Search for exotic neutrino interactions using solar neutrinos in XMASS-I

arXiv:2005.11891
Submitted to PLB

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on behalf of the XMASS collaboration

Abstract : We have searched for exotic neutrino-electron interactions that could be produced by a neutrino millicharge, by a neutrino magnetic moment, or by dark photons using solar neutrinos in the XMASS-I liquid xenon detector. No significant signals have been observed with predicting the backgrounds in detector and upper limit of these constant values are estimated as preliminary. For the neutrino millicharge search, 5.4×10^{-11}e for all flavors of neutrino is obtained. We also set individual flavors to be 7.3×10^{-12} e for νe, 1.1×10^{-11} e for νμ, and 1.1×10^{-11} e for ντ. These limits ate the most stringent yet obtained from direct measurements. For the neutrino magnetic moment search, 1.8×10^{-10} μ_B is obtained. In addition, we obtain upper limits for the coupling constant of dark photons in the $U(1)_{B\text{-}L}$ model and almost exclude the possibility to understand the muon *g-2* anomaly by dark photons.

1. introduction

- XMASS: a multi purpose experiment with liquid xenon (target : dark matter, low energy solar neutrino, neutrino-less double beta decay.)
  - ✓ Features : **Low energy threshold, low backgrounds and large target mass.**

In XMASS, it is possible to verify the topics of low energy neutrino physics, ex) exotic neutrino interactions using solar neutrinos.

- ✓ Neutrino millicharge : The existence of a neutrino millicharge would give hints on models beyond SM. Also an experimental study on millicharge of individual neutrino flavors is still of interest.
- ✓ Neutrino magnetic moment : Predicted by minimally extension of SM as $3.2\times10^{-19}(m_\nu/1\text{eV})\ \mu_B$ (Very small!) But other extensions of SM theory yield at currently observed level.
- ✓ Dark photon : contained the hidden sector and thought to influence the interactions of neutrinos. Now we assume the deriving from a gauged $U(1)_{B\text{-}L}$ symmetry.

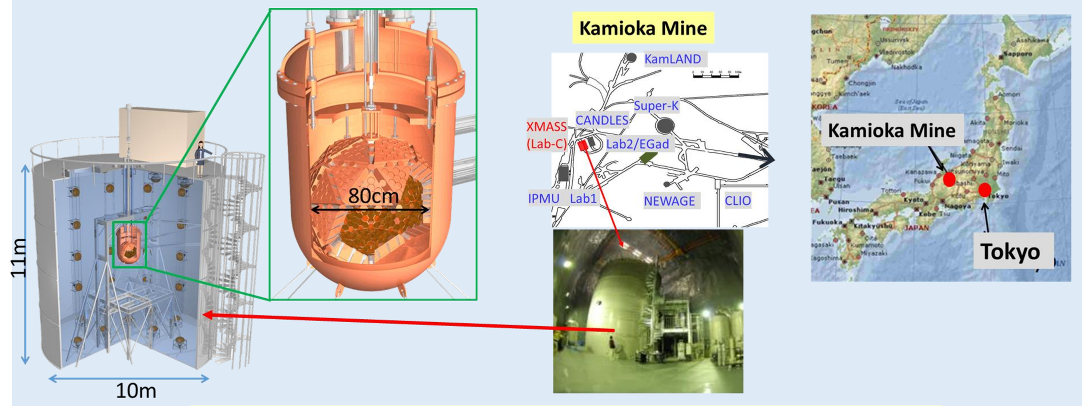
☐ *Low energy event increasing through exotic neutrino-electron interaction in xenon helps the search ability for these topics.*

☐ *Solar neutrinos (the largest available flux) is useful in this study*

2. XMASS detector

- Located 1,000 m underground (2,700 m.w.e.) at the Kamioka Observatory in Japan
- Liquid xenon detector
  - 832 kg of liquid xenon (-100 °C)
  - Single phase (scintillation only)
  - 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

Feb. 2019 : Observation completed.



XMASS detector : Site and detector view

3. Analysis method

Signal

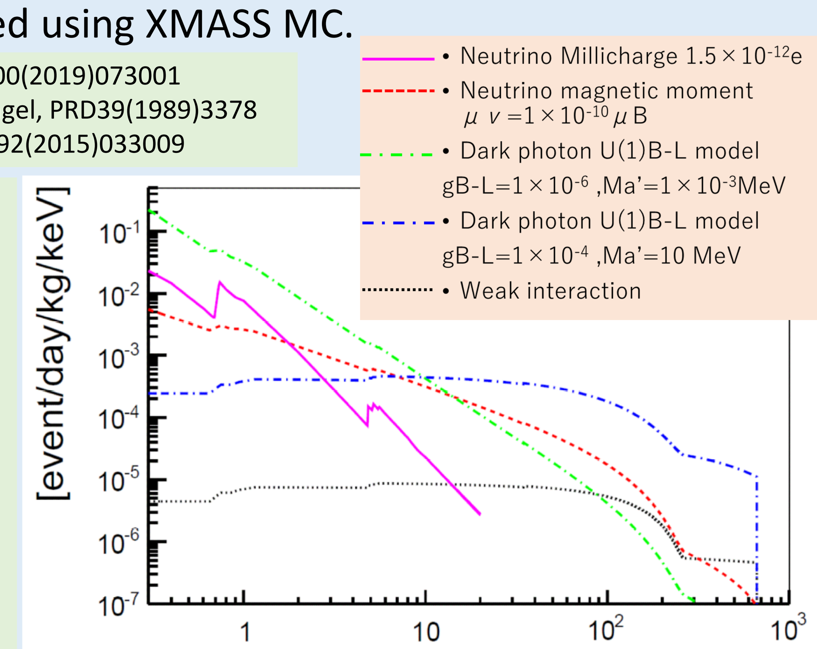
The total # of events N_{tot} in the process of an interaction between a neutrino and an electron produced by SM weak/exotic interactions :

$$\frac{dN_{tot}}{dT} = t\times N\times\int\left[\left(\frac{d\sigma_{\nu e^-}}{dT}\right)_{SM}+\left(\frac{d\sigma_{\nu e^-}}{dT}\right)_{ex}\right]\sum_{i=1}^{Z}\theta(T-B_i)\left(\frac{d\Phi_\nu}{dE_\nu}\right)dE_\nu$$

Signal MC is processed using XMASS MC.

Millicharge : C.Hsieh et al.,PRD100(2019)073001
Magnetic moment : P.Vogel&J.Engel, PRD39(1989)3378
Dark photon : S.Bilmis et al.,PRD92(2015)033009

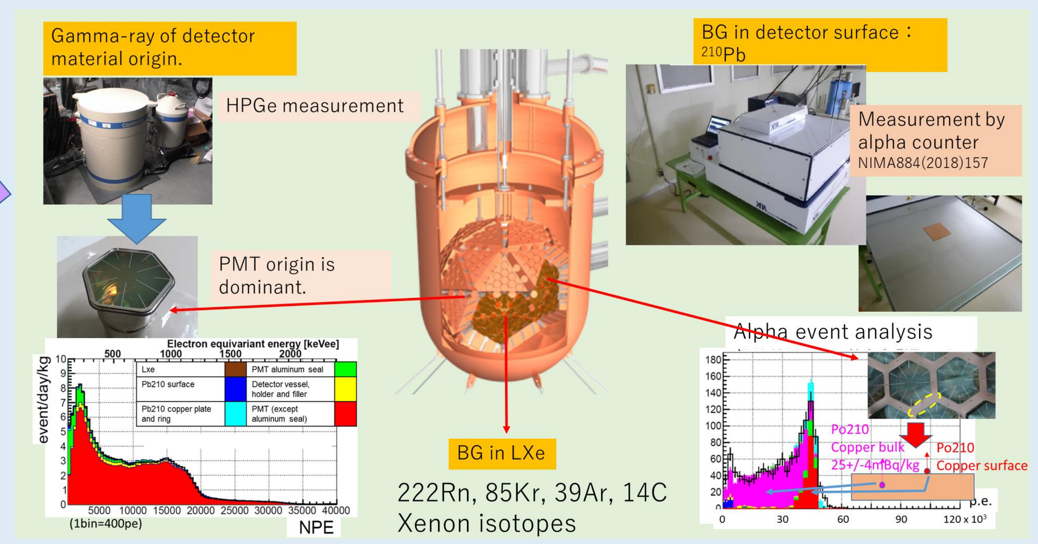
- ✓ Φ: solar neutrino flux (5.98×10^{10}cm^{-2}s^{-1} for pp chain and 5.00×10^{9}cm^{-2}s^{-1} ^{7}Be chain)
- ✓ Interference effect with weak interaction is assumed for dark photon analysis.
- ✓ Atomic effects : Free electron approximation for neutrino magnetic moment and dark photon analyses. Relastivistic random phase approximation for neutrino millicharge analysis.



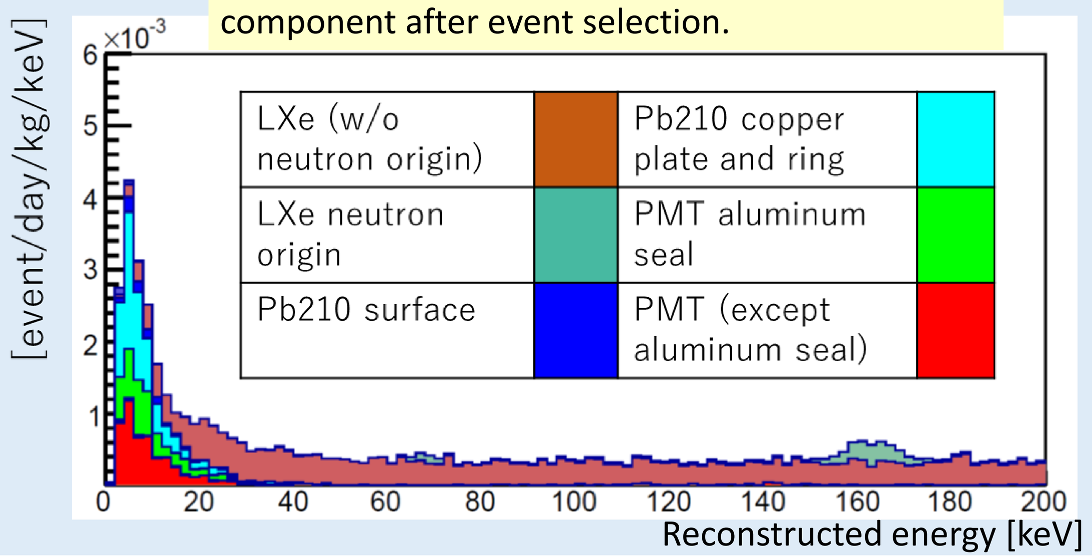
The deposited energy spectra for neutrino interactions in xenon

Background

- ✓ Background MC is generated using XMASS MC for each RI's decay mode and its activity.
- ✓ Several kind of method for RI estimation are applied
- ☐ For <30keV : ~90% of remaining BG is of detector surface origin (not internal BG).
- ☐ For > 30keV : Internal BGs are dominant components.



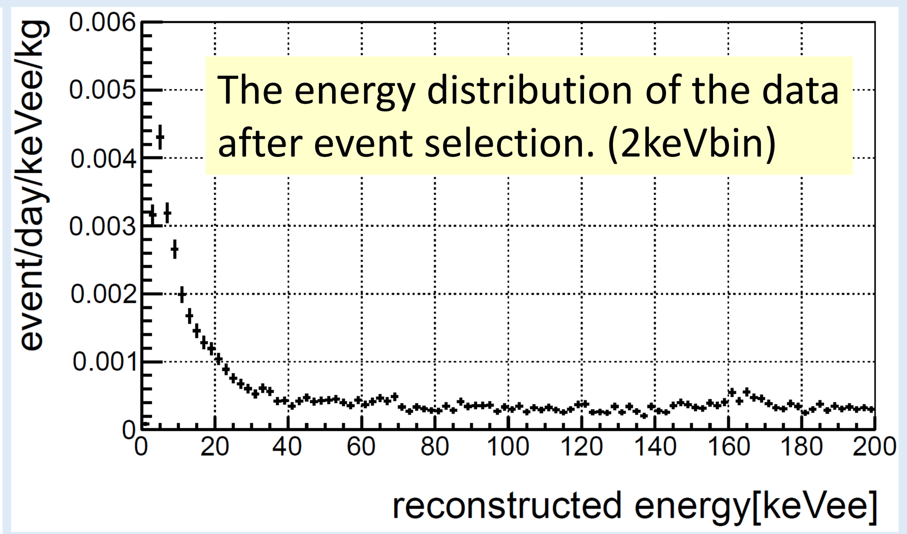
The energy distribution of the BG MC for each BG component after event selection.



Dataset and event selection

- ✓ 2013Nov-2016Mar. 711days livetime
- ✓ Cut criteria : noise event cut + Cherenkov event cut + Fiducial volume cut (Timing and PE base)
- ✓ Fiducial mass : 97kg of xenon
- ✓ *Same event selections are applied for data, signal MC and background MC*

The energy distribution of the data after event selection. (2keVbin)



Systematic uncertainty

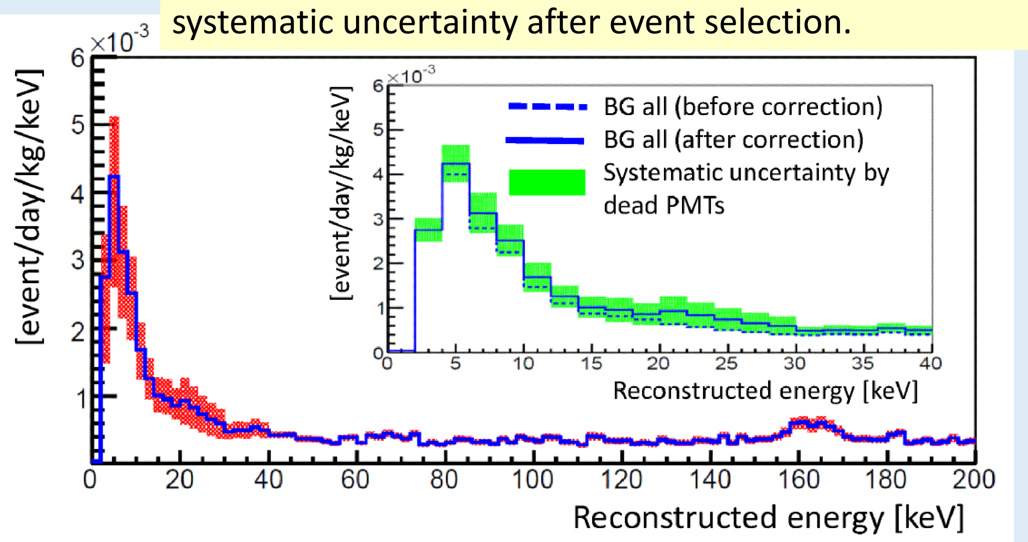
Signal

- ✓ Theoretical calculation :
- ☐ solar neutrino flux, The uncertainty in the cross section with atomic effect.
- ✓ The detector response :
- ☐ Scintillation efficiency, optical parameter / scintillation-decay time of xenon, the reduction efficiency.

Background

- ✓ The validity of reconstruction, dependence on optical properties of Lxe, detector response at detector surface and so on are treated as systematic errors.
- ✓ The background MC spectrum was corrected in order to take into account the systematic difference in the mis-reconstruction rate caused by dead PMTs.

The energy distribution of the BG MC for accumulated systematic uncertainty after event selection.



4. Search for neutrino-electron interactions

Fitting the energy spectrum

- ✓ Based on the BG estimate, we searched the signature of exotic interactions by fitting the energy spectrum of data, BGMC and respective signal MC. ⇒

$$\chi^2=\sum_i\frac{\left(D_i-\sum_j p(j)\left(B_{ij}+\sum_k \boldsymbol{\sigma}(\boldsymbol{B_{sys}})_{ijk}\cdot q(k)\right)-\alpha\cdot\left(S_i+\sum_l\sigma(S_{sys})_{il}\cdot r(l)\right)\right)^2}{\left(D_i+\sum_j p(j)^2\cdot\boldsymbol{\sigma}(\boldsymbol{B_{stat}})_{ij}^2+\alpha^2\sigma(S_{stat})_i^2\right)}+\sum_j\frac{(1-p(j))^2}{\boldsymbol{\sigma}(\boldsymbol{RI})_j^2}+\sum_k\frac{(q(k))^2}{1}+\sum_l\frac{(r(l))^2}{1}$$

(data; BGMC; Signal MC; Pull term χ^2)

※According to the majority of expected signal, the fitting energy range is changed : 2-15keV for millichagre, 2-200keV for others.

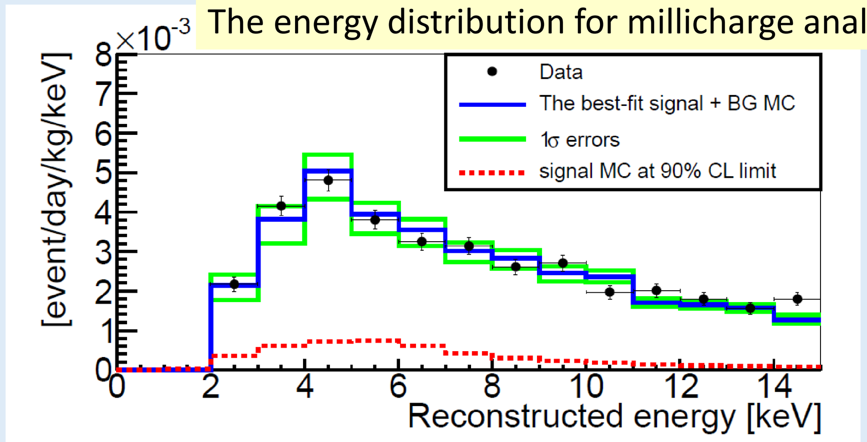
Neutrino millichagre (search for 2-15keV)

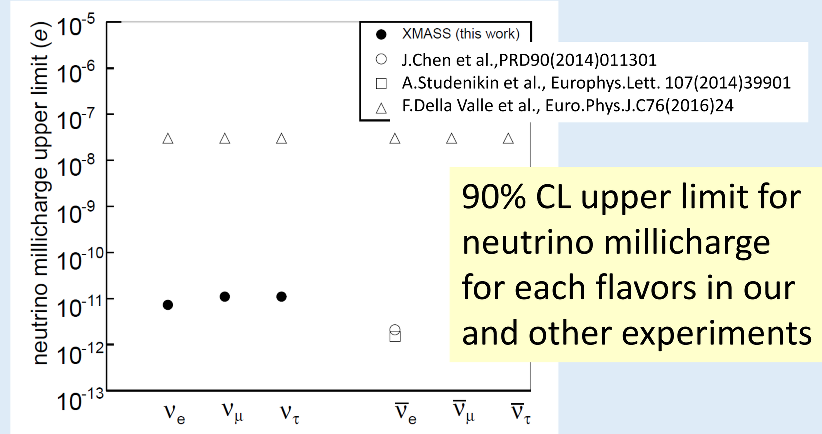
- ✓ No significant signal excess. Upper limit for millicharge (90%CL) : < 5.4×10^{-12}e

=> This limit for neutrino (not anti-neutrino) is more stringent than the previous experimental limit.

- ✓ Assuming the ratio of 3 neutrino flavor at Earth by neutrino oscillation, we set upper limits for each flavor : 7.3×10^{-12} e for ν_e, 1.1×10^{-11} e for ν_μ, and 1.1×10^{-11} e for ν_τ

The energy distribution for millicharge analysis



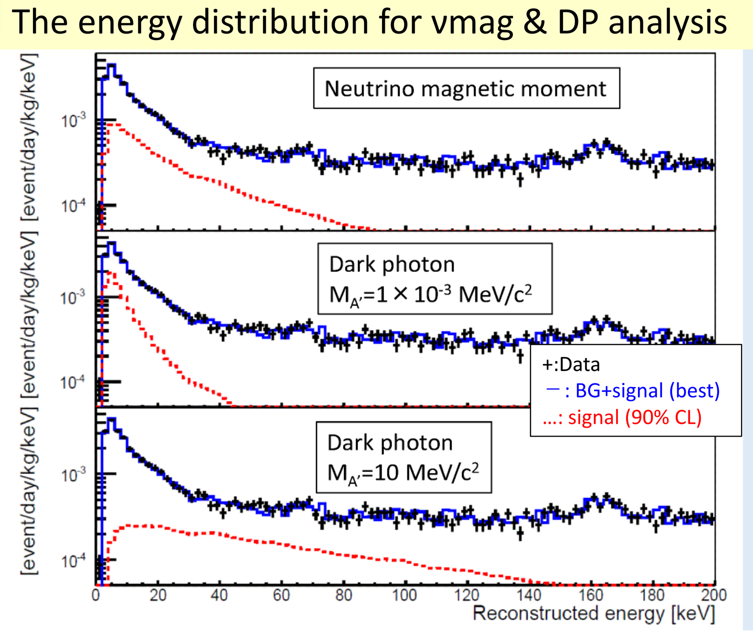


90% CL upper limit for neutrino millicharge for each flavors in our and other experiments

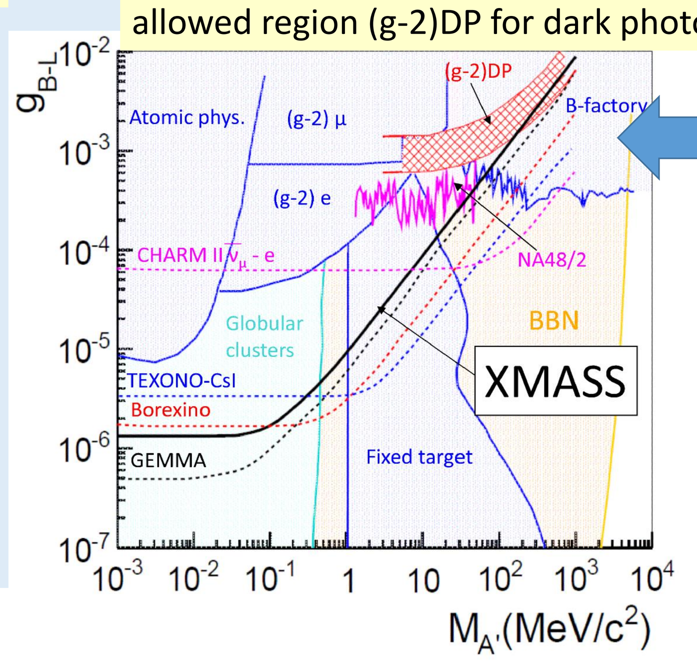
Neutrino magnetic moment & dark photon (search for 2-200keV)

- ✓ Neutrino magnetic moment : No significant signal excess. Upper limit (90%CL) : < $1.8\times10^{-10}\mu_B$
  ⇒First time to estimate using pp- solar neutrinos.
- ✓ (Experimental best limit : Borexino ^{7}Be as <$2.8\times10^{-11}\mu_B$) [M.Agostini et al., PRD96(2017)091103]
- ✓ Dark photon : searched the value of coupling constant $g_{B\text{-}L}$ in the mass range from $M_{A'}=1\times10^{-3}$MeV/c^2 to 1×10^3MeV/c^2.
- ✓ No significant signal excess, Upper limit of $g_{B\text{-}L}$(90%CL) : 1.3×10^{-6} for 1×10^{-3}MeV/c^2 and 8.8×10^{-5} for 10MeV/c^2.
- ✓ The most of parameter space for the g-2 dark photon prediction was excluded.

The energy distribution for vmag & DP analysis



90% CL exclusion limits (XMASS, others) and allowed region (g-2)DP for dark photon analysis.



Note : While the exclusion area derived in[S.Bilmis et. Al., PRD92(2015)033009] from other experiments' publications already excluded an area larger than the one excluded by our analysis, our analysis is a dedicated one, incorporating our full knowledge of the detector response and our validated background models.

5. Conclusions

- ✓ Search for exotic neutrino interactions (via neutrino millcharge, magnetic moment and dark photon) using solar neutrinos in XMASS-I .
- ✓ No significant signal excess were found. Upper limit for each property are estimated.
- ✓ For neutrino millicharge, the limits are the most stringent yet obtained from direct measurement.
- ✓ For dark photon, we almost exclude the area in which the dark photon can solve the g-2 anomaly.