Recent results from XMASS

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Revealing the history of the universe with underground particle and nuclear research, May 11-13, 2016

Contents

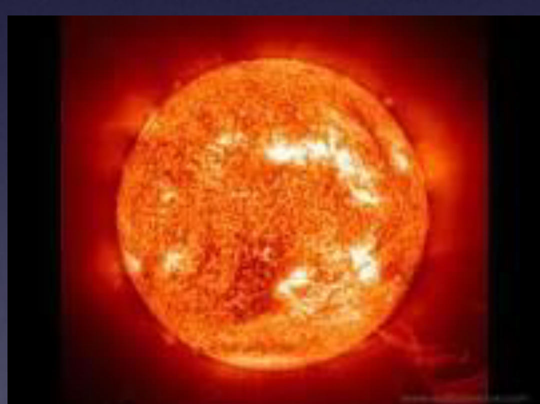
- XMASS experiment
- Recent results from XMASS
  - direct dark matter search by annual modulation
  - two neutrino double electron capture on ^{124}Xe
- Toward next phase : XMASS-1.5

The XMASS experiment

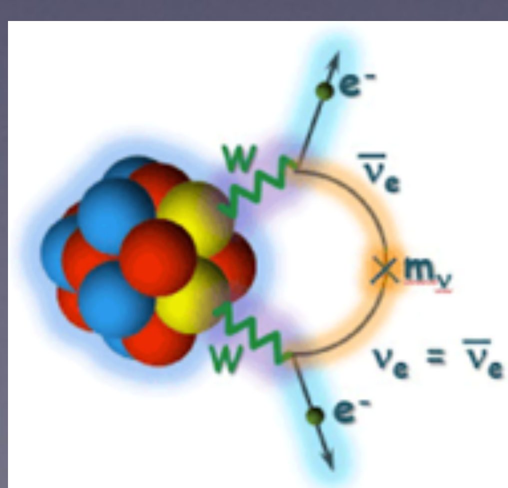
★ Multi purpose low-background experiment with LXe

- Xenon MASSive detector for solar neutrino (pp/^{7}Be neutrino)
- Xenon neutrino MASS detector ($\beta\beta$ decay)
- Xenon detector for Weakly Interacting MASSive Particles (DM)

solar neutrino



$0\nu\beta\beta$



Dark Matter

The XMASS collaboration:

Kamioka Observatory, ICRR, the University of Tokyo:
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R. Fujita, K. Hosokawa, K. Miuchi, Y. Ohnishi, N. Oka, Y. Takeuchi

Tokai University:
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Yokohama National University:
S. Nakamura

Miyagi University of Education:
Y. Fukuda

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

IBS:
N. Y. Kim, Y. D. Kim

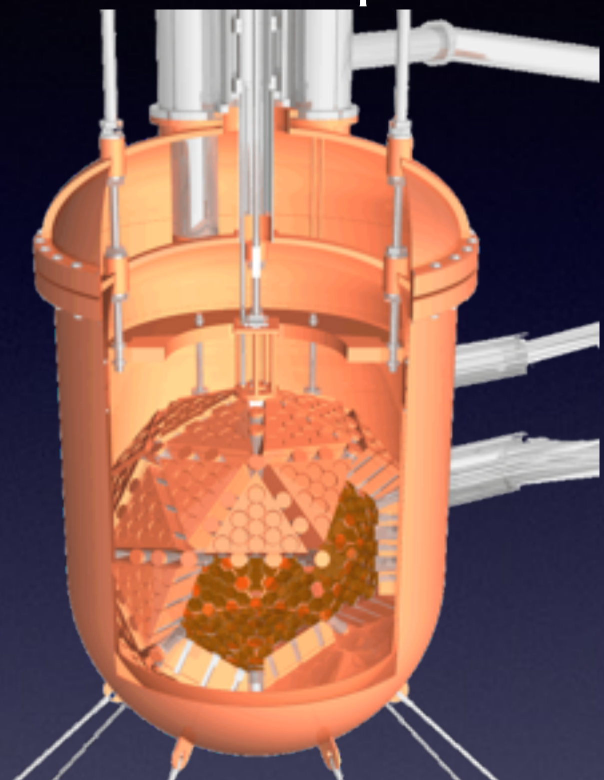
KRISS:
Y. H. Kim, M. K. Lee, K. B. Lee, J. S. Lee

Tokushima University:
K.Fushimi

10 institutes ~40 researchers.

The XMASS experiment

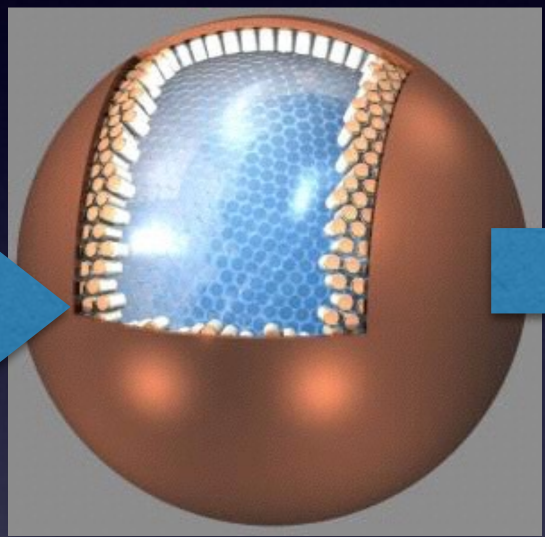
XMASS-I
Current phase



100kg (FV)/832 kg
80cm ϕ

DM search

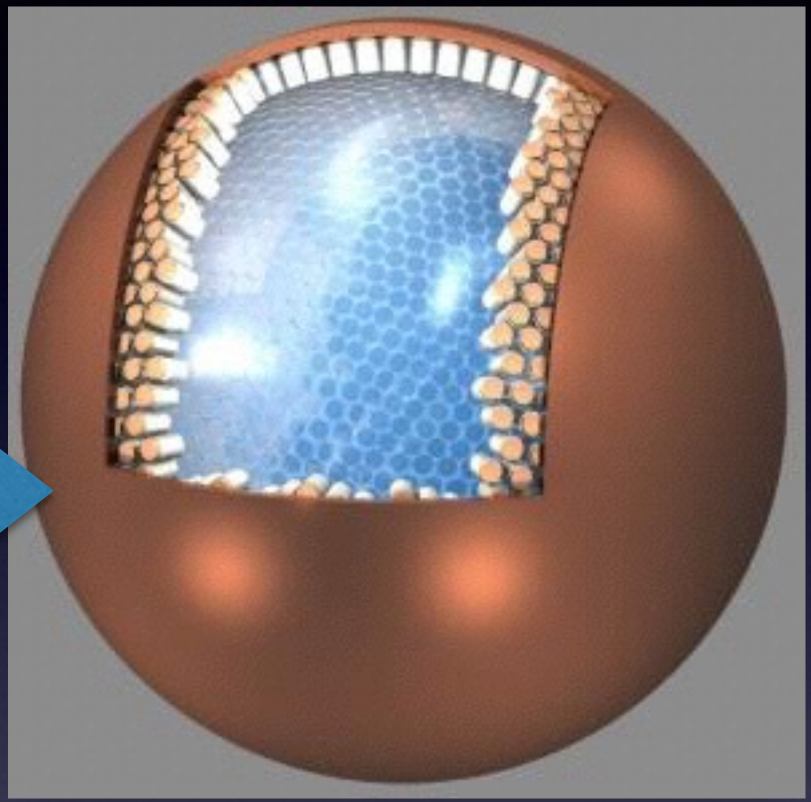
XMASS 1.5
next phase



1~3 ton (FV)/ 6 ton
1.5m ϕ

DM search
$\sigma_{SI} < 10^{-46}$ cm^2
pp solar neutrinos
~a few events/day

XMASS-II



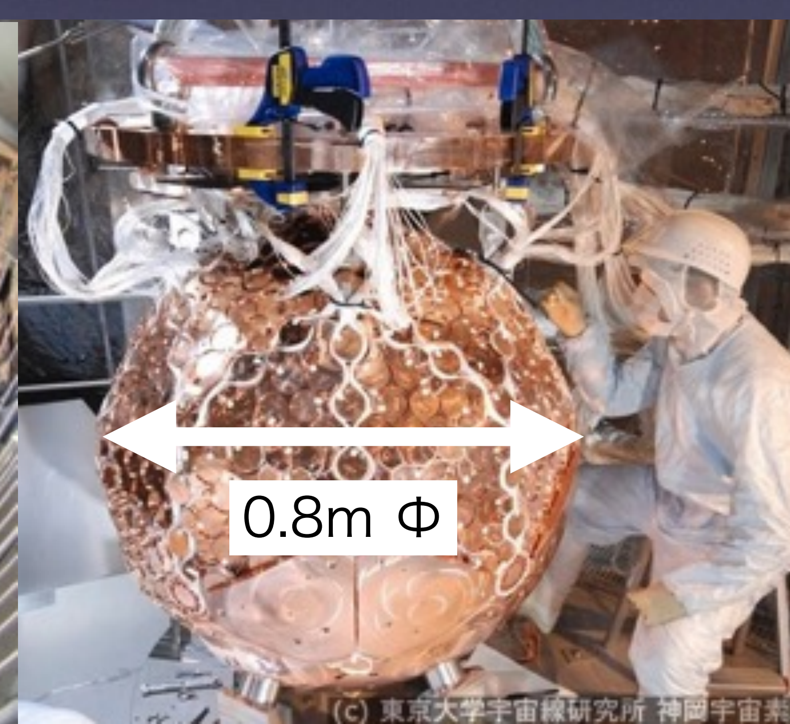
>10 ton (FV)/ 24 ton

Multi purpose :
DM search $\sigma_{SI} < 10^{-48}$ cm^2
pp-solar neutrinos: 10 cpd
double-beta decay of ^{136}Xe

- Phasing Approach
- XMASS-I aims at the search for dark matter

Detector and its characteristic(1)

- Located in the Kamioka mine in Japan (~2700 m.w.e.)
- Single phase liquid xenon detector with 832 kg LXe sensitive volume.
    - its scalability for further detector upgrade
- 642 low background 2inch PMTs : 62% photo-cathodes coverage
- **<u>High light Yield (~15 p.e. / keV) and Low energy threshold</u>**
    - Achieved 0.3 keV in XMASS-I (full volume)
    - 2 keV for fiducial volume analysis
- **<u>High sensitivity for e/γ events as well as nuclear recoil</u>**
    - Able to detect Axion Like Particles (ALP), hidden photon, inelastic scattering and so on, as well as “Standard” WIMPs

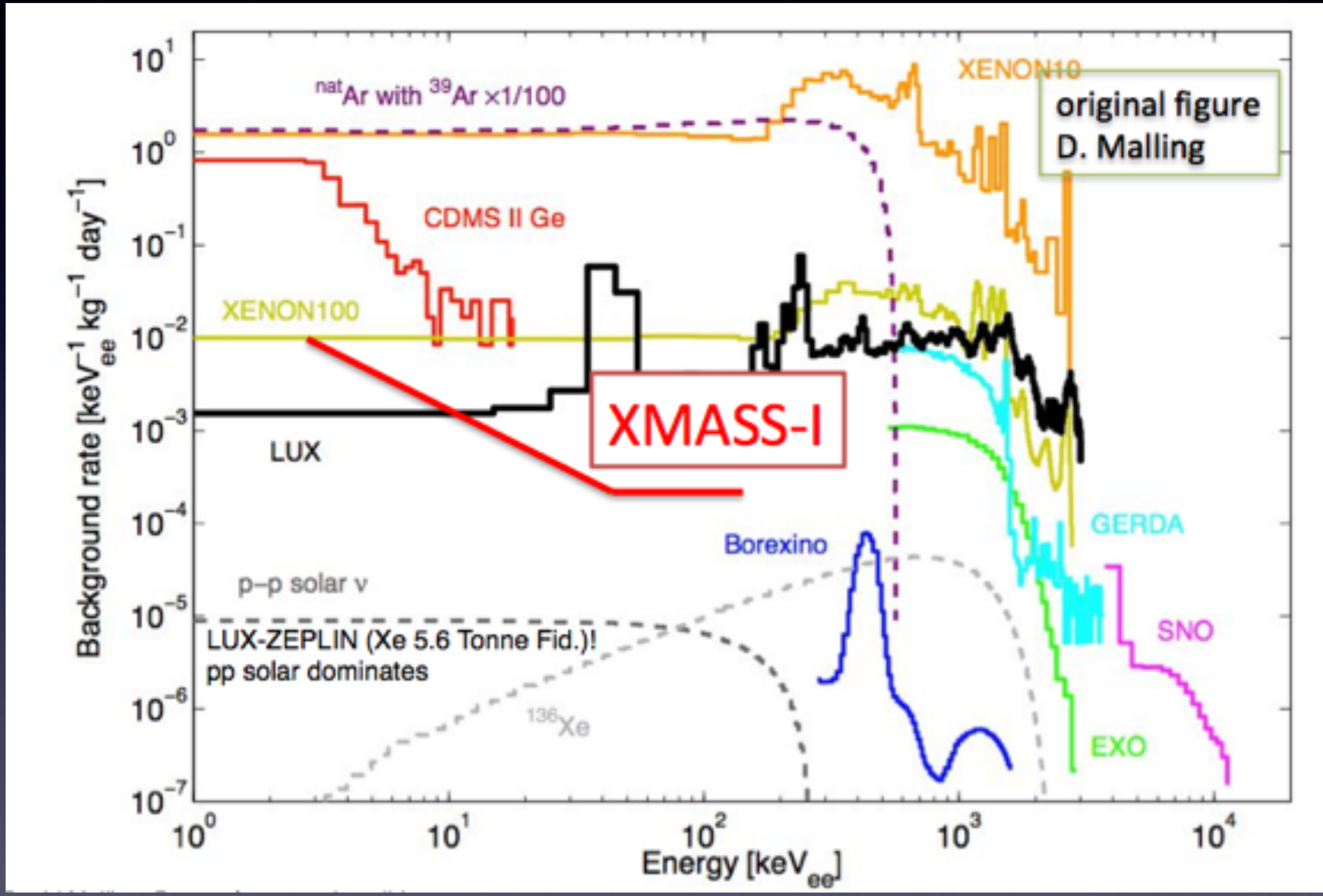


PMT R10789

Detector and its characteristic(2)

- **<u>Lowest BG rate at a few 10's keV</u>**
- XMASS achieved O(10^{-4}) events/day/kg/keV$_{ee}$ at a few 10's keV
  - Sensitive to WIMP inelastic scattering, bosonic super-WIMPs, 2ν double electron capture etc.
- Even modest background at low energy, XMASS has good sensitivity with a large mass and low energy threshold.

Background rate in the fiducial volume before separation of nuclear recoils from e/γ



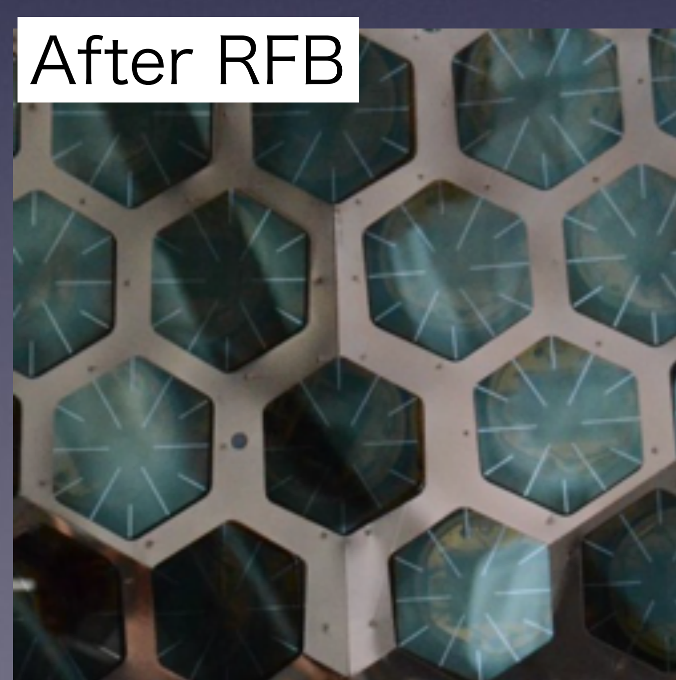
Added to D.C.Malling thesis (2014) Fig.1.5

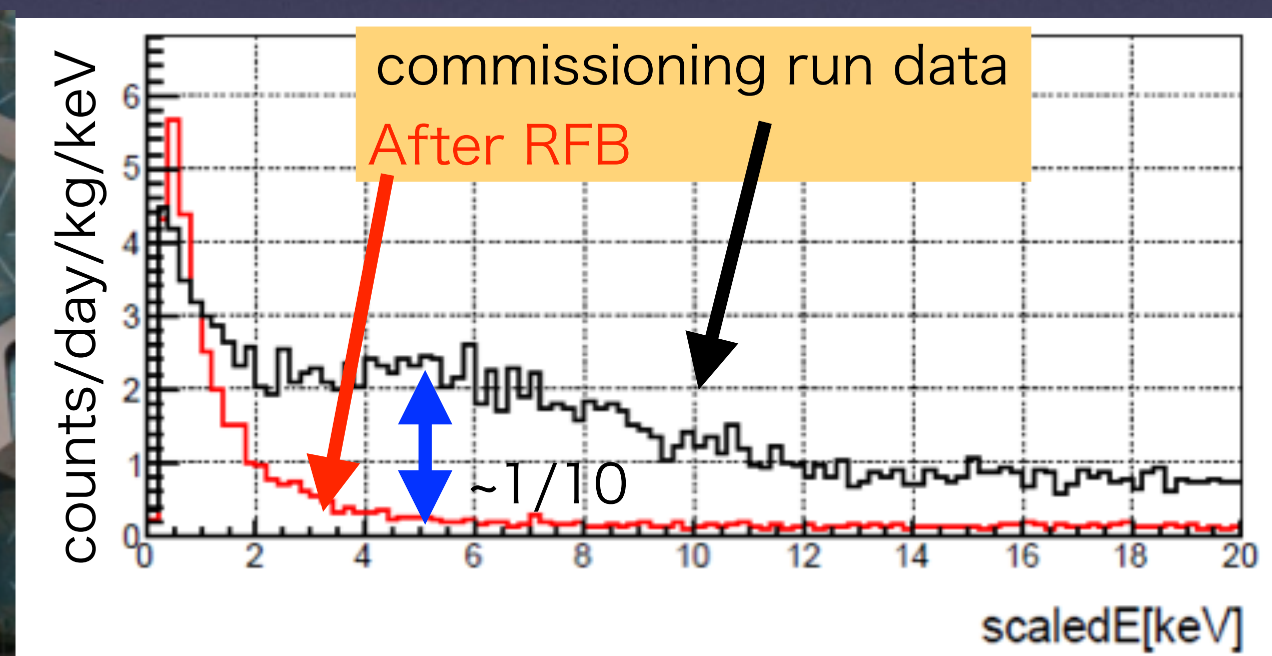
History of XMASS-I

Dec. 2010 | May 2012 | Nov. 2013

construction → commissioning run → Refurbishment → Data Taking resumed → **Now**

- PMT Al seal were covered by copper ring and plate to reduce BG as detector refurbishment
- After refurbishment, event ~5 keV is reduced to ~1/10.
- Now, the 3rd year continuity operation is ongoing.
  - **The longest running time among LXe detectors!**

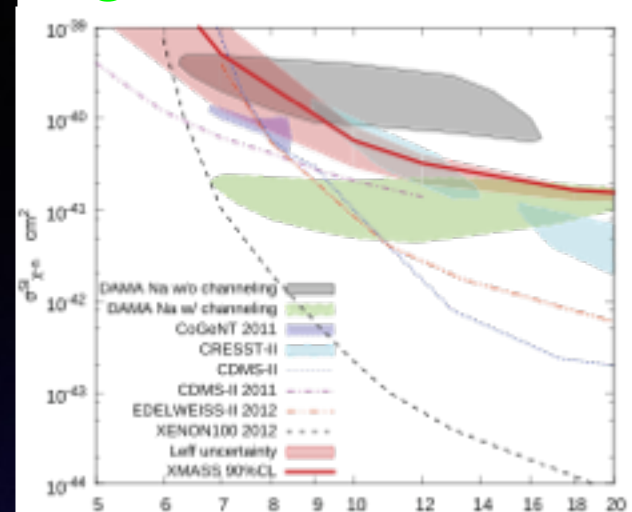




Diversity of physics in XMASS

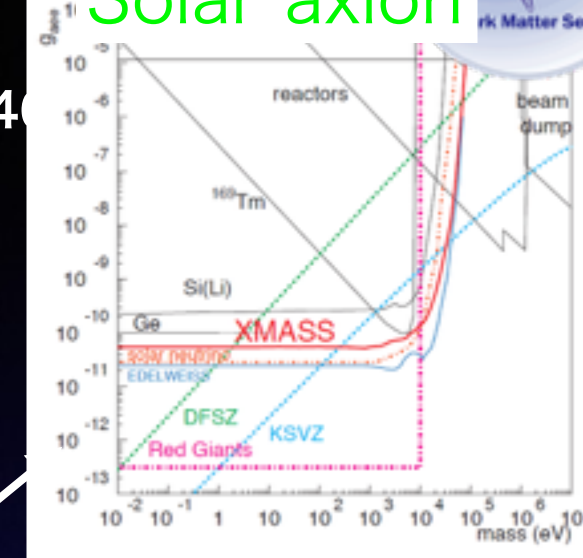
Light mass WIMP

Phys. Lett. B 719 (2013) 78

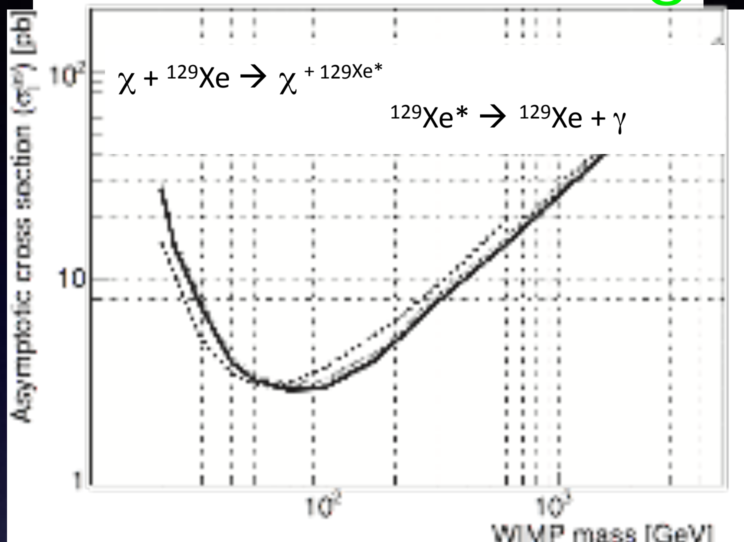


Solar axion

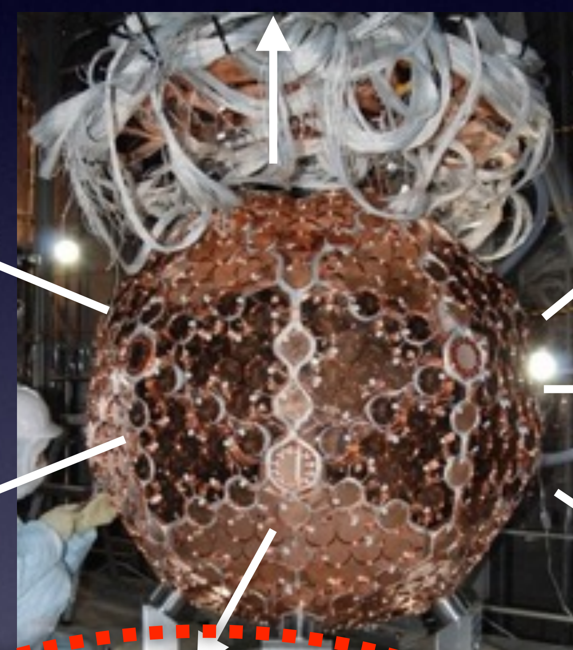
Phys. Lett. B 724 (2013) 46



Inelastic scattering



PTEP 2014, 063C01

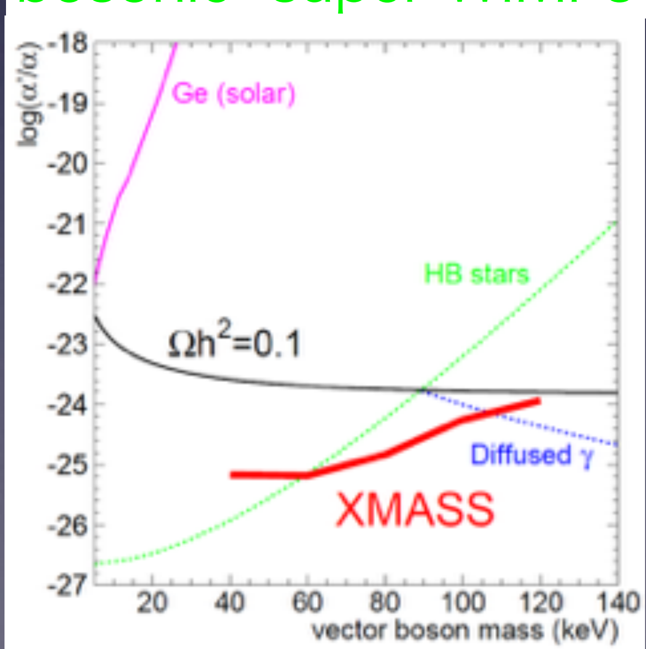


Supernova

arXiv:1604.01218

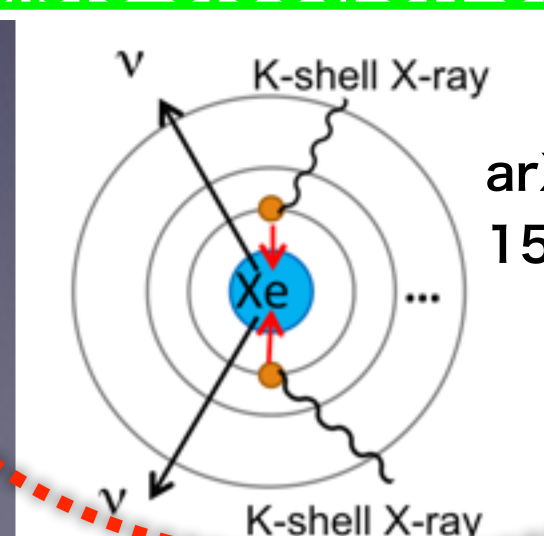
coherent elastic
ν-nucleus scattering

bosonic super-WIMPs



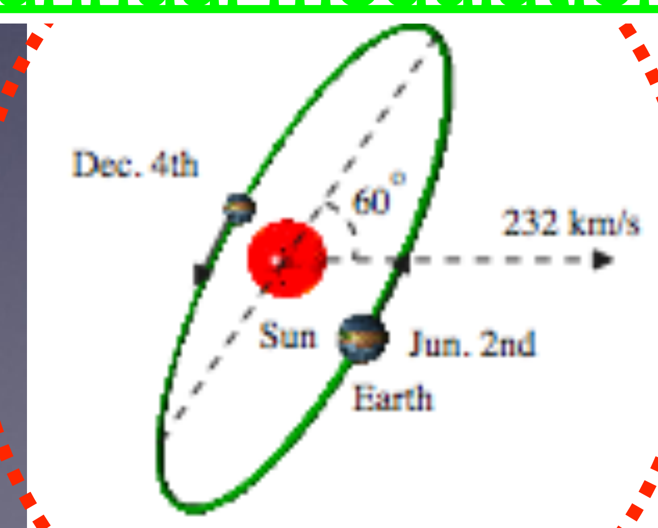
Phys. Rev. Lett.
113 (2014) 121301
Editor's Suggestion

Double electron capture



arXiv : 1510.00754

annual modulation

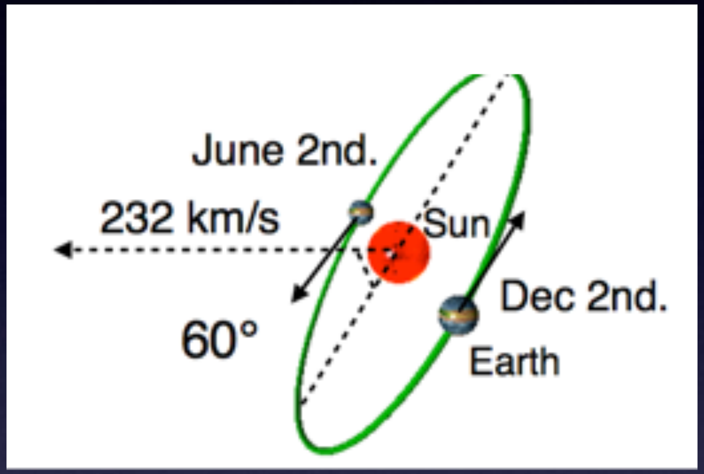


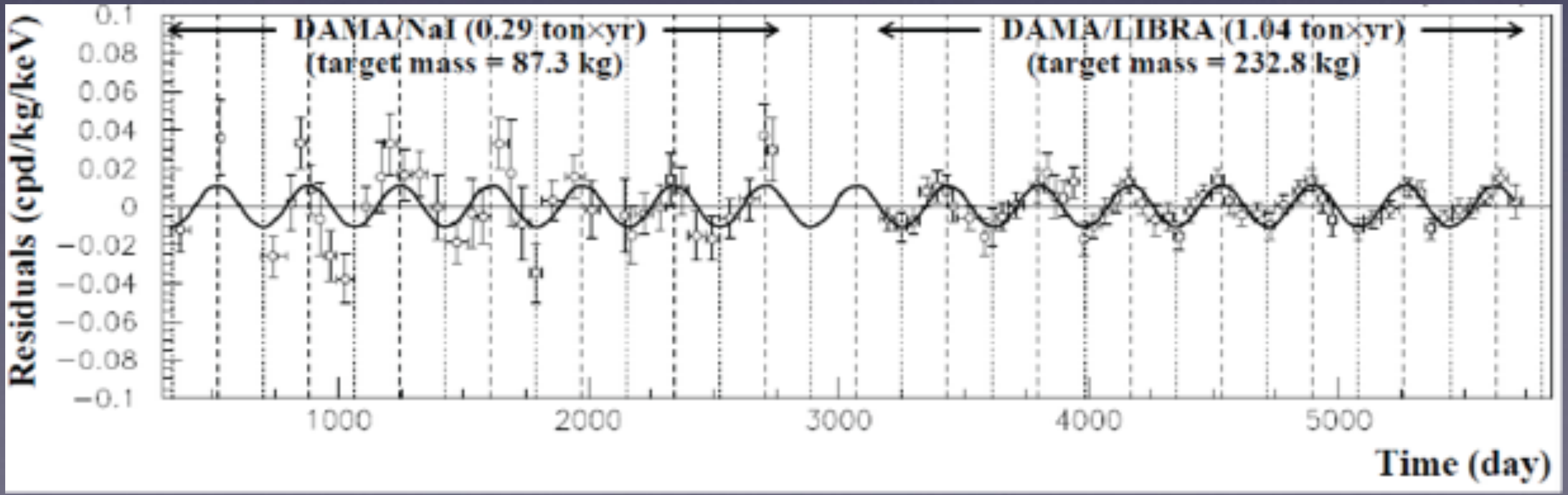
arXiv : 1511.04807

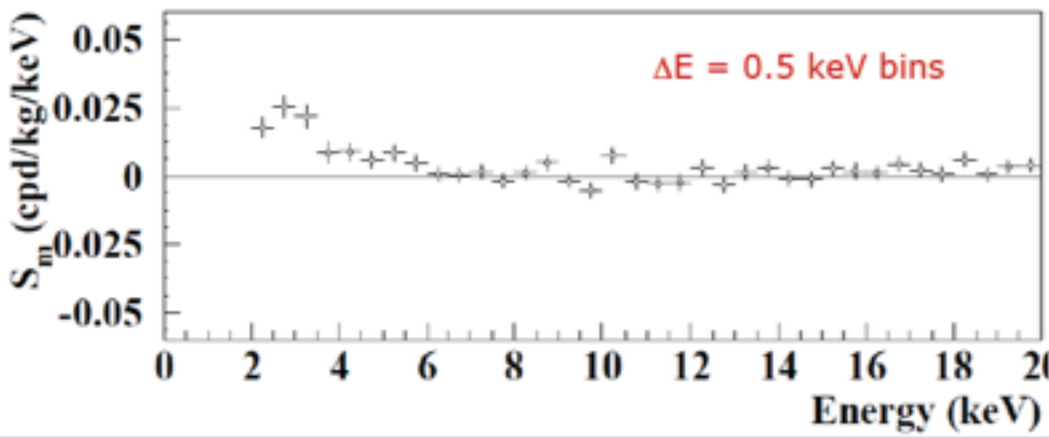
Direct dark matter search by annual modulation in XMASS-I

annual modulation

- Event rate of dark matter signal is expected to modulate annually due to relative motion of the Earth around the Sun
- Annual modulation claimed by DAMA/LIBRA
  - Total exposure : 1.33 ton・year, 14 cycles.
  - 9.3σ significance
  - Modulation amplitude : (0.0112±0.0012) cpd/kg/keV for 2-6 keV
  - No particle ID (including electron signals)
- XMASS-I annual modulation analysis
  - 1 year exposure (= 0.83 ton・year) is comparable exposure time.
  - Low analysis threshold (1.1 keV_{ee}) without particle ID



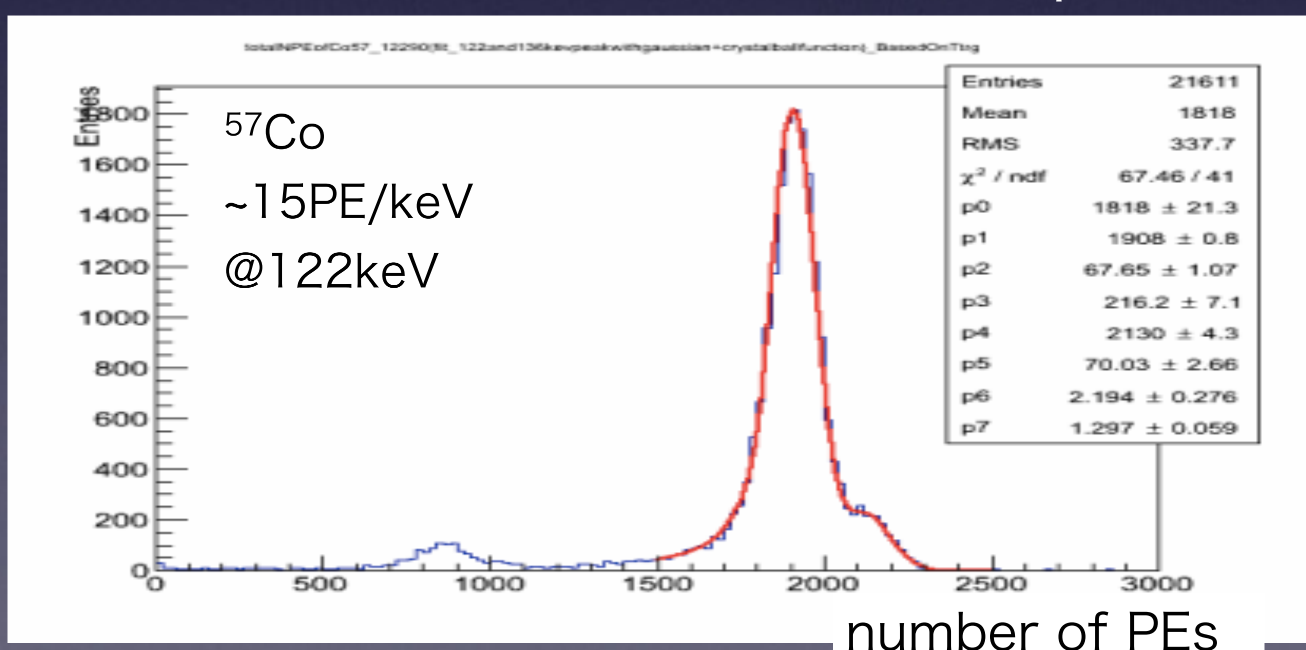


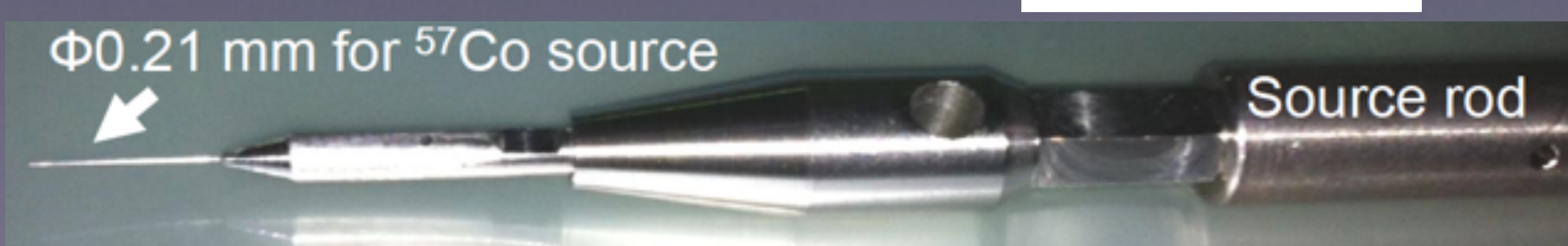


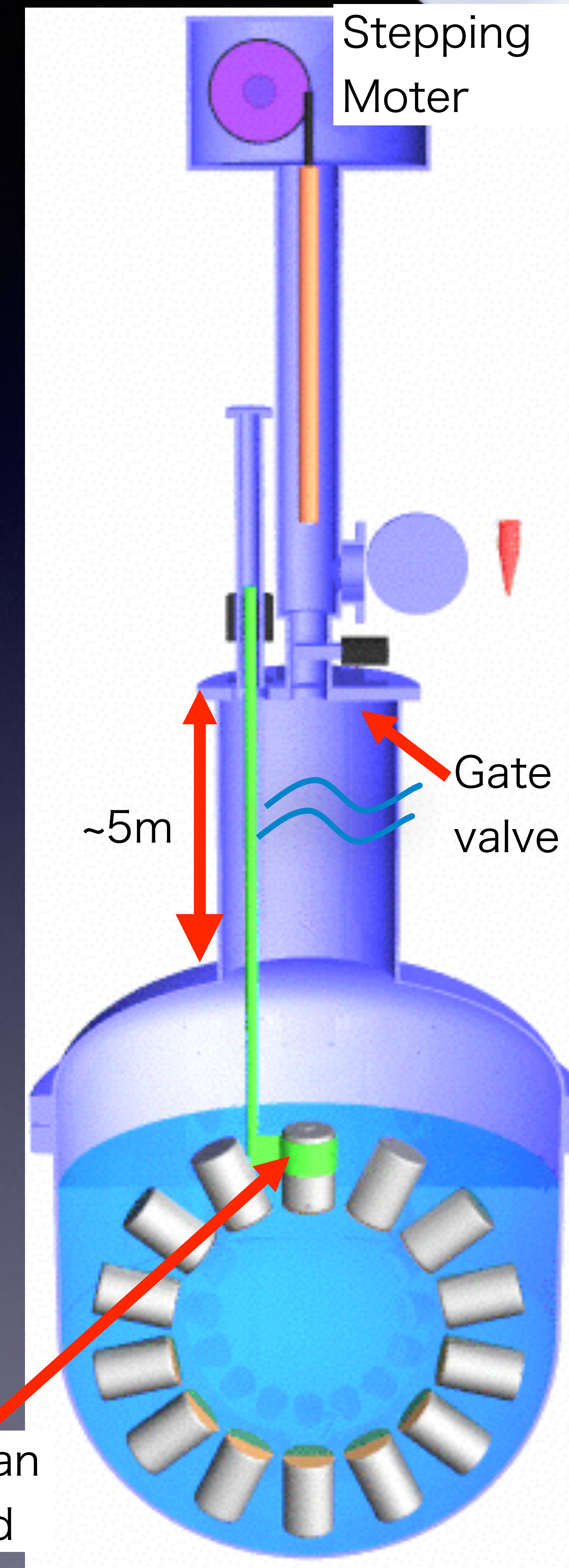
R. Bernabei et al., Eur. Phys. J. C (2013) 73:2648

Stability Check by Detector calibration

- Inner Calibration sources : ^{55}Fe, ^{109}Cd, ^{241}Am, ^{57}Co and ^{137}Cs
- The scintillation light yield response was traced by ^{57}Co 122 keV calibration data taken every (bi-)week, from Z=-40cm to +40cm
- Intrinsic light yield of the liquid xenon scintillator, absorption and scattering length for the scintillation light extracted from the data/MC comparison







Stability Check by Detector calibration

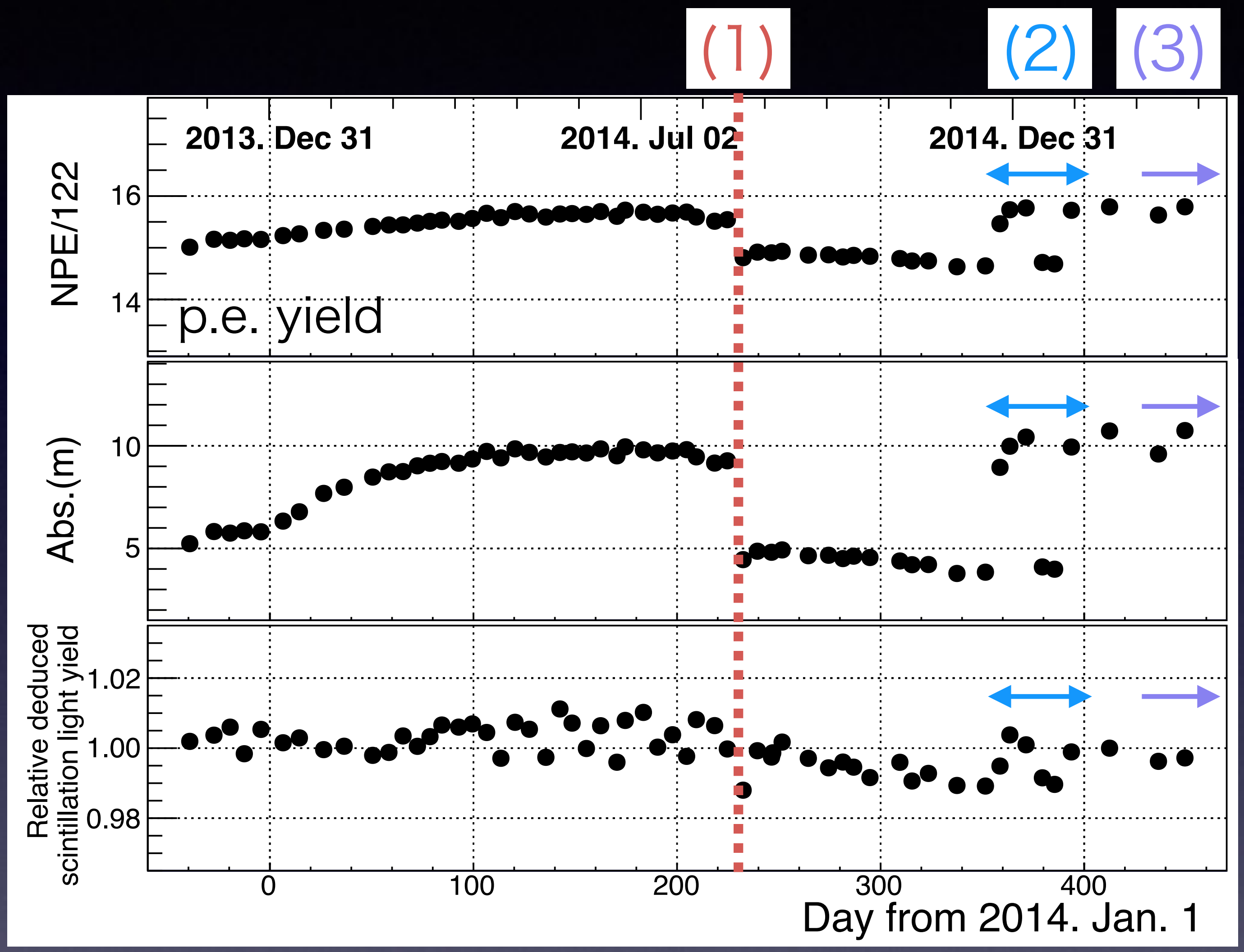
- From the ^{57}Co calibration data, We observed p.e. yield changes :

1)sudden drop at the power failure

2)It recovered after purification work in gas phase

3)we continuously circulate the gas purification

- We can trace observed p.e. yield change as a changes the absorption length.
- Absorption length change : 4m ~ 11m
- Scattering length : remains stable at 52cm
- Relative intrinsic light yield : stayed within ±0.6%
- Uncertainties due to this instability is taken into account.



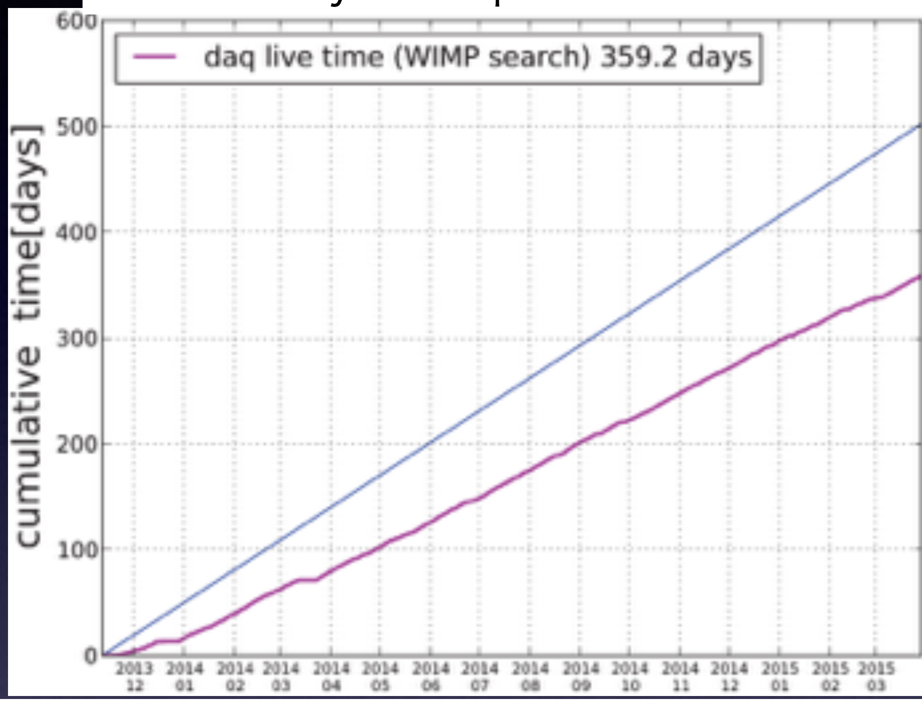
Data set & event selection

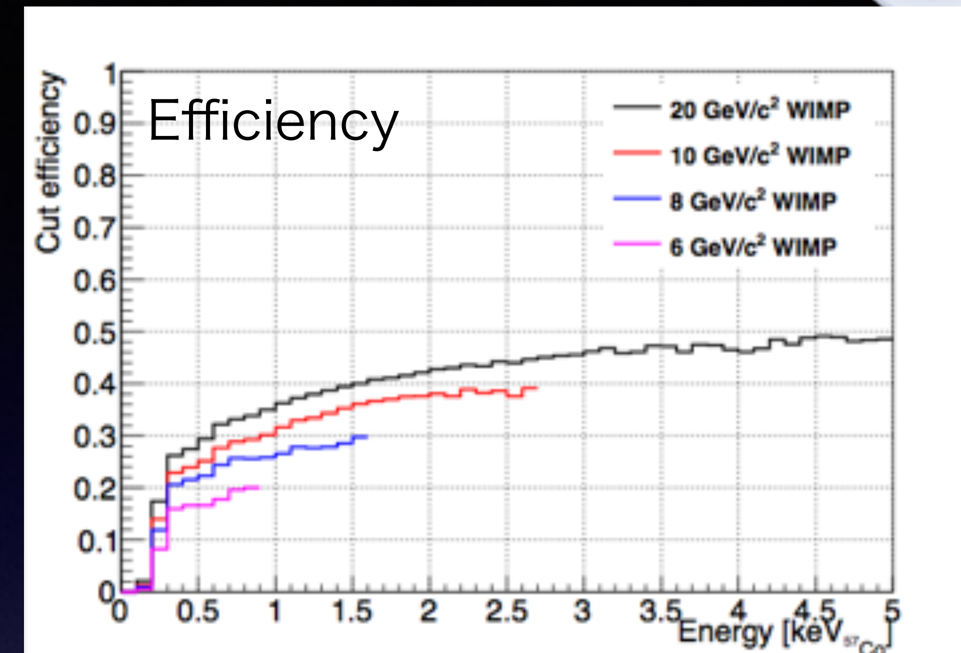
Nov. 20, 2013 - Mar. 29, 2015

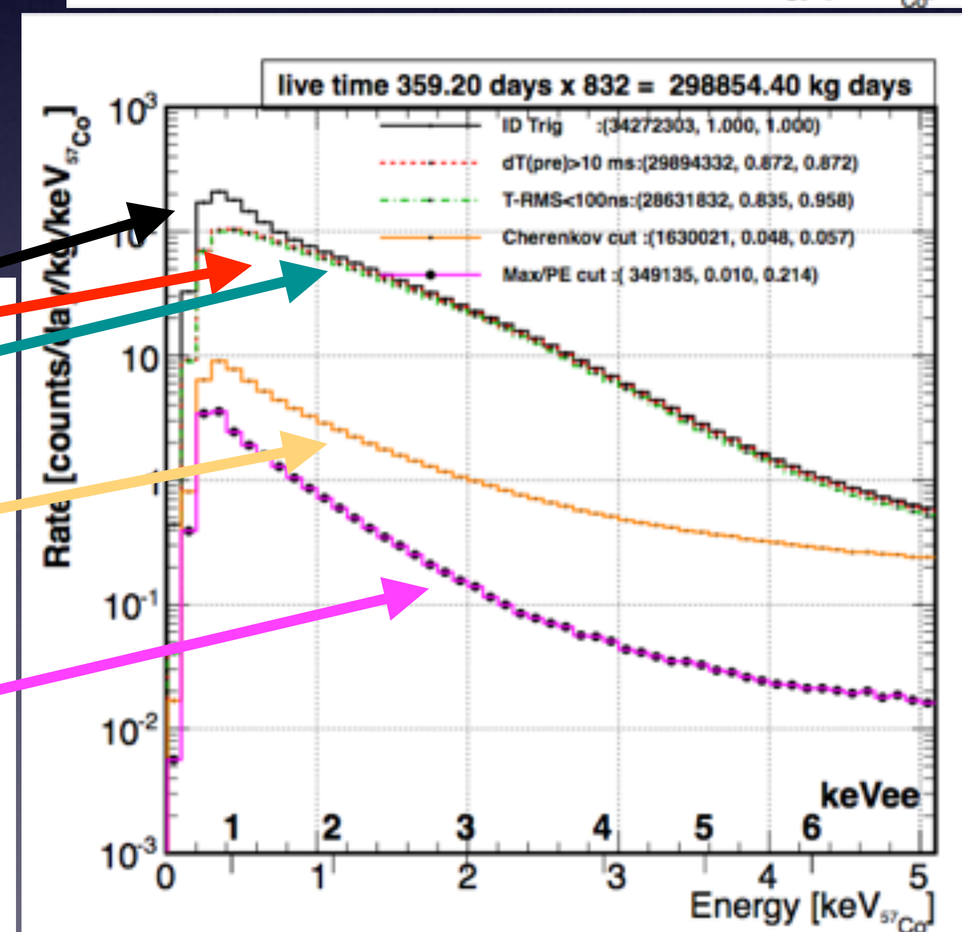
504.2 calendar days

359.2 live days for analysis

0.82 ton・year exposure



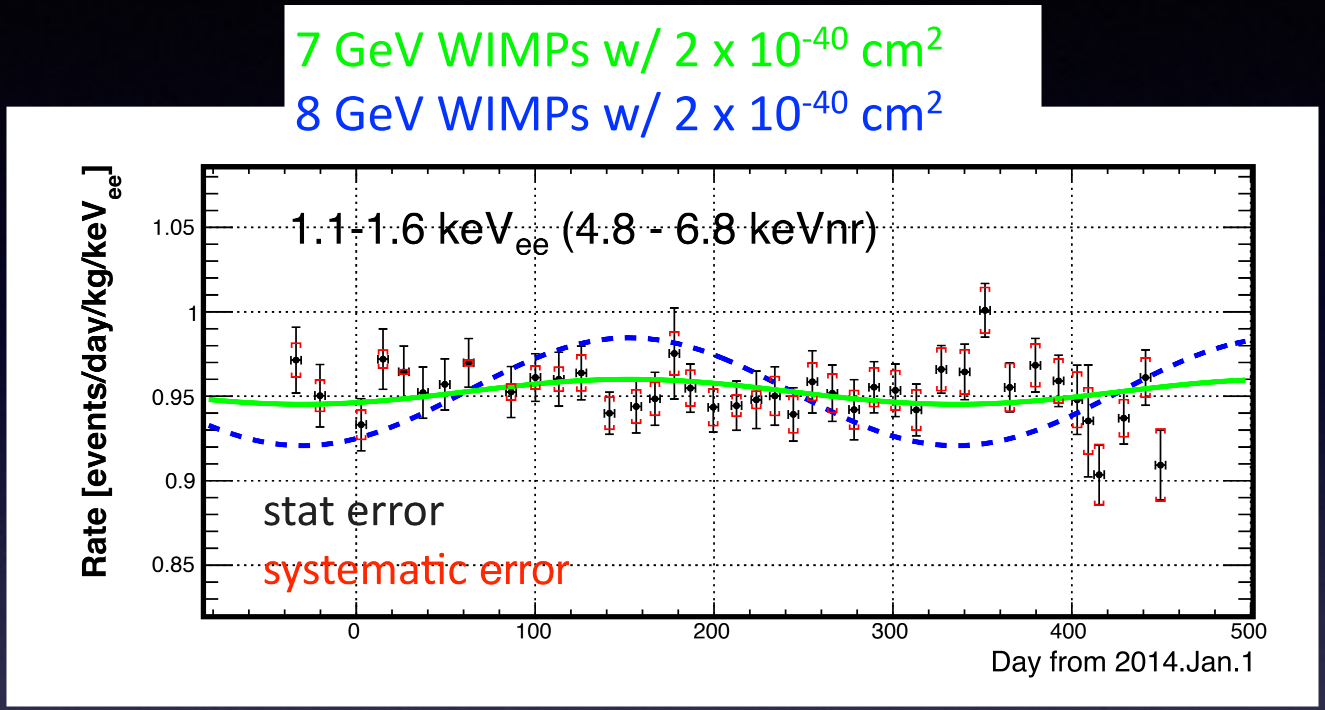




1. ID trigger event (≧4 hit), no outer detector hits.
2. Veto 10ms after the events
3. RMS of time hits < 100 ns
4. Remove Cherenkov events (orig. in glass)
   - remove events which have num. of hits in earlier 20ns > 60% of total hits.
5. Remove events in front of PMT
   - remove events which have higher maxPE/totalPE ratio

Modulation analysis method

- The data set was divided into 40 time-bin (roughly 10 days livetime each)
- The data in each time-bins were further divided into energy-bin (bin width = 0.5 keV_{ee})
- Two fitting methods were performed. Both of them fit all energy/time bins simultaneously
- Systematic error due to time dependence of light yield was treated by following two method as a relative efficiency difference



Method 1 : pull term

$$\chi^2 = \sum_{i}^{E_{bins}} \sum_{j}^{t_{bins}} \left(\frac{(R_{i,j}^{\rm data} - R_{i,j}^{\rm ex} - \alpha K_{i,j})^2}{\sigma({\rm stat})_{i,j}^2 + \sigma({\rm sys})_{i,j}^2} \right) + \alpha^2,$$

R^{data}: observed data, R^{ex}: expected rate

σ (stat) : statistical error, σ (sys) : systematic error

K_{ij} : 1 σ correlated syst. error on the expected event rate based on the relative cut effciency

Method 2 : covariance matrix

$$\chi^2 = \sum_{k,l}^{N_{\rm bins}} (R_k^{\rm data} - R_k^{\rm ex})(V_{\rm stat} + V_{\rm sys})_{kl}^{-1} (R_l^{\rm data} - R_l^{\rm ex}),$$

R^{data}: observed data, R^{ex}: expected rate, Nbins:Ebins x tbins

WIMP case

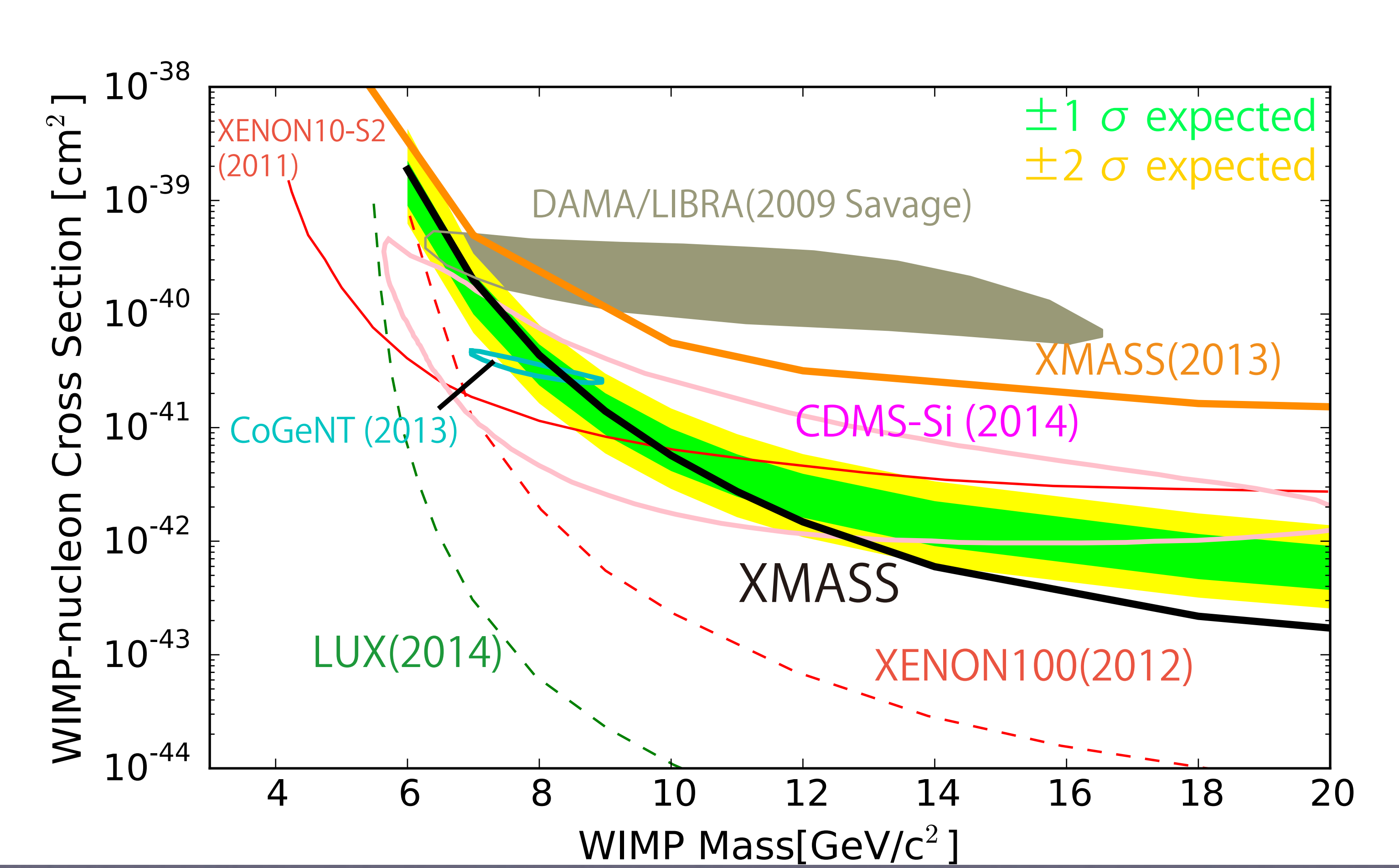
time variation data was fitted by:

$$R_{i,j}^{\mathrm{ex}} = \int_{t_j-\frac{1}{2}\Delta t_j}^{t_j+\frac{1}{2}\Delta t_j} \left(C_i + \sigma_{\chi n} \cdot A_i(m_\chi) \cos 2\pi \frac{(t-t_0)}{T}\right) dt,$$

A_i : Amplitude
C_i : Constant
σ_χ : WIMP-nucleus cross section
m_χ: WIMP mass
t_0 : 152.5 day
T : 1 year

- WIMP case :
  - Modulation amplitude becomes a function of the WIMP mass
  - 2D fitting (time and energy bin), Fitted in 1.1-15 keV_{ee} energy range
  - No significant signal, derived < 4.3×10^{-41} cm^2 at 8 GeV (90% C.L.)
  - **DAMA/LIBRA region is mostly excluded by annual modulation search**

V_0 : 220 km/s
V_{esc} : 650 km/s
ρ_{dm} = 0.3 GeV/cm3
V_{esc} : 544 km/s gives < 5.4×10^{-41} cm^2

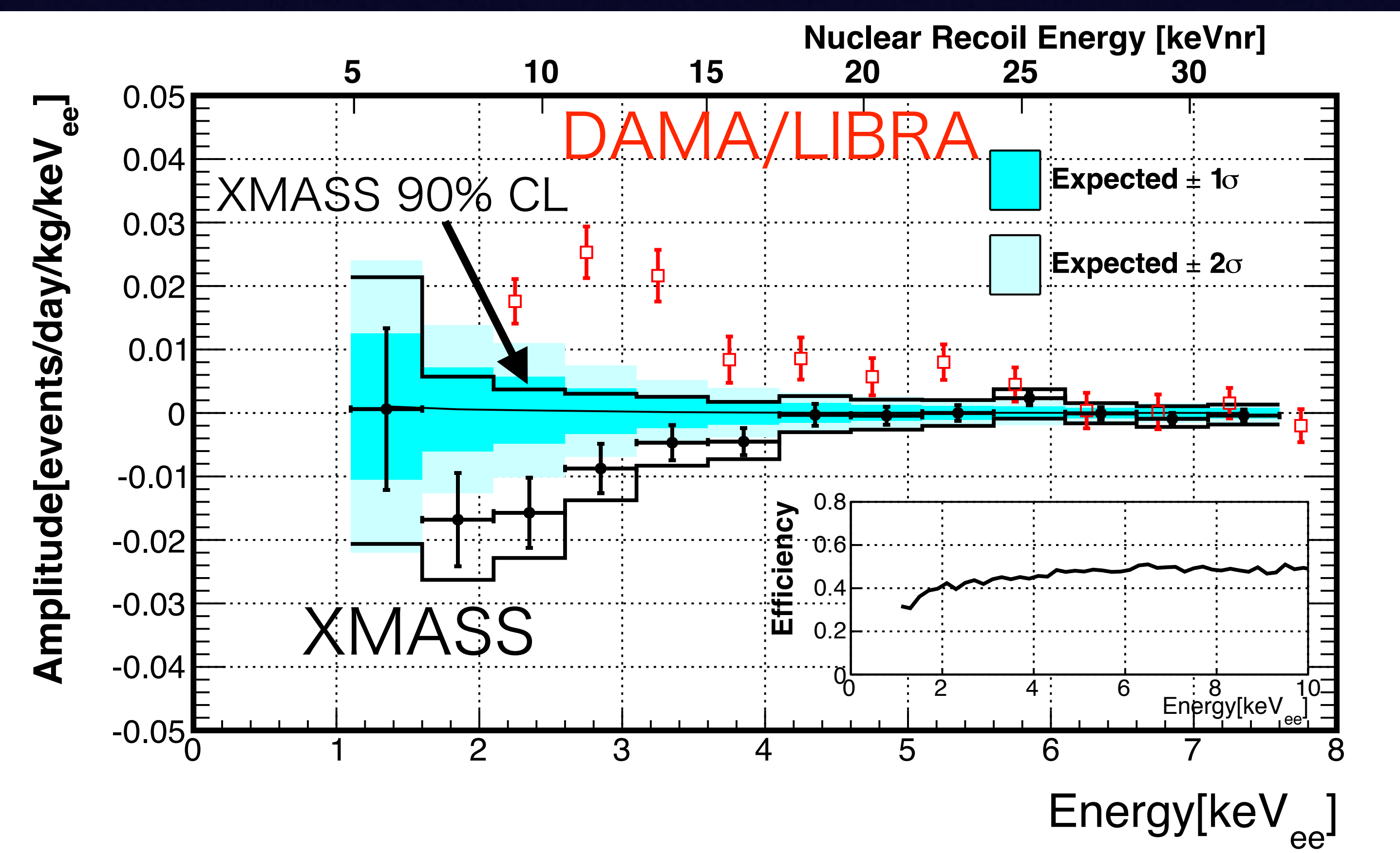


Model independent case

time variation data was fitted by:

$$R^{\mathrm{ex}}_{i,j} = \int_{t_j - \frac{1}{2}\Delta t_j}^{t_j + \frac{1}{2}\Delta t_j} \left(C_i + A_i \cos 2\pi \frac{(t - t_0)}{T} \right) dt$$

A_i : Amplitude(free)
C_i : Constant (free)
t_0 : 152.5 day
T : 1 year

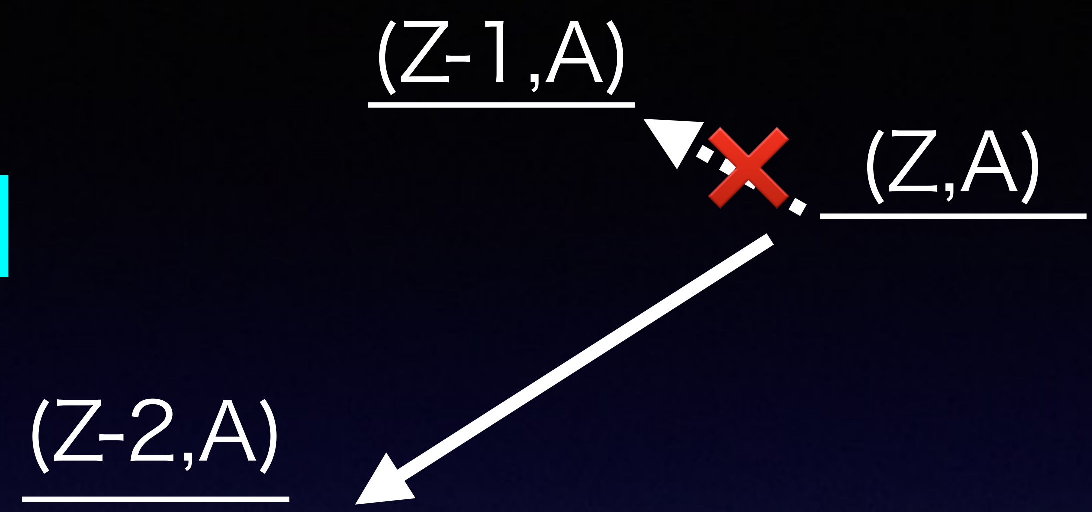


- Independent of any specific dark matter model
- 1.1-7.6 $\mathrm{keV_{ee}}$ energy range was used for fitting procedure
- Significance was evaluated with test statistic (10,000 samples) and no significant modulated signal has been observed. (p-value = 0.014 (2.5 σ), 0.068(1.8 σ) for 2 fitting method)
- (1.7 - 3.7) x 10^{-3} counts/day/kg/$\mathrm{keV_{ee}}$ in 2-6 $\mathrm{keV_{ee}}$ (0.5 $\mathrm{keV_{ee}}$ bin width, 90% C.L. Bayesian)
  - 0.02 counts/day/kg/$\mathrm{keV_{ee}}$ by DAMA/LIBRA, closed to XENON100 sensitivity
  - More stringent constraint
- Another one year cycle data with more stable data has been taken.

Search for two-neutrino double electron capture on ^{124}Xe with the XMASS-I detector

double electron capture

$(Z,A)+2e^{-}\rightarrow(Z-2,A)+(2\nu_e)$

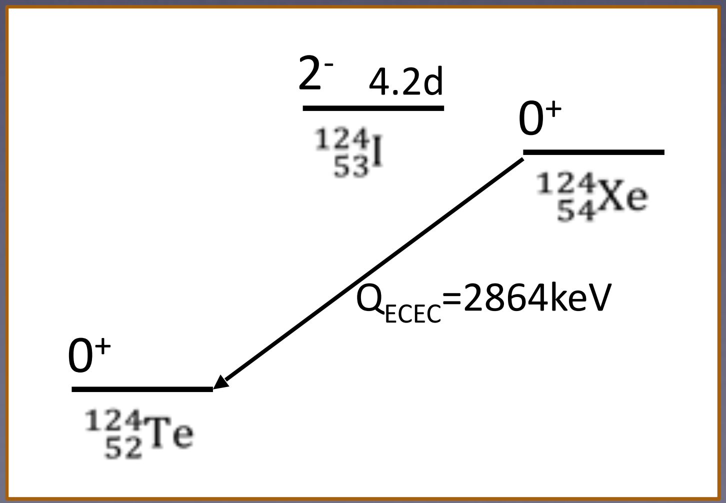


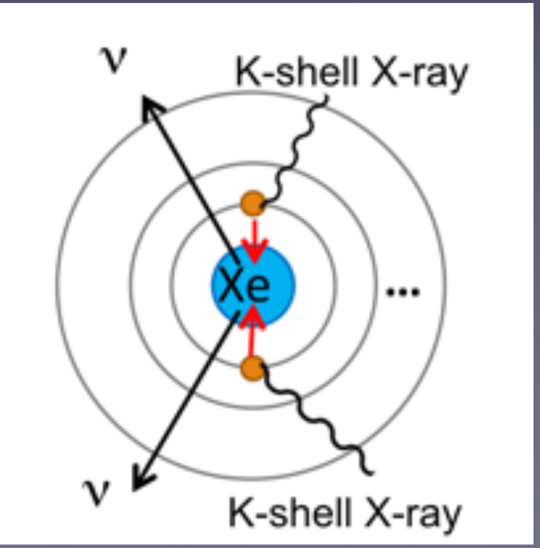
- Two orbital electrons are captured simultaneously
- 2ν mode : allowed in the standard model, but there exists only a few experimental result :
  - ^{130}Ba : $T_{1/2}$ = (2.2±0.5)x10^{21} years
  - ^{78}Kr : $T_{1/2}$ = $(9.2^{+5/5}{}_{-2.6}$(stat)±1.3(sys))x10^{21} years
  - Any measurement of 2ν mode will provide a new reference for the calculation of nuclear matrix elements from the proton-rich side of the mass parabola of even-even isobars
- 0ν mode : lepton number violating process as well as $0\nu\beta\beta$ decay

^{124,126}Xe 2ν double electron capture

Isotope	^{124}Xe	^{126}Xe	^{128}Xe	^{129}Xe	^{130}Xe	^{131}Xe	^{132}Xe	^{134}Xe	^{136}Xe
n.a.	0.095%	0.089%	1.9%	26.4%	4.1%	21.2%	26.9%	10.4%	8.9%

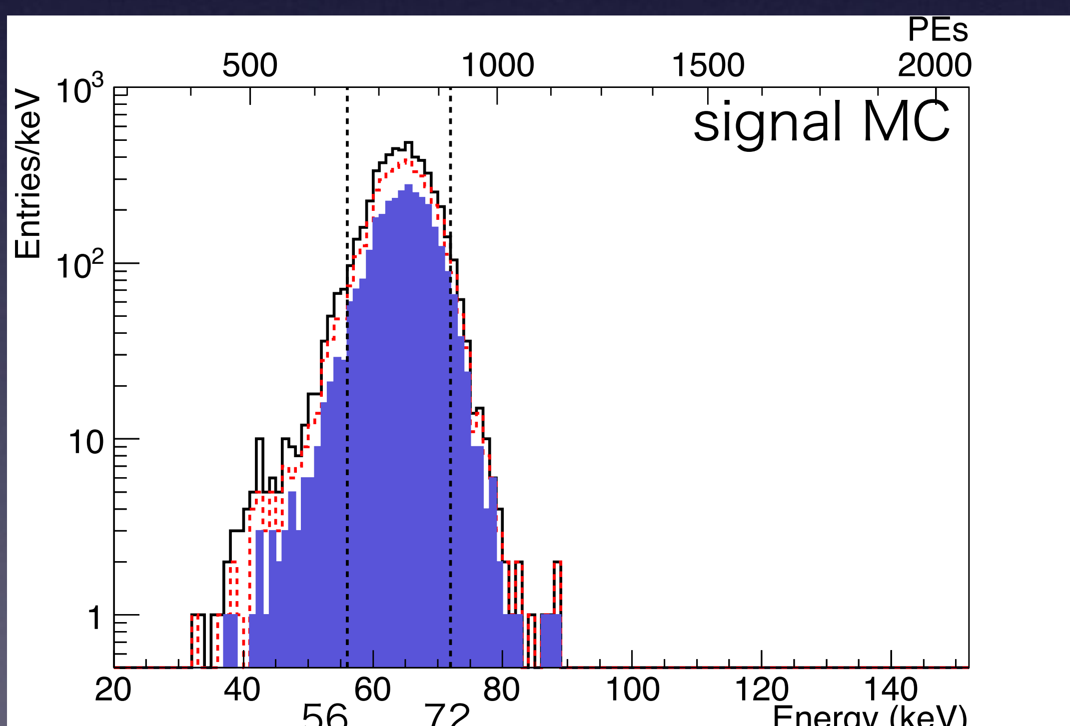
- Natural xenon contains <u>double electron capture nuclei</u> as well as double beta decay nuclei
- ^{124}Xe 2ν double electron capture (2νECEC) :
  - <u>**^{124}Xe (g.s., 0^+) + $2e^-$ → ^{124}Te (g.s., 0^+) + $2\nu_e$ + 2864 keV**</u>
  - In case that 2 K-shell electron capture, signal is total energy deposition of 63.6 keV from atomic X-rays and Auger electrons.
  - Theoretical prediction of $T_{1/2}^{2\nu 2K}$(^{124}Xe) : 10^{20} ~ 10^{24} year
  - experimental results : $T_{1/2}^{2\nu 2K}$(^{124}Xe) > 2.0×10^{21} years (90% C.L.), w/ proportional counter
- ^{126}Xe can also undergo 2νECEC, but this reaction is much slower (Q_{ECEC} = 896 keV)



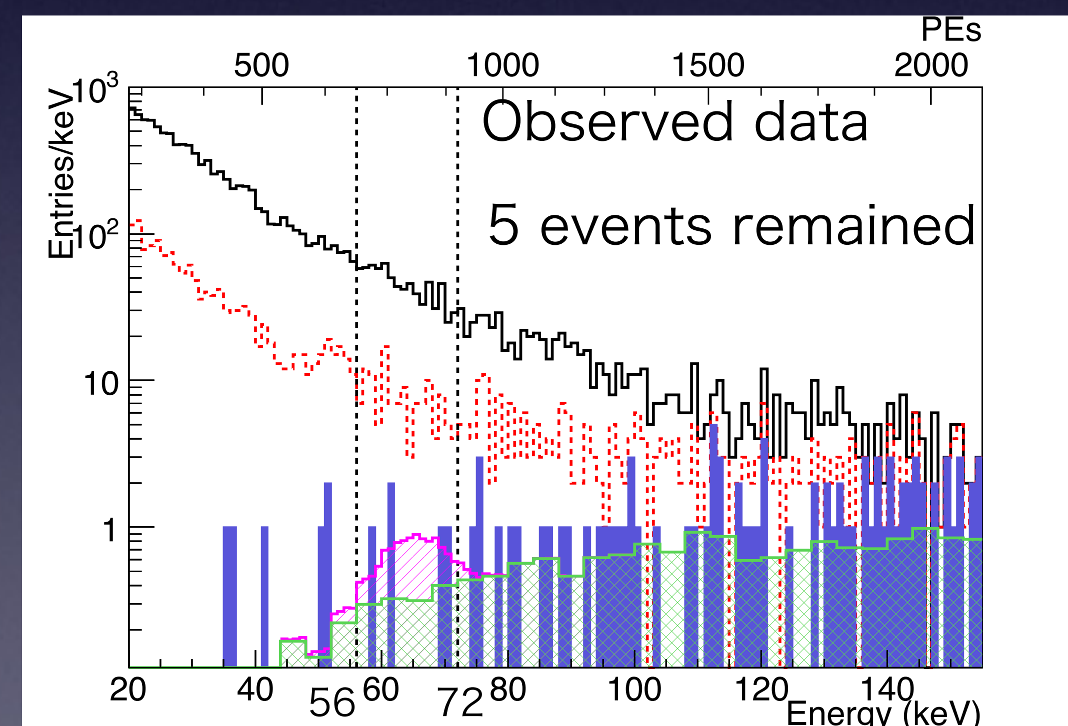


^{124,126}Xe 2ν double electron capture

- Signal MC :
  - X-rays and Auger electrons after 2ν 2K capture are simulated
  - The energy window (56-72 keV) is determined so that it contains 90% of the simulated signal
  - Signal Detection efficiency = 59.7%
- Data set : 165.9 days LiveTime commissioning run data, R ≦ 15cm fiducial volume (41kg natural Xe, 39g ^{124}Xe, 36g of ^{126}Xe)
  - 5 events are left in the signal region after all cuts



(1)Pre-Selection+ 15cm radius cut
(2) (1)+ Timing cut
(3) (2)+ Band-like pattern cut

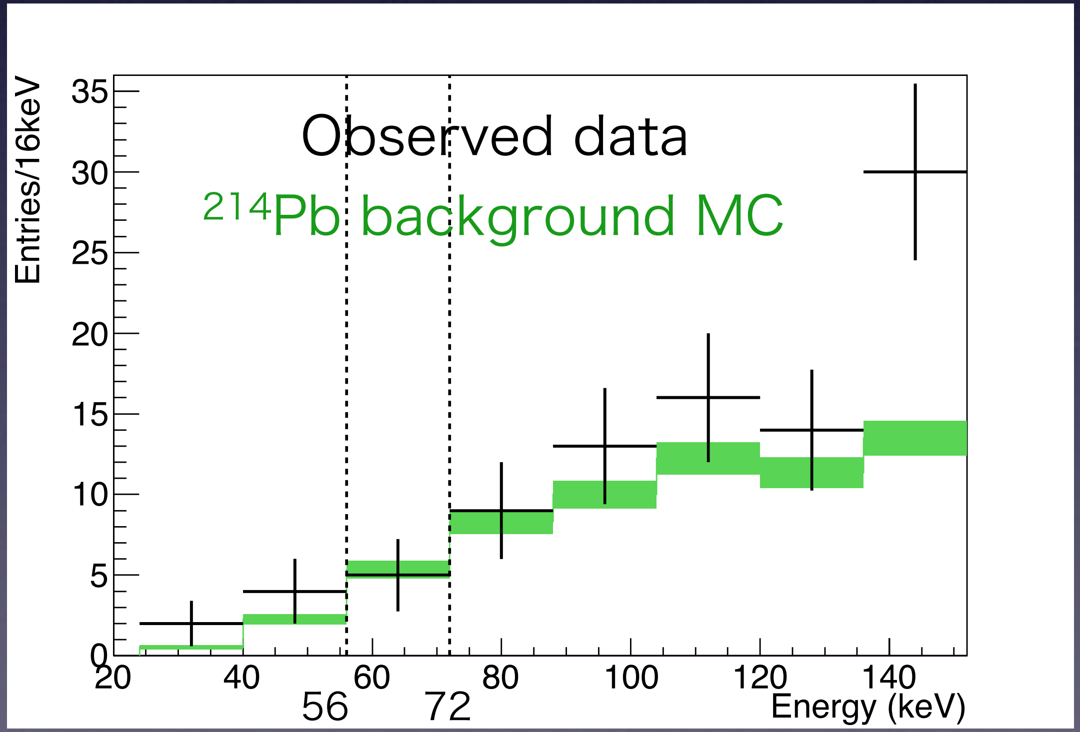


(1)Pre-Selection+ 15cm radius cut
(2) (1)+ Timing cut
(3) (2)+ Band-like pattern cut

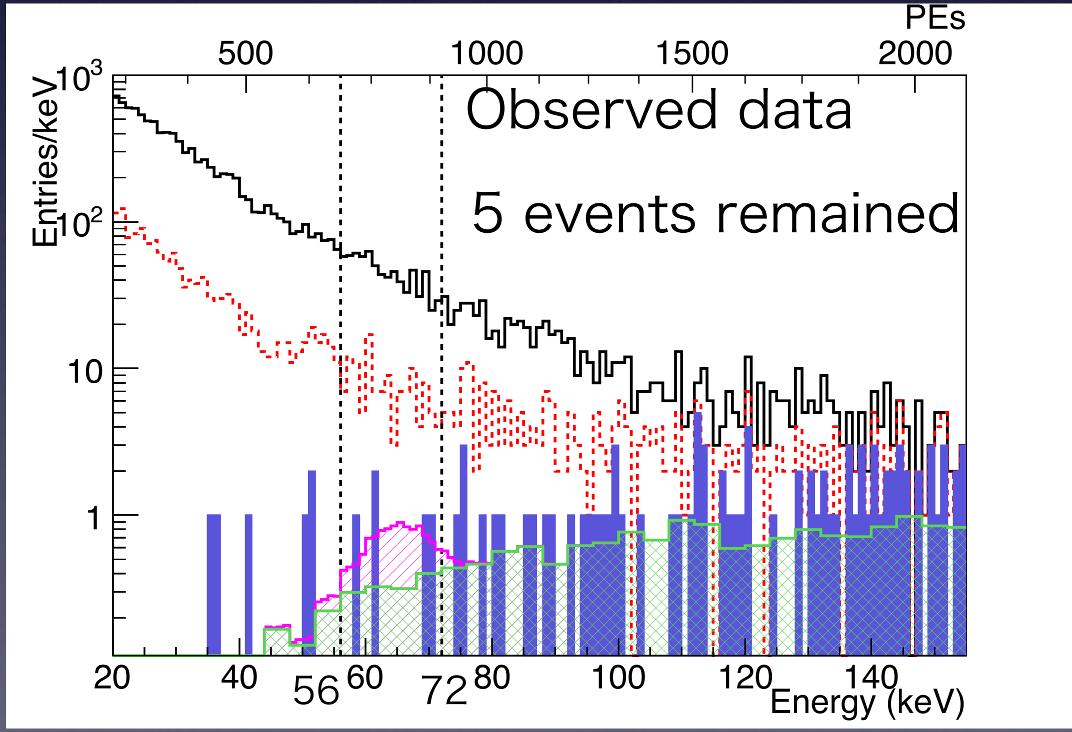
Expected signal with $T_{1/2}(2\nu 2K) = 4.7 \times 10^{21}$ yr.
Expected ^{214}Pb background

^{124,126}Xe 2ν double electron capture

- The main contribution to the remaining BG is the ^{214}Pb (^{222}Rn : 8.2±0.5 mBq/det.)
  - Expected ^{214}Pb BG is 5.3±0.5 events, no significant excess above BG was observed
- **We set the world best limit on the half life :**
  - **$T_{1/2}^{2\nu 2K}(^{124}Xe) > 4.7\times10^{21}$ years (90% C.L.)**
  - **$T_{1/2}^{2\nu 2K}(^{126}Xe) > 4.3\times10^{21}$ years (90% C.L.)**



Excess in the highest bin :
due to γ ray from ^{131m}Xe (163.9 keV)



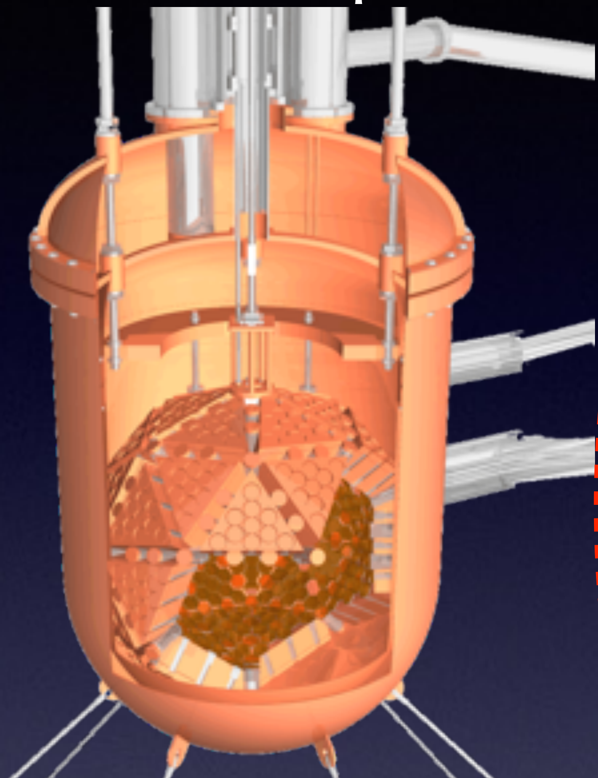
(1)Pre-Selection+ 15cm radius cut
(2) (1)+ Timing cut
(3) (2)+ Band-like pattern cut

Expected signal with $T_{1/2}(2\nu 2K) = 4.7\times10^{21}$ yr.
Expected ^{214}Pb background

Future of XMASS,
Toward next phase : XMASS-1.5

Toward XMASS1.5 and II

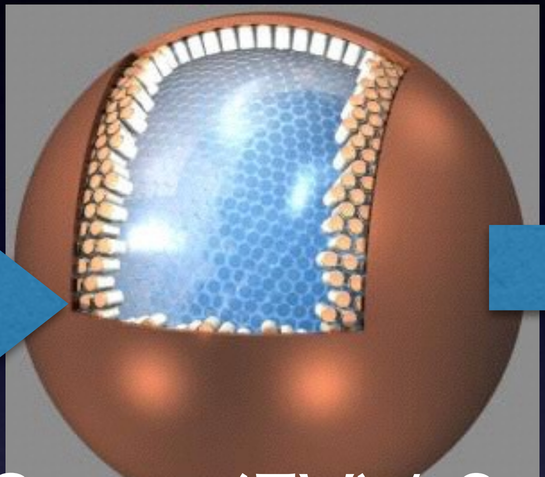
XMASS-I
Current phase



100kg (FV)/832 kg
80cm ϕ

DM search

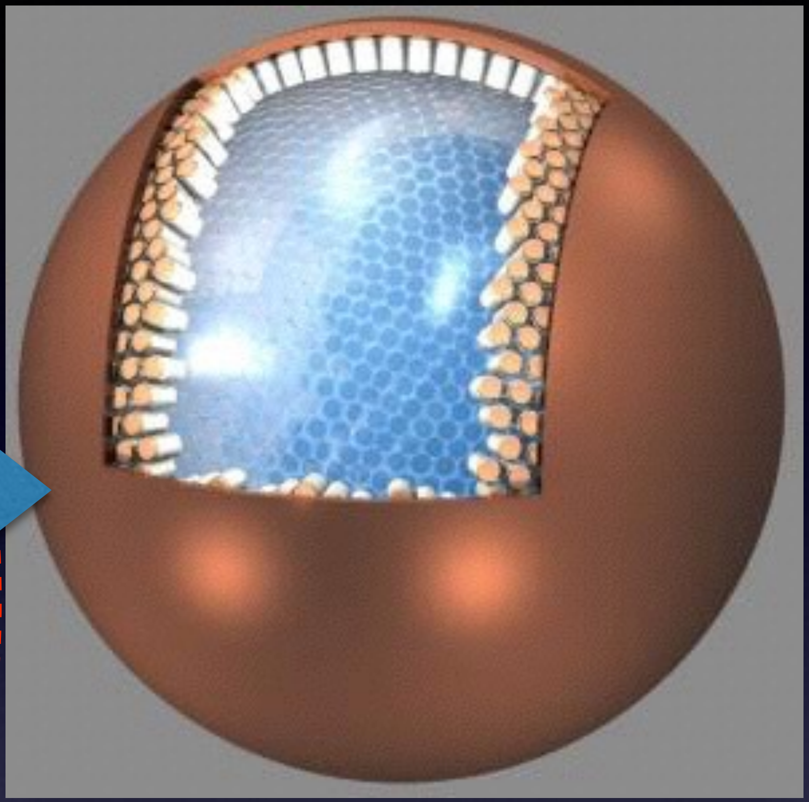
XMASS 1.5
next phase



1~3 ton (FV)/ 6 ton
1.5m ϕ

DM search
$\sigma_{SI} < 10^{-46}$ cm^2
pp solar neutrinos
~a few events/day

XMASS-II



>10 ton (FV)/ 24 ton

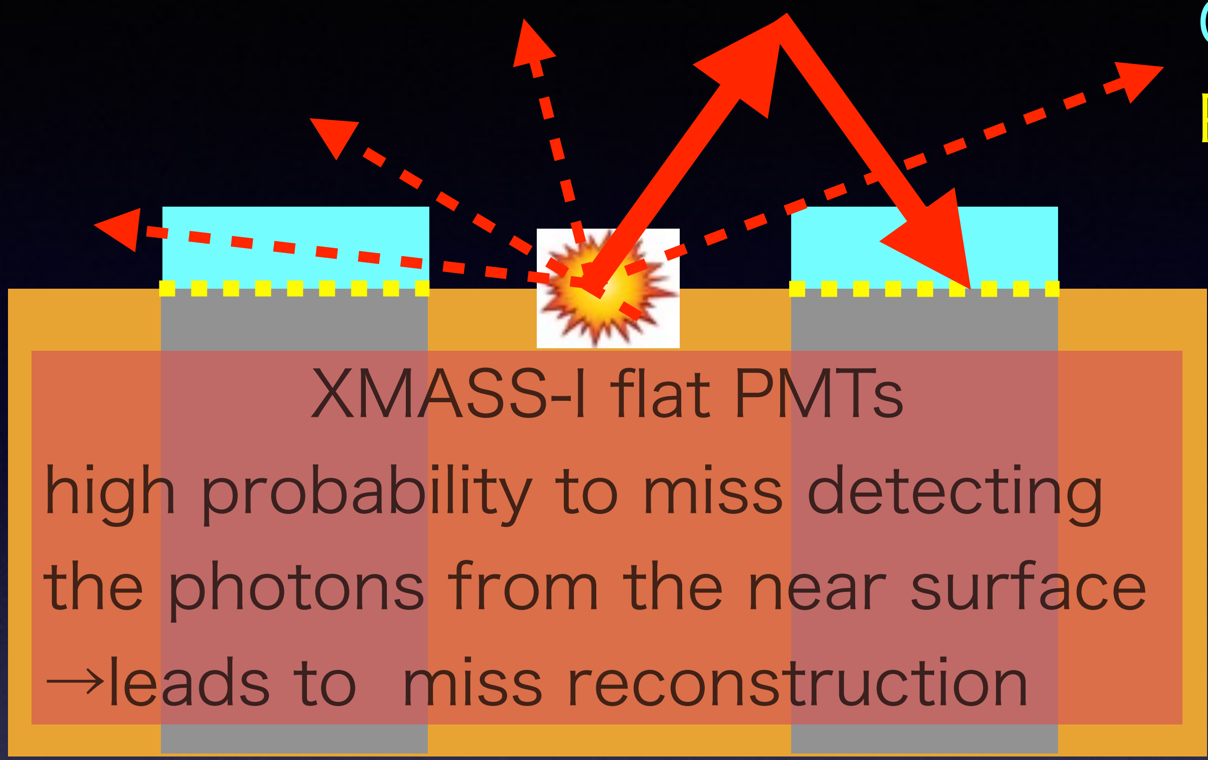
Multi purpose :
DM search $\sigma_{SI} < 10^{-48}$ cm^2
pp-solar neutrinos: 10 cpd
double-beta decay of ^{136}Xe

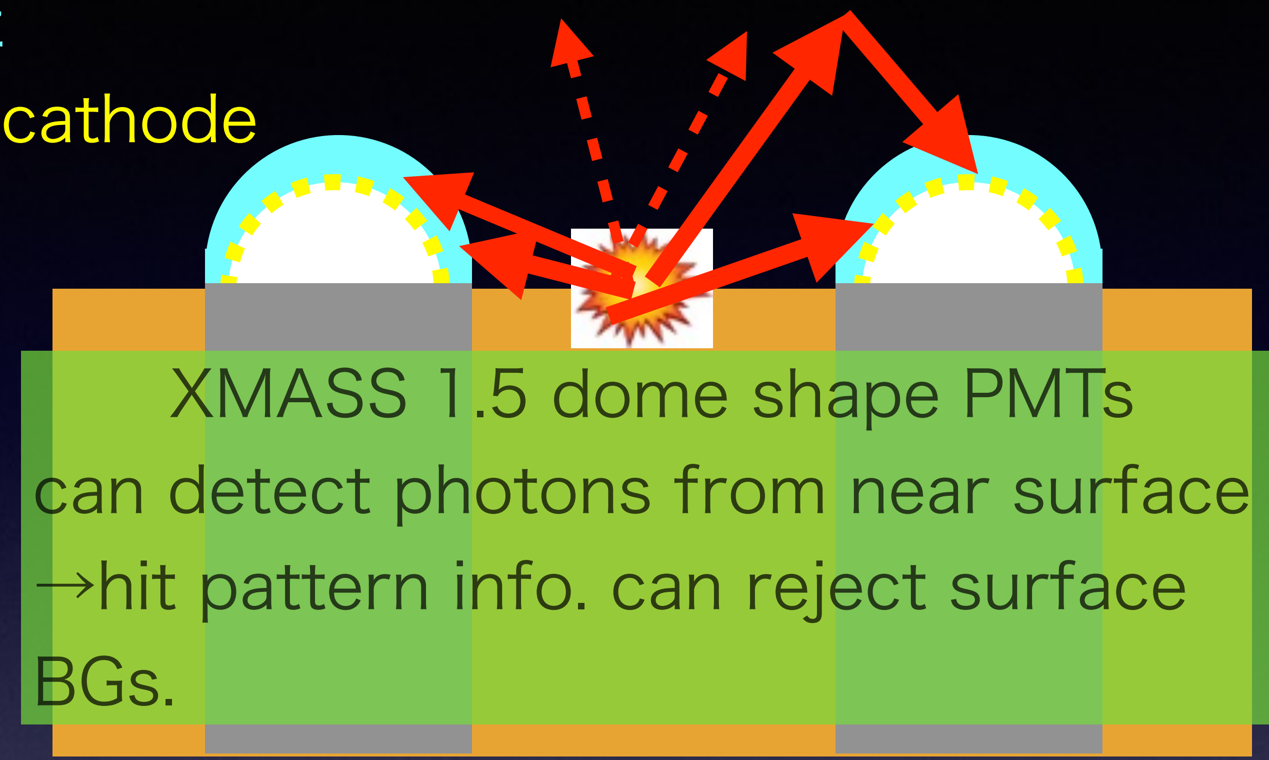
✓ To improve the sensitivity,
- increase the fiducial volume
- discriminate against BG events,especially surface BG
- select ultra low BG detector material

are needed

surface BG identification

Scintillation Photons
Quartz
Photo cathode



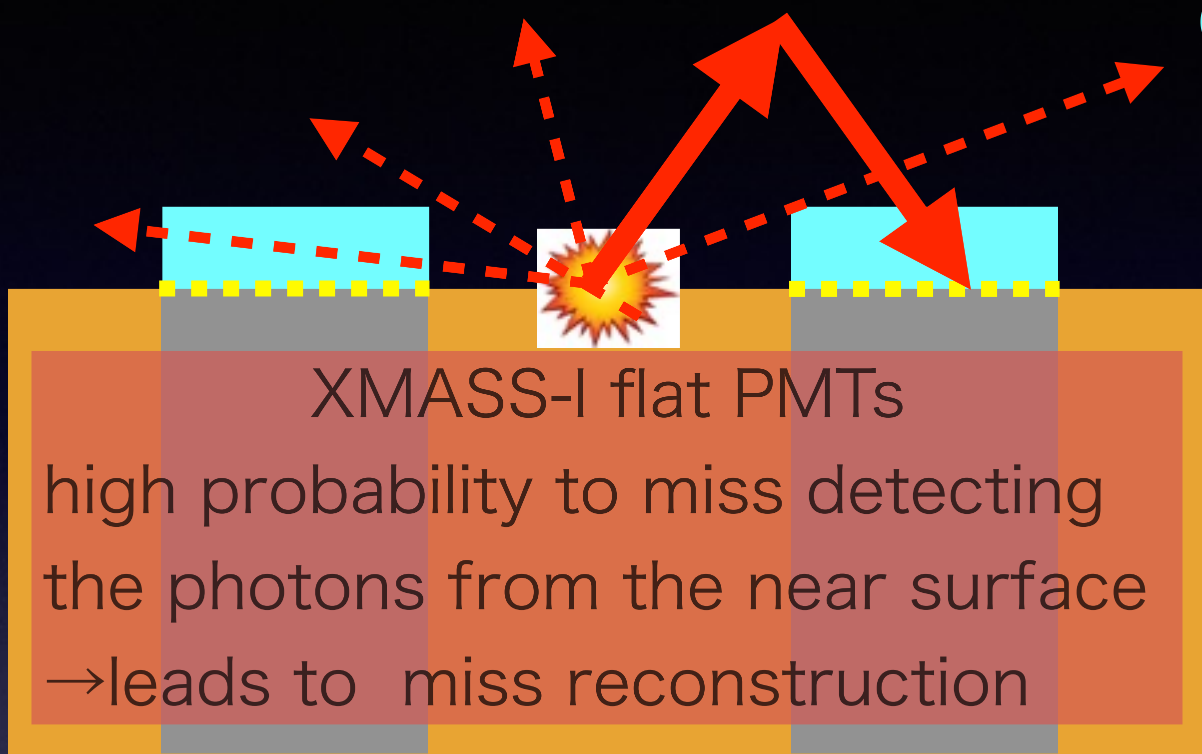


flat window 2-inch PMT R10789

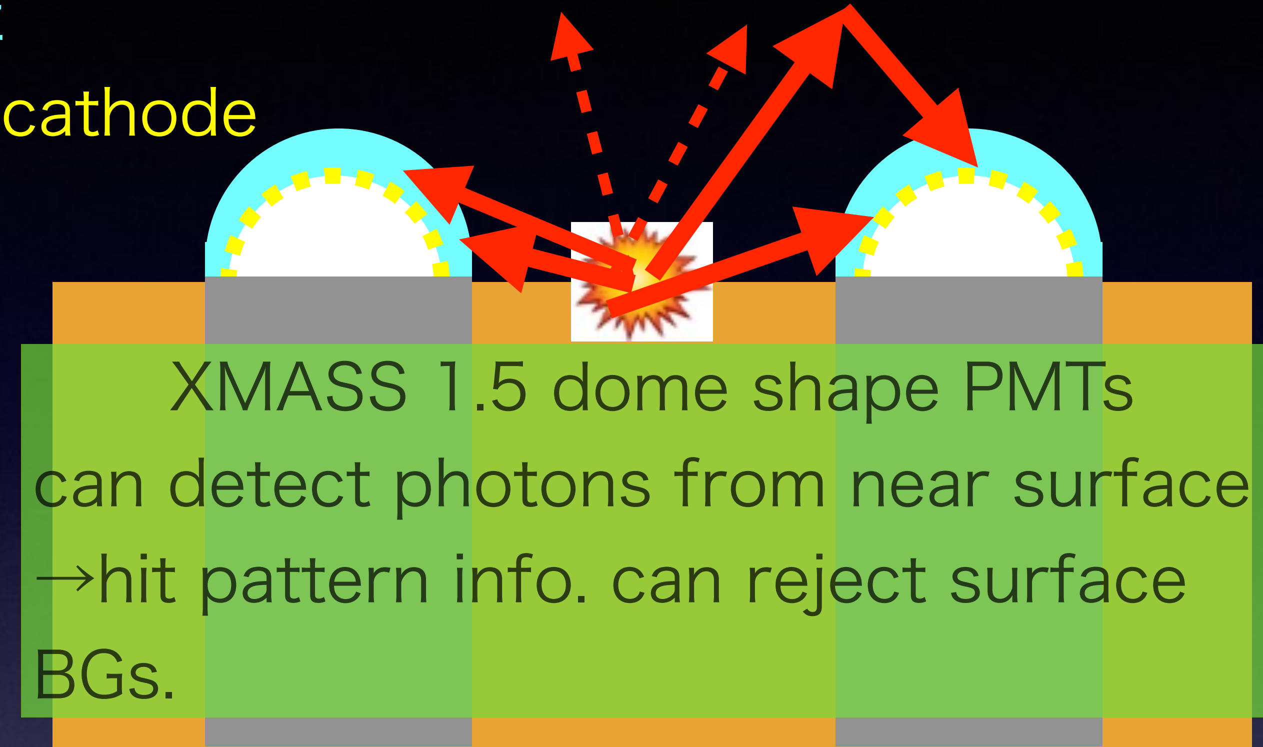
Dome shape window 3-inch PMT R13111
Large detection efficiency for nearby events.

surface BG identification

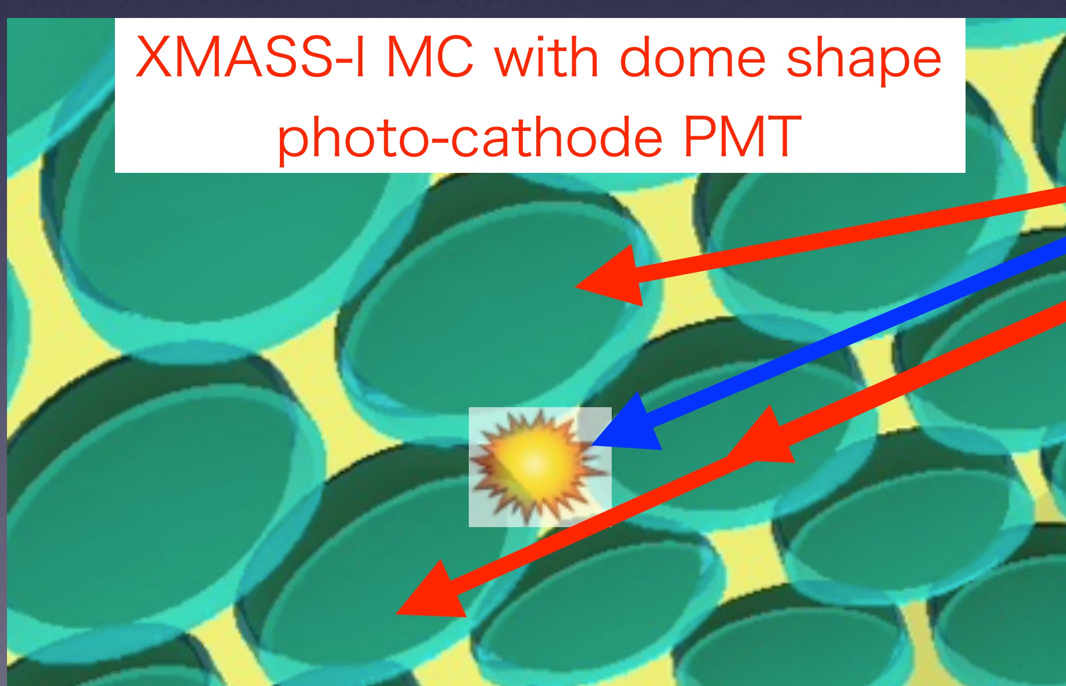
Scintillation Photons
Quartz
Photo cathode



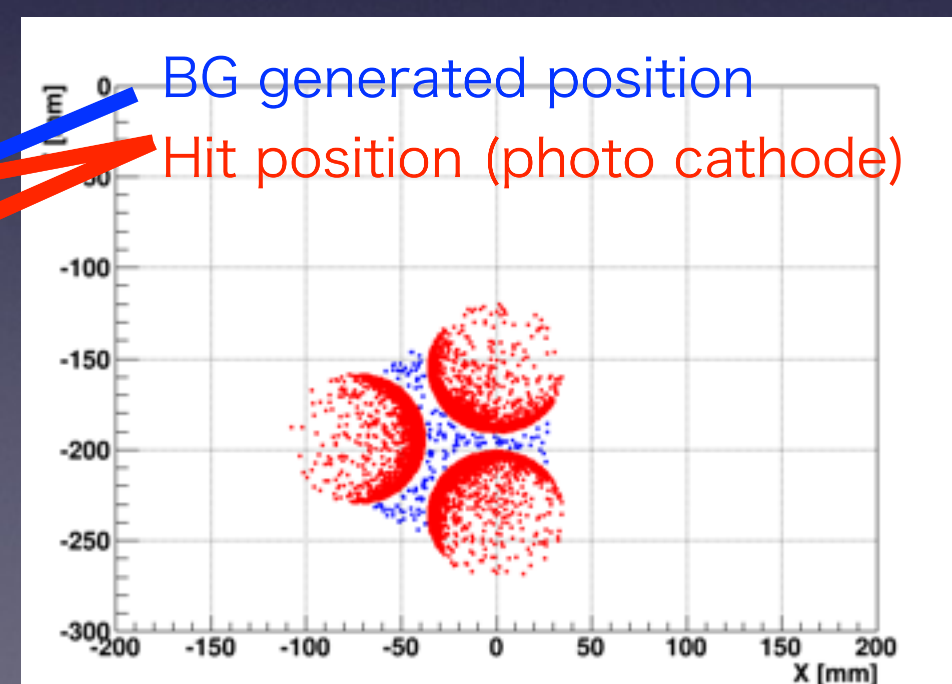
XMASS-I flat PMTs
high probability to miss detecting the photons from the near surface
→leads to miss reconstruction



XMASS 1.5 dome shape PMTs
can detect photons from near surface
→hit pattern info. can reject surface BGs.



XMASS-I MC with dome shape photo-cathode PMT



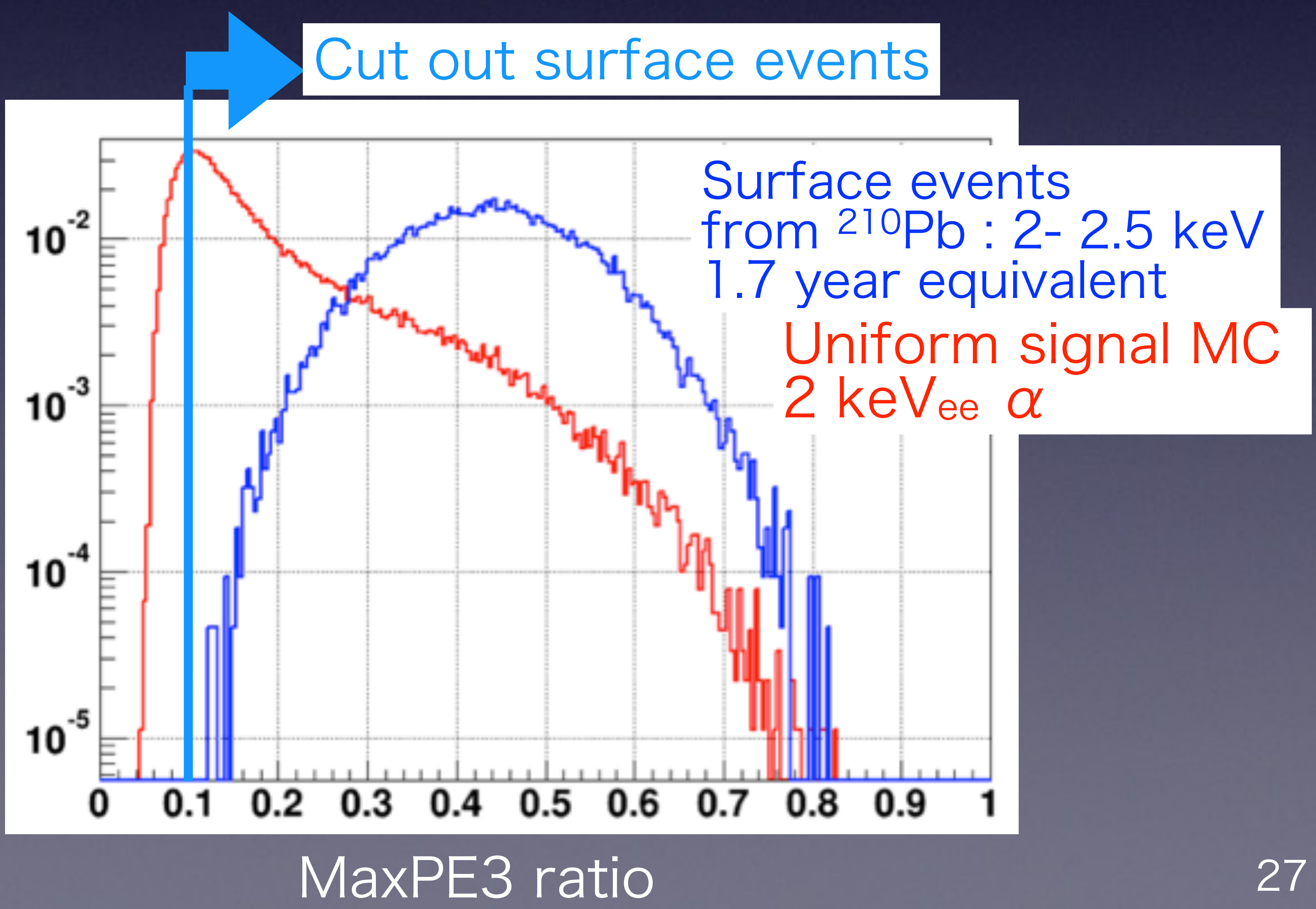
<u>Neighbor 3 PMTs detects ~50% photon from surface BG</u>

surface BG identification

- BG rejection ~ 10^{-5} while keeping 20% signal efficiency
- Even for the same BG level as in the XMASS-I detector, we can achieve 10^{-5} counts/day/keV/kg level
- Further material screening and improvement of the analysis will achieve much lower BG level.
- Reduction of surface BG may leads to increase fiducial mass from 1 ton to ~ 3 ton

MaxPE3 ratio :

$$\frac{\text{maximum p.e. in 3 adjoint PMTs}}{\text{Total observed p.e.}}$$

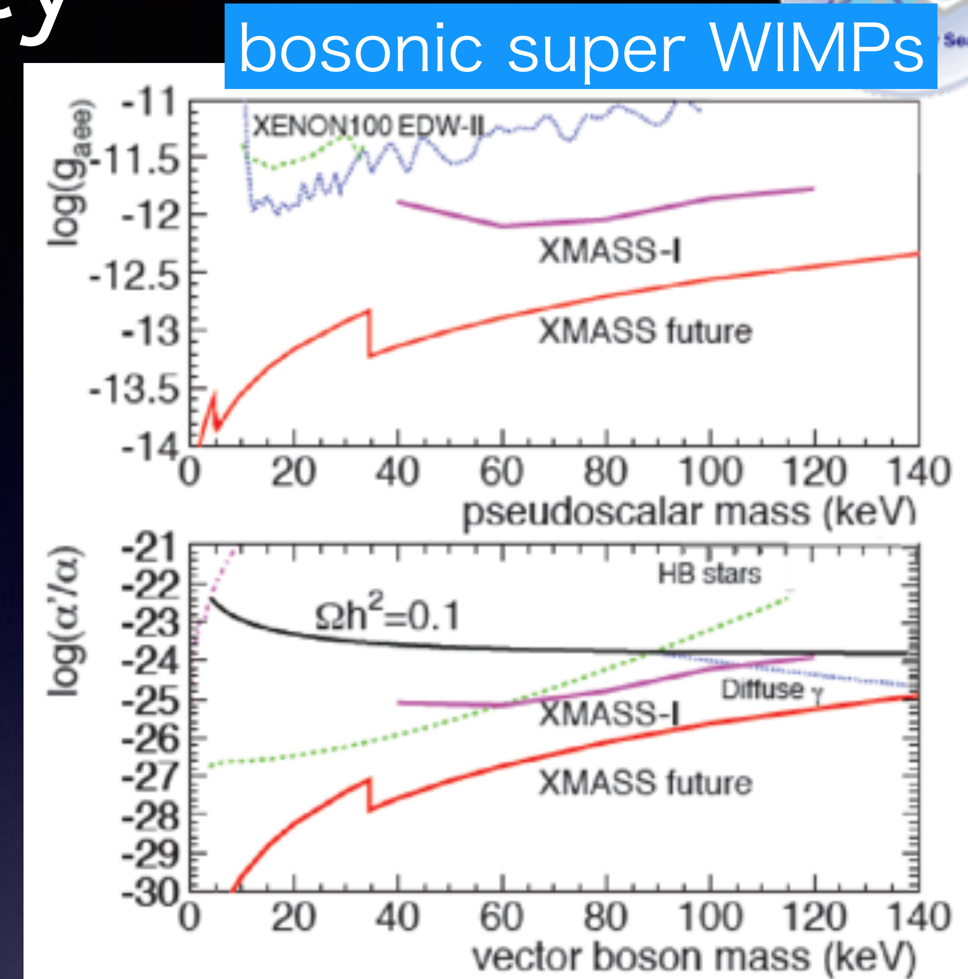


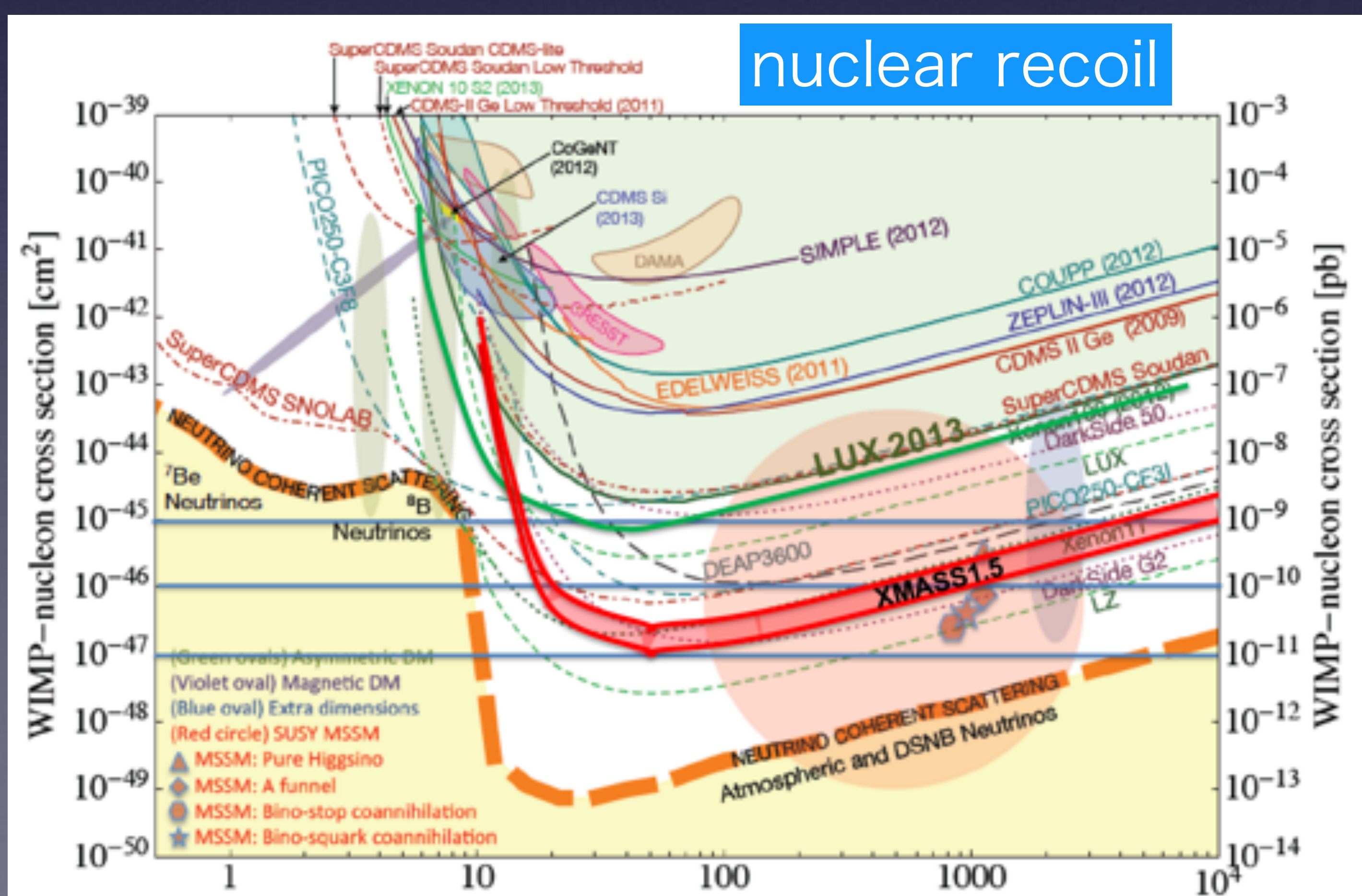
Other feature of R13111

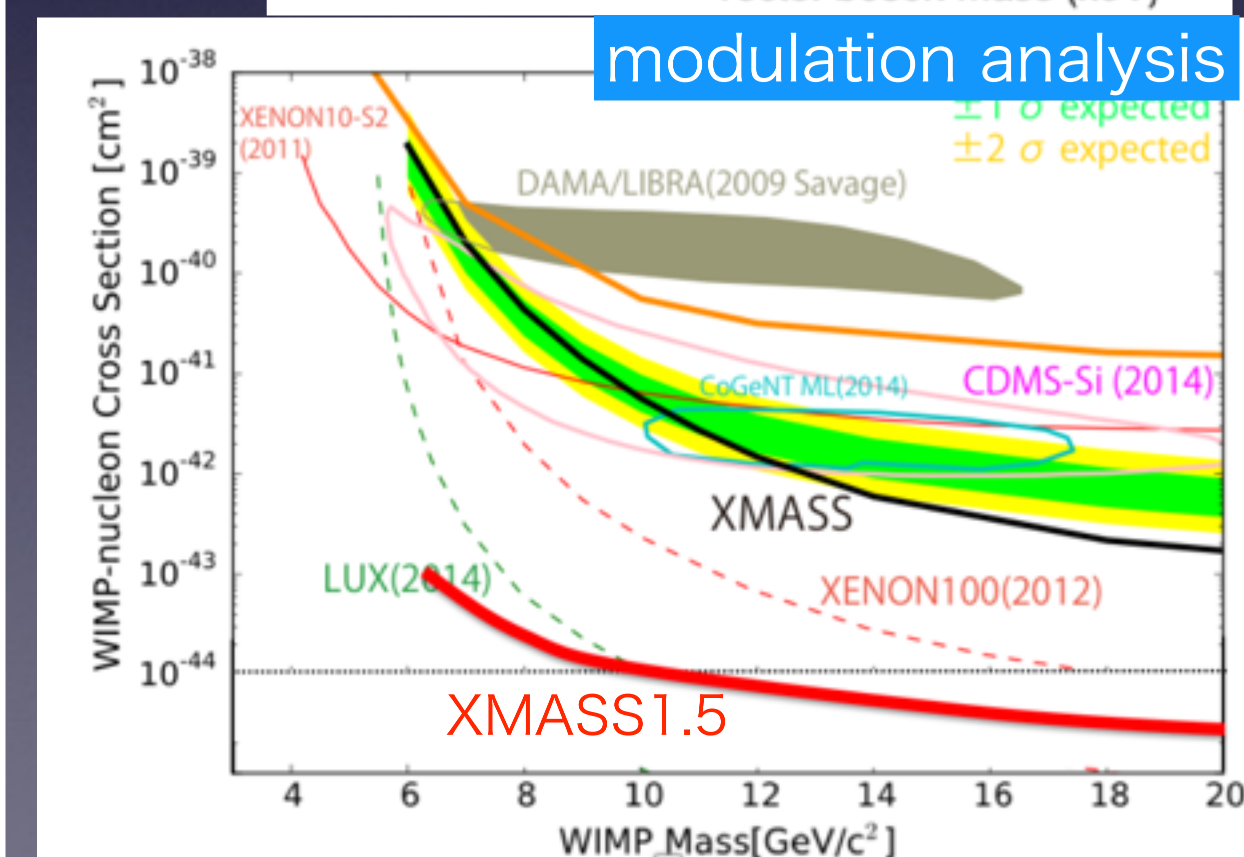
- Material screening
  - Target RI level : 0.1 mBq/PMT for U/Th chain
  - No dirty Al is used for seal (> 3 order magnitude lower U)
  - Kovar (large ^{60}Co RI) metal is replaced to Co free metal
  - Parts-by-parts RI measurement using HPGe, Alpha counter, ICPMS/GDMS
- High and uniform collection efficiency for whole area (side part of dome shape).
  - > 80% collection eff. Q.E. ~ 30%
- TTS : shorter TTSand high timing resolution (TTS ~5.6ns→ 2.9ns)
  - improve the reduction power of Cherenkov events
- Shorter total length : 101.5mm → 87.5mm
  - Thinner PMT holder gives reducing the holder weight, can enlarge sensitive LXe region.
- Not only Surface/PMT BG reduction, but also inner detector RI reduction
  - ^{85}Kr : distillation
  - ^{222}Rn : material screening such as cables (Rn emanation measurement using Rn detector),

Expected Sensitivity

- XMASS1.5 : 1~3 ton fiducial / Total ~6 ton
- Target sensitivity : < 10^{-46} cm^2 for 100 GeV WIMPs
- ~1×10^{-5} counts/keV/kg/day
- Target : Both nuclear recoil and electron recoil processes (ex. ALPs)







Summary

- Recent Results from XMASS-I are shown.
  - Annual modulation
    - WIMP : < 4.3×10^{-41} cm^2 at 8 GeV, DAMA/LIBRA region is mostly excluded by annual modulation search
    - Model Independent Analysis : upper limit amplitude < $(1.7\text{-}3.7)\times10^{-3}$ counts/kg/day/keV$_{ee}$, more stringent constraint
  - Search for 2ν double electron capture
    - We set the world best limit on the half life :
    - $T_{1/2}^{2\nu 2K}(^{124}Xe) > 4.7\times10^{21}$ years (90% C.L.)
    - $T_{1/2}^{2\nu 2K}(^{126}Xe) > 4.3\times10^{21}$ years (90% C.L.)
- Next step : XMASS1.5
  - Use dome shape PMTs to identify surface BG effectively
  - with further reduction of BG (Material screening, distillation etc.)
    - Reach < 10^{-46} cm^2 for SI interaction of WIMPs with 1×10^{-5} counts/day/kg/keV$_{ee}$ BG rate