XMASS experiment

Yongpyong-High1 2015: Joint Winter Conference on Particle Physics, String and Cosmology
High1 resort, Korea, Jan. 25–31, 2015
28th of Jan. 2015

Atsushi Takeda for XMASS Collaboration

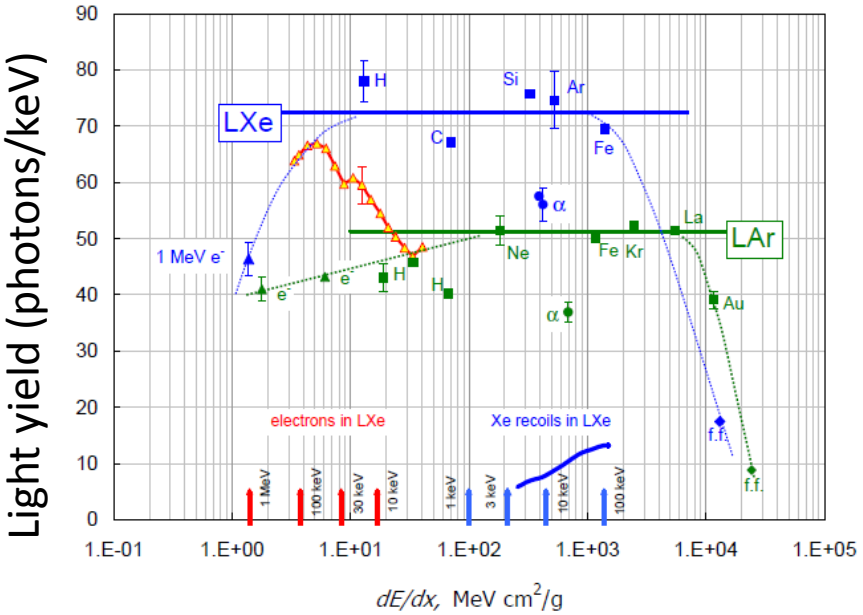
Contents

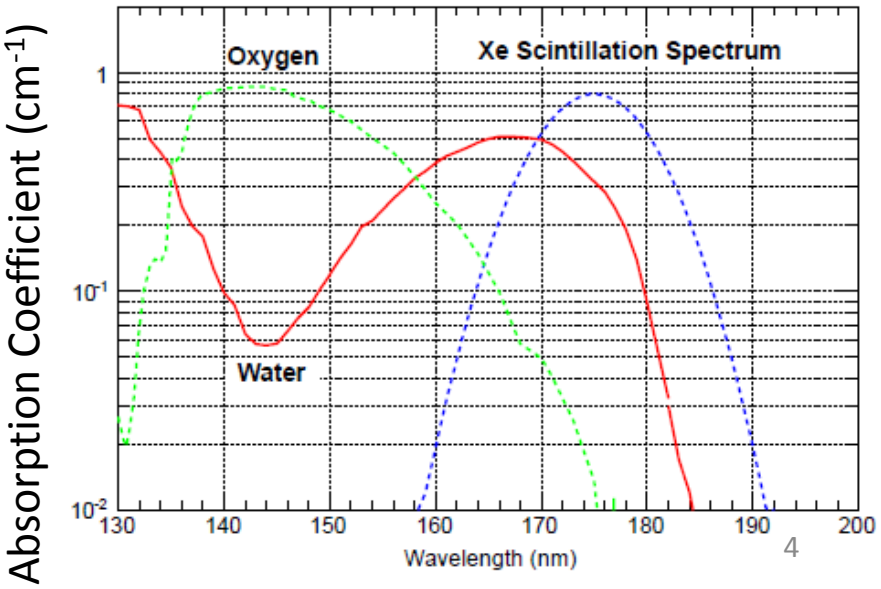
1. Direct DM search with LXe detector
2. XMASS project
3. Results from XMASS-I commissioning run
4. Refurbishment of XMASS-I
5. XMASS-1.5
6. Summary

1. Direct DM search with LXe detector

Characteristic of liquid xenon

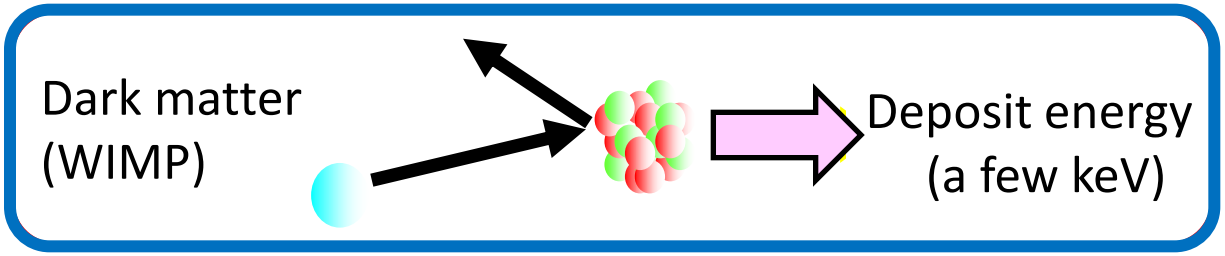
- -100 degree Celsius: easy to liquefy and handing.
- High density (~3 g/cm^3): compact detector. (~2m dia. for 10t scale)
- Large Z (= 54): effective self shielding for external BG.
- Large photon yield: low threshold can be achieved.
- Scintillation wavelength ~175nm: directly detected by PMTs
- Purification: absorption material (ex. water and oxygen) can be purified by Zr getter.





Direct DM detection

WIMPs elastically scatter off nuclei in target material, producing nuclear recoils.



- Event rate and cross section

$$\frac{dR}{dE_R} = \frac{R_0 F^2(E_R)}{E_0 r} \frac{k_0}{k} \frac{1}{2\pi v_0} \int_{v_{min}}^{v_{max}} \frac{1}{v} f(\mathbf{v}, \mathbf{v_E}) d^3\mathbf{v}$$

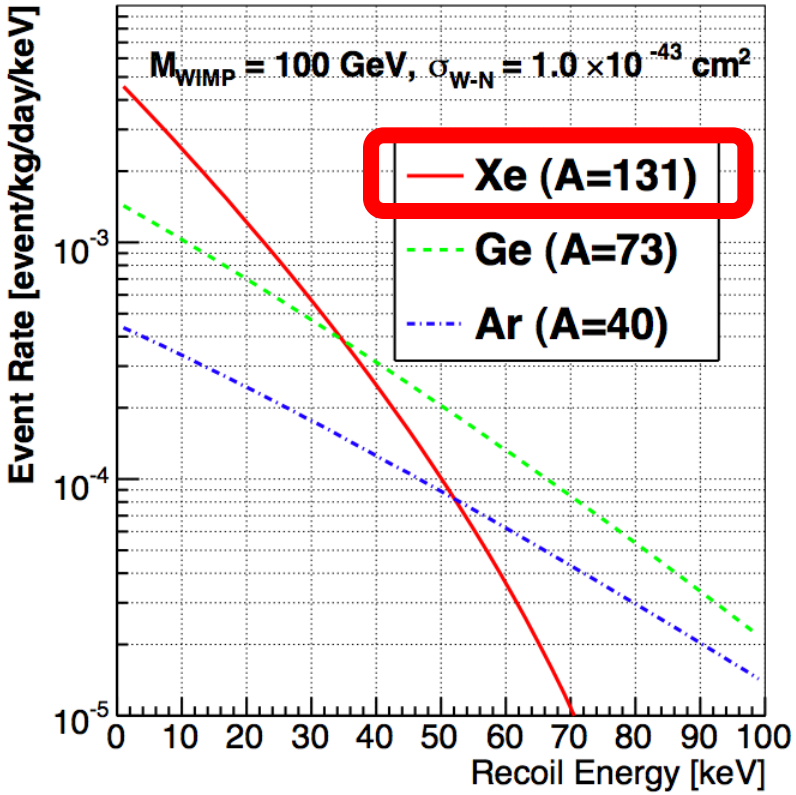
R_0 : event rate
F: nucleus form factor

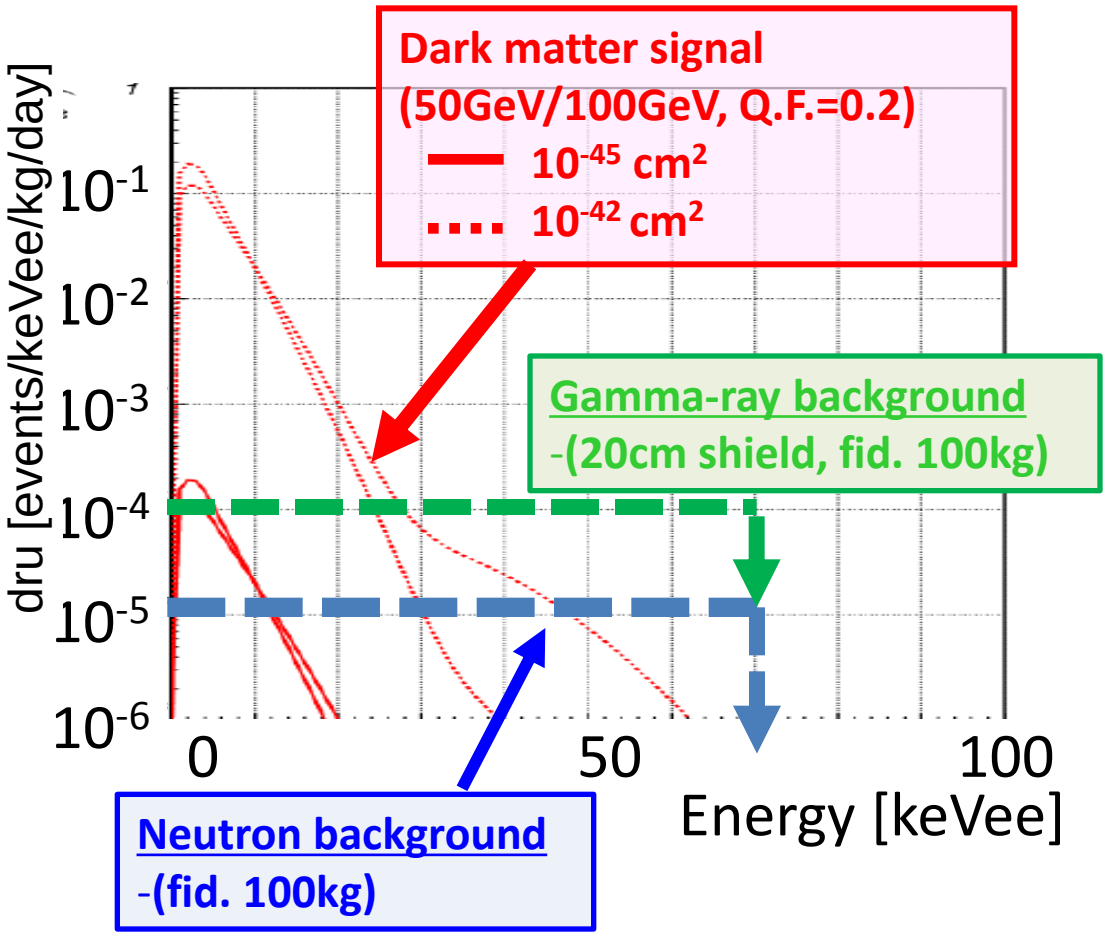
Maxwellian distribution for DM velocity is assumed.
v_0 : dispersion
v: velocity onto target
v_E: Earth's motion around the Sun

$$R_0 = \frac{377}{M_\chi M_N} \left(\frac{\sigma_0}{1\text{pb}}\right) \left(\frac{\rho_D}{0.3\text{GeVc}^{-2}\text{cm}^{-3}}\right) \left(\frac{v_0}{230\text{km s}^{-1}}\right) \text{kg d}^{-1}$$

Spin independent case: $\sigma_0 = A^2 \frac{\mu_T^2}{\mu_p^2} \sigma_{\chi-p}$ → Large A gives higher event rate.

Expected WIMP event rate



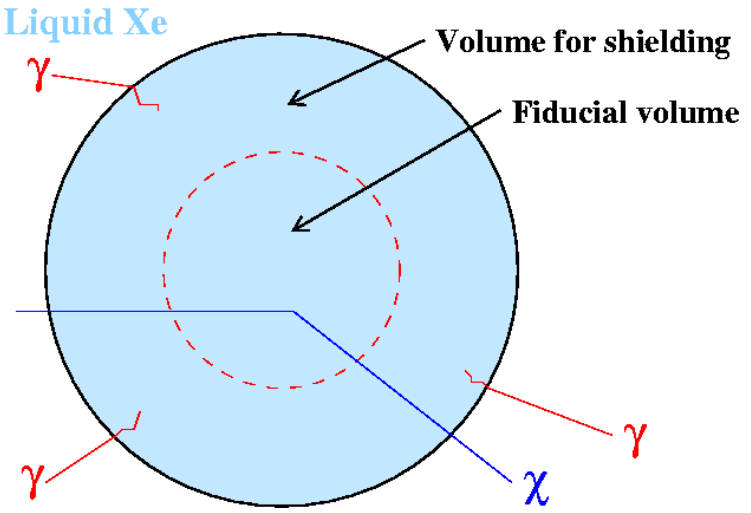


→ Xe (A=131) is one of the best target

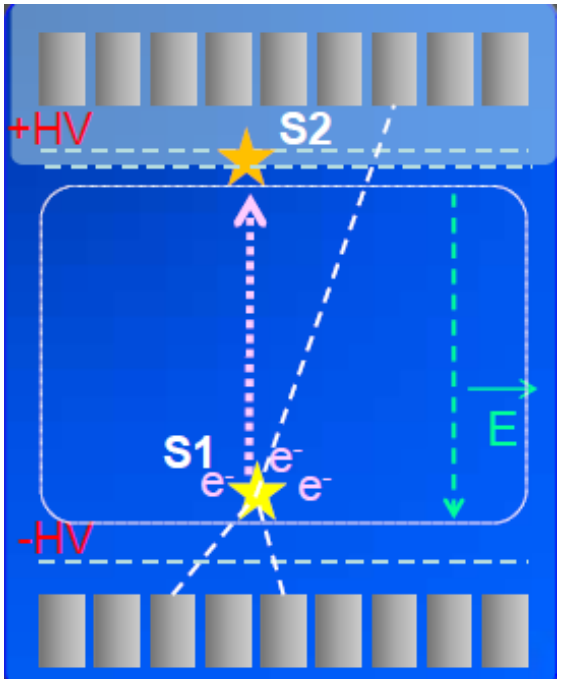
6

Single phase vs. double phase LXe detector

- Single phase :
  - DM signal (uniformly distributed) are identified by fiducial volume analysis.
  - Also PSD may reduce background.
    - Scintillation decay time difference between nuclear recoil (DM) and electron recoil can be used.

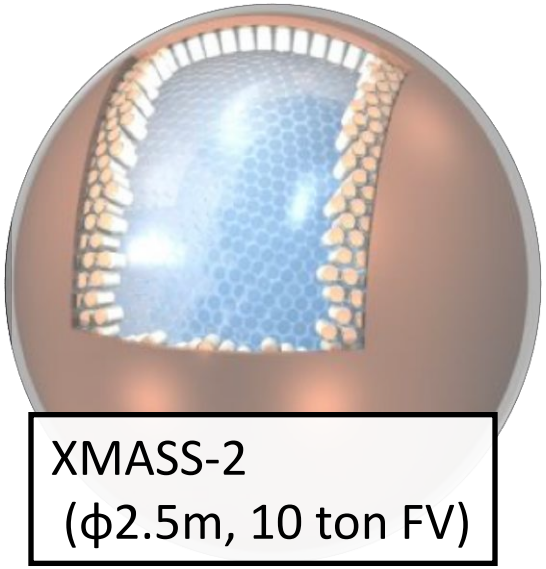


- Double phase :
  - DM signal (nuclear recoil) are identified by fiducial volume and ionization(S2) / scintillation(S1) ratio.

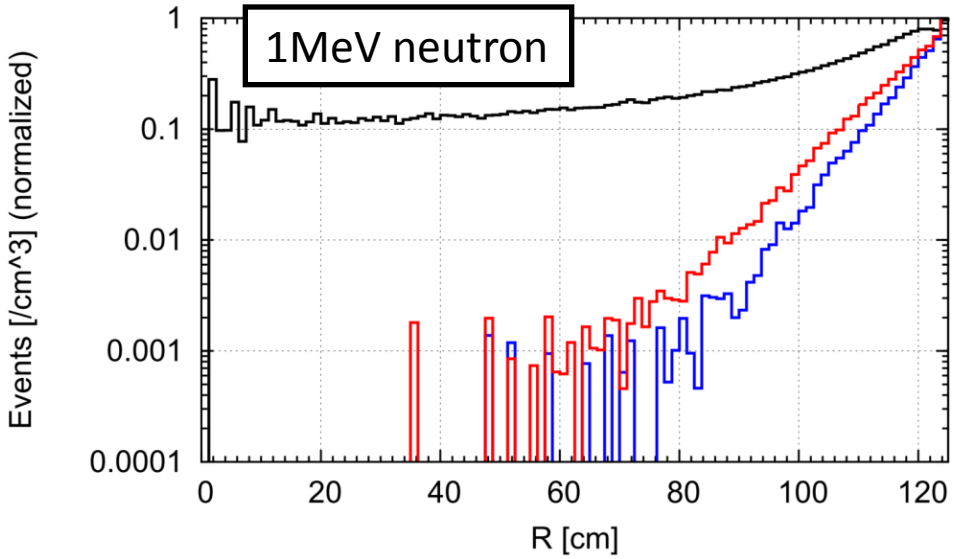


Advantage of single phase detector

- Simple and good scalability
  No need for complicate structure like an HV
- BG reduction by self-shielding
  Effective even for neutron BG (lower figure)
- High light yield & low energy threshold
  (XMASS-I: 14.7 pe/keV and 0.3 keV threshold)
- Sensitive for e/γ events



XMASS-2
(ϕ2.5m, 10 ton FV)

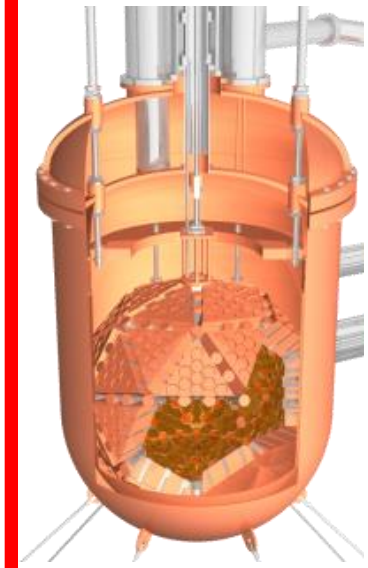


ϕ2.5m LXe detector
Black: all events
Blue: 2 < E(keVee) < 5 keV
Red: 2 < E(keVee) < 10 keV

Current DM experiment with LXe detector

Single phase

XMASS



XMASS-I is ongoing
since 2010
835kg xenon
100kg FV

Double phase

XENON100/1T

XENON100:
161kg xenon
50kg FV
Continue data taking 2014
XENON1T:
Commissioning phase 2015–

LUX

350kg xenon
118kg FV
First result:
PRL 112, 091303 (2014)
using Apr–Aug 2013

PandaX

PandaX-I
37kgFV x 17.4days
First result:
arXiv:1408.5114
using May–Jul 2014
PandaX-Ib
300kgFV x 180days

2. XMASS project

The XMASS Collaboration

Kamioka Observatory, ICRR, the University of Tokyo:
K. Abe, K. Hiraide, K. Ichimura, Y. Kishimoto, K. Kobayashi, M. Kobayashi, S. Moriyama, M. Nakahata, T. Norita, H. Ogawa, H. Sekiya, O. Takachio, A. Takeda, M. Yamashita and B. Yang

Kavli IPMU, the University of Tokyo: J.Liu, K.Martens and Y. Suzuki

Kobe University: R. Fujita, K. Hosokawa, K. Miuchi, Y. Ohnishi, N. Oka and Y. Takeuchi

Tokai University: K. Nishijima

Gifu University: S. Tasaka

Yokohama National University: S. Nakamura

Miyagi University of Education: Y. Fukuda

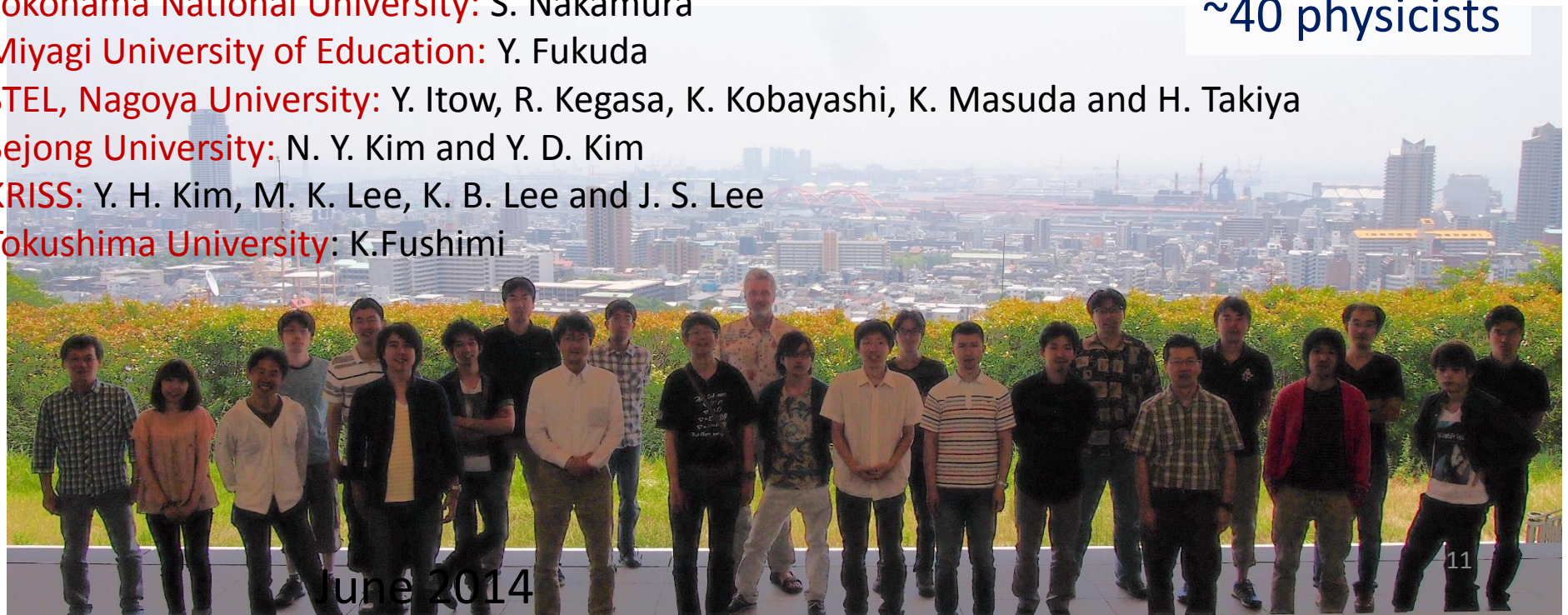
STEL, Nagoya University: Y. Itow, R. Kegasa, K. Kobayashi, K. Masuda and H. Takiya

Sejong University: N. Y. Kim and Y. D. Kim

KRISS: Y. H. Kim, M. K. Lee, K. B. Lee and J. S. Lee

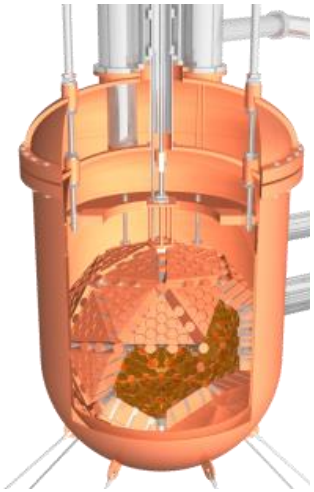
Tokushima University: K.Fushimi

11 institutes
~40 physicists

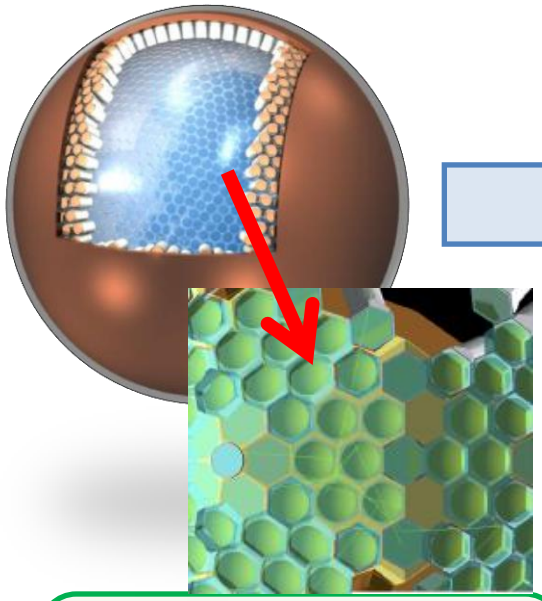


XMASS project

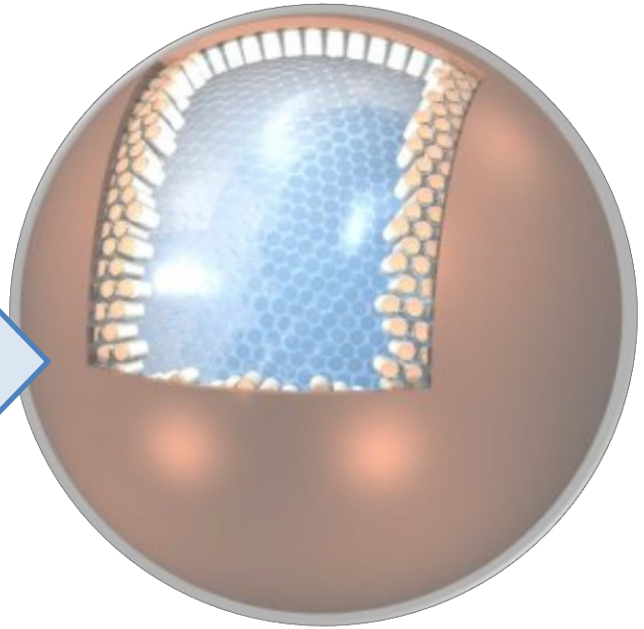
XMASS-I



XMASS-1.5



XMASS-II



Now

835 kg,
100 kg Fiducial volume (FV)
ϕ80 cm, 642 PMTs
Since 2010 Nov.

・Dark matter search

5 ton,
1 ton FV
(x 10 of XMASS-I)
ϕ1.5 m, ~1000 PMTs

・Dark matter search

25 ton, **10 ton FV**
ϕ2.5 m

Multi purpose
・Dark matter
・pp solar neutrino
・$0\nu2\beta$ decay

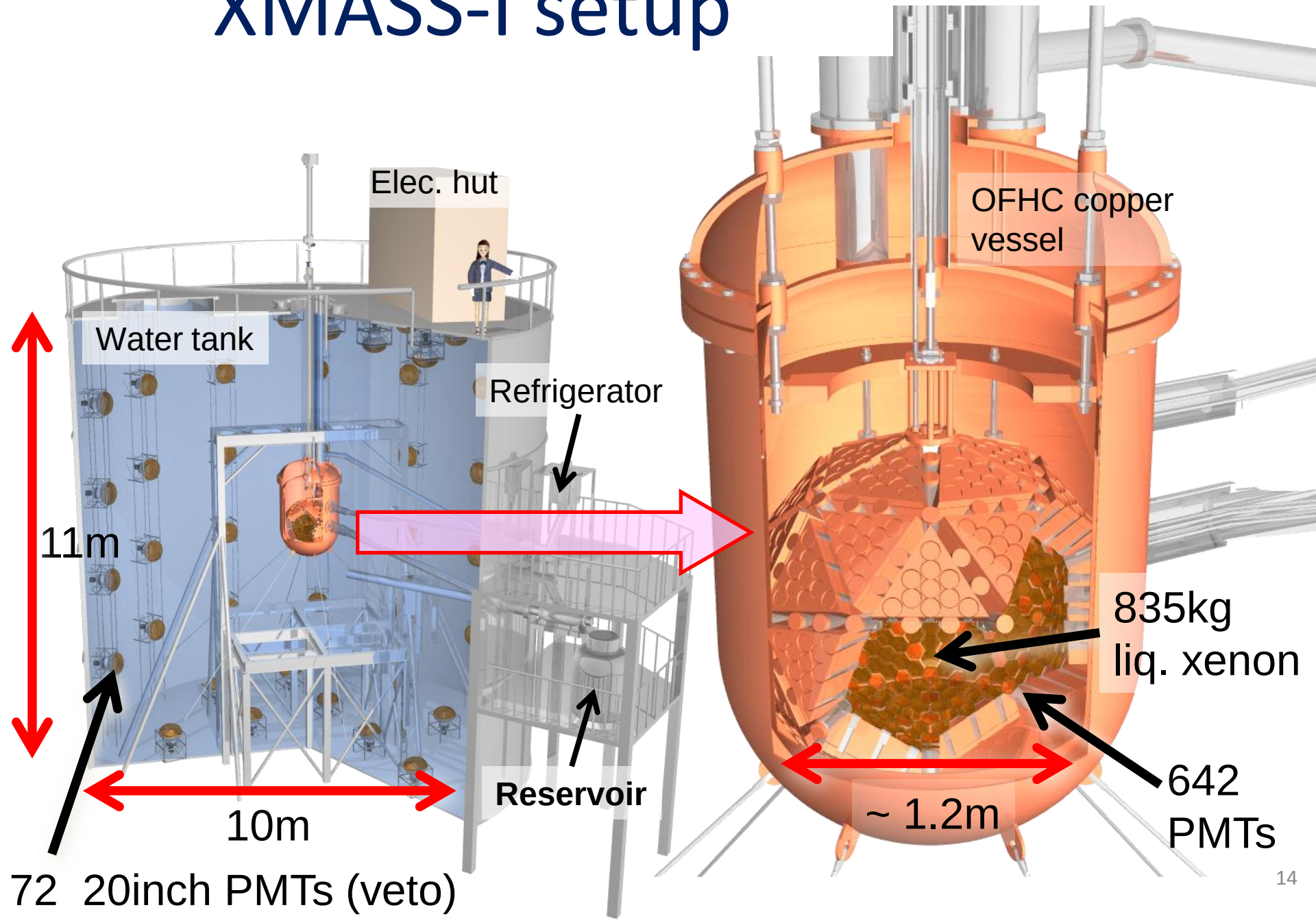
Y. Suzuki, hep-ph/0008296

Site

Kamioka mine
Lab-C

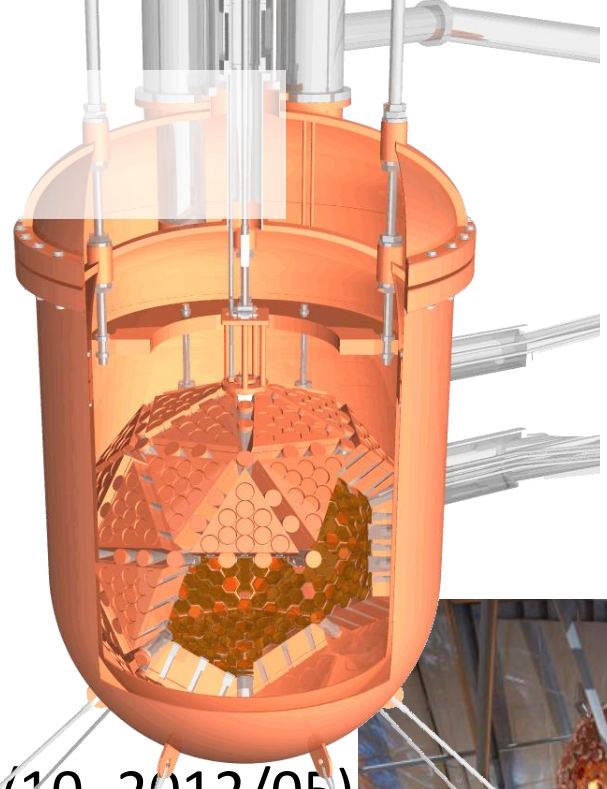
~1000m underneath
Mt. Ikenoyama.
(2700 m.w.e.)

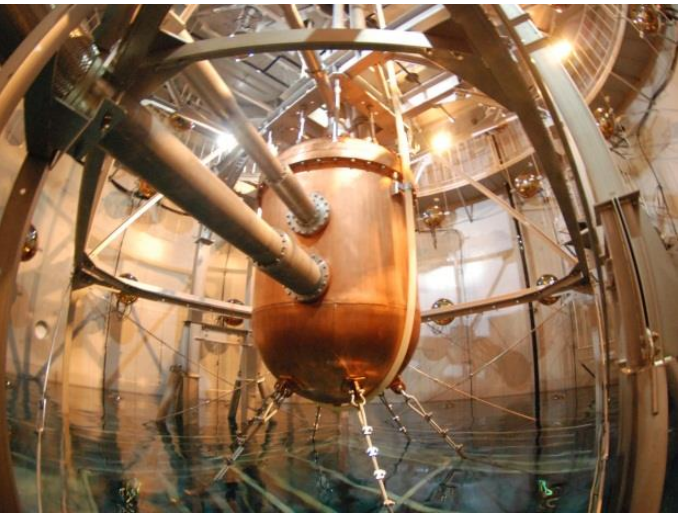
XMASS-I setup



XMASS-I detector

- Detail: ***NIMA 716 (2013) 78***
- Single phase LXe detector.
- **World's largest (835kg)**
  dark matter detector
- **Low threshold (0.3keVee)**
- **High light yield (14.7 pe/keV)**
- Commissioning data taking (2010/10–2012/05)
- Resuming of data taking after refurbishment (2013/11～)





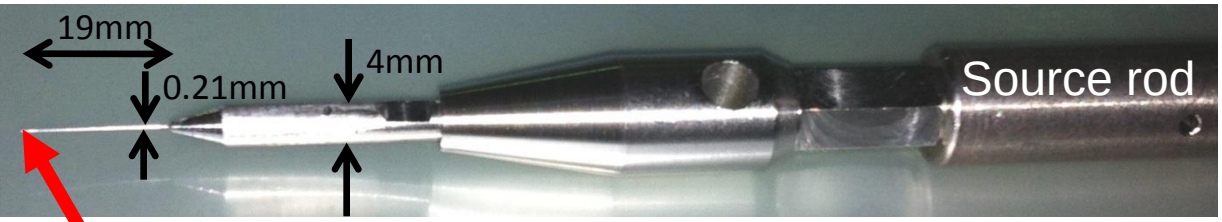
Detector calibration (inner)

- Light yield and position reconstruction

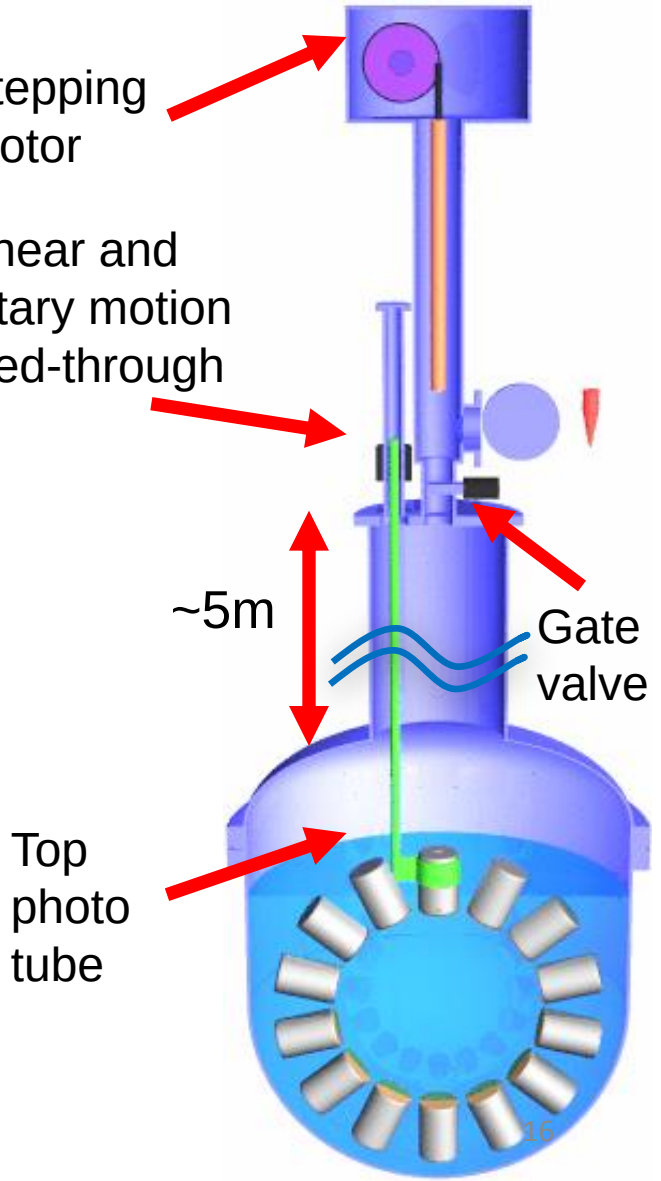
RI	Energy [keV]	[Hz]	dia. [mm]
(1) Fe-55	5.9	~5	5
(2) Cd-109	8, 22, 25, 88	~800	5
(3) Am-241	17.8, 59.5	~500	0.17
(4) Co-57	59.3, 122	~30	0.21
(5) Cs-137	662	~200	5

(3), (4) : Micro-source made at KRISS.
Diameters of source are much shorter than attenuation length of gamma in liquid xenon to minimize the shadowing effect from source itself

Φ0.21 mm for ^{57}Co source

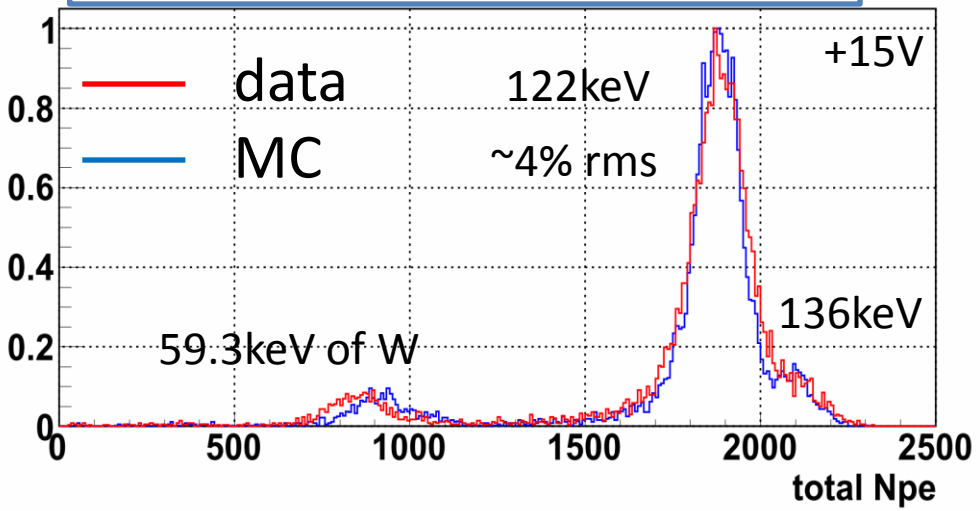


Active region is concentrated on 1.8 mm edge region



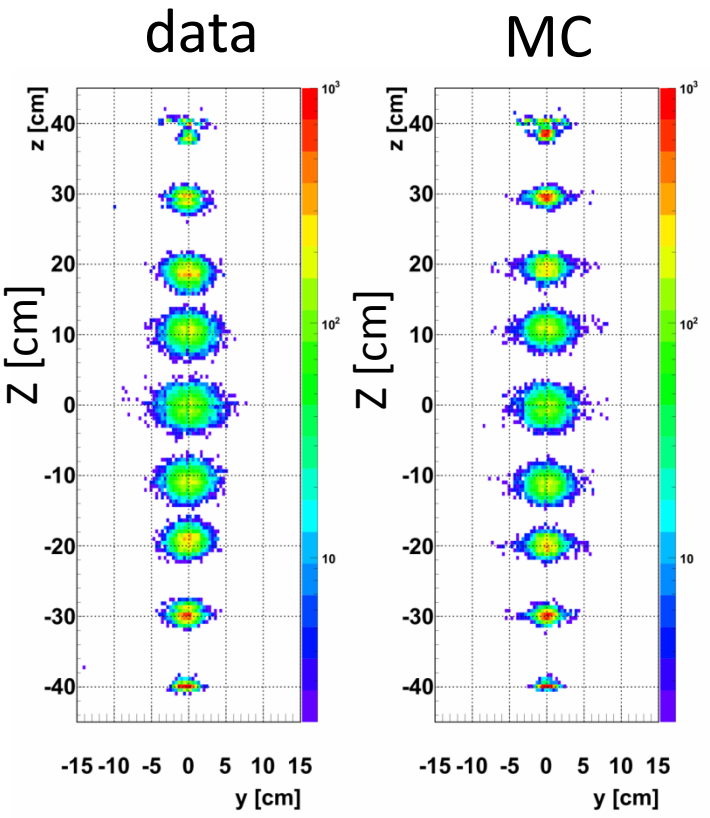
Detector response for a point-like source (~WIMPs)

Total photo electron (z=0cm)



^{57}Co micro source is moved inside the detector along z axis

Reconstructed vertex



- ^{57}Co source @ center (z=0cm) gives a typical response of the detector.
- Large light yield, 14.7 p.e./keV$_{ee}$ ($\Leftrightarrow$ 2.2 for S1 in XENON100)
- The pe dist. well as vertex dist. were reproduced by a simulation well.

History of XMASS-I

2010	2011	2012	2013	2014	2015

Dec. May Nov.

Const-ruction

Commissioning Run Data taking

Several physics results from this term were published later

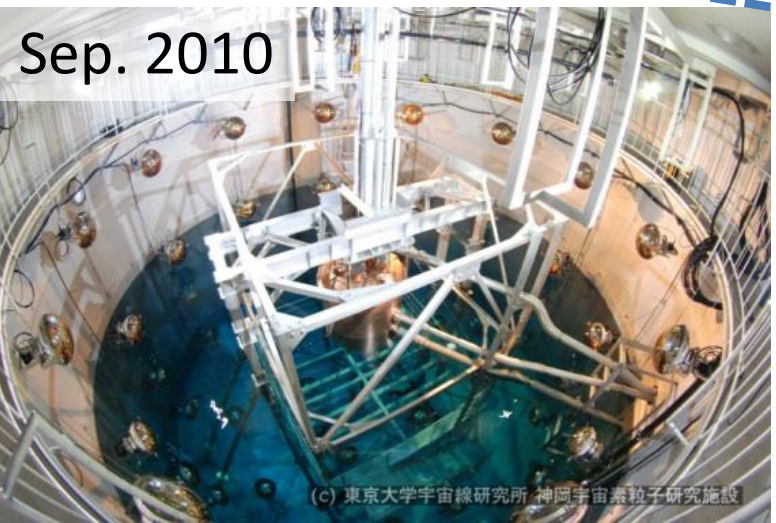
Refurbishment

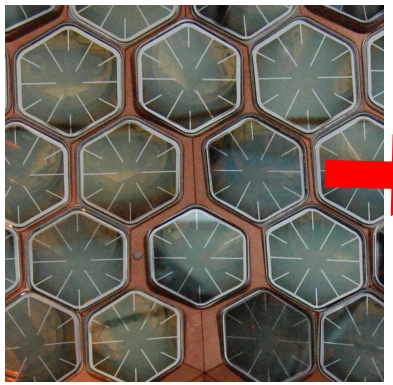
Main BG source was identified, and it was cover with copper ring and plate.

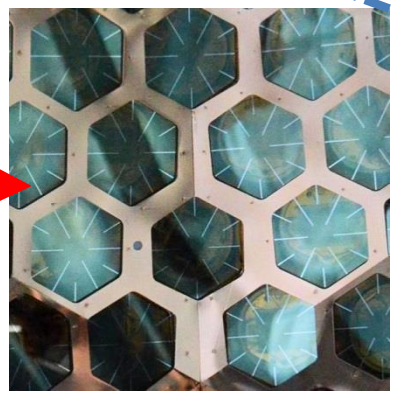
Data taking

Stable and long term data taking is ongoing.

Sep. 2010







Physics results of XMASS-I

Published

- Light WIMP search, ***Phys. Lett. B 719 (2013) 78***
- Solar axion search, ***Phys. Lett. B 724 (2013) 46***
- Bosonic Super-WIMPs, ***Phys. Rev. Lett. 113 (2014) 121301***
  → Chosen as Editor's suggestion
- Inelastic scattering on ^{129}Xe, ***PTEP 2014, 063C01***

Results to come soon

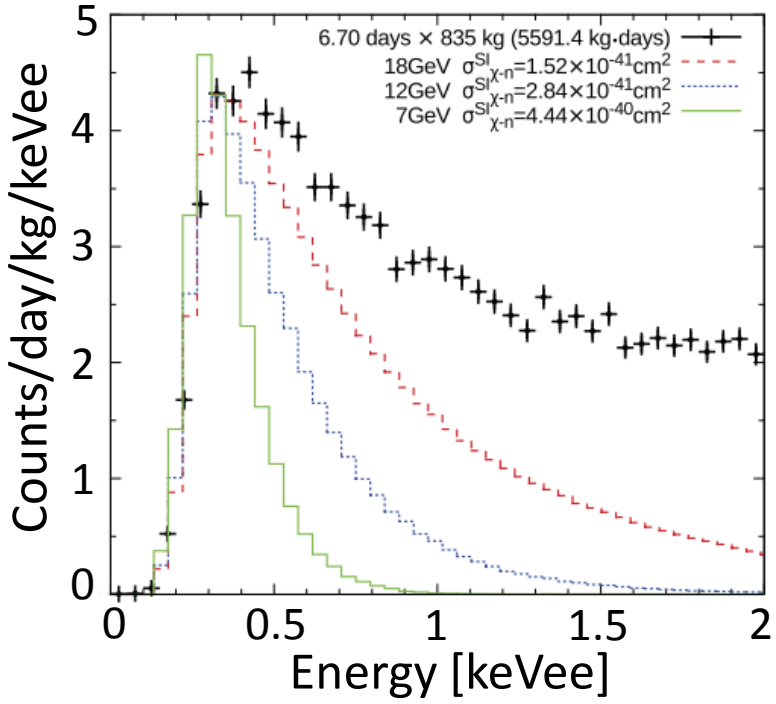
- Seasonal modulation with full volume of LXe
- Fiducial volume analysis for heavy WIMPs
- Double electron capture of ^{124}Xe

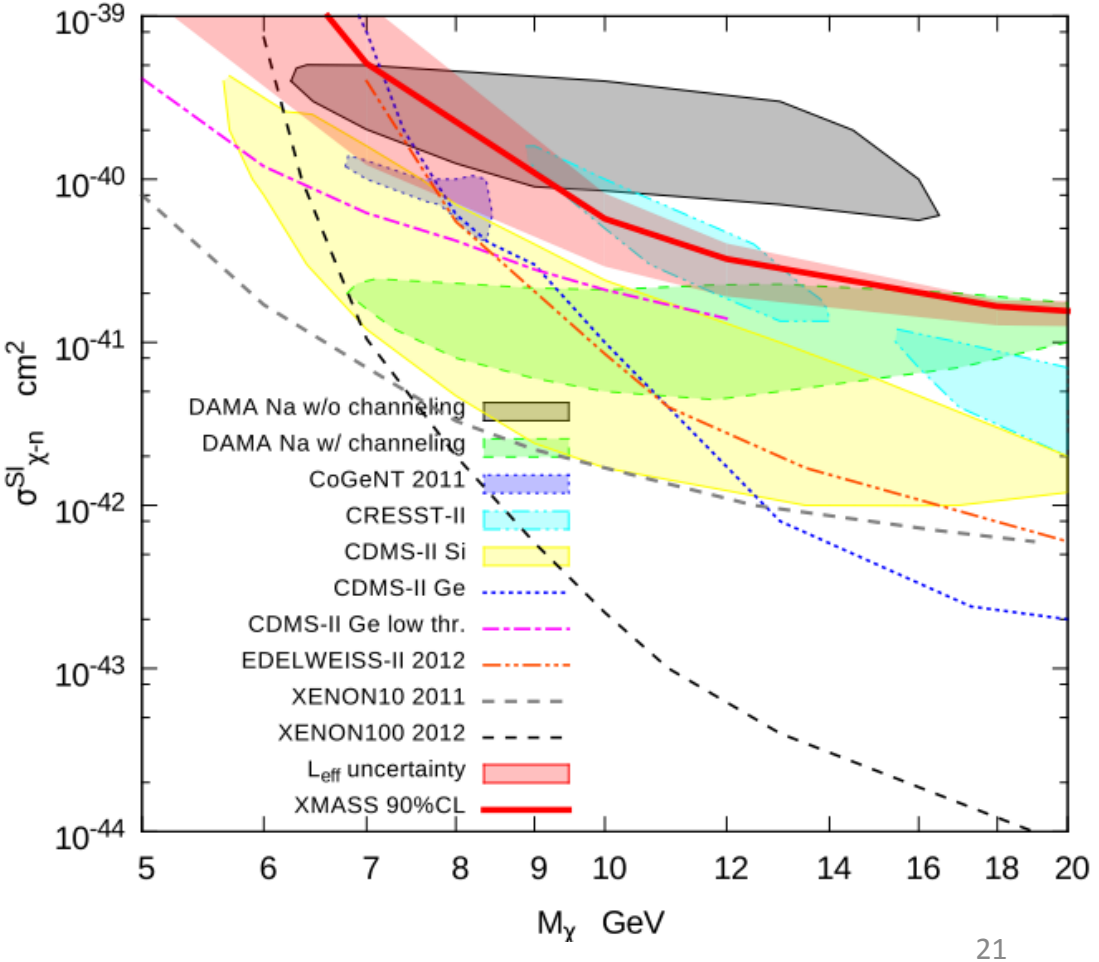
3. Physics results from XMASS- I commissioning run

Low mass WIMPs search

PLB 719 (2013) 78-82

- Full volume (835 kg) analysis
- 6.80 days in 2012 Feb.
- 5591.4 kg day exposure
- 0.3 keVee threshold



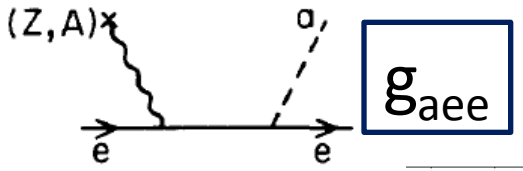


Solar Axion search

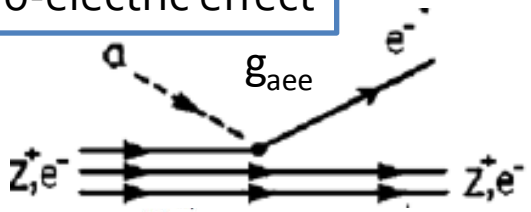
PLB 724 (2013) 46-50

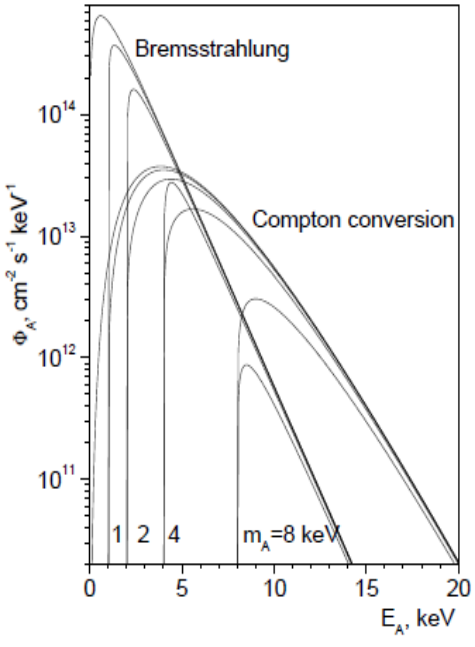
- Axion is a hypothetical particle to solve the strong CP problem
- Produced in the Sun by bremsstrahlung and Compton effect, and detected in the detector by axio-electric effect.
- XMASS is suitable to search because of a large mass and low BG

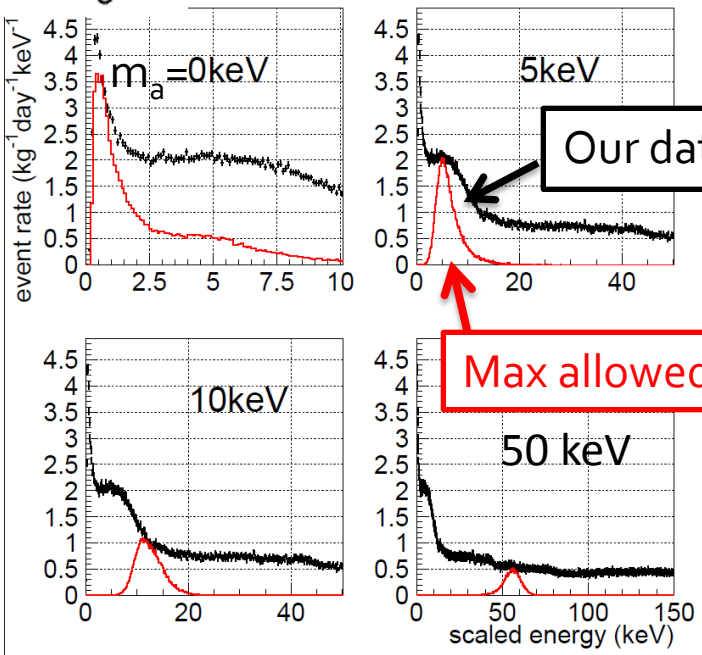
Bremsstrahlung and Compton effect



Axio-electric effect

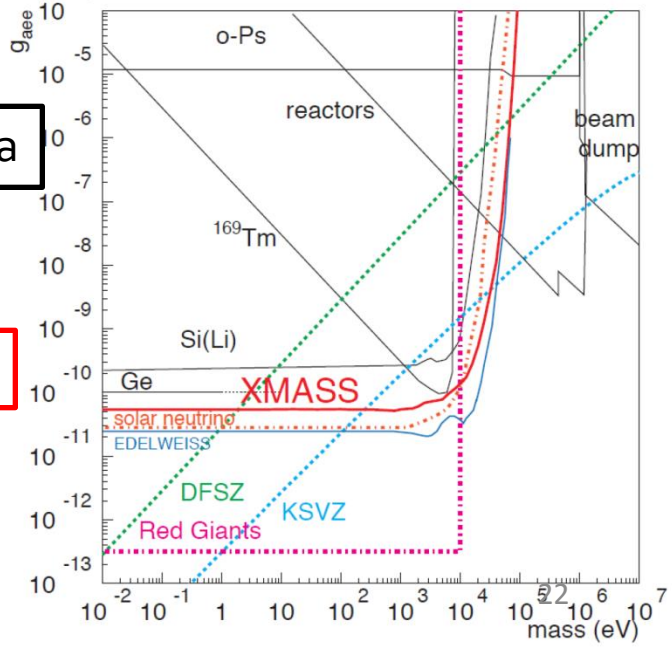






Our data

Max allowed



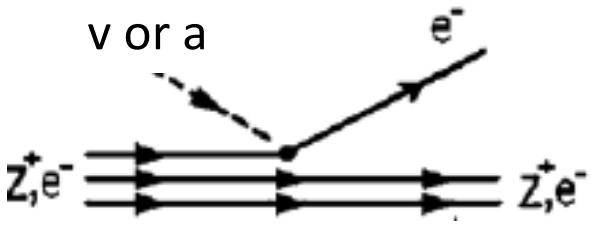
Bosonic super-WIMP (1/3)

PRL 113 (2014) 121301

- Search for lighter and more weakly interacting particles is attracting attention, because
  - So far no evidence of SUSY particles at the LHC.
  - Expectation on the structure on garactic scales of the CDM scenario is richer than observed.

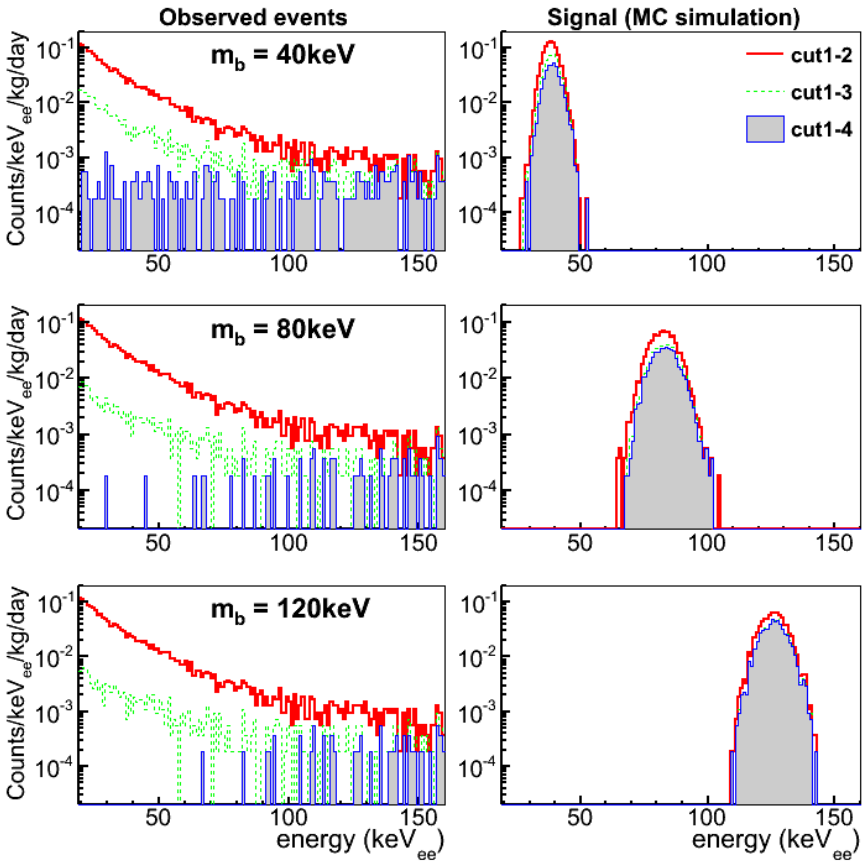
- Bosonic super-WIMPs search
  (*M. Pospelov et. al., Phys. Rev. D 78 115012 (2008),*
  J. Redondo and M. Postma, J. Cosmol. Astropart. Phys. 02 (2009) 005)
  - A lukewarm dark matter candidate, and lighter and more weakly interacting particles than WIMPs.
  - Deposit energy in a target material would essentially equivalent to the super-WIMP rest mass.
  - Search for pseudoscalar and vector boson (called as dark, para, or hidden photon) with photoelectric-like interaction.
  - For vector boson, no experimental constraint so far.

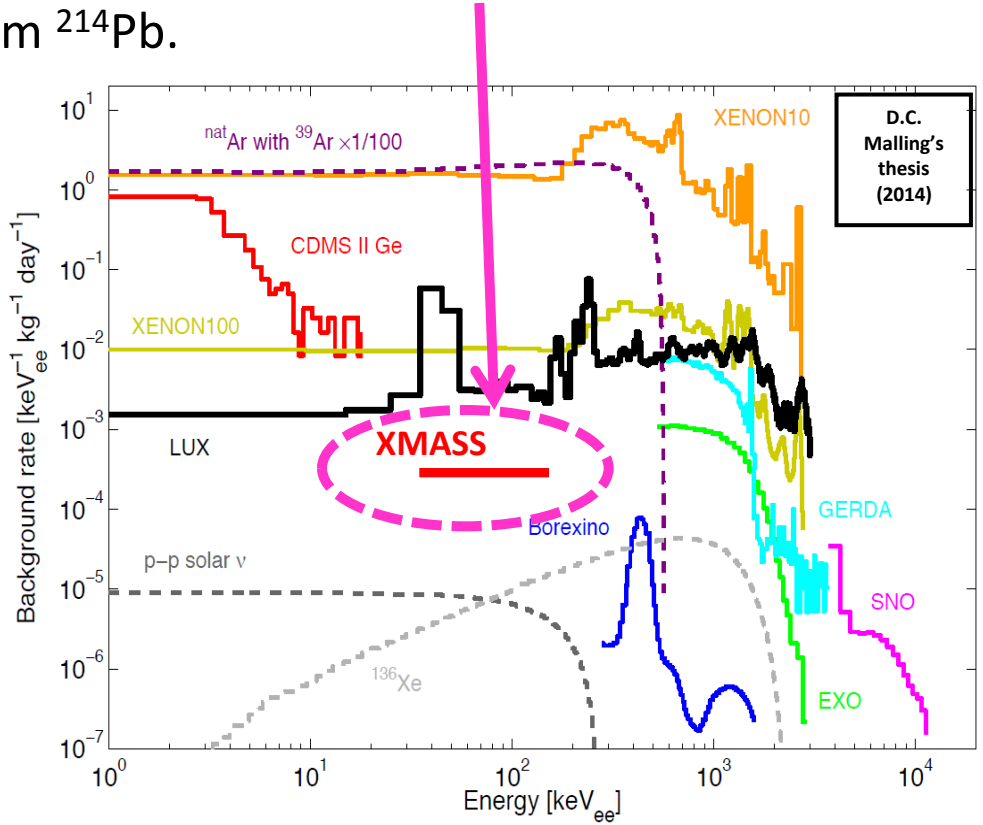
Photoelectric-like interaction



Bosonic super-WIMP (2/3)

- 166 days and 41 kg fiducial volume data.
- Search for mono-energetic peak at m_b (the rest mass of a bosonic super-WIMP) using various cuts optimized for each m_b.
  ((1) pre-selection, (2) reconstructed radius (R<15cm) cut, (3) timing cut, (4) pattern cut)
- The remaining event rate of O(10^{-4}) /day/keVee/kg is the lowest ever achieved and consistent with expected BG from ^{214}Pb.



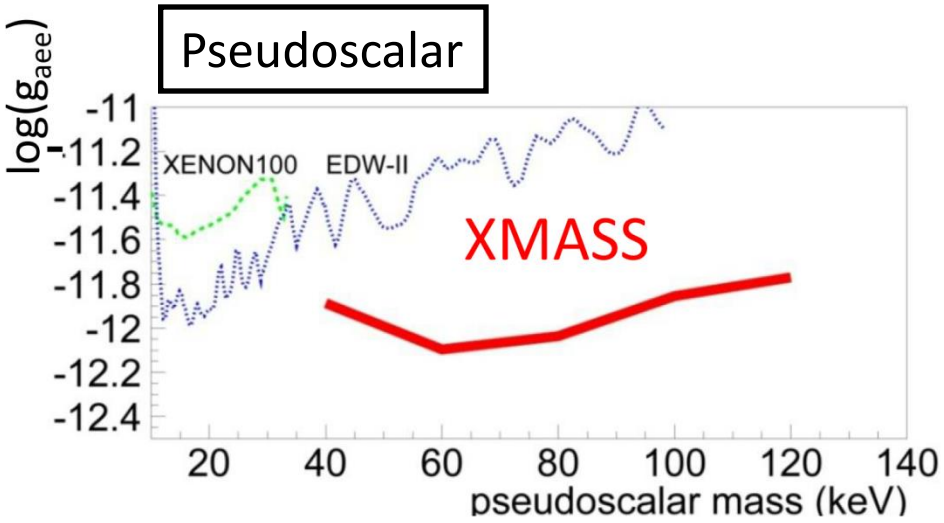


↑BG level of each experiment (before separation for nuclear recoil in 2–phase DM search detector)

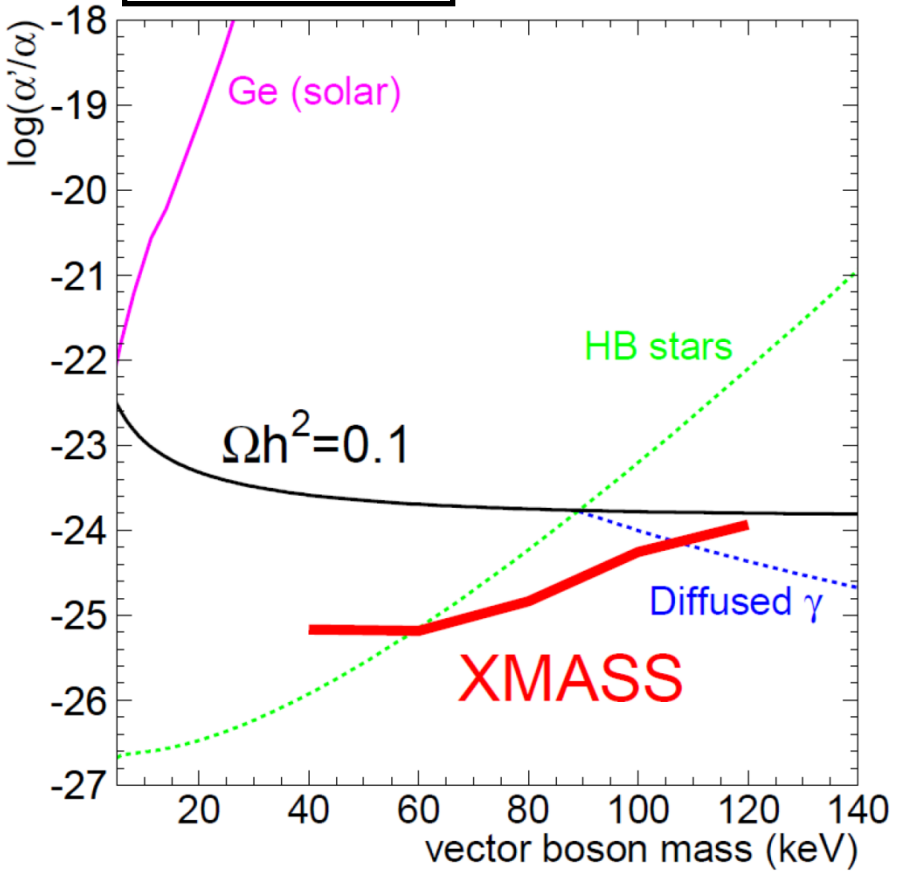
Bosonic super-WIMP (3/3)

- Constraint on coupling constant.
- For vector bosonic super-WIMPs, the first direct search in the 40–120 keV range.
  The limit excludes the possibility that such particles constitute all of dark matter.
  The most stringent direct constraint on g_{aee} thanks to the low BG in this energy region.

Pseudoscalar



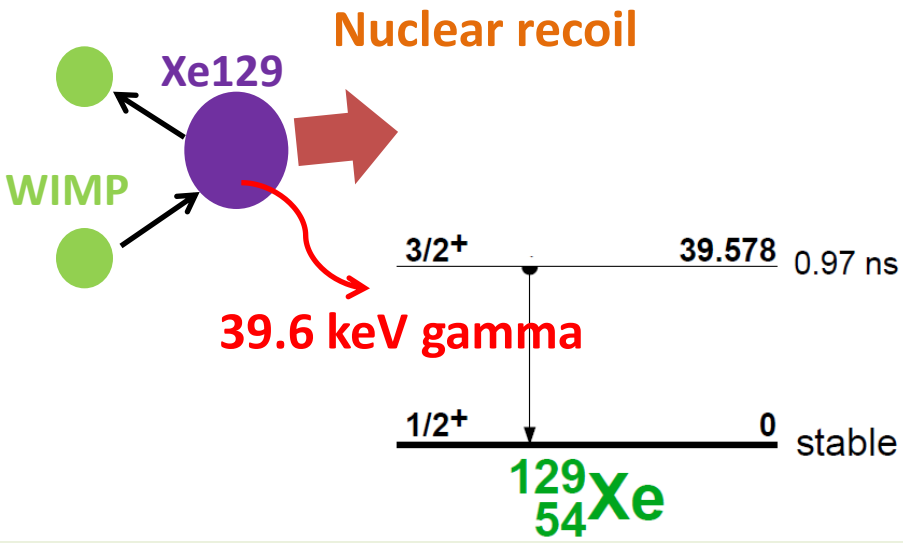
Vector boson



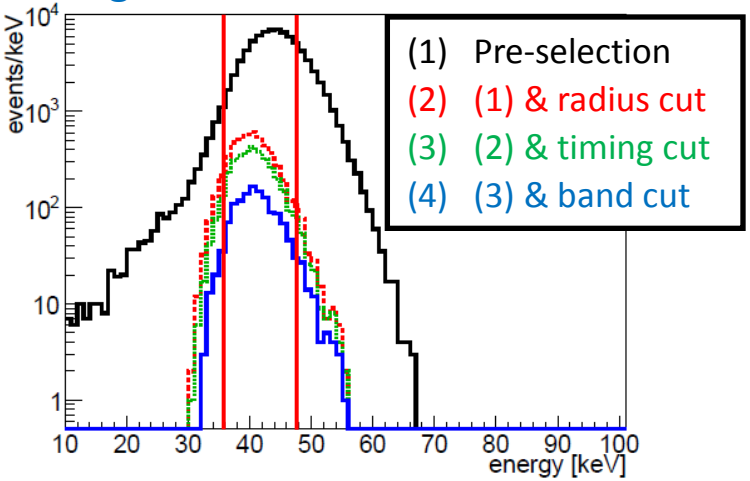
Inelastic scattering DM search (1/2)

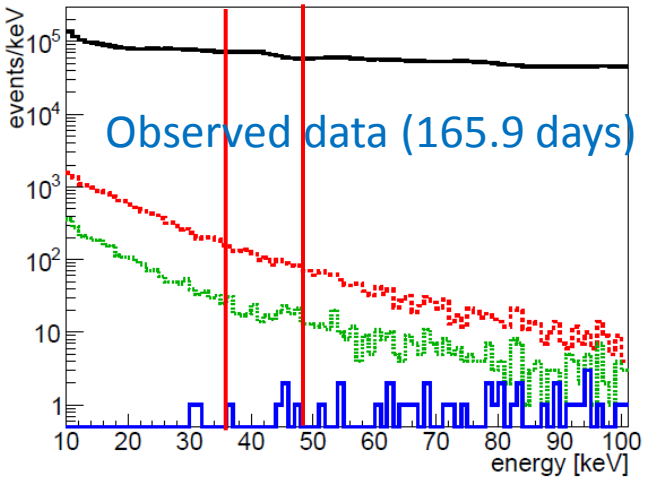
PTEP 063C01 (2014)

- WIMPs would cause inelastic scattering on ^{129}Xe.
  Nuclear recoil as well as 39.6 keV γ ray emission are expected.
- Peak search at 39.6 keV with various cuts are used.
  Reconstructed radius cut (R<15cm), timing cut, and pattern cut.



Signal MC for 50GeV WIMP

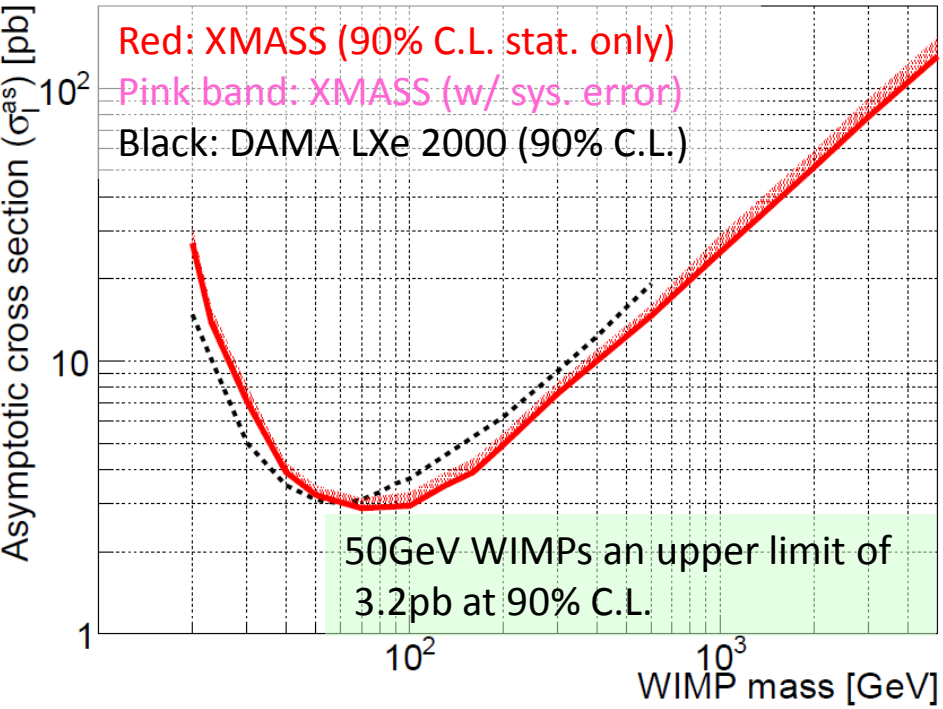


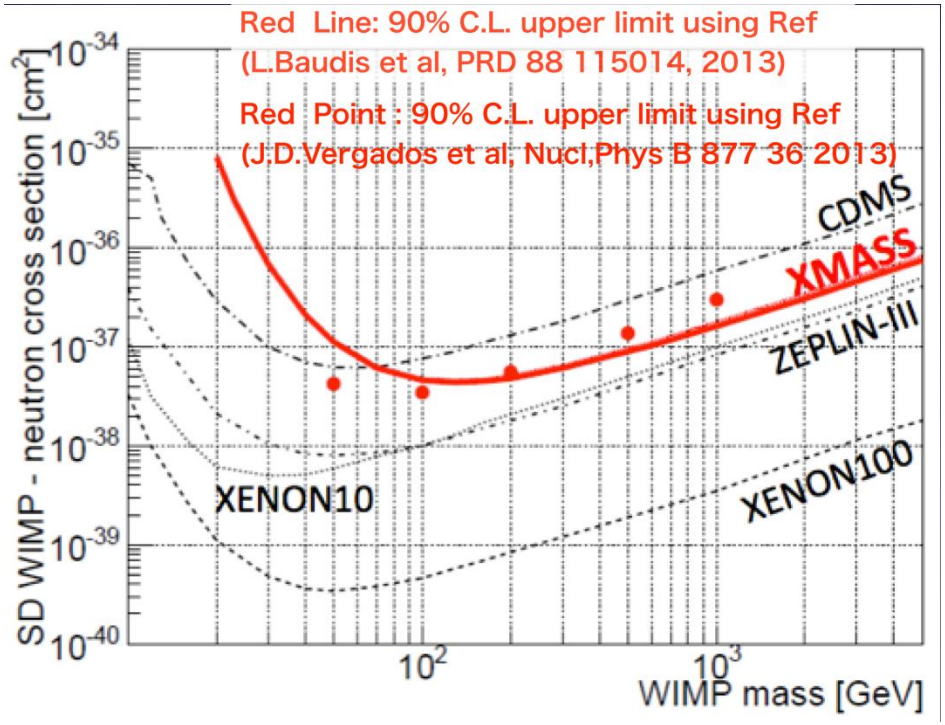


- $\chi + {}^{129}\mathrm{Xe} \rightarrow \chi + {}^{129}\mathrm{Xe}^*$
  ${}^{129}\mathrm{Xe}^* \rightarrow {}^{129}\mathrm{Xe} + \gamma$ (39.6keV)
- Natural abundance of ^{129}Xe: 26.4%

Inelastic scattering DM search (2/2)

- 41 kg fiducial volume (^{129}Xe: 11 kg) w/o BG subtraction
- Better limit than DAMA for > 50 GeV WIMPs
- Another way for study on SD interaction.



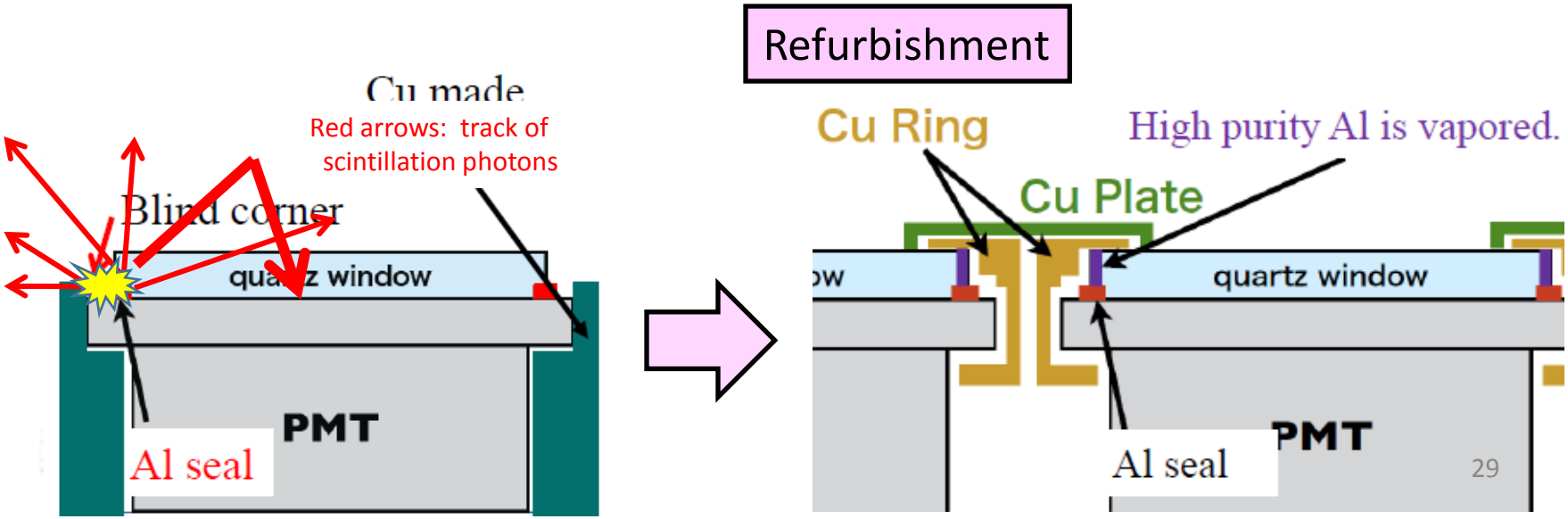


4. Refurbishment of XMASS-1

Identification of BG source

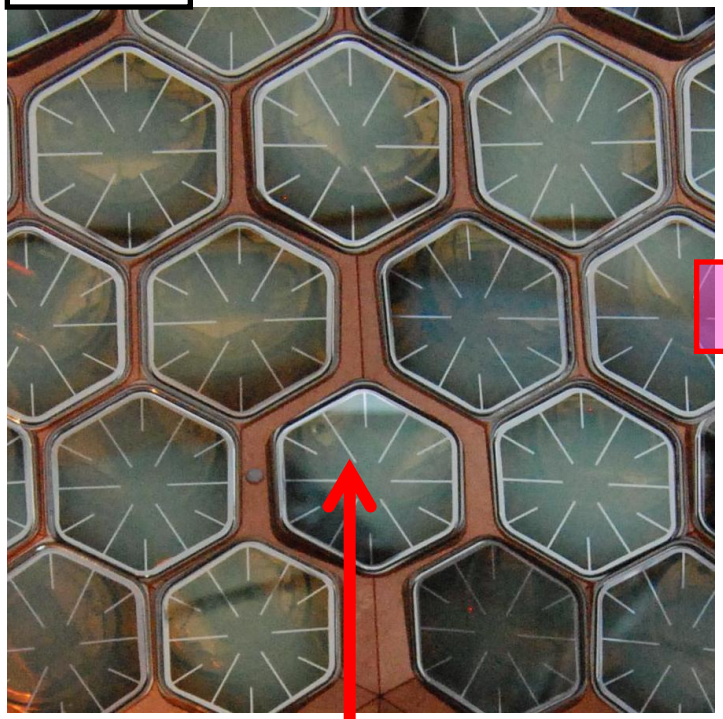
- Dominant BG in the commissioning run is originated from “detector surface”.
  - RI in PMT Al seal and on surface of PMT and PMT holder.
  - Such events are likely to be reconstructed inside the fiducial volume, because photons are hardly detected in neighboring PMTs.

- Refurbishment from May 2012 to Nov. 2013
  - PMT Al seal were covered by copper ring and plate to reduce the beta and X-ray and make a simple and flat surface.
  - Electro-polish is applied to those ring, plate and PMT holders.

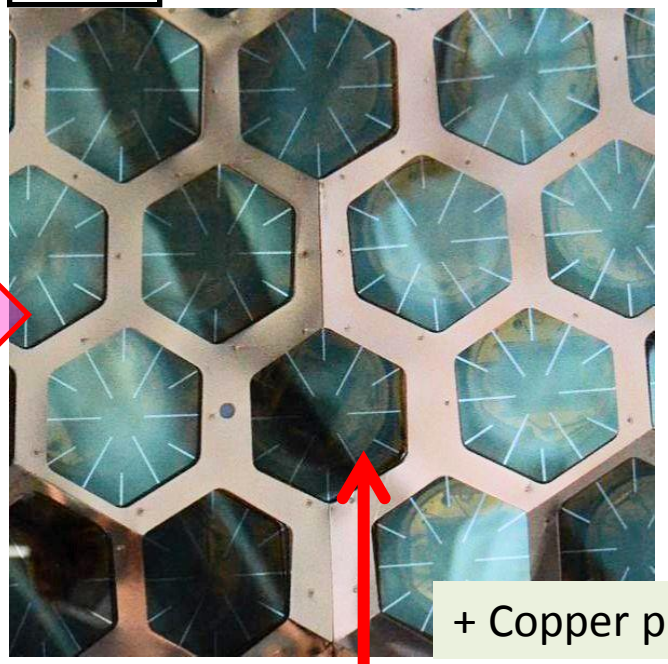


XMASS Refurbishment

Before

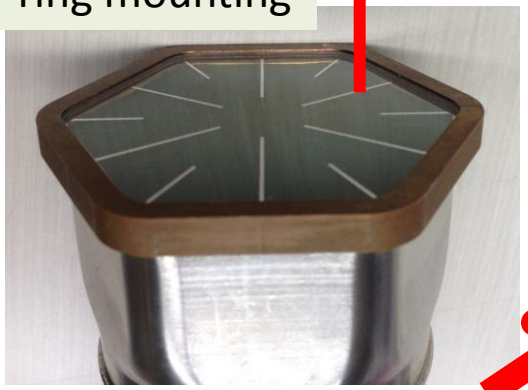


After



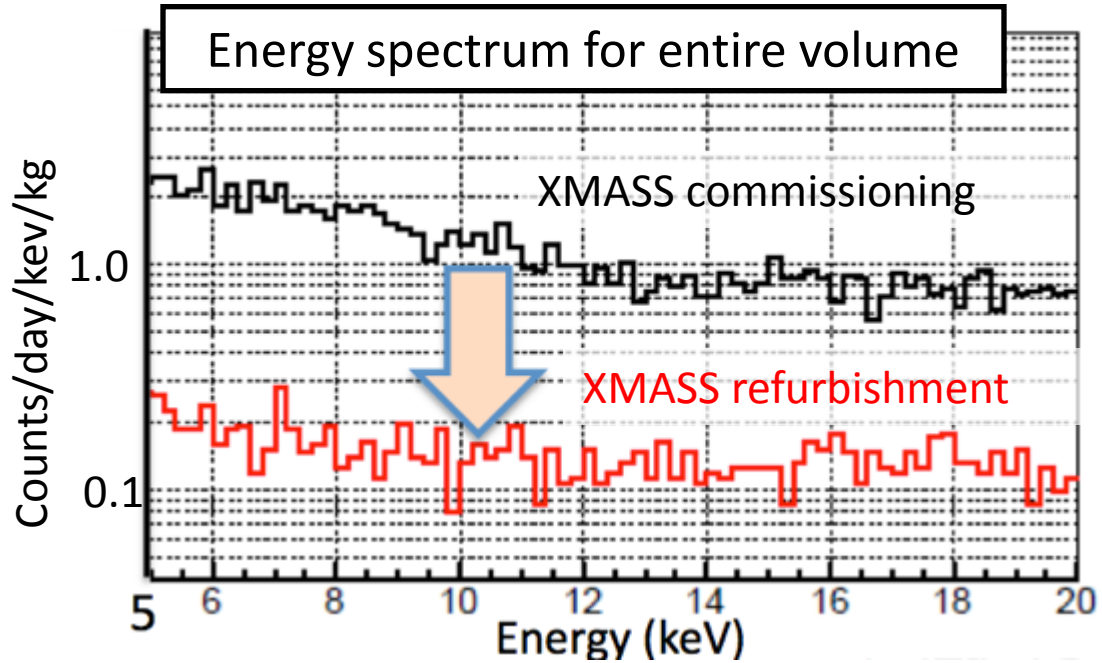
+ Copper plate

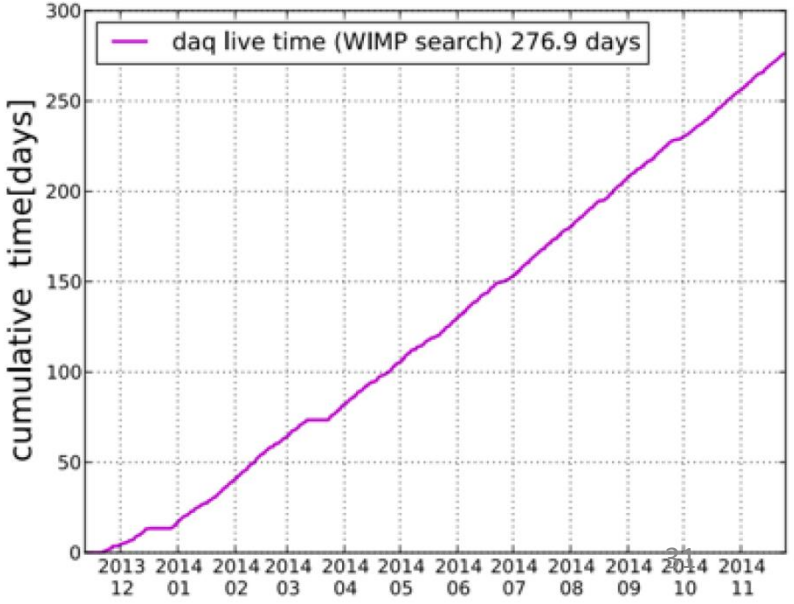
Copper ring mounting



Current status (1/3)

- Restarted data taking from Nov. 2013.
- Quick check of energy spectrum indicates one order reduction of BG from commissioning run data.
- ATM (charge and timing) → FADC analysis.
- Energy threshold is reduced from 1keV to 0.3 keV.
- Already accumulated 277 days data for WIMP search till Dec. 2014.
- Using this data, physics analyses including WIMP search with fiducialization and seasonal modulation are on-going.

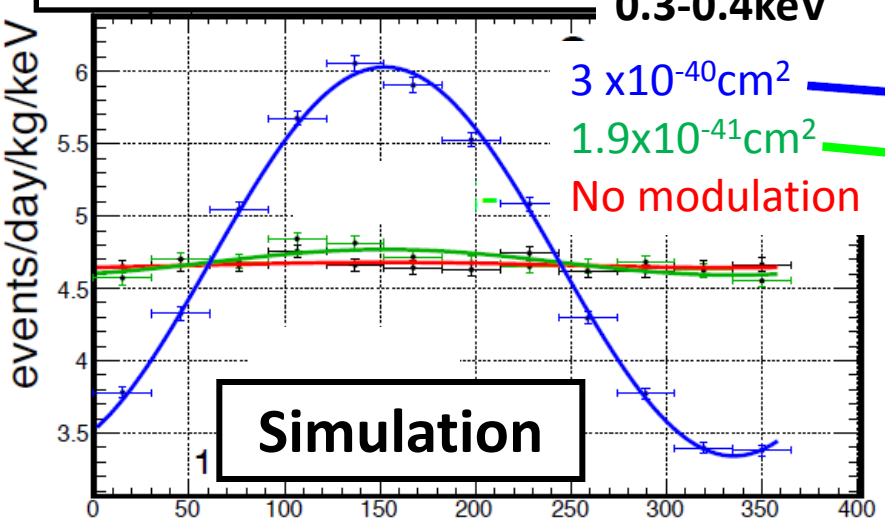




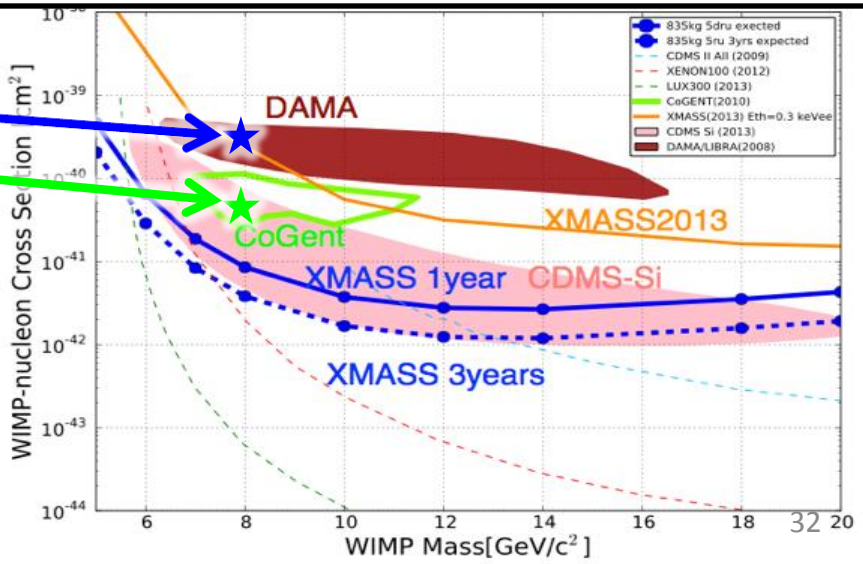
Current status (2/3)

- Seasonal modulation analysis
  - World's largest mass (832 kg after refurbishment):
    1 year data of XMASS ~ 14 years data of DAMA/LIBRA
    0.8 ton*year ~ 1.33 ton*year
    → Current statistics is already half of DAMA/LIBRA data.
  - Low energy threshold: 0.3 keVee.
  - For several physics (DM, axion) w/o PID.
  - The results for 1 year data will come soon.

Expected modulation in XMASS for 8 GeV WIMP

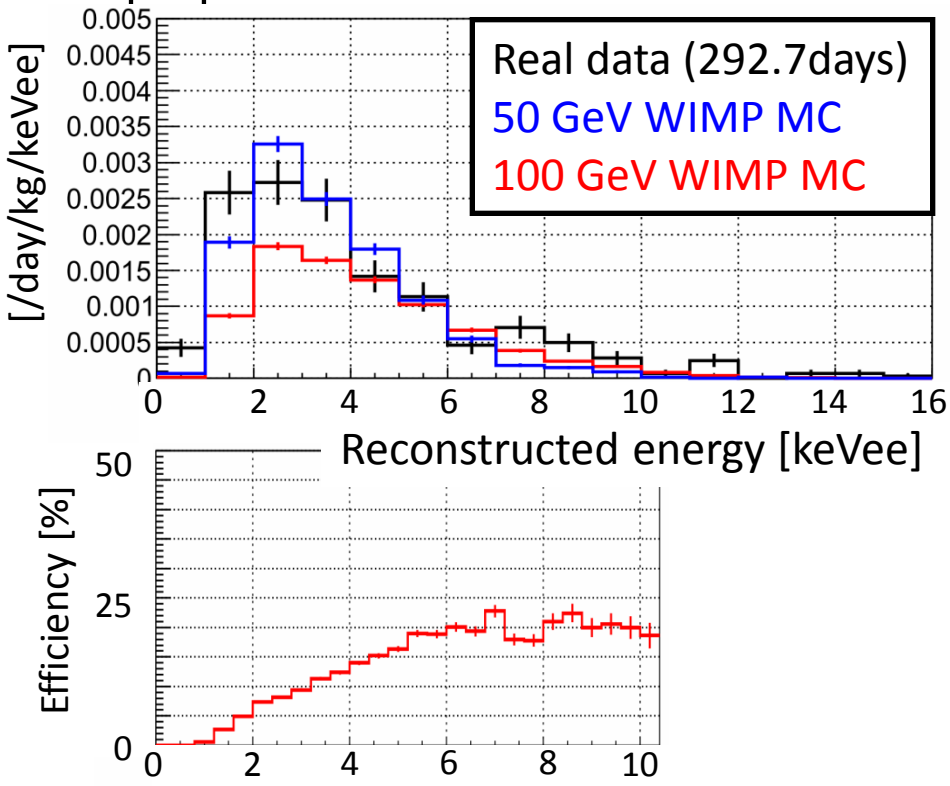


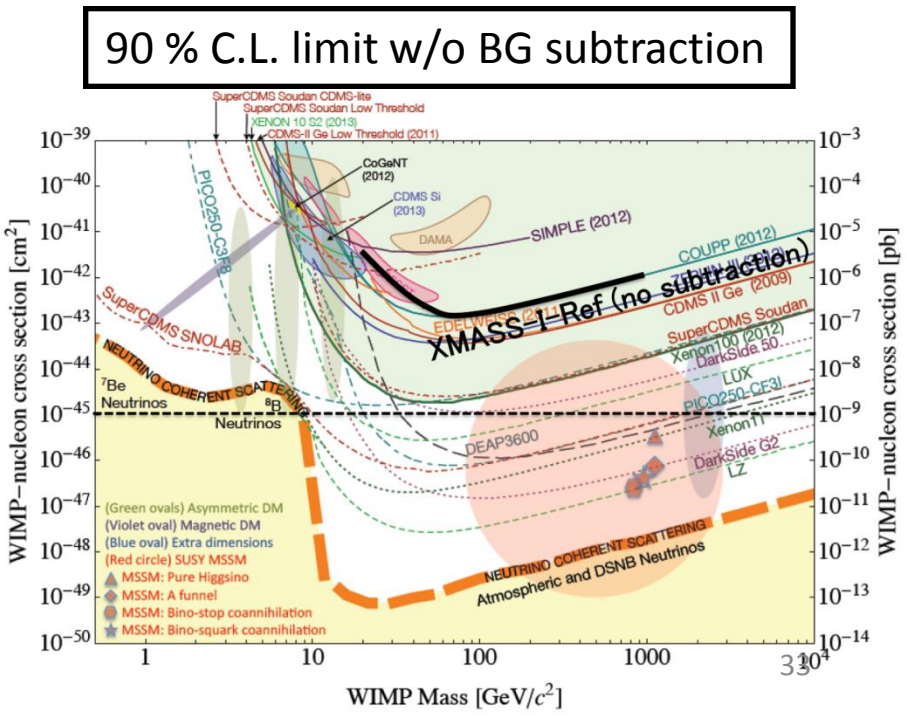
Prospects after refurbishment for full volume



Current status (3/3)

- Fiducial volume (FV) analysis
  - 292.7days (live time) data were used.
  - Surface events sometimes miss-reconstructed as events happened inside the FV.
  - Conservative limit assuming all remaining events are caused by WIMP without BG subtraction are derived. $\sigma_{SI} < 2.7 \times 10^{-43}$ cm^2 (50GeV WIMPs). Possible all the systematic errors are taken into account.
  - Remaining BG sources are identified. Results with BG subtraction is now being prepared.

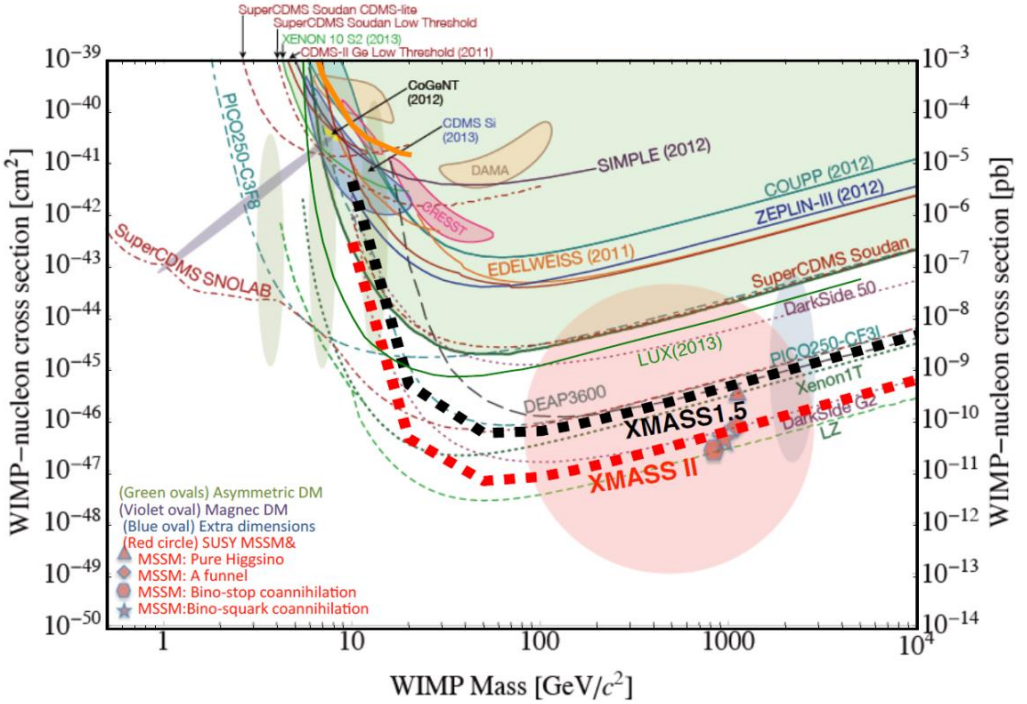




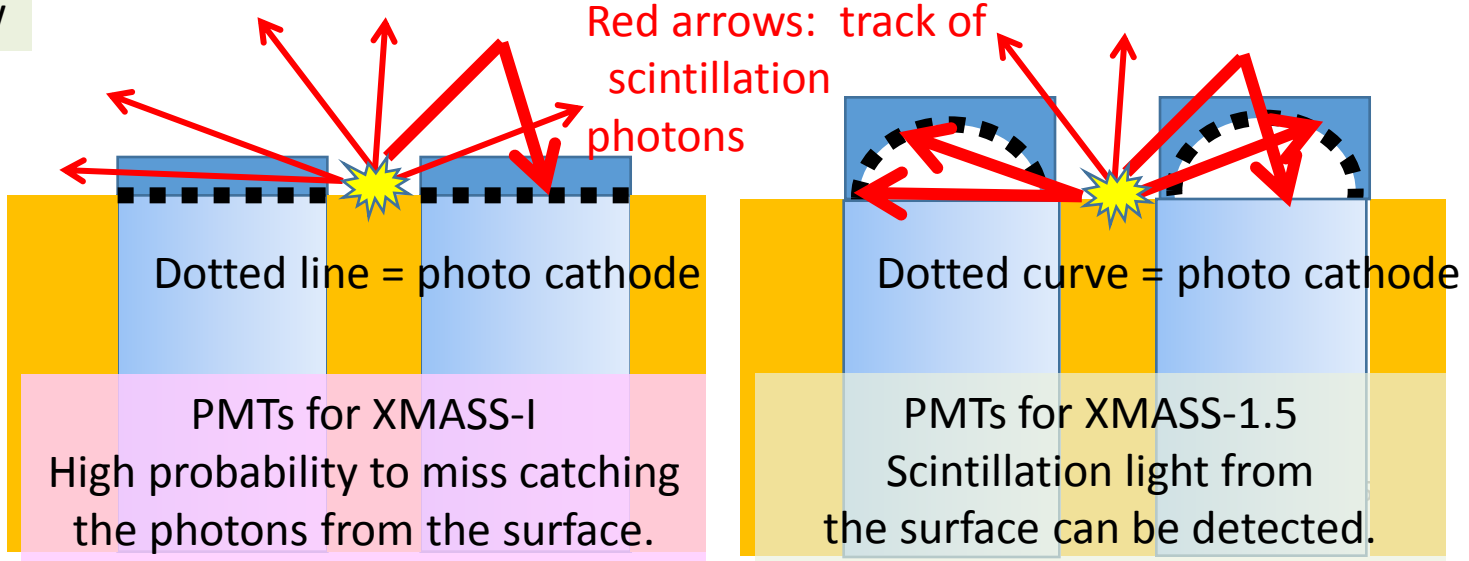
5. XMASS 1.5

XMASS-1.5

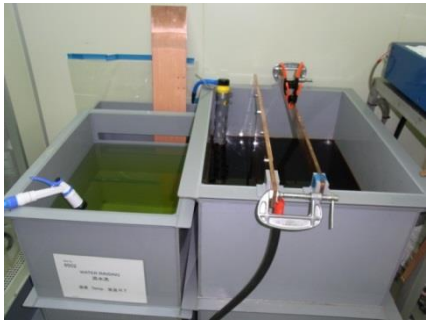
- Total 5 ton (FV 1 ton)
- BG reduction:
  - No dirty Al seal
  - Less surface ^{210}Pb (< 1/100)
- New PMT with round shape window to identify surface event is being developed. MC study for evaluation of miss-reconstruction rate is on-going.



Round shape window

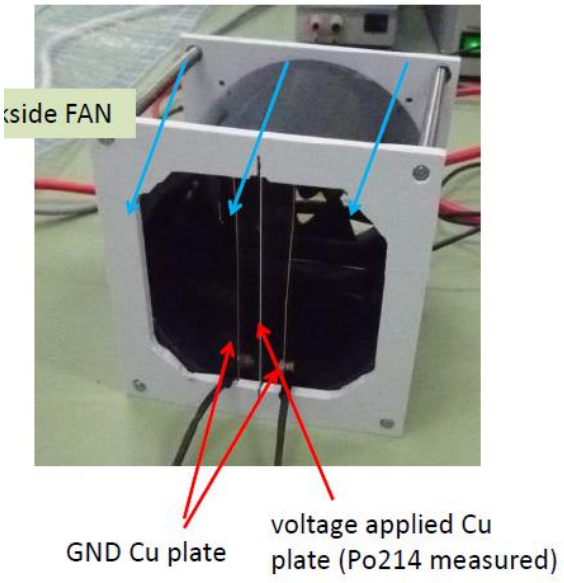


Less surface ^{210}Pb (<1/100)



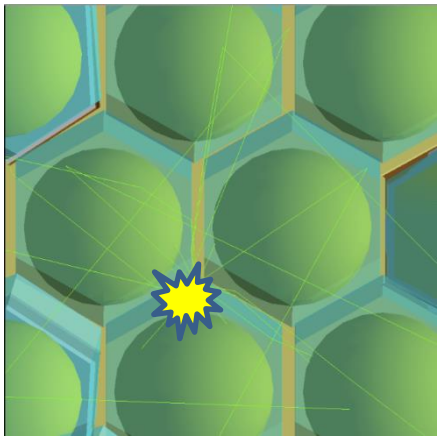
- Environment controlling during machining of detector
  (1) All the works should be done under Rn free air
  with Rn concentration of ~10mBq/m^3 (usually 20Bq/m^3)
  (2) All the surfaces should be cleaned by electro-polishing (EP)

- Controlling of Rn exposure after EP
  (1) Minimization during machining:
  Optimization of all process
  (2) Minimization during storage:
  Packed with Rn barrier sheet (EVOH) and
  conductive bag.
  (3) Less Rn environment during assembling (<10mBq/m^3)
  Rn removing device with electro-static collection
  is being developed.
  (Rn decay products (especially, ^{218}Po) tend to have
  positive charge and collected with high voltage)

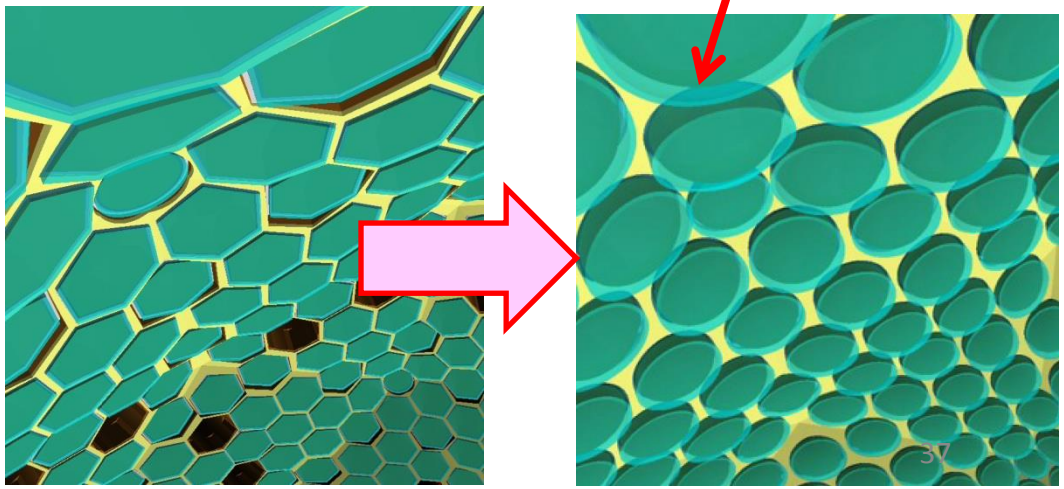


PMT with round shape window

- Mass-production is OK.
- Optimization of shape and cost-cutting are being concerned.
- Less radio-active impurities.
- MC study of miss-reconstruction rate is being evaluated:
  Reduction rate of $< 10^{-5}$ at 2.5keV was obtained
  for events occurred in the side of window.



- 3 PMTs around event vertex detect 40–50% of pe.
- Cut criteria: Fraction of pe in 3 PMTs > 10%



Summary

- XMASS-I is the world's largest (835kg) and low threshold (0.3keVee) detector for dark matter search.
- Physics results from commissioning data with the full advantage of sensitivity to e/γ events as well as nuclear recoil with low BG at a few 10's keV at a level of 10^{-4} /day/kg/keVee.

  - Low mass WIMP search (PLB 719(2013)78)
  - Solar Axion search (PLB 724 (2013) 46)
  - Bosonic super-WIMPs (PRL 113, 121301 (2014)): For vector boson, the first direct search in the 40–120 keV range.
  - Inelastic scattering WIMP search (PTEP 063C01 (2014))

- Current status.
  - The refurbishment of detector completed and data taking resumed in Nov. 2013.
  - One order reduction of BG from commissioning run data.
- Future
  - Designing of XMASS-1.5 is on-going.
  - Aim to $\sigma_{SI} < 10^{-46}\,cm^2$ (>5keV) for fiducialization.