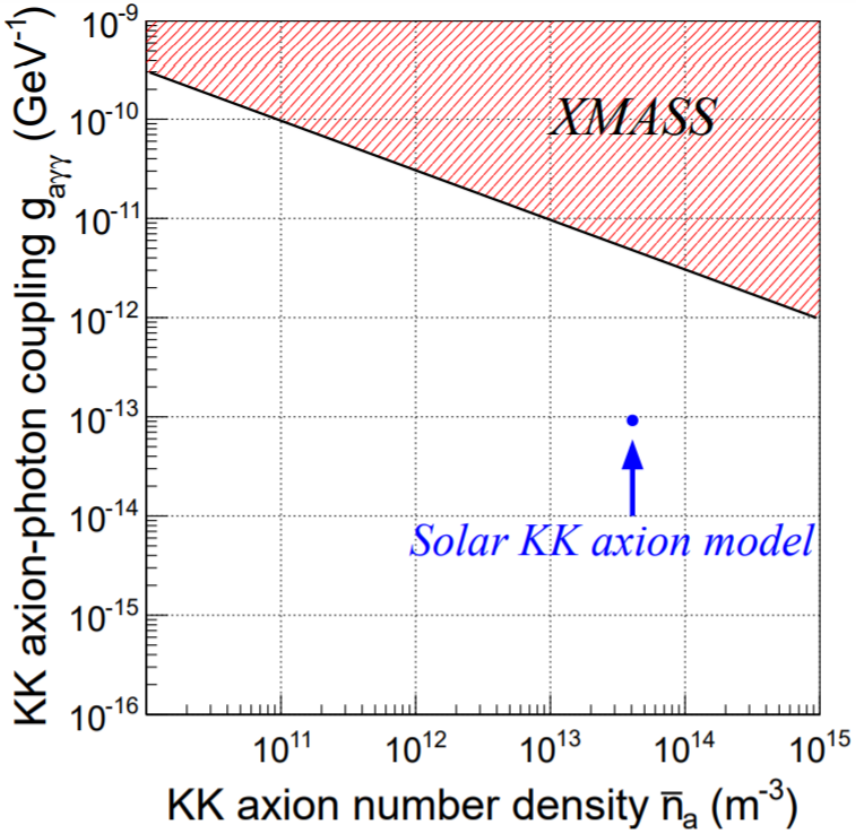


sum of two photons

difference between Perihelion and Aphelion



Result of search



Blue point as a benchmark
from L. Di Lella and K.Zioutas APP 19 (2003) 145
To explain X-ray surface brightness of the quiet Sun

$$R = (2.5 \times 10^{11} m^{-3} day^{-1})(\frac{g_{a\gamma\gamma}}{GeV^{-1}})^2(\frac{n_a}{m^{-3}})$$

Summary

- XMASS
  - Single phase liquid xenon detector.
  - Stable data taking is ongoing from 2013
- Many targets are searched with XMASS.
  - WIMP
    - Search with fiducialized volume.
      - 705.88 live days data
      - 2.2×10^{-44} cm^2 for 60 GeV WIMP mass
    - Modulation.
      - 2.7 years of data. (800 live days x 832 kg)
      - No significant modulation.
    - Inelastic search.
  - Solar axion.
  - Bosonic super WIMPs.
  - Solar KK axion