

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

K. Abe

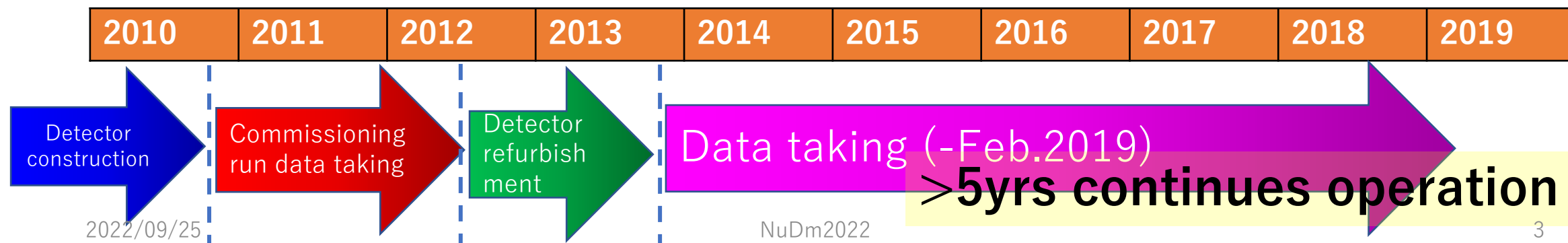
Kamioka observatory, ICRR, the University of Tokyo
for the XMASS collaboration

Contents

- XMASS-I experiment
- Full data set of XMASS
 - ~5 years long stable observation
- Analysis and results
 - Fiducial volume analysis
 - Modulation analysis
- Summary

XMASS-I experiment

- Unique experiment
 - Single phase (scintillation photon only) liquid xenon detector.
 - Large volume $\sim 1\text{t}$
 - Long stable observation period, 5 years
 - Large light yield $\sim 14\text{pe/keV}$ and low threshold $\sim 0.5\text{keVee}$
- 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.

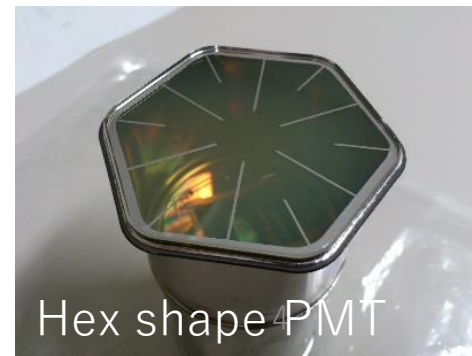
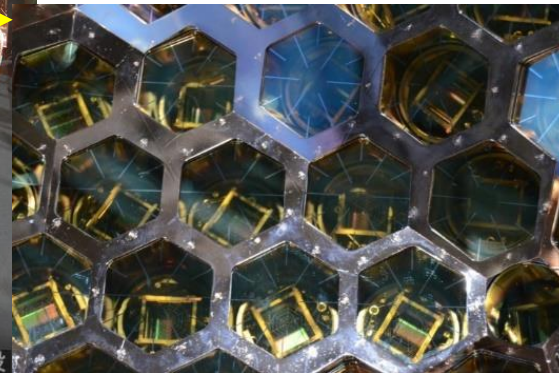
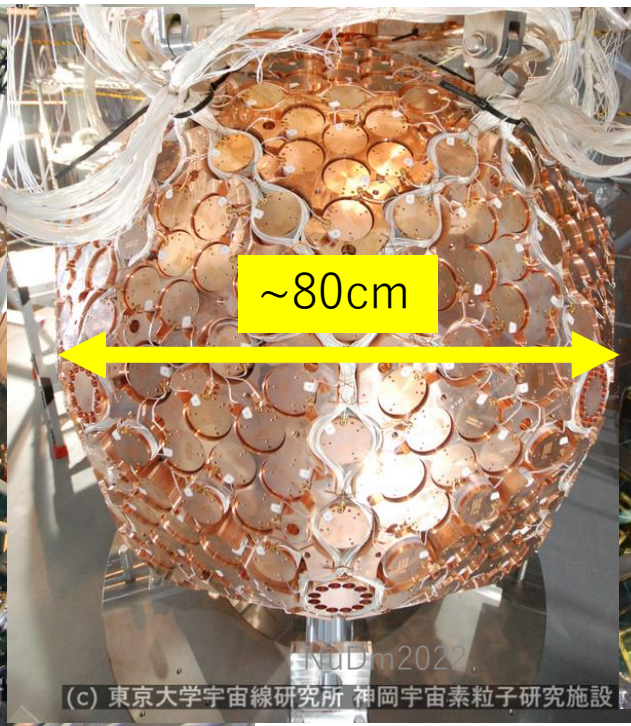
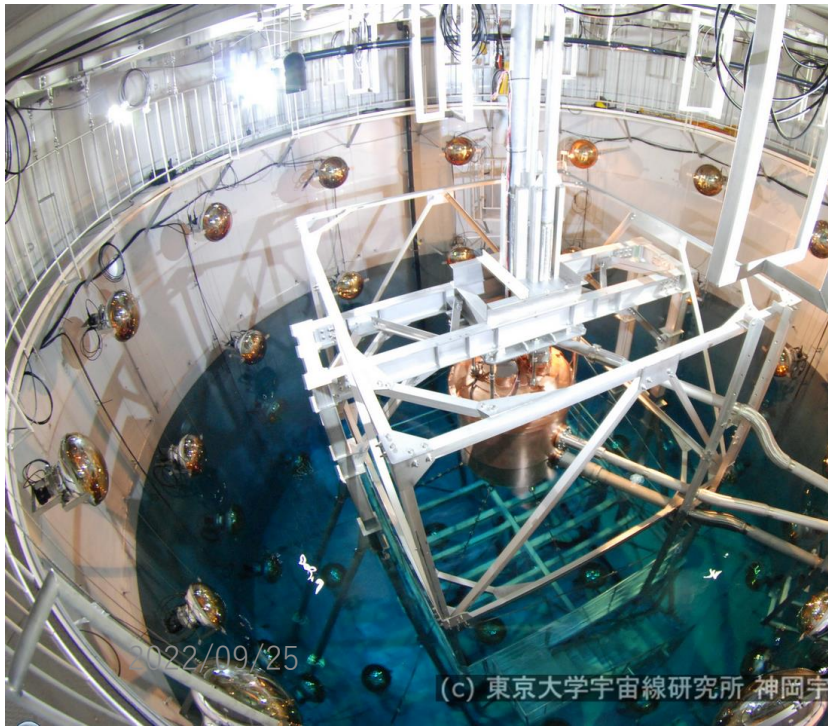
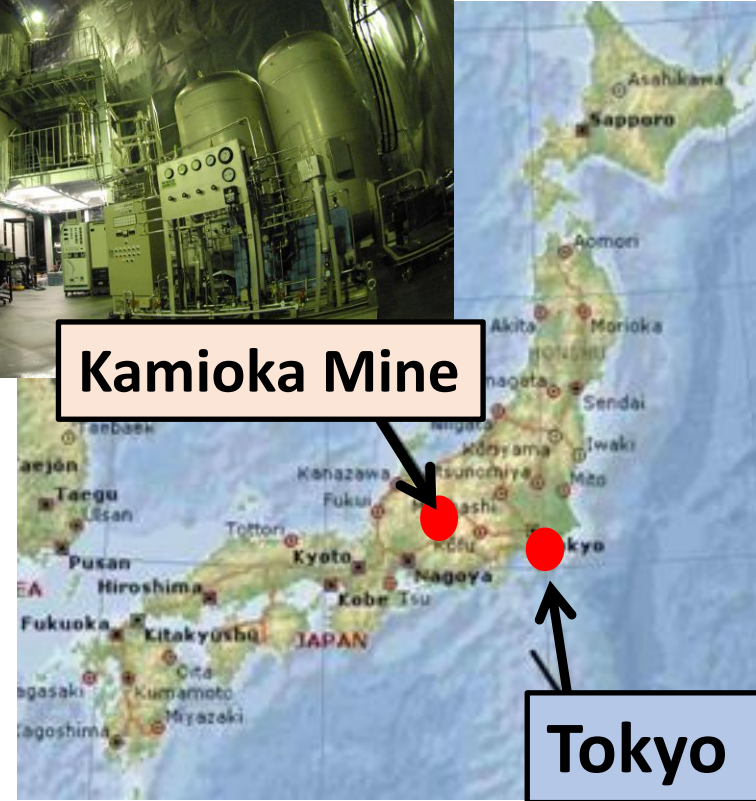


XMASS detector

- 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



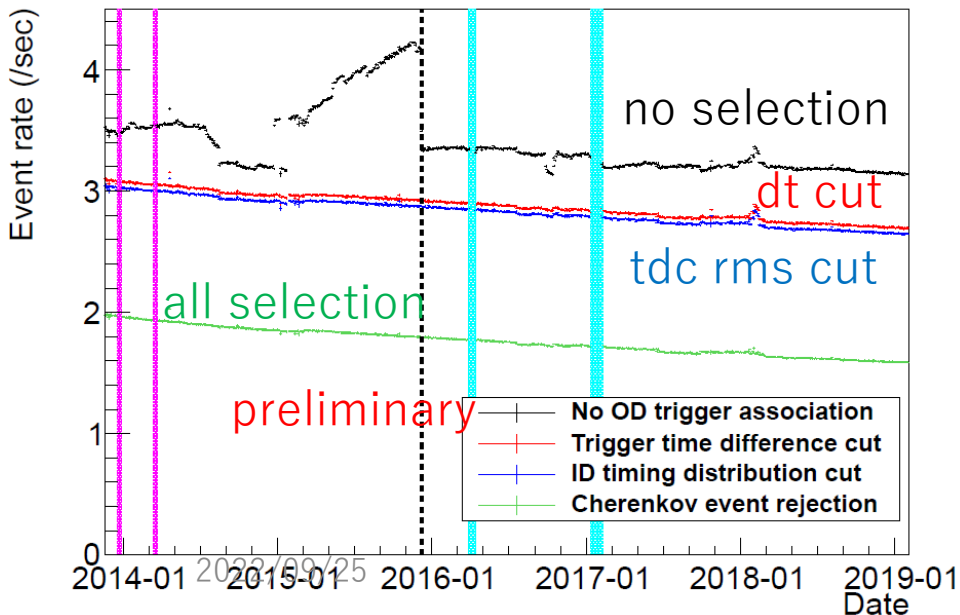
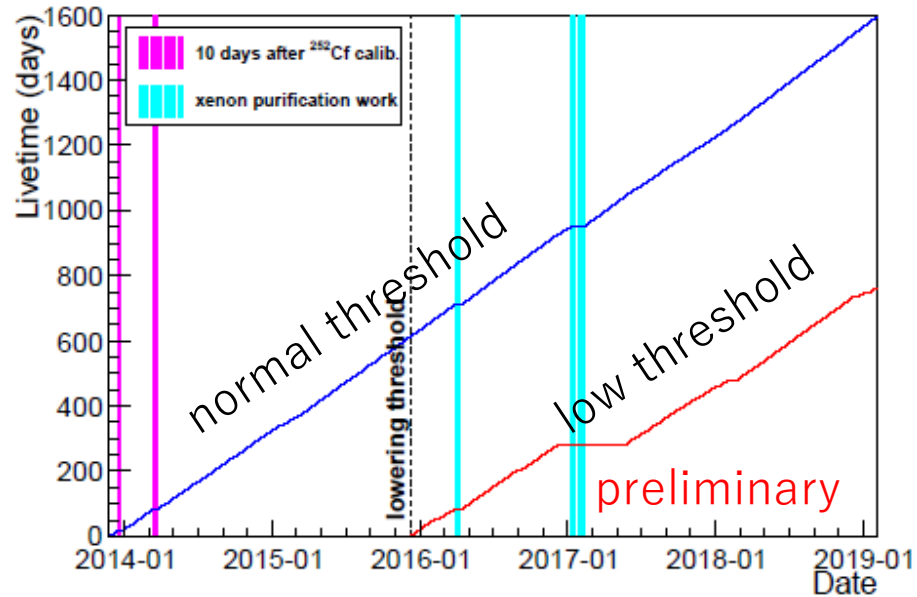
Hex shape PMT

2022/09/25

(c) 東京大学宇宙線研究所 神岡宇

(c) 東京大学宇宙線研究所 神岡宇宙素粒子研究施設

Full data set of analysis

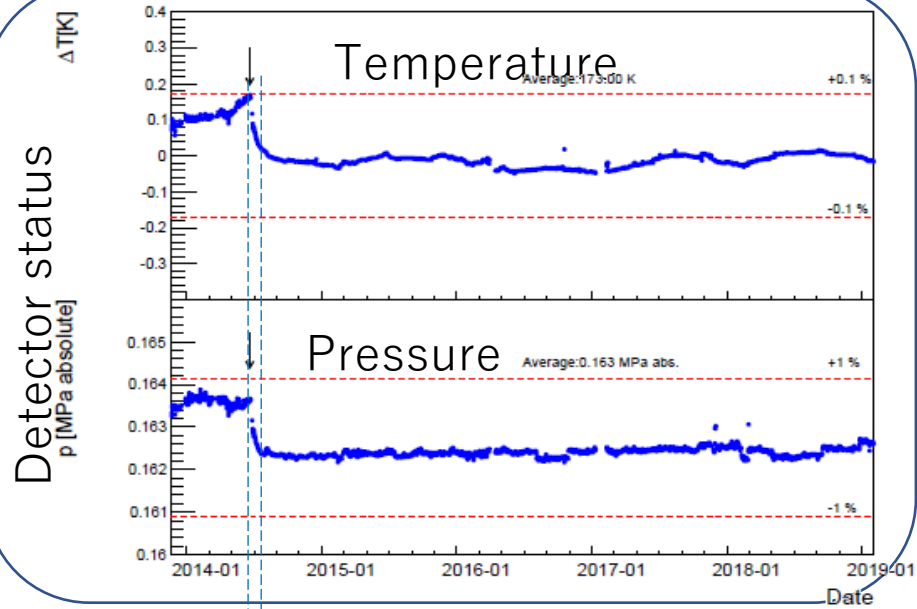


- ~5 years long stable observation
- Stable observation was realized
 - Top, steadily accumulated data
 - 2013/11/20~2019/2/1
 - Normal threshold 4hit ~1keVee
 - live time 1590.9 days
 - Low threshold 3hit ~0.5keVee
 - Started from middle of the experiment
 - live time 768.8 days
 - Relatively longer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

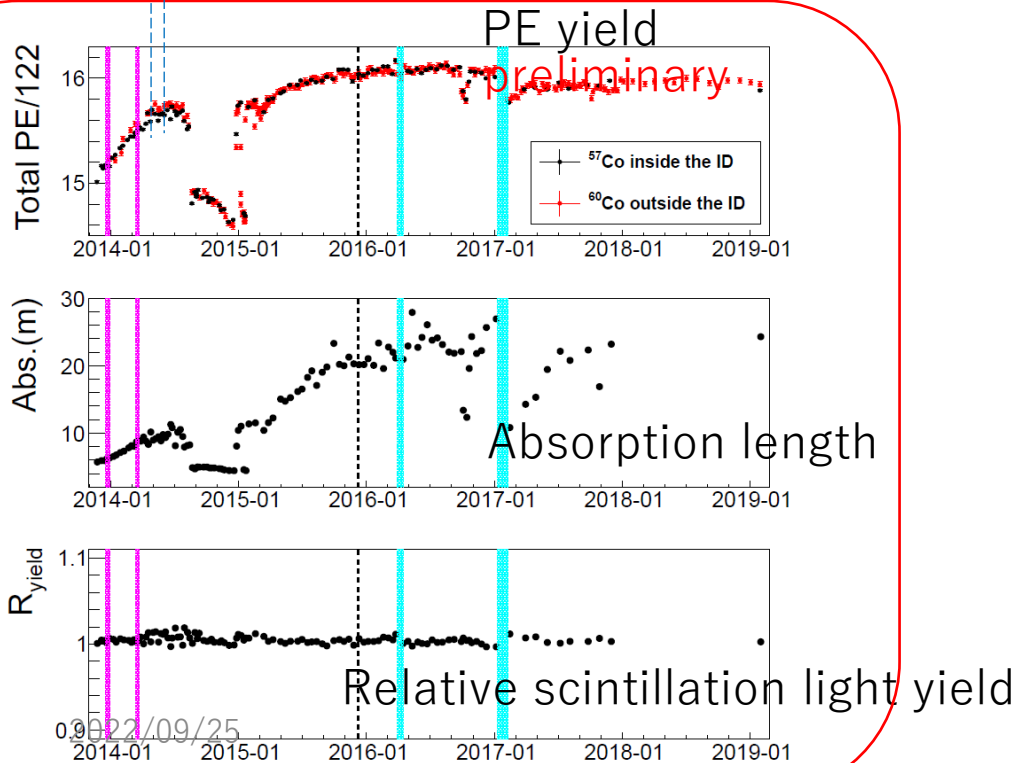
Detector stability

- 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.

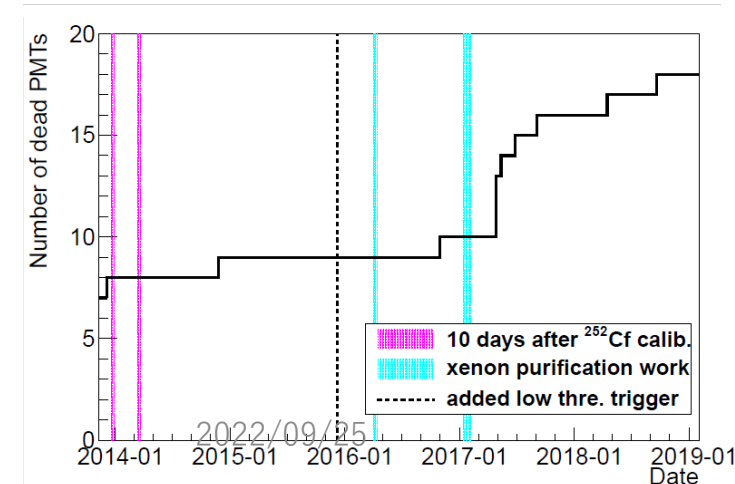
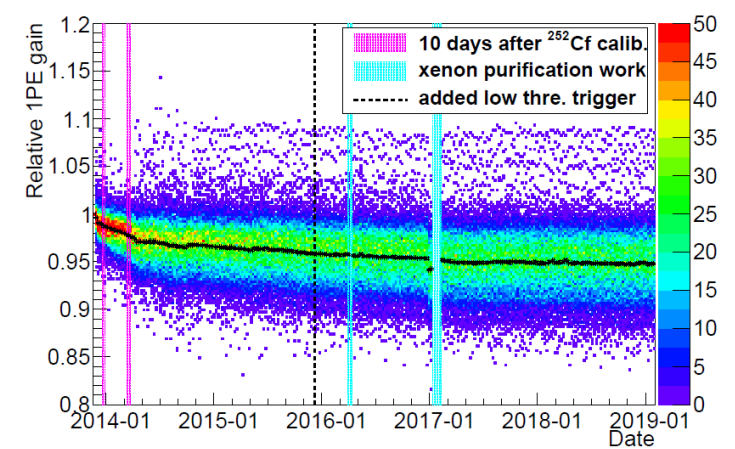
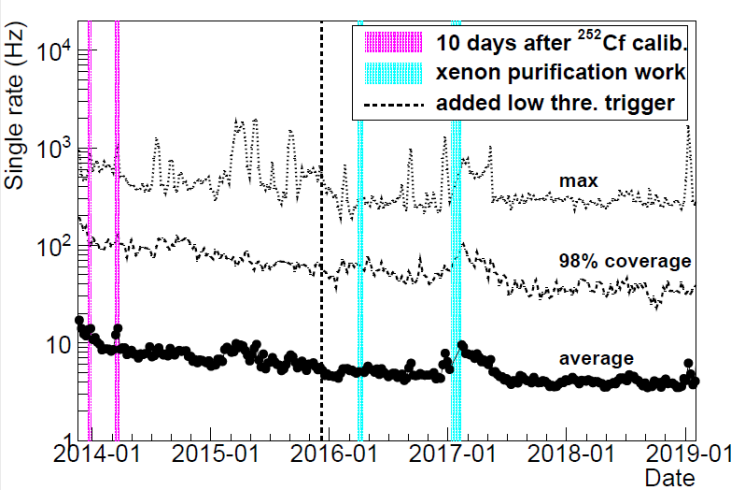
Detector status



Optical property of Xenon



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

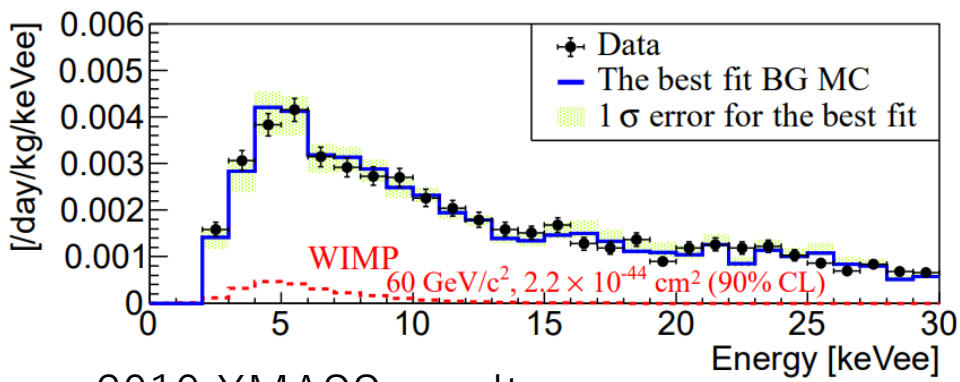
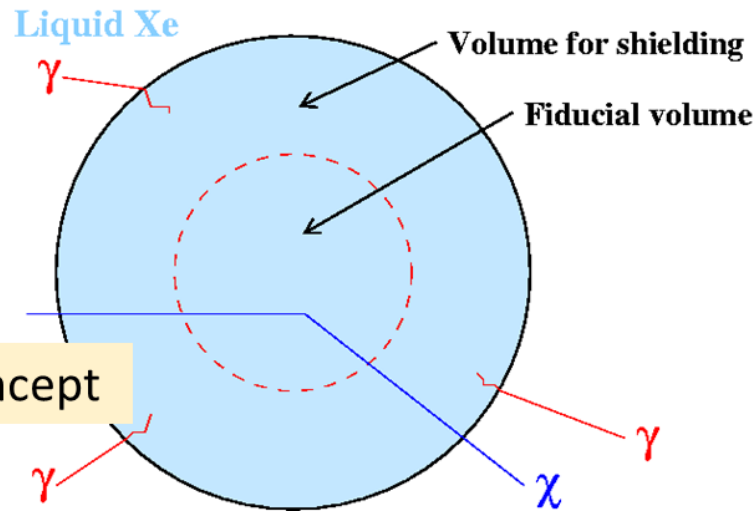
- By using ~5 years full data set, WIMP dark matter searches were done.
- Fiducial volume analysis
 - Search signal inside fiducial volume
- Modulation analysis
 - Search “modulation” signal

Dark matter search with full data set

- Fiducial volume analysis

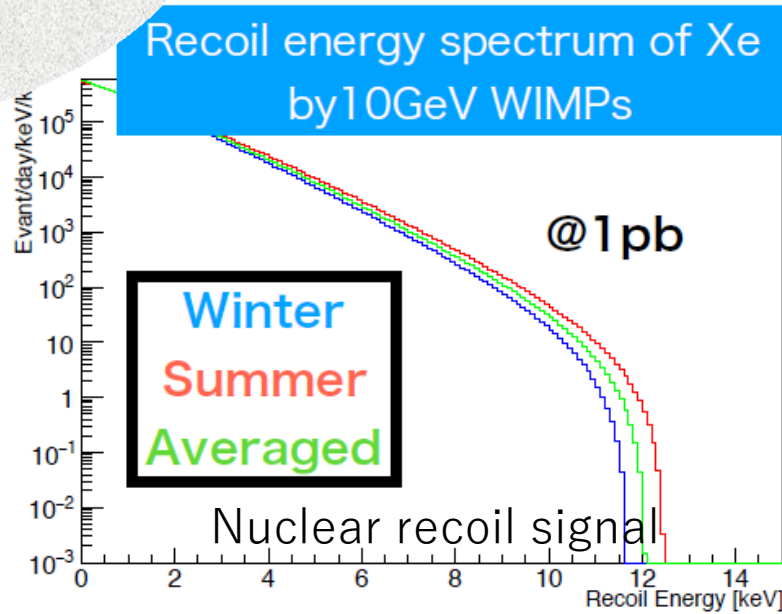
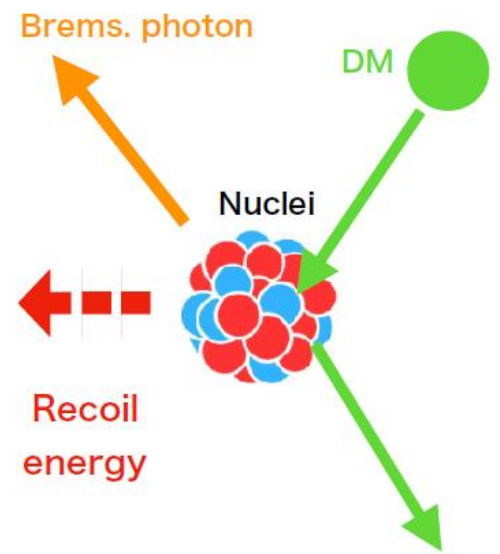
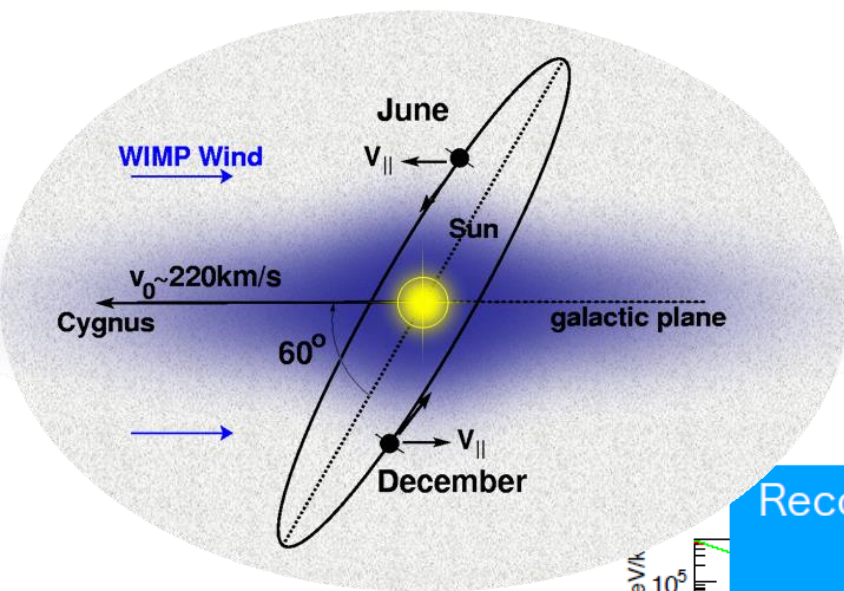
- Select fiducial volume event by using reconstructed position information.
- BG from outside can be stopped by the outside shielding region.
- Search signal by fitting data with BG + expected signal
- Previous report,

[Phys. Lett. B 789 \(2019\)4553](#), [arXiv:1804.02180](#)
result by 705.9days data.



2019 XMASS results

Dark matter search with full data set



- Modulation analysis
 - Search modulation signal.
 - ~% seasonal modulation is expected.
- Results so far by XMASS
 - Search for nuclear recoil
 - 4~20 GeV DM mass
 - [Physical Review D 97, 102006 \(2018\)](#), [arXiv:1801.10096](#), 2.7 years livetime 800 days
 - Search for signal from bremsstrahlung
 - 0.32~1 GeV 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

C. Kouvaris and J. Pradler
PRL 118, 031803
2022/09/25

Modulation analysis with Migdal effect

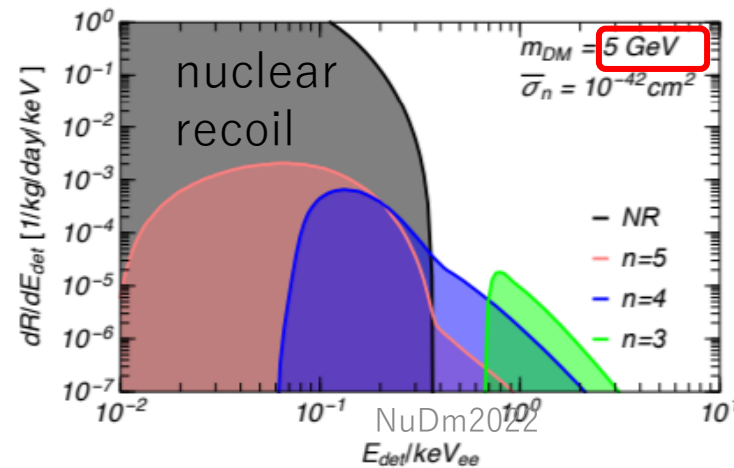
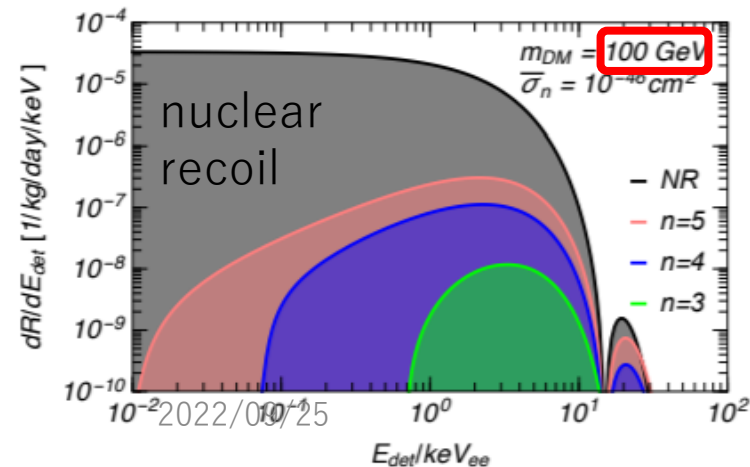
• Migdal effect

- 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

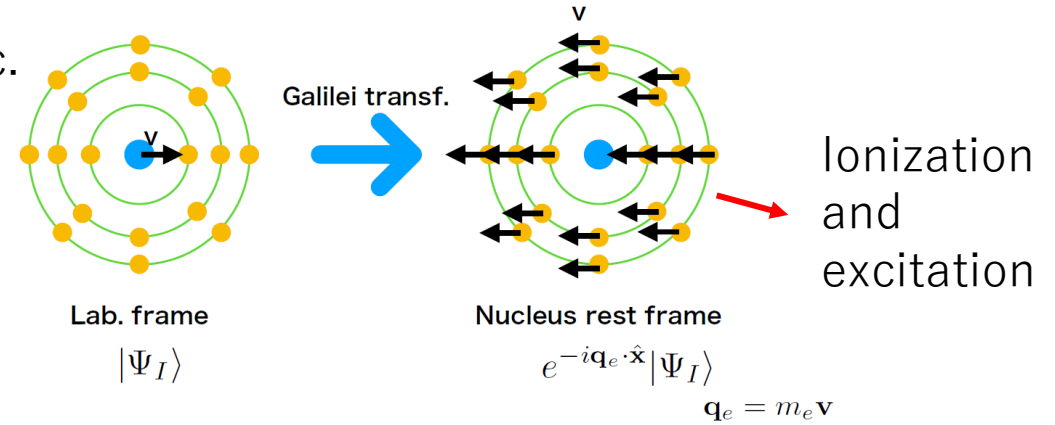


Migdal effect

[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



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

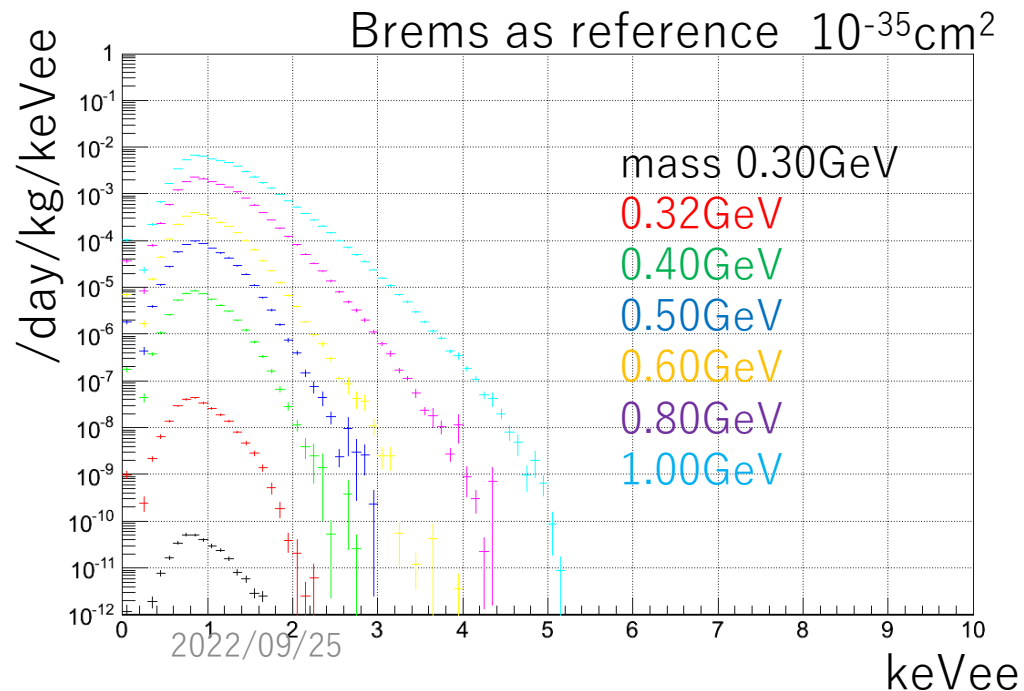
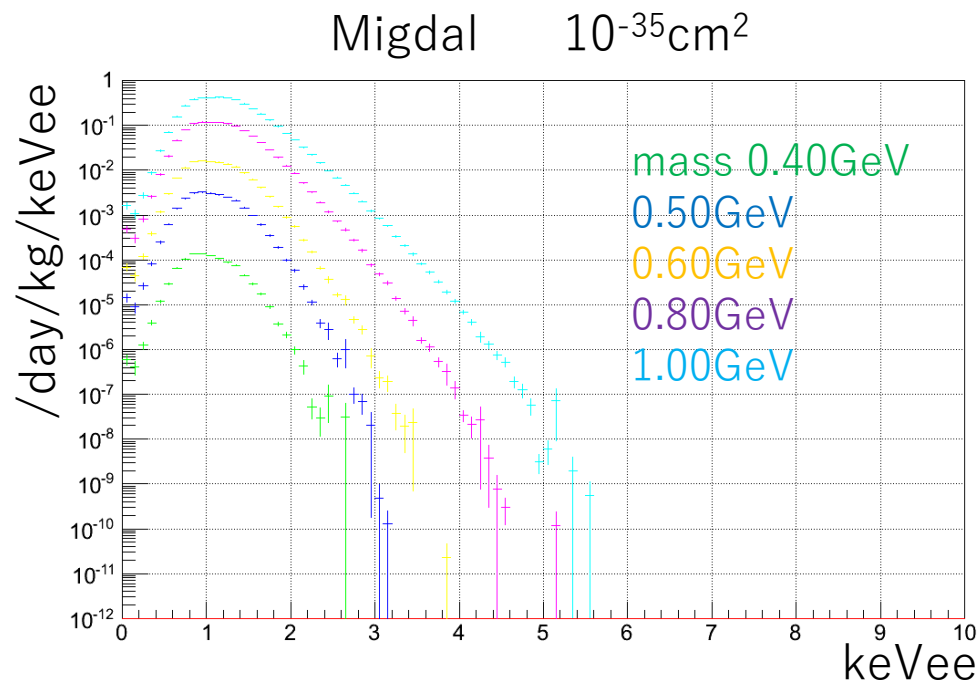
Migdal factor

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

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

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. (Limit from our detector calibration, escape X-ray from ^{55}Fe)
 3. de-excitation component was negligible.
- Two order larger 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

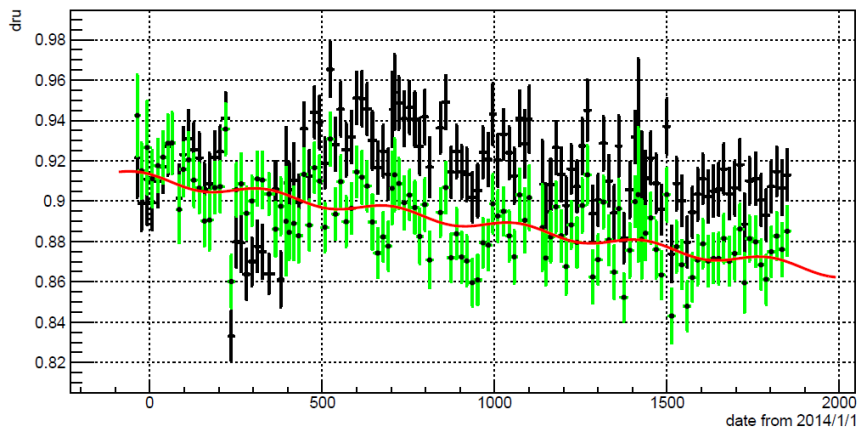
Number of event of data (points to $R_{data}^{i,j}$)
Expected number of event (BG + signal) (points to $R_{exp}^{i,j}(\alpha_k)$)

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

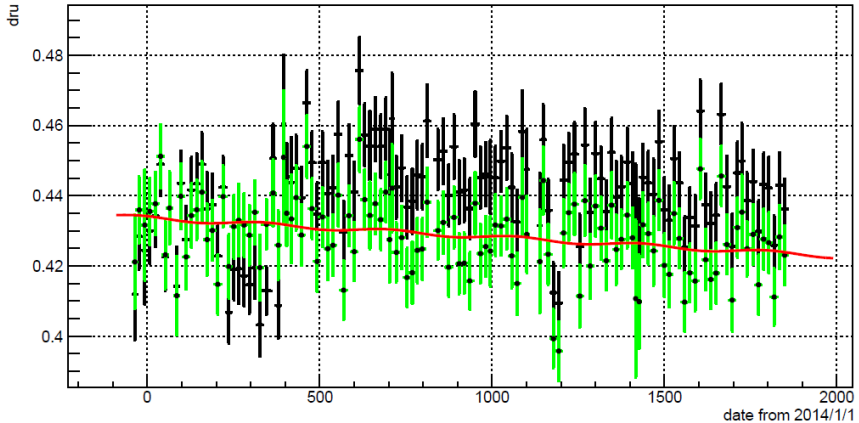
- Expected events

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

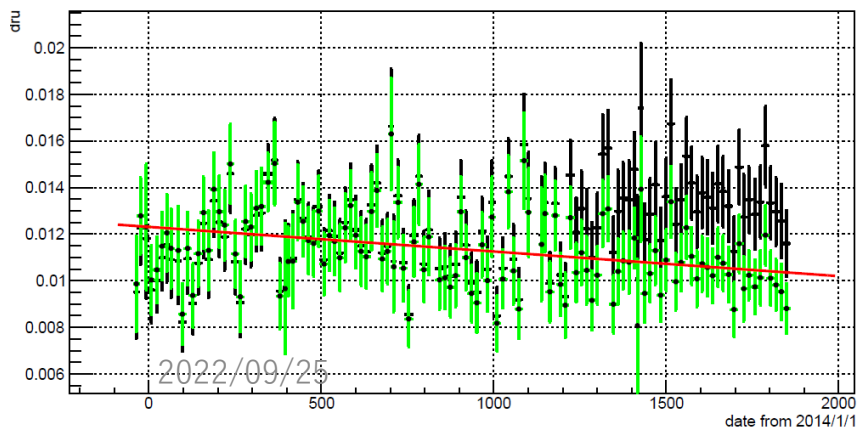
Energy 1.0 - 1.5 keV



Energy 1.5 - 2.0 keV



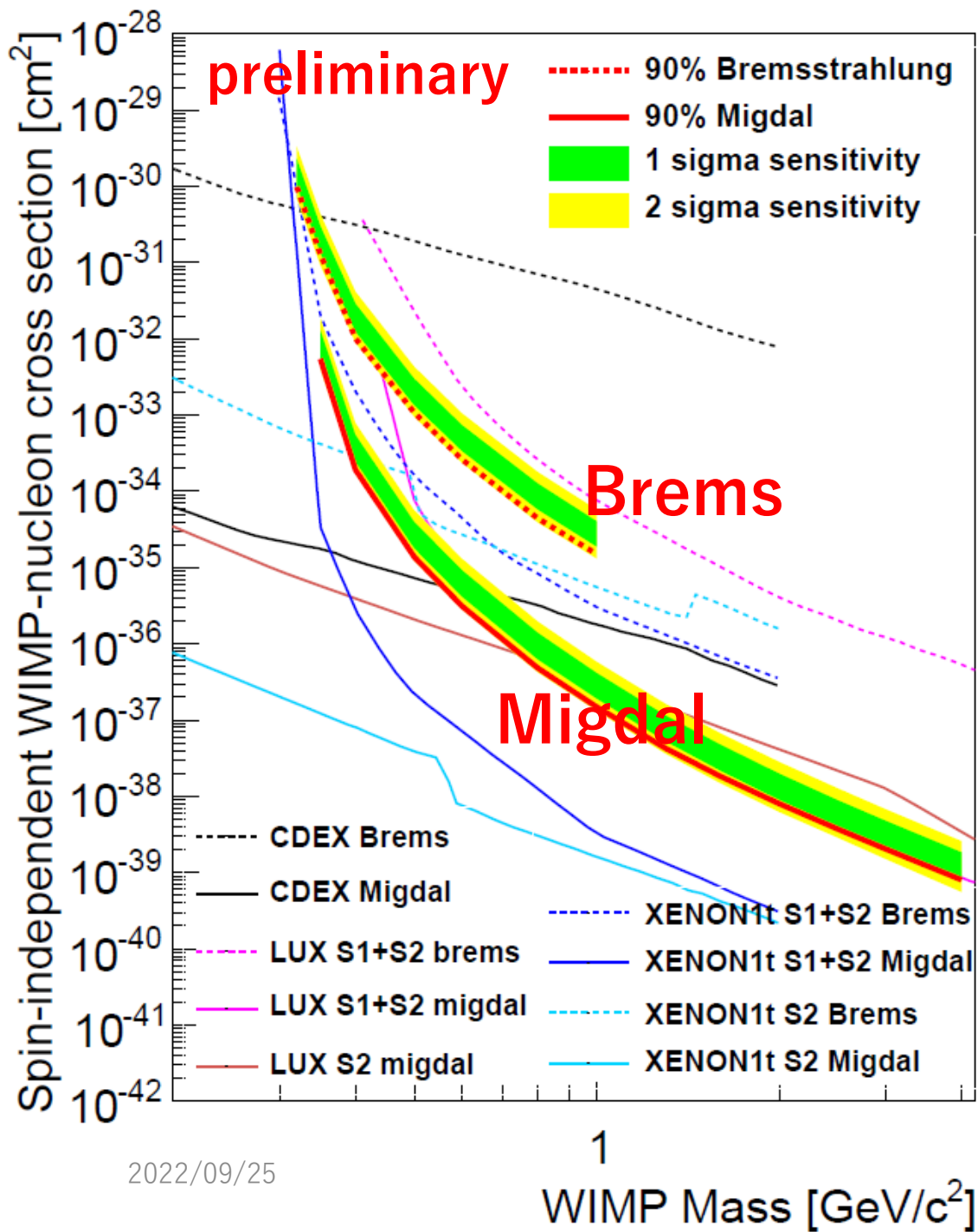
Energy 19.5 - 20.0 keV



Fitting results

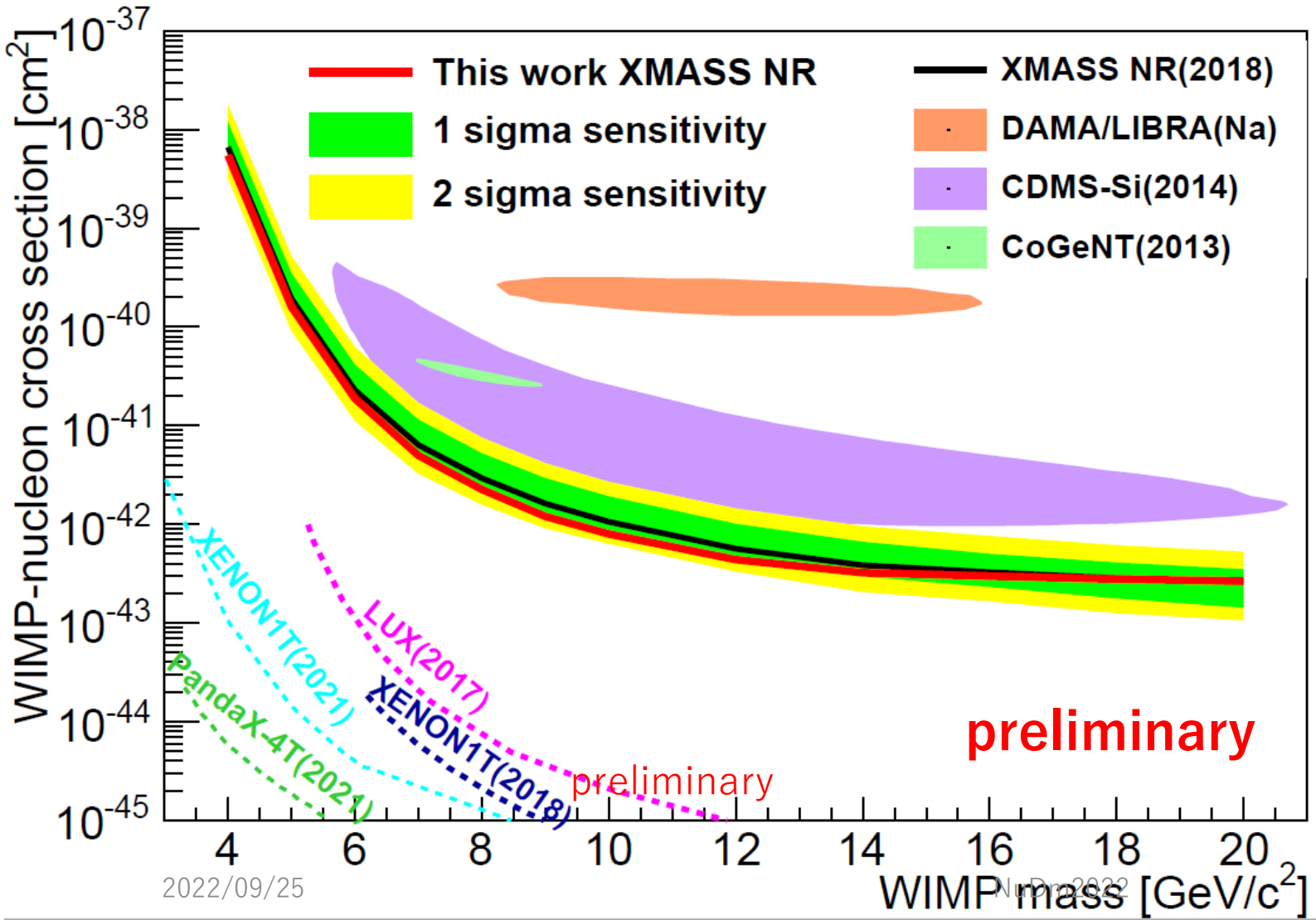
- Best fit result for Migdal signal
- DM mass $0.5 \text{ GeV} / c^2$
- Fit with signal(with modulation)+BG(assume decrease over time)
- 1~20keVee range
- Observed data (black)
- Corrected data (green)
 - Corrected effects from PE yield change and dead PMT increase.
 - Correction factor was estimated 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
 - $0.35 \sim 4 \text{ GeV}/c^2$ Migdal
 - $0.32 \sim 1 \text{ GeV}/c^2$ 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.

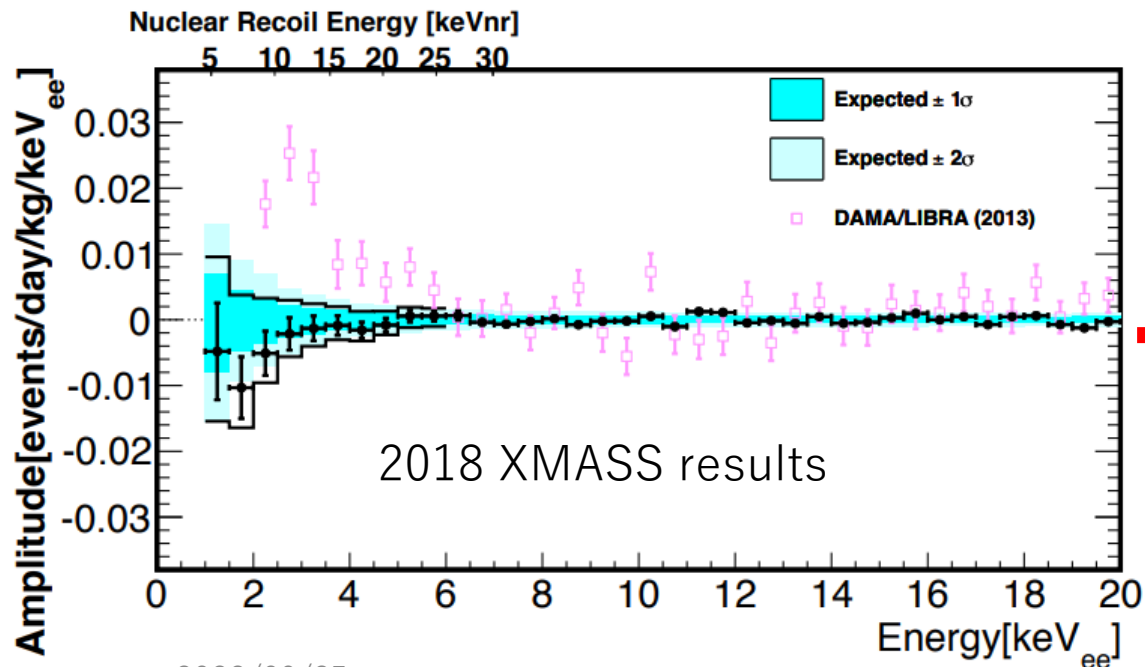
Results for nuclear recoil signal



- Multi-GeV region
 - 4~20 GeV /c²
- Use lowest energy bin
 - 3hit low threshold data
 - 0.5~20keVee regions were searched.
- At most ~1.4 improved from 2018 XMASS results.

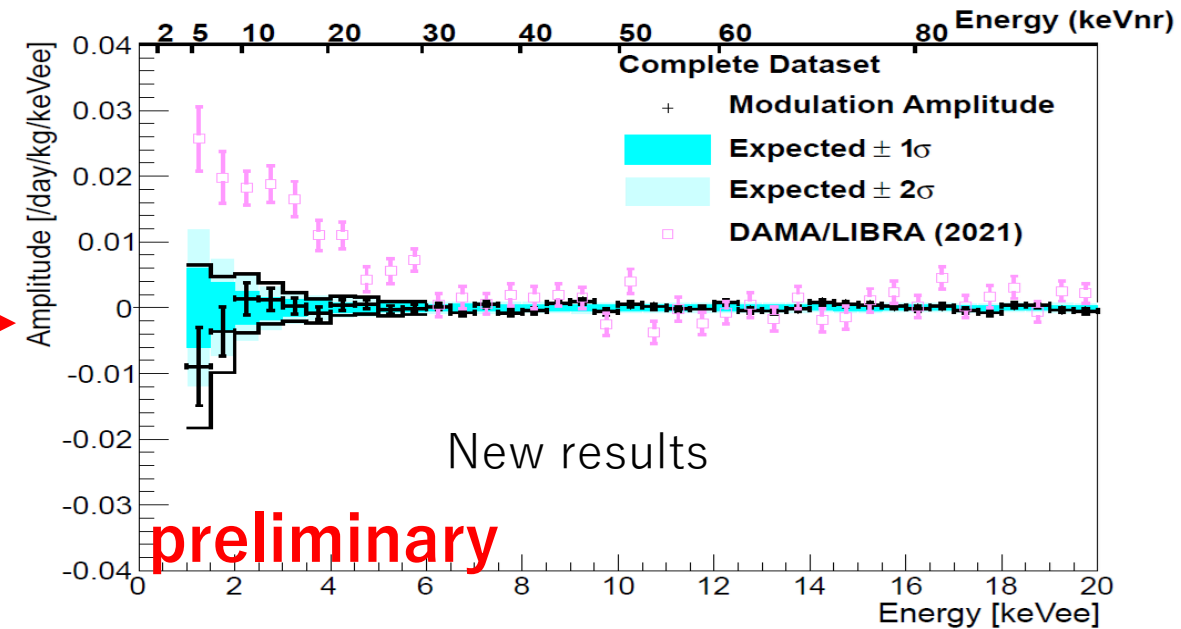
NR Model independent

- Simply estimate amplitude of annual modulation components.
- To look for variety of candidate
- Cycle and period is fixed
 - $t_0=152.5$ days (Jun. 2nd), $T = 1$ year



2022/09/25

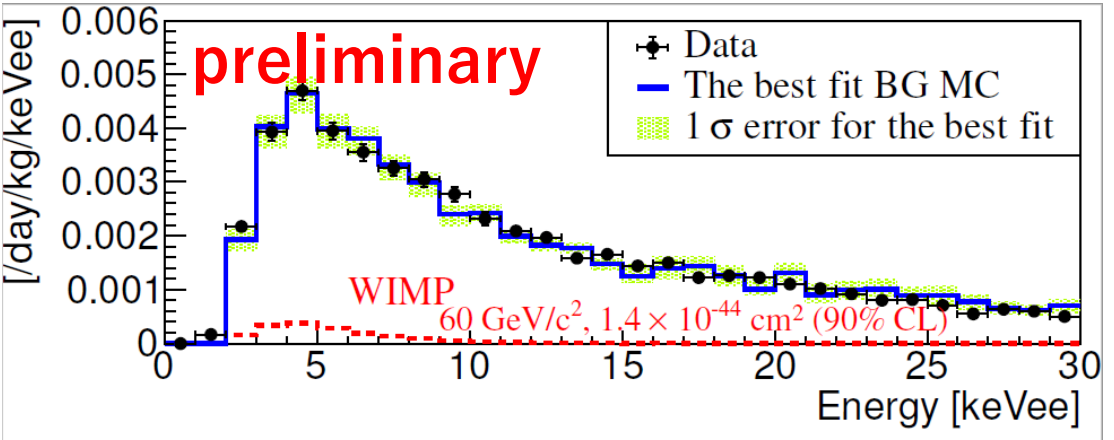
NuDm2022



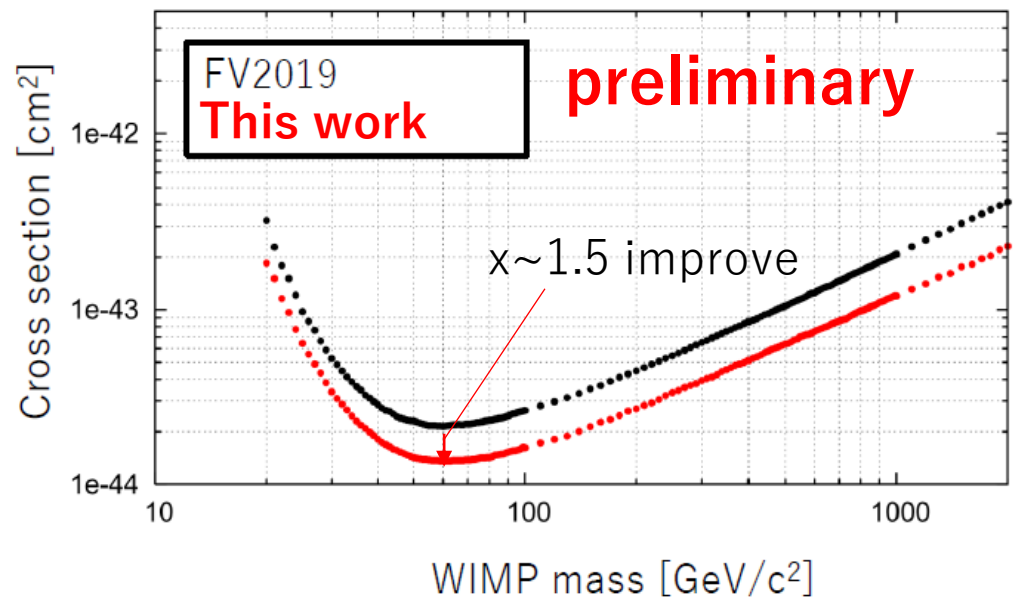
17

Results for fiducial volume analysis

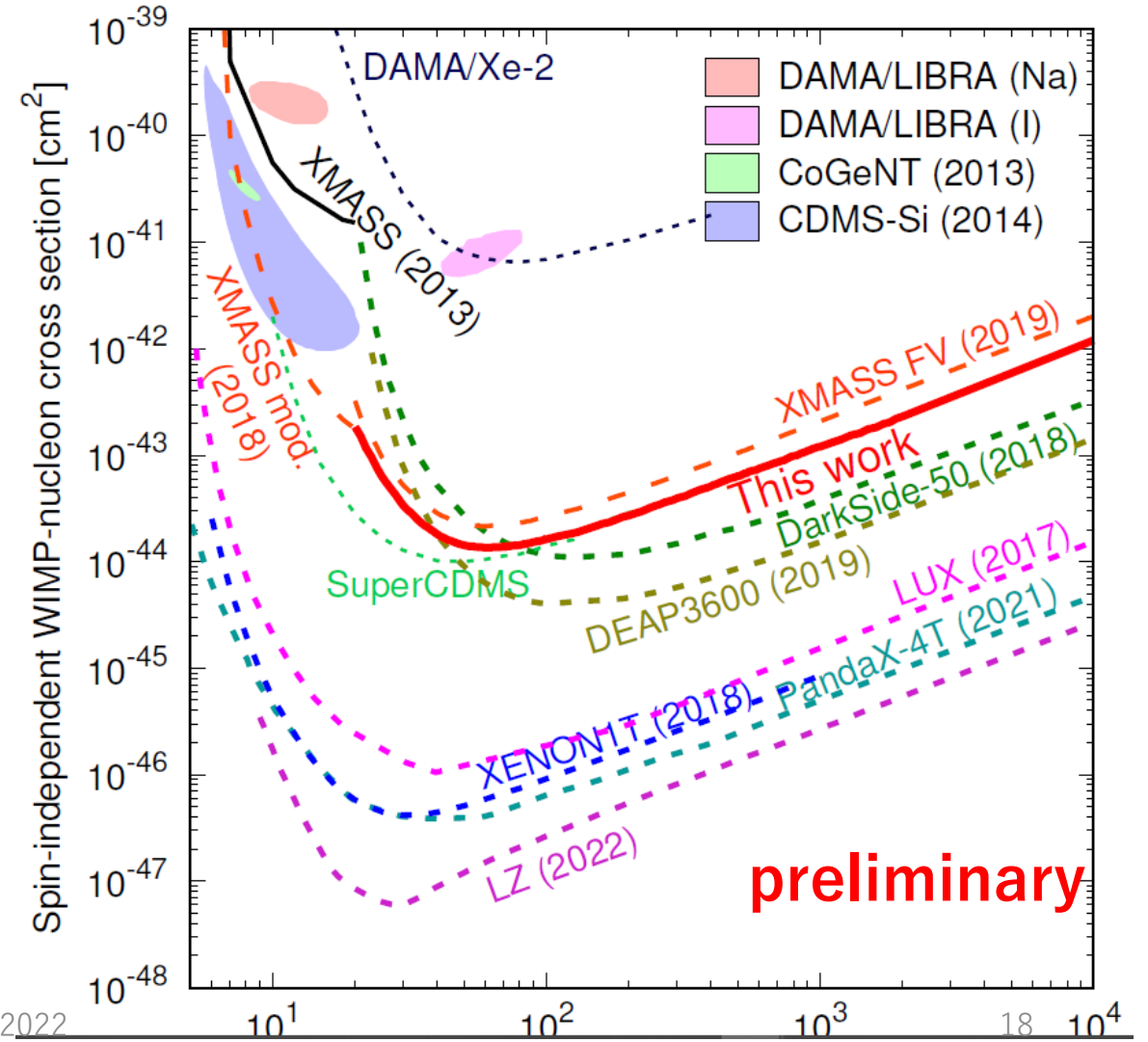
- Factor 1.5 improve from 2019 results.



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



2022/09/25
comparison to 2019 XMASS result



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

