Search for exotic neutrino interactions by XMASS-I detector

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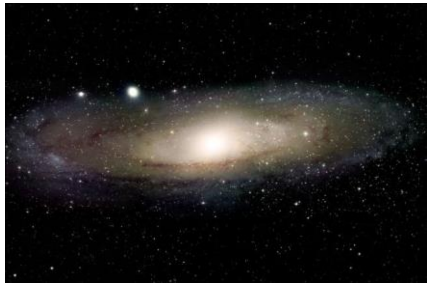
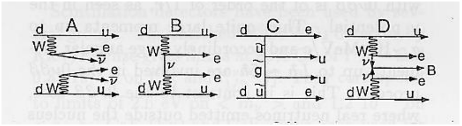
XMASS experiment

- Single phase (scintillation only) liquid xenon detector.
- Multi-purpose detector using LXe with ultra-low background.
  - Dark matter, solar neutrino $0\nu\beta\beta$ etc..
- Site : Kamioka Observatory, Japan.
- Data taking including commissioning and refurbishment phase since Sep.2010.
- Feb. 2019 : Observation completed.

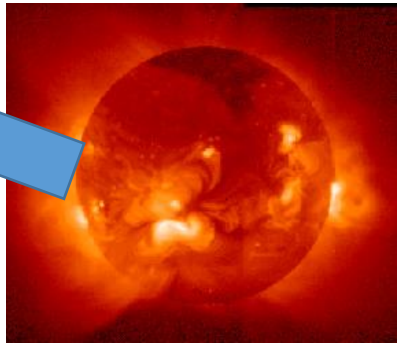


Neutrino-less double beta decay



Dark matter

Solar neutrino



2010	2011	2012	2013	2014	2015	2016	2017	2018	2019

Detector constructio n

Commissionin g run data taking

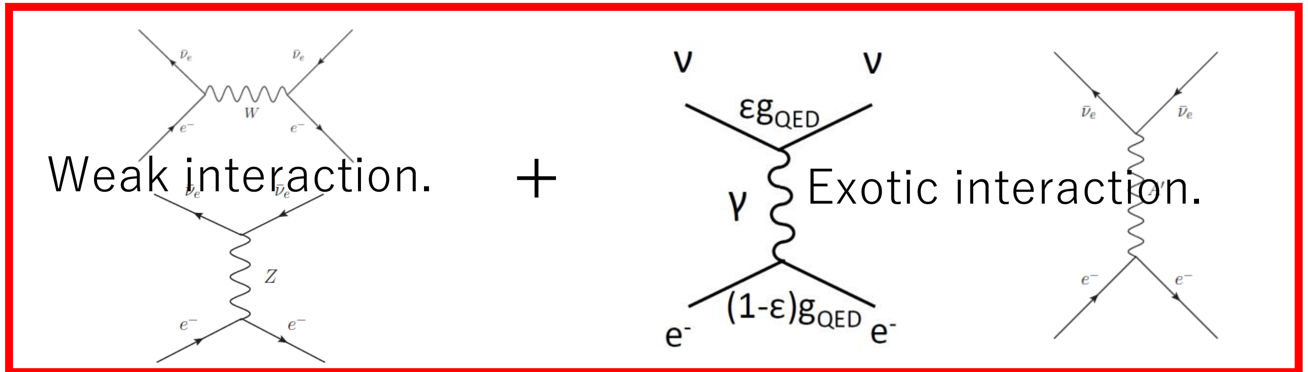
Detector refurbish ment

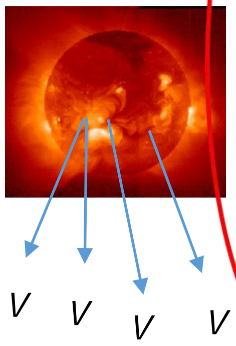
Data taking (-Feb.2019)

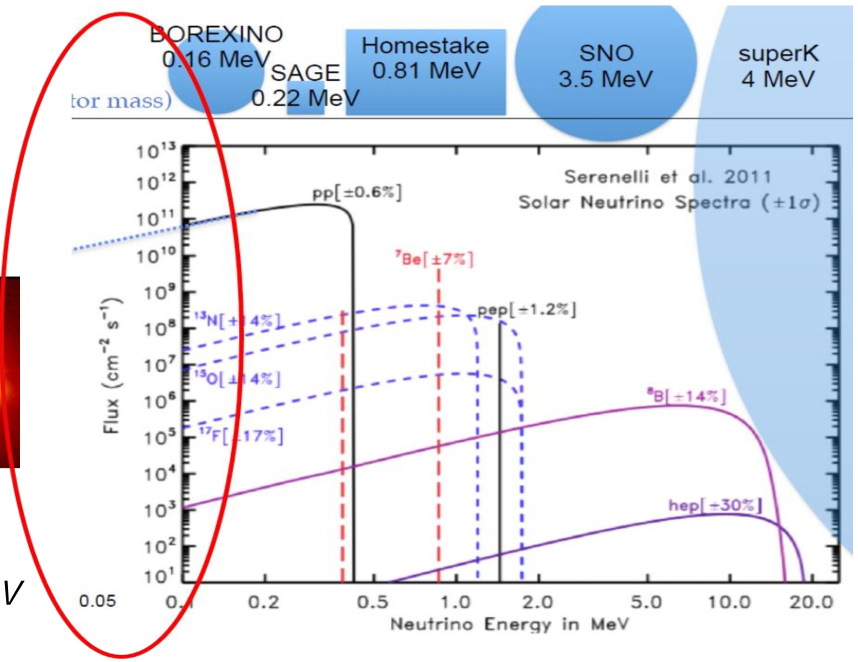
>5yrs continues operation

Search for exotic neutrino interactions using solar neutrinos

- Observation of solar neutrino via neutrino-electron weak interaction in current DM detectors ⇒ ~1/100 background reduction is required.
- Exotic neutrino interaction by expanding of standard model allows the increasing of the event in low energy region ⇒ More advantage in DM detector with low threshold.
- Search for exotic neutrino interactions with solar neutrinos and electrons in XMASS-I LXe by bellows :
    - Millicharge, magnetic moment and dark photon via $U(1)_{B-L}$

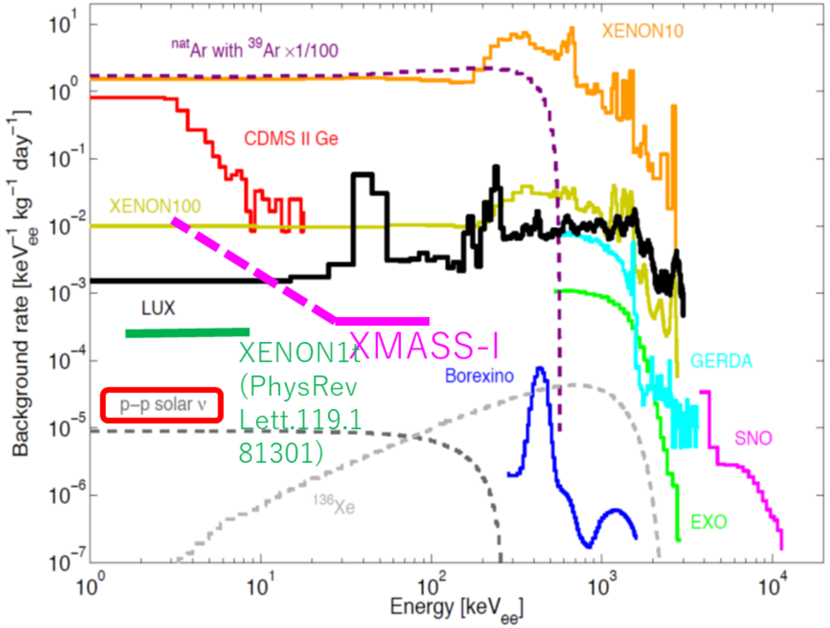






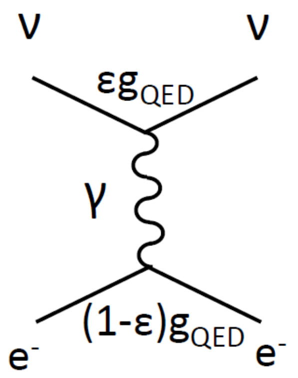
Peter Sorensen Neutrino2016

Original figure ; D.C.Mailing Ph.D (2014) Fig 1.5



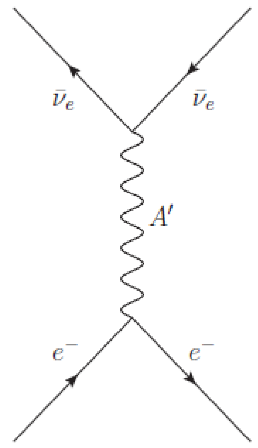
Candidates for exotic interactions

- <u>Milli-charge :</u>
  - Neutrinos may have a slight charge, as charge quantization has not been proven.
    - (GEMMA's data, A.Studenikin, Europhys.Lett. 107 (2014) 39901) $\delta e < 1.5 \times 10^{-12} e$,
    - (PVLAS, F. Della Valle et al., Eur. Phys. J. C 76 (2016) 24) $\delta e, \mu, \tau < 3 \times 10^{-8}$ e @ m_ν <10meV



- <u>Magnetic moment :</u>
  - Further extension of the Standard Model, Majorana neutrino may have a magnetic efficiency of $10^{-(10\text{-}12)} \mu_B$ (PRL 58.1807 (1987)).
    - Borexino μ_νs(E_ν <1MeV) < $2.8\times10^{-11} \mu_B$ (90% C.L.) [solar ν] 10.1103/PhysRevD.96.091103
    - XENON1T : $\mu_\nu \subset (1.4\text{-}2.9)\times 10^{-11} \mu_B$ [solar ν] Phys. Rev. D 102, 072004
    - GEMMA $\mu_{\bar{\nu}e} < 2.9 \times 10^{-11} \mu_B$ (90% C.L.)[reactor ν] Adv.High Energy Phys. 2012 (2012) 350150

- <u>Medicated by dark photon :</u>
  - There is a model in which dark photons included in the Hidden sector can be gauge-bosoned to influence neutrino-electron interactions.
    - S.Bilmis et al, Phys.Rev.D 92, 033009 (2015)



(a)

Expected energy distribution in LXe detector

- Search for low-energy solar neutrinos (pp, 7Be) as neutrino sources.
- Cross section terms for exotic interactions

➢ Millichagre : $\left(\frac{d\sigma}{dT_e}\right)_{EM} \cong \frac{2\pi\alpha}{m_e T_e^2}\delta^2$

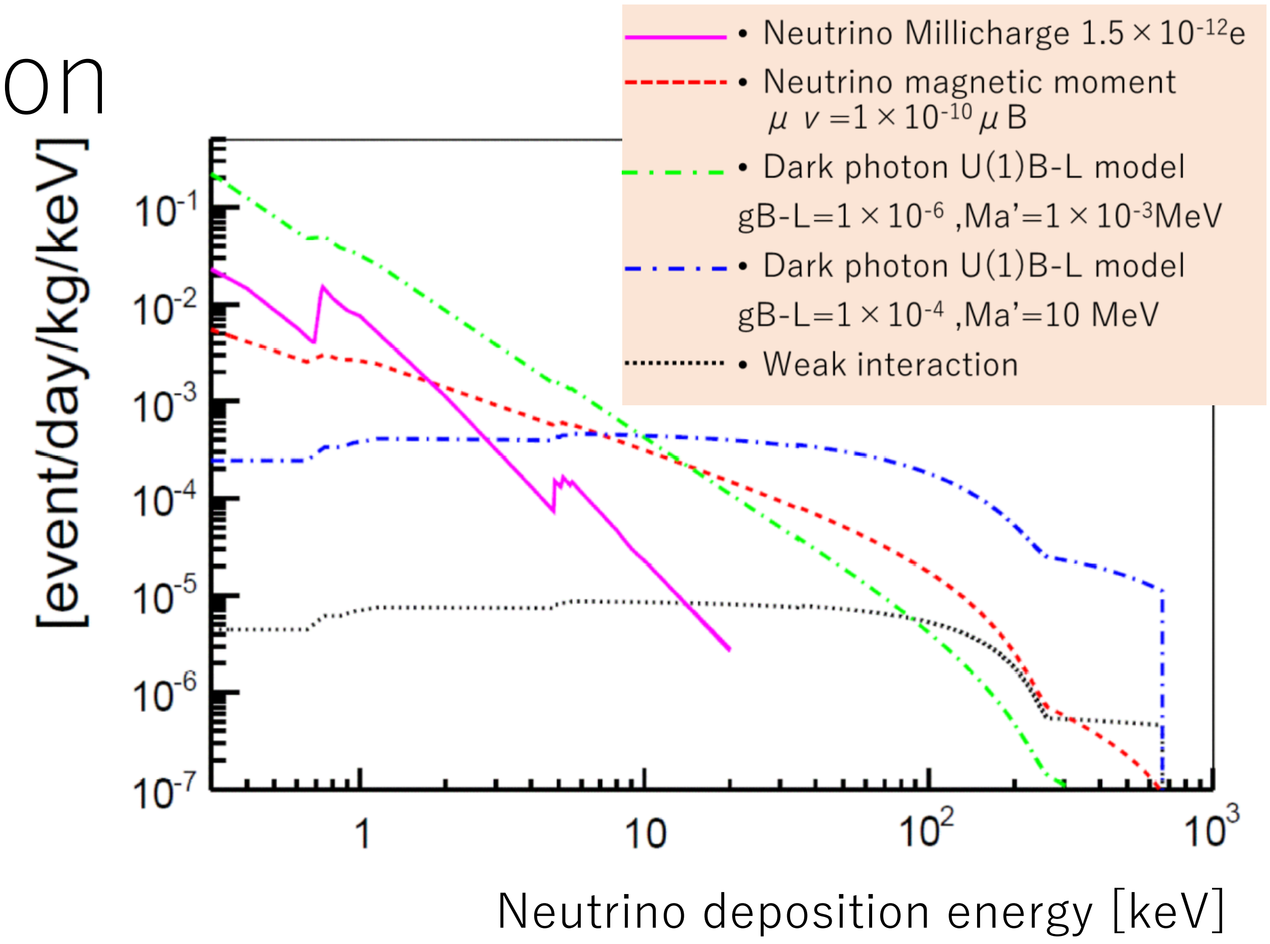
➢ Magnetic moment :

$$\left(\frac{d\sigma_{\nu_\ell e^-}}{dT_e}\right)^{\mathrm{FE}}_{\mathrm{mag}} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)\left(\frac{\mu_{\nu_\ell}}{\mu_{\mathrm{B}}}\right)^2$$

➢ Mediated dark photon :

$$\left[\frac{d\sigma}{dT}(\nu e^- \to \nu e^-)\right]_{\mathrm{DP}} = \frac{g^4_{B-L} m_e}{4\pi E_\nu^2 (M_{A'}^2 + 2m_e T)^2}\left(2E_\nu^2 + T^2 - 2TE_\nu - m_e T\right)$$

- Considering the atomic effect for neutrino-electron interaction in xenon



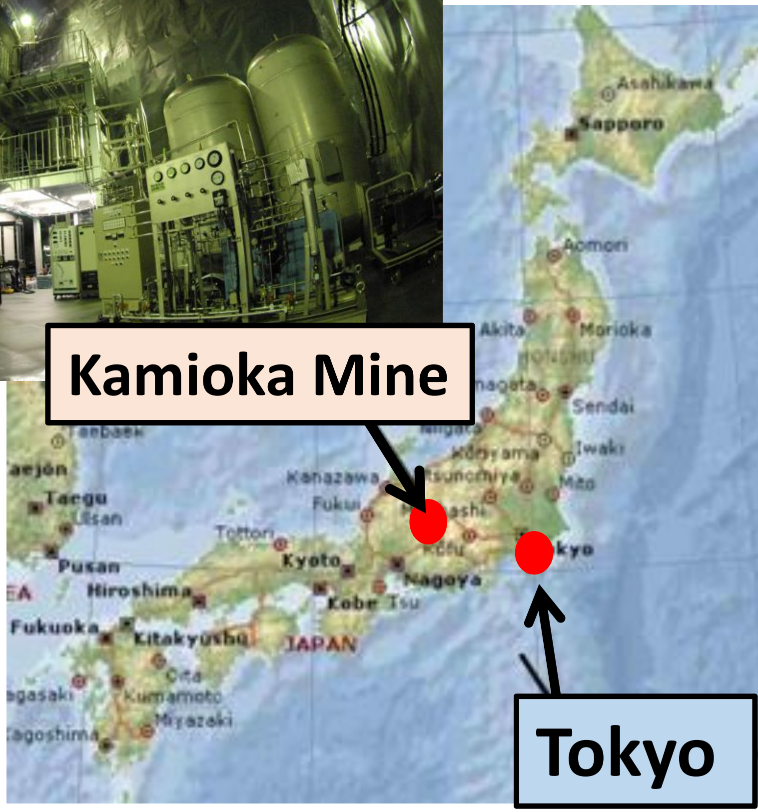
$$\frac{dN_{\mathrm{tot}}}{dT} = t \times N \times \int \left[\left(\frac{d\sigma_{\nu e^-}}{dT}\right)_{\mathrm{SM}} + \left(\frac{d\sigma_{\nu e^-}}{dT}\right)_{\mathrm{ex}}\right] \sum_{i=1}^{Z} \theta(T - B_i) \left(\frac{d\Phi_\nu}{dE_\nu}\right) dE_\nu$$

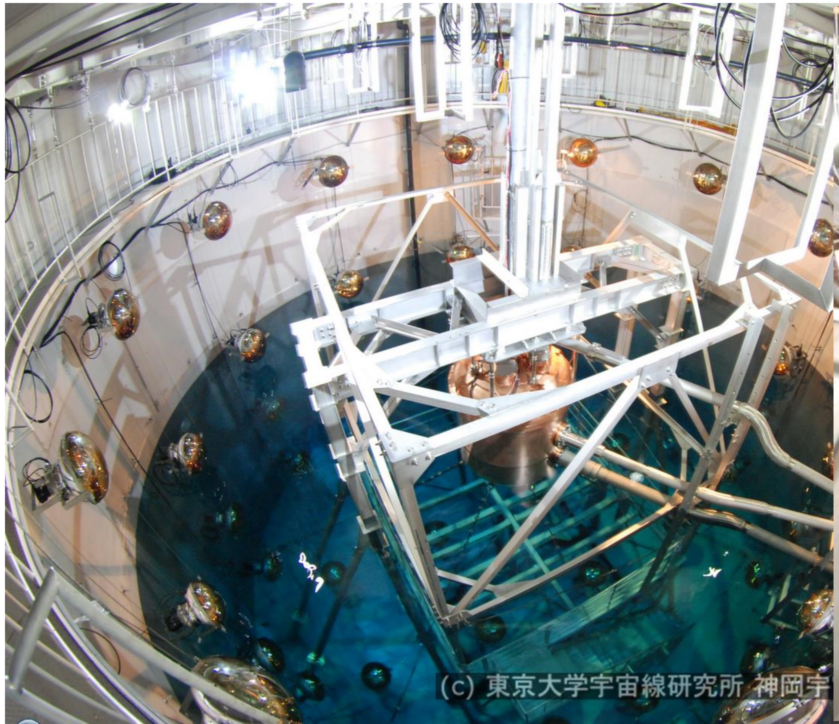
(FEA case)

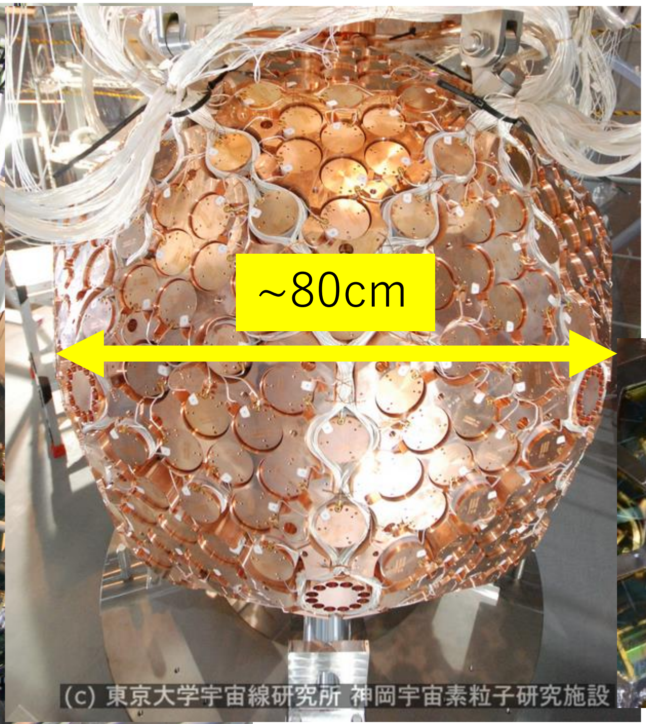
1. Φ: solar neutrino flux (5.98×1010cm-2s-1 for pp chain and 5.00×109cm-2s-1 7Be chain)
2. Interference effect with weak interaction is assumed for dark photon analysis.
3. Assuming atomic effects : Free electron approximation for neutrino magnetic moment and dark photon analyses. Relastivistic random phase approximation for neutrino millicharge analysis.

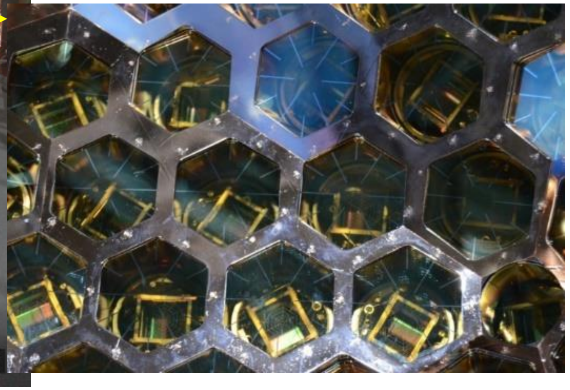
XMASS detector

- Kamioka Laboratory (~2700m.w.e.), Japan.
- 832kg (Φ~80cm) liquid xenon for active volume.
- ~2inch PMT (Hex. and Cylinder) ×642 : 62% photo-coverage
- 10x10m water tank for muon veto with 20 inch PMT×70.



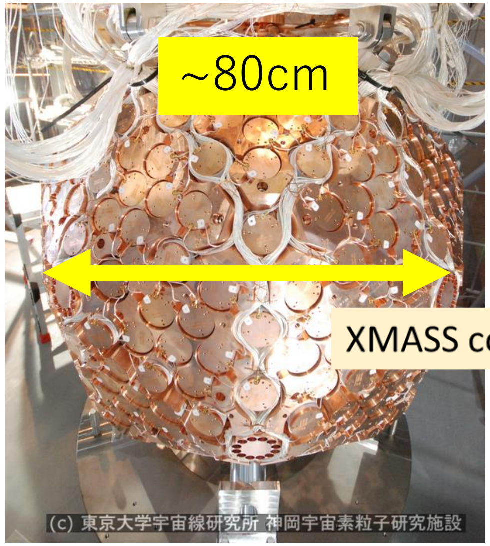


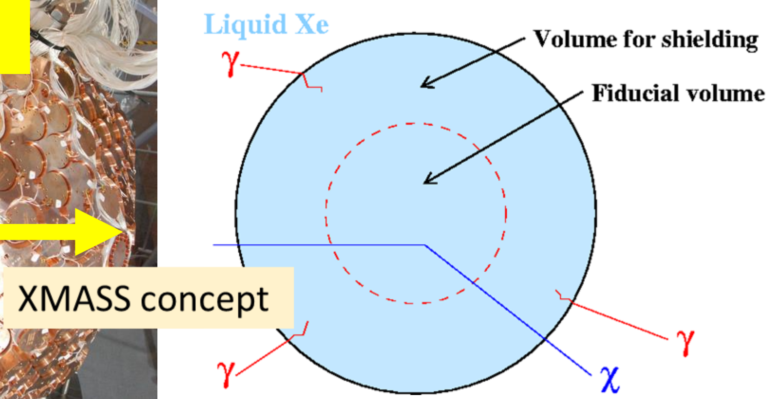


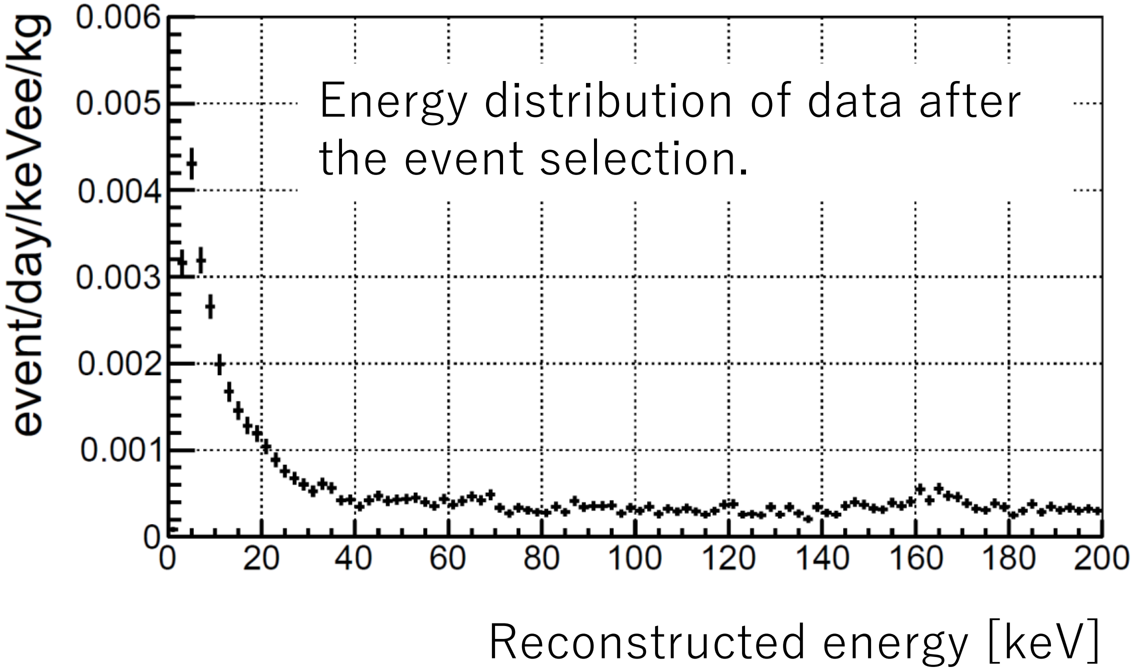


Event selection

- Data：
  - 2013Nov-2016Mar livetime = 711 days
  - Analyzed energy region：
    - **2-15 keV for millicharge analysis**
    - **2-200 keV for magnetic moment & dark photon analysis**
  - Event selection :
    - Noise, Cherenkov event cut
    - Fiducial volume cut with ~97kg effective mass:
      - Timing base reconstruction R(T)<38cm
      - PE base reconstruction R(PE)<20cm
- Expected signal MC：
  - Simulated event is generated by XMASS MC and same event selections are applied.
  - main systematic uncertainty：scintillation efficiency (~15% for the millicharge signal).



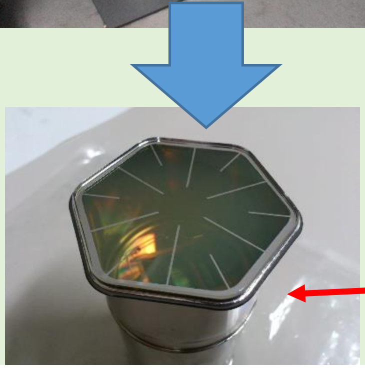




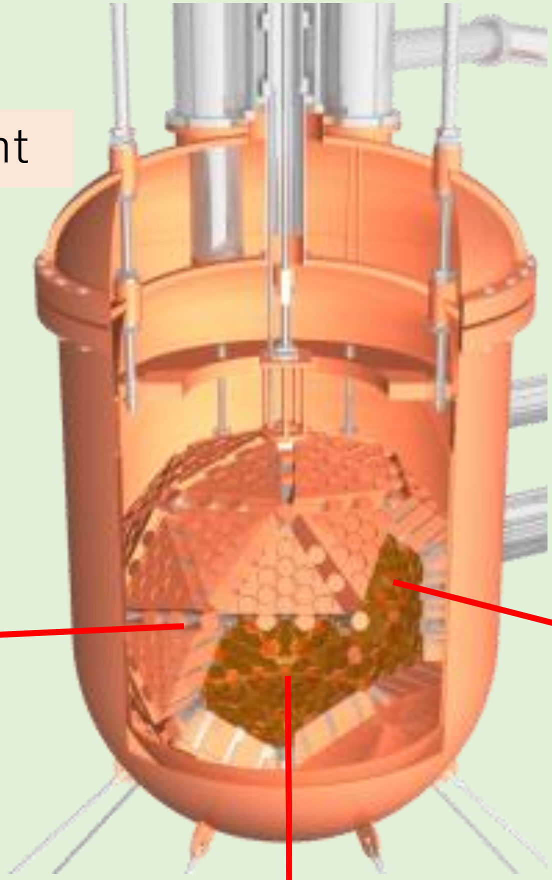
Background evaluation in XMASS-I

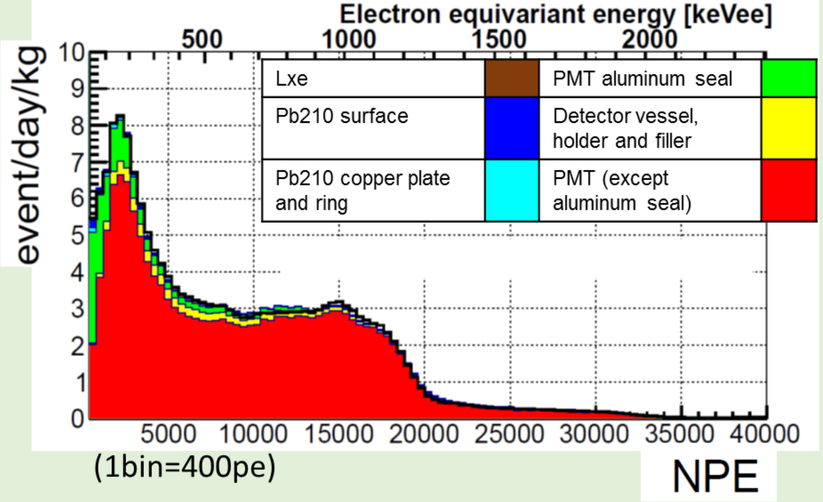
Gamma-ray of detector material origin.

HPGe measurement



PMT origin is dominant.



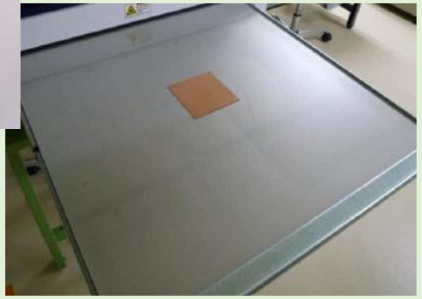


BG in LXe

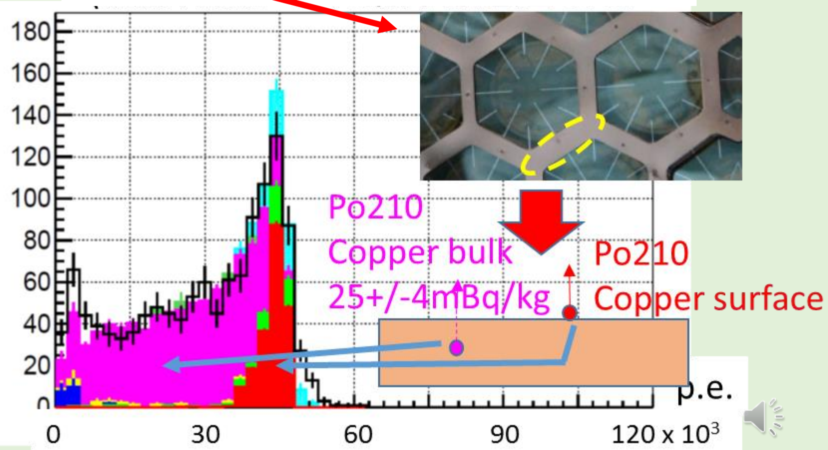
222Rn, 85Kr, 39Ar, 14C
Xenon isotopes

BG in detector surface：^{210}Pb

Measurement by alpha counter
NIMA884(2018)157

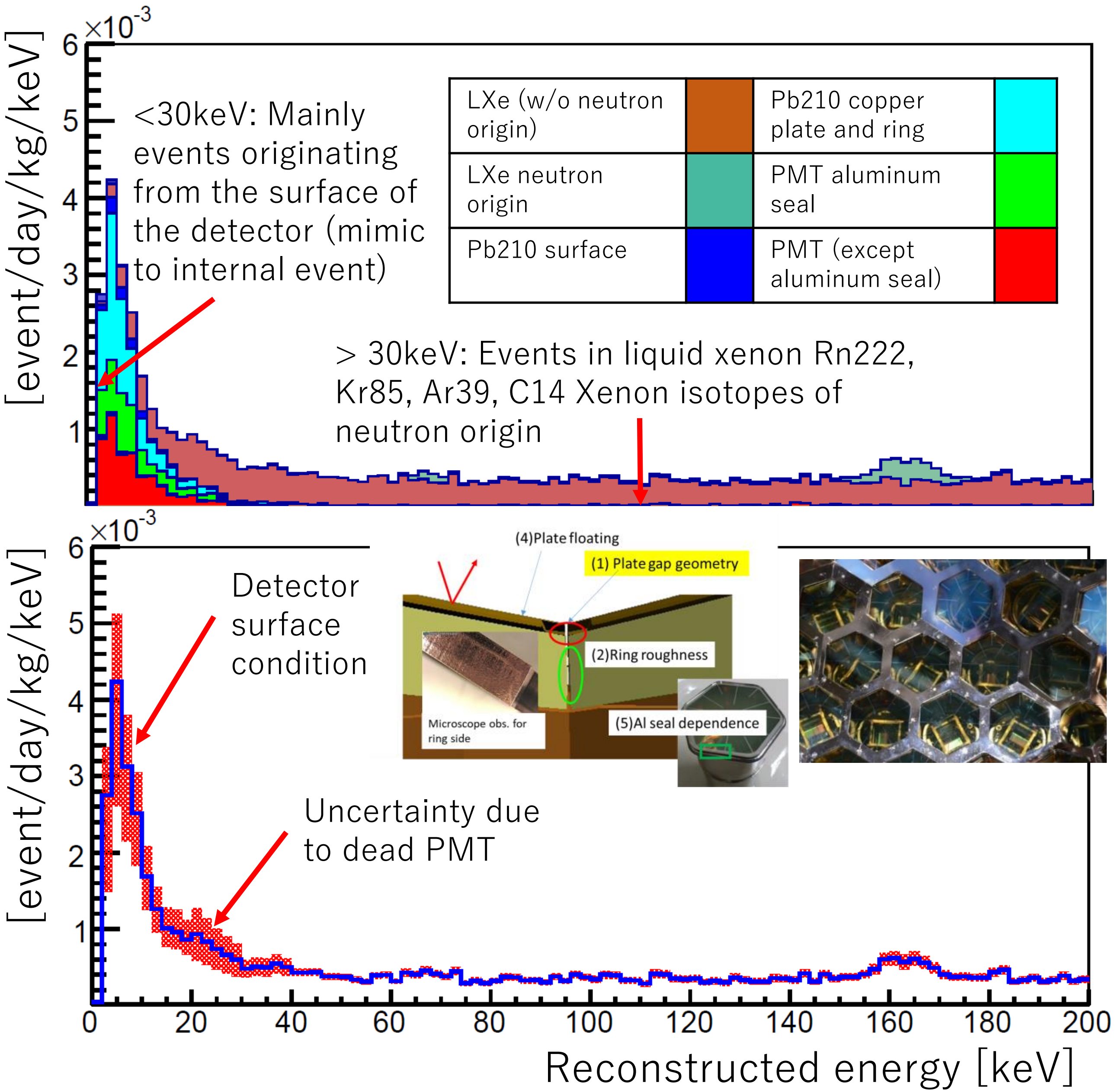


Alpha event analysis



BG after event selection :

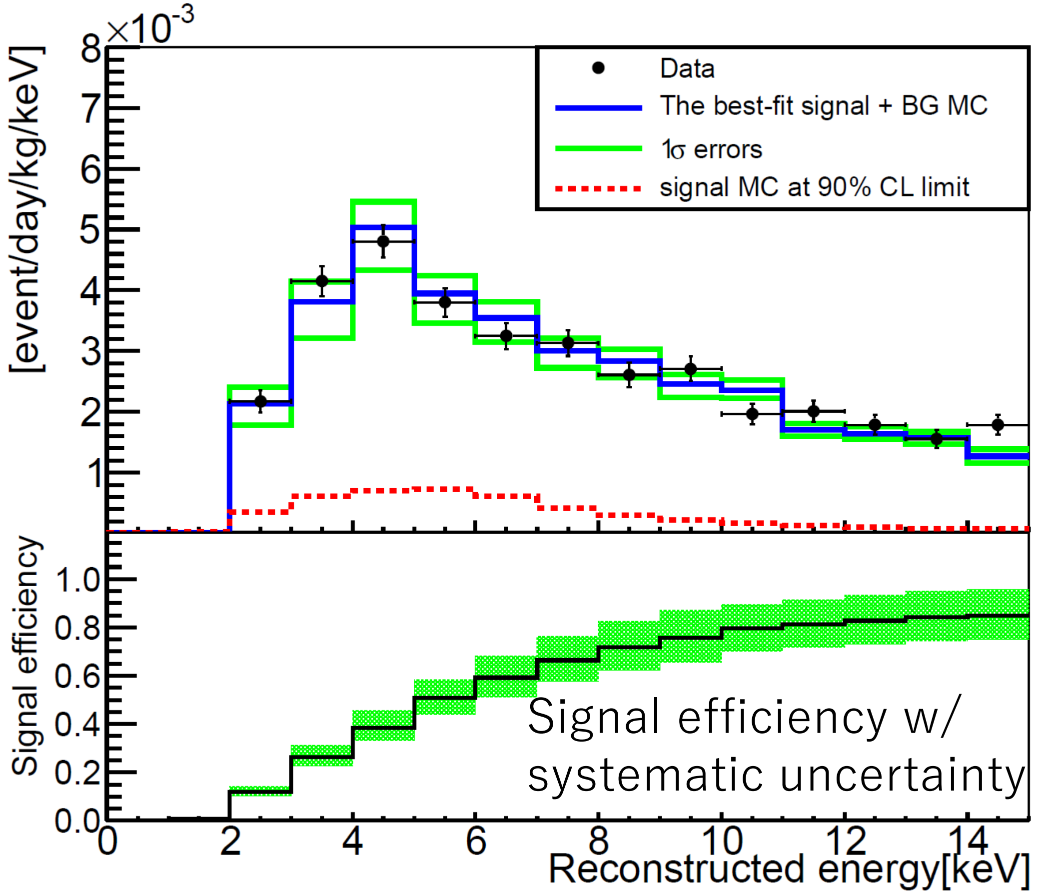
- Background MC is generated for each materials / RIs by XMASS MC.
- The same event reductions are applied with the same statistics as the data.
- Follow the changes in the optical parameter of liquid xenon during the dataset period.
  - Regular Co57 / Co60 calibration is carried out. This cancels the systematic error due to the change of xenon property over time.



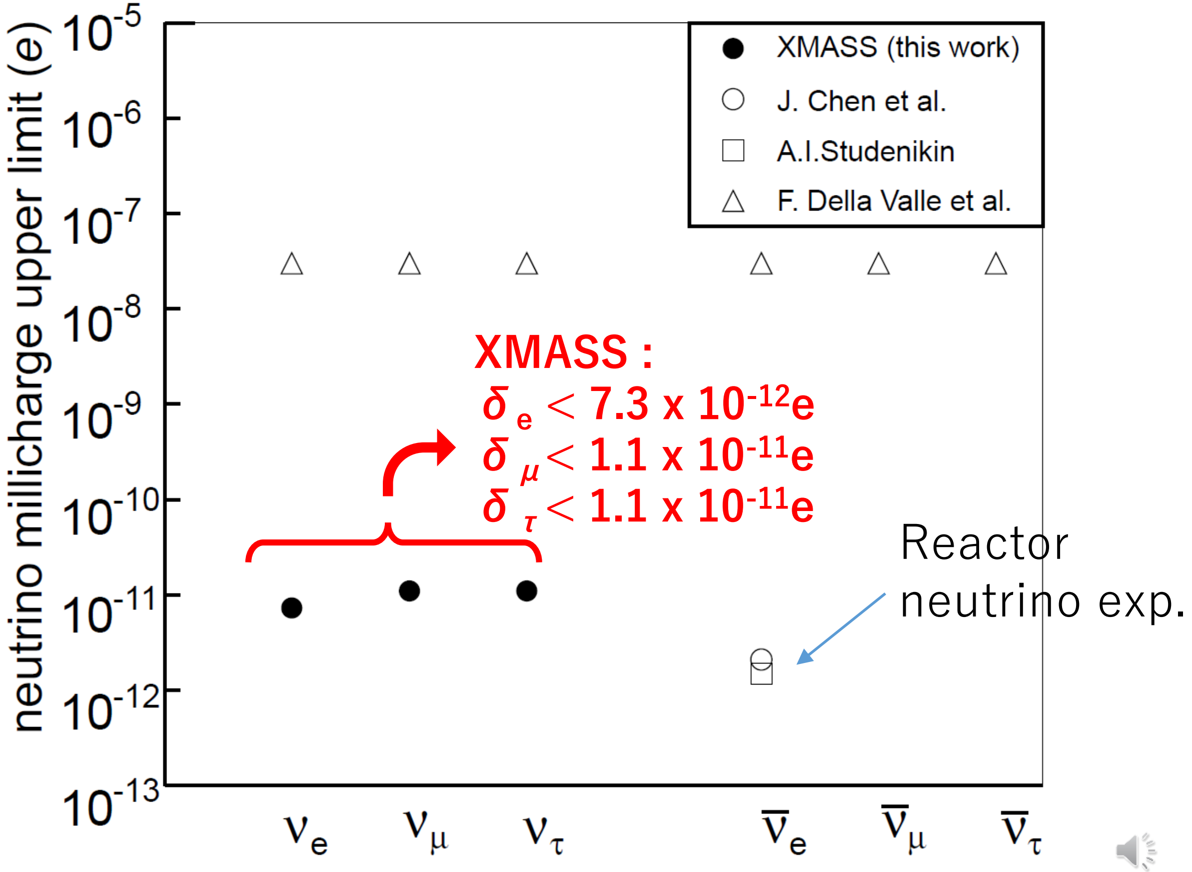
The signal was searched by χ^2 fitting the data, expected signal and energy distribution of the background MC.

Search result for neutrino millicharge (2-15keV)

- No significant signal was observed
- Upper limit 90% C.L. : 5.4×10^{-12}e



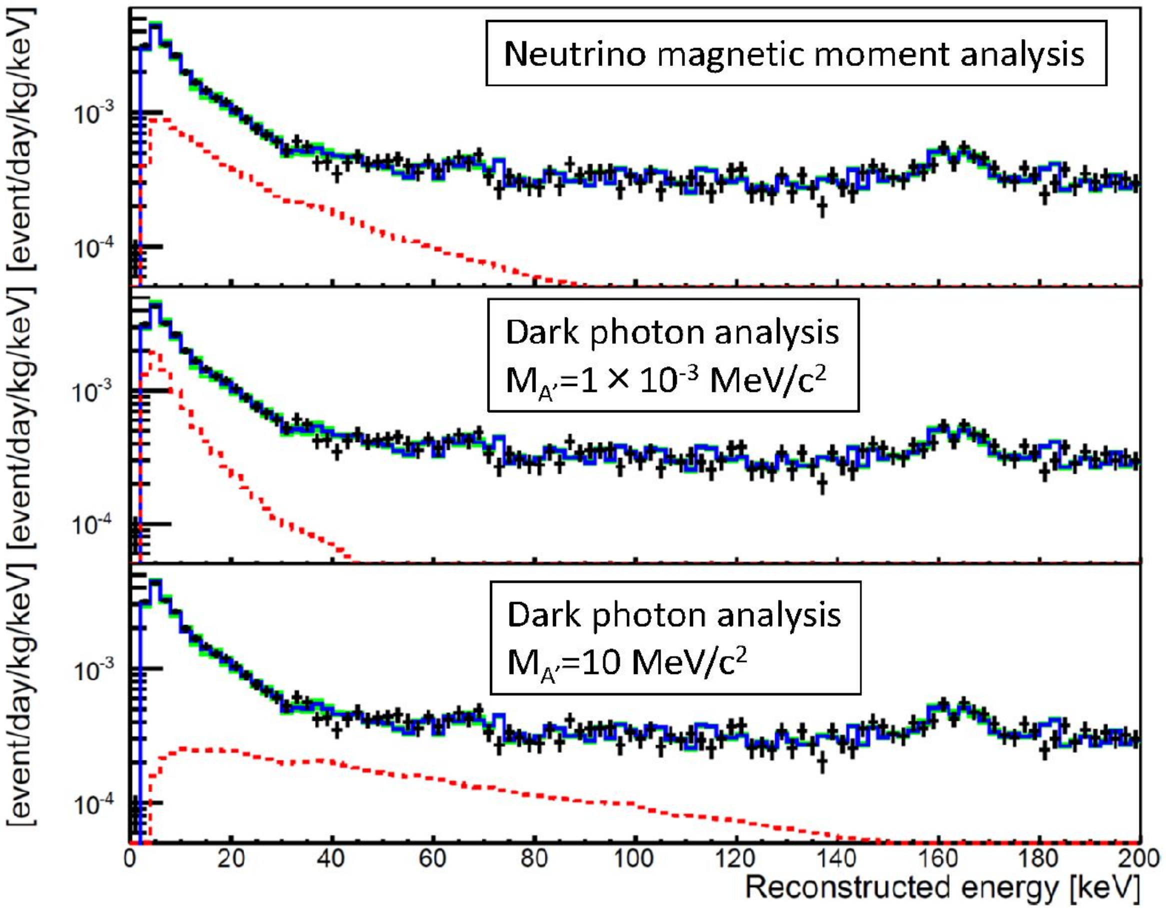
- The upper limit for each flavor was calculated, and the strongest limit was given for positive neutrinos.



Search result for neutrino magnetic moment and dark photon($U(1)_{B\text{-}L}$ gauge boson) : 2-200keV

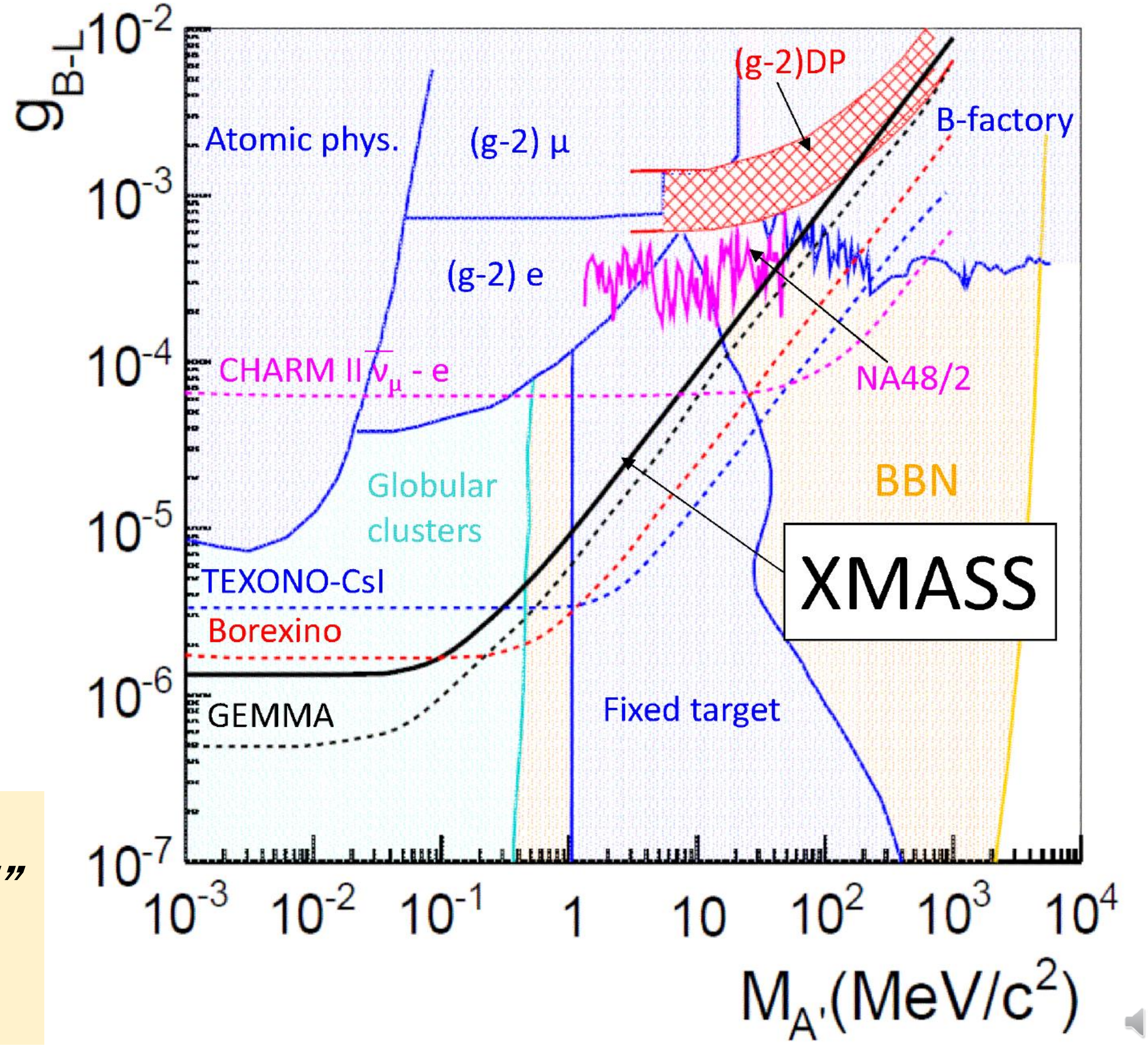
- No significant signal was observed.
- Magnetic moment:
  - Best fit : $\mu_\nu = 1.3 \times 10^{-10} \mu_B$ (χ^2/d.o.f=85.9/98)
  - Null signal : χ^2/d.o.f = 88.2/98
  - 90% CL upper limit : $\mu_\nu = 1.8 \times 10^{-10} \mu_B$
- dark photon :
- $M_{A'} = 1 \times 10^{-3}$ MeV/c^2
  - Best fit : $g_{B\text{-}L} = 1.1 \times 10^{-6}$ (χ^2/d.o.f=85.3/98)
  - 90% CL upper limit : $g_{B\text{-}L} = 1.3 \times 10^{-6}$
- $M_{A'} = 10$ MeV/c^2
  - Best fit : $g_{B\text{-}L}$ = Null (χ^2/d.o.f=88.2/98)
  - 90% CL upper limit : $g_{B\text{-}L} = 8.8 \times 10^{-5}$

Data
BG+signal (best fit)
BG+signal (1sigma err)
Signal (90% upper limit)



Exclude region for Dark photon ($U(1)_{B-L}$ gauge boson) :

- Exclude region from other experiments and observation : S.Bilmis et al, Phys.Rev.D 92, 033009 (2015)
- XMASS : Similar exclude region with the estimation from ν -e scattering in other experiment (dot line).
- Almost exclude the explaining (g-2) anomaly explaining by dark photon



"search for exotic neutrino-electron interactions using solar neutrinos in XMASS-I"
K. Abe et al. (XMASS collaboration),
Published to PLB 809 (2020) 135741

Conclusion :

- XMASS: Ultra-low background multipurpose detector with ~ 1 ton of liquid xenon. Observation completed in February 2019.
- A search for neutrino millicharge, magnetic moment, and dark photon-mediated interactions was performed with an XMASS detector. => published to PLB 809 (2020) 135741
- As a result of the search, no significant signal was observed, so the upper limits were shown.
    - Neutrino milliharge: $\delta\nu < 5.4\text{x}10^{-12}e$: Achieves the highest sensitivity for weak charge search in positive neutrinos
- Neutrino magnetic efficiency: $\mu_\nu < 1.8 \times 10^{-10}\,\mu_B$
- dark photon: $g_{B\text{-}L} < 1.3 \times 10^{-6}$ ($M_{A'} = 1 \times 10^{-3}$ MeV / c^2), $g_{B\text{-}L} < 8.8 \times 10^{-5}$ ($M_{A'} = 10$ MeV / c^2),
    - (g-2) The area where anomaly is explained by dark photon is almost eliminated.
- *Our result opens the door for observation with low threshold dark matter search detector!*