



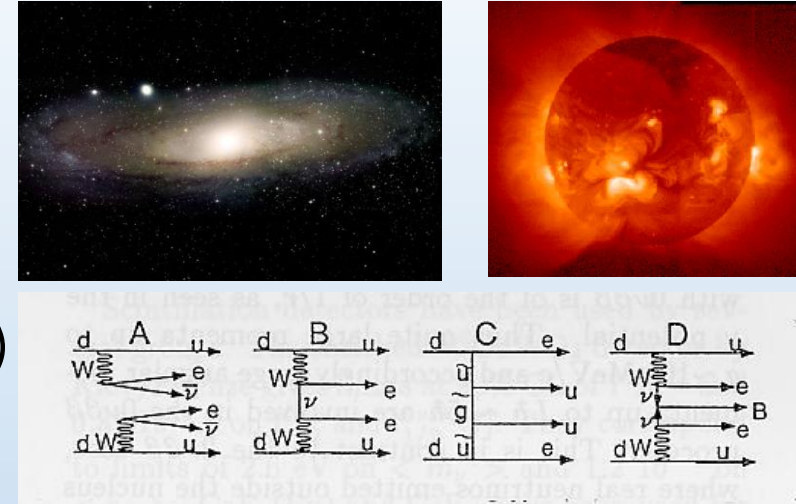
# Recent results of direct dark matter search with XMASS

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for the XMASS Collaboration

August 5<sup>th</sup>, 2016  
ICHEP2016@Chicago

# XMASS project

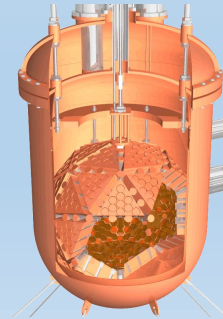
- XMASS: a multi purpose experiment with liquid xenon
  - Xenon detector for Weakly Interacting **MASS**ive Particles (**dark matter**)
  - Xenon **MASS**ive detector for solar neutrino (**pp/<sup>7</sup>Be solar neutrino**)
  - Xenon neutrino **MASS** detector (**double beta decay**)



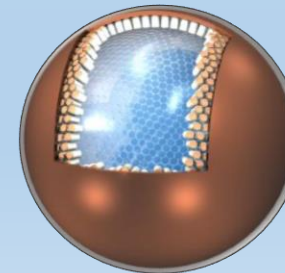
- Features

- Low energy threshold
- Sensitive to e/γ events as well as nuclear recoil
- Large target mass and its scalability

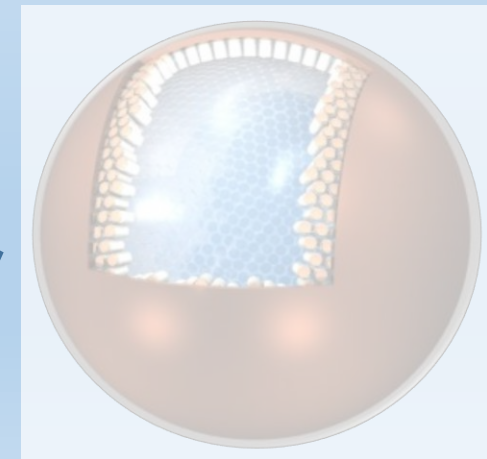
XMASS-1  
(total ~1ton)



XMASS-1.5  
(total ~6tons)

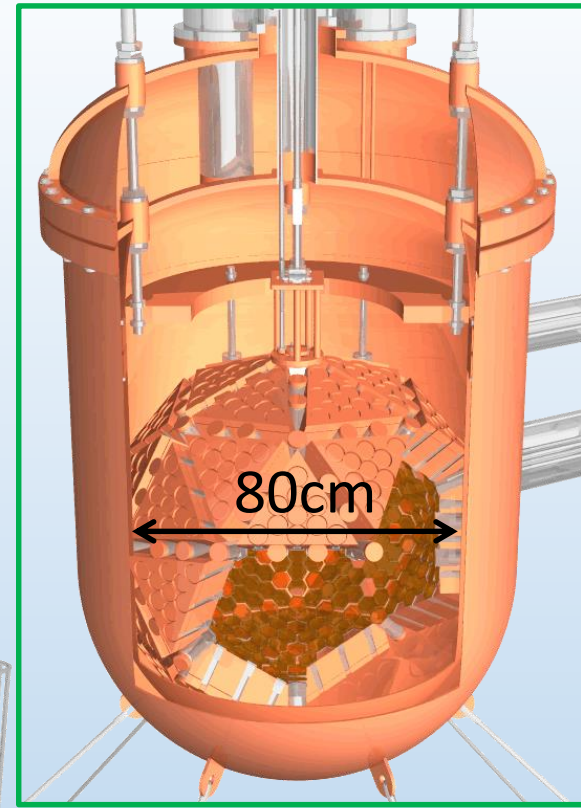
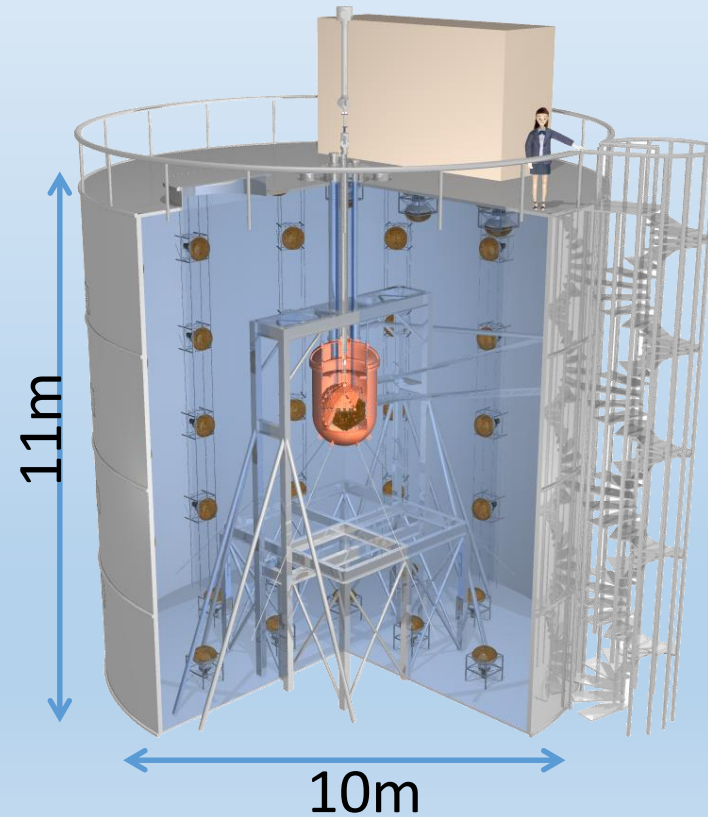
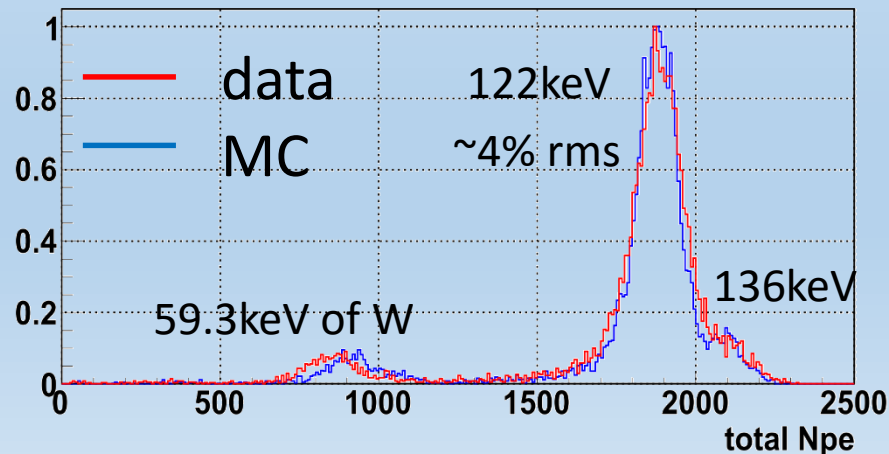


XMASS-2  
(total ~24tons)

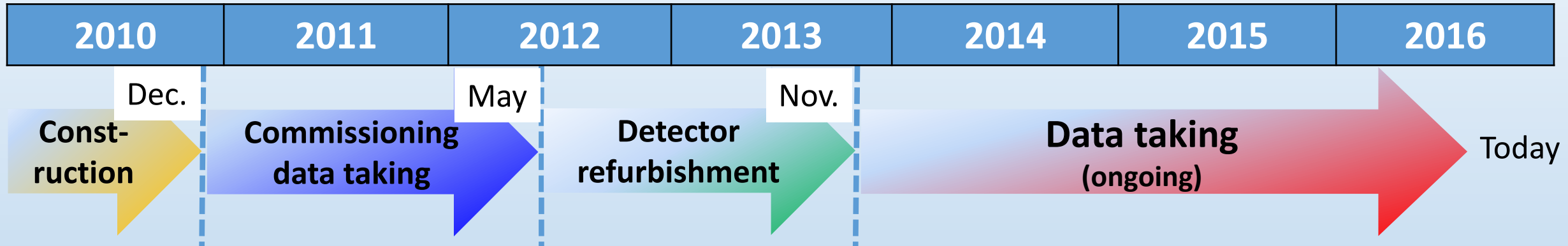


# Single-phase LXe detector: XMASS-I

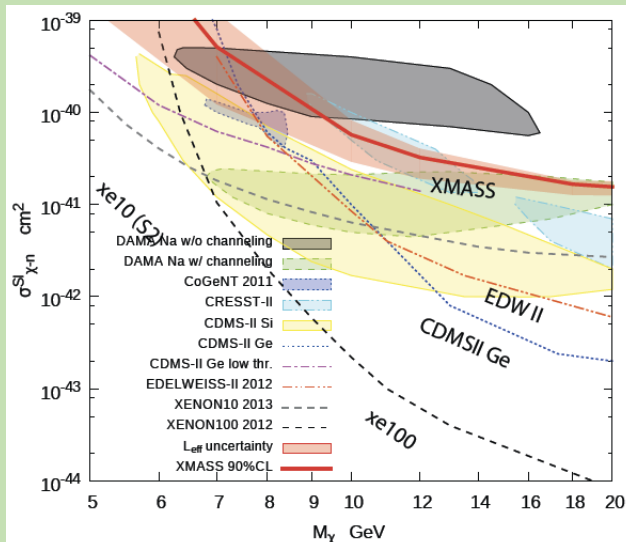
- Located in the Kamioka mine in Japan (~2,700m water equivalent)
- ~830kg LXe viewed by 642 PMTs (Photocathode coverage >62%)
- Active water shield for cosmic-ray muons
- Large photoelectron yield ~14 PE/keV for 122keV  $\gamma$ -ray



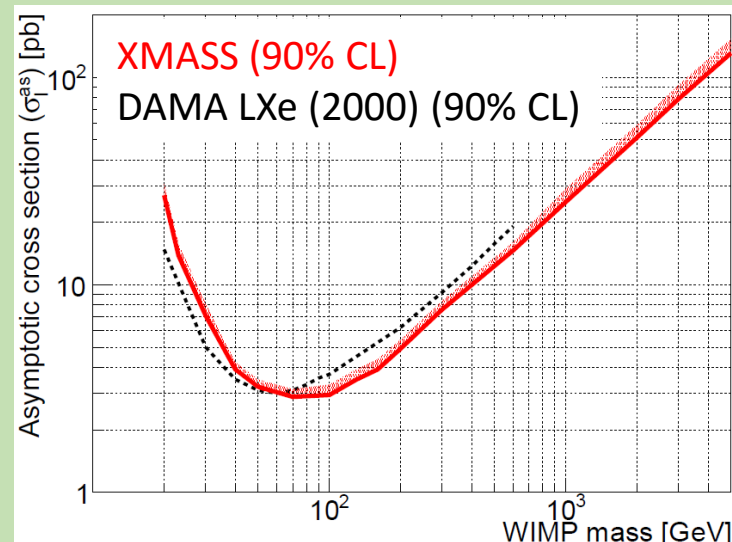
# Direct dark matter searches with XMASS-I



Low mass WIMP search  
*Phys. Lett. B719 (2013) 78*



WIMP-<sup>129</sup>Xe inelastic scattering  
*PTEP (2014) 063C01*



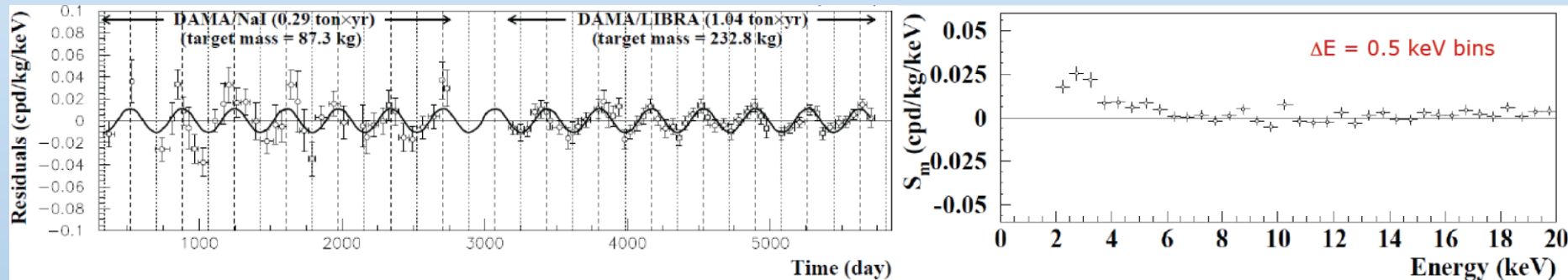
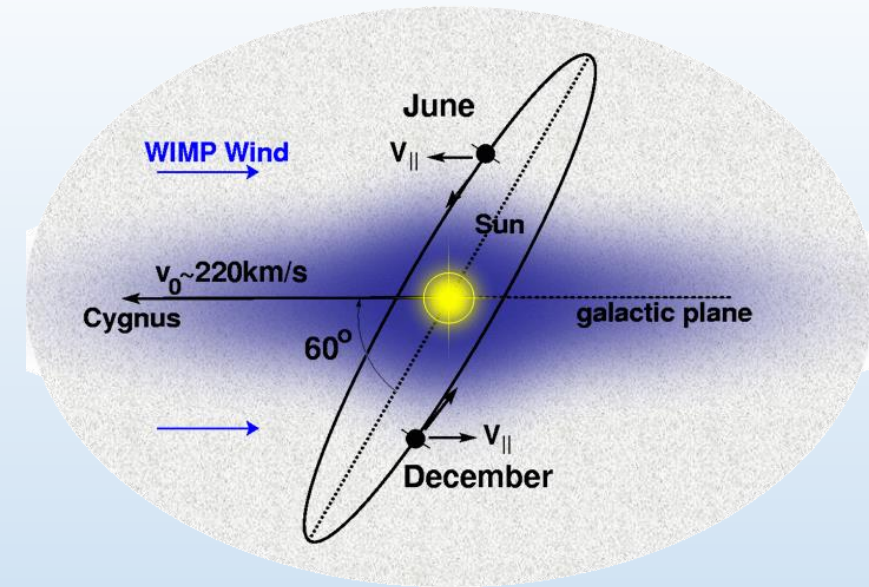
## Latest results

**New!**

- Annual modulation search  
*Phys. Lett. B759 (2016) 272*
- Bosonic super-WIMPs search  
*Phys. Rev. Lett. 113 (2014) 121301*

# Search for annual modulation

- Expect annual modulation of event rate of dark matter signal due to Earth's rotation around the Sun.
- DAMA/LIBRA claims modulation at  $9.3\sigma$ 
  - Total exposure of 1.33 ton year (14 cycles)
  - Modulation amplitude of  $(0.0112 \pm 0.0012)$  cpd/kg/keV for 2-6 keV



- Annual modulation search in XMASS
  - 359.2 live days x 832 kg (=0.82 ton year)
  - Analysis threshold 1.1 keVee (=4.8 keVnr)
  - Look for event rate modulation not only for nuclear recoil but also for  $e/\gamma$  events

# Modulation analysis

- Two different fitting methods

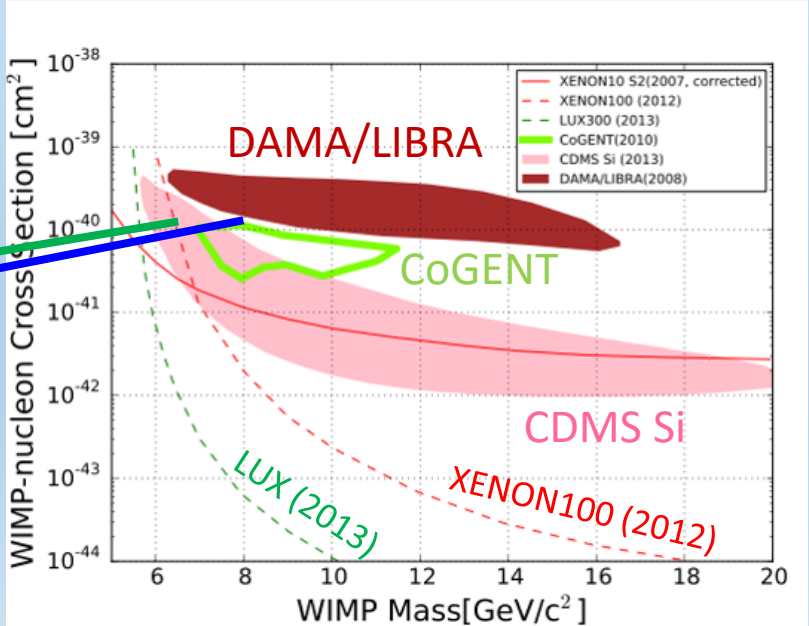
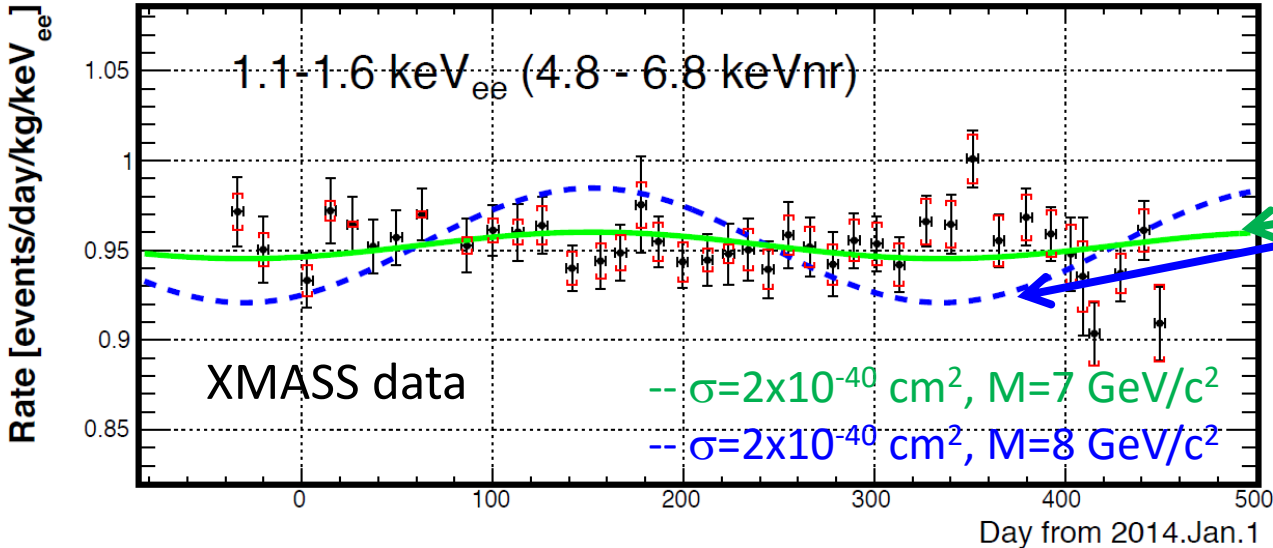
Pull term  
(Method-1)

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

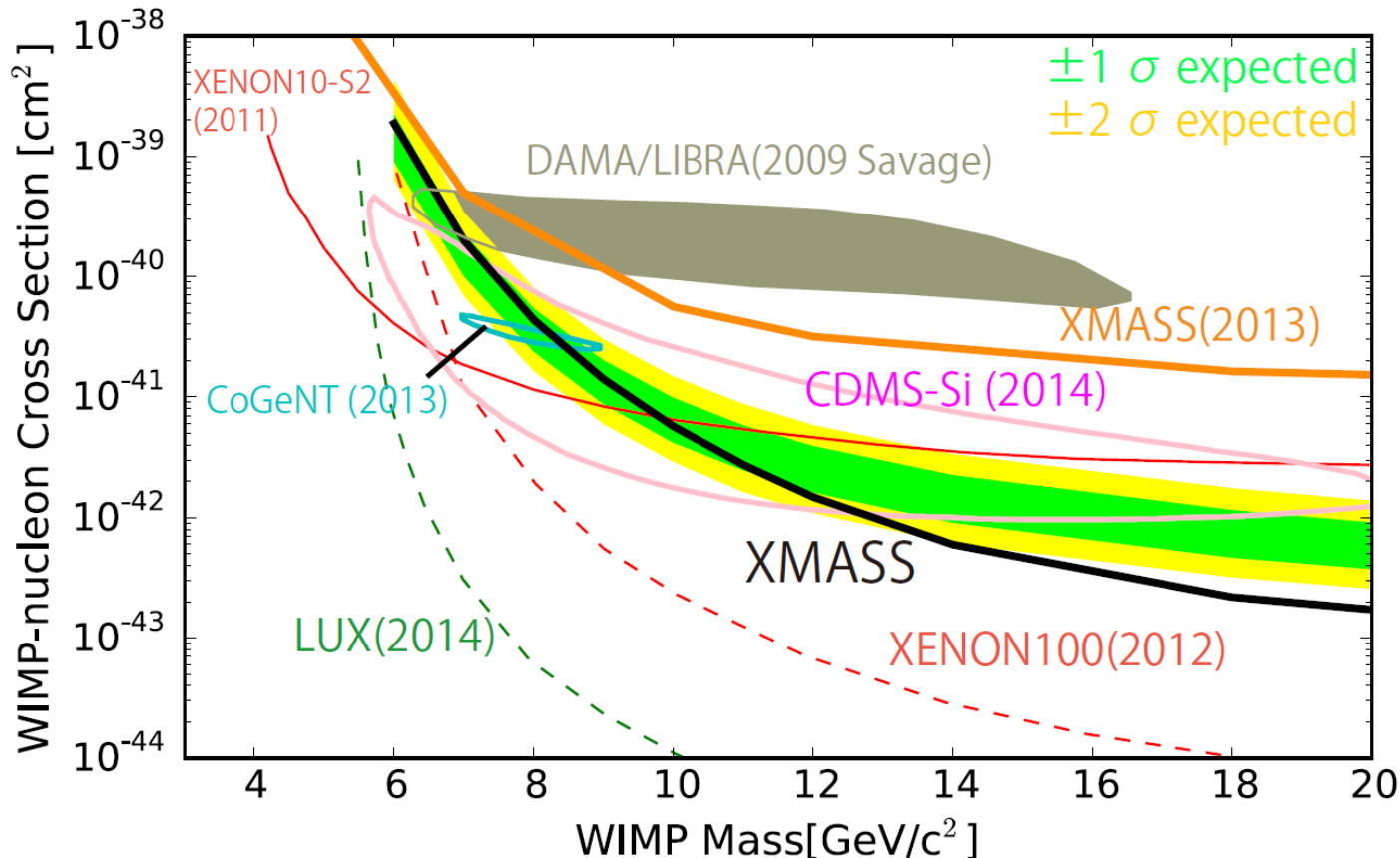
Covariance matrix  
(Method-2)

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

- Our data demonstrate high sensitivity to modulation



# Modulation analysis: WIMP results



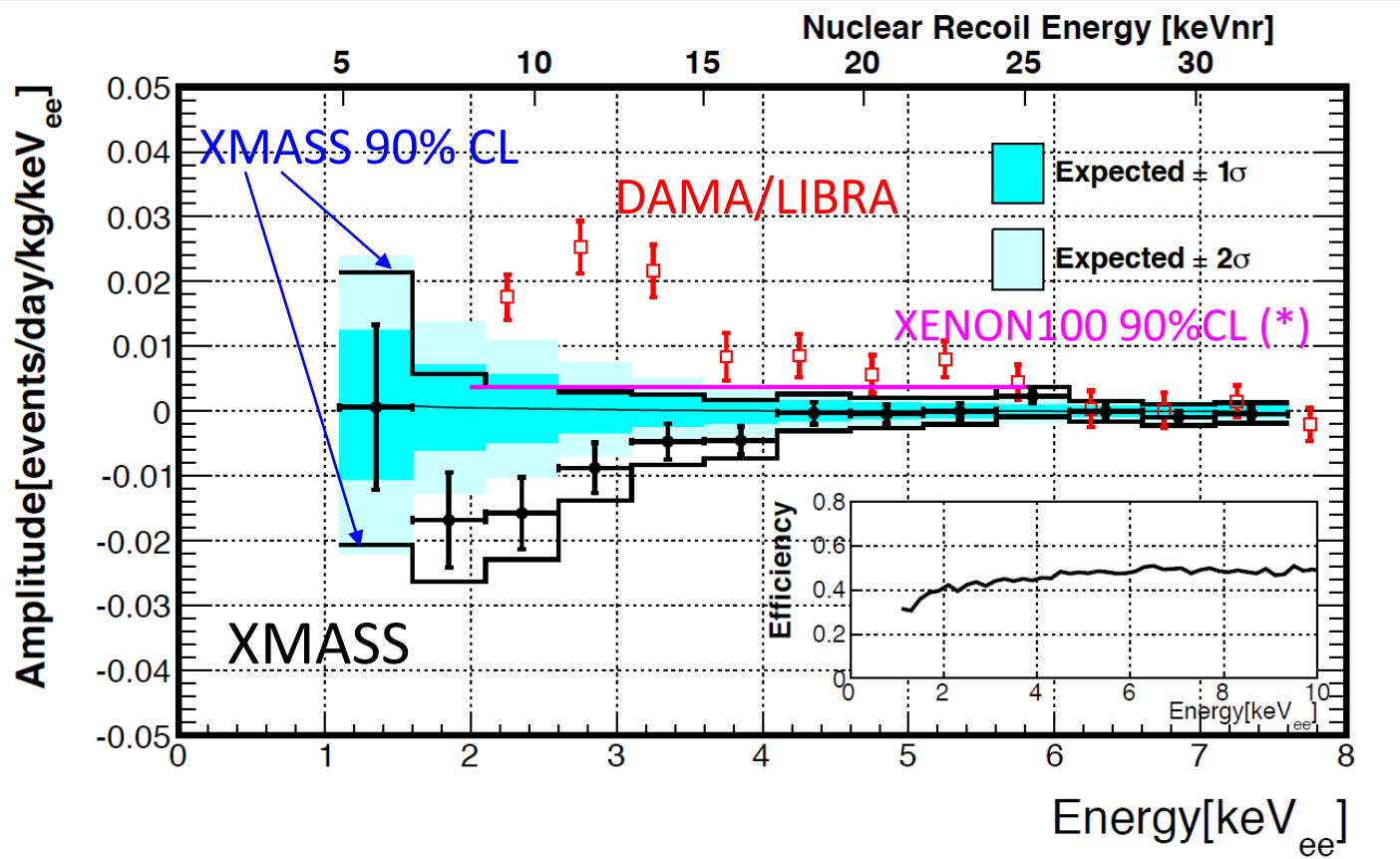
- Expected event rate

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

- $T = 1$  year,  $t_0 = 152.5$  day (fixed)
- $A_i(m_\chi)$ : modulation amplitude
- $C_i$ : unmodulated event rate

- WIMP mass range 6 to 20  $\text{GeV}/c^2$
- Both fitting methods give similar results
- Exclude almost all the DAMA/LIBRA allowed region by modulation search

# Modulation analysis: model independent results



(\*) We estimated the XENON100 90% CL limit based on PRL 115 (2015) 091302 and Science 349 (2015) 852.

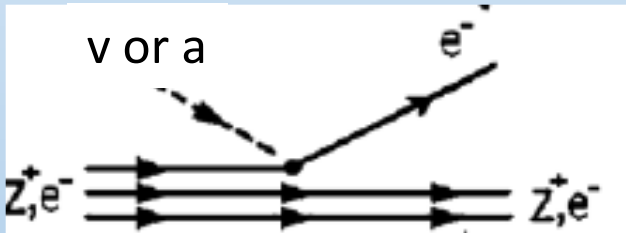
- Without assuming any specific model except for  $T=1$  year,  $t_0=152.5$  day
- Includes both NR and  $e/\gamma$  signals
- Shows slightly negative amplitudes in the 1.6-4.1 keV<sub>ee</sub> range.
- P-values
  - 0.014 ( $2.5\sigma$ ) for method-1
  - 0.068 ( $1.8\sigma$ ) for method-2
- Gives 90% CL limits for positive and negative amplitude separately

*Phys. Lett. B759 (2016) 272*

# Search for bosonic super-WIMPs

- Bosonic super-WIMPs

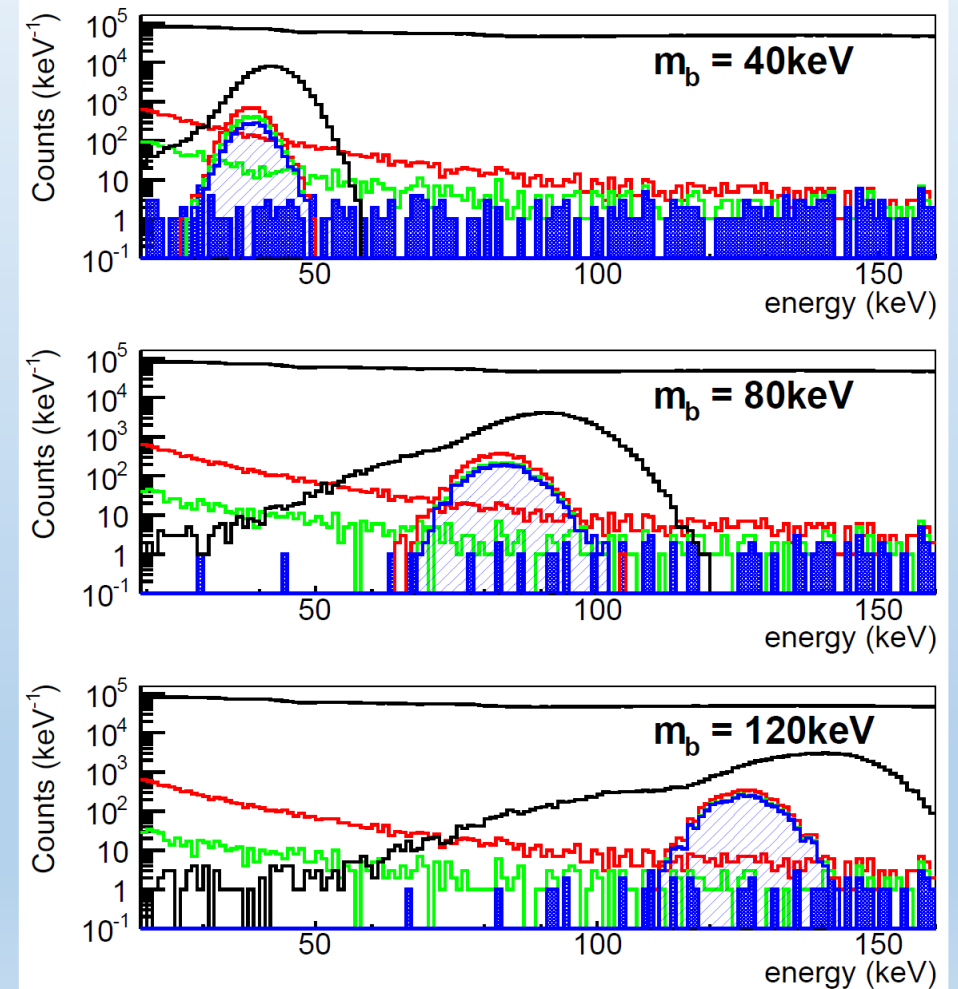
- Lighter and more weakly interacting than WIMPs
- Candidate for lukewarm dark matter
- Can be pseudoscalar or vector boson.
- Can be detected by absorption of the particle, which is similar to the photoelectric effect.



- Search for bosonic super-WIMPs in XMASS

- 165.9 days data taken in Dec. 2010 – May 2012
- 41 kg fiducial mass
- Remaining event rate  $\sim 10^{-4}$  dru ( $^{214}\text{Pb}$  from  $^{222}\text{Rn}$ )

- Pre-selection
- Fiducial volume cut
- Timing balance cut
- Topological cut



# Constraint on coupling constants

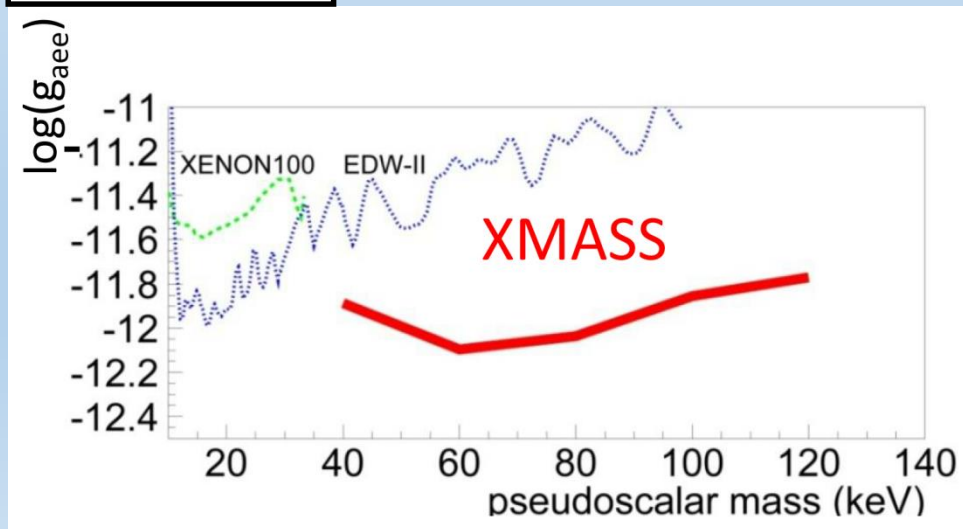
- Vector boson case

- The first direct search in the 40–120 keV range.
- We exclude the possibility that such particles constitute all of dark matter.

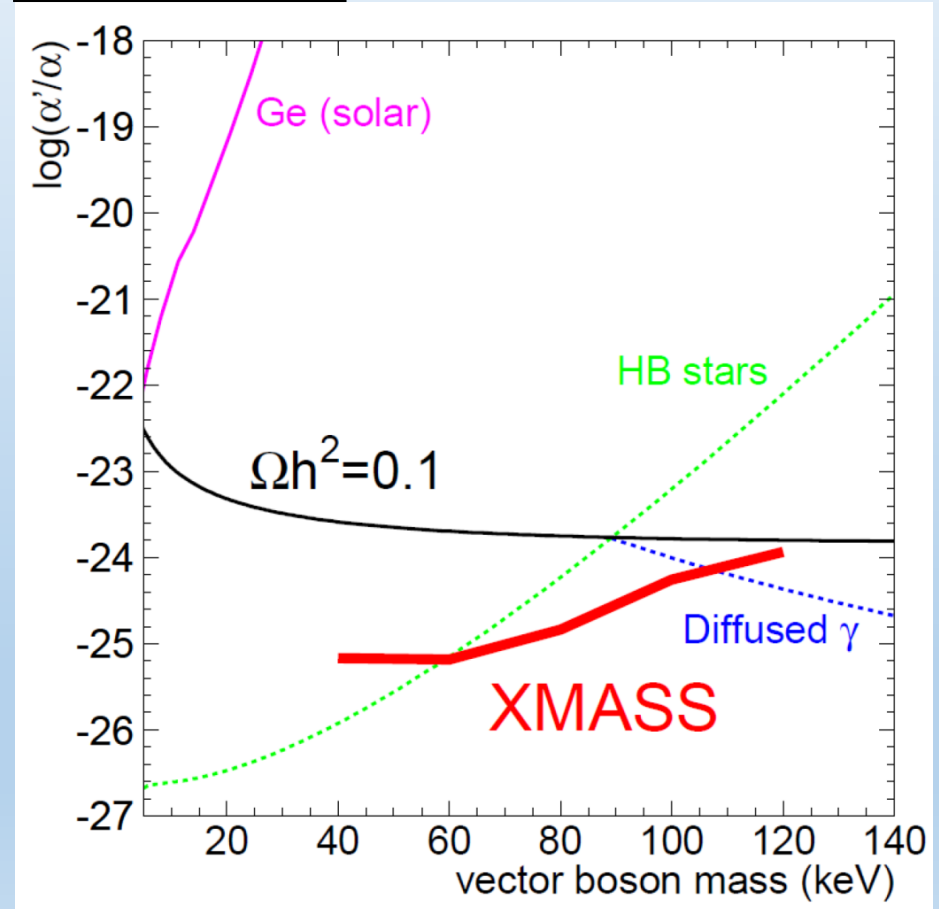
- Pseudoscalar case

- The most stringent direct constraint on  $g_{aee}$ .

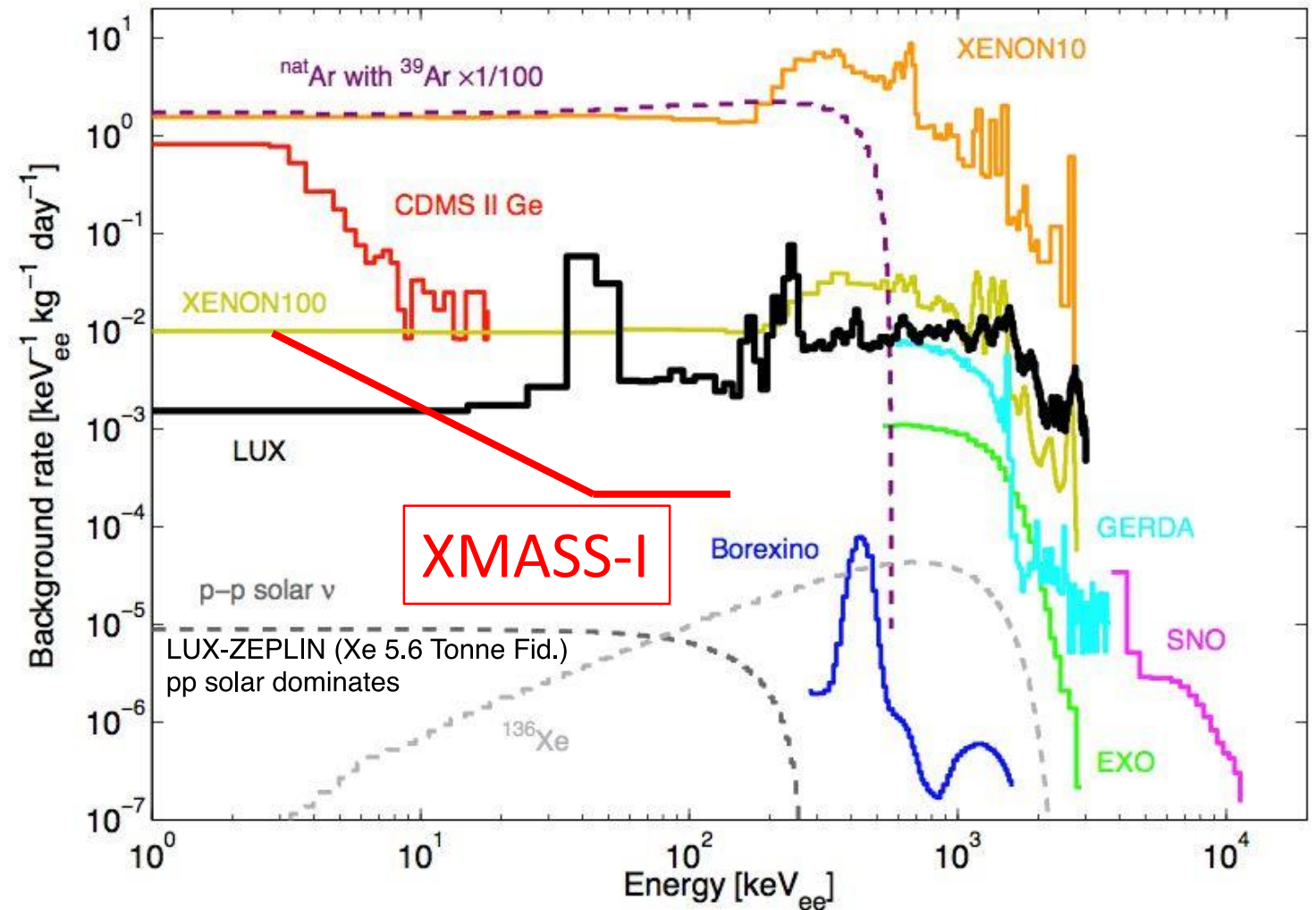
Pseudoscalar



Vector boson



# Comparison of background rate in fiducial volume including both nuclear recoil and e/ $\gamma$ events

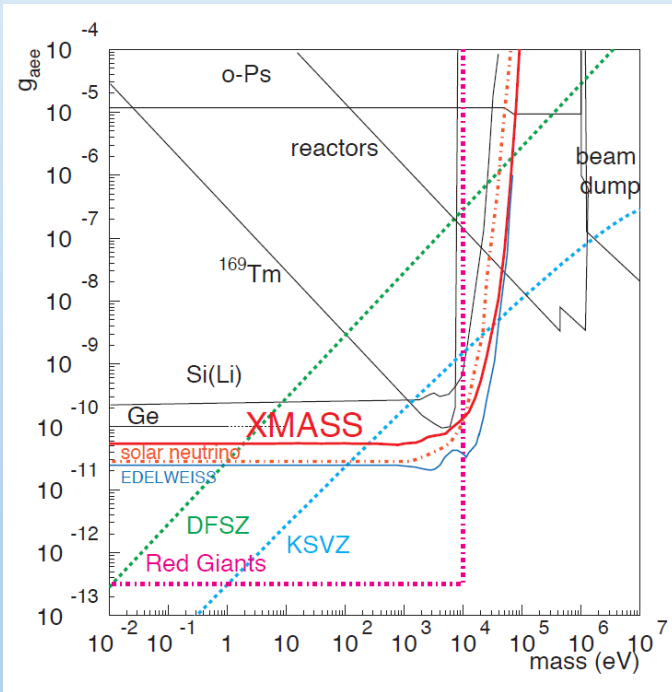


- XMASS achieved low background rate of  $O(10^{-4})$  dru in a few 10s keV including e/ $\gamma$  events
- Low background rate for e/ $\gamma$  events is good for searching for dark matter other than WIMPs.

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

# Diversity of XMASS (non dark matter physics)

solar axion search  
via axio-electric effect

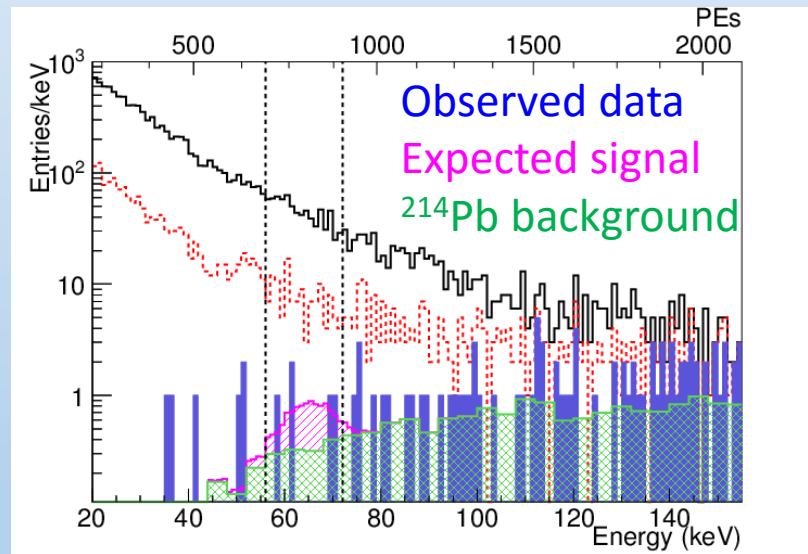


$$g_{aee} < 5.4 \times 10^{-11} \text{ (90\%CL)}$$

*Phys. Lett. B724 (2013) 46*

**New!**

Search for two-neutrino  
double electron capture  
(2νECEC) on  $^{124}\text{Xe}$ ,  $^{126}\text{Xe}$



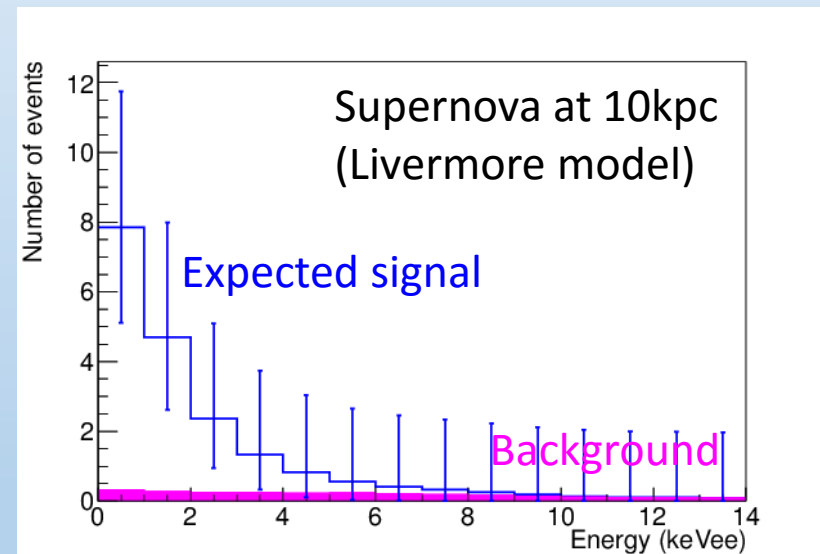
$$T_{1/2}^{2\nu 2K(^{124}\text{Xe})} > 4.7 \times 10^{21} \text{ years}$$

$$T_{1/2}^{2\nu 2K(^{126}\text{Xe})} > 4.3 \times 10^{21} \text{ years}$$

*Phys. Lett. B759 (2016) 64*

**New!**

Possibility of detecting  
galactic supernova neutrinos  
via coherent scattering (CEvNS)



$O(10^4)$  events in the case of  
Betelgeuse (200 pc)

*arXiv: 1604.01218*

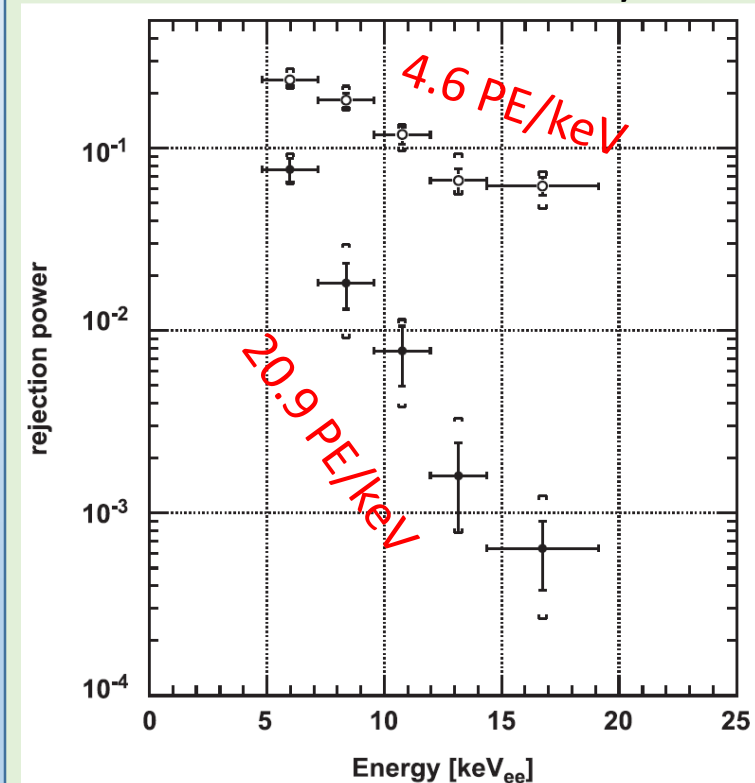
# Prospects for pulse shape discrimination (PSD) using LXe scintillation

- LXe scintillation processes
  - Excitation:
    - Singlet ( $^1\Sigma_u^+$ ):  $\tau \sim$  a few ns
    - Triplet ( $^3\Sigma_u^+$ ):  $\tau \sim 20$  ns
  - Recombination:  $\tau \sim 30$  ns or more
- Singlet/triplet ratio, recombination time depend on ionization density
- Early study of PSD with a small set up
  - Electron rejection power of  $\sim 8 \times 10^{-2}$  for 50% NR efficiency at 4.8-7.2 keV<sub>ee</sub>
- Detail measurement of scintillation time profile for low energy  $e/\gamma$  has been conducted

New!

## PSD study with a small setup

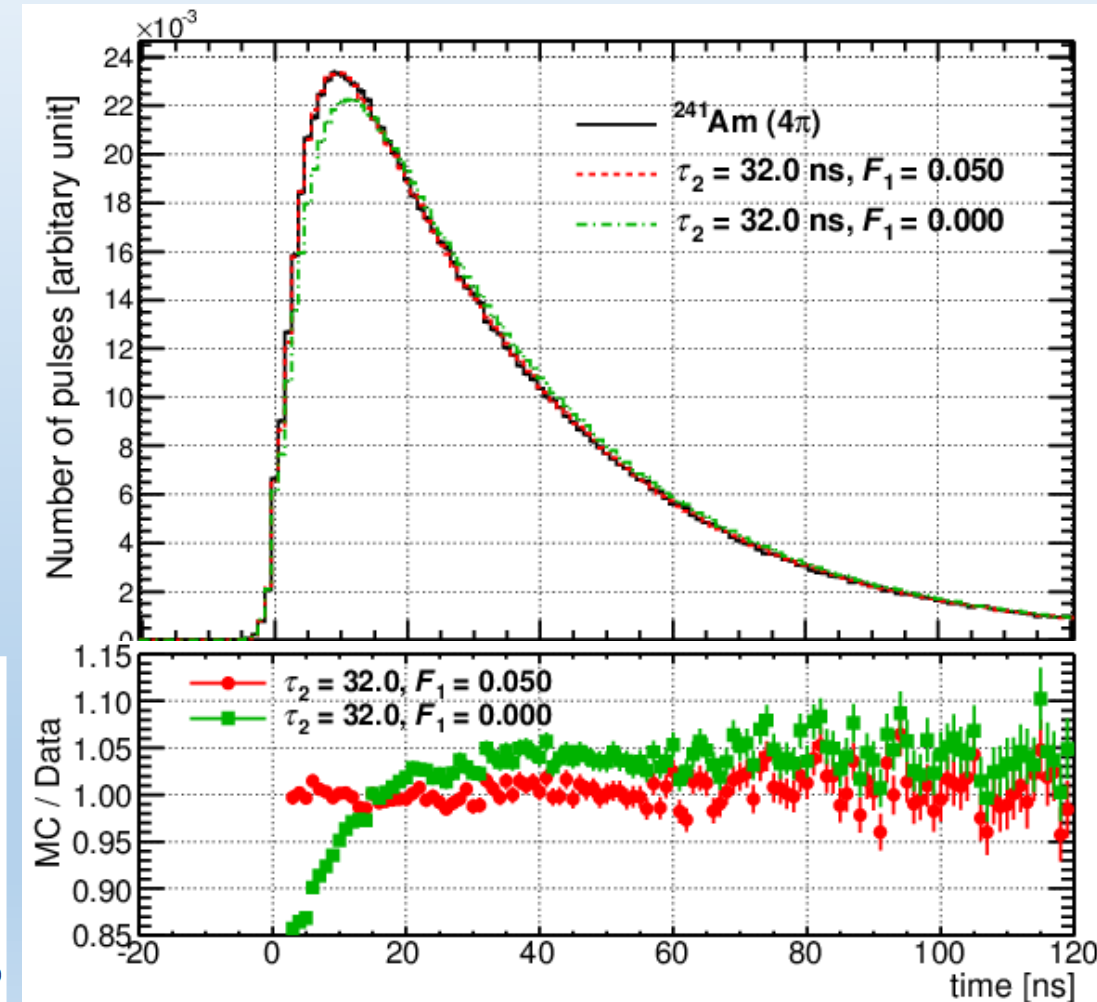
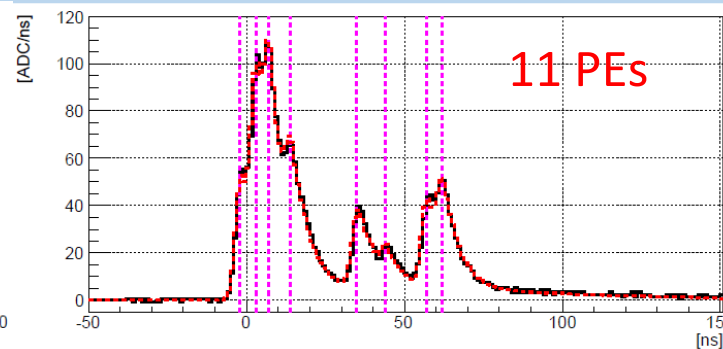
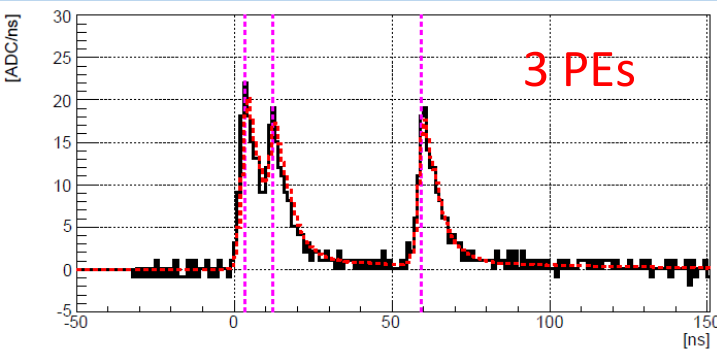
Electron rejection power for 50% NR efficiency



NIM A659 (2011) 161

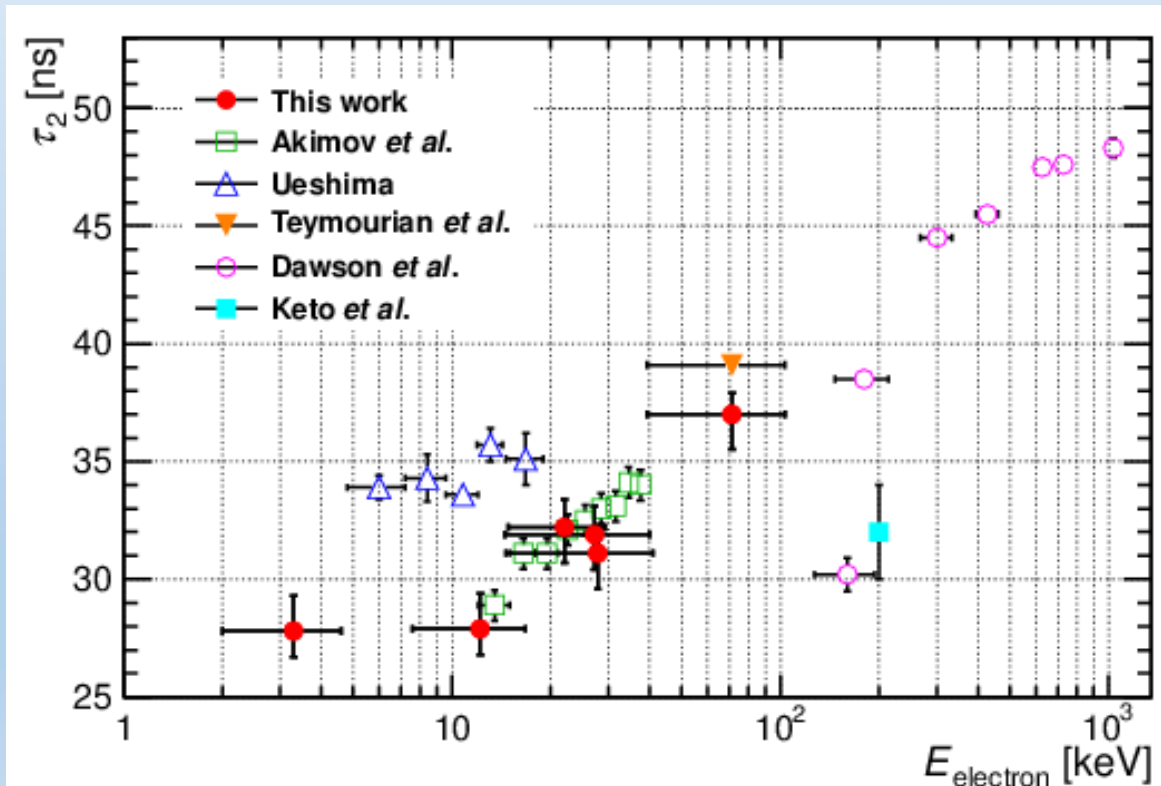
# Measurement of LXe scintillation time profile for low energy gamma-ray induced events

- Using  $^{55}\text{Fe}$ ,  $^{241}\text{Am}$ , and  $^{57}\text{Co}$  sources ( $E_\gamma=5.9\text{-}120\text{keV}$ )
- Waveforms are decomposed into “single PE” pulses
- MC simulation takes into account optical parameters (absorption, scattering, ...), electronics response
- Timing distributions of data and MC are compared to obtain intrinsic decay time parameters.



# Measurement of LXe scintillation time profile for low energy gamma-ray induced events

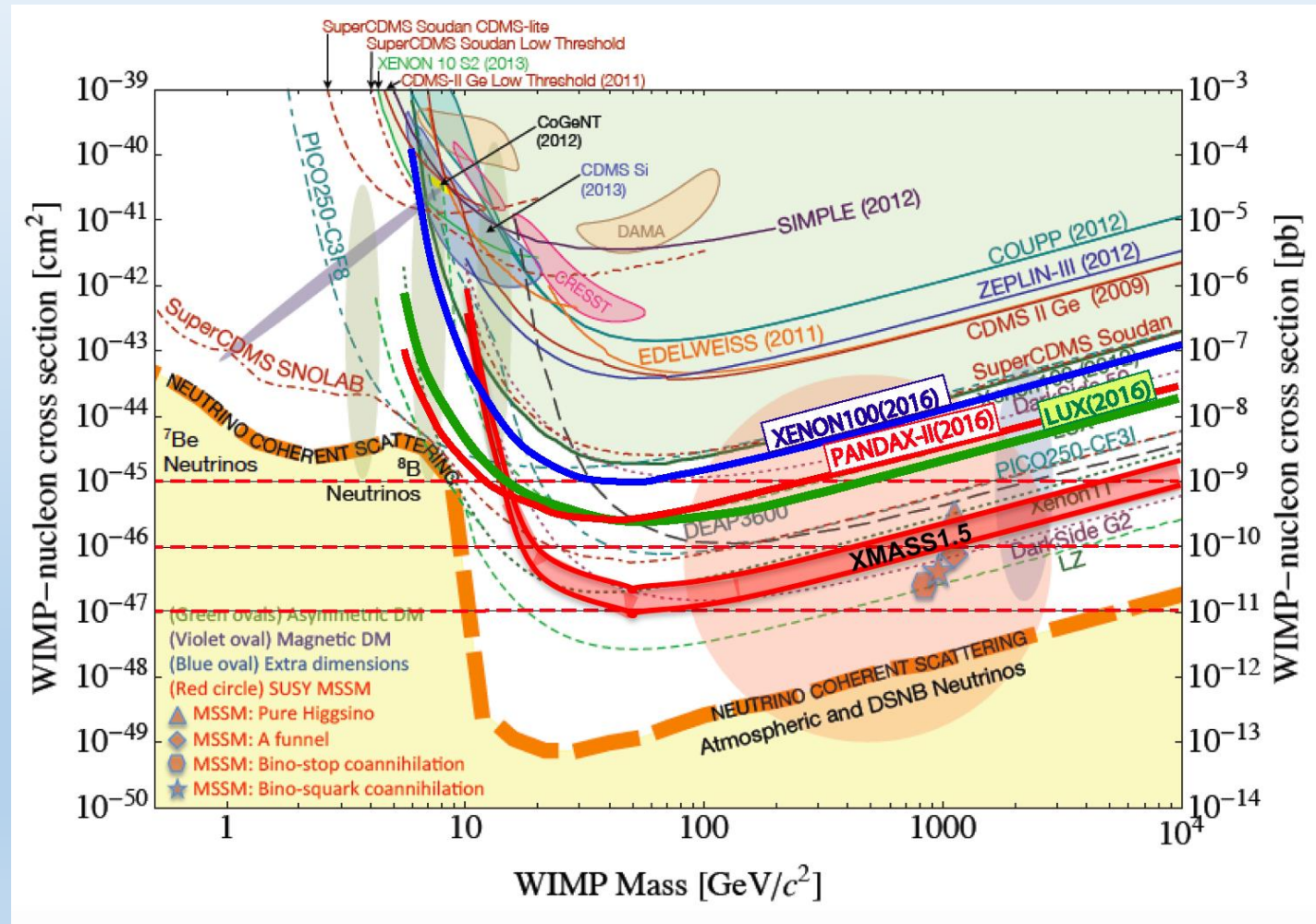
$$f(t) = \frac{F_1}{\tau_1} \exp\left(-\frac{t}{\tau_1}\right) + \left(\frac{1-F_1}{\tau_2}\right) \cdot \exp\left(-\frac{t}{\tau_2}\right)$$



- Fast decay component is needed to reproduce our calibration data.
  - $\tau_1=2.2$  ns (fixed)
  - $F_1$ : 0.05~0.15 (increase at low energy)
- Energy dependence of decay time was studied as a function of mean kinetic energy of electrons induced by  $\gamma$ -ray
- Time profile for neutron under study

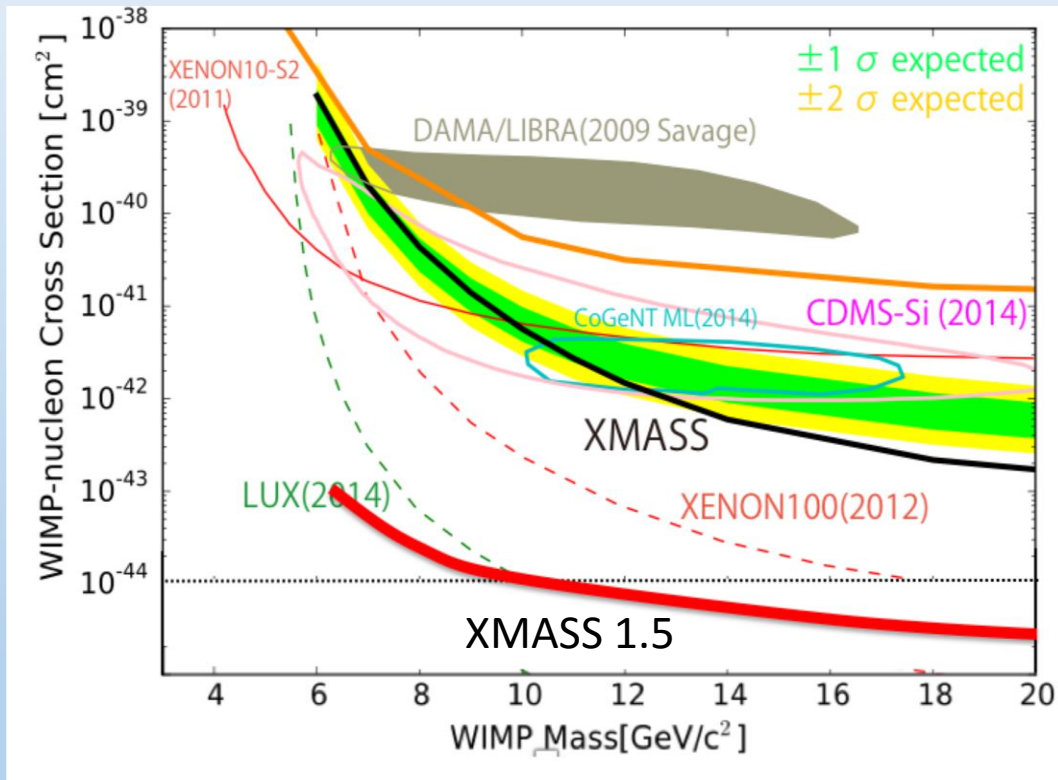
# Next step: XMASS-1.5

- Total ~6 tons (Fiducial mass ~3 tons)
- Newly developed low-background 3-inch dome-shape PMT
- R&D detail presented in poster “Future XMASS project” by K. Abe
- Background level of  $\sim 1 \times 10^{-5}$  dru ( $pp$  solar neutrinos) assumed
- Sensitivity to WIMP SI cross section  $(1-3) \times 10^{-47} \text{ cm}^2 @ 50 \text{ GeV}/c^2$



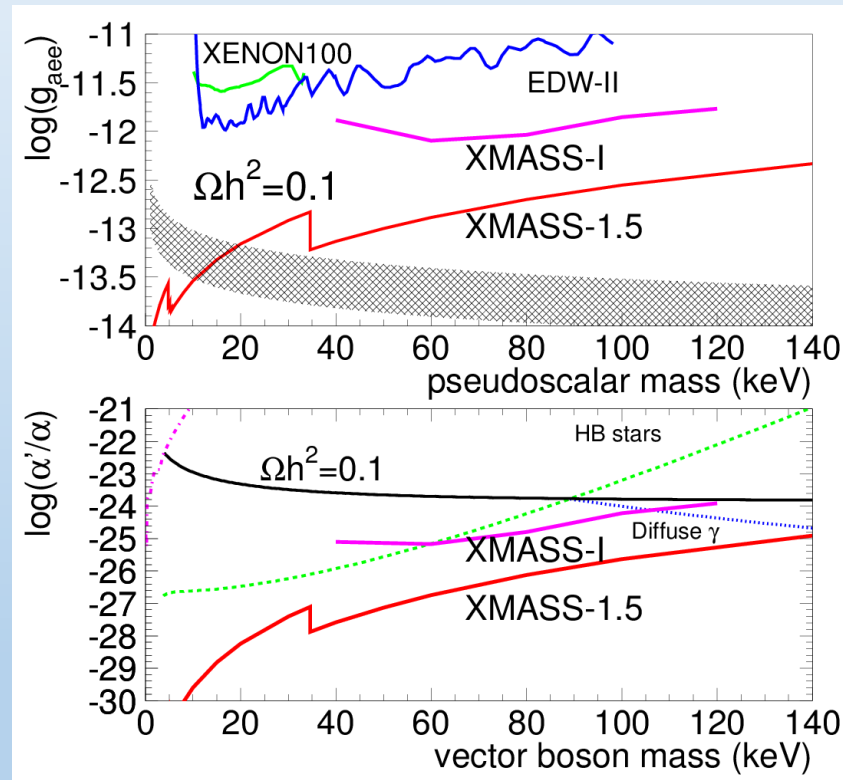
# Sensitivity to low mass WIMPs/bosonic super-WIMPs

## Low mass WIMPs



- Analysis threshold  $\sim 1$  keV<sub>ee</sub>
- Whole volume (no vertex reconstruction)
- Expect to reduce BG to 1/500 ( $< 10^{-2}$  dru)

## Bosonic super-WIMPs



- Higher energy  $O(100 \text{ keV})$  e/ $\gamma$  events
- Background level  $10^{-5}$  dru assumed
- Ultimate BG:  $pp$  solar neutrino &  $^{136}\text{Xe } 2\nu\beta\beta$

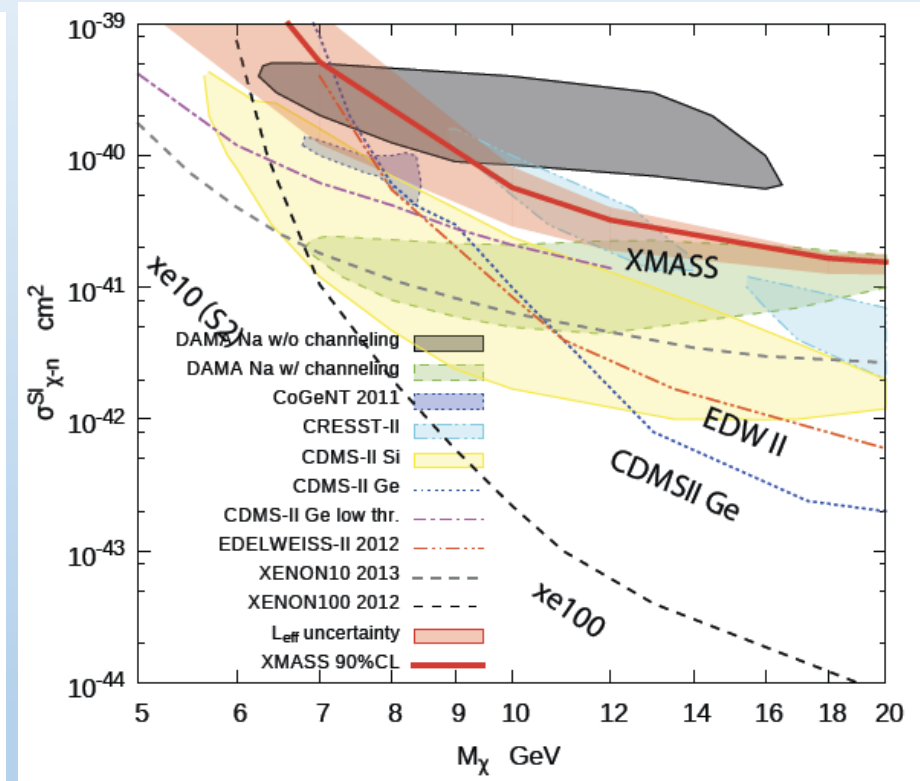
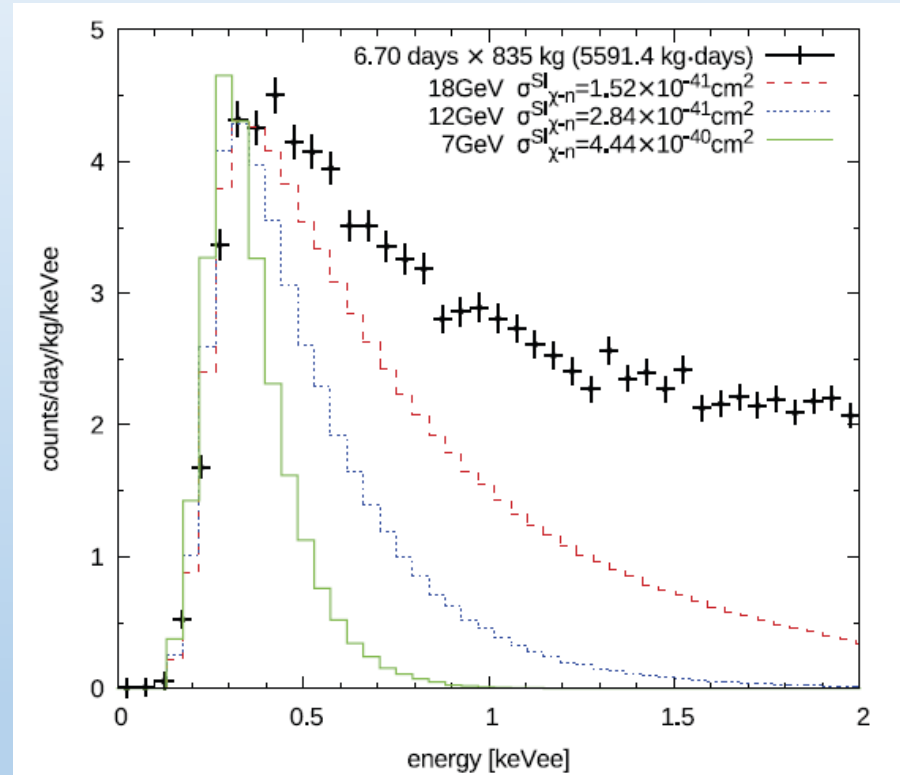
# Summary

- XMASS is a large-volume single-phase LXe detector designed for multiple particle and astroparticle physics targets.
- Various dark matter searches have been conducted with XMASS-I.
  - The first extensive modulation search with an exposure comparable to DAMA/LIBRA → shows a slight negative amplitude but not significant.
  - Search for bosonic super-WIMPs gives stringent limits on their coupling constants.
- XMASS demonstrate high sensitivity to  $e/\gamma$  events and diversity of physics targets of the experiment.
  - Solar axion,  $2\nu$ ECEC on  $^{124}\text{Xe}$ , supernova neutrino, etc.
- XMASS is stably taking data for more than 2 years. More results will come soon.
- The next phase, XMASS-1.5, will reach the WIMP SI cross section sensitivity of  $(1-3)\times 10^{-47} \text{ cm}^2 @ 50 \text{ GeV}/c^2$ .

# Backup slides

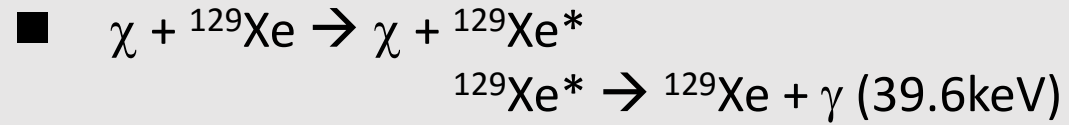
# Search for light WIMPs

- Use full volume of LXe
- 6.7 days x 835 kg
- 0.3 keVee threshold

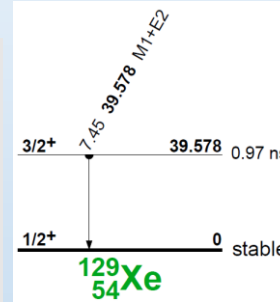


Published in Phys. Lett. B 719 78 (2013)

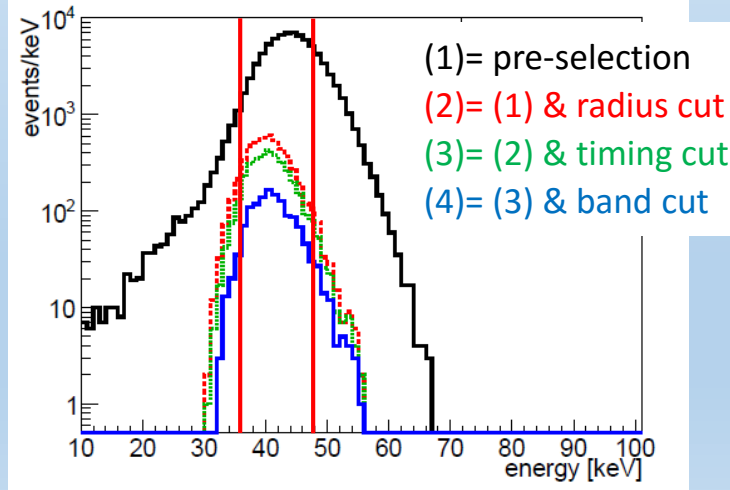
# Search for $^{129}\text{Xe}$ inelastic scattering by WIMPs



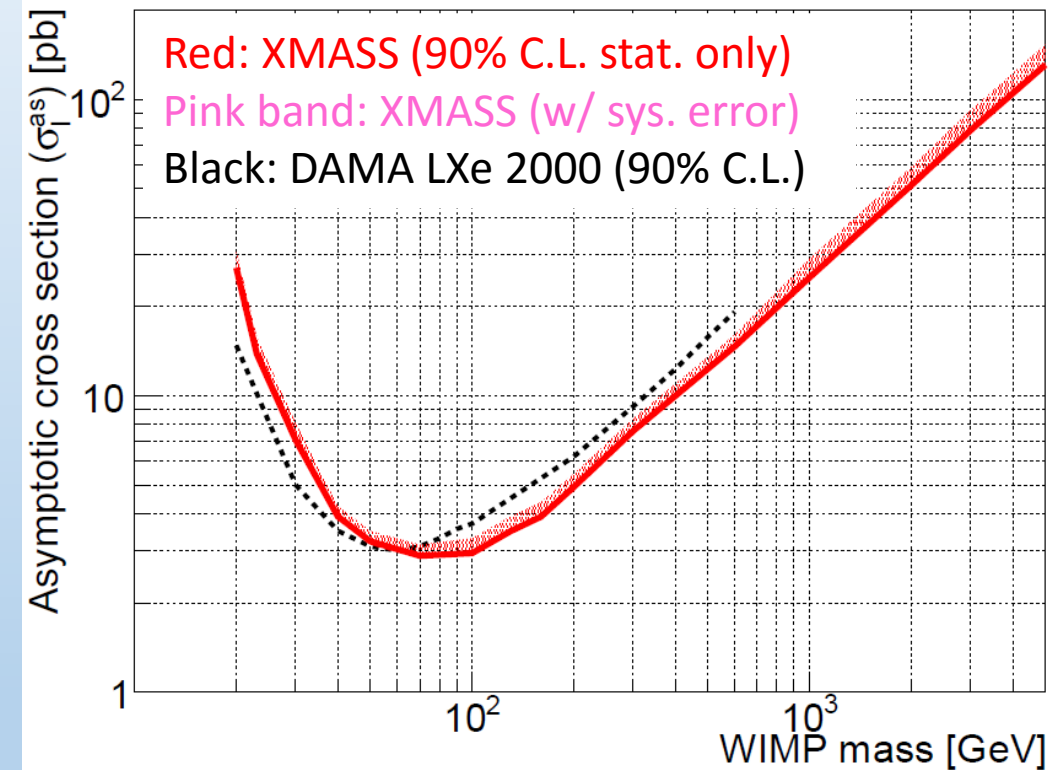
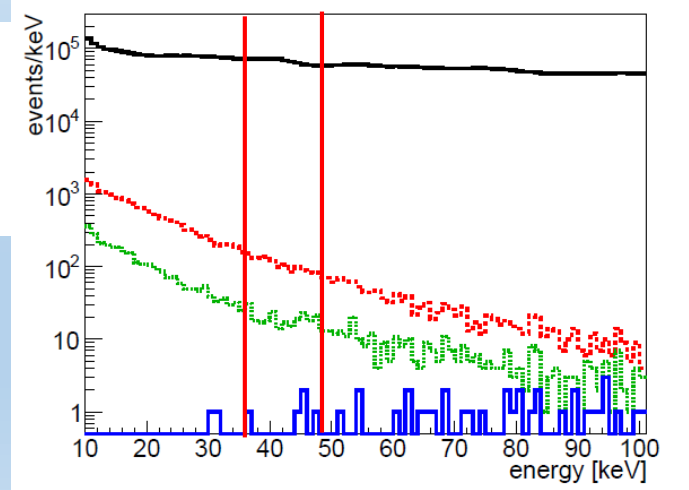
- Natural abundance of  $^{129}\text{Xe}$ : 26.4%



Signal MC for 50GeV WIMP



Observed data (165.9 days)



Published in PTEP 063C01 (2014)