XMASS実験の現状と将来

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- Overview
- Current situation (XMASS phase I)
- XMASS 1.5
  - 1 ton fid volume
  - Intermediate stage of XMASS between phase I (100 kg fid. vol.) and phase II (10ton fid. vol.)

Physics Objectives of XMASS

Multi-purpose liq. Xenon detector

Y. Suzuki, hep-ph/0008296

- Final Goal: 10 ton fiducial mass, 25 ton total(2.5mϕ)
  - pp-solar neutrinos: ν+e → ν+e
  - Double beta decay $^{136}Xe \rightarrow {}^{136}Ba + 2e^-$
  - Dark Matter: χ+Xe → χ+Xe

➔ Phase-I (100 kg fid.): dedicated to a search for WIMPs (Weakly Interacting Massive Particles) dark matter
  - ***Search down to σ_{SI} ~ a few x 10^{-45} cm^2***
  - ***BG level in the fiducial volume: ~ 10^{-4} /kg/keV/day (dru)***

- XMASS1.5: 1 ton fiducial mass, 5 ton total(1.5mϕ)
  - Dedicated to Dark Matter

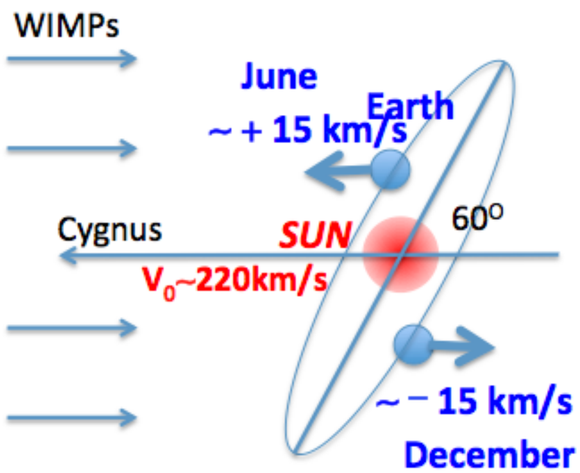
Galactic Dark Matter

- Isothermal Halo Model (Standard Halo Model)
  - with a Maxwellian velocity distribution
  - Typical Values:
    - v_0 = 220km/s, v_{esc} ~ 550km/s,
    - $<v_{DM}^2>$ = 270km/s, ρ_χ = 0.3 GeV/cm
- Seasonal variations (±15 km/s)

  < ~ 10% modulation effects

  (depend upon spectrum shape, trigger efficiency, analysis cuts….)
- Detect Nuclear Recoils: $\chi + N \rightarrow \chi + N$

$$f(v)dv = \frac{4\pi v^2}{(v_0^2\pi)^{\frac{3}{2}}} e^{-\frac{v^2}{v_0^2}} dv$$

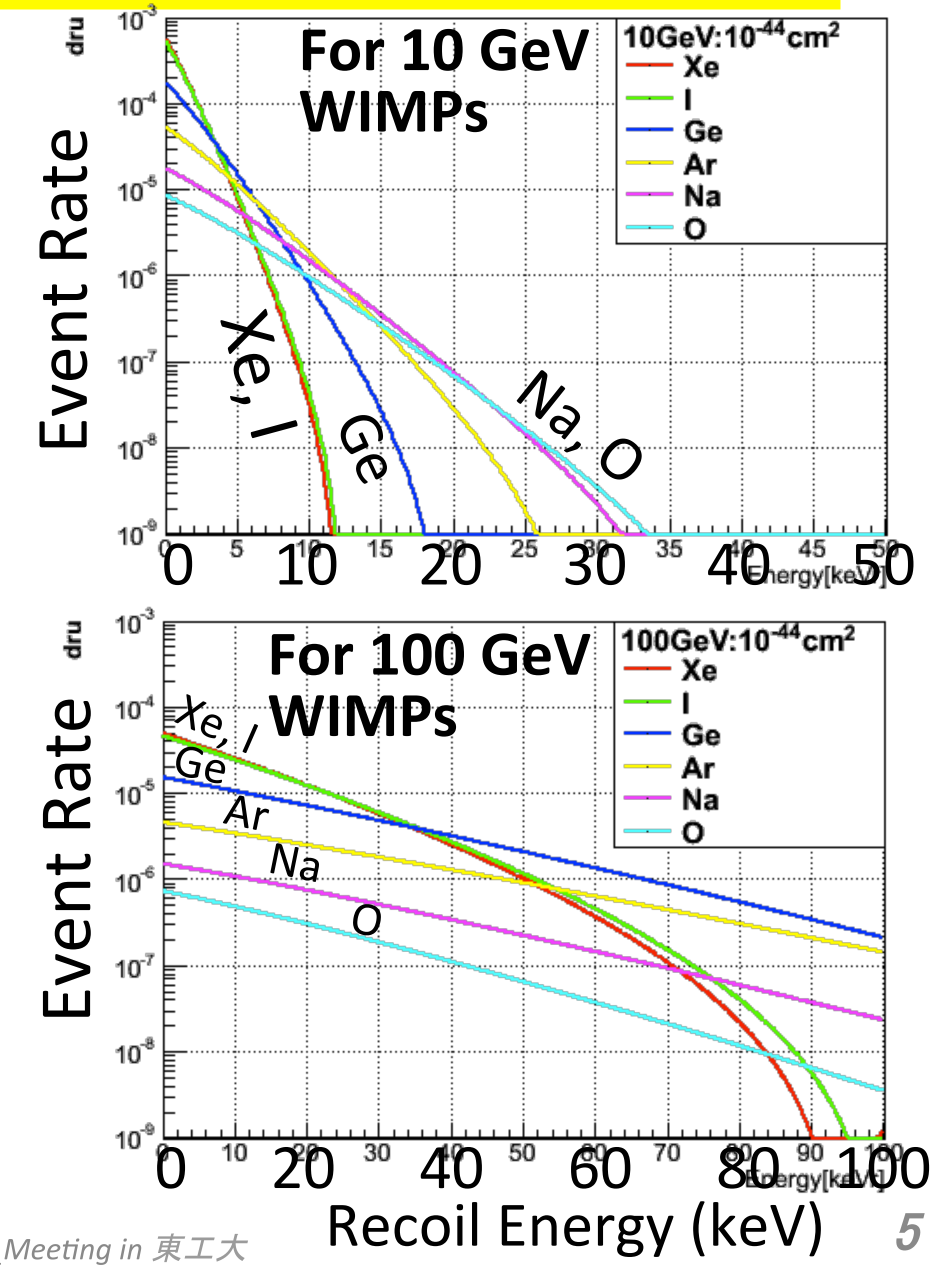


$$R \sim n_t \times \sigma_{\chi N} \times (\frac{\rho_\chi}{M_\chi}) \times \int v f(\vec{v}) d\vec{v}^3$$

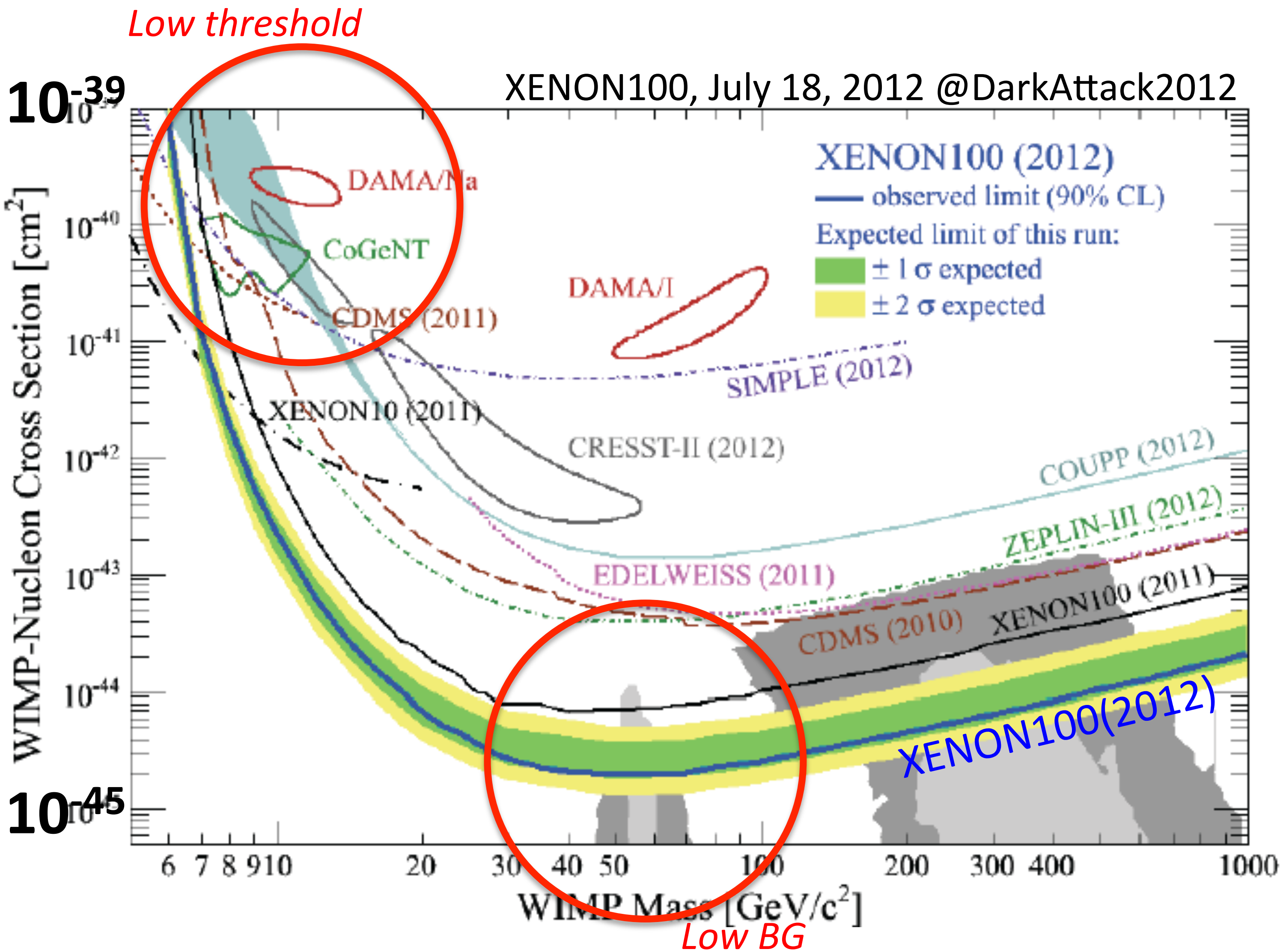
$$\sigma_{\chi N} = \sigma_{\chi N}^{SI} + \sigma_{\chi N}^{SD}$$

Signal

- Event rate:
  - ~ 0.1 ev/day/100kg-Xenon for m_χ = 50 GeV and $\sigma_{SI}=10^{-44}$ cm^2
- Recoil Energy:
  - Kinetic energy of DM: $\beta\sim10^{-3}$
  - E_R (Typical)~ 50 keV_{NR} for m_χ=100 GeV
- For low mass DM, spectrum become very soft for large target masses like Xe, Ge,…



Current Experimental Situation



Liquid Xenon

- Atomic Number (Z=54)
  - Good for a few 10s to 100 GeV MIMPs search
- High density (ρ=3g/cm^3)
  - Compact detector
- Can use scintillation and ionization (TPC)
  - XMASS uses only scintillation light
- Purification
  - Many methods in gas and liquid phase
- Study Spin dependence (option)

  ← Easier isotope separation (odd $ even)

ββ-decay

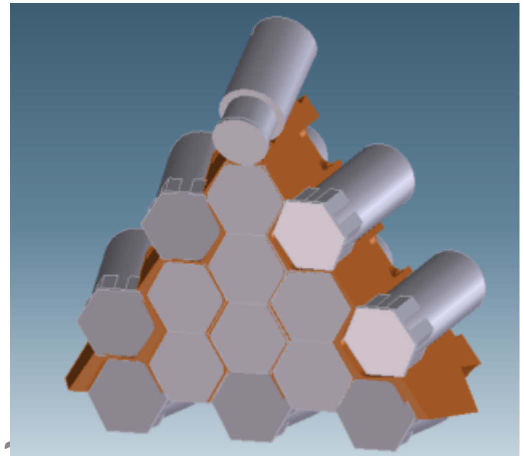
^{124}Xe	^{126}Xe	^{128}Xe	^{129}Xe	^{130}Xe	^{131}Xe	^{132}Xe	^{134}Xe	^{136}Xe
(0.10%)	(0.09%)	(1.92%)	(26.4%)	(4.07%)	(21.2%)	(26.9%)	(10.4%)	(8.87%)

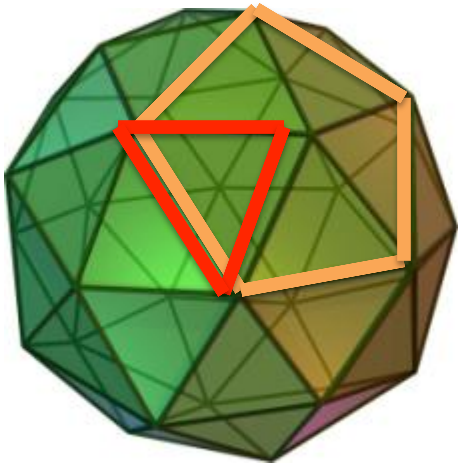
Mostly Odd | **Mostly Even**

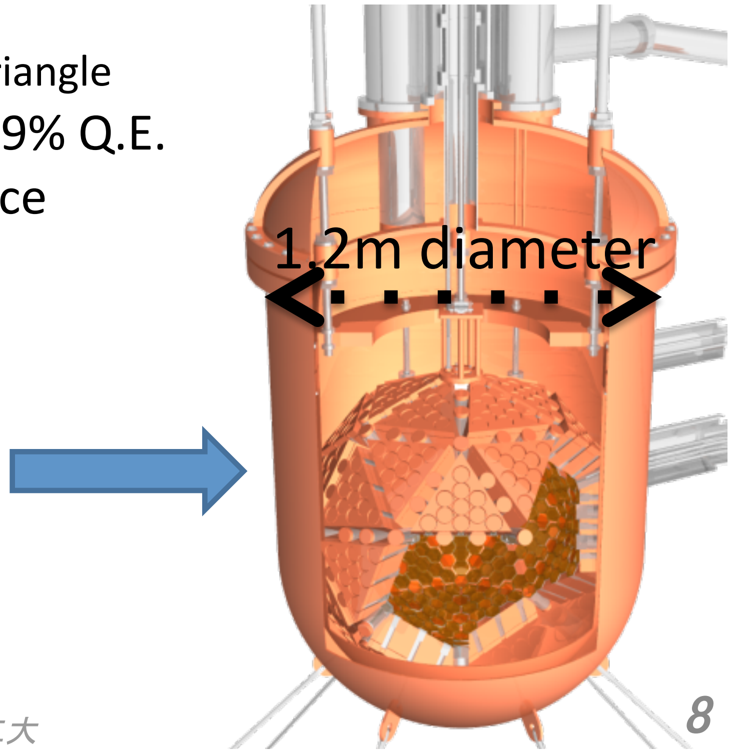
The phase-I XMASS detector

- Detector
  - Single phase (scintillation only) liquid Xenon detector
  - Operated at -100ºC and ~0.065MPa
  - 100 kg fid. mass, [835 kg inner mass (0.8 mϕ)]
  - Pentakis-dodecahedron

    ← 12 pentagonal pyramids: Each pyramid ← 5 triangle
  - 630 hexagonal & 12 round PMTs with 28-39% Q.E.
  - photocathode coverage: > 62% inner surface

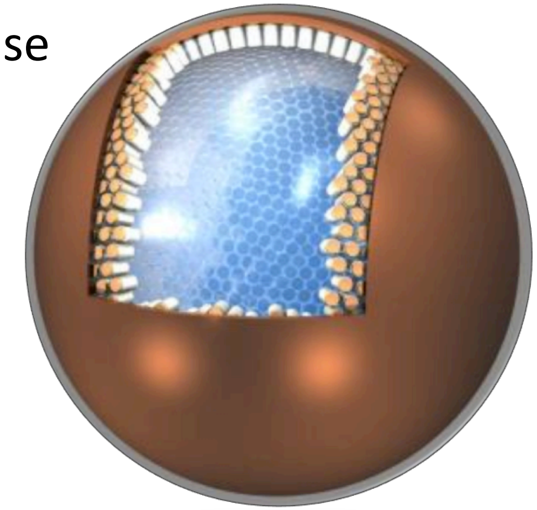


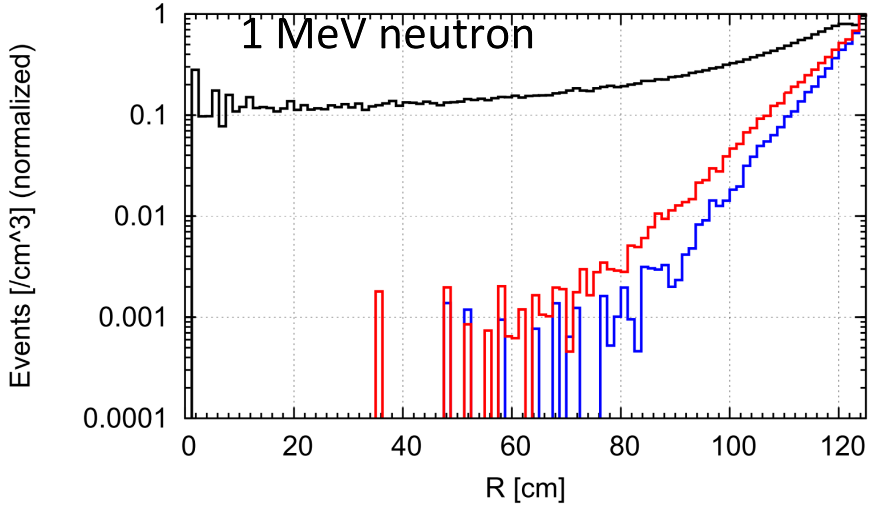




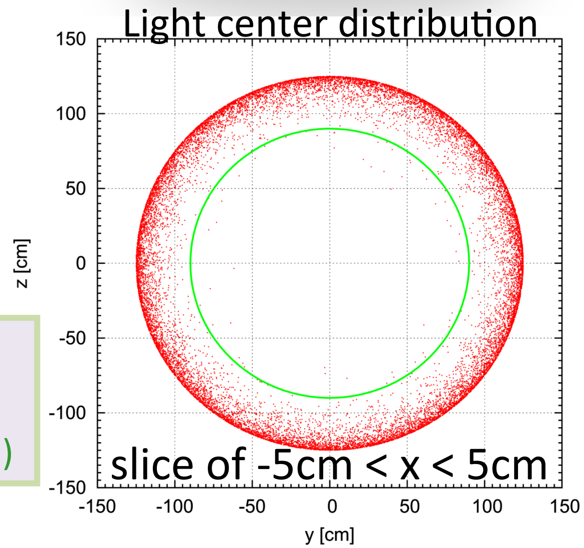
Characteristics
Why single phase

- XMASS is a new type of detector
  - Single phase (suited for a large detector) ⇔ Double phase
    Background rejection through S2/S1: ~10^2~10^3
- Sensitive also electron/γ events
- Large volume and BG less fiducial volume inside
  - Large self-shielding effect
  - Eventual neutron BG rejection
- Large Scalability, simple to construct and operate
- High light yields & Large photon coverage (15 pe/keV)
  - Low energy threshold (< 5 keVee ~ 25 keVNR) for fiducial volume
  - Lower energy threshold: 0.3 keV for whole volume





Black: all events
Blue: 2 < E(keVee) < 5 keV
Red: 2 < E(keVee) < 10 keV
Green: F.V. (30cm from wall)



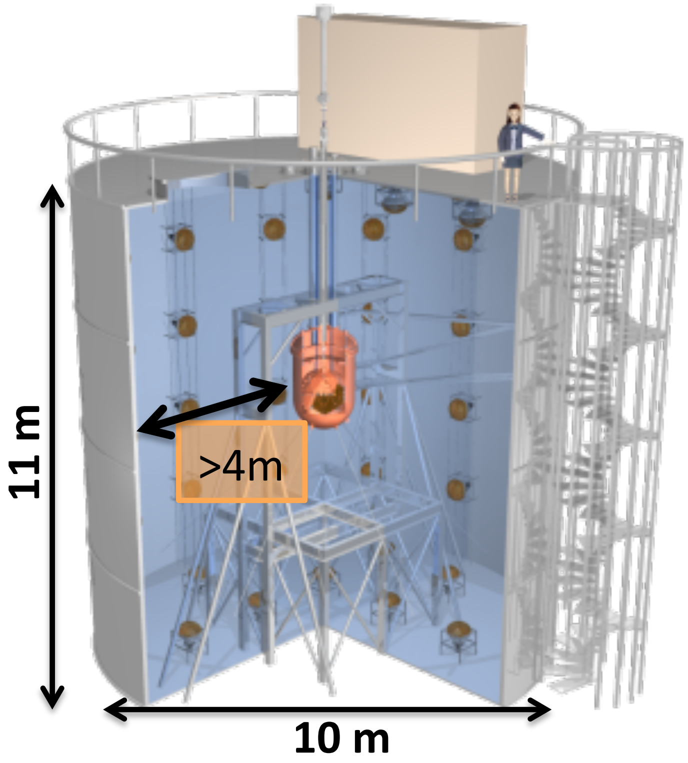
Efforts to reduce BG in advance

Backgrounds are crucial for a single phase detector

External Backgrounds

- XMASS detector was placed in the 800 ton water tank
  - First experiment to use a Water Tank
  - Active: 72 20" PMTs
  - Giving > 4m water shields
  - γ: 10^3 reduction by 2m (smaller than PMT BG)
  - n << 10^{-4}/d/kg (by 2m)
- Screening of the materials
  - we have measured ~250 parts by HP Ge detector.

    (smaller than PMT BG)



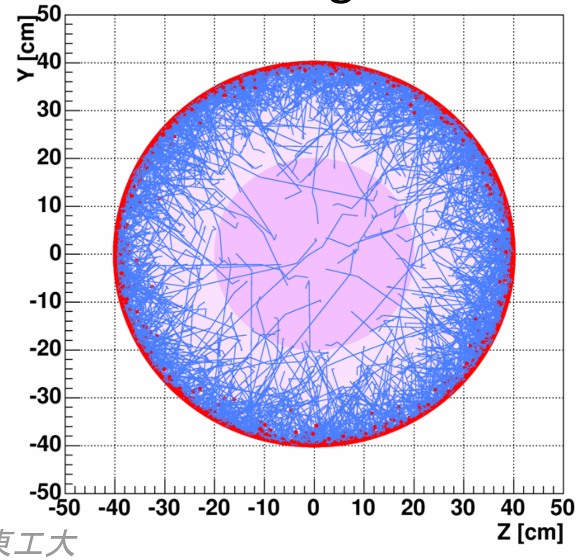
Efforts to reduce BG in advance

External Backgrounds

- Development of low BG PMTs
  - 1/100 BG of regular PMT
  - + Self-Shielding effect
    - $\gamma_{BG} < 10^{-4}$ /keV/day/kg

	BG/PMT with base parts
U chain	0.70 ± 0.28 mBq
Th chain	1.5 ± 0.31 mBq
40K	< 5.1 mBq
60Co	2.9 ± 0.16 mBq

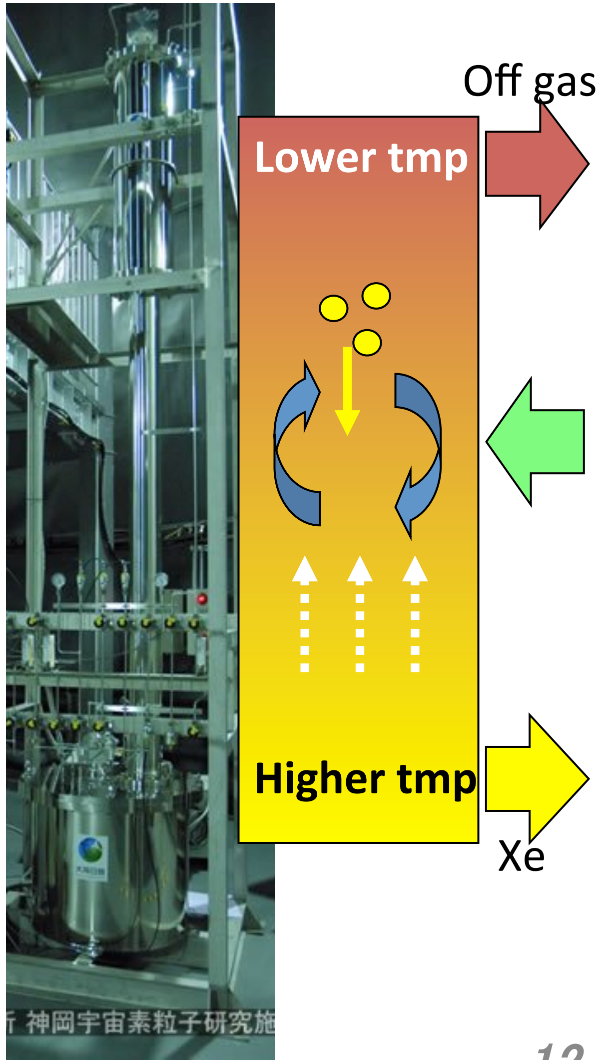
Self shielding effect



Efforts to reduce BG in advance

Internal Backgrounds

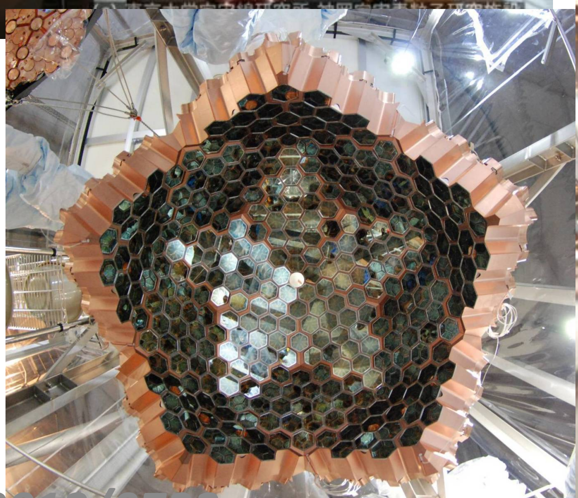
- Distillation to remove Kr (^{85}Kr (Q_β = 687 keV))
  - Kr has lower boiling point than Xe
  - Distillation was done: 10 days before filling into the detector (~ 1 ton)
- Charcoal for Rn deduction
  - target value
    - ^{222}Rn: target 1.0mBq for 835 kg inner volume
    - ^{220}Rn: target 0.43mBq for 835 kg inner volume
- Prepared liq. phase circulation (a few litter-LXe/min) to remove contamination: not used yet

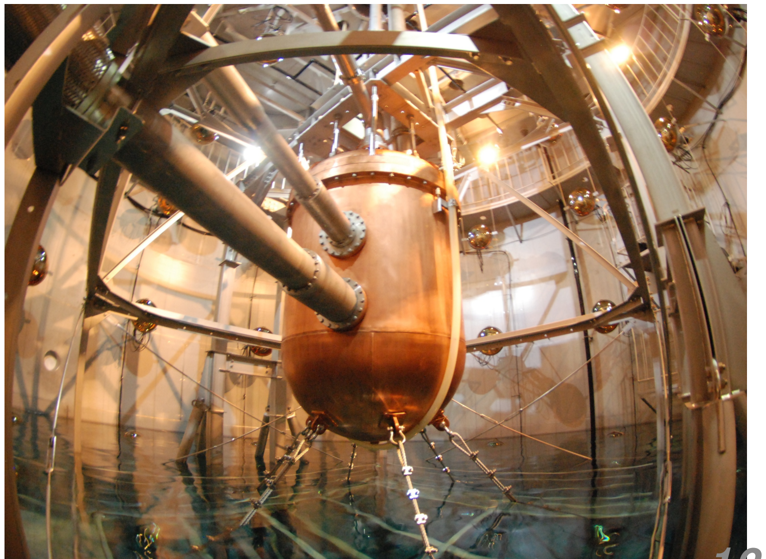


Detector Construction

- 2009.11: PMT holder and PMT installation

- 2010.09: Construction Completed

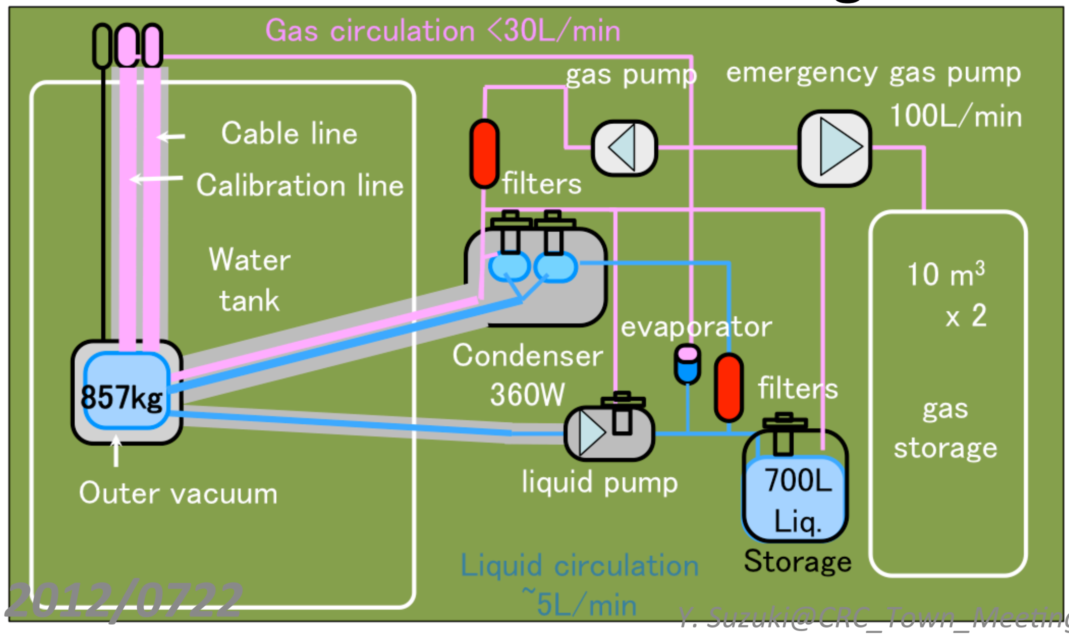




Xe filling

- Evacuation and Baking
- 2010.10.16 Test filing 100kg
- 2010.10.16 Xe Collection
- 2010.10.24 1st Filling 1129kg
- 2010.10.26 Xe Collection
- 2010.10.31 2nd filling 1065kg

Recover Xe as in a liquid phase to clean up the inside of the detector

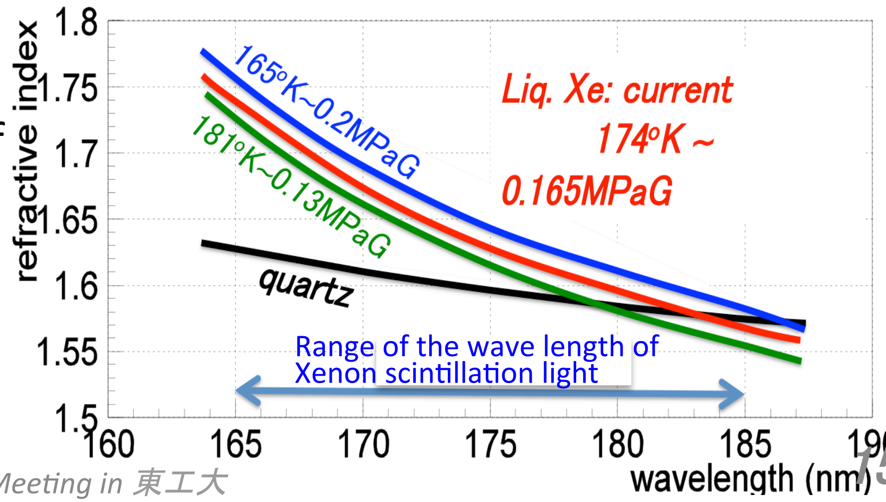


- 2011.01.21 Xe Collection for the work to fix the stacked calibration rod
- 2011.01.31 3rd filling 1085kg

Commissioning run

- Calibration
  - Source Rod (57Co, 241Am, 137Cs, 109Cd, 55Fe)
  - External sources: 60Co, 137Cs, 232Th, Neutron
- Normal Data taking (physics runs)
- Development of Software
- Change of the physical condition of Xenon.
  - High/Low pressure run
    - Change of the refractive index of Xe
  - O2 runs: change of the absorption length
  - Boiling runs: create convection inside of the detector

- Gas run
  - Important to identify the surface BG
- BG measurement of the detector parts（attach the material at the end of the calibration source rod）
  Al, GORE-TEX, Cu, Ni plate



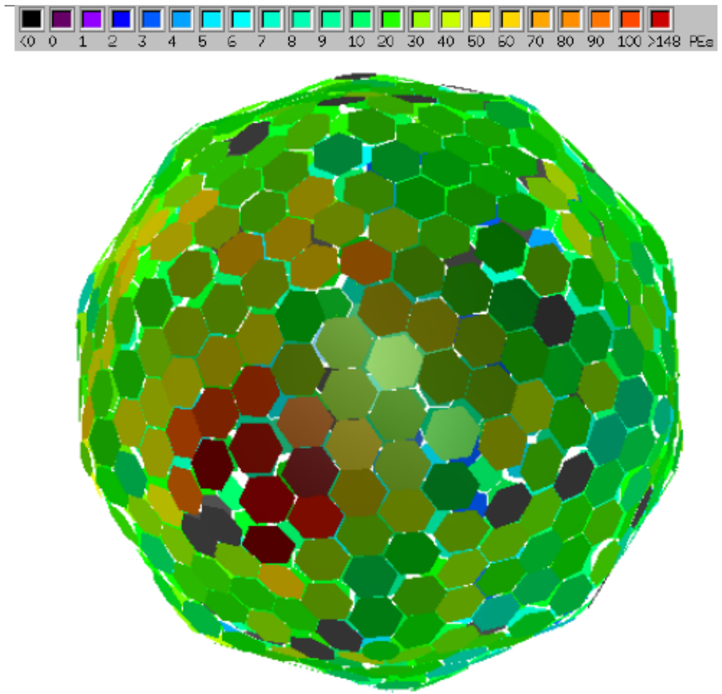
Commissioning run

Year	Month	Activity	Run	Electronics
2010	12			
2011	01	3rd Xe filling		◎ ATM (Old SK Elc (ADC/TDC)) ➔
	02			
	03		**Low Pressure Run**	◎ FADC (60 channels)
	04		**High Pressure Run**	(using 10~12 PMT sum) ➔
	05	Xe Collection		
	06	4th Xe filling	**Gas Run**	
	07			
	08			
	09	Add 1ppm O2	**O2 Run (add O2 1ppm) started**	
	10			
	11			
	12		**O2 Run ended** and Boiling **run**	
2012	01	Xe collection	Remove O2	
	02	5th Xe filling	**Gas Run**	
	03			
	04			◎ FADC (642 individual channels) ➔
	05	Calibration rod falled and stack		
	06	Xe collection		
	07			

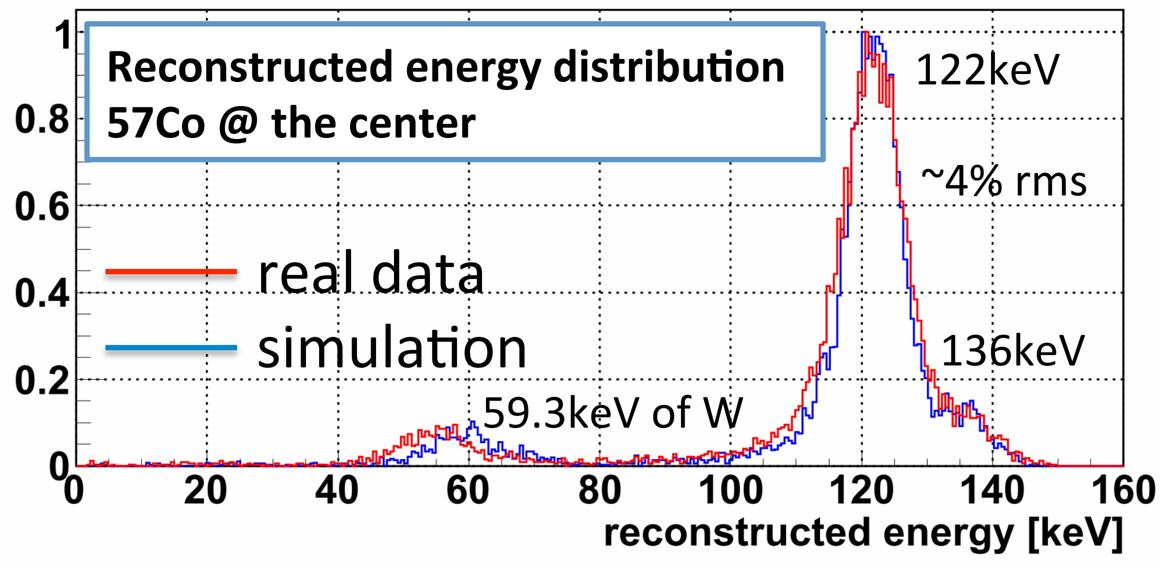
Now XMASS is empty and ready for refurbishment

Event Reconstruction

- Pattern and detected photoelectron based event reconstruction
  - Grids in the detector
    - Make expected pe for each PMTs
  - Look for a vertex grid to have a maximum likelihood.
  - Energy is also reconstructed for the vertex position
  - Likelihood to evaluate the goodness of fit
  - Works for E > 2~5 KeV
- Leakage of the reconstructed vertex into the fiducial volume
  - Under the evaluation



Energy Calibration

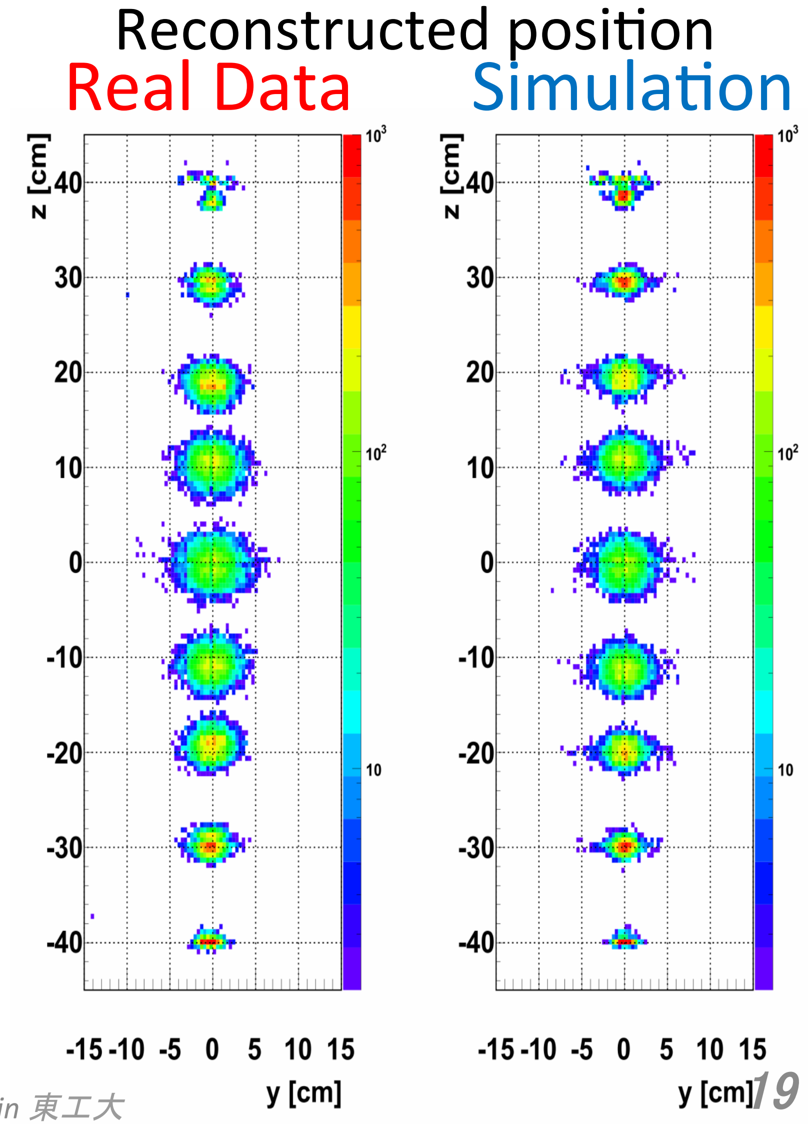


- Energy resolution for ^{57}Co (122keV, γ-rays)
  - 4% rms
- High p.e. yield: 14.7±1.2 pe/keV

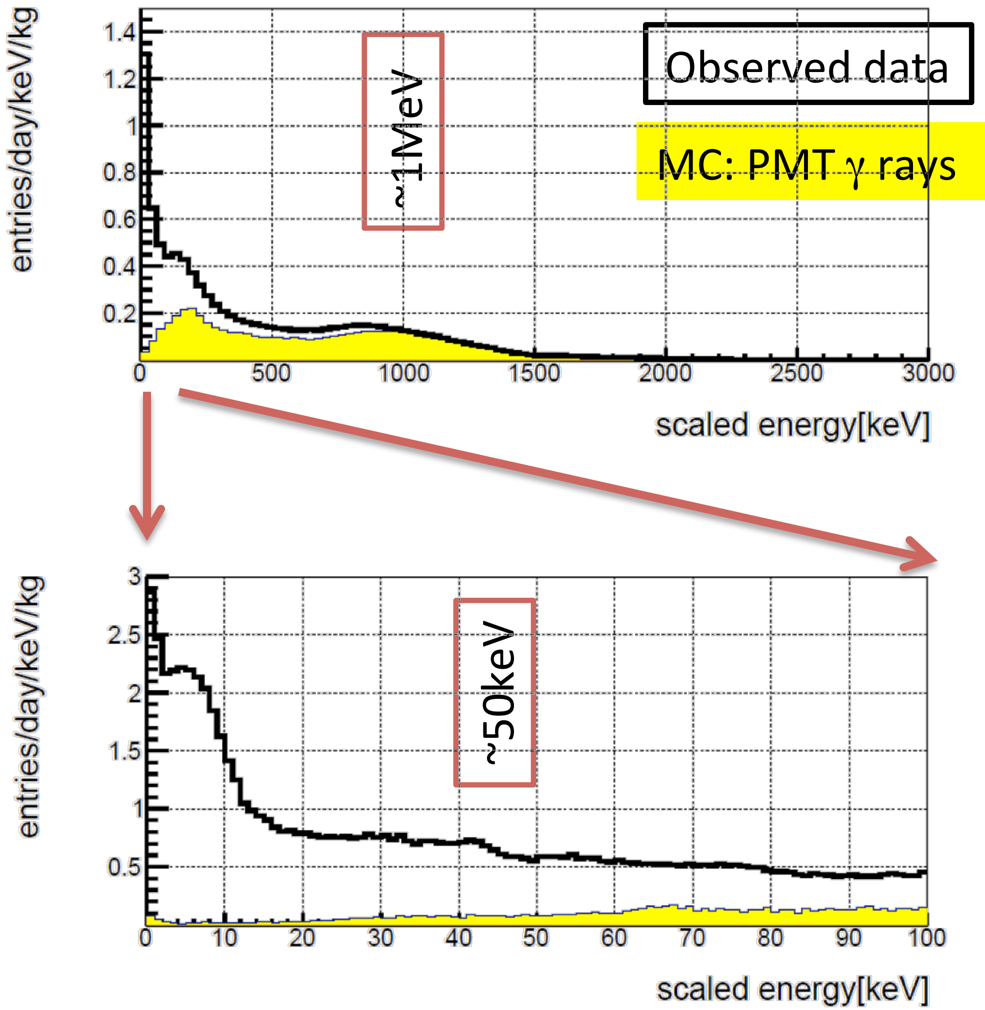
  ⇔ 2.2pe for XENON100

Vertex reconstruction

- Position Resolution for ^{57}Co (122keV γ rays)
  - 1.4 cm rms (0cm: center)
    1 cm rms (±20cm)



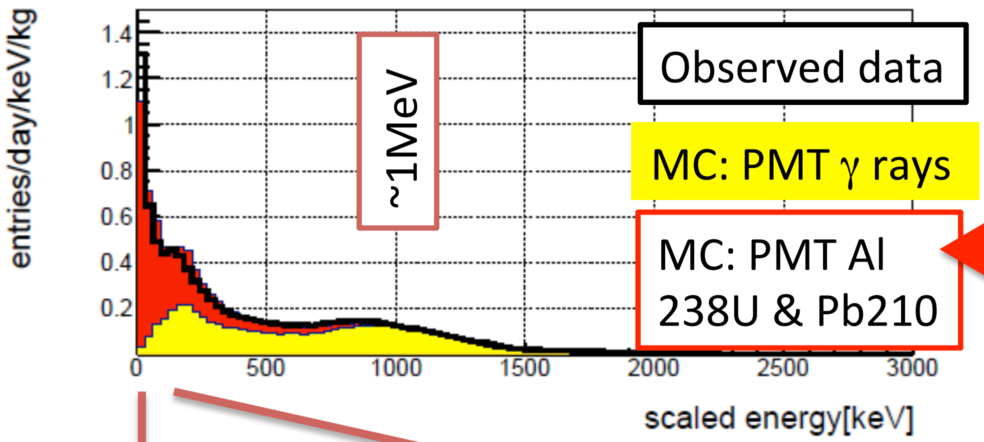
Measured Spectrum (Whole Volume)
Unexpected backgrounds

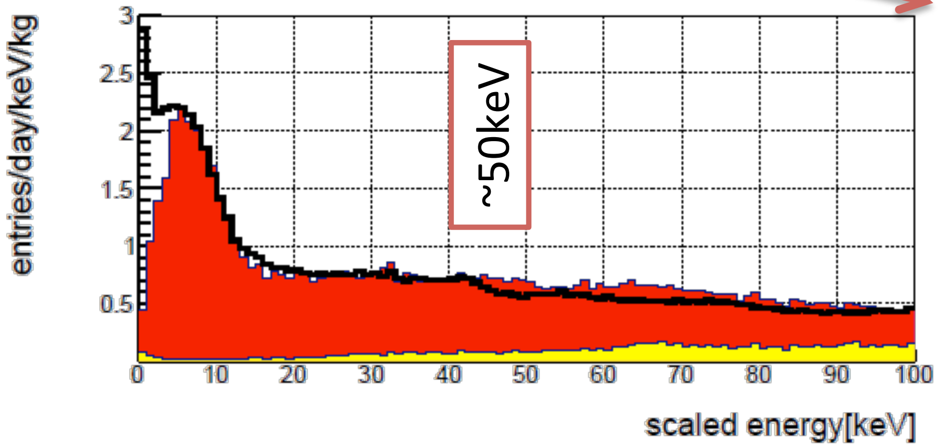


- We anticipated that the most backgrounds come from PMT γ (Measured by Ge detector)

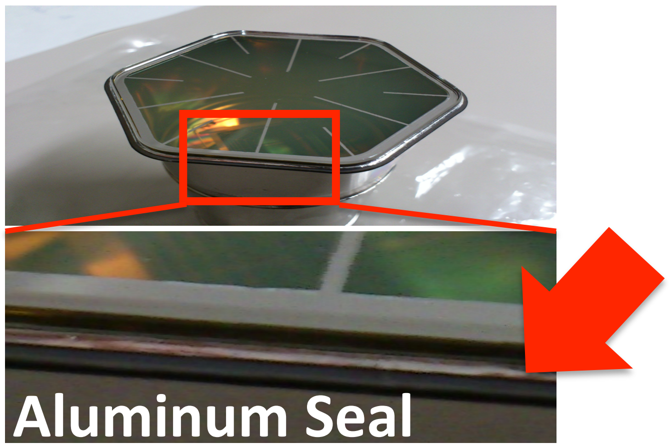
  (shown by yellow)
- But we found unexpected BG which dominates below 100~200 keV.

Measured Spectrum (Whole Volume)
Unexpected backgrounds

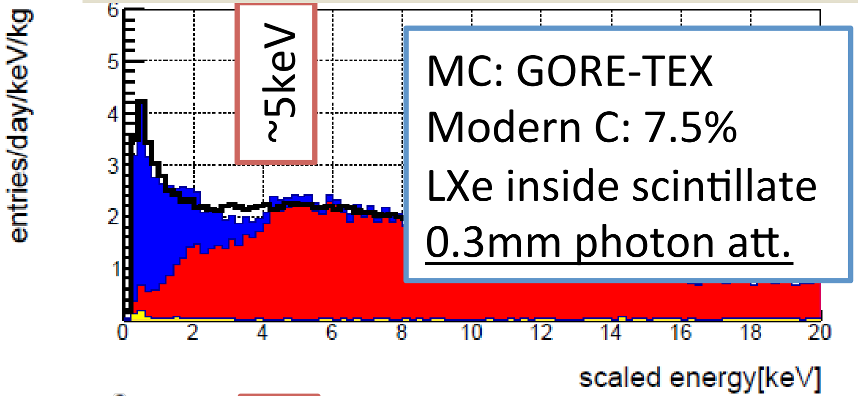


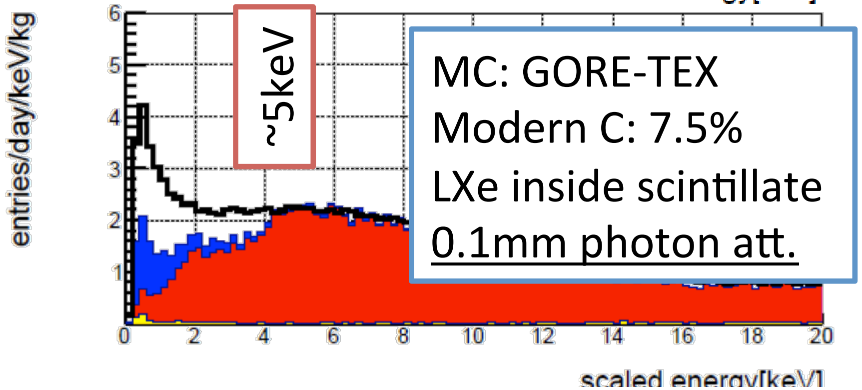


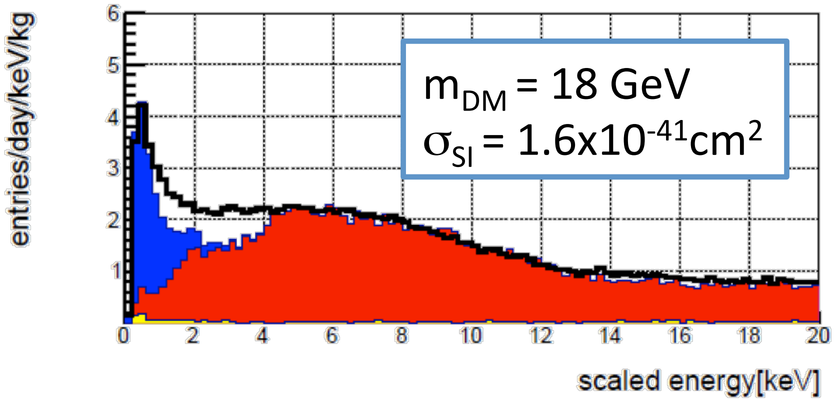
- Suspected detector parts were examined again, and found
  - Aluminum sealing used for the PMT between quarts window and metal body contains ^{238}U and ^{210}Pb
  - ^{210}Pb on surface

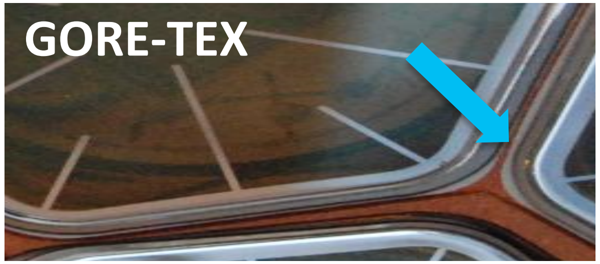


Measured Spectrum (Whole Volume)
Unexpected backgrounds below 5 keV







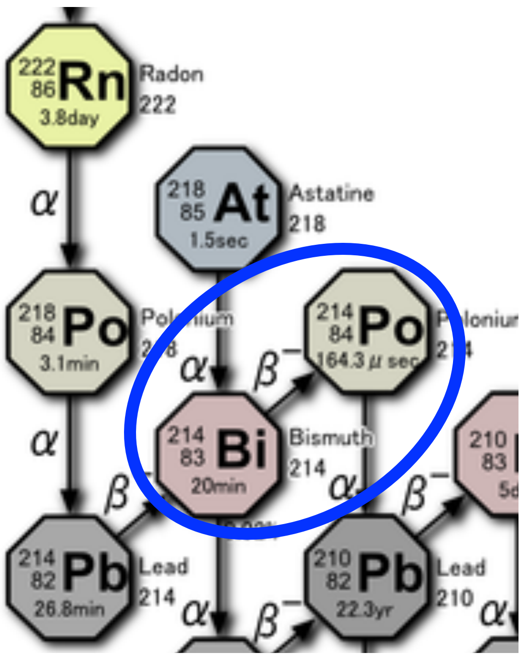


- GORE-TEX: between PMT and holder used for a light seal contains 0~6±3% of modern carbon
- Understudy
  - GORE-TEX might explain
    - But parameters (ex. transparency of light inside of GORE-TEX) are not well known
    - We will remove GORE-TEX in future detector refurbishment
- There may be unidentified sources of BG or something else.

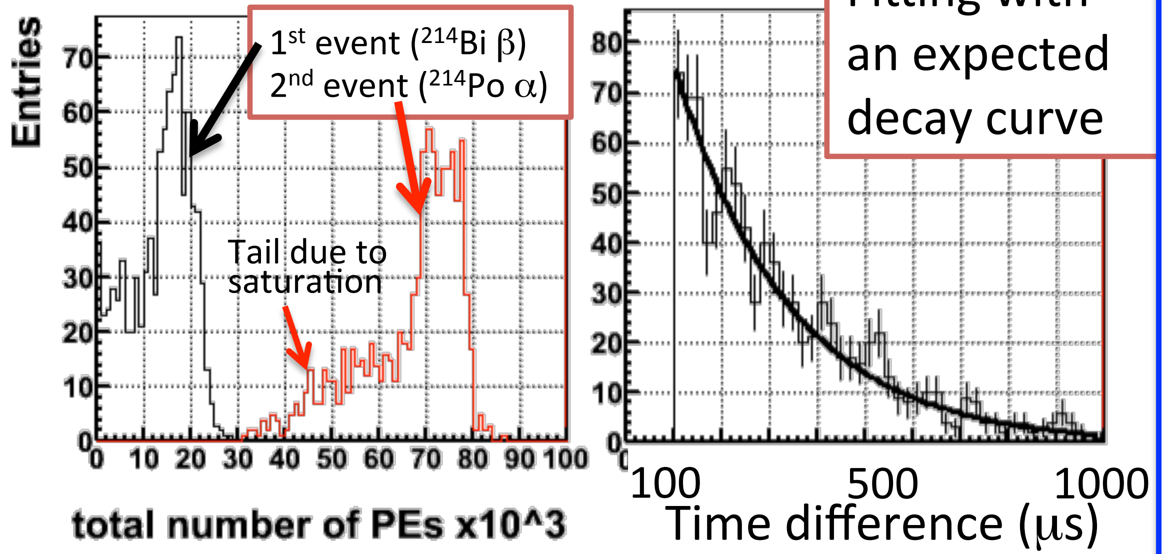
Background estimates

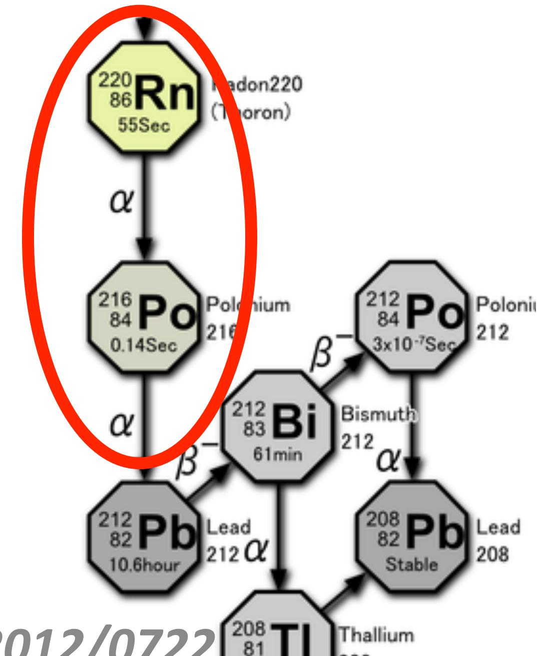
Material	Measured RI and activity	Methods of the measurements
PMTs (per PMT)	238U: 0.704 ± 0.282 mBq 232Th: 1.51 ± 0.31 mBq 60Co: 2.92 ± 0.16 mBq 40K: 9.10 ± 2.15 mBq	HPGe detector measurement for each parts and whole PMT
PMT aluminum (210g)	238U-230Th: 1.5 ± 0.4 Bq 210Pb: 5.6 ± 2.3 Bq 232Th: 96 ± 18 mBq 235U: ~67 mBq	HPGe detector measurement. → By calculation
Detector surface	210Pb: ~40 mBq	Alpha candidates using FADC data Surface: PMT window 59%, PMT Al 7.0% PMT rim 7.0%, GORETEX 3.7%, Cu 23.3% (surface 7.8%, wall 14.2%, bottom 1.3%)
GORE-TEX for PMTs (120g)	14C: 0.4 ± 0.2 Bq (6±3% of modern carbon) 210Pb: 26.5 ± 11.9 mBq	14C: modern carbon measurement. 210Pb: Ge measurement.
Internal RI in xenon	85Kr: <2.7 ppt 214Pb: 7.1 mBq	85Kr : API-MS measurement 214Pb : ~222Rn concentration in detector

Internal BG (Rn)



- ^{222}Rn: Identify ^{214}Bi → ^{214}Po → ^{210}Pb decays
  - ^{214} Po decays with 164 μs half life
  - β and α coincidence
  - 8.2±0.5mBq in the inner volume



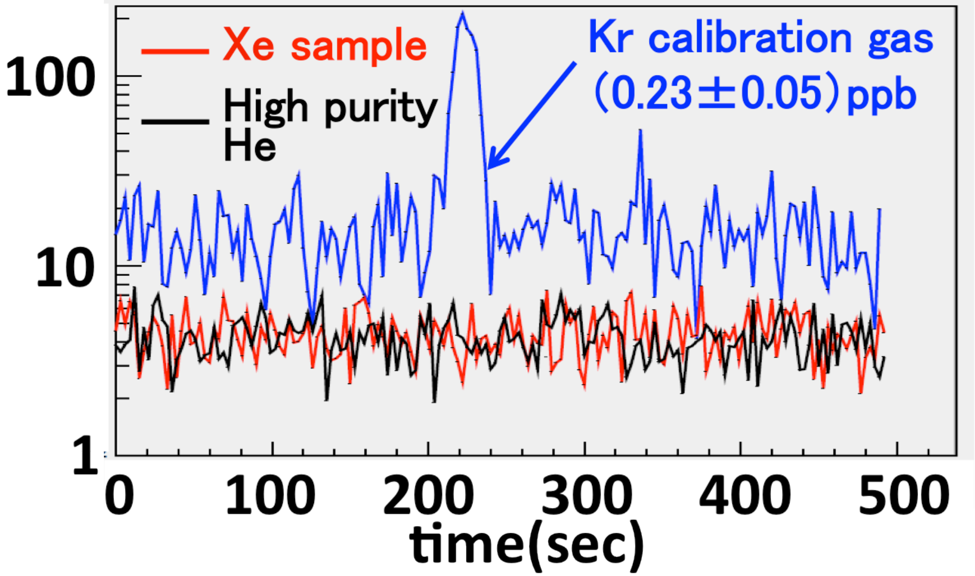


- ^{220}Rn: Identify ^{220}Rn → ^{216}Po → ^{212}Pb decays
  - ^{216}Po decays with 0.14sec half life
  - two α's with short coincidence
  - Upper limit <0.28mBq (90%C.L.)

^{85}Kr

API-MS

Kr < 2.7ppt, goal: 2ppt

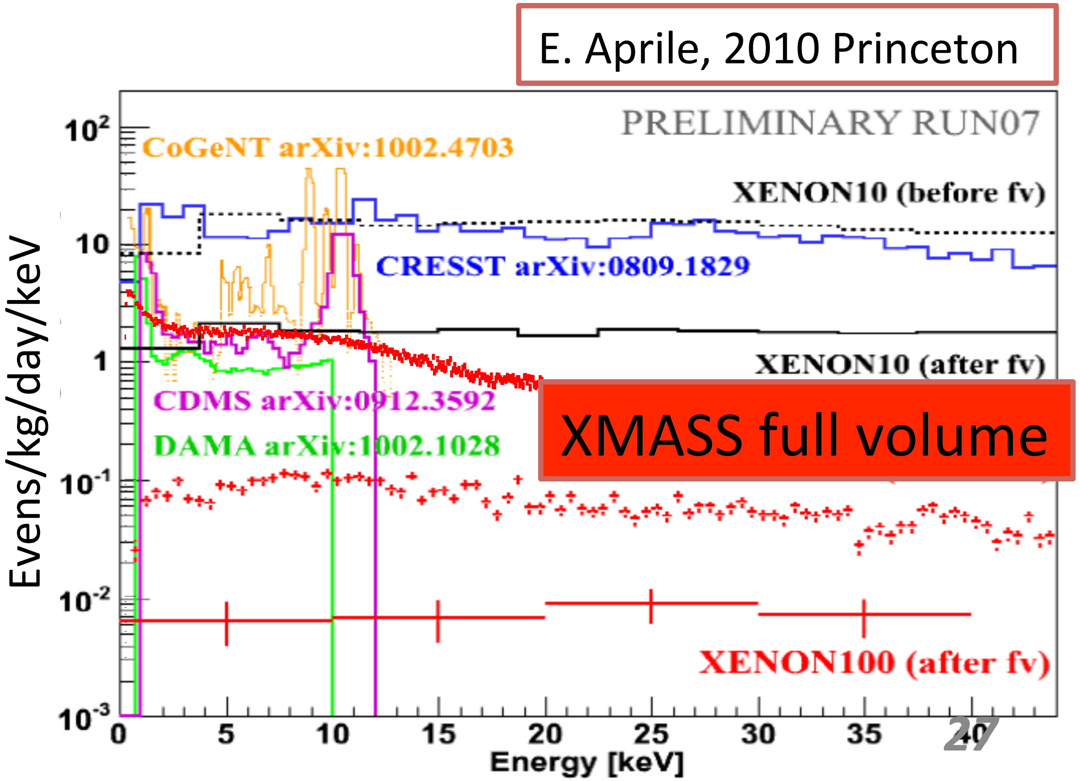


Summary (Measured spectrum)

- Around 5 keV region, we have more than 2 orders of magnitude larger BG from PMT Al seal and 210Pb surface BG although we understand those backgrounds above 5 keV.
  - They are all surface BG, but there is a reconstruction tail into the fiducial volume.
- Below 5 keV
  - There may be a contribution from 14C contaminated in GORE-TEX, but not proved yet
  - There may be unknown BGs or others
- No problem for the internal backgrounds

Summary (Measured spectrum)

- Our BG level (whole volume) is still 'low' even with the unexpected surface backgrounds.



Physics analysis
(sensitivity study)

Different analysis volumes and thresholds

- Whole Volume Analysis

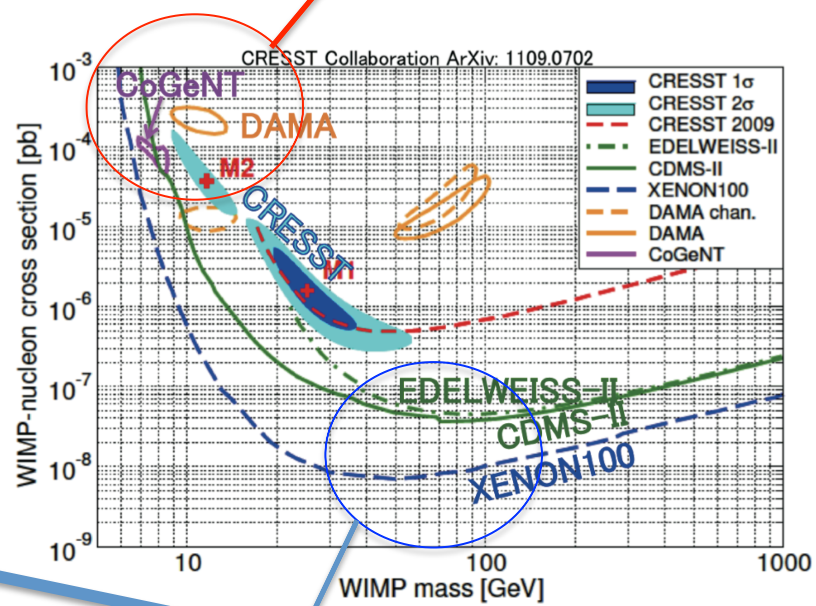
(Large BG, Large target mass of 835 kg, low energy threshold, no reconstruction)

1) 4 hit threshold analysis
   - Low mass region search
2) 2keVee threshold analysis
   - Check DAMA modulation
3) Axion DM (super-WIMPs)
4) Solar Axions

- Fiducial Volume analysis

1) Standard WIMPs search (> 5 keV)
   - Event reconstruction/reduction program

Light WIMPs & ALP:
Low threshold
BG less important



Standard WIMPs:
Prefer heavy mass
Low BG

Whole Volume Analysis with lowest threshold

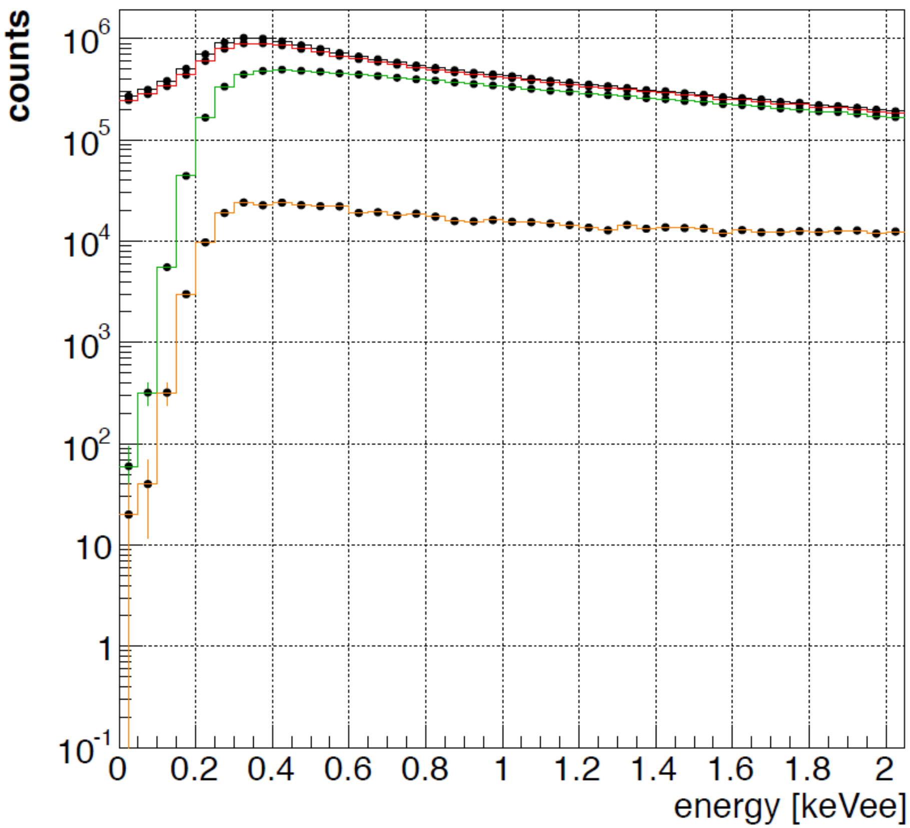
- The lower the threshold, the higher the sensitivity for low mass WIMPs
- Even with the current high BG level, we have similar sensitivity for other running experiments
- Most backgrounds in the low energy side come from the Cherenkov events from ^{40}K decay in the photo cathodes.

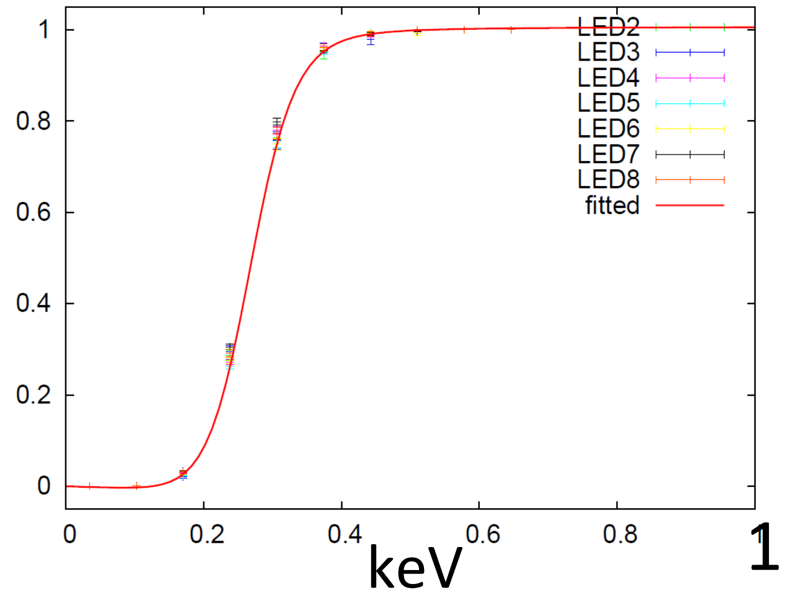
Whole Volume Analysis with lowest threshold

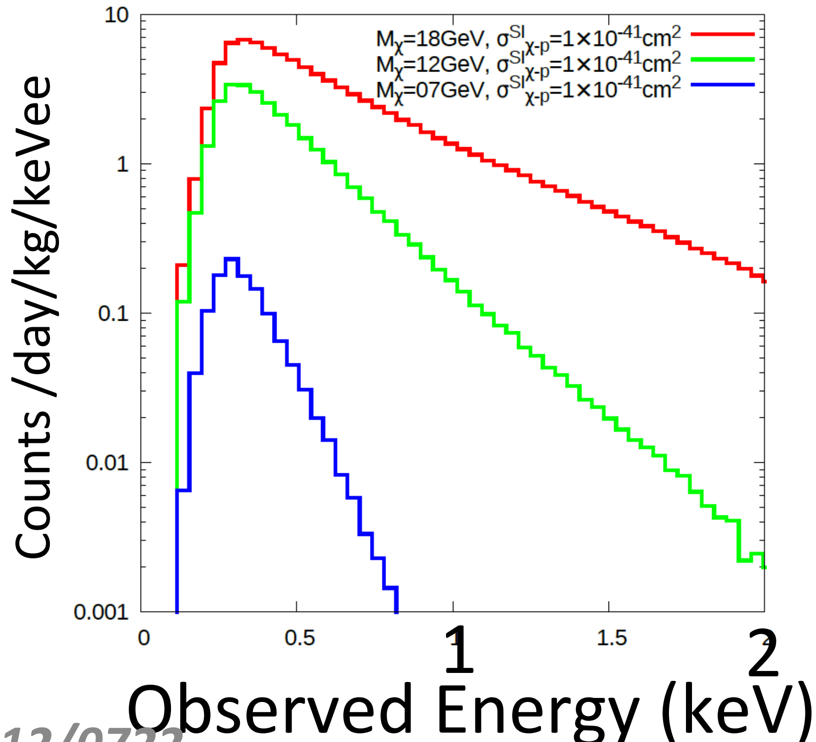
We took the data with 4 hits threshold and analyze the events above **> 0.3 keVee** for entire volume

6.75 days in Feb

- Clean up 1: time difference to the previous/next events > 10ms
- Clean up 2: RMS of the hit timing < 100ns (rejection of after pulses of PMTs)
- Cut: Cherenkov rejection
  - 40K decay in photo cathodes to create Cherenkov in the window of PMT
  - Most BG in this energy regiion







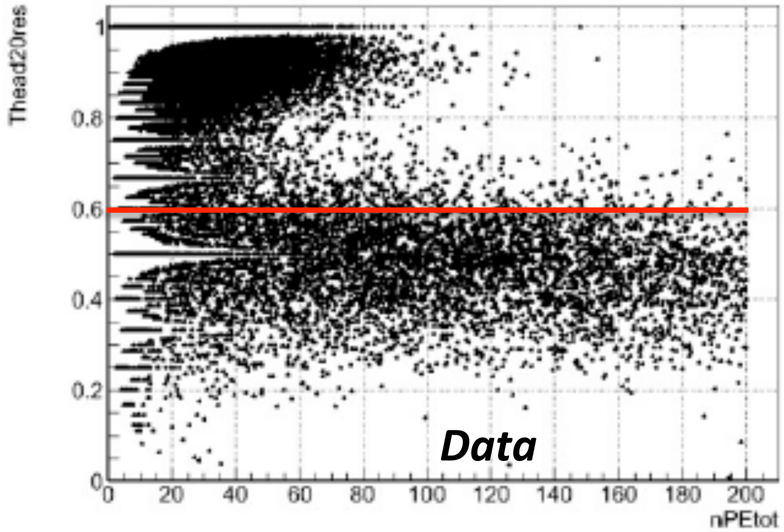
Trigger threshold and Expected DM signal

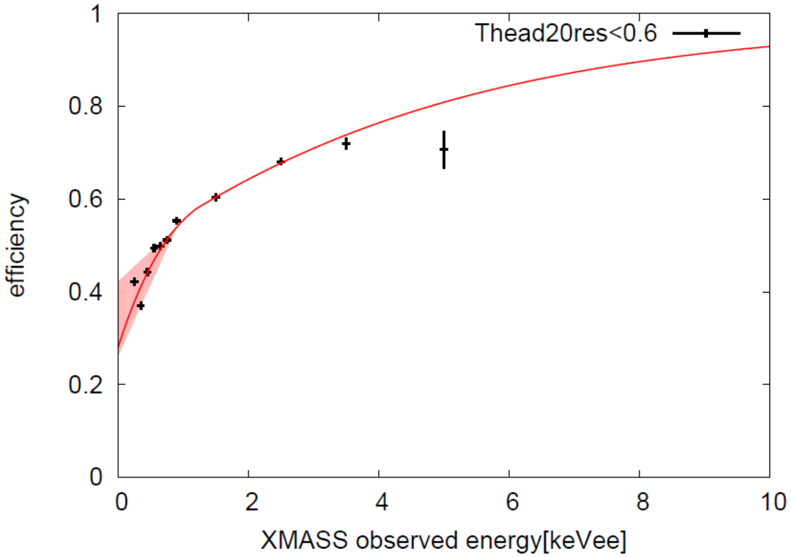
- Trigger efficiency (4 hits)
  - For 7 GeV DM
  - 30% @0.25 keV
  - 50% @0.30 keV

Expected DM signal

- w/ trigger efficiency
- Before any cuts
- Poison distribution for energy resolution

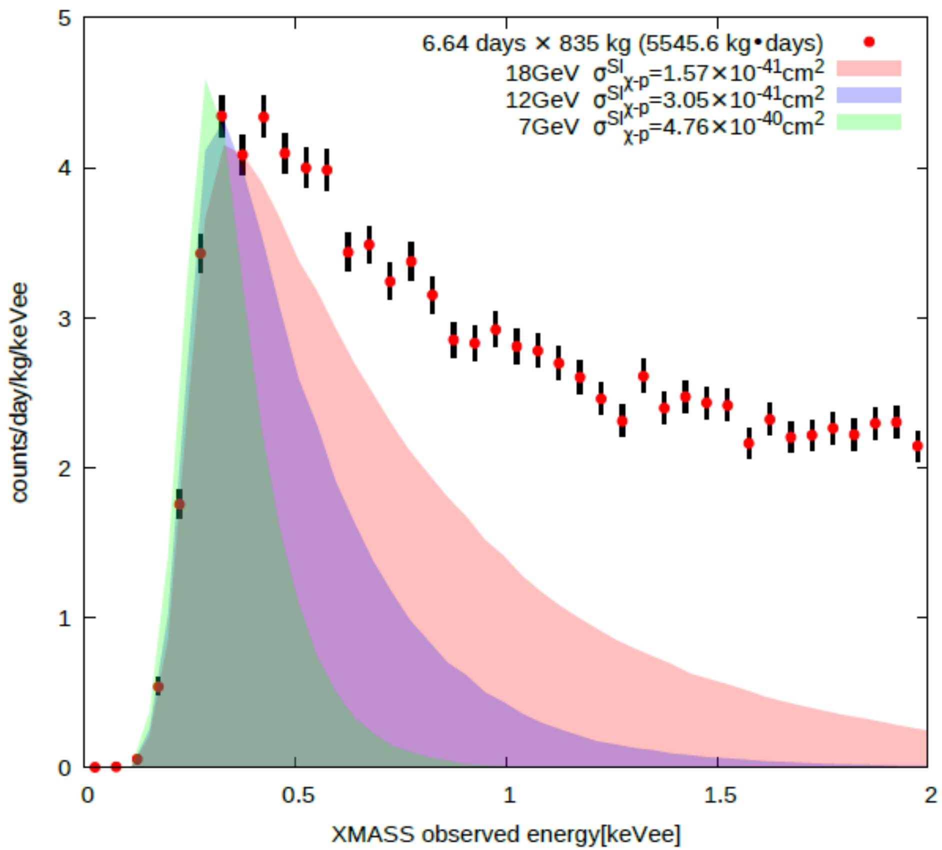
Cherenkov cut





- "head to total ratio"
  = (# of hits in 20ns window)
  / (total # of hits)
- Cherenkov event: ~1
  scintillation: ~ 0.5
- Low energy events observed in Fe55 calibration source and DM simulation (t=25ns) show similar distributions
- Efficiency ranges from 40% to 70% depending on the p.e. range.

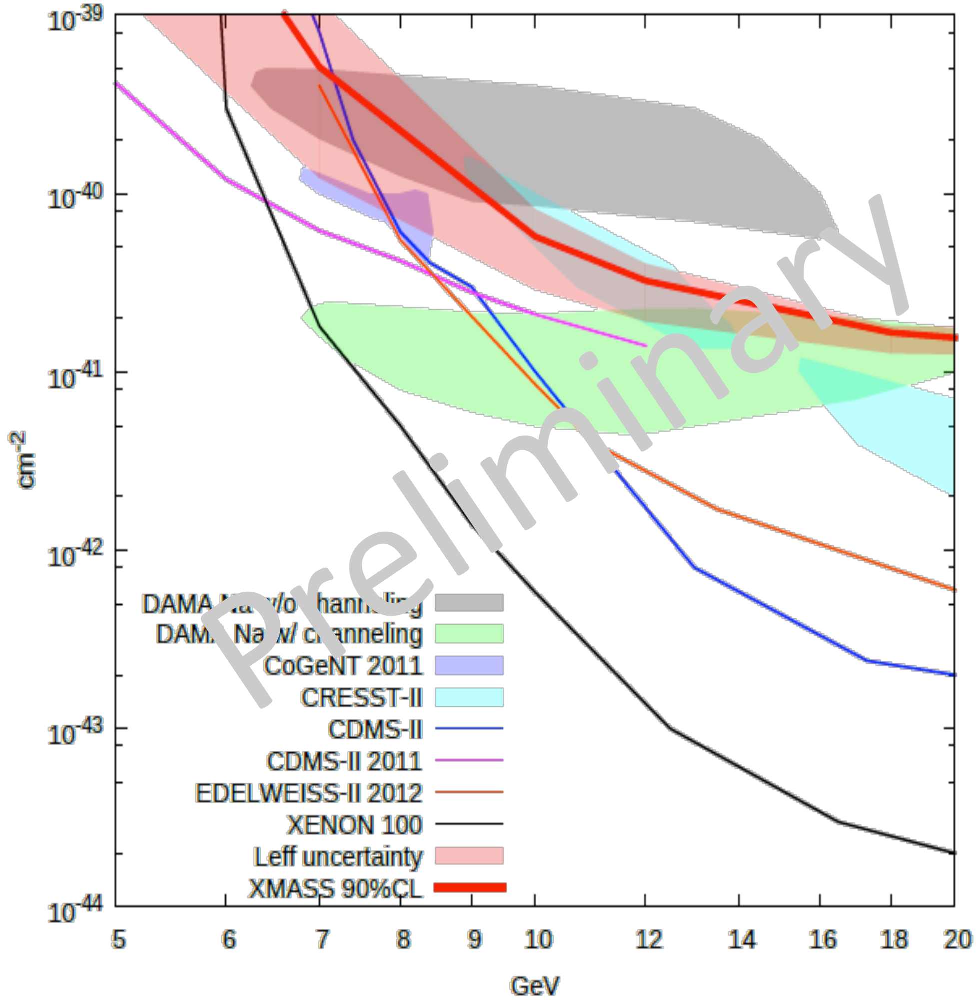
Extraction of the limit

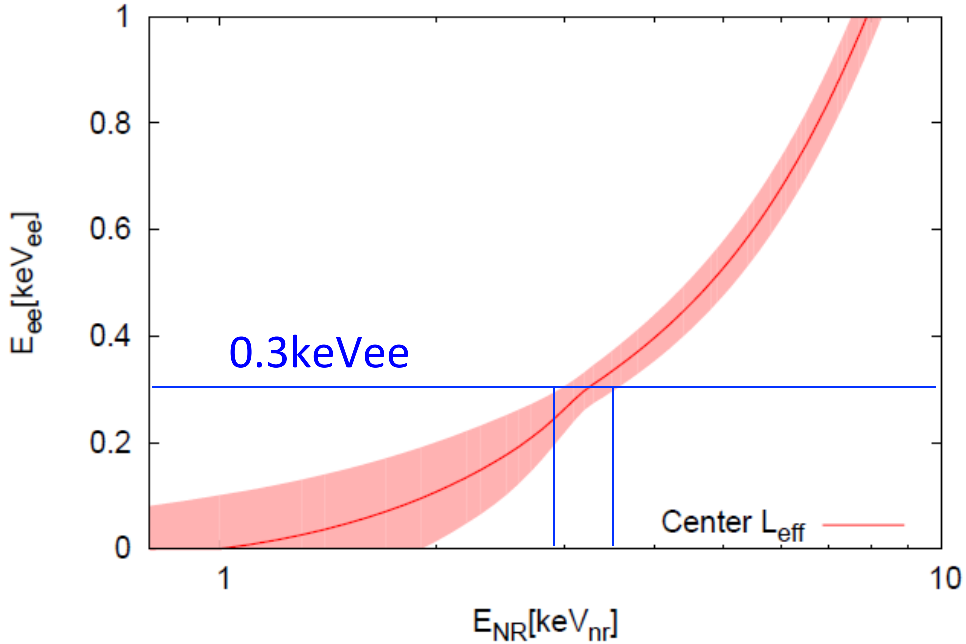


- Compare Dark Matter MC to the data above the analysis thresholds
- Obtain the maximum cross section (upper limits) of the spectrum not to exceed the observed data points.
- Then, statistical and systematic errors are assigned

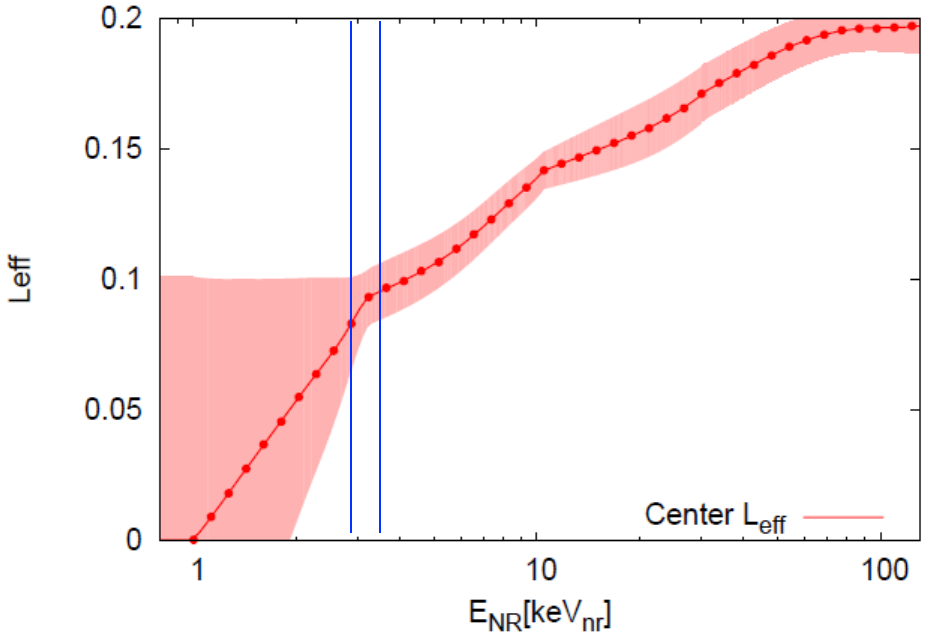
Results on low mass dark matter

- The line (90% lower bound) includes all the systematic errors except Leff .
- Leff uncertainty band is shown separately.
- Current XMASS is sensitive to the allowed regions of DAMA/CoGeNT/CRESST.
- Some part of the allowed regions are excluded.
- We expect to reduce backgrounds further soon





Most systematics (Leff)



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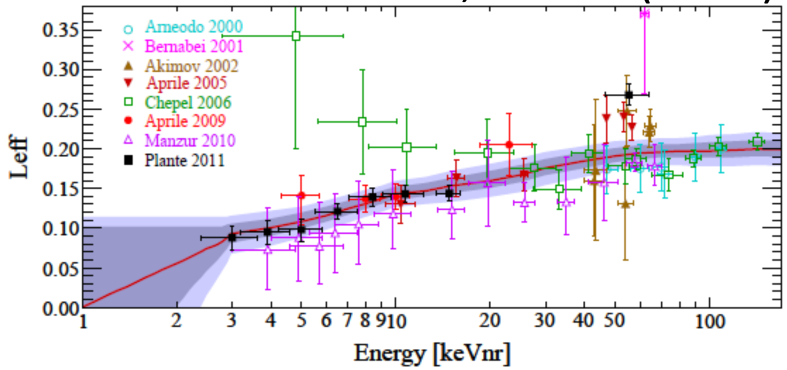
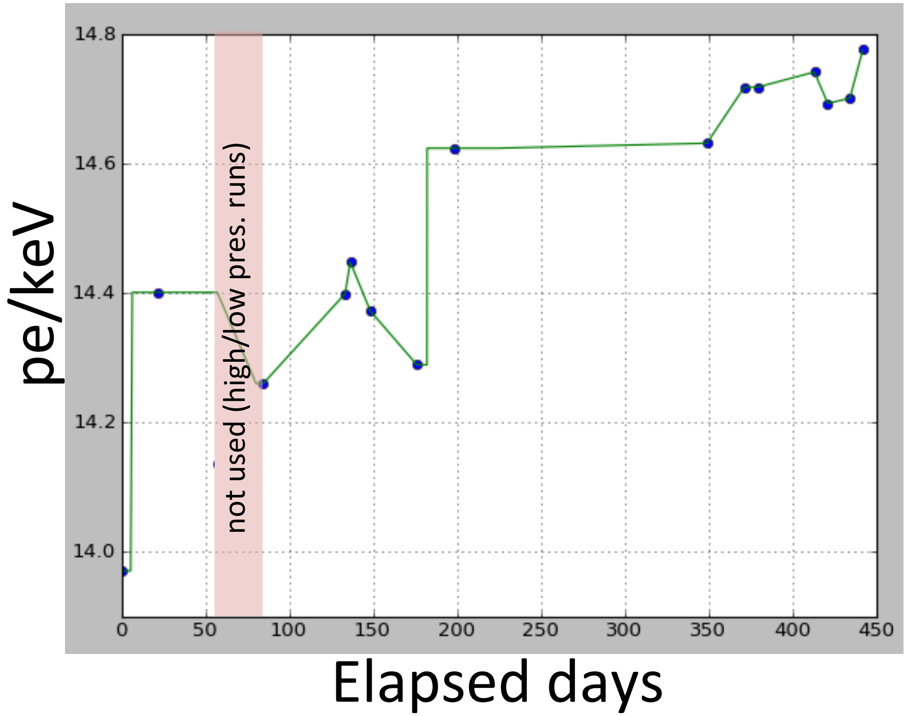


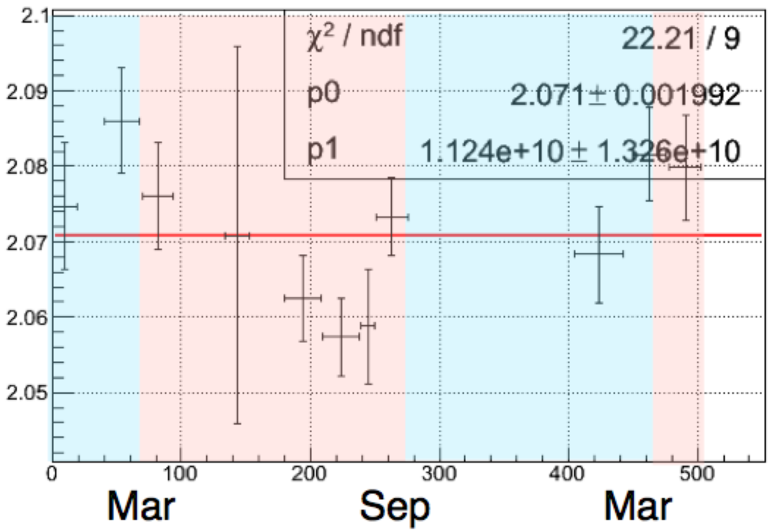
FIG. 1: All direct measurements of $\mathcal{L}_{eff}$ [12, 13] described by a Gaussian distribution to obtain the mean (solid line) and the uncertainty band (1σ and 2σ). Below 3 keV$_{nr}$ the trend is logarithmically extrapolated to $\mathcal{L}_{eff} = 0$ at 1 keV$_{nr}$.

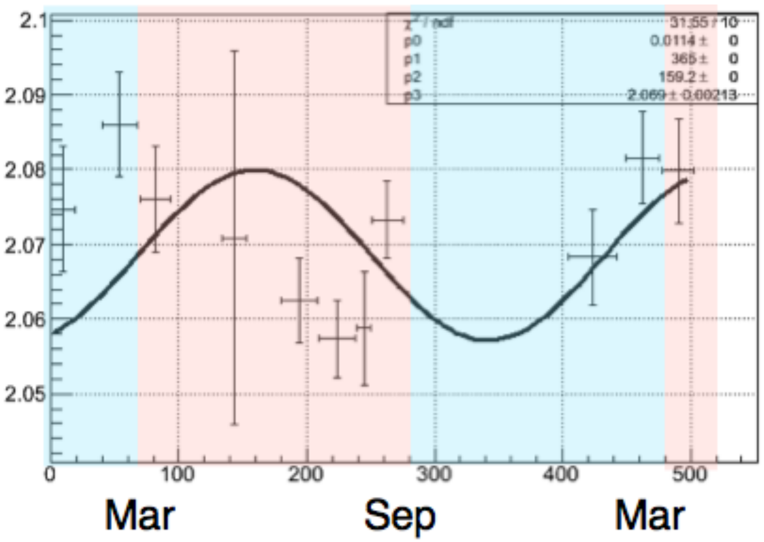
Annual modulation

- In a few keVee region including 2 to 6 keVee
- Same event reduction for low energy whole volume analysis
- Use most of the available data from commissioning runs: 165 days
- Energy scale based on 57Co data (±3% at most)
- Data sets in 11 periods
- Scale factor re-adjustment by 60Co in each periods (0.1 ~ 0.6 %)
- Count number of events



2-6 keVee



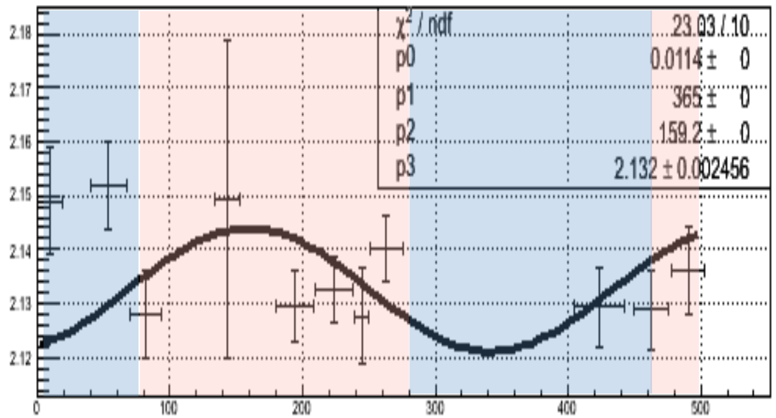


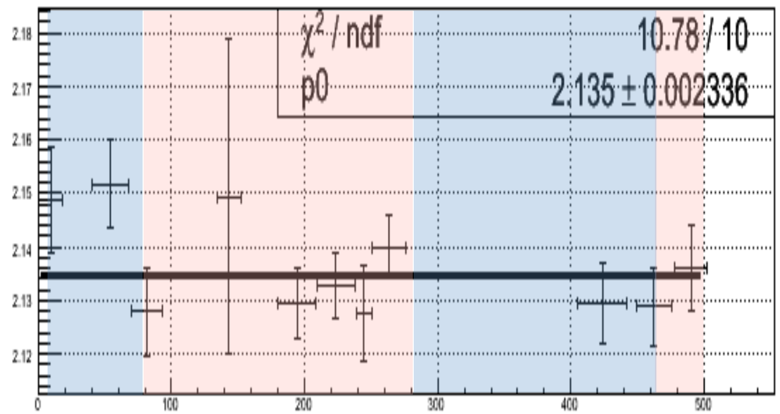
- DAMA modulation
  - Parameters: A=0.0098, 365 days, peak=159.2 days, 2-6 keVee
- Good test for electron/gamma events
- χ^2
  - 22.2 for flat
  - 31.6 for 'DAMA moduration'

Xe ⇔ Na

- QF(Na)~0.25, Leff(Xe)~0.15
- 2~6keVee(Na) ➔ 8~24 keV_{NR} ➔ 1~4keVee(Xe)
  - but 1/30 sensitivity ⟸ recoil shape, A^2
- χ^2: 10.8 for flat, 23.8 for a modulation

1-4 keVee(Xe) ⇔ 2-6 keVee (Na)





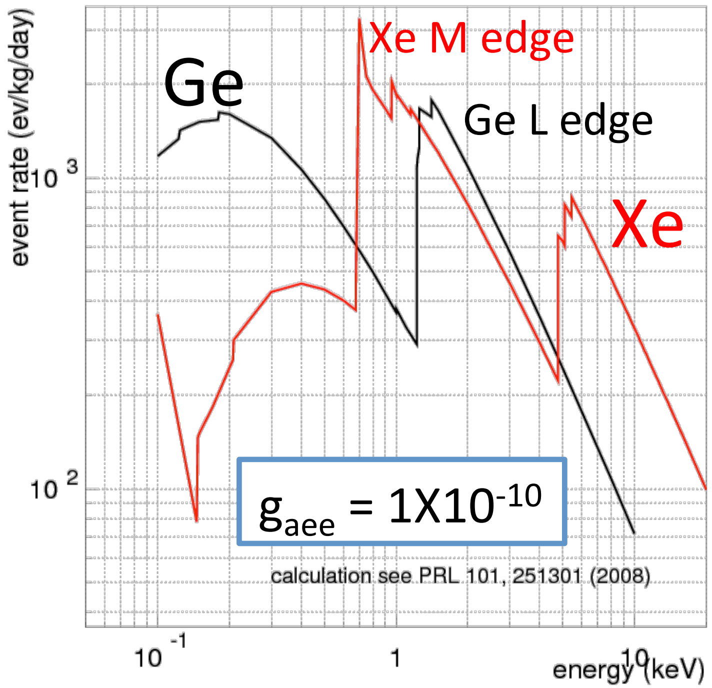
- 2~6 keVee (I) ➔ 3.5~13 keV keVee(Xe): understudy

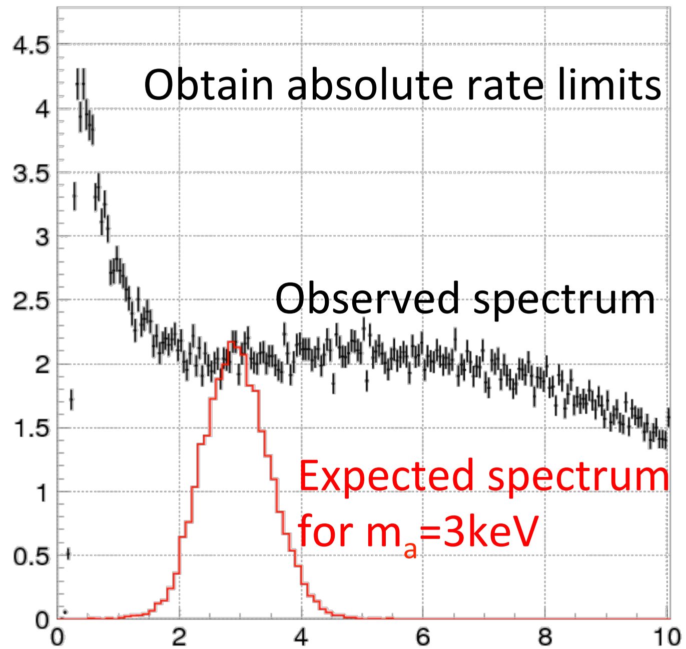
DM Axions

- Event Rate for the axion dark matter (through axio-electric effect)

$$R[kg^{-1}d^{-1}] = 1.2 \times 10^{19} A^{-1} g_{aee}^2 m_a \sigma_{\rm pe}$$

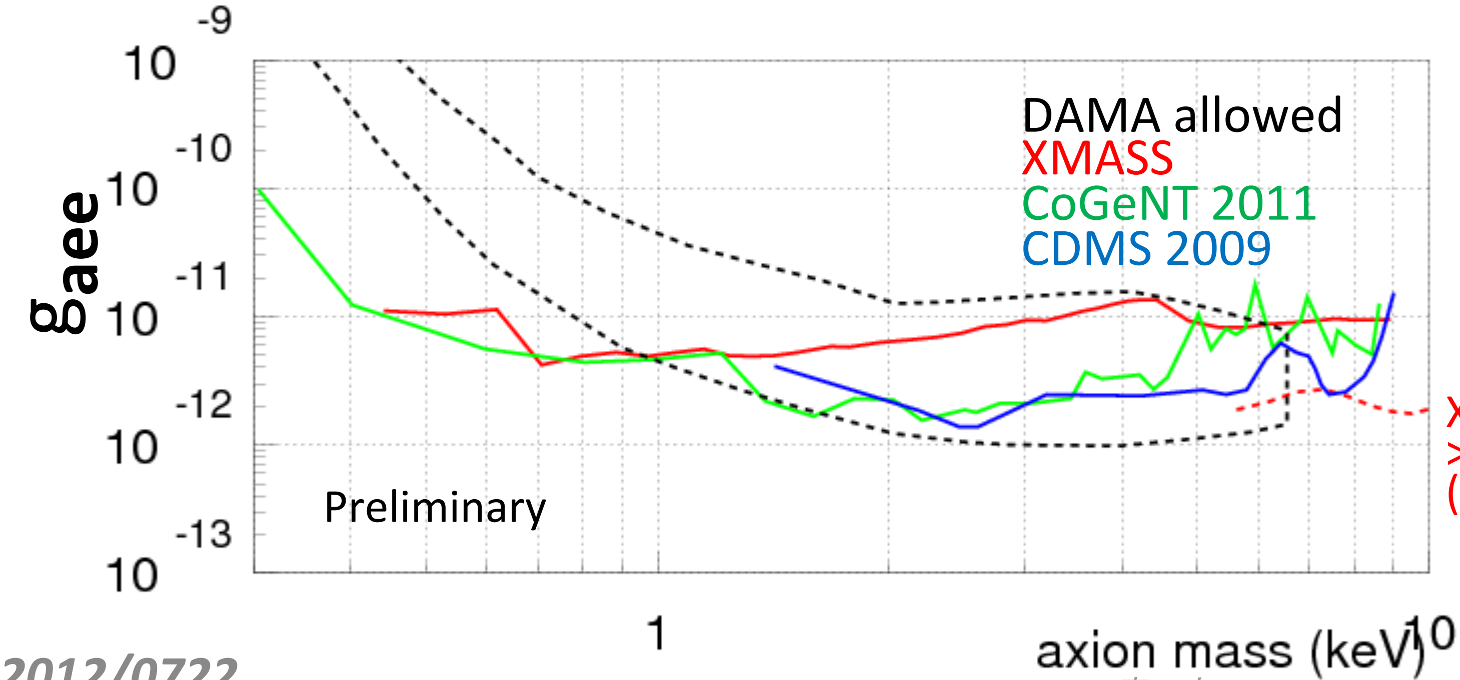
- g_{aee}: strength of the coupling constant, m_a: axion mass in keV, σ_{pe}: photo-electric cross section in barns/atom





DM Axions

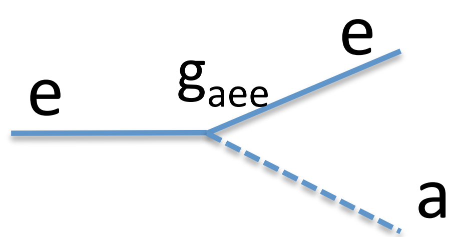
- XMASS results have similar sensitivity to the current experiments.
- The fitting the signal with backgrounds above 5 keV, where we know the background very well, will increase the sensitivity by factor of 5 (in future)

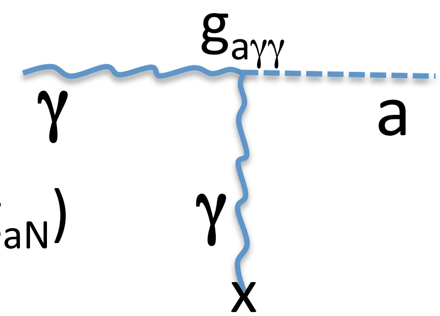


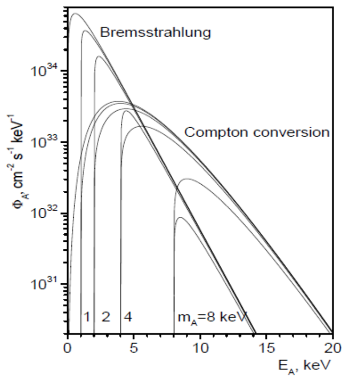
XMASS fitting result
> 5 keV
(sensitivity study)

Solar Axions

- Production: Various mechanism
  1. Bremsstrahlung and Compton scattering (g_{aee})
  2. Primakoff effect ($g_{a\gamma\gamma}$)
  3. Nuclear de-excitation (57Fe) (g_{aN})
     - Line signal @14.4 keV







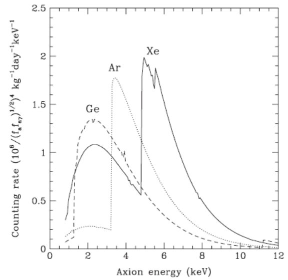
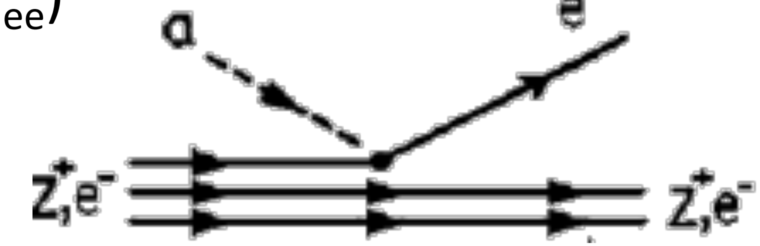


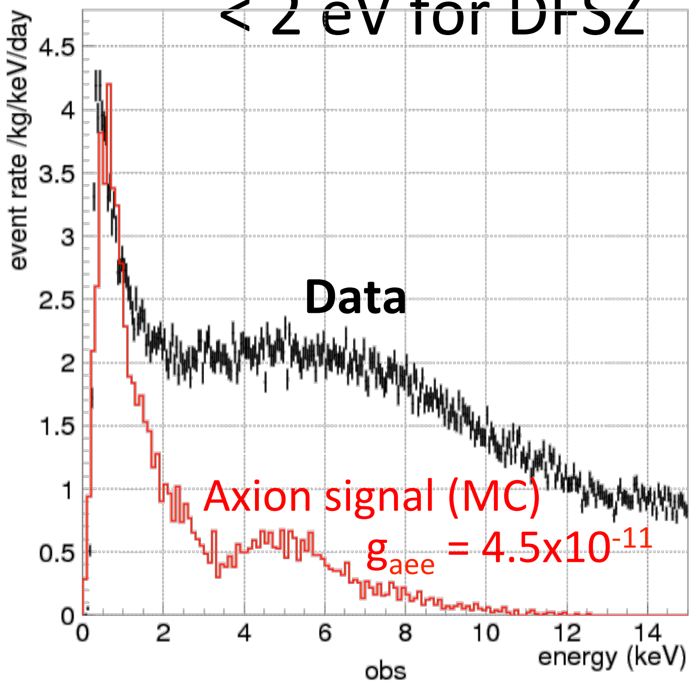
FIG. 4. Counting rate for the axio-electric effect for Ar, Ge, and Xe as a function of axion energy.

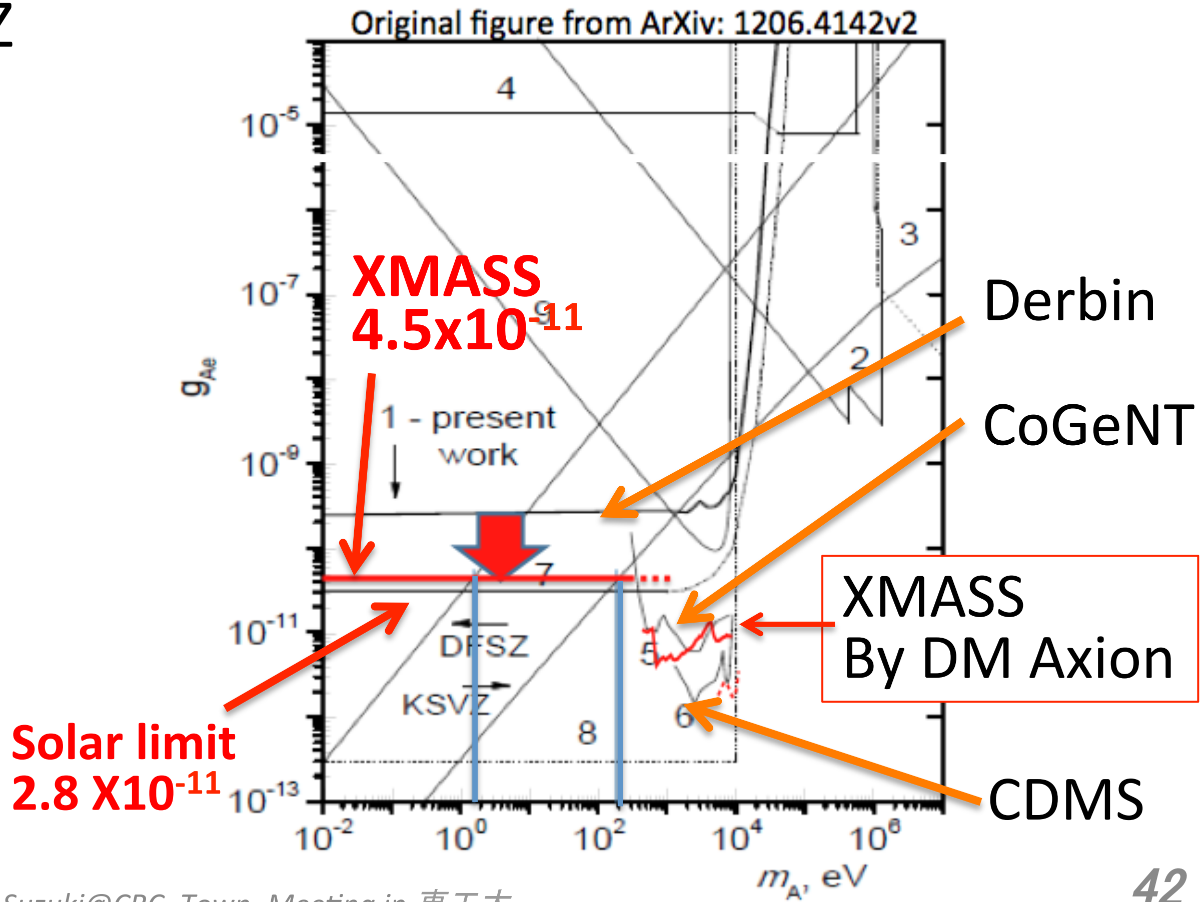
- Observation through axio electric effect (g_{aee})



Solar Axions (gaee)

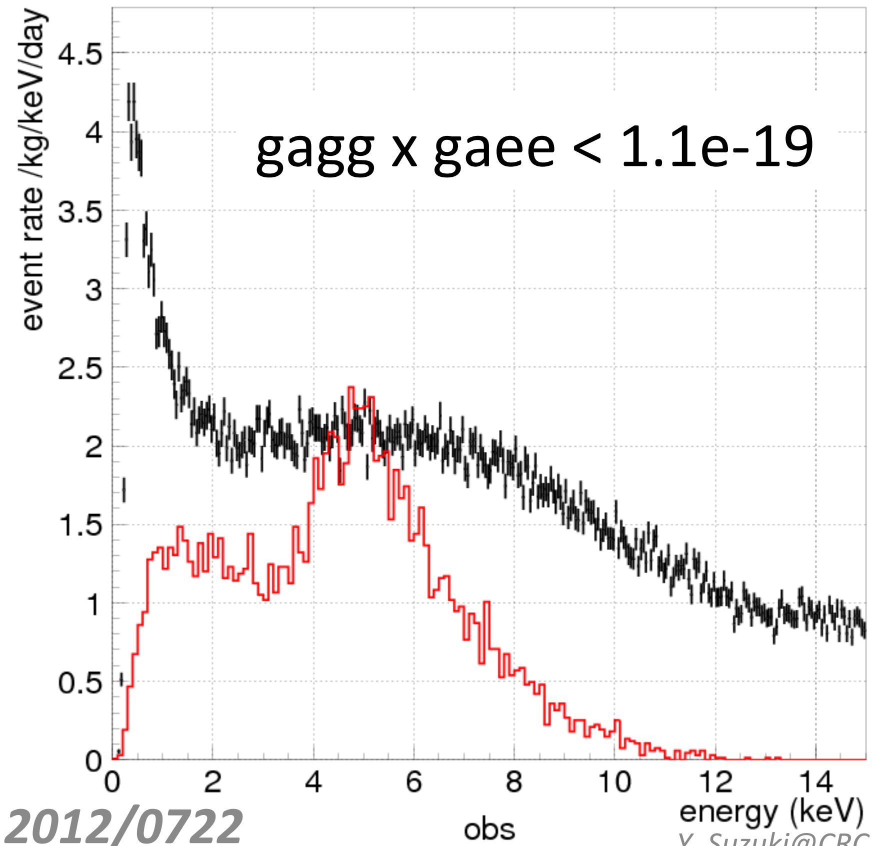
- Limits from absolute maximum: $g_{aee} = 4.5 \times 10^{-11}$
- Allowed mass for particular models:
  < 200 eV for KSVZ
  < 2 eV for DFSZ

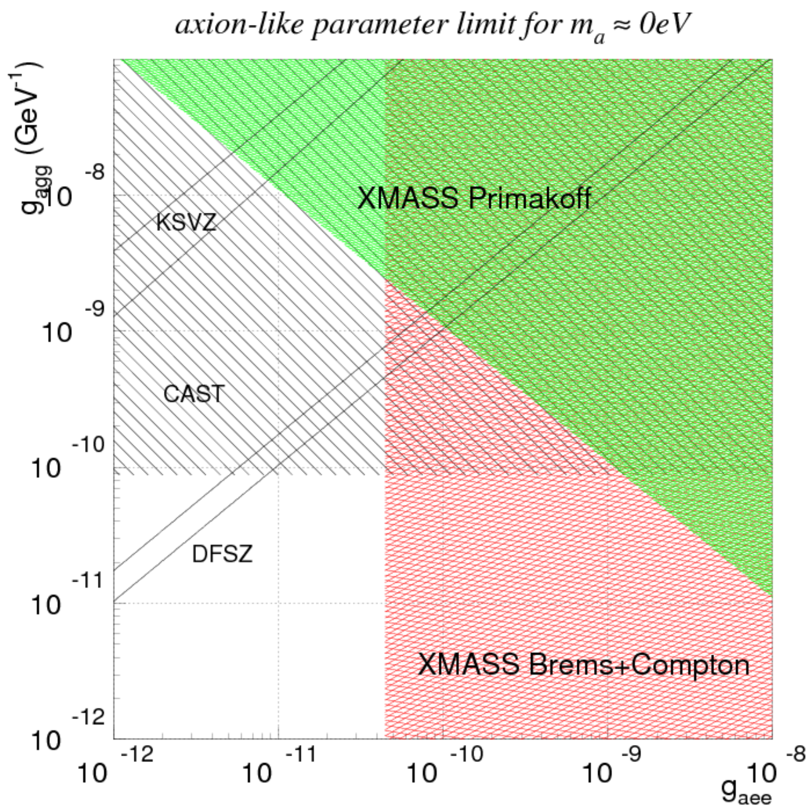




Solar Axion (Primakoff: $g_{agg} \otimes g_{aee}$)

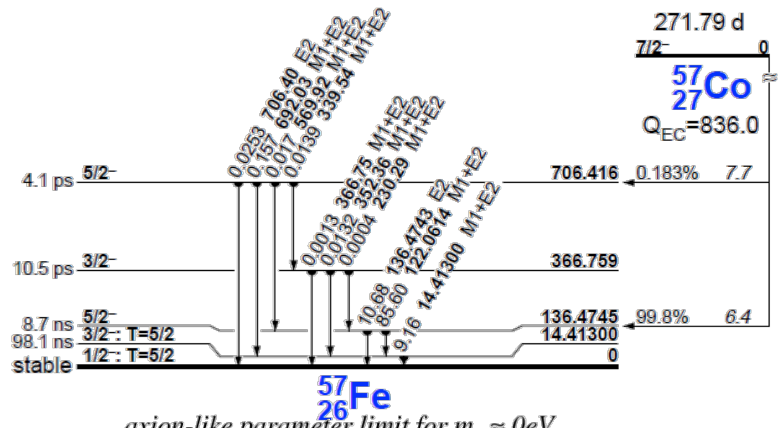
- Black body spectrum with ~ 4 keV peak
- $g_{a\gamma\gamma} \otimes g_{aee} < 1.1\text{x}10^{-19}$

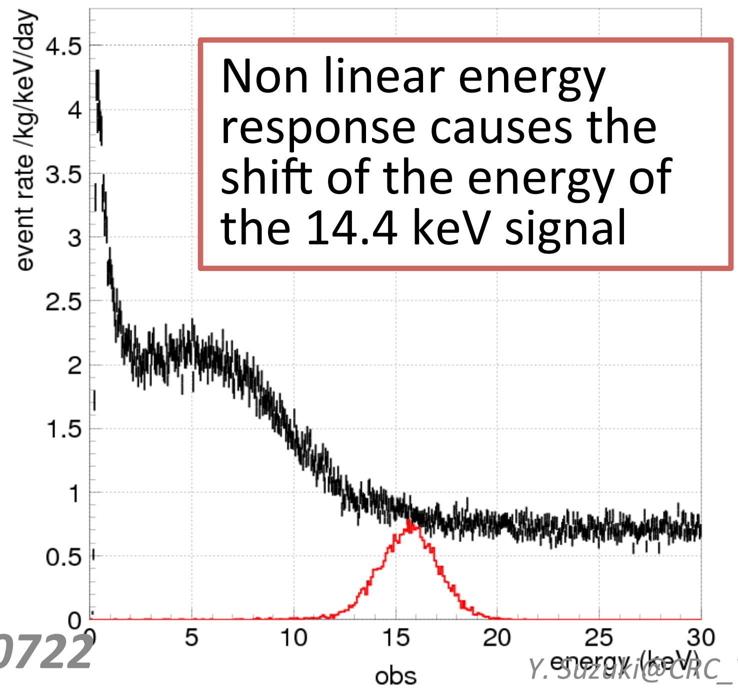


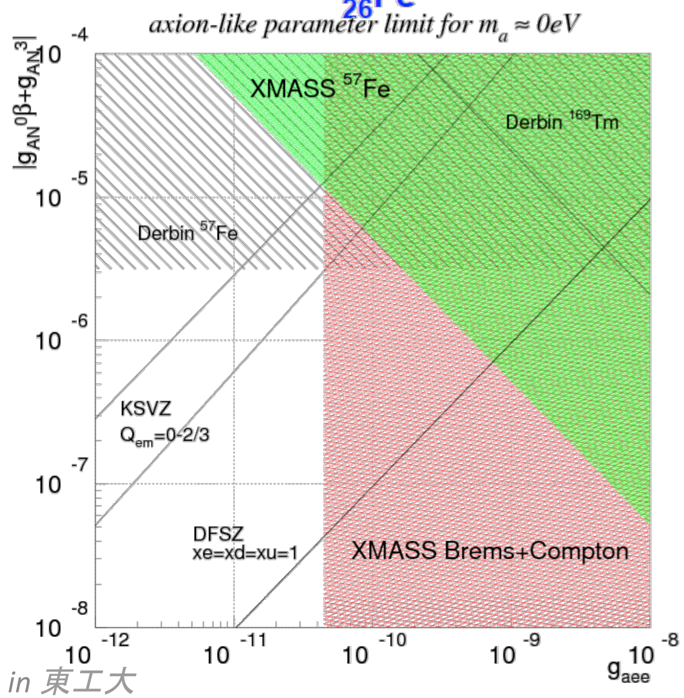


Solar Axion (Nuclear de-excitation: g_{aN} & g_{aee})

- Axion emission through M1 transition level instead of γ
- The low energy excited state is highly populated due to the temperature of the sun
- 57Fe is the best candidate of the source of axions.



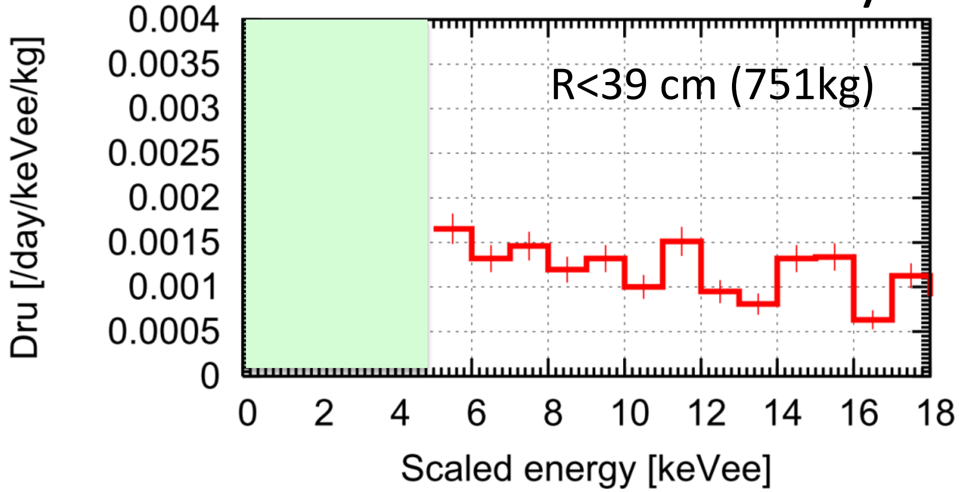


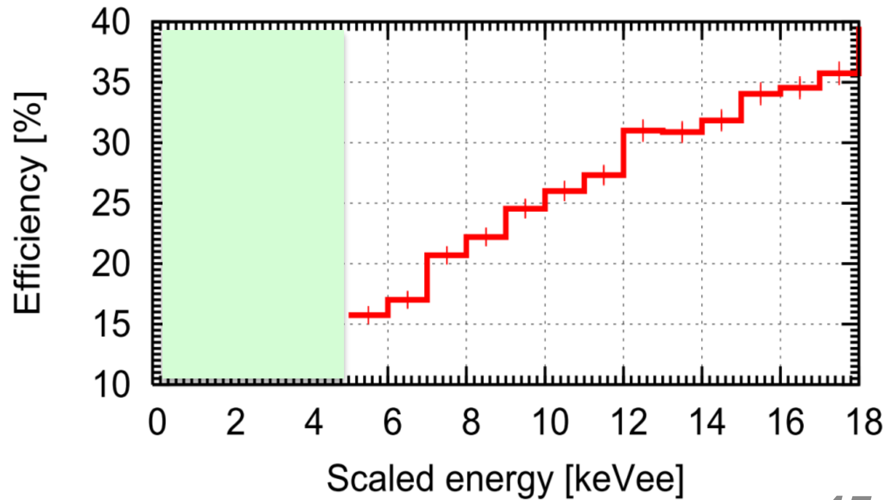


Fiducial Volume Analysis

- We are still developing the software to reduce backgrounds further
- Today: intermediate report
  - Eobs > 5 keV
  - Reconstruction of the energy and vertex position
  - Fid. Volume cut 39 cm (751 kg)
  - Topological pattern cut
- Total efficiency at 5 keV: 14%
- Background level 1.8 x 10^{-3} dru (events/ day/ kg /keV)@ 5 keV
- ~ 100 times larger than originally designed
  - Software to reduce backgrounds further
  - Signal + backgrounds fit
  - Removal of the origin of the backgrounds ➔ refurbishment

79.6 days





Summary (Analysis)

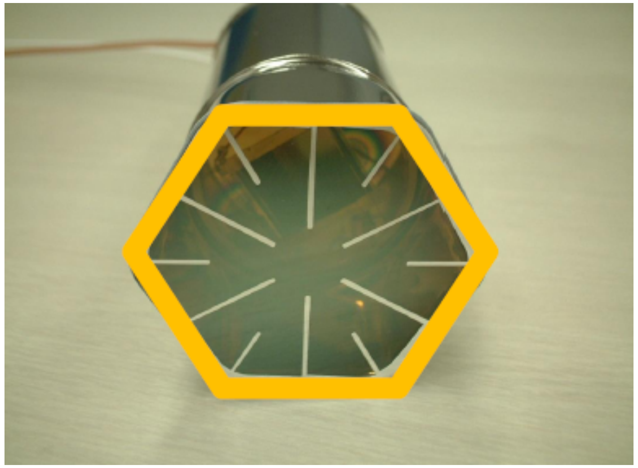
- We have obtained similar sensitivities to the other current experiments in the following analysis:
  - Low mass dark matter search
  - Annual variations
  - Axion dark matter
  - Solar axions

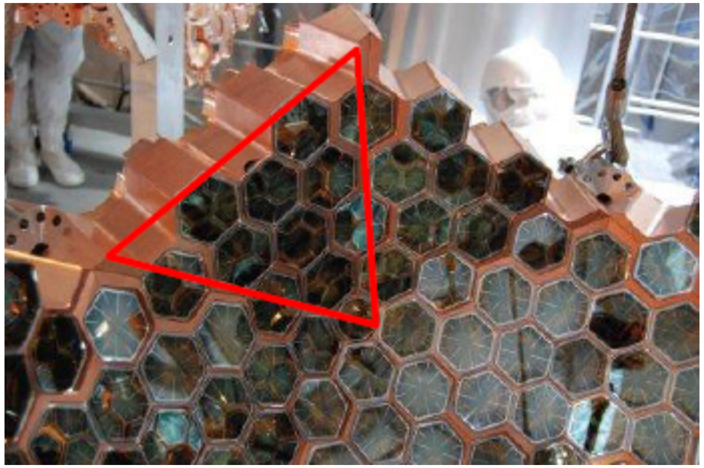
  Even with the situation more than two orders of magnitude higher backgrounds than we anticipated.
- This is due to, large total mass, Low threshold, sensitive to the electro-magnetic events as well as nuclear recoils
- But fiducial analysis: two orders worse
- So the results :: encouraging? or discouraging ?
- In anyway we will reduce those backgrounds physically in next several months and we can expect one to two orders of magnitude improvements.

Refurbishment

- PMT Al-seal
  - Difficult to remove
  - Installation of Cu ring around the PMT quartz window
- Place a Cu-cover on the gap
- Remove GORE-TEX
- Clean up surface

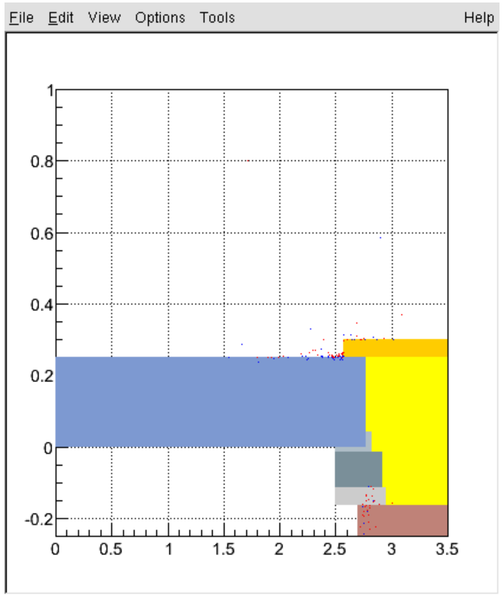
- Dis-assemble of the detector will start in September

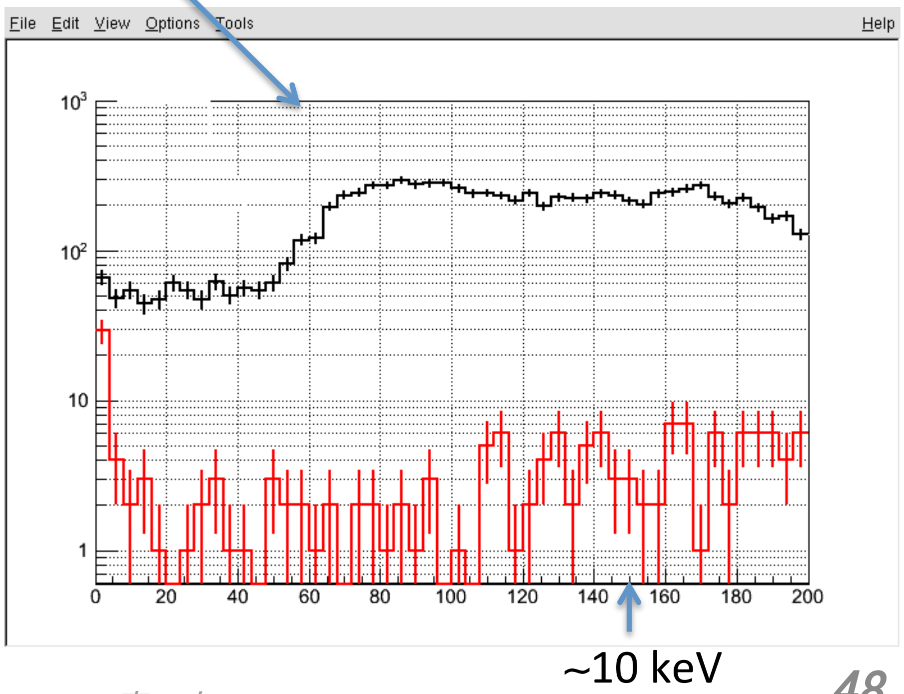




Improvements by refurbishment

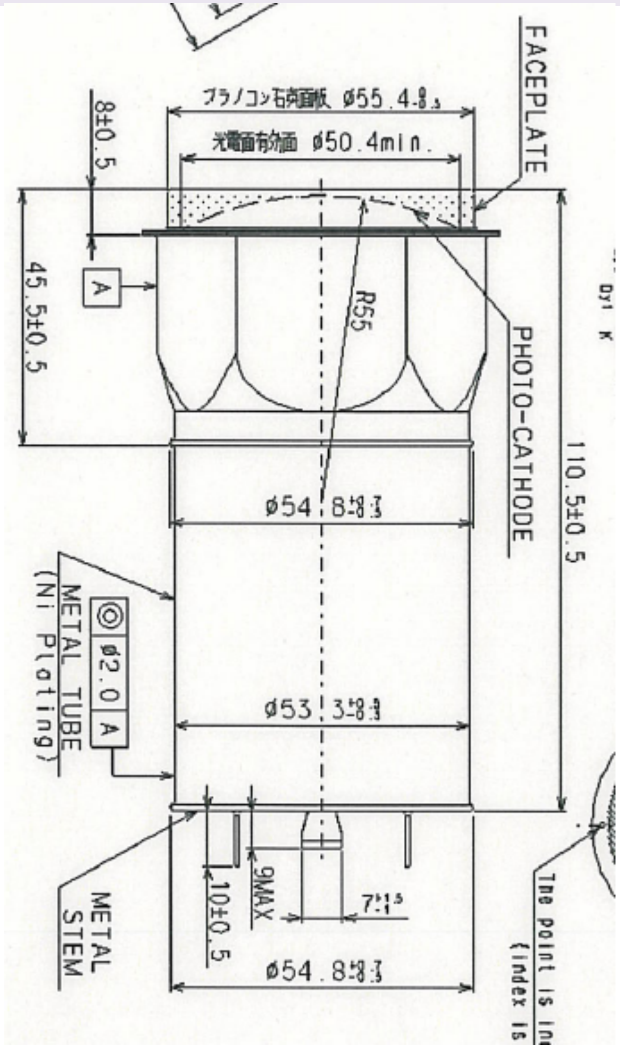
- Expected background reduction
  - Cu-ring and Cu-cover over the Al-seal
    - ~1/100 reduction above > 5 keV
  - Remove GORETEX
    - ~1/100 reduction < a few keV
  - Reduce surface 210Pb
    - ~1/100 reduction above > 5 keV



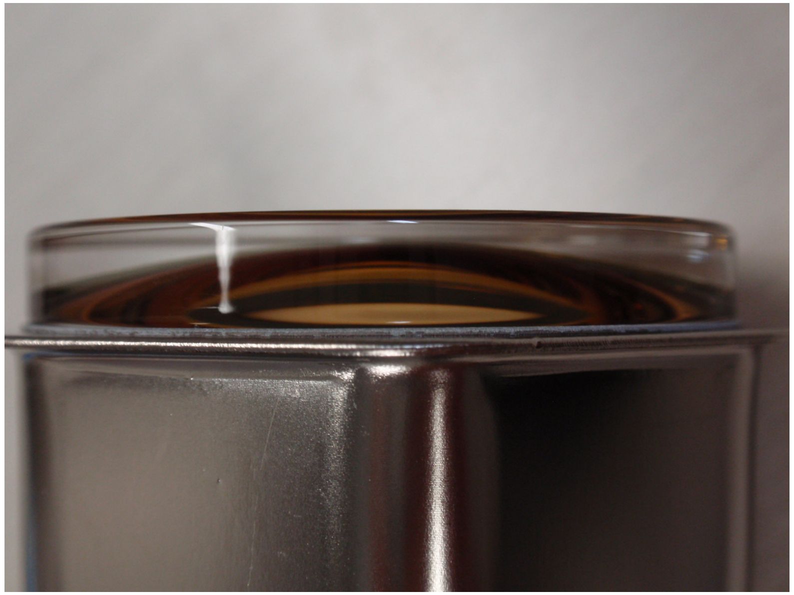


XMASS 1.5

- Total mass: 5 tons
- Fiducial mass: 1 ton
  ← 100kg
- Backgrounds
  - No dirty aluminum
  - No GORETEX
  - Less surface ^{210}Pb
- Identification of the Surface BG new round shape windows of PMT

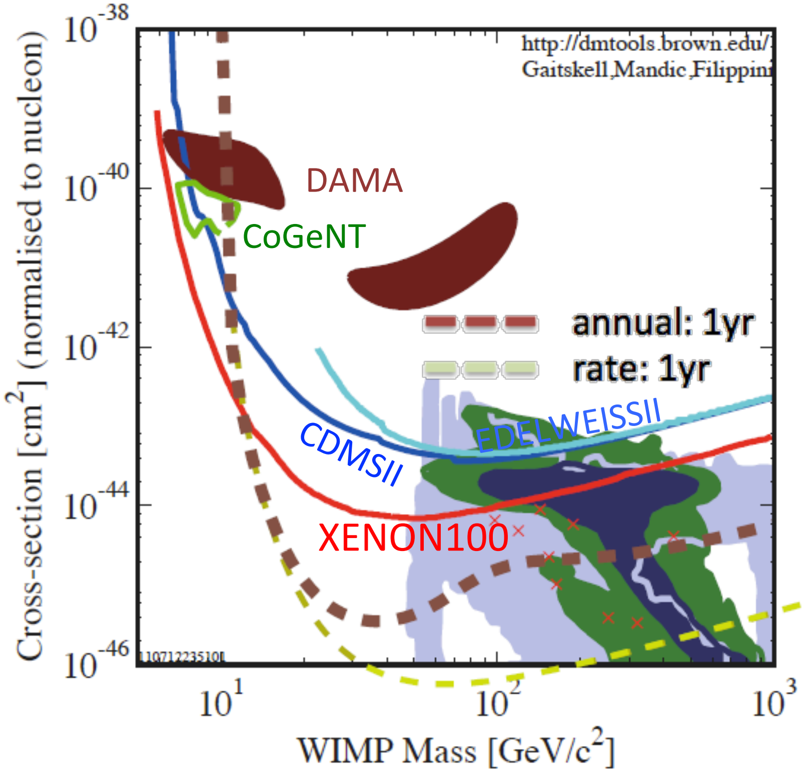


PMT for XMASS1.5

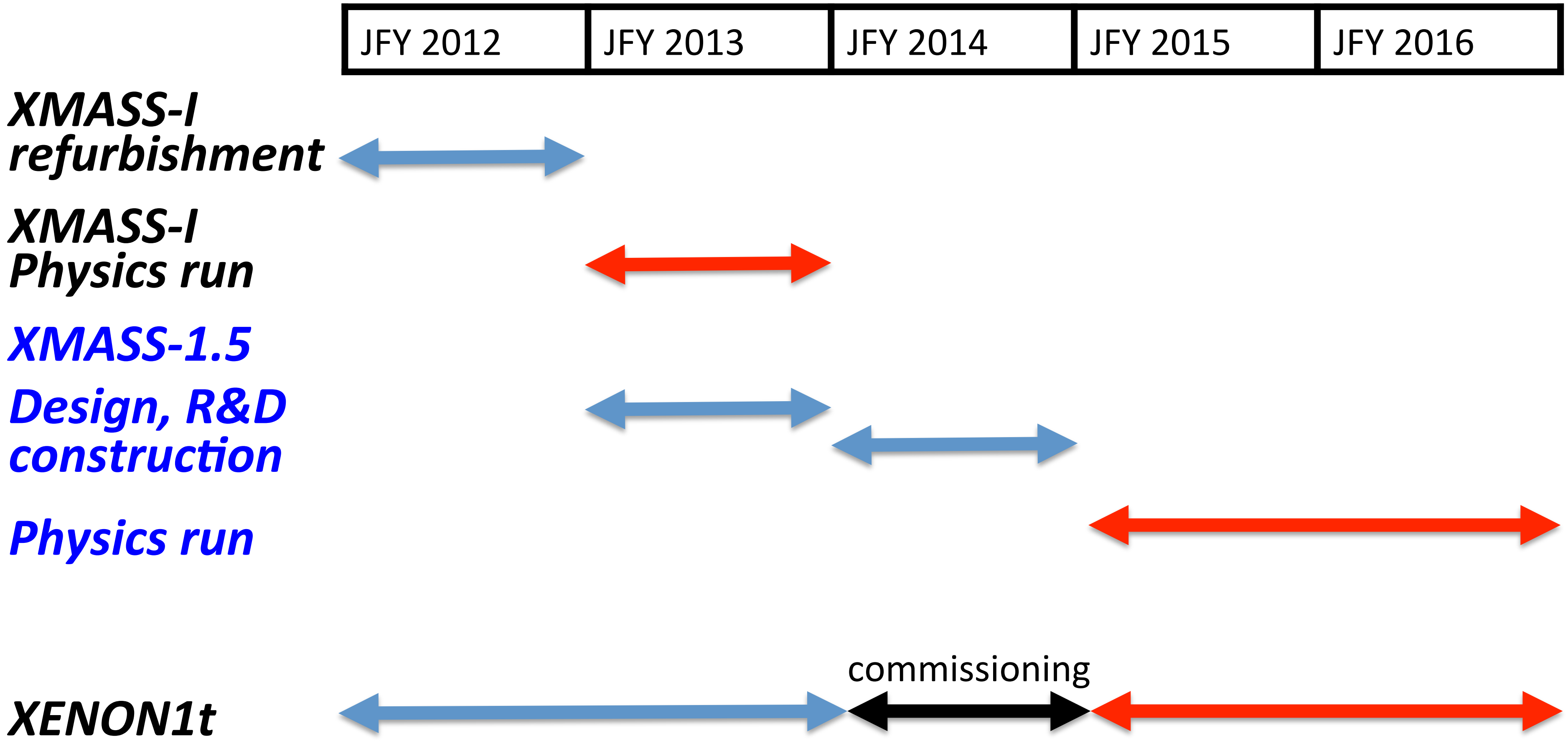


Sensitivity for XMASS1.5

- Expect 10^{-5} dru
- Sensitivity $s_{SI} < 10^{-46}$ cm^2 (> 5 keV)
- Low threshold analysis could reach a few x 10^{-42} cm^2 around a few GeV region
- ALP search: two orders better than the current experiments (DM axions, Solar axions [Bremsstrahlung and Compton])



Time schedule



予算（減額後）

- 総額　１３ 億円
  - キセノン　3トン：　３億円 （すでに2トンある）
  - 光センサー1800本：3．6億円
  - 電子回路（1800チャンネル）：0．6億円
  - データー収集モニター系：　０．９億円
  - 容器：2億円
  - 配管等：0．９億円
  - 低温設備：1．5億円
  - その他：0．5億円

研究組織

- 東京大学宇宙線研究所神岡宇宙素粒子研究施設
- 東京大学国際高等研究所カブリ数物連携宇宙研究機構
- 神戸大学
- 東海大学
- 岐阜大学
- 横浜国立大学
- 宮城教育大学
- 名古屋大学太陽地球環境研究所
- Sejong University
- KRISS

まとめ

- 今回のXMASS-Iで、バックグラウンドの源がほぼ理解できた。したがって、将来の測定器ではバックグラウンドを取り除く方策をとれる。
- ３年後に実験開始ができれば、標準的なWIPMs探索で、最高感度が得られる。早くやる必要がある。
  - XENON1tとの競争
- 今回のWhole Volume Analysisの結果により、low mass regionにも、高い感度を持つものができる。
- XMASSは、電子散乱にも感度をもっている。
  - Axion like particles (ALP) の探索にも高い感度を持っていることがわかった。
- 標準的なWIMPs探索のみでなく、多目的なdark matter の研究が行える。