Dark Matter Search with XMASS

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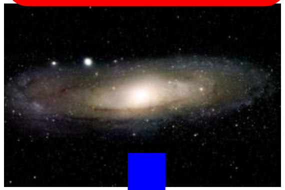
On behalf of the XMASS collaboration

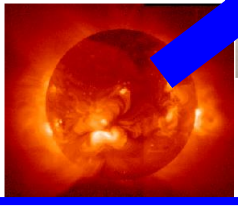
June 4th, 2016
Warsaw Workshop on Non-Standard Dark Matter: multicomponent scenarios and beyond, Warsaw, Poland

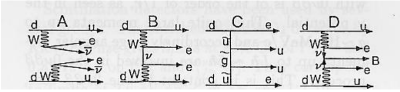
XMASS experiment

Dark Matter



- **XMASS**
  Multi purpose low-background and low-energy threshold experiment with liquid Xenon
  - **X**enon detector for Weakly Interacting **MASS**ive Particles (**dark matter search**)
  - **X**enon **MASS**ive detector for solar neutrino (**pp/^{7}Be**)
  - **X**enon neutrino **MASS** detector (**ββ decay**)





Purpose of the first phase is the dark matter search.

Solar neutrino

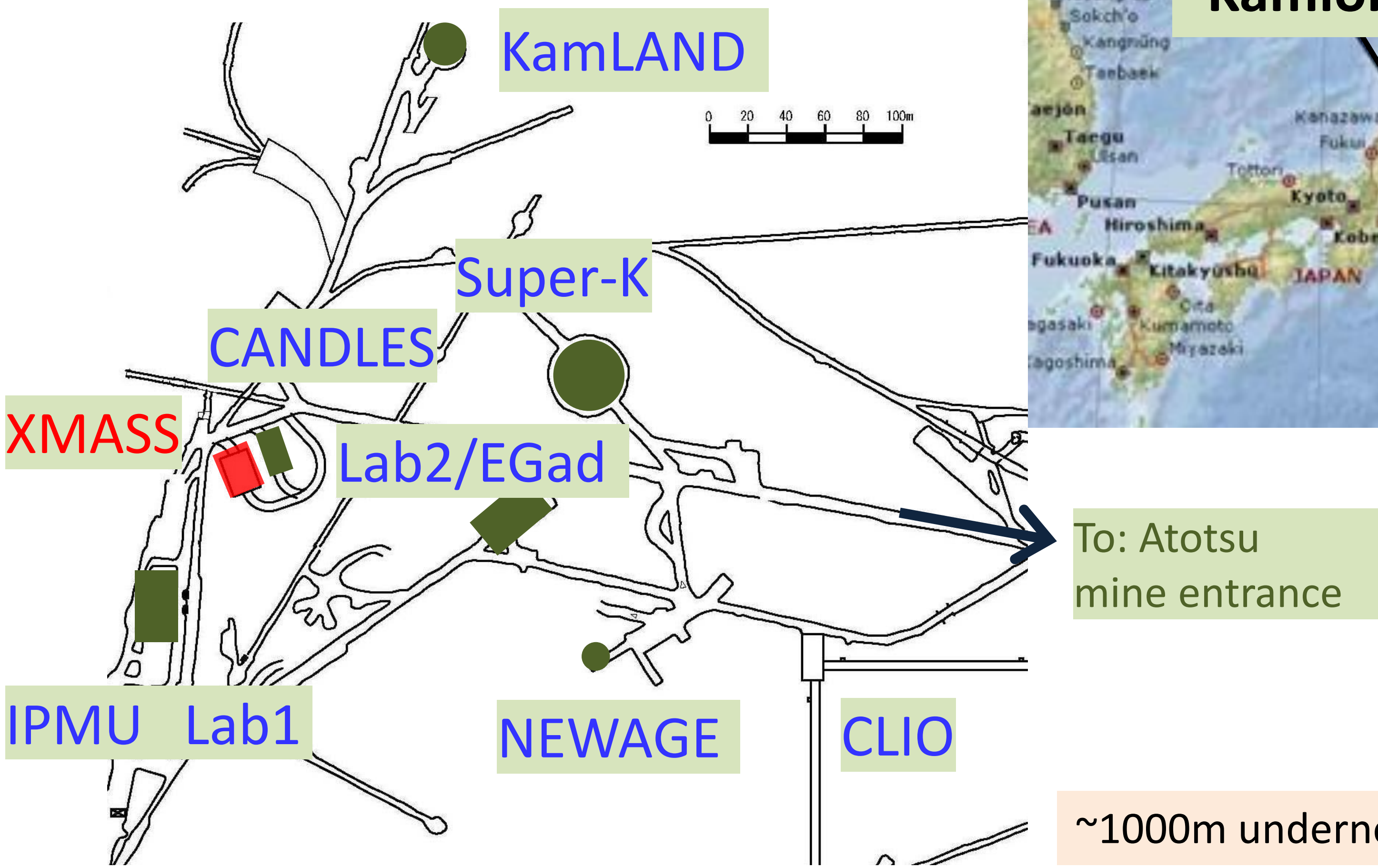
Double beta decay

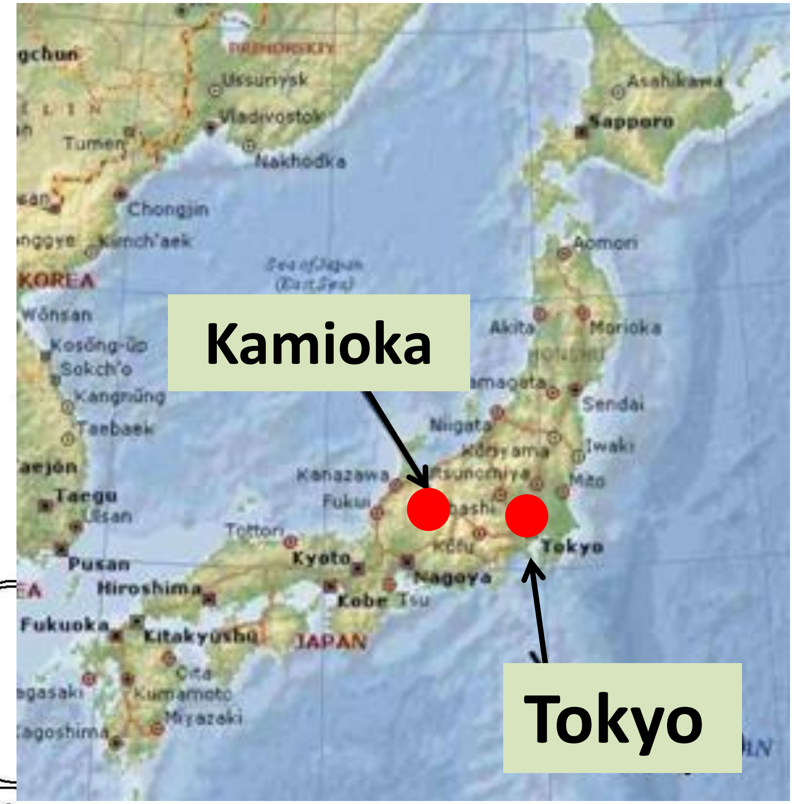
history of XMASS

2010	2011	2012	2013	2014
detector construction completed (Sep. 2010)	commissioning run data taking (Dec. 2010 - May 2012)		detector refurbishment (RFB) (Aug. 2012 - Oct. 2013)	resume data taking (Nov. 2013 -)

We have already taken data for >2.5year.

Kamioka mine

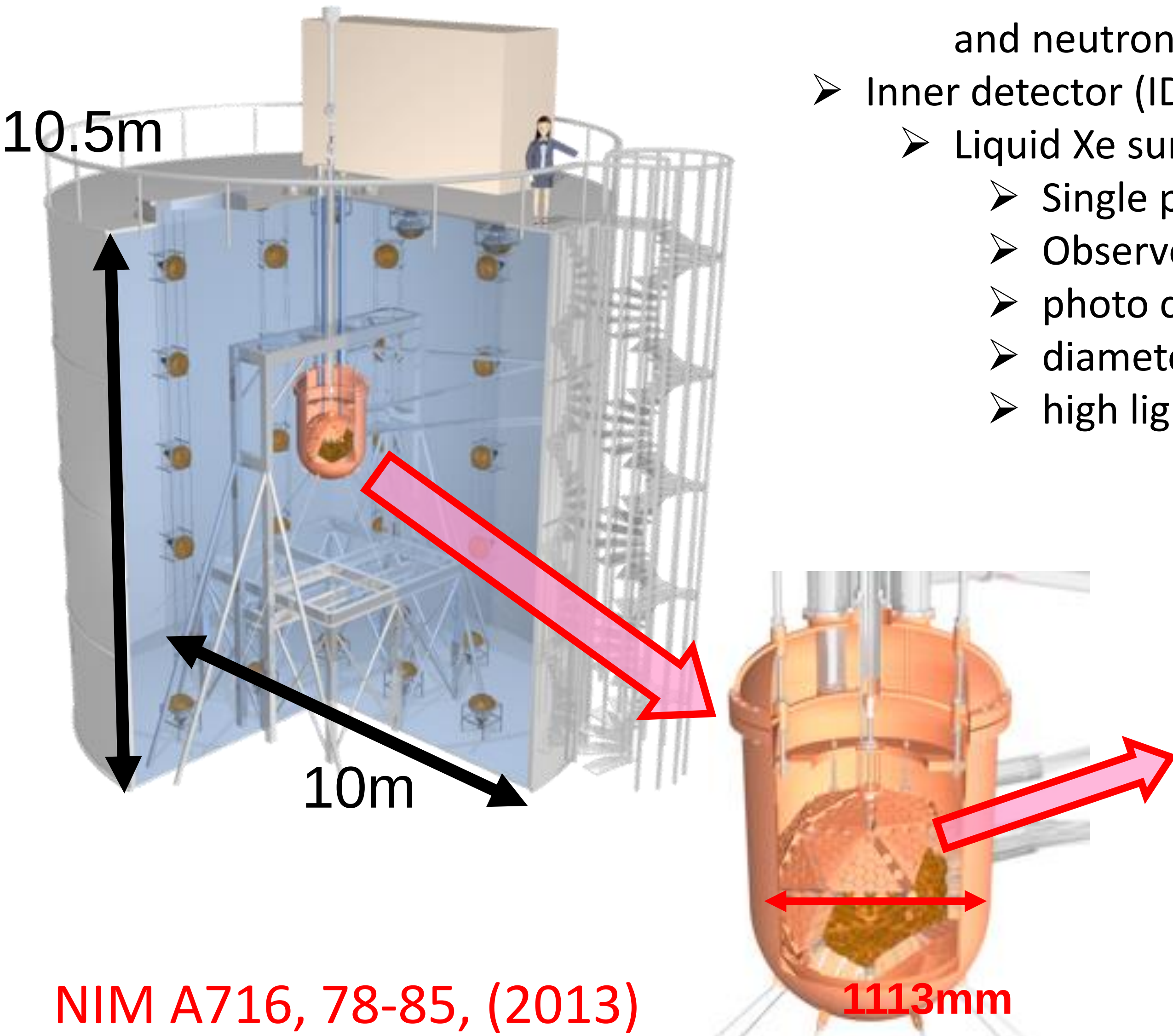




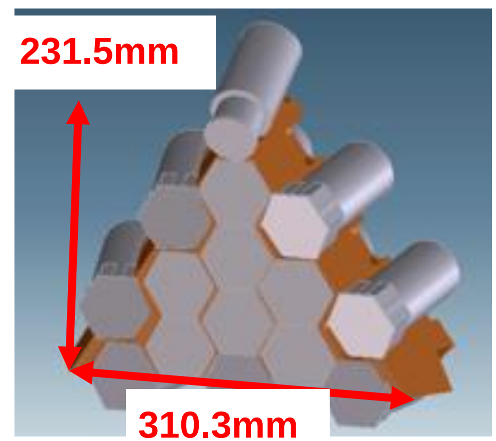
~1000m underneath Mt. Ikenoyama

XMASS detector

- Outer detector (OD, water tank)
  - 72 20-inch PMTs for cosmic-ray muon veto.
  - Water is also passive shield for gamma-ray and neutron from rock/wall.
- Inner detector (ID, Liquid Xe)
  - Liquid Xe surrounded by 642 2-inch PMTs.
    - Single phase
    - Observed scintillation light.
    - photo coverage: 62%
    - diameter: ~800mm
    - high light yield: 14.7 PE/keV



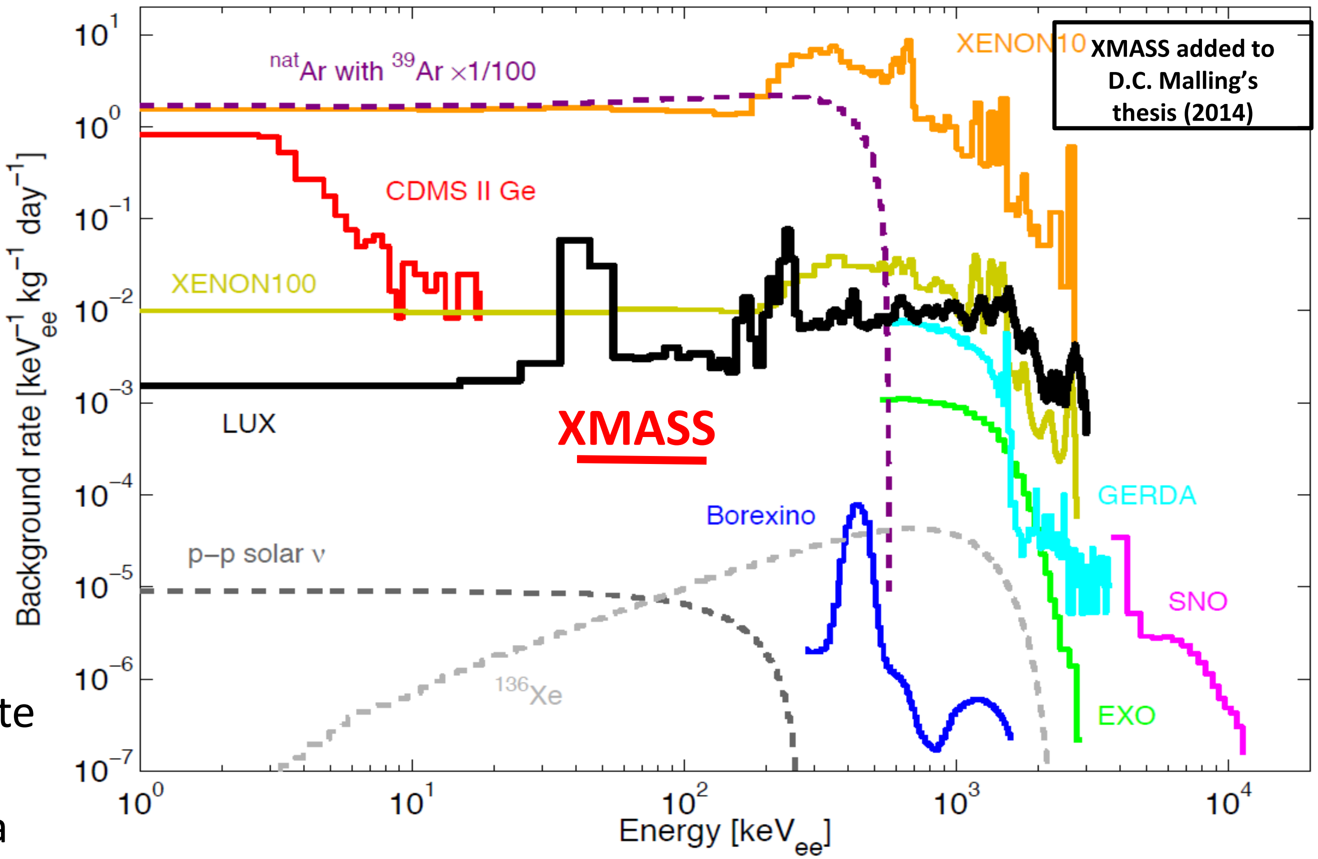
NIM A716, 78-85, (2013)



pentakisdodecahedron

Hexagonal PMT
Hamamatsu R10789

background level in XMASS



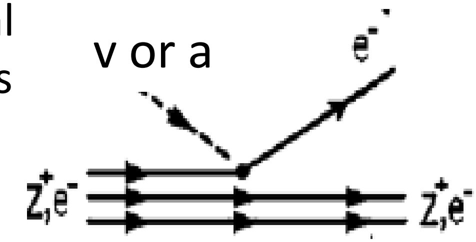
- The remaining event rate (O(10^{-4})/day/kg/keV_{ee}), the lowest event rate (a few 10s keV) ever achieved, is in good agreement w/ expected BG from 214Pb w/ keeping > 50% signal efficiency

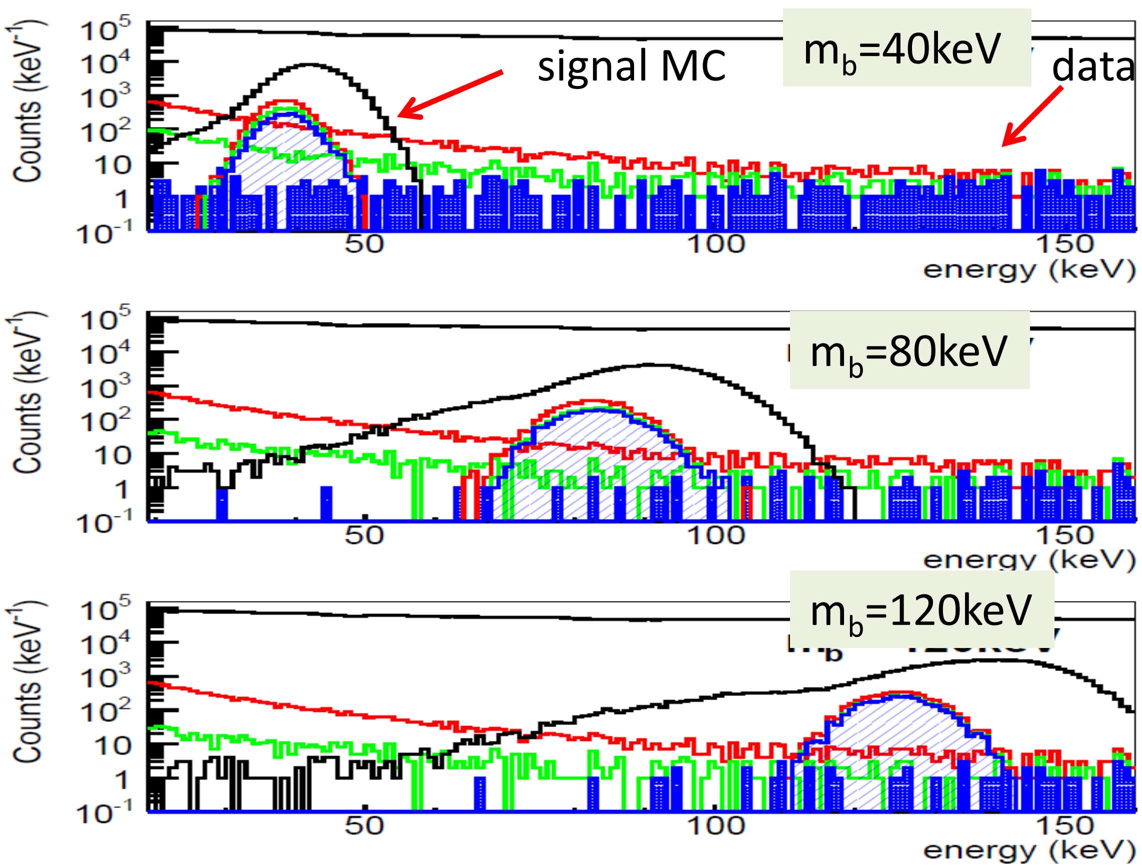
Various kind of dark matter candidates /physics topics has been searched for!

- These analysis can be done mainly due to low background in both nuclear recoil and beta/gamma, high light yield.
  - Light mass WIMP (Phys. Lett. B 719(2013) 78)
  - Solar axion (Phys. Lett. B 724(2013) 46)
  - Inelastic scattering by ^{129}Xe (PTEP 2014, 063C01)
  - Bosonic super-WIMP (Phys. Rev. Lett. 113(2014) 121301)
  - Double electron capture by ^{124}Xe (Phys. Lett. B759(2016) 64-68)
  - Supernova coherent elastic scattering study (arXiv:1604.01218)

Bosonic super-WIMP search

Bosonic super-WIMPs (Pospelov et, al. Phys. Rev. D 78 115012 (2008)) is a lukewarm dark matter candidate, and lighter and more weakly interacting particles than WIMPs.
Experimentally interesting since their absorption in a target material would deposit an energy essentially equivalent to the super-WIMP's rest mass. Search for pseudoscalar and vector boson (sometimes called as dark, para, or hidden photon).





- Commissioning data (165.9days data) is used.
- Fiducial cut, timing cut, band cut are applied to remove backgrounds from aluminum seal in the PMTs.

event reduction

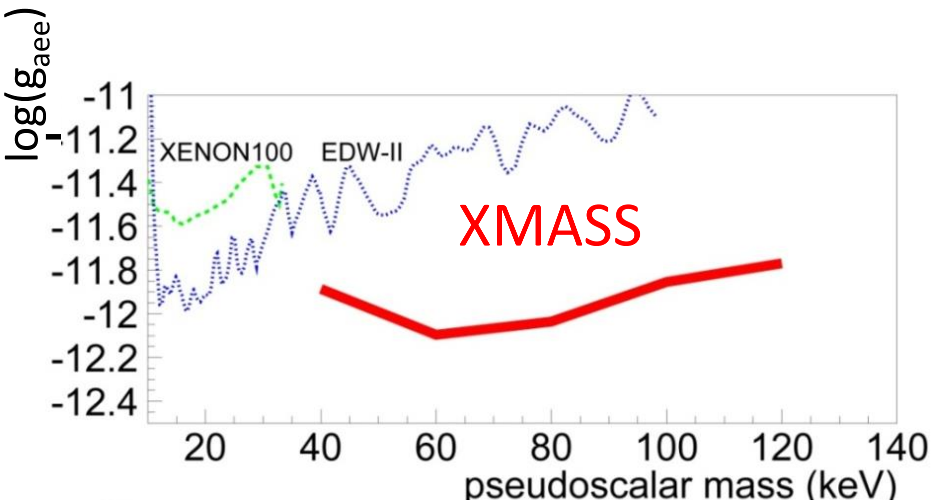
(1) pre-selection

(2) (1)&fiducial cut (R<15cm)

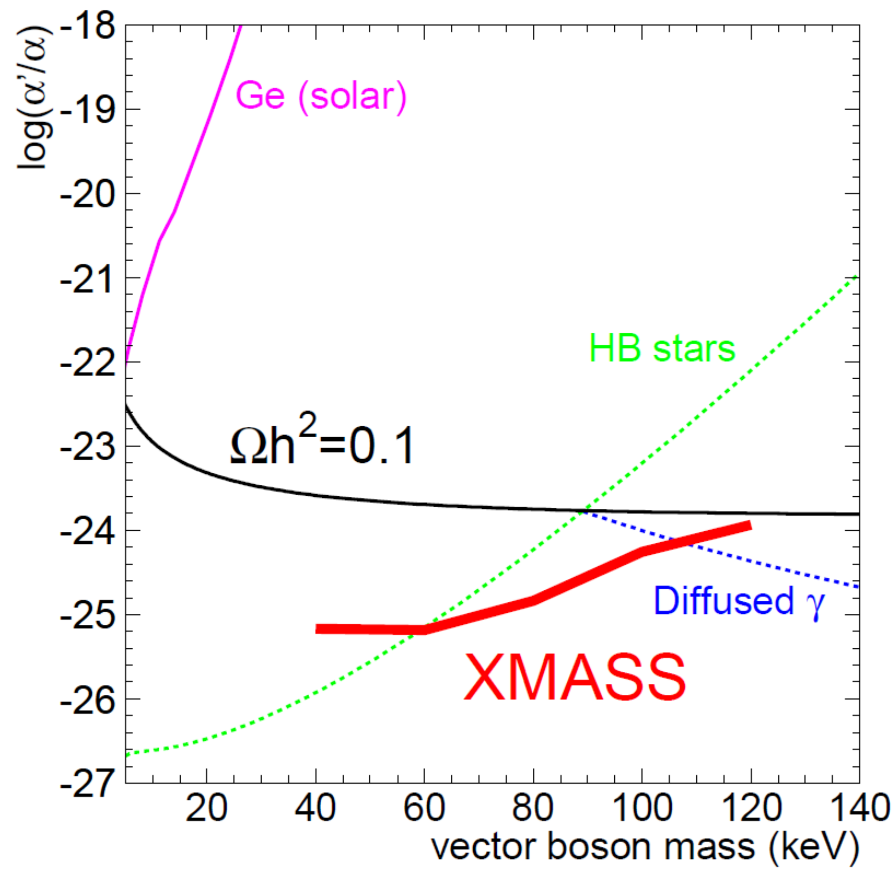
(3) (2)& timing cut

(4) (3)&band cut

constraint on coupling constants



pseudoscalar case



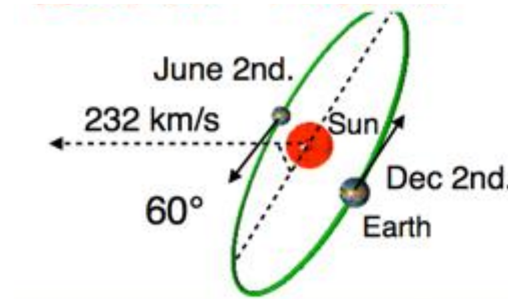
vector boson case

The limit excludes the possibility that such particles constitute all of dark matter.

mass (keV)	α'/α	g_{aee}
40	8.0×10^{-26}	1.3×10^{-12}
60	6.8×10^{-26}	8.0×10^{-13}
80	1.6×10^{-25}	9.2×10^{-13}
100	6.0×10^{-25}	1.4×10^{-12}
120	1.2×10^{-24}	1.7×10^{-12}

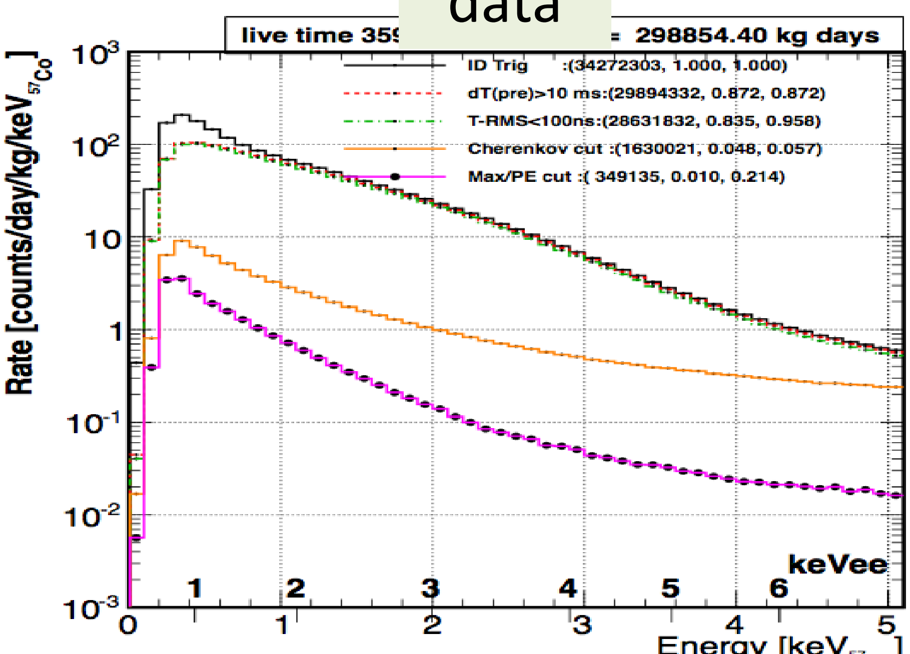
Modulation analysis using data after RFB

Dark matter event rate is expected to modulate annually due to relative motion of the Earth around the Sun. Annual modulation claimed by DAMA/LIBRA with 9.3σ significance (1.33 ton･year, 14 cycles).

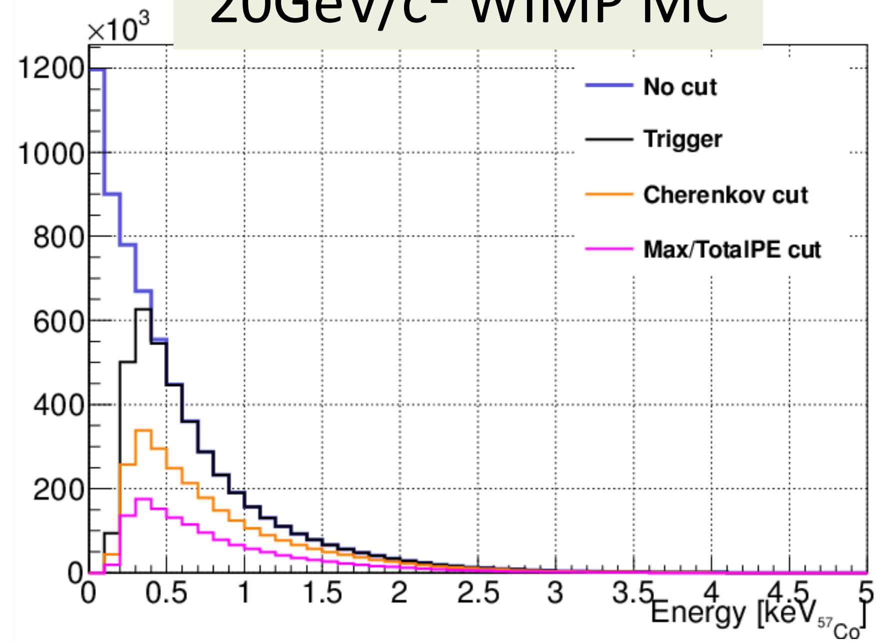


- 1year cycle data (0.83ton･year) with low threshold (1.1keVee)
- No particle ID (just like DAMA/LIBRA)
- Accepted by PLB (arXiv : 1511.04807)

data

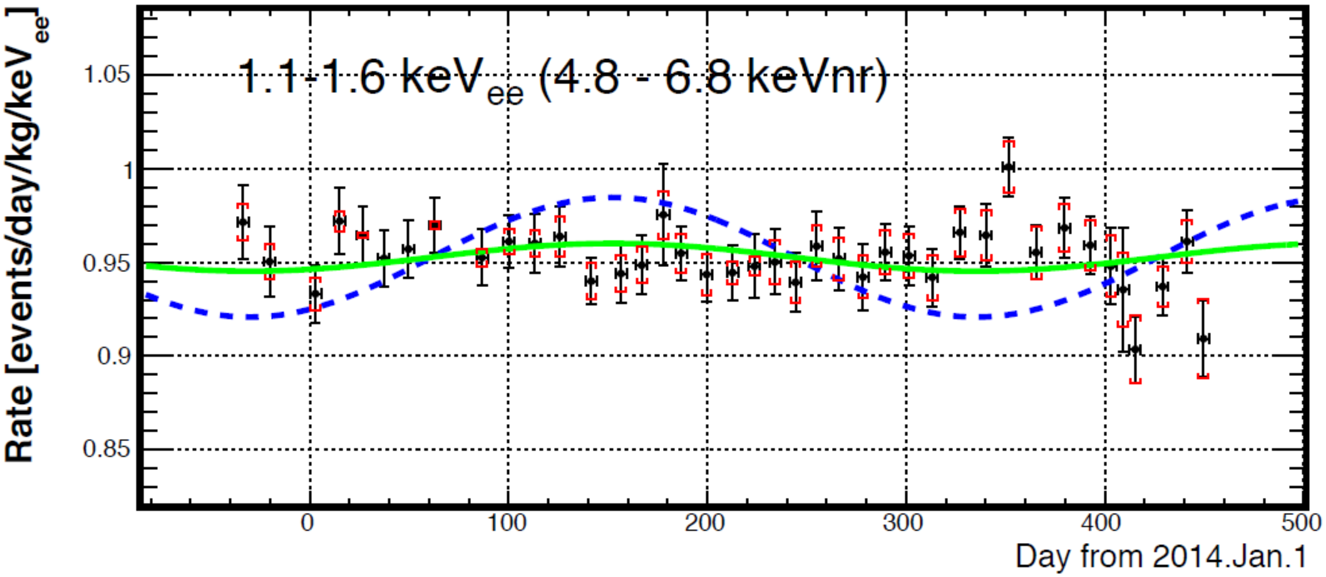


20GeV/c^2 WIMP MC



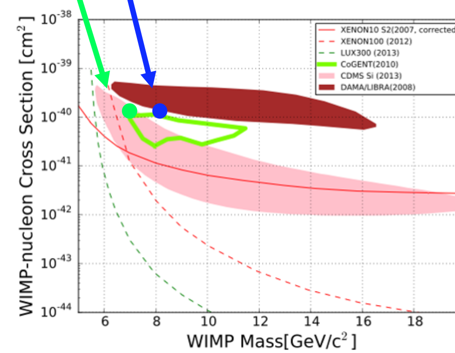
Time variation of event rate

1.1<E<1.6keV$_{ee}$



7GeV/c^2 2x10^{-40}cm^2

8GeV/c^2 2x10^{-40}cm^2



Statistical error

systematic error

We can clearly see the modulation signal if WIMP parameters are in the range where DAMA/LIBRA experiment indicates

Two independent modulation analyses were performed using different χ^2 definition

Systematic errors (1σ)

Method 1 (pull term)

$$\chi^2 = \sum_{i}^{E-bins}\left(\sum_{j}^{t-bins}\frac{(R_{i,j}^{obs} - R_{i,j}^{Pred} - \alpha K_{i,j})^2}{\sigma(\mathrm{stat})_{i,j}^2 + \sigma(sys)_{i,j}^2}\right) + \alpha^2$$

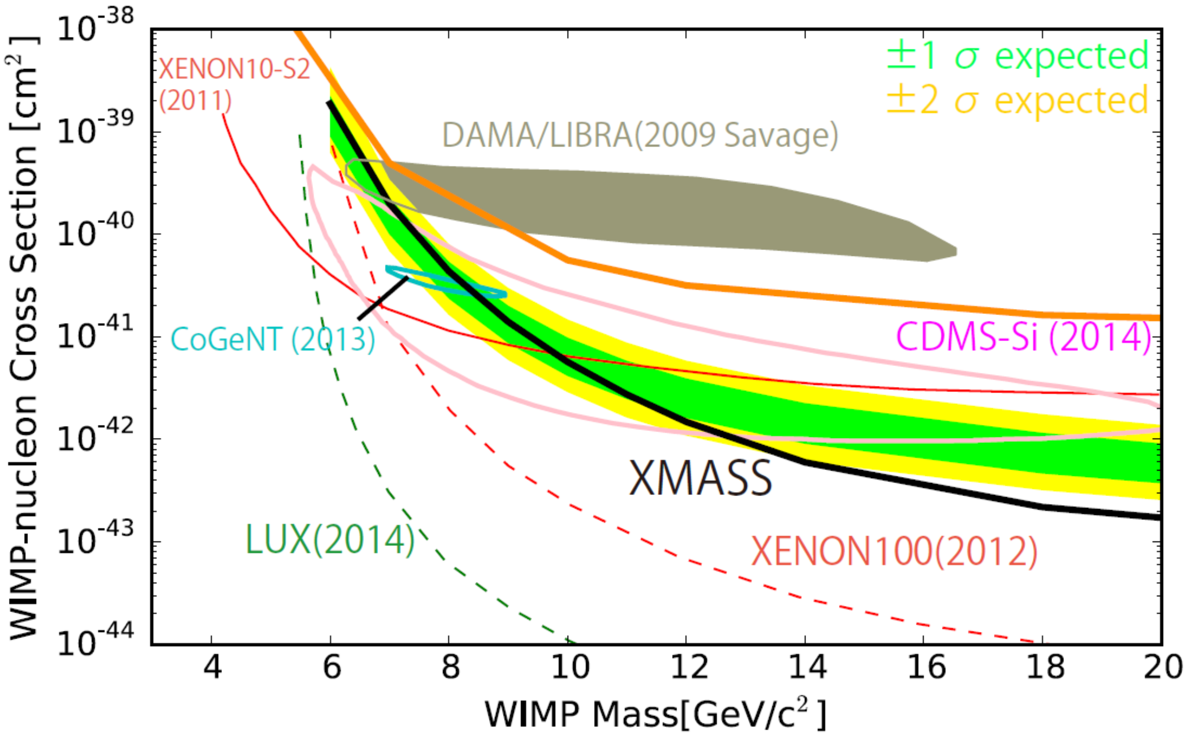
Method 2 (covariance matrix)

$$\chi^2 = \sum_{i,j}^{Et-\mathrm{bins}} (R_i^{\mathrm{obs}} - R_i^{\mathrm{pred}})(V_{\mathrm{stat}} + V_{\mathrm{sys}})_{ij}^{-1}(R_j^{\mathrm{obs}} - R_j^{\mathrm{pred}})$$

Standard WIMP search

Assuming standard WIMP, data is fitted with the following equation:

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

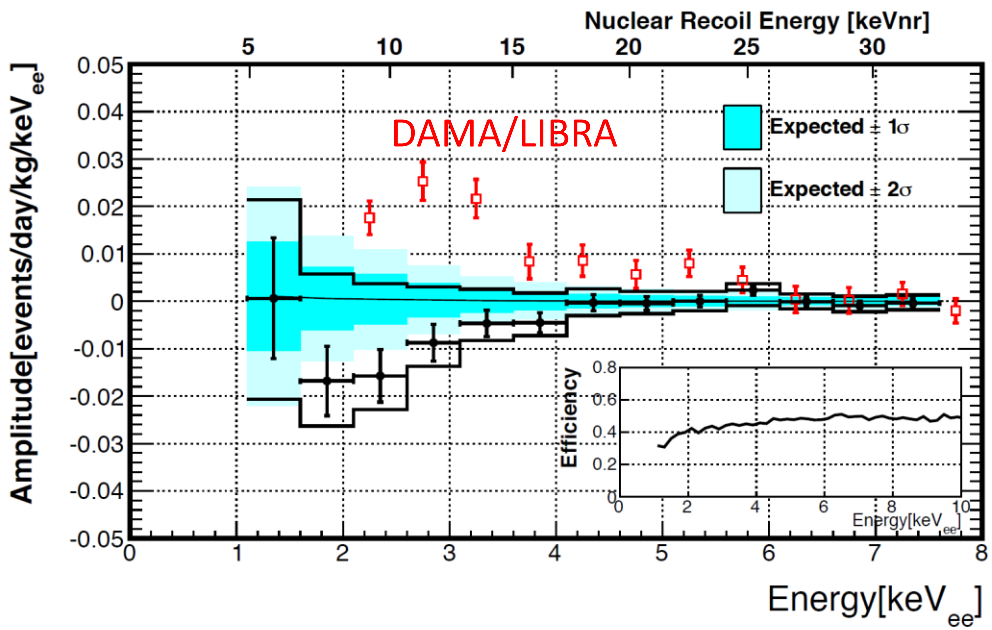


- Leff uncertainty is taken into account.
- Figure is drawn by Method 1. The difference between two methods are within 30%.
- DAMA/LIBRA region is mostly excluded by our measurement.

Model assumption

V_0: 220.0 km/s
V_{esc}: 650.0 km/s
ρ_{dm}: 0.3 GeV/cm^3
Lewin, Smith (1996)

Model independent analysis



Annual modulation signal is searched for without any model assumption. Phase and term are fixed at t_0=152.5days and T=365.25days, respectively. following equation.

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

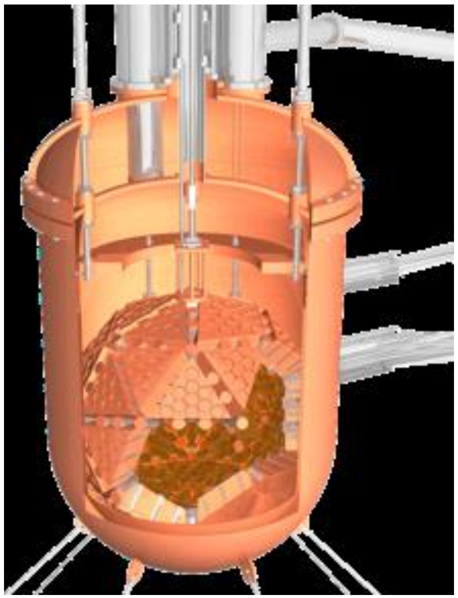
A_i (modulated amplitude) and C_i (unmodulated amplitude) are fitted in the

- 1.1keV$_{ee}$ (5keV$_r$) analysis threshold
- The difference of two methods are small.
- Small negative amplitude is observed in 0.5-3keV$_{ee}$ region. But both results are consistent, but not statistically significant.
- (1.7 - 3.7) x 10-3 counts/day/kg/keVee in 2-6 keVee (0.5 keVee bin width, 90% C.L. Bayesian) which is close to XENON100 sensitivity (cf. 0.02 counts/day/kg/keVee by DAMA/LIBRA)

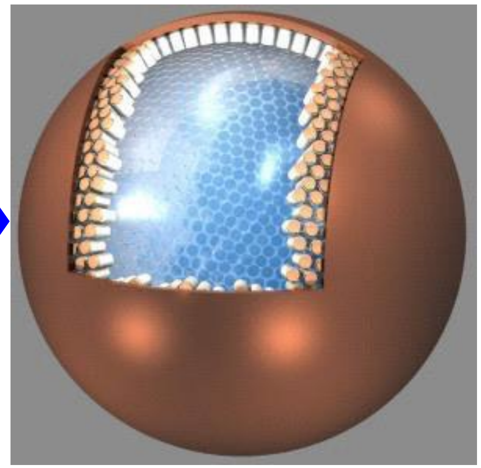
	Method 1 (pull term)	Method 2 (covariant matrix)
p-value	0.014 (2.5σ)	0.068 (1.8σ)

Future plan of XMASS experiment

XMASS-I
(FV:100kg, ϕ80cm)

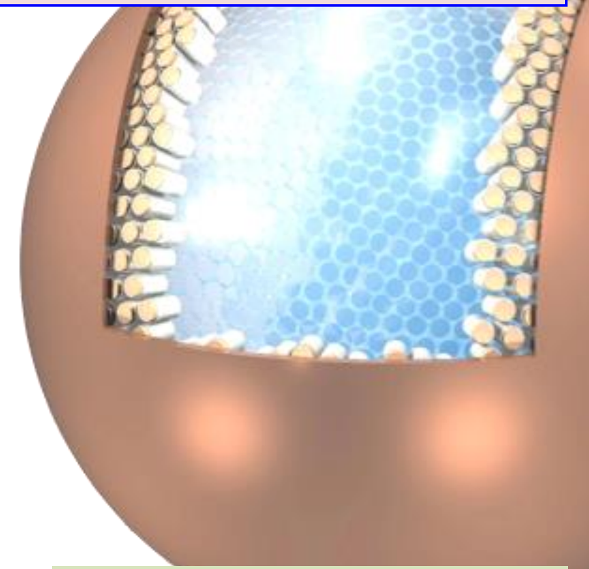


XMASS-1.5
(FV:1~3ton, ϕ~1.5m)



DM: σ_{SI}<10^{-46}cm^2
pp solar ν : a few cpd

XMASS-2
(FV:>10ton, ϕ~2.5m)

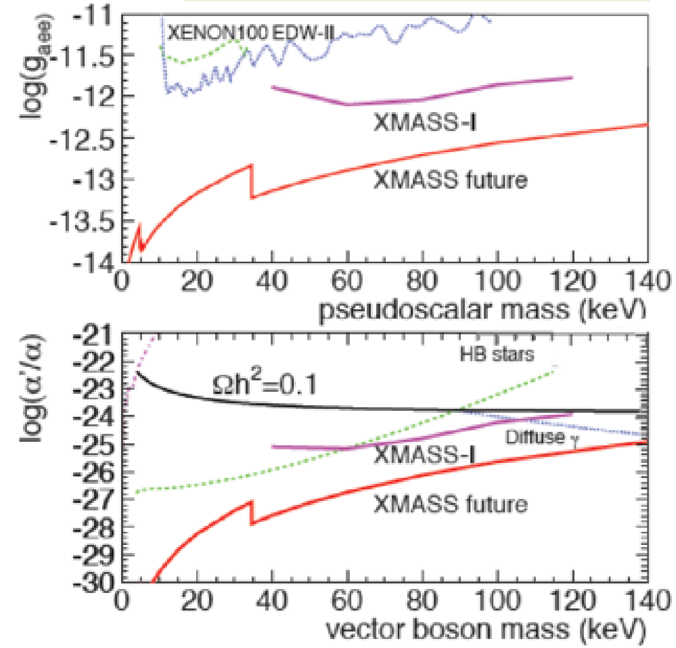


DM: σ_{SI}<10^{-46}cm^2
pp solar ν : 10 cpd
Double beta decay

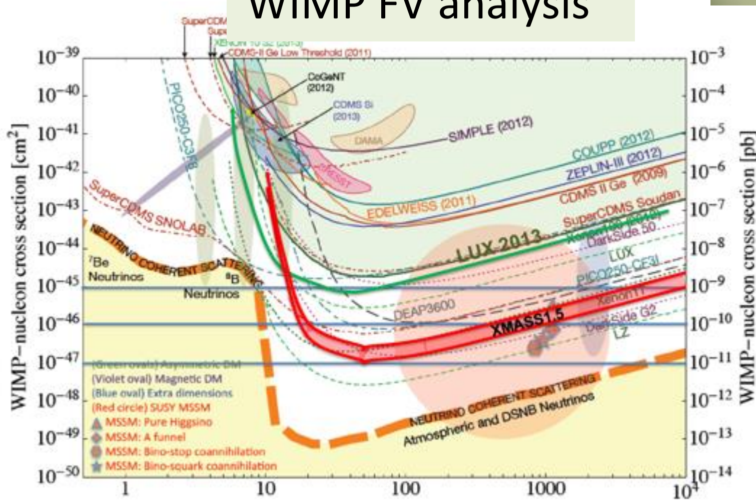
XMASS 1.5

- Larger detectors have many advantages. 1~3ton FV (5ton total).
  - 10^{-5}count/day/kg/keV
  - Sensitive both nuclear recoil and beta/gamma
- Detector design is ongoing
  - PMT
    - We can use U-free Al in hand.
    - Lower RI (~1/10 of current PMT)
    - New round Photo cathode helps to identify surface events.
  - Lower Surface/bulk background.
    - Purer copper for PMT mounter

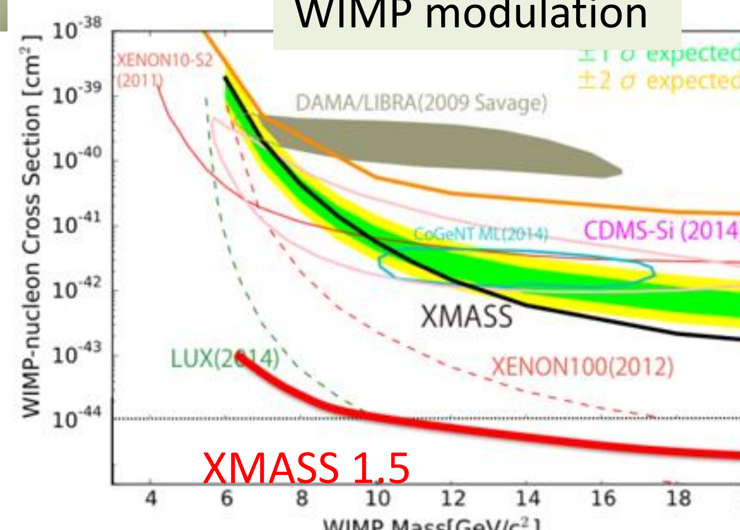
Bosonic super-WIMP



WIMP FV analysis



WIMP modulation



summary

- XMASS is sensitive to both nuclear recoil and beta/gamma and suitable to search for various kinds of dark matter candidates (WIMP, bosonic super-WIMP, axion etc).
- Annual modulation analysis has been performed using large exposure, 0.82ton·year data. No significant modulated WIMP signal has been observed. The result excluded most of all DAMA/LIBRA allowed region.
- We continue to take 3rd year of data to obtain more sensitive result with smaller systematic uncertainties.
- Preparation of XMASS 1.5 project is ongoing.

backup

XMASS collaboration

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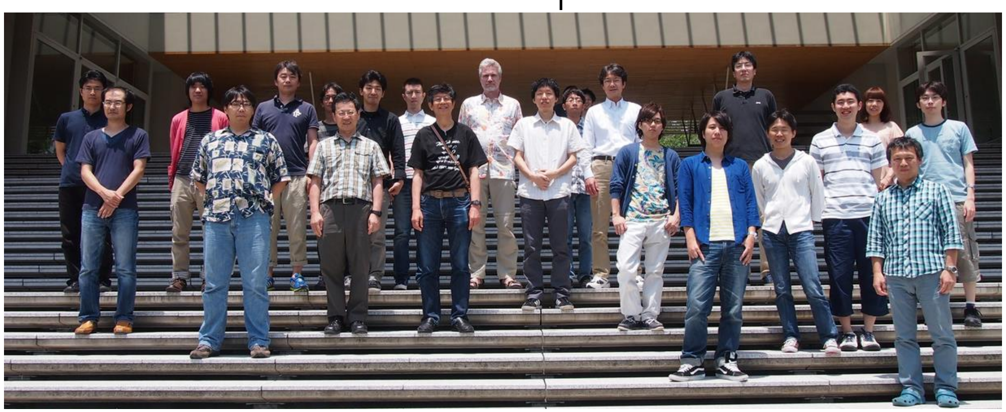
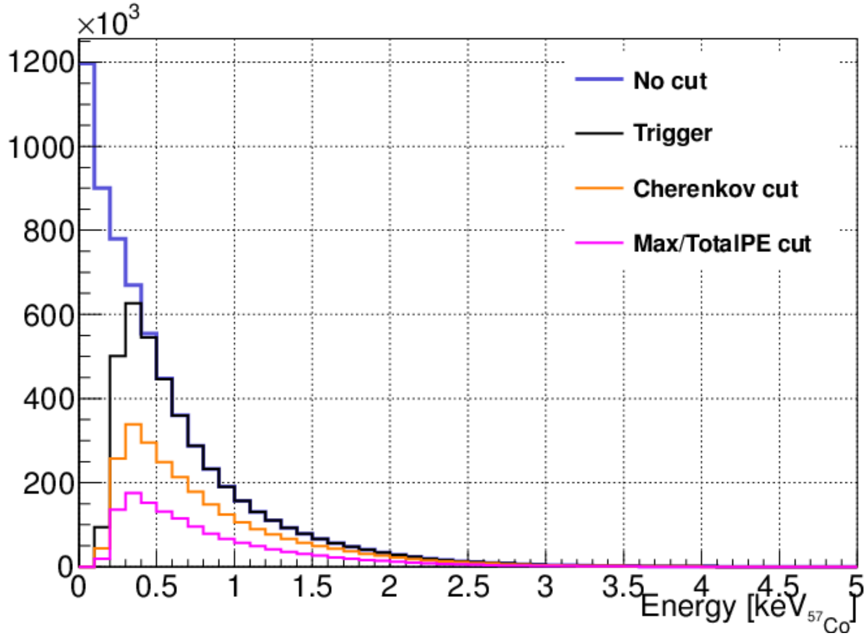
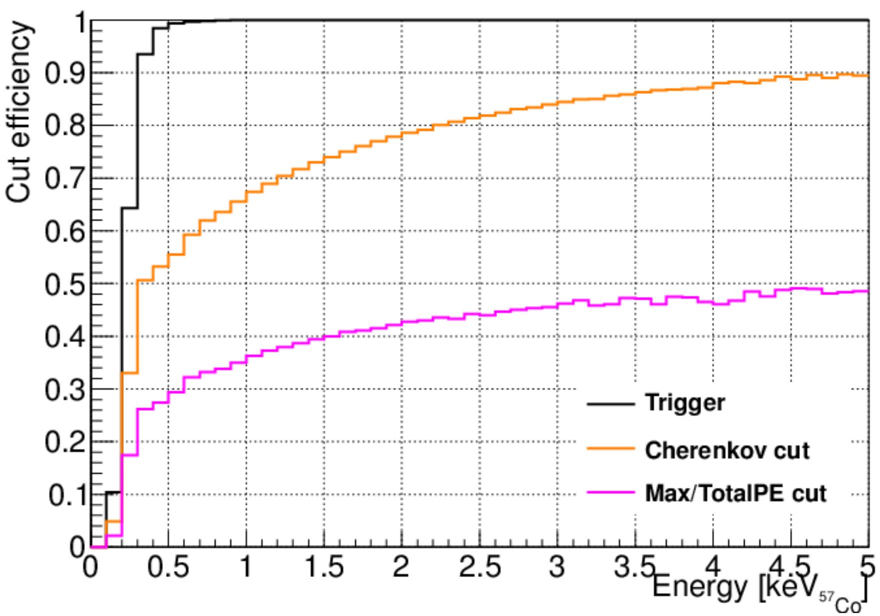
Tokushima University	K. Fushimi, G. Kanzaki
Yokohama National University	S. Nakamura
Miyagi University of Education	Y. Fukuda
STEL, Nagoya University	Y. Itow, K. Kanzawa, R. Kegasa, K. Masuda, H. Takiya
IBS	N.Y. Kim, Y. D. Kim
KRISS	Y. H. Kim, M. K. Lee, K. B. Lee, J. S. Lee



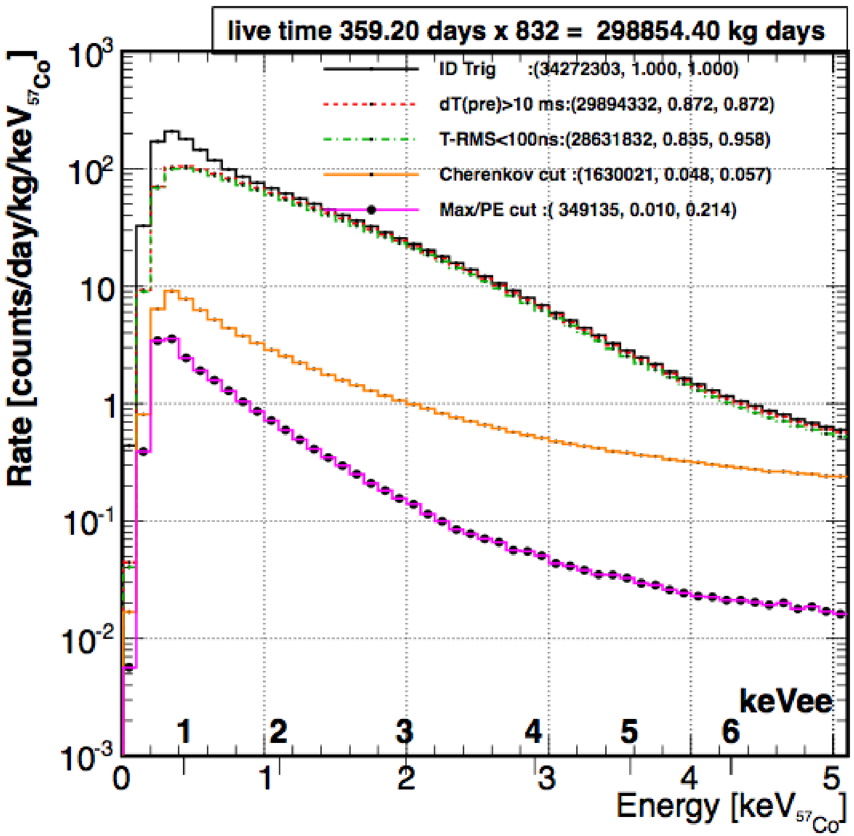
10 institutes, 42 collaborators

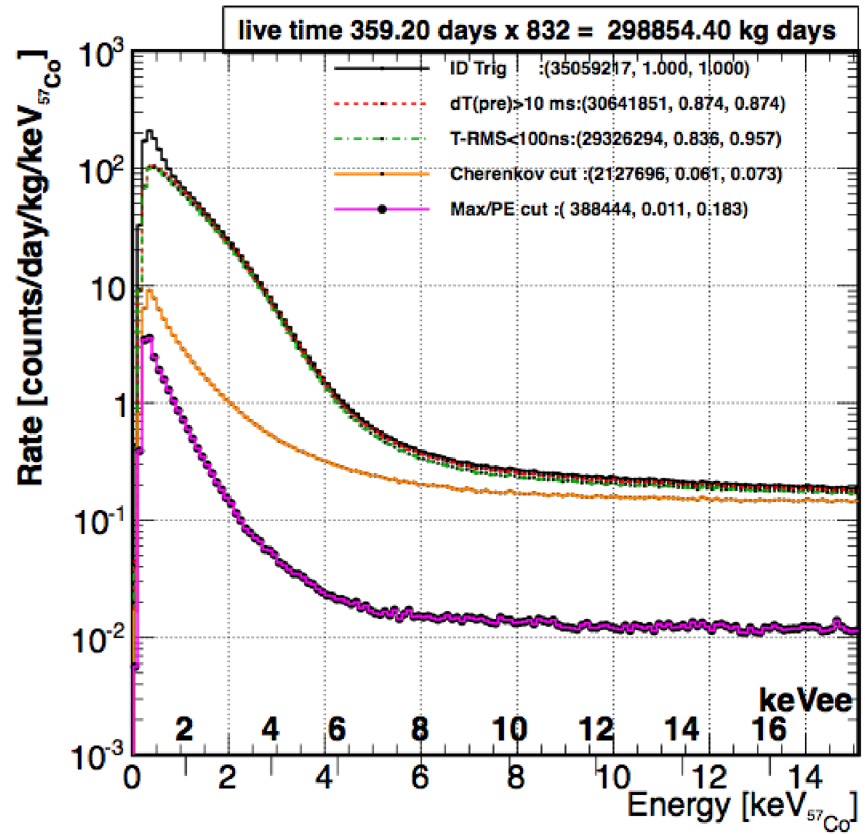
20GeV/c^2 WIMP MC energy spectra and efficiencies



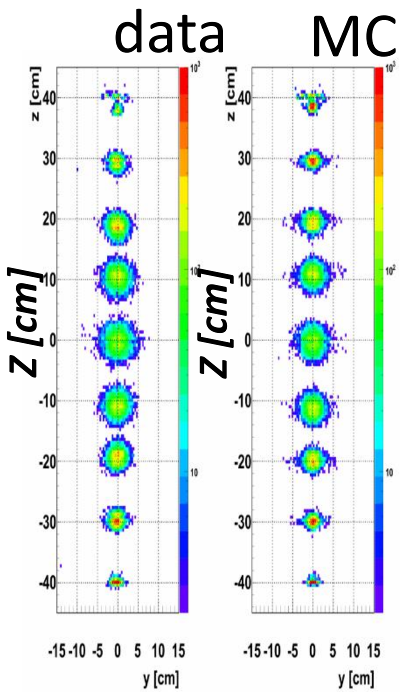


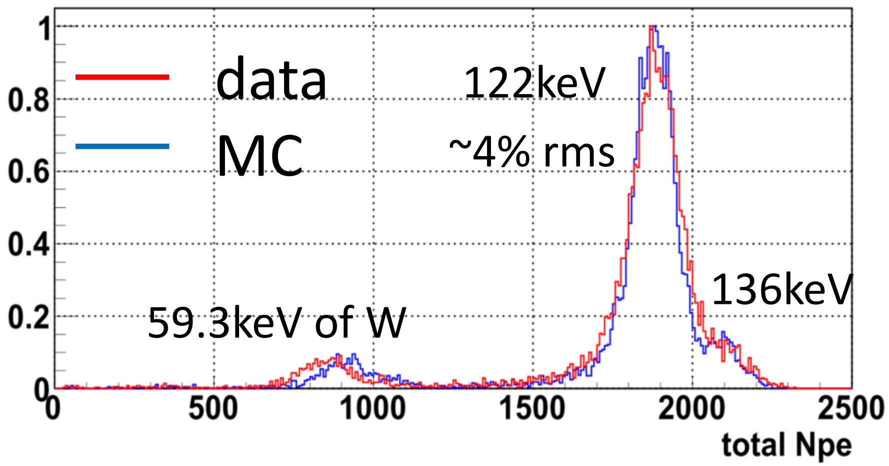
Energy spectra (data)

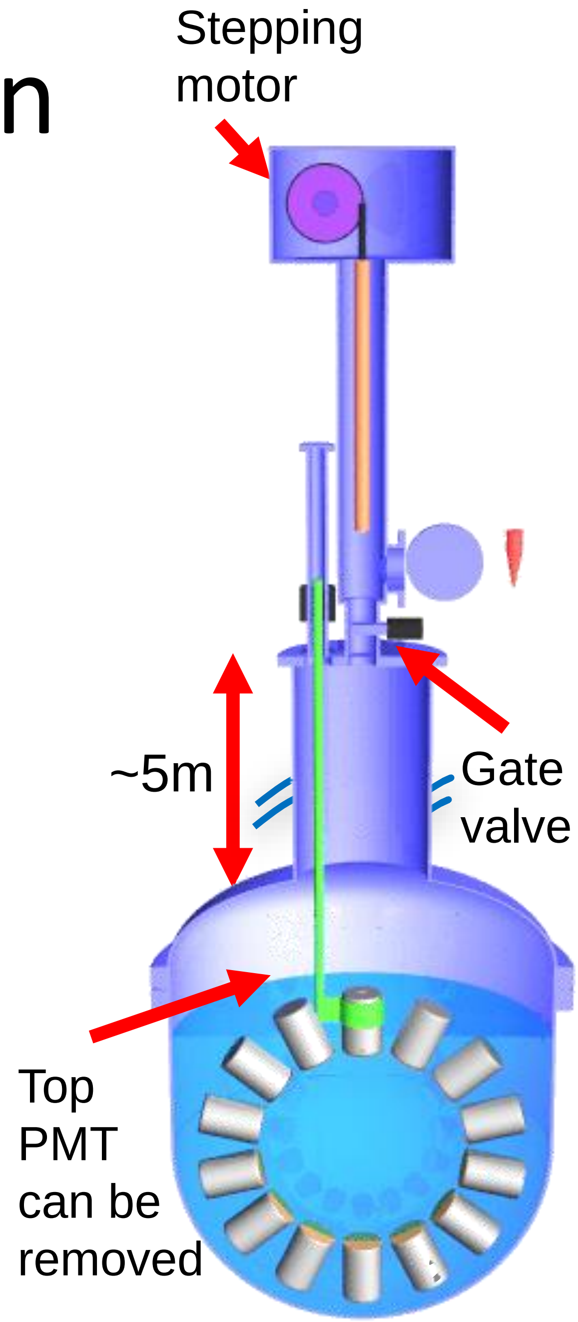




Inner calibration

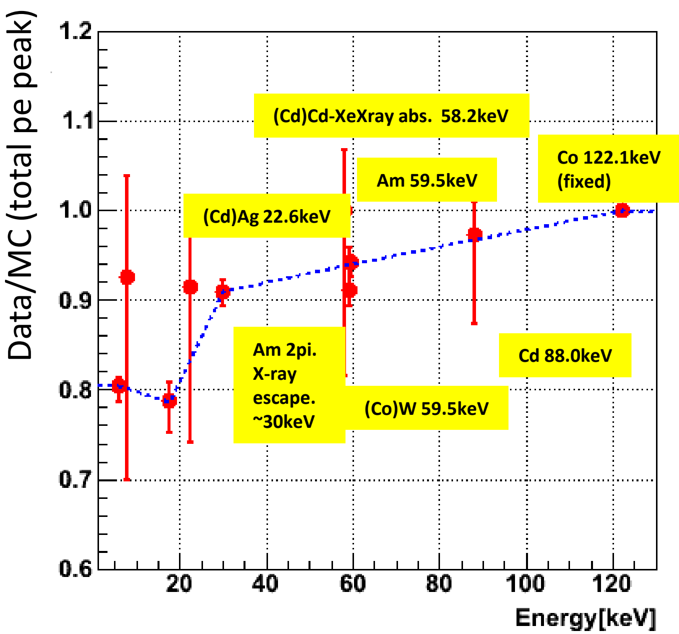


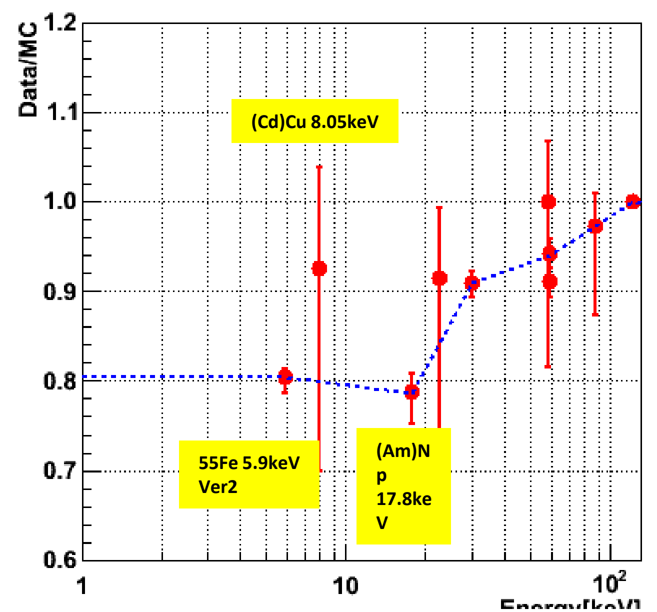




Energy scaling

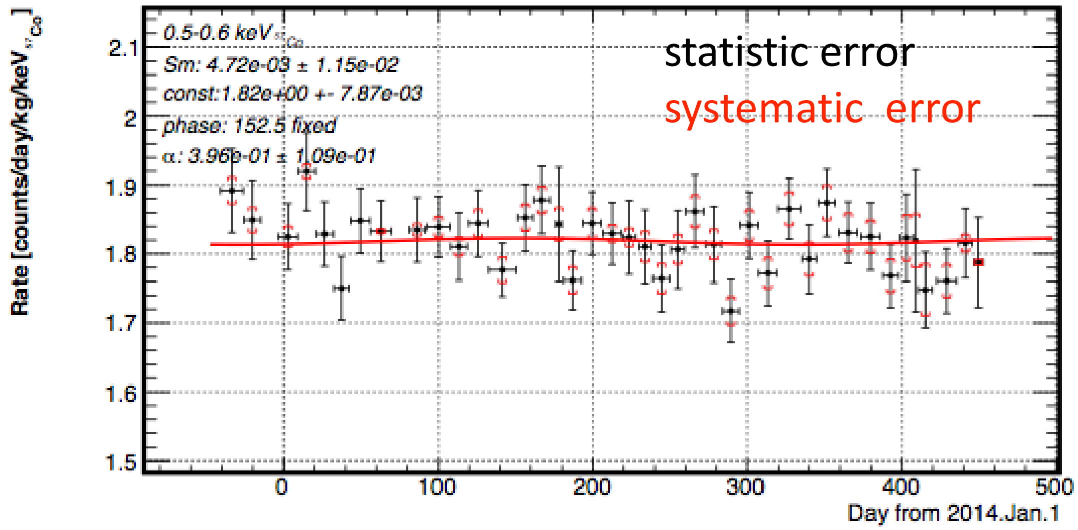
- Energy scale at 5.9keV
  - 0.804 +0.010/ -0.018 (total uncertainty)





Gamma energy(keV)

Pull term



Model Independent

$$\chi^2 = \sum_{i}^{E_{bins}} \sum_{j}^{t_{bins}} \frac{(\mathrm{R}_{\mathrm{j}}^{\mathrm{data}} - \mathrm{R}_{\mathrm{i,j}}^{\mathrm{expected}} - \alpha \mathrm{K}_{\mathrm{i,j}})^2}{\sigma(\mathrm{stat})_{\mathrm{j}}^2} + \alpha^2$$

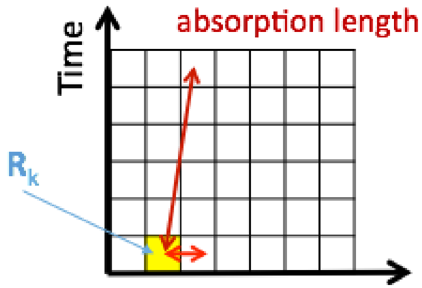
Model dependent (WIMP)

$$\chi^2 = \sum_{i}^{E_{bins}} \sum_{j}^{t_{bins}} \frac{(\mathrm{R}_{\mathrm{j}}^{\mathrm{data}} - \mathrm{R}_{\mathrm{i,j}}^{\mathrm{WIMP\ expected}} - \alpha \mathrm{K}_{\mathrm{i,j}})^2}{\sigma(\mathrm{stat})_{\mathrm{j}}^2} + \alpha^2$$

$\mathrm{R}_{i,j}^{data}$:observed rate
$\mathrm{R}^{expected}(E_i, t_j) = \mathrm{A}(\mathrm{E}_i)\cos\omega(\mathrm{t_j} - \mathrm{t_0}) + \mathrm{C}_{t_j}$
$\mathrm{R}^{\mathrm{WIMP\ expected}}(E_i, t_j, m_\chi) = \mathrm{A}(\mathrm{E}_i, m_\chi)\cos\omega(\mathrm{t_j} - \mathrm{t_0}) + \mathrm{C}_{t_j}$
$\omega = 2\pi/T$
A: amplitude
C: constant
T:(=365.24) period in days
$\mathrm{t_0}$:(=152.5) phase in days

Covariance Matrix

Covariance matrix



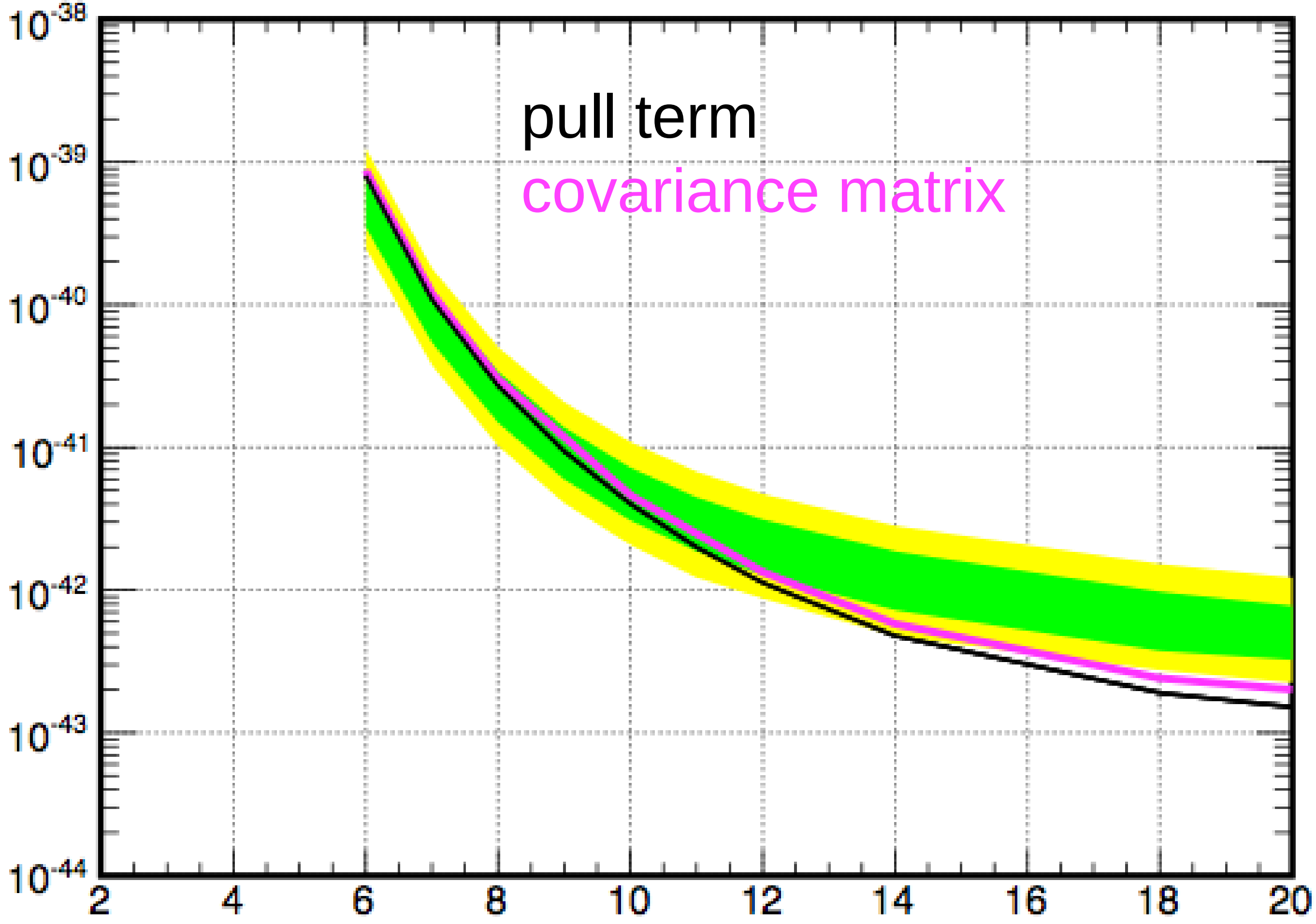
$$\chi^2 = \sum_{k=1}^{N} \sum_{l=1}^{N} (R_k^{data} - R_k^{exp}) (V_{stat} + V_{sys})_{k,l}^{-1} (R_l^{data} - R_l^{exp})$$

$$V_{stat} = \begin{pmatrix} (\sigma_1^{stat})^2 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & (\sigma_N^{stat})^2 \end{pmatrix}$$: N x N matrix

$$(V_{sys})_{k,l} = \frac{1}{M} \sum_{m=1}^{M} (\delta R)_k (\delta R)_l$$: N x N matrix

$$R^{exp}(E_i, t_j) = C_i + A_i \times \cos \frac{2\pi}{T} (t_j - t_0)$$

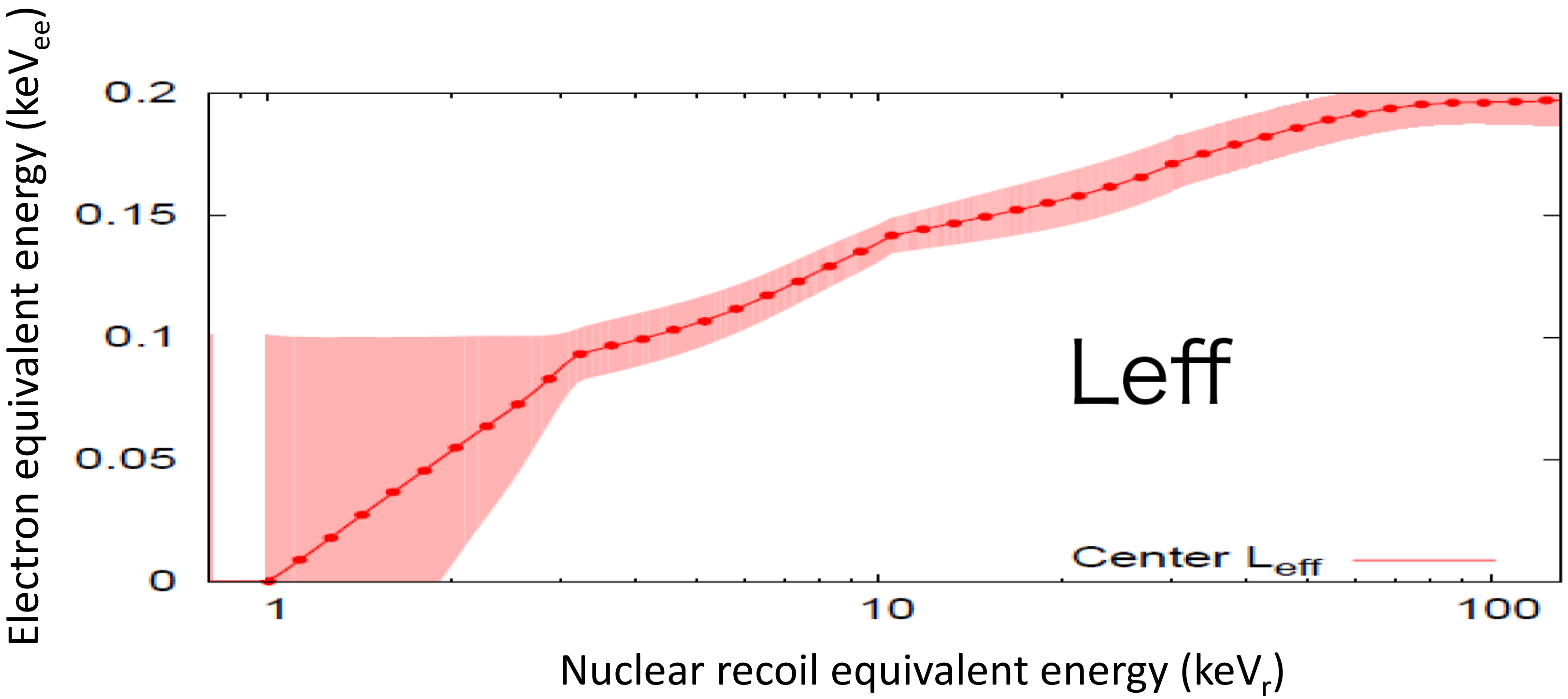
Two methods difference



Systematic error summary

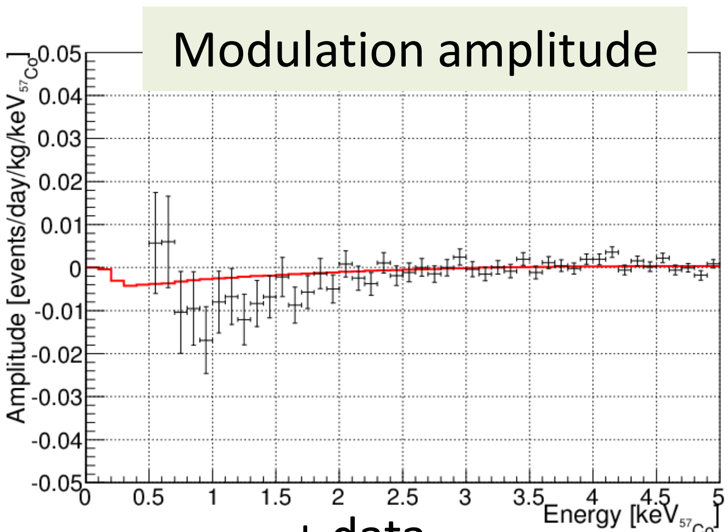
DAQ	PMT gain	<0.3*statistical error
	FADC reset	0.3%
	Timing	<0.2*statistical error
	Livetime	<0.02%
	threshold	0<0.022%
parameters	Escape velocity	Cross section: +10% at 8Gev/c^2, +5% at 20GeV/c^2 (544/650km/sec)
	Time variation	<0.15%
	Leff	30% at 10GeV/c^2
background	Muon	<<1%
	Radon in water	<10^{-5}dru at maximum
	Radon in LXe	<1%
analysis	Energy range	<7% (difference between 0.5-5keV$_{57Co}$ and 0.5-15keV$_{57Co}$ at <20GeV/c^2)

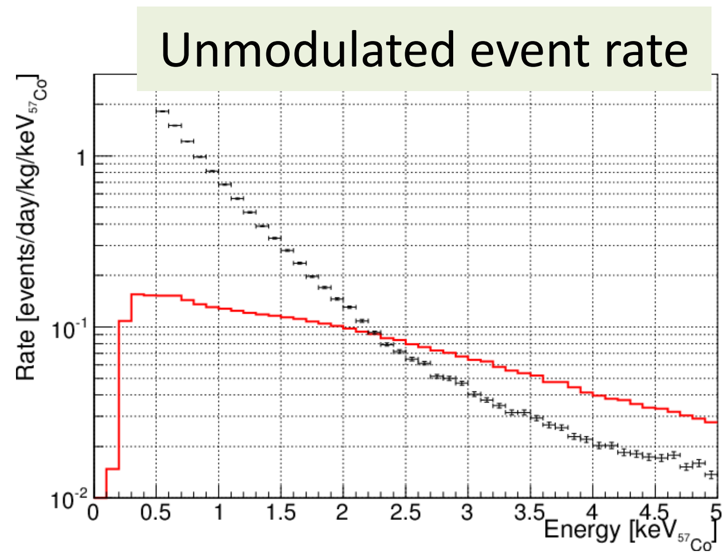
Leff uncertainty



Best fitted point in the standard WIMP search

- In the standard WIMP search, we obtained the best fit for the WIMP-nucleon cross section, $2.1*10^{-42}cm^2$ at $100GeV/c^2$ with 2.6 sigma level. However, unmodulated part of the expected signal for the best fit exceed the number of the observed events.
- For the upper limit in the $60\text{-}400GeV/c^2$ WIMP mass range, the situation is same as above.

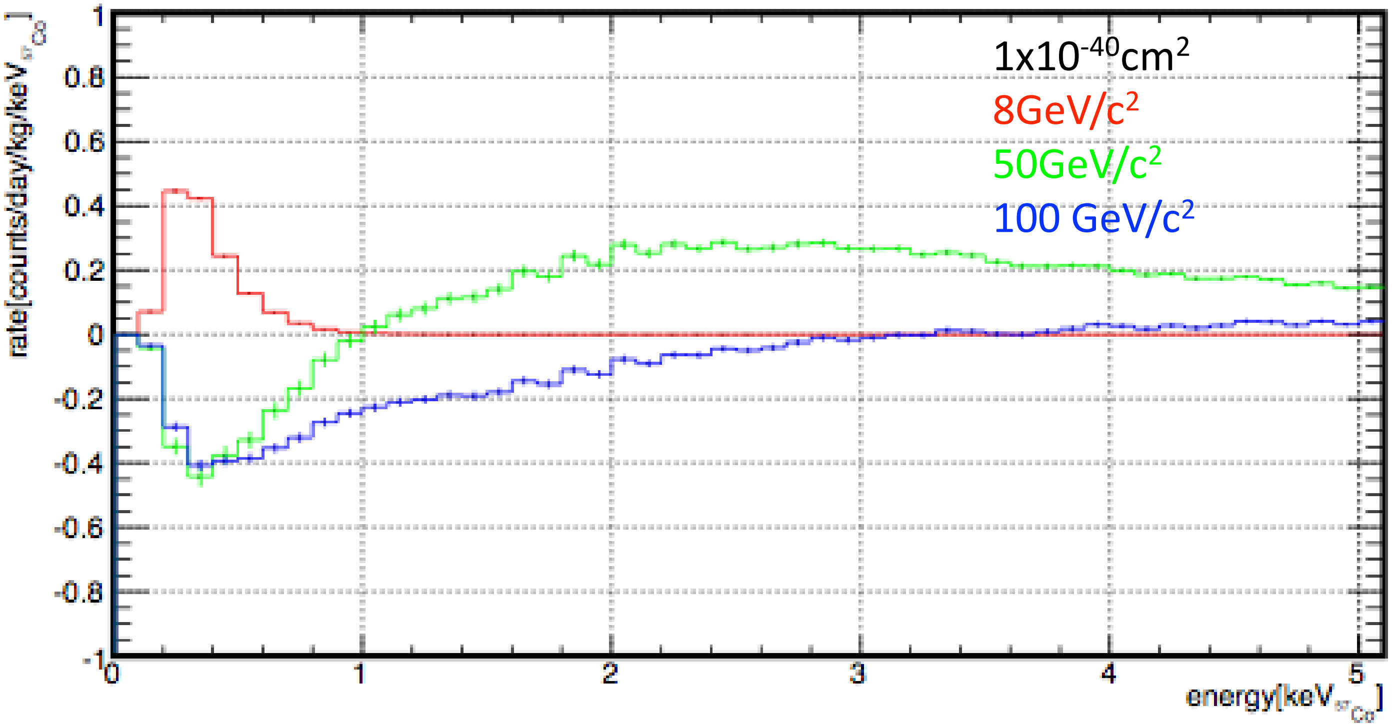




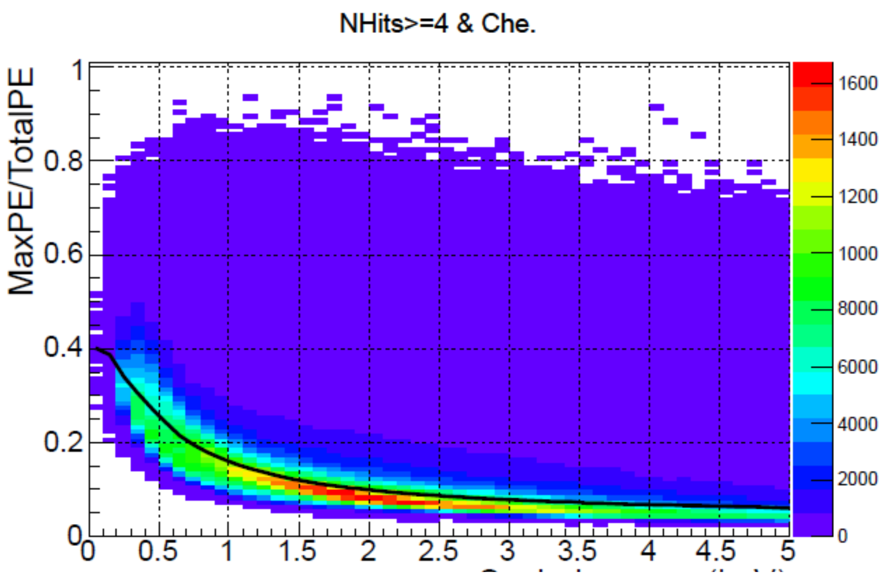
+ data

-- WIMP best fit ($100GeV/c^2$, $2.1x10^{-42}$ cm^2)

(summer - winter), energy spectrum
same cuts are applied for those WIMP MC.



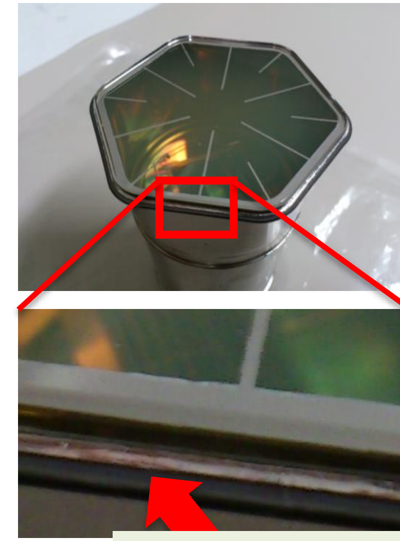
maxPE/totalPE (WIMP MC)



keV$_{57Co}$

Detector refurbishment (RFB)

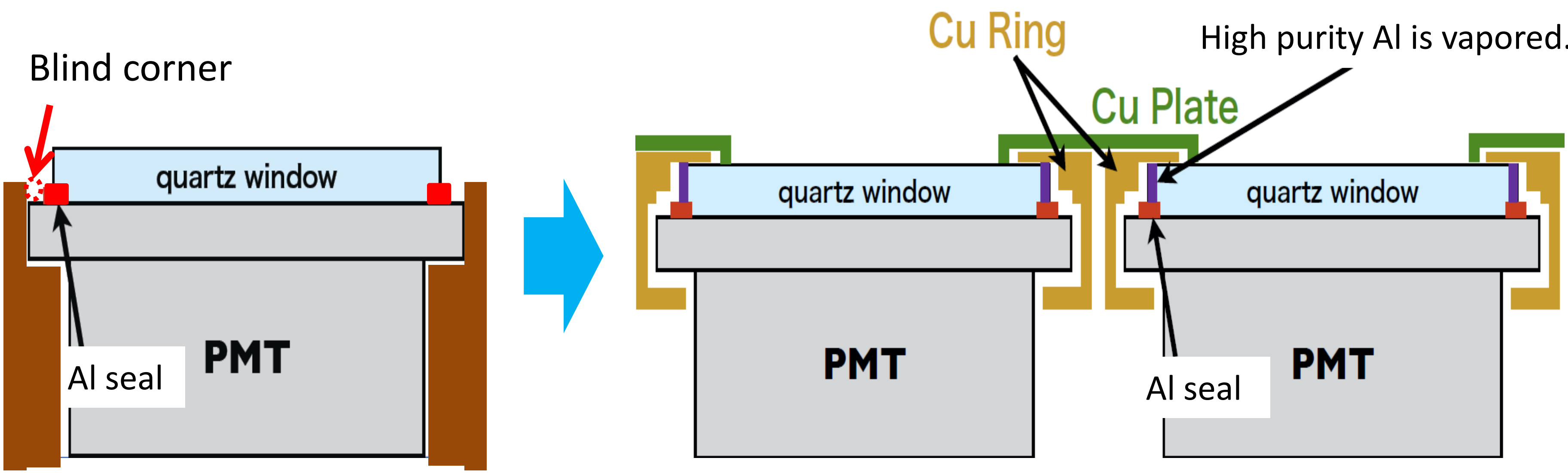
- We found RIs (210Pb, 238U) in the Aluminum sealing part of PMT (secular equiv. broken).
- Background events at the blind corner of PMT are often misidentified as events in the fiducial volume.
- To reduce this background, new structures to cover this Al seal were installed in 2012/2013.



PMT Al sealing

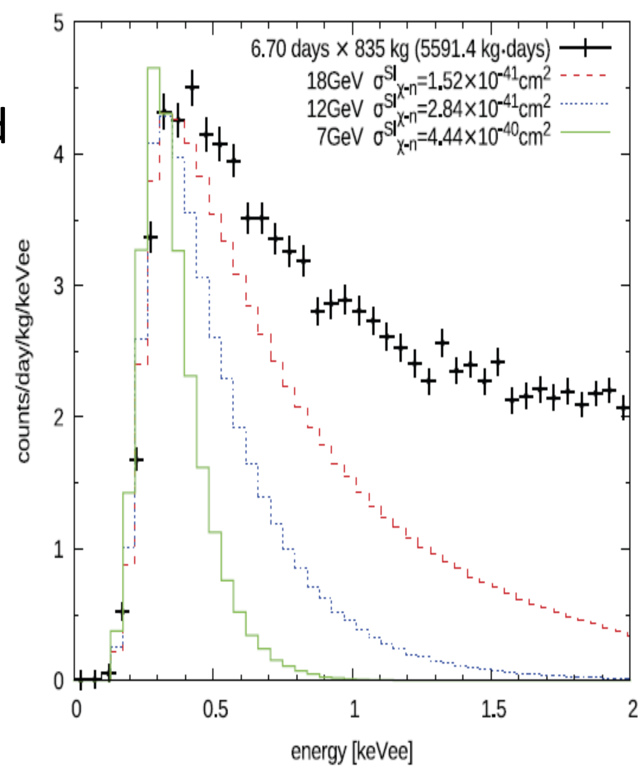
Before RFB

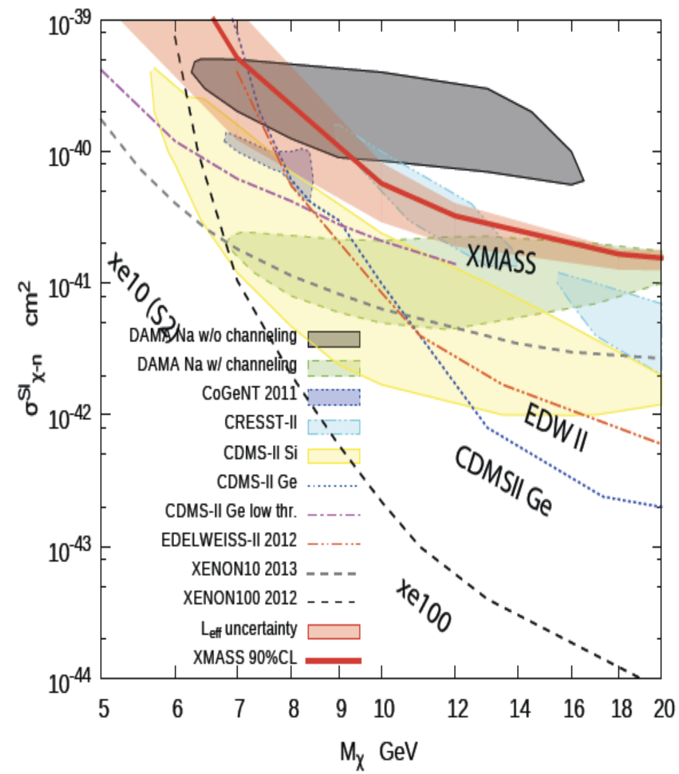
After RFB



--- result from commissioning run ---
1. Search for light WIMPs

- 6.7 days x 835 kg
- 0.3 keVee threshold





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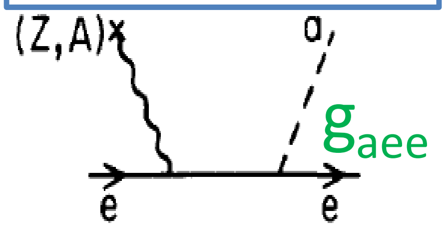
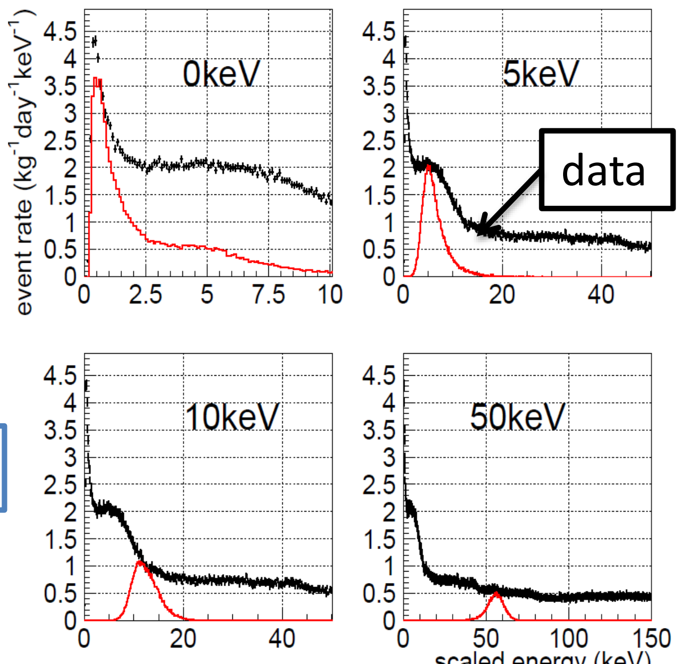
--- result from commissioning run ---
2. Search for solar axions

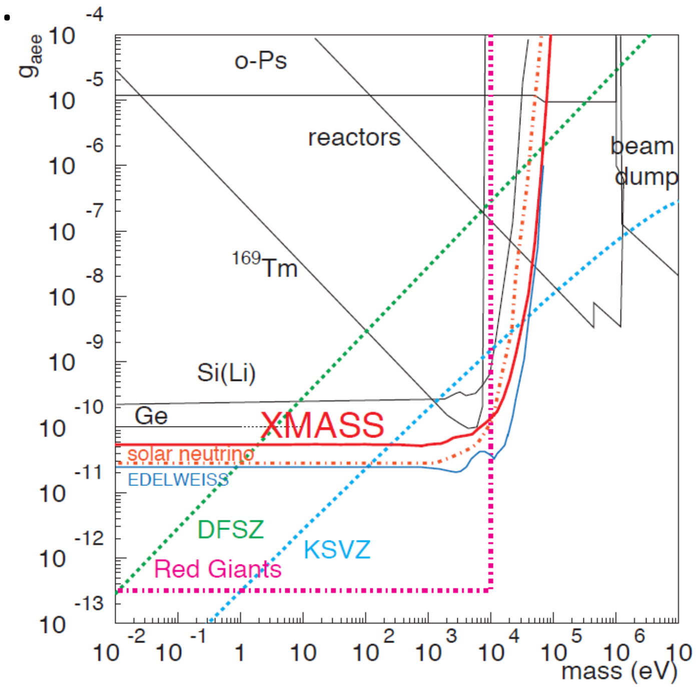
- Axions can be produced in the sun by bremsstrahlung and Compton effect, and detected by axio-electric effect in XMASS.
- Used the same data set as the light WIMPs search.

Bremsstrahlung and Compton effect



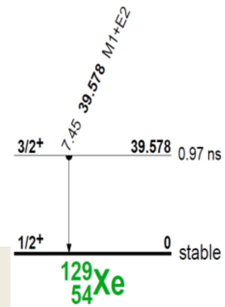
Axio-electric effect





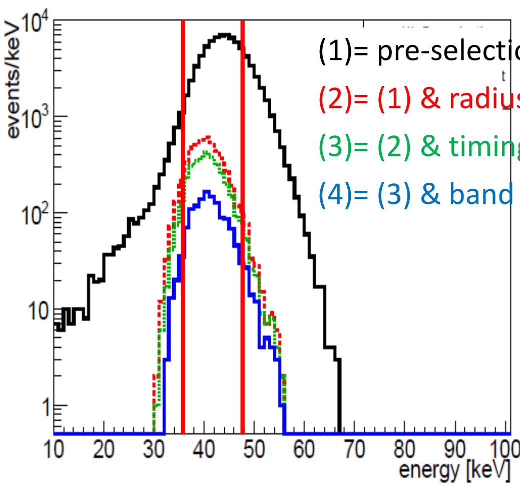
Phys. Lett. B 724 46 (2013)

--- result from commissioning run ---
3. Search for ^{129}Xe inelastic scattering by WIMPs

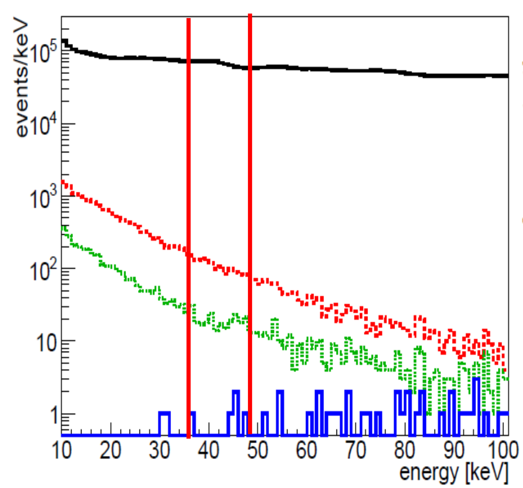


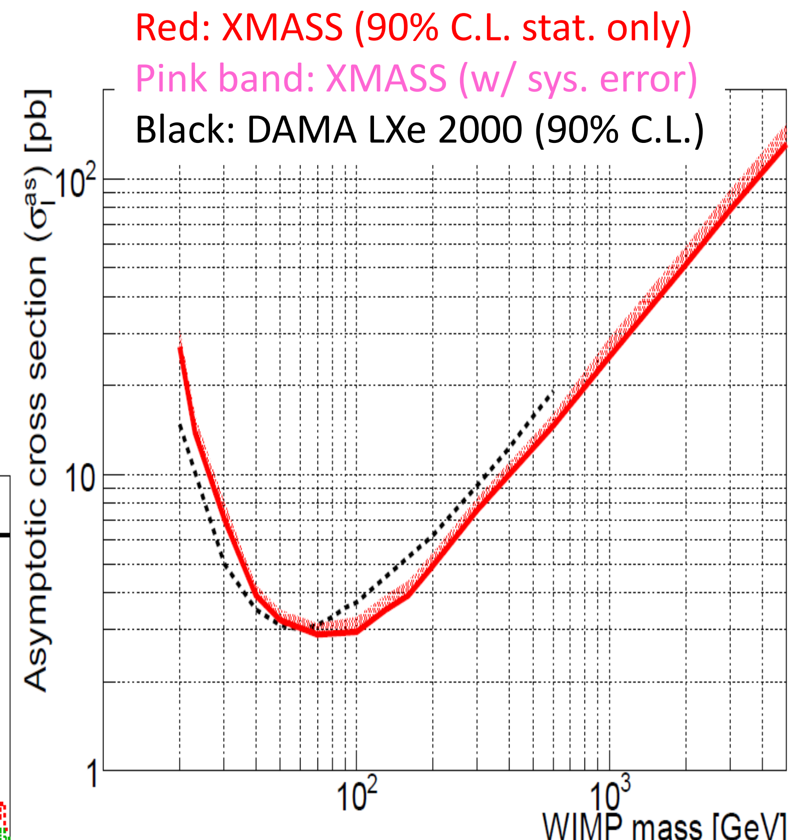
- $\chi + {}^{129}Xe \rightarrow \chi + {}^{129}Xe^*$
  $^{129}Xe^* \rightarrow {}^{129}Xe + \gamma$ (39.6keV)
- Natural abundance of ^{129}Xe: 26.4%

Signal MC for 50GeV WIMP



data (165.9 days)

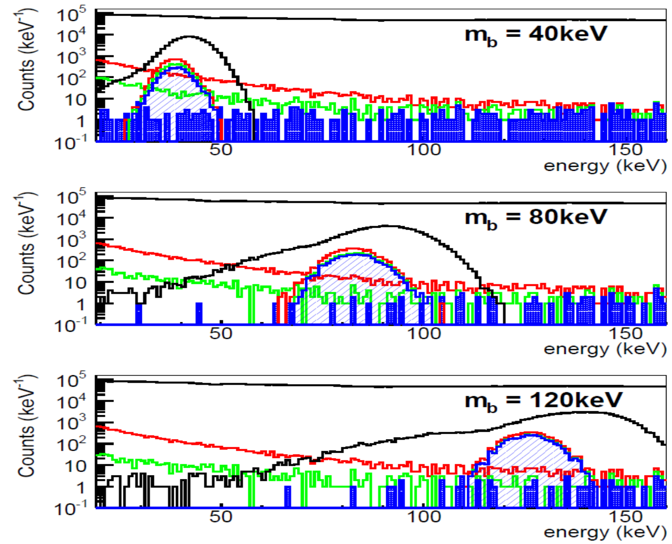




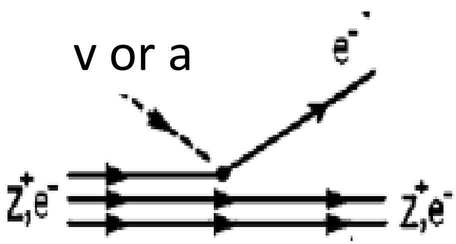
PTEP 063C01 (2014)

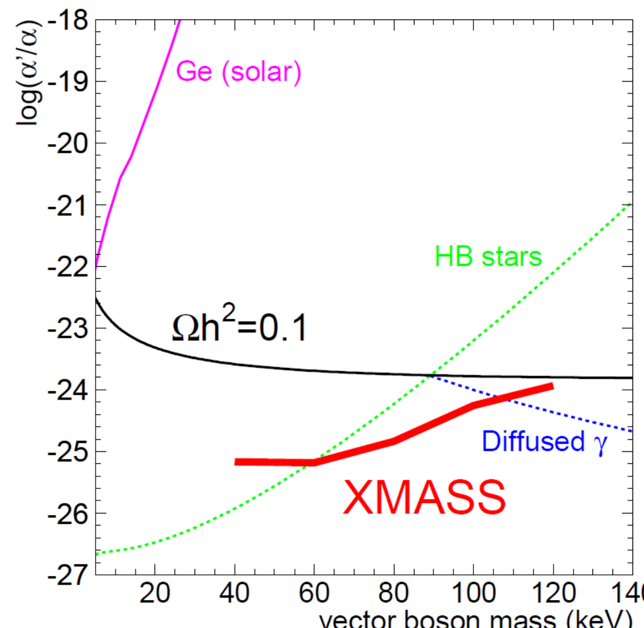
Background level is ~3x10^{-4}count/sec/kev/kg.

--- result from commissioning run ---
4. Search for bosonic super-WIMPs



- Candidate for lighter dark matter
- 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





PRL 113, 121301 (2014)

vector super-WIMPs

- Cross section (σ_{abs}) is:

$$\frac{\sigma_{\rm abs}\, v}{\sigma_{\rm photo}(\omega = m_V)c} \approx \frac{\alpha'}{\alpha}$$

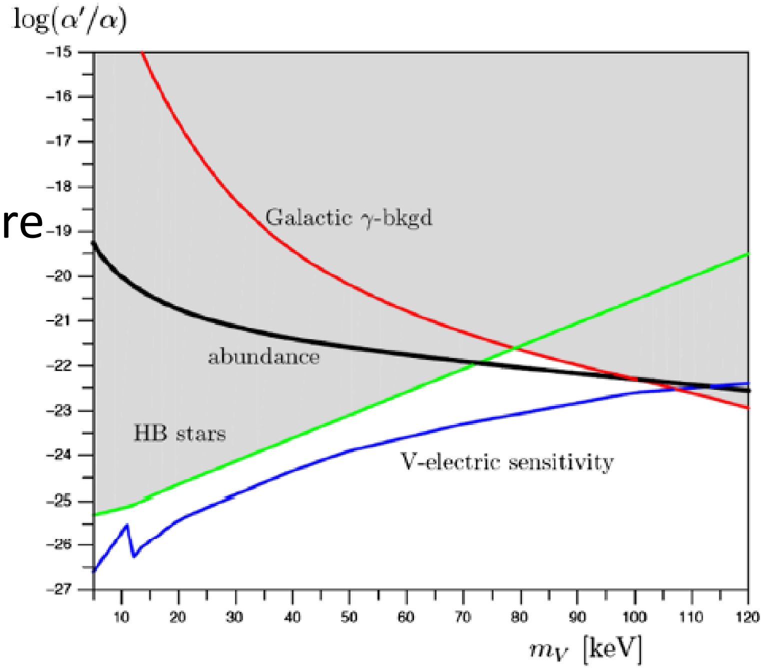
(α' : the vector boson analogue to the fine structure constant. v: velocity of the vector boson)

- Can be detected by absorption of the particle, which is similar to the photoelectric effect.
- The counting rate (S_v) in the detector is:

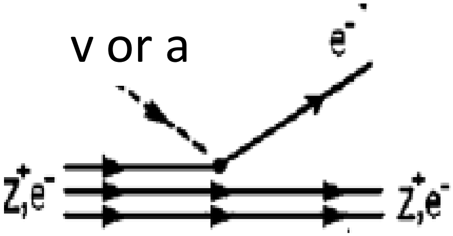
$$S_v \approx \frac{4\times 10^{23}}{A}\frac{\alpha'}{\alpha}\left(\frac{\rm keV}{m_V}\right)\left(\frac{\sigma_{\rm photo}}{\rm barn}\right)\ {\rm kg}^{-1}\,{\rm day}^{-1}$$

(A: atomic mass, standard local matter density: 0.3GeV/cm^3)

- This is the first direct search in the 40-120keV energy range.



Pospelov et, al. Phys. Rev. D 78 115012 (2008)

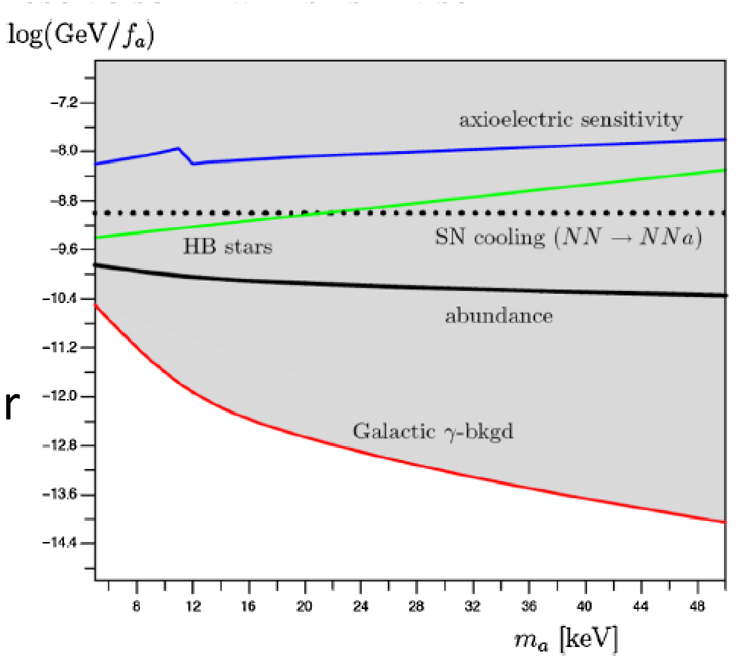


pseudoscalar super-WIMPs

- Cross section (σ_{abs}) is:

$$\frac{\sigma_{\rm abs} v}{\sigma_{\rm photo}(\omega = m_a)c} \approx \frac{3m_a^2}{4\pi\alpha f_a^2}$$

(v: velocity of the vector boson, m_a: pseudoscalar mass, f_a: dimensionful coupling constant.)



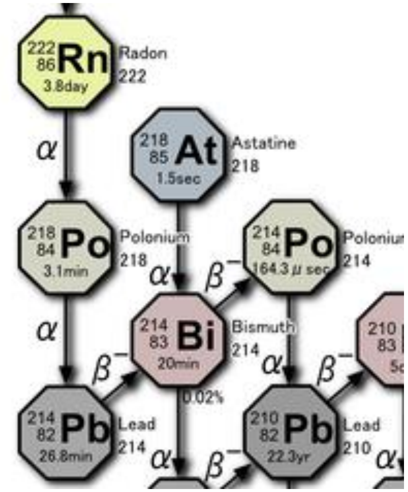
Pospelov et, al. Phys. Rev. D 78 115012 (2008)

- The counting rate in the detector is:

$$S_a \approx \frac{1.2 \times 10^{19}}{A} g_{aee}^2 \left(\frac{m_a}{\rm keV}\right)\left(\frac{\sigma_{\rm photo}}{\rm barn}\right) {\rm kg}^{-1}\,{\rm day}^{-1}$$

($g_{aee}=2m_e/f_a$, m_e: electron mass)

event summary (Bosonic super-WIMP search)



mass (keV)	efficiency (%)	# of observed events	# of expected BKG events from ^{214}Pb
40	51±13	48	7.9±0.7
60	63±16	12	11.6±1.0
80	59±18	8	9.6±0.8
100	65±20	15	11.4±1.0
120	74±23	18	14.4±1.1

Remaining events can be explained by background events produce by radon in liquid xenon. By ^{214}Bi-^{214}Po coincident analysis, radon concentration is estimated to be 8.2±0.5mBq/detector. Based on this estimate, most right column shows the # of expected background events from ^{214}Pb.