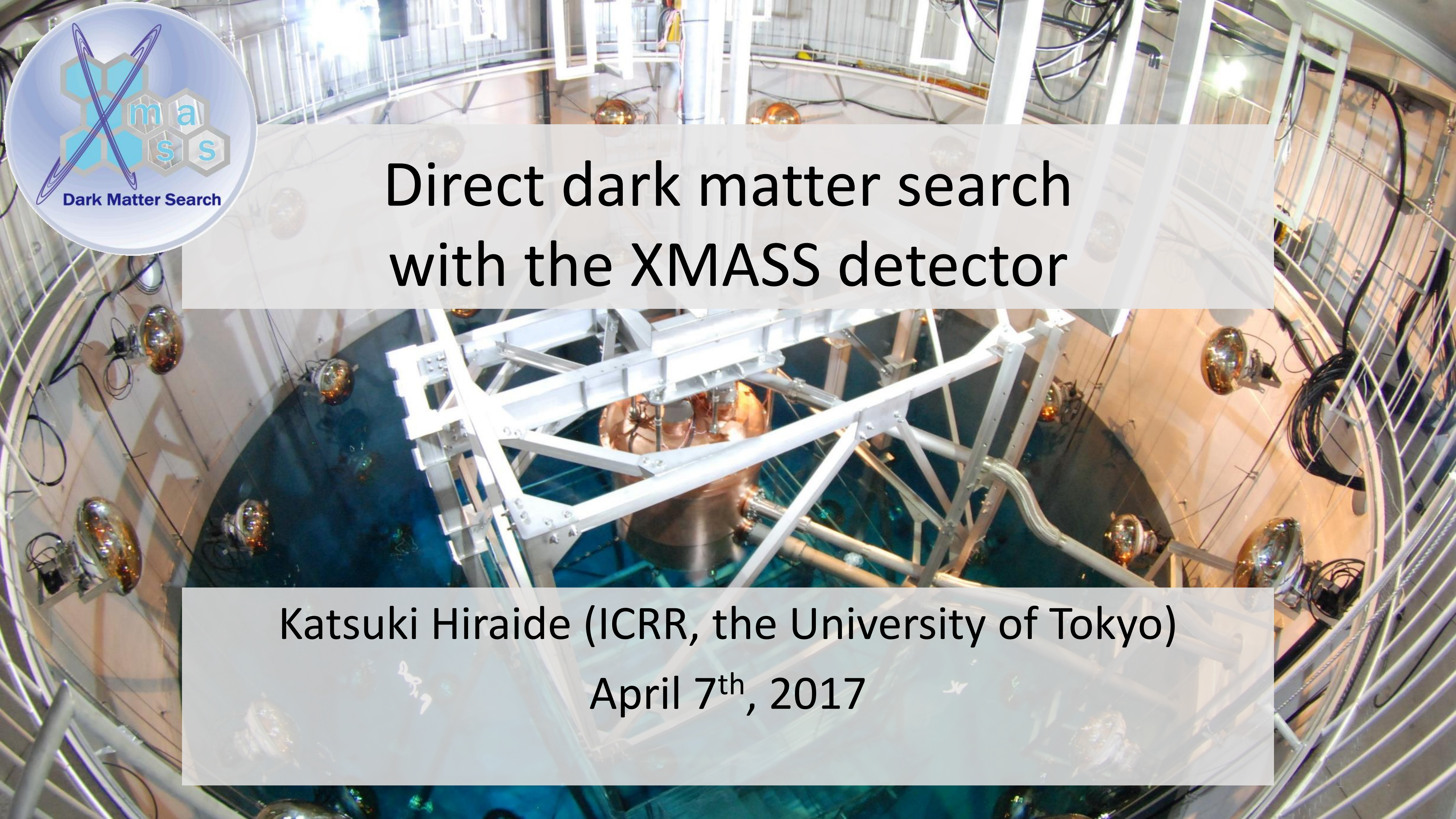


Direct dark matter search with the XMASS detector

Katsuki Hiraide (ICRR, the University of Tokyo)

April 7th, 2017

Self-introduction

- Research field
  - Experimental particle and astroparticle physics (especially dark matter and neutrino)

- 2003-2009: Graduate student at Kyoto University
  - Involved in various neutrino experiments (K2K/T2K/Super-Kamiokande/SciBooNE)
  - Stayed and worked at Fermi National Accelerator Laboratory in USA (2.5 years)
  - Dissertation: "A study of charged current single charged pion productions on carbon in a few-GeV neutrino beam," Kyoto University (2009)

- 2009-present: JSPS fellow (PD) → project assistant professor at ICRR
  - Direct dark matter search and neutrino physics in XMASS
  - Electronics/DAQ, PMT calibrations, simulation, and data analyses
  - Flash-ADC software convener (2013-2016), analysis convener (2016-present)

Contents

- Introduction to XMASS
- XMASS DAQ system and calibrations
- Dark matter search results
  - Search for low mass (~10GeV/c^2) WIMPs
  - Search for annual modulation
  - Search for bosonic super-WIMPs
- Diversity of physics targets with XMASS
  - Supernova neutrino observation via coherent ν-nucleus scattering
  - Search for double electron capture on ^{124}Xe
- Future prospects and my research plan
- Summary

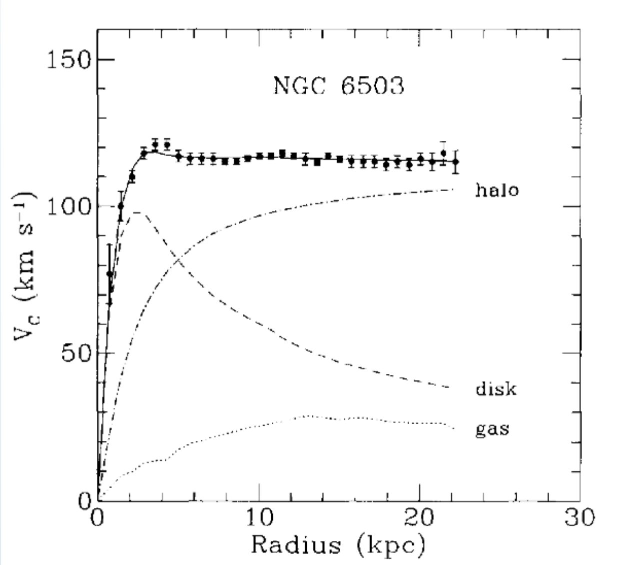
Introduction

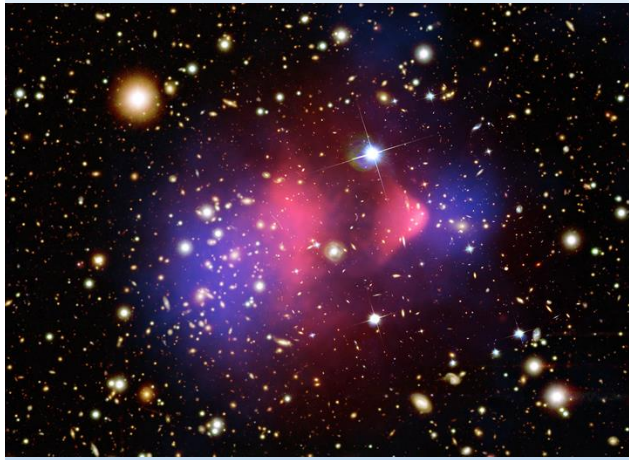
Dark matter

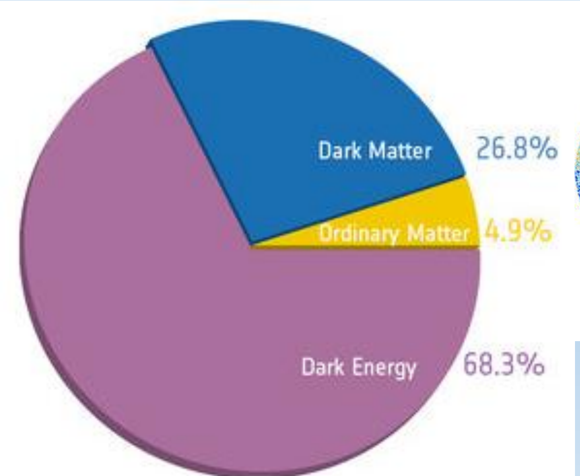
- There are substantial astronomical observation which support the existence of dark matter in the universe.
  - ➢ Rotation curve of galaxies
  - ➢ Bullet clusters
  - ➢ Gravitational lensing
  - ➢ Cosmic microwave background
  - ➢ etc

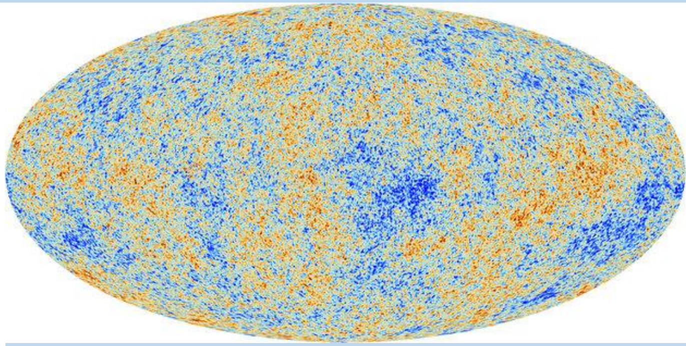
- However, its identity is still unknown.

- The most plausible candidate is Weekly Interacting Massive Particles (WIMPs).



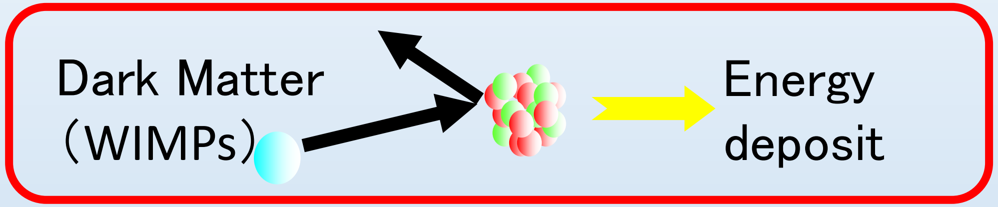


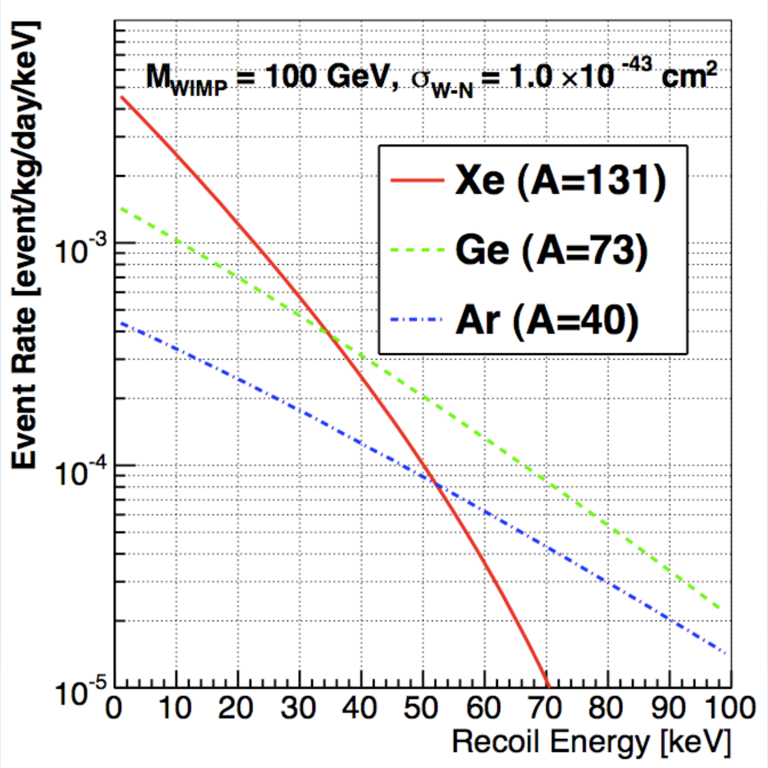


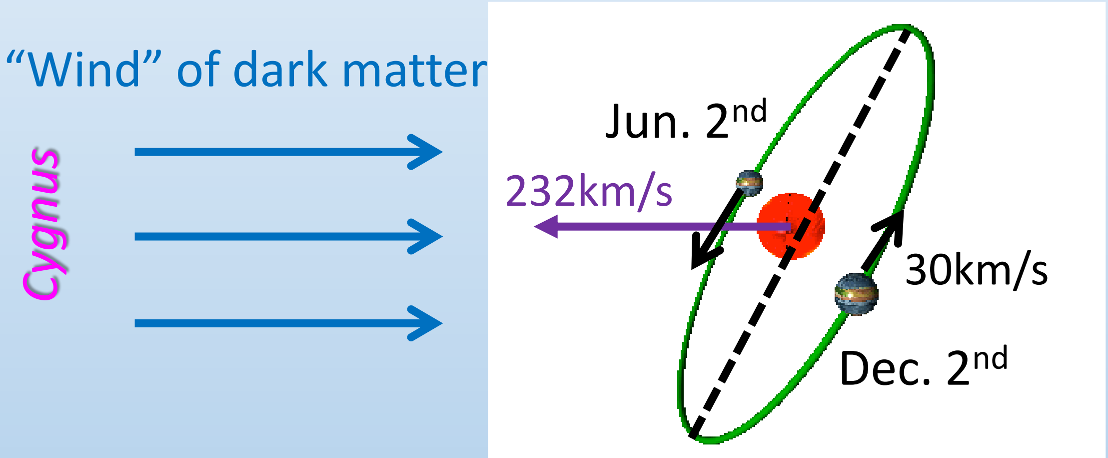


Strategy of direct dark matter searches

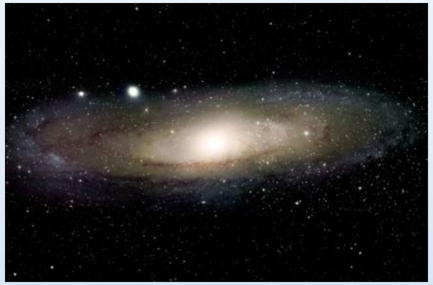
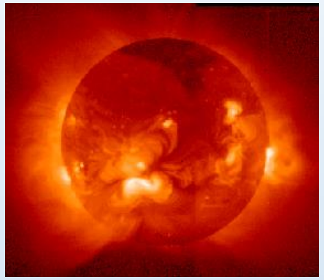
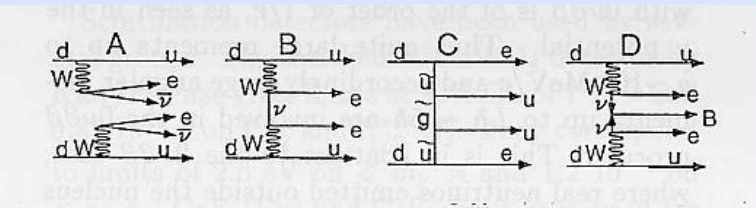
- Look for scattering of dark matter and detector material
  - Energy spectrum (or number of events)
  - Annual modulation of event rate
  - Direction of dark matter "wind"



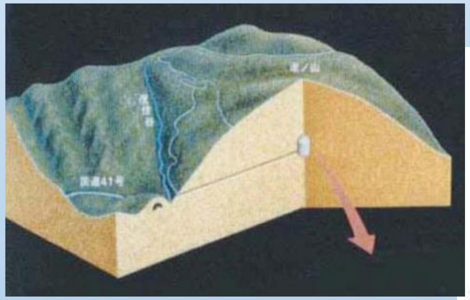
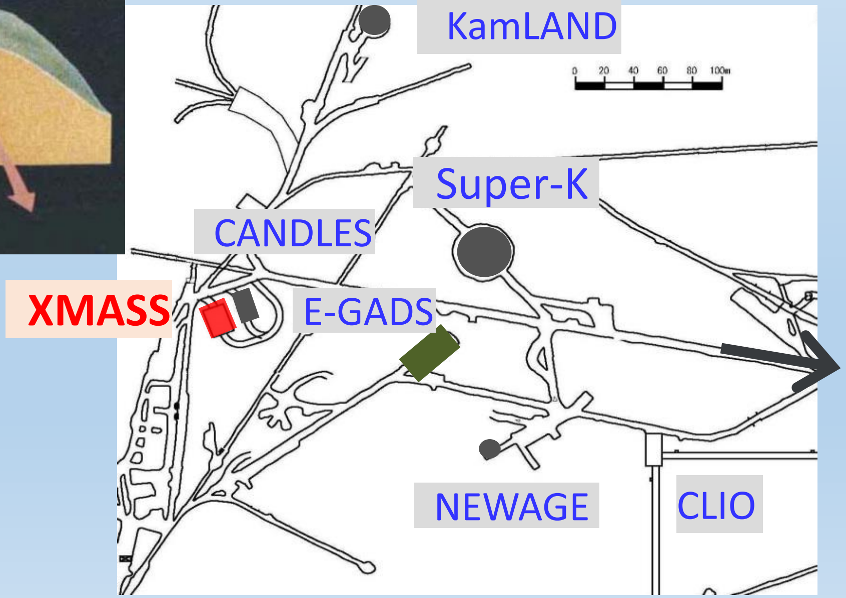




The XMASS experiment

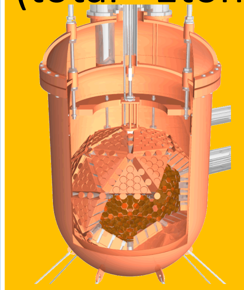




- **A multi-purpose experiment using liquid xenon in the Kamioka mine (1,000 m underground) in Japan.**
  - Direct detection of dark matter
  - Observation of pp/^{7}Be solar neutrinos
  - Search for neutrinoless double beta decay

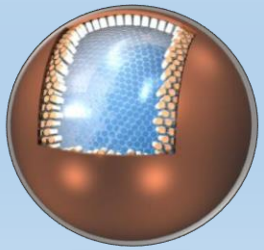



Operating

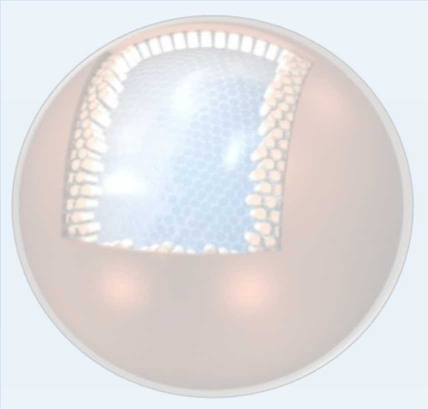
XMASS-1
(total ~1ton)



XMASS-1.5
(total ~6tons)



XMASS-2
(total ~24tons)



History of XMASS-1

2010	2011	2012	2013	2014	2015	2016	2017

Dec. May Nov.

Const-ruction → Commissioning data taking → Detector refurbishment → Data taking (ongoing) → Today

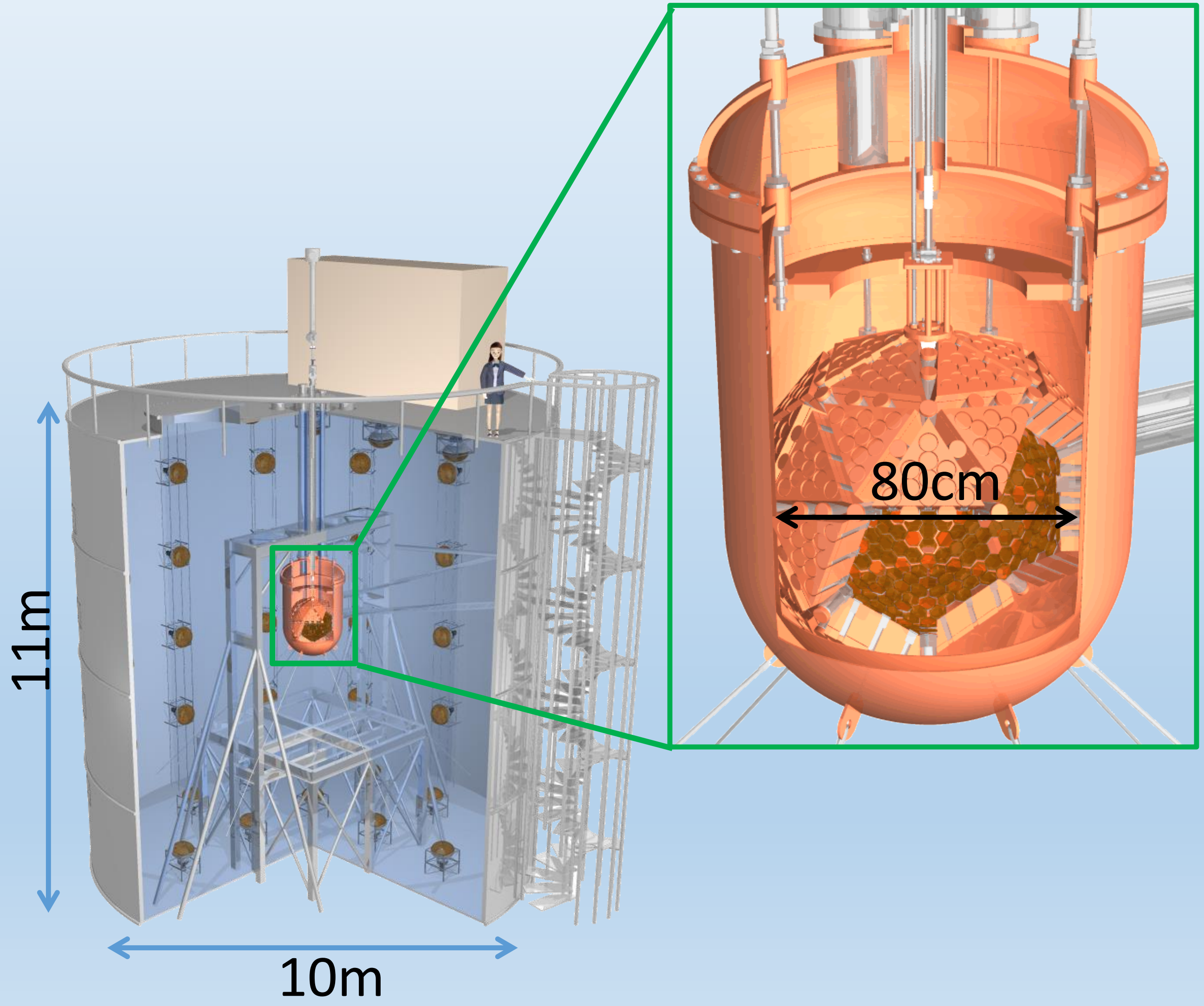
Commissioning data results

- Low mass WIMPs
- Solar axion
- WIMPs-^{129}Xe inelastic scattering
- Bosonic super-WIMPs
- 2ν double electron capture

Results after refurbishment

- Annual modulation (1year data)
- Many results will come soon.
  - Annual modulation (2years)
  - ~100 GeV WIMPs
  - Hidden photon dark matter
  - 2ν double electron capture
  - Solar axion etc.

The XMASS-1 detector

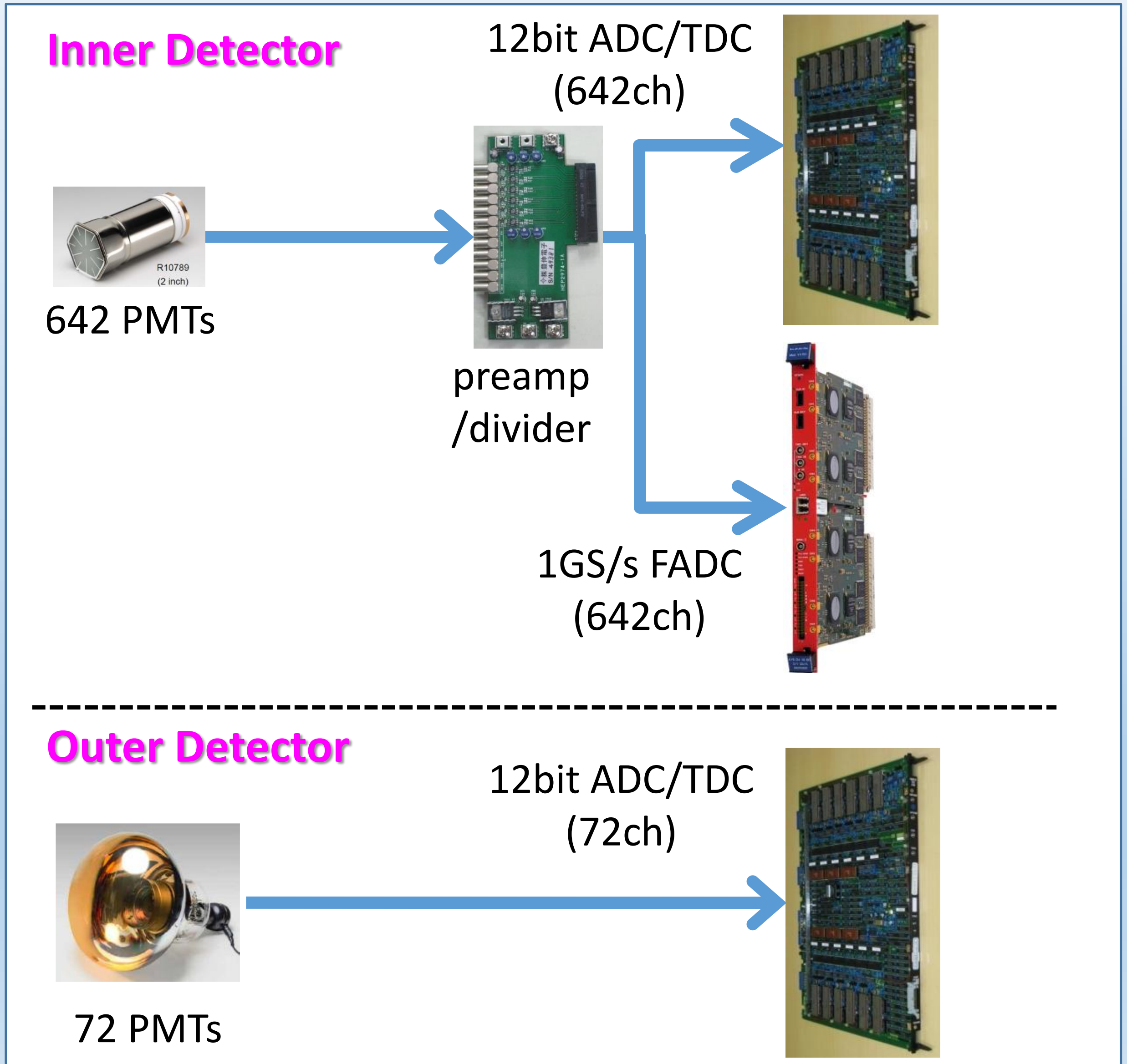


- Single-phase liquid xenon detector
  - ~830 kg of liquid xenon (-100 ^{o}C)
  - 642 2-inch PMTs
    (Photocathode coverage >62%)
  - ~14 photoelectrons/keV

- Water Cherenkov detector
  - 10m diameter, 11m high
  - 72 20-inch PMTs
  - Active shield for cosmic-ray muons
  - Passive shield for *n*/γ

XMASS DAQ system and calibrations

Readout electronics/DAQ



- ADC/TDC (ATM)
  - ➢ 642ch (ID) + 72ch (OD)
  - ➢ 12 bit resolution
  - ➢ ADC dynamic range: 0-450pC
  - ➢ TDC dynamic range: 1.3 μsec
  - ➢ Readout through VME
- Flash-ADC (CAEN V1751)
  - ➢ 642ch
  - ➢ 10 bit resolution, $1V_{pp}$
  - ➢ Readout through optical links

PMT calibrations

- PMT gain monitoring
  - Gain of each PMT is continuously monitored by flashing LED.
  - The precision is better than 1%.
- Waveform of single photoelectron pulse
  - Measured using LED and implemented in the detector simulation
- 2 photoelectron (PE) emission in VUV-sensitive PMTs
  - Found this phenomena in case of xenon scintillation light (λ~175nm) with a probability of ~10% for 1 photon incident.
  - This is because xenon scintillation photon is energetic enough to excite 2 photoelectrons from photocathode.
  - Take into account this effect when counting number of photons.

Inner calibration system

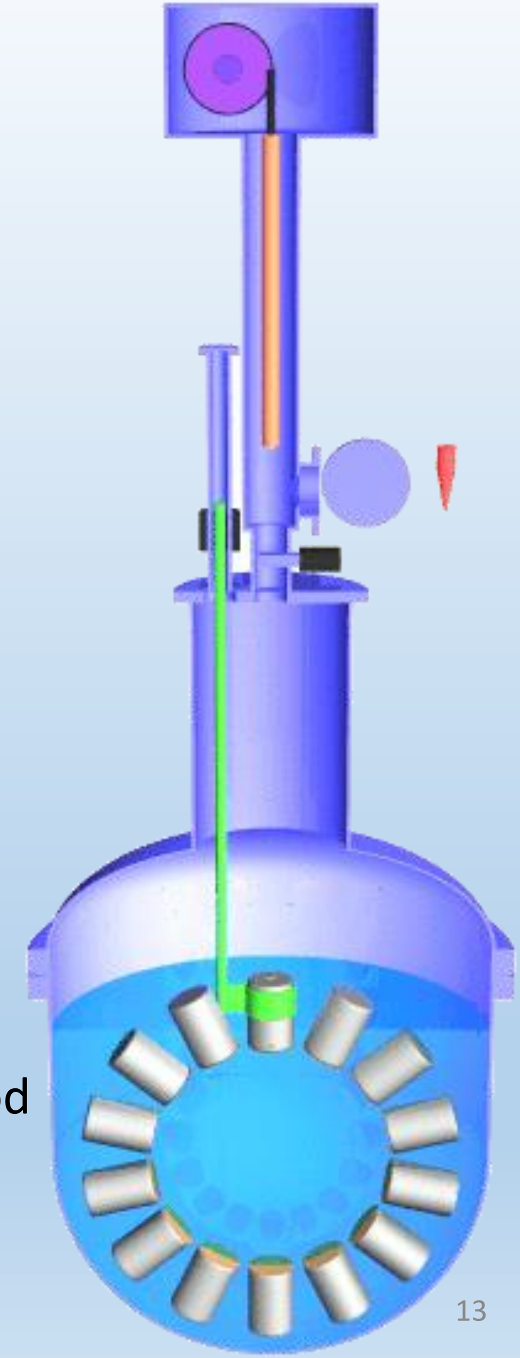
- Various RI sources can be inserted
- Used for light yield monitoring, optical parameter tuning, energy and timing calibrations etc.

RI	Energy [keV]	Diameter [mm]	Geometry
^{55}Fe	5.9	10	2pi source
^{109}Cd	8, 22, 25, 88	5	2pi source
^{241}Am	17.8, 59.5	0.17	2pi/4pi source
^{57}Co	59.3 (W X-ray), 122	0.21	4pi source
^{137}Cs	662	5	cylindrical

^{57}Co source

Source rod (Ti)

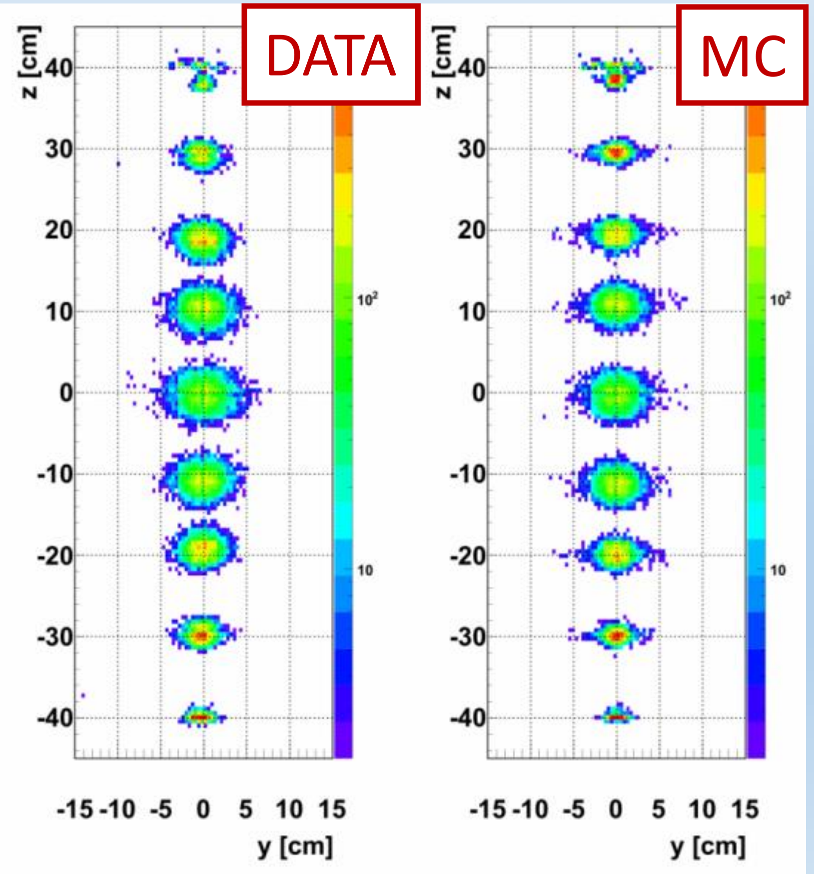
Active region is concentrated on the 1.8 mm edge region



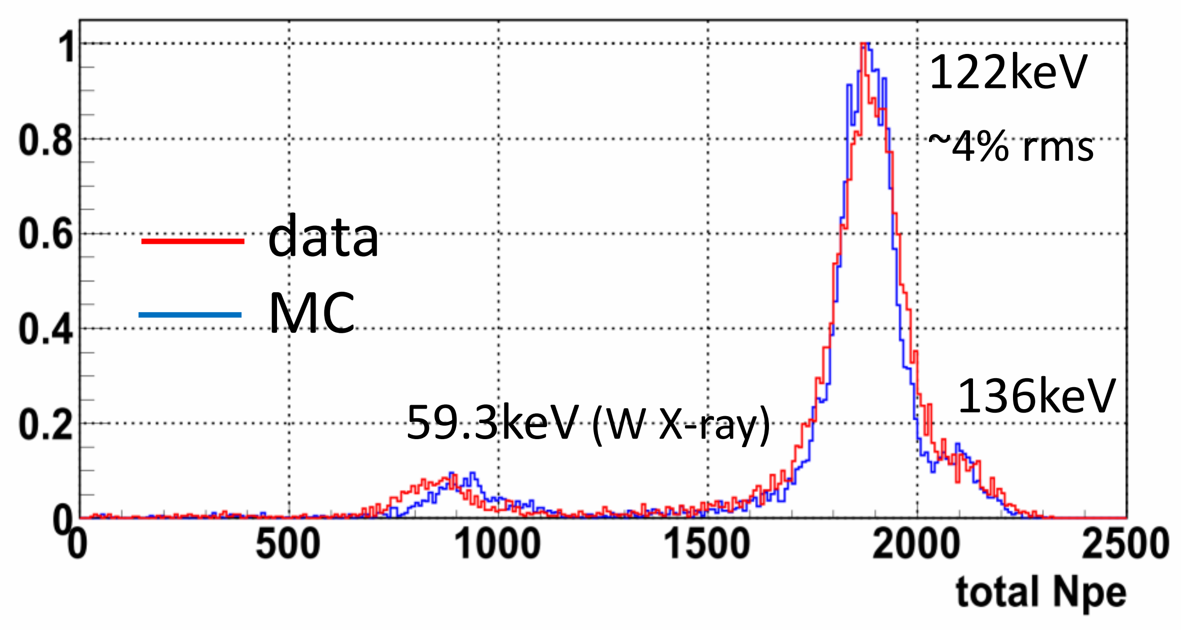
Detector response

- Photoelectron yield is monitored by the ^{57}Co source.
- The distributions are reproduced by simulation well.

Reconstructed vertex



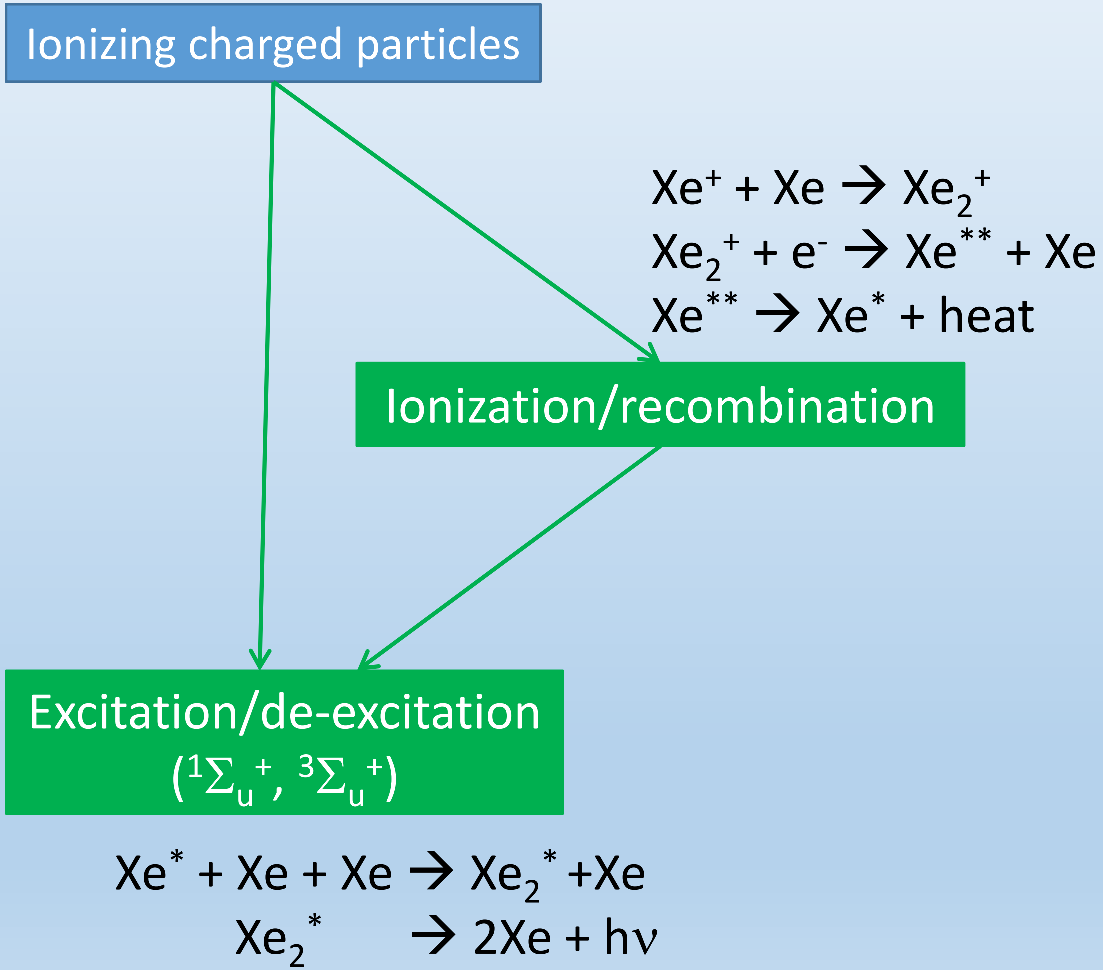
Total number of photoelectrons



Scintillation time profile

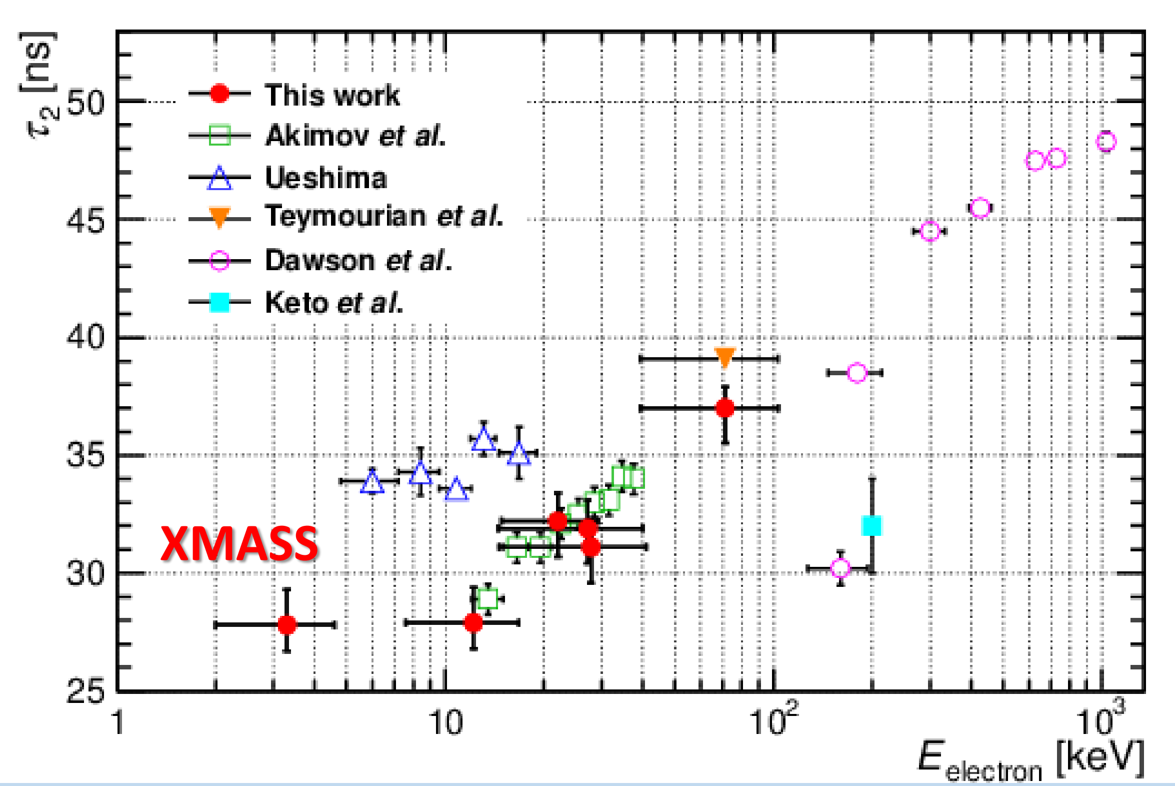
- Scintillation time profile is important for
  - Discrimination between nuclear recoil and electron/gamma-ray
  - Vertex reconstruction using hits' timing

- Liquid xenon scintillation processes
  - Direct excitation
    - Singlet ($^1\Sigma_u^+$): τ ~ a few ns
    - Triplet ($^3\Sigma_u^+$): τ ~ 20 ns
  - Recombination: τ >~30 ns



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

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



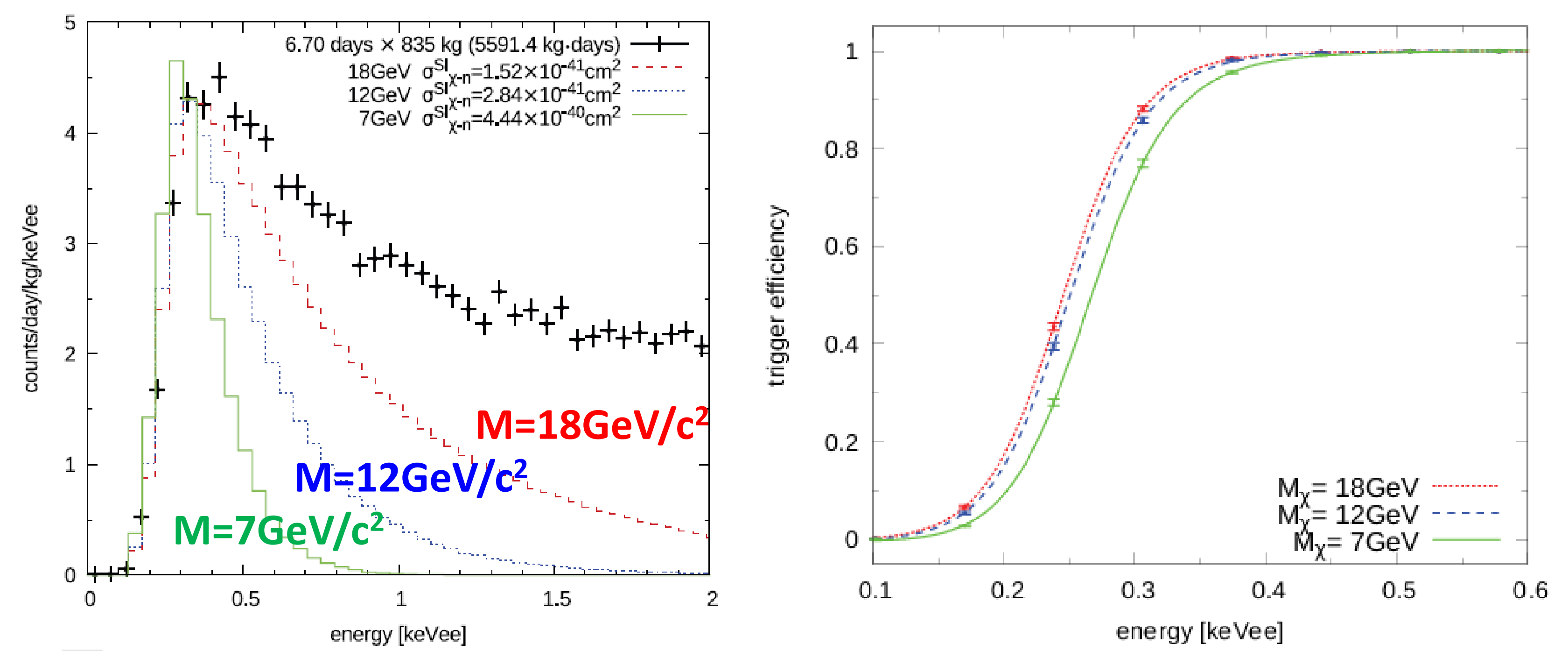
- Fast decay component is needed to reproduce our calibration data.
  - τ_1=2.2 ns (fixed)
  - F_1: 0.05~0.15 (increase at low energy)
- Energy dependence of decay time was studied as a function of mean kinetic energy of electrons induced by γ-ray

Nucl. Instrum. Meth. A834 (2016) 192

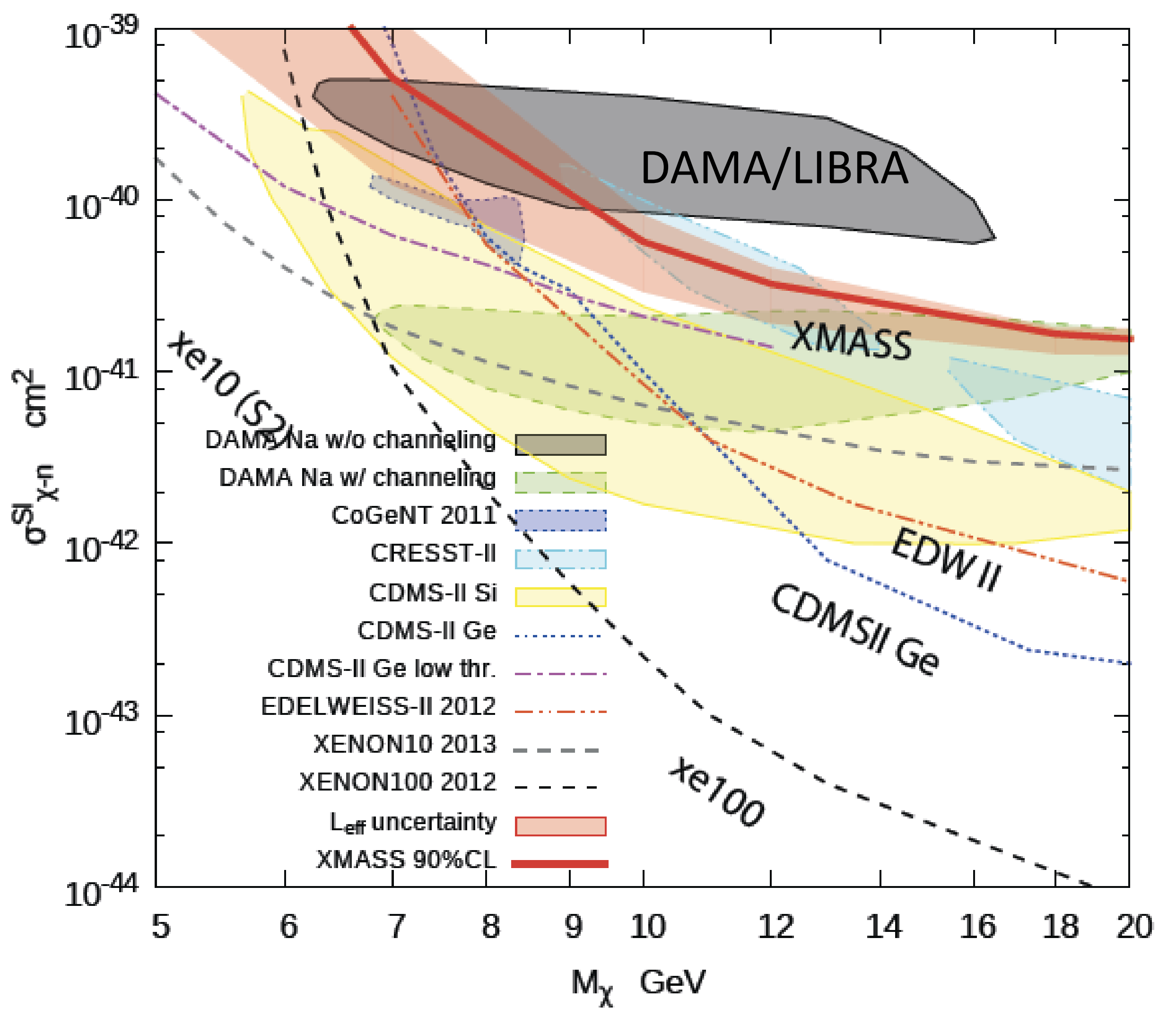
Dark matter search results

Search for low mass (~10GeV/c^2) WIMPs

- Acquired 6.7 days of low threshold data
- Used entire volume (835kg) with simple event selections
- Understanding trigger efficiency is crucial
  - The efficiency curve depends on energy spectrum shape (WIMP mass)
  - It was measured using LED calibration data



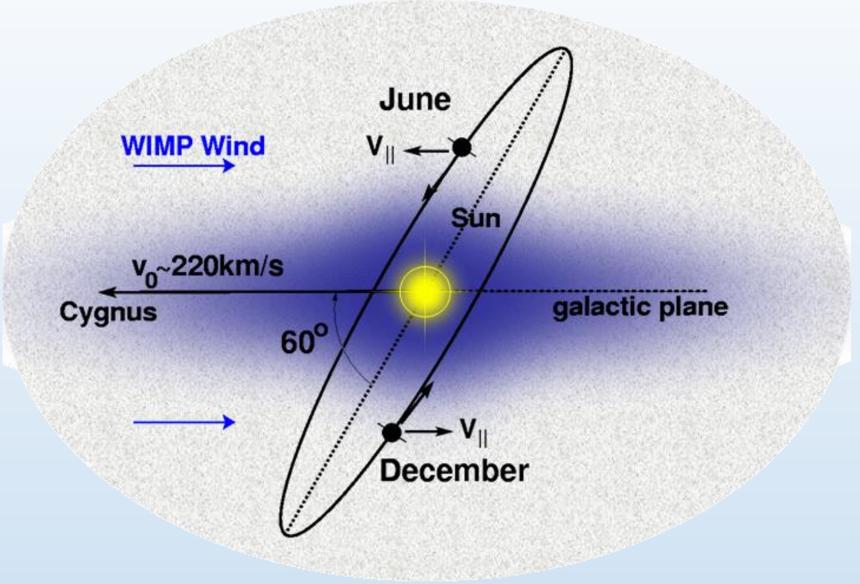
Search for low mass (~10GeV/c^2) WIMPs



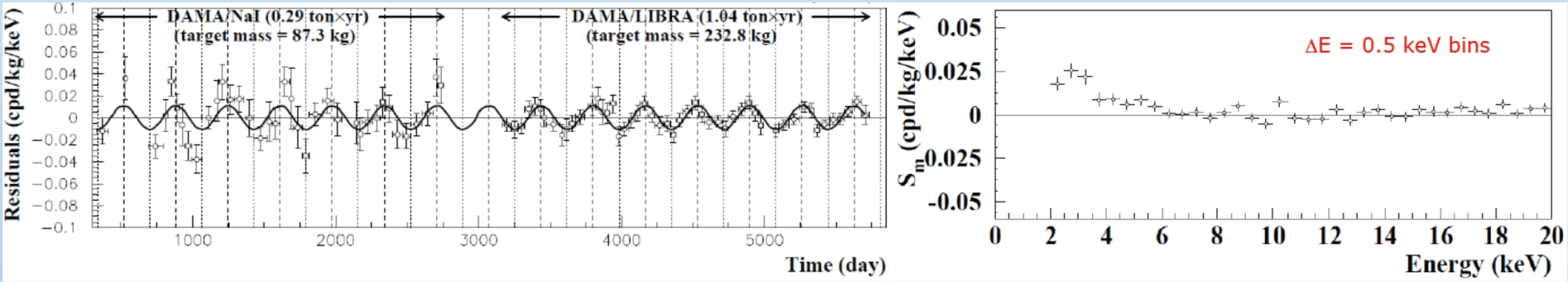
- We obtained conservative upper limits on spin independent cross section, so that the WIMP signal does not exceed the observed spectrum.
- We excluded part of parameter space favored by DAMA/LIBRA.

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

Search for annual modulation



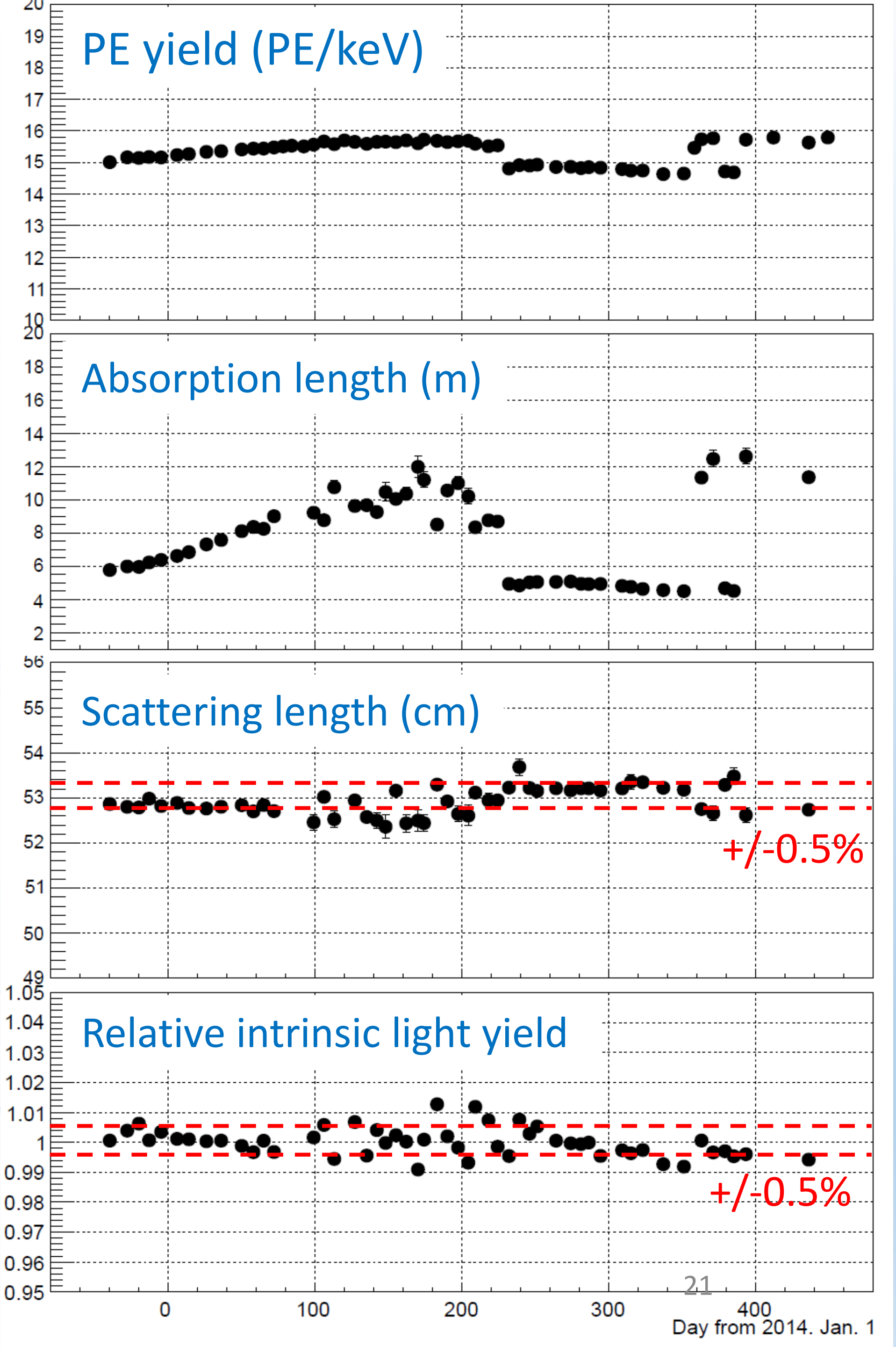
- Expect annual modulation of event rate of dark matter signal due to Earth's rotation around the Sun.
- DAMA/LIBRA claims modulation at 9.3σ
  - Total exposure of 1.33 ton year (14 cycles)
  - Modulation amplitude of (0.0112+/-0.0012) cpd/kg/keV for 2-6 keV



- 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/γ events

Detector stability

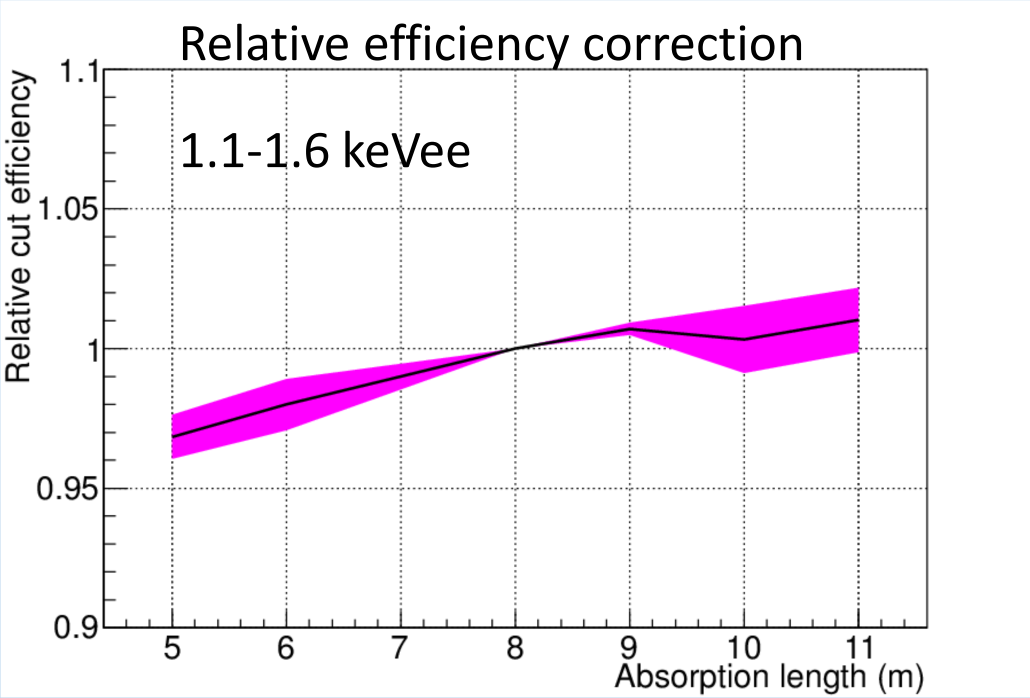
- Calibration by a ^{57}Co source every week to monitor
  - ➢ Photo-electron (PE) yield
  - ➢ Optical properties of liquid xenon
- These PE yield changes can be explained by the change of the absorption length in liquid xenon
  - ➢ Scattering length: stable within +/-0.5%
  - ➢ Intrinsic light yield extracted: stable within +/-0.5%
- How should we take into account this instability in the analysis?



Relative efficiency correction

- The change of absorption length affects cut efficiency.
- The relative change of cut efficiency is evaluated using Monte Carlo simulation.
- Its uncertainty band is estimated to cover the position dependence of detector response.

➔ A dominant systematic error for this analysis



Modulation analysis

- Binned chi-square method
  - Data set is divided into 10 days time bins and 0.5 keVee energy bins.
  - All energy and time bins are fitted simultaneously.

- Two independent analyses for systematic error treatment

R^{obs}: observed event rate

R^{pred}: predicted event rate

Analysis 1: With a pull term

$$\chi^2 = \sum_{i}^{E-\text{bins}} \left(\sum_{j}^{t-\text{bins}} \frac{(R^{\text{obs}}_{i,j} - R^{\text{pred}}_{i,j} - \alpha_i K_{ij})^2}{\sigma(\text{stat})^2_{i,j}} + \alpha_i^2 \right)$$

Analysis 2: With a covariance matrix

$$\chi^2 = \sum_{i,j}^{Et-\text{bins}} (R^{\text{obs}}_i - R^{\text{pred}}_i)(V_{\text{stat}} + V_{\text{sys}})^{-1}_{ij}(R^{\text{obs}}_j - R^{\text{pred}}_j)$$

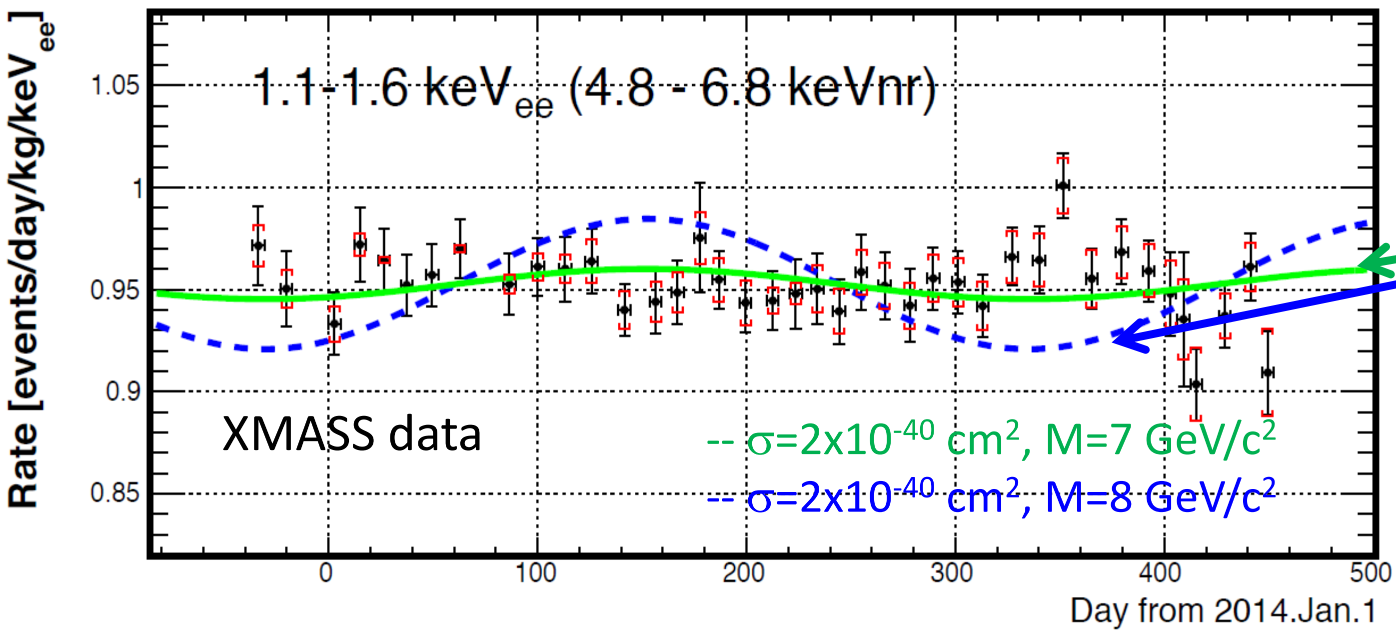
Systematic errors

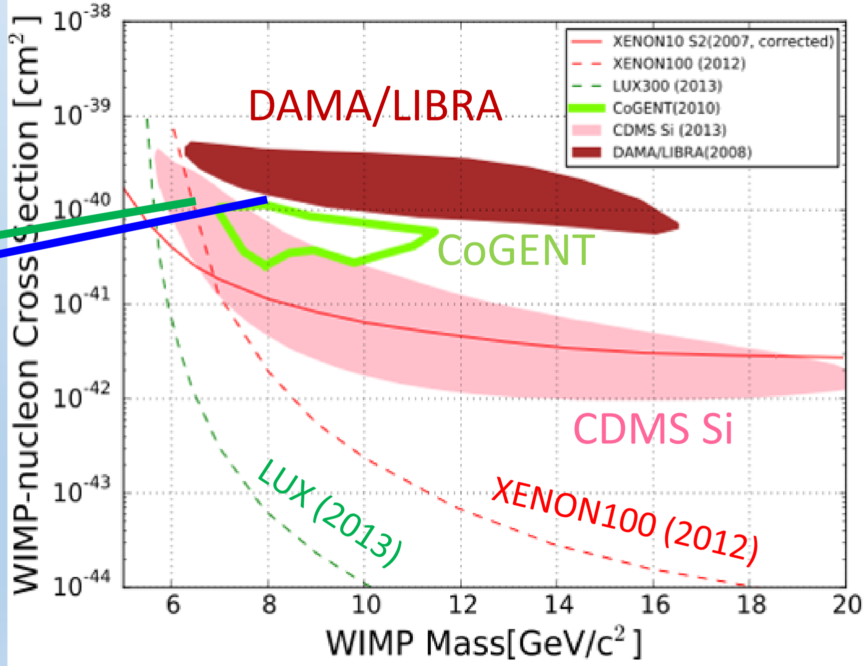
K_{ij} or $(V_{sys})_{ij}$ represents 1σ systematic error

Modulation results (1-year XMASS data)

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

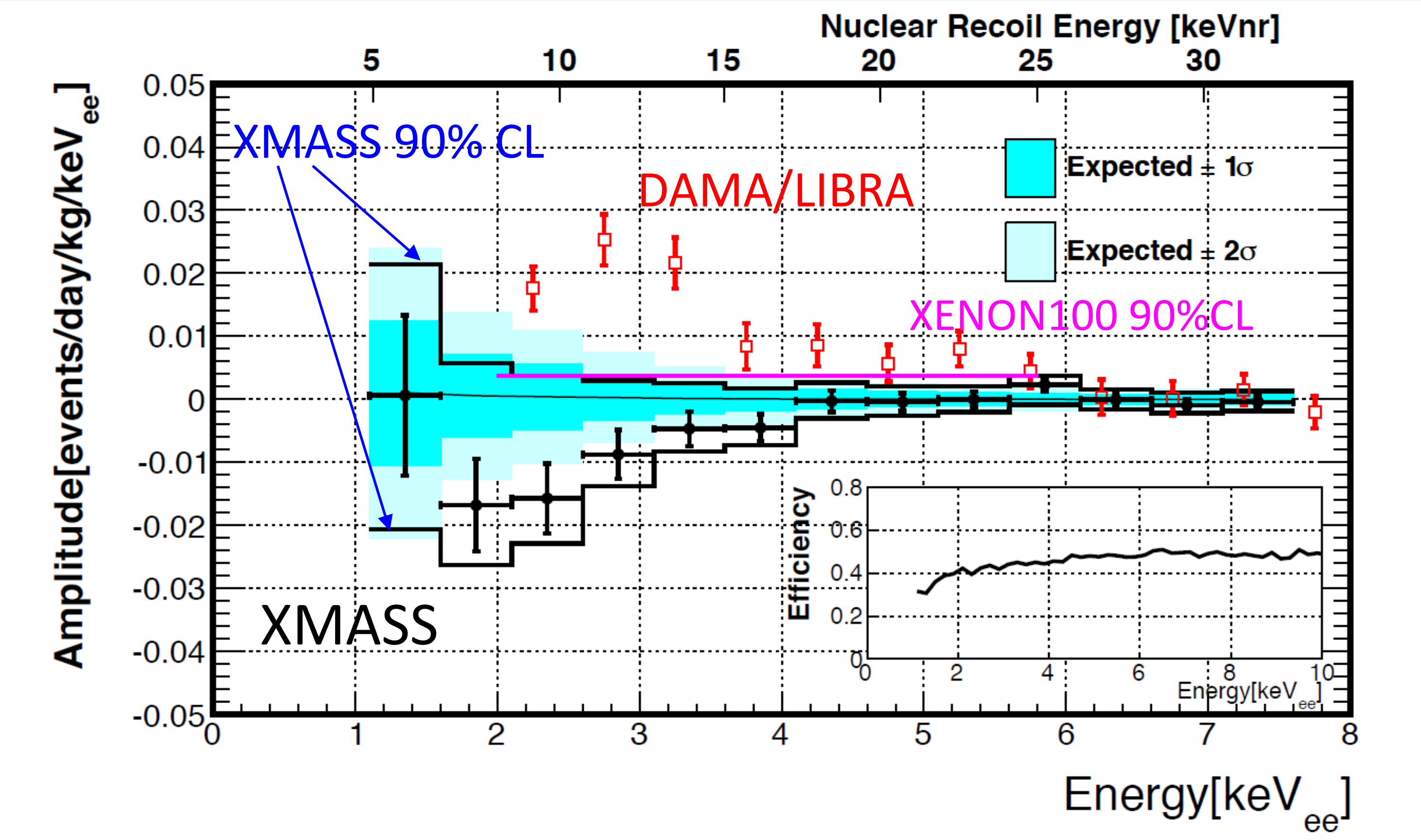
- T= 1year, t_0=152.5 day (fixed)
- Ai(m_χ): modulation amplitude
- Ci: unmodulated event rate





Our data demonstrate high sensitivity to modulation

Modulation results (1-year XMASS data)

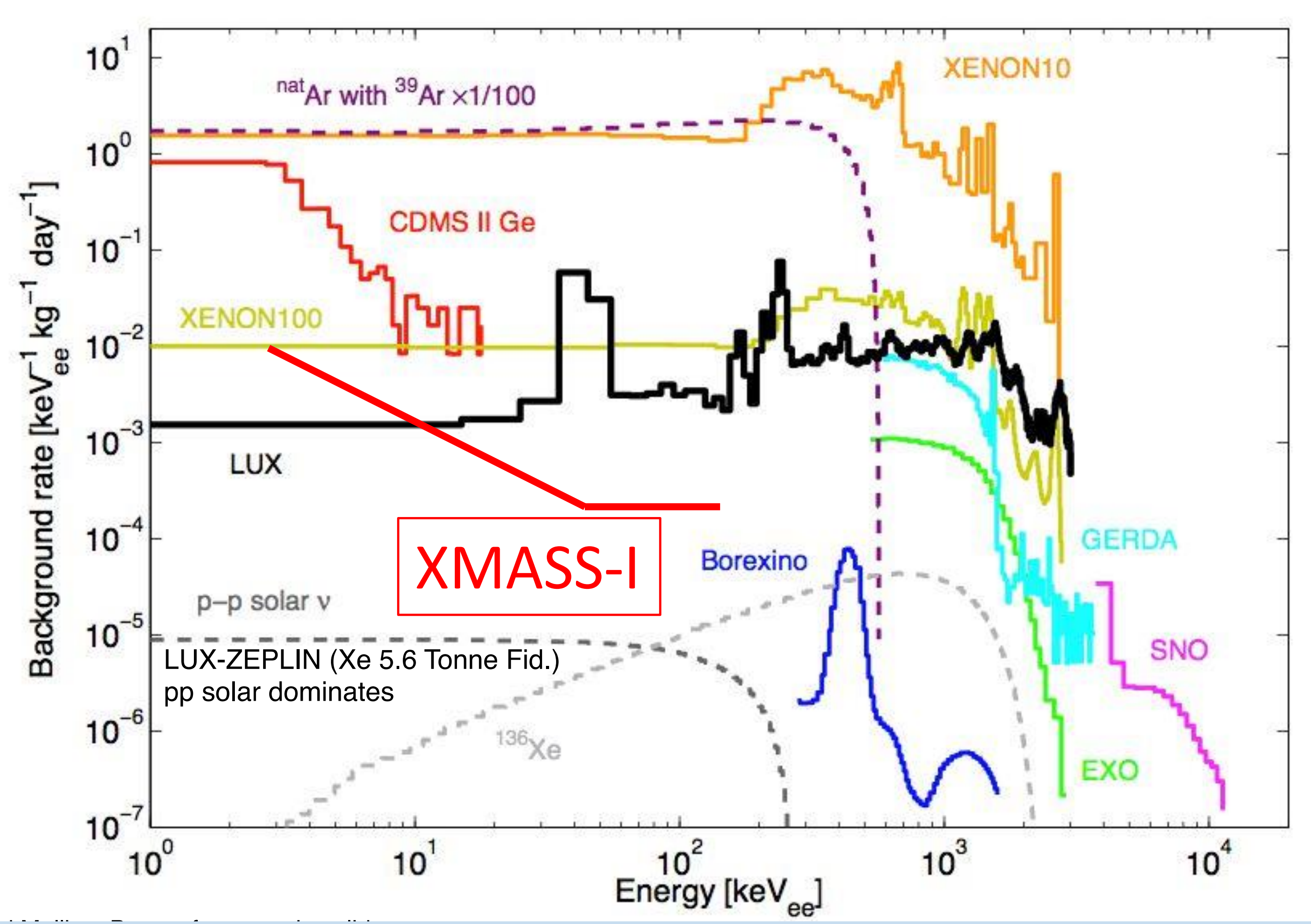


- Without assuming any specific model except for T=1 year, t_0=152.5 day (includes both NR and e/γ signals)
- Shows slightly negative amplitudes in the 1.6-4.1 keVee range.
- P-values
  - 0.014 (2.5σ) for method-1
  - 0.068 (1.8σ) for method-2
- Gives 90% CL limits for positive and negative amplitude separately

Modulation results with 2-year data will come soon

Phys. Lett. B759 (2016) 272

Comparison of background rate in fiducial volume including both nuclear recoil and e/γ events

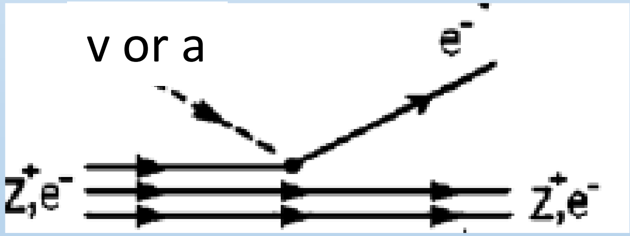


Original figure taken from D. C. Mailing, Ph.D (2014) Fig 1.5

- XMASS achieved low background rate of O(10^{-4}) dru in a few 10s keV including e/γ events
- Low background rate for e/γ events is good for searching for dark matter other than WIMPs.
- We have searched for bosonic super-WIMPs in the range of 40 keV/c^2 to 120 keV/c^2. PRL 113 (2014) 121301

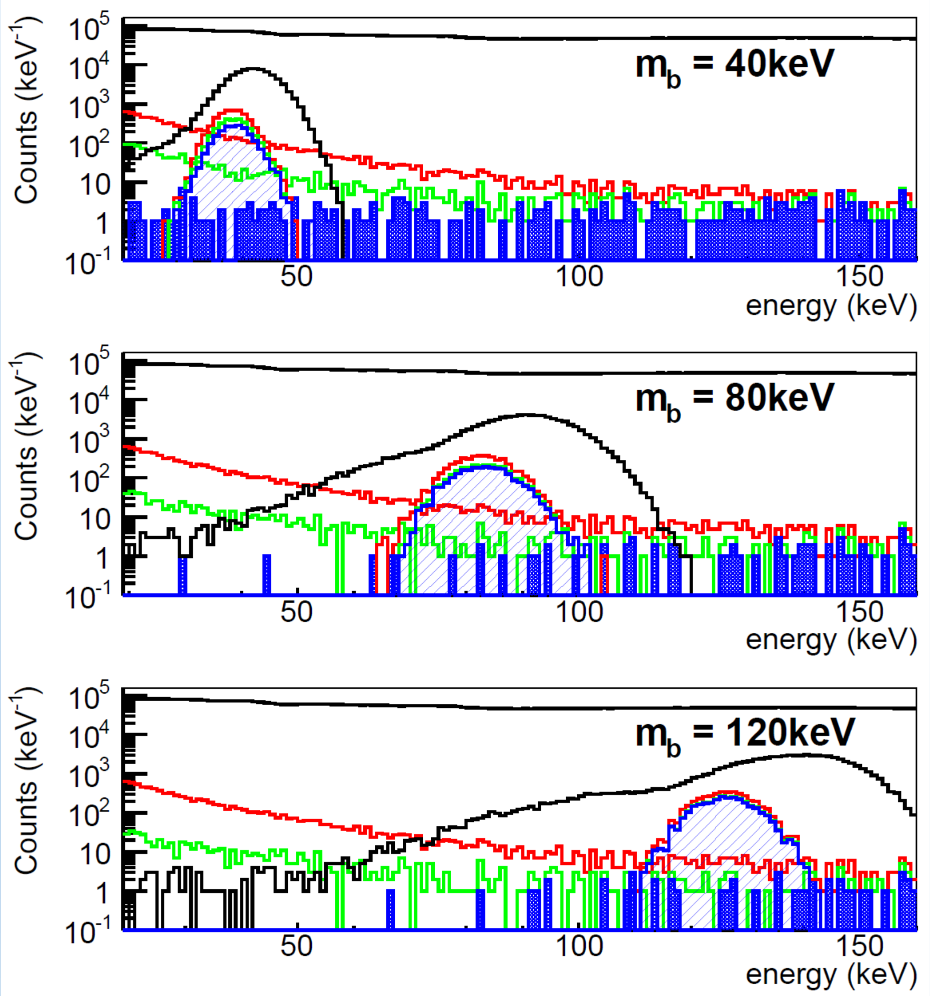
Search for bosonic super-WIMPs

- Bosonic super-WIMPs
  - Lighter and more weekly interacting than WIMPs
  - Candidate for lukewarm dark matter
  - Can be pseudoscaler 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 ~10^{-4} dru (^{214}Pb from ^{222}Rn)

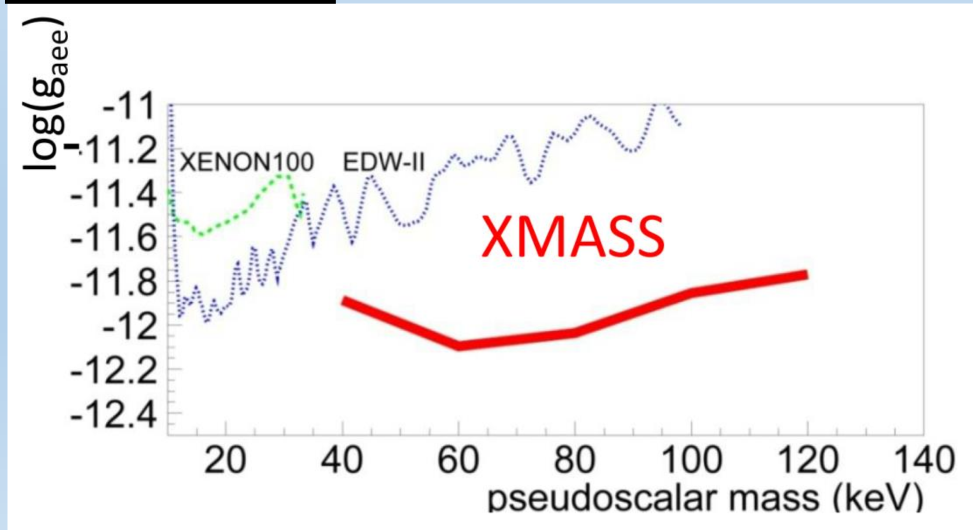
-- Pre-selection
-- Fiducial volume cut
-- Timing balance cut
-- Topological cut



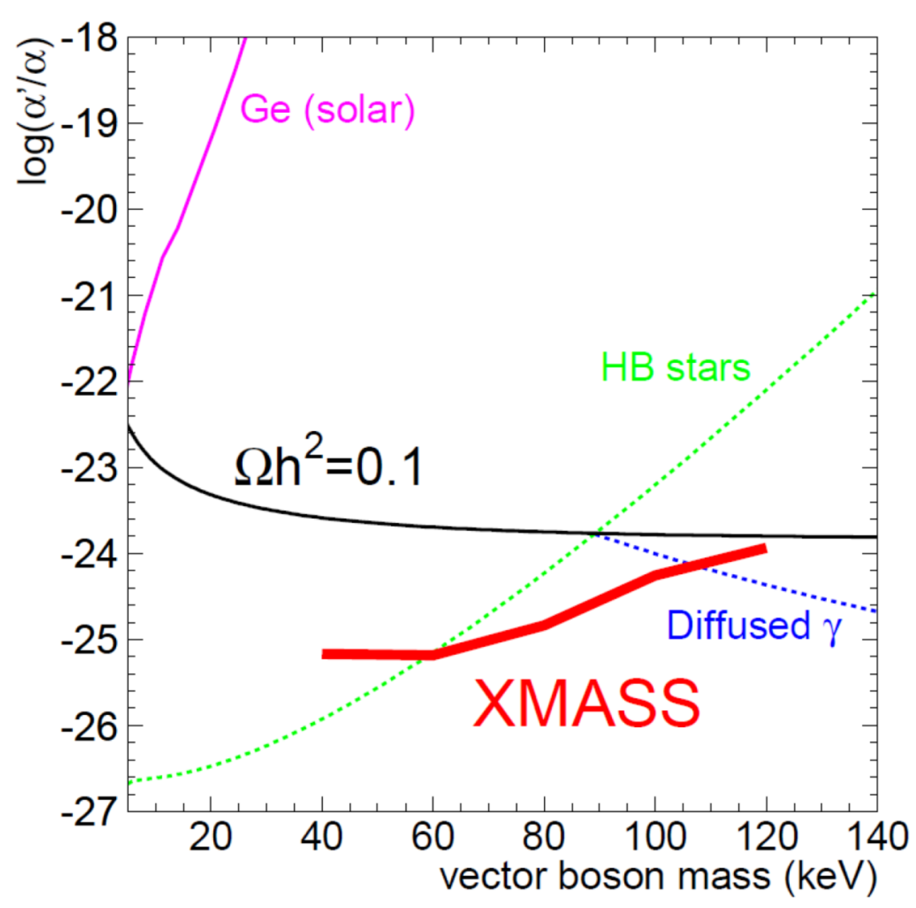
Search for bosonic super-WIMPs
Constraint on coupling constants

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

Pseudoscalar



Vector boson

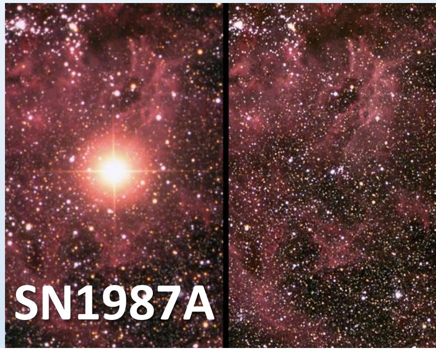


Phys. Rev. Lett. 113 (2014) 121301

Diversity of physics targets with XMASS

Supernova neutrino observation via coherent elastic ν-nucleus scattering

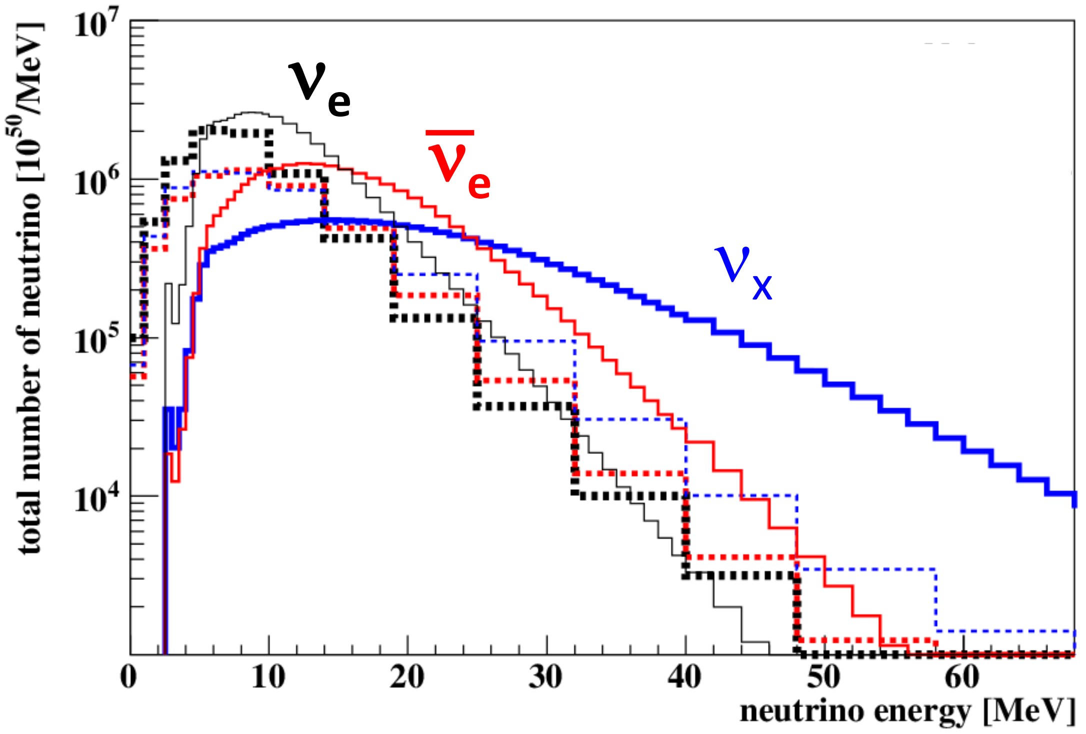
Supernova neutrino via coherent ν-nucleus scattering



- In 1987, Kamiokande and IMB observed neutrinos from supernova for the first time. → Opening of "Neutrino Astronomy"

- Several neutrino detectors in the world (Super-Kamiokande, KamLAND, IceCube etc.) are waiting for a next supernova neutrino burst.

- XMASS has a unique possibility to observe supernova neutrinos:
  - ➢ via coherent elastic ν-nucleus scattering (CEvNS)
  - ➢ 1st observation of this neutrino interaction
  - ➢ information on ν_x (=ν_μ, $\overline{\nu}_\mu$, ν_τ, $\overline{\nu}_\tau$) component



Coherent elastic ν-nucleus scattering (CEvNS)

$$\nu + A \rightarrow \nu + A$$

- Neutrino is scattered off by all the nucleons in a nucleus coherently
  - Weak neutral current interaction
  - Cross section ~ N^2
  - Recoil energy ~ O(10) keV

$$\frac{d\sigma}{dE_{nr}}(E_\nu, E_{nr}) = \frac{G_F^2 M}{2\pi} G_V^2 \left[1 + \left(1 - \frac{E_{nr}}{E_\nu}\right)^2 - \frac{M E_{nr}}{E_\nu^2}\right]$$

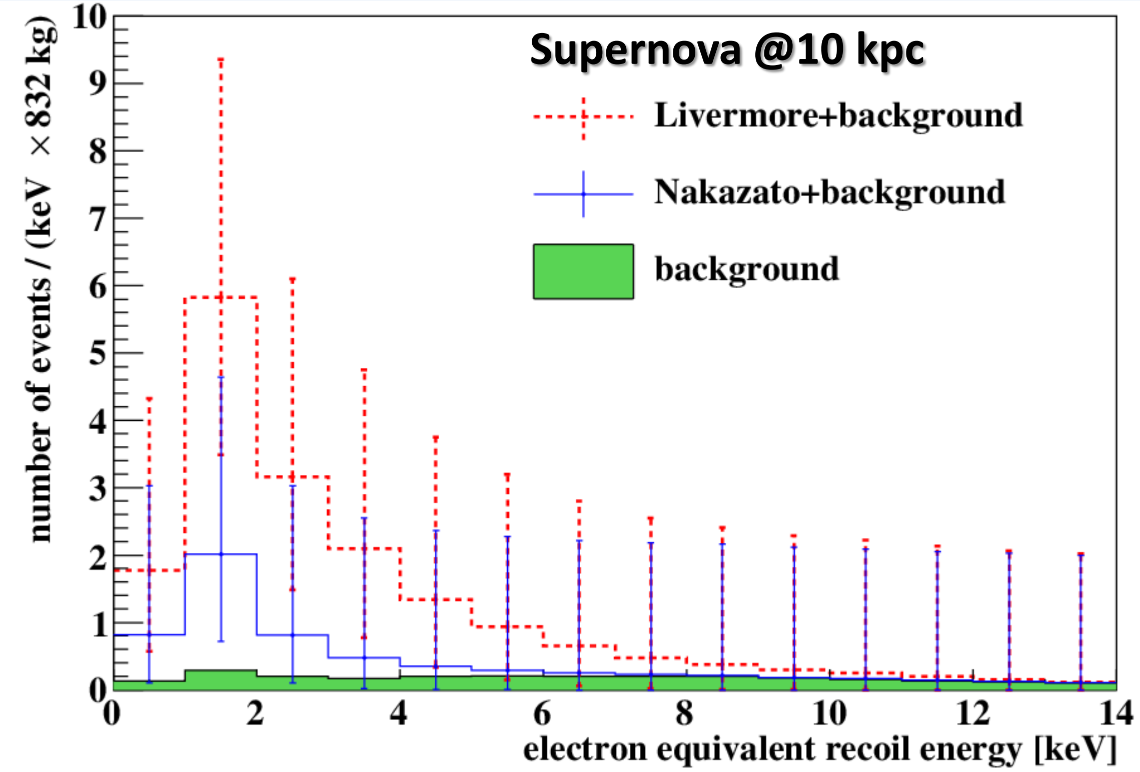
$$G_V = [(\frac{1}{2} - 2\sin^2\theta_W)Z - \frac{1}{2}N]F(q^2)$$

- Has not been observed yet

- Main mechanism of trapping neutrinos in the core of a supernova

- Ultimate background for direct dark matter searches (solar ν, atm. ν, and DSNB ν)

Expected supernova neutrino events in XMASS



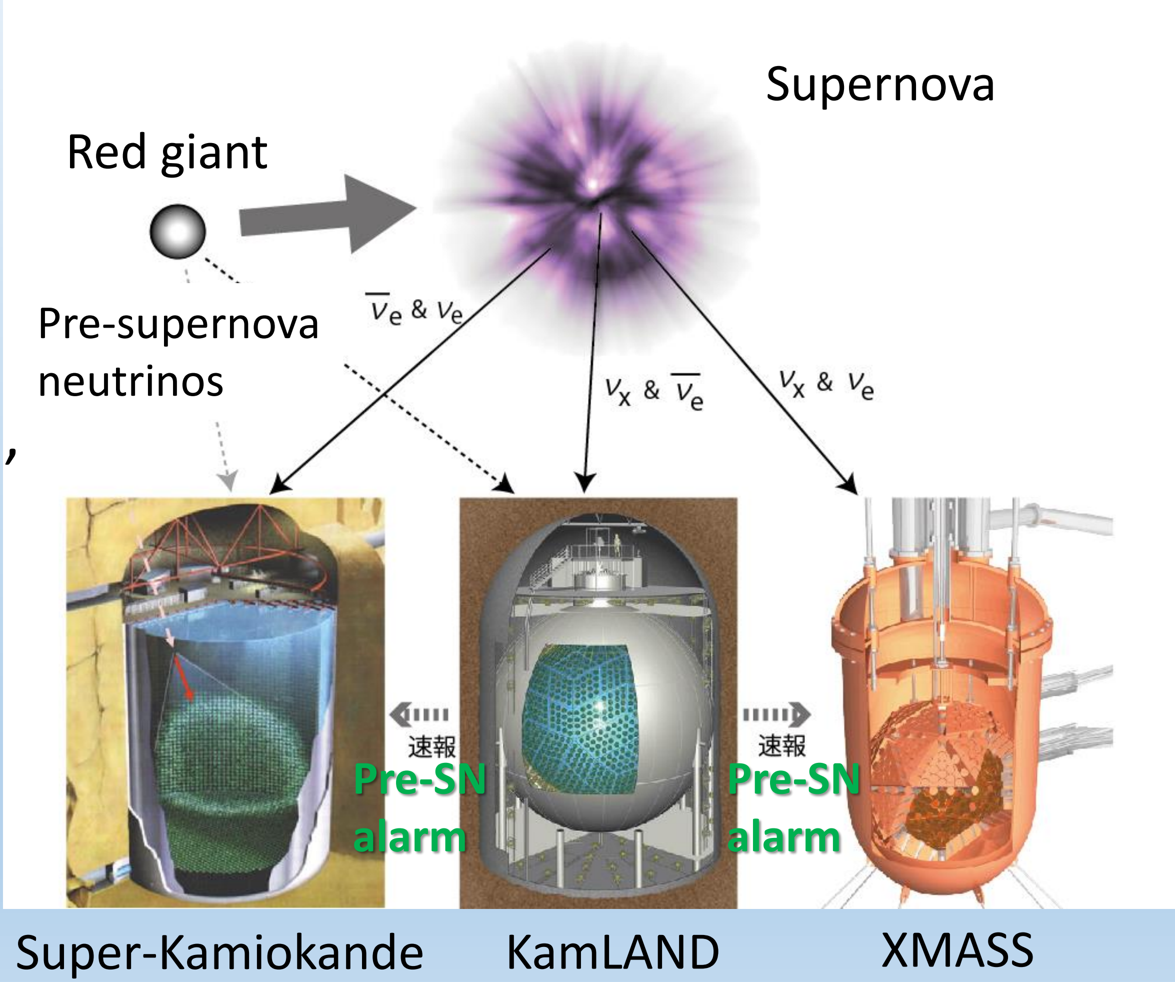
- Expect 3.5 ~ 21 events in the case of supernova at 10 kpc
- Expect O(10^4) events in the case of Betelgeuse (196 pc)
- Should be able to detect supernova neutrinos via coherent scattering in XMASS !!

Supernova model	d=10 kpc	d=196 pc
Livermore	15	3.9×10^4
Nakazato ($20M_{solar}$, Z=0.02, t_{rev}=100ms)	3.5	0.9×10^4
Nakazato ($30M_{solar}$, Z=0.02, t_{rev}=300ms)	8.7	2.3×10^4
Nakazato (black hole)	21	5.5×10^4

Published in Astropart. Phys. 89 (2017) 51

Comprehensive observation network in Kamioka

- To compare the XMASS event timings with other detectors' events,
  - ➢ GPS time synchronization was introduced in the XMASS DAQ system.
- In the case of nearby supernovae (e.g. Betelgeuse), KamLAND has possibility to detect "pre-supernova neutrinos" a few days before explosion.
  - ➢ KamLAND provides a semi-realtime pre-supernova alarm to the community.
  - ➢ XMASS is monitoring the alarm.

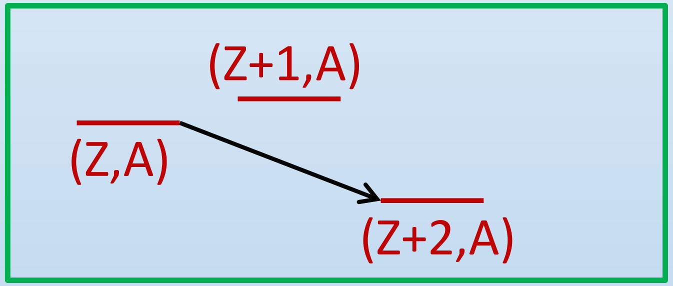


- XMASS is also waiting for a next supernova !!

Double electron capture on ^{124}Xe

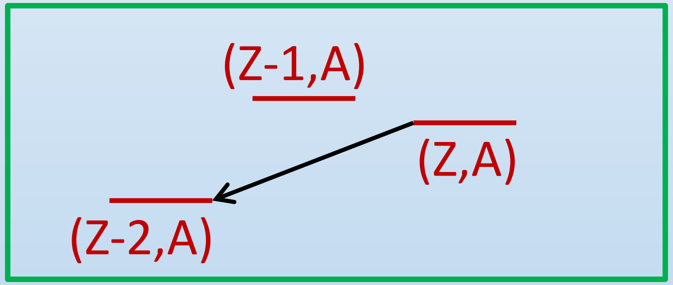
What is double electron capture?

Double beta decay ($\beta^-\beta^-$)
$(Z,A) \rightarrow (Z+2,A) + 2e^- + (2\overline{\nu}_e)$



- Two β^- decays occur simultaneously.
- 2ν modes have been observed in 11 nuclei with half-life of 10^{18}-10^{24} years.

Double electron capture (ECEC)
$(Z,A) + 2e^- \rightarrow (Z-2,A) + (2\nu_e)$



- Two orbital electrons are captured simultaneously.
- There are only two positive results on 2ν modes
  ^{78}Kr : $T_{1/2} = (9.2^{+5.5}_{-2.6}(stat) \pm 1.3(sys)) \times 10^{21}$ years
  ^{130}Ba : $T_{1/2} = (2.2 \pm 0.5) \times 10^{21}$ years

In both cases, if 0ν modes are observed,
they would be evidence of lepton number violation and Majorana neutrino.

2ν double electron capture (ECEC) on ^{124}Xe

- Natural xenon contains ^{124}Xe (N.A.=0.095%) which can undergo 2νECEC.

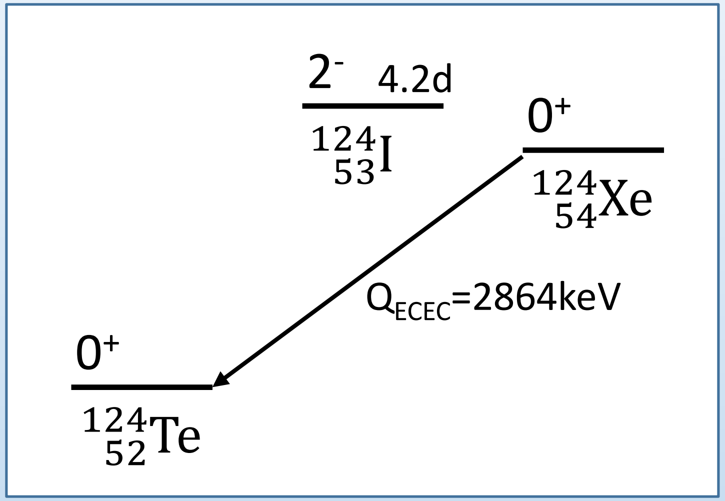
^{124}Xe (g.s., 0^+) + $2e^-$ → ^{124}Te (g.s., 0^+) + $2\nu_e$ + 2864keV

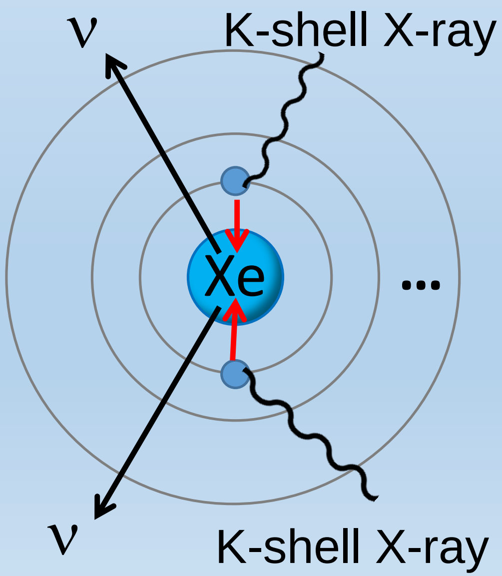
- Only X-rays and Auger electrons are observable

- In the case of 2 K-shell electrons are captured, total energy deposit is 2 x E_B =63.6 keV.

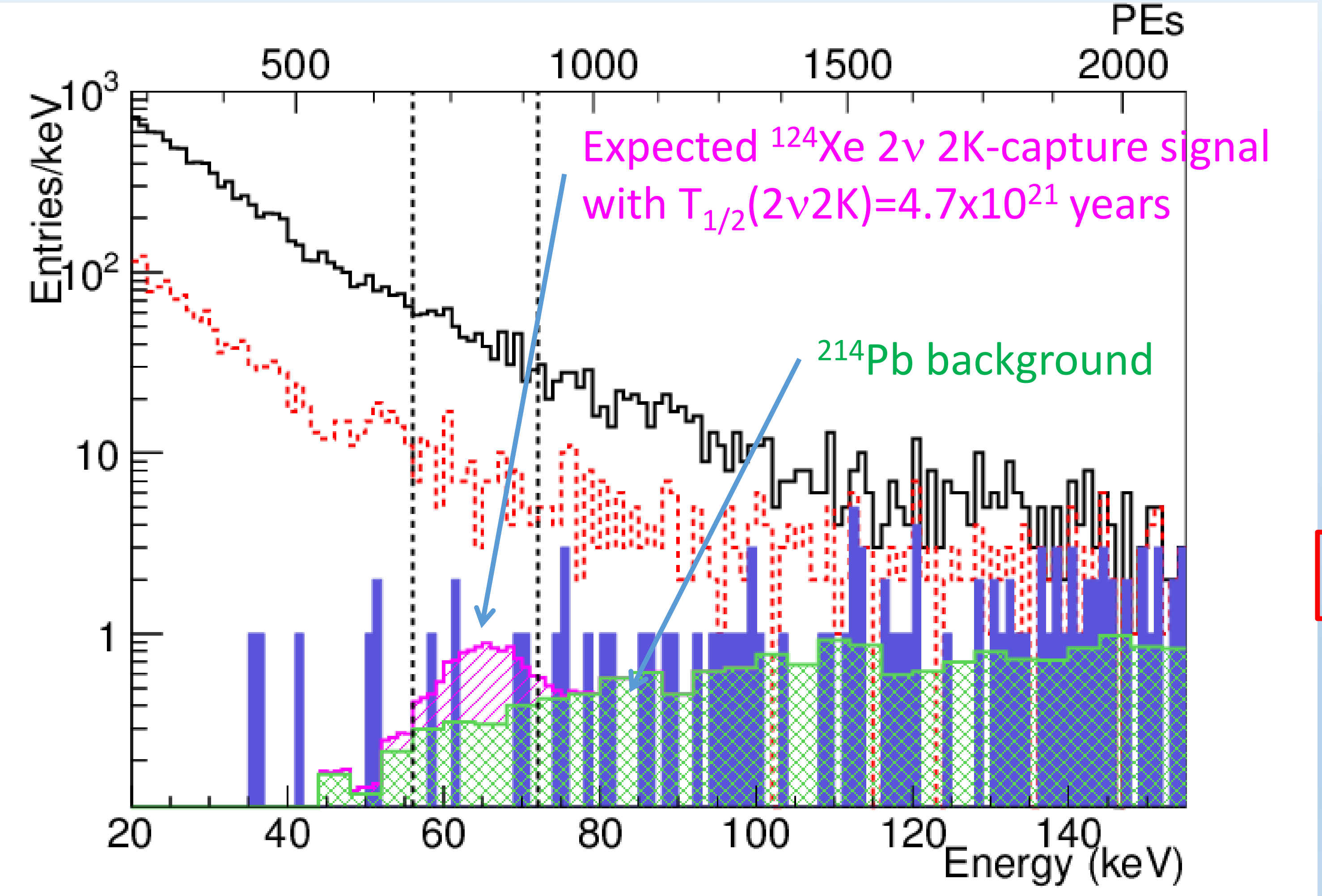
- Expected half-life is 10^{20}-10^{24} years.

- Any measurement of 2νECEC will provide a new reference for the calculation of nuclear matrix elements.





Limits on 2ν 2K-capture half-lives



- No significant signal above background was observed.
- We set the 90% CL lower limit on ^{124}Xe 2νECEC half-life.

$T_{1/2}^{2\nu 2K}(^{124}Xe) > 4.7 \times 10^{21}$ yrs (90%CL)

The world best limits to date !!

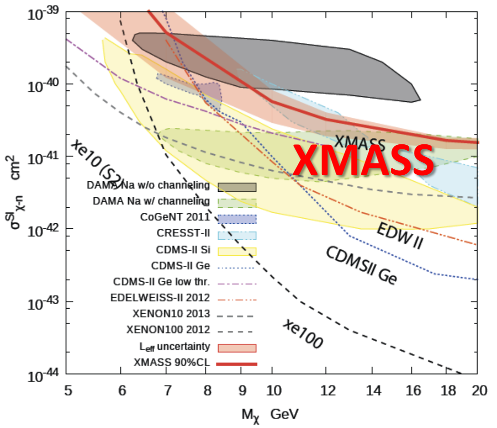
Published in Phys. Lett. B759 (2016) 64.

Diversity of physics targets with XMASS

Dark matter searches

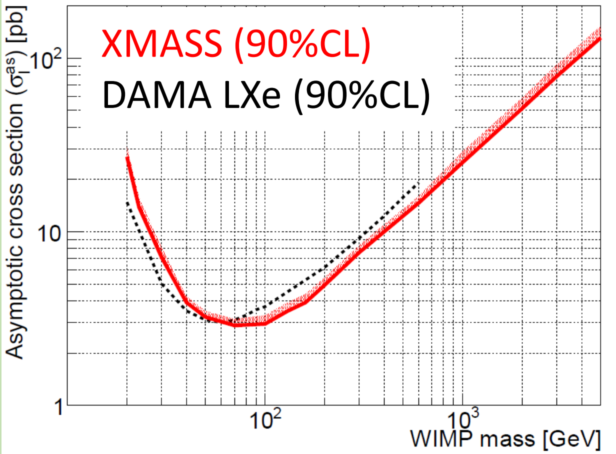
Low mass WIMP search

Phys. Lett. B719 (2013) 78



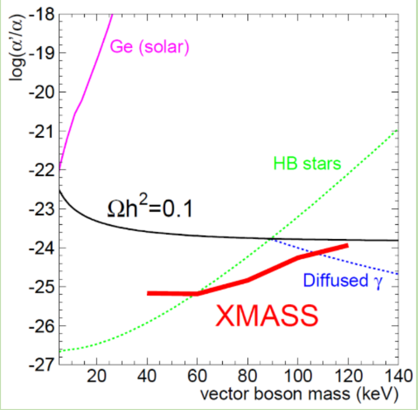
WIMP-^{129}Xe inelastic scattering

PTEP (2014) 063C01



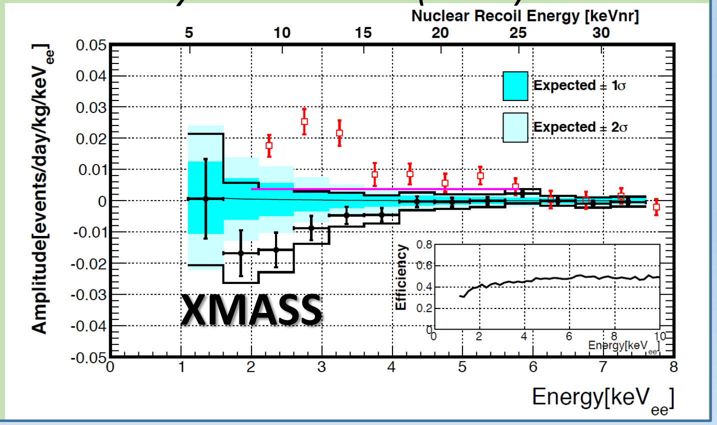
Bosonic super-WIMPs search

Phys. Rev. Lett. 113 (2014) 121301



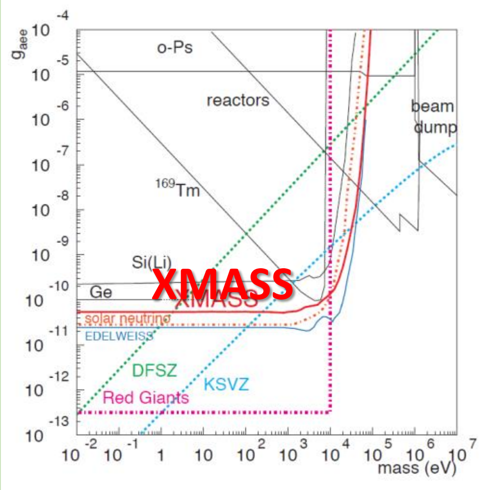
Annual modulation search

Phys. Lett. B759 (2016) 272



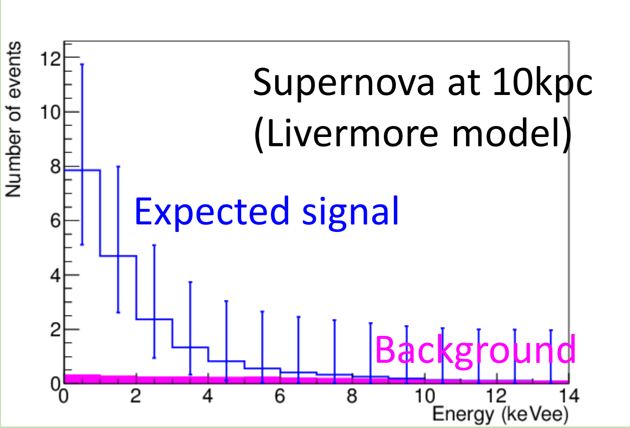
Solar axion search

Phys. Lett. B724 (2013) 46

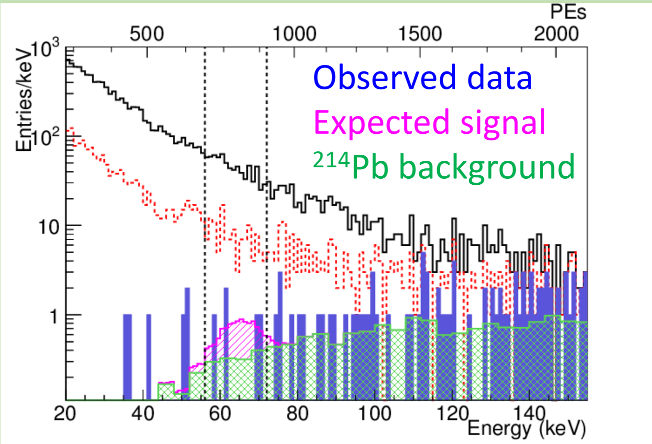


Possibility of supernova neutrino detection

Astropart. Phys. 89 (2017) 51



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

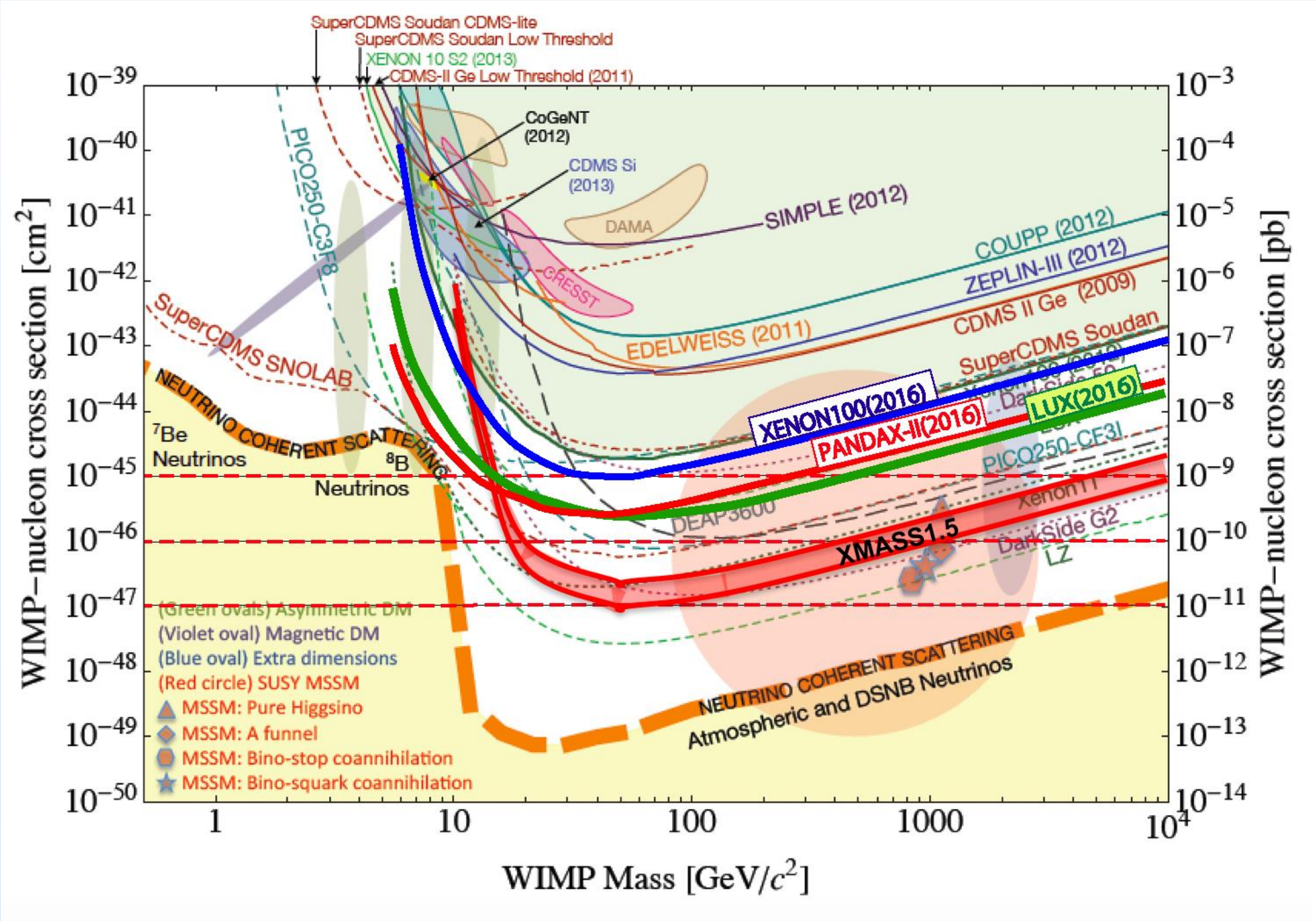


Phys. Lett. B759 (2016) 64

Future prospects and my research plan

XMASS-1.5

- Total ~6 tons (Fiducial mass ~3 tons)
- Newly developed low-background 3-inch dome-shape PMT
- Background level of ~1x10^{-5} event/day/kg/keV assumed (*pp* solar neutrinos)
- Sensitivity to WIMP SI cross section (1-3)x10^{-47} cm^2 @50 GeV/c^2
- Other future programs in the world: XENON-1T, LZ, XENON-nT, (DARWIN)



My research plan

- Continue to lead dark matter analyses in XMASS
  - Investigate various types of dark matter as well as WIMPs.
  - Have close contacts with researchers in theoretical and astronomical fields.
- Establish the next generation dark matter experiment
  - Contribute to hardware. I have expertise in electronics/DAQ, PMT calibrations etc.
  - Lead dark matter analyses.
- Pursue wide variety of particle and astroparticle researches
  - supernova neutrinos, double electron capture, solar axion, solar neutrinos etc.

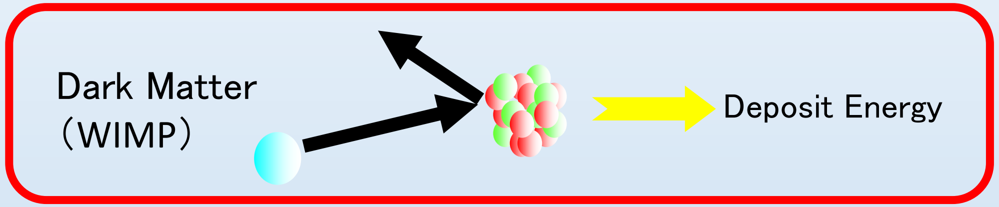
Summary

- XMASS is hunting for dark matter using liquid xenon at Kamioka in Japan.
- Stable data-taking is continuing for more than 3 years.
- Some dark matter results were presented and more results will come soon.
- Diversity of physics targets has been demonstrated.

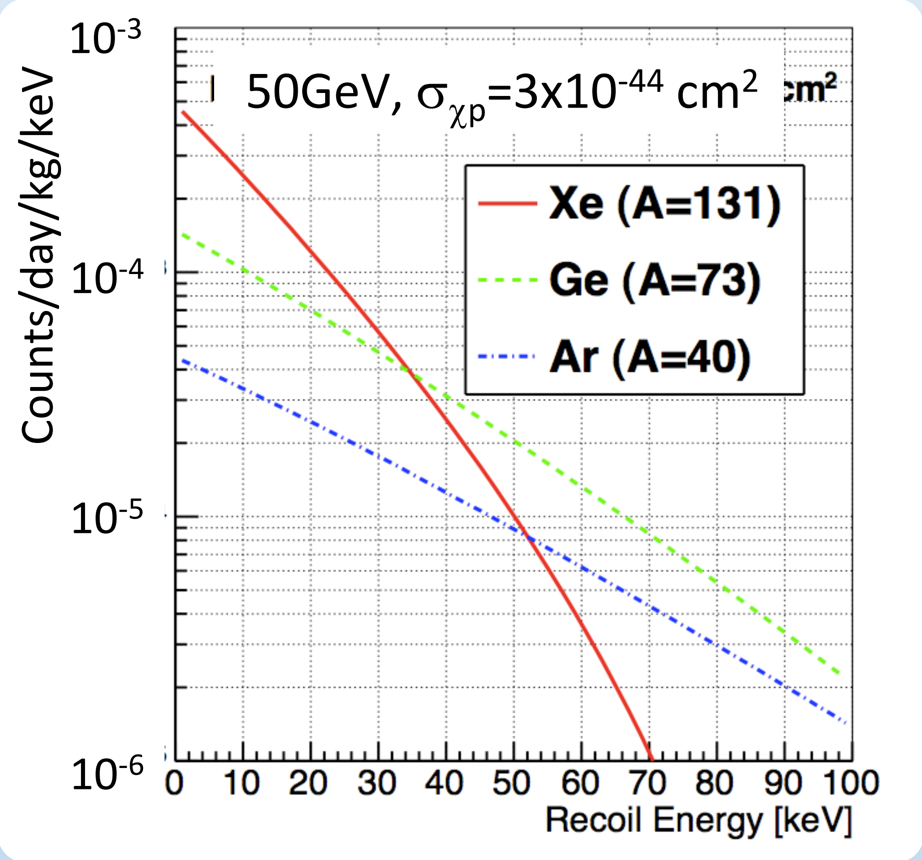
- My research plan
  - Would like to investigate various types of dark matter as well as WIMPs
  - Will establish the next generation experiment
  - Will pursue wide variety of particle and astroparticle physics

Backup slides

WIMP search in XMASS



Expected recoil energy spectra
for different target nuclei



Expected total event rate
for spin independent case

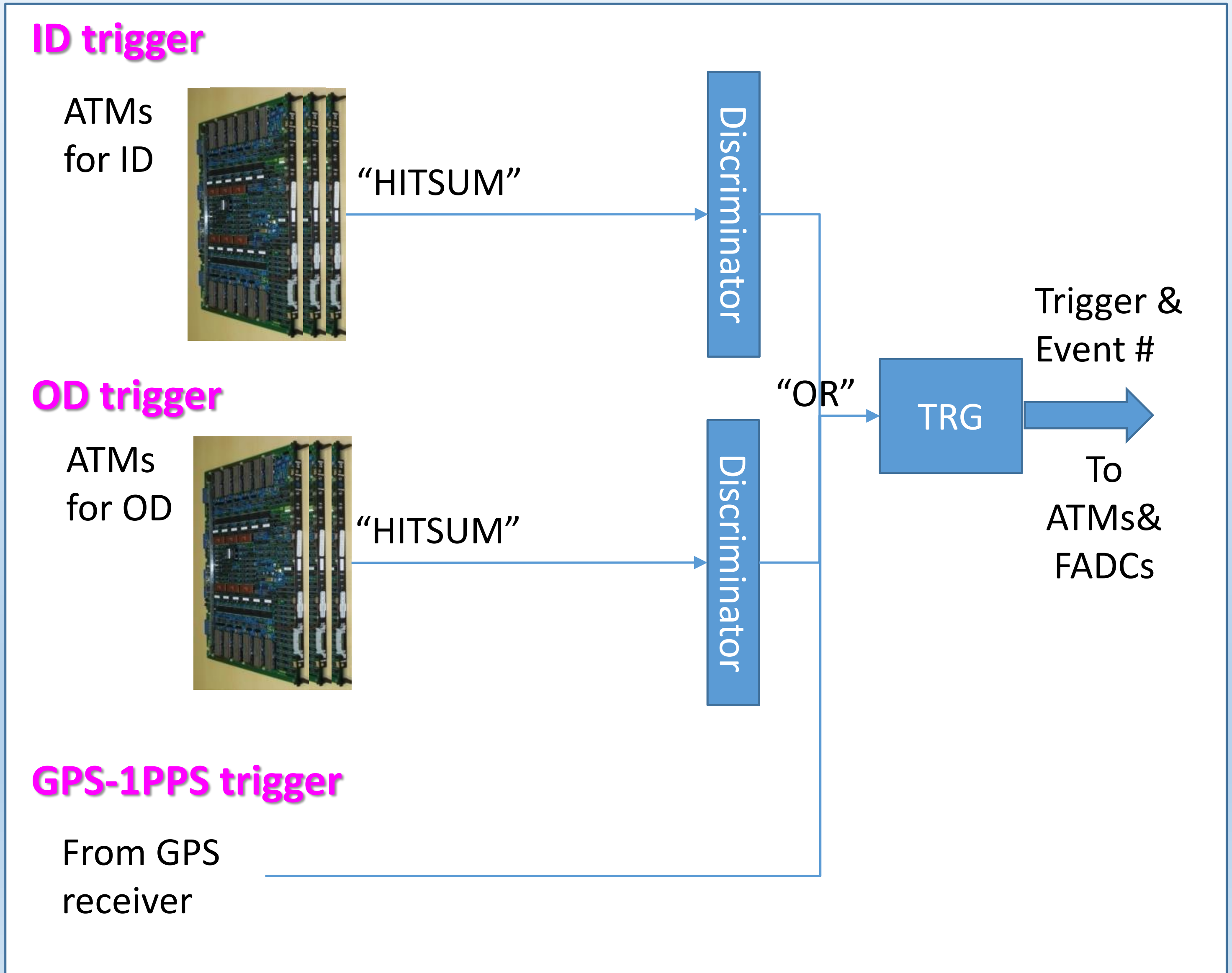
$$R = \sigma_{\chi N} n < v >$$

$$\propto \sigma_{\chi p} \frac{\mu_N^2}{\mu_p^2} A^2$$

μ: reduced mass

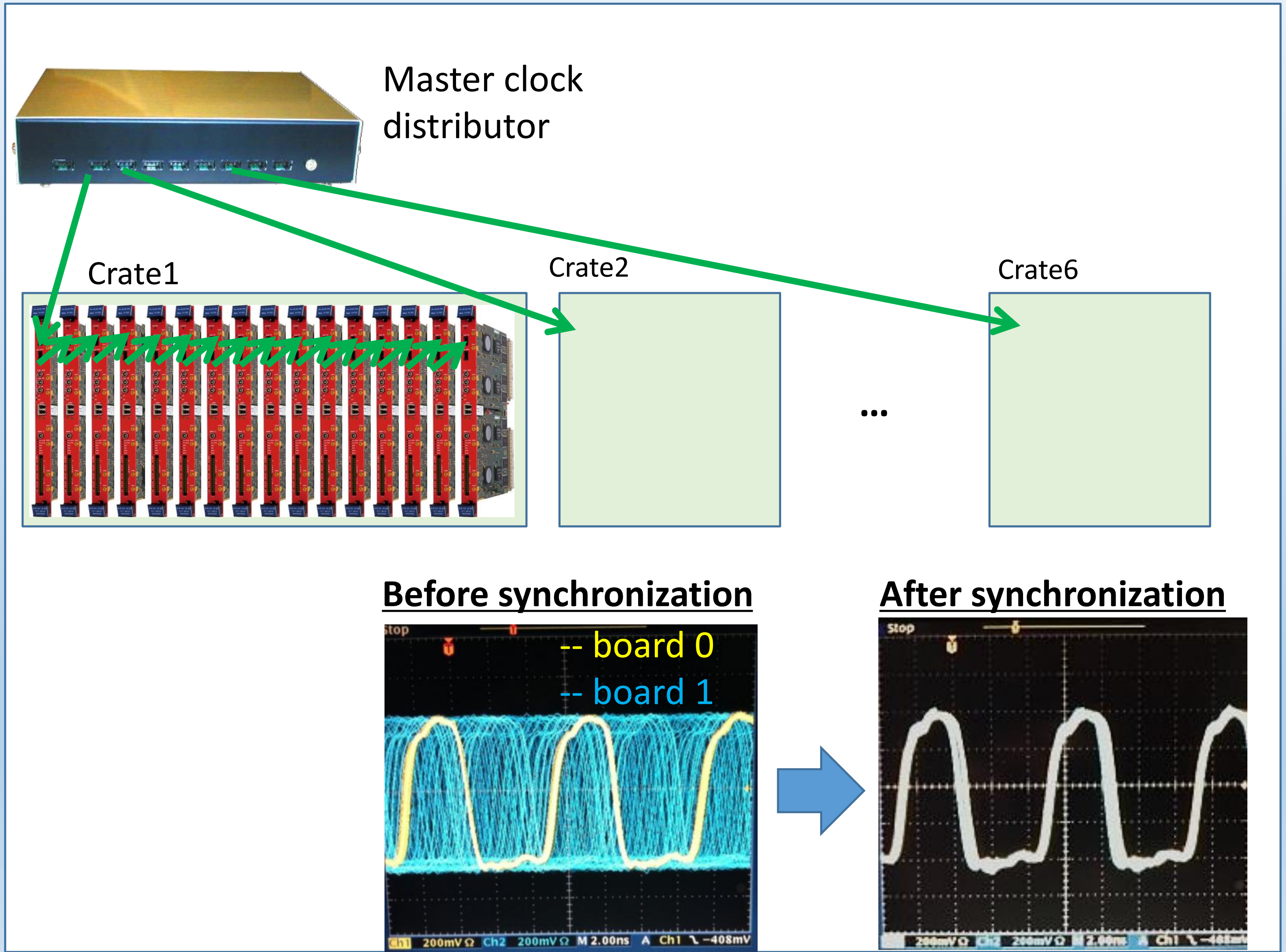
Xenon has an advantage
due to its large A

Trigger system



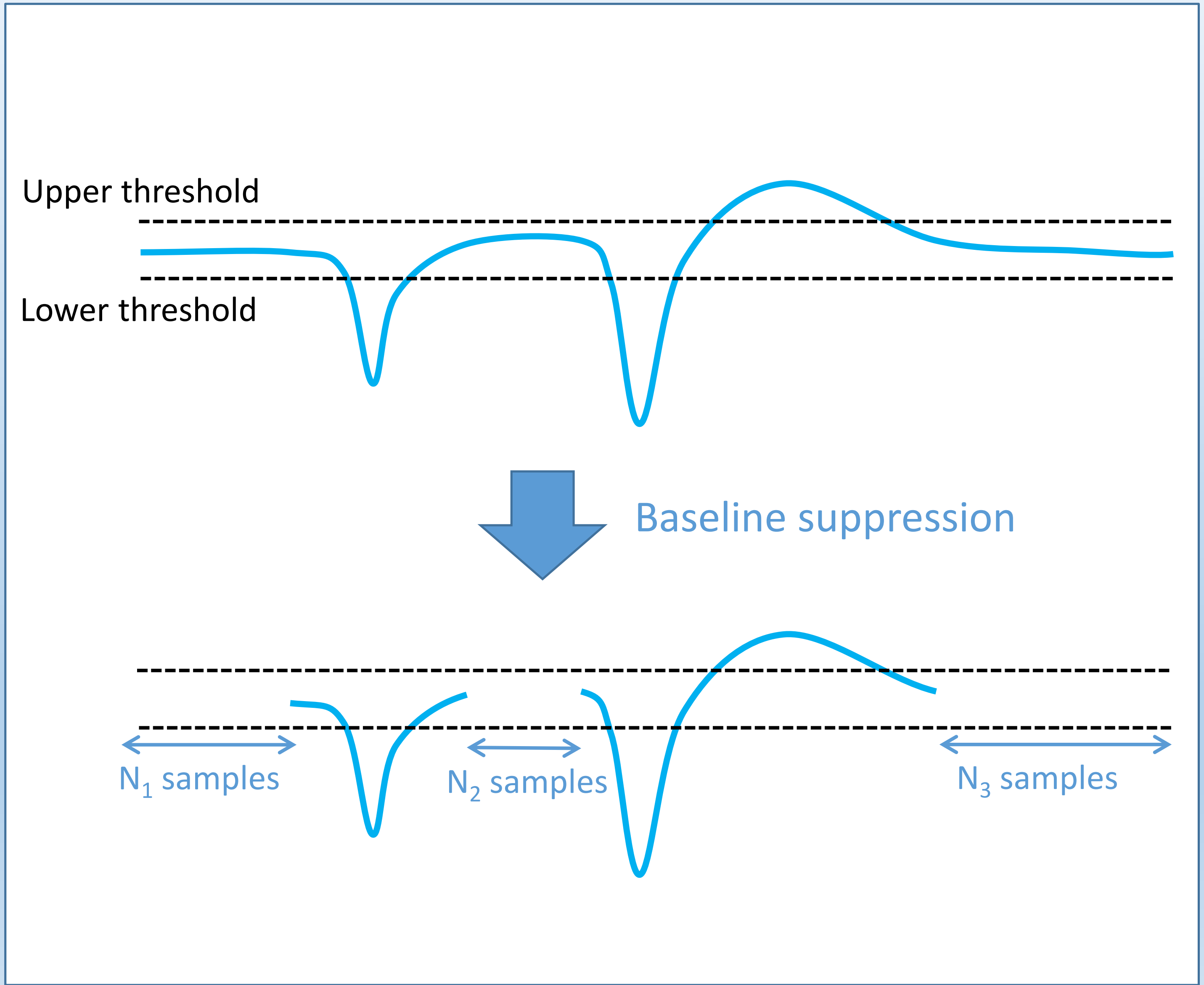
- ID (or OD) trigger
  - ATM outputs the analog signal whose height is proportional to the number of hits within 200 nsec (HITSUM).
- GPS-1PPS trigger
  - To calibrate absolute time.
  - Also used to monitor PMTs' dark rate and gain by flashing LED.
- Trigger module (TRG)
  - 8ch input at maximum.
  - Assign event number.
  - Record type of trigger and trigger time with 20 ns resolution.

FADC clock synchronization



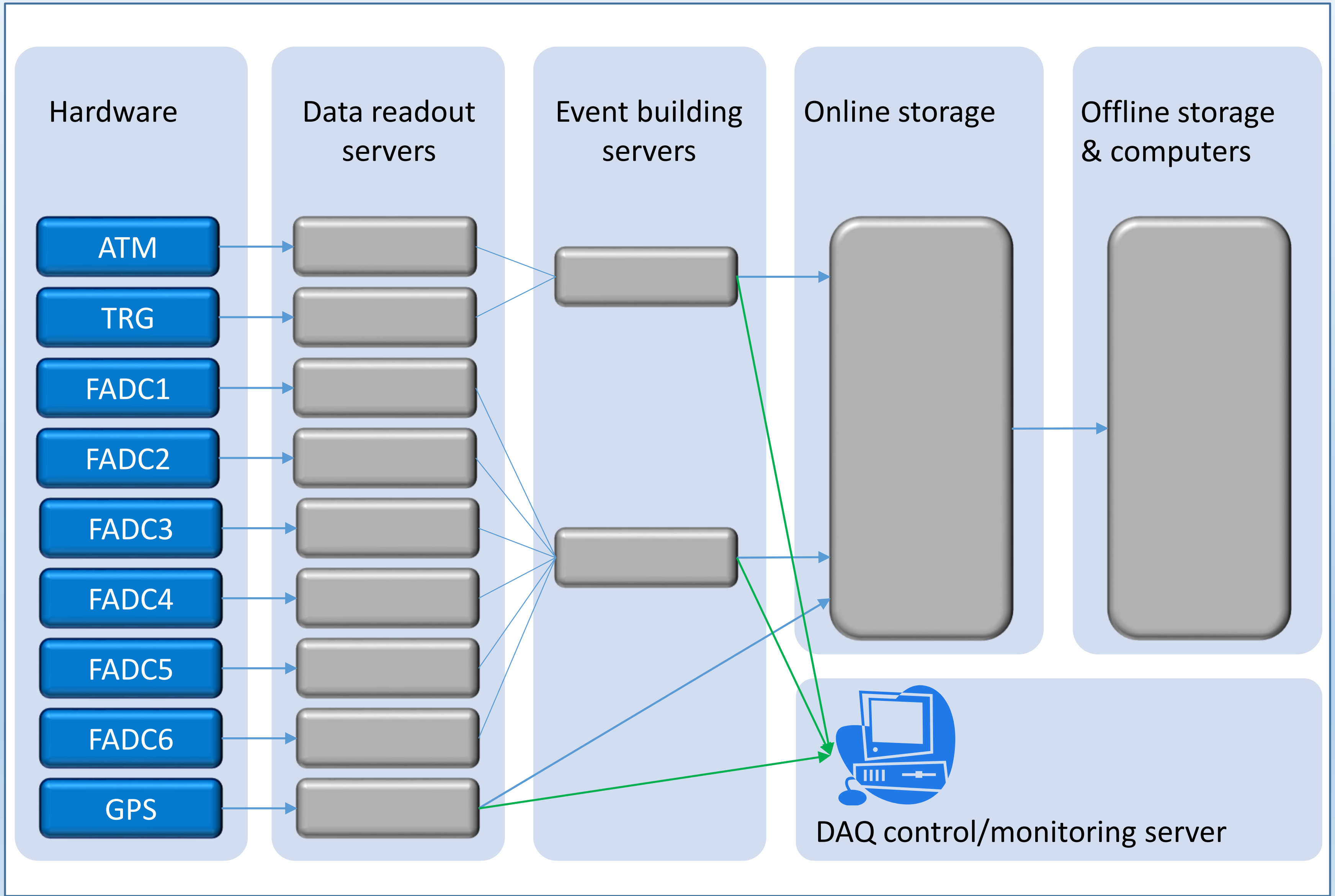
- **Master clock distributor**
  - Custom made
  - 8ch LVDS + 1ch NIM out
  - Frequency: 62.5 MHz
  - Accuracy: +/-0.5 ppm
  - Jitter: 13 psec
- **Clock synchronization**
  - Clock signal is distributed to each crate.
  - Within the crate, the clock is distributed sequentially.

FADC on-board baseline suppression



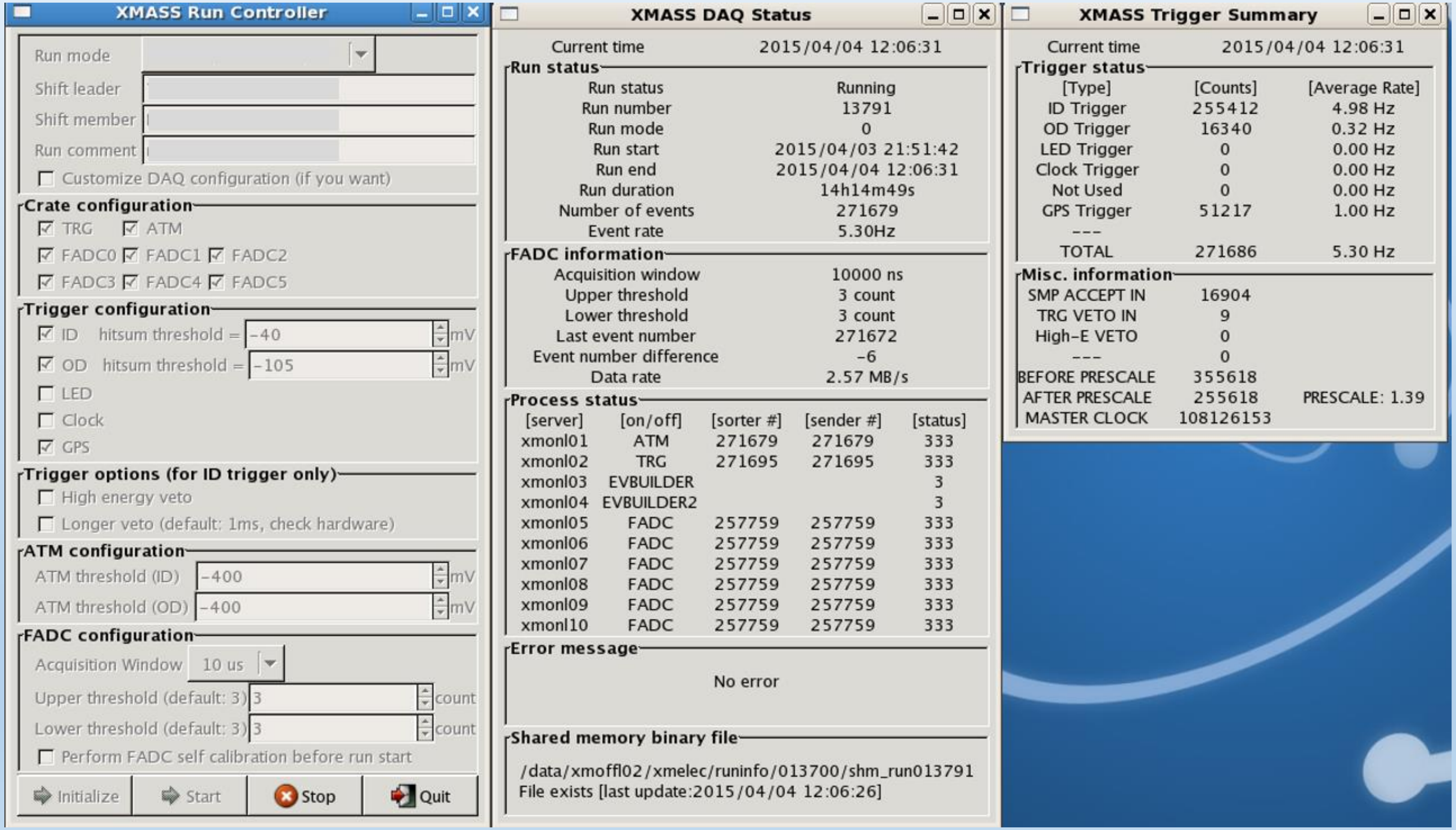
- We record waveforms in a 10 μs time window, while most of signal gather within 1 μs.
- To reduce readout data size, on-board baseline suppression was implemented.
- By setting threshold in both sides, overshoot can also be recorded.

Data flow



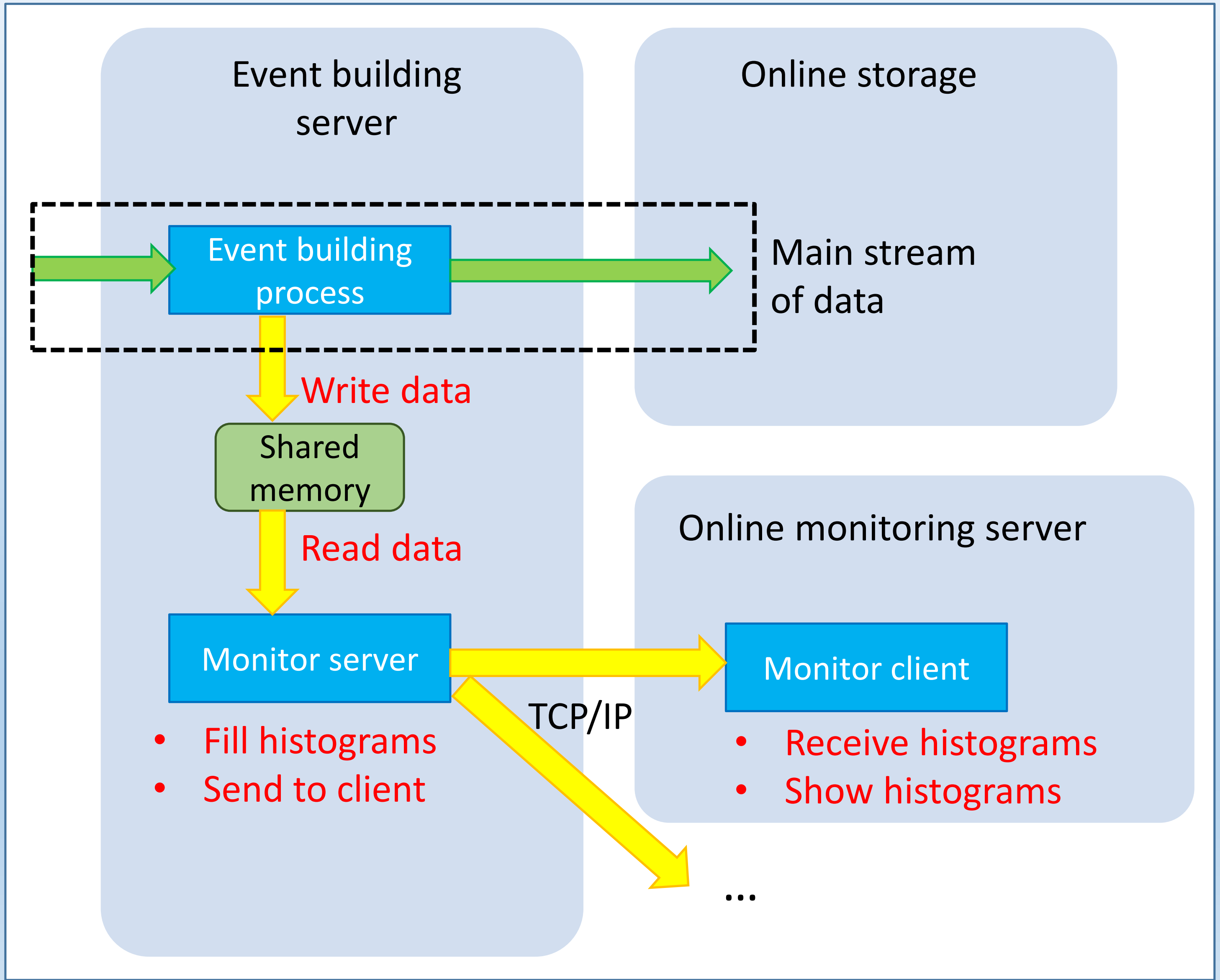
- **Data readout**
  - Read data from boards.
  - Sort them by event #.
  - Send them to the event building server.
- **Event building**
  - Merge data from data readout servers.
  - Store them as binary file.
  - ATM/TRG and FADC data are separately saved.
- **Online data monitoring**
  - Online histograms and event displays are sent from event building servers.

DAQ control



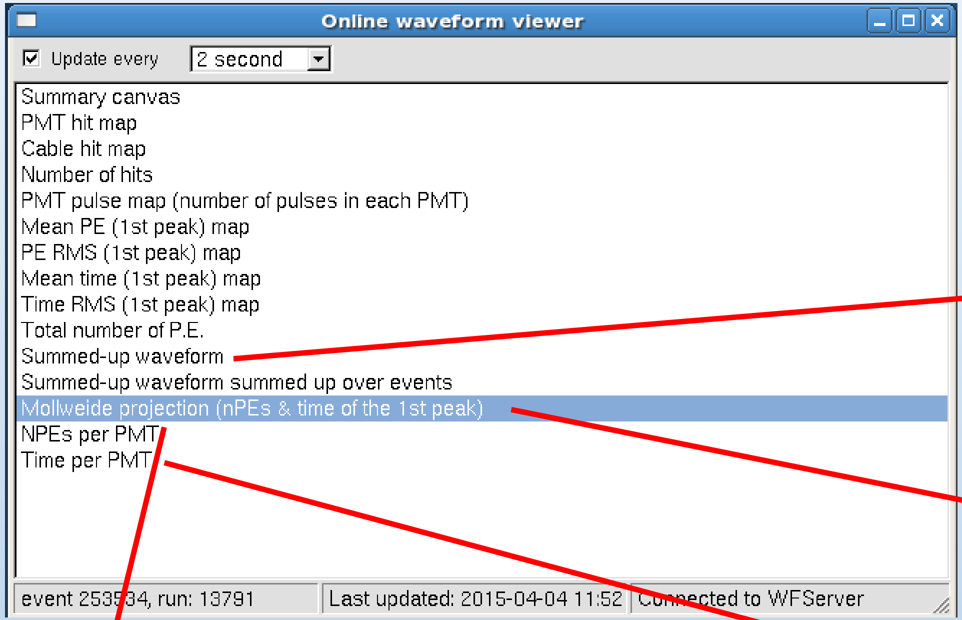
- **GTK+2 based program was developed.**
- **Run control window**
  - Run mode (calibration etc)
  - Shift name, comments
  - Trigger configuration
  - Electronics configuration
- **DAQ status window**
  - Run status
  - Status of computer nodes
- **Trigger summary window**
  - Trigger rates

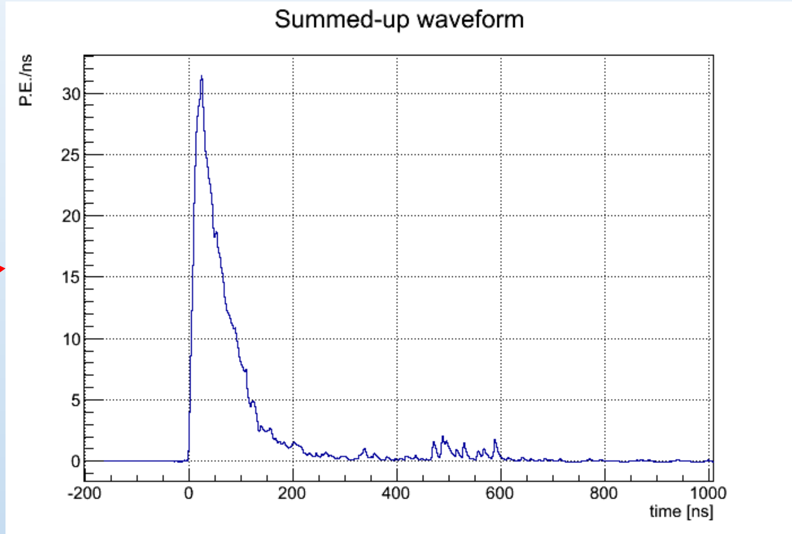
Online data monitoring (1)

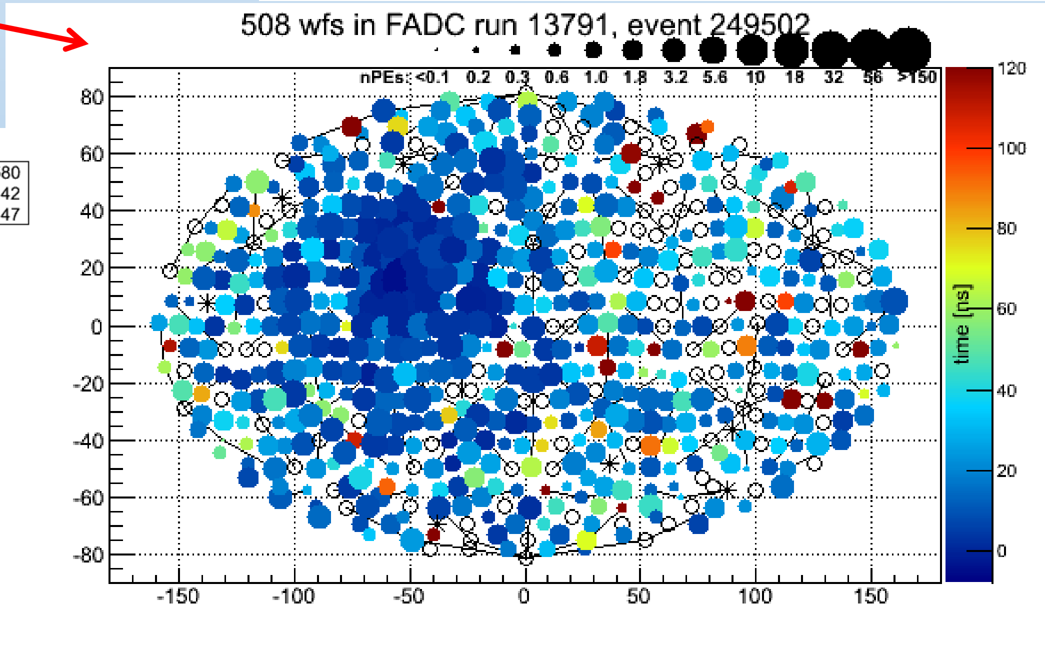


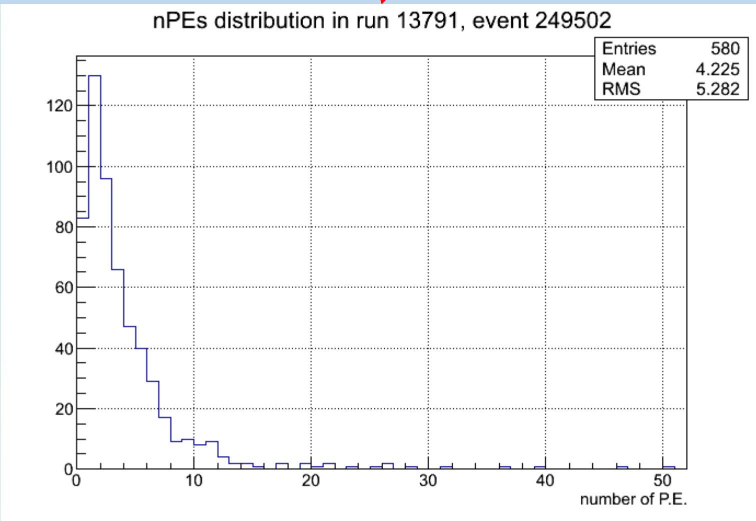
- **In event building server, the data is also written in the shared memory.**
- **The monitor server reads data from the shared memory and make histograms.**
- **The monitor client connects to the server via TCP/IP, receive histograms.**
- **Multiple clients can be connected to the server.**

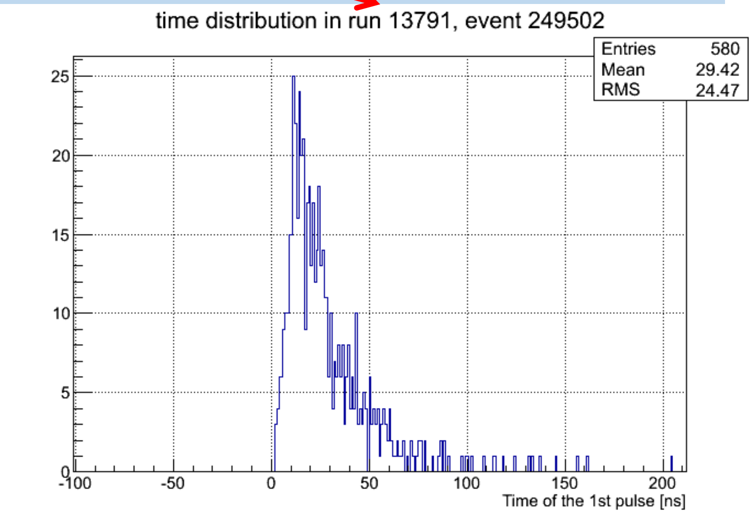
Online data monitoring (2)





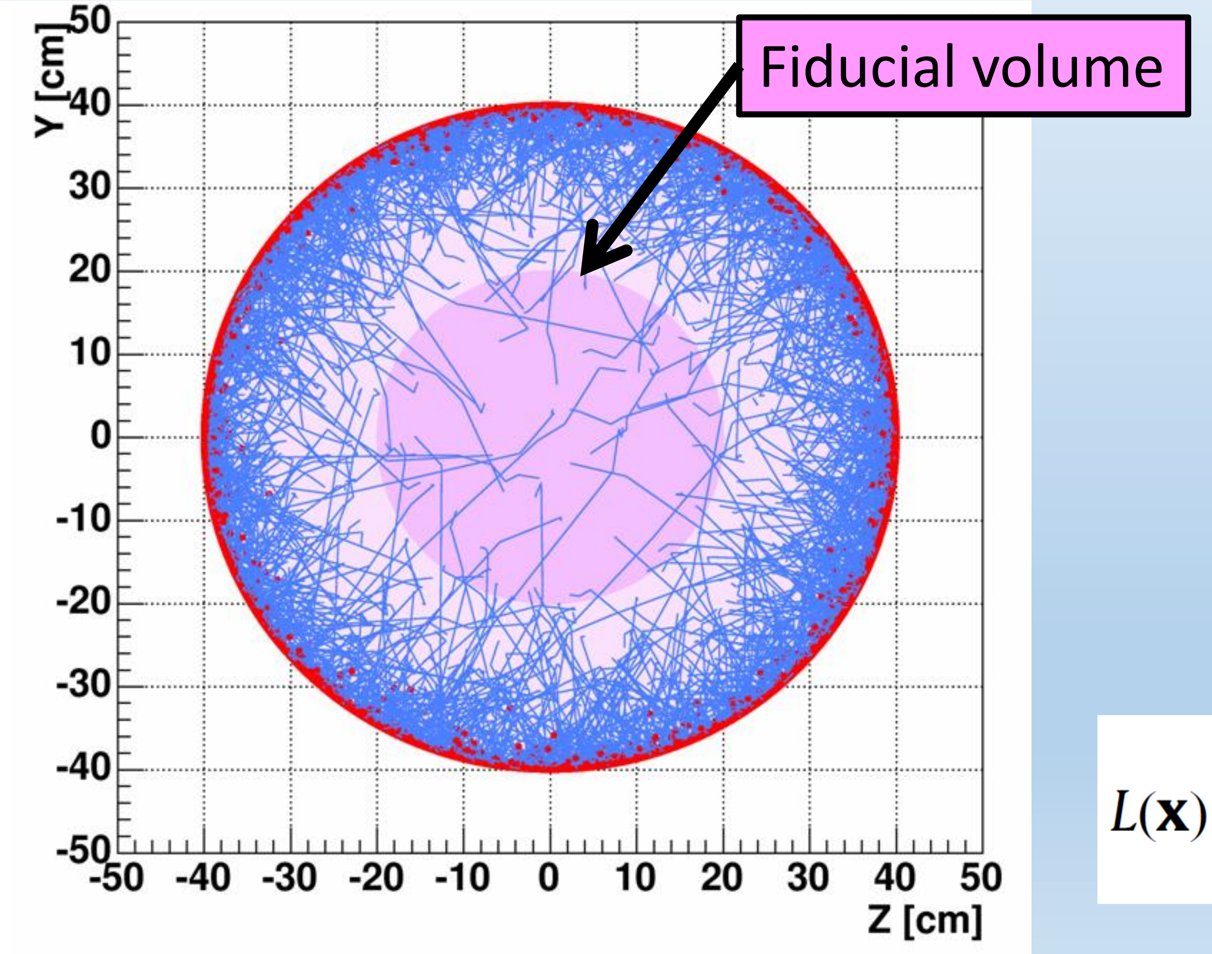






Self-shielding of gamma-ray background

Traces of U-chain gamma-rays from PMT



- Owing to high atomic number Z=54, external gamma-ray background can be shielded by liquid xenon itself.
- By selecting events occurred in the restricted inner volume (fiducial volume), low background can be achieved.
- Event vertex position and energy are reconstructed using "PE" in each PMT

$$L(\mathbf{x}) = \prod_{i=1}^{642} p_i(n_i)$$

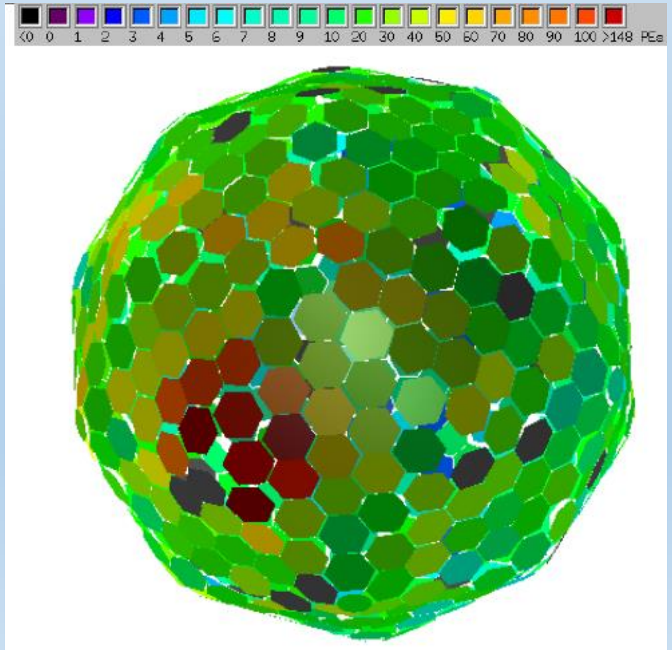
P_i (n) : probability that the i-th PMT detects n PE

Vertex reconstruction

- Event vertex position and energy are reconstructed using “PE” in each PMT

$$L(\mathbf{x}) = \prod_{i=1}^{642} p_i(n_i)$$

P_i (n) : probability that the i-th PMT detects n PE

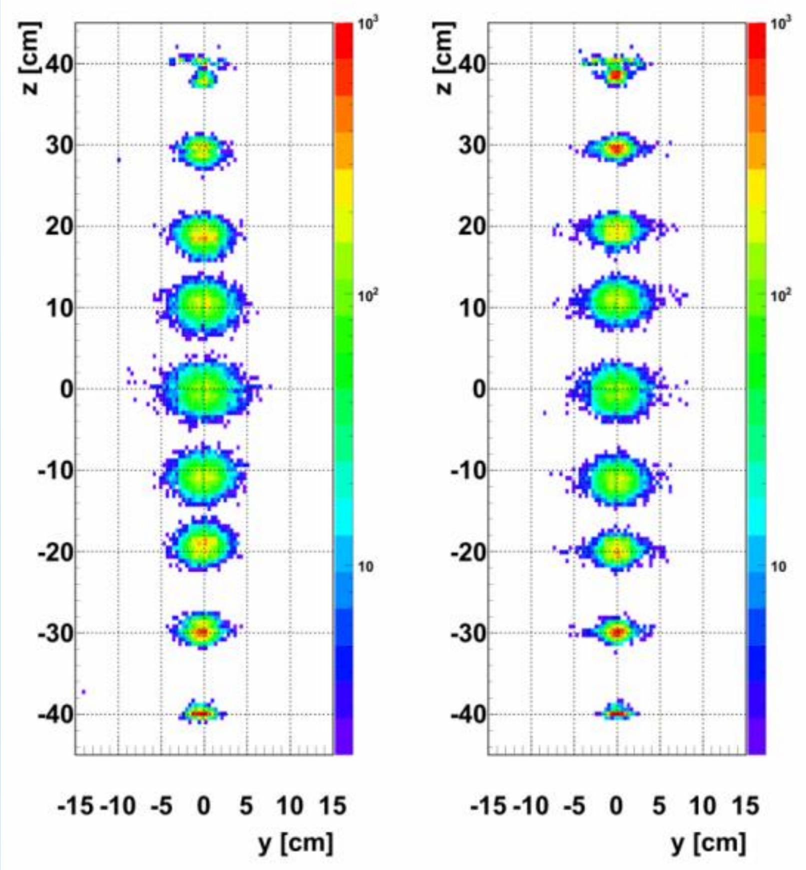


Reconstructed vertex

^{57}Co 122keV

DATA

MC

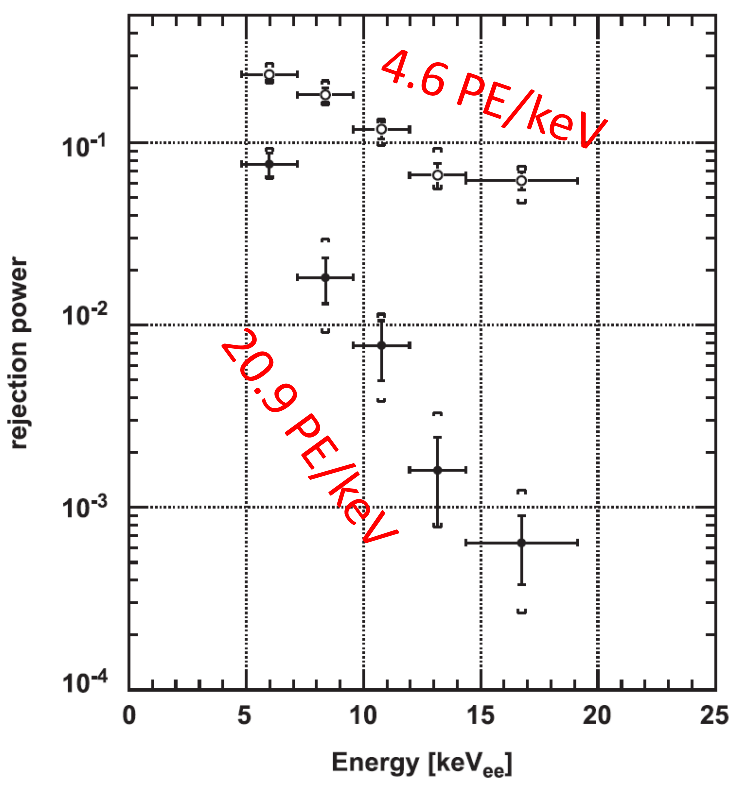


Prospects for pulse shape discrimination (PSD) using LXe scintillation

- LXe scintillation processes
  - Excitation:
    - Singlet ($^1\Sigma_u^+$): τ~ a few ns
    - Triplet ($^3\Sigma_u^+$): τ~ 20 ns
  - Recombination: τ~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 ~8x10^{-2} for 50% NR efficiency at 4.8-7.2 keVee
- Detail measurement of scintillation time profile for low energy *e*/γ has been conducted

PSD study with a small setup

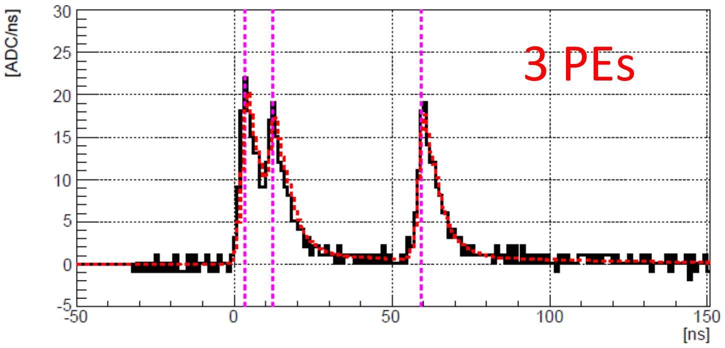
Electron rejection power for 50% NR efficiency

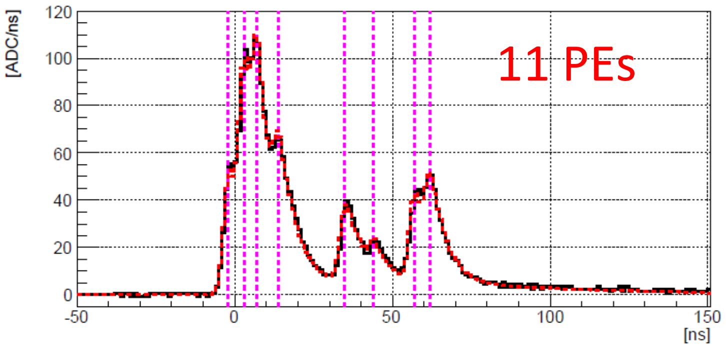


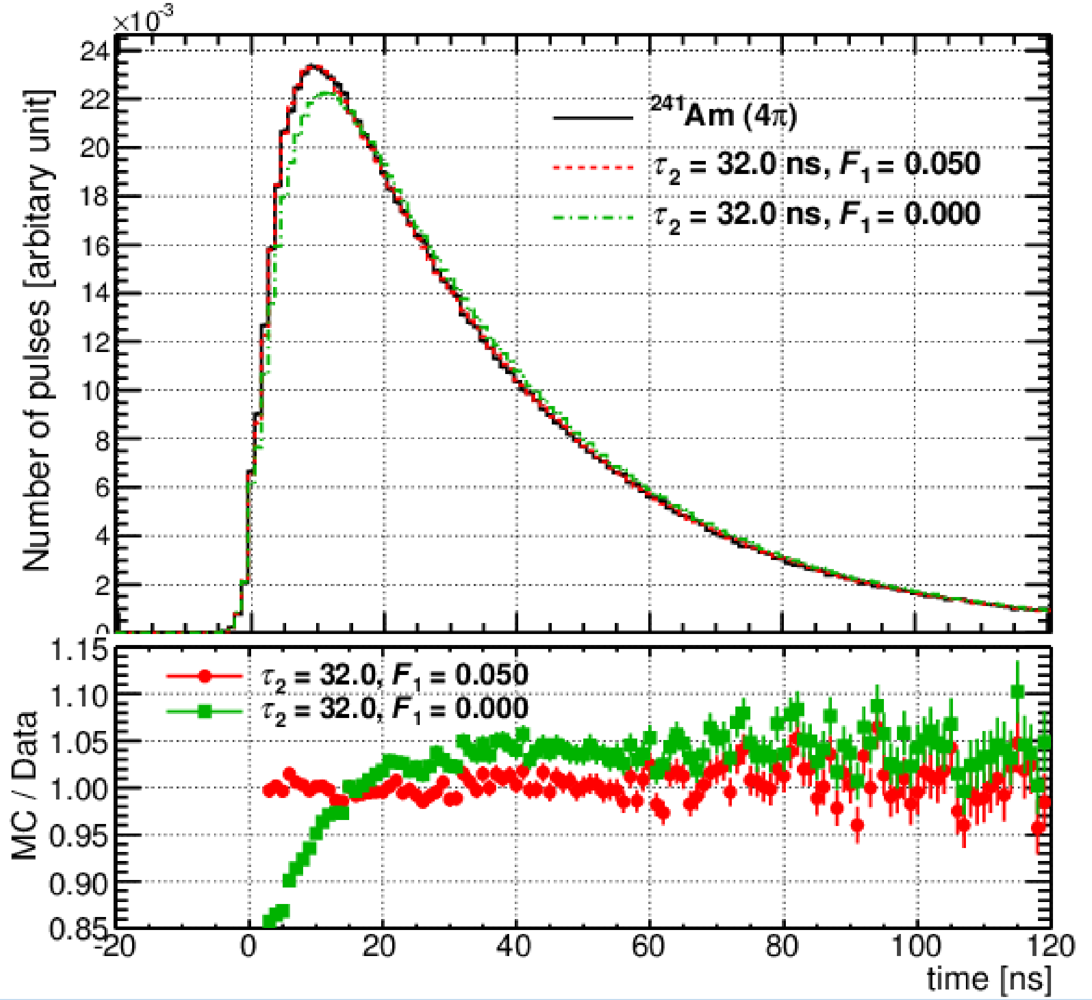
NIM A659 (2011) 161

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

- Waveforms are decomposed into "single PE" pulses
- Timing distributions of data and MC are compared to obtain intrinsic decay time parameters.
- MC simulation takes into account optical parameters (absorption, scattering, …), electronics response.

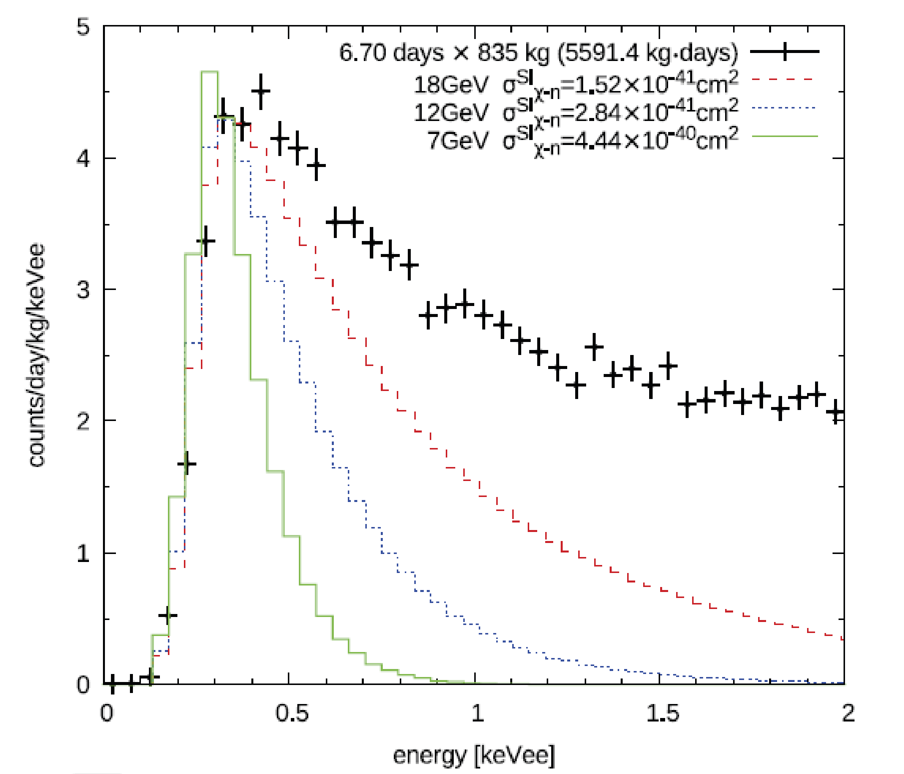


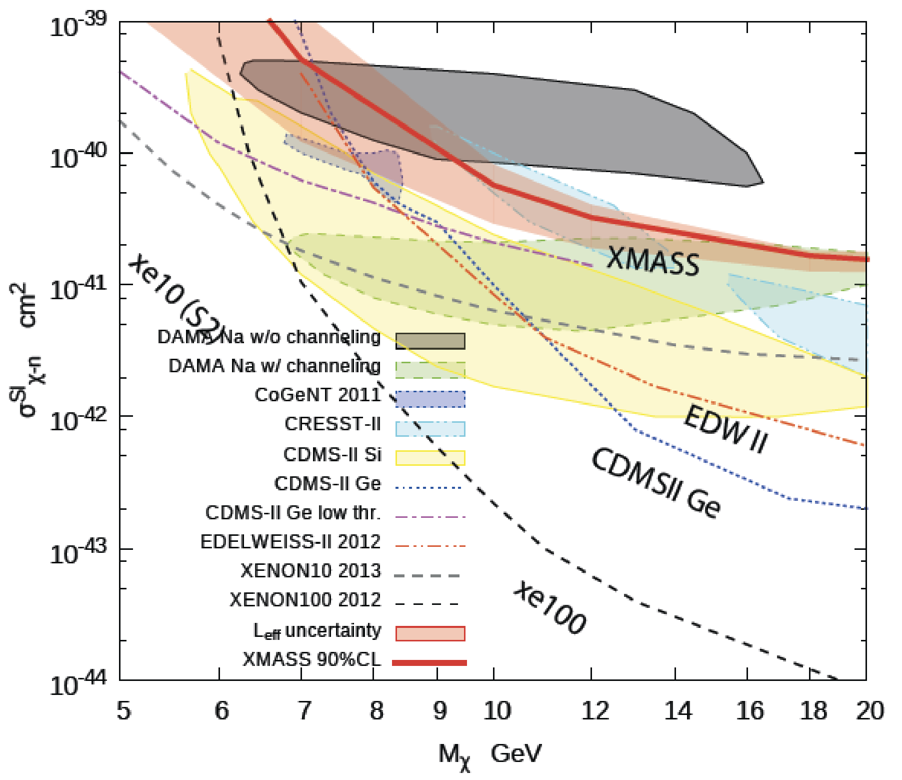




Search for light WIMPs

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



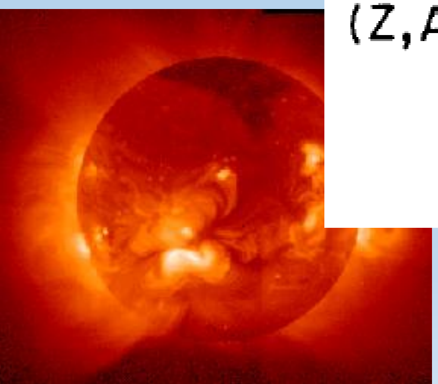


Published in Phys. Lett. B 719 78 (2013)

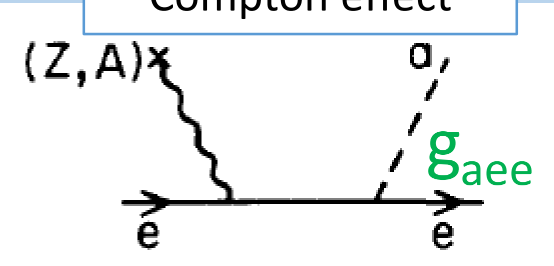
Search for solar axion in XMASS

- Axion is proposed to solve the strong CP problem.
- Axions would be produced in the Sun via
  - Primakoff effect (γ+Z→a+Z)
  - Compton scattering (e+γ→e+a)
  - Bremsstrahlung (e+Z→e+a+Z)
  - etc.
- Solar axions can be detected through axio-electric effect (a+Z→e+Z) in the XMASS detector

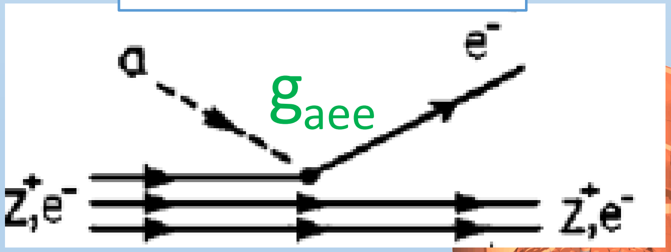
Coupling with electron

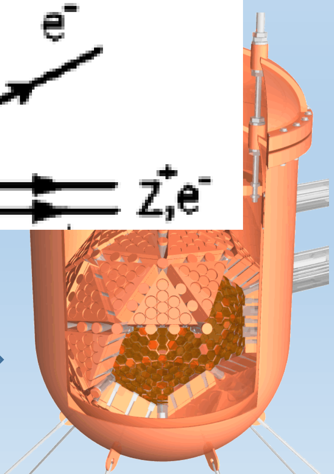


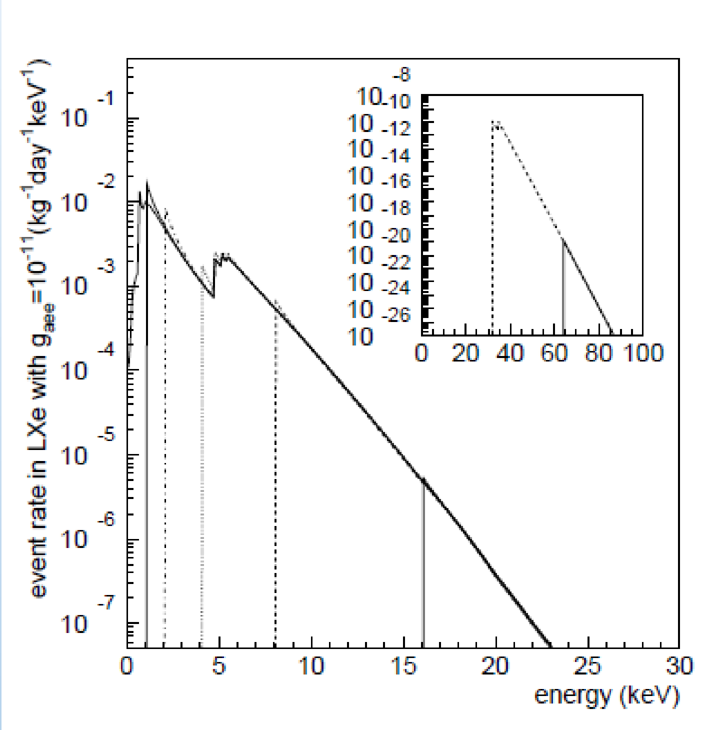
Bremsstrahlung and Compton effect



Axio-electric effect



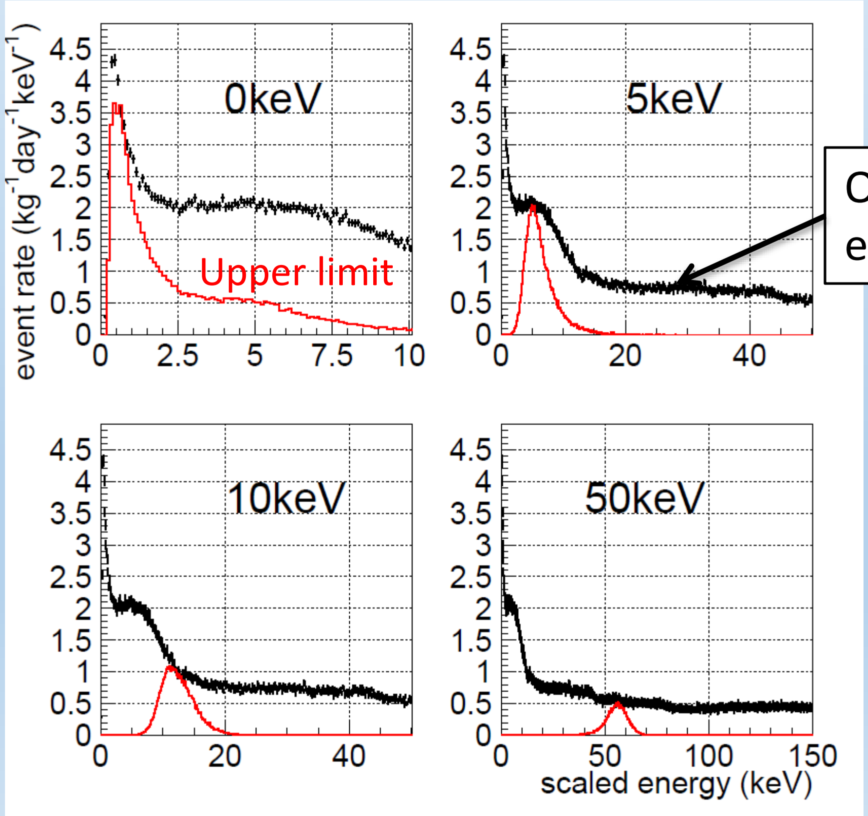




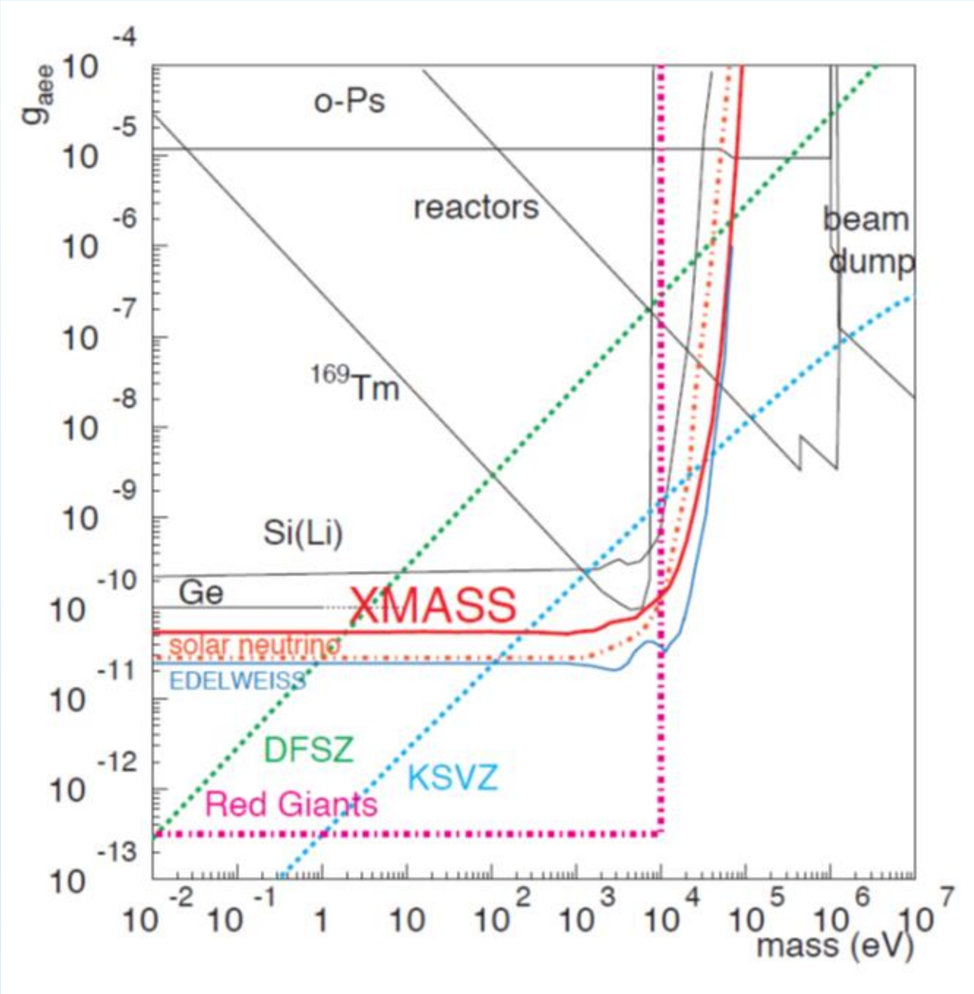
Expected energy spectra of solar axions (m_a=0, 1, 2, 4, 8, 16 keV/c^2)

Search for solar axion in XMASS

- 6.7 days data
- Obtained the 90% confidence level upper limits on coupling constant g_{aee}, so that the solar axion signal does not exceed the observed spectrum.



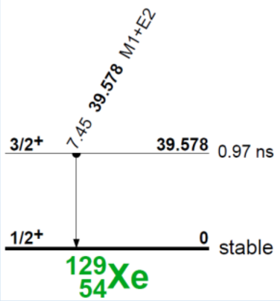
Observed energy spectrum



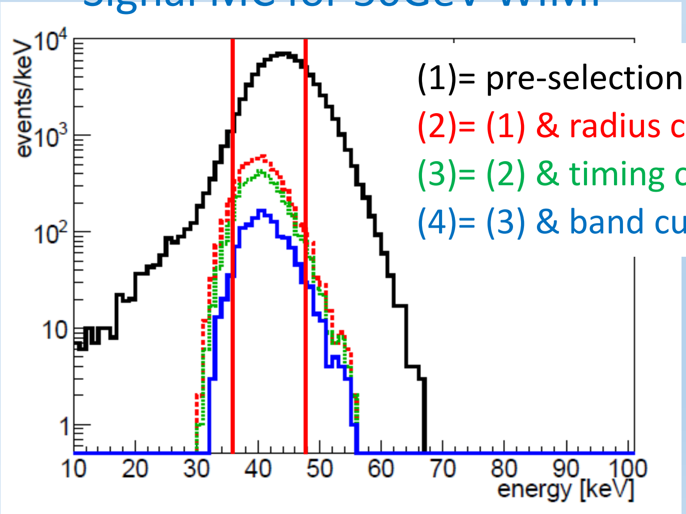
Published in Phys. Lett. B 724 46 (2013)

Search for ^{129}Xe inelastic scattering by WIMPs

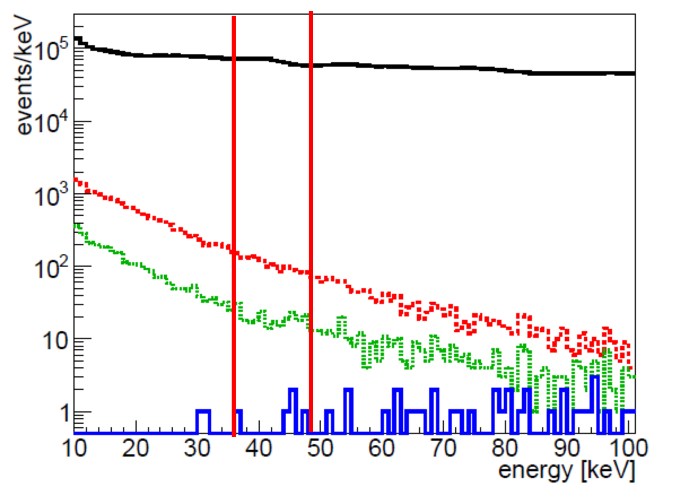
- $\chi + {}^{129}Xe \rightarrow \chi + {}^{129}Xe^*$
  $^{129}Xe^* \rightarrow {}^{129}Xe + \gamma$ (39.6keV)
- Natural abundance of ^{129}Xe: 26.4%

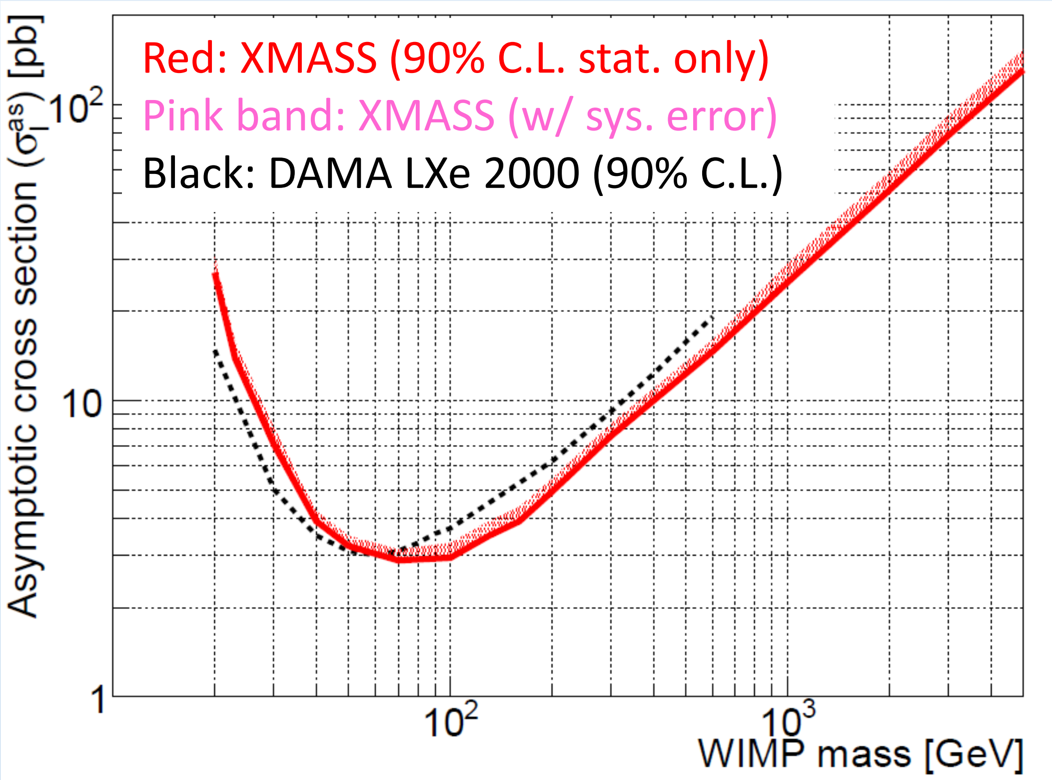


Signal MC for 50GeV WIMP



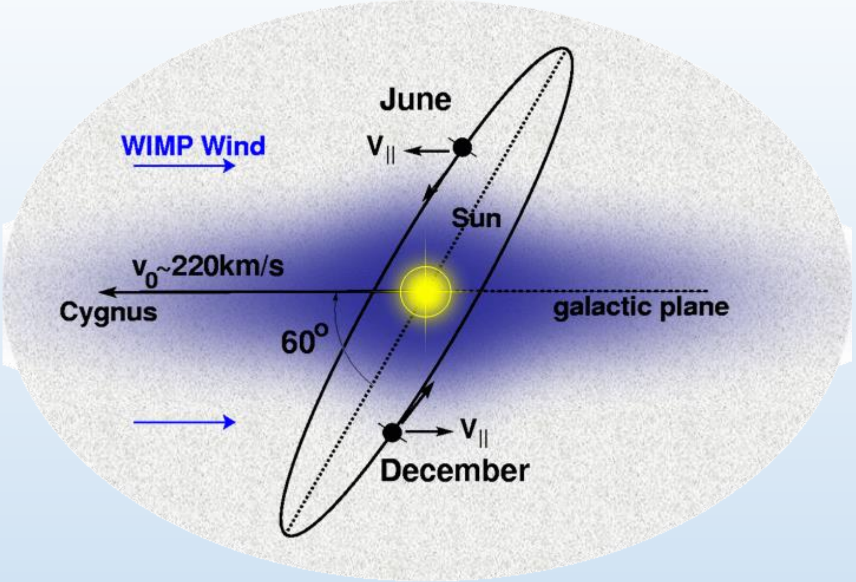
Observed data (165.9 days)



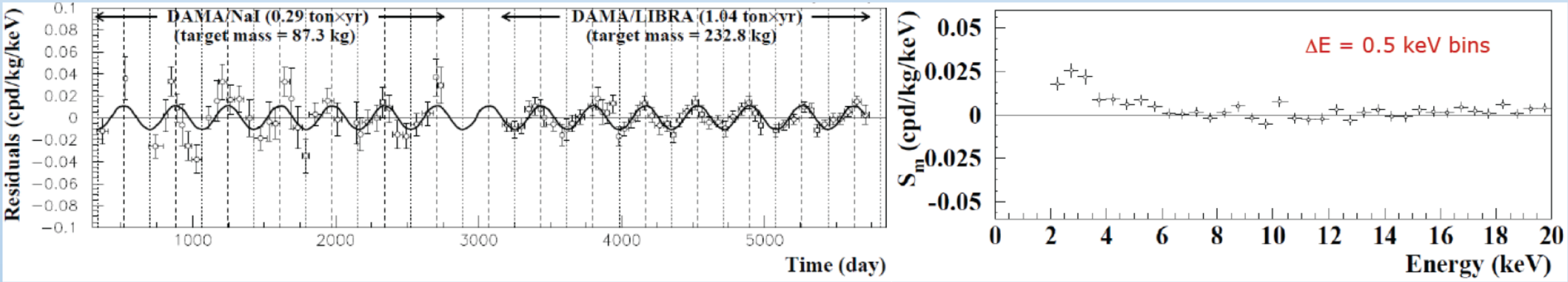


Published in PTEP 063C01 (2014)

Search for annual modulation

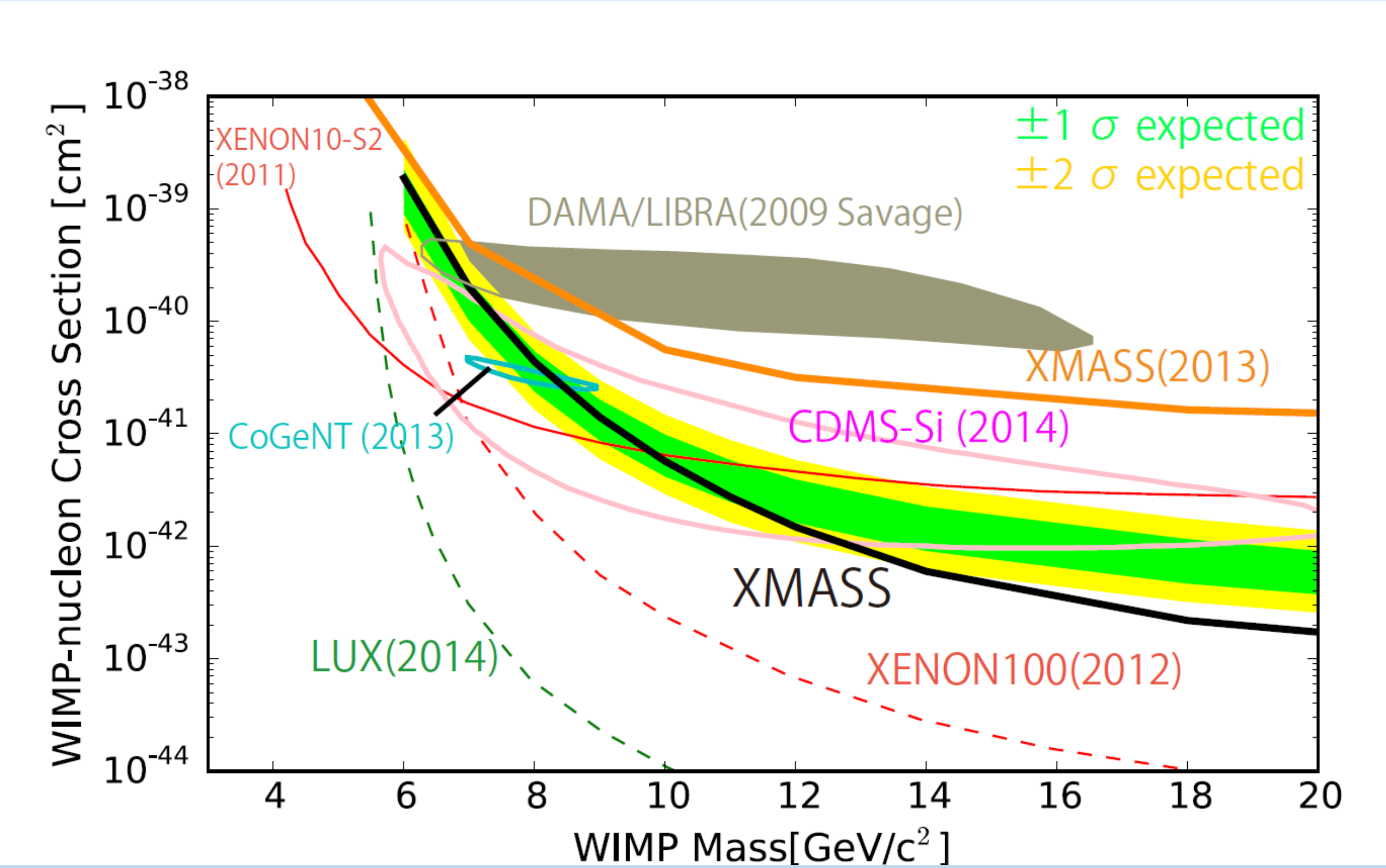


- Expect annual modulation of event rate of dark matter signal due to Earth's rotation around the Sun.
- DAMA/LIBRA claims modulation at 9.3σ
  - Total exposure of 1.33 ton year (14 cycles)
  - Modulation amplitude of (0.0112+/-0.0012) cpd/kg/keV for 2-6 keV



- 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/γ events

Modulation analysis: WIMP results



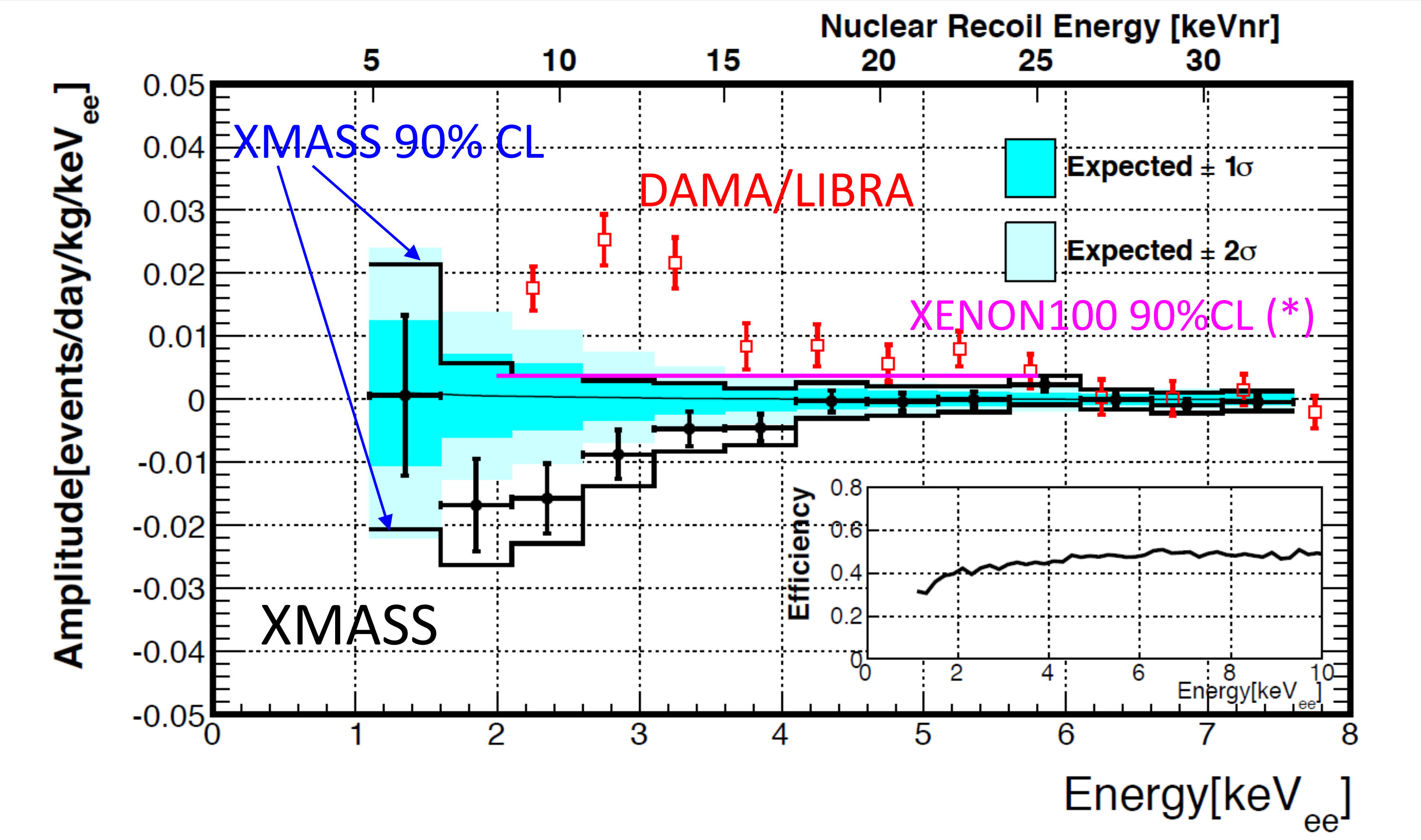
- Expected event rate

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

  - T= 1year, t_0=152.5 day (fixed)
  - Ai(m_χ): modulation amplitude
  - Ci: unmodulated event rate

- WIMP mass range 6 to 20 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/γ signals
- Shows slightly negative amplitudes in the 1.6-4.1 keVee range.
- P-values
  - 0.014 (2.5σ) for method-1
  - 0.068 (1.8σ) for method-2
- Gives 90% CL limits for positive and negative amplitude separately

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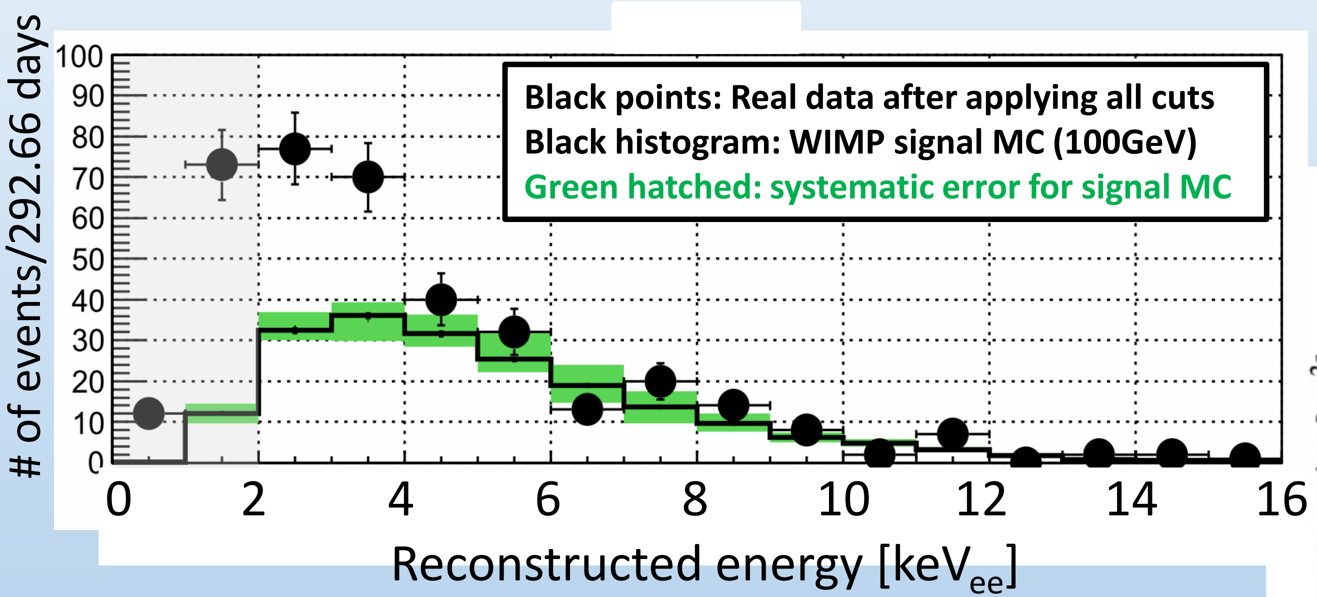
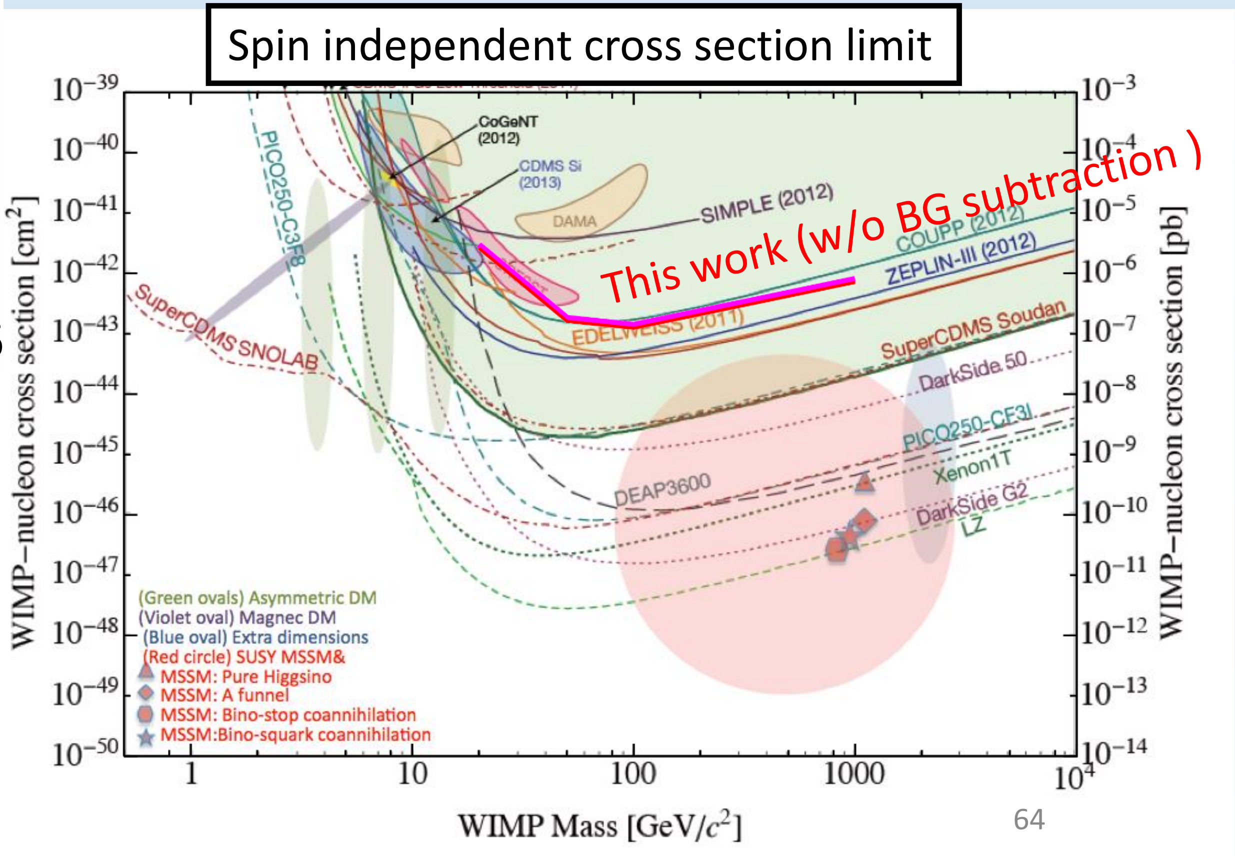
Upper limit for WIMP signal

Remaining events after applying all cuts were considered as WIMP signal conservatively.
Upper limit in cross section was calculated so that expected WIMP signal did not exceed the real data.





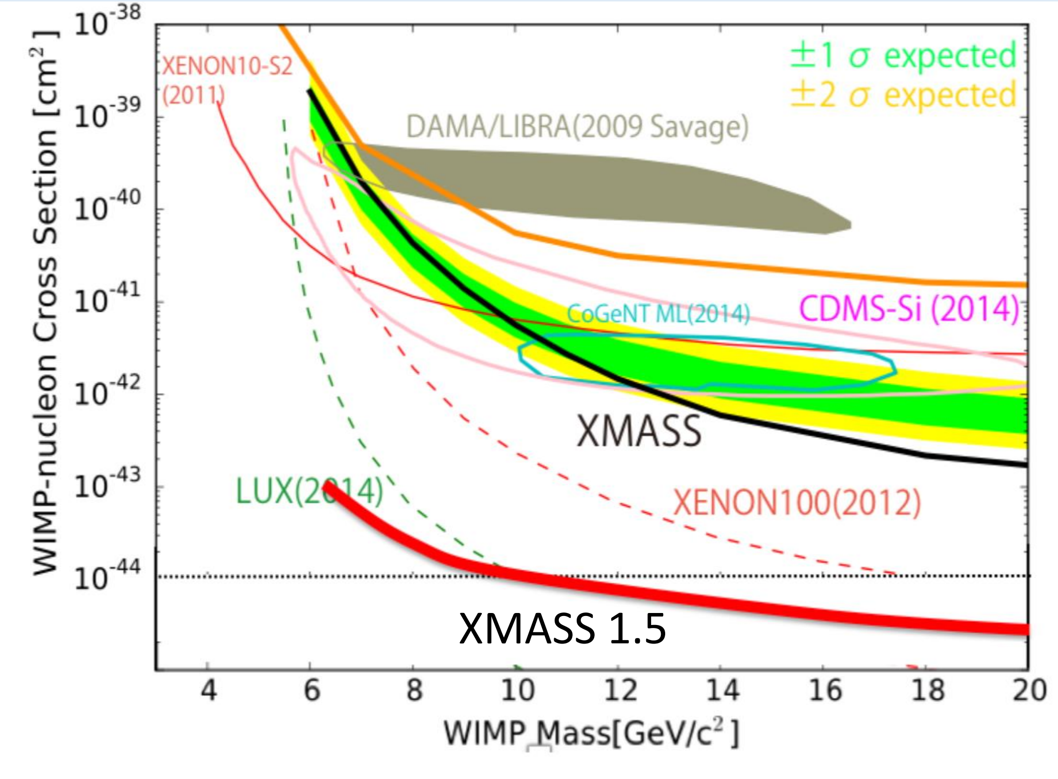
90% CL upper limit for 100GeV WIMP :

1.23×10^{-43} cm² (w/o systematic errors)

1.60×10^{-43} cm² (w/ systematic errors)

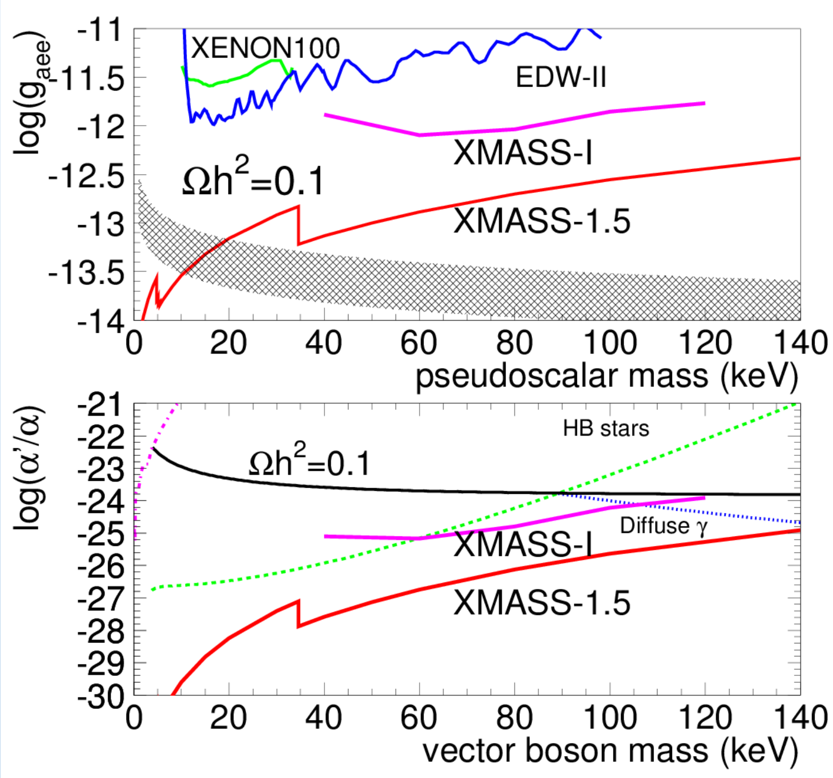
Future sensitivity to low mass WIMPs and bosonic super-WIMPs

Low mass WIMPs



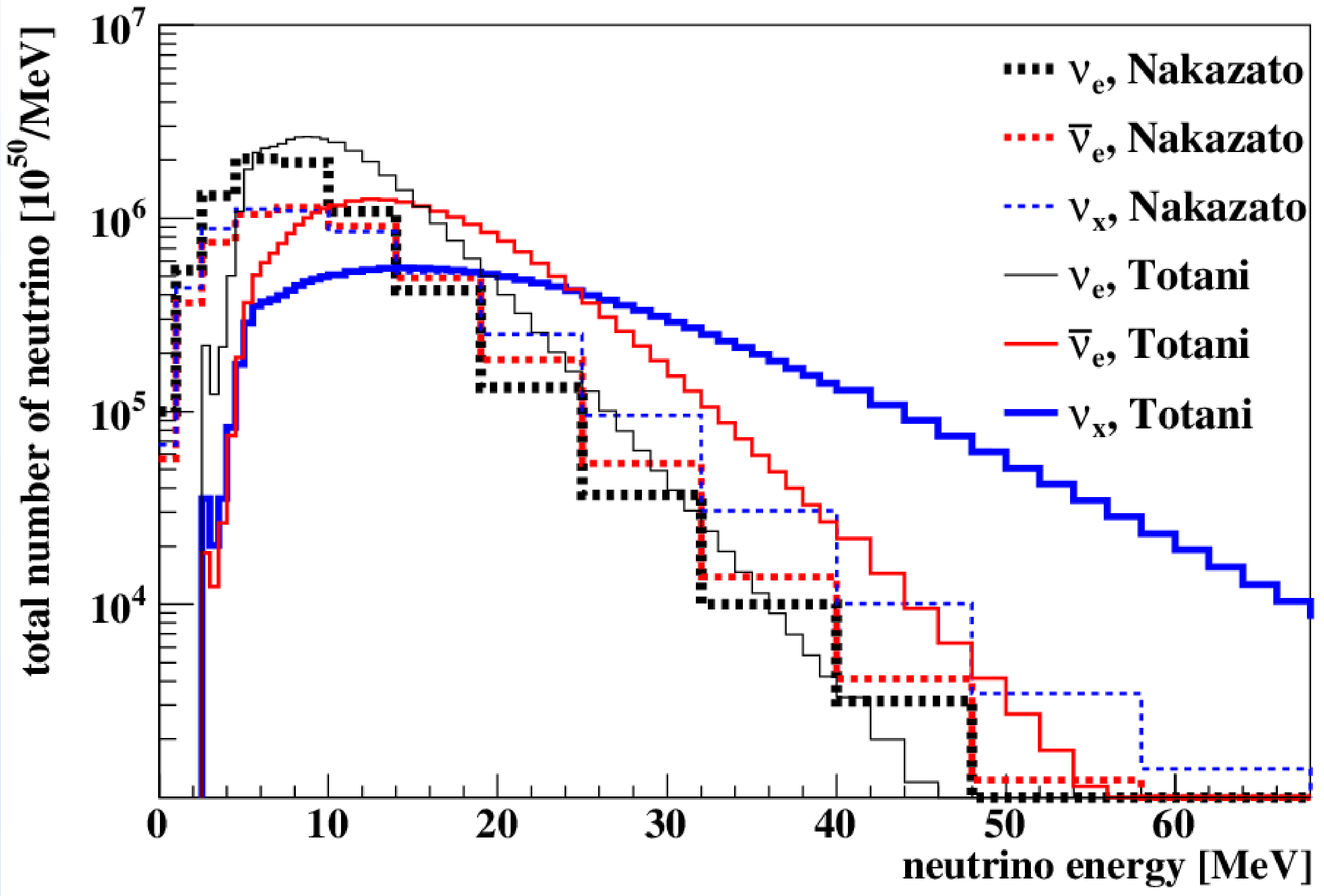
- Analysis threshold ~1 keVee
- Whole volume (no vertex reconstruction)
- Expect to reduce BG to 1/500 ($<10^{-2}$ dru)

Bosonic super-WIMPs

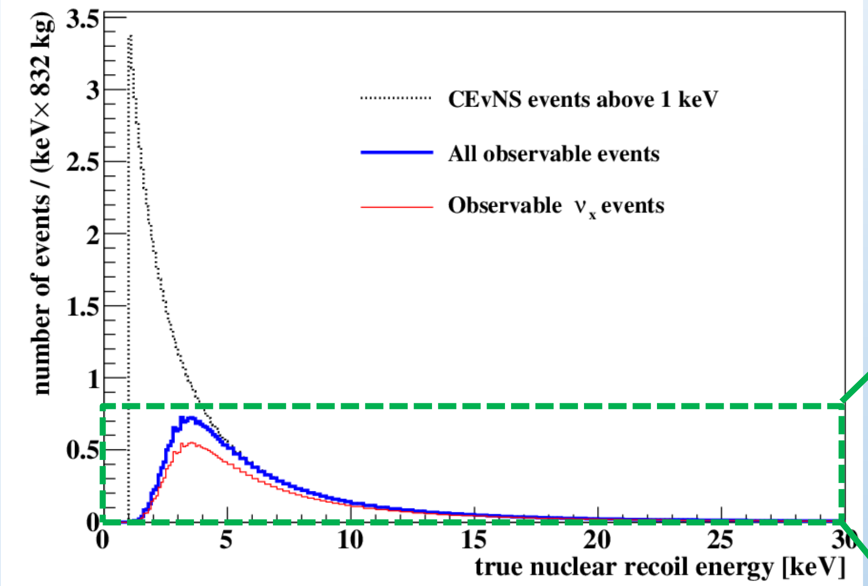


- Higher energy O(100 keV) e/γ events
- Background level 10^{-5} dru assumed
- Ultimate BG: *pp* solar neutrino & ^{136}Xe $2\nu\beta\beta$

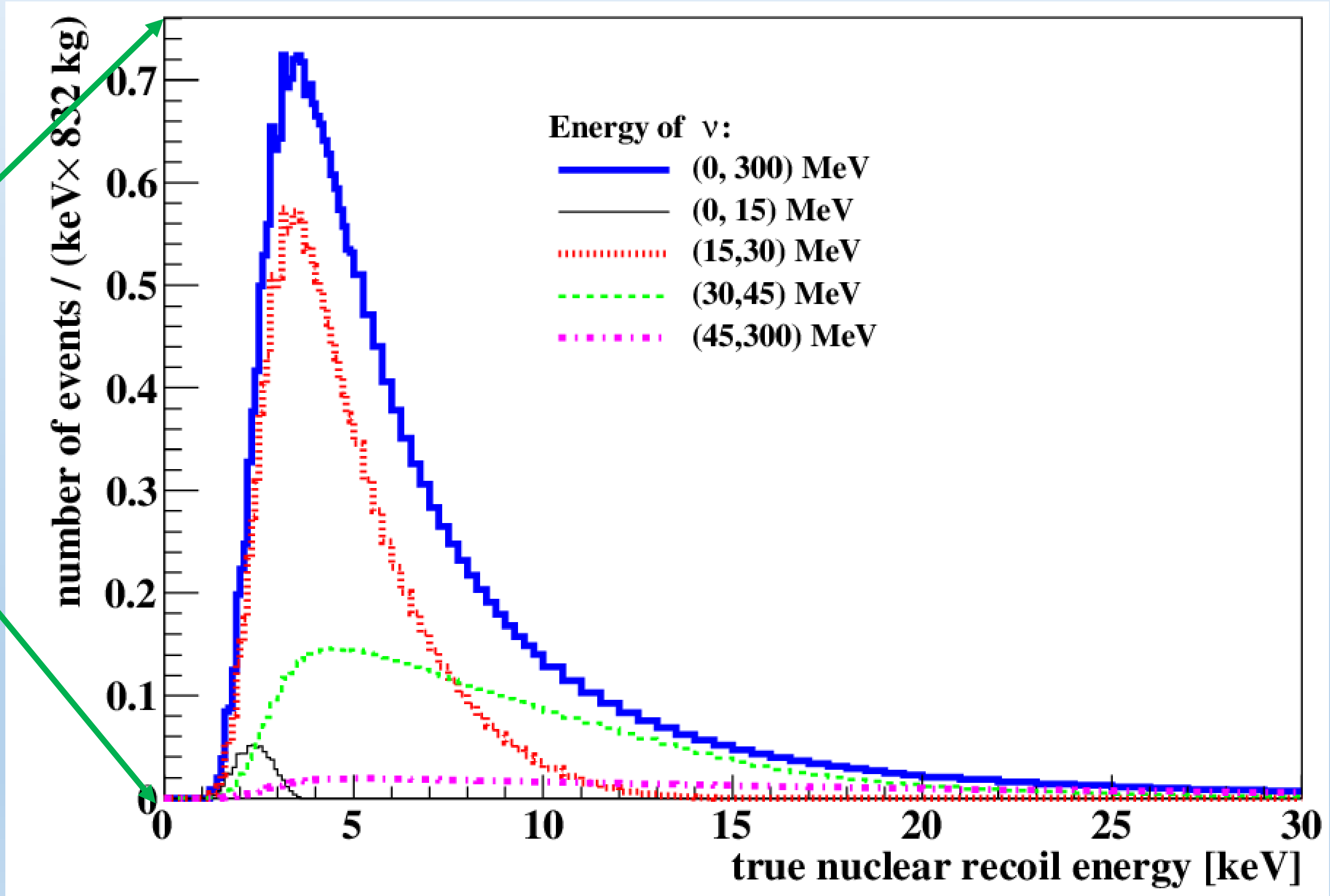
Supernova neutrino spectra



Nuclear recoil spectra for supernova neutrino

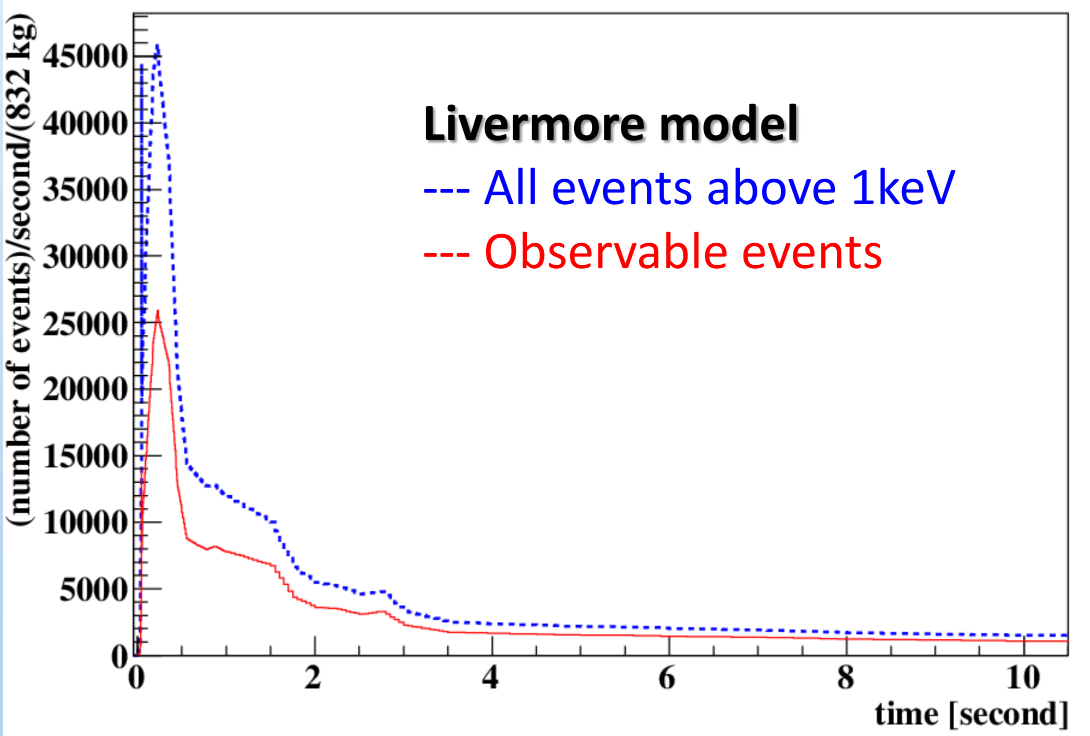


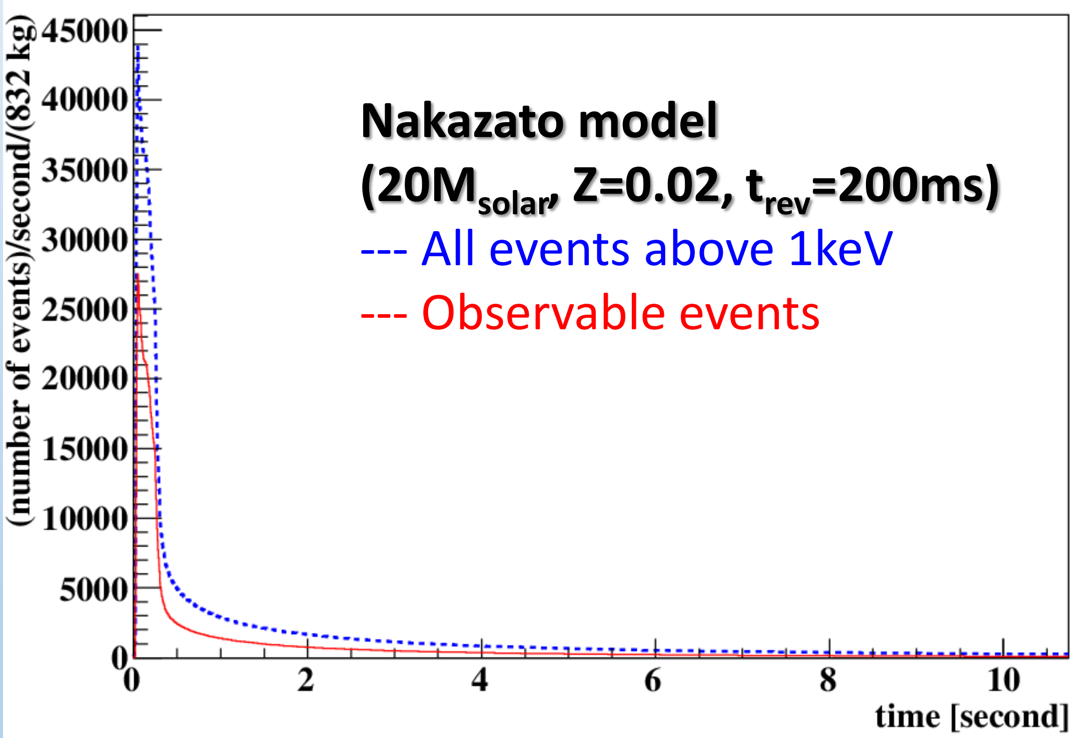
Neutrino energy dependence



- XMASS is sensitive to
  - ➢ ν_x component
  - ➢ E_ν > 15 MeV

Expected supernova neutrino event time profile





Can be distinguishable in the case of nearby supernova (~200pc)

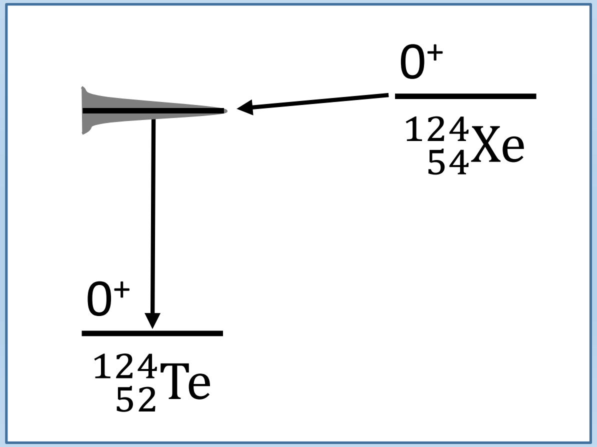
Why is ^{124}Xe interesting?

- ^{124}Xe has the largest Q-value among all the 35 ECEC candidates.
  It is large enough so that β^+EC and $\beta^+\beta^+$ channels are also allowed.
  - β^+EC: $(Z,A) + e^- \rightarrow (Z-2,A) + e^+ (+2\nu_e)$
  - $\beta^+\beta^+$: $(Z,A) \rightarrow (Z-2,A) + 2e^+ (+2\nu_e)$

- The $0\nu\beta^+$EC mode has an enhanced sensitivity to right-handed weak current.
  - It can help to disentangle the contributions of different mechanisms if observed.

- The 0νECEC process may be resonantly enhanced
  if there exists an excited state with $\Delta = Q_{ECEC} - 2E_x - E_\gamma \sim 0$.

- And… any measurement of 2νECEC will provide a new
  reference for the calculation of nuclear matrix elements.



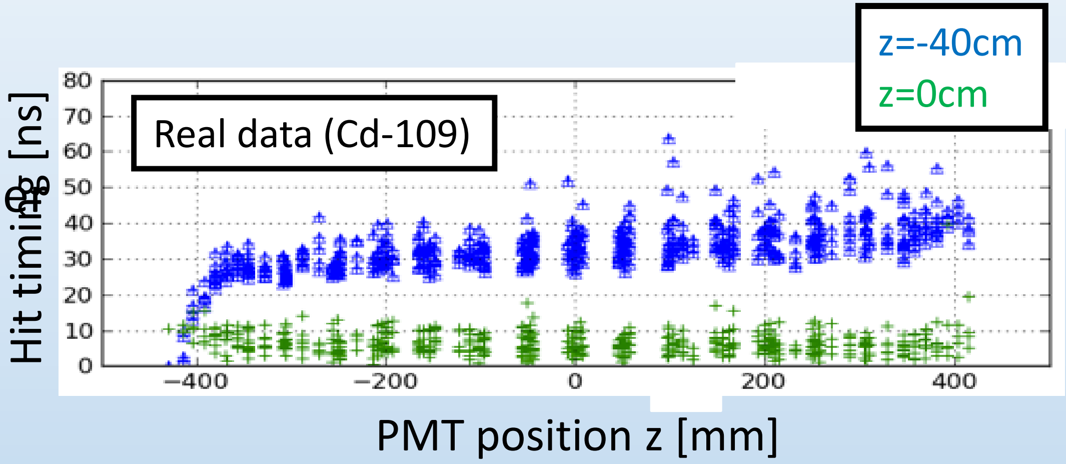
Data set and event selection (1/2)

- Data set
  - Dec 24, 2010 ~ May 10, 2012 (Total livetime of 165.9 days)
- Pre-selection
  - No outer detector trigger is associated with the event.
  - The event is separated from the nearest event by at least 10 msec.
  - RMS spread of hit timings of the event is less than 100 nsec.
  - Dead time due to pre-selection reduces the total effective livetime to 132.0 days.
- Fiducial volume cut (Radius cut)
  - Event vertex is reconstructed based on the observed light distribution in the detector.
  - Select events with the reconstructed position is within 15 cm from the center.
  - Fiducial mass of natural xenon is 41kg (It contains 39g of ^{124}Xe)

Data set and event selection (2/2)

- Timing cut
  - Hits' timing is used to reject events from the detector inner surface that are wrongly reconstructed.

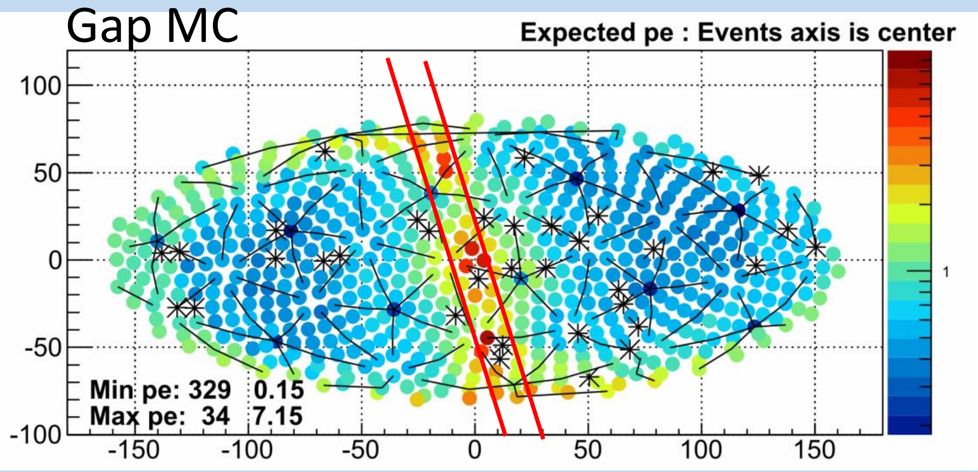
$$\delta T_m = t_{\text{mean of 2nd half of hits}} - t_{\text{1st hit}}$$



  - Events with smaller δTm are less likely to be surface BG and selected.

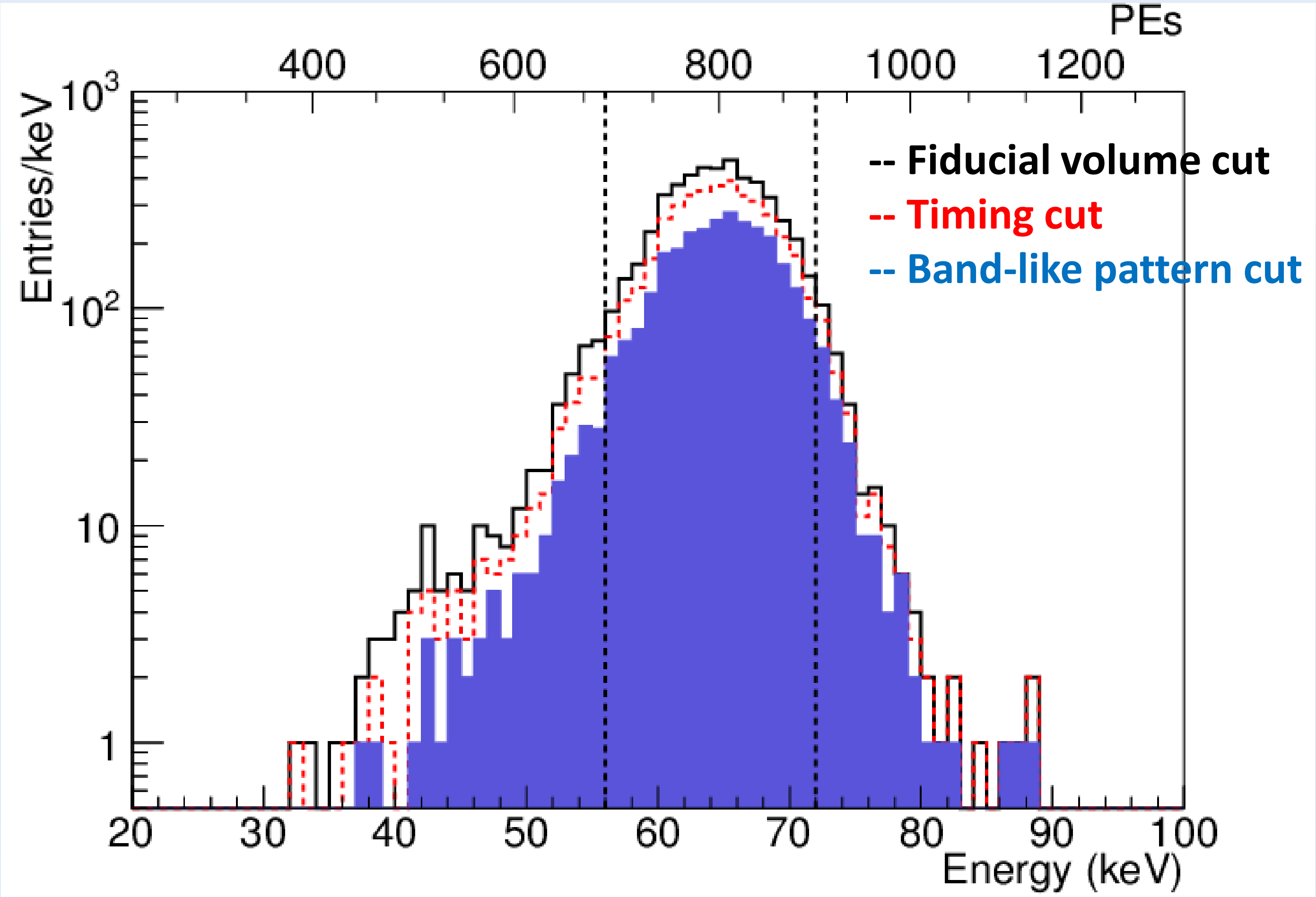
- Band-like pattern cut
  - BG events occurred in groves in the inner detector surface make band-like pattern.

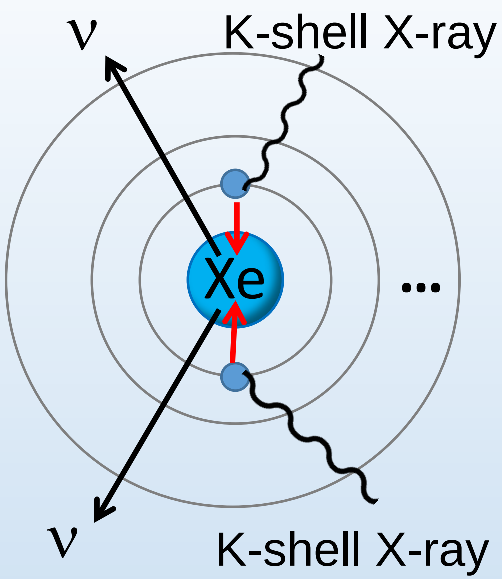
$$F_B = \frac{\text{Max. PE in a band of width 15cm}}{\text{Total PE in the event}}$$



  - Events with larger F_B are likely to be those BG and rejected.

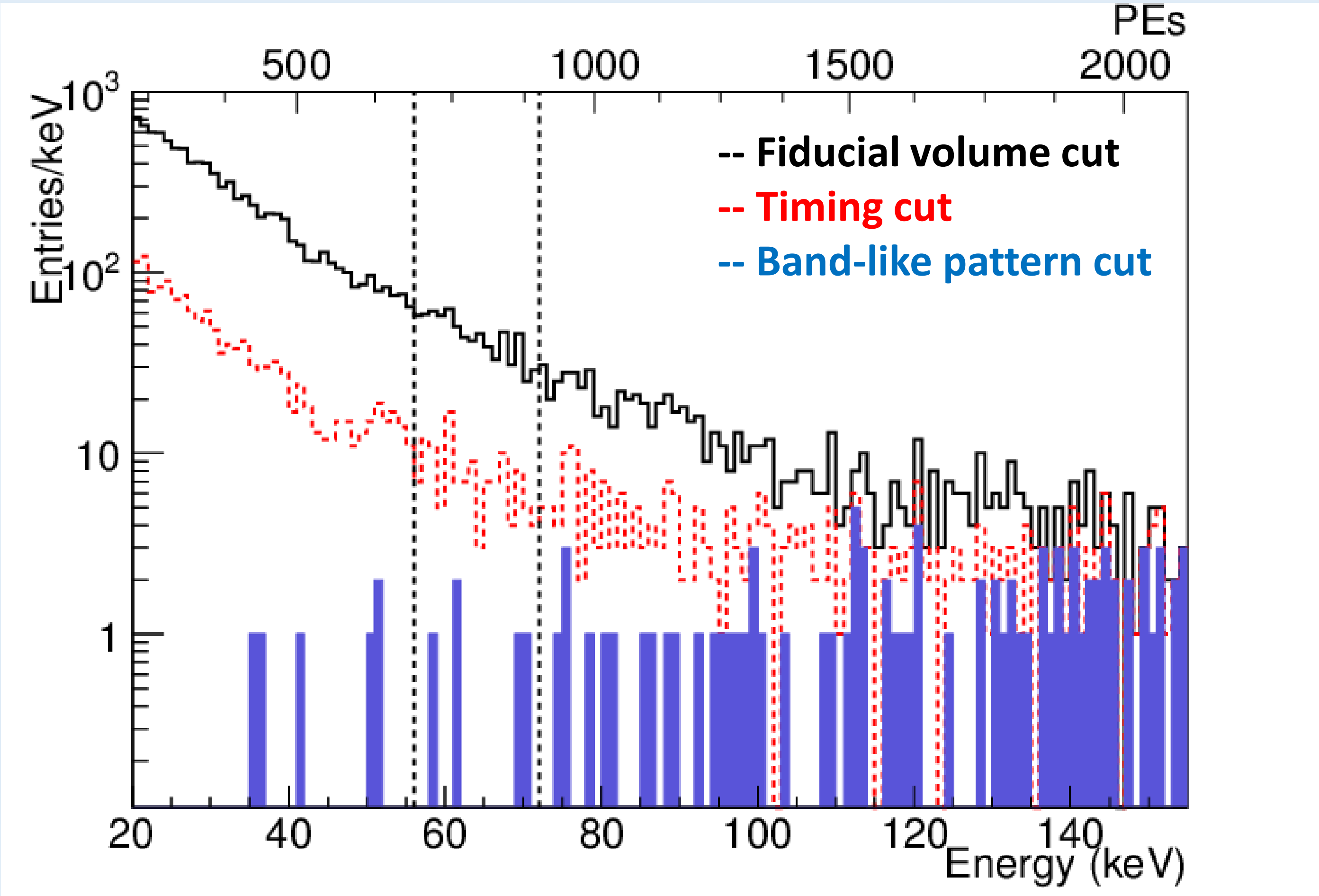
Expected ^{124}Xe 2ν 2K-capture signal





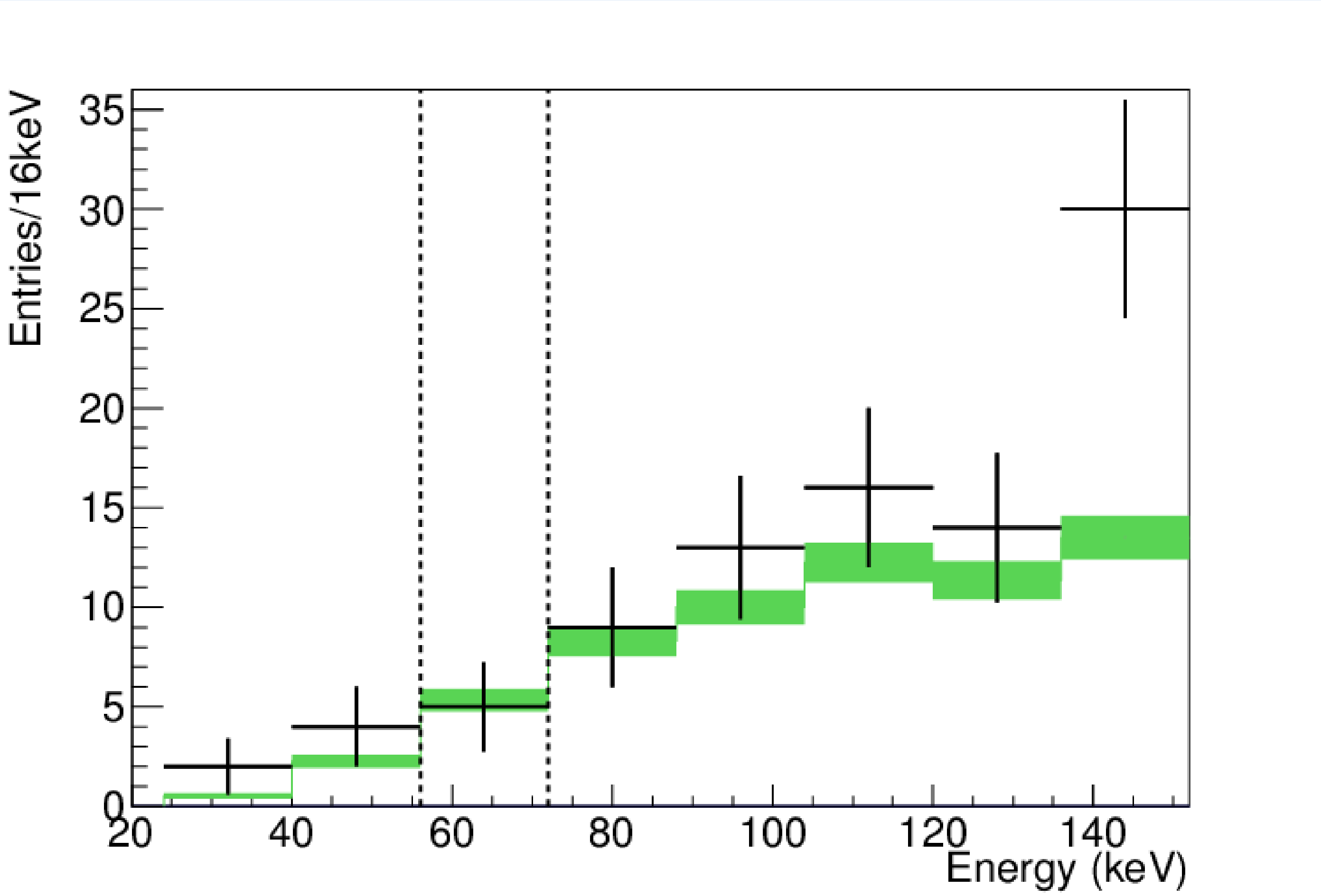
- X-rays and Auger electrons after 2ν 2K-capture are simulated.
- The energy window (56-72keV) is determined so that it contains 90% of the simulated signal.
- Efficiency for signal is 59.7%.

Observed data



- Data taken between Dec. 2010 and May 2012 (132.0 live days)
- Fiducial mass is 41kg (It contains 39g of ^{124}Xe)
- 5 events remained in the signal region

Comparison with background prediction



+ Data

-- Pb-214 background MC (w/ sys. error)

- Main background is ^{214}Pb (daughter of ^{222}Rn) in the detector.
- The amount of ^{222}Rn was estimated from the observed rate of ^{214}Bi-^{214}Po decay.
- Expected number of ^{214}Pb BG events in the signal region: 5.3+/-0.5 events
- No significant excess above background.

Systematic uncertainty in signal prediction

Item	Fractional uncertainty
Abundance of ^{124}Xe	+/-8.5%
Liquid xenon density	+/-0.5%
Energy scale	+0%, -8.6%
Energy resolution	+0%, -5.3%
Scintillation decay time	+0%, -7.1%
Radius cut (R<15cm)	+0%, -6.7%
Timing cut (T<12.54ns)	+3%, -0%
Band cut (B<0.248)	+/-5%
Total	**+10.3%, -17.2%**

- A sample was taken from our detector and its isotope composition was measured.
- Systematic uncertainty in signal efficiency was estimated from comparisons between data and MC simulation for ^{241}Am (60keV γ) calibration data at various positions.

Limit on ^{124}Xe 2ν 2K-capture half-life

- We derive a lower limit using a Bayesian method
- Conditional probability density function for the decay rate Γ

$$P(\Gamma|n_{obs}) = \iiint \frac{e^{-\mu}\mu^{n_{obs}}}{n_{obs}!} \times P(\Gamma)P(\lambda)P(\varepsilon)P(\varepsilon_{corr})P(b)d\lambda d\varepsilon d\varepsilon_{corr}db$$

where $\mu = (\Gamma\lambda\varepsilon + b)\varepsilon_{corr}$

λ: exposure
ε: signal efficiency (uncorrelated with BG)
ε_{corr}: correlated efficiency
$b\varepsilon_{corr}$: number of BG events in the signal region

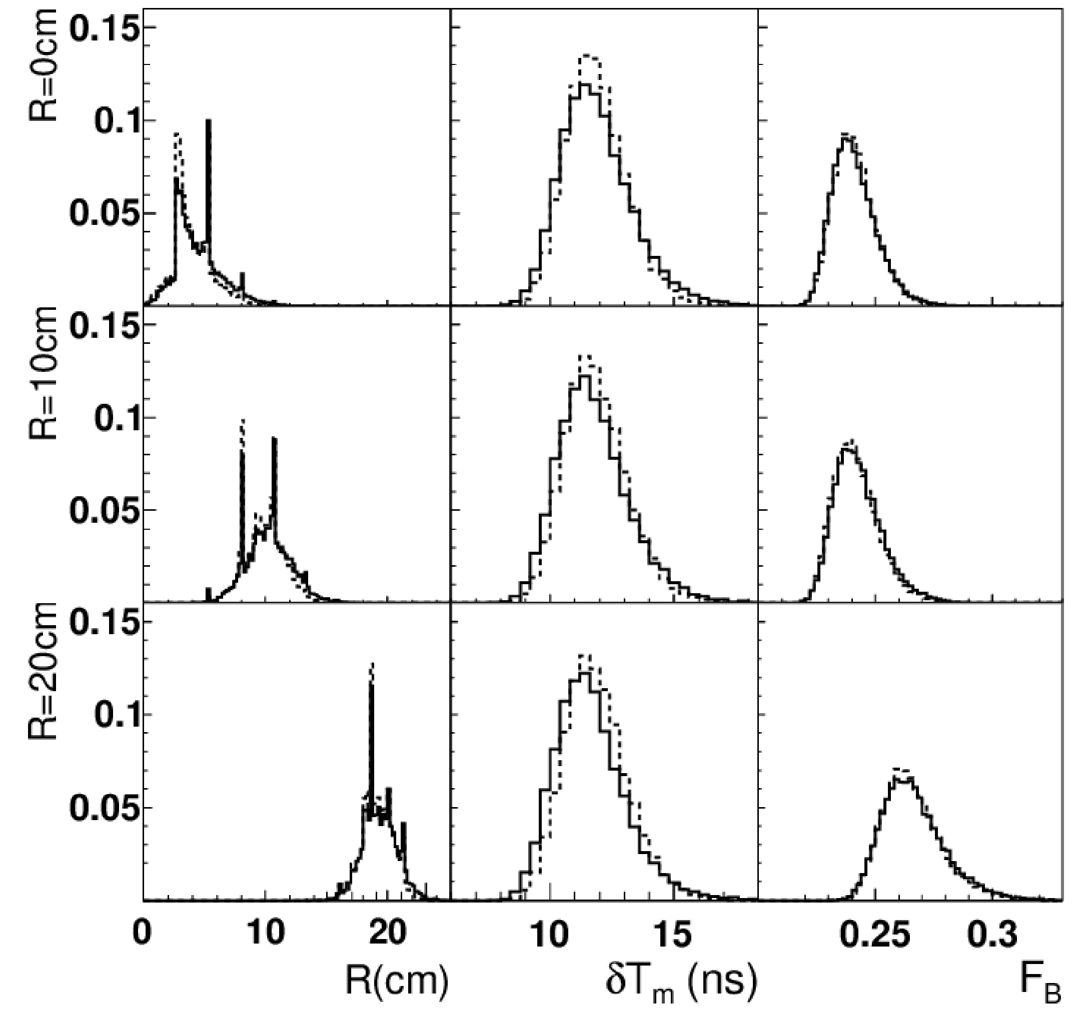
- 90% confidence level limit

$$\frac{\int_0^{\Gamma_{limit}} P(\Gamma|n_{obs})d\Gamma}{\int_0^{\infty} P(\Gamma|n_{obs})\, d\Gamma} = 0.9$$

$$T_{1/2}(2\nu 2K) > \frac{\ln 2}{\Gamma_{limit}} = 4.7 \times 10^{21} \text{ years (90\%CL)}$$

Data/MC comparison for 241Am calibration data

Reconstructed radial position | Timing parameter | Band pattern parameter



(Solid) Data
(Dashed) MC

Theoretical calculation for ^{124}Xe 2ν ECEC

Model	$T_{1/2}$ (2νECEC) (yr)	Reference
QRPA	(0.4-8.8)x10^{21}	Suhonen (2013)
QRPA	(2.9-7.3)x10^{21}	Hirsch et al. (1994)
$SU(4)_{\sigma\tau}$	(7-17.7)x10^{21}	Rumyantsev et al. (1998)
PHFB	(7.1-18.0)x10^{21}	Singh et al. (2007)
PHFB	(61.4-155.1)x10^{21}	Shukla et al. (2007)
MCM	(390-986.1)x10^{21}	Aunola et al. (1996)

Experimental results on ^{124}Xe 2nECEC

Experiment	$T_{1/2}$ (10^{21} yr)	^{124}Xe mass	Livetime	Reference
Abe et al. (XMASS)	>4.7	39 g	132 days	This work
Gavrilyuk et al.	>2.0	59 g	134 days	arXiv:1507.04520
Mei et al.	>1.66	34 g	225 days	Phys. Rev. C89 (2014) 014608
Aprile et al. (XENON100)	>0.65	29 g	225 days	arXiv:1609.03354

Contributions from right-handed current

$$H_{eff} = \frac{G_F}{\sqrt{2}}\left(J_L J_L^\dagger + \eta J_R J_L^\dagger + \lambda J_R J_R^\dagger\right) + h.c.$$

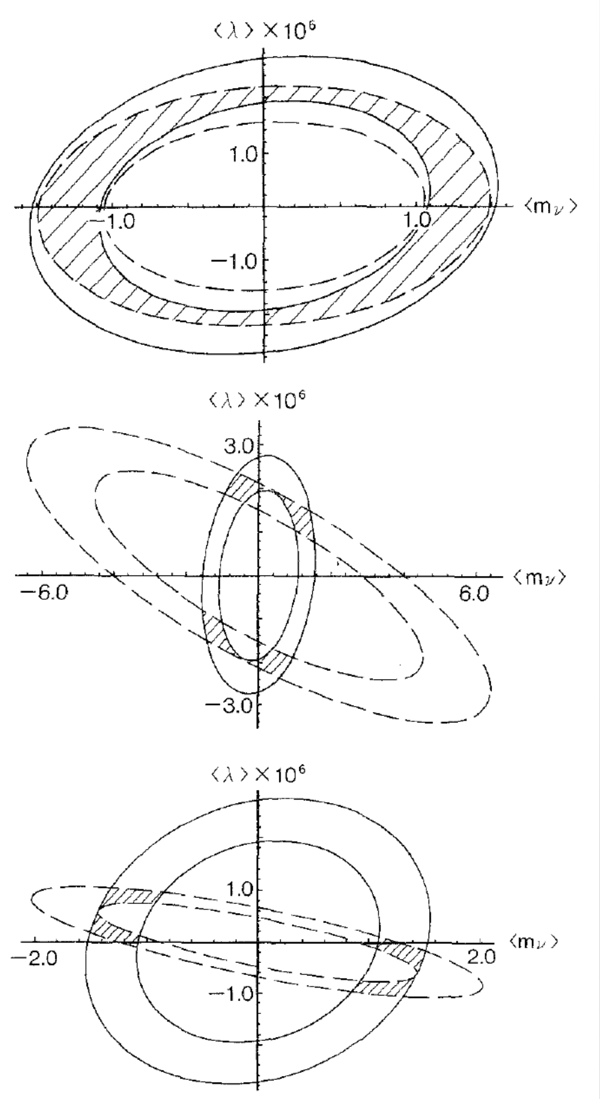
$$T_{1/2}^{-1} = C_{mm}\left(\frac{\langle m_\nu\rangle}{m_e}\right)^2 + C_{\eta\eta}\langle\eta\rangle^2 + C_{\lambda\lambda}\langle\lambda\rangle^2$$
$$+C_{m\eta}\frac{\langle m_\nu\rangle}{m_e}\langle\eta\rangle + C_{m\lambda}\frac{\langle m_\nu\rangle}{m_e}\langle\lambda\rangle + C_{\eta\lambda}\langle\eta\rangle\langle\lambda\rangle$$

$$\langle\eta\rangle = \sum \eta U_{ej}V_{ej} \quad , \langle\lambda\rangle = \sum \lambda U_{ej}V_{ej}$$

(a)
^{76}Ge: $T_{1/2}$=(1.5+/-0.5)x10^{24} yr (solid)
^{136}Xe: $T_{1/2}$=(1.5+/-0.5)x10^{24} yr (dash)

(b)
^{76}Ge: $T_{1/2}$=(1.5+/-0.5)x10^{24} yr (solid)
^{124}Xe: $T_{1/2}$=(1.5+/-0.5)x10^{25} yr (dash)

(c)
^{76}Ge: $T_{1/2}$=(1.5+/-0.5)x10^{24} yr (solid)
^{124}Xe: $T_{1/2}$=(1.5+/-0.5)x10^{26} yr (dash)

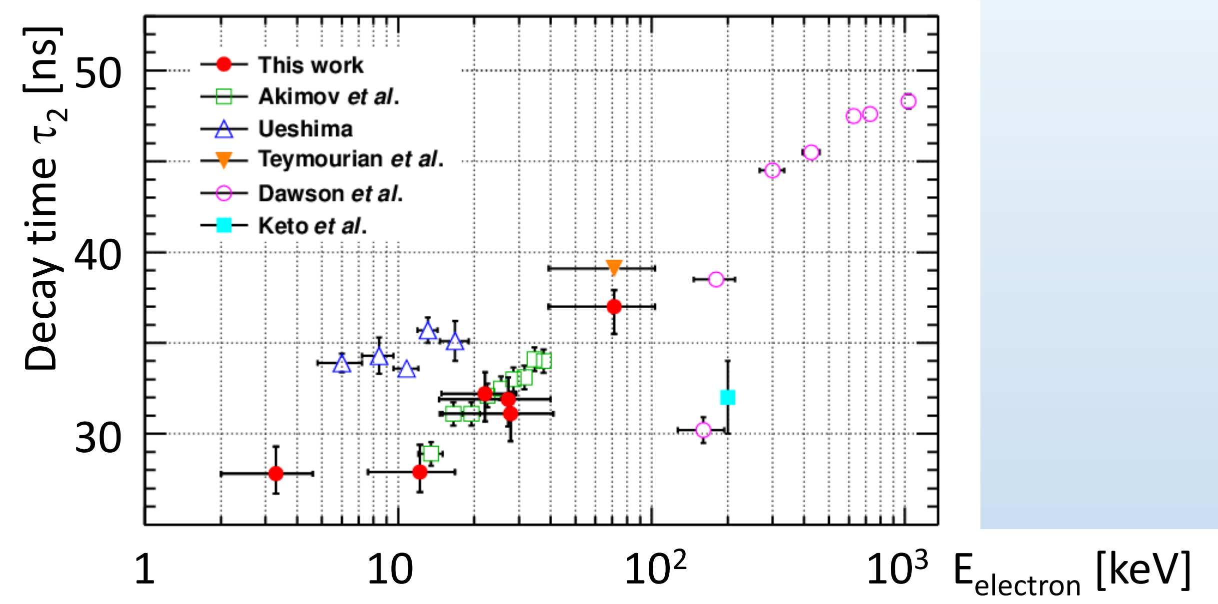


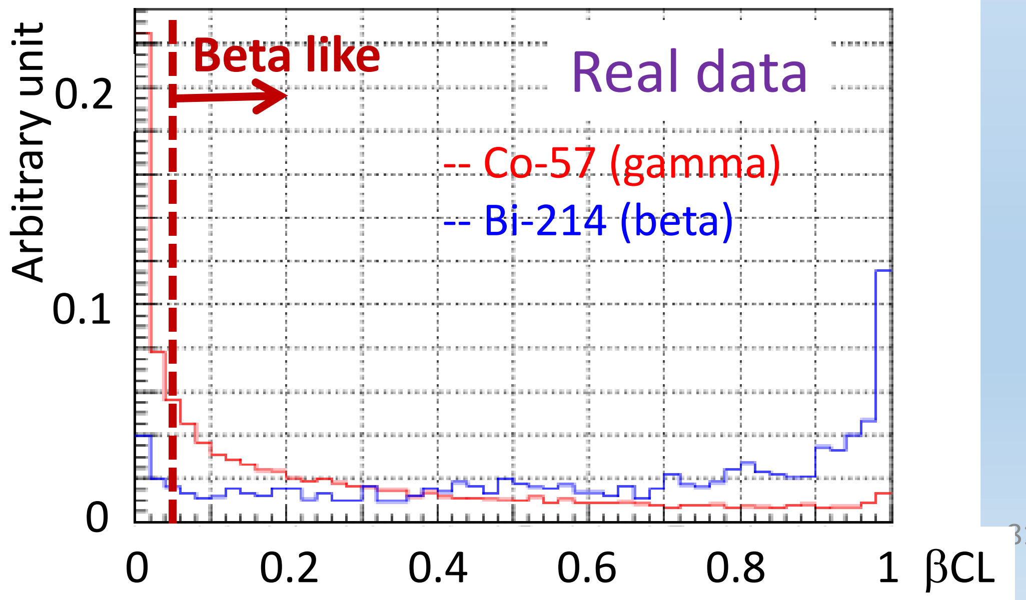
M. Hirsch et al., Z. Phys. A347 (1994) 151

Discrimination of γ/X-rays from β-rays using scintillation time profile

- Scintillation time profile depends on electron energy.
- In the case of γ/X-rays, they are converted to low energy electrons in the detector
  - e.g.) 122 keV γ → 87.5 keV photoelectron + ~25 keV Auger electron + …
- Compared with β-rays with the same energy deposit, γ/X-ray events tend to have faster time profile.
- A discriminant variable βCL is constructed from timings of each hit in an event.
  → This can be used to suppress β-ray background !!

$$\beta\text{CL} = P \times \sum_{i=0}^{n-1} \frac{(-\ln P)^i}{i!} \qquad P = \prod_{i=1}^{n} CL_i$$





Future prospects of double electron capture search

- We have already accumulated more than 3 years of data after refurbishment.
- Assuming 100 kg fiducial mass (95g ^{124}Xe) and BG level of 10^{-4} event/day/kg/keV, the 90%CL sensitivity will reach $T_{1/2}$ = (2-3)x10^{22} years.
- Will search for 0νECEC and $0\nu\beta^{+}$EC as well