XMASS/NEWAGE

Dark Matter Search

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Kick Off Symposium for Honolulu Office of Kobe University

Dark Matter Group in Kobe

- **Members**
  - Professor: Y. Takeuchi (2010～)
  - Associate Professor: K. Miuchi (2011~)
  - graduate Students: Doctor course 3 students
    Master course 3 students
- **Projects**
  - XMASS: large mass
    - low BG liquid scintillator
    - 1ton XMASS-I largest running
    - future ～5ton XMASS-1.5
  - NEWAGE: direction-sensitive
    - current background study @ underground
    - best direction-sensitive limit

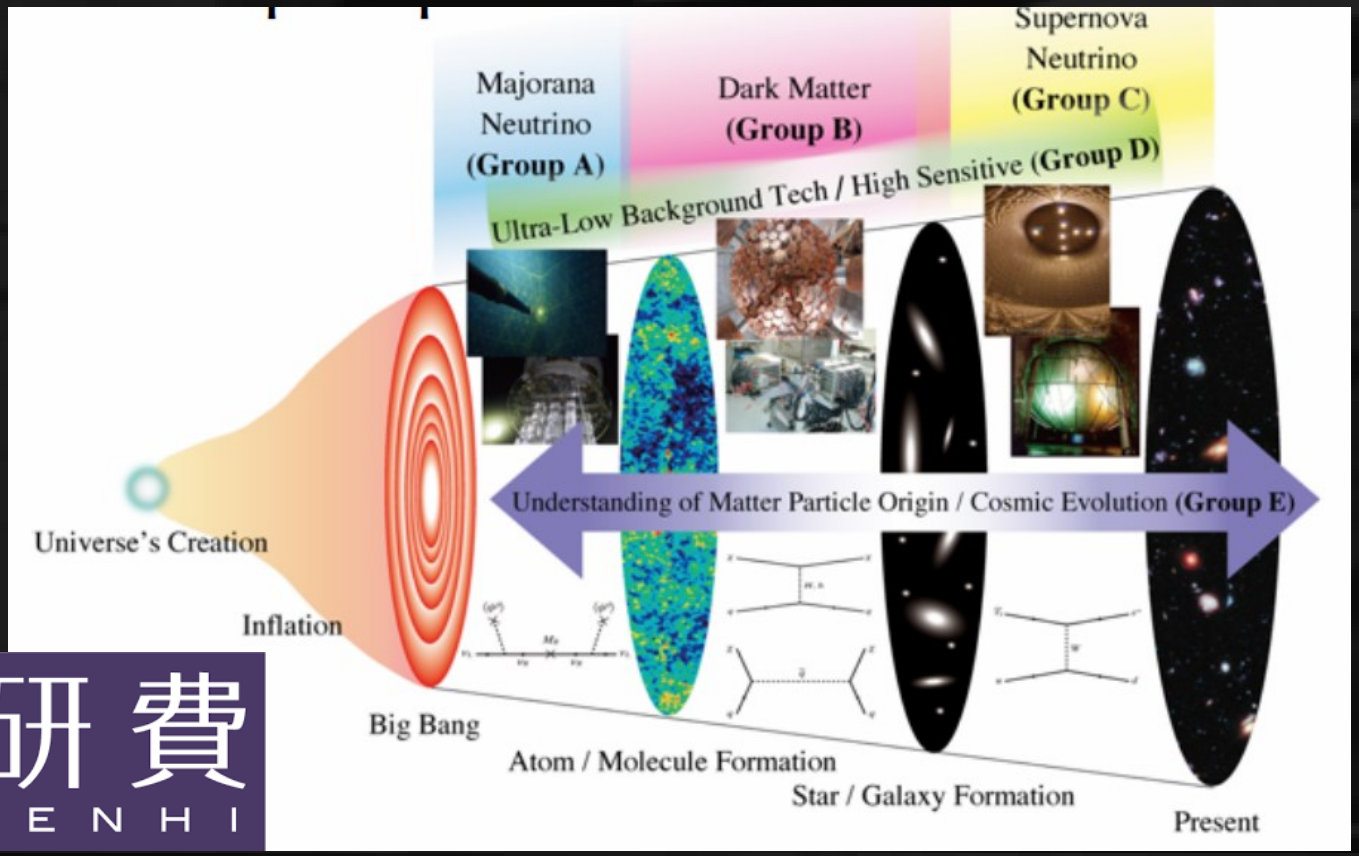
Dark Matter Activities in Japan

- XMASS (ICRR+)
  - Liq. xenon, underground, large mass
- NEWAGE (Kobe+)
  - Gas, underground, direction-sensitive

- NEWS (Nagoya+)
  - Emulsion, surface R&D, direction-sensitive
- ANKOK (Waseda+)
  - Liq argon, surface R&D, large number of photon
- PICO-LON (Tokushima+)
  - NaI, surface R&D, pure crystal, inelastic

Related Activities in Japan

- KAKENHI group Funding (FY 2014-2018)
  - New Innovative area:
    "Revealing the history of the universe with underground particle and nuclear research"



科研費
KAKENHI


XMASS

XMASS project

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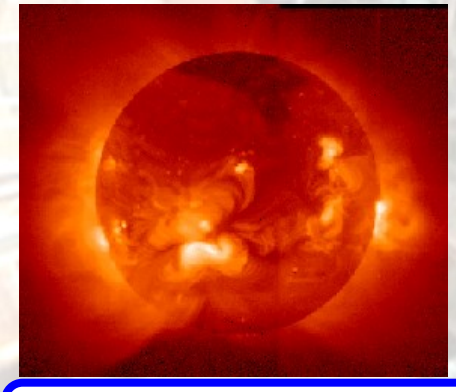
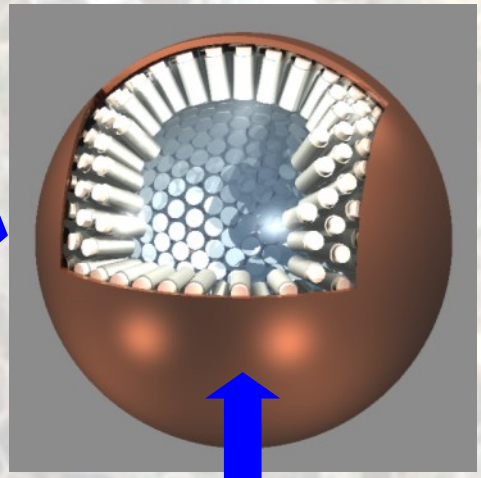
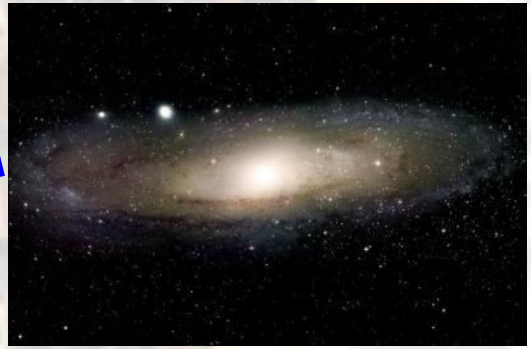
- XMASS experiment is a multi purpose, low-background and low-energy threshold experiment with large volume of liquid Xenon
  - **X**enon detector for Weakly Interacting **MASS**ive Particles (**DM search**)
  - **X**enon **MASS**ive detector for solar neutrino (**pp/^{7}Be**)
  - **X**enon neutrino **MASS** detector (**ββ decay**)
- XMASS-I, the first phase of the XMASS project, is dedicated to a direct dark matter search.

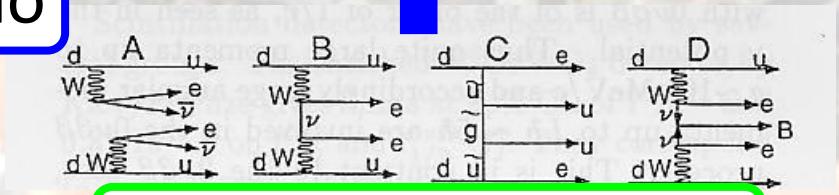


Solar neutrino





Dark Matter



Double beta decay

+axion, supernova, etc

XMASS detector

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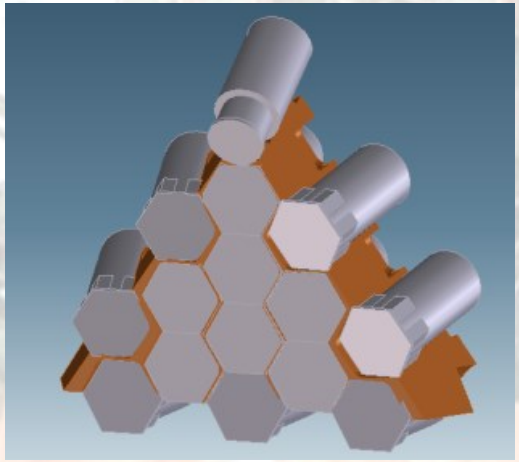
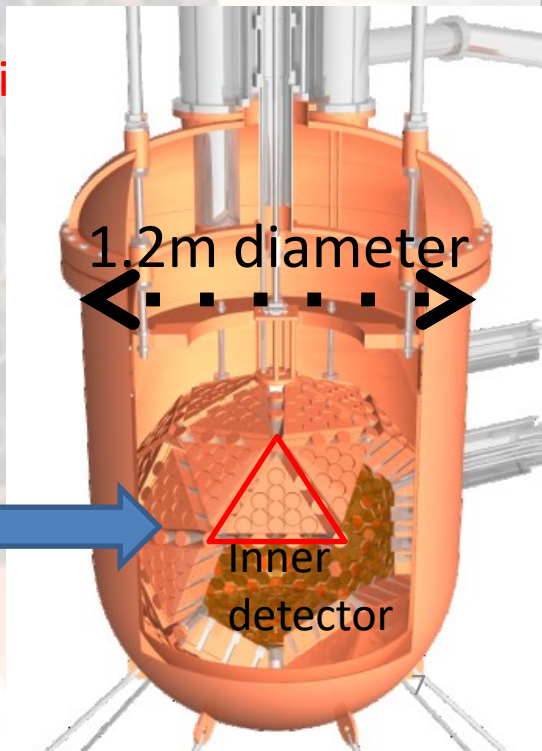
- Single phase (scintillation only) liquid Xenon detector : sensitive to e/γ events with very low backgrounds as well as nuclear recoil events
- Large 100 kg fid. mass & 835 kg inner mass (0.8 mϕ)
- 630 hexagonal & 12 round PMTs with 28-39% Q.E.
- High light yields(13.9 pe/keV) & Large photon coverage (> 62% of inner surface)
  - Low energy threshold : < 5 keV_{ee} (~ 25 keV_{NR}) for fiduci volume and 0.3 keV_{ee} for full volume





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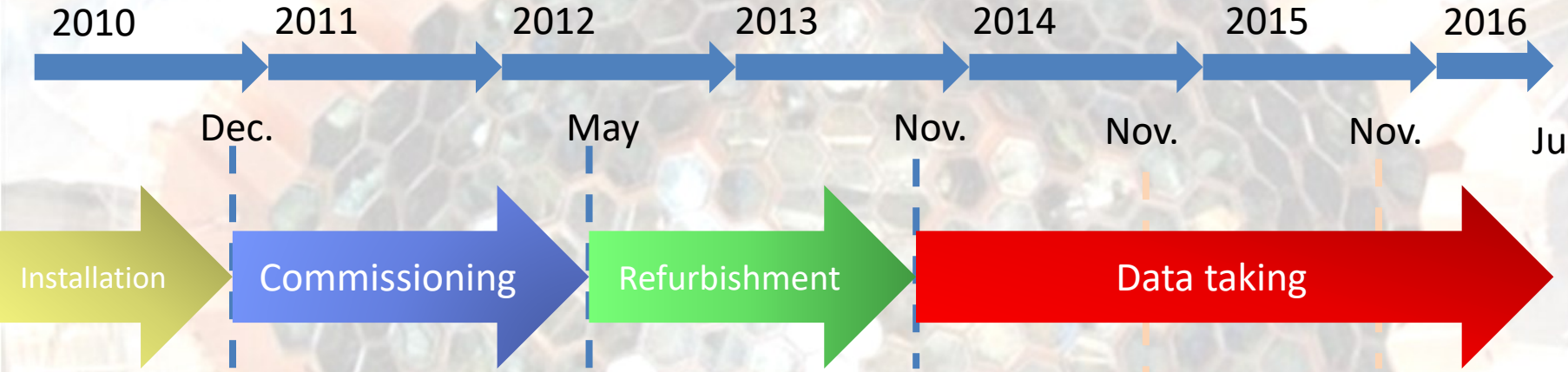
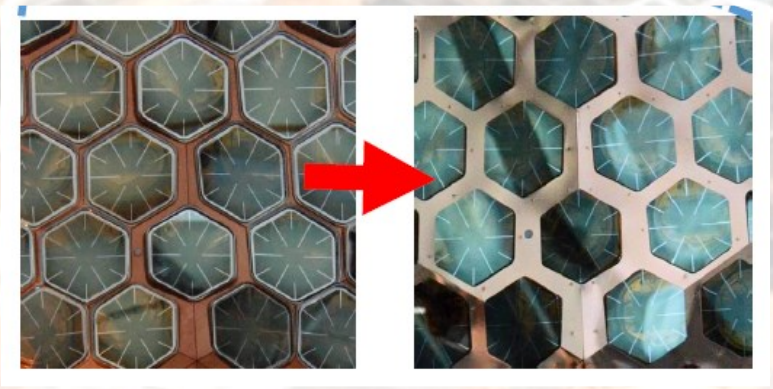
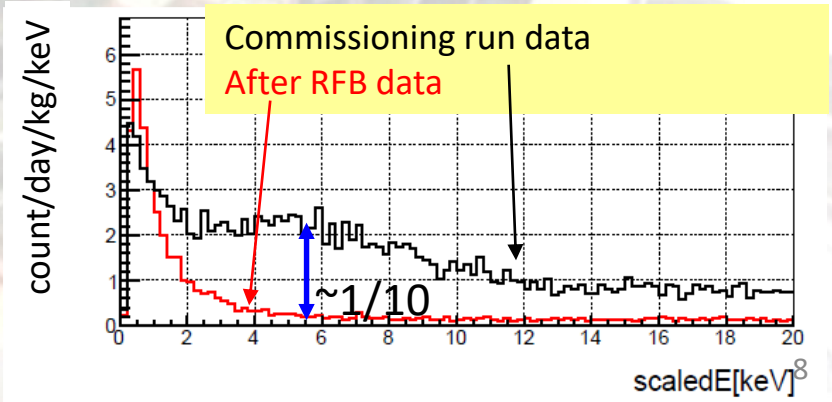
History of XMASS-I



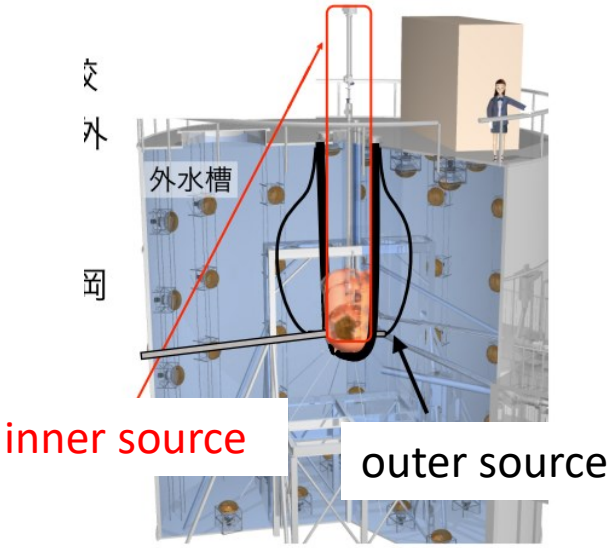
PMT Al seal were covered by copper ring and plate to reduce BG as detector refurbishment. After refurbishment, event ~ 5keV is reduced to ~1/10. **Now, the 3rd year continuity operation (2 years and 7 months) is ongoing. The longest running time among LXe detectors!**



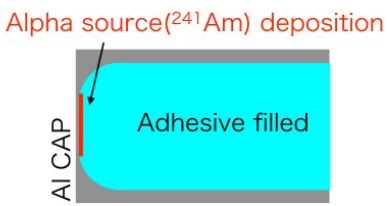


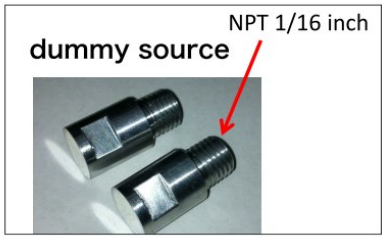
Kobe in XMASS

- Annual modulation analysis
  - K. Hosokawa PhD thesis 2016/3
- Calibration(source development and conduct calibration)
- Radon BG monitoring in the water
  - PTEP(2015) 033H01
- new PMT development



low energy inner source





XMASS physics results

XMASS physics results

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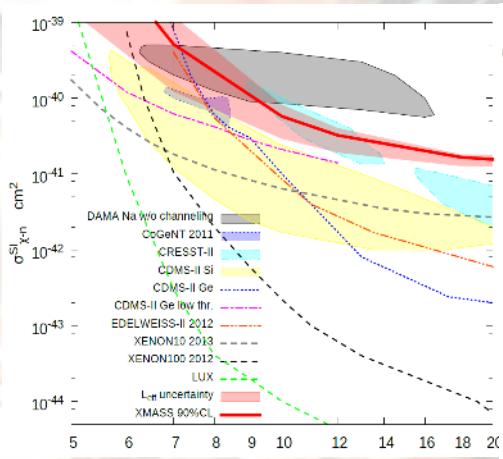
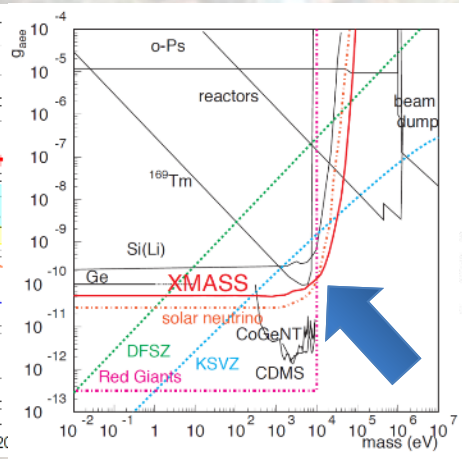
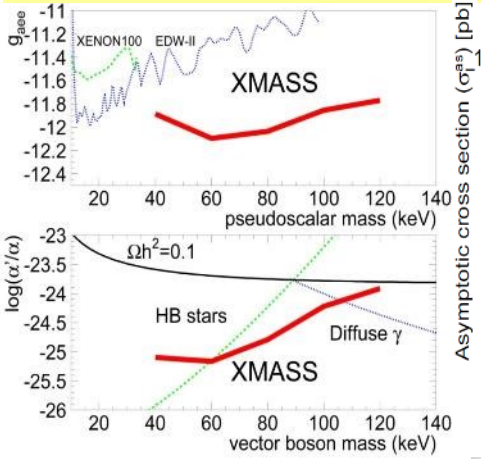
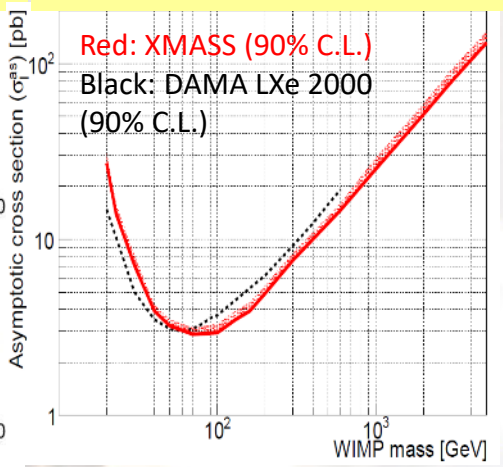
- various kinds of dark matter candidates and physics

Low mass WIMPs search, PLB 719 (2013) 78	Solar axion search, PLB 724 46 (2013)	Bosonic super-WIMPs search, PRL 113, 121301 (2014)	Inelastic WIMP nucleus scattering search, PTEP 063C01 (2014)









- Recent results
  - Direct dark matter search by annual modulation (PLB 759 272 (2016))
  - Search for 2ν double electron capture on ^{124}Xe (PLB 759 272 (2016))

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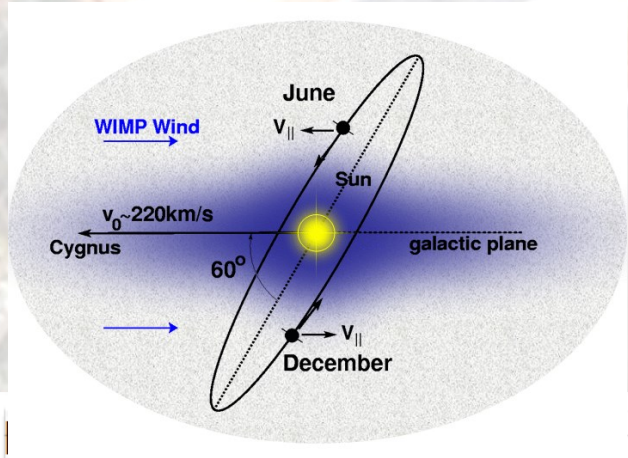
Search for annual modulation (1)

Physics Letters B 759 (2016) 272–276

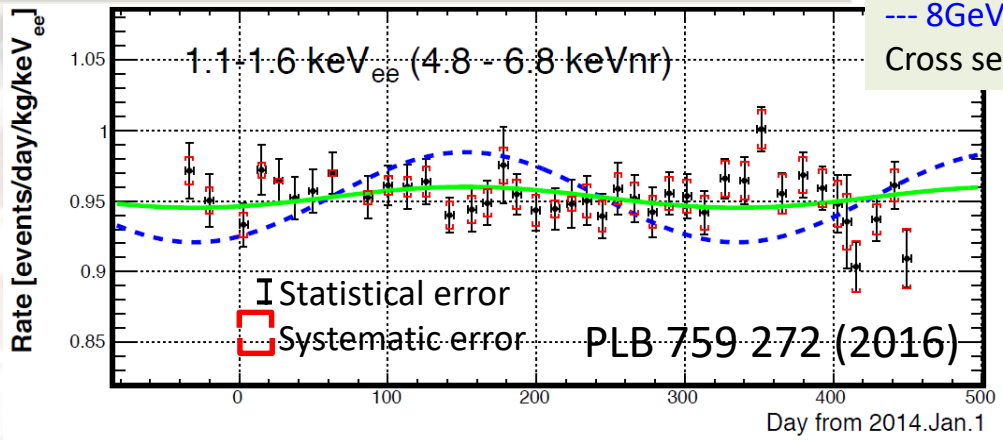
KOBE : K. Hosokawa's Doctor thesis

- Dataset: after refurbishment (Nov 2013-Mar 2015)
  - 0.83ton*year data(1 year cycle) with low threshold (1.1keV$_{ee}$). Comparable to 1.33ton*year of DAMA/LIBRA data (14 cycles)
  - Rejection of noise, Cherenkov and front of PMT event.
  - No particle ID just like DAMA/LIBRA
- The observed count rate as function of time in each energy bin.
- Clear modulation signal is expected if WIMP parameters are in the range where DAMA/LIBRA experiment indicates.

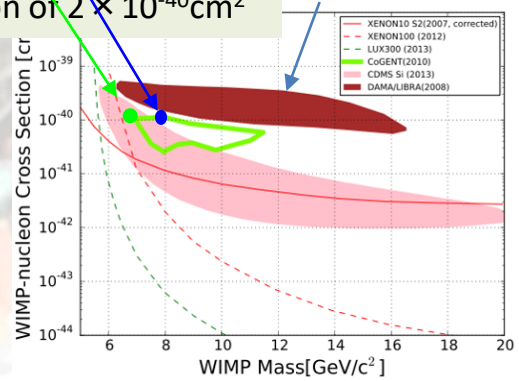


The expected WIMP flux variation due to eart h's orbit.

Time variation of event rate from 1.1 to1.6keV$_{ee}$



Expected rates for
— 7GeV/c^2 WIMPs
--- 8GeV/c^2 WIMPs
Cross section of 2×10^{-40}cm^2



Search for annual modulation (2)

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- Assuming standard WIMP, data is fitted with the following equation:

$$\mathrm{R}^{\mathrm{pred}}(E_i, t_j) = C_i + \sigma \times A(m_\chi, E_i)\cos 2\pi(t_j - t_0)/T$$

t_0(phase)=152.5days, T(period)=365.25days, A(modulated amplitude) and C_i (unmodulated amplitude)

- Two independent modulation analyses were performed using different χ^2 definition.
- Leff uncertainty is taken into account.
- The difference between two methods are within 30%.
- Figure is drawn by Method 1.
- DAMA/LIBRA region is mostly excluded by our measurement.

Method 1 (pull term)

$$\chi^2 = \sum_i^{E-bins}\left(\sum_j^{t-bins}\frac{(R_{ij}^{obs} - R_{ij}^{pred} - \alpha K_{i,j})^2}{\sigma(\mathrm{stat})_{ij}^2}\right) + \alpha^2$$

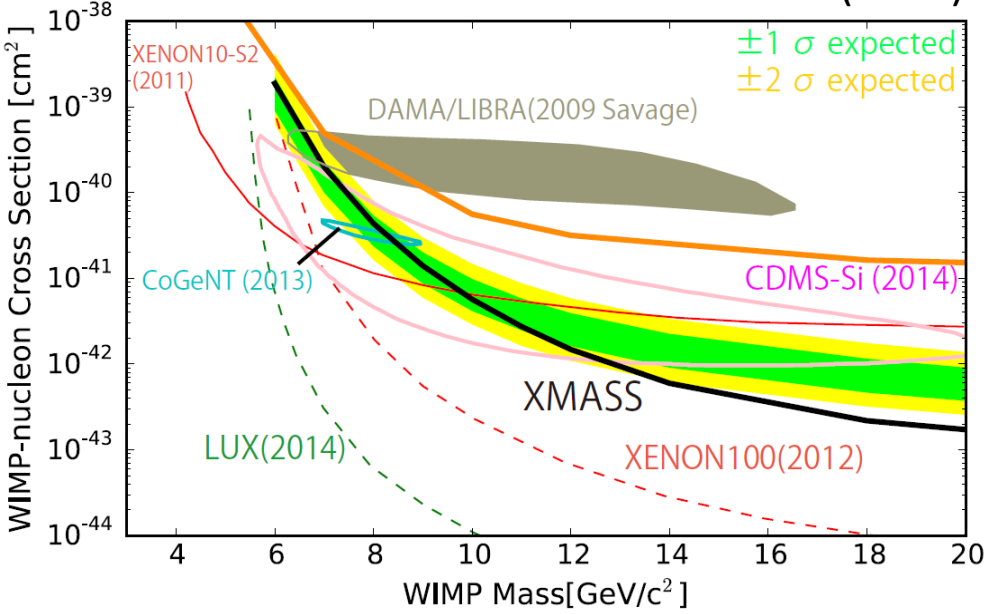
Method 2 (covariance matrix)

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

Model assumption

V_0: 220.0 km/s
V_{esc}: 650.0 km/s
ρ_{dm}: 0.3 GeV/cm^3
Lewin, Smith (1996)

PLB 759 272 (2016)



The first extensive search against the DAMA region, including electron recoils.

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Search for annual modulation (3)

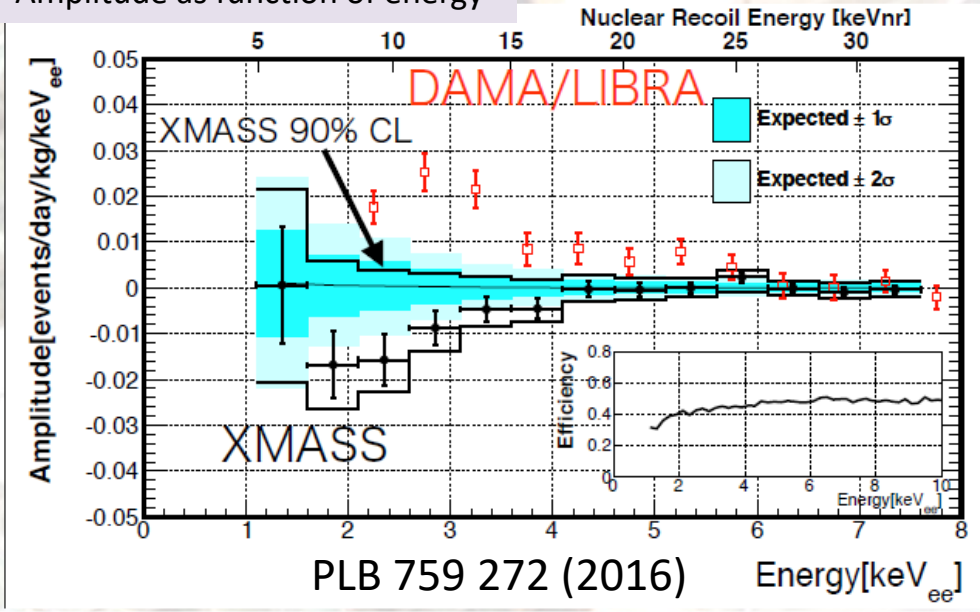
- Annual modulation signal is searched for without any model assumption.
- A_i (modulated amplitude) and C_i (unmodulated amplitude) are fitted by :

$$R^{ex}_{i,j} = \int_{-\frac{1}{2}\Delta t_j}^{\frac{1}{2}\Delta t_j} (C_i + A_i \cos 2\pi(t_j - t_0)/T) dt_j$$

t_0=152.5days, T=365.25days, fitting range : 1.1-7.6keV$_{ee}$

- Small negative amplitude is observed in 1.6-4.1keV$_{ee}$ region. Significance was evaluated with test statistic (10,000 dummy samples) and no significant modulated signal has been observed. (p-value=0.014(2.5σ) and 0.068(1.8σ) for 2 methods.)
- Direct comparisons with other experiments: more stringent constraint.

Amplitude as function of energy



Experiments	Amplitude(events/day/kg/keV$_{ee}$)
DAMA/LIBRA	~0.02, 2.0-3.5keV$_{ee}$
XENON100	3.7 x 10^{-3}, 90% C.L. upper limit, 2.0-5.8keV$_{ee}$(*)
XMASS	(1.7-3.7)x 10^{-3}, 90% C.L. positive upper limit, 2-6keV$_{ee}$

*Estimated based on PRL 115 (2015) 091302 and Science 349 (6250) (2015) 852

Search for double electron capture (1)

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Physics Letters B 759 (2016) 64–68

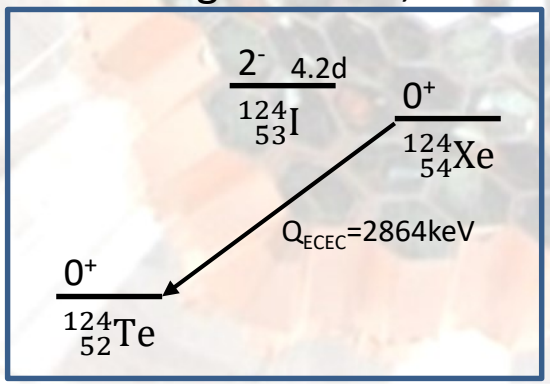
- 2ν double electron capture: new reference for the calculation of nuclear matrix elements from the proton-rich side of the mass parabola of even-even isobars.
- 0ν double electron capture is lepton number violating process as well as 0νββ decay.

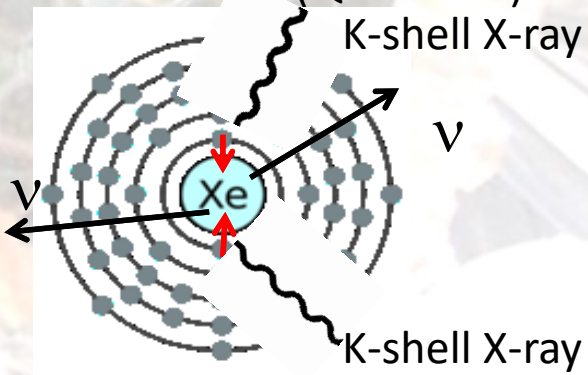
Isotope	^{124}Xe	^{126}Xe	^{128}Xe	^{129}Xe	^{130}Xe	^{131}Xe	^{132}Xe	^{134}Xe	^{136}Xe
Natural abundance	0.095%	0.089%	1.9%	26.4%	4.1%	21.2%	26.9%	10.4%	8.9%

- Natural xenon contains double electron capture nuclei as well as double beta decay nuclei
- 2ν double electron capture on ^{124}Xe (2νECEC)

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

  - In the case of 2K-capture, signal is total energy deposition of 63.6keV from atomic X-rays and Auger electrons.
  - Theoretical predictions of $T_{1/2}=10^{20}\sim10^{24}$years
  - Previous experimental results : $T_{1/2}>2.0\times10^{21}$ years, w/ proportional counter.
- ^{126}Xe can also undergo 2νECEC, but this reaction is much slower. (Q=896keV)





Search for double electron capture (2)

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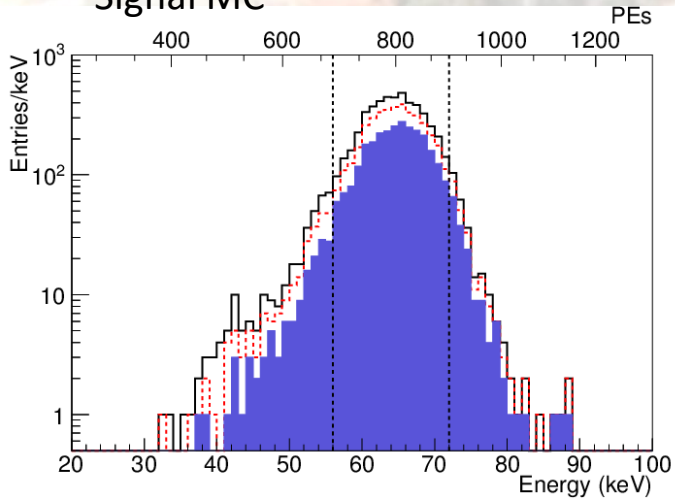
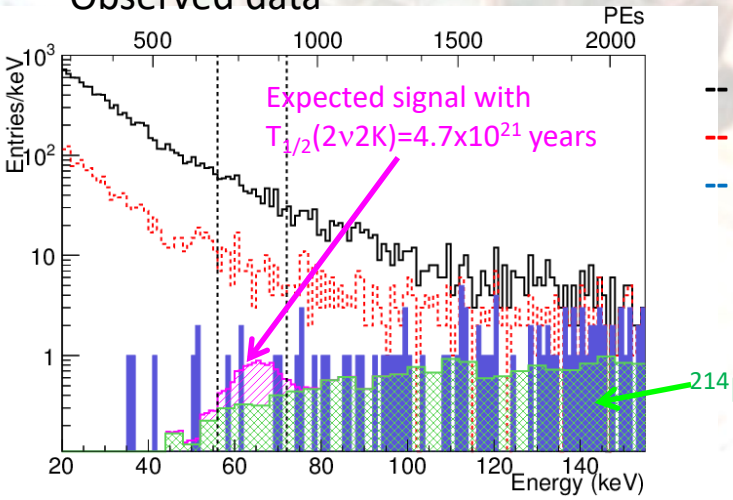
- Signal MC
  - X-rays and Auger electrons after 2ν 2K-capture are simulated.
  - Energy window: 56-72keV 90% of the simulated signal.
  - Efficiency for signal is 59.7%.
- Observed data
  - Commissioning run data were analyzed.
  - Effective live time is 132.0 days, and fiducial mass of natural xenon is 41kg (It contains 39g of ^{124}Xe).
  - 5 events remained in the signal region. Main background in this energy region is ^{214}Pb (daughter of ^{222}Rn) in the detector, and expected number of ^{214}Pb BG events in the signal region is 5.3+/-0.5. No significant excess above background was observed.
- Set the world best lower limit of half-life : $T_{1/2}>4.7\times10^{21}$ years (90%CL).
- Also for ^{126}Xe, set the lower limit : $T_{1/2}>4.3\times10^{21}$ years (90%CL).

Signal MC



Observed data



(arXiv:1510.00754)

-- Fiducial volume cut
-- Timing cut
-- Band-like pattern cut

^{214}Pb background MC

Future plans of XMASS

XMASS future plans

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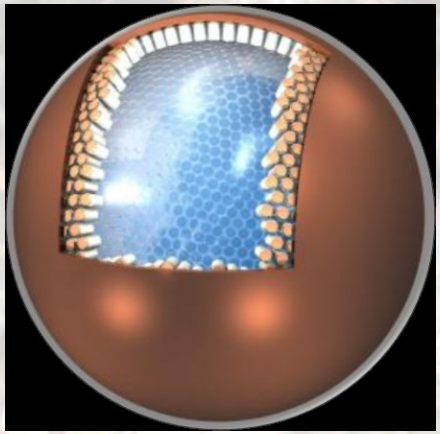
XMASS-I

835kg, **100kg FV**
80cmϕ
DM search

XMASS-1.5



6ton,**1~3ton FV**
1.5mϕ, ~1800 PMTs
DM search :
$\sigma_{SI} < 10^{-46}$ cm^2
pp solar ν : ~a few cpd

XMASS-II

Multi purpose
DM search : $\sigma_{SI} < 10^{-48}$ cm^2
pp solar ν : ~10 cpd
$0\nu2\beta$ decay of ^{136}Xe

- To improve the sensitivity,
  - increase the fiducial volume
  - select ultra low BG detector material ➜ Continues material screening
  - discriminate against BG events, especially surface BG. ➜ Developed a new PMT.
  - reduce inner detector RI ➜ Distillation (^{85}Kr) and screening for Rn emanating material

New PMTs for future XMASS

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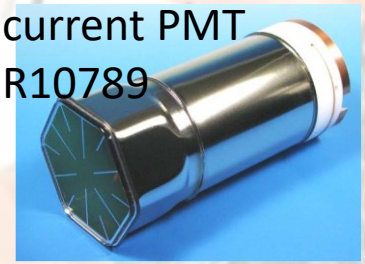
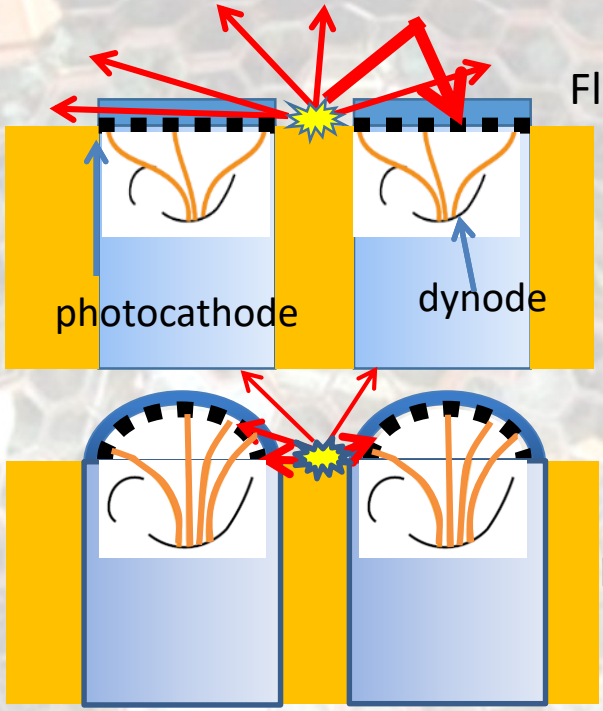
2inch hex shape
current PMT
R10789



3inch dome shape
new PMT
R13111

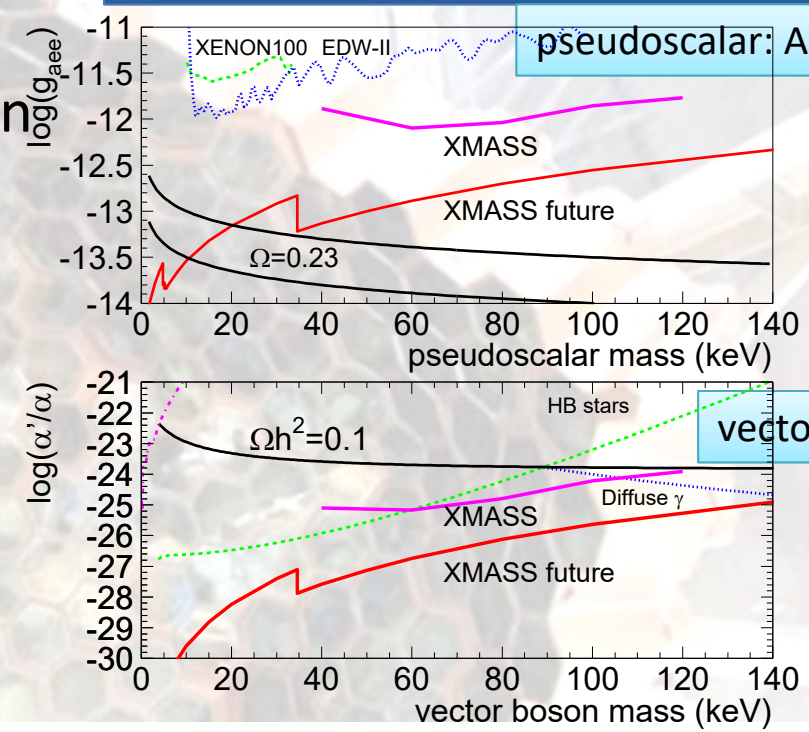


- Surface events can be identified and rejected very effectively by new dome-shaped PMTs, which have high and uniform collection efficiency for whole area.
- TTS(Transit Time Spread) of the new PMT is improved, and it will result in improvement of Cherenkov BG rejection and position reconstruction using timing.
- Performance test was carried out using the first batch of the new PMTs.
- Reduction of radioactivity in PMT parts was done. KOBE's contribution

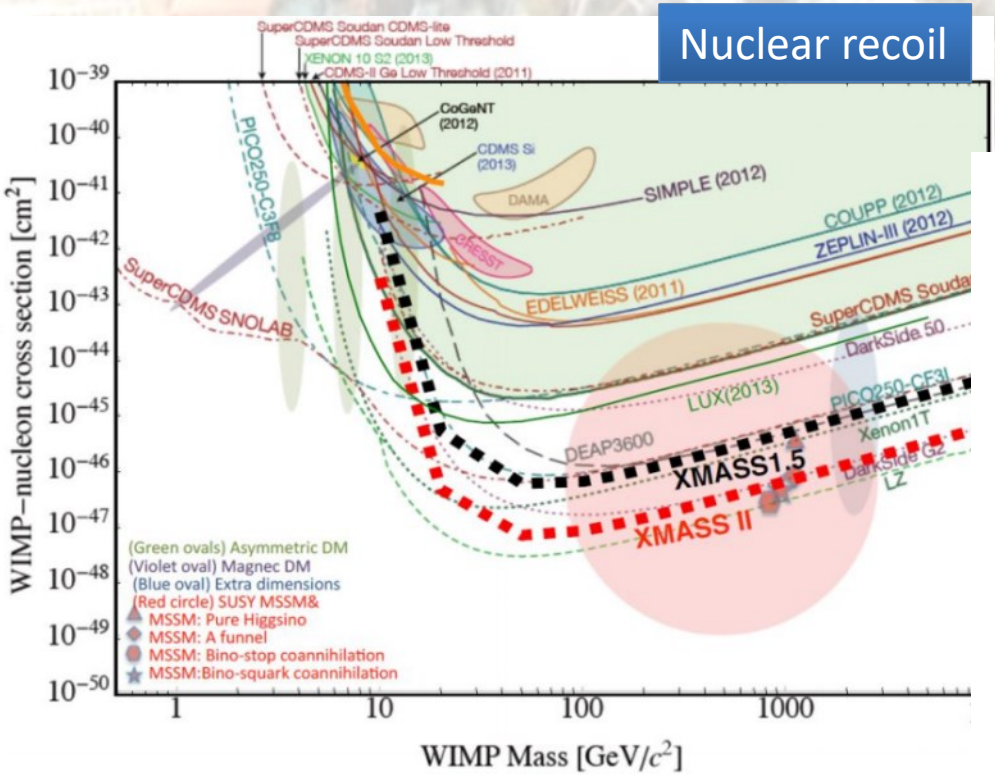
Expected sensitivity

- XMASS-1.5 : Total 5ton/fiducial 1-3ton
- XMASS-II : Total 25ton/fiducial 10ton
- $<10^{-46}cm^2$ & $2x10^{-47}\ cm^2$ @100GeV
- $\sim 1x10^{-5}$/keV/kg/d (~1 x pp solar ν)
- Sensitive both nuclear recoil and e/γ

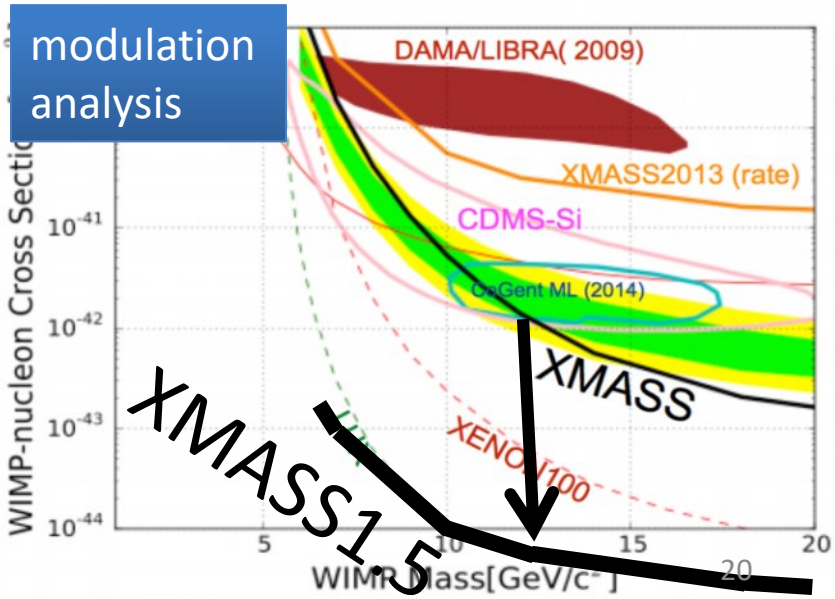
bosonic super-WIMPs in XMASS-1.5



Nuclear recoil



modulation analysis



NEWAGE

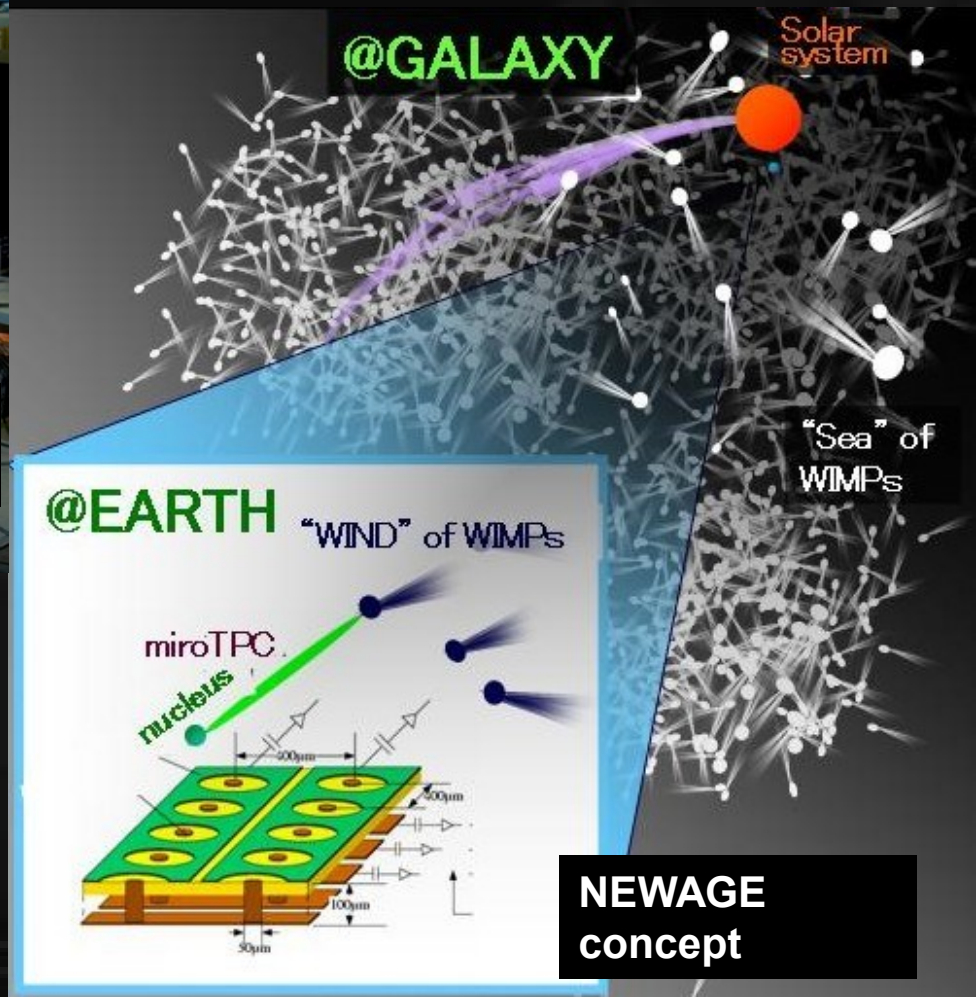
NEWAGE：run by Kobe university

- WIMP-wind detection
- μ-PIC three dimensional gas tracking device

Direction-Sensitive WIMP-search NEWAGE

detector NEWAGE-0.3b

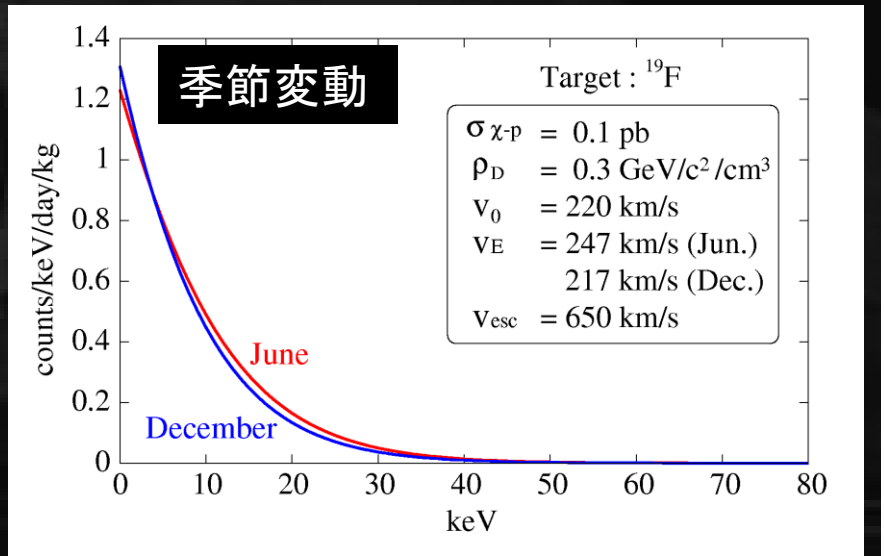
NEWAGE-0.3b inside

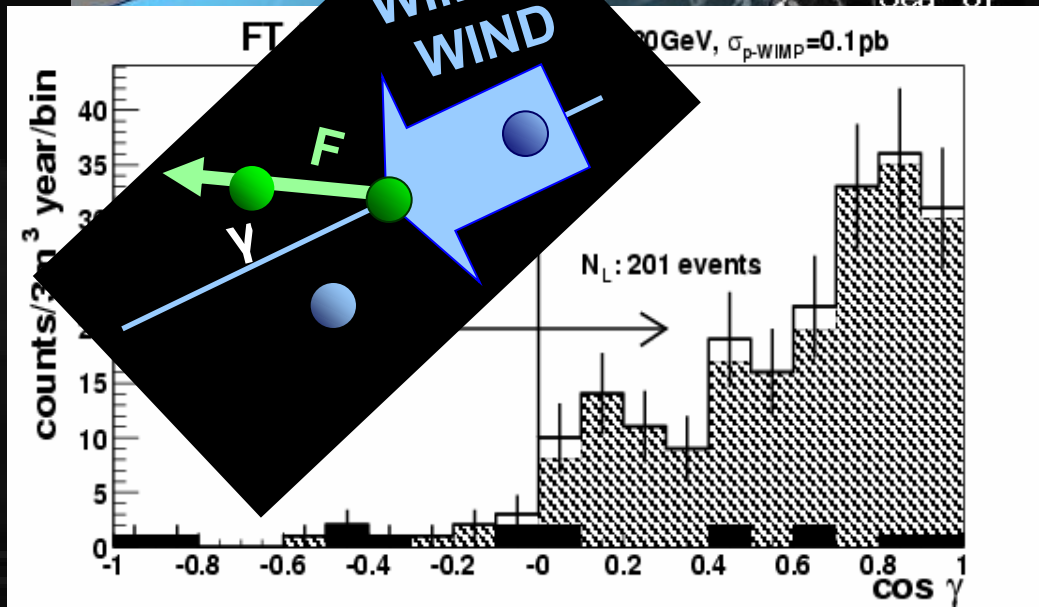


NEWAGE concept

Advantages of directionality

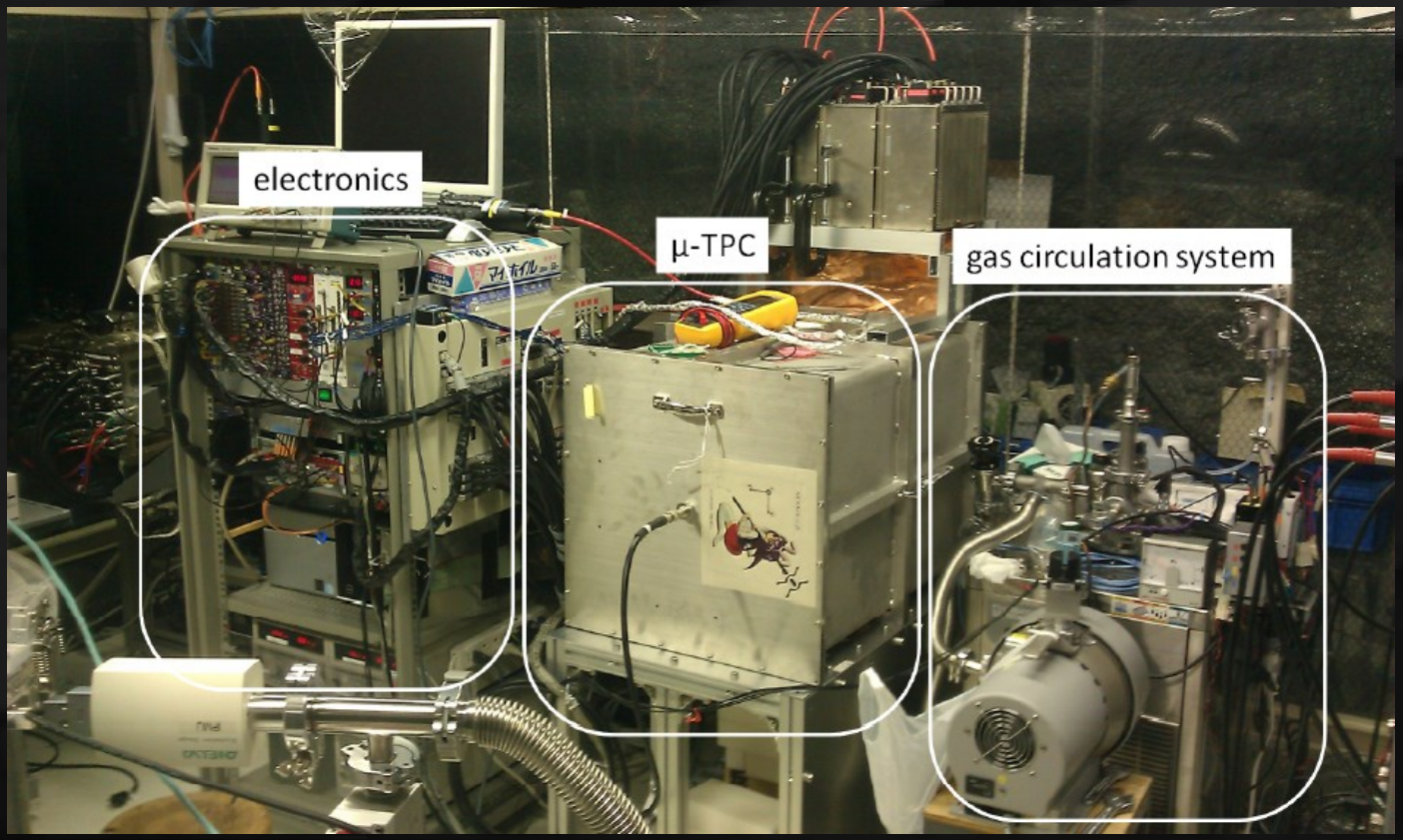
- large asymmetry compared with annual modulation
- detailed study after “detection”





NEWAGE detector

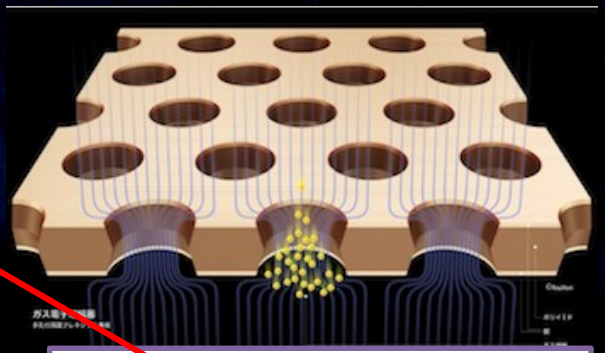
- NEWAGE-0.3b'
- Detection Volume: 31×31×41cm^3
- Gas: CF4 at 0.1atm (50keVee threshold)
- Gas circulation system with cooled charcoal

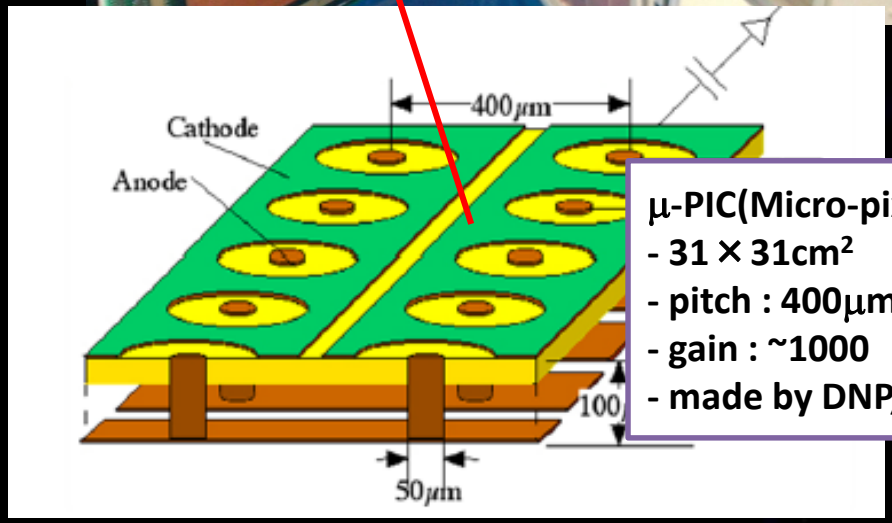


NEWAGE-0.3b' inside view

Detection Volume: 30×30×41cm^3

Field cage
Drift length: 41cm
PEEK + copper wires



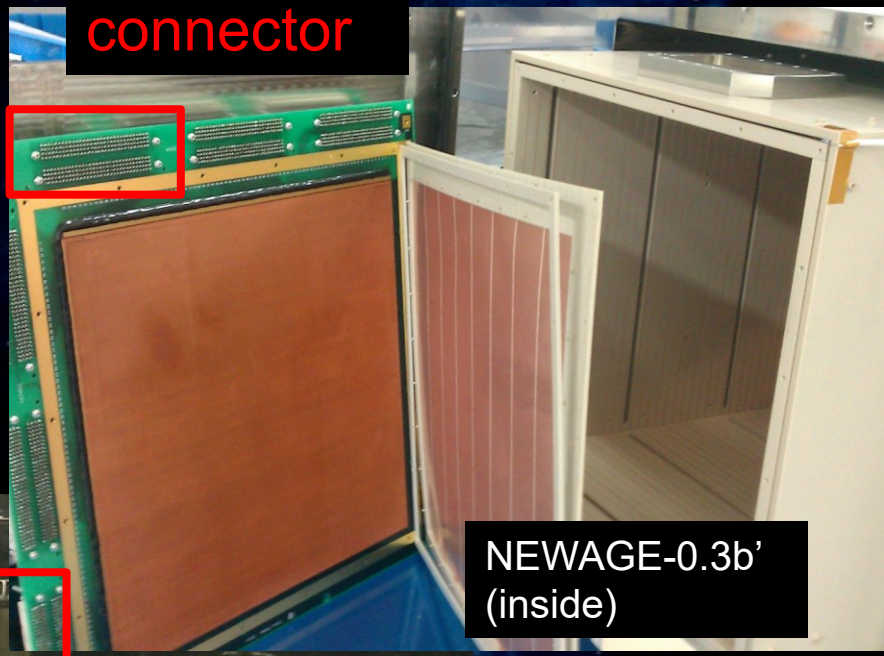


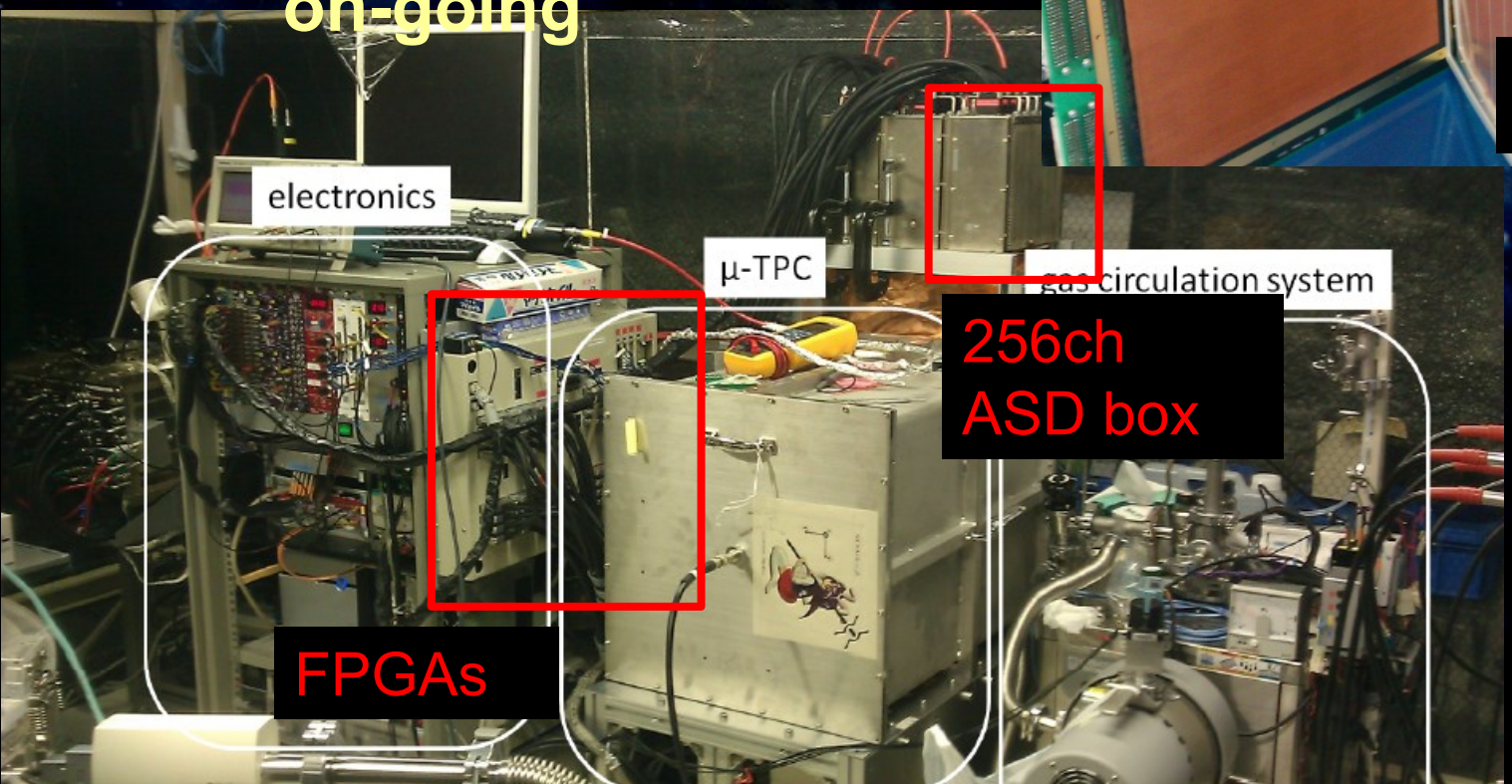
μ-PIC(Micro-pixel chamber)
- 31×31cm^2
- pitch : 400μm
- gain : ~1000
- made by DNP, Japan

GEM
- 31×32 cm^2
- 8-segmented
- hole pitch : 140μm
- hole diameter: 70μm
- insulator : LCP 100μm
- gain : ~5
- made by Scienergy, Japan

NEWAGE-0.3b' readouts

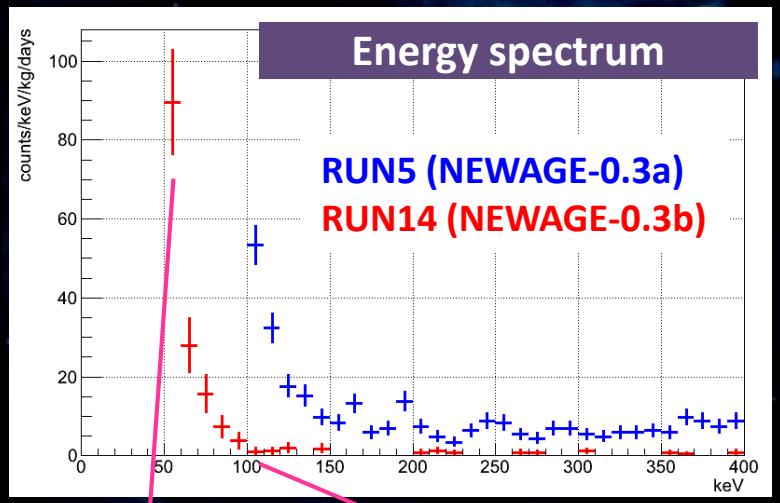
- μ-PIC is X-Y readout
- General purpose FPGA-based electronics since early 2000's.
- Updates are always on-going





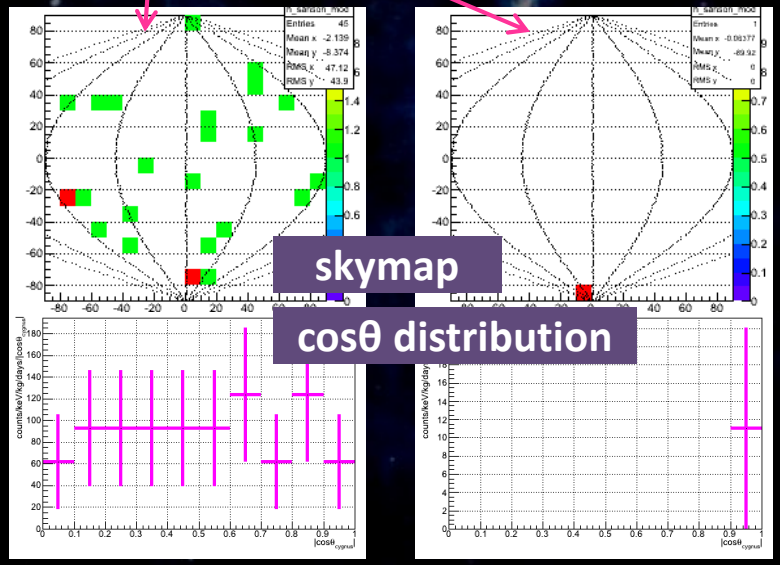
NEWAGE underground run

RUN14
- period : 2013/7/20-8/11, 10/19-11/12
- live time : 31.6 days
- fiducial volume : 28x24x41cm^3
- mass : 10.36g
- exposure : 0.327 kg･days

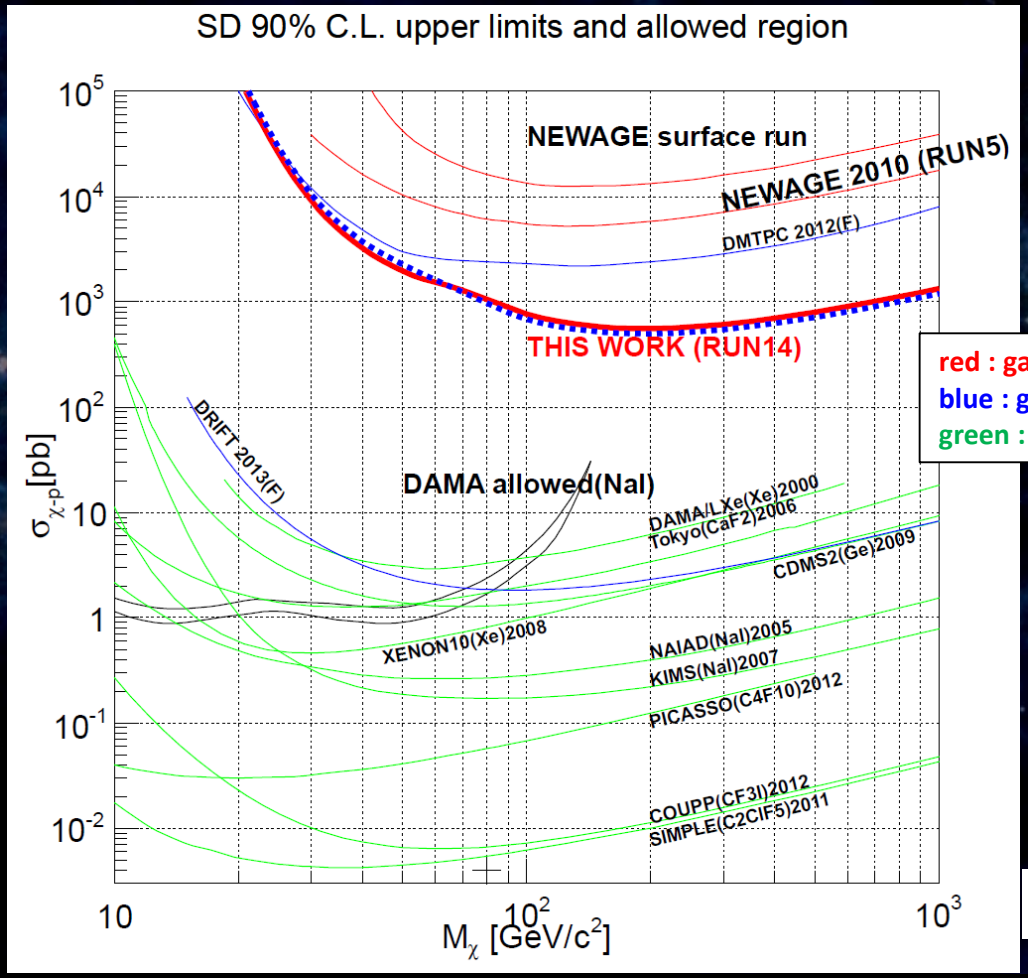


- *Energy spectrum*
  - Threshold : 100 => **50keV**
  - BG rate : **1/10**@100keV

- *Skymap, cosθ distribution*
  - Set limit by significant difference in 2-binned measured cosθ and DM-wind simulated cosθ



Direction-sensitive limit



red : gas, with directional analysis
blue : gas, without directional analysis
green : solid, liquid detector

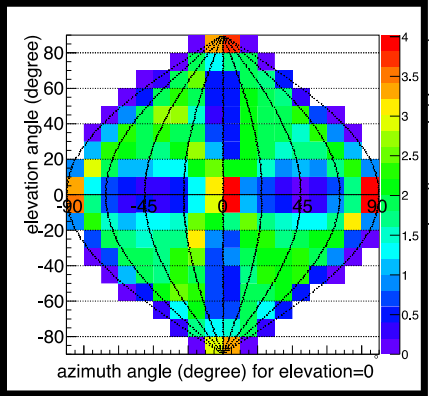
PTEP (2015) 043F01s

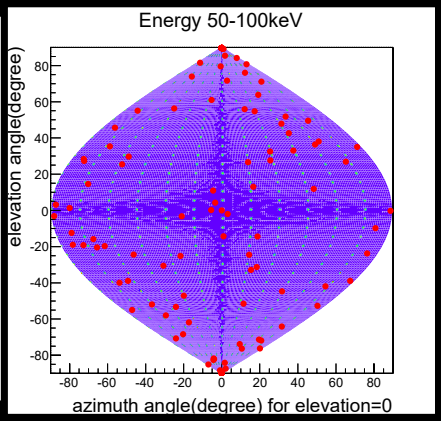
- Obtained limit : 557pb @200GeV
  (Best direction-sensitive limit)
- Improved one order of magnitude from previous RUN5

Galactic-plane sky-map

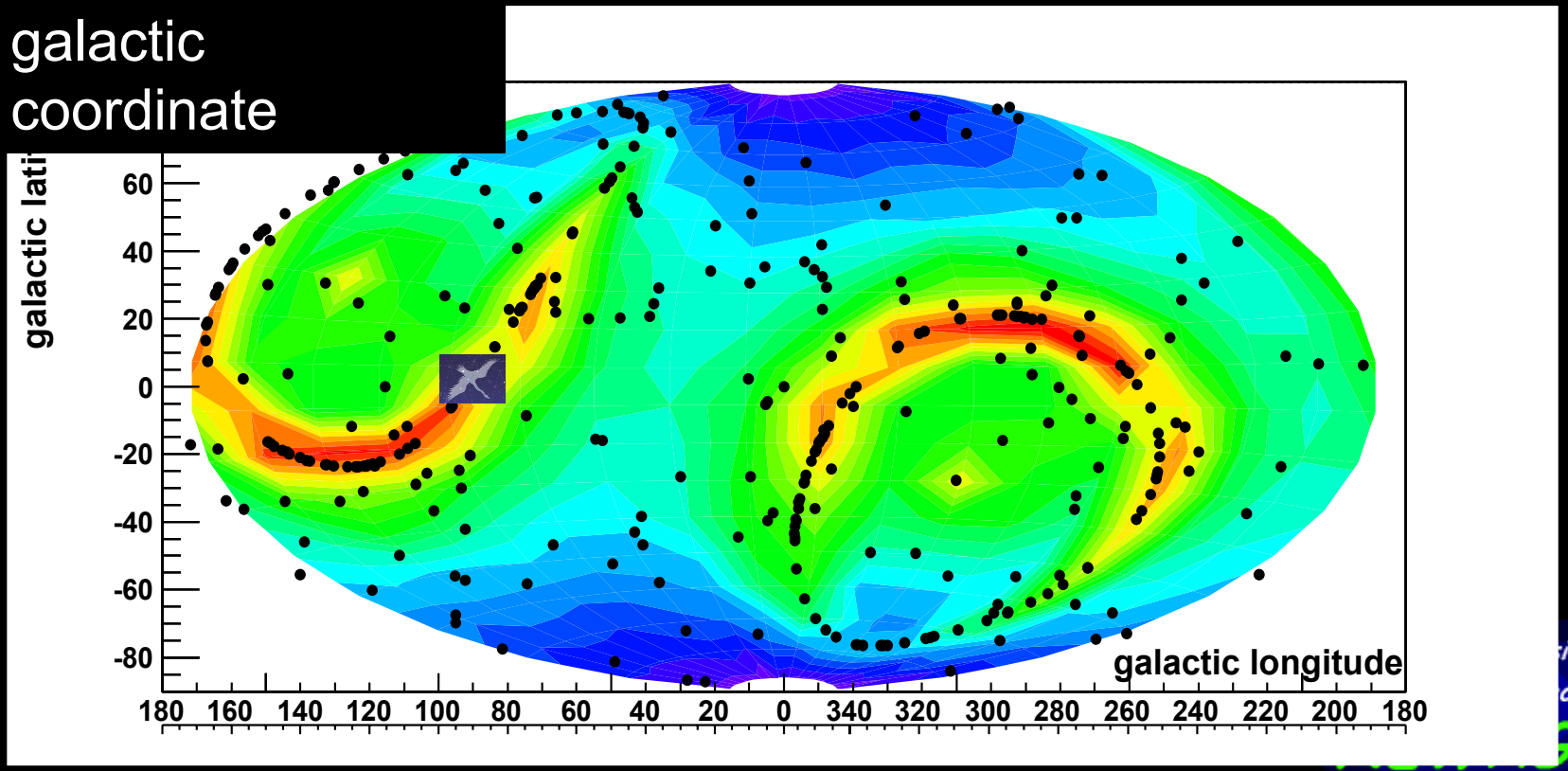
- correlation with efficiency = consistent with isotropic

lab-coordinate





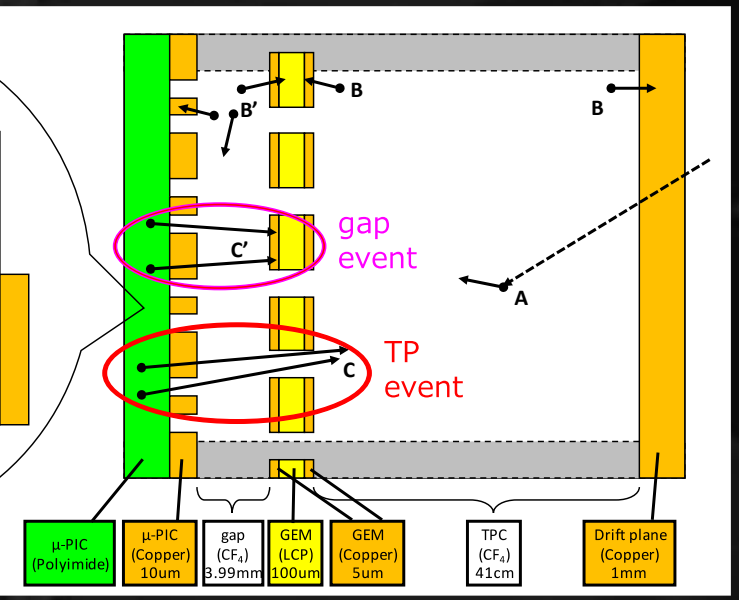
galactic coordinate

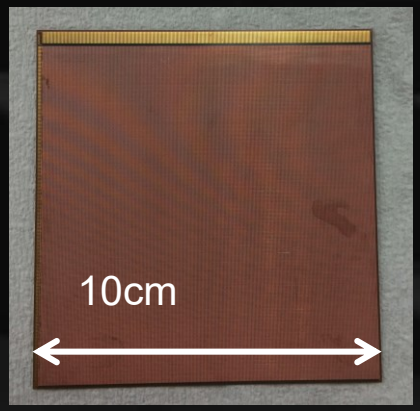


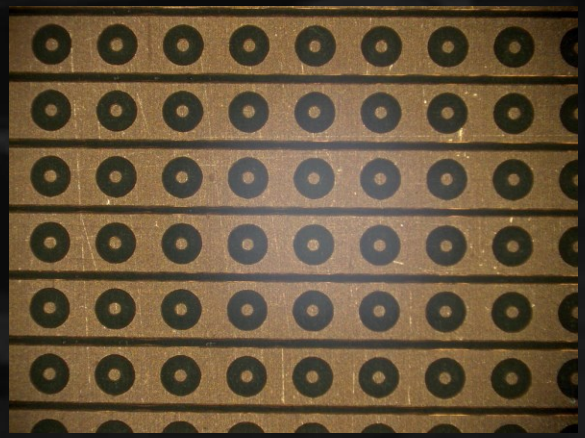
BG study and more

Poster by HASHIMOTO

- Largest BG source: alpha particle from μ-PIC
- Development of radio-pure μ-PIC:
  10×10㎠ μ-PIC was made and tested







- FY2016: development of 30×30㎠ μ-PIC
- FY2017~: underground run

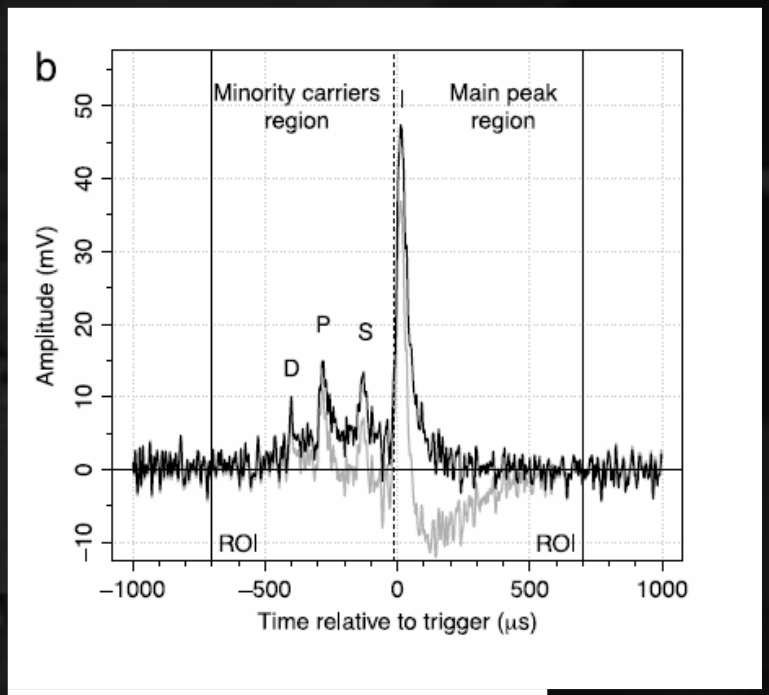
Direction Sensitive WIMP-search NEWAGE

Z-fiducialization

Poster by IKEDA

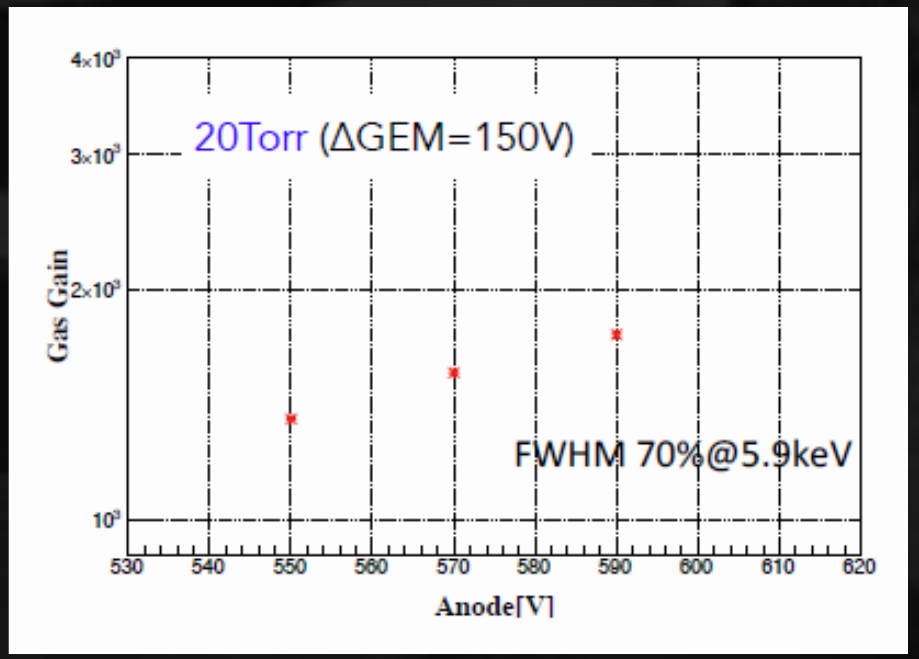
- minority peaks “discovery” by DERIT group
- SF_6 study for GEM+μPIC system

minority peaks (DRIFT group)



J.B.R. Battat et al. / Physics of the Dark Universe 9–10 (2015) 1–7

SF6 study



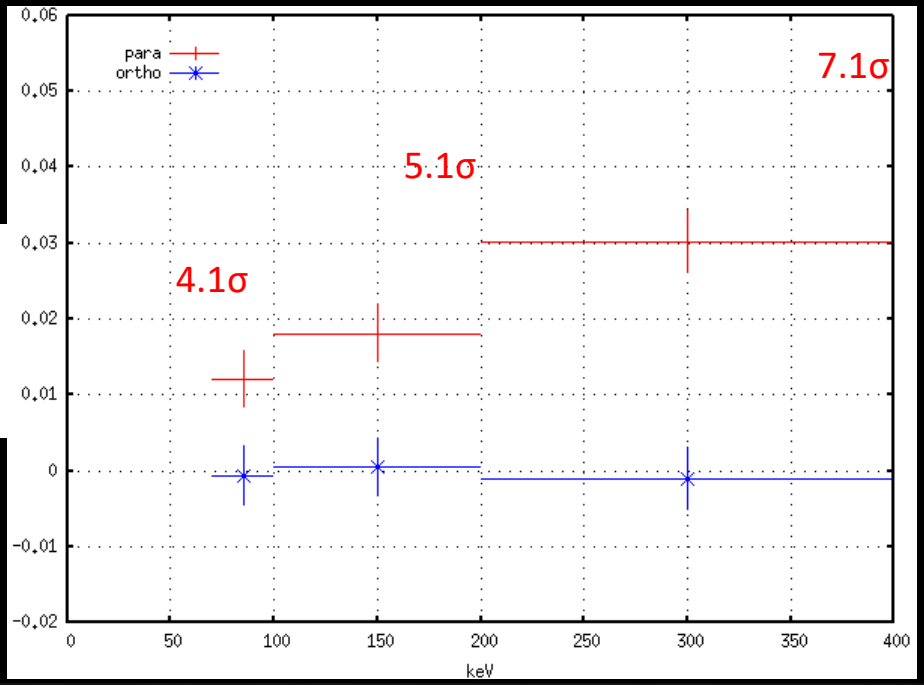
Direction Sensitive WIMP-search NEWAGE

Head/tail study

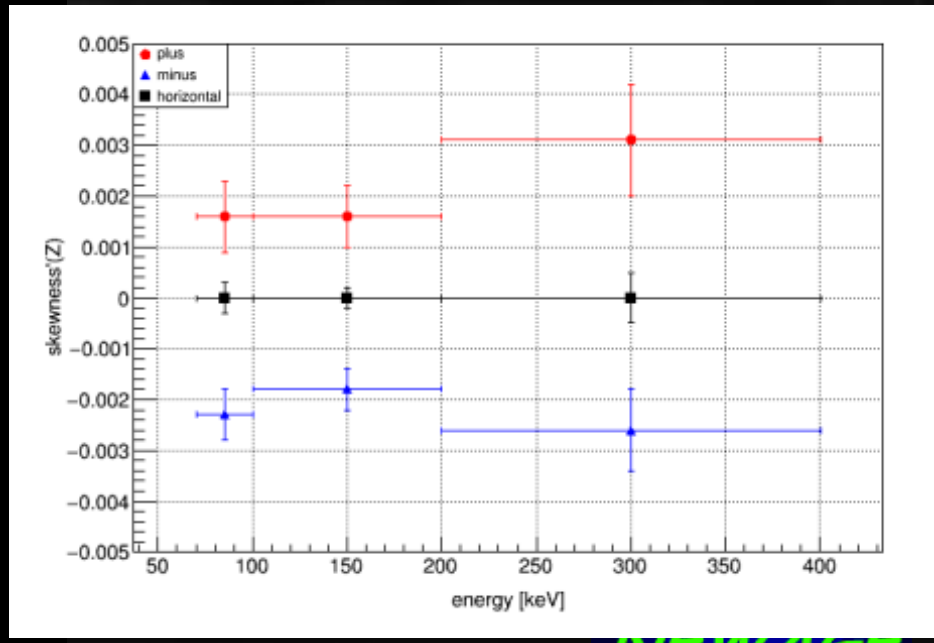
Poster by YAKABE

- Head tail in X-Y plane, Z-axis
- Proof of concept, DONE.
- Improvement for practical use: being studied

X-Y plane



Z axis



Dark Matter group in Kobe

- XMASS: large mass・low BG liquid scintillator
  - 1tonのXMASS-I largest running
  - future ～5ton XMASS-1.5
- NEWAGE:direction-sensitive
  - current background study @ underground
  - best direction-sensitive limit
- strategy：XMASS indication and detection
  -> NEWAGE confirmation and detailed study