Direct dark matter search with XMASS

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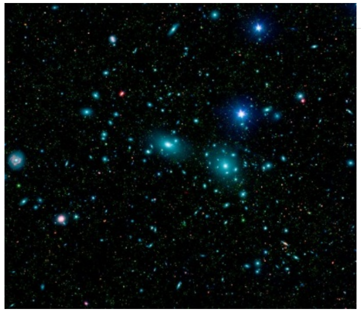
KMI seminar
2015/7/1

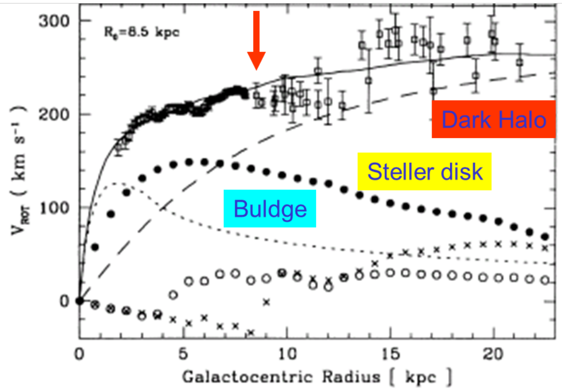
Scientific importance of dark matter search

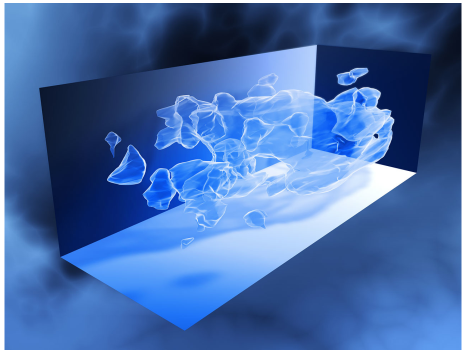
- Understanding the nature of dark matter is one of the most important issues in the particle astrophysics.
- Strong evidences on dark matter
  - Cluster of galaxies, rotation curve of galaxies, lensing effect, large scale structure, cosmic microwave background, etc.

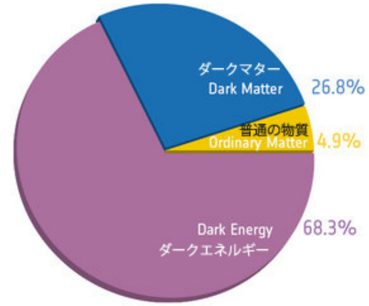
Identification of dark matter must be a breakthrough in understanding the universe filled with “unknowns”.

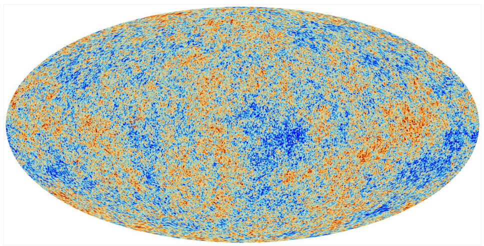


R.P.Olling and M.R.Merrifield MNRAS 311, 369- (2000)



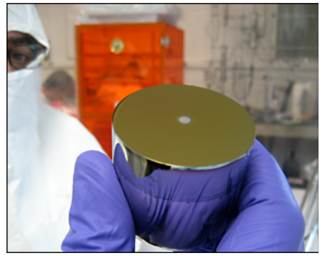




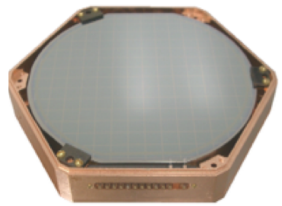


Positive evidences from direct dark matter experiments?

- Some experimental groups showed data consistent with detection of dark matter over the recent 10-20yrs.
  - DAMA/NaI, DAMA/LIBRA: annual modulation consistent with a dark matter signal was observed → New data being taken.



  - CoGeNT: a special Ge detector sensitive to low energy gave an energy spectrum which cannot explained by background. An indication of modulation also observed. → Surface background may be underestimated. Statistical significance of modulation weakened.

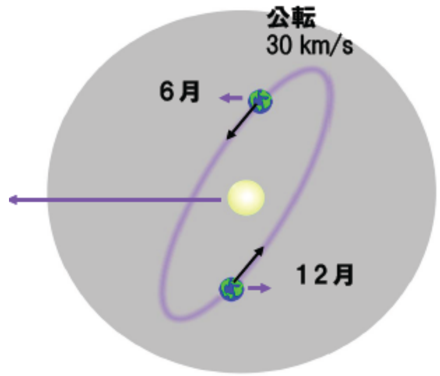


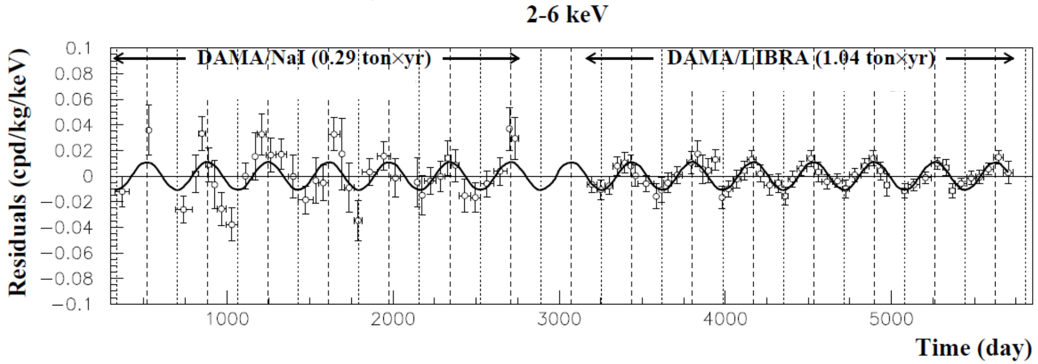
  - CDMS-Si: Event excess at low energy observed. → Excluded by low energy CDMS-Ge data.

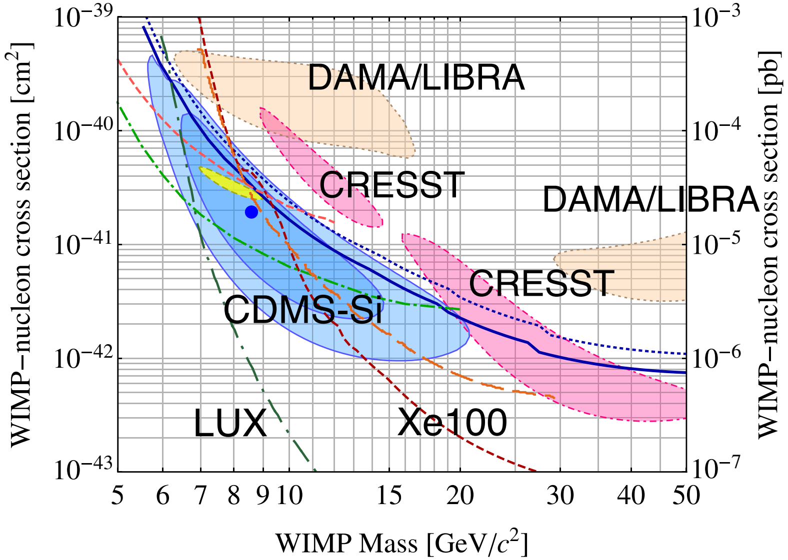
  - CRESST-II: Event excess at low energy observed → After an improvement in handling surface background no excess observed.

DAMA signal consistent with DM

- Dark matter "wind" changes over the sidereal yr
  - The galaxy is the rest frame of the dark matter.
  - The Sun is moving in the galaxy.
  - The Earth is rotating around the Sun.
- This causes an event rate modulation.
- DAMA observations consistent with the expectation including its phase.
- However, the cross section implied by this signal is inconsistent with other exp. if we assume standard halo/interaction model.







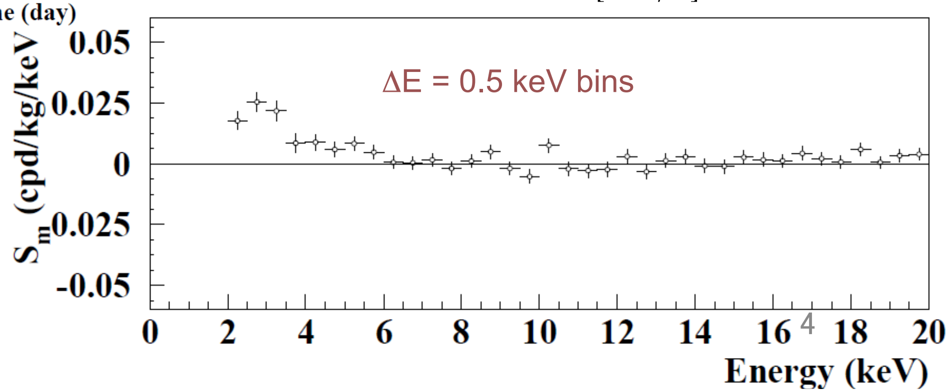
2-6 keV

A=(0.0110±0.0012) cpd/kg/keV

χ^2/dof = 70.4/86 **9.2 σ C.L.**

Absence of modulation? No

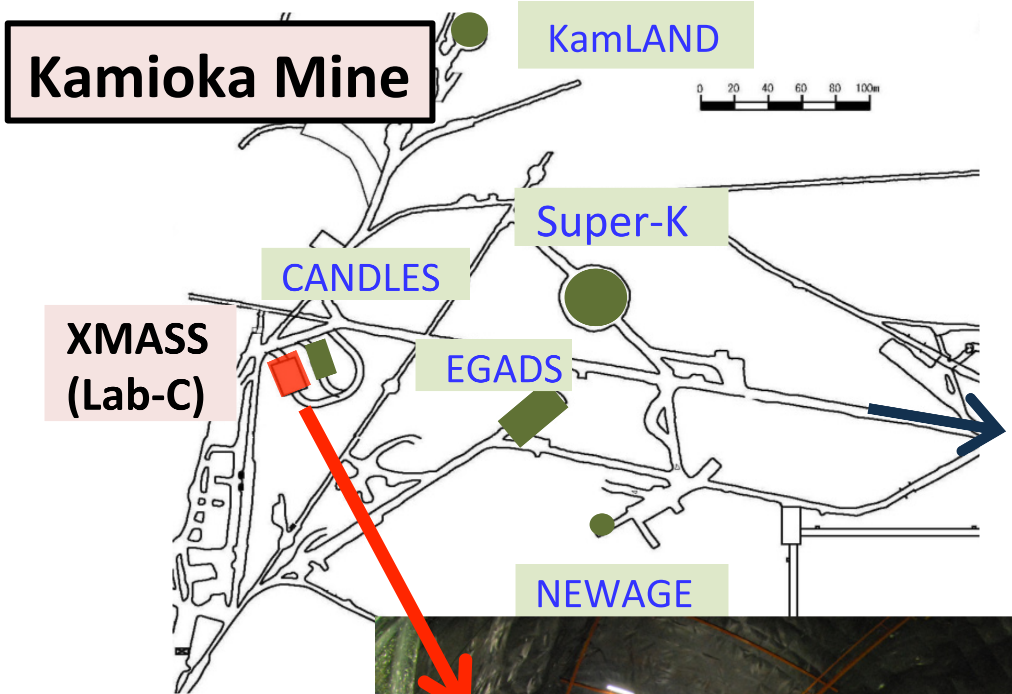
χ^2/dof=154/87 ⇒ P(A=0) = 1.3×10^{-5}



The XMASS collaboration:

- *Institute for Cosmic Ray Research, the University of Tokyo*
- *Kavli Institute for the Physics and Mathematics of the Universe, the University of Tokyo*
- *Kobe University*
- *Tokai University*
- *Gifu University*
- *Yokohama National University*
- *Miyagi Educational University*
- *STE lab., Nagoya University*
- *Tokushima University*
- *Center for Underground Physics, Institute for Basic Science*
- *KRISS*

Site



Kamioka mine
Lab-C

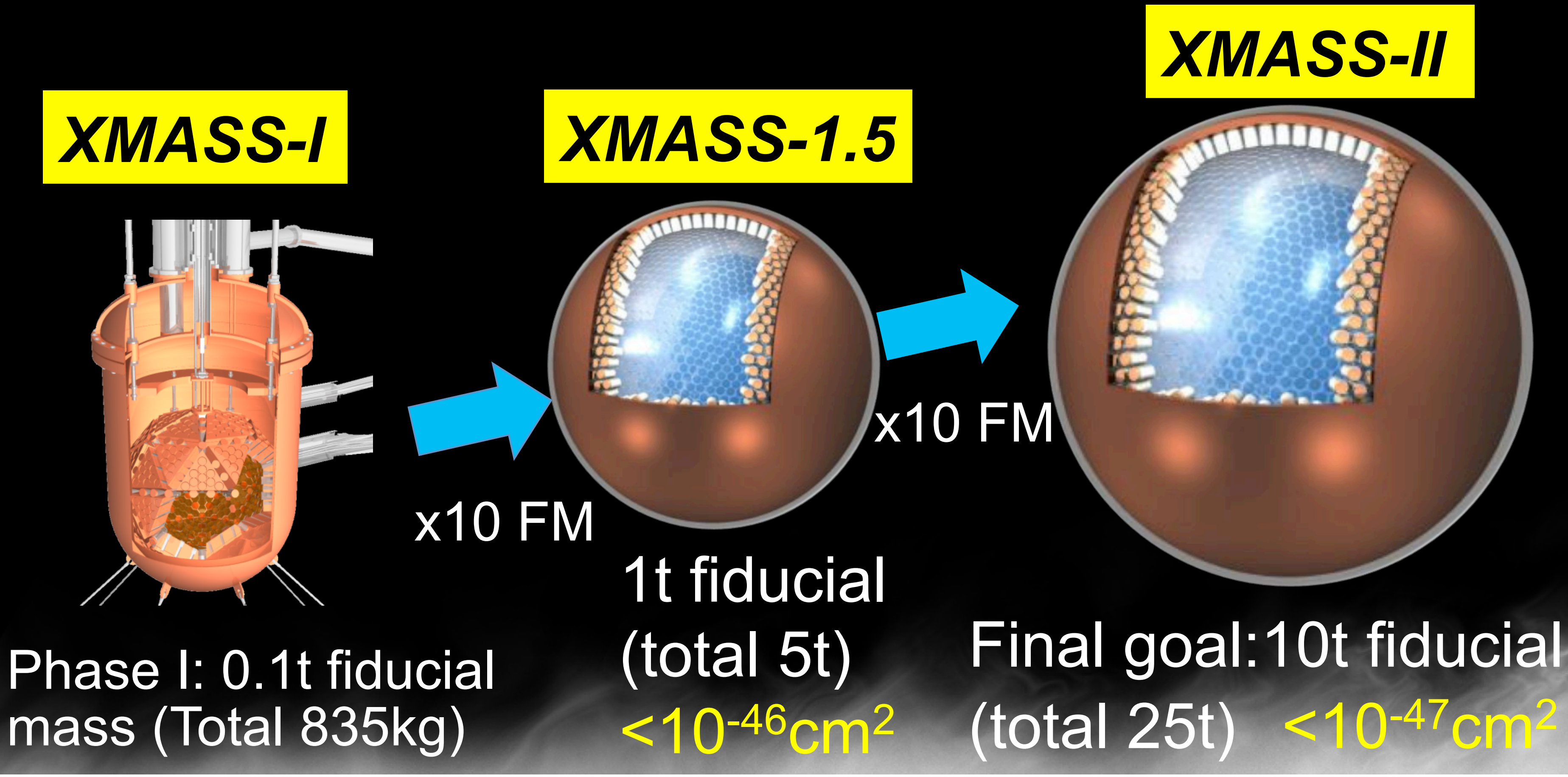
~1000m underneath
Mt. Ikenoyama.
(2700 m.w.e.)

XMASS project

Y. Suzuki, hep-ph/0008296

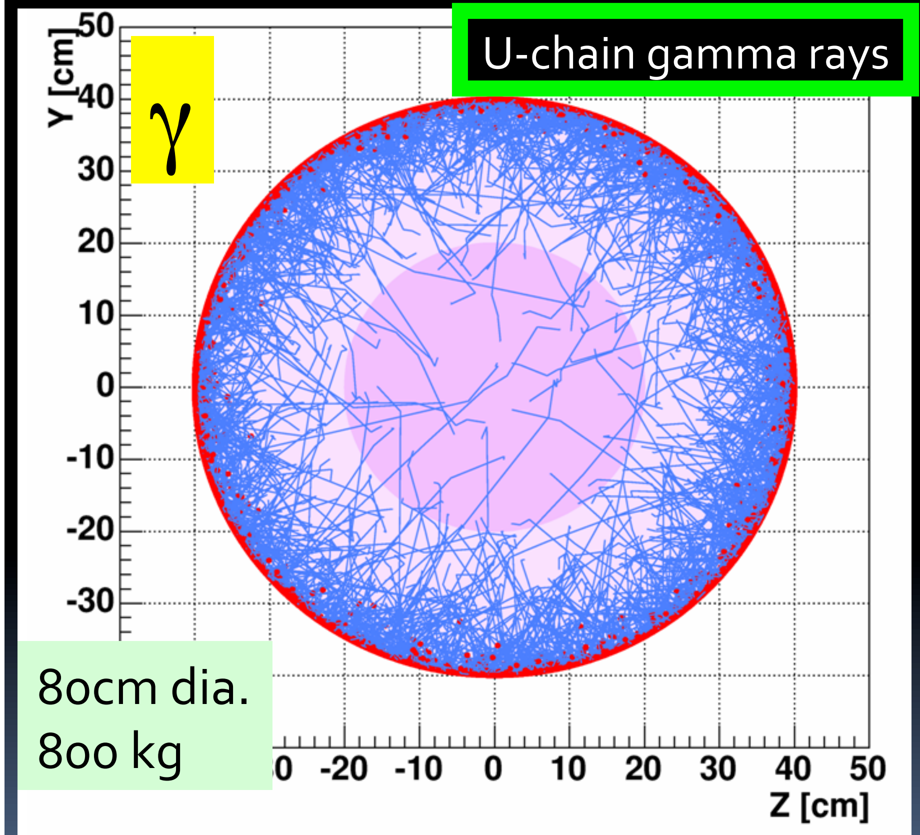
Multi purpose low-background experiment with liq. Xe

- **X**enon **MASS**ive detector for solar neutrino (**pp/^{7}Be**)
- **X**enon neutrino **MASS** detector (**ββ decay**)
- **X**enon detector for Weakly Interacting **MASS**ive Particles (**DM search**)

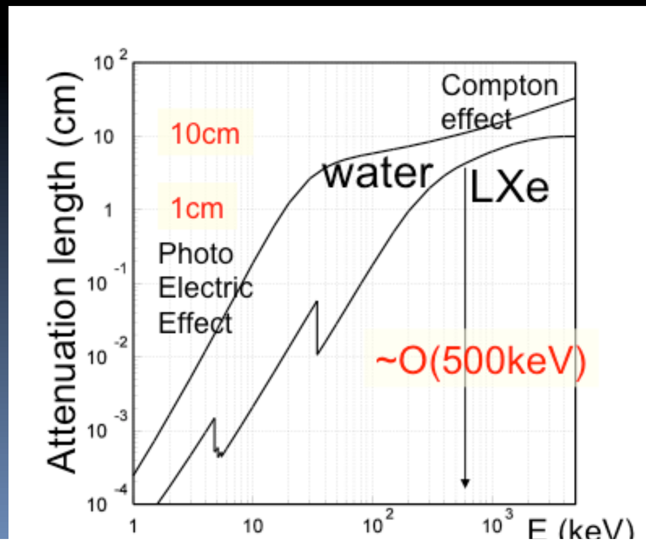


Large scale && low background

- Self shielding with Xe (large atomoic number)
- Large scintillation ~NaI(Tl), -100C, high density (3g/cm³)



- Large size is advantageous for suppressing external radiation.
- Low BG can be achieved by selecting central events.

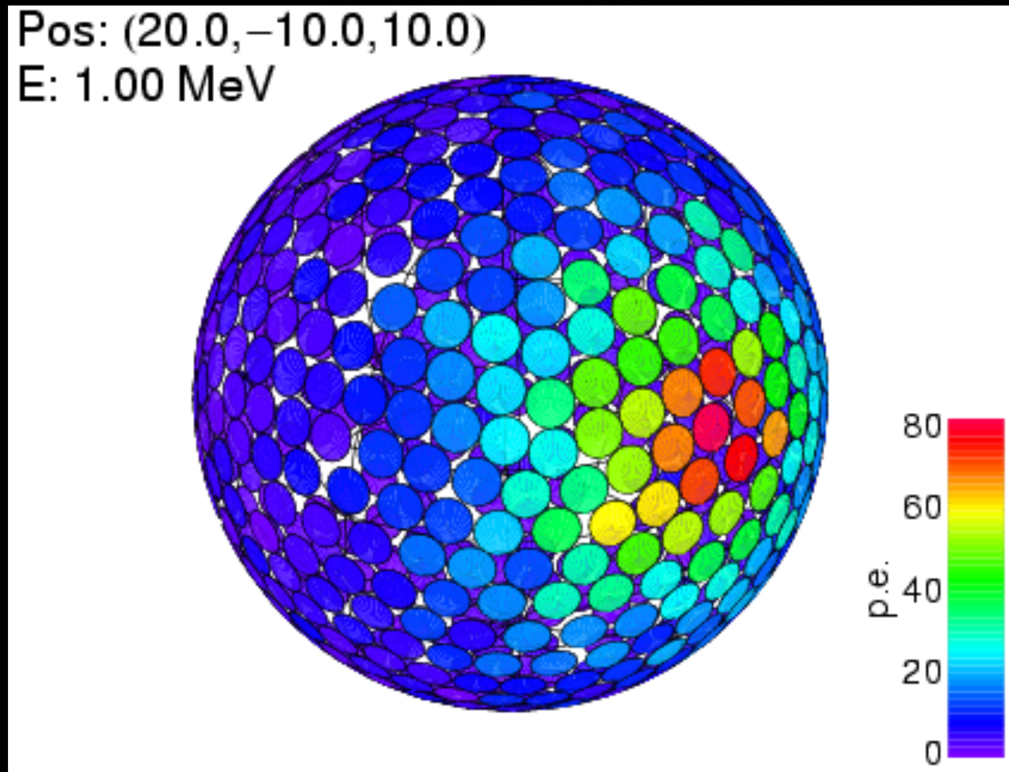


Event reconstruction

Interaction vertices can be reconstructed based on observed p.e. pattern.

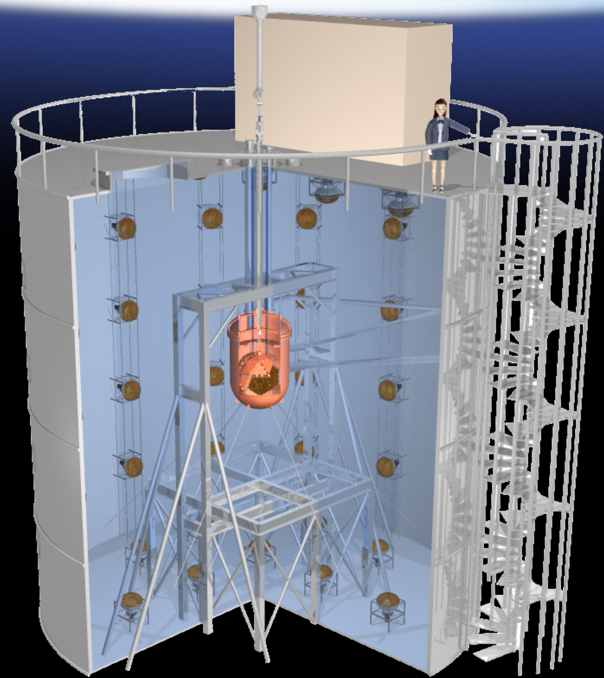
$$L(\mathbf{x}) = \prod_{i=1}^{642} p_i(n_i)$$

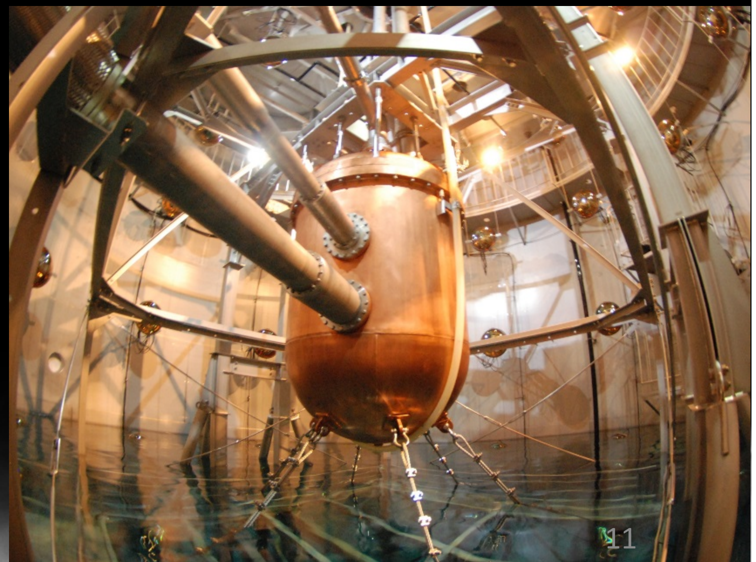
pi(ni) shows a probability for i-th PMT to have an observed number of photo electrons ni from assumed vertex. We maximize L(x).



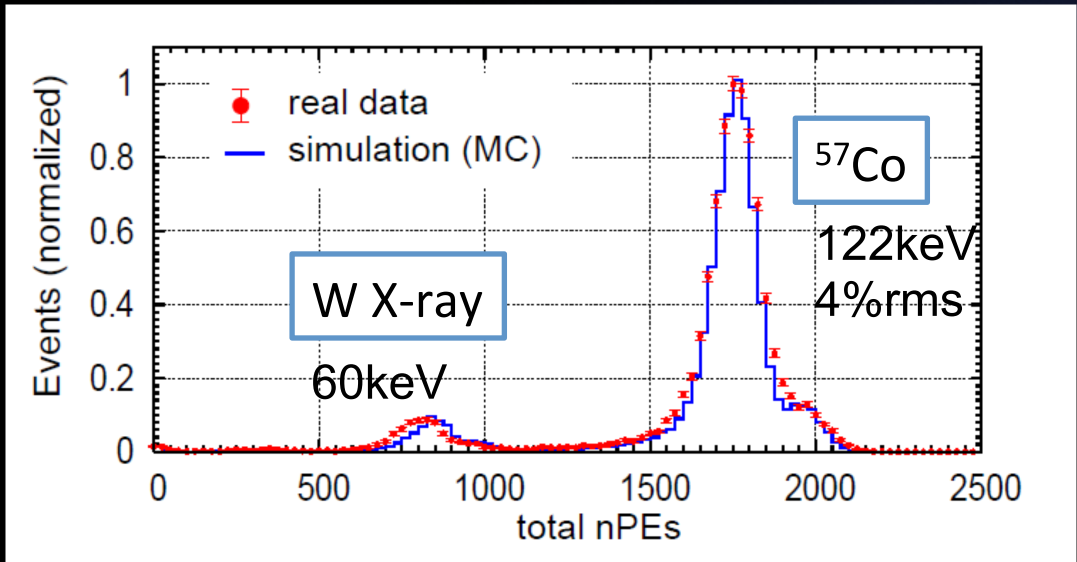
XMASS-I detector

XMASS-I detector construction ~2010



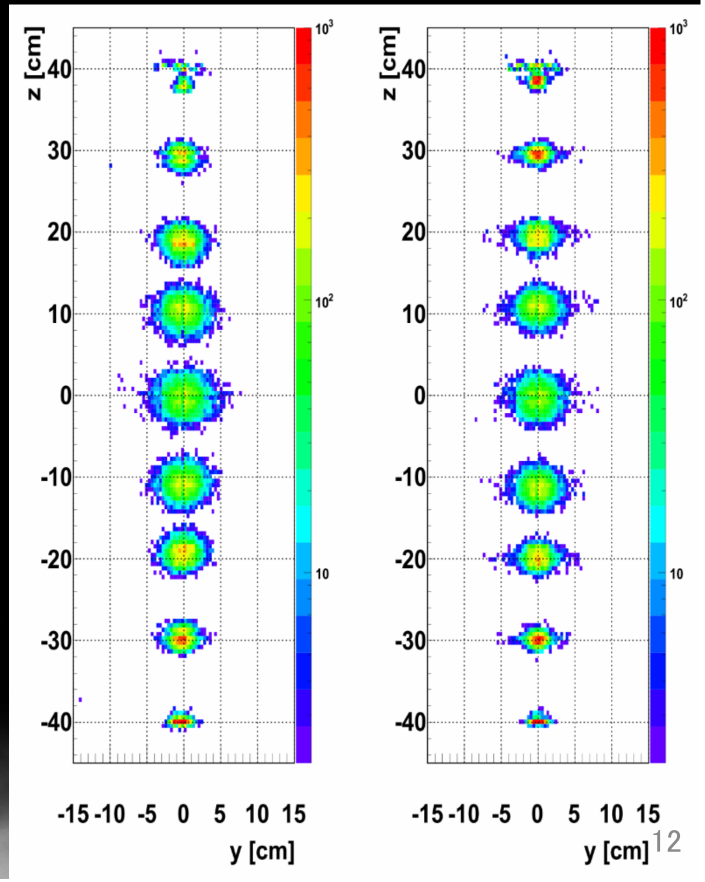


Detector performance



Reconstructed Position distribution

Real Data Simulation



- The detector has high photo-electron yield ~14.7p.e./keV Largest among DM detectors.
- Vertex recon. by pattern of p.e.
- Detailed description of the detector: NIMA 716 (2013) 78

Results from XMASS-I

Physics results of XMASS-I

Published results (low threshold & low BG, no reconst.)

- Light WIMP search, Phys. Lett. B 719 (2013) 78
- Solar axion search, Phys. Lett. B 724 (2013) 46
- Inelastic scattering on ^{129}Xe, PTEP 2014, 063C01
- Bosonic Super-WIMPs, Phys. Rev. Lett., 113, 121301 (2014): Chosen as Editors' Suggestion

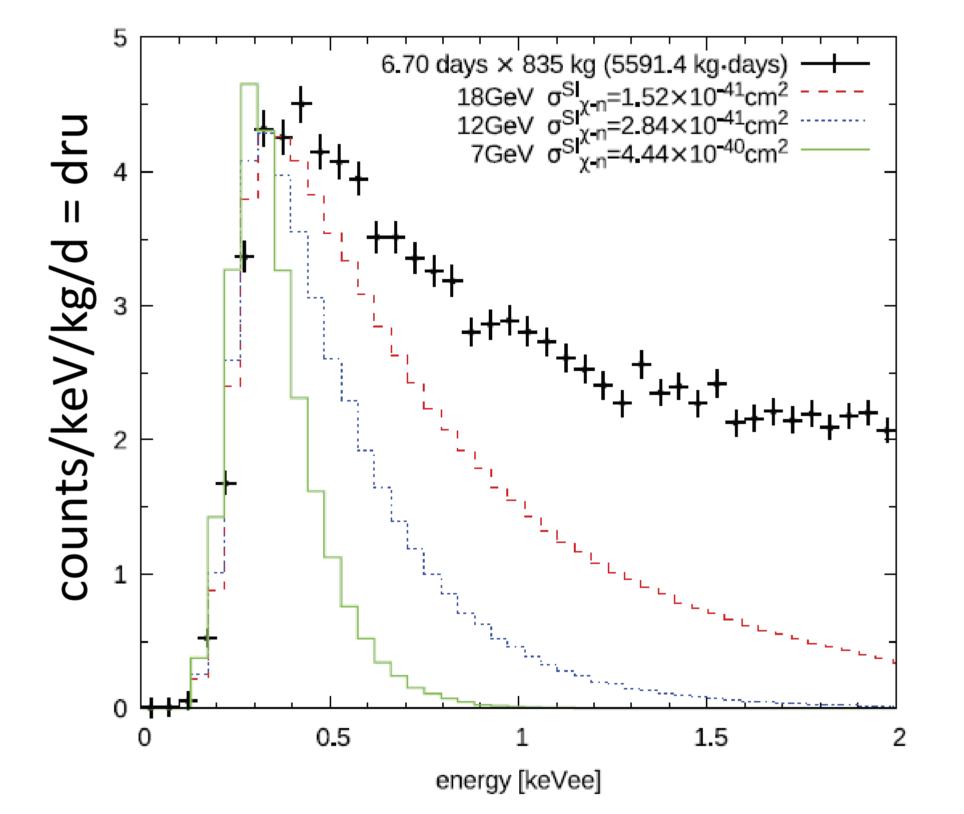
Results coming soon

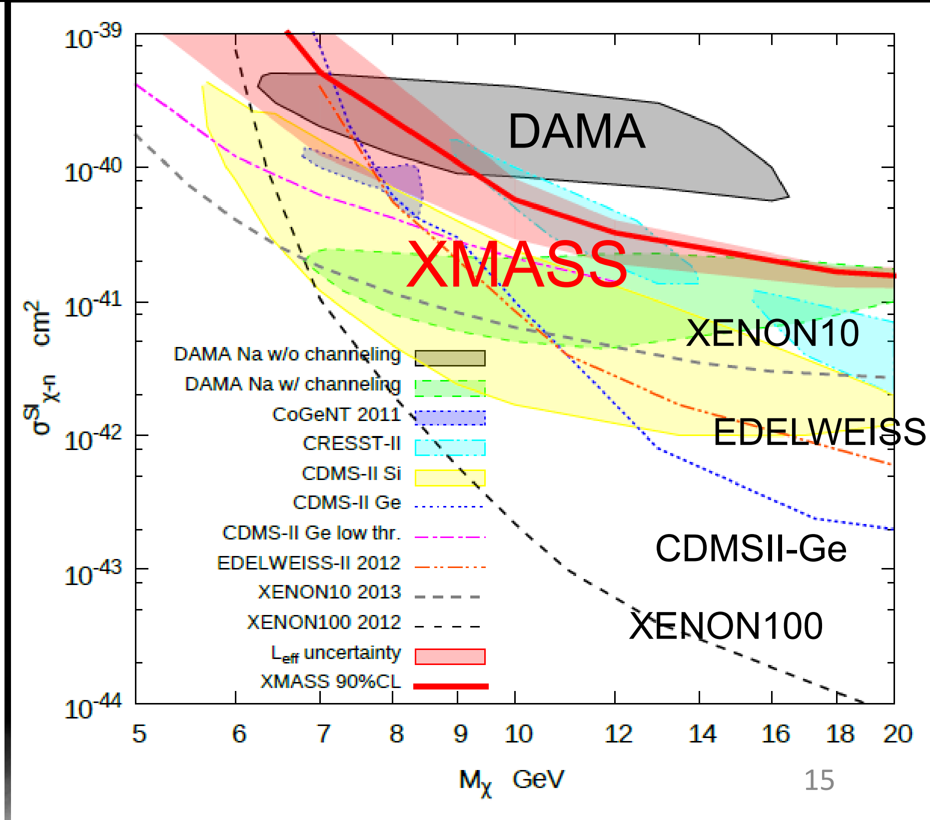
- Seasonal modulation with 832kg LXe
- Fiducial volume cut analysis (heavy WIMPs)
- Double electron capture of ^{124}Xe

Phys. Lett. B 719 (2013) 78

Light WIMP search

- All volume (835kg of LXe w/o fiducialization), >=4hits.
- Large p.e. yield, 14.7p.e./keV, thre. confirmed by LED's data ➔ low Energy threshold 300eVee was achieved.
- Simple cut to remove Cherenkov events was used.

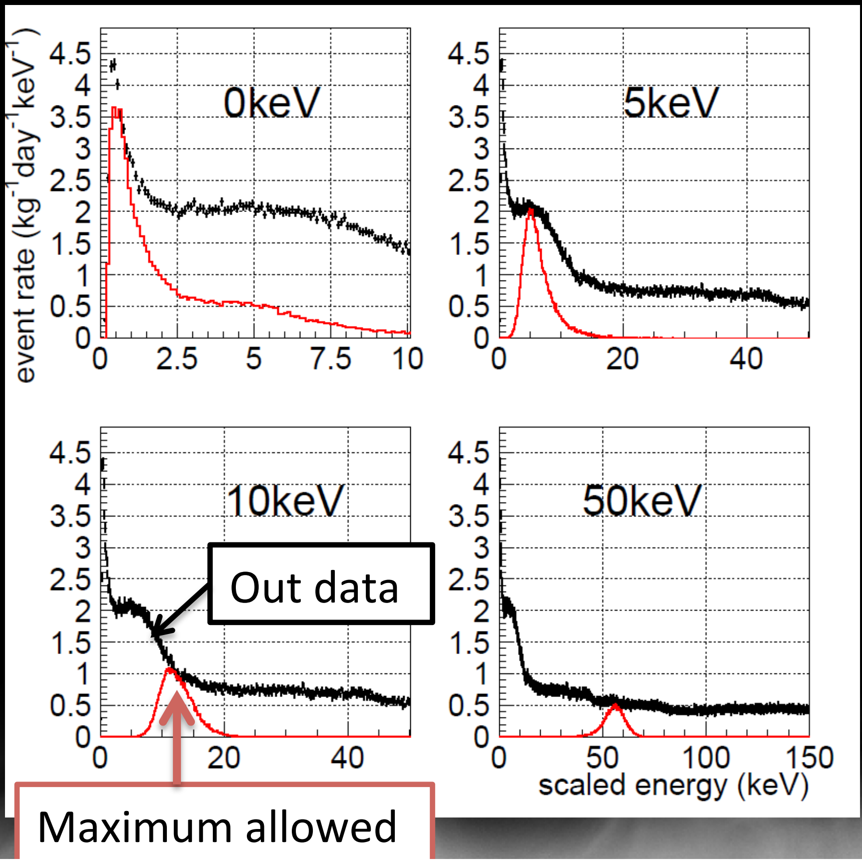


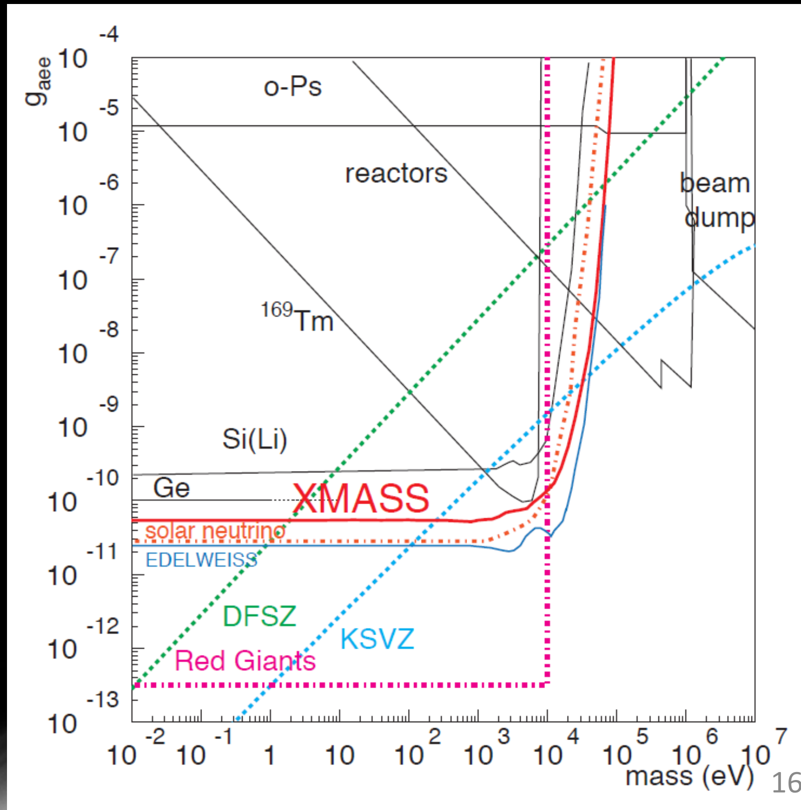


Phys. Lett. B 724 (2013) 46

Solar axion search

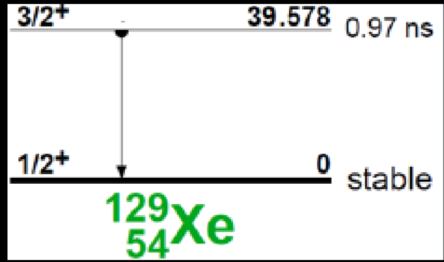
- Same data set as the light WIMPs search
- Generated in the Sun by bremsstrahlung and Compton effect, observed by the axio-electric effect in XMASS.
- Strong experimental constraint <40keV on a-e-e coupling.

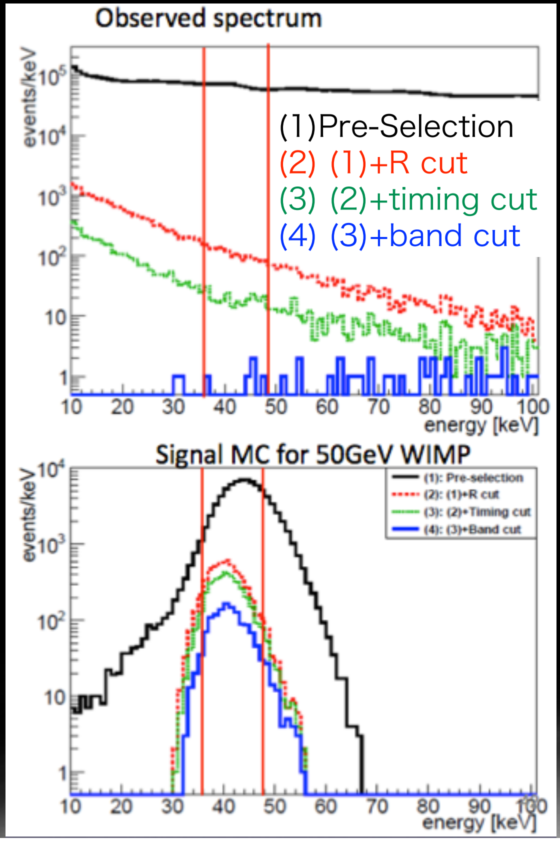


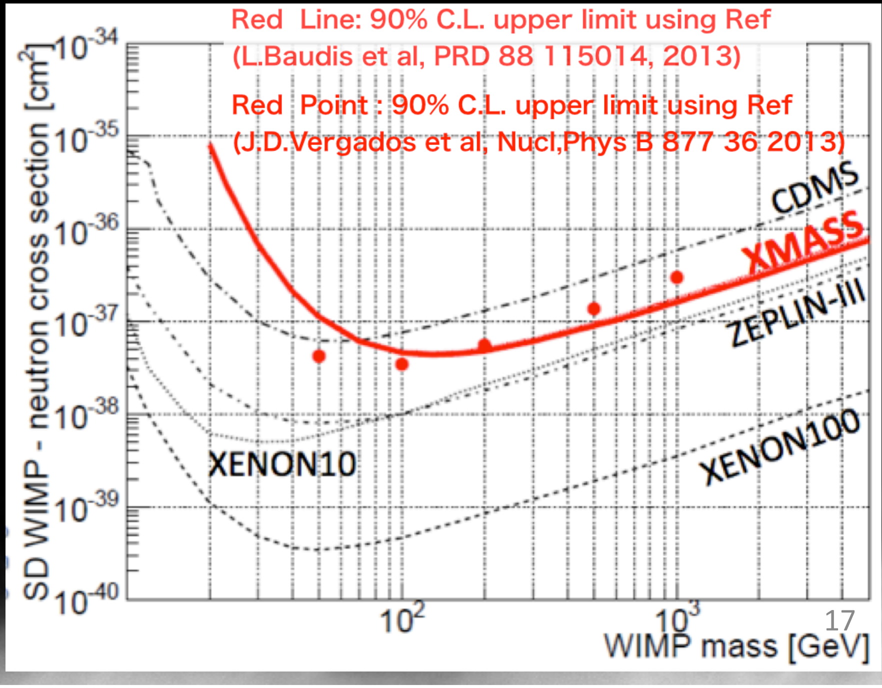


Inelastic scattering

- WIMPs would cause inelastic scattering on ^{129}Xe. Nuclear recoil as well as 40keV γ ray emission are expected. Peak search @40keV.Various cuts are used (reconstructed radius cut, timing cut, and pattern cut "band cut")
- Another way to study on spin dep. int.







Search for bosonic super-WIMPs

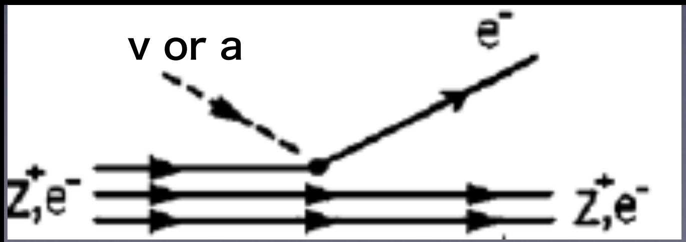
- Motivation
  - No exp. evidence of standard WIMPs even from LHC.
  - Simple CDM predicts richer structure on galaxy scale.
  - Properties of DM totally unknown.

  → Strong motivation to search for DM particles other than standard WIMPs!

- Expected properties
  - Lighter than WIMPs → Lukewarm dark matter
  - Weaker interactions → Still visible signal in detectors.
  - Bosonic particles allow to deposit the rest mass energy to an electron → A peak in the energy spectrum!

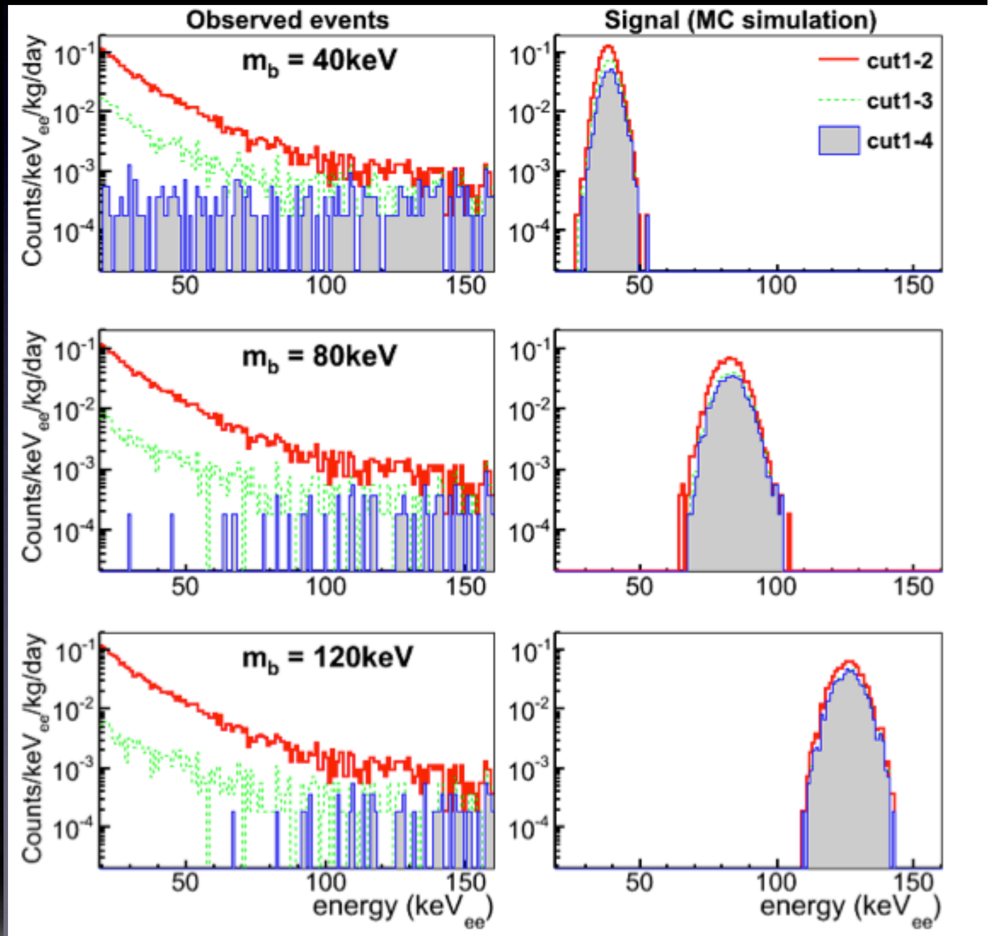
Bosonic super-WIMPs

- Expected signal: a peak in the energy spectrum at the rest mass of the particle (+small kinetic energy) M. Pospelov et al., PRD 78, 115012 (2008)



- 166days, 41kg fiducial mass. Cuts optimized to see each Super-WIMP mass.

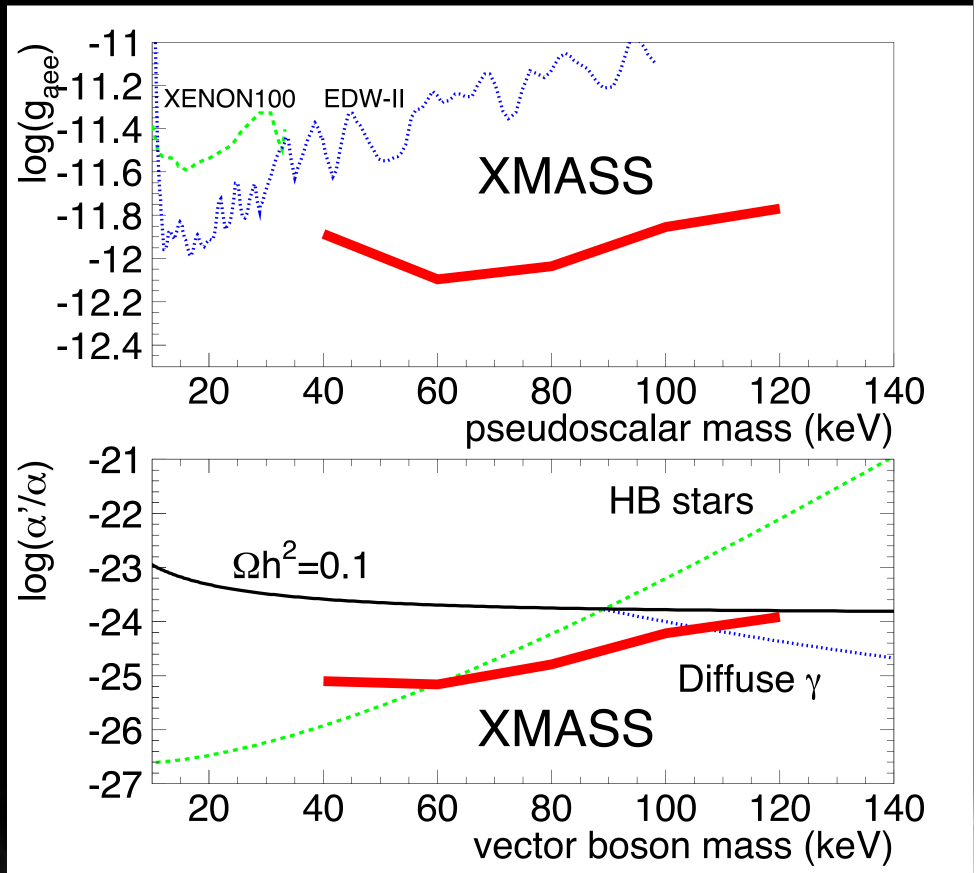
(1) reconstructed R<15cm
(2) (1) & rejection of surface BG using timing
(3) (1) & rejection of surface BG using pattern



Bosonic super-WIMPs

- This is the first direct test in the mass range 40-120keV and most strict constraint so far.
- For vector bosons, this excludes the possibility that the vector bosons constitute all the DM.
- Published in PRL 113, 121301 (2014) as Editors' Suggestion.

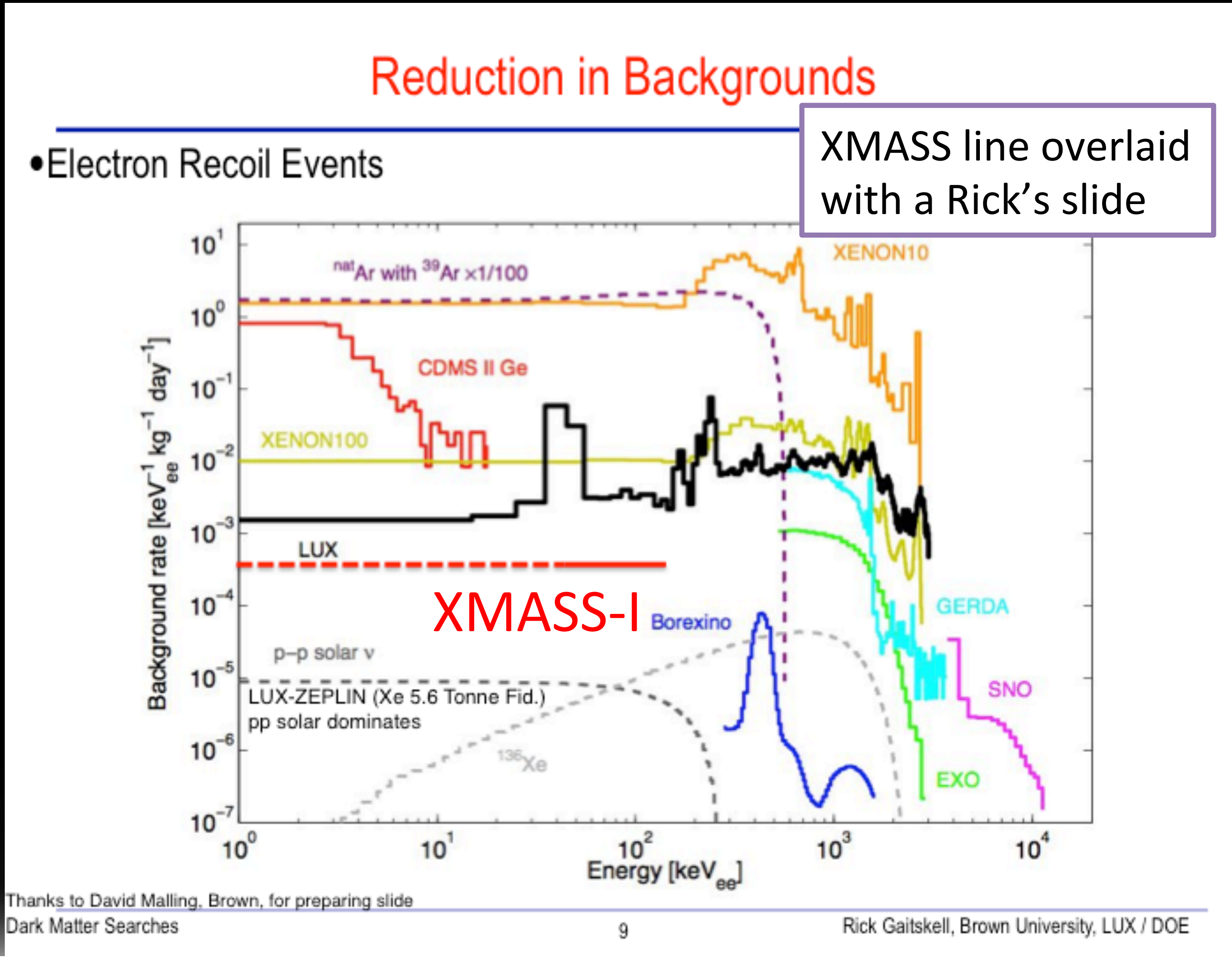
constraints on the coupling constants for electrons and super-WIMPs



Bosonic super-WIMPs

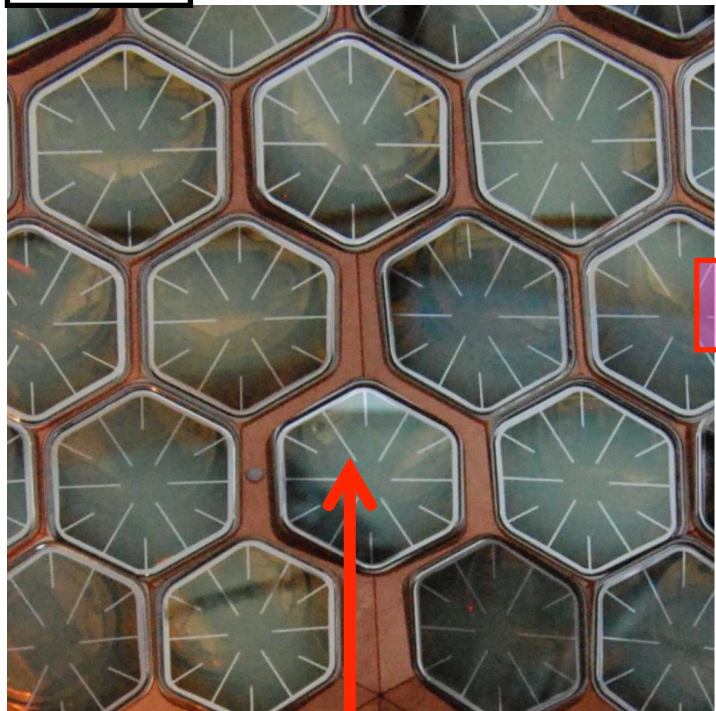
- More importantly, BG level is ~10^{-4}/kg/keV/day which is the world best background without particle identification.
- Remaining events are consistent with int. BG ^{214}Pb (^{222}Rn).

Demonstrait the advantage of XMASS!

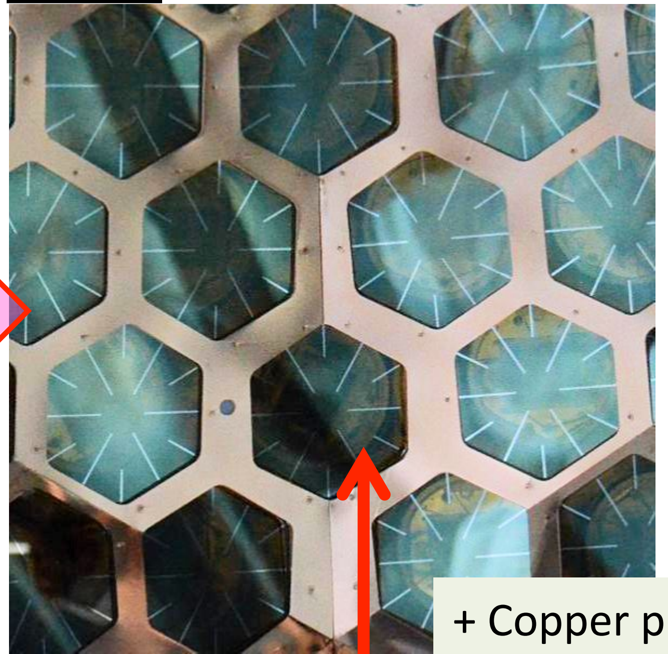


XMASS Refurbishment

Before

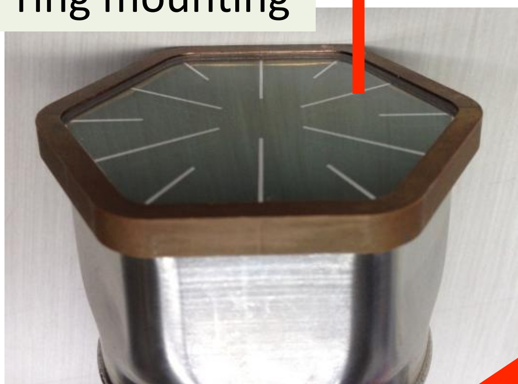


After



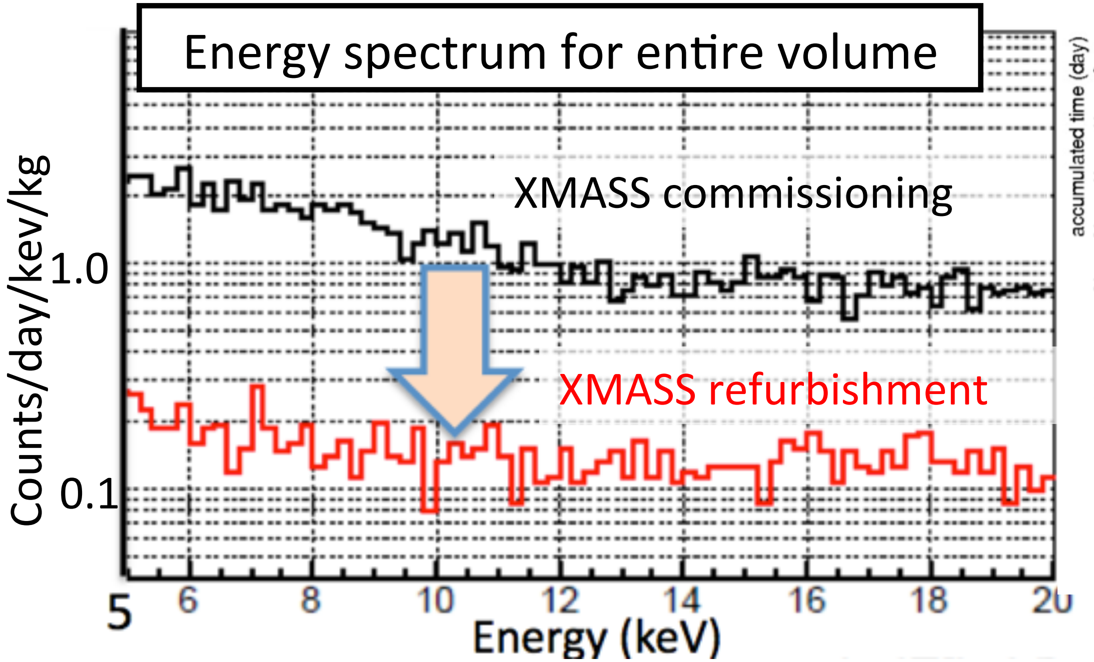
+ Copper plate

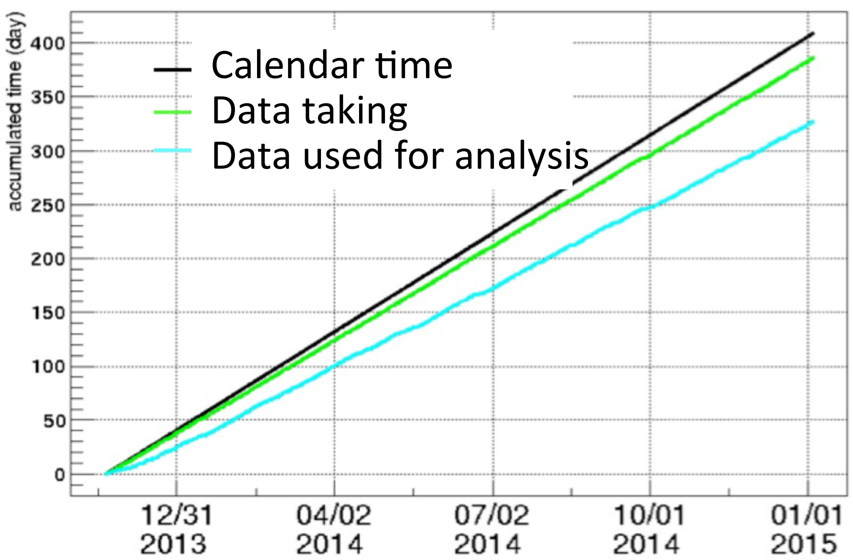
Copper ring mounting



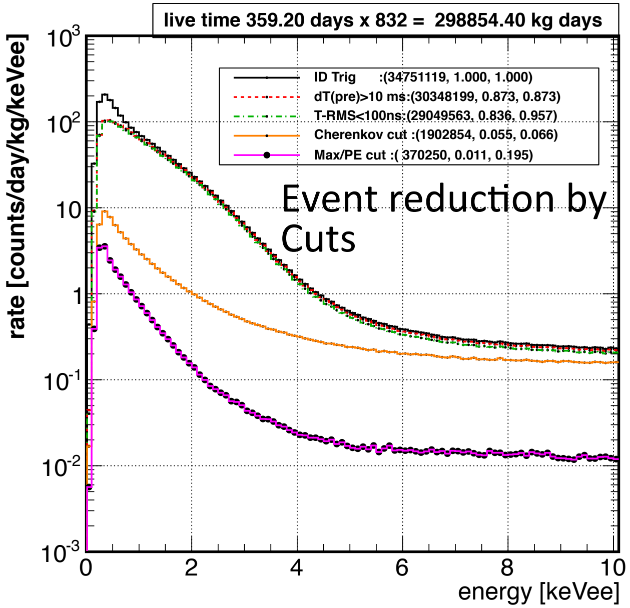
After refurbishment

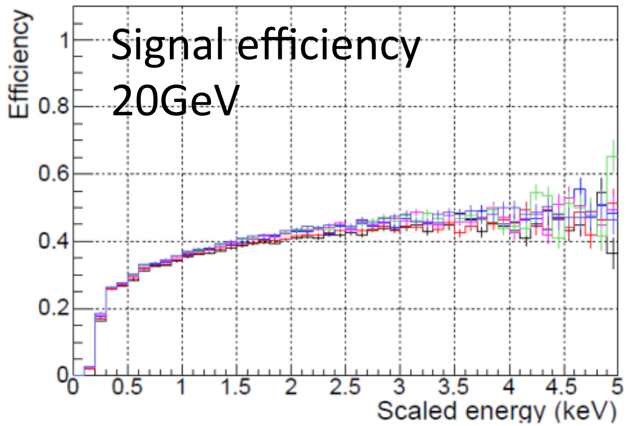
- Restarted data taking from Nov. 2013.
- ATM (charge and timing) → FADC analysis.
- Energy threshold is reduced from 1keV to 0.3 keV.
- Already accumulated 277 days data for WIMP search by Dec. 2014.
- Using this data, physics analyses including WIMP search with fiducialization and seasonal modulation are on-going.





Modulation analysis





So far no direct crosscheck on DAMA

Data set

- November-20, 2013 to March-29, 2015
  - 504.2 calendar days,
  - 359.2 effective days (71%) for analysis
  - **0.82 ton･yr** exposure (⇔1.33tyr DAMA)
- No PID
  - Both NR and e/γ events are retained
- Trigger: 4 hits (no outer detector trigger)

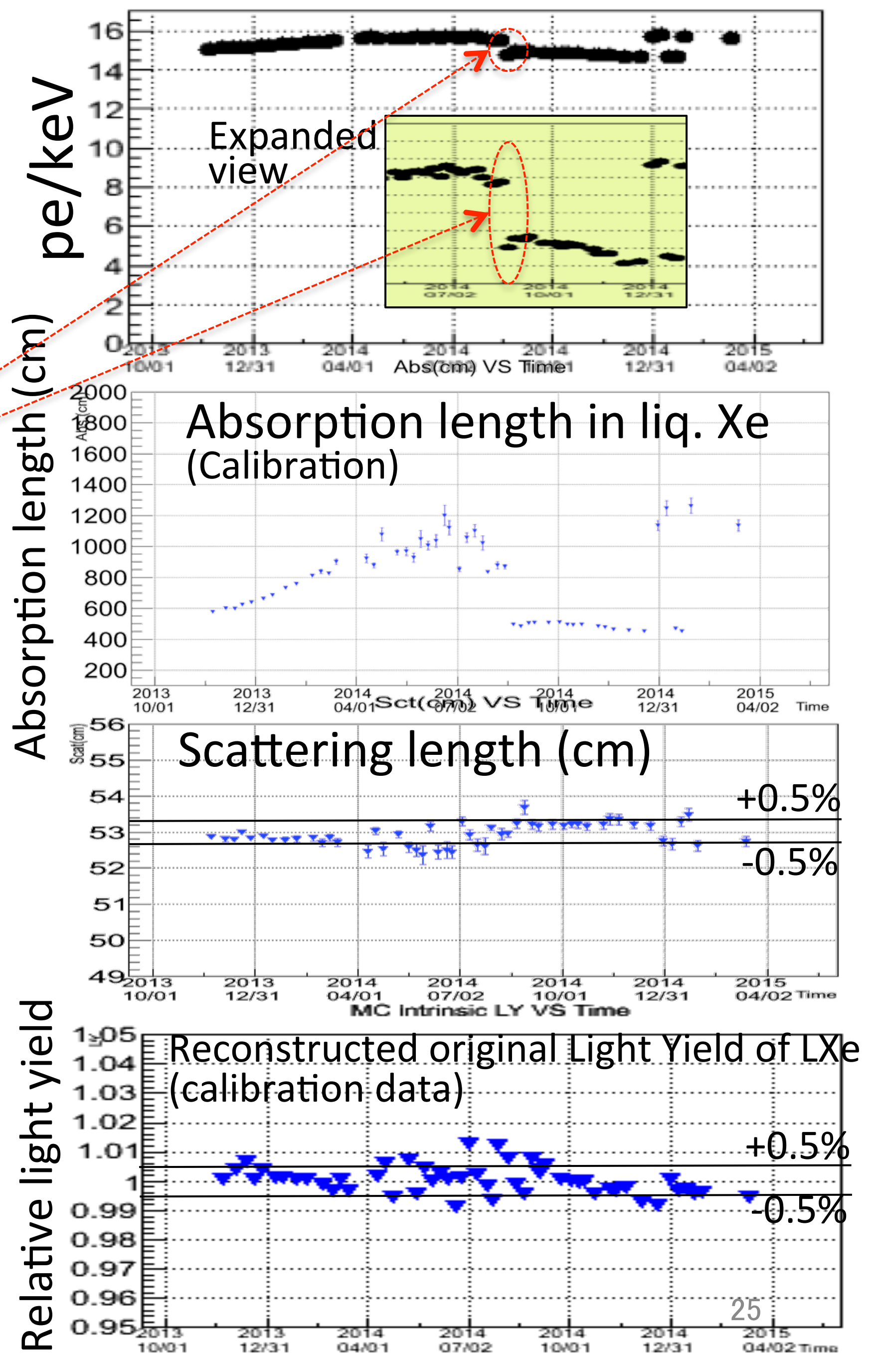
Cuts

- Simple noise reduction
  - Veto 10ms after the events
  - RMS of time hits < 100 ns
- Remove Cherenkov events (orig. in glass)
  - # hits in earlier 20 ns > 60% of total hits
- Remove events in front of PMT
  - Maxpe/totalpe cuts (50% eff for signal)

Detector Stability

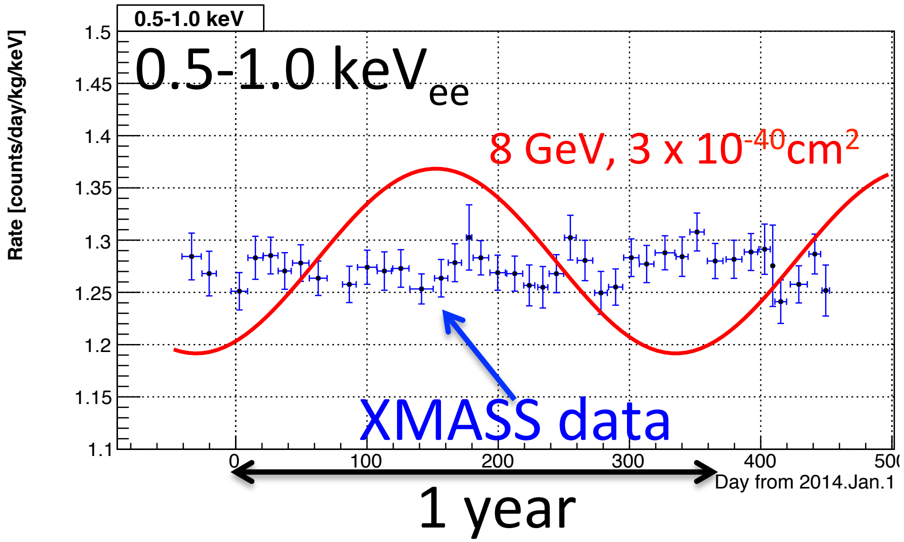
- every week: ^{57}Co calibration
- Observed photo-electron yields
  - gradual drift
  - Sudden jump at power failure (~5%)
- Those photo-electron changes can be explained by the a change of the absorption length.
  - Scattering length: stable< 0.5%
  - the 'original' light yields extracted: stable< 0.5%
- Uncertainty due to this instability will be taken into account and is currently being finalized.
- Much better stability now

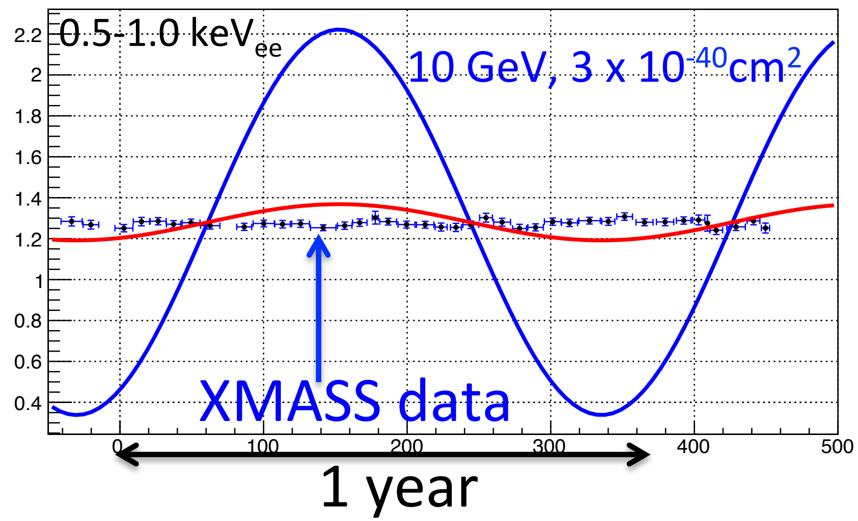
Photo-electron yield (^{57}Co calibration data)

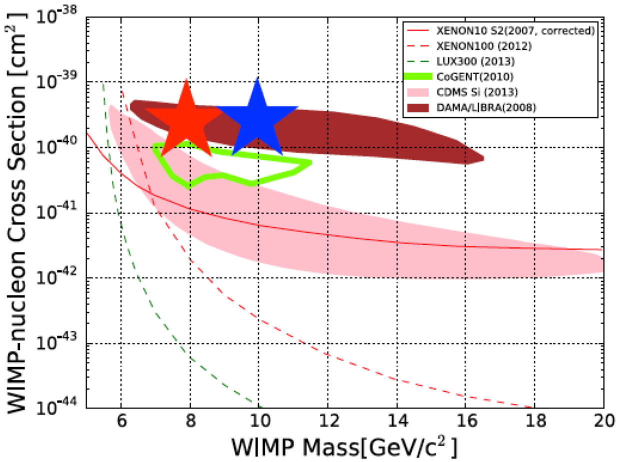


Sensitivity to modulation

XMASS 'real' data (359 days); 0.5 -1.0 keVee (4.8 – 8.0 keVr) w/o syst.





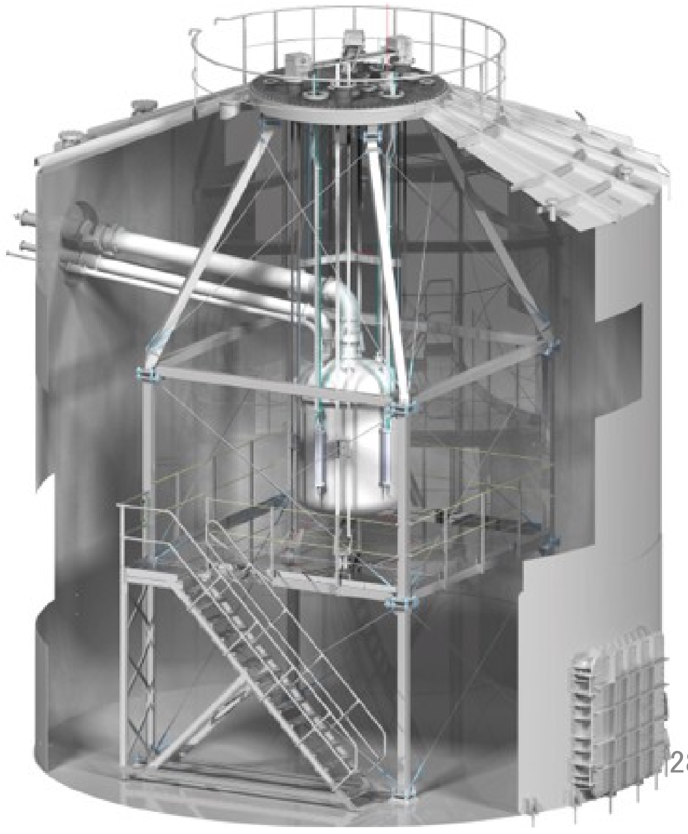


- XMASS has high sensitivity to modulation
  - Largest mass (835kg)
  - Low threshold (0.5 keVee)
- No PID
  - Same as DAMA
  - If NR
    - Direct comparison is possible (lines)
  - If e/γ signal
    - Need models to compare

Future dark matter searches

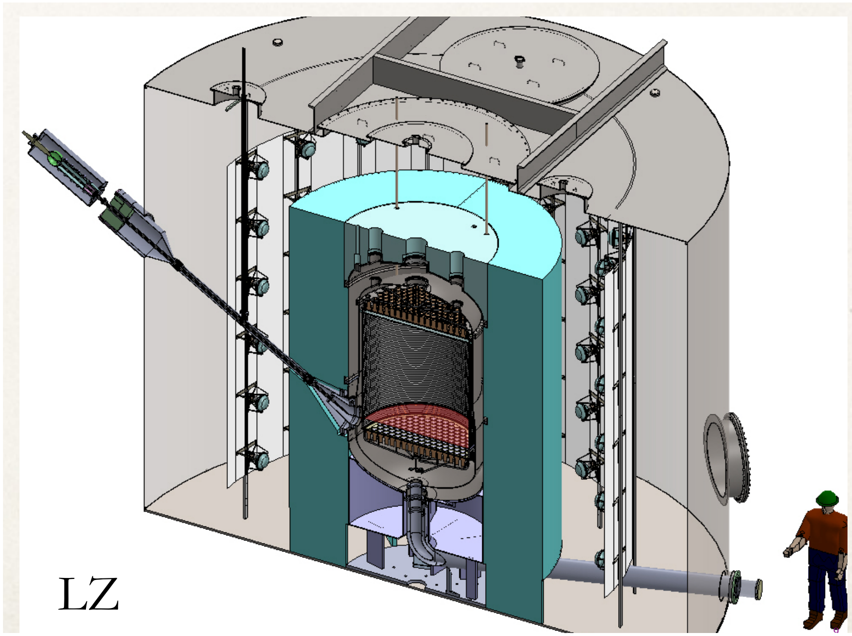
Status of other experiments I

- XENON1T (1t FV/3t all)
  - two phase liquid xenon detector
  - Commissioning run started
  - First data expected in this year



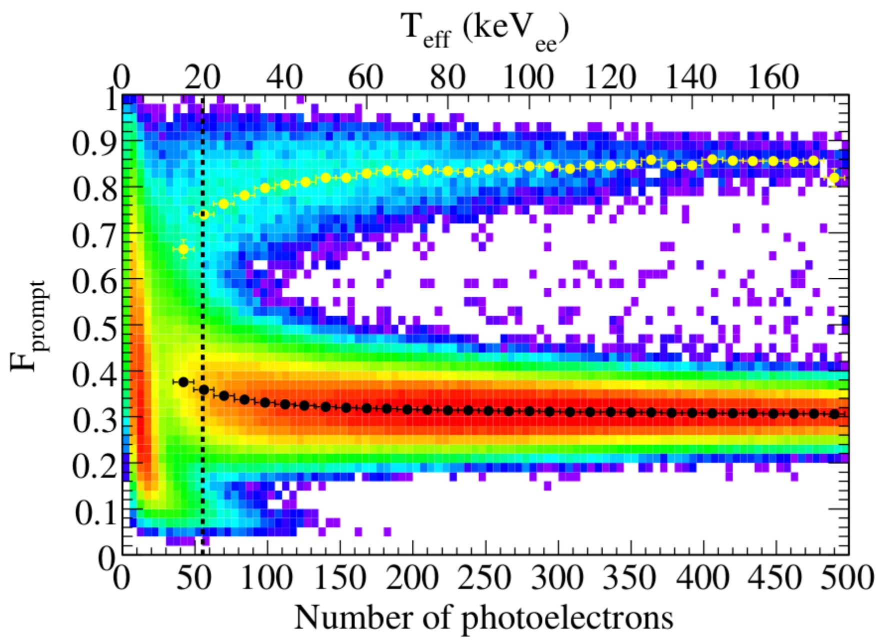
Status of other experiments II

- LUX (0.12t FV/0.37t all)
  - Data taking started Sep 2014. ~100 days data.
  - 300 days data until June 2016 is expected to give a factor 2-4 improvement.
- LZ (5.6t FV/7t all)
  - 3 years run from 2018+
  - Expected to reach the sensitivity ~ background limited by atmospheric neutrinos.

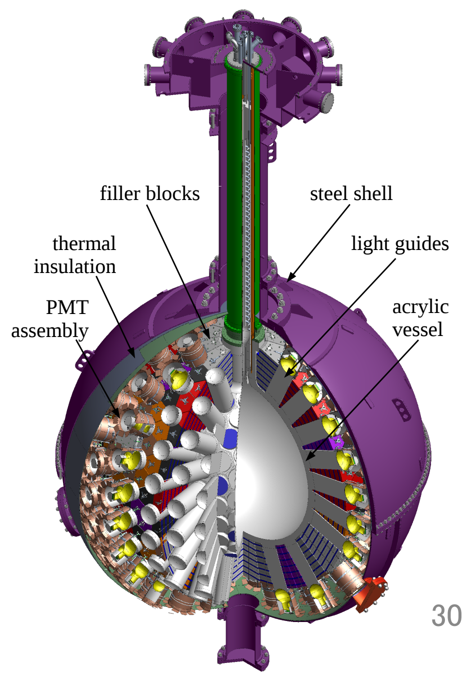


Status of other experiments III

- DEAP3600 (1t FV/3t all)
  - single phase, electron/nuclear recoil signal discrimination based on pulse shape
  - Large BG and high threshold due to 39Ar, ~kHz/ton.
  - Commissioning started. First result late 2015.



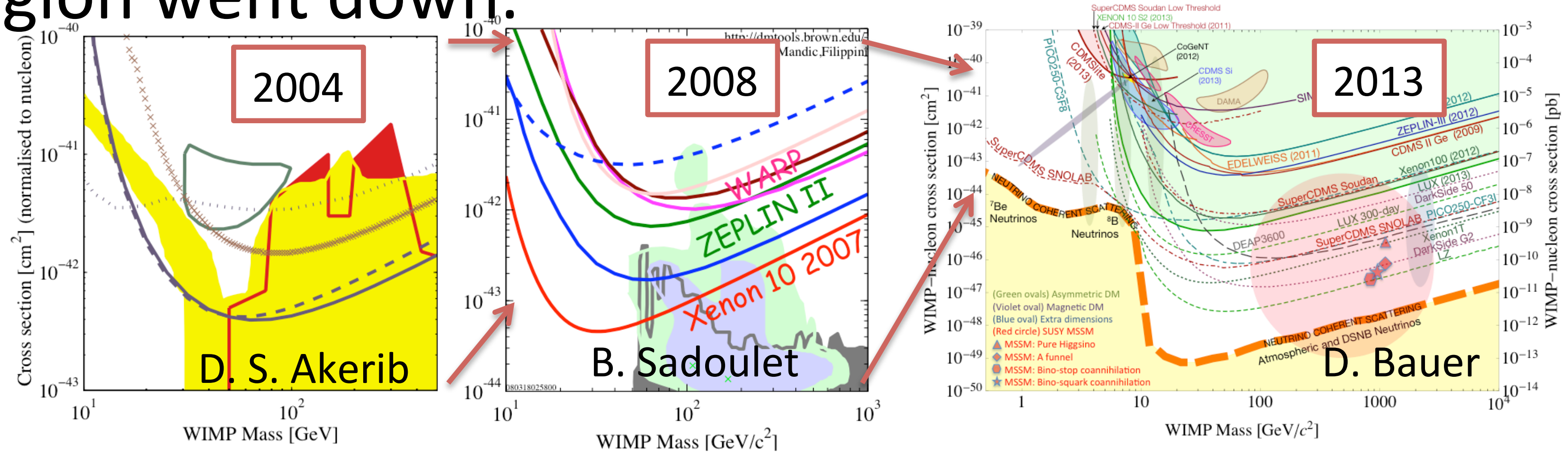
singlet/
triplet
= 7n/1.5μs



What about XMASS?

Situation of direct dark matter search

- In this 25 years, five orders of magnitude improvements did not reveal the nature of dark matter. Every time a better limit is obtained, the most likely region went down.



- Although SUSY LSP=DM is still an appealing hypothesis, the real answer might be very much different. Under this situation, it is important to push experimentally viable searches for various types of DM candidates as much as possible.

Future XMASS

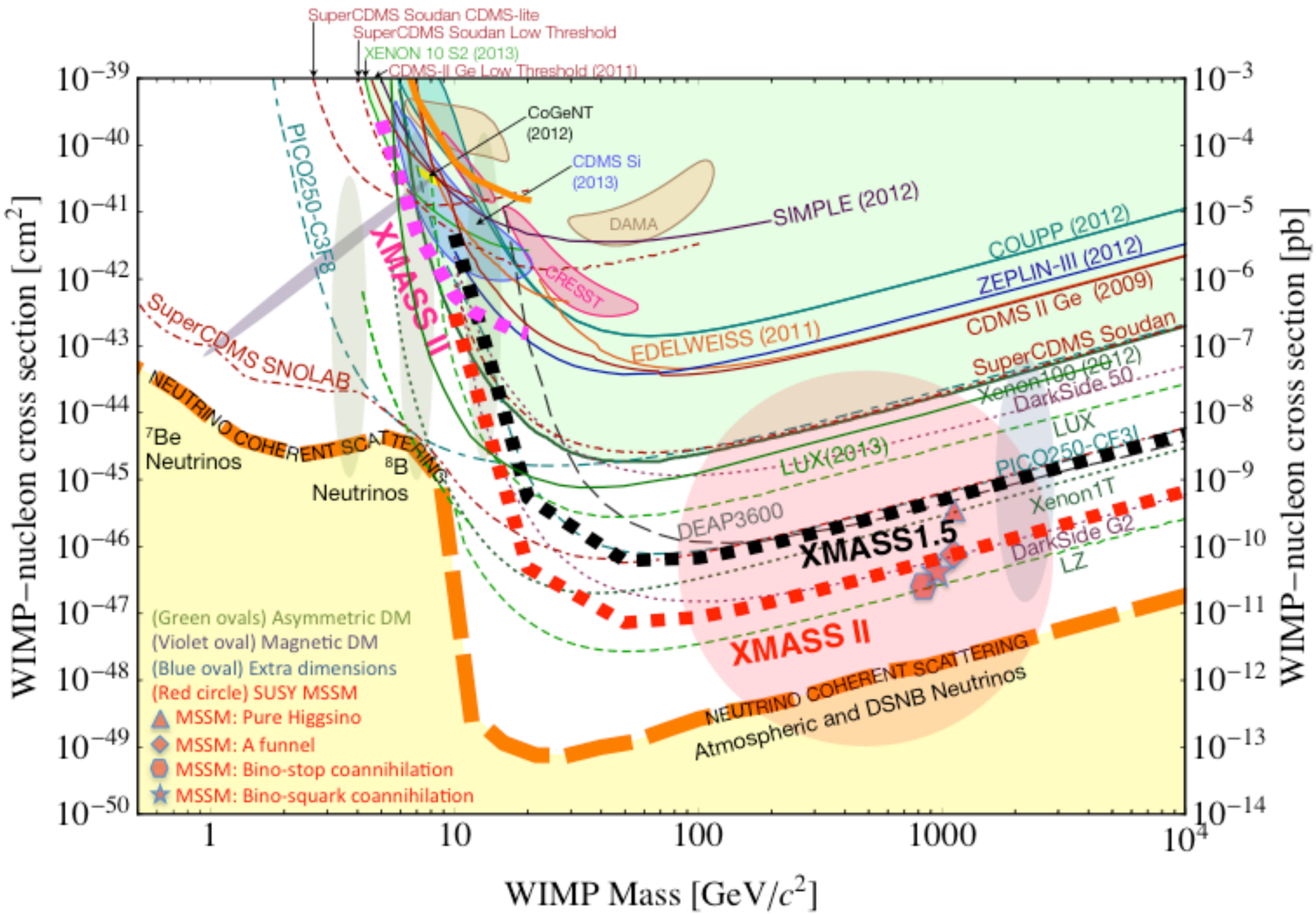
- As we saw in the study for Super-WIMPs, XMASS-I has an advantage for electron recoil signals. Though we need to lower the background to achieve a good sensitivity for a standard WIMP search, it makes the detector unique and powerful for a wider range of dark matter candidates!
  - In indirect searches, people are already using various channels to see signals. (e+/e-, anti-p, D, ν, etc. from long before!)
  - XMASS can do in parallel to the pp solar neutrino observation if the target mass is large enough.
  - We also have to search for standard WIMPs at the world best sensitivity.

➔ XMASS-1.5! (5ton total, 1ton fiducial mass)

Physics targets

- Search for standard WIMPs
  - 10^{-46}-10^{-47}cm^{2}（current best limit is 8x10^{-46}cm^{2}@50GeV by LUX）
- yearly/monthly/daily modulation using large statistics
  - Model independent and more robust signal
- Solar axions
  - Solving the strong CP problem
- Super-WIMPs
  - Different type of dark matter search
- Electron recoil events
  - Explanation of DAMA? Search for dark matter through more wider interaction channels.
- pp solar neutrinos
  - S/N~1 (S/N~0.1 @ Borexino)
- Magnetic moment study using solar neutrinos
  - Better limit than reactor experiments

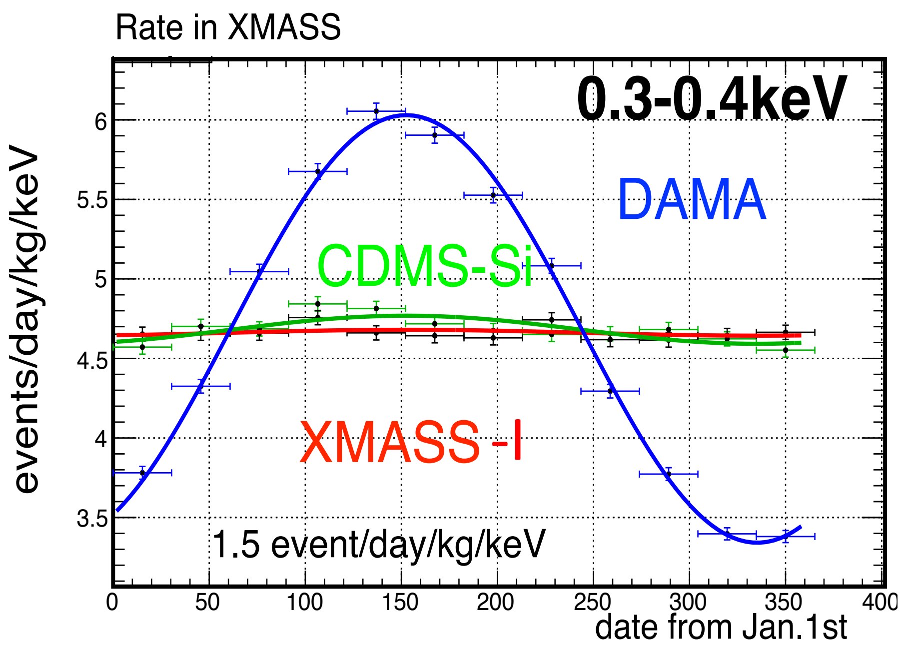
Sensitivity on the WIMP search

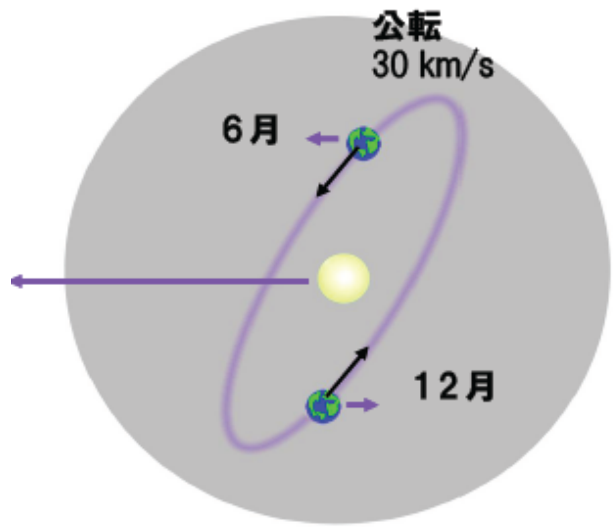


1-2 orders of magnitude improvement expected

yearly/monthly/daily modulation

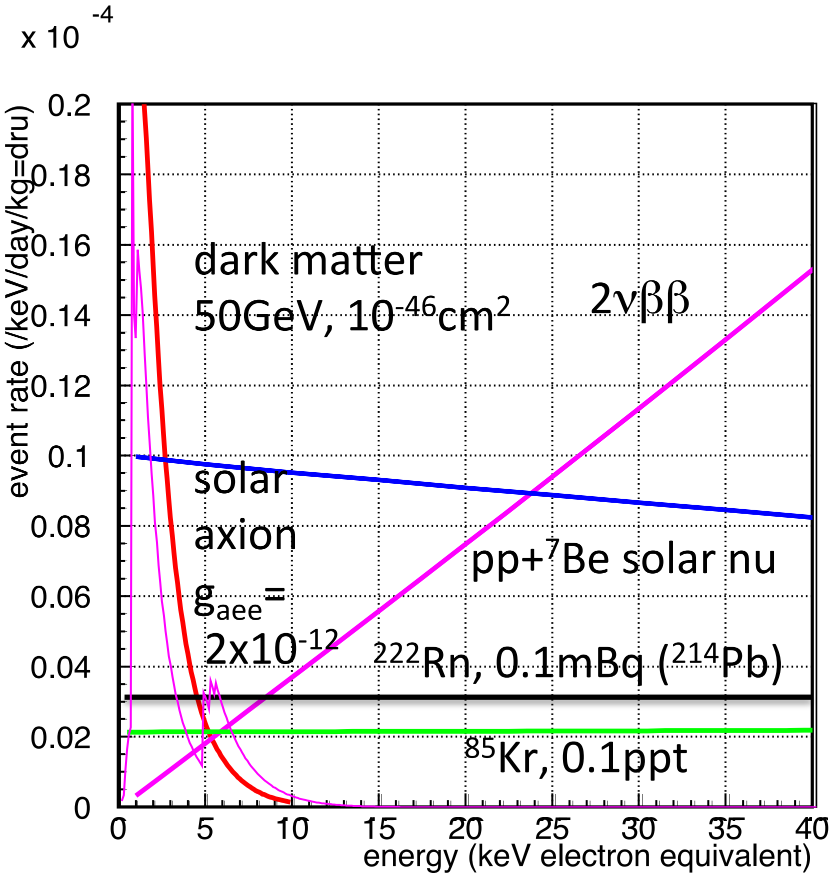
- Low threshold, the largest mass
- Model independent way to id DM contribution
- BG caused by solar neutrinos is opposite phase

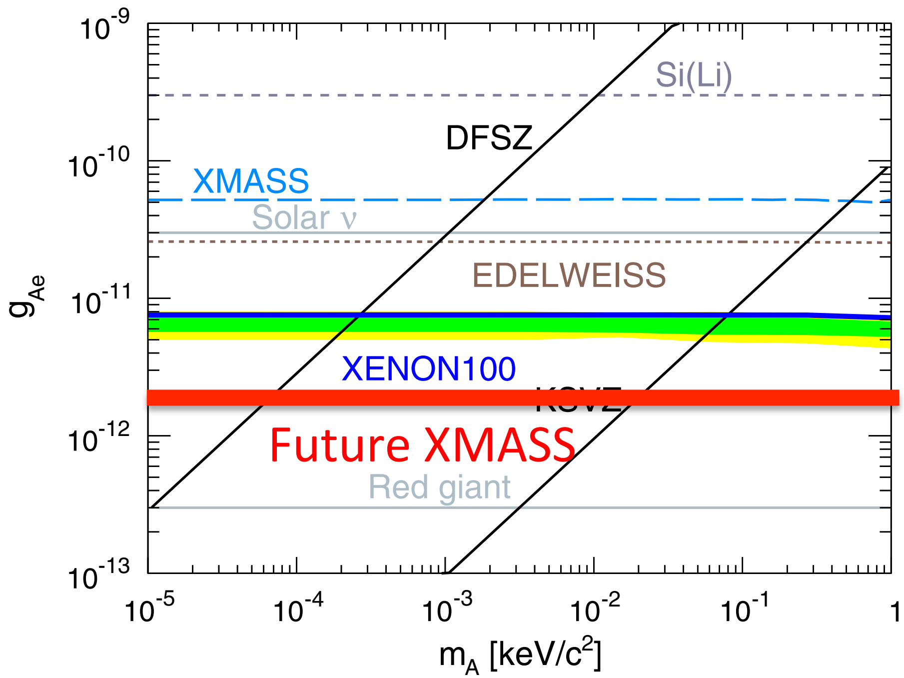




daily = yearly x 1-2%, much robust
>>monthly

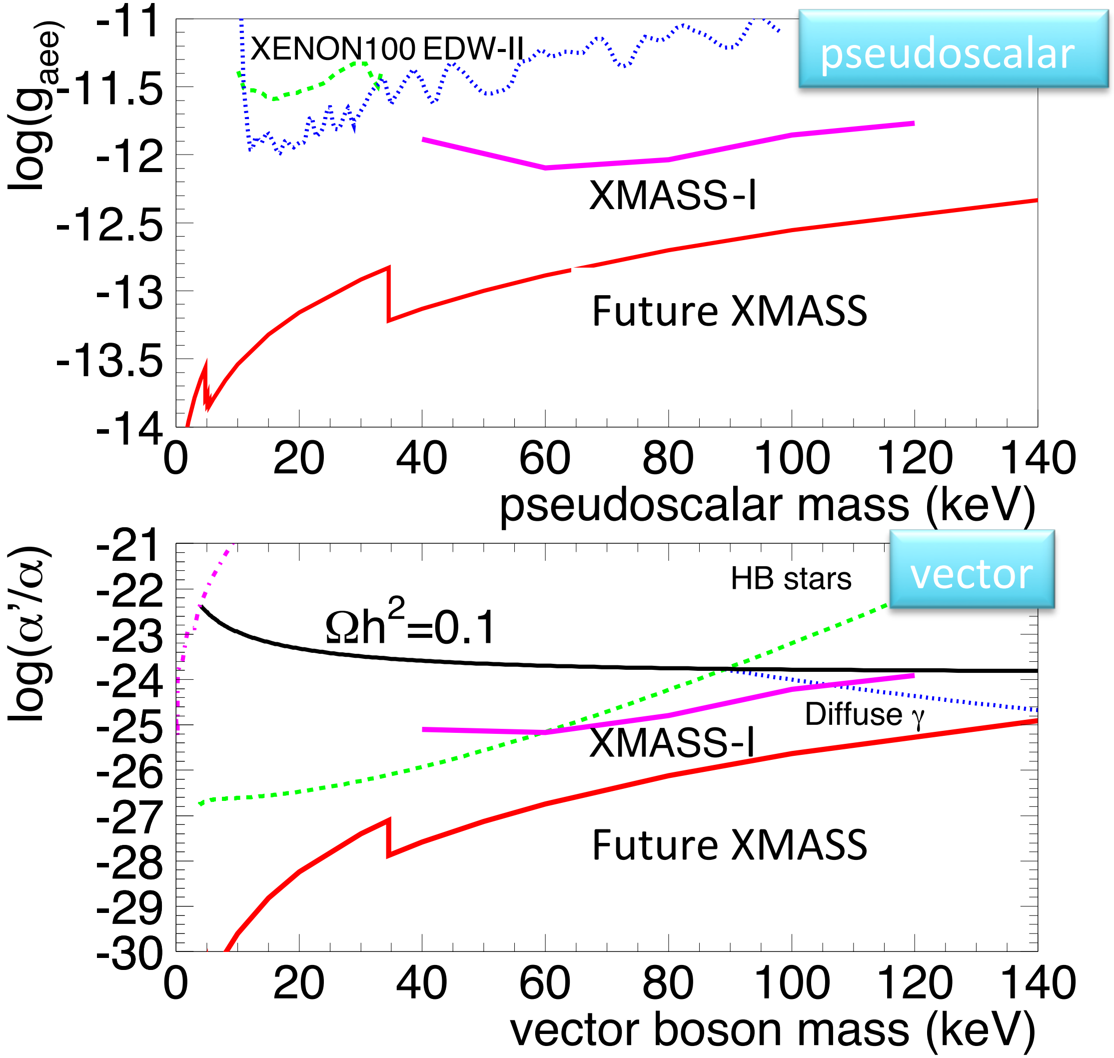
Solar axions





Search for solar axions (axion-like particles) through electron coupling. Factor 4 improvement on gaee compared with recent XENON100 limit (signal ∝ $gaee^4$).

Super-WIMPs



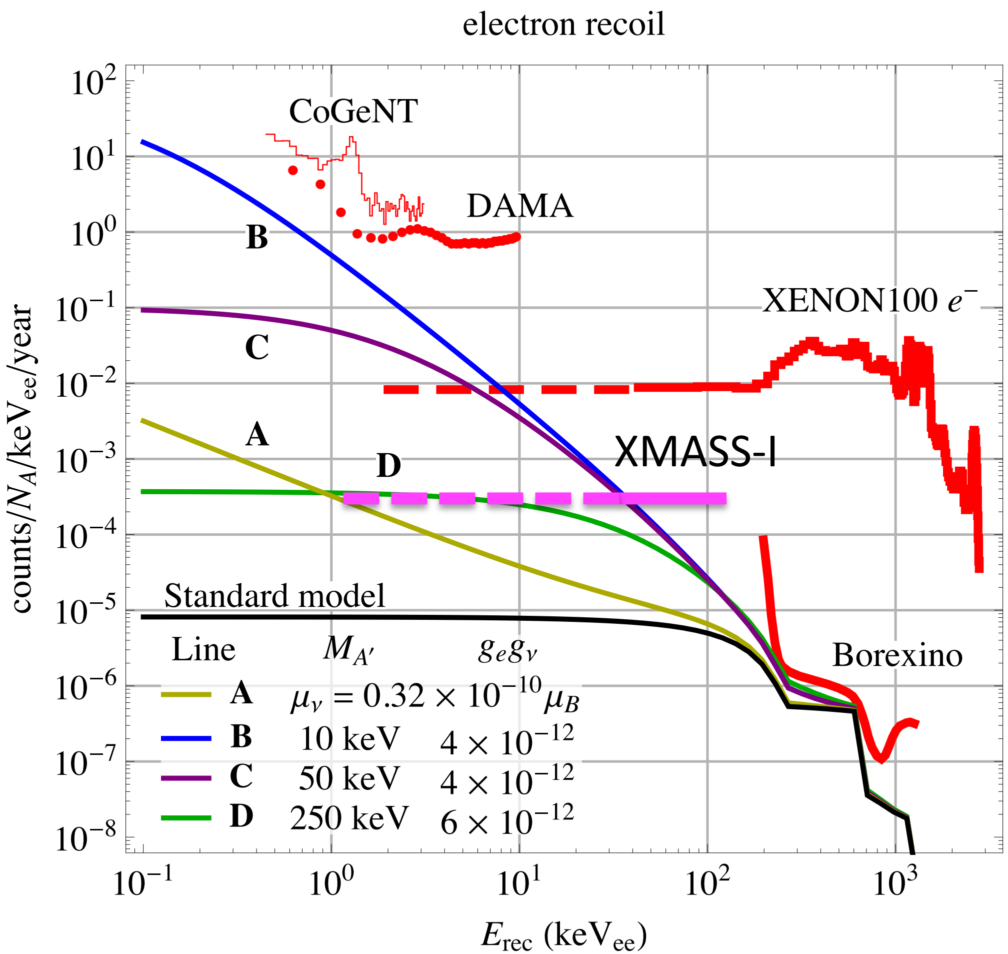
Much better search with 10^{-5}dru.

Both lighter and heavier super-WIMPs can be searched for

Explanation of DAMA?

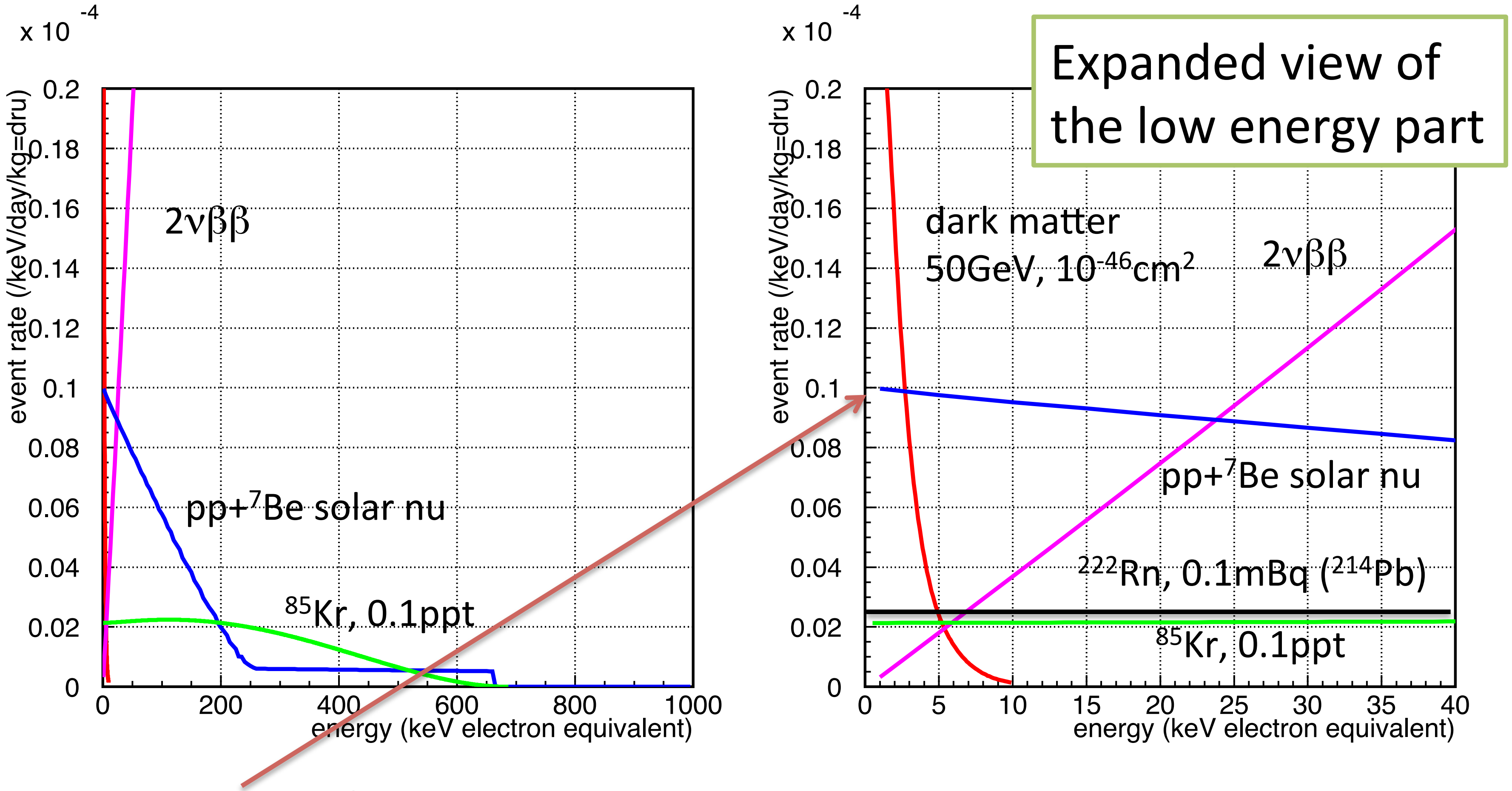
- Various models have been proposed, most of them are models devised to explain DAMA data.
  - Mirror dark matter
  - Electron interacting dark matter
  - Luminous dark matter
  - …
- Experimentally, we should have a high sensitive search through the electron scattering channel since DAMA does not use particle identification!

Neutrino magnetic moment



- An enhancement at low energy is expected (line A) with a finite value of mag. moment.
- 7% modulation due to the eccentricity expected.

Background for dark matter search



- 0.1×10^{-4}/keV/day/kg (=dru)

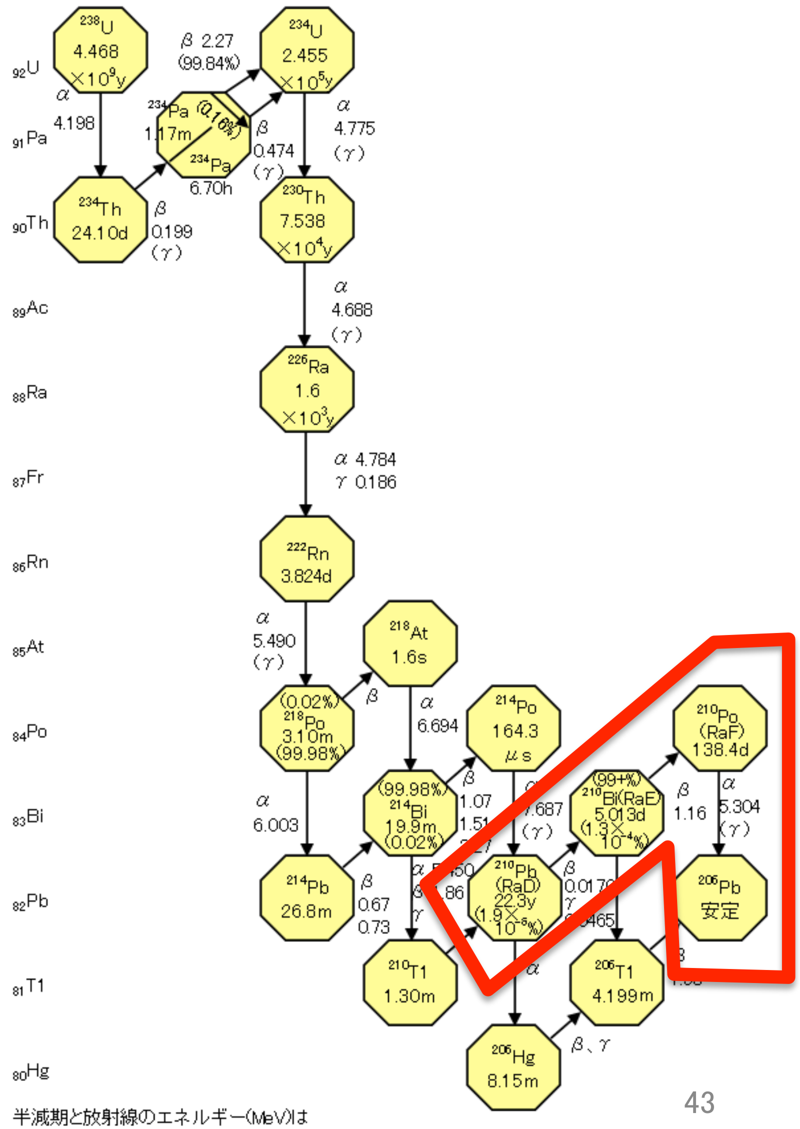
  → 1events/10keV bin width/10day/1ton FV

Requirements for future XMASS

- Achieve 10^{-5} dru (=/keV/kg/day) for pp solar neutrinos.
- Realize 2keVee energy threshold in the fiducial volume.
- Search for nuclear recoil events with the world best sensitivity better than $10^{-46}cm^2$.
- Optimize electron recoil event signature searches in the presence of solar neutrino background.
- We can expect an observation of pp solar neutrino signals.
- To achieve this BG, surface background (210Pb) and internal background need to be well controlled.

Surface background

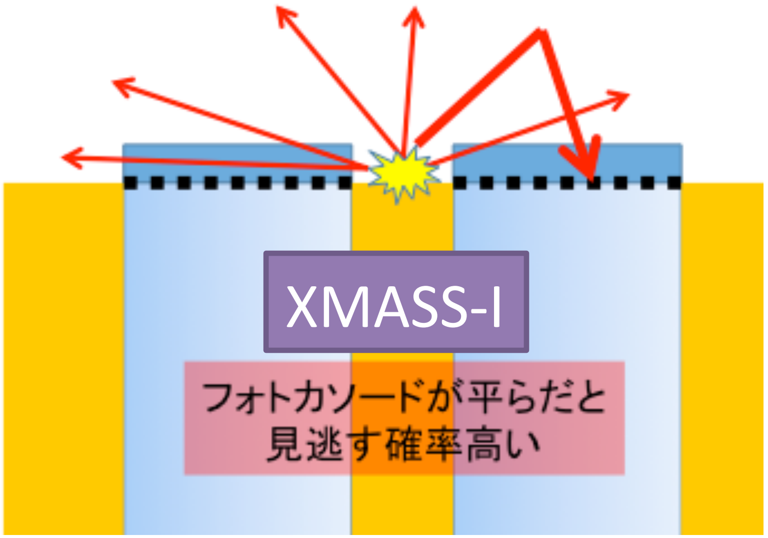
- a passive measure: reduction of surface contamination, cleaning
  – Radon daughter, 210Pb causes troubles in most of dark matter (double beta) experiments.
  – XMASS-I: a few mBq in the inner surface → a large progress in understanding this.

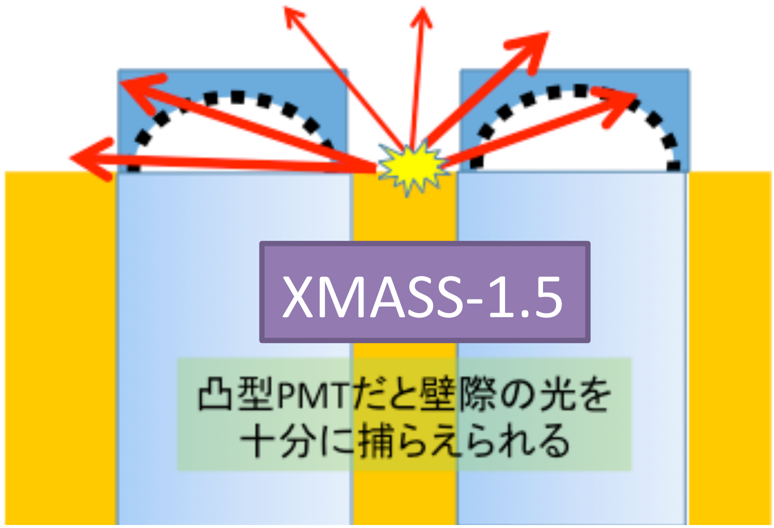


半減期と放射線のエネルギー(MeV)は
Evaluated Nuclear Structure Data File(1995年2月)

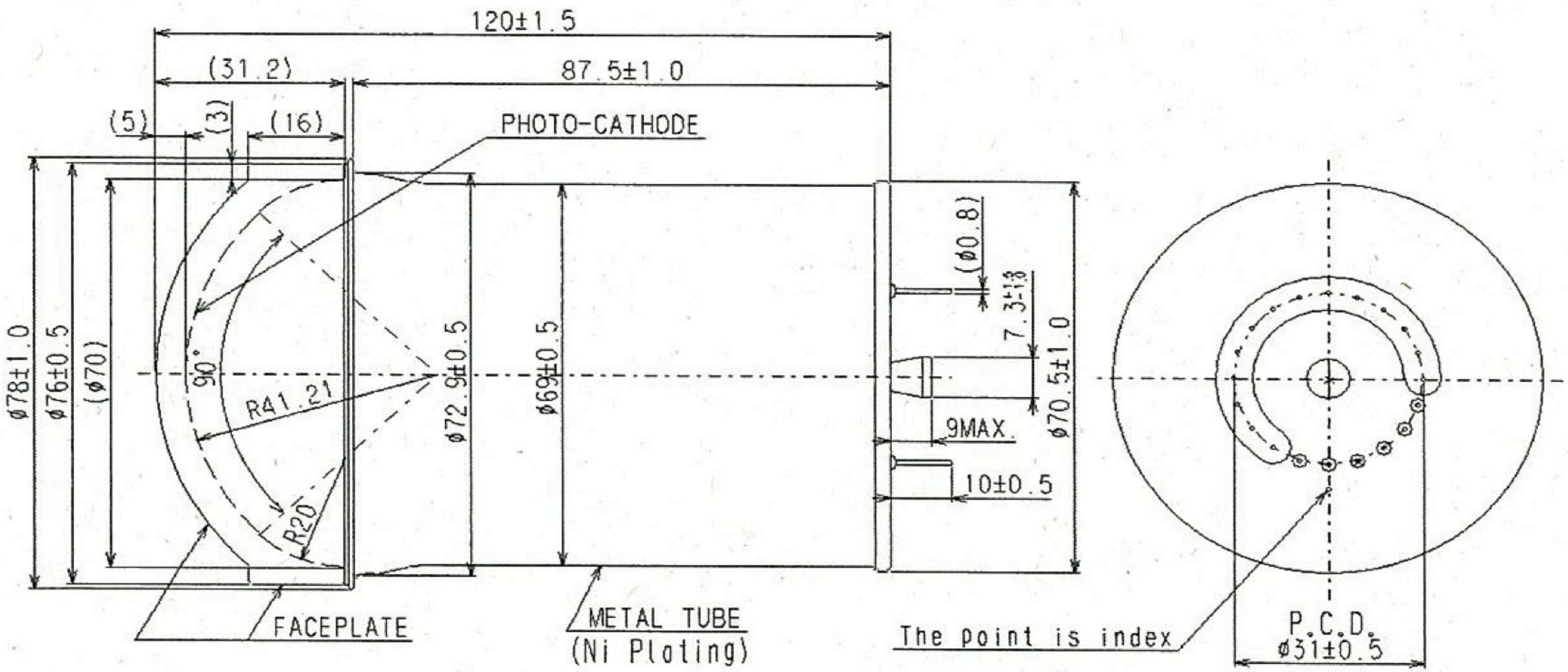
Active rejection of surface background

- We cannot suppress the surface background to be zero. We need an active rejection method to achieve the goal.
  - In the next stage, we will use PMTs which can easily identify surface events. ➔ large rejection factor is expected from MC simulation.



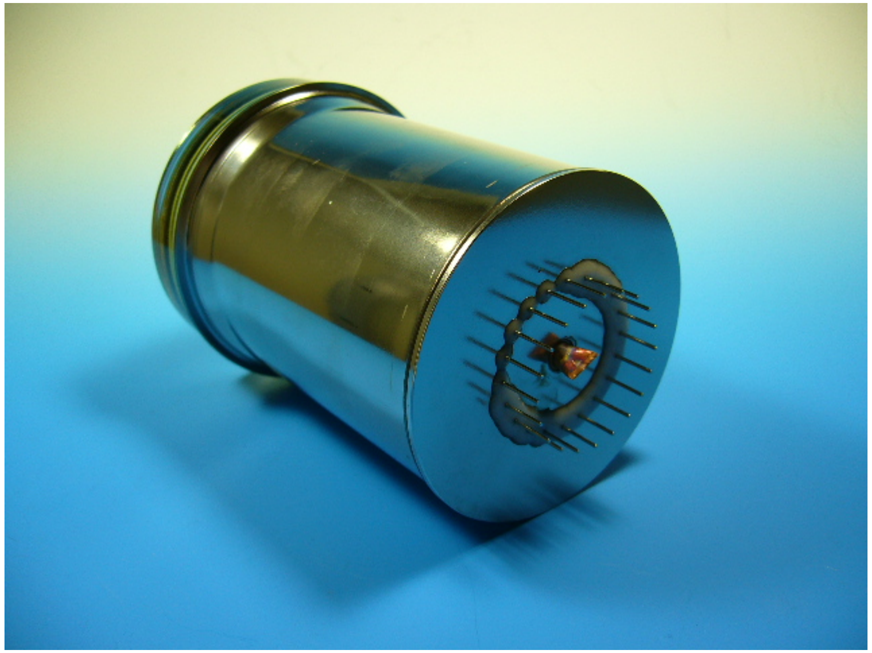


PMT R13111



- It is required to have good sensitivity even for the side part. The electric field and shape of dynodes were optimized to realize it as well as good transit timing spread.

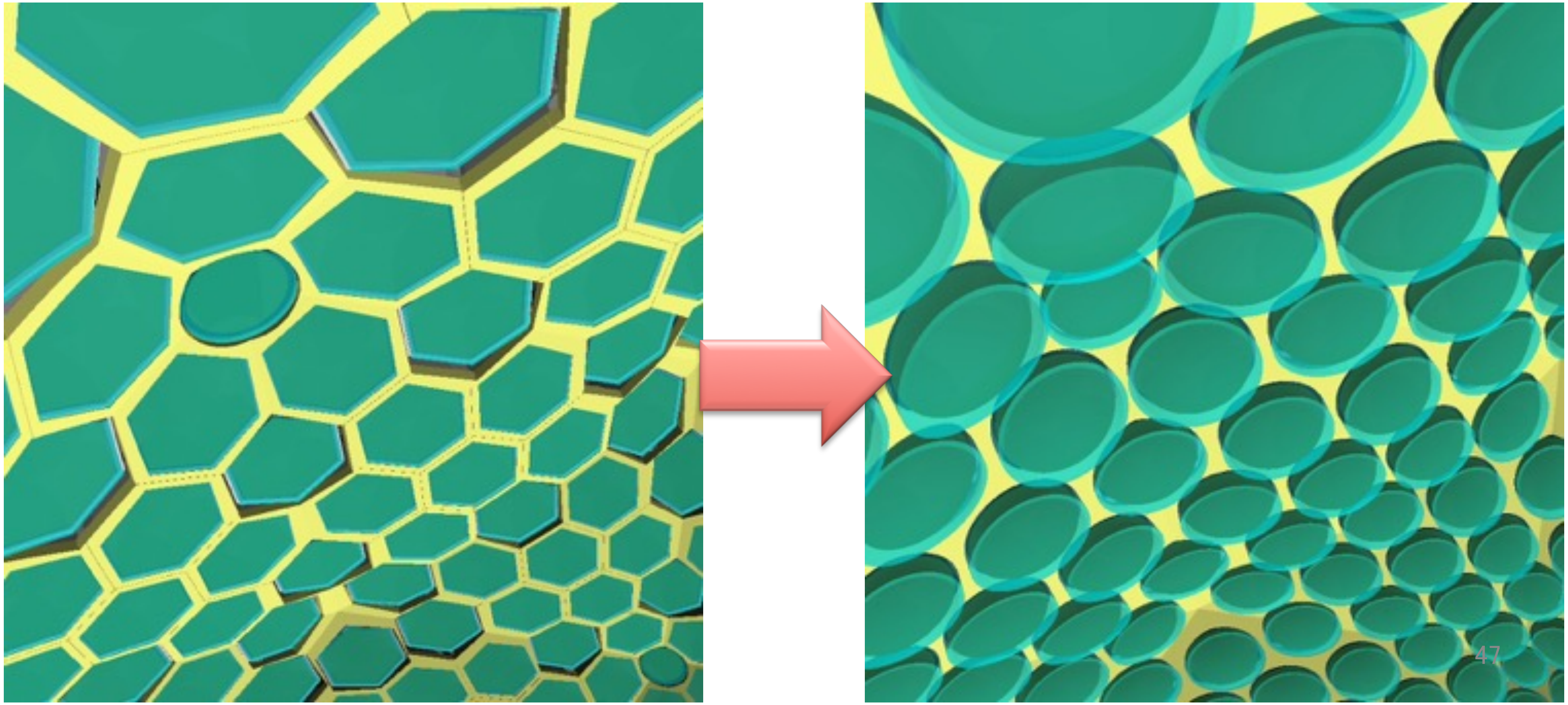
Production of dome-shape PMTs



- First batch is being studied toward mass production
- Good uniformity of photocathode sensitivity down to its edge part.

Demonstration of its performance

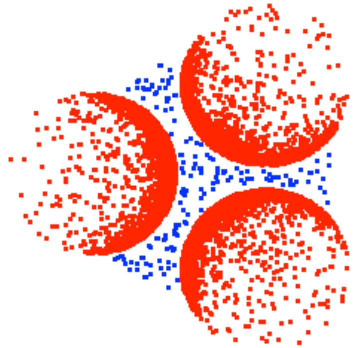
- Replacing PMTs in the existing simulation program makes possible to give a reliable prediction.
- It can be shown that a simple cut significantly reduces the surface background.

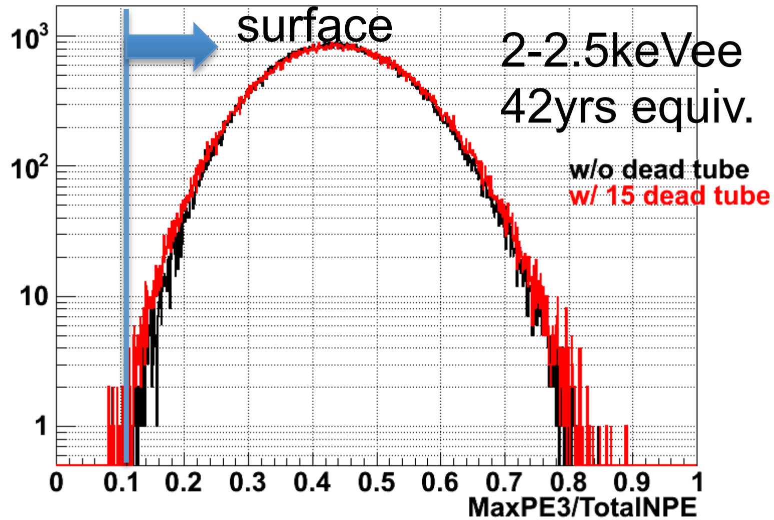


Evaluation of surface ID performance

- surrounding 3 PMTs accept 40-50%
- Condition to identify surface events: 3 PMT > 10% of total
- surface RI of XMASS-I ^{210}Pb → $<10^{-6}$dru, safe enough
- DM efficiency~ 20% (~1tFV/5t all volume)

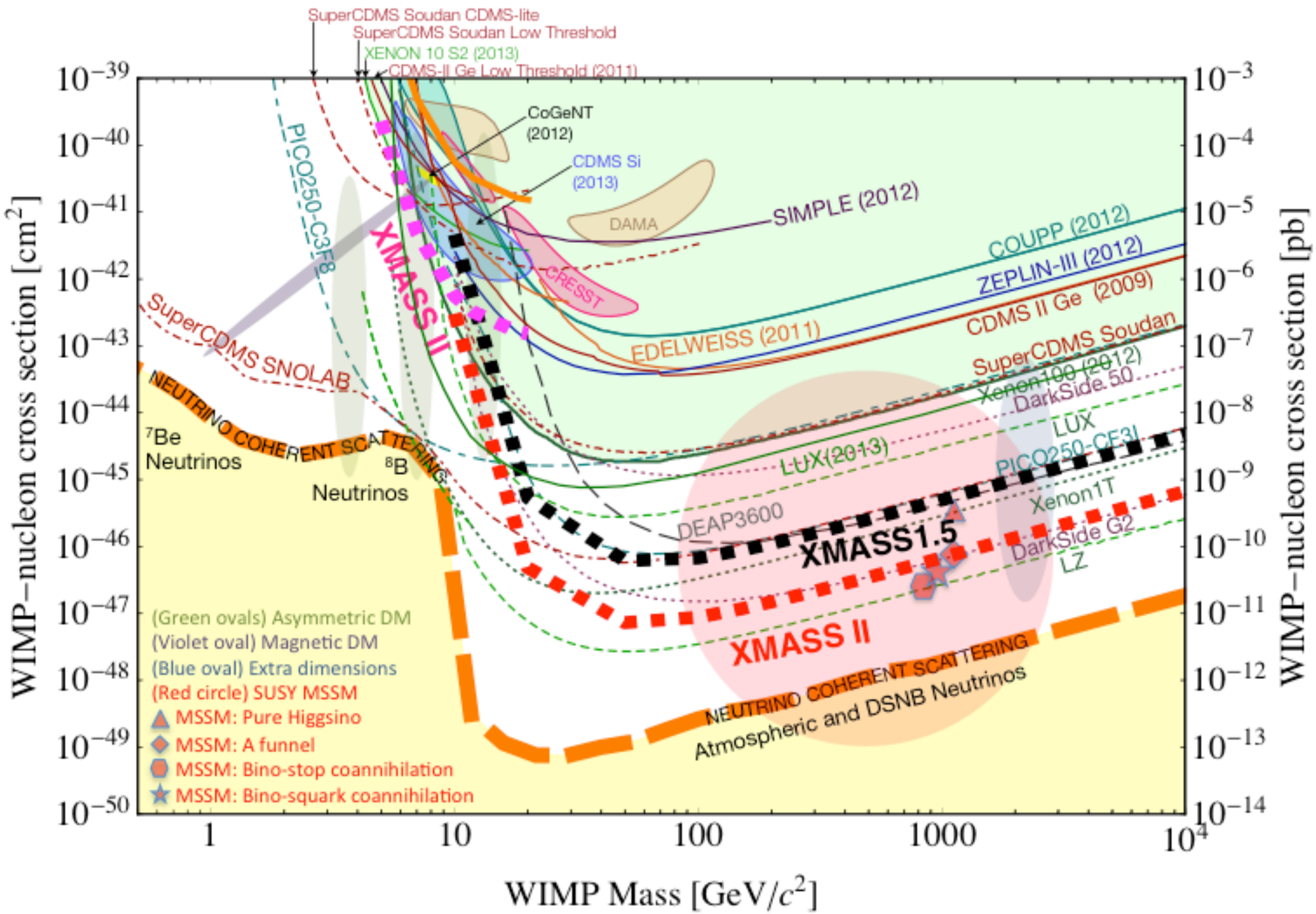
BG generated position
Hit position (photocathode)





Dome-shape PMTs can effectively identify surface BG.

Sensitivity on the WIMP search



1-2 orders of magnitude improvement expected

Summary

- Identification of dark matter is one of the important issues in particle astrophysics.
- XMASS is a unique experiment for its largest target mass and for its high sensitivity both for nuclear recoil and electron recoils.
- We have achieved the world-best sensitivity to search for super-WIMPs with XMASS-I.
- Next stage detector, XMASS-1.5, is proposed. It is expected to realize the best and ultimate sensitivity for electron recoils.
- XMASS-1.5 signal sensitivity improvement summary:
  - Nuclear recoils : $<10^{-46}cm^2$
  - super-WIMPs and similar DM: >30 sensitive
  - Annual modulation
  - Solar axion: >250 sensitive
  - other unknown signals…