Dark Matter Search in XMASS

DBD'16 in Osaka
10th Nov. 2016
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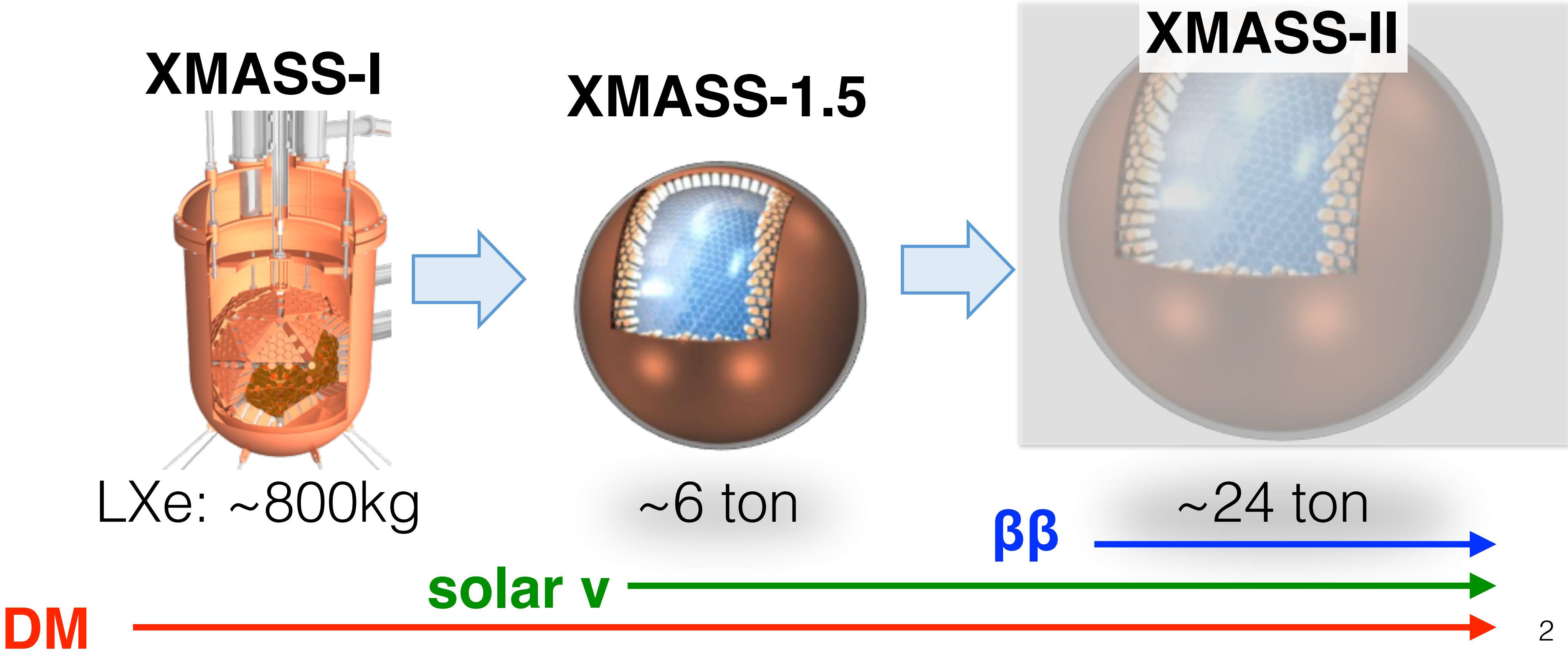
XMASS project

XMASS: a multi purpose experiment with liquid Xenon

- Xenon detector for Weakly Interacting MASSive Particles (DM search)
- Xenon MASSive detector for Solar neutrino (pp/^{7}Be solar ν)
- Xenon neutrino MASS detector (ββ decay)



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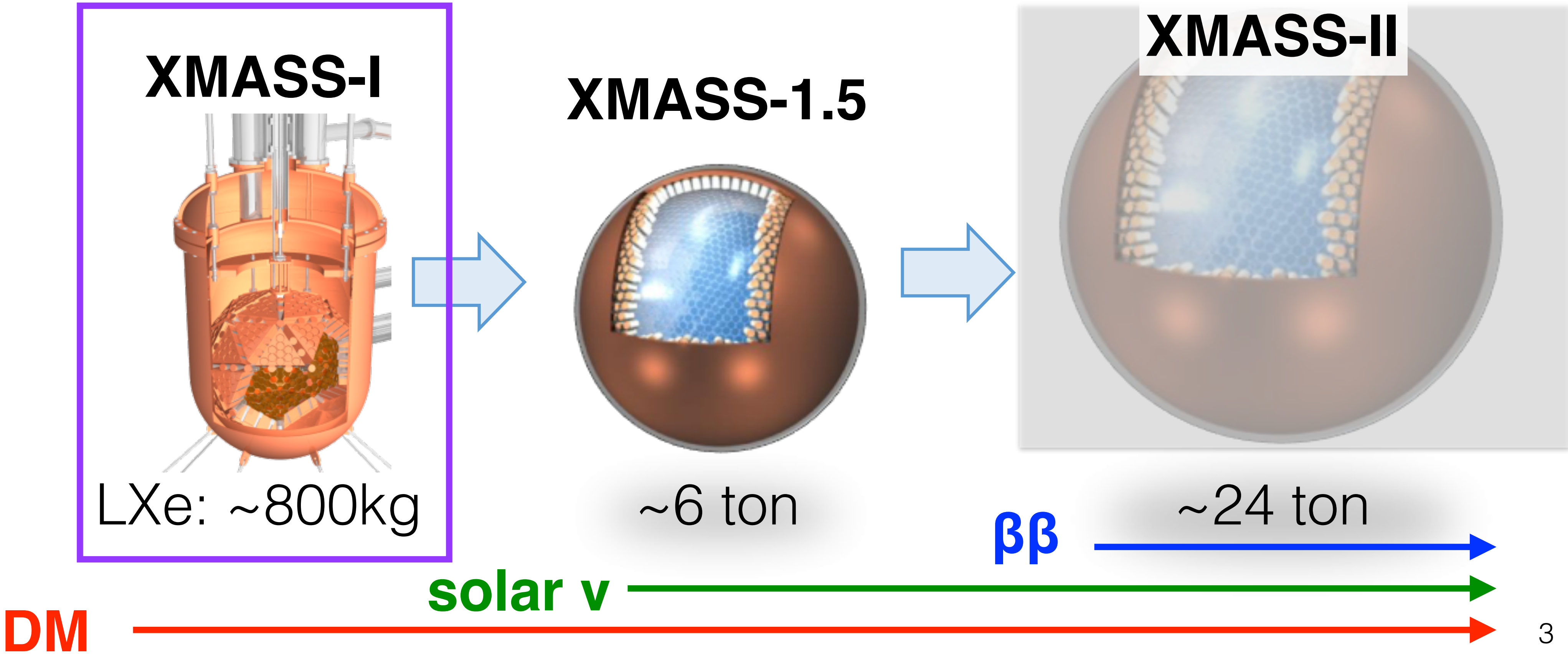
- Xenon detector for Weakly Interacting MASSive Particles (DM search)
- Xenon MASSive detector for Solar neutrino (pp/^{7}Be solar ν)
- Xenon neutrino MASS detector (ββ decay)

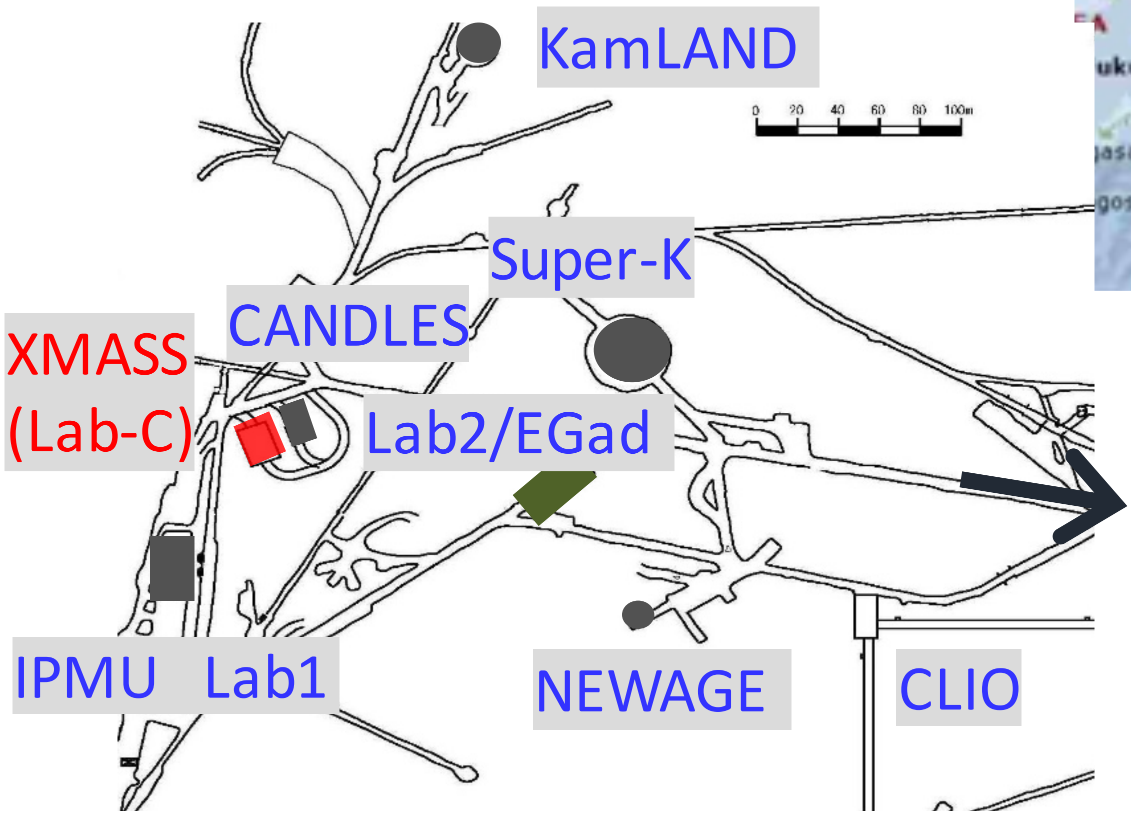
→ the main purpose of the first phase is **DM search**



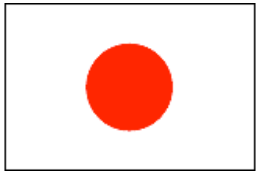
Kamioka Observatory

The site of Kamioka mine

- 1000 m underground
  = **2700 m.w.e**



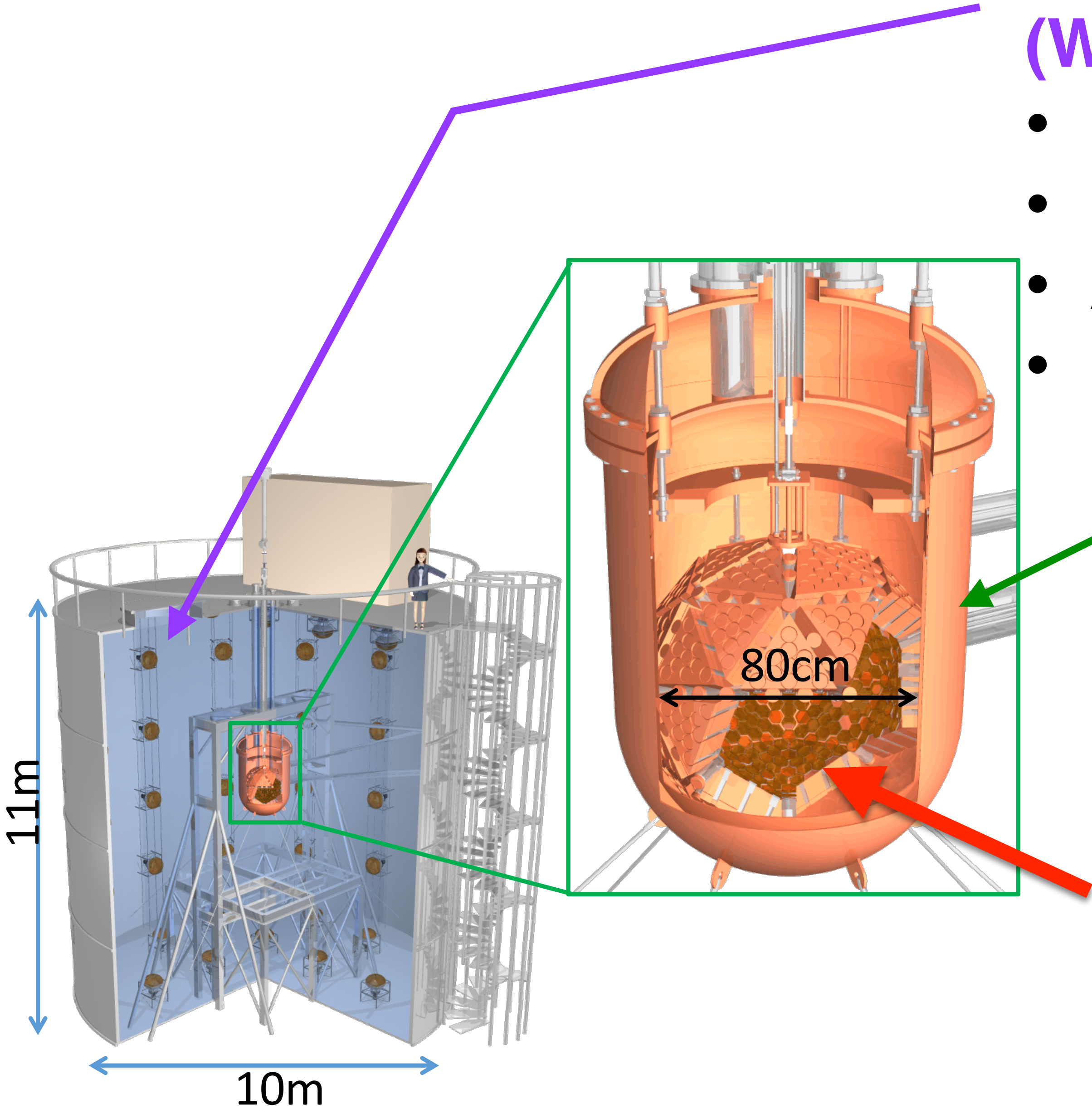
collaborators



U of Tokyo, ICRR	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
U of Tokyo, IPMU Kavli	K.Martens, Y. Suzuki, B. Xu
Kobe Univ.	R. Fujita, K.Hosokawa, K. Miuchi, N. Oka, Y.Takeuchi
Tokai Univ.	M. Miyasaka, K. Nishijima
Tokushima Univ.	K. Fushimi, G. Kanzaki
Yokohama National Univ.	S.Nakamura
Miyagi Univ. of Education	Y.Fukuda
Nagoya Univ.	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, ~40 participants

Detector



Outer Detector
(Water Cherenkov detector)

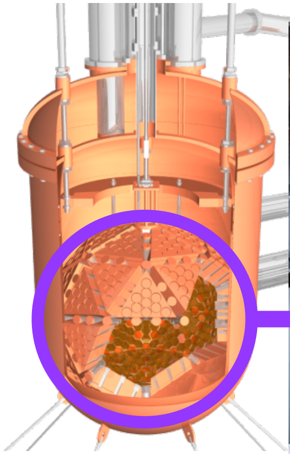
- 10-m Φ ×11 m height
- 72 20-inch PMTs
- Active shield for cosmi. μ
- Passive shield for external neutrons and γ's

OFHC Copper vessel

- hold liquid xenon
- vacuum insulation

Inner Detector

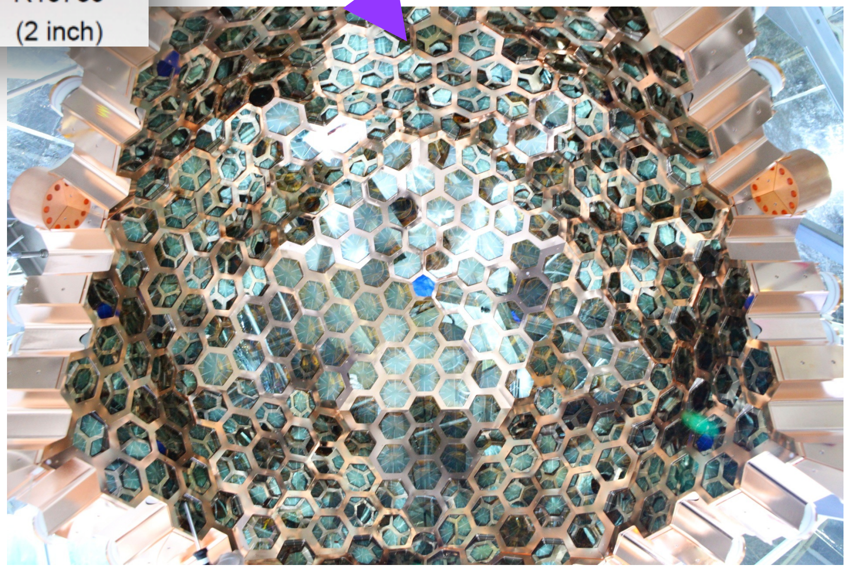
cont.



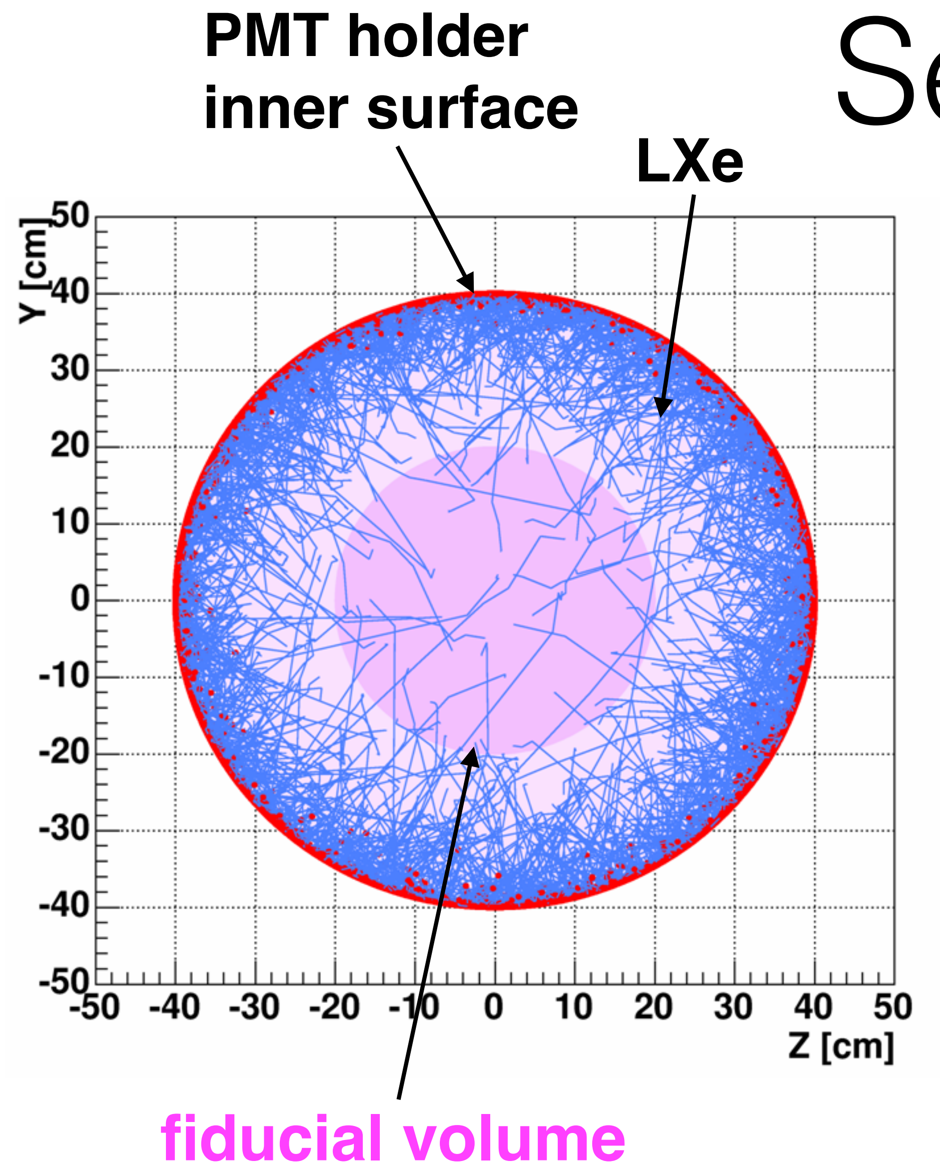
Inner Detector (Liquid Xenon detector)

- **single-phase** detector
  = scintillation (*S1*) only
  → compact, scalability
- **832 kg LXe** sensitive volume
- 642 2-inch PMTs
  - HAMAMATSU **R10789**
    - QE: 28~39%
    - Hexagonal window
    - held by OFHC Cu holder
  - photo. coverage **> 62%**
- High light yield
  - **~15 p.e / keV**

spread over the inner surface



Self-shielding



- γ's from RI's in PMTs & vessel are **shielded by LXe itself.**
- vertex position is reconstructed from a pattern of p.e. distribution

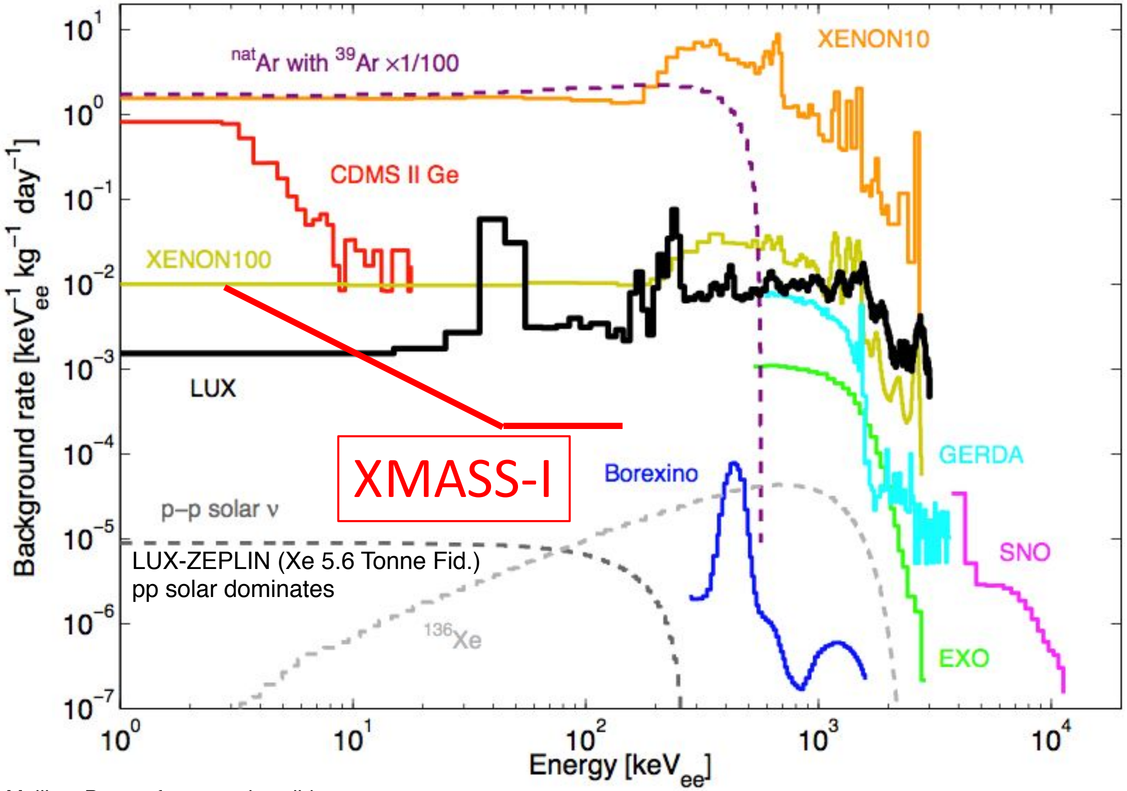
$$L(\vec{r}) = \prod_{i=1}^{642} p_i(n_i)$$

p_i (n): probability that n p.e. are detected in the i-th PMT

→ require $|\vec{r}| <\sim 20\mathrm{cm}$ (= fiducial volume : 100 kg)

BG rate for DM search

BG rate including e/γ events



Original figure taken from
D. C. Mailing, Ph.D (2014) Fig 1.5

With fiducial volume cut …

- O(10^{-4}) events/day/keV/kg at a few 10s keV
  - including e/γ events

→ widely explore **various DM candidates with e/γ**, as well as standard WIMPs

Status of XMASS

2010	2011	2012	2013	2014	2015	2016

Dec. May Nov.

constr-uction

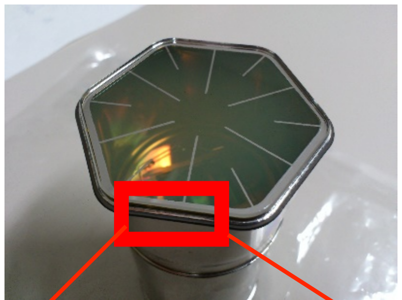
commissio-ning run

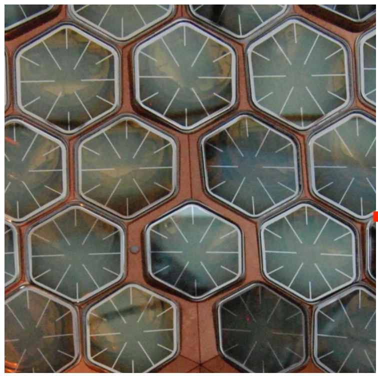
identify BG source

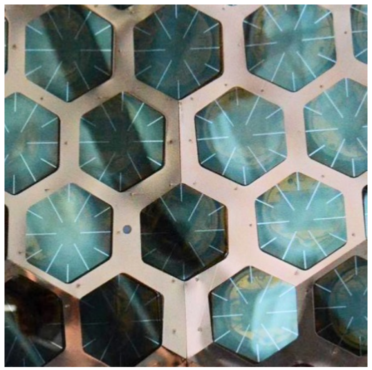
refurbish-ment

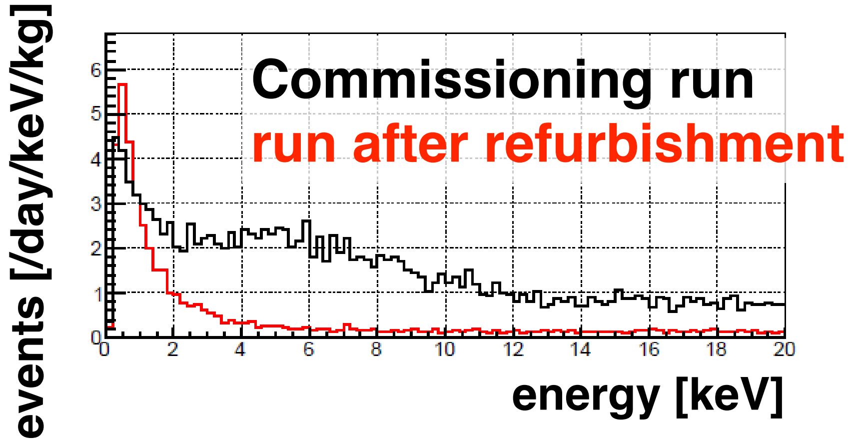
Put Cu cover on the Al seal

continuous data taking









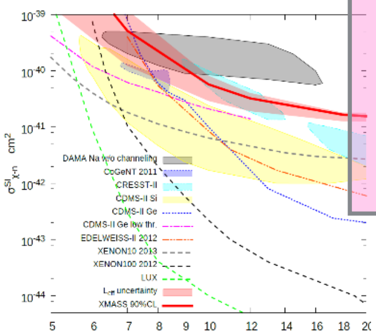
- # events: **~1/10** @ 5 keV
- ~ 3 years operation

physics results

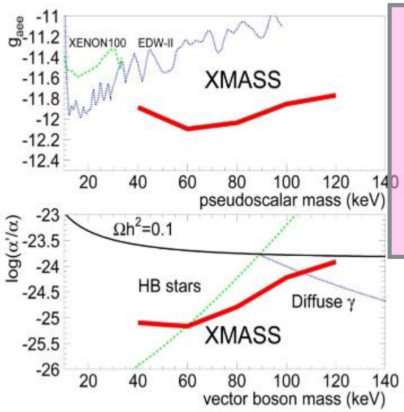
2010	2011	2012	2013	2014	2015	2016

Dec. May Nov.

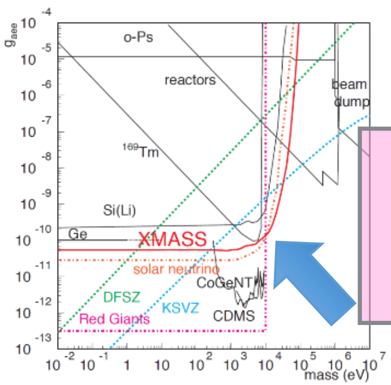
constr-uction → **commissioning run** → **refurbish-ment** → **continuous data taking** →



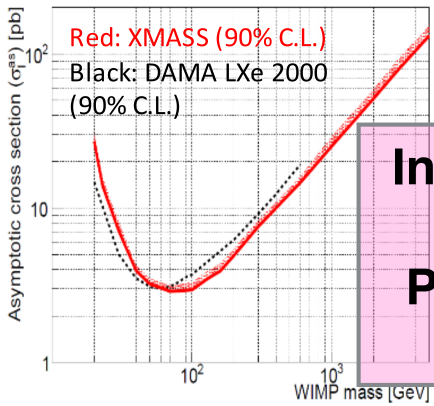
low mass WIMP
PLB 719 78 (2013)



bosonic super WIMPs
PLB 724 46 (2014)



solar axion
PLB 724 46 (2013)



Inelastic WIMP scattering
PTEP 063C01 (2014)

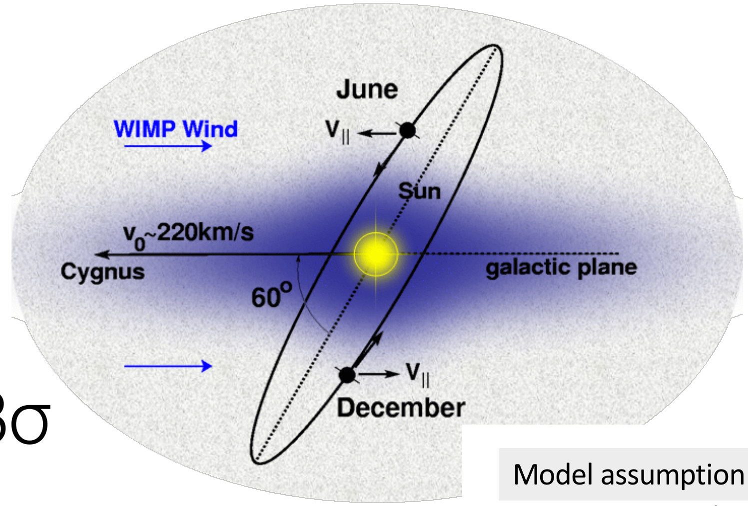
latest results

annual modulation
PLB 759 64 (2016)
→ ***this talk***

2νECEC
PLB 759 272 (2016)
→ ***Hiraide's talk in session VI***

latest result : annual modulation

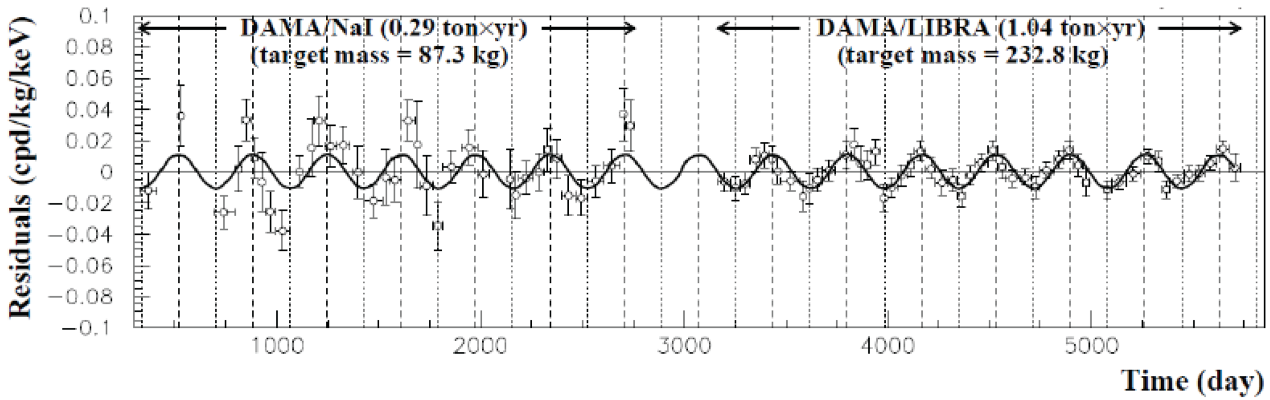
- event rate of DM should modulate annually

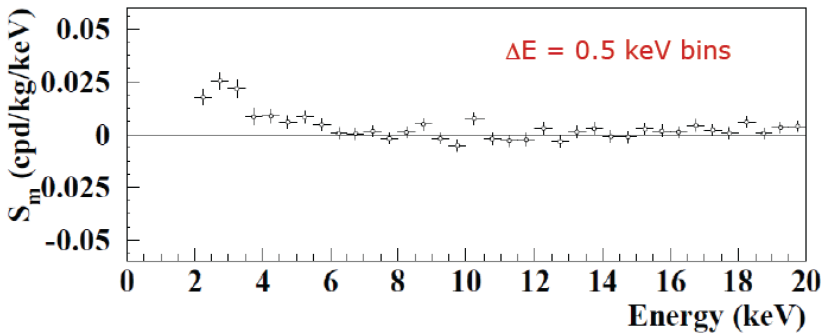


Model assumption

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

- DAMA/LIBRA claims modulation at 9.3σ
  - 1.33 ton-year exposure
  - No particle ID (= including electron signals)





→ inspect the modulation with XMASS data

- **comparable exposure time** (0.83 ton-year)
- **No particle ID**

event selection

Data : Nov. 2013 - Mar. 2015 after the refurbishment

= **359.2 live days, 0.83 ton-year exposure**

- use LXe full volume
- E thre. ~ 1.1 keVee

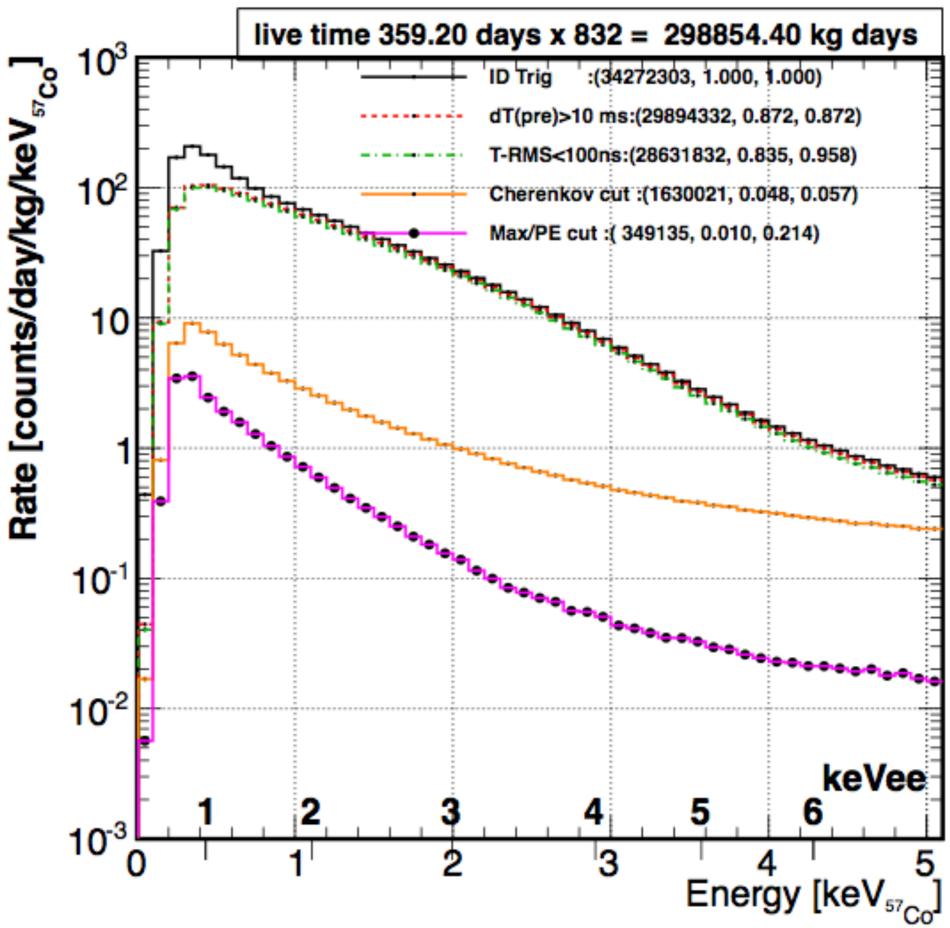
— — — : cuts to reject noises and after-pulses

— : after Cherenkov events rejection

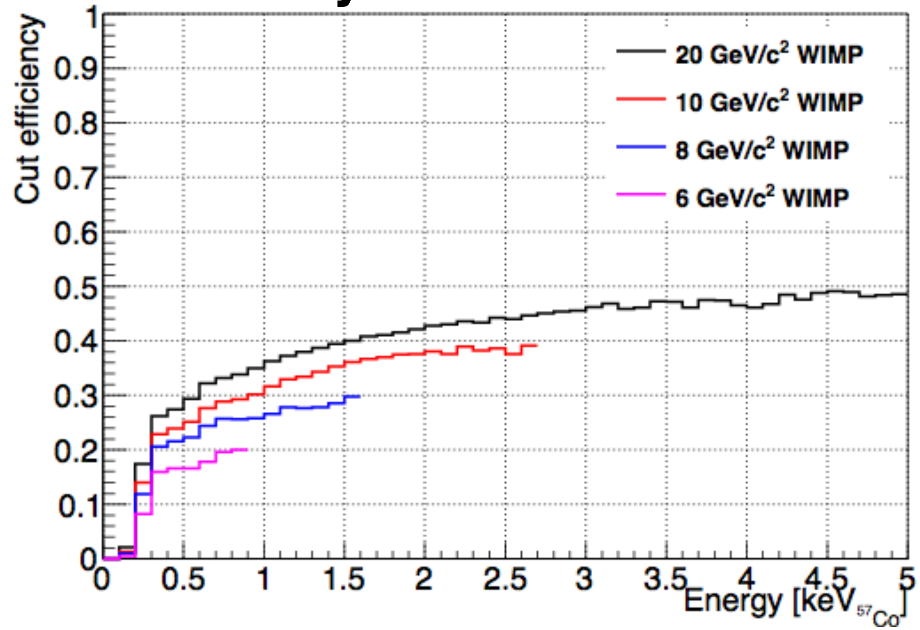
- # hits in 20 ns < 60 % of total hits

— : after rejecting events IFO PMT

- cut by max p.e. / total p.e

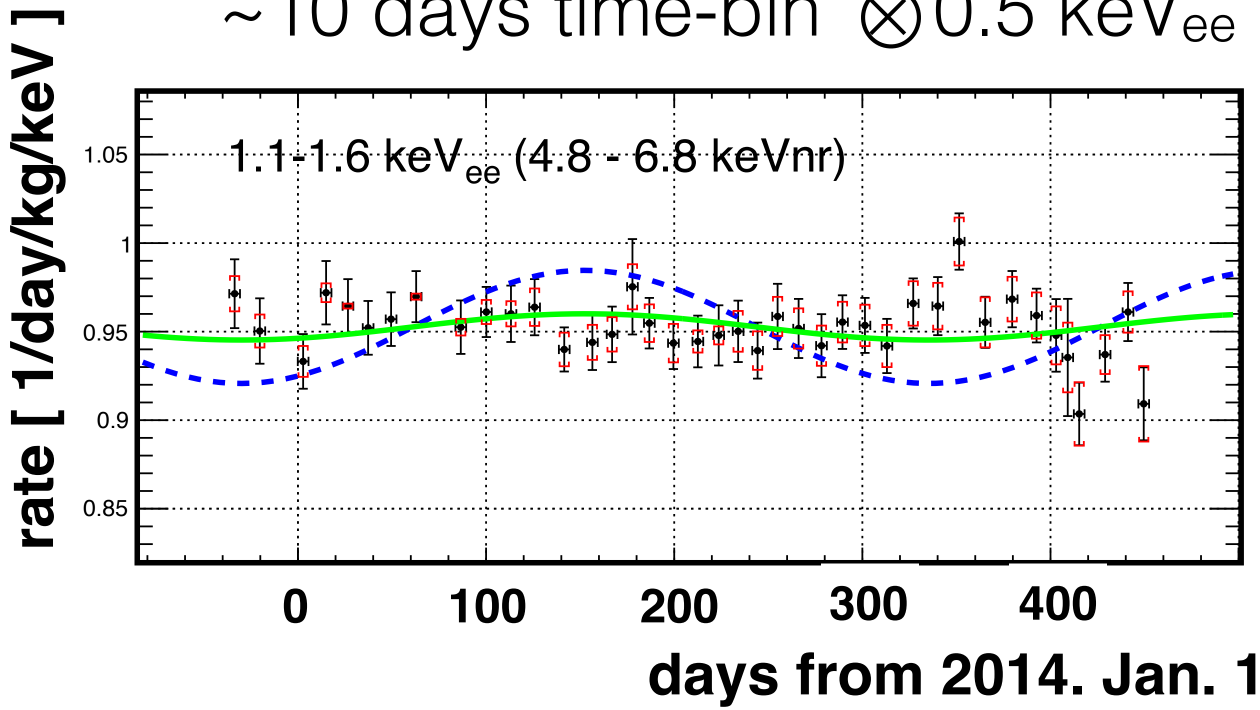


efficiency after the selection



Modulation Analysis

- The data was divided into …
  - ~10 days time-bin $\otimes$ 0.5 keV_{ee} energy-bin



• : data
stat error
systematic error

: expectation
7 GeV WIMPs w/ 2 x 10^{-40} cm^2
8 GeV WIMPs w/ 2 x 10^{-40} cm^2

- Perform two least square fitting methods
  - all the time-energy bins are fitted simultaneously

Method 1: "pull term"

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

Method 2: "covariance matrix"

$$\chi^2 = \sum_{k,l}^{N_{\text{bins}}} (R^{\text{data}}_k - R^{\text{ex}}_k)(V_{\text{stat}} + V_{\text{sys}})^{-1}_{kl} (R^{\text{data}}_l - R^{\text{ex}}_l)$$

WIMP result

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

Assuming standard WIMP, expected rate $R^{ex}_{i,j}$ is given as

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

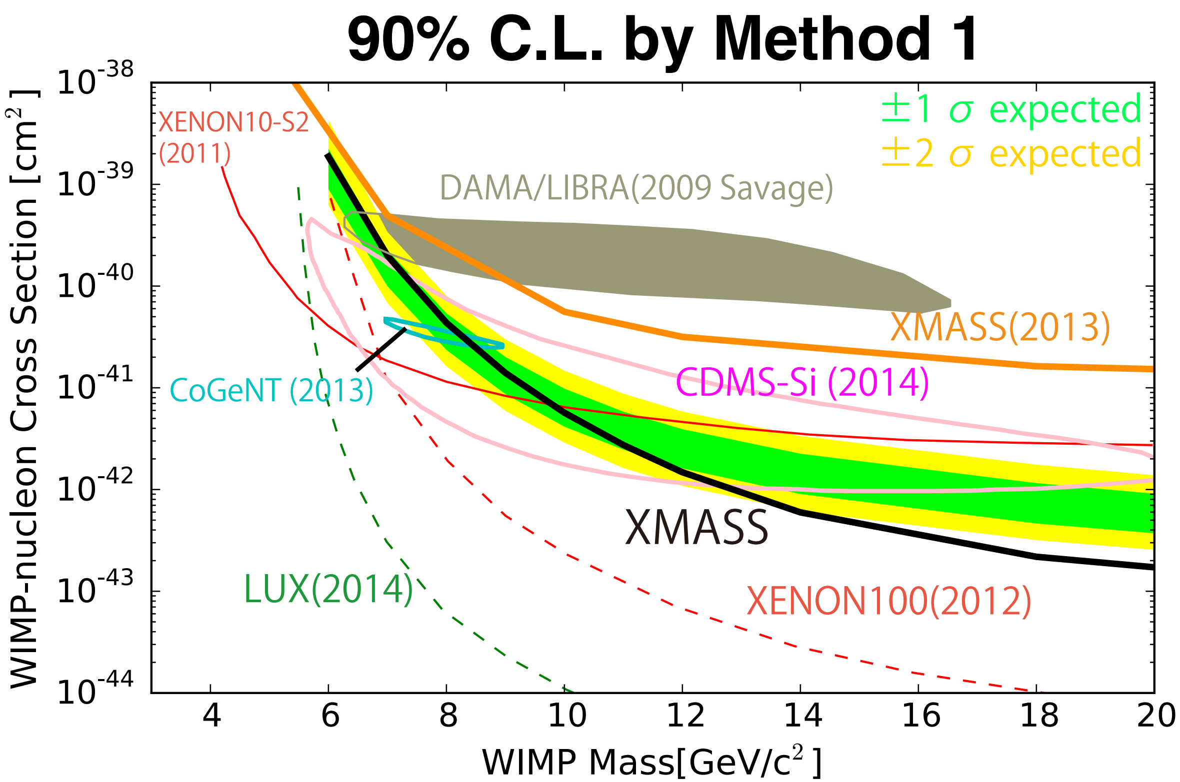
t_0: 152.5 days

T: 365 days

$\sigma_{\chi n}$: cross section

A_i: Amplitude

m_χ: WIMP mass



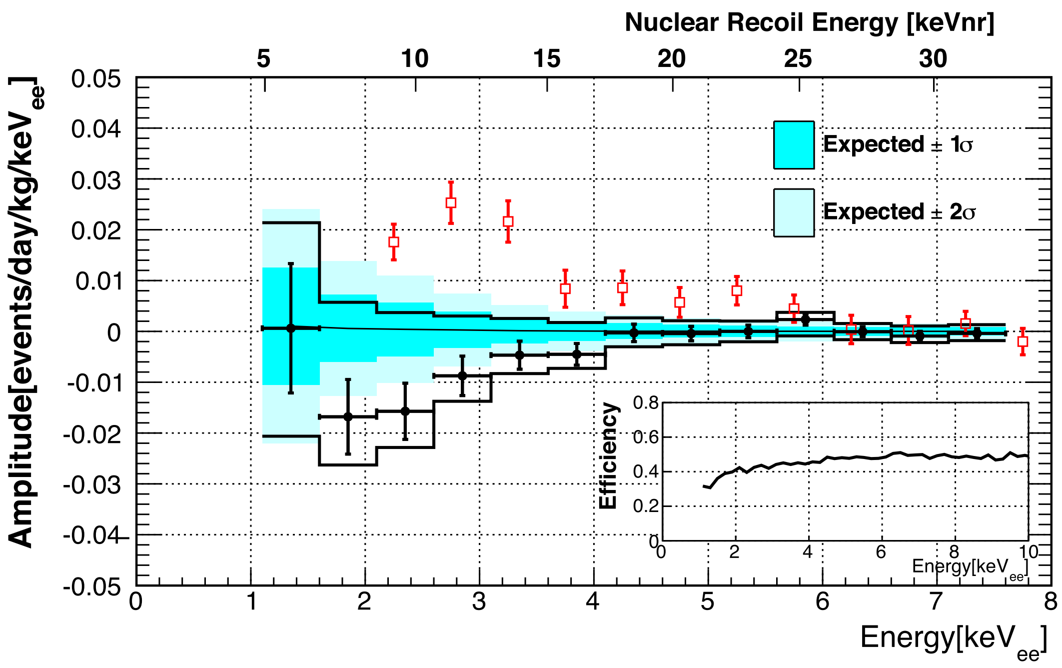
- difference between Method 1 and 2 is within 30%
- **almost exclude DAMA/LIBRA region.**

model-independent result

Not assuming any specific DM model

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

* A_i & C_i : *free parameters*



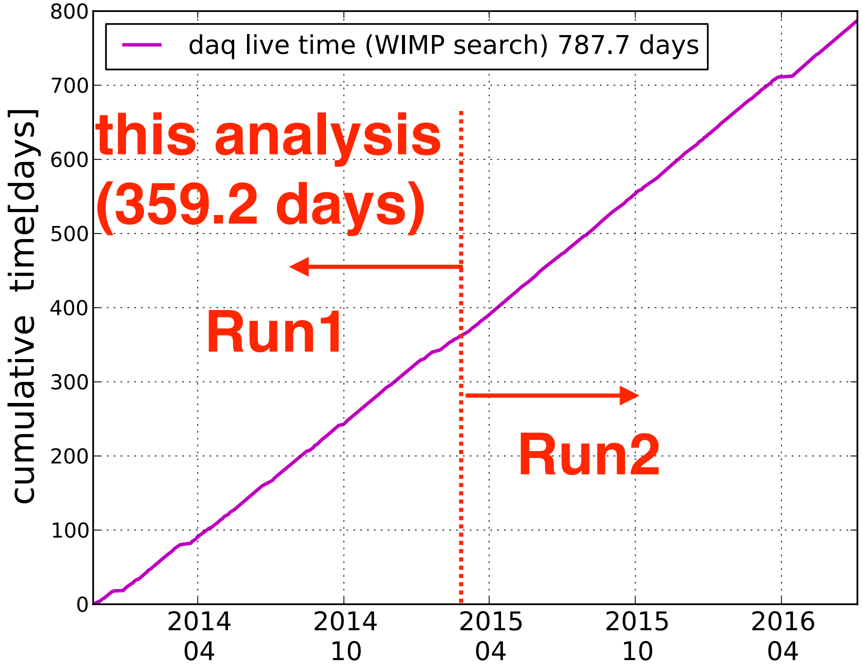
□ **DAMA/LIBRA**
● **XMASS**
— 90% C.L.

	Method 1 "pull term"	Method 2 "cov. mat."
p-value	0.014 (2.5σ)	0.068 (1.8σ)

No significant modulated signal was observed.

analysis update

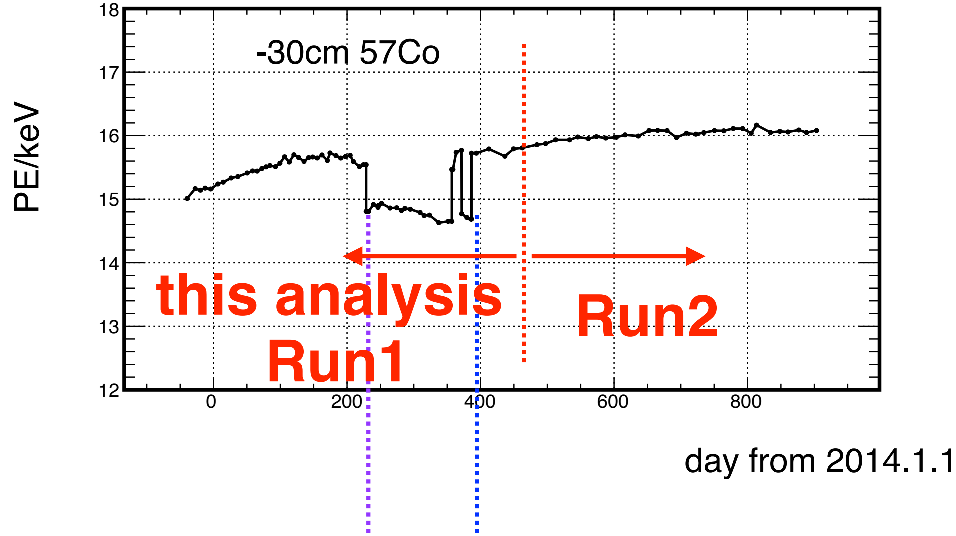
modulation analysis using Run2 (2015 Apr~) is ongoing.



more than ×2 statistics

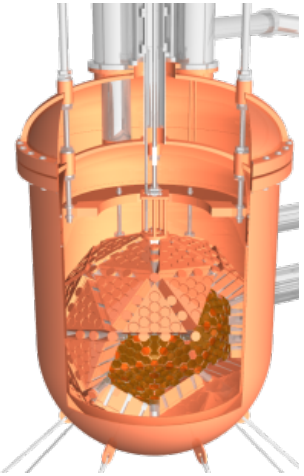
stable light yield

- can reduce systematic error
- can set low E threshold
  - 1.1 keV_{ee} -> ~0.5 keV_{ee}



future plan

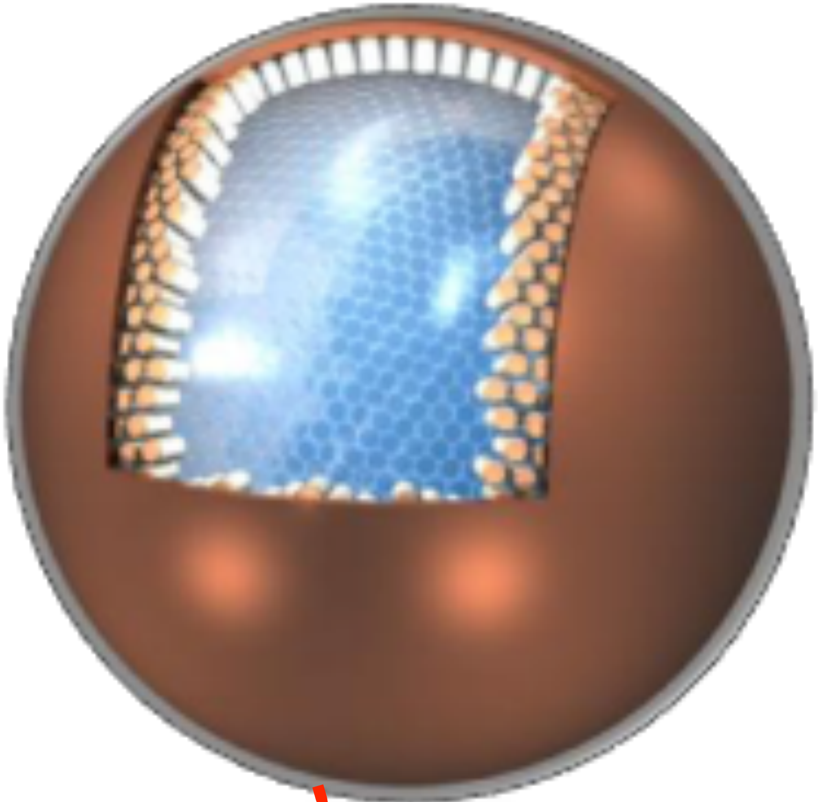
XMASS-I
in operation



(XMASS1+)

832 kg LXe
fiducial (FV)
100 kg
Φ ~ 80cm

XMASS-1.5



scalability!

- **~6 ton (FV > 1~3 ton)**
- **Φ ~ 1.5 m**
- **~ 1800 PMTs**

XMASS-II

25 ton
(FV > 10ton)
Φ ~ 2.5 m

future plan

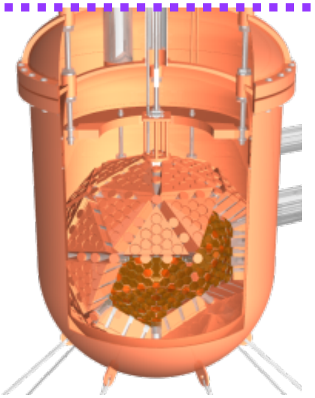
XMASS-I

0.8 ton (FV: 100 kg)

10^{-2} ~10^{-4} events/day/keV/kg

↓ **improve inner detector**

XMASS-1+

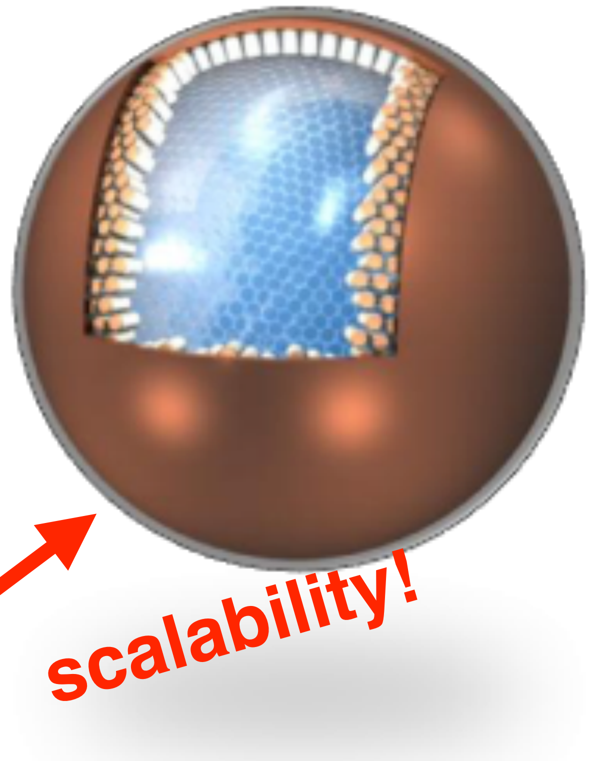


1ton LXe
(FV: 500 kg)
Φ ~ 80cm

- replace PMT & PMT holders only
  → don't change 1.5 schedule

- introduce new techniques
  - FV : **500kg**
  - BG rate : **10^{-5} evt/day/keV/kg**

XMASS-II



XMASS-1.5

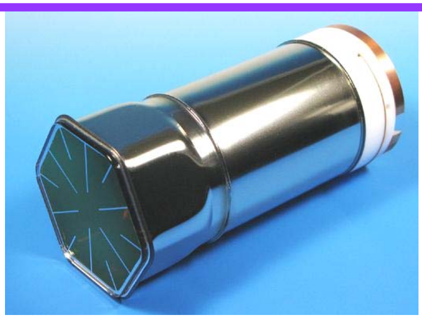
- **~6 ton**
  (FV > 1~3 ton)

Dome PMT

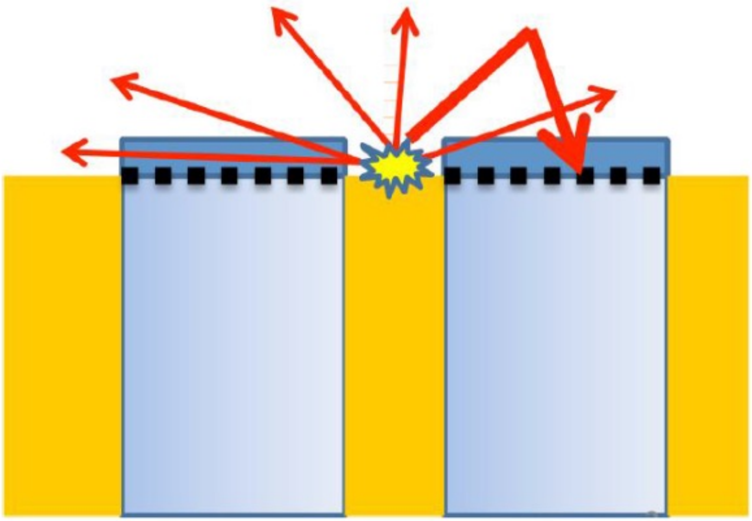
Surface event is the main BG in low E region in XMASS-I

→ introduce **Dome-shaped PMT**

XMASS-I



R10789
2 inch

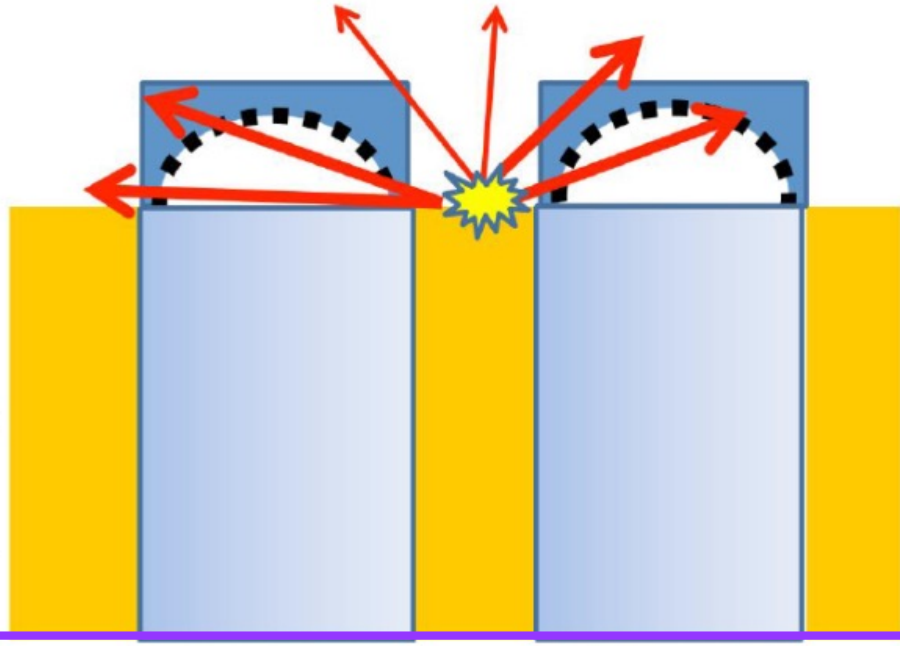


due to ^{210}**Pb**
on/inside Cu holder

XMASS-1+, 1.5

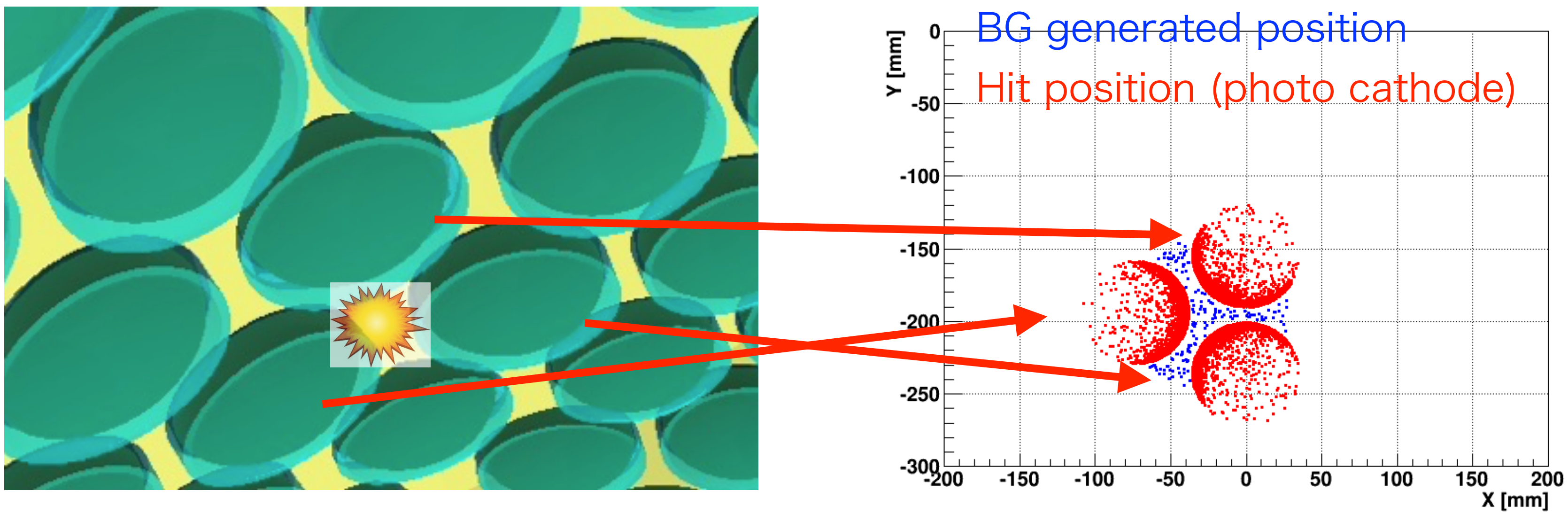
R13111

- **dome shaped photo cathode**
- **3 inch**



MaxNPE3

MC for 210Pb on the Cu surface

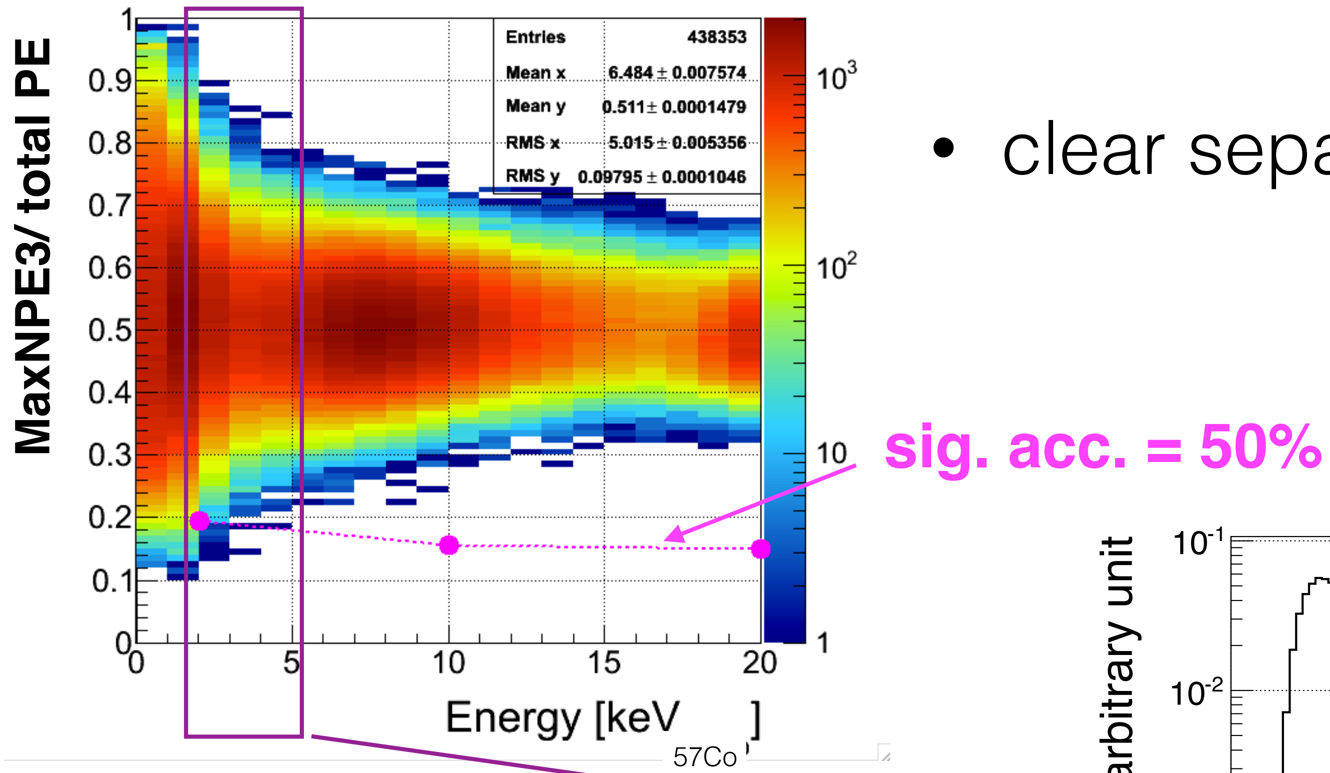


- Surface BG is identified by the maximum p.e. in 3 (or 4~5) adjoint PMTs (= **MaxNPE3**)

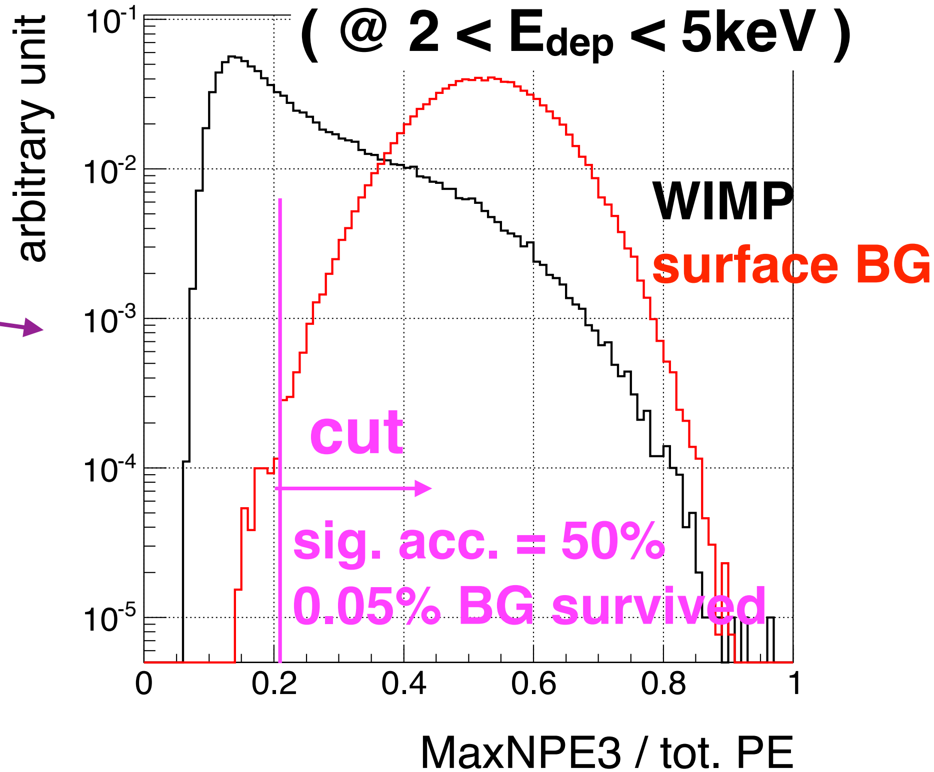
- MaxNPE3 performance was checked by MC
  - configuration of XMASS-1+
  - generate 2×10^{6} ^{210}Pb's from the surface of the Cu holder
    - ^{210}Pb on Cu surface in XMASS-I : 0.24 mBq / detector
    - MC stat : ~ 100 years data

identification by MaxNPE3

MaxNPE3 of ^{210}Pb on Cu surface



- clear separation in E >10 keV



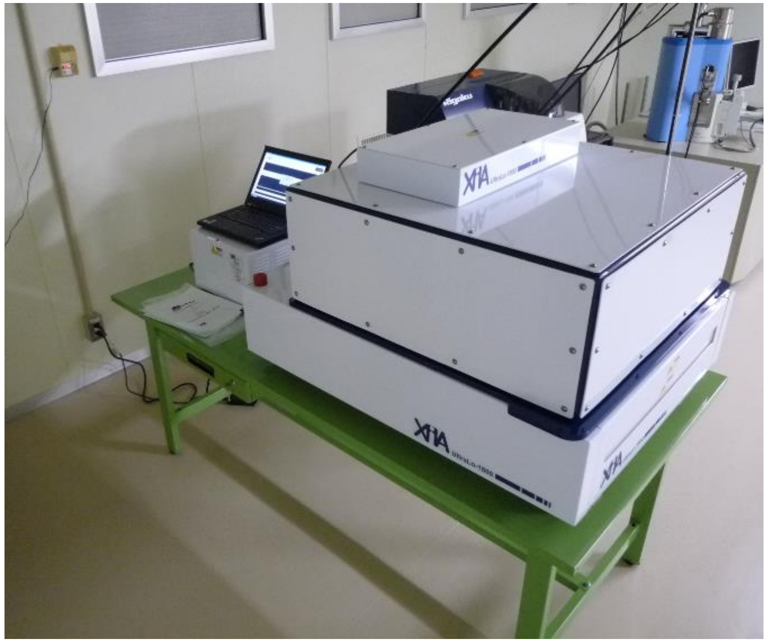
Even in energy near threshold (2<E<5 keV), **O(10^{-4}) reduction** with 50% acceptance loss!

→ O(10^{-6}) events/day/keV/kg

reduction of ^{210}Pb in Cu

try to reduce ^{210}Pb contamination itself

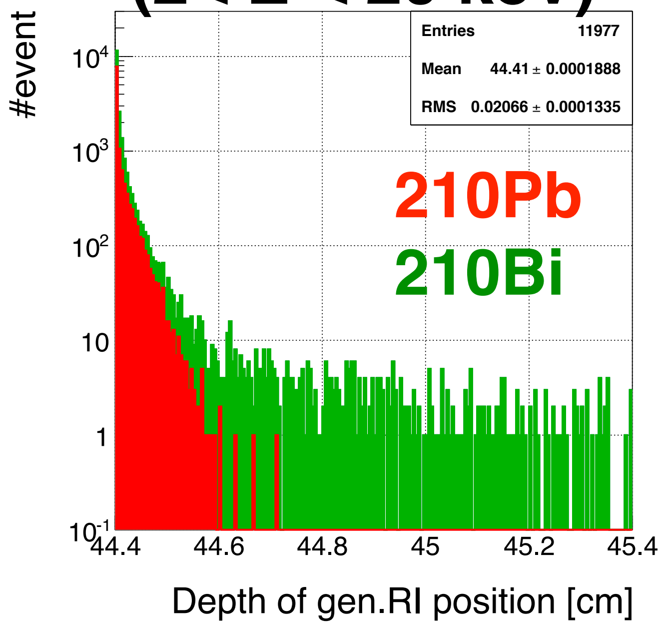
XIA Ultra-Lo-1800



We already found clean Cu candidate

- screening by new α counter
- 6N copper (Mitsubishi Material)
  - ~1/10 contamination of the current Cu holder

RI position in Cu (2< E < 20 keV)



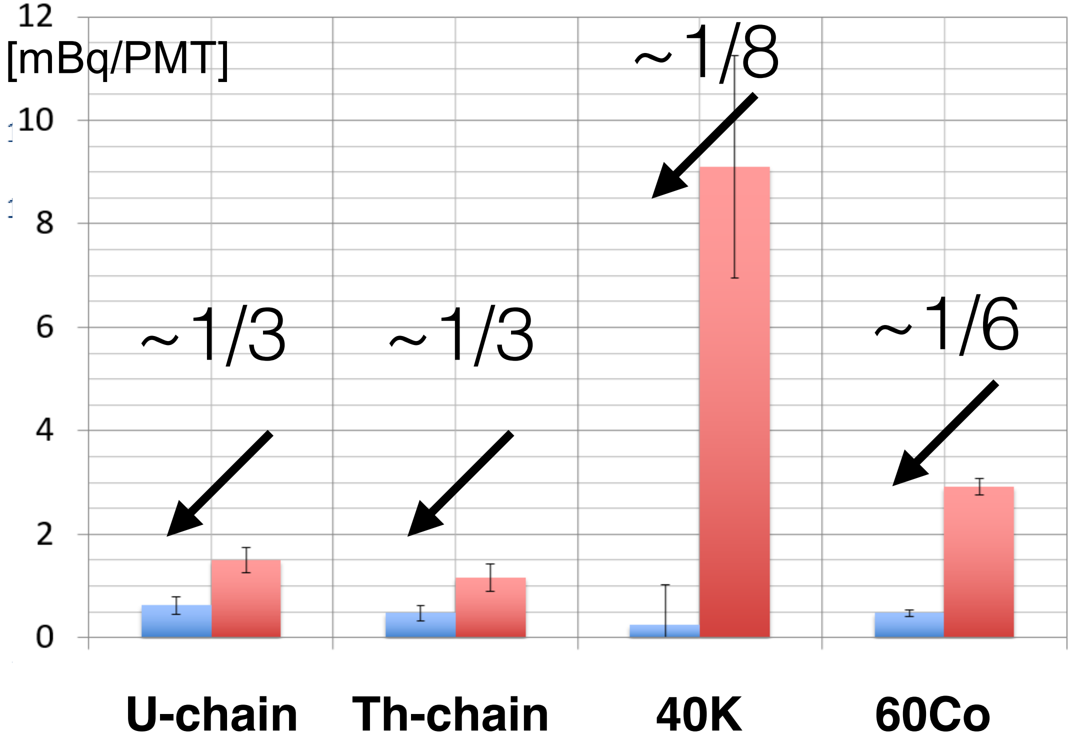
MC study for ^{210}Pb in Cu bulk

- Only ^{210}Pb's at < 3mm depth from the detector surface contribute to BG dominantly.

→ install several milimeters-thick 6N-Cu layer

PMT screening

- PMT Al seal is replaced to pure Al
- RI screening for other PMT parts is also ongoing

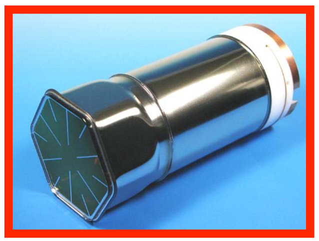


- using Ge, GDMS, ICPMS …

←**current achievement of RI reduction**

- so far 1/3~1/8 reduction was achieved.

new PMT **current PMT(R10789)**

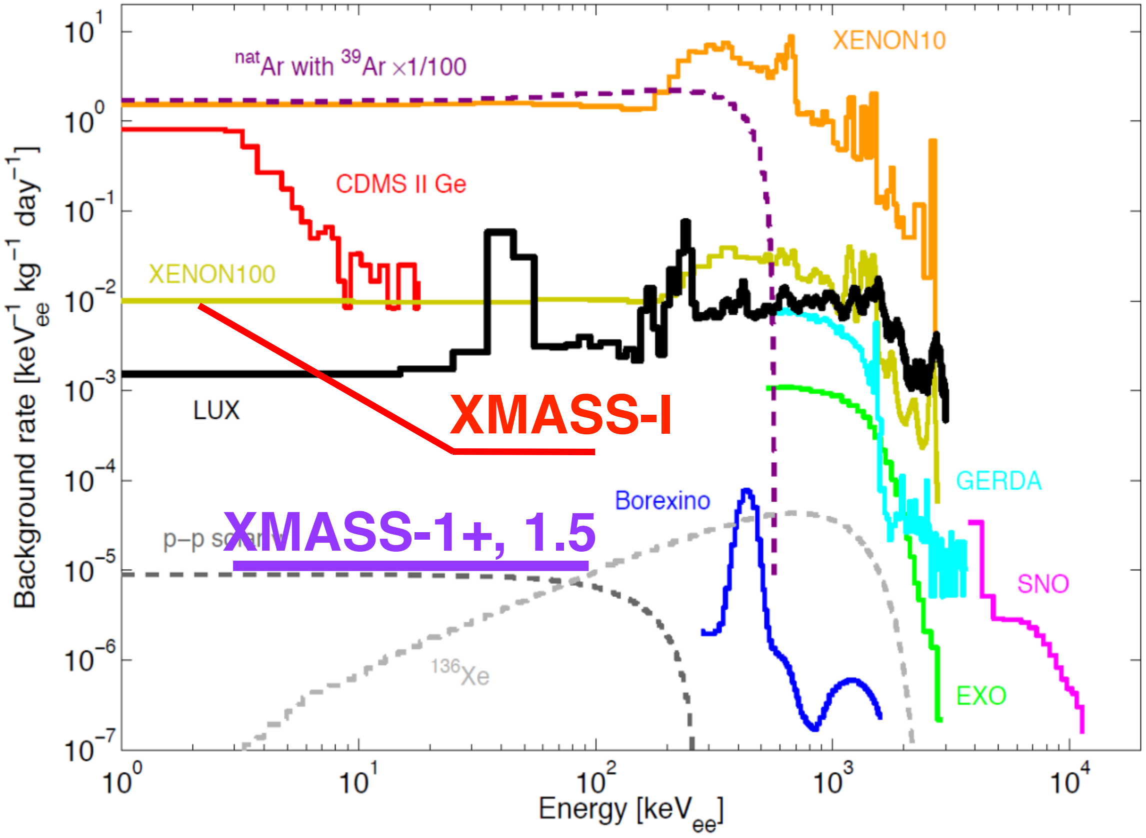


- Goal: **~1/10 reduction** compared to the current PMT

background rate

Original figure taken from
D. C. Mailing, Ph.D (2014) Fig 1.5

target BG rate:
10^{-5} events/day/keV/kg
(= rate of *pp solar ν* events)

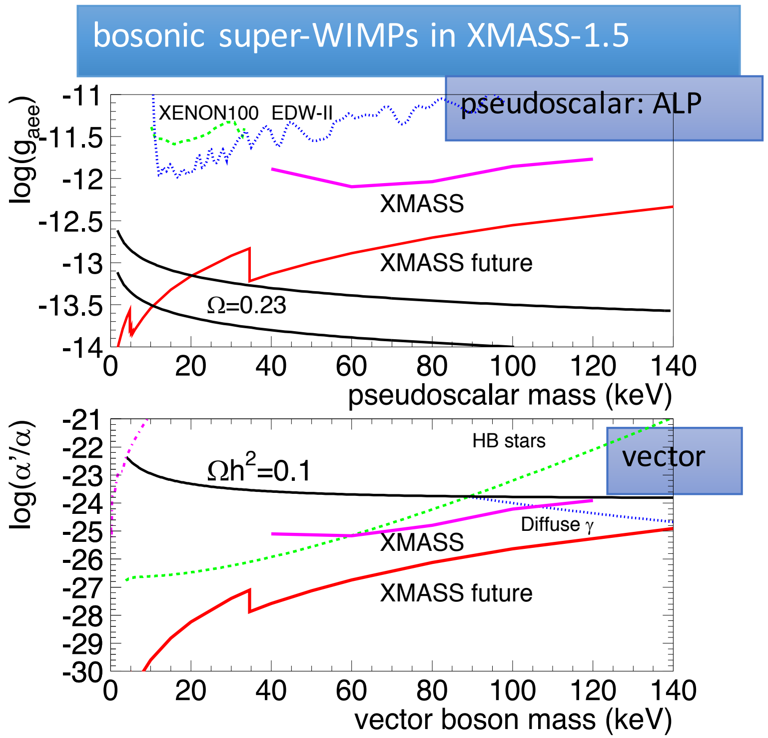


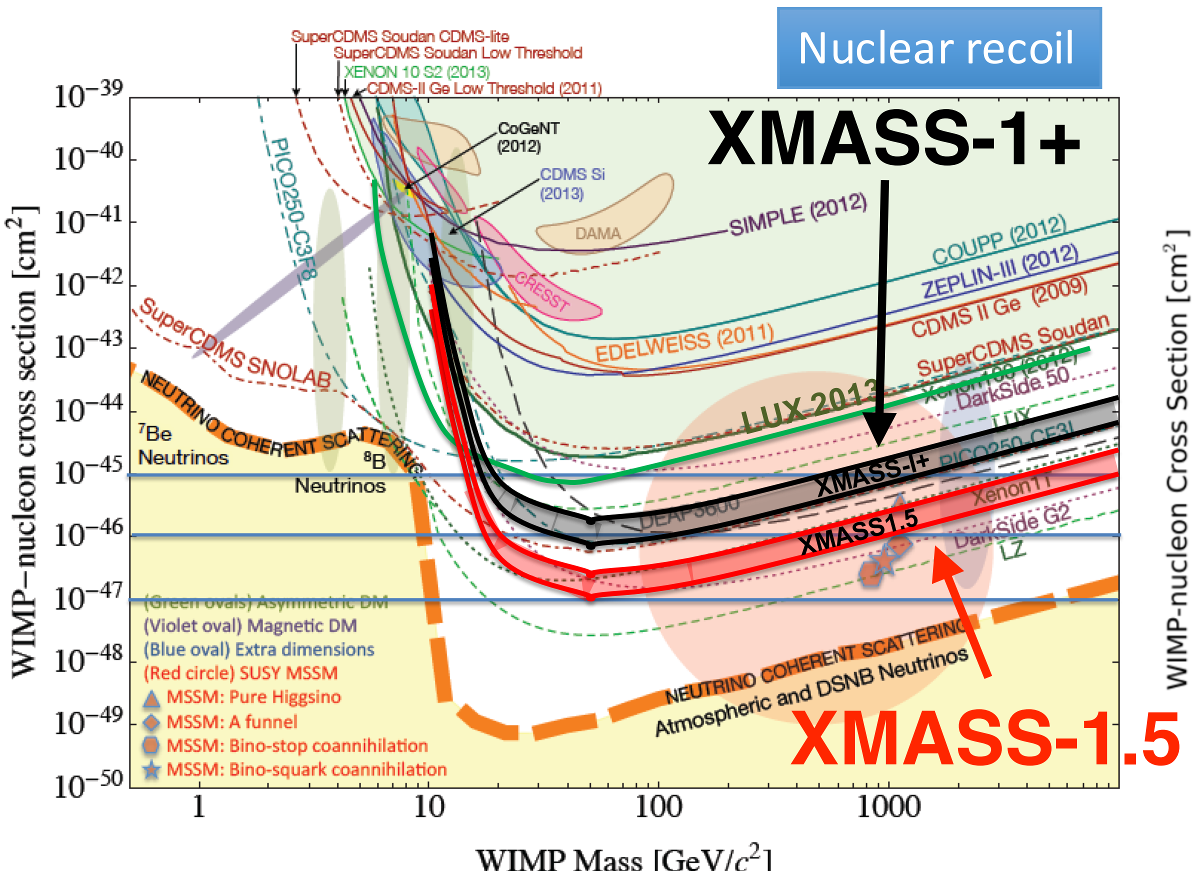
* pp solar ν is one of the physics targets in XMASS1.5.
We will be able to detect a few counts/day

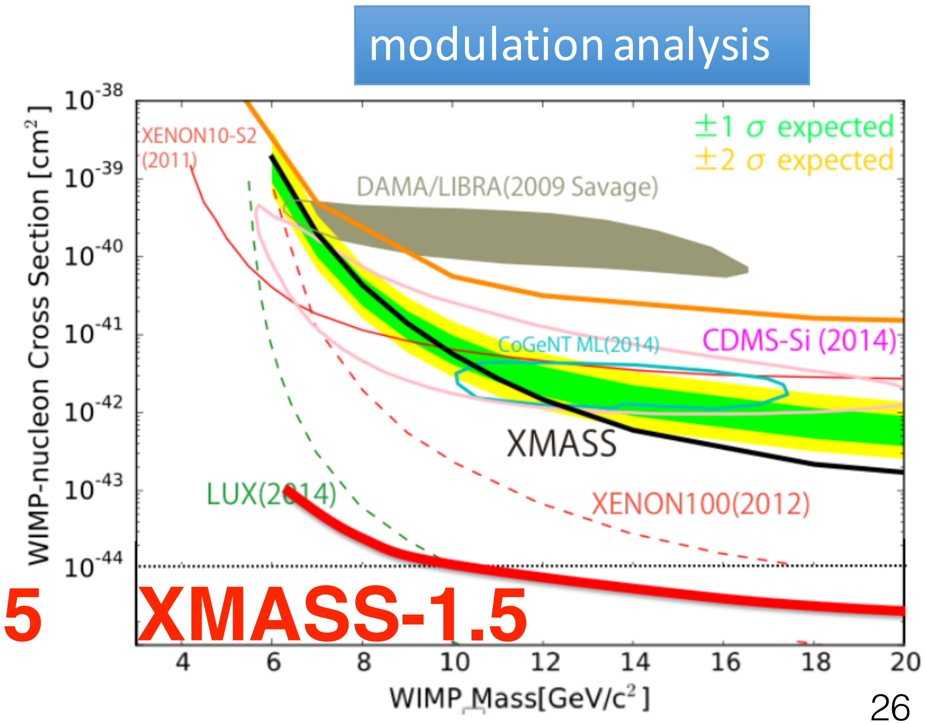
sensitivity

XMASS 1.5

- WIMP
  - σ_{SI} : **1~3 x 10^-47^ cm^2^** @ 50GeV
    [FV 3ton, 3~5 years,
    (1~0.6) x 10^-5^ evt/keV/day/kg]
- high sensitivity for e/γ detection







Summary

DM search in XMASS

- a single-phase liquid Xenon detector
  - Scalability
    - WIMP search with large target volume
      - 835 kg (current) -> 6 ton (future XMASS1.5)
  - Sensitive to e/γ as well as nuclear recoil
    - explore non-WIMP DM candidates
- Annual modulation search
  - recently published in Phys. Lett. B (2016) 272
  - Almost exclude DAMA/LIBRA allowed region
- Future plan : XMASS1.5
  - Full volume: 5 ton, Fiducial volume: ~3 ton
  - install new Dome PMT
    - BG rate: $\sim 10^{-5}$ dru
    - sensitivity: $\sigma \sim (1\text{-}3) \times 10^{-47}$ cm^2 @ 50GeV WIMP
    - demonstrated in XMASS1+