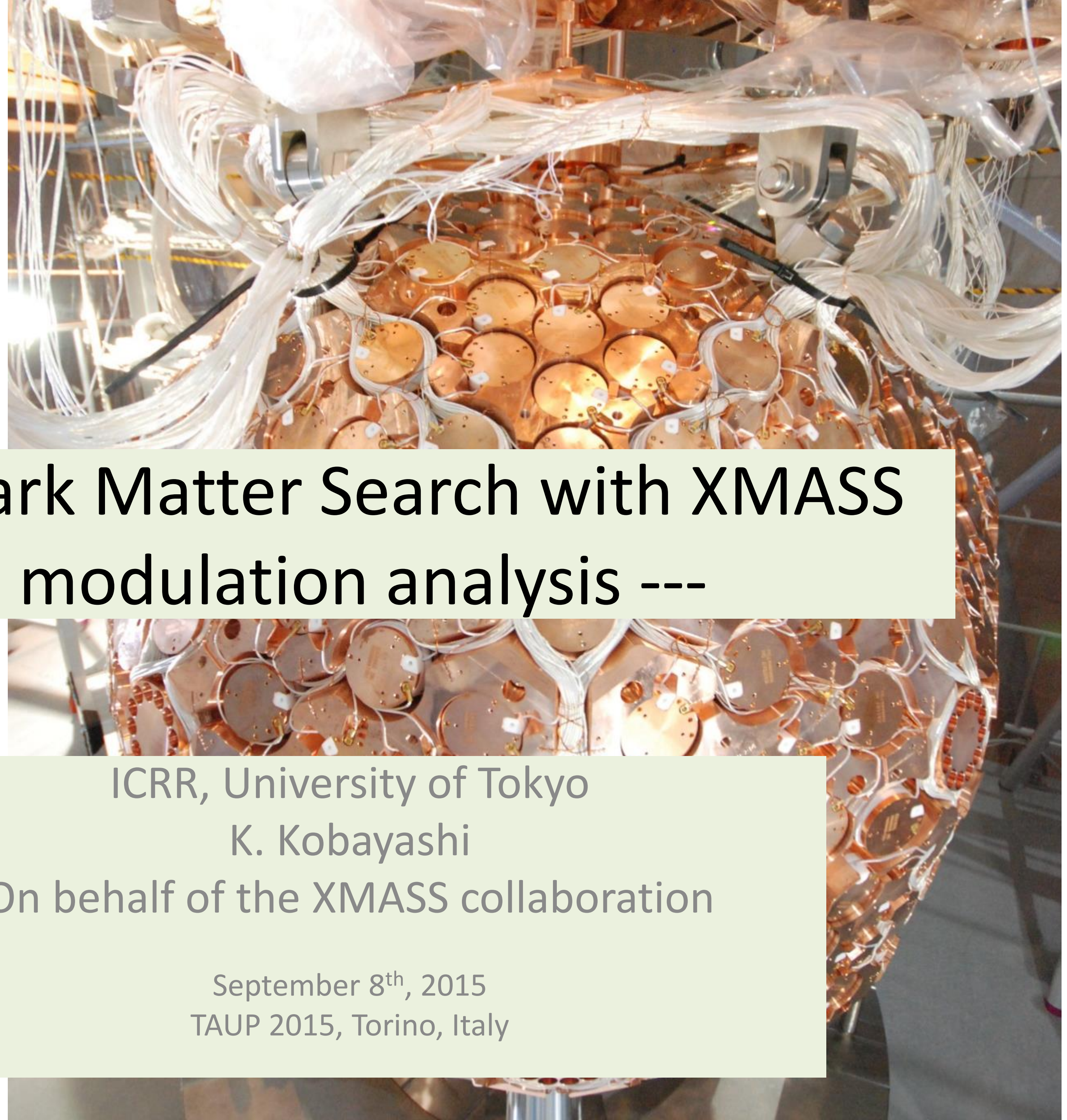


Direct Dark Matter Search with XMASS
--- modulation analysis ---

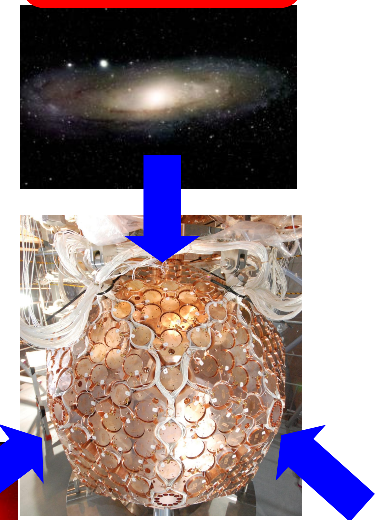
ICRR, University of Tokyo
K. Kobayashi
On behalf of the XMASS collaboration

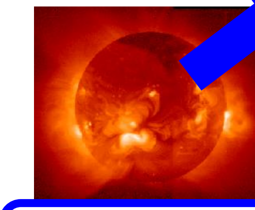
September 8th, 2015
TAUP 2015, Torino, Italy

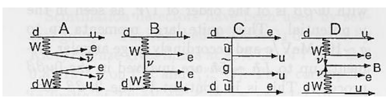
XMASS experiment

- ## 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**)







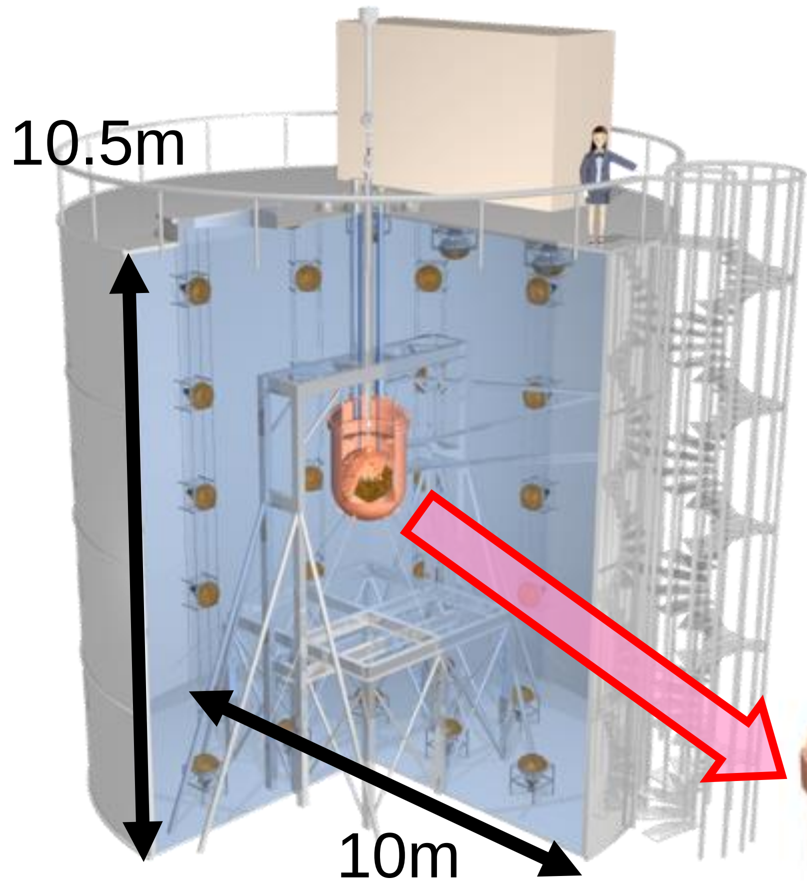
Purpose of the first phase is the dark matter search.

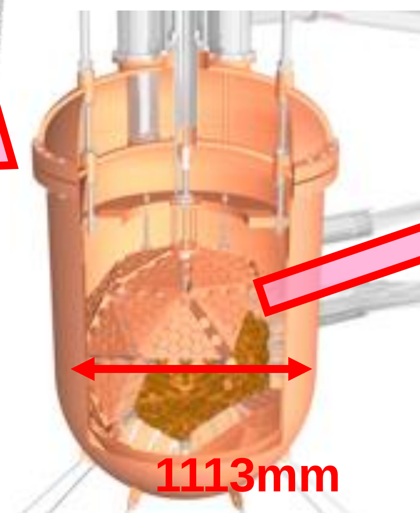
history of XMASS

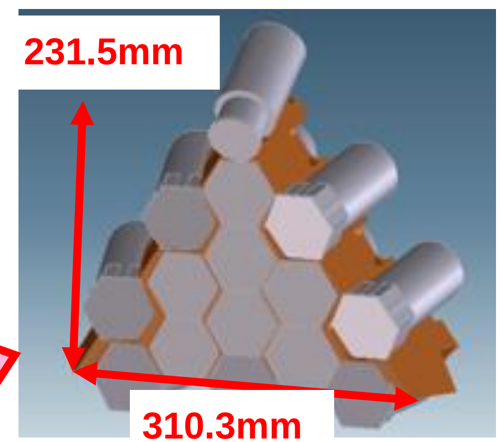
2010	2011	2012	2013	2014
detector construction completed (Sep. 2010)	commissioning run data taking (Dec. 2010 - May 2012)		detector refurbishment (Aug. 2012 - Oct. 2013)	resume data taking (Nov. 2013 -)

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
    - photo coverage: 62%
    - diameter: ~800mm
    - high light yield: 14.7 PE/keV







pentakisdodecahedron

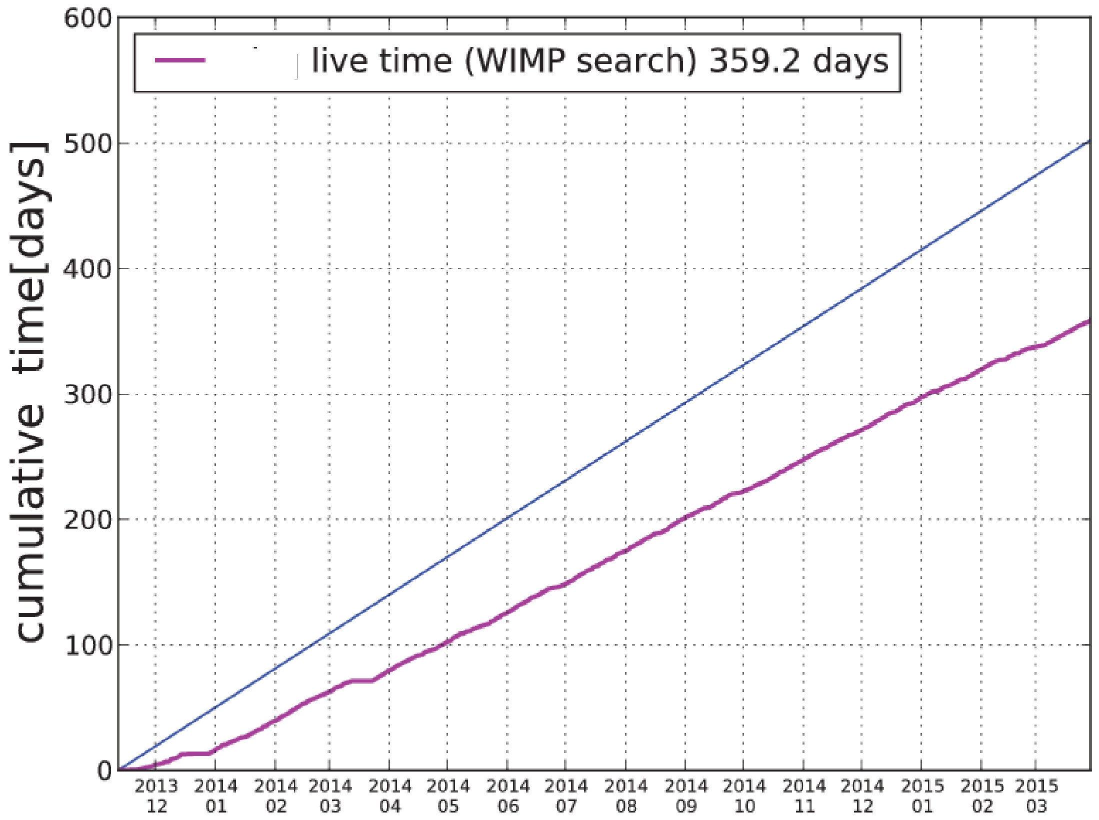
Hexagonal PMT
Hamamatsu R10789

NIM A716, 78-85, (2013)

Data set

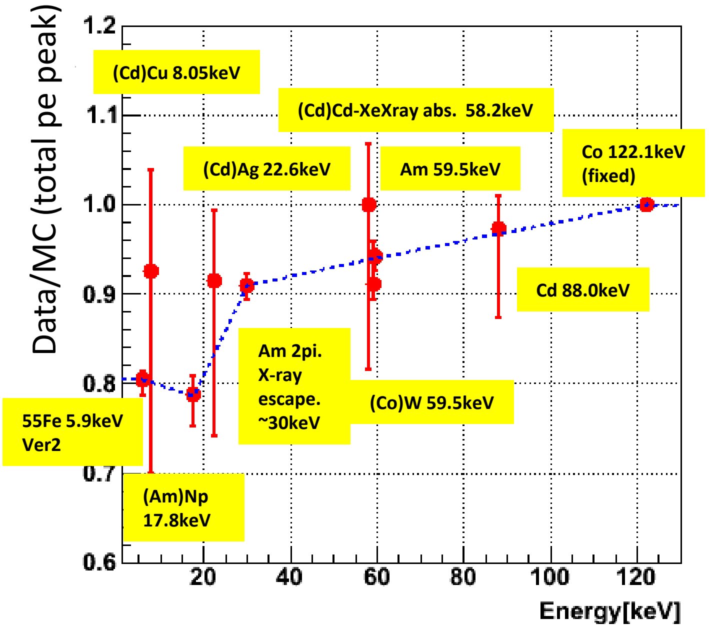
Data set

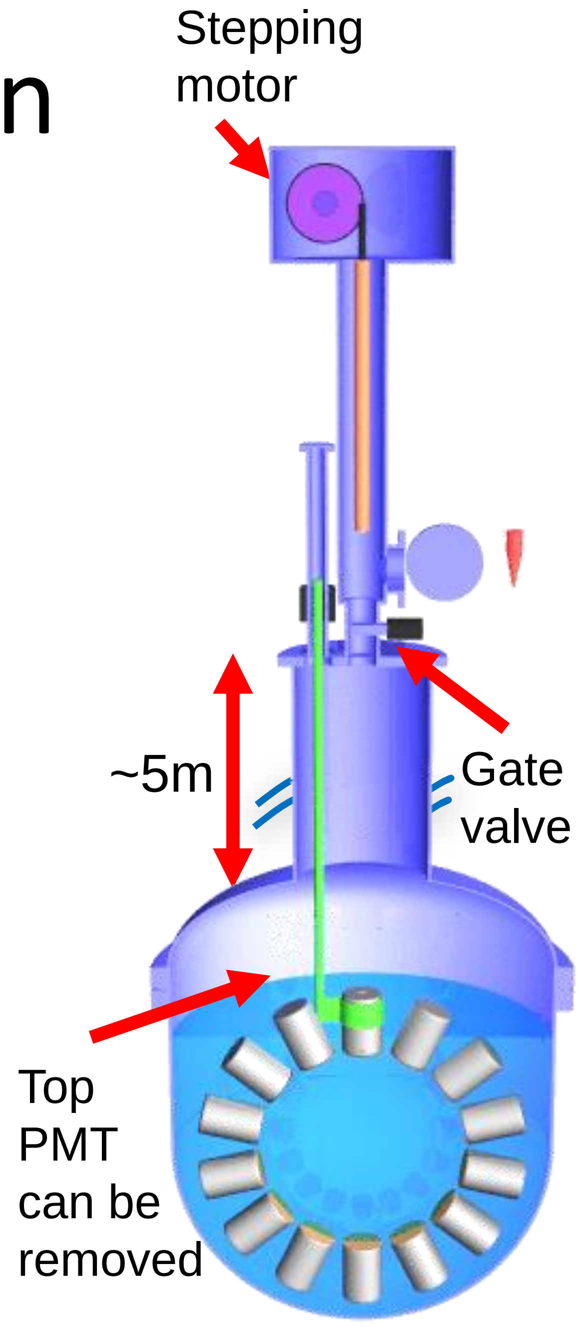
- 359.2 days live time (during 504.2 calendar days)
    - Nov. 2013 - Mar. 2015
    - 0.82 ton·year exposure (cf DAMA 1.33 ton·year)
- Trigger threshold: 4 ID PMT hits
- 10bit 1GS/s flash-ADCs record waveforms of individual PMT.



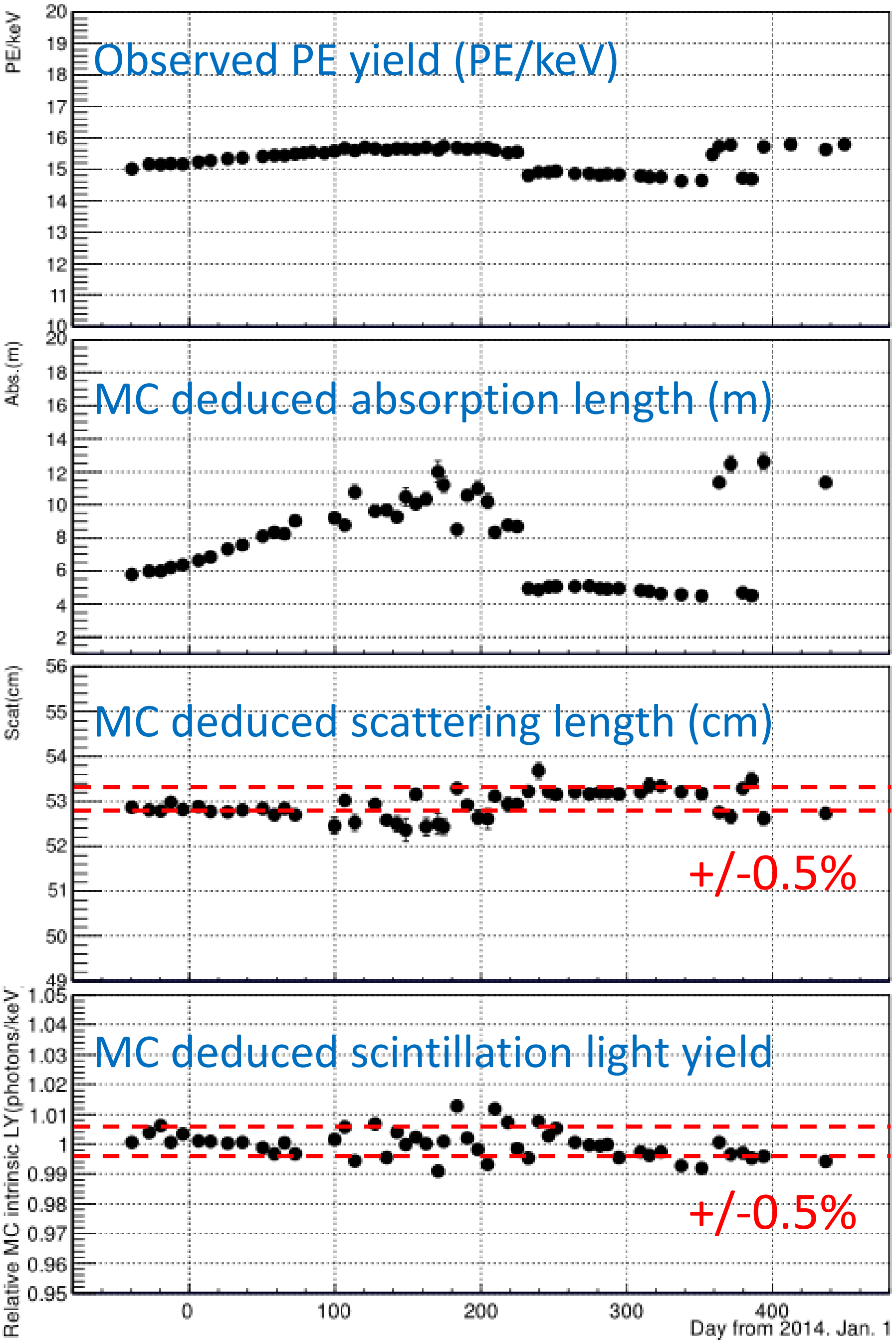
Inner calibration

We performed the inner calibration with ^{55}Fe, ^{109}Cd, ^{241}Am, ^{57}Co, ^{137}Cs.





In this presentation, we use energy with keV_{57Co}, that is determined ^{57}Co by Z=-30cm calibration.



Detector stability

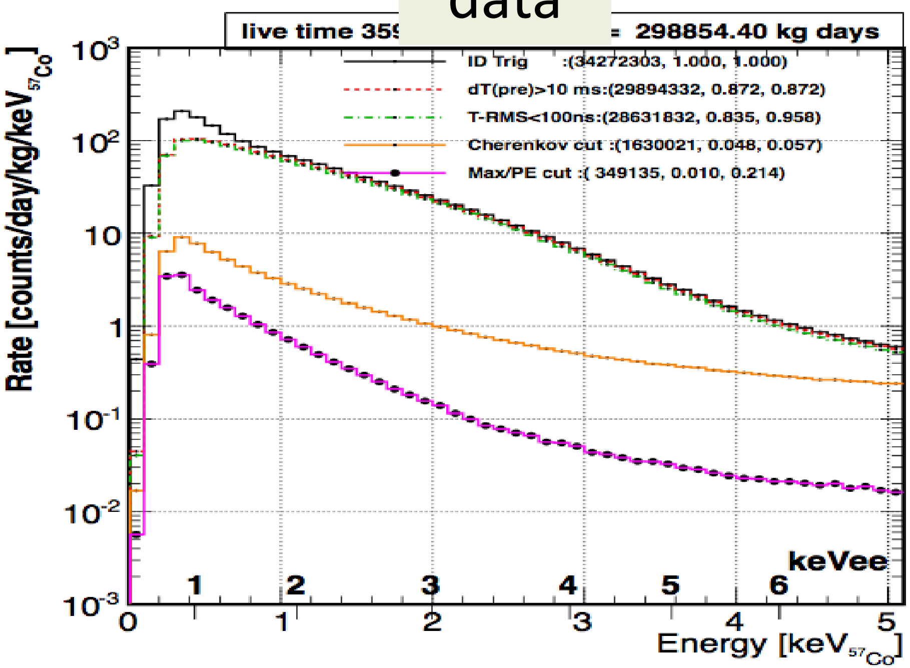
- We carried out weekly ^{57}Co calibration to monitor PE yield.
- We observed PE yield changes at power outage. According to the MC simulation, it is due to the change of the absorption parameter.
- In our analysis, the systematic error of this data handling is taken into account.

Modulation analysis

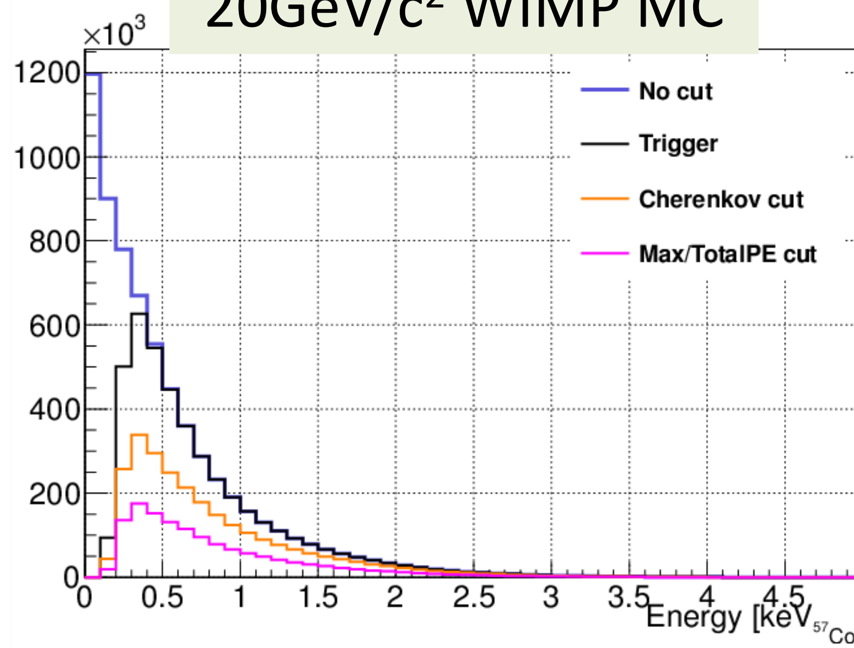
Selection criteria (No particle identification)

- Nhit (ID)>=4 (Nhit (OD)=0)
  - Remove muon and muon induced events.
- dT(pre)>10msec veto
  - Remove noise events
- Trms (timing RMS of event)<100nsec
  - Remove remaining noise events.
- Nhit in the first 20nsec<=0.6 of total Nhit
  - Remove Cherenkov events.
- Max PE/total PE cut
  - Remove events in front of PMTs by higher max PE/total PE cut.

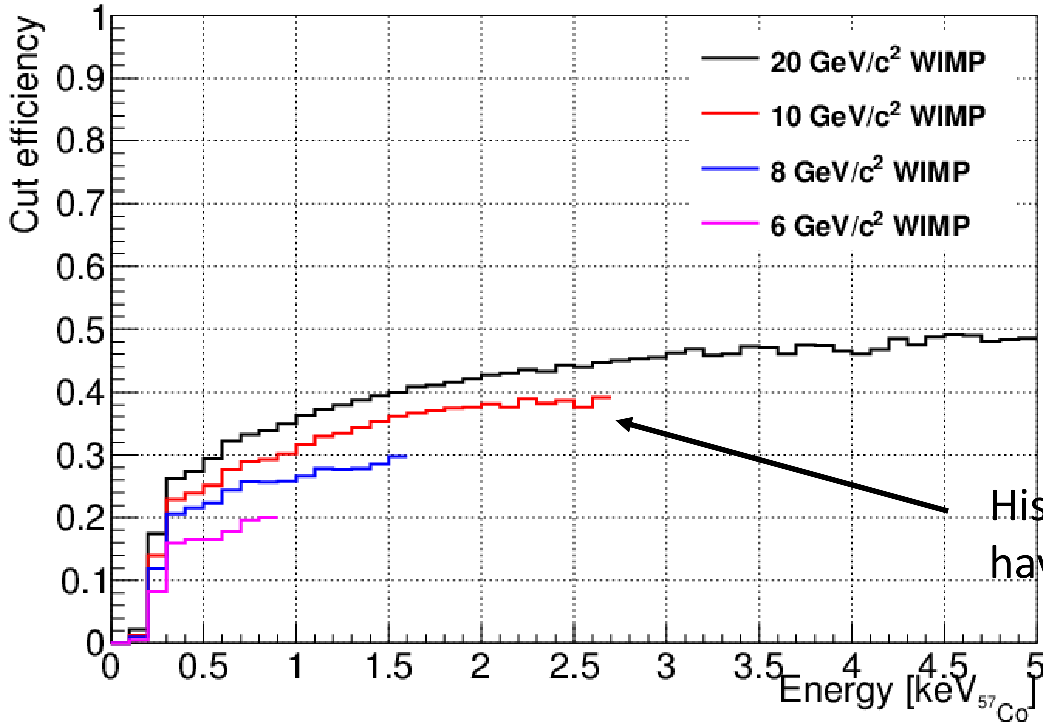
data



20GeV/c² WIMP MC



WIMP signal detection efficiency

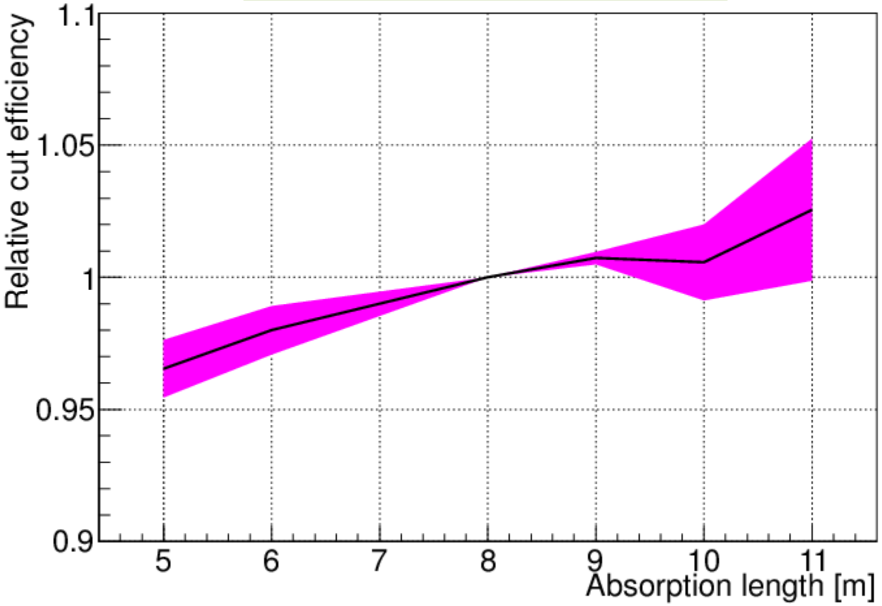


Histograms end because they don't have statistics in the higher energy.

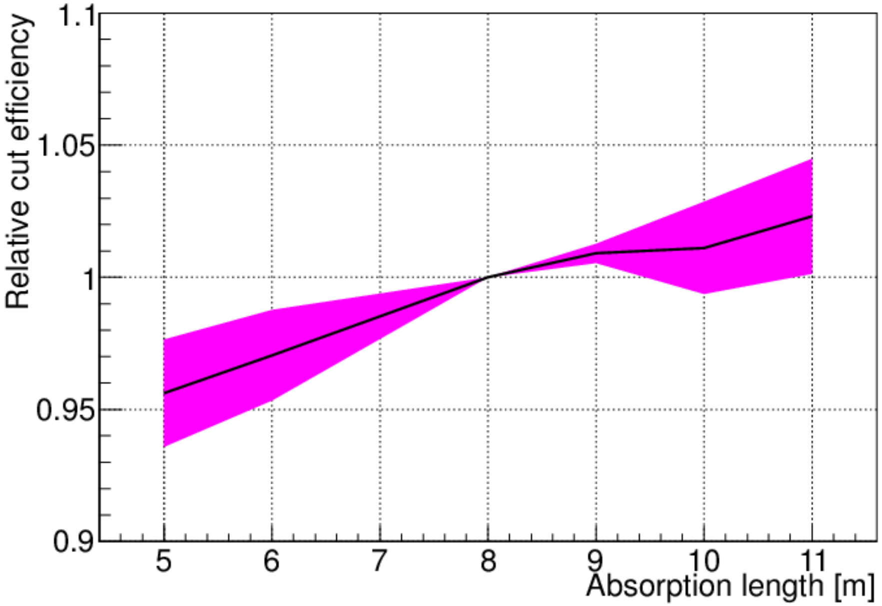
Efficiency depends on WIMP mass.

Relative efficiency

$0.5<E<1.0keV_{57Co}$



$1.0keV_{57Co}<E$



- Relative efficiency to the absorption length=8m data.
- The PE yield changes in time effect the efficiency of the cuts due to not only the threshold but also the position dependency of the scintillation light response. Those uncertainties are taken into account as systematic error by MC for the different energy ranges.

-> This is the dominant systematic error.

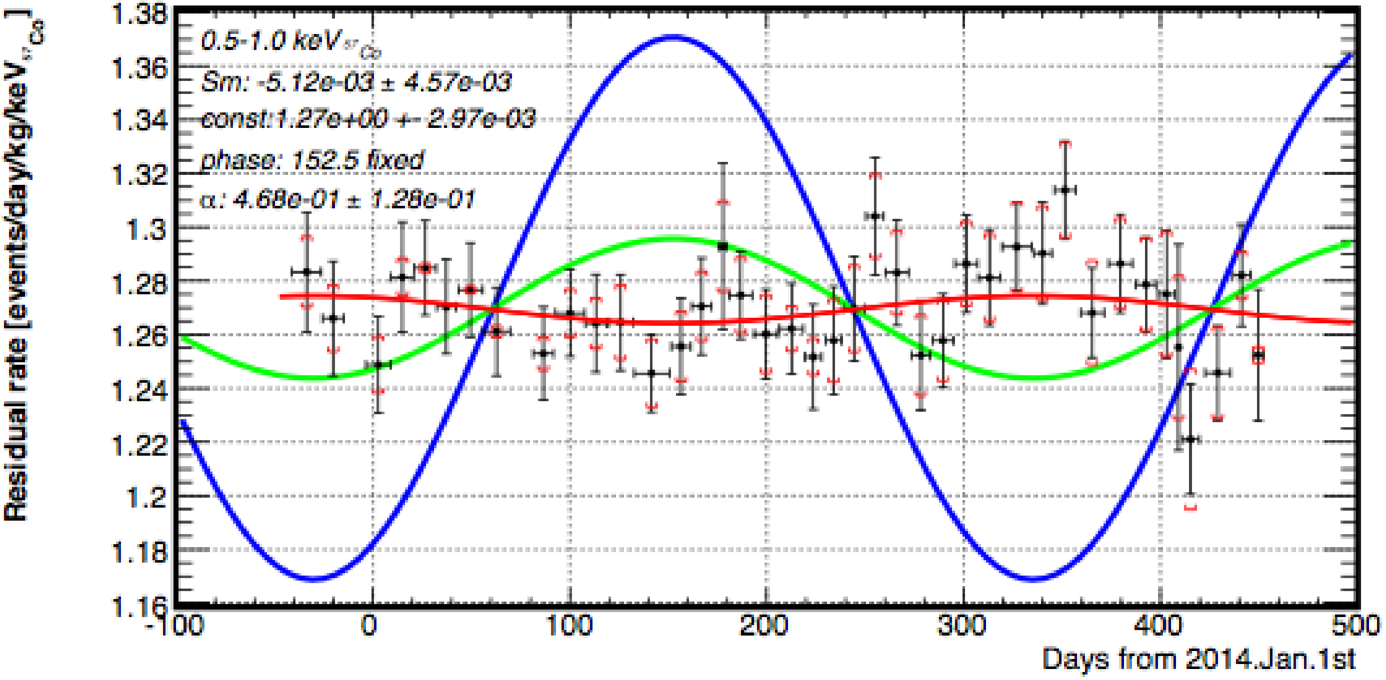
Time variation of event rate

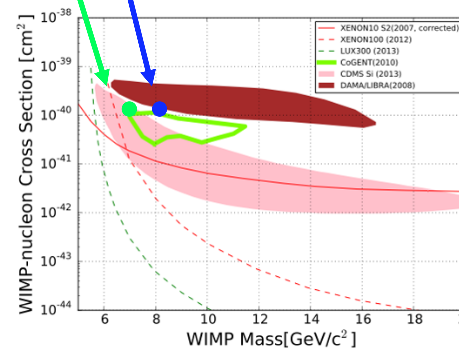
0.5<E<1.0keV$_{57Co}$

model independent

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

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





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

Statistical error

systematic error

Fitted by WIMP phase

Modulation analysis method

Data is divided into 38 time bins × 45energy bins (~10days/(time bin), 0.1keV$_{57Co}$/(energy bin) in 0.5-5.0keV$_{57Co}$) and then all data bins are fitted simultaneously.

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

Method 1 (pull term)

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

Systematic errors (1σ)

Method 2 (covariance matrix)

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

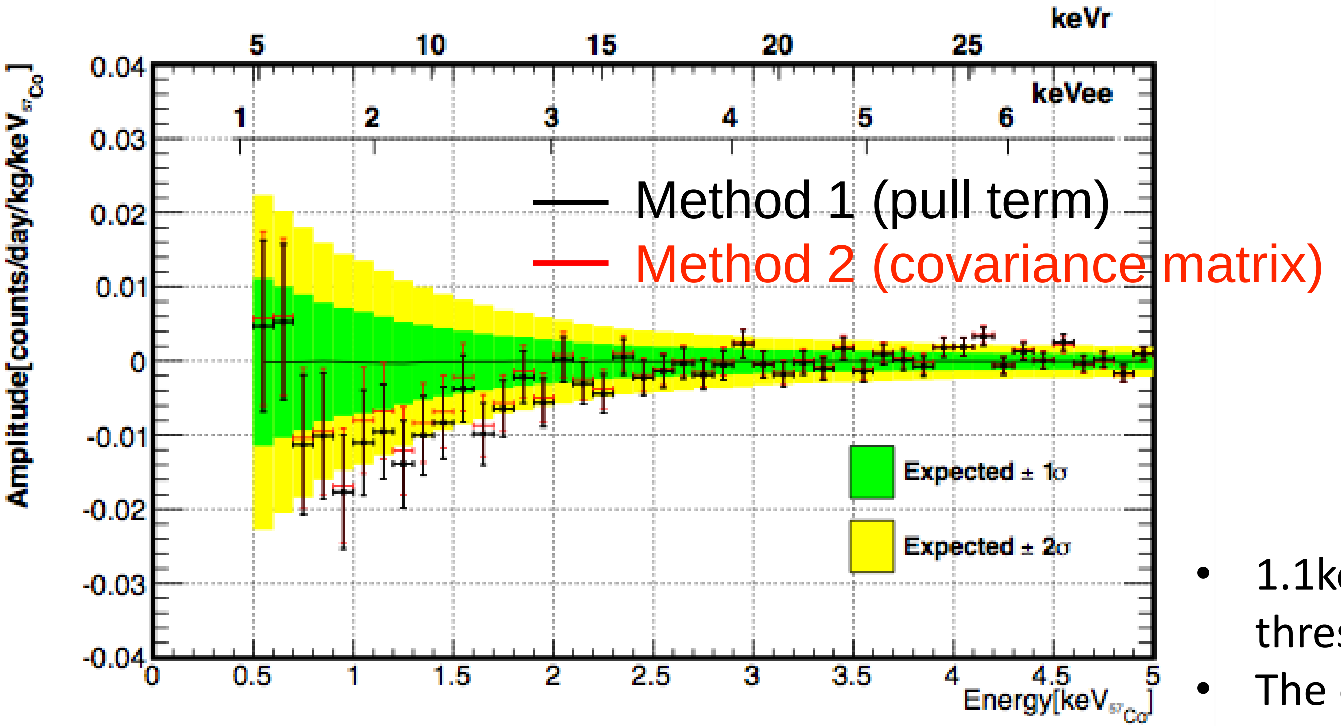
Model independent analysis 1/2

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

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

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.

Model independent analysis 2/2



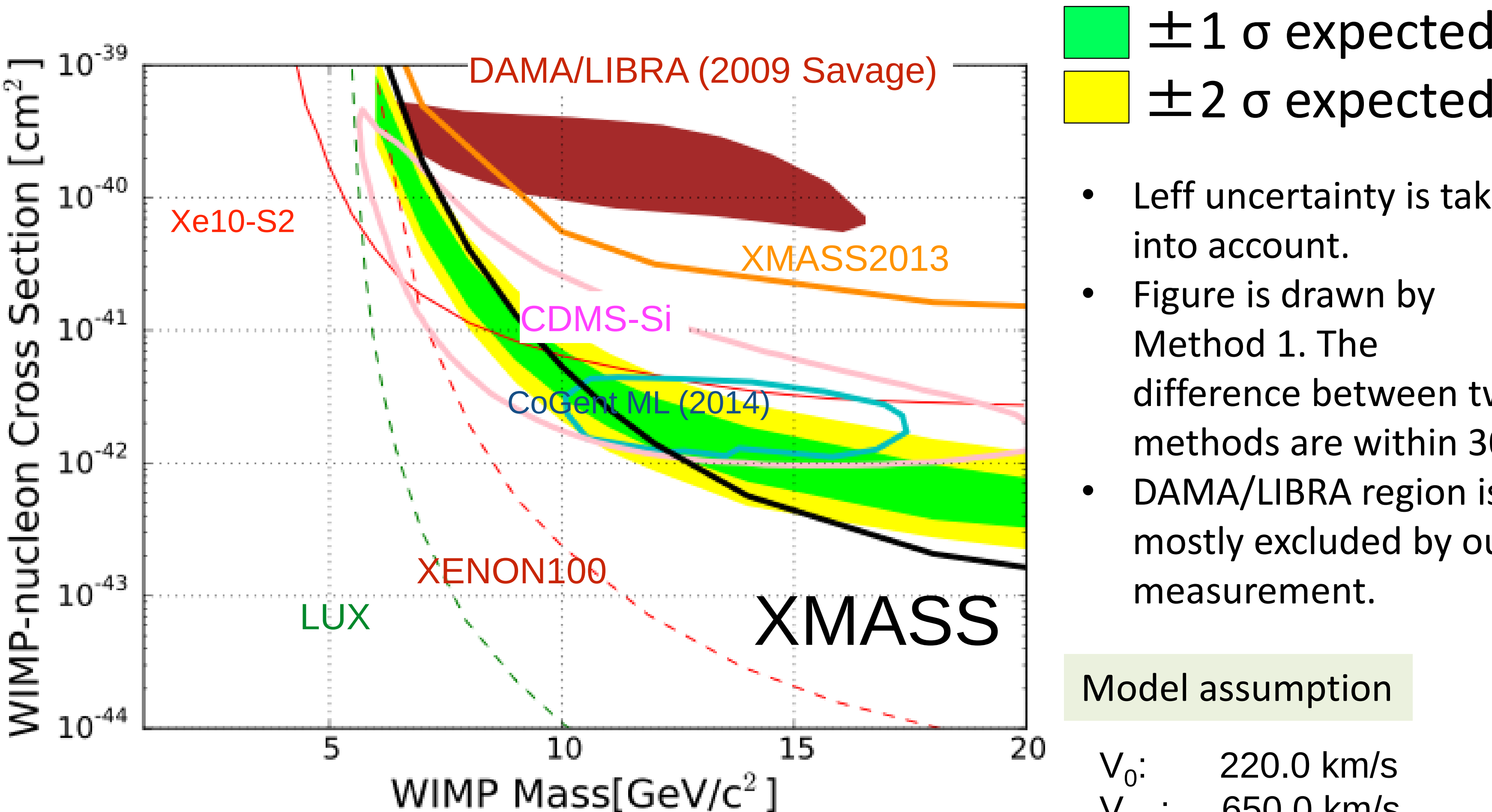
	Method 1 (pull term)	Method 2 (covariant matrix)
ndf	1709	1710
Minimum χ^2	1845.0	1901.7
χ^2 at no modulation	1912.3	1961.8
p-value	0.068 (1.8σ)	0.17 (1.4σ)

- 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.

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)

summary

- 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 2nd year of data to obtain more sensitive result with smaller systematic uncertainties.
- Also fiducial volume analysis with background subtraction is ongoing.
- Future XMASS project will be presented at 15:10- on Sep. 10th by Benda Xu (Dark Matter A).

backup

XMASS collaboration

ICRR, University of Tokyo	K. Abe, K. Hiraide, K. Ichimura, Y. Kishimoto, K. Kobayashi, M. Kobayashi, S. Moriyama, M. Nakahata, T. Norita, H. Ogawa, K. Sato, H. Sekiya, O. Takachio, S. Tasaka, A. Takeda, M. Yamashita, B. Yang
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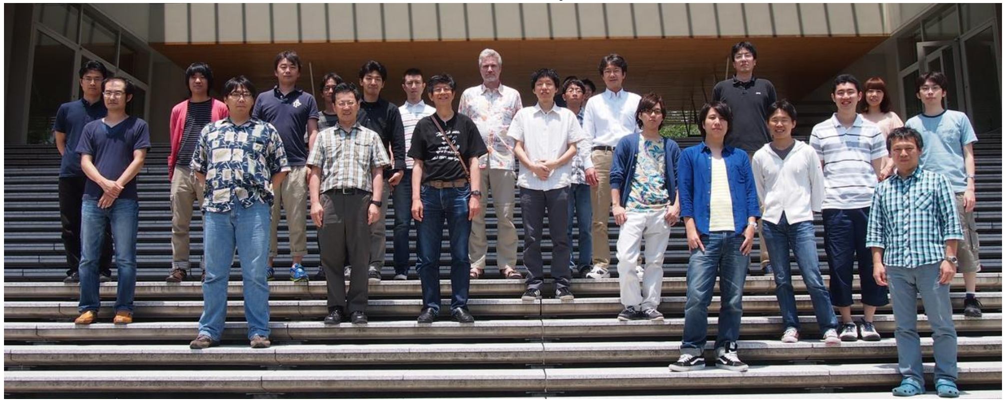
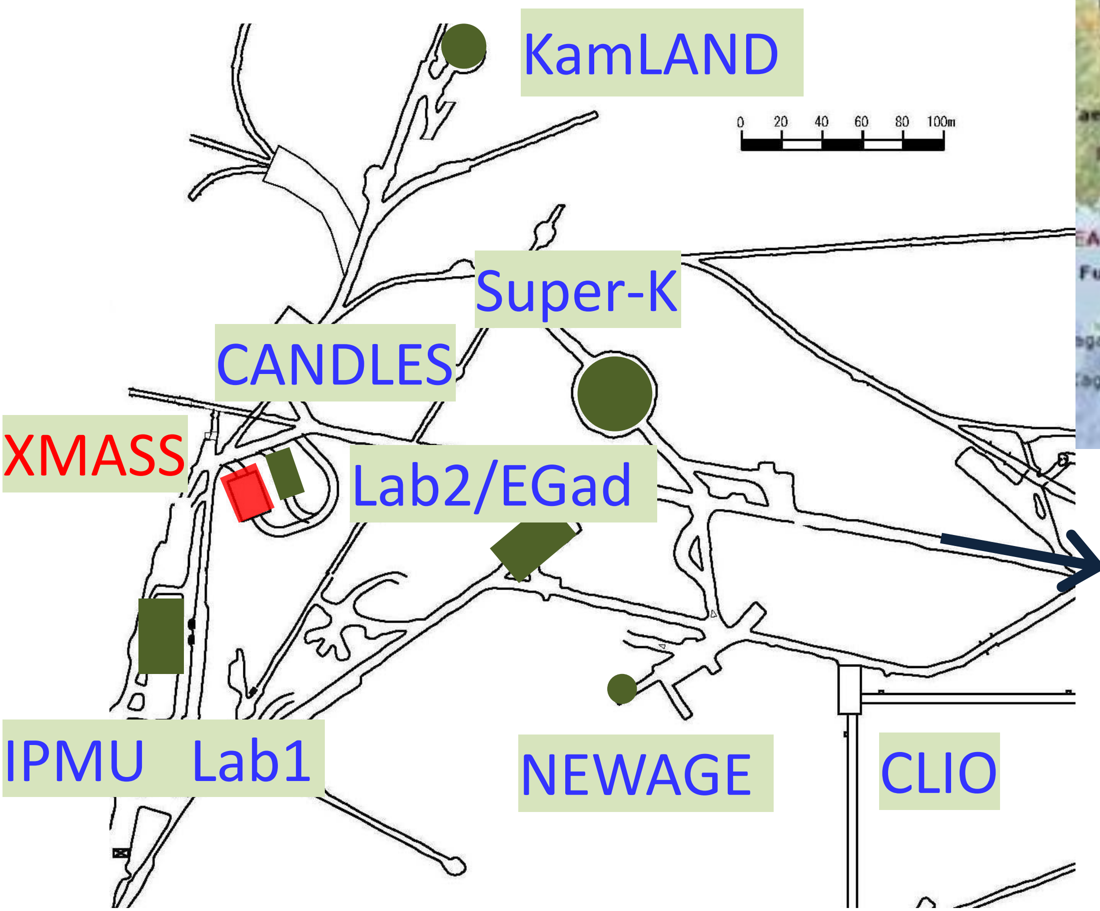
Kobe University	R. Fujita, K. Hosokawa, K. Miuchi, N. Oka, Y. Takeuchi
Tokai University	M. Miyasaka, K. Nishijima
Tokushima University	K. Fushimi, G. Kanzaki
Yokohama National University	S. Nakamura
Miyagi University of Education	Y. Fukuda
STEL, Nagoya University	Y. Itow, K. Kanzawa, R. Kegasa, K. Masuda, 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

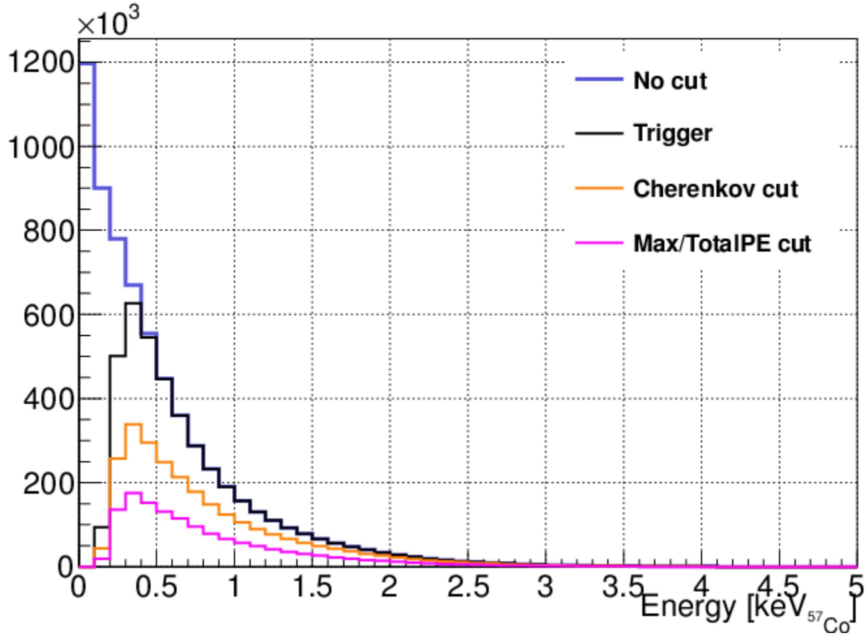
Kamioka mine

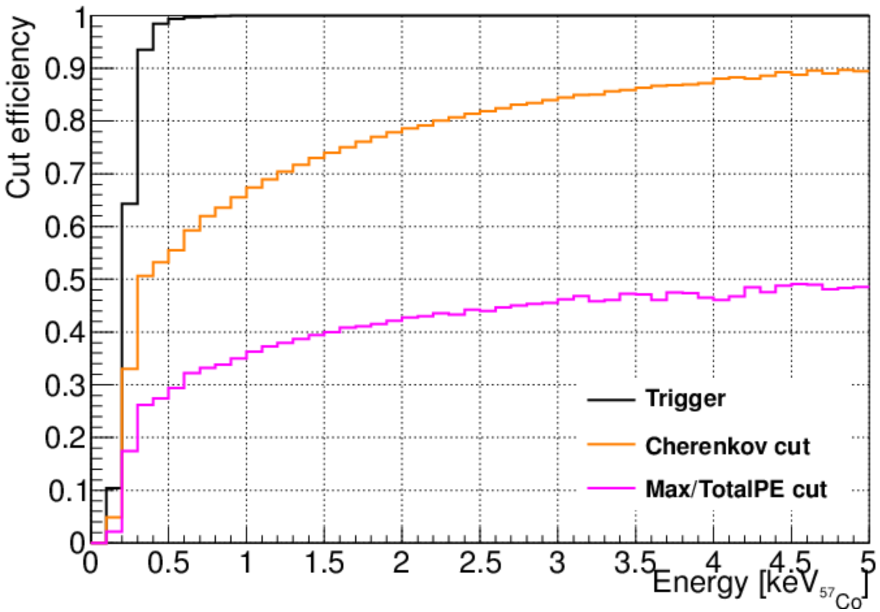


To: Atotsu
mine entrance

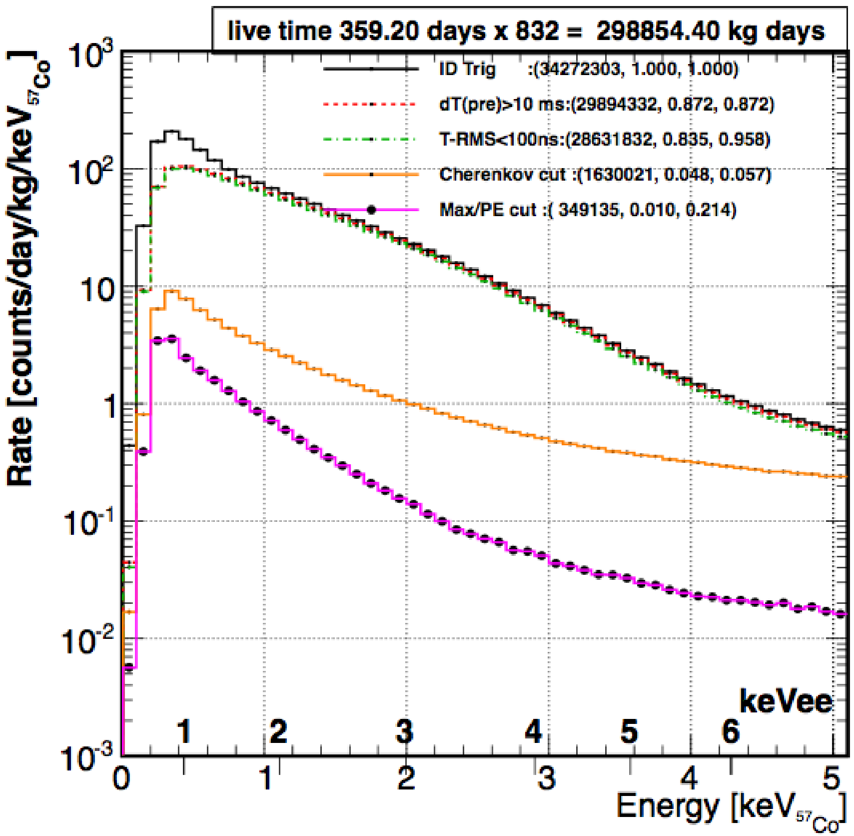
~1000m underneath Mt. Ikenoyama

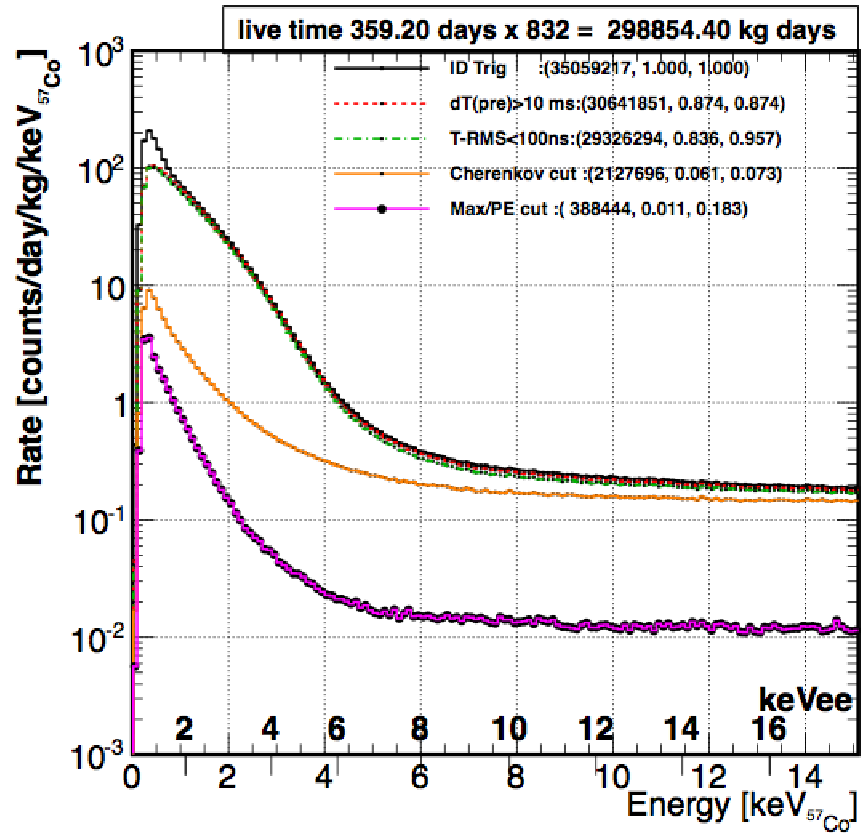
20GeV/c^2 WIMP MC energy spectra and efficiencies



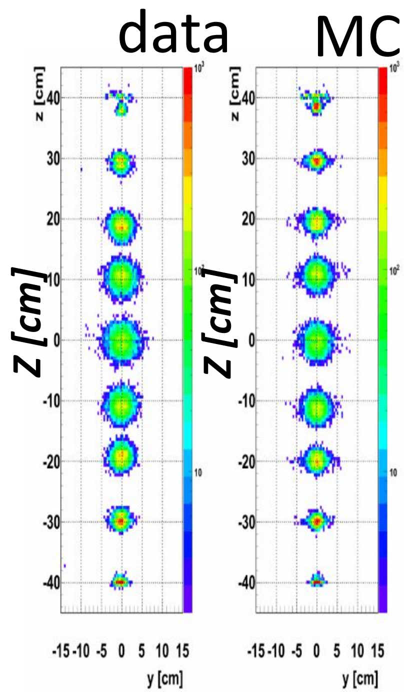


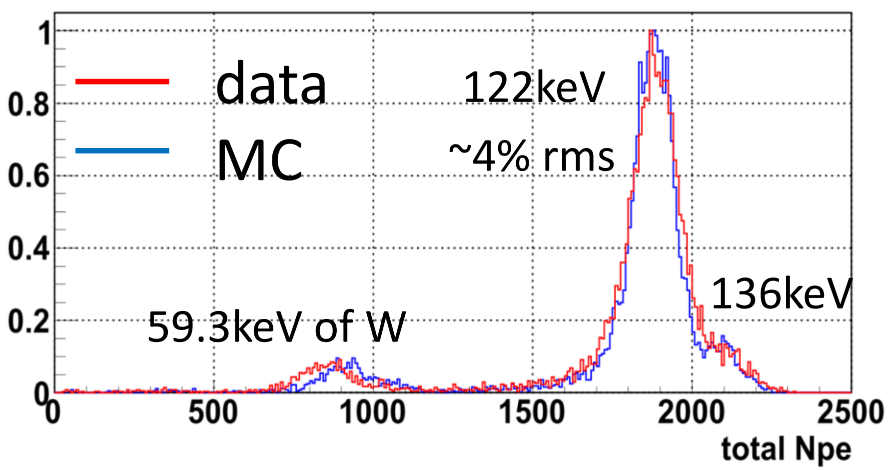
Energy spectra (data)

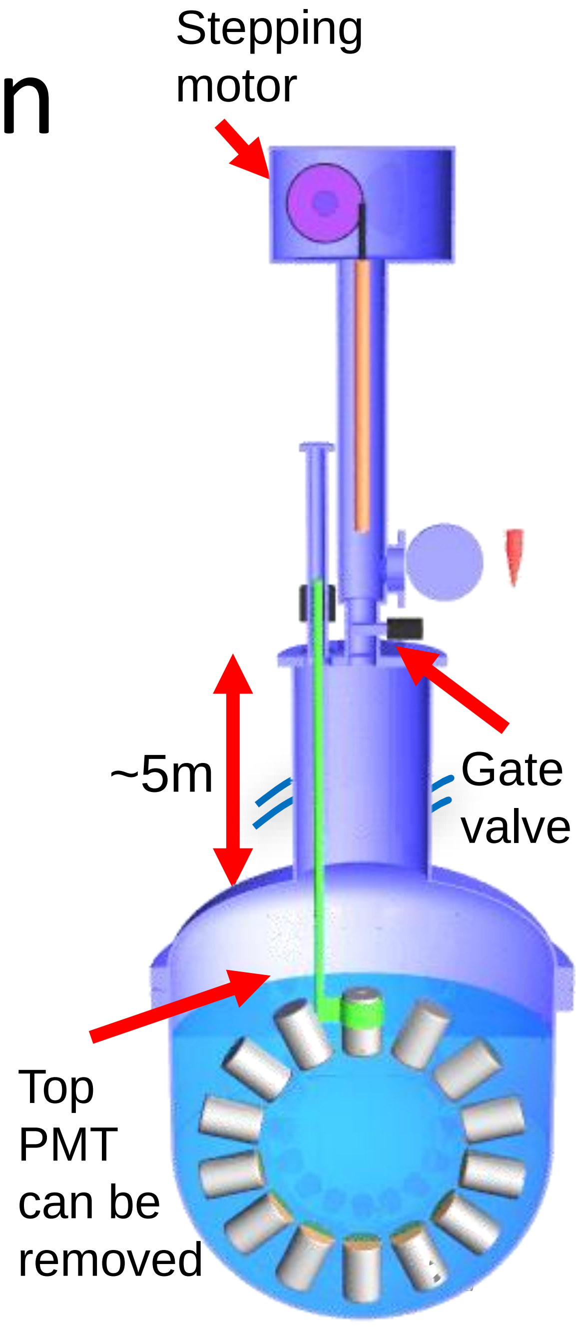




Inner calibration

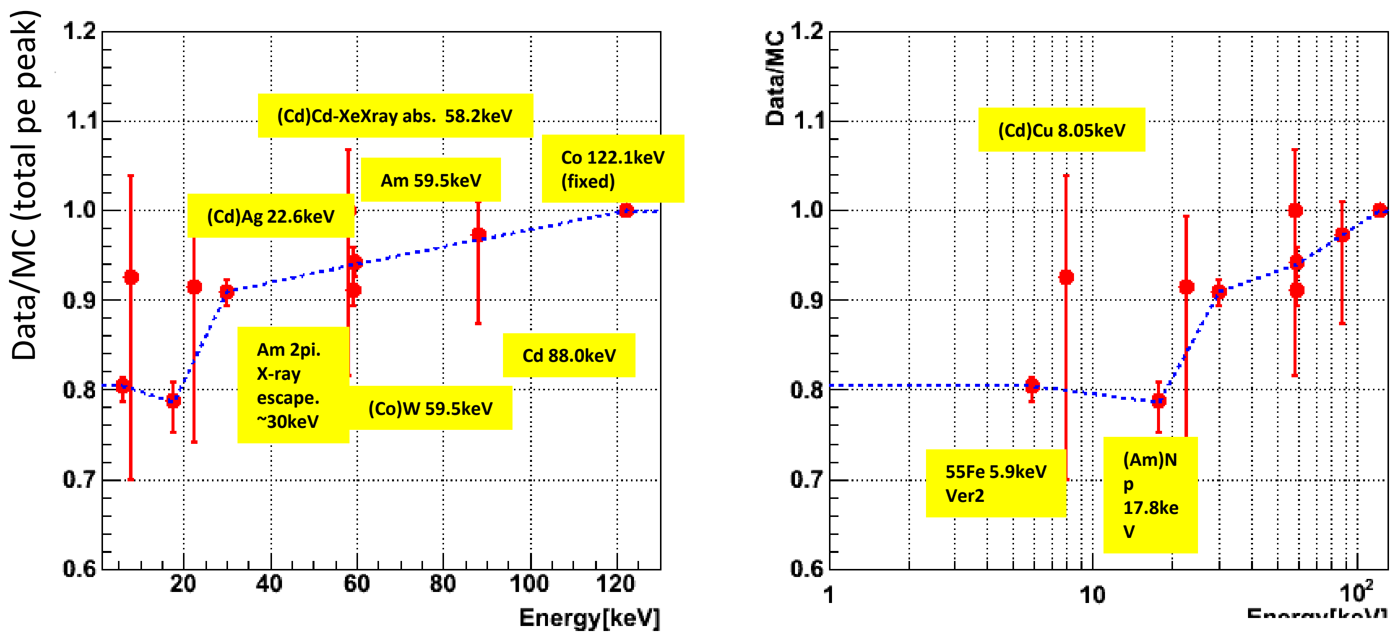






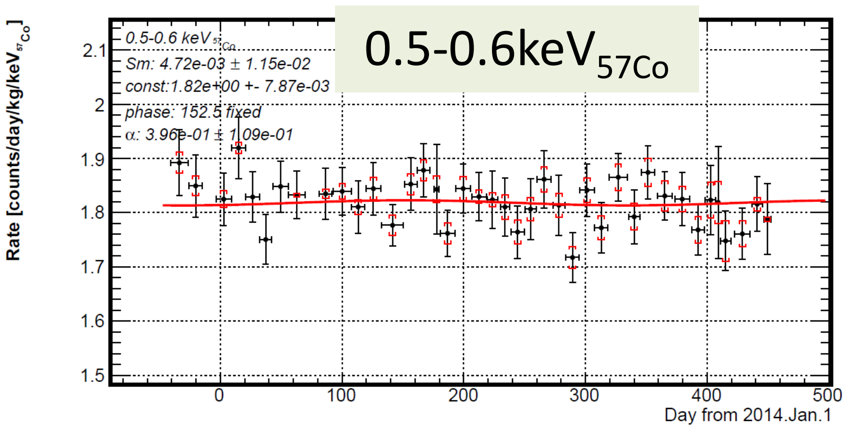
Energy scaling

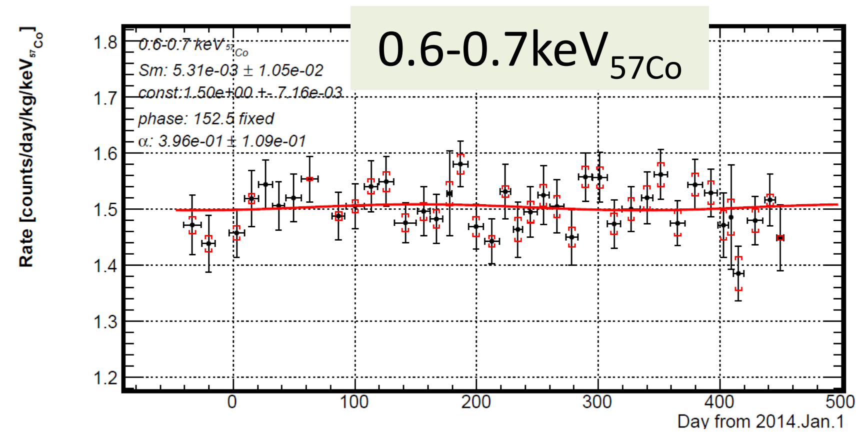
- Energy scale at 5.9keV
  - 0.804 +0.010/ -0.018 (total uncertainty)

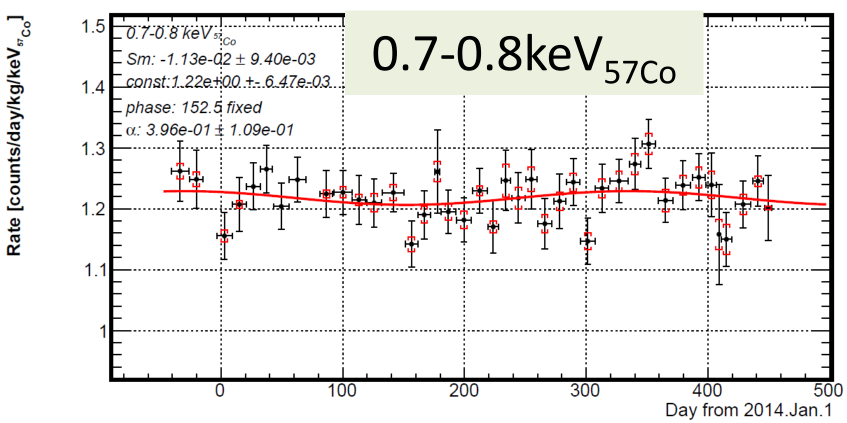


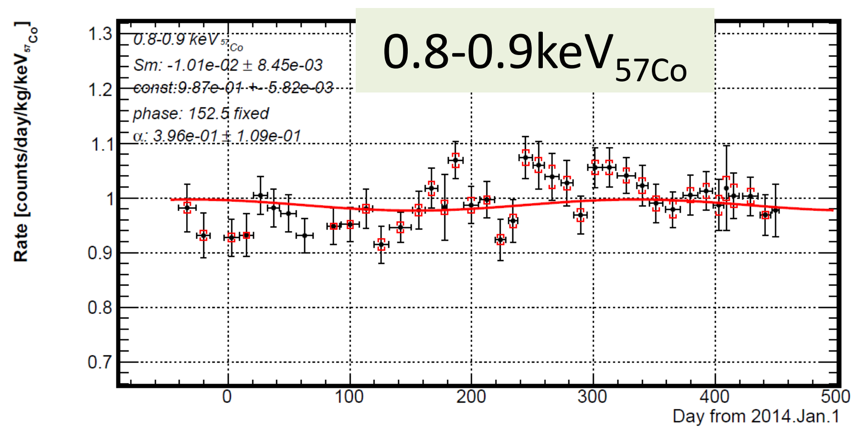
Gamma energy(keV)

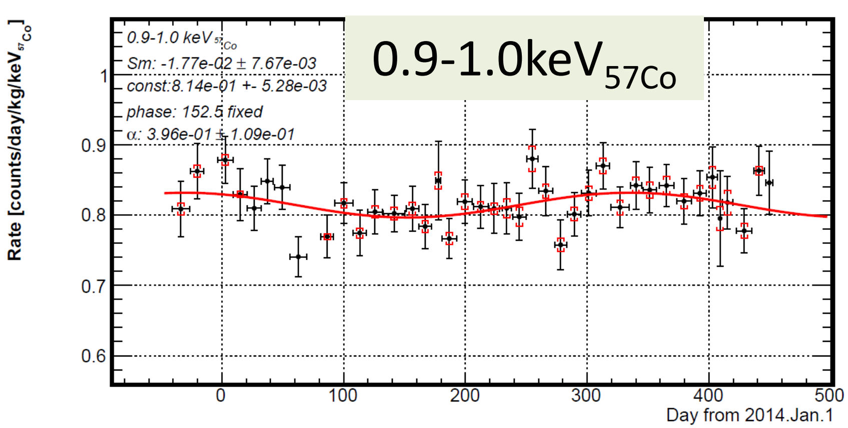
0.5-1.0keV$_{57Co}$









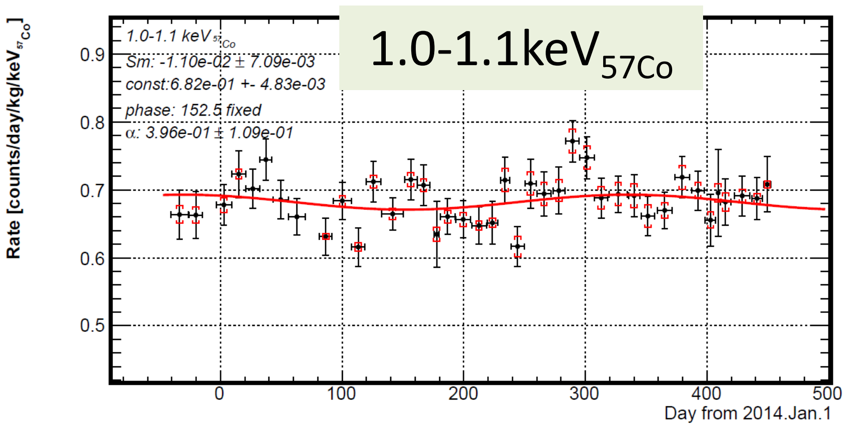


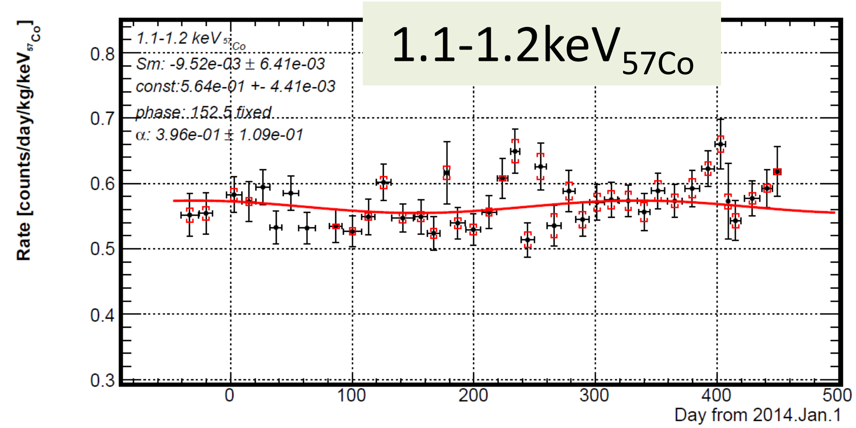
Statistical error

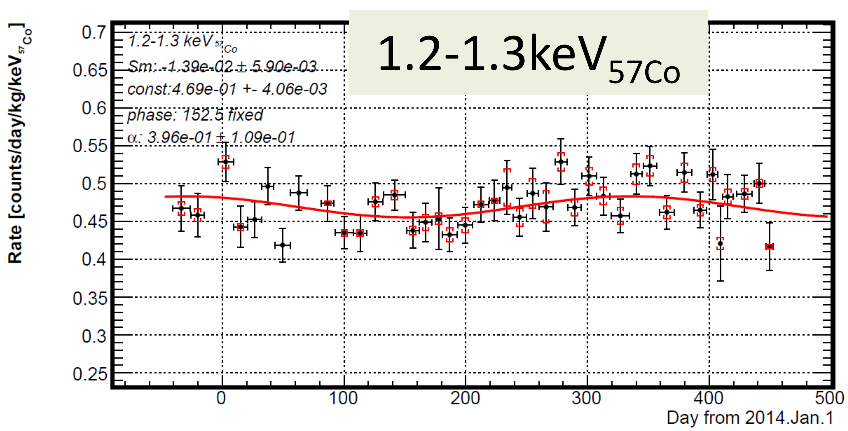
systematic error

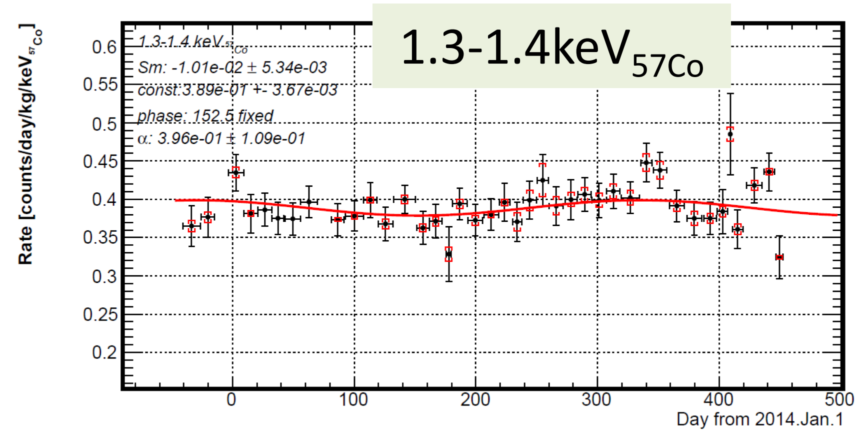
Fitted by WIMP phase

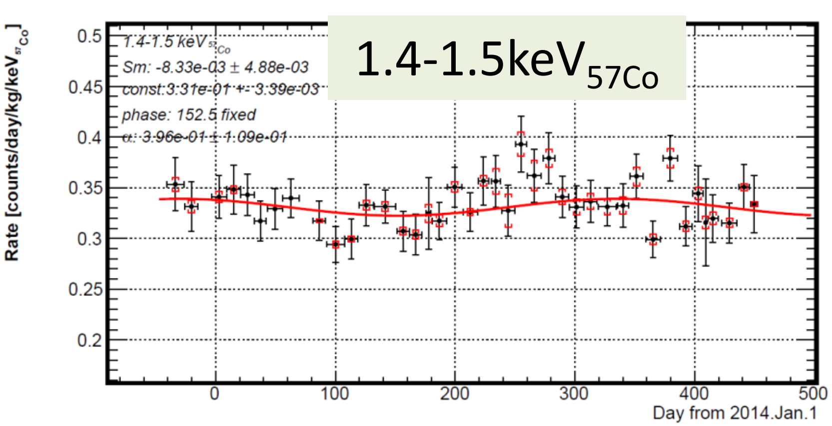
1.0-1.6keV$_{57Co}$

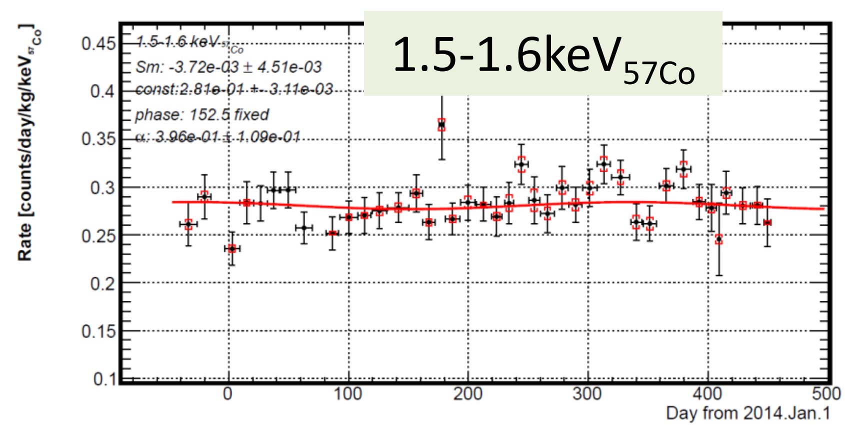




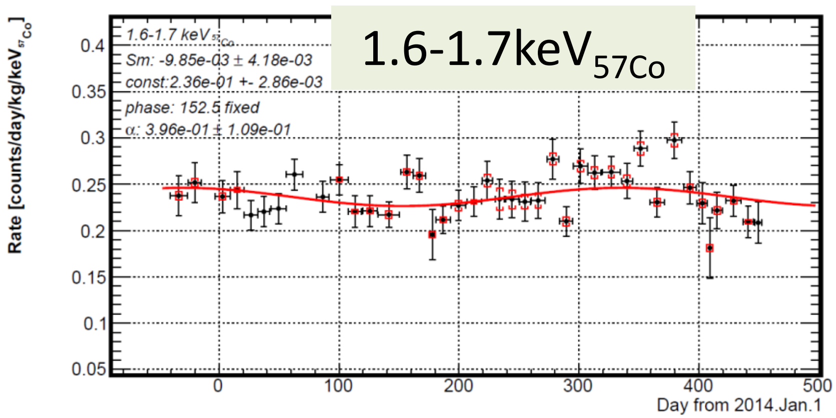


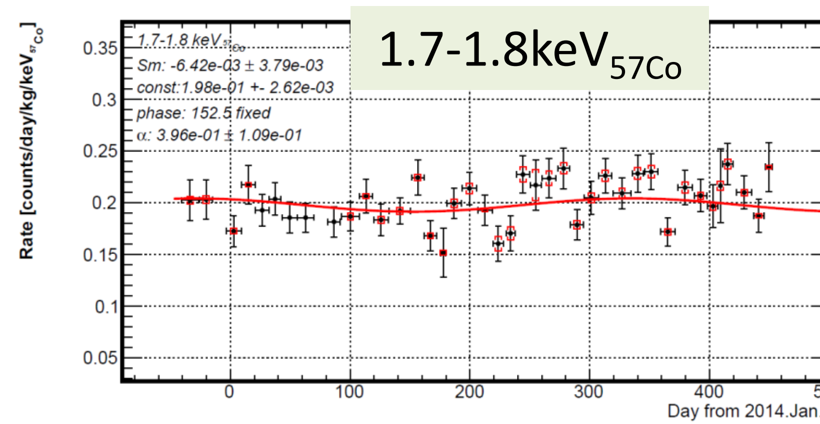


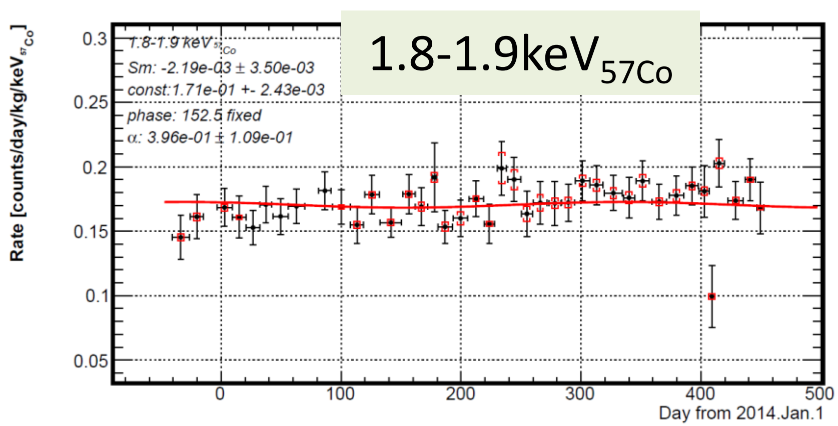


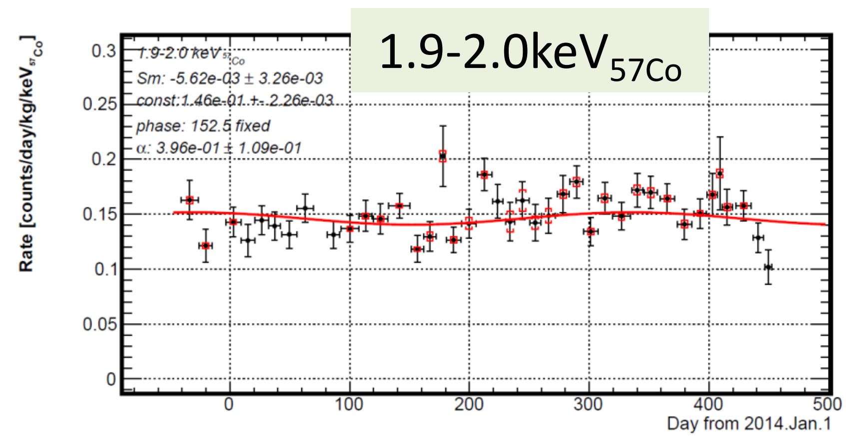


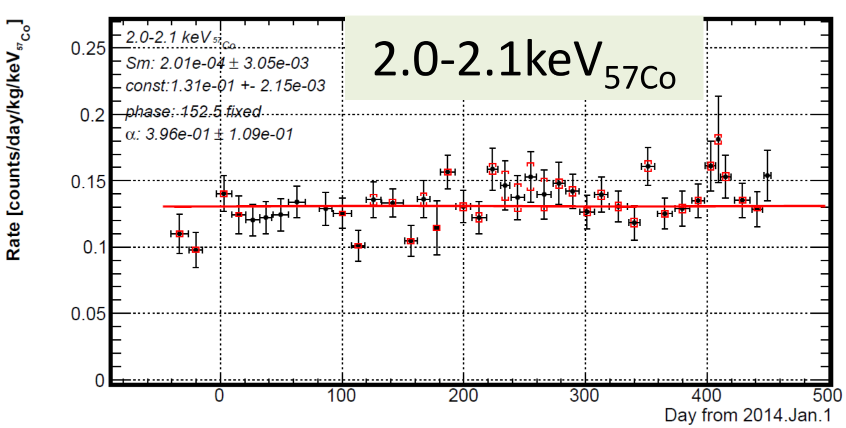
1.6-2.2keV$_{57Co}$

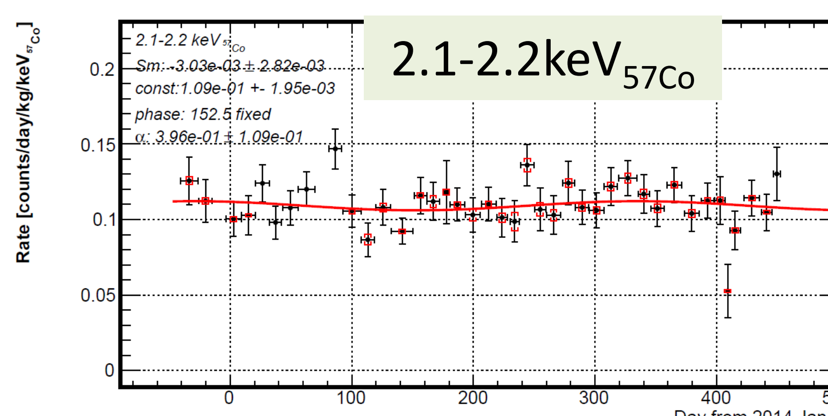




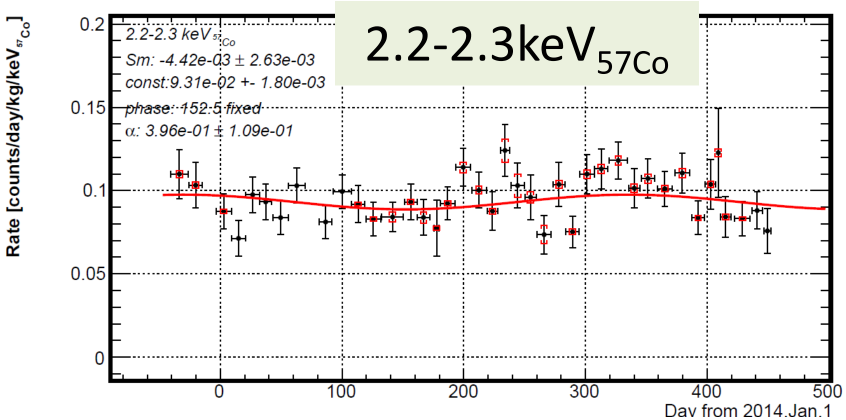


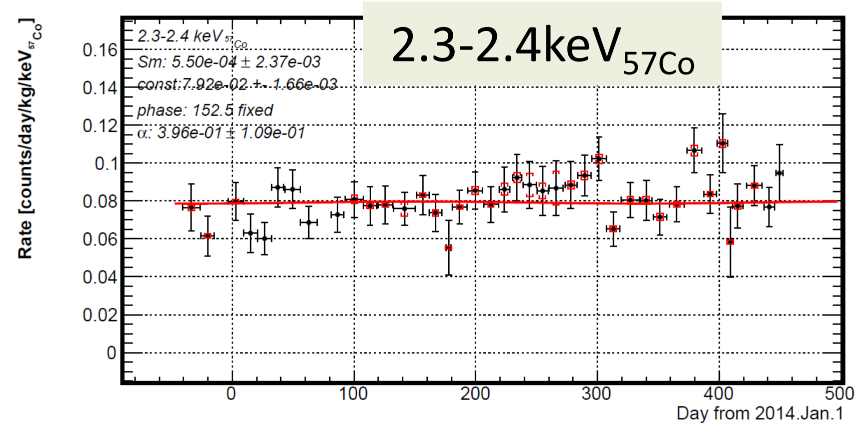


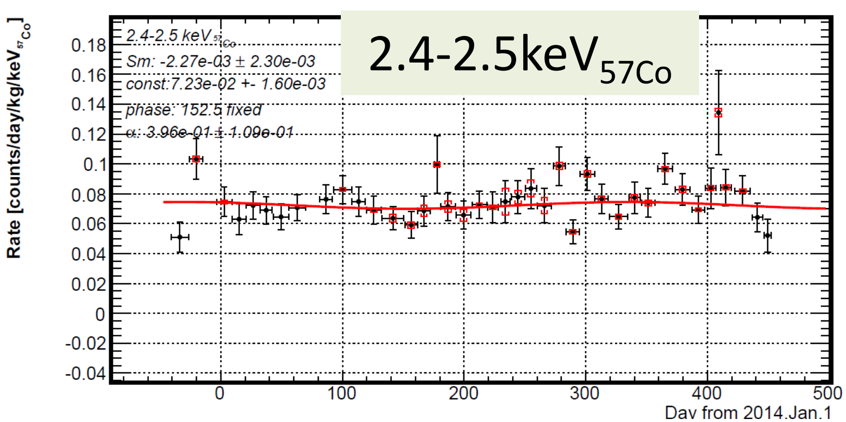


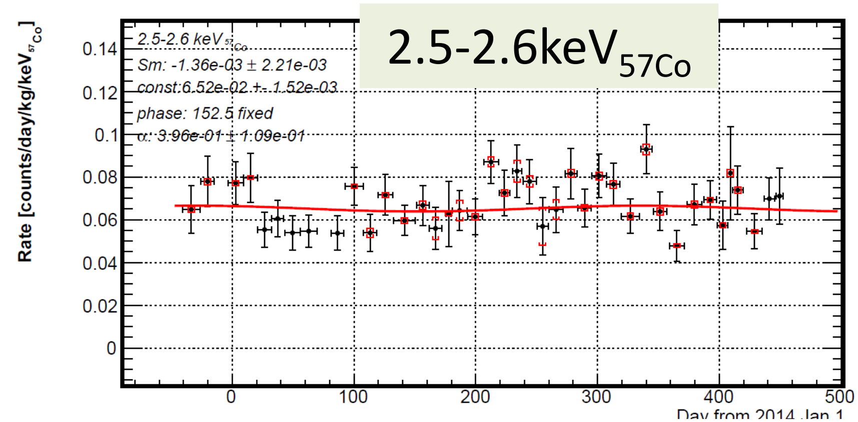


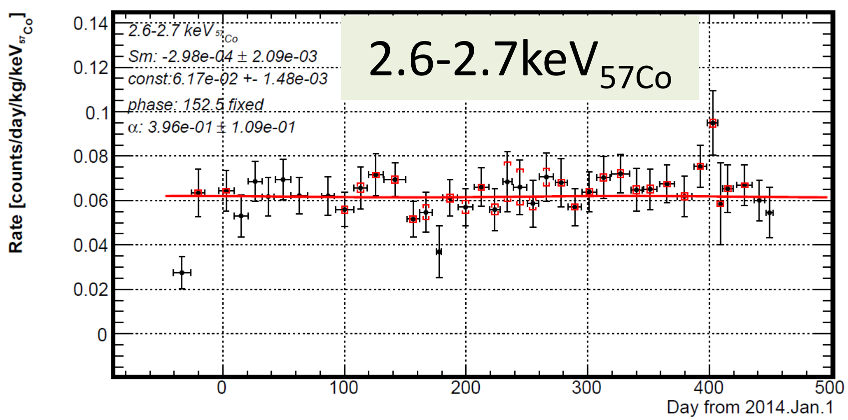
2.2-2.8keV$_{57Co}$

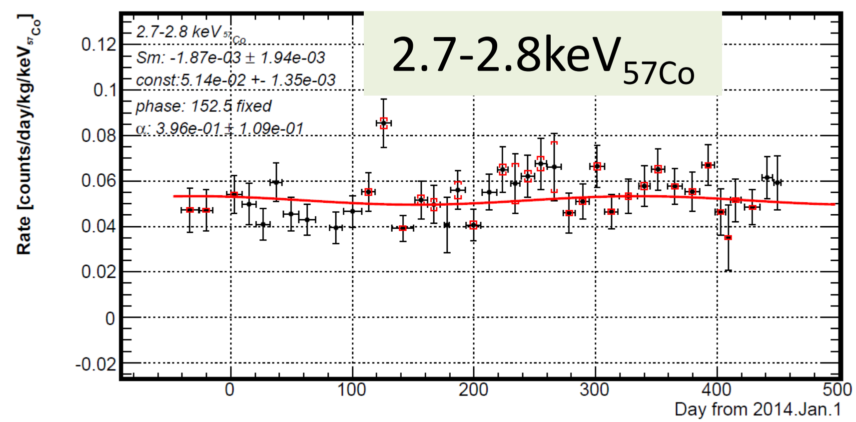




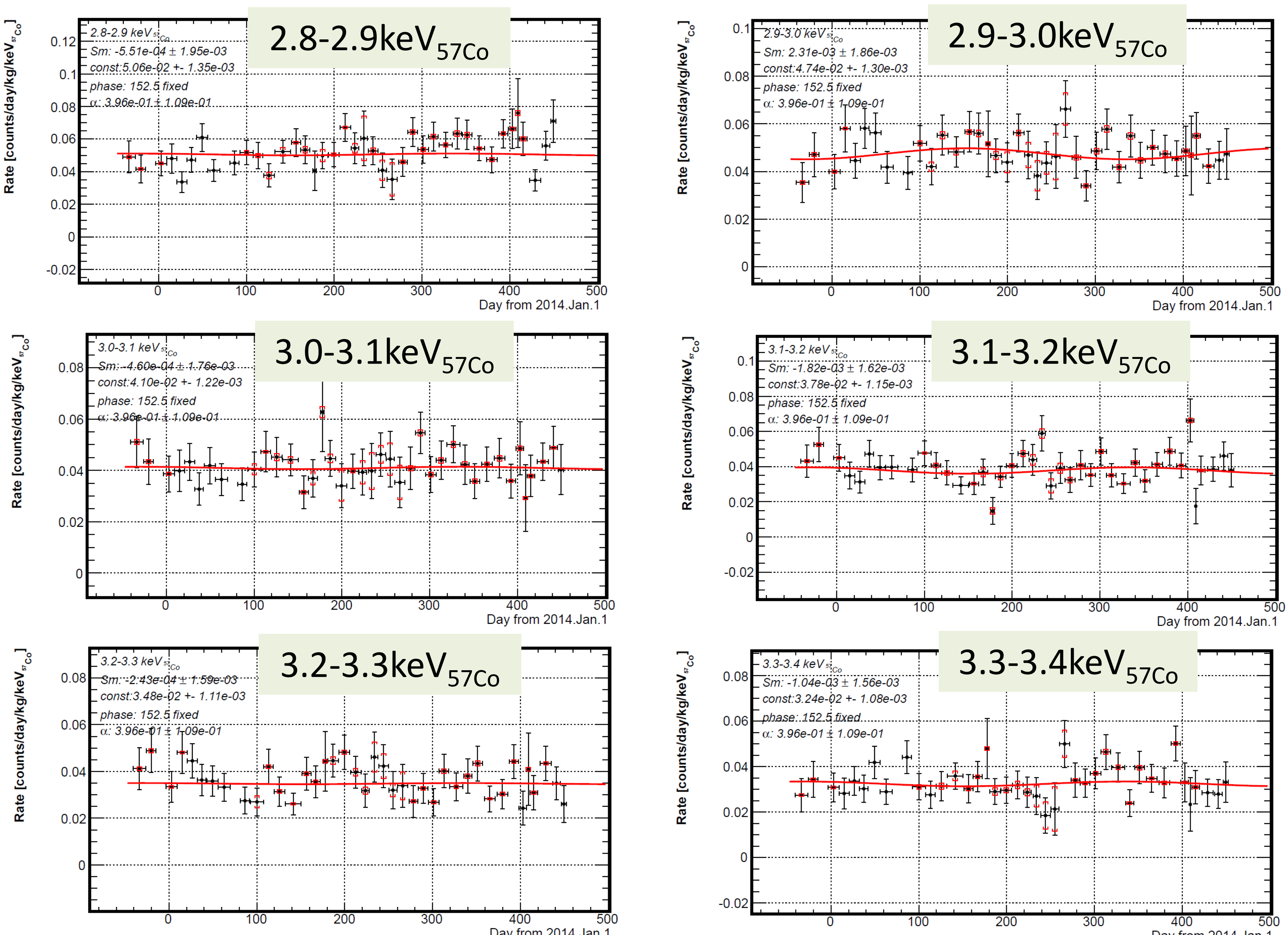




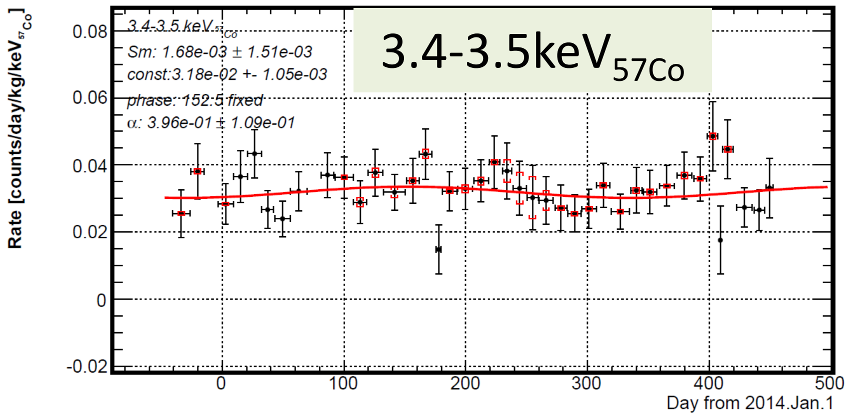


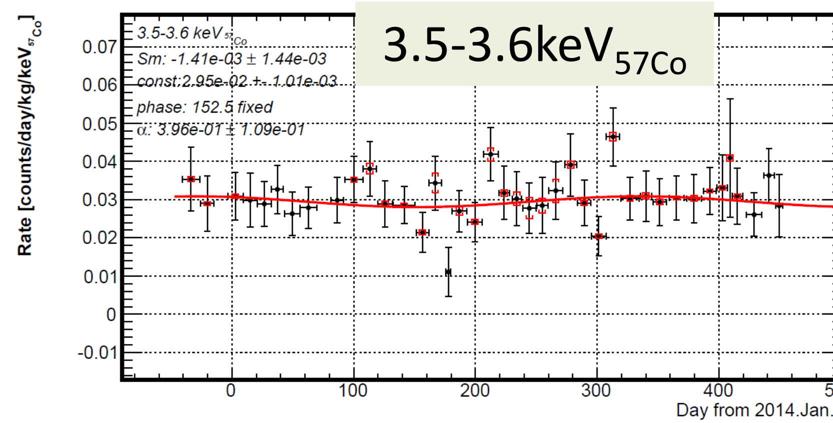


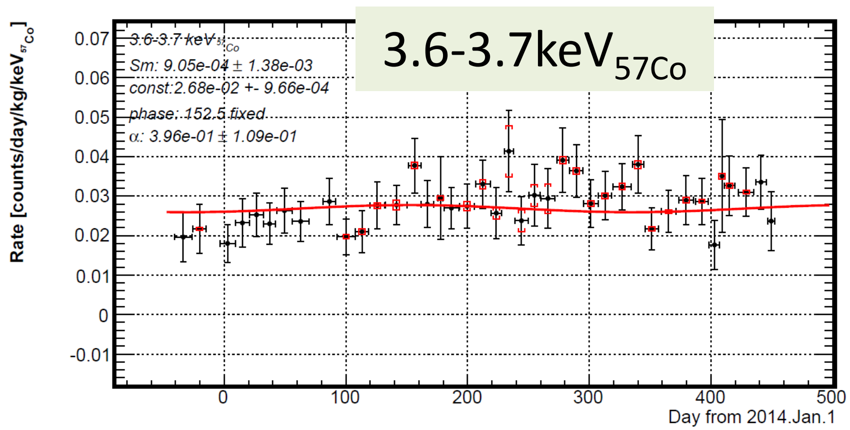
2.8-3.4keV$_{57Co}$

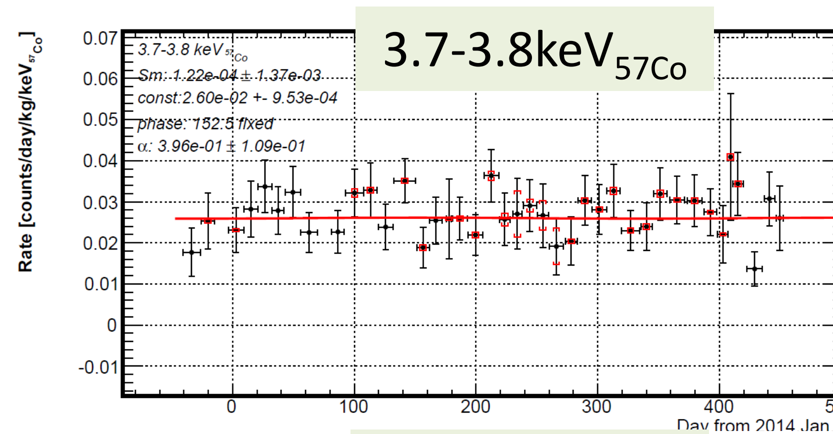


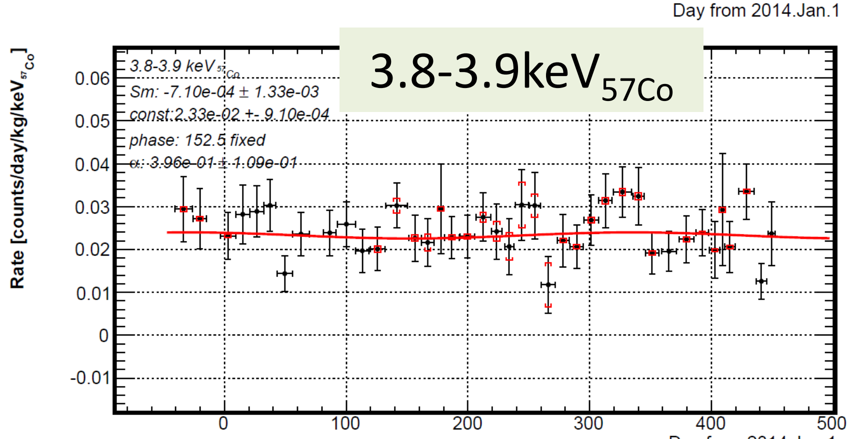
$3.4\text{-}4.0keV_{57Co}$

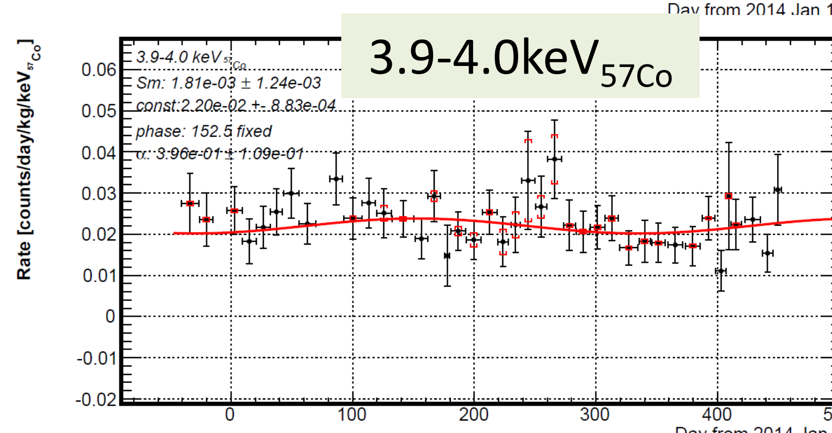




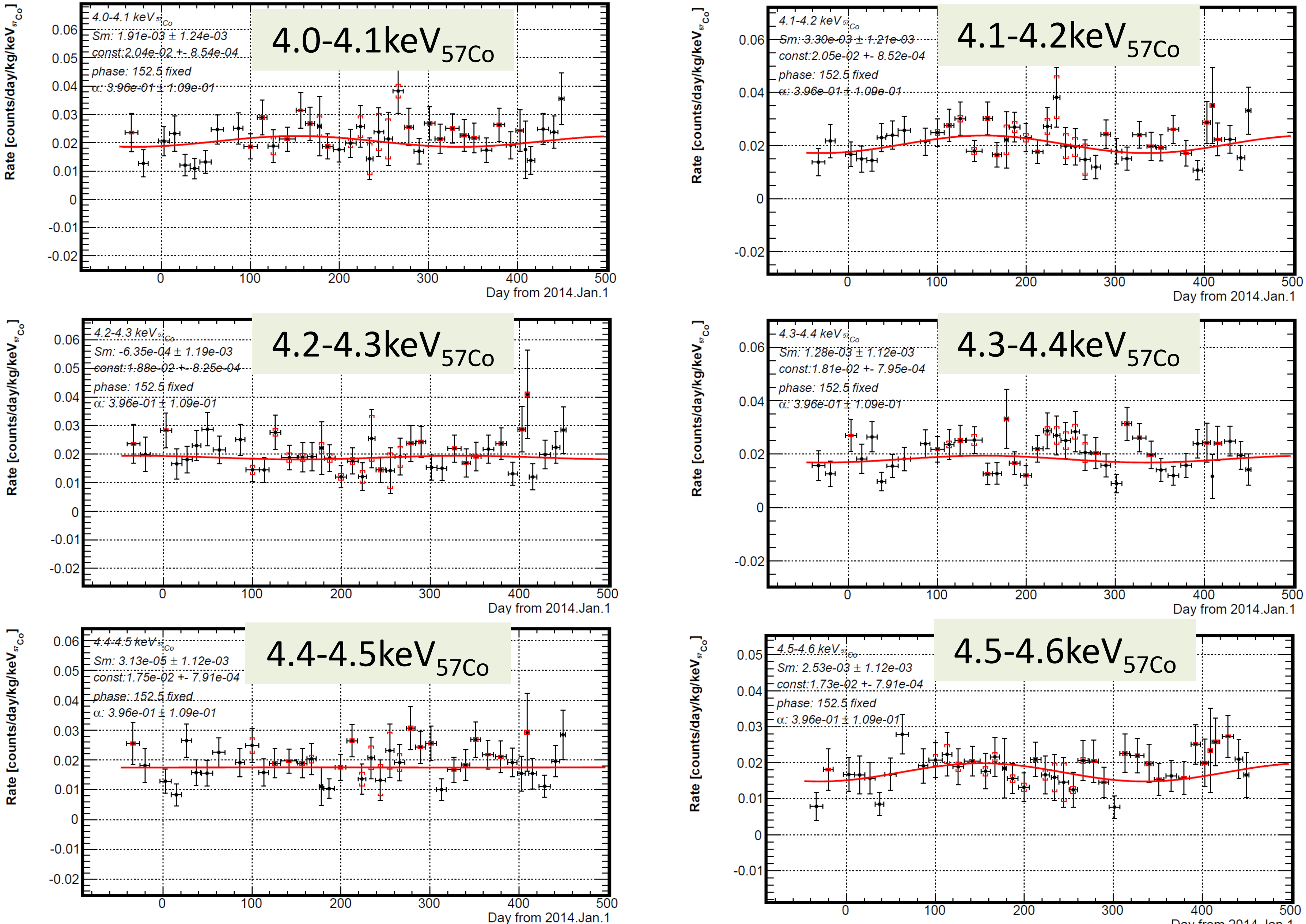




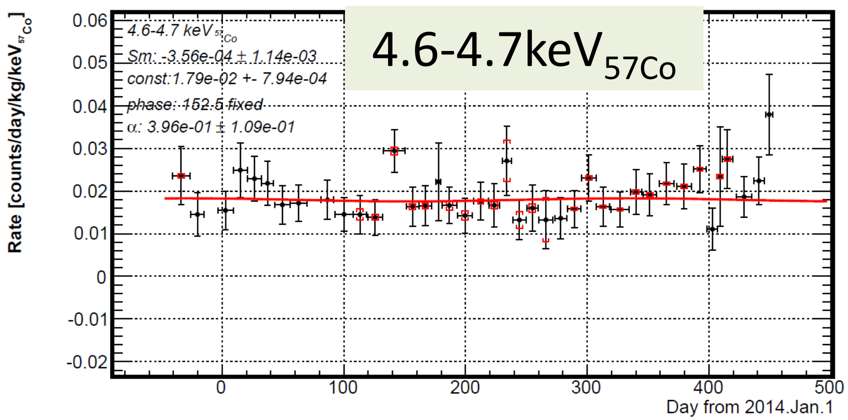


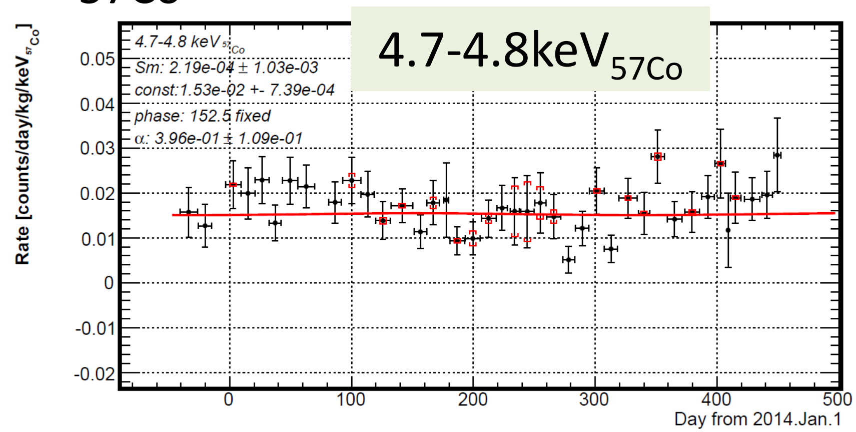


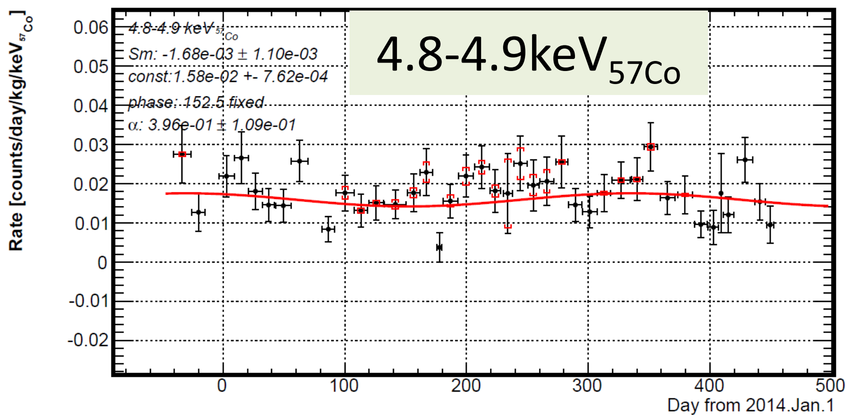
04.0-4.6keV$_{57Co}$

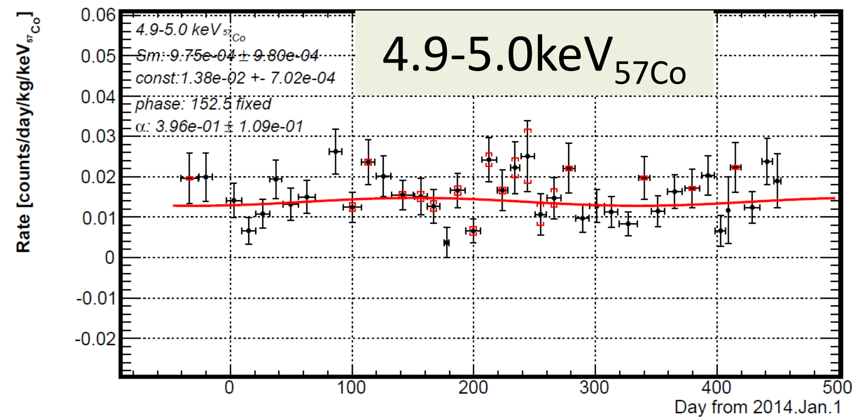


4.6-5.0keV$_{57Co}$

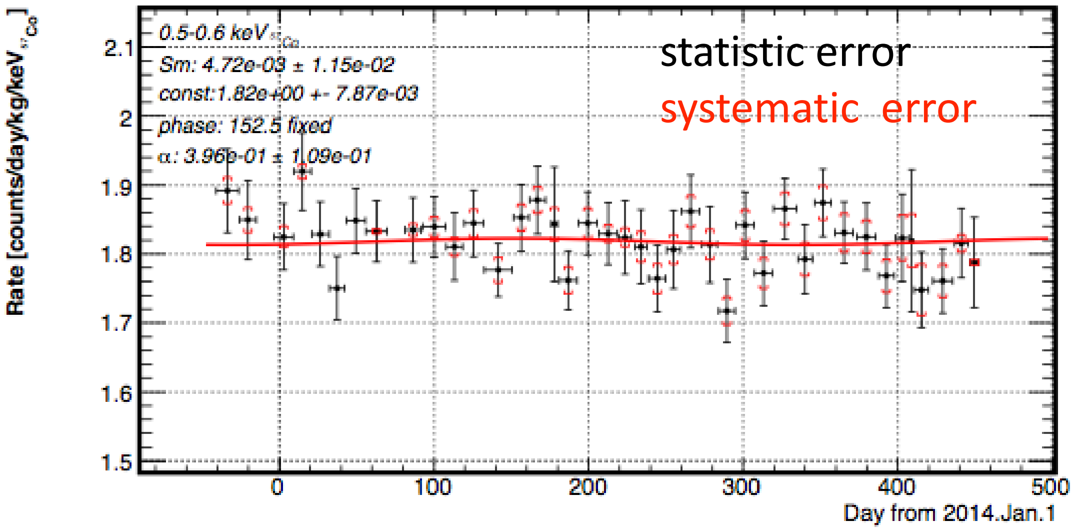








Pull term



Model Independent

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

Model dependent (WIMP)

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

$\mathrm{R}_{i,j}^{data}$: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

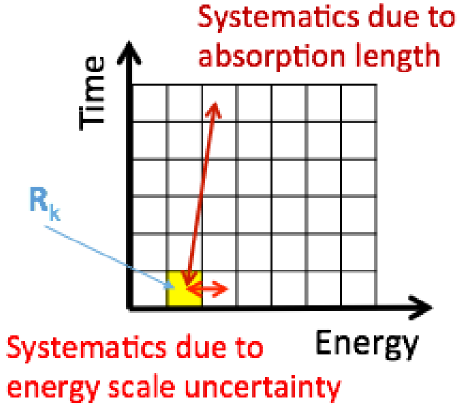
C: constant

T:(=365.24) period in days

$\mathrm{t_0}$:(=152.5) phase in days

Covariance Matrix

Covariance matrix



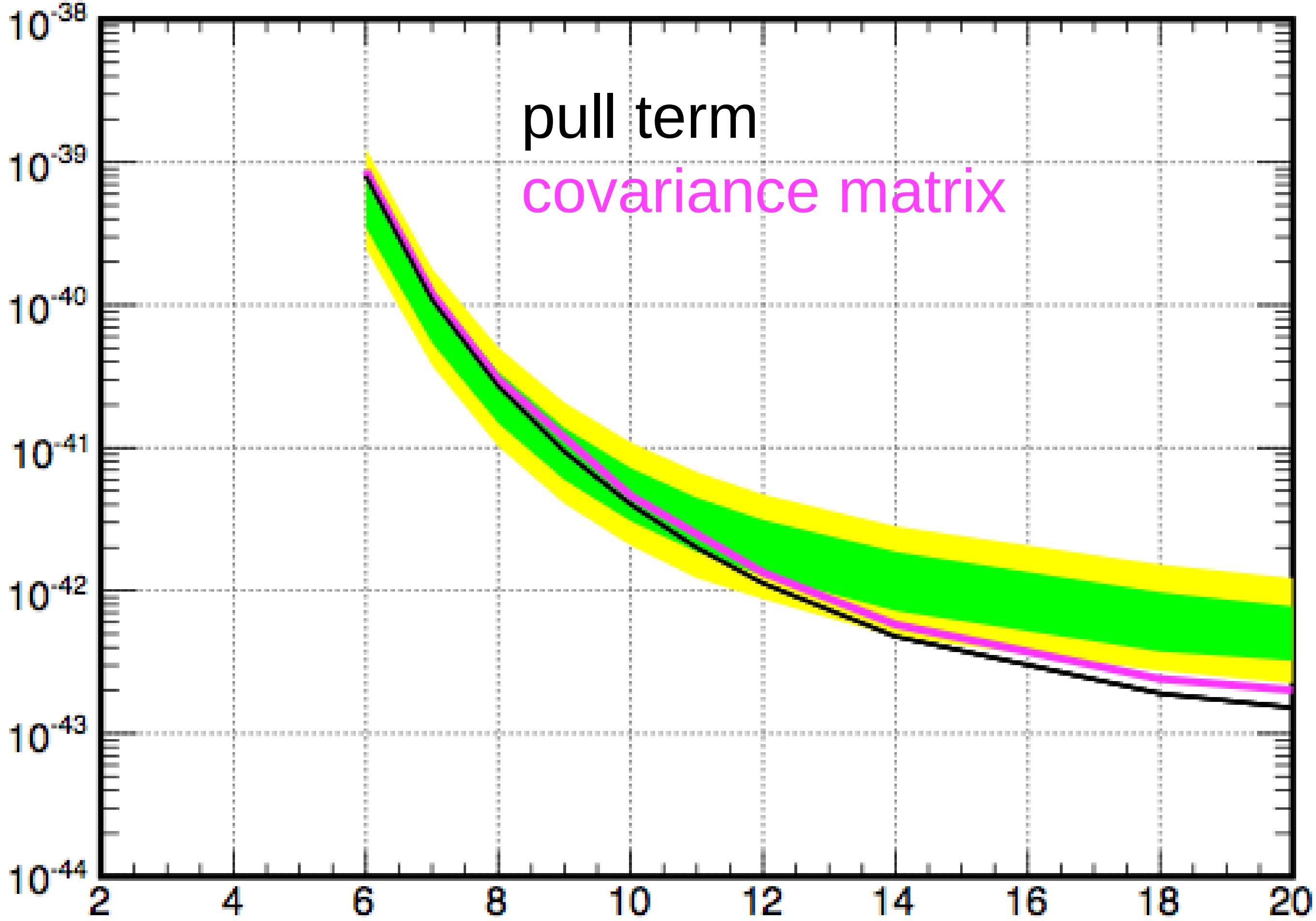
$$\chi^2 = \sum_{k=1}^{N}\sum_{l=1}^{N}\left(R_k^{data} - R_k^{exp}\right)\left(V_{stat} + V_{sys}\right)_{k,l}^{-1}\left(R_l^{data} - R_l^{exp}\right)$$

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

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

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

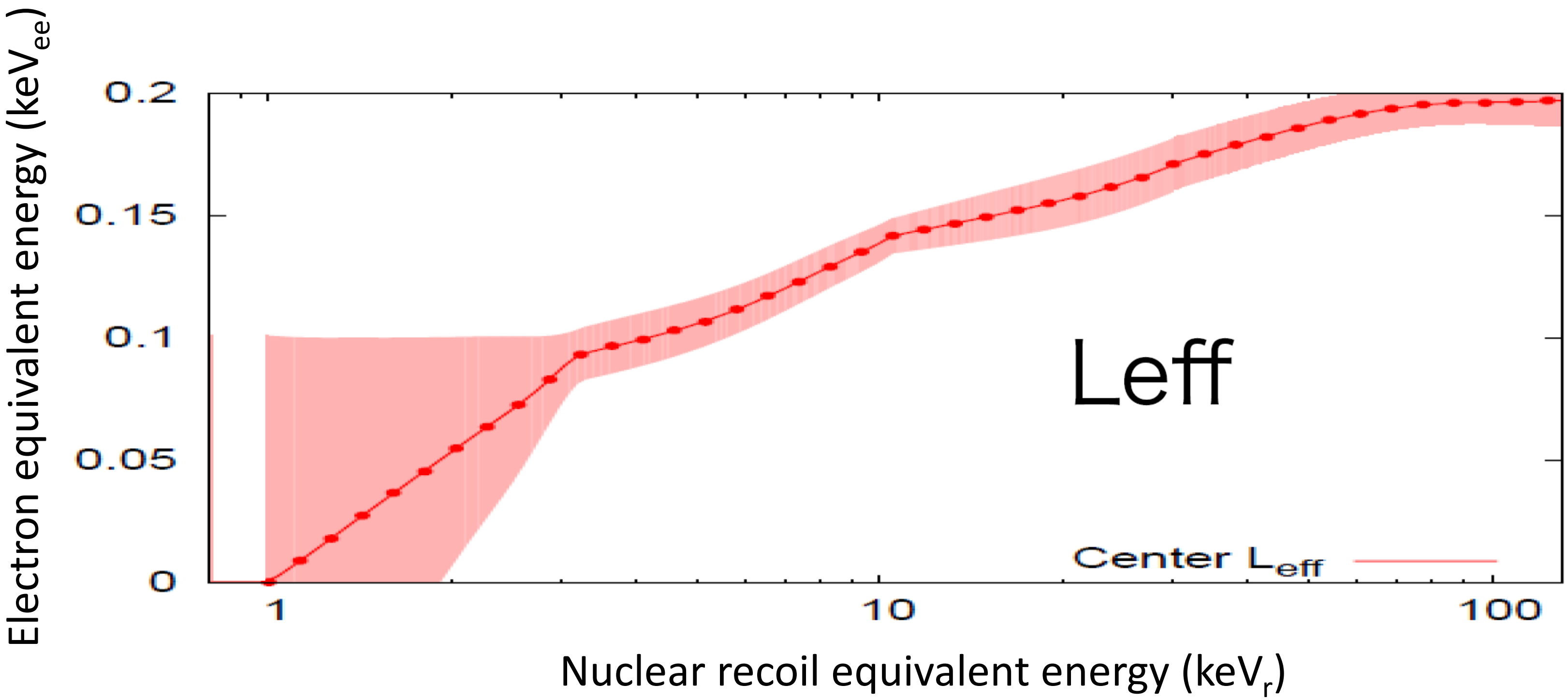
Two methods difference



Systematic error summary

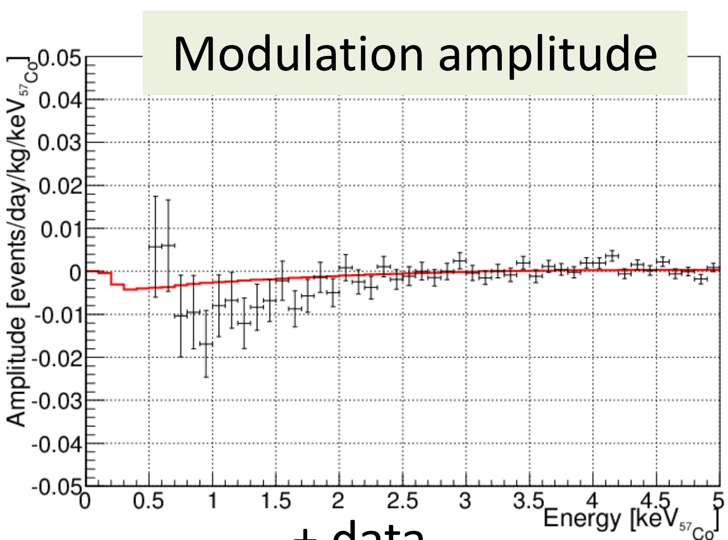
DAQ	PMT gain	<0.3*statistical error
	FADC reset	0.3%
	Timing	<0.2*statistical error
	Livetime	<0.02%
	threshold	0<0.022%
parameters	Escape velocity	Cross section: +10% at 8Gev/c^2, +5% at 20GeV/c^2 (544/650km/sec)
	Time variation	<0.15%
	Leff	30% at 10GeV/c^2
background	Muon	<<1%
	Radon in water	<10^{-5}dru 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)

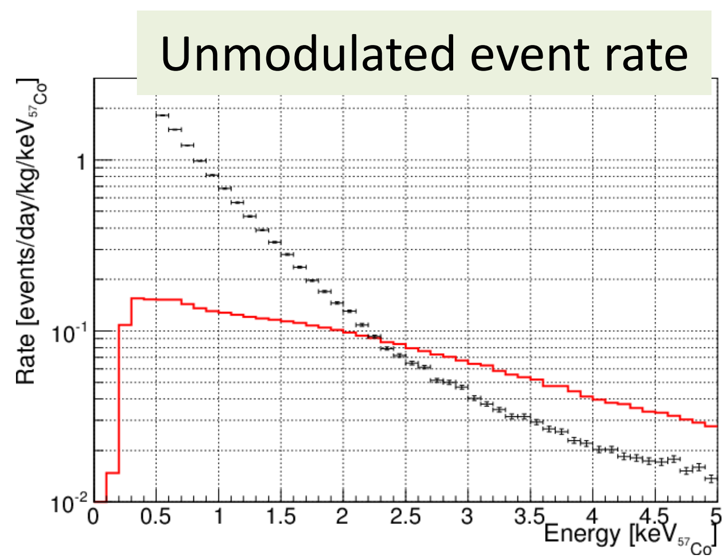
Leff uncertainty



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.

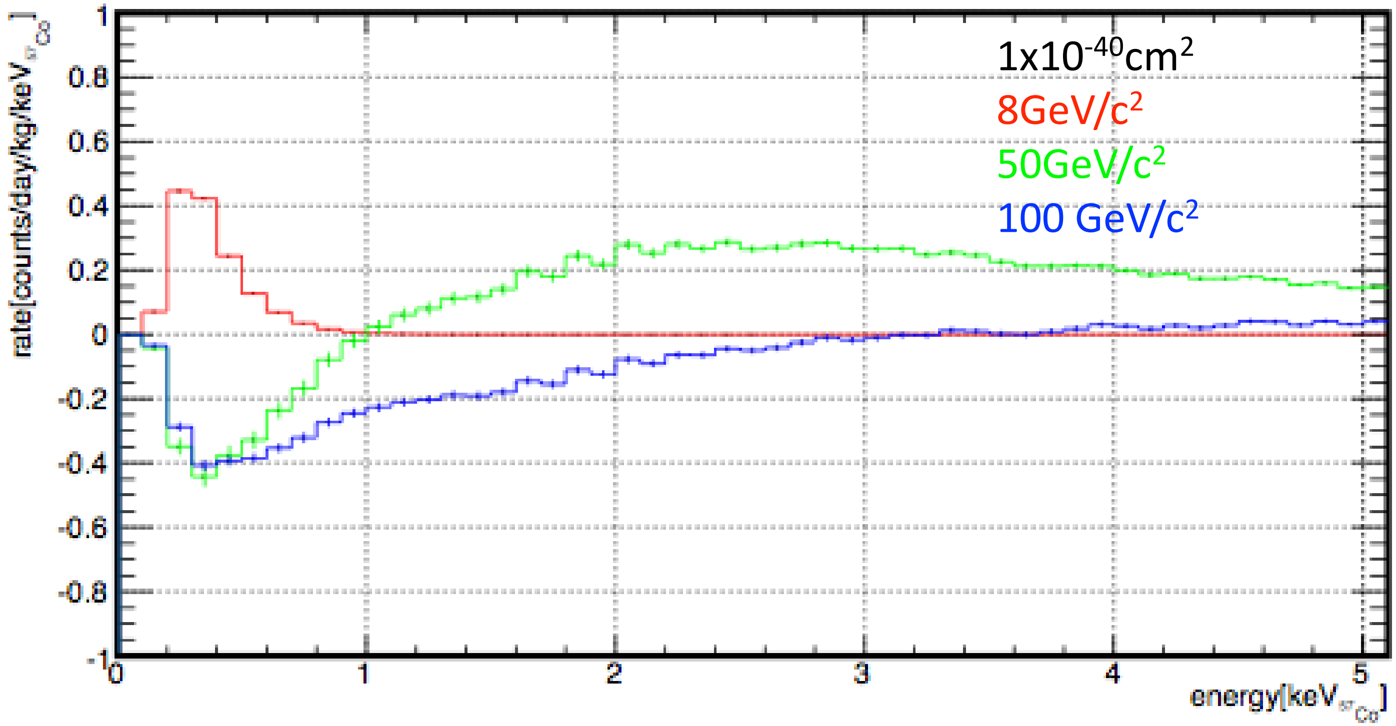




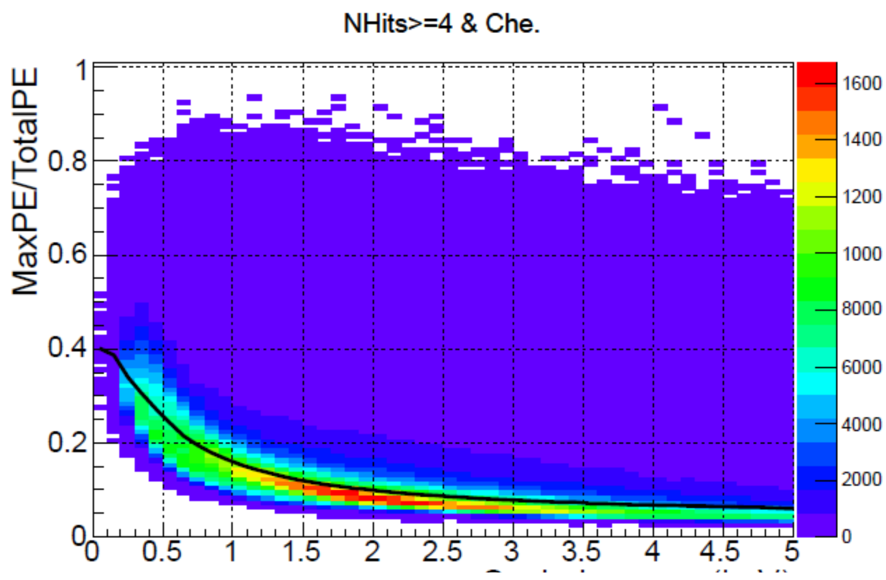
\+ data

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

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

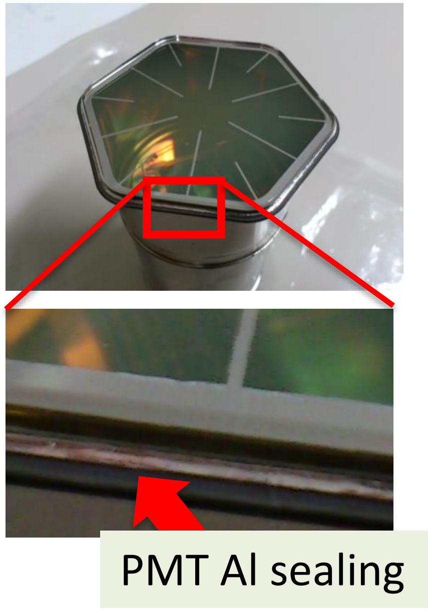


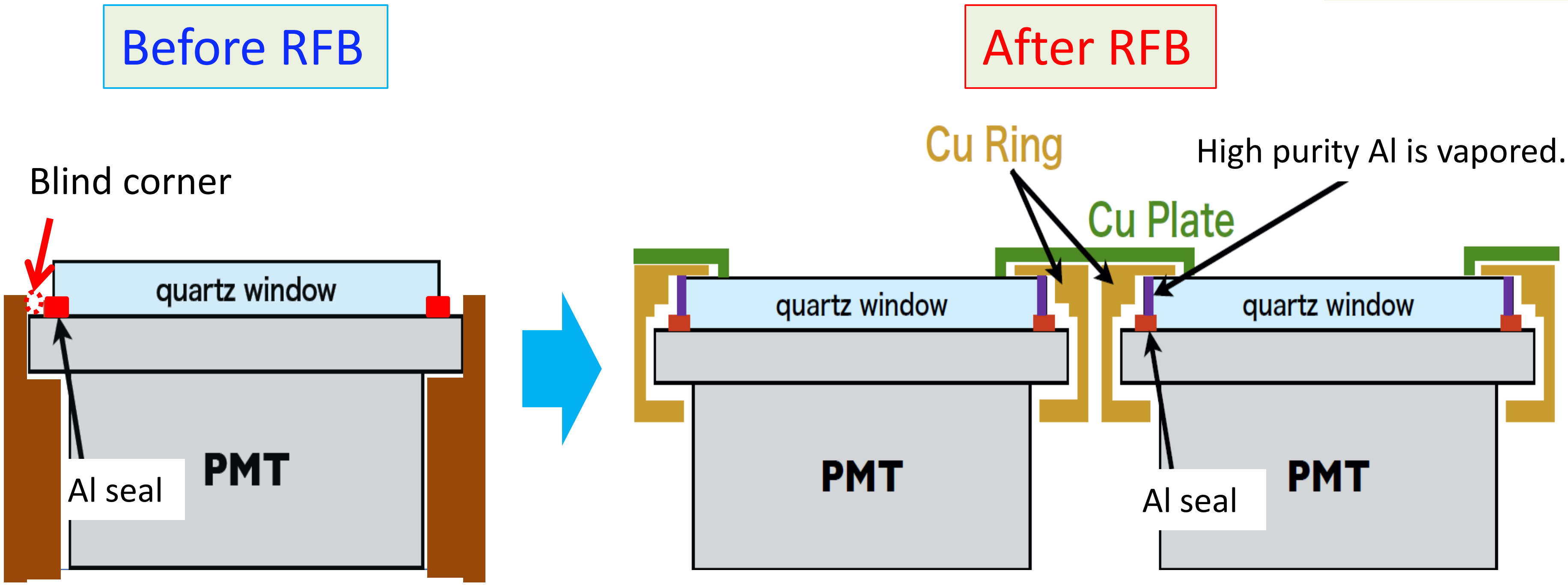
maxPE/totalPE (WIMP MC)



Detector refurbishment (RFB)

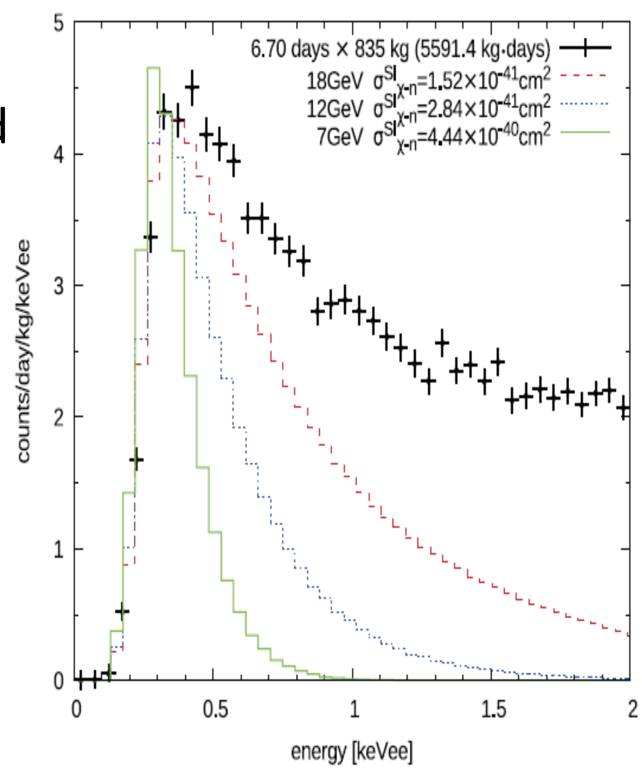
- We found RIs (210Pb, 238U) in the Aluminum sealing part of PMT (secular equiv. broken).
- Background events at the blind corner of PMT are often misidentified as events in the fiducial volume.
- To reduce this background, new structures to cover this Al seal were installed in 2012/2013.

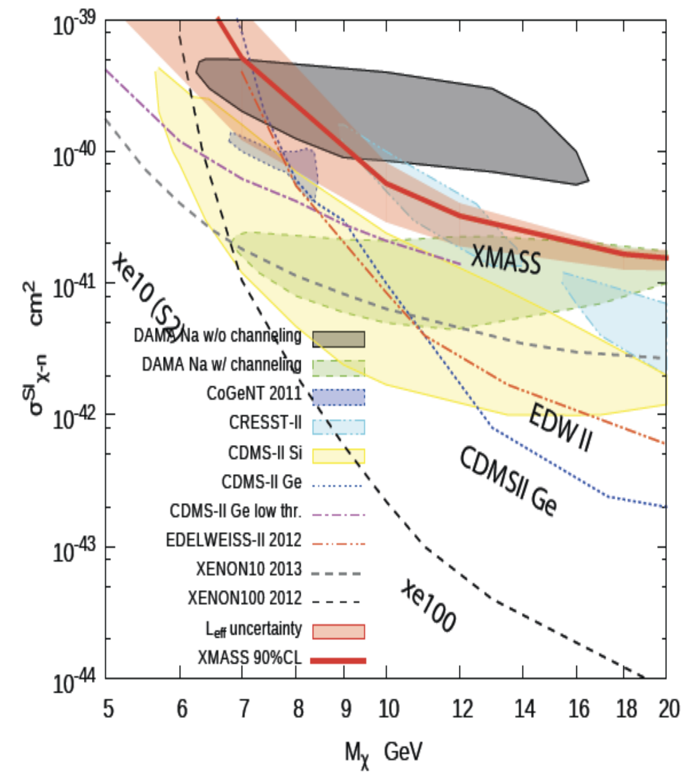




--- result from commissioning run ---
1. Search for light WIMPs

- 6.7 days x 835 kg
- 0.3 keVee threshold





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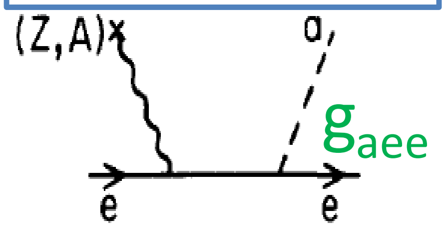
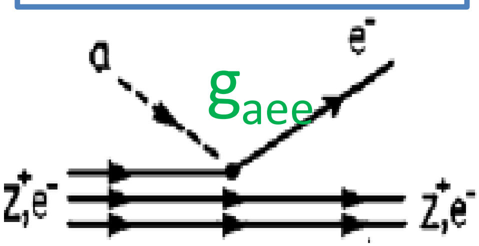
--- result from commissioning run ---
2. Search for solar axions

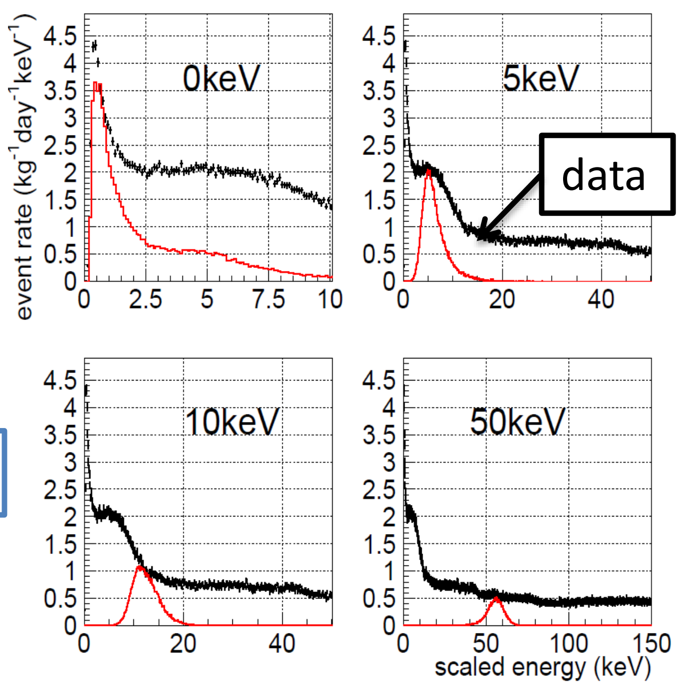
- Axions can be produced in the sun by bremsstrahlung and Compton effect, and detected by axio-electric effect in XMASS.
- Used the same data set as the light WIMPs search.

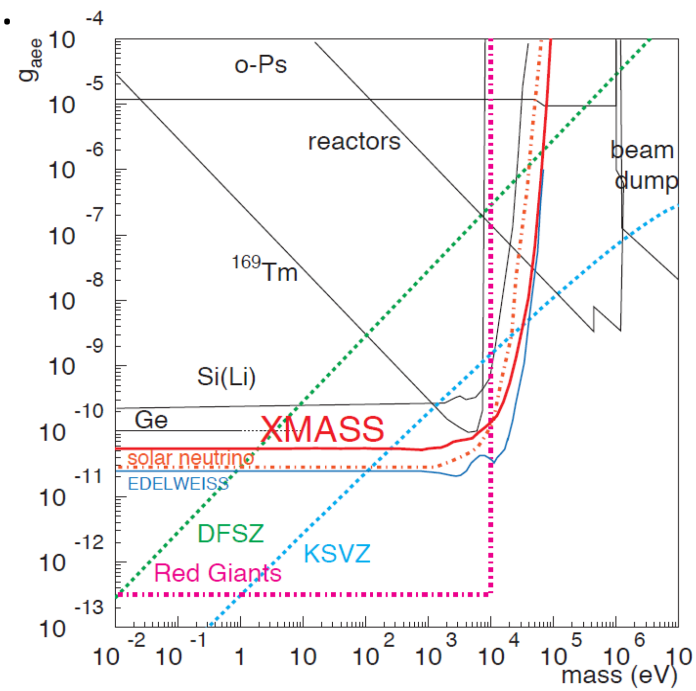
Bremsstrahlung and Compton effect



Axio-electric effect







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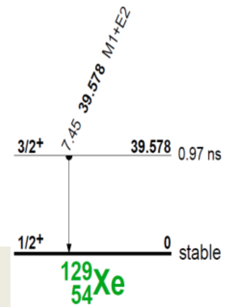
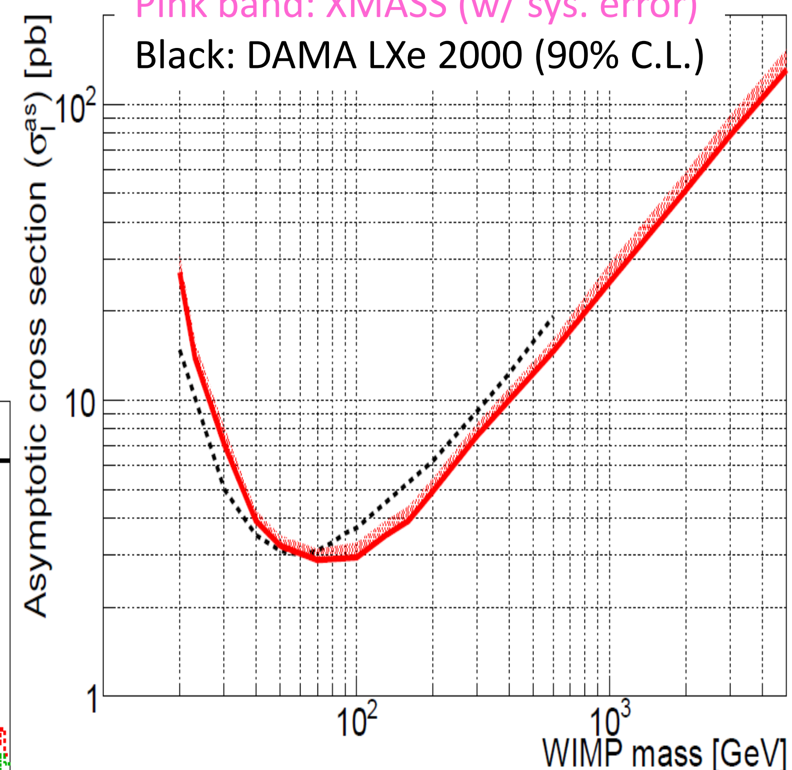
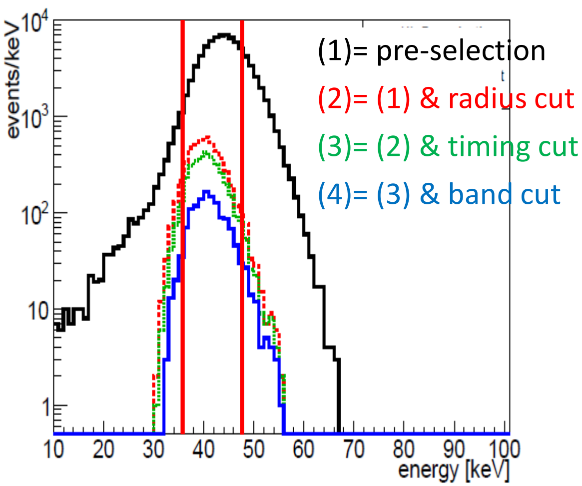
--- result from commissioning run ---
3. Search for ^{129}Xe inelastic scattering by WIMPs



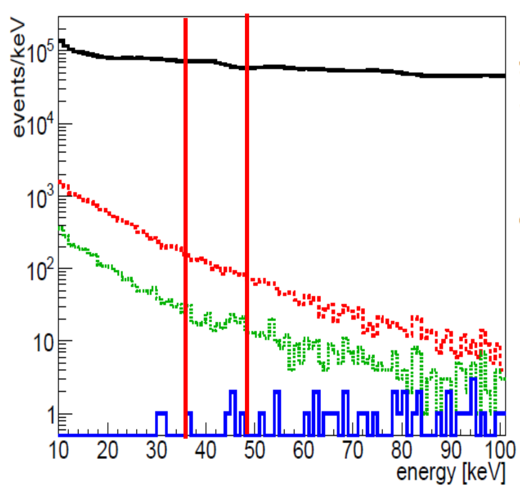
- $\chi + {}^{129}Xe \rightarrow \chi + {}^{129}Xe^*$
  $^{129}Xe^* \rightarrow {}^{129}Xe + \gamma$ (39.6keV)
- Natural abundance of ^{129}Xe: 26.4%



Signal MC for 50GeV WIMP



data (165.9 days)

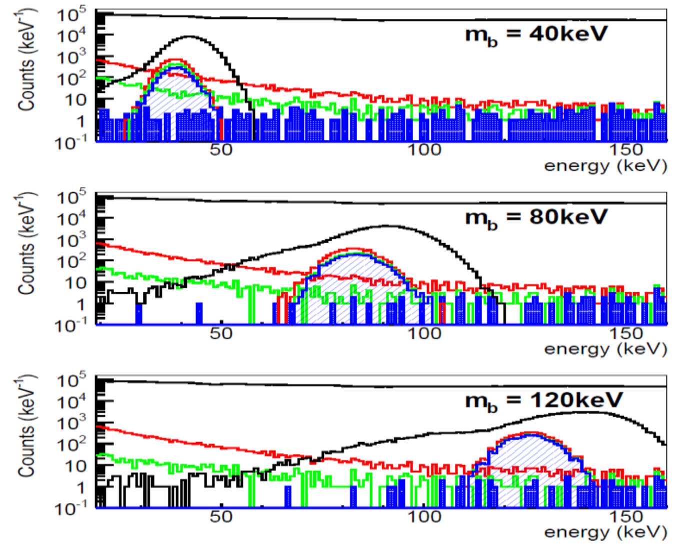


PTEP 063C01 (2014)

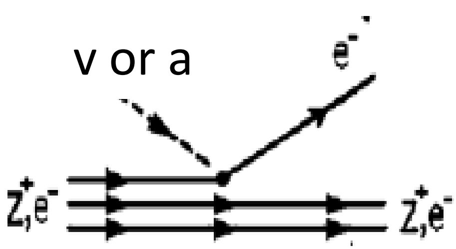
Background level is ~3x10^{-4}count/sec/kev/kg.

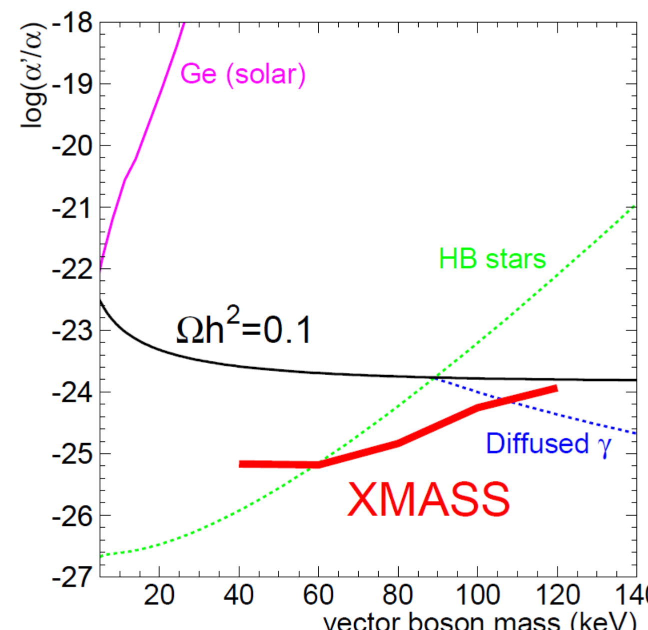
--- result from commissioning run ---

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





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