Direct dark matter search with the full data set of XMASS-I

K. Abe
Kamioka observatory, ICRR, the University of Tokyo
for the XMASS collaboration

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- XMASS-I experiment
- Full data set of XMASS
  - ~5 years long stable observation
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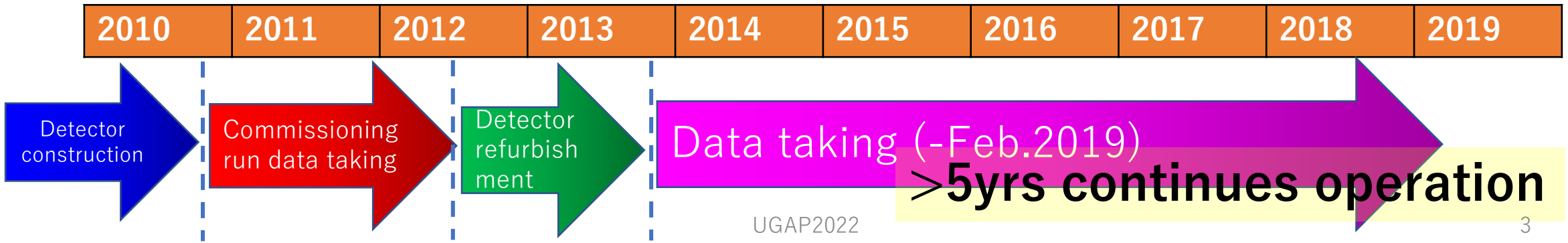
- Summary

XMASS-I experiment

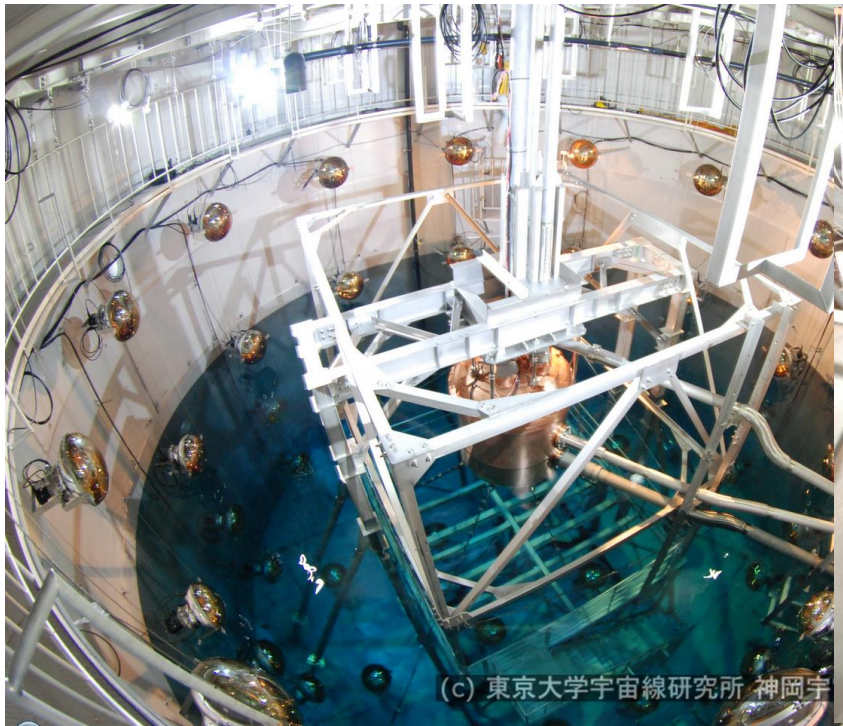
- Unique experiment
  - Single phase (scintillation photon only) liquid xenon detector.
  - Large volume ~1t
  - Long stable observation period, 5 years
  - Large light yield ~14pe/keV and low threshold ~0.5keVee
- Variety of rare events search
  - Dark matter
    - modulation, low mass, inelastic, hidden photon
  - Solar axion, 2nECEC, GW, exotic neutrino interaction
- For present dark matter search situation, wide variety results are quite important.

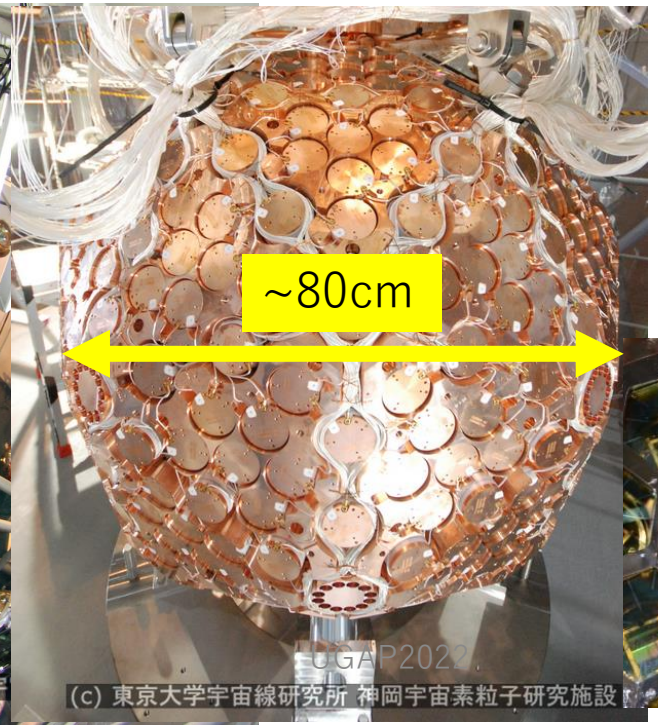


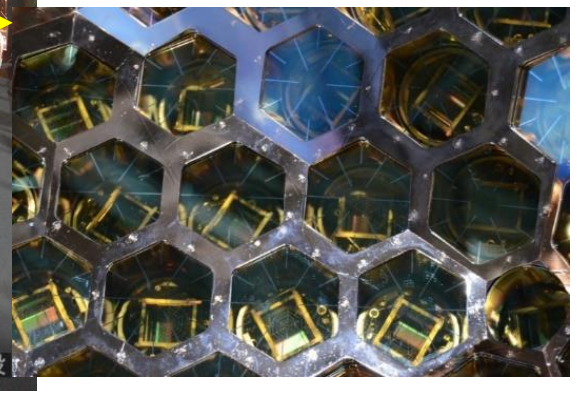
XMASS detector

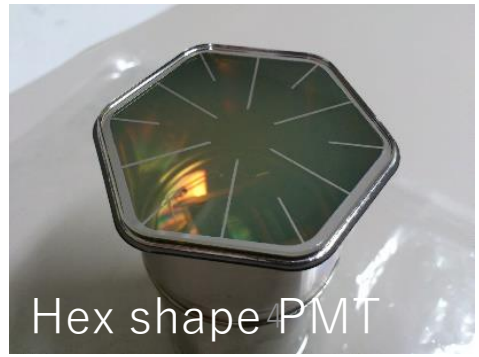
- Kamioka Observatory (~2700m.w.e.), Japan.
- 832kg (~80cm) liquid xenon for active volume.
- ~2-inch PMT (hex and round shape) ×642 : 62% photo-coverage
- 10x10m water tank for passive shield and active shield as muon veto, 20-inch PMT×70.

Japan

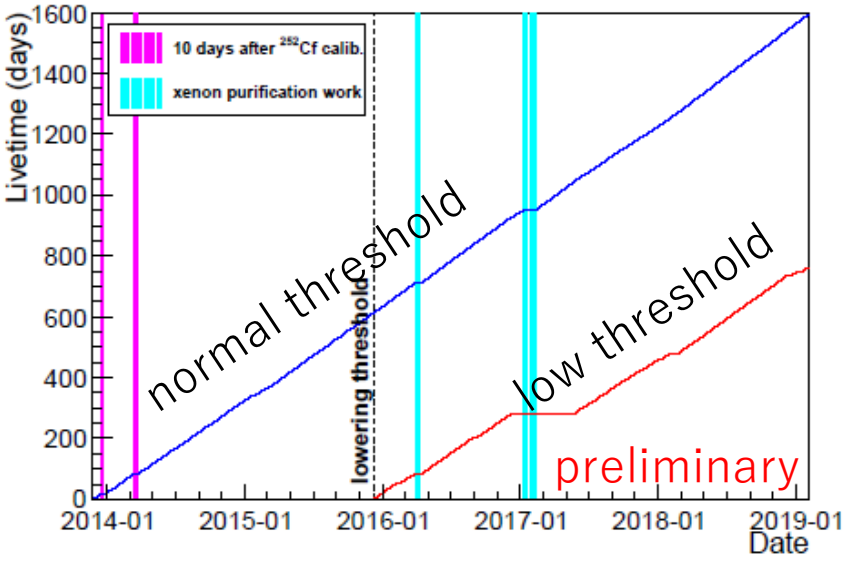


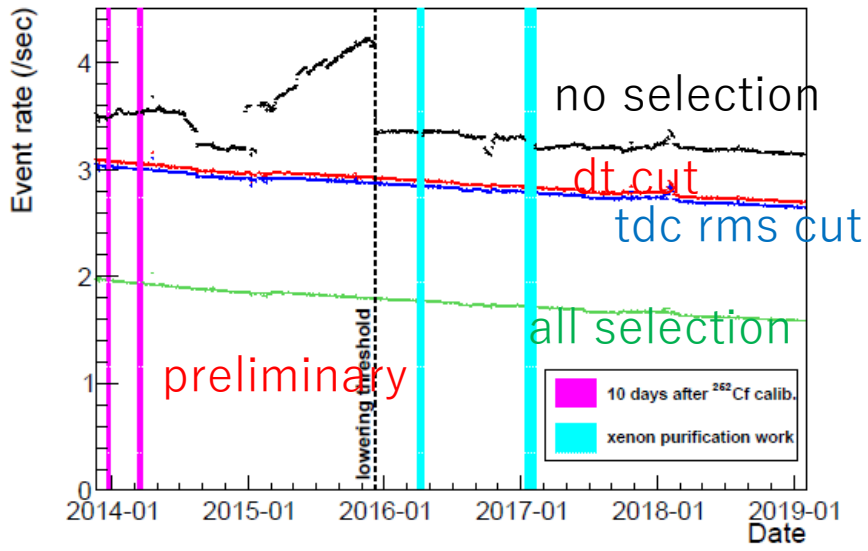






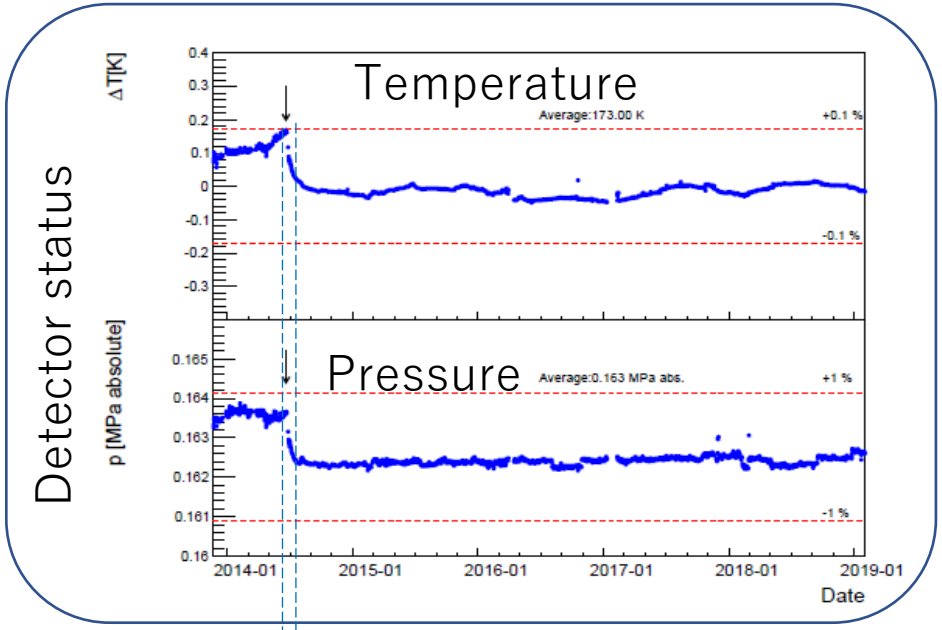
Full data set of analysis

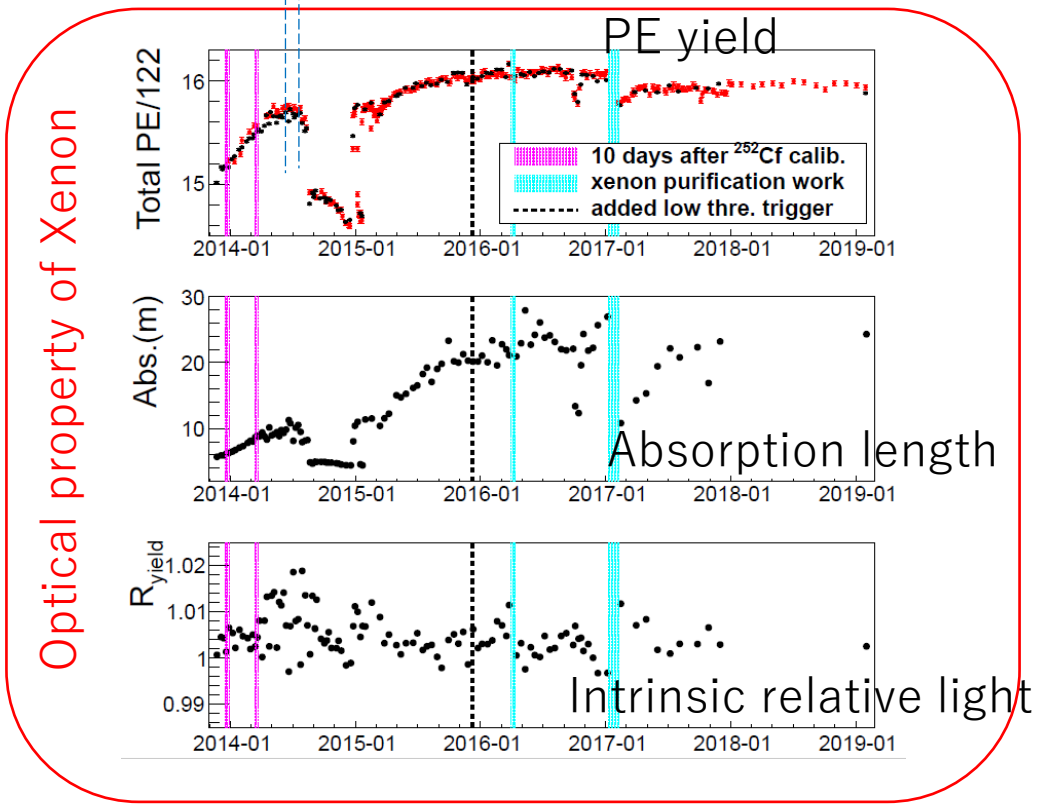




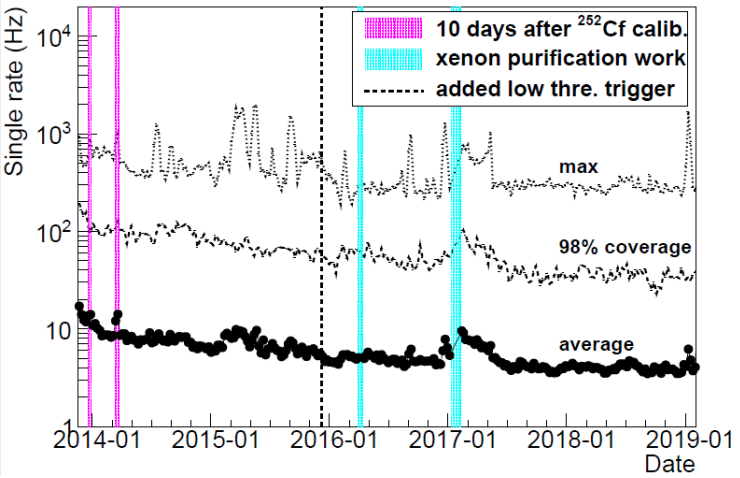
- ~5 years long stable observation
- 2013/11/20~2019/2/1
  - Normal threshold 4hit ~1keVee
    - live time 1590.9 days
  - Low threshold 3hit ~0.5keVee
    - live time 768.8 days
- Stable observation was realized
  - Steadily accumulated data
    - Low threshold data started from middle of the experiment
  - Relatively longer down time came from xenon purification work for impurity removal.
  - Trigger rate change for before selection disappeared after noise removal.

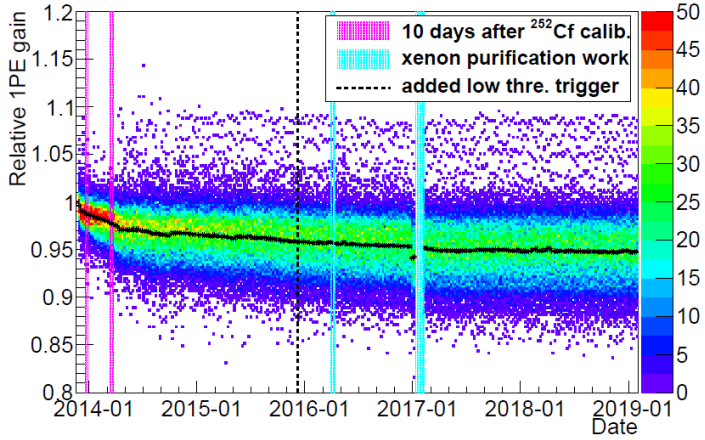
Detector stability

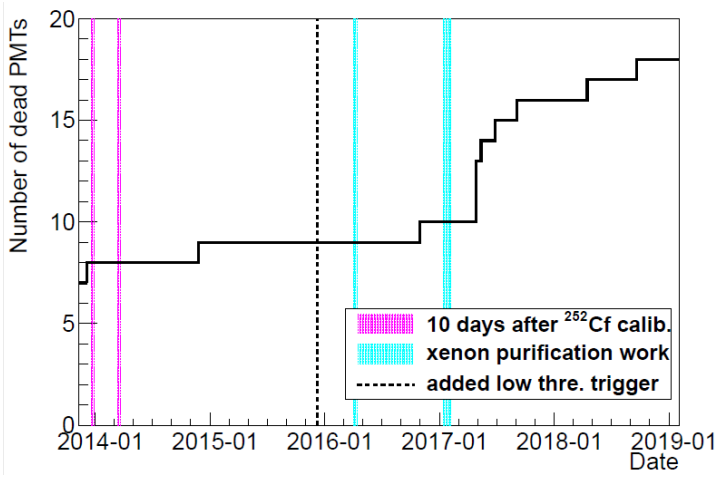




- Pressure and temperature
  - Stable except one drop.
  - One large drop caused by change of reference sensor controlling the refrigerator.
- Optical parameter of liquid xenon
  - PE yield had larger change in former part.
    - Affected by absorption length change.
    - Correction applied in the analysis.
    - latter half was quite stable
  - Absorption length gradually increased by circulation.
    - getter to remove impurity.
  - Intrinsic relative light yield was not changed within 2% estimation error.







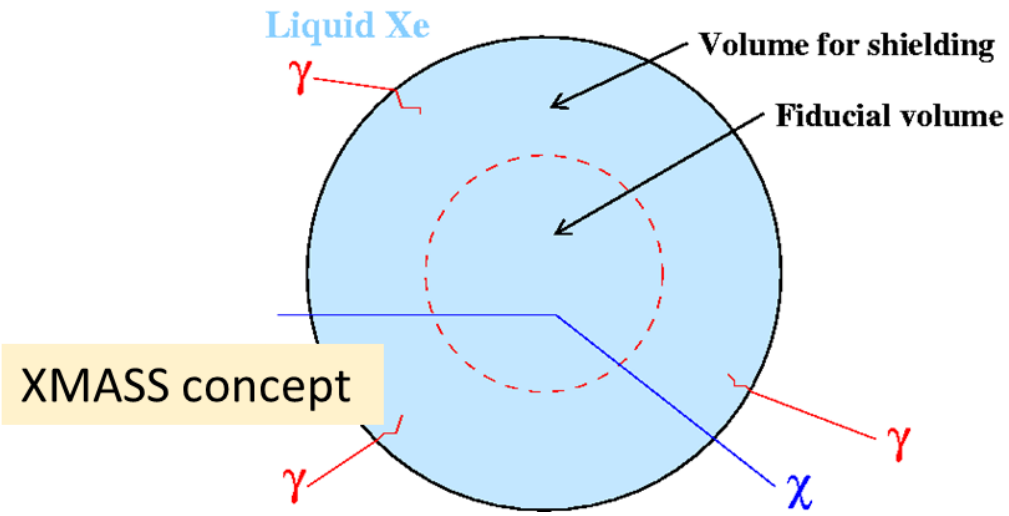
Detector stability, PMT

- 642 PMTs
- Single rate
  - Max ~kHz, average ~Hz
  - Max rate and total single rate change were used as run selection criteria for lowest energy bin 0.5~1 keVee.
- PMT gain
  - Monitored by LED
  - Small decrease of gain was observed
  - Correction in the analysis
- Dead PMT
  - Increase later part
  - Effect to surface BG were considered during analysis.

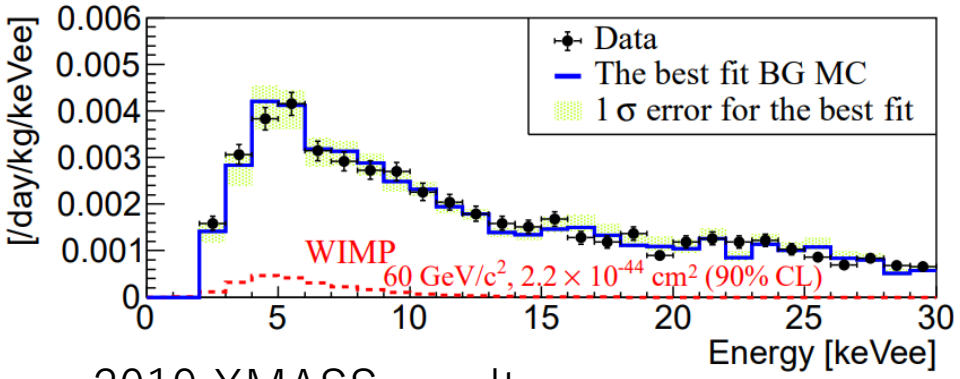
Analysis and results

- By using ~5 years full data set, WIMP dark matter searches were done.
- Fiducial volume analysis
  - Search signal inside fiducial volume
- Modulation analysis
  - Search “modulation” signal

Dark matter search with full data set



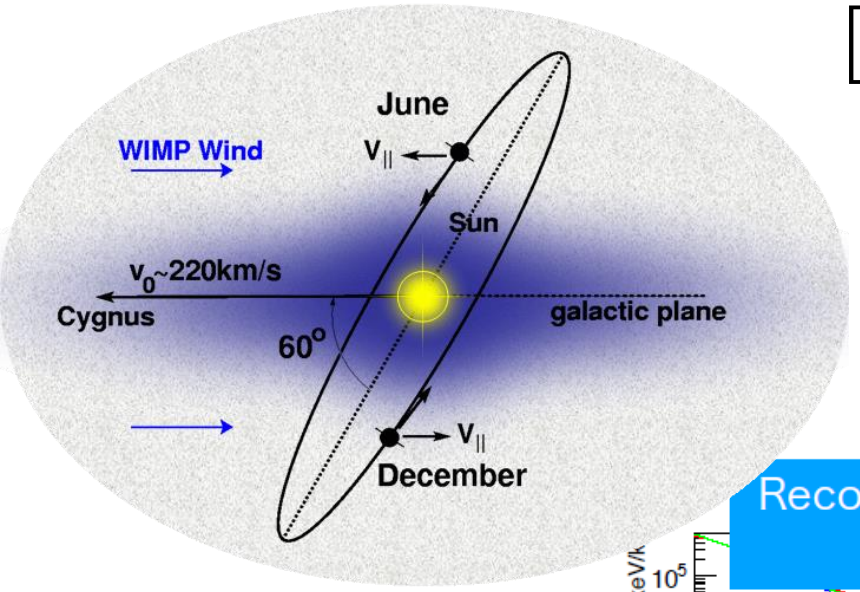
XMASS concept

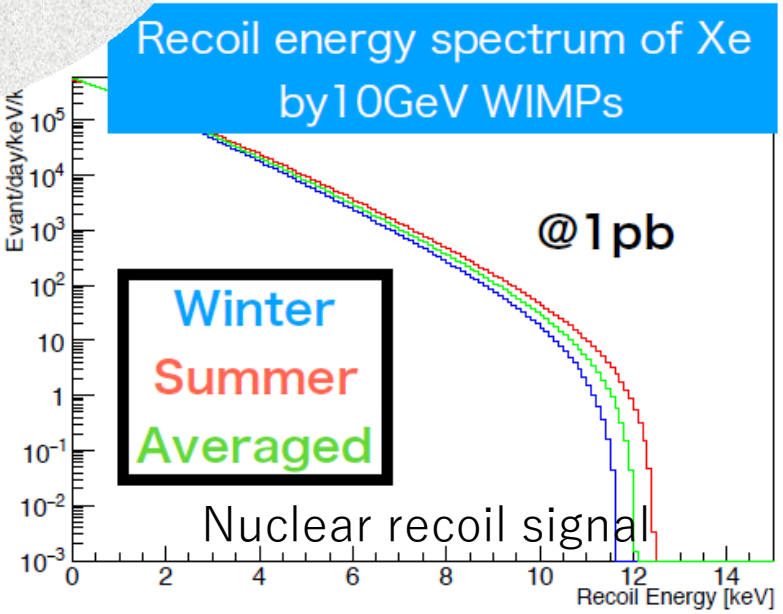


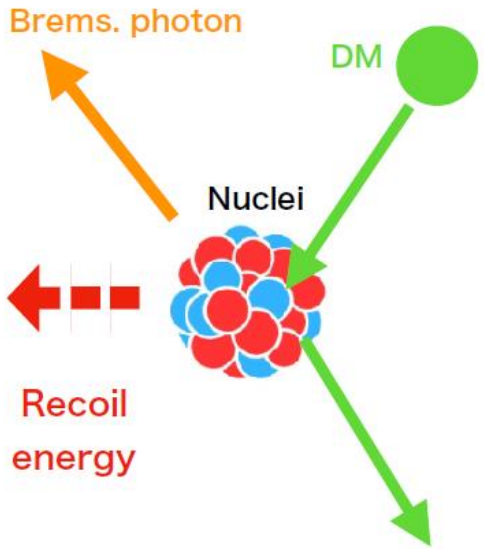
2019 XMASS results

- Fiducial volume analysis
  - Select fiducial volume event by using reconstructed position information.
  - BG from outside can be stopped by the outside shielding region.
  - Search signal by fitting data with BG + expected signal
  - Previous report, Phys. Lett. B 789 (2019) 45-53, arXiv:1804.02180 result by 705.9days data.

Dark matter search with full data set







C. Kouvaris and J. Pradler
PRL. 118, 031803

- Modulation analysis
  - Search modulation signal.
    - ~% seasonal modulation is expected.
- Results so far by XMASS
  - Search for nuclear recoil
    - 4~20GeV DM mass
    - Physical Review D 97, 102006 (2018), arXiv:1801.10096、 2.7 years livetime 800 days
  - Search for signal from bremsstrahlung
    - 0.32~1GeV DM mass
    - Physics Letters B 795 (2019) pp. 308-313, arXiv:1808.06177 [astro-ph.CO], 3.5 years, livetime 2.8 years
- In addition to update of these results, newly added, search signal from Migdal effect

Modulation analysis with Migdal effect

- Migdal effect
  - At nuclear recoil, nuclei and electrons do not move in sync.
  - Separate move causes ionization and excitation of atom.
- In M.Ibe et al., *Journal of High Energy Physics* **volume 2018**, Article number: 194 (2018)

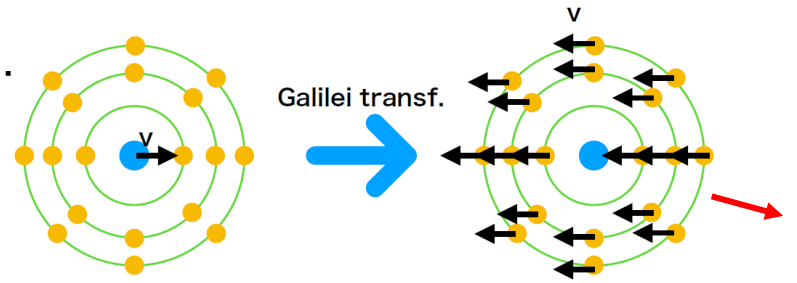
  arXiv:1707.07258v3 [hep-ph]
  - Expected energy loss in Xe
  - Though expected event rate is small, larger energy loss is expected for light dark matter.
  - Another channel for search

Migdal effect

[A. B. Migdal; 1939]

$$Z_{FI}(q_e) = \langle \Psi_F | e^{-i\mathbf{q}_e \cdot \hat{\mathbf{x}}} | \Psi_I \rangle$$

electron wave functions



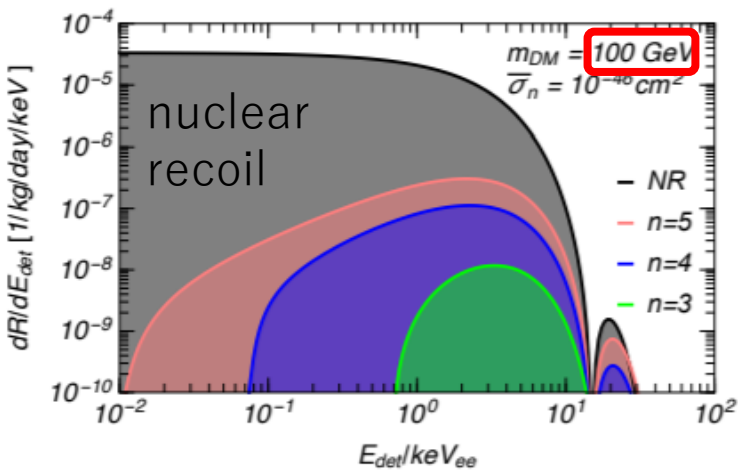
Ionization and excitation

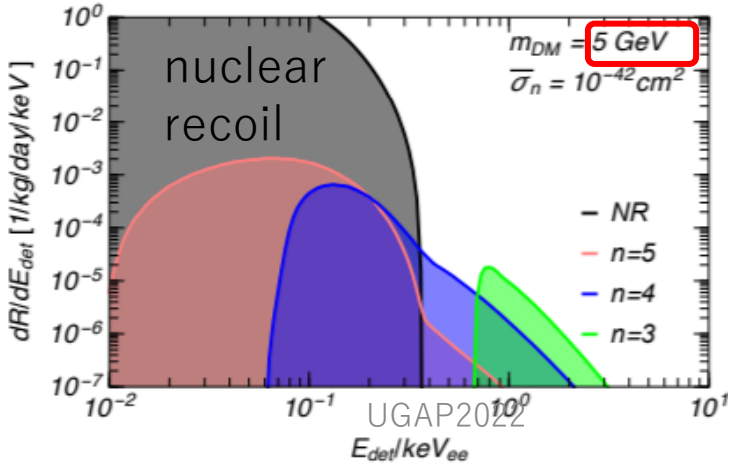
$$\frac{d\sigma}{dE_R} \simeq \sum_{E_{ec}^F} \frac{1}{2} \frac{m_A}{\mu_N^2 v_{DM}^2} |F_A(q_A^2)|^2 \bar{\sigma}_N |Z_{FI}(q_e)|^2,$$

Migdal factor

$$Z_{FI}(q_e) = \langle \Psi_F | e^{-i\mathbf{q}_e \cdot \hat{\mathbf{x}}} | \Psi_I \rangle$$

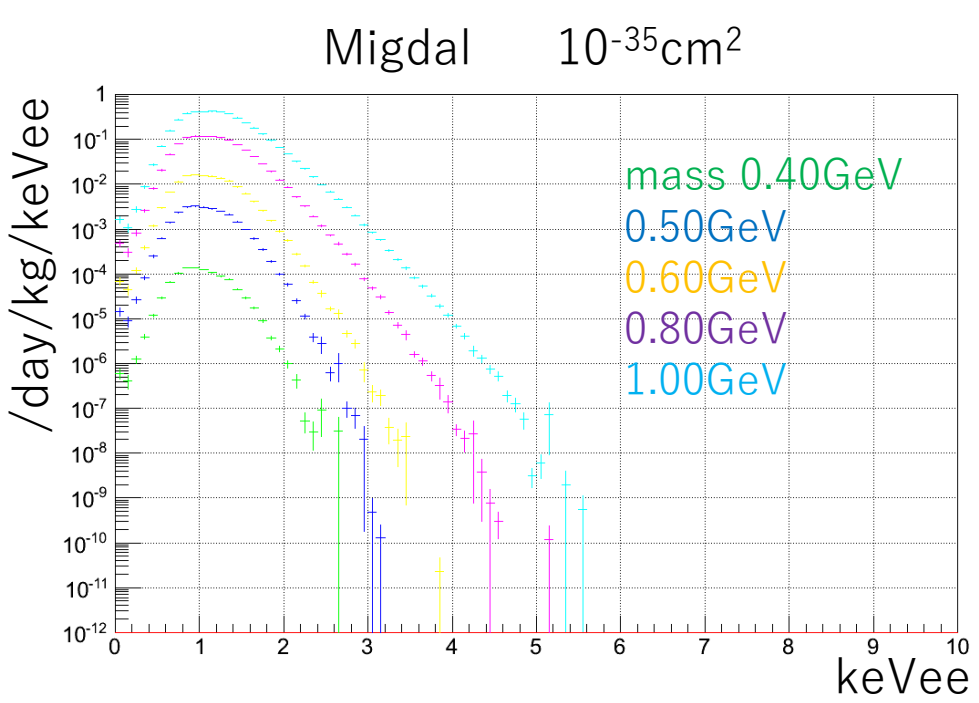
$$q_e = \frac{m_e}{m_A} q_A$$

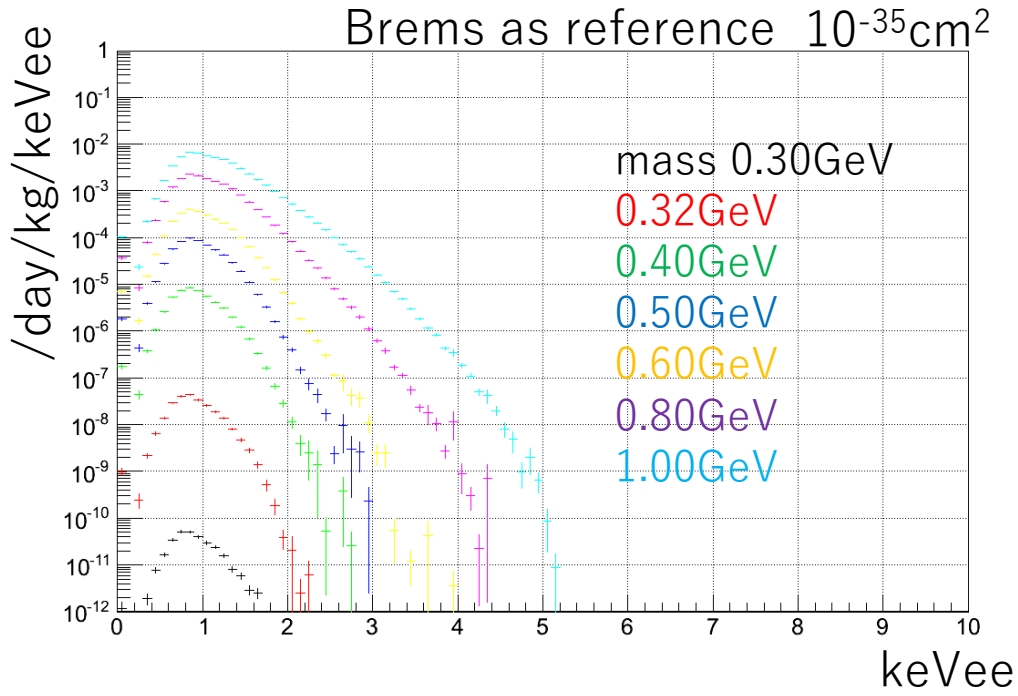




M.Ibe et al., arXiv:1707.07258v3 [hep-ph]

Modulation analysis with Migdal effect





- Step of expected signal calculation
  1. Expected energy loss calculation
     1. Energy from emitted electron and de-excitation are considered separately.
     2. Calculate energy loss spectrum for each
  2. Apply detector response
     1. Apply MC based response to each energy loss.
     2. Only above 1keVee energy loss was used.
     3. Limit from our detector calibration (escape X-ray from ^{55}Fe)
     4. de-excitation component was negligible.
- Two order lager expected signal than bremsstrahlung.

Modulation fitting

- χ^2 fit

$$\chi^2 = \sum_i^{E_{bin}} \sum_j^{t} \frac{\left(R_{data}^{i,j} - R_{exp}^{i,j}(\alpha_k)\right)^2}{\sigma_{stat}^2 + \sigma_{sys}^2} + \sum_k^{N_{sys}} \alpha_k^2$$

i : energy bin
j: time bin

Number of event of data

Expected number of event (BG + signal)

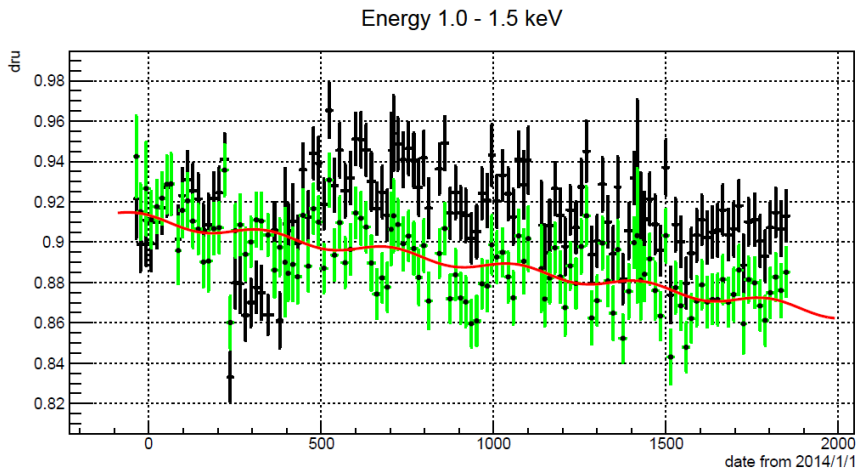
- α_k : Correlated systematics (light yield, etc)
- σ_{sys} : Others (stability of DAQ modules, etc.)

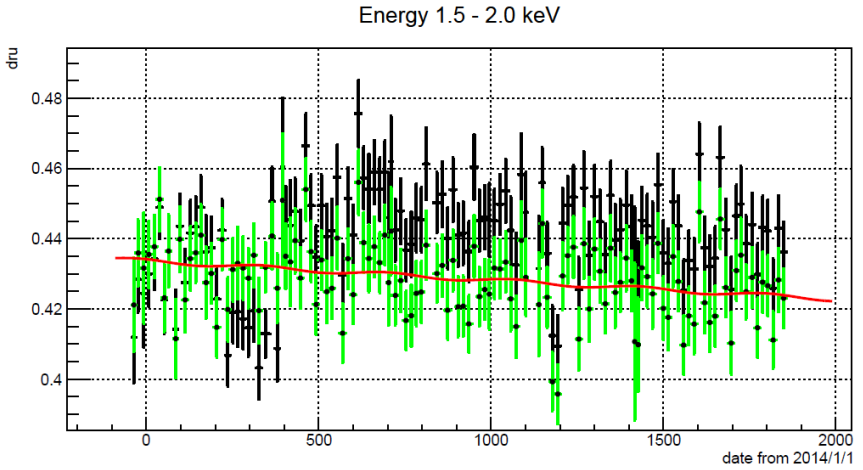
- Expected events

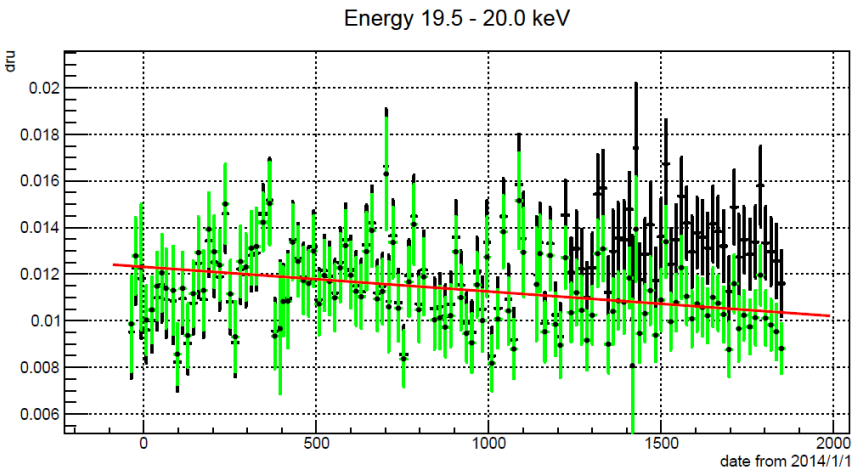
$$R_{exp} = \int_{t_j-\delta t_j}^{t_j+\delta t_j} dt \left[E_{bg} \cdot (C_{bg} + S_{bg} \cdot t) + \sigma \cdot E_{sig} \left\{ C_{sig} + A_{sig} \cos 2\pi \frac{t - t_0}{T} \right\} \right]$$

BG

Signal



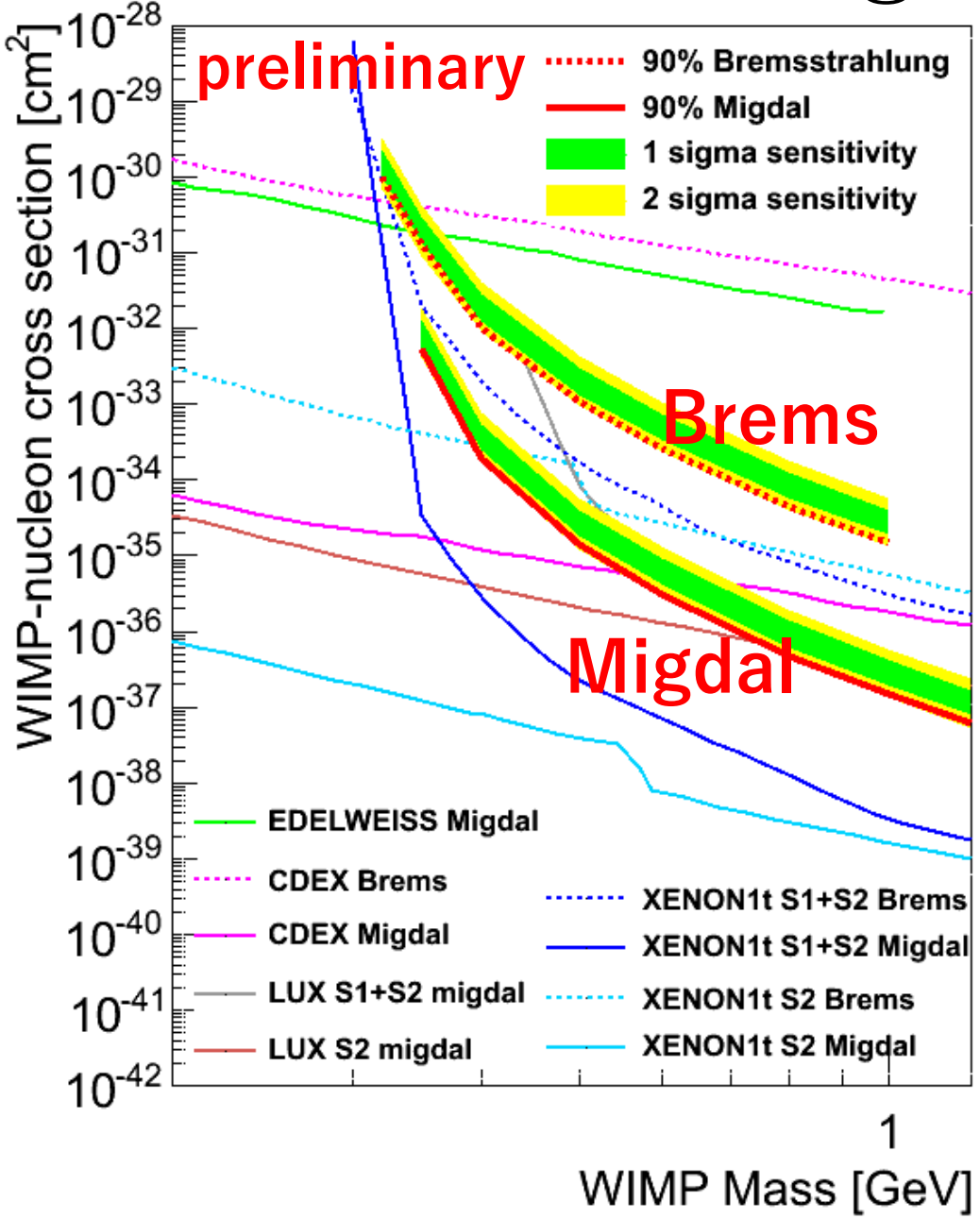




Fitting results

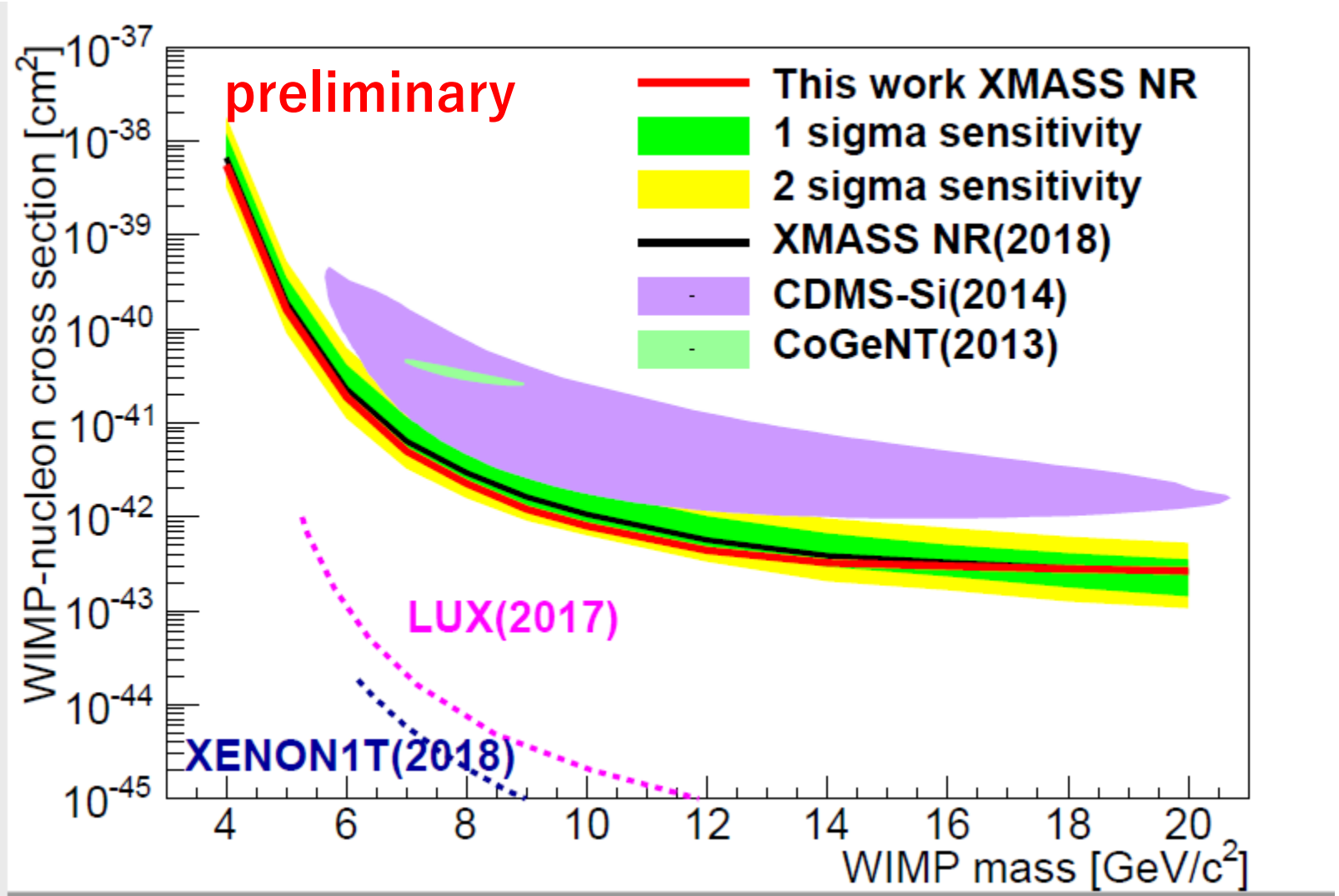
- Best fit result for Migdal signal
- DM mass 0.5GeV /c^2
- Fit with signal(with modulation)+BG(assume decrease over time)
- 1~20keVee range
- Observed data (black)
- Corrected data (green)
  - Corrected effects from PE yield change and dead PMT increase.
  - Correction factor was estimated by MC and sample data.
- linearly decrease BG + modulated signal
- No significant signal
  - Upper limit

Results for Migdal and Brems



- 90% upper limit
- Sub-GeV region
  - 0.35~4GeV /c^2 Migdal
  - 0.32~1GeV /c^2 Brems
- Brems update from 2018 results, factor ~2 improve.
- Migdal, new results
  - Migdal search realize 2 orders higher result than Brems as expected.
- World lowest modulation limits.

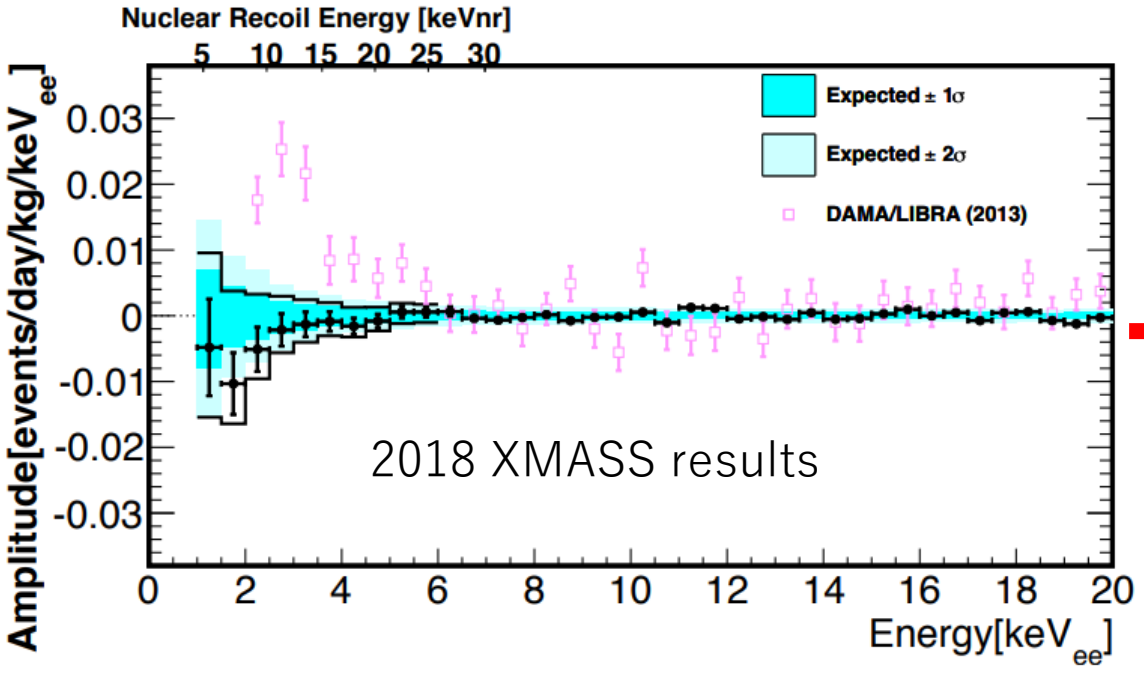
Results for nuclear recoil signal

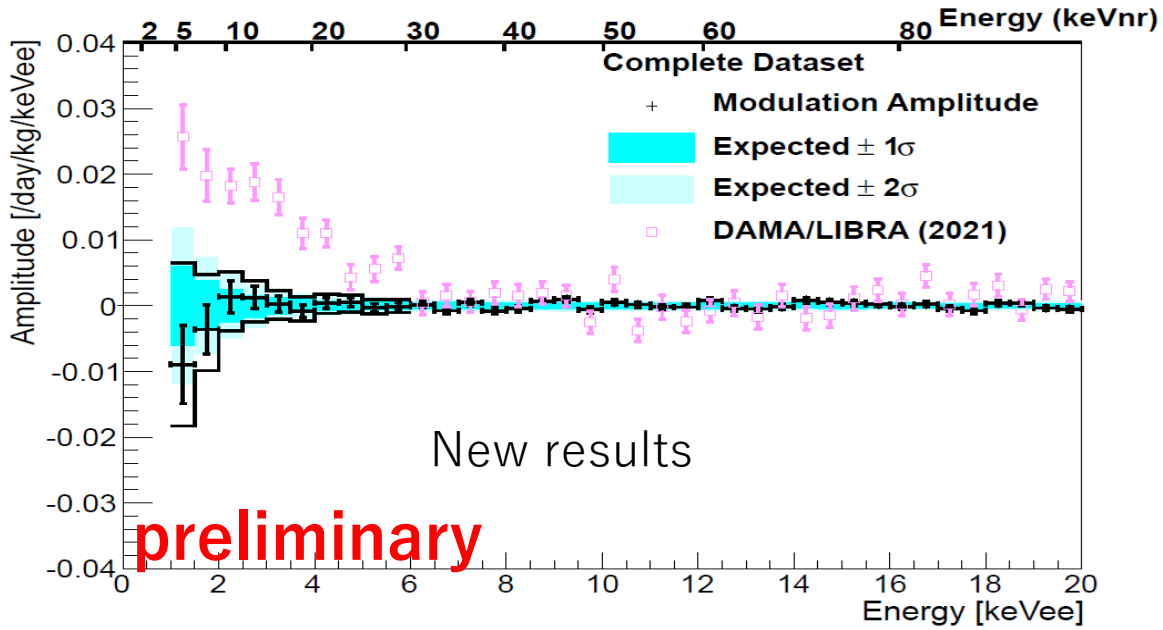


- Multi-GeV region
  - 4~20GeV /c^2
- Use lowest energy bin
  - 3hit low threshold data
  - 0.5~20keVee regions were searched.
- At most ~1.4 improved from 2018 XMASS results.

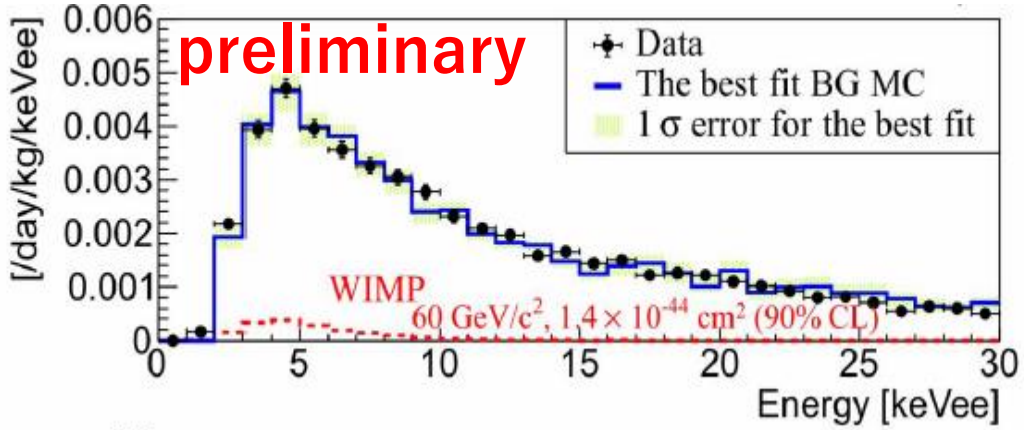
NR Model independent

- Simply estimate amplitude of annual modulation components.
- To look for variety of candidate
- Cycle and period is fixed
  - t0=152.5 days (Jun. 2nd), T = 1 year

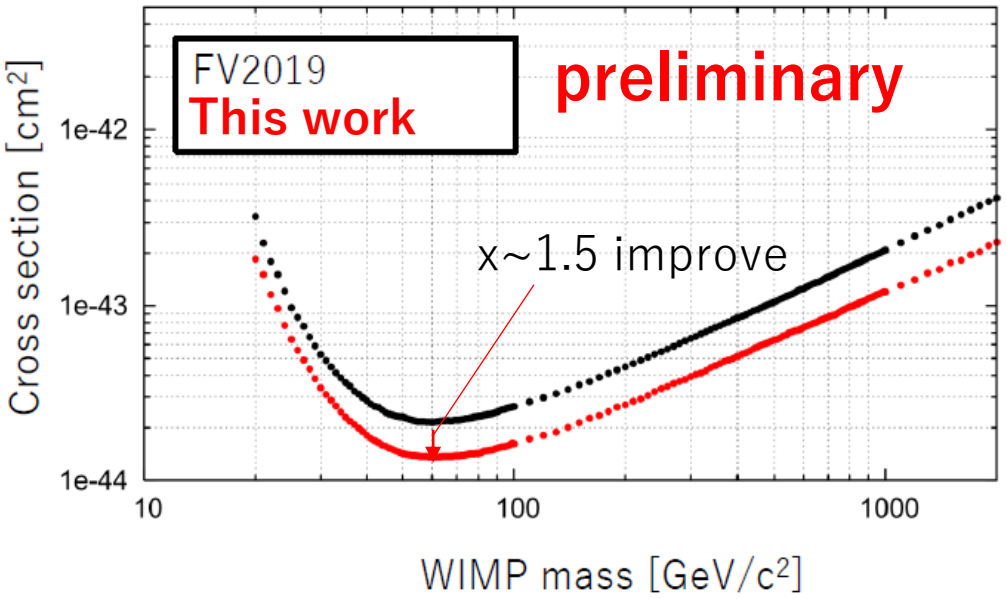




Results for fiducial volume analysis

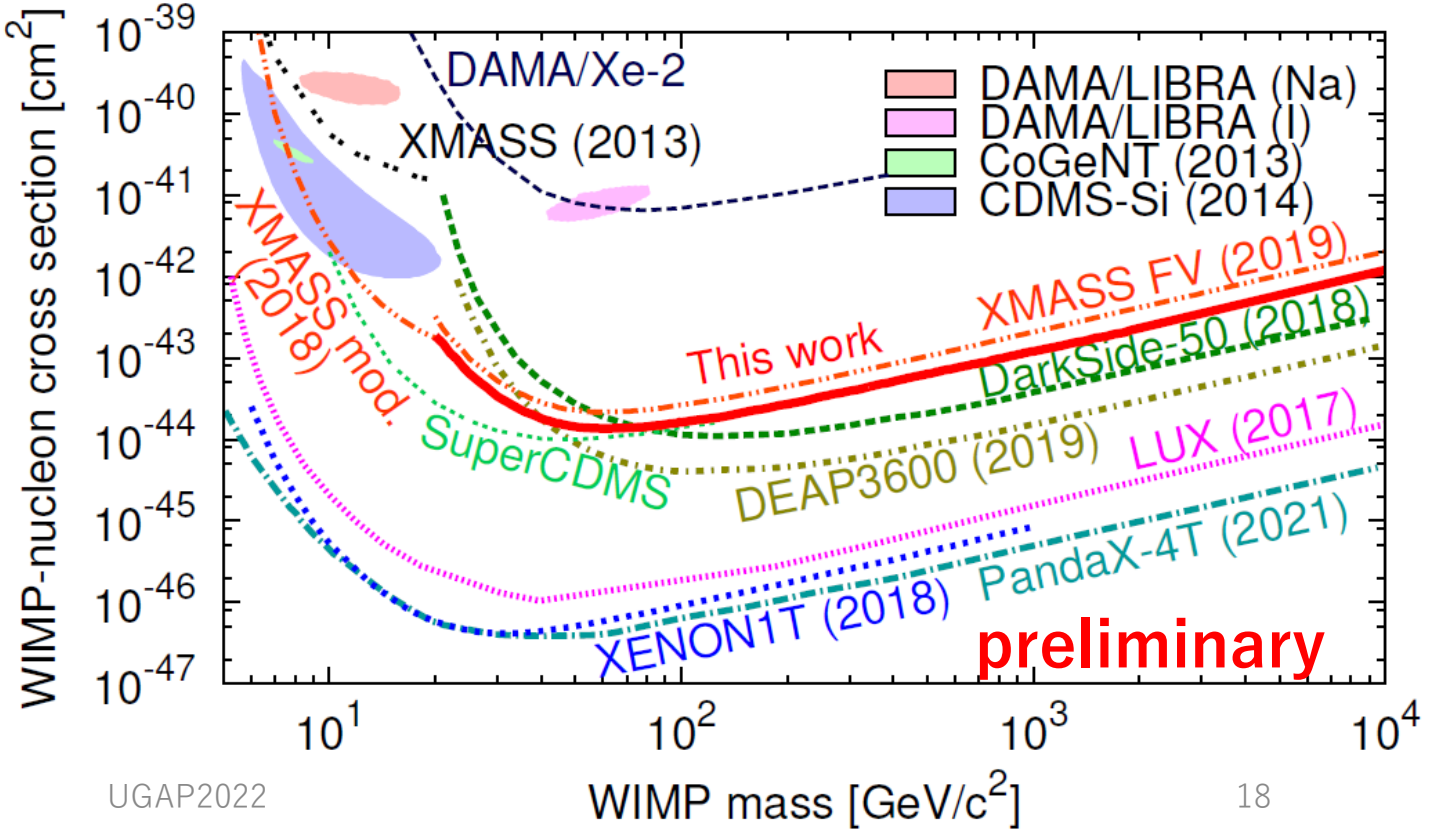


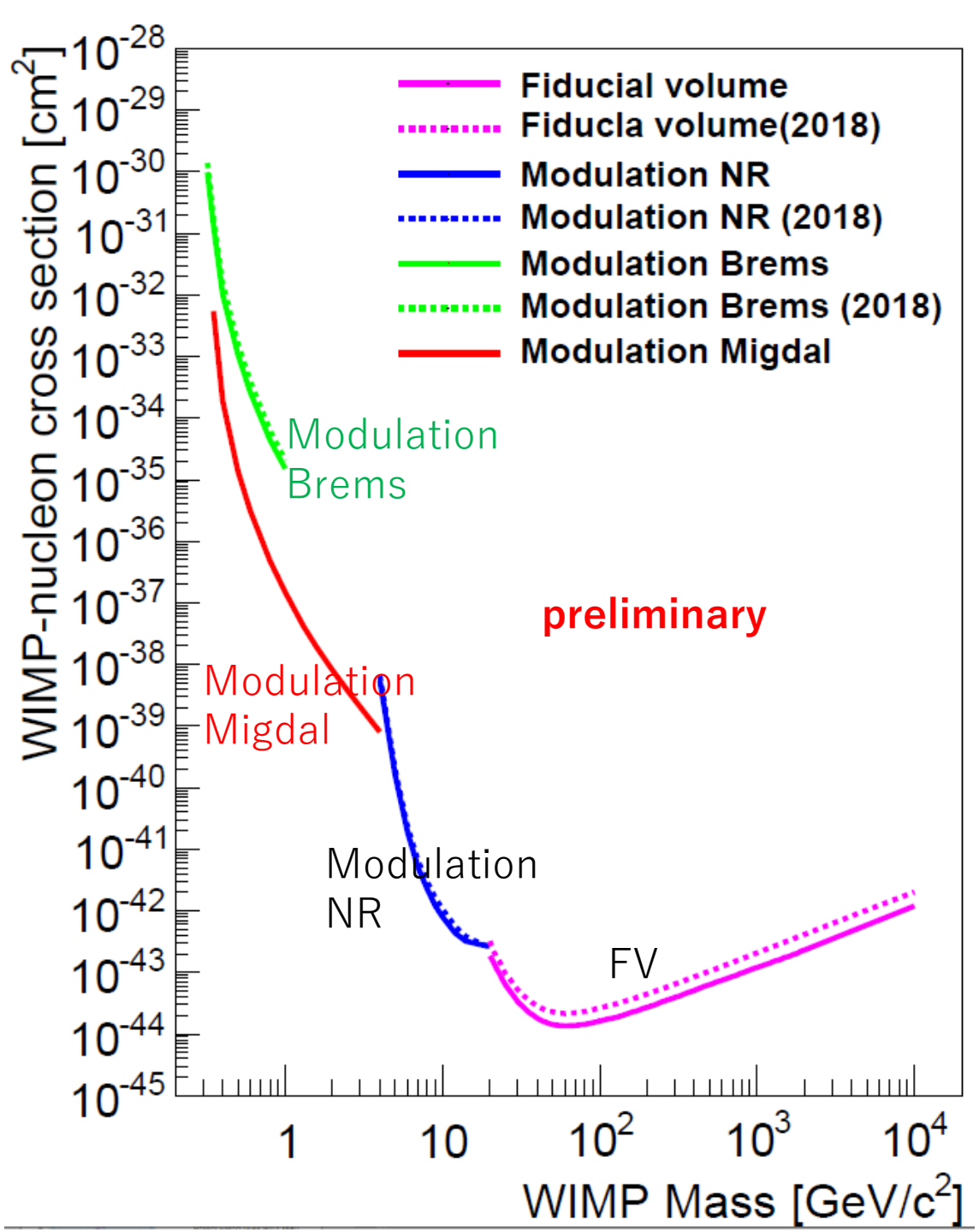
Fitting result with signal (60GeV/c²)+BG



comparison to 2019 XMASS result

- Factor 1.5 improve from 2019 results.





Summary

- XMASS-I experiment
  - Unique experiment.
  - Single phase, large volume liquid xenon detector.
  - 5 years long stable observation 2013/11~2019/3
    - live time 1590.9 days
    - stable DAQ and detector status
- Dark matter search with full data set
  - Modulation analysis
    - Update Nuclear recoil, Brems and model independent
    - Add Migdal effect signal search
      - 2 orders better results than Brems results
    - World best modulation limit.
  - Fiducial volume analysis
    - factor ~1.5 improve from 2019 result
- Preparing paper