

# Direct dark matter search with XMASS: modulation analysis

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**Abstract.** Dark matter search by means of the annual modulation was done using large single-phase liquid-xenon detector, XMASS. With the data from November-2013 to March-2015, model independent analysis showed a weak modulation effect, however, the result can be explained by a fluctuation of the background at the level of 7-17%. If we assume the standard weekly interacting massive particles dark matter, we exclude almost all the allowed region claimed by the DAMA/LIBRA experiment. This is the first extensive search over their allowed region exploiting the annual modulation with high statistics data.

## 1. Introduction

Various astronomical observations provide strong evidence for a large amount of dark matter in the universe. However, its nature is still unknown. Among various candidates of dark matter, one of the most well-motivated dark matter is Weakly interacting massive particles (WIMPs). Although many experiments have searched for WIMPs, high sensitive experiments such as LUX, XENON100 have not found yet. Moreover, LHC has not showed any indication of WIMP candidate particles. On the other hand, DAMA/LIBRA experiment claimed that they observed the positive annually modulated signal with more than  $9\sigma$  in the 1.33 ton-years of data taken over the 13 annual cycles with 100-250kg of NaI scintillator crystals [1]. Their signal can be due to light WIMPs or the electron recoil signal from other types of dark matter. Since XMASS is sensitive not only to nuclear recoils but also electron recoils, various candidates of dark matter can be searched for. The XMASS detector is also large and is capable to search the signal with a compatible exposure to DAMA/LIBRA. We report dark matter search with XMASS using the annual modulation signal.

## 2. XMASS project

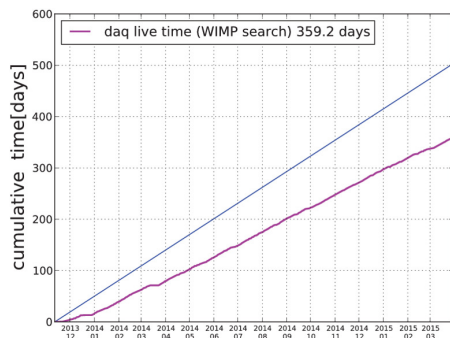
The XMASS project aims at detecting dark matter, pp and  $^7\text{Be}$  solar neutrinos, and neutrino less double beta decay using large volume of pure liquid xenon. The original idea is presented in Ref. [2]. The first physics target is to detect dark matter. The XMASS detector [3] is located in the Kamioka mine 1000m underneath the top of Mt. Ikenoyama (i.e. 2700 m water equivalent underground) in Japan. The detector consists of two components, the inner and outer detectors (ID and OD, respectively). The ID is equipped with 642 inward-facing photomultiplier tubes



(PMTs) in an approximate spherical shape in a copper vessel filled with pure liquid xenon. Six hundred and thirty hexagonal PMTs (HAMAMATSU R10789-11) and twelve round PMTs (HAMAMATSU R10789-11MOD) are mounted in an oxygen free high conductivity (OFHC) copper holder with an approximately spherical shape called a pentakis-dodecahedron. The entire structure is immersed in liquid xenon. The amount of liquid xenon in the sensitive region is 832 kg. The vessel which holds liquid xenon and the PMT holder is made of OFHC copper and the size is 1120 mm in diameter. To reduce the amount of liquid xenon, an OFHC copper filler is installed in the gap between the PMT holder and the inner vessel. The vessel is covered with another vessel for vacuum insulation. The ID is installed at the centre of the OD, which is a cylindrical water tank with seventy two 20-in. PMTs. The OD is used as an active shield for cosmic ray muons and a passive shield for low-energy gamma rays and neutrons. Construction of the detector started in April 2007 and was completed in September 2010. Commissioning runs were conducted from October 2010 to June 2012 and we have published various results [4, 5, 6, 7] thanks to the high light yield and low background. In the commissioning run, we found major background coming from the PMT part. To minimize the background contribution, detector refurbishment are performed. Data taking then restarted in November-2013.

### 3. Modulation analysis

Data until March-2015 is used in this analysis. Figure 1 shows the accumulated livetime since November-2013. After the conservative good run selection, data for the analysis is selected. Total livetime is estimated to be 359.2 days.

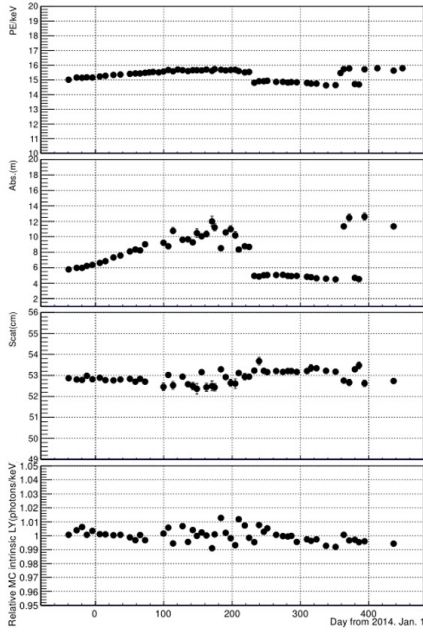


**Figure 1.** Accumulated livetime of XMASS data taking.

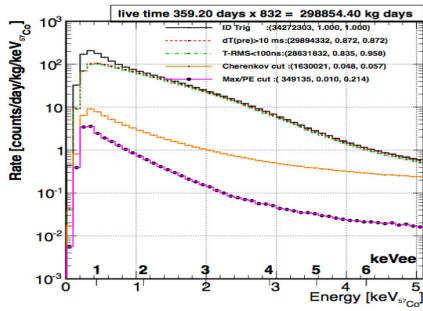
To monitor the detector stability, we have been carried out weekly  $^{57}\text{Co}$  source calibration to monitor photoelectron (PE) yield. We observed PE yield changed at the power outage. According to the MC simulation, it is due to the change of the absorption parameter. As shown in Figure 2, MC deduced scattering length and scintillation light yield are stable within about  $\pm 0.5\%$  level.

Data selection has the following five steps: (1) Trigger should be issued by ID. Four or more PMTs should have hits simultaneously. No OD trigger should not be issued. Muon and muon induced events are removed. (2) Timing difference to the previous events should be more than 10 msec. Noise events are removed. (3) Timing RMS of the event should less than 100 nsec. Remaining noise events are removed. (4) Number of hits in the first 20 nsec over total number of hits should be 0.6 or less. Cherenkov events are removed. (5) Maximum PE in one PMT over total PE cut. Events in front of PMTs are removed. Figure 3 and 4 shows the energy distribution at each reduction steps in data and WIMP MC, respectively.

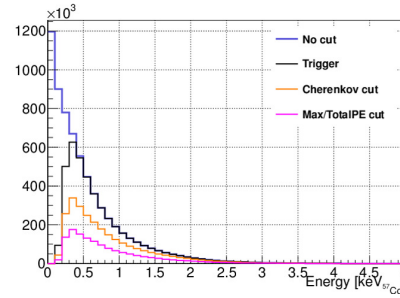
The dominant systematic error is due to the efficiency dependence on the absorption length. As shown in Figure 2, absorption changes in time. The PE yield changes in time effect the efficiency of the scintillation light response. Magenta region in Figure 5 and 6 show the uncertainty to the relative efficiency.



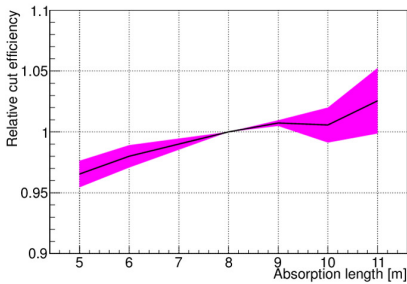
**Figure 2.** Detector stability. Each figure shows: (top) Observed PE yield (PE/keV<sub>57Co</sub>), (second top) MC deduced absorption length (m), (third top) MC deduced scattering length (cm), (bottom) MC deduced scintillation light yield.



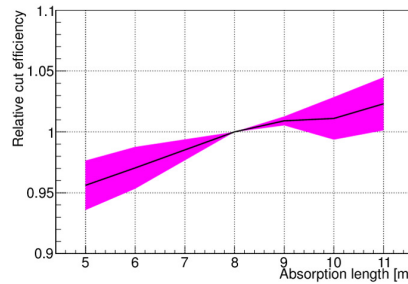
**Figure 3.** Energy distribution after each 0.5 < E < 1.0keV<sub>57Co</sub>.



**Figure 4.** Energy distribution after each reduction step in 20 GeV/c<sup>2</sup> WIMP MC simulation.



**Figure 5.** Relative efficiency to absorption length is 8 m data in the 0.5 < E < 1.0keV<sub>57Co</sub>.



**Figure 6.** Relative efficiency to absorption length is 8 m data in the 1.0 keV<sub>57Co</sub> < E.

For the modulation analysis, the remained data is divided into 38 time bins and 45 energy bins (0.1 keV<sub>57Co</sub>/bin in 0.5-5.0keV<sub>57Co</sub>. Energy with keV<sub>57Co</sub> unit is obtained from the PE

normalized by the scaled factor which is estimated using the  $^{57}\text{Co}$  122 keV calibration). Two independent analyses were performed using different  $\chi^2$  definition. Method 1 (pull term) uses the following  $\chi^2$  definition.  $R_j^{obs}$ ,  $R_{i,j}^{Pred}$  are the number of observed and predicted events, respectively.  $K_{i,j}$  represents the  $1\sigma$  correlated systematic error on the expected event rate.  $\alpha$  is the pull term.

$$\chi^2 = \sum_i^{E-bins} \left( \sum_j^{t-bins} \frac{(R_j^{obs} - R_{i,j}^{Pred} - \alpha K_{i,j})^2}{\sigma(stat)_j^2} \right) + \alpha^2 \quad (1)$$

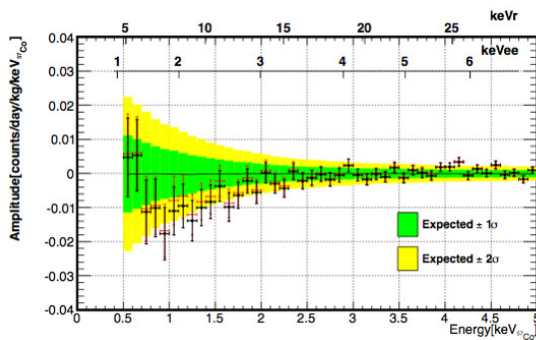
Method 2 (covariance matrix) use the following  $\chi^2$  definition. The matrices  $V_{stat}$  and  $V_{sys}$  contain the statistical and systematic error terms, respectively.

$$\chi^2 = \sum_{i,j}^{E,t-bins} (R_i^{obs} - R_i^{Pred})(V_{stat} + V_{sys})_{ij}^{-1} (R_i^{obs} - R_i^{Pred}) \quad (2)$$

In both methods, annual modulation signal is searched for without any model assumption. Phase and term are fixed at  $t_0 = 152.5$  days and  $T = 365.25$  days, respectively. Modulation amplitude,  $A_i$ , and unmodulated amplitude,  $C_i$ , are fitted by the following equation.

$$R^{Pred}(E_i, t_j) = C_i + A_i \cos 2\pi(t_j - t_0)/T \quad (3)$$

To calculate the probability to have the modulation, we made dummy data sets based on our averaged energy spectrum. Taking into account the systematic uncertainty from absorption length dependence, we made 10,000 unmodulated dummy data sets. Figure 7 shows the modulation search result. The small negative amplitude is observed in 0.5-3keV $_{ee}$  region. But both results are consistent and not statistically significant. P-value in method 1 and 2 are 0.068 and 0.17, respectively.

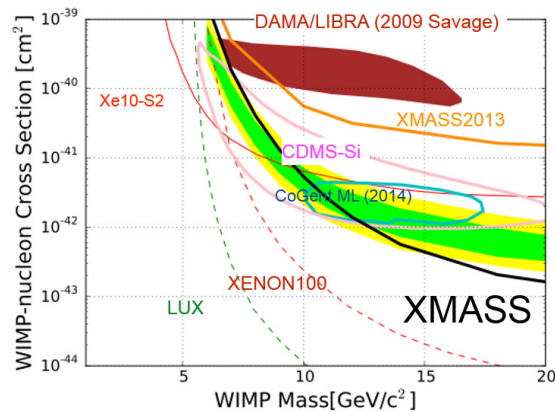


**Figure 7.** Modulation amplitude. Black and Red are obtained by Method 1 and 2, respectively. Green and yellow area shows expected one and two sigma region assuming no modulation calculated by toy MC.

Standard WIMP search is also performed using the following equation.

$$R^{Pred}(E_i, t_j) = C_i + \sigma A(m_\chi, E_i) \cos 2\pi(t_j - t_0)/T \quad (4)$$

, where  $\sigma$  is the WIMP-nucleon cross section and  $m_\chi$  is the WIMP mass. In this calculation we assume that  $v_{esc} = 650.0$  km/s,  $v_0 = 220.0$  km/s, and  $\rho_{dm} = 0.3$  GeV/cm $^3$ . No significant excesses are observed. Figure 8 shows the upper limit of XMASS using method 1. The difference between method 1 and 2 are within 30%. DAMA/LIBRA region is mostly excluded by our measurement. Detail of this analysis can be obtained at [8].



**Figure 8.** Standard WIMP search. Black line shows the upper limit obtained by the XMASS search compared to other experiments.

#### 4. Summary

Using large single-phase liquid-xenon detector, XMASS, we performed dark matter search by means of the annual modulation. With the 359.2 days livetime  $\times$  832kg of exposure data, model independent analysis showed a weak modulation effect, however, the result can be explained by a fluctuation of the background. In case of the standard WIMPs dark matter search, we exclude almost all the allowed region claimed by the DAMA/LIBRA experiment. This is the first extensive search over their allowed region exploiting the annual modulation with high statistics data. We continue to take second year of data to obtain more sensitive result with smaller systematic uncertainties.

#### References

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