

# 地下から解き明かす宇宙の歴史と物質の進化

Unraveling the History of the Universe and Matter Evolution with Underground Physics



# Direction sensitive dark matter search with gaseous TPCs

Satoshi Higashino (Kobe U.)

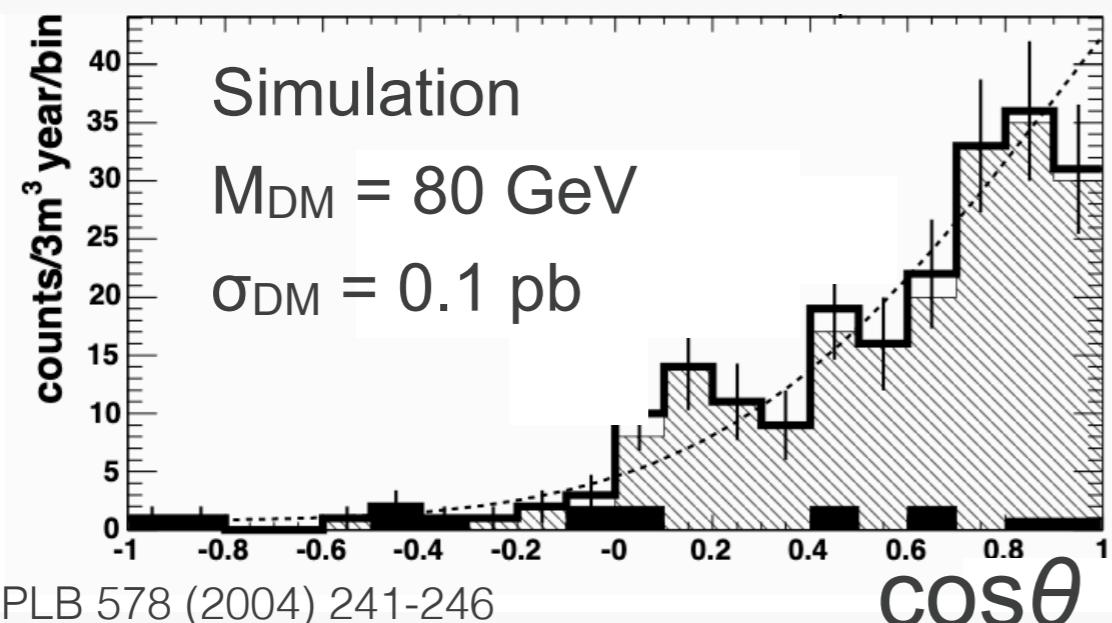
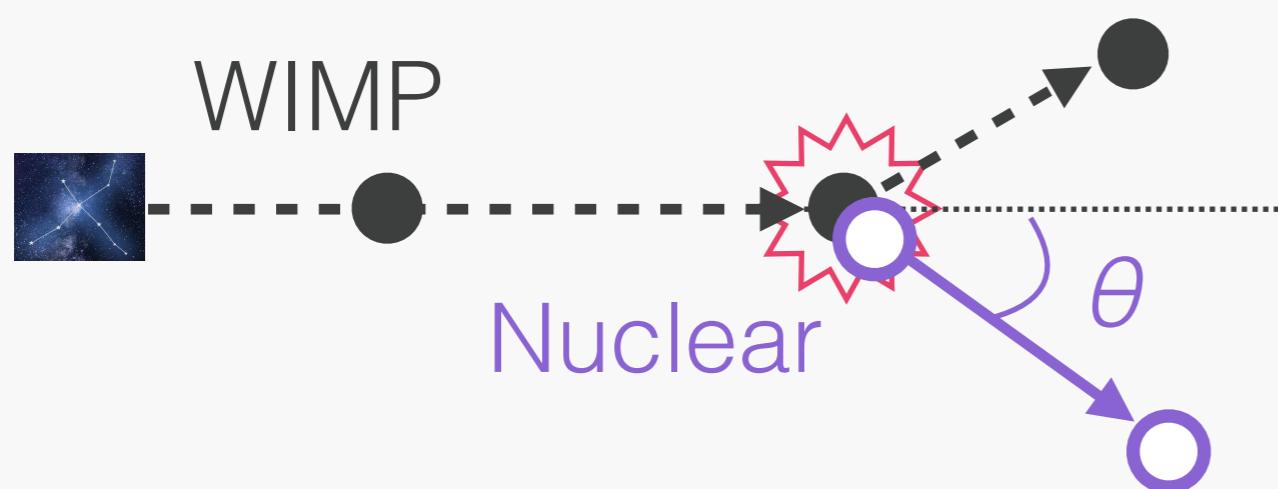
on behalf of NEWAGE collaboration

5 / 3 / 2024

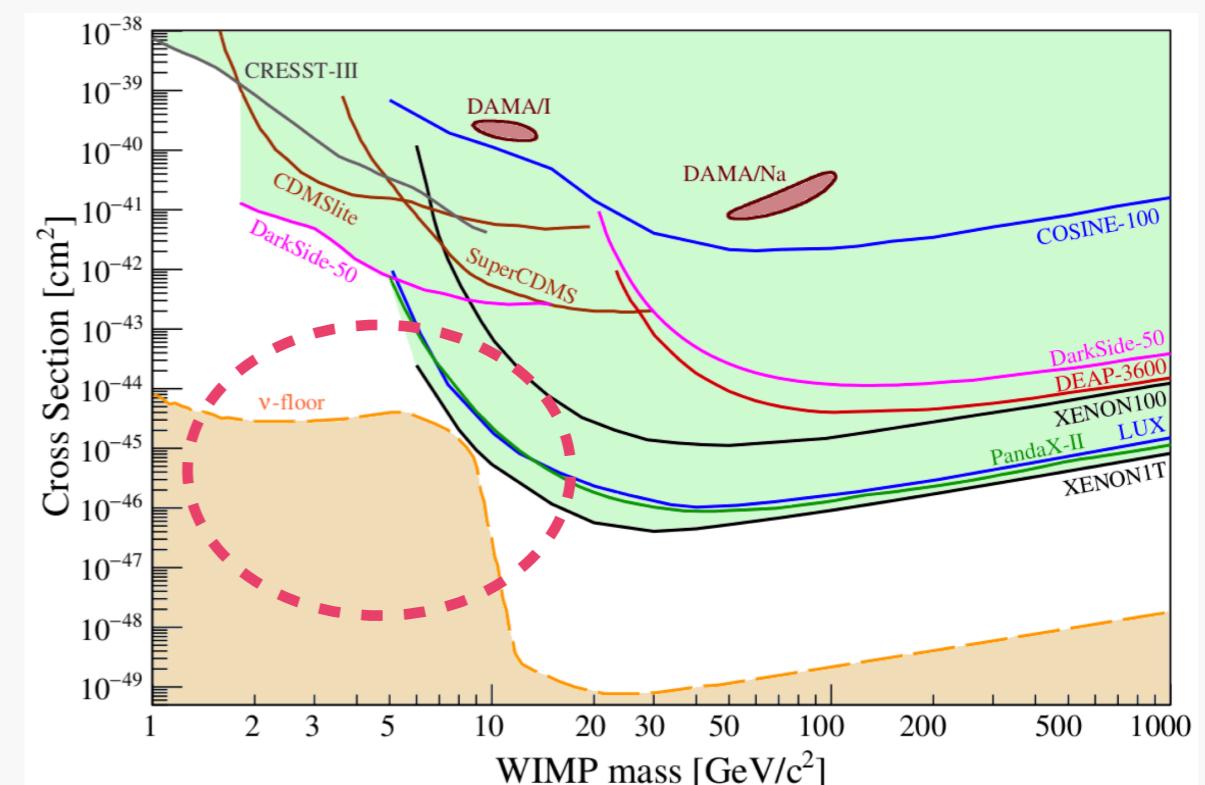
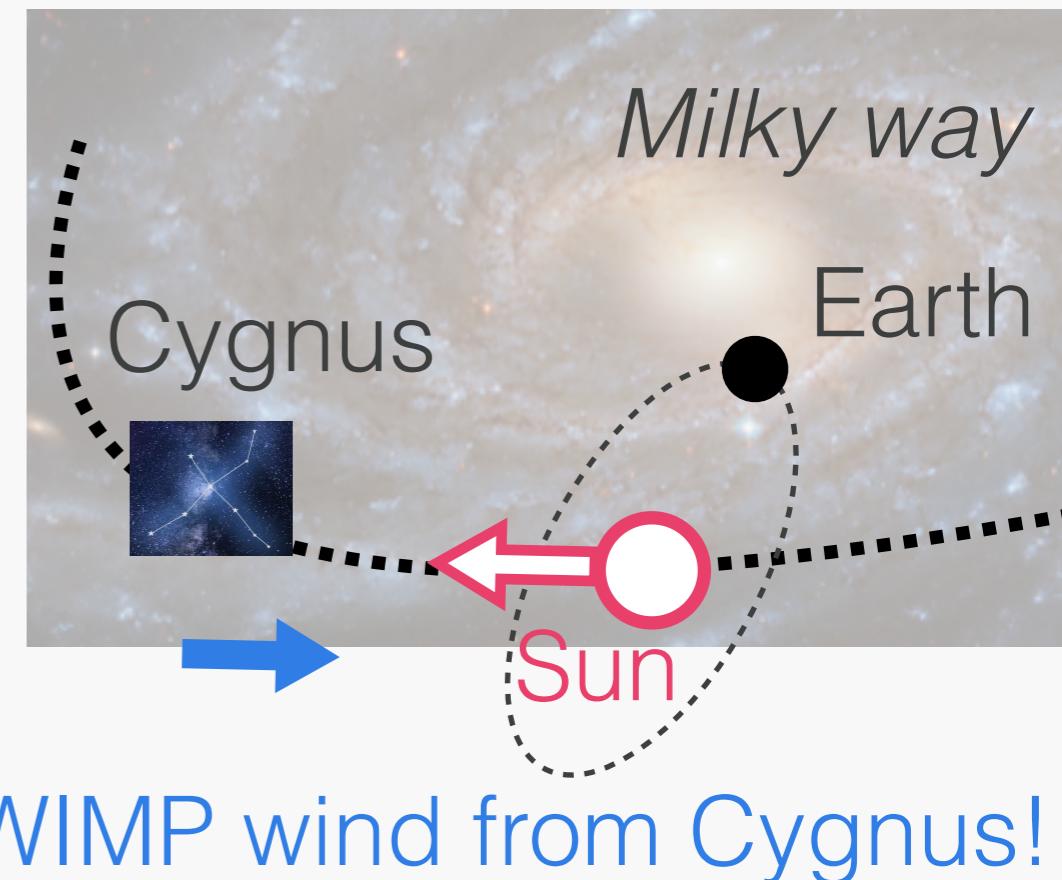
# Introduction

# Direction-sensitive DM searches

- Detect scattering angle of nuclear recoils (NR) from the “Cygnus direction”
  - leads a strong signature of WIMP
  - allows to explore beyond the neutrino fog
- Also sensitive for other directional DM candidates such as “CRDM” (see talk by K. Nagao)

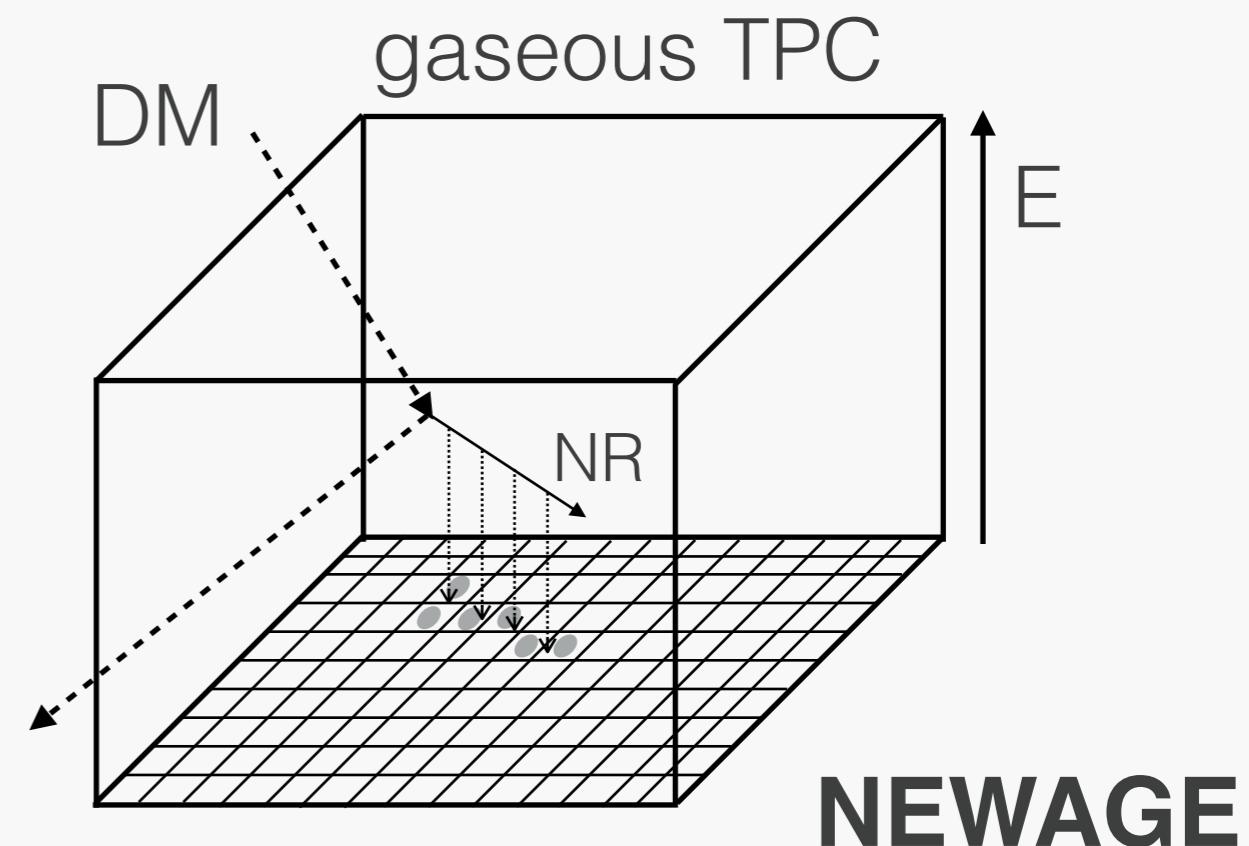
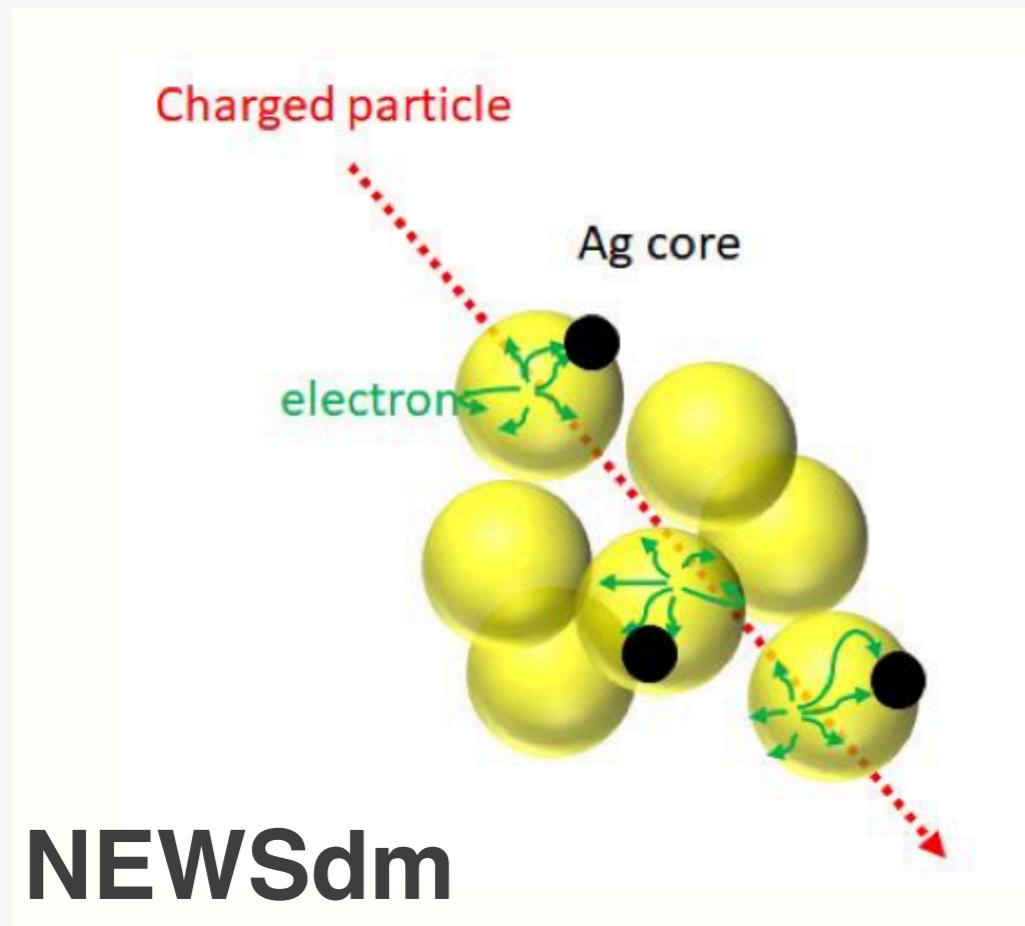


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# Directional search methods

- **Particle tracking** is necessary to measure scattering angle from the Cygnus direction
  - Need to measure  $< 10$  keV nuclear recoil (**VERY short track!**)
- To achieve  $< 10$  keV nuclear recoil track reconstruction, ...
  - ultra-fine granularity detector (NEWSdm: *next talk by T.Naka*)
  - use **low pressure gas** to extend trajectory (e.g. **NEWAGE**)



# Publications related to NEWAGE

- FY2023 publication (New!)

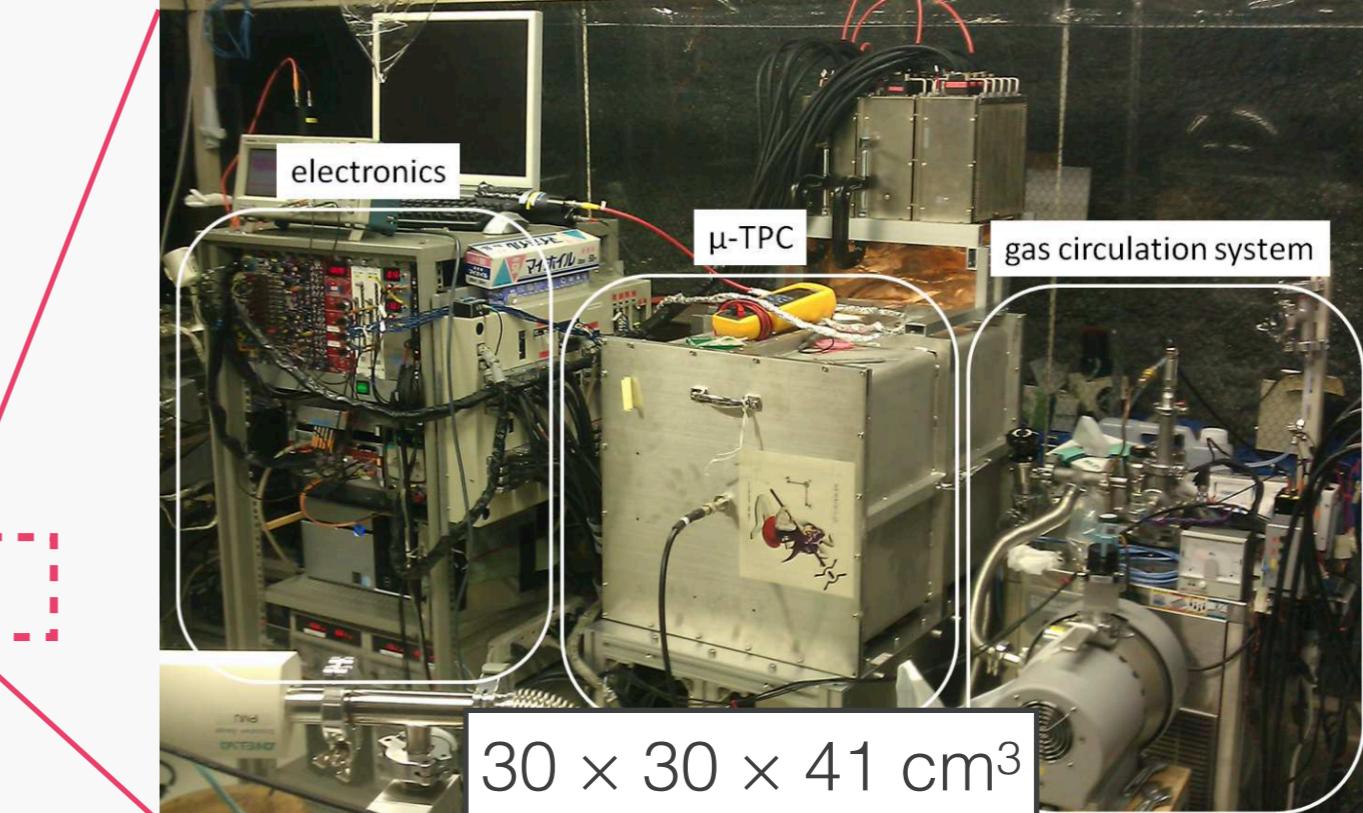
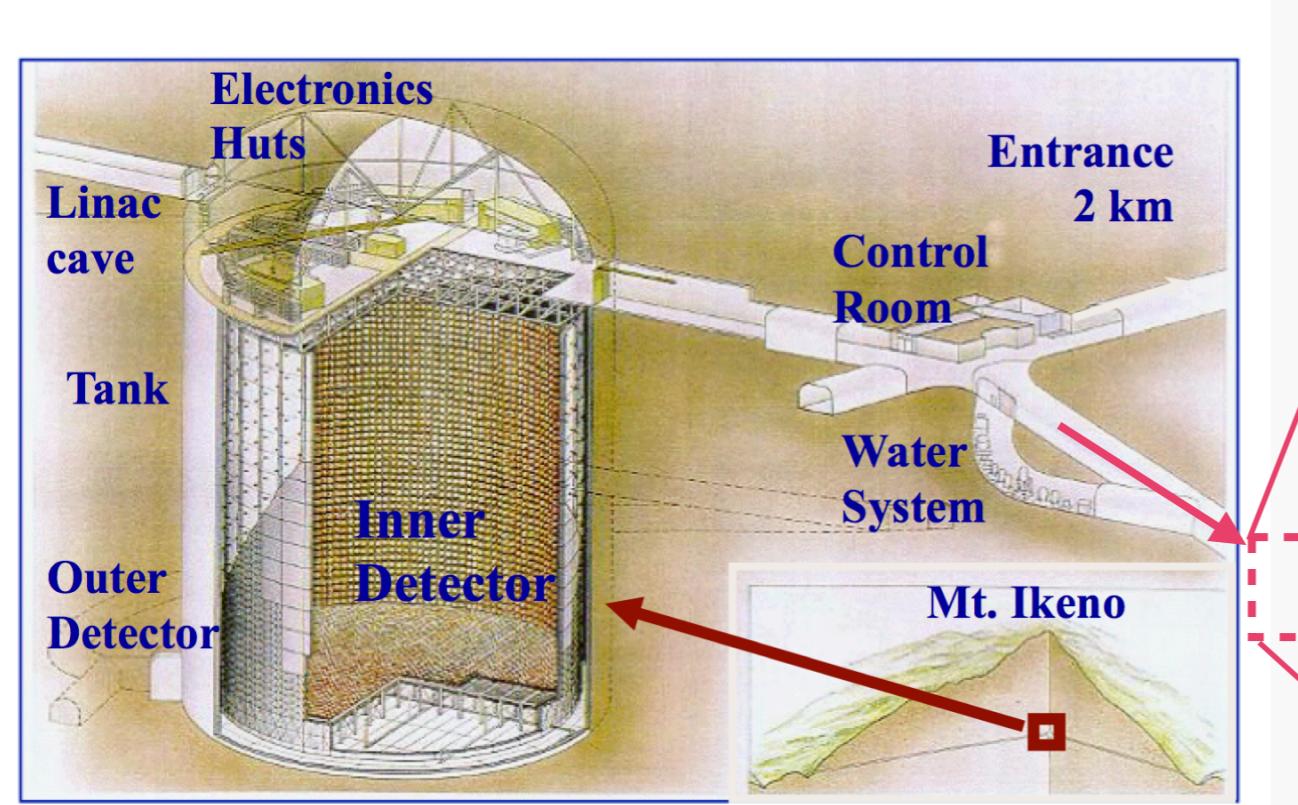
- "Measurement of radon emanation and impurity adsorption from argon gas using ultralow radioactive zeolite", 2024 JINST 19 P02004
  - ▶ H. Ogawa, K. Iyoki, M. Matsukura, T. Wakihara, K. Abe, K. Miuchi, S. Umehara
- "Direction-sensitive dark matter search with three-dimensional vector-type tracking in NEWAGE", PTEP (2023) 10, 103F01
  - ▶ T. Shimada, S. Higashino, T. Ikeda, et. al.
- "Directional direct detection of light dark matter up-scattered by cosmic rays from direction of the Galactic center", JCAP07(2023)061
  - ▶ K. Nagao, S. Higashino, T. Naka, K. Miuchi
- "Development of negative-ion gaseous TPC using micro pattern readout for direction-sensitive dark matter search", 2023 JINST 18 C06012
  - ▶ S. Higashino, T. Ikeda, A. Nakayama, M. Ofuji, K. Miuchi
- "Challenges for the directional dark matter direct detection", arXiv:2309.13923 → JAIS (accepted yesterday!)
  - ▶ K. Miuchi

- FY2019 - FY2022

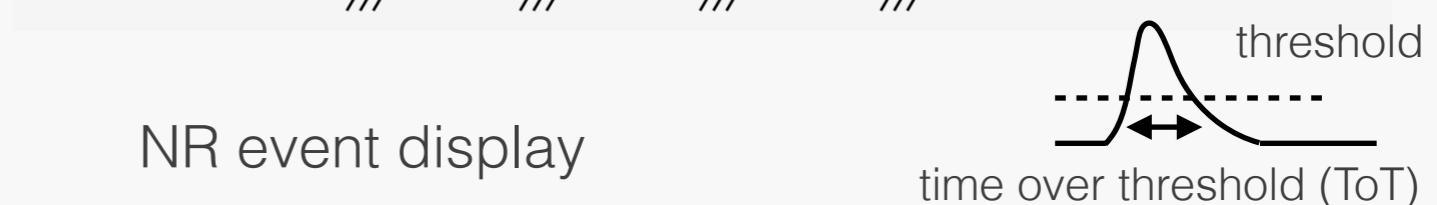
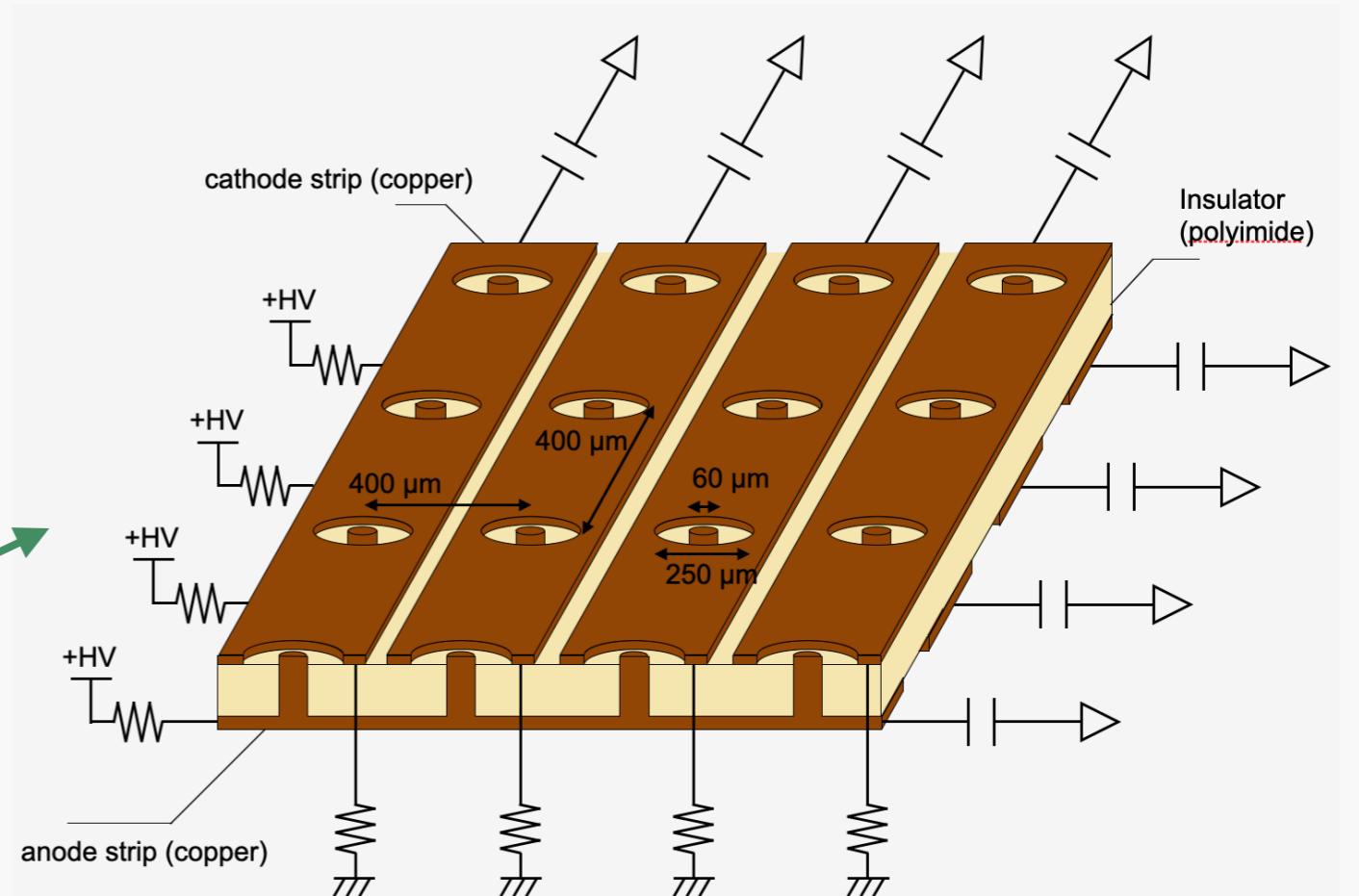
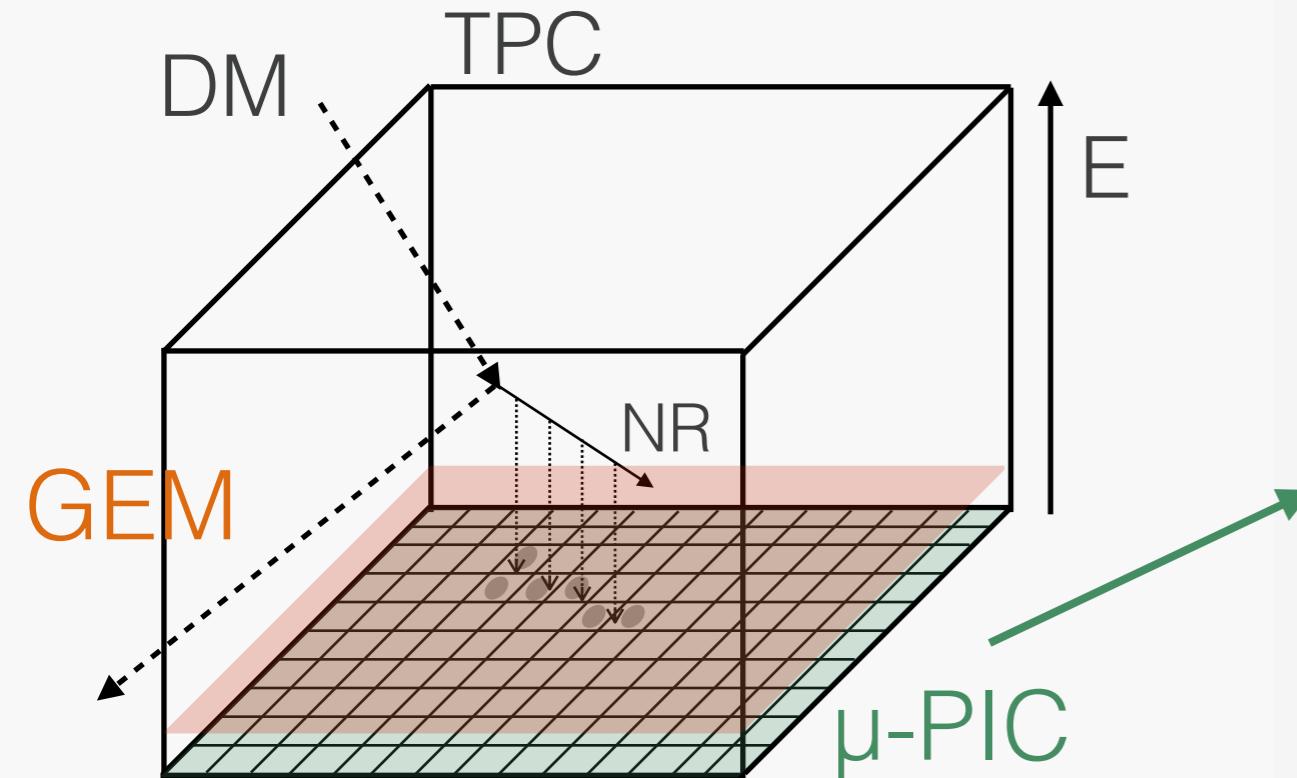
- 10 papers published

# NEWAGE

- 1,000 m underground experiment in the Kamioka mine
- Low pressure gaseous TPC
  - $30 \times 30 \times 41 \text{ cm}^3$  fiducial volume
  - filled with  $\text{CF}_4$  gas (0.1 atm): spin-dependent search

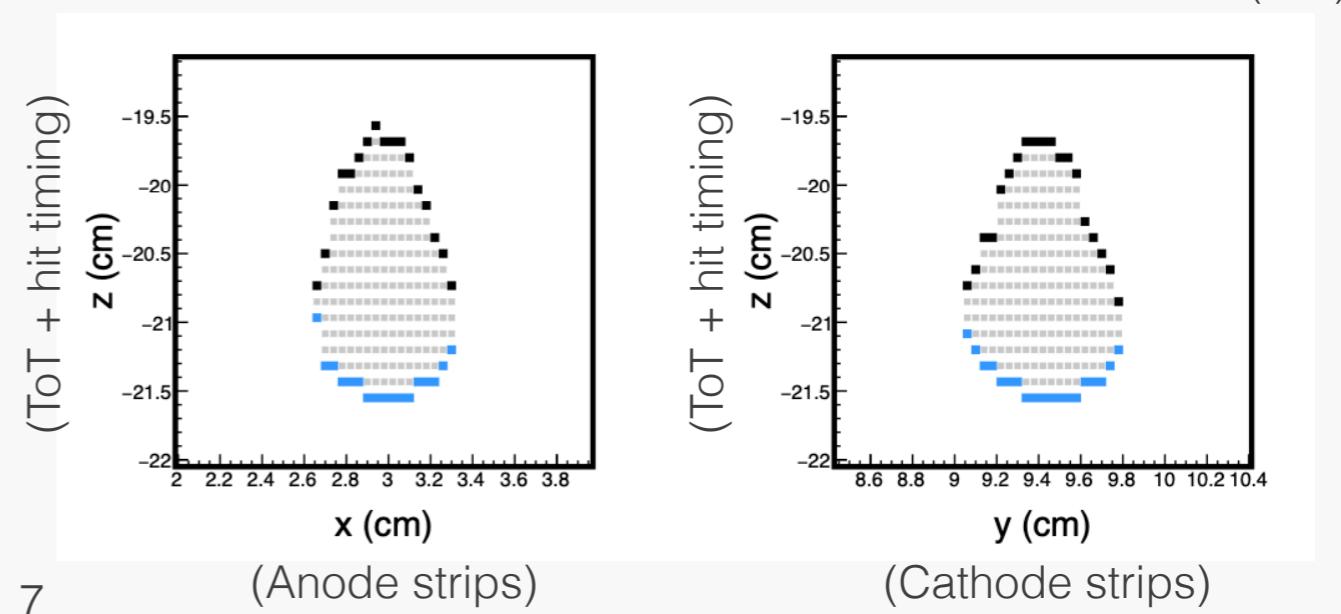


# NEWAGE: 3D track reconstruction



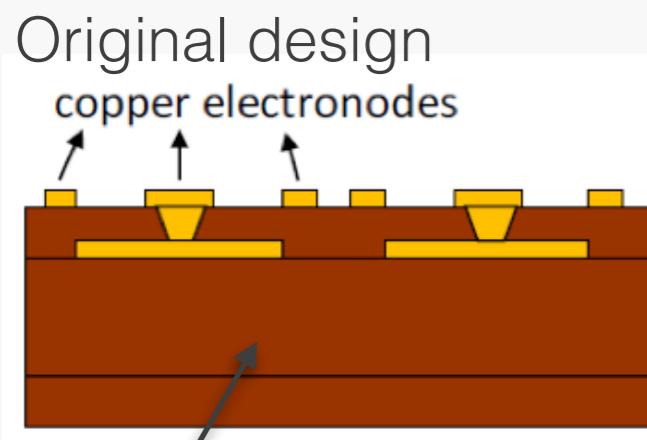
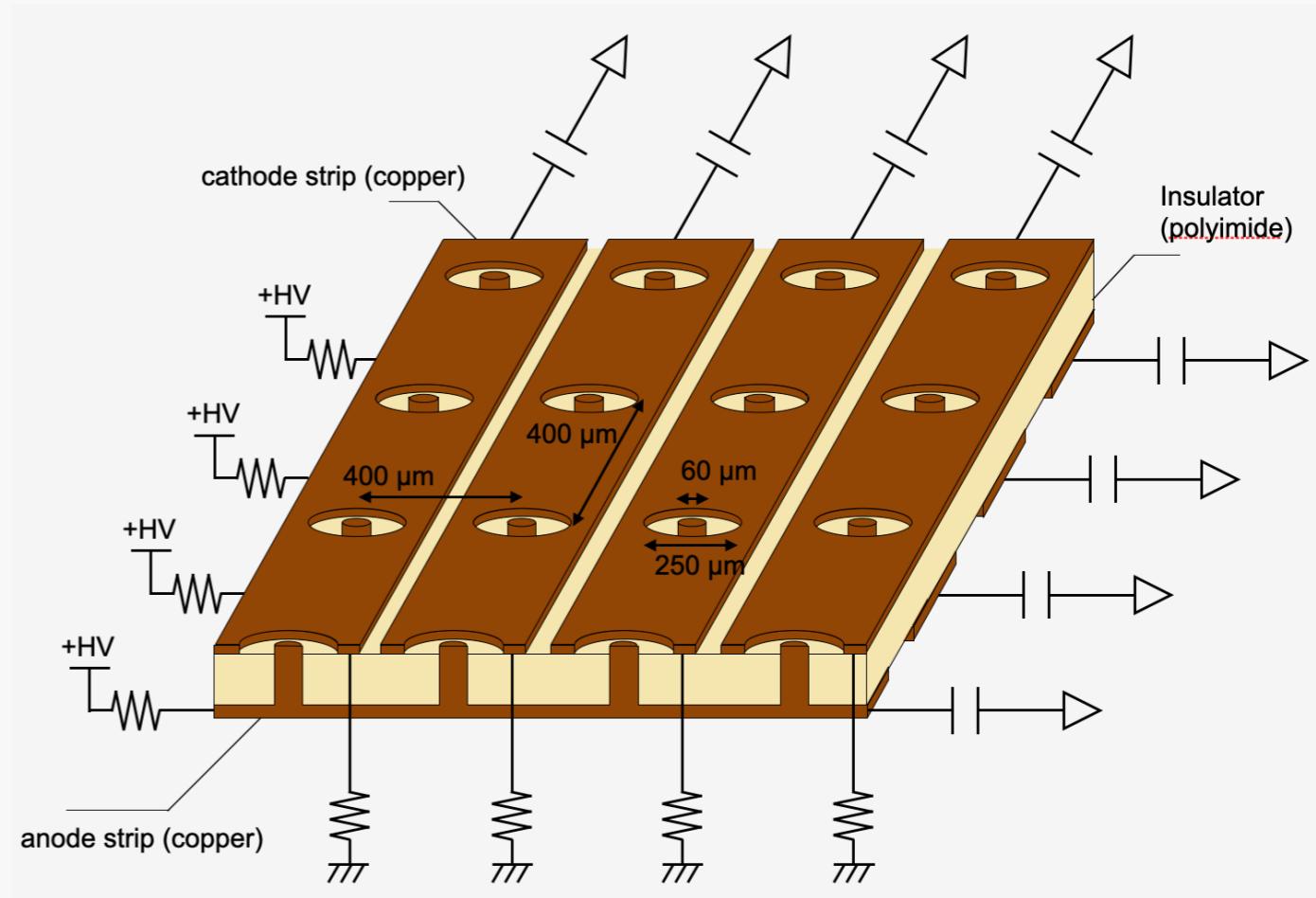
- GEM: Gas amplification
- $\mu$ -PIC:
  - 400  $\mu\text{m}$  pitch 2D strip readout
  - Gas amplification

2D position + drift time  
→ WIMP search with 3D track



# Our history w.r.t. $\mu$ -PIC developments

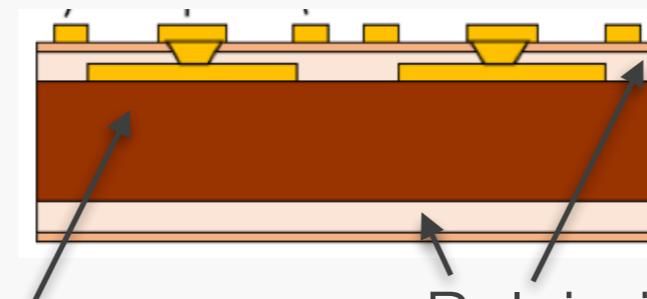
- “Clean” detector development
  - based on material screening
- Known that glass cloth is U/Th-rich
  - progressively reduced
- Finally replaced to Quartz+Resin



Polyimide  
w/ glass cloth  
(Rn contaminated)

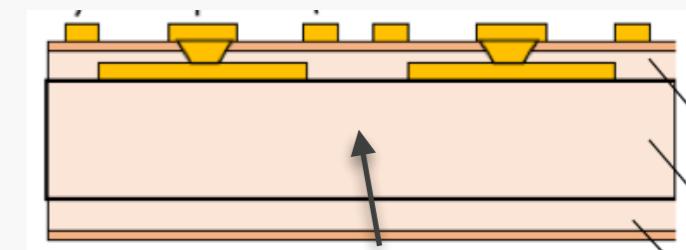
Original design  
copper electrodes

Low **surface** alpha version  
LA $\mu$ -PIC: 2017- (ugnd)



Polyimide  
w/ glass cloth

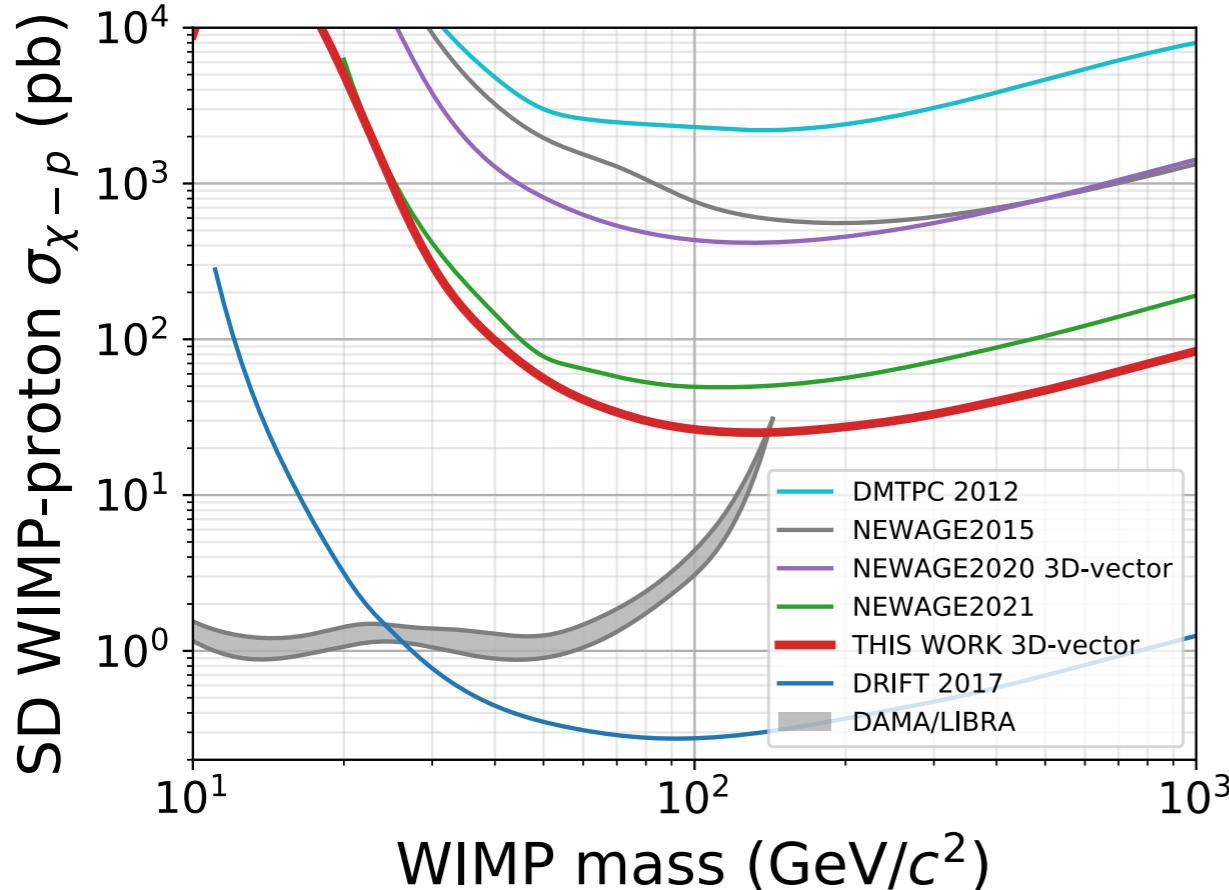
Low-BG  $\mu$ -PIC  
ver0: 2020, ver1: 2023 (ugap)



Quartz + Resin

# Our history w.r.t. $\mu$ -PIC developments

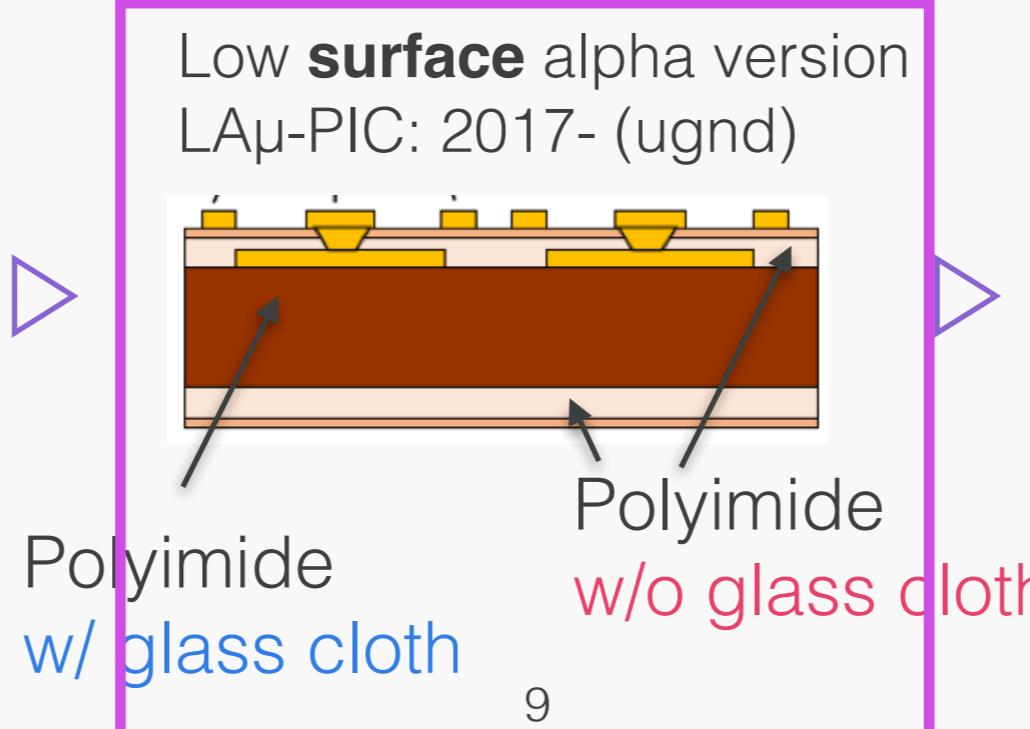
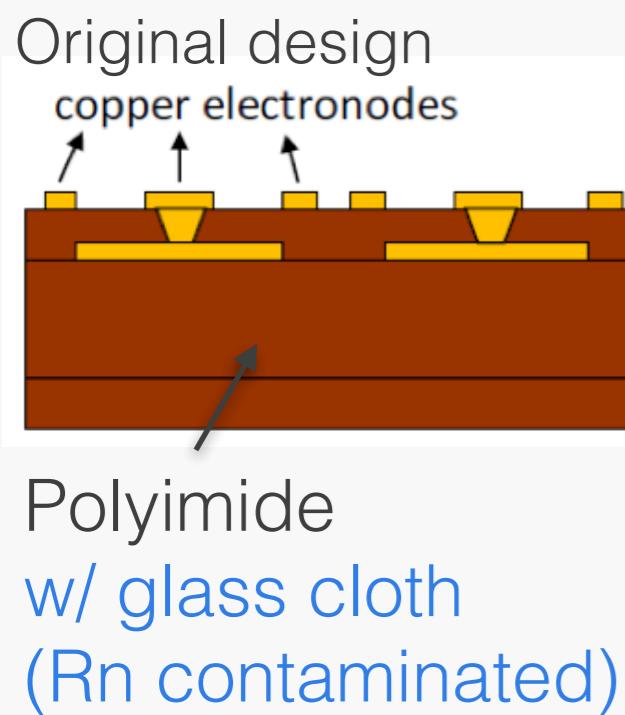
PTEP 2023 (2023) 10, 103F01



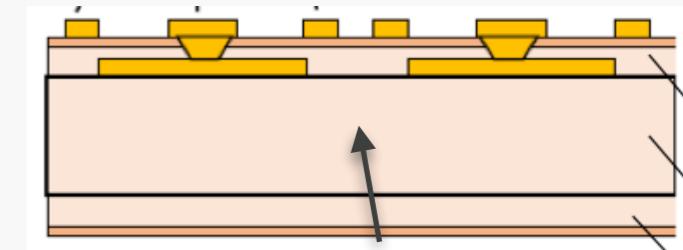
NEWAGE2015 & 2020 (Original design)

**NEWAGE2021 & 2023**

Low surface alpha  $\mu$ -PIC:  
Developed and installed in ugnd period  
Analyzed in ugap period

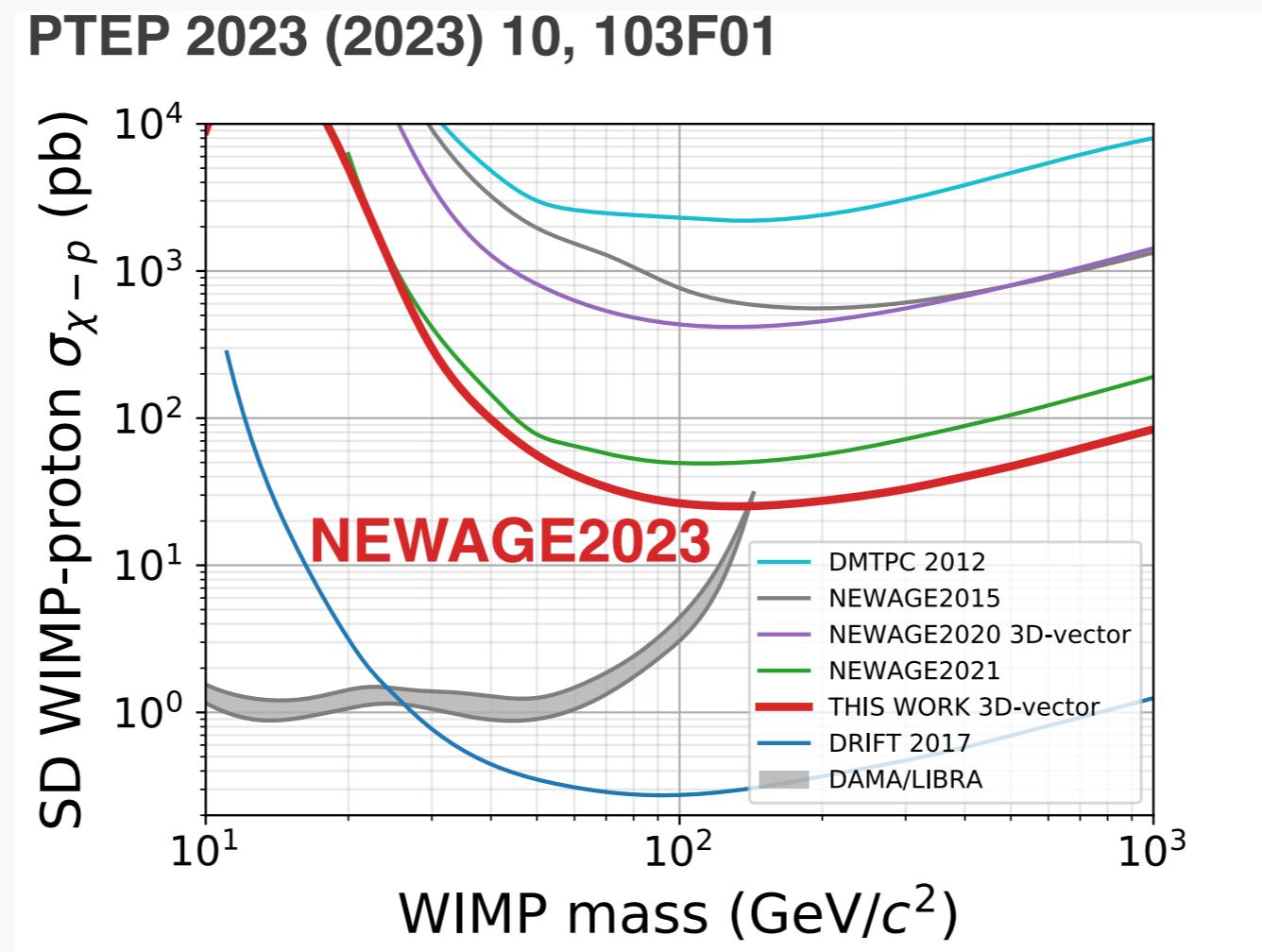


**Low-BG  $\mu$ -PIC**  
ver0: 2020, ver1: 2023 (ugap)



Quartz + Resin

# The latest analysis result

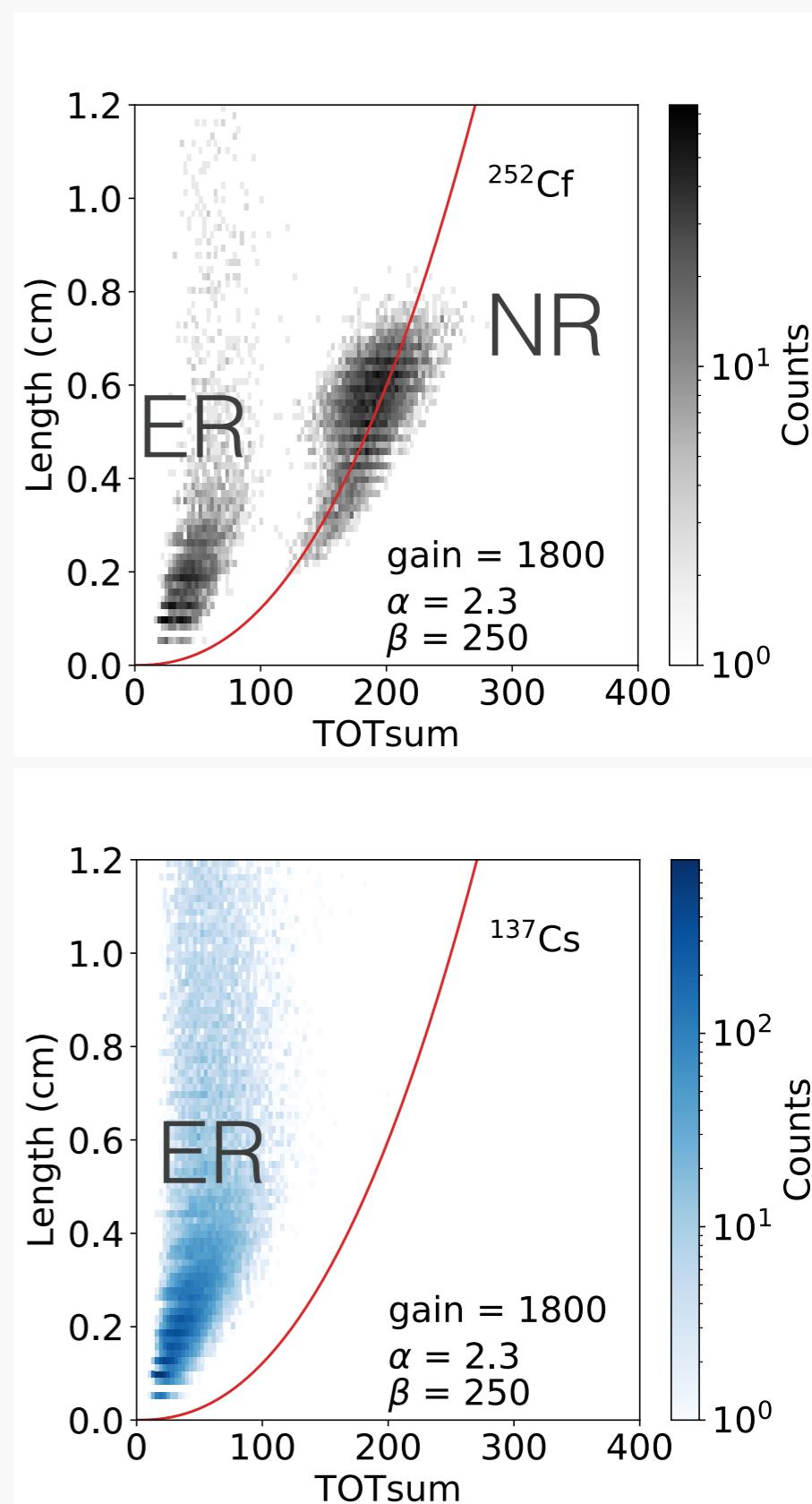
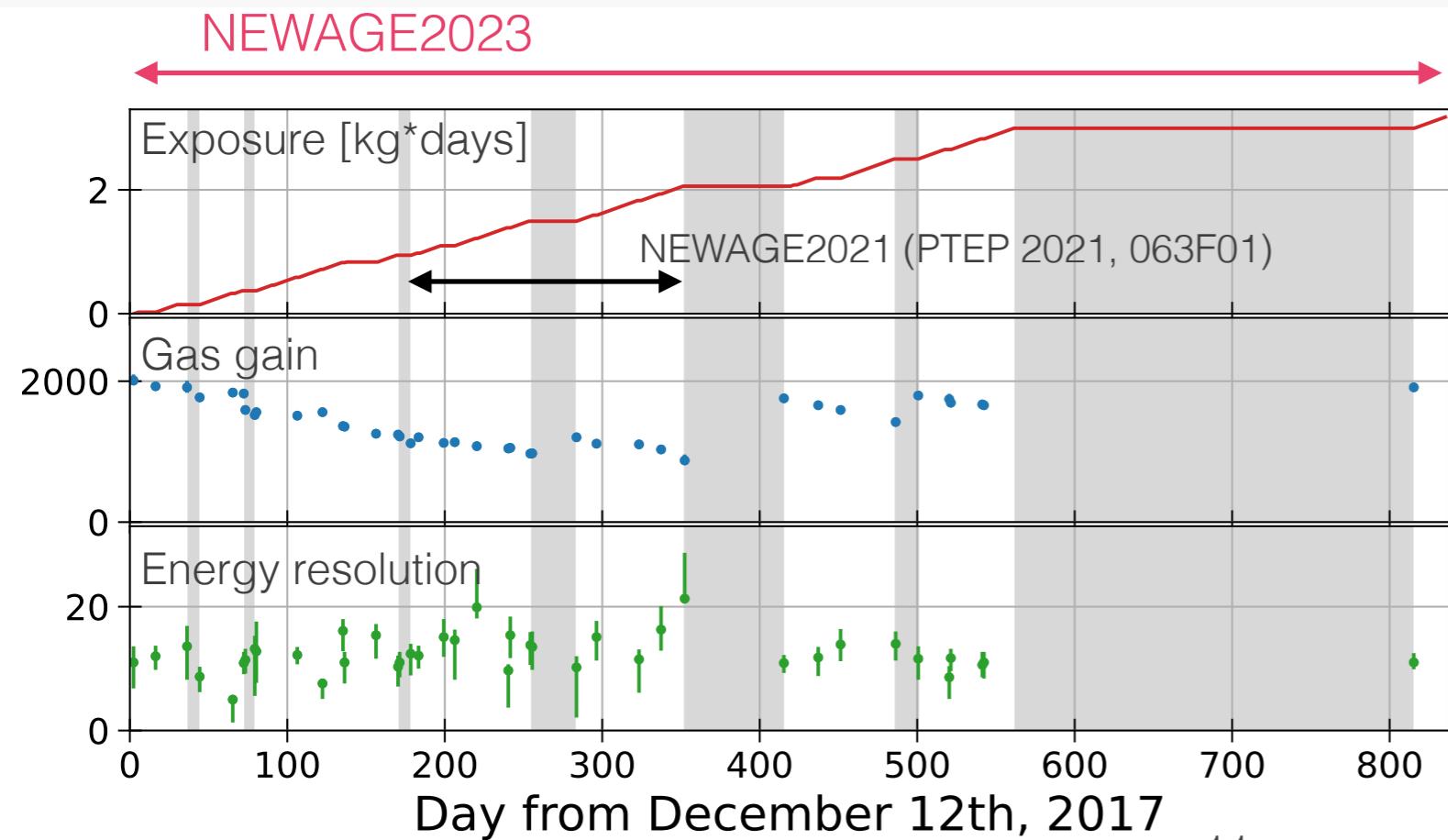


# The latest publication of underground measurement (2023)

- Increase statistics: 108 days → 318 days ( $\times 3$ )
 

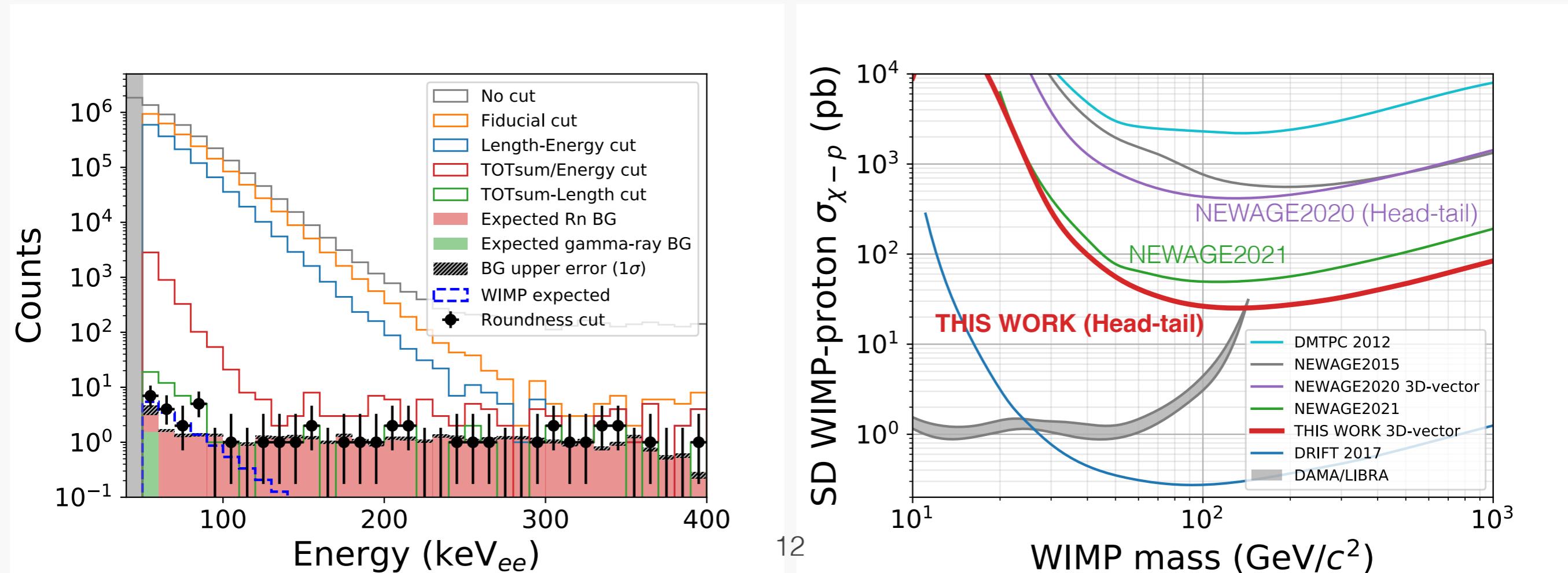
PTEP 2021, 063F01 (NEWAGE2021)

  - Use higher gas gain operation run
  - Electron recoil (ER) by gamma rays should be removed
- Additional selection applied using multi-variate analysis
  - correlation between track length, ToT and energy



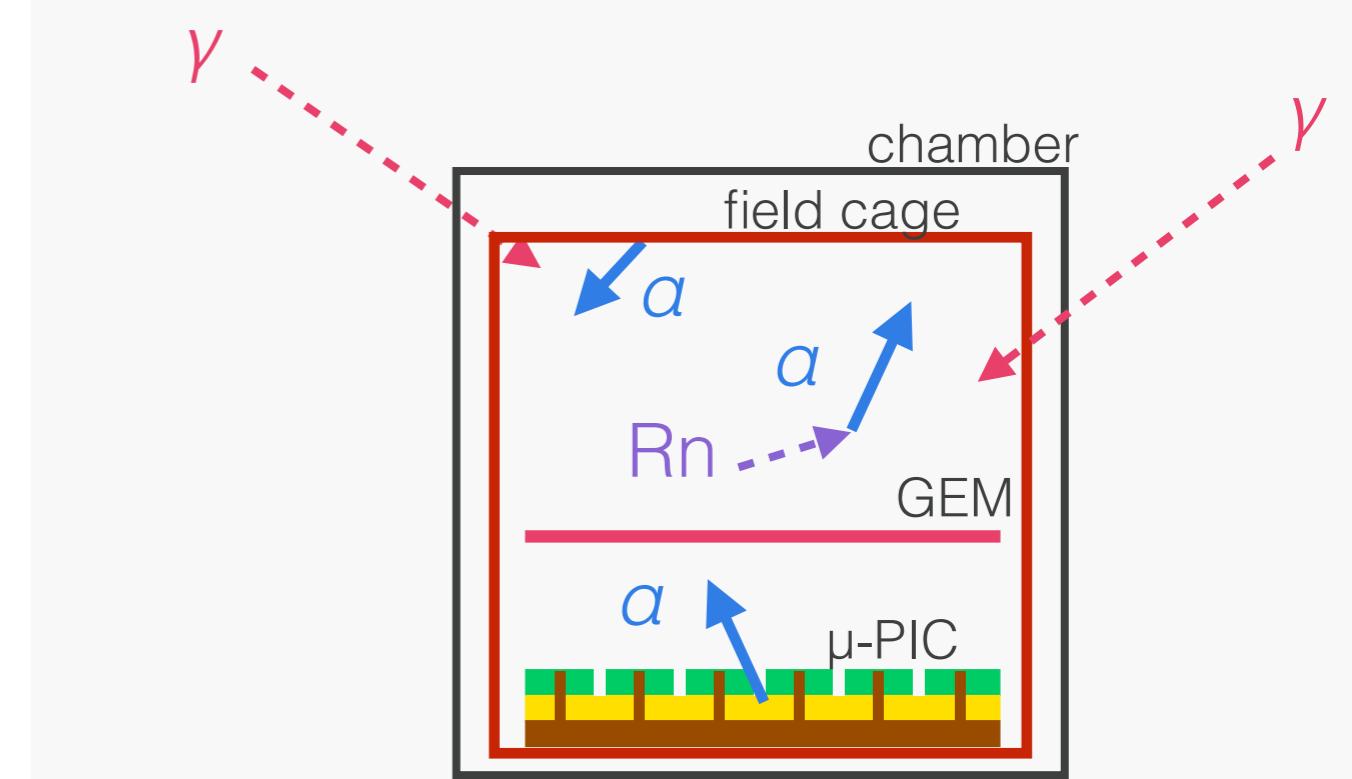
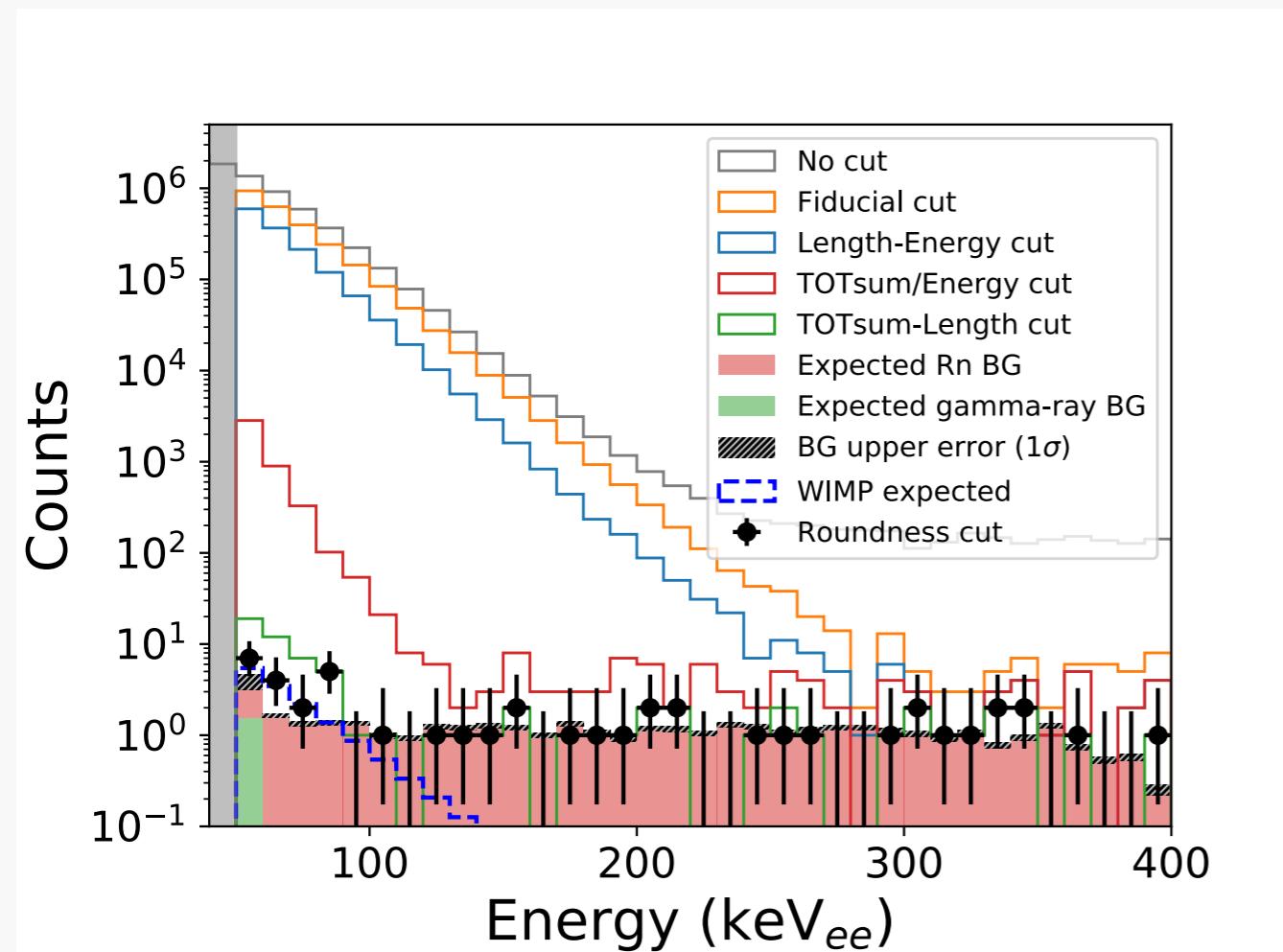
# Result

- $\times \sim 2$  improvement in a DM mass range of  $> 100$  keV
  - Limit is reached to DAMA/LIBRA allowed region
  - Head-tail recognition successfully implemented
    - ▶  $\times 10$  improvement from NEWAGE2020 (first head-tail analysis)
- Future work: **MORE BG rejection** and **large target volume**



# Strategy of BG rejection

- External BG
  - Ambient gamma (and neutron): shielding
- Internal BG
  - Radon emanation: development of Low-BG  $\mu$ -PIC
  - Surface alpha BG from materials may still remain: negative-ion gas



# Strategy of BG rejection

- External BG

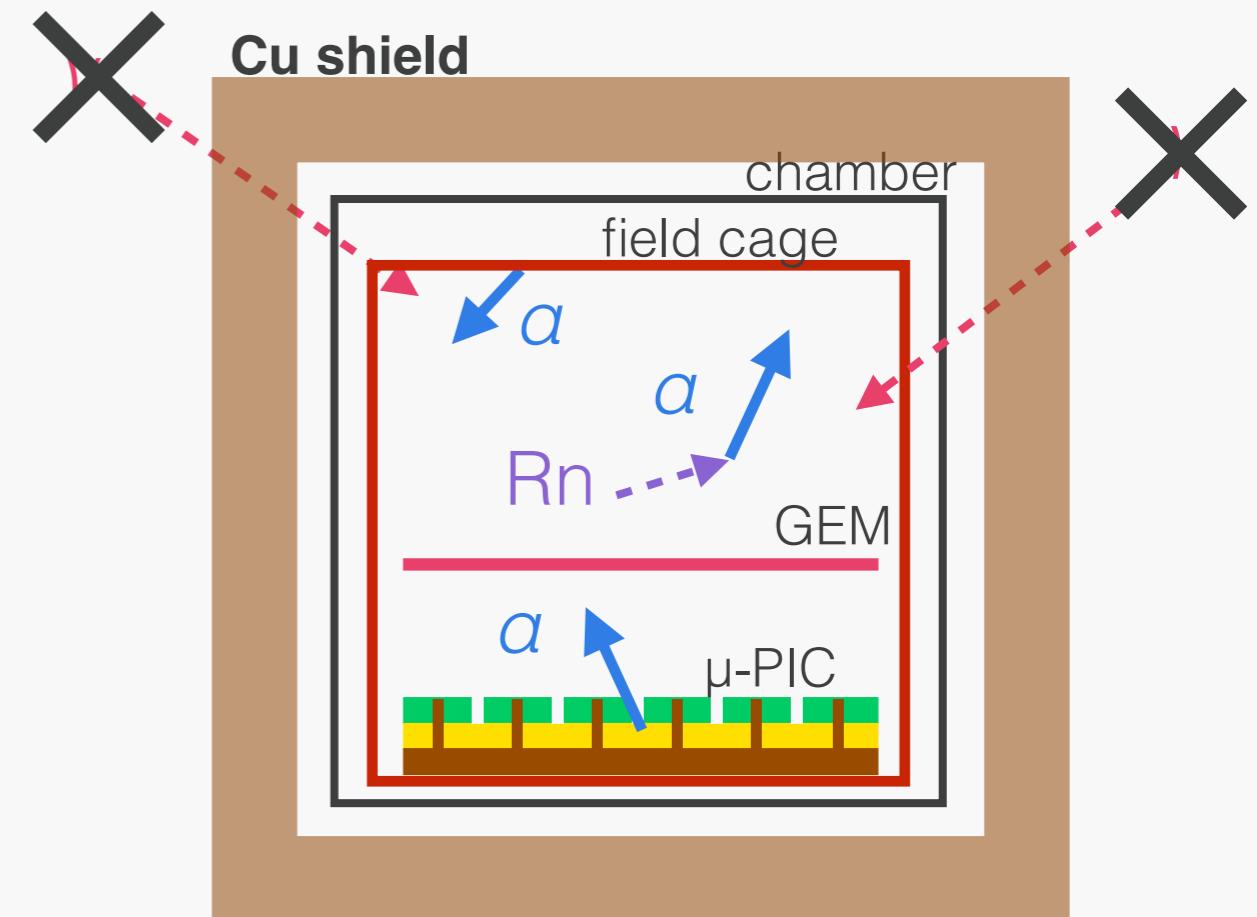
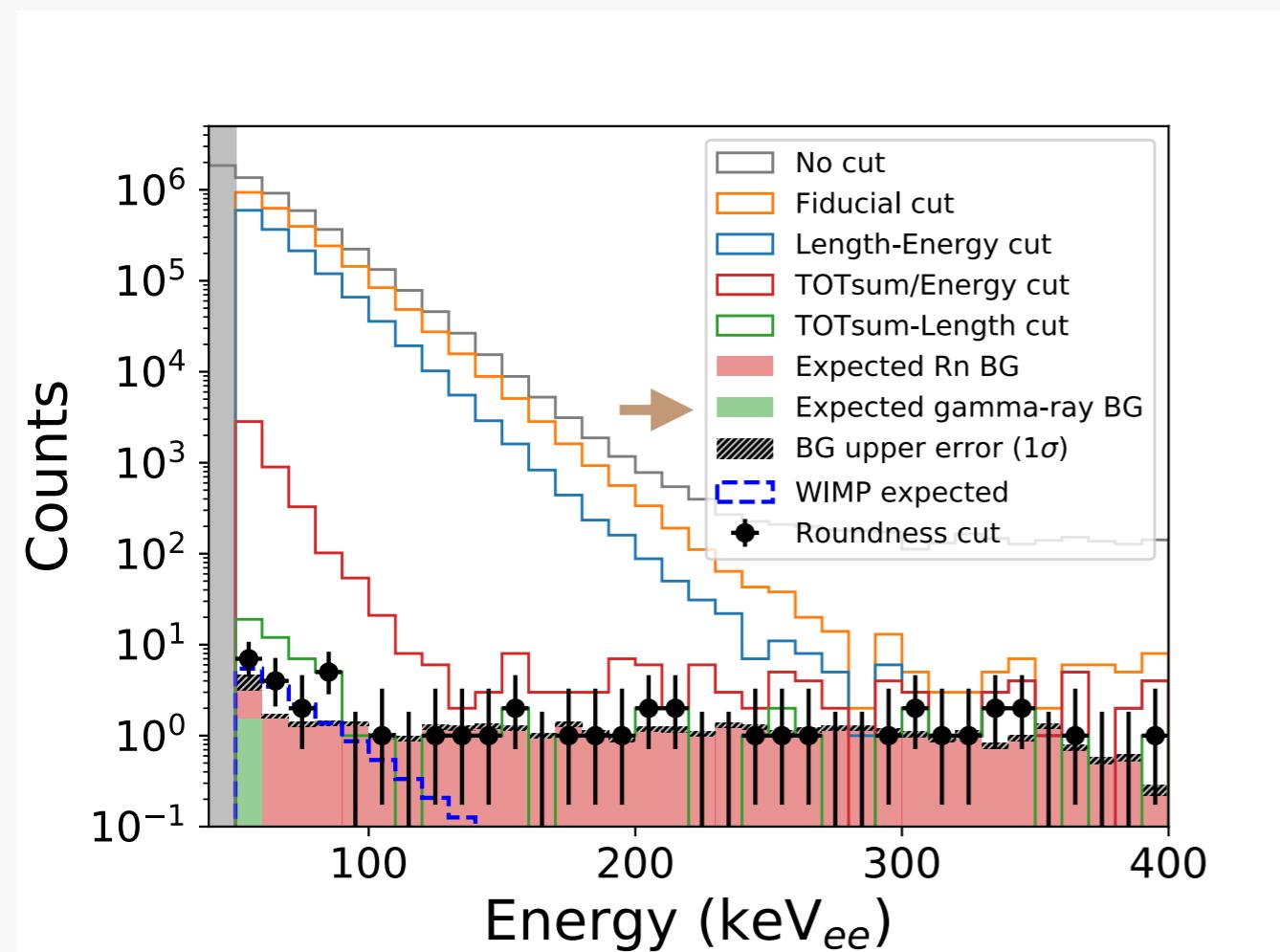
- Ambient gamma (and neutron): shielding



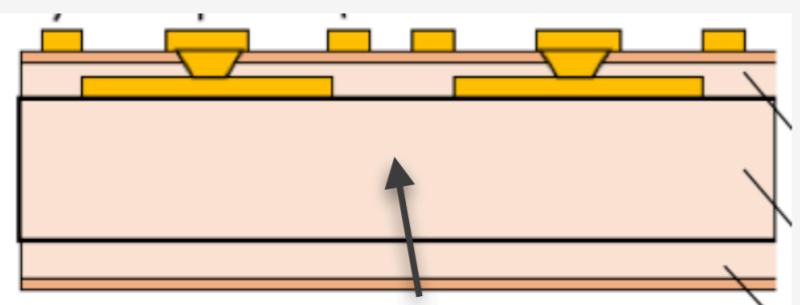
- Internal BG

- Radon emanation: development of Low-BG  $\mu$ -PIC
- Surface alpha BG from materials may still remain: negative-ion gas

<30% gamma injection  
estimated with Geant4 simulation



## Low-BG $\mu$ -PIC (ver0: 2020, ver1: 2023)



Quartz + Resin

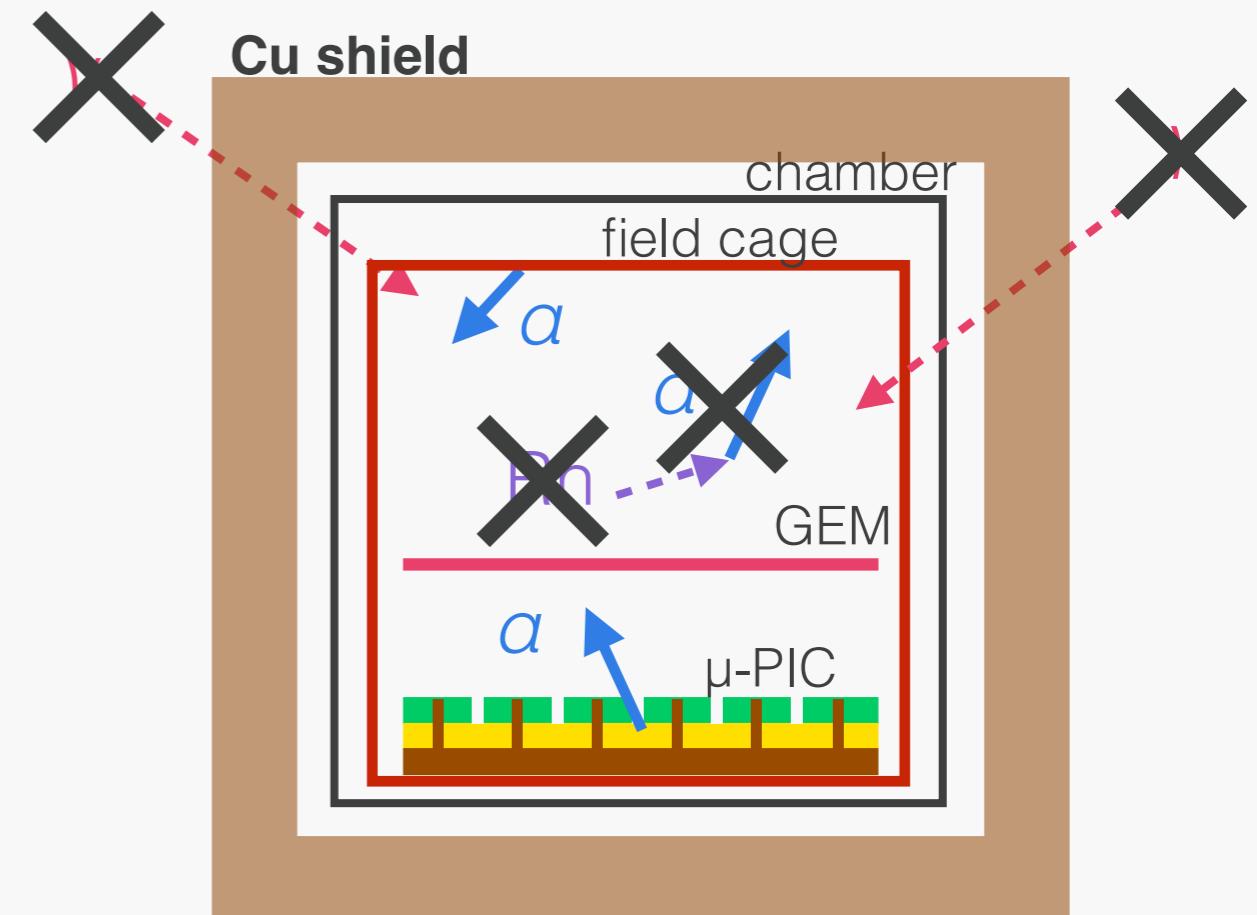
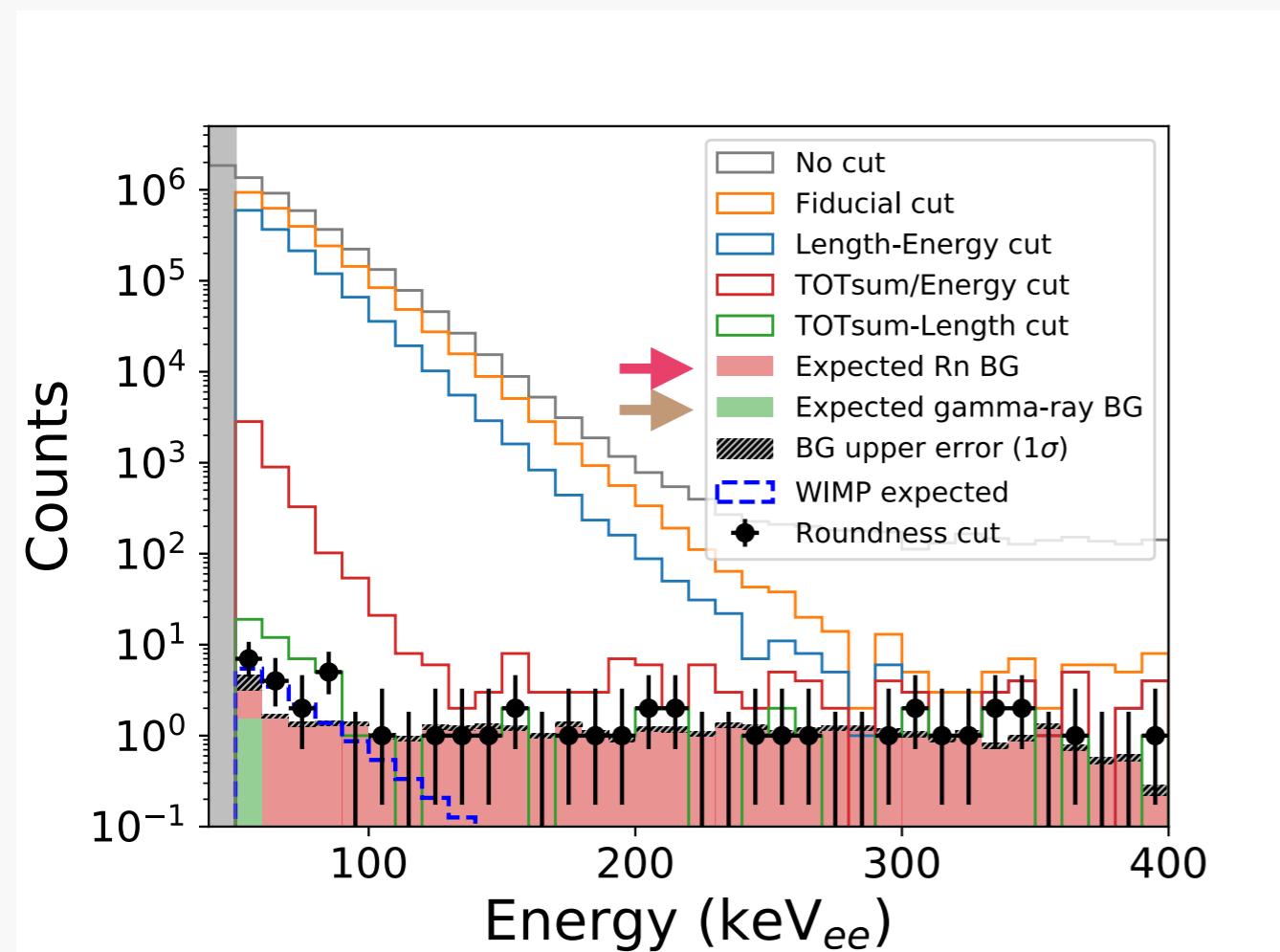
# Strategy of BG rejection

neutron): shielding

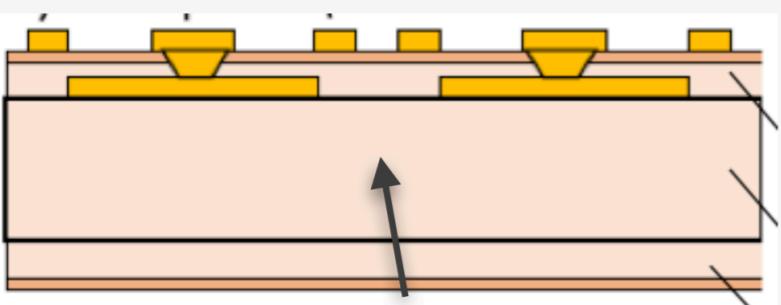


<30% gamma injection  
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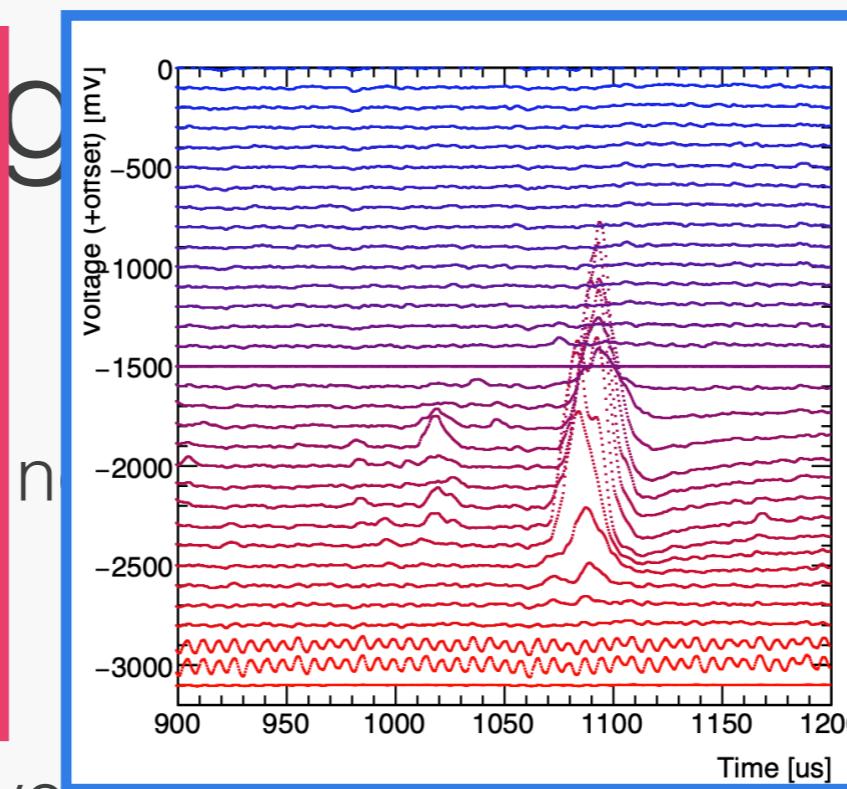
- Radon emanation: development of Low-BG  $\mu$ -PIC
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## Low-BG $\mu$ -PIC (ver0: 2020, ver1: 2023)

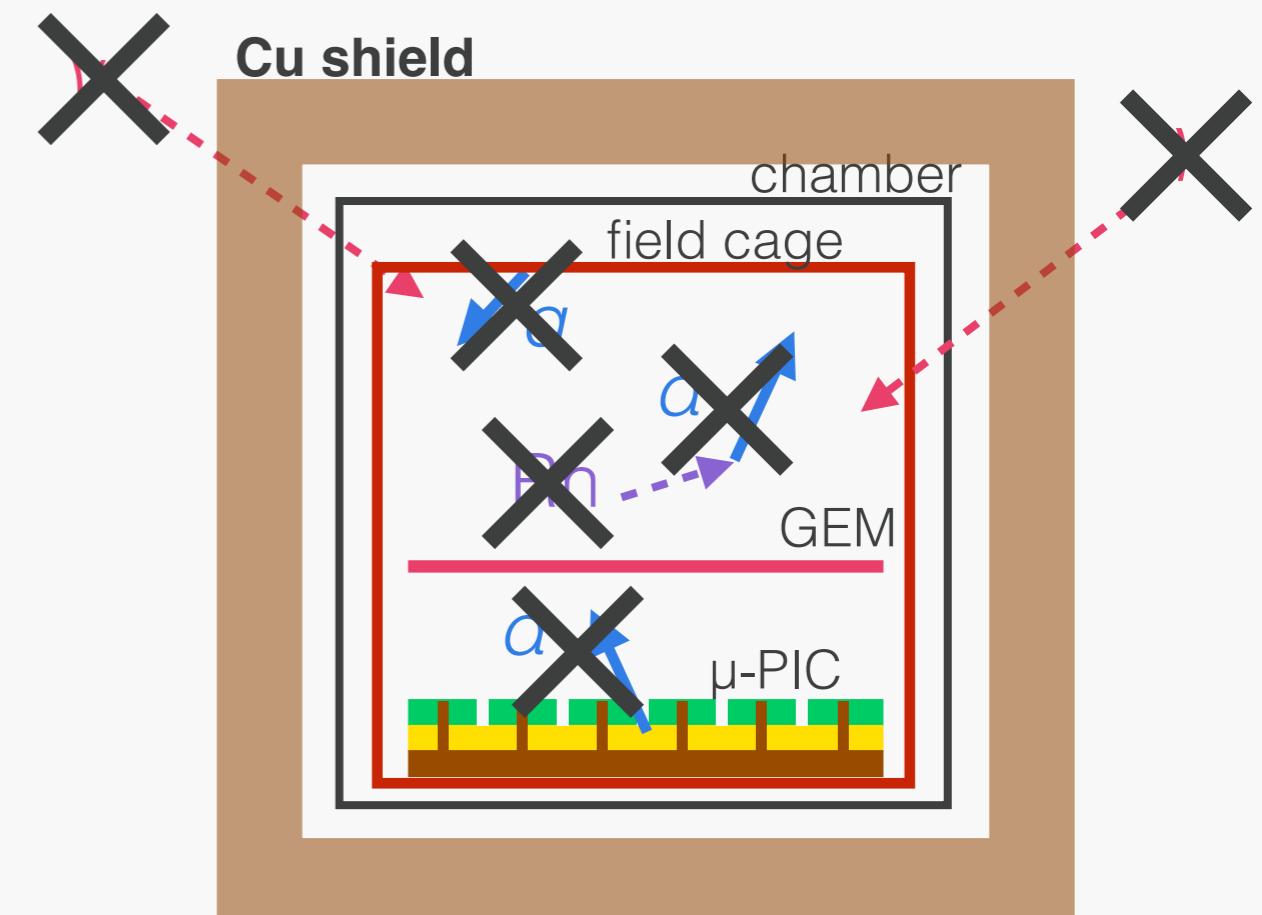
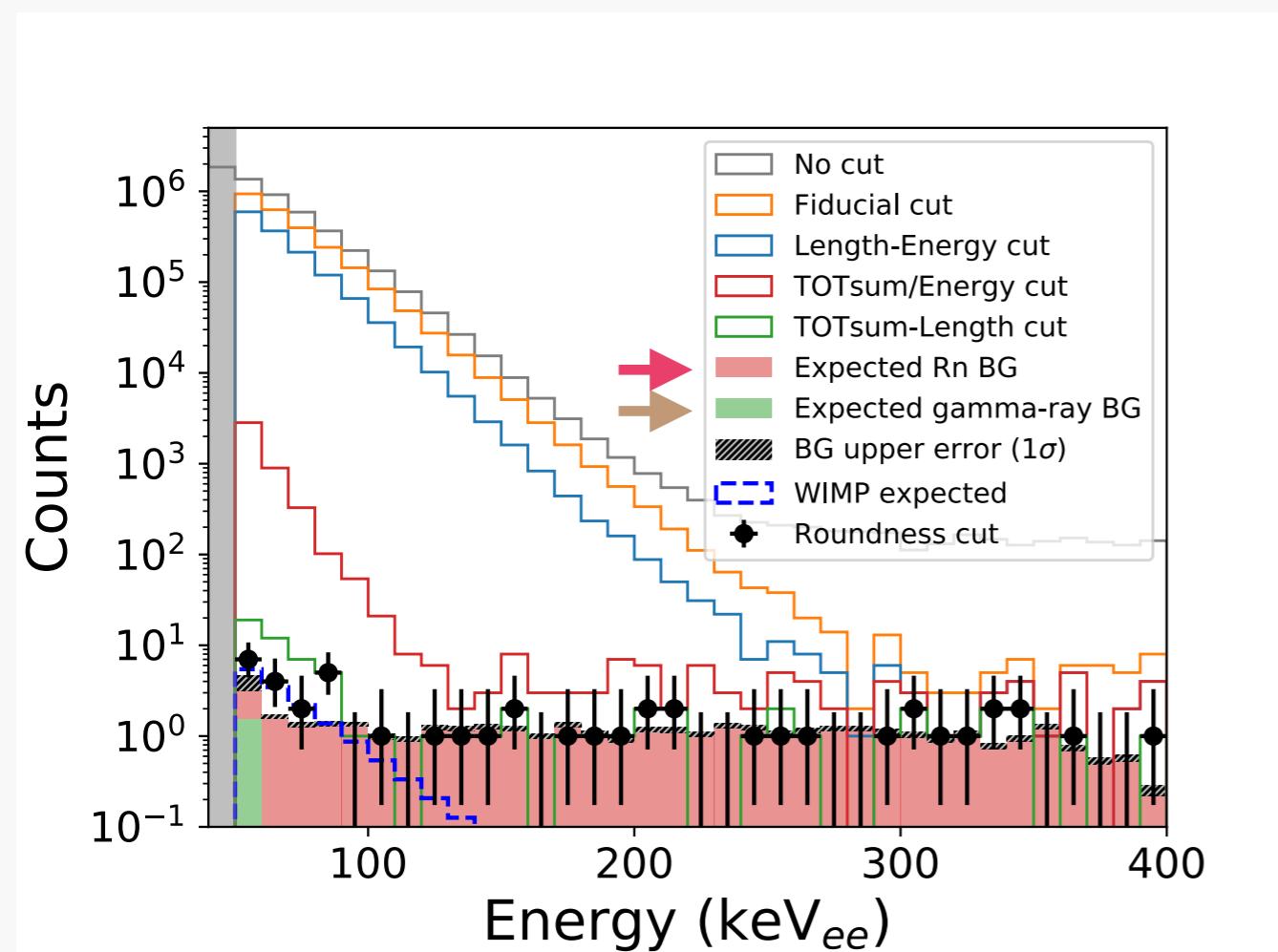


Quartz + Resin

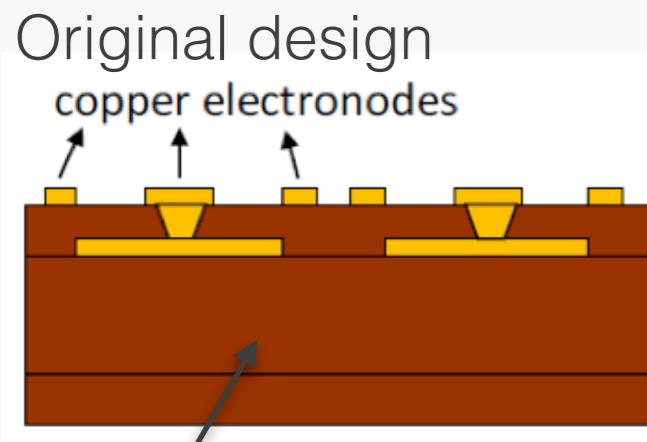


<30% gamma injection  
estimated with Geant4 simulation

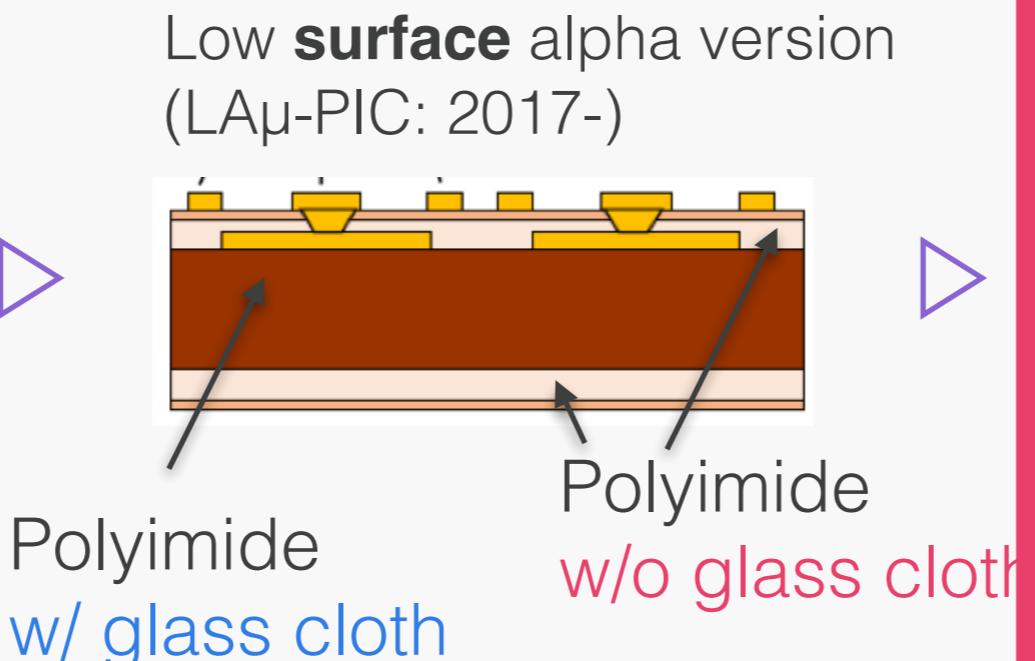
- Radon emanation: development of LOW-BG  $\mu$ -PIC
- Surface alpha BG from materials may still remain: negative-ion gas



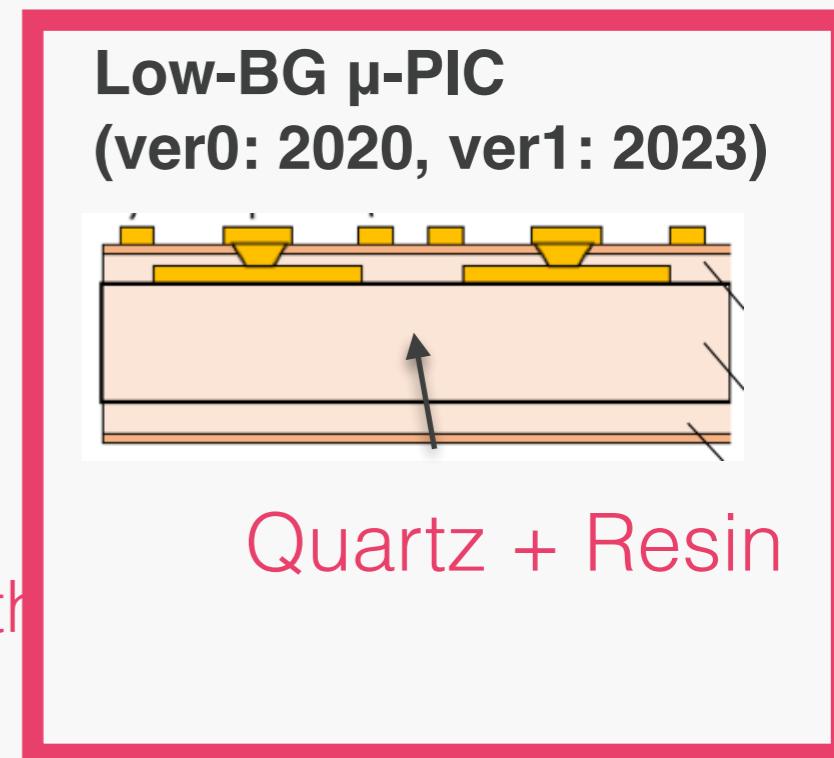
# Underground Measurement with NEW Detector



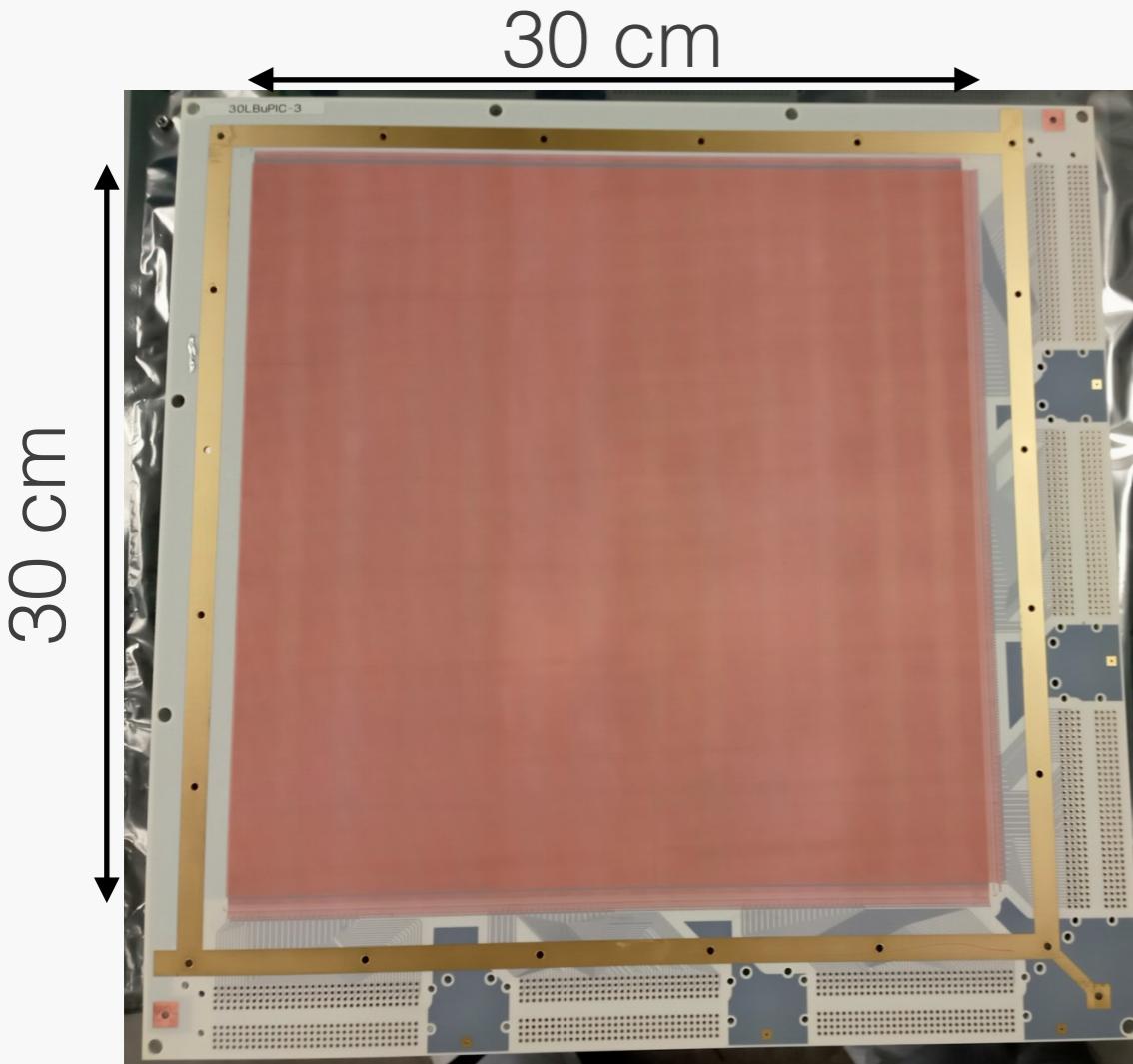
Polyimide  
w/ glass cloth  
(Rn contaminated)



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# Radon emanation measurement for the “clean” detector



LBG $\mu$ -PIC ver1 (thanks to DNP)



Radon detector  
(27 L, electrostatic collection)

Radon emanation measurement:

L $\mu$ -PIC:  **$2.3 \pm 0.5$**  [mBq /  $\mu$ -PIC]

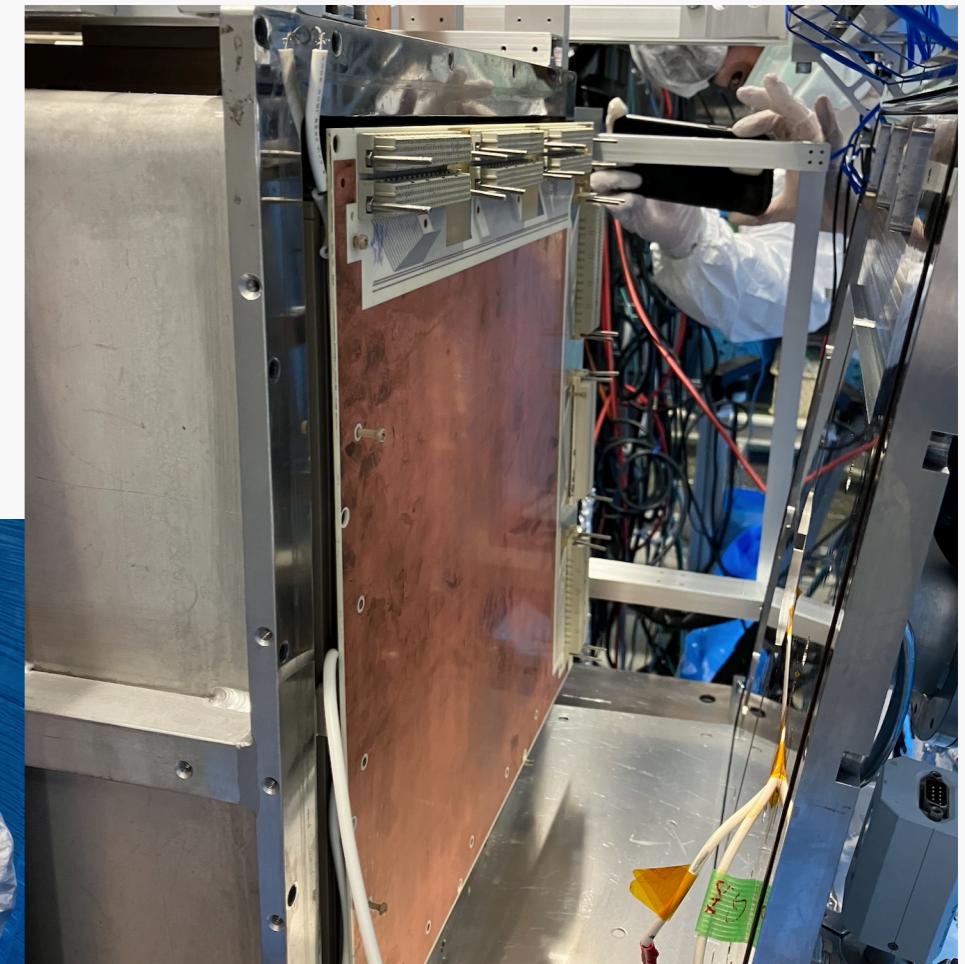
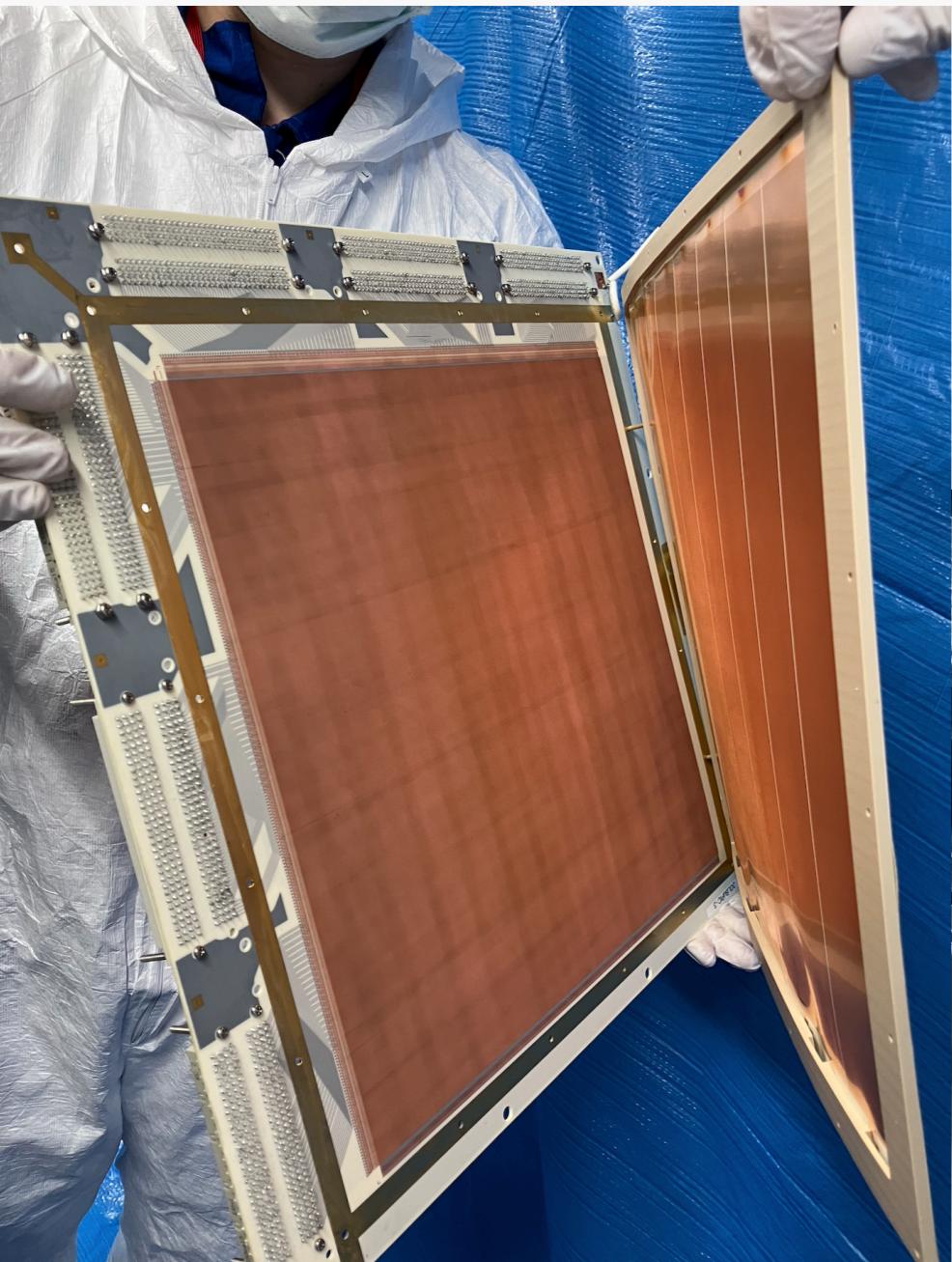


LBG $\mu$ -PIC: <**0.03** [mBq /  $\mu$ -PIC]  
(90% C.L.)

Consistent with material screening result

Paper in preparation  
(see poster P05 by R. Namai)

# Detector installation (Dec. 2023)

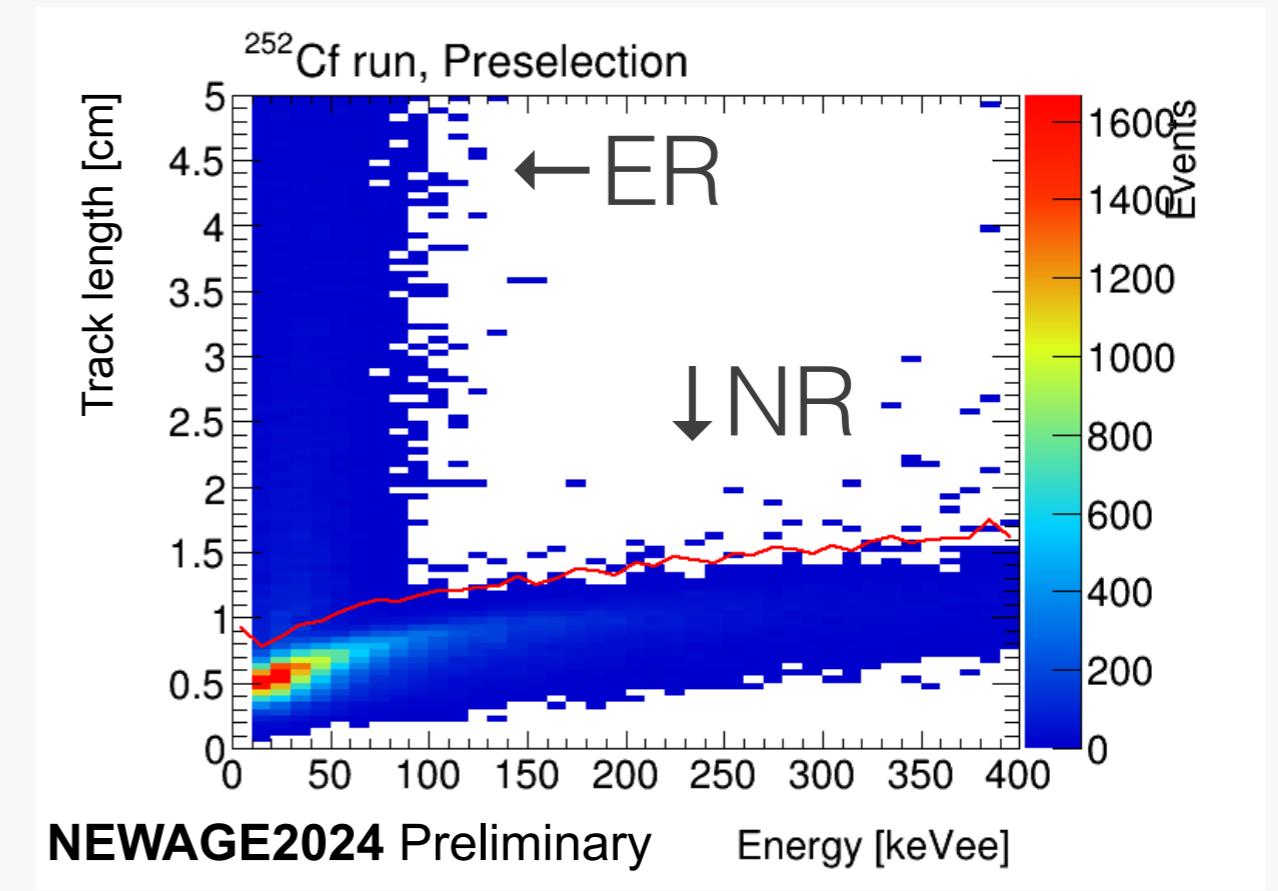
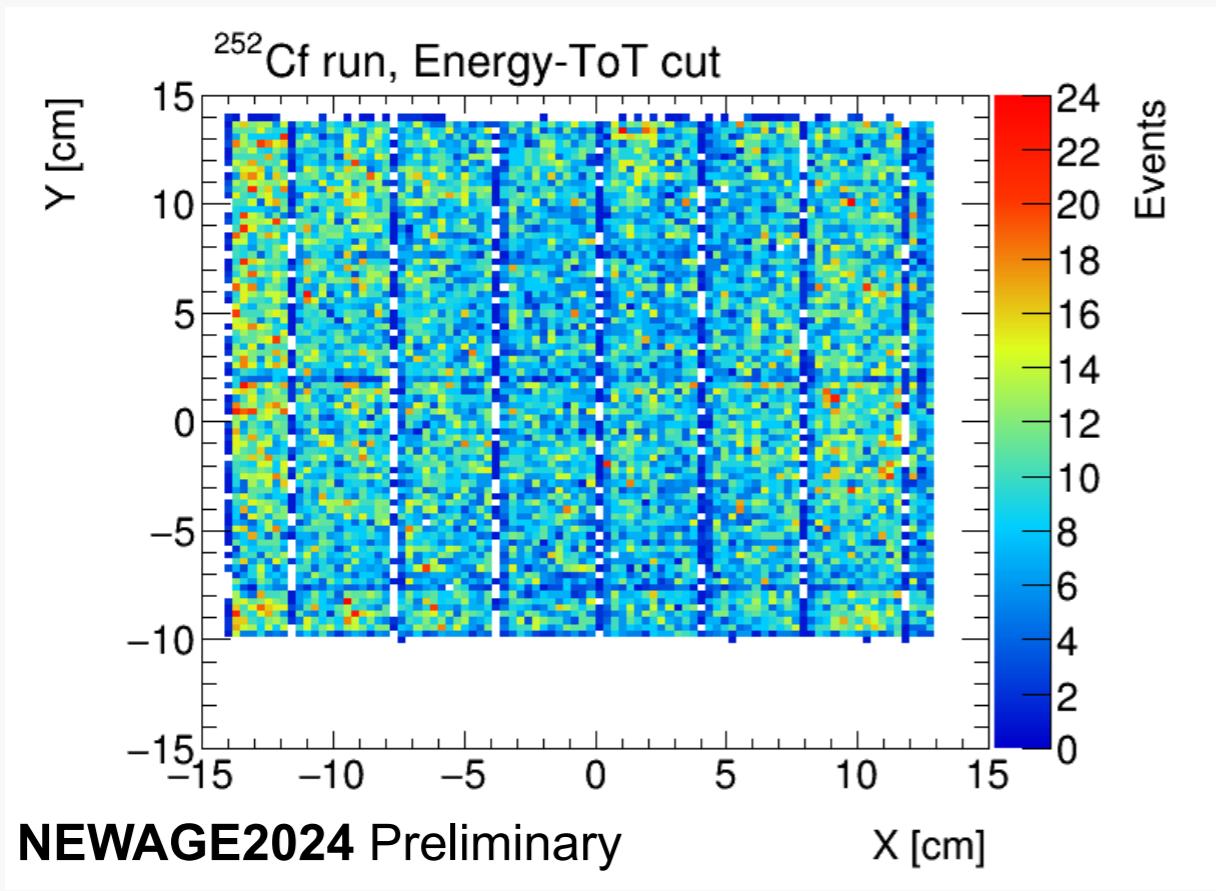


μ-PIC↑



# Detector performance

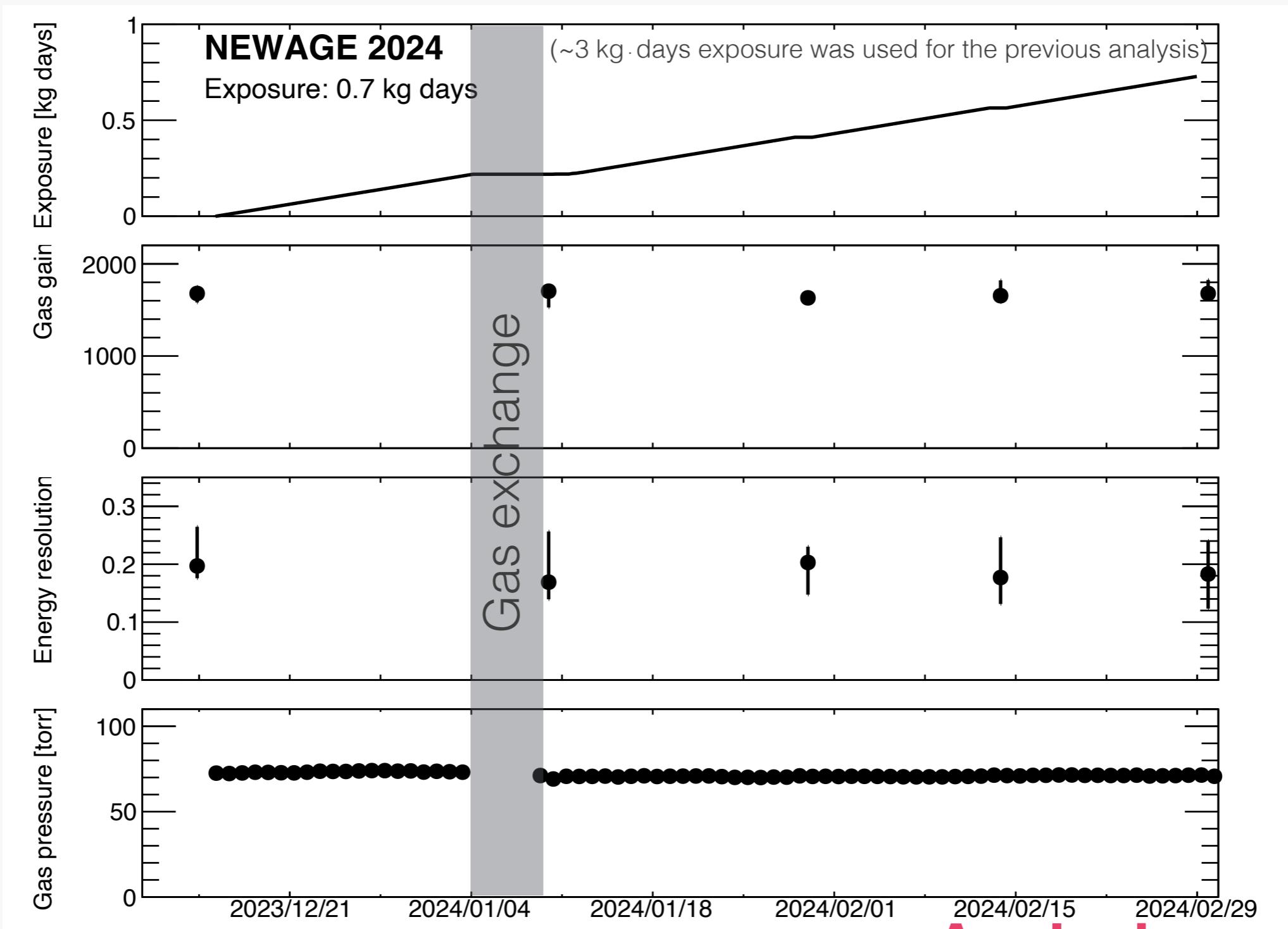
- Uniform irradiation test using a neutron source ( $^{252}\text{Cf}$ )
  - Hit positions and tracks successfully reconstructed
- NR - ER is separated by its difference of  $dE/dx$



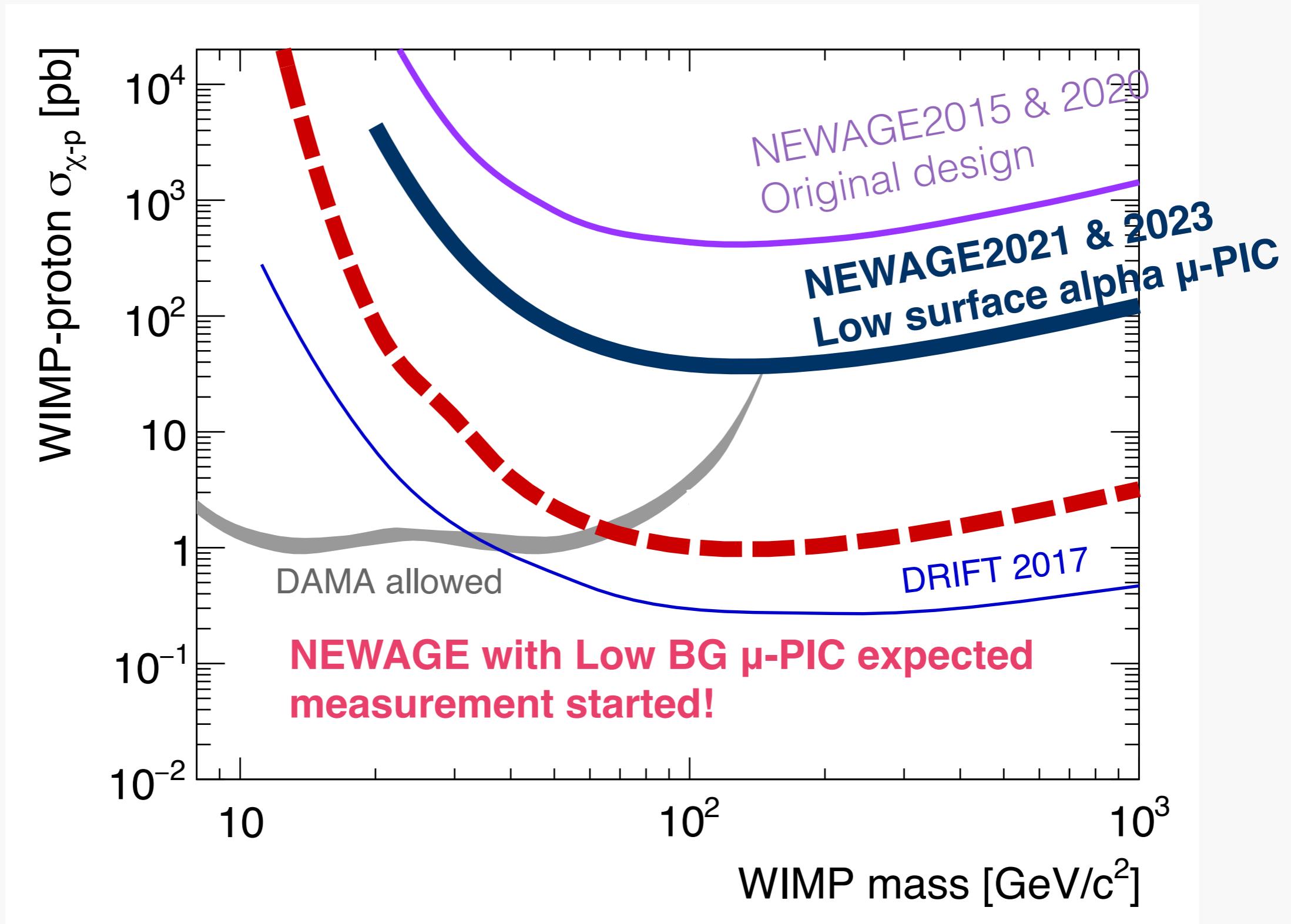
Detector is successfully working!

# “Dark Matter Run”

- Started from 15th, Dec. 2023, filled with 76 Torr CF<sub>4</sub> gas
- Stable operation is ongoing until today!



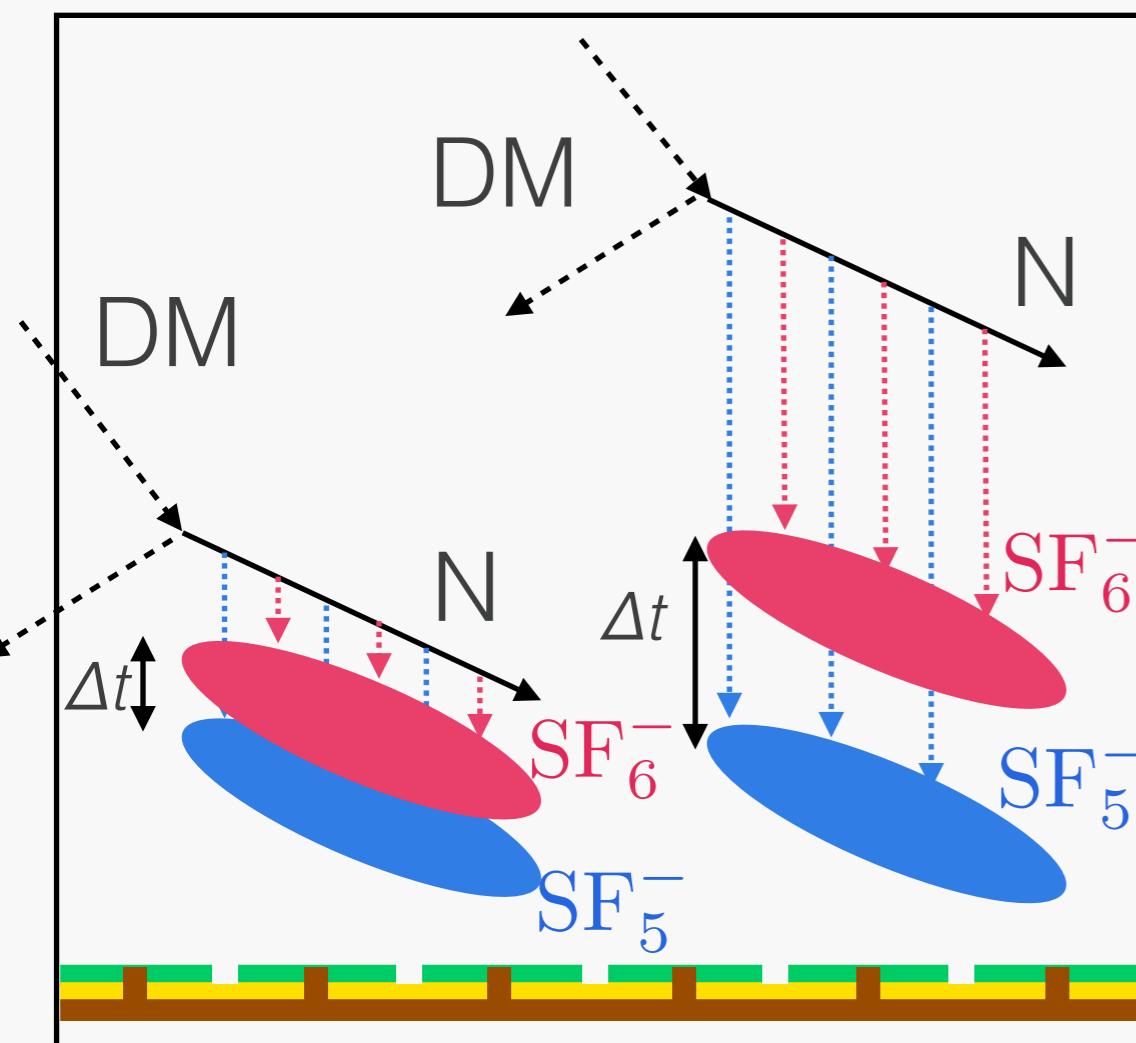
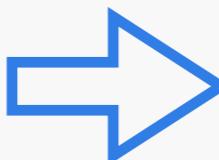
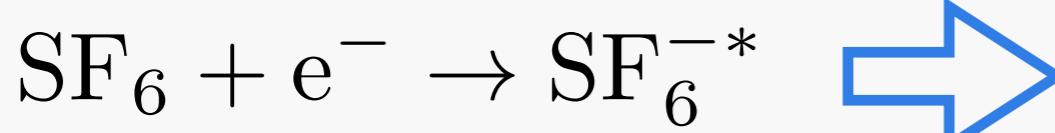
# Summary of underground experiments



# Future upgrades

# TPC using negative-ion gas: SF<sub>6</sub>

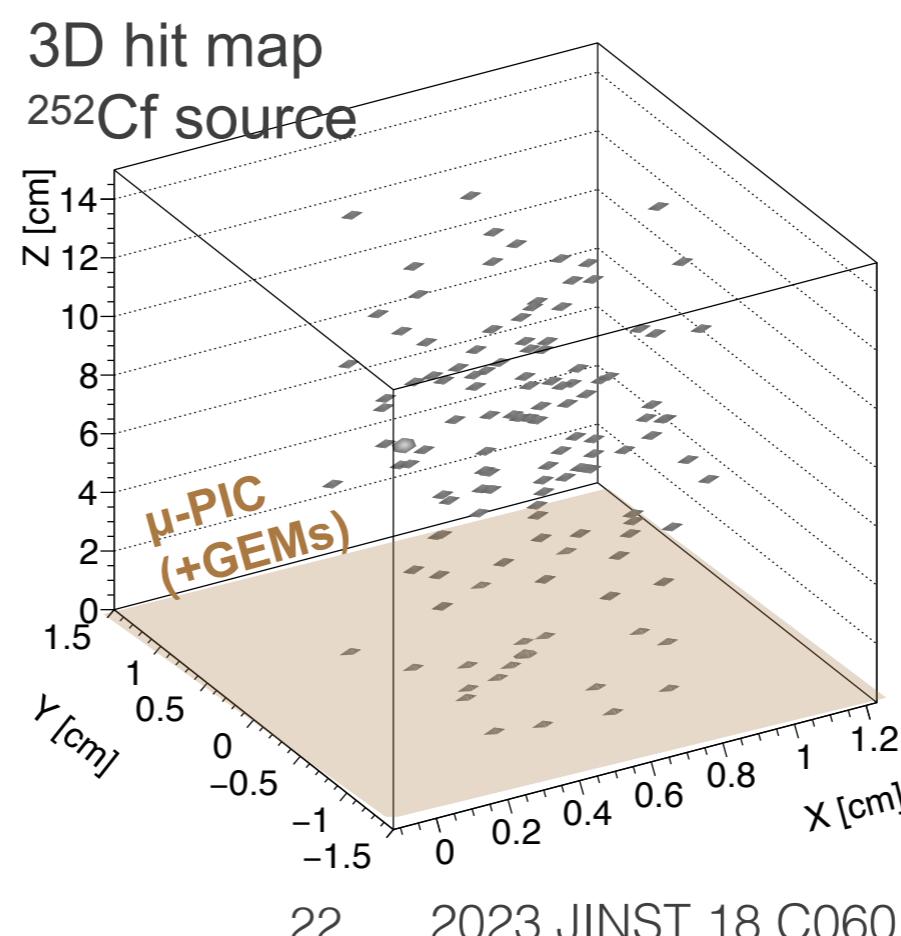
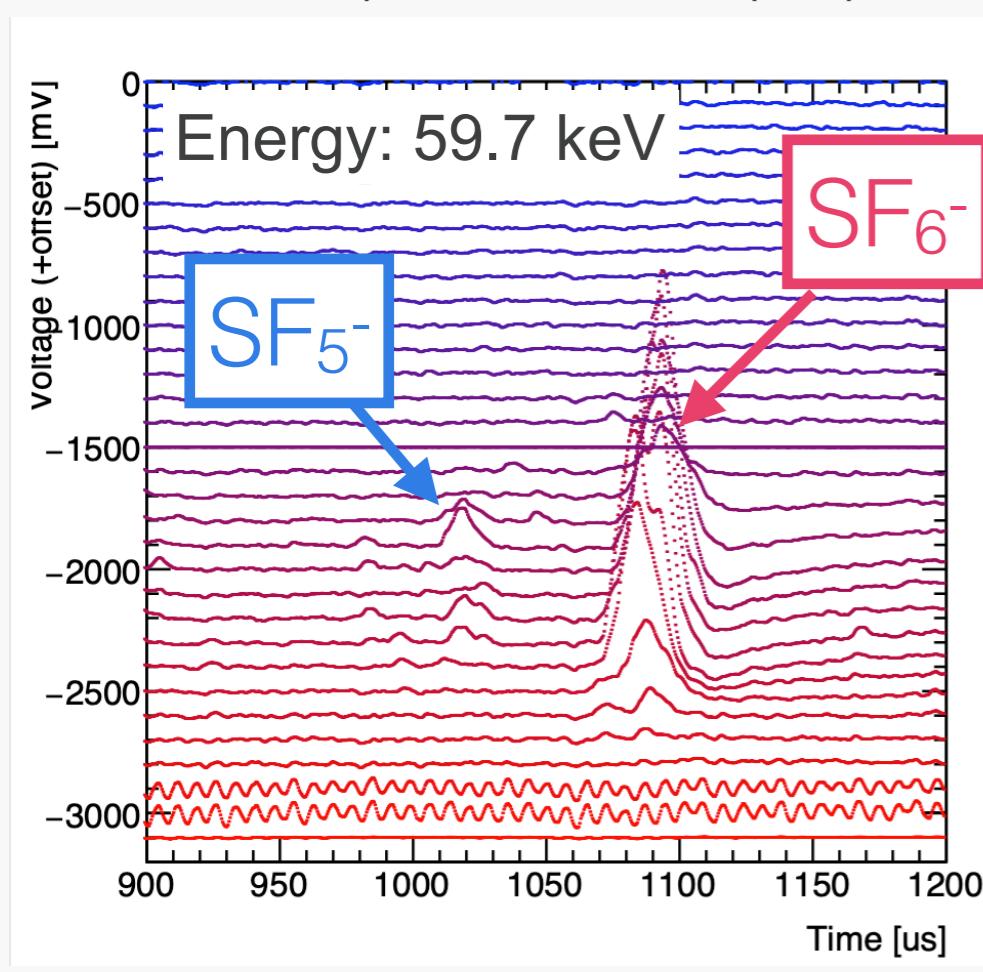
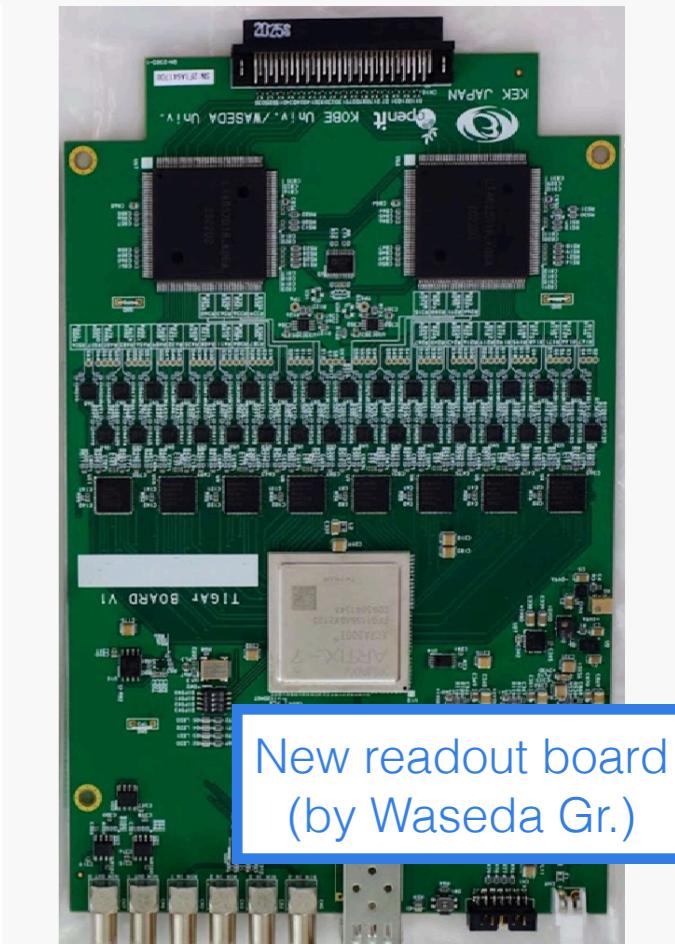
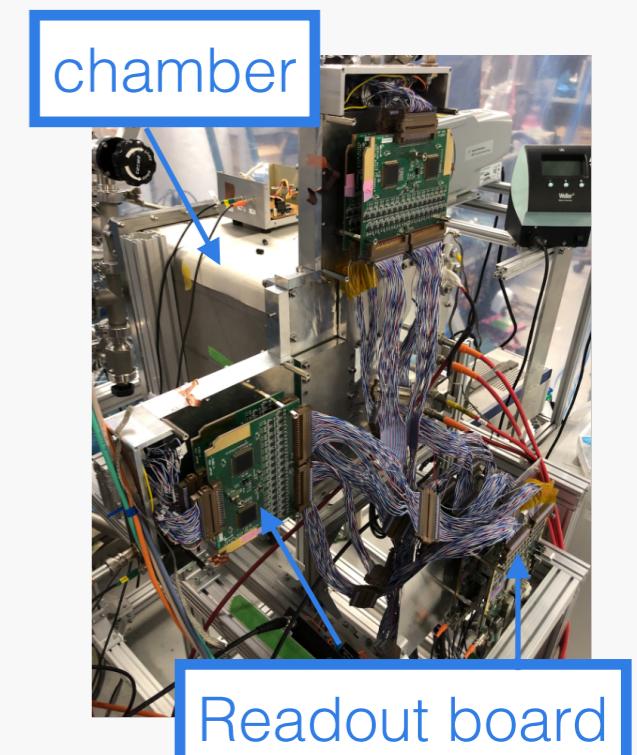
- Molecules capture ionized electrons and form 2 types of negative-ions



- Absolute 3D position can be determined by  $\Delta t$ 
  - allowing to reject surface alpha from materials
  - especially from GEM/ $\mu$ -PIC or drift plane
- Dedicated electronics was required
  - Slow drift velocity  $\rightarrow$  slow charge collection
  - Wide dynamic range
  - O(1000) ch readout

# Absolute 3D position reconstruction

- Tested using small detector with prototype electronics
- 2-peak signals are detected with a  $^{252}\text{Cf}$  source
  - SF<sub>5</sub><sup>-</sup> peak detection efficiency is 70%
  - succeeded in reconstructing 3D position
- New readout board is developed by Waseda Gr.
  - Mass production is preparing to allow O(1000) ch readout

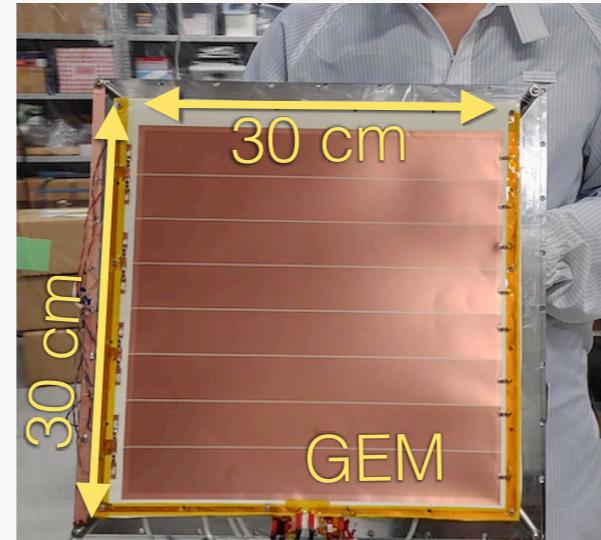


# CYGNUS-KM / NEWAGE (C/N-1.0)

- Modulated chamber ( $\sim 1 \text{ m}^3$ ) developed w/ “CYGNUS” international collaboration
  - 18 module windows are available
  - Chamber preparation is completed

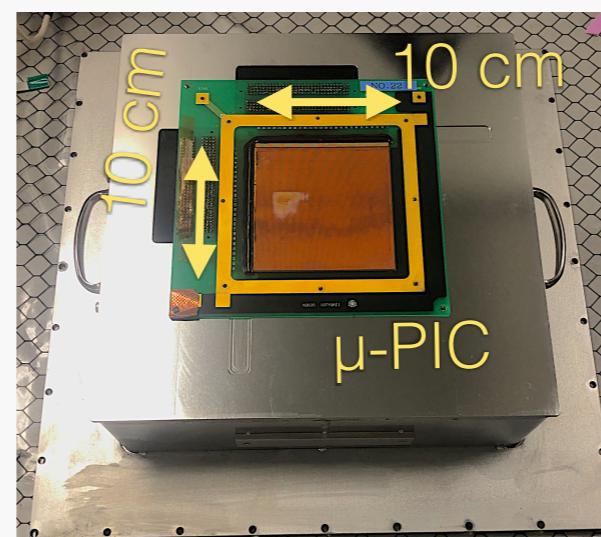


Two modules under commissioning in parallel



“Module-0”  
(3 GEMs+pad)

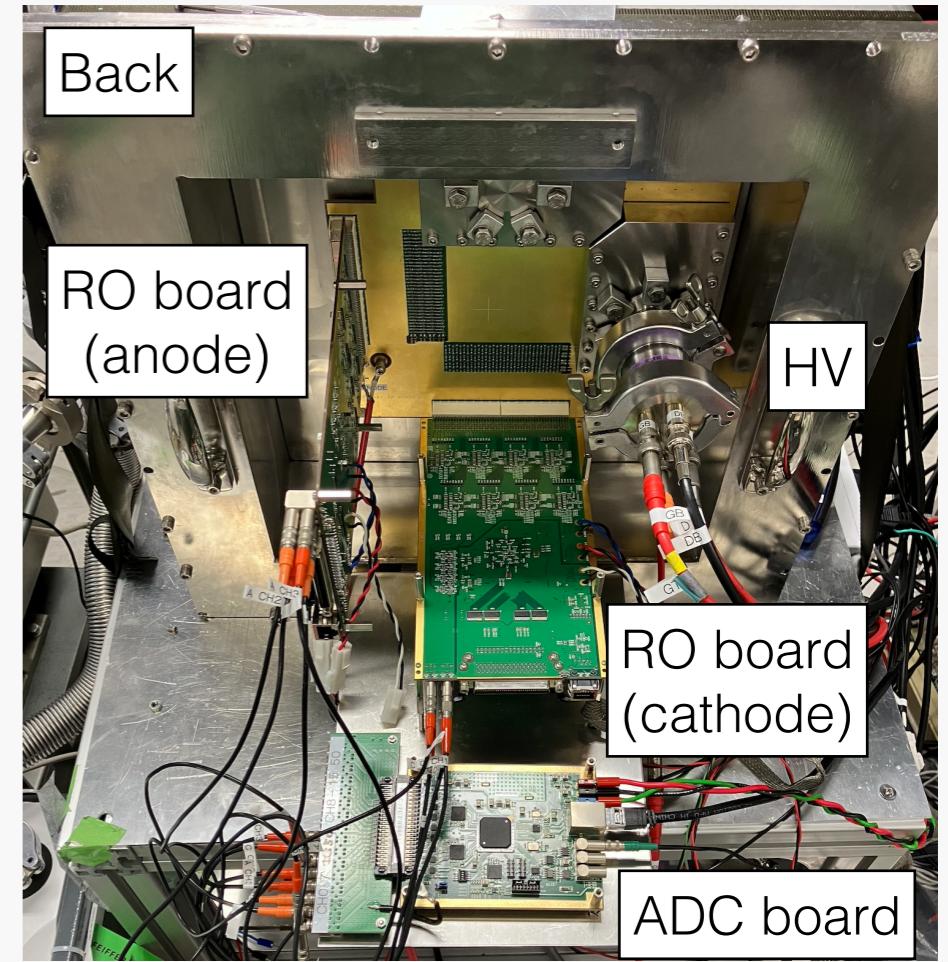
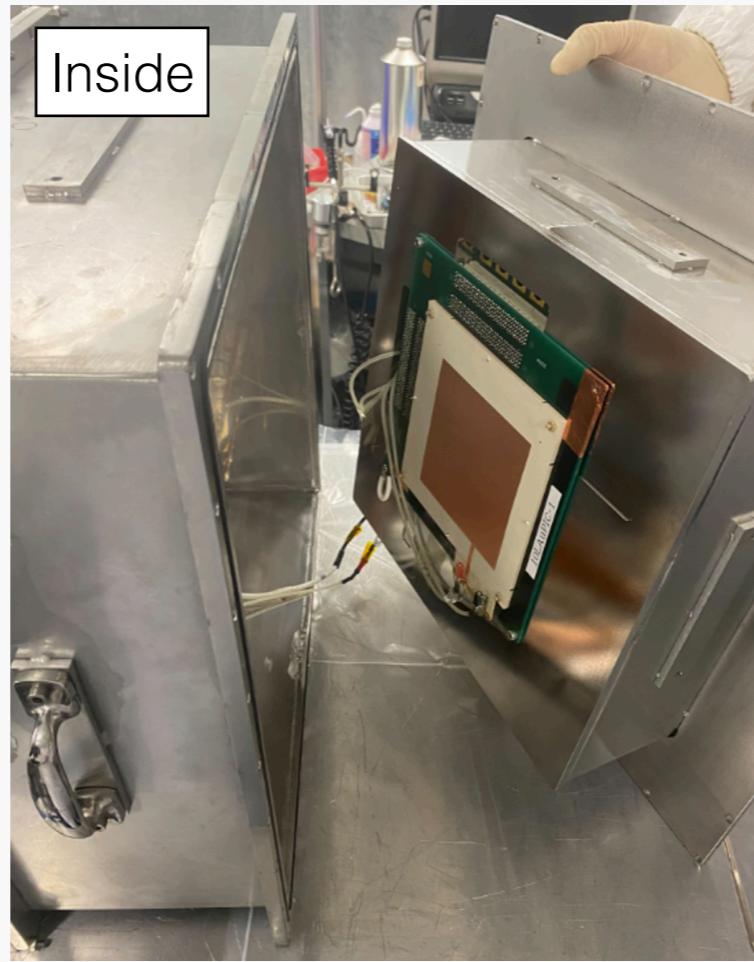
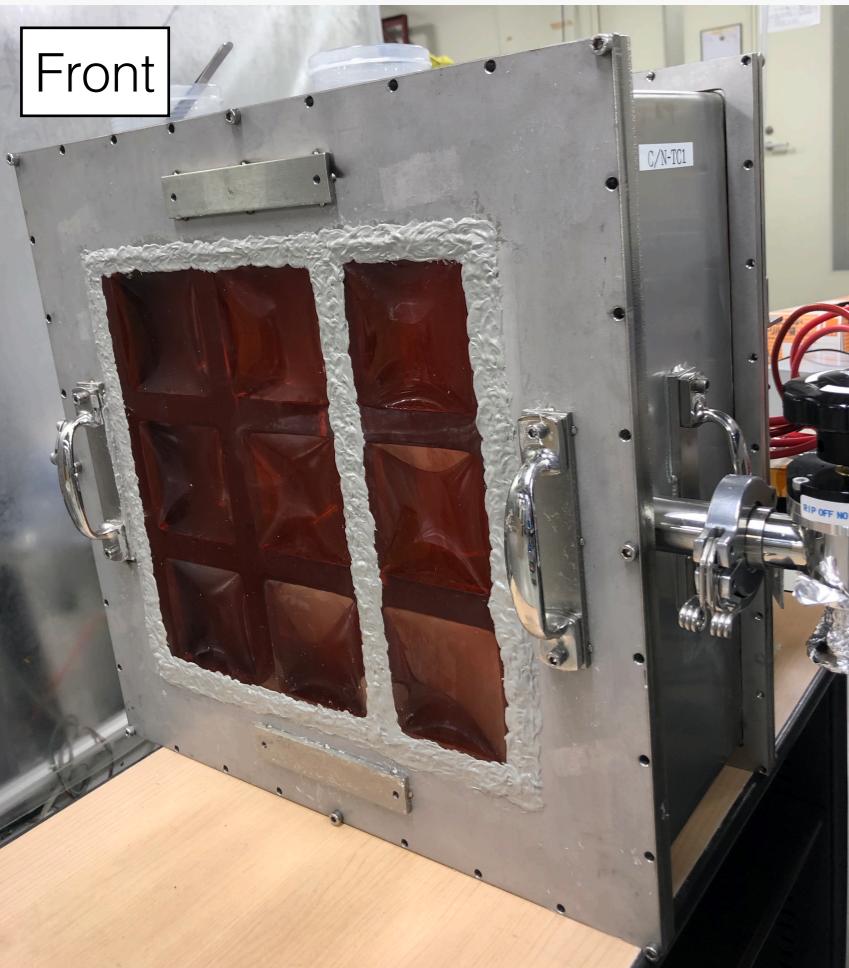
30×30 cm<sup>2</sup> fiducial volume  
Less readout channels



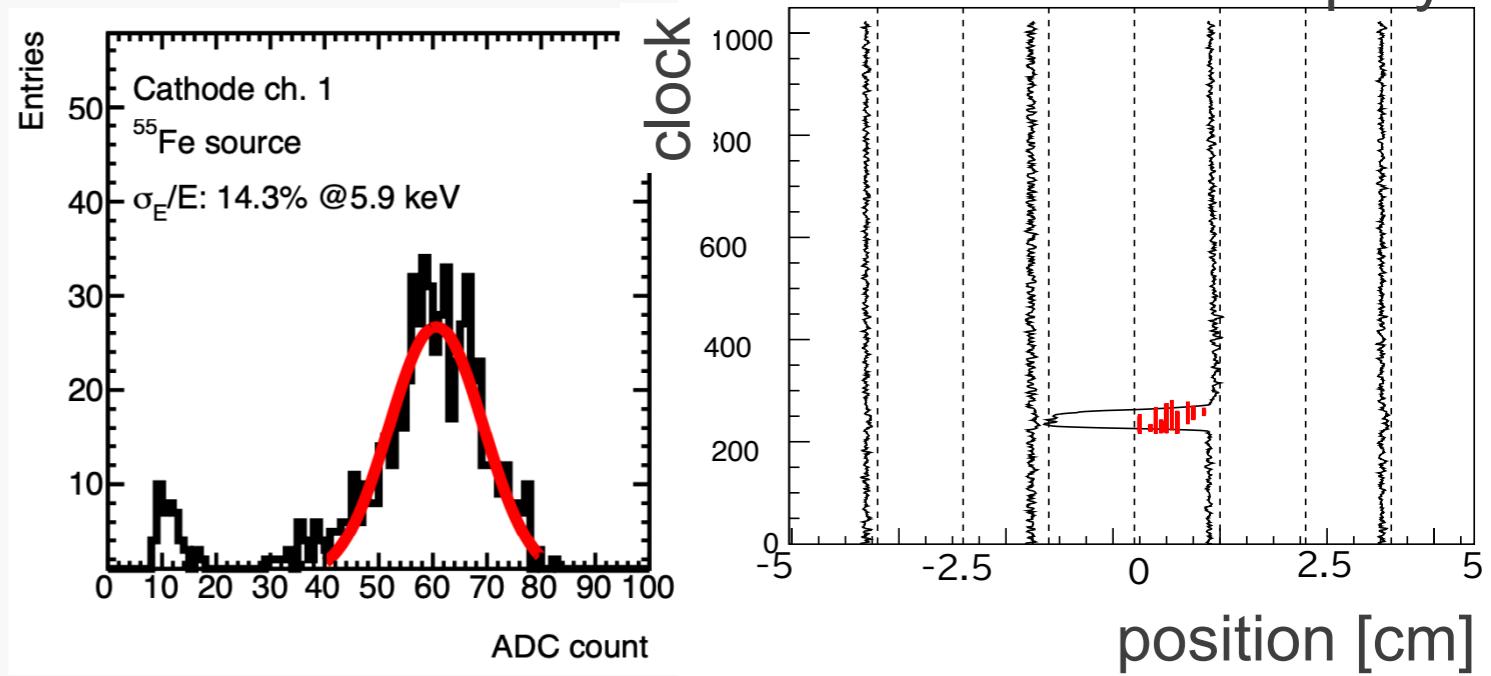
“Module-1”  
(GEM + μ-PIC)

Small fiducial volume  
Track reconstruction

# Module-1 test

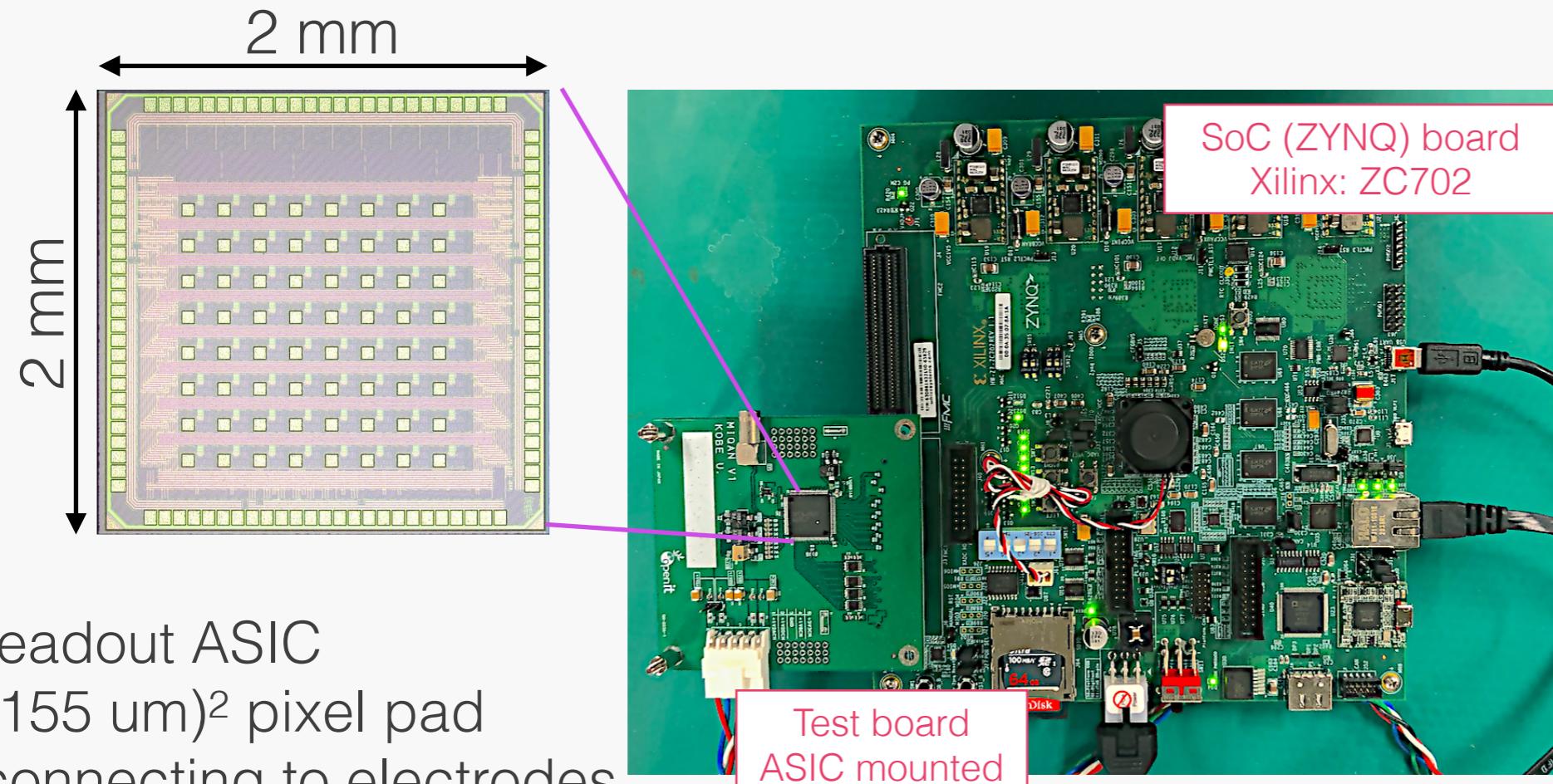


- Testing with module-size chamber
- Energy calibration is working using  $^{55}\text{Fe}$  source
- Nuclear recoil events are successfully reconstructed  
→ ready for installation to C/N-1.0 !

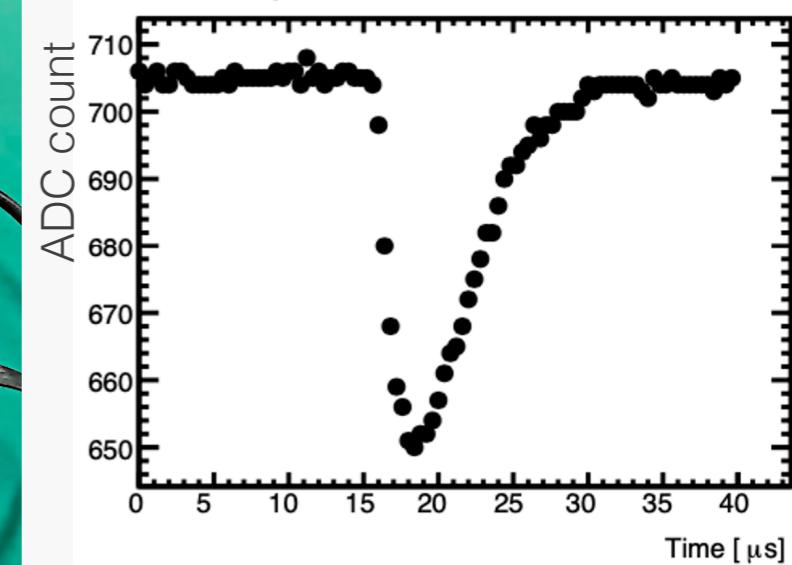


# Strategy of short tracks detection

- Equal to low energy nuclear recoil detection
- Energy threshold is limited due to electrode's strip pitch (400  $\mu\text{m}$ )
  - Started to develop fine granularity “pixel” readout detector
  - 64 ch ASIC developed and testing its performance

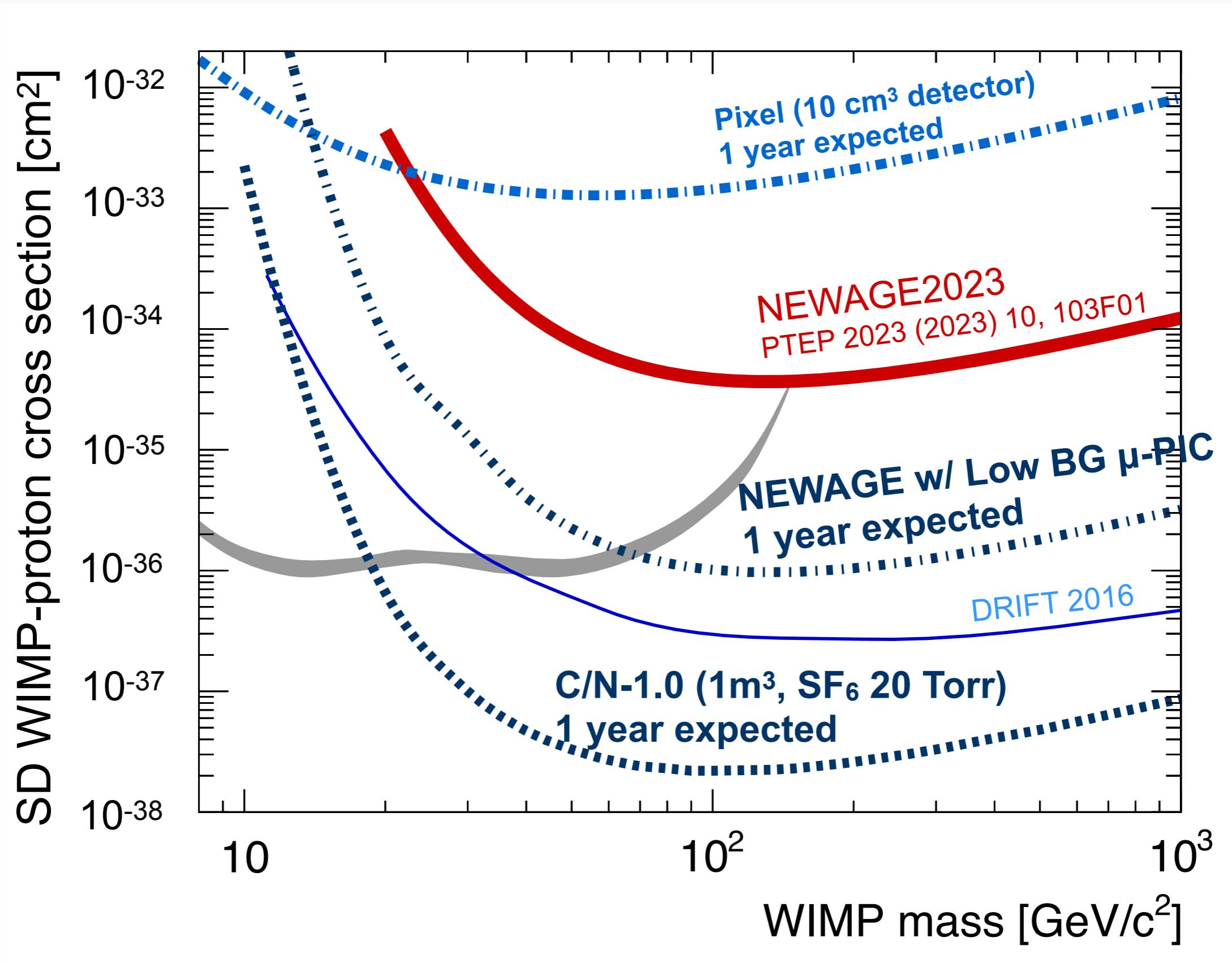


Test pulse waveform for a particular ch.



Analog circuit + ADC successfully working!

# Expected sensitivity



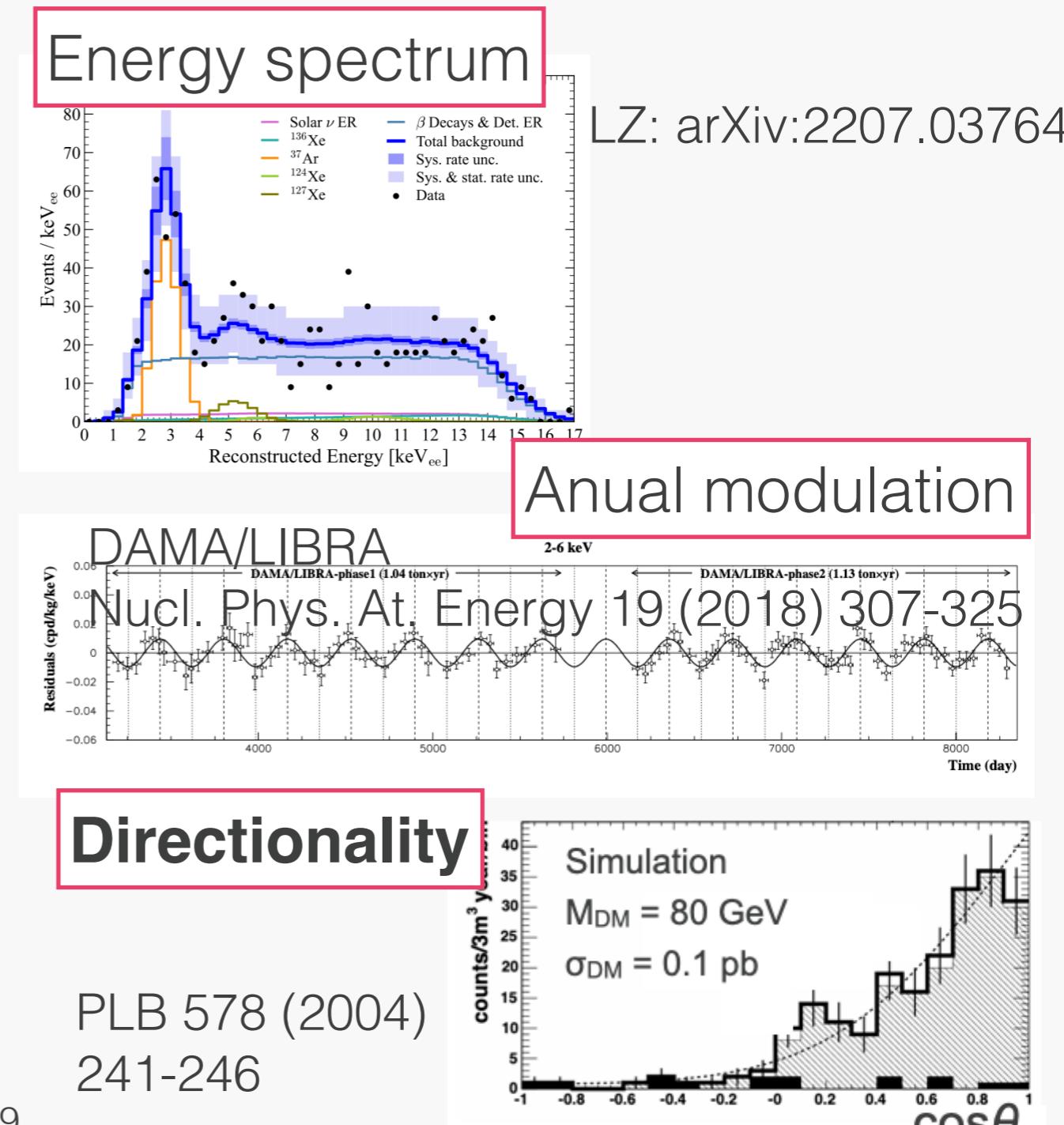
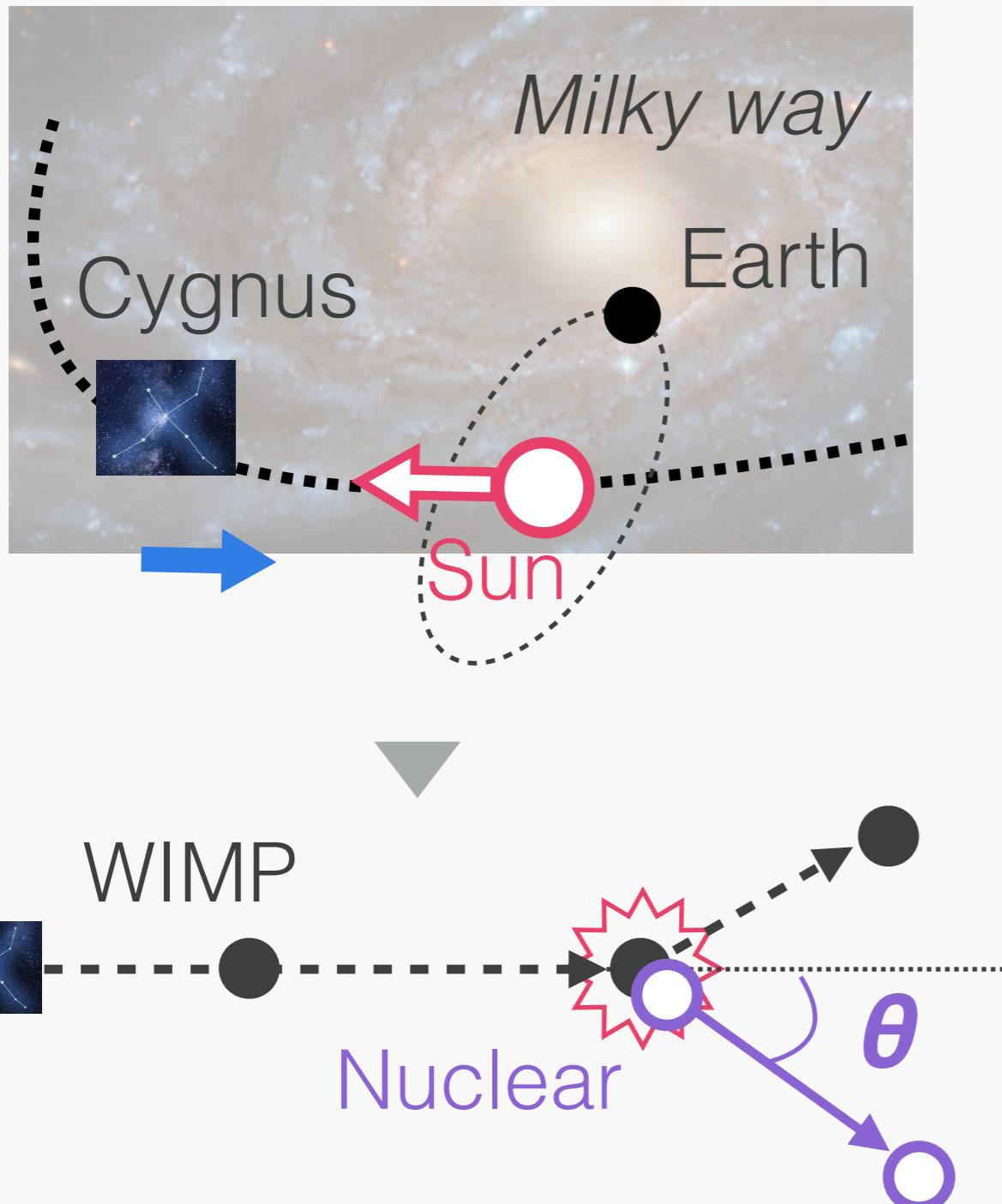
# Conclusion

- NEWAGE is a direction-sensitive direct dark matter search experiment
  - Limit reached to DAMA/LIBRA region in 2023
- Measurement with low-BG detector was started from Dec. 2023
  - Results will be reported in the next funding period!
- Future updates ongoing
  - Mass production of the electronics for negative-ion TPCs is preparing
  - The modulated detector for large scale chamber was developed
  - “Pixelization” project: development of prototype electronics was completed

# Backup

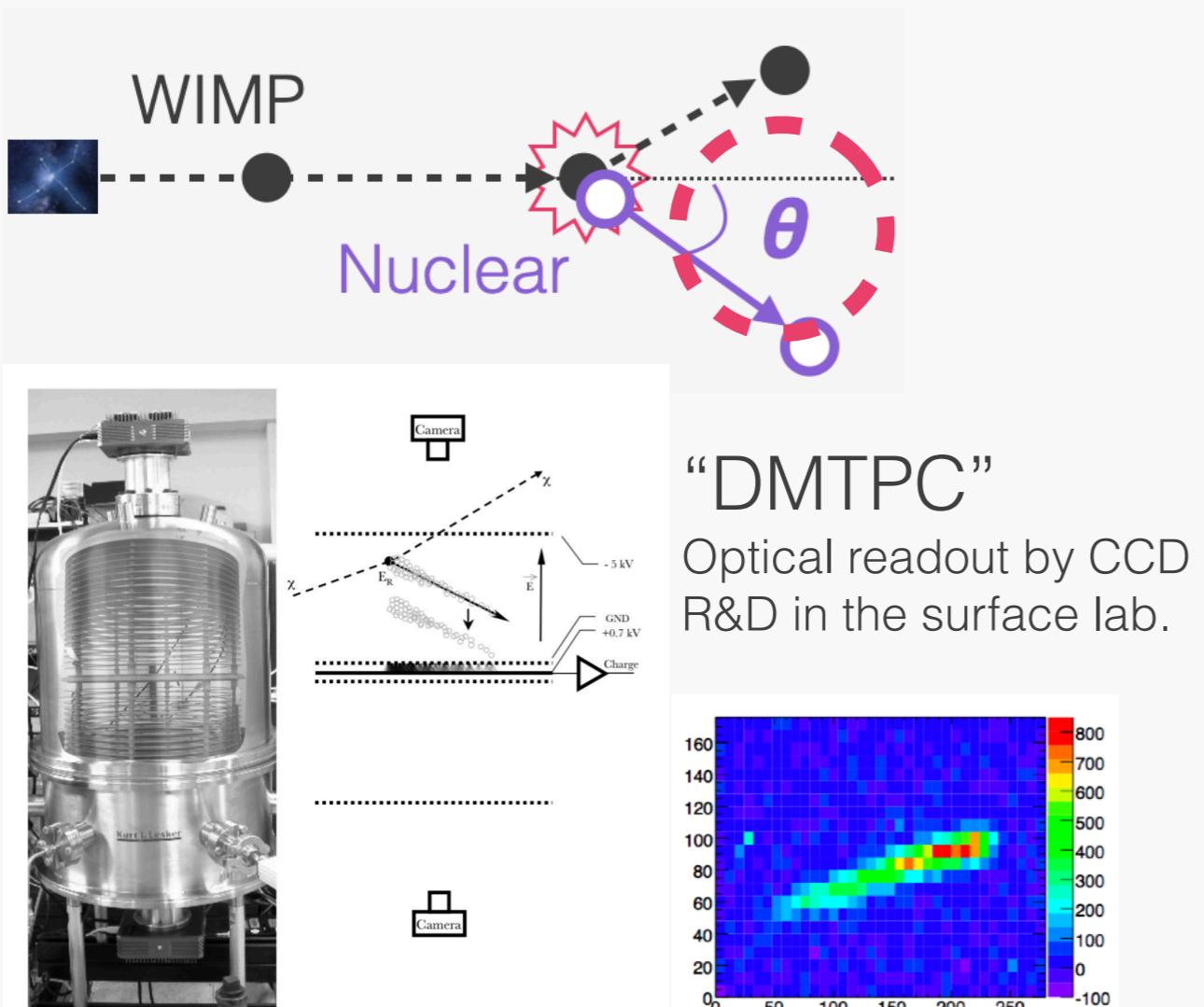
# Direct dark matter (WIMP) searches

- Direct search = SM particle recoil detection
  - Its kinematics depends on the motion of the Earth, the sun, and the Milky Way Galaxy



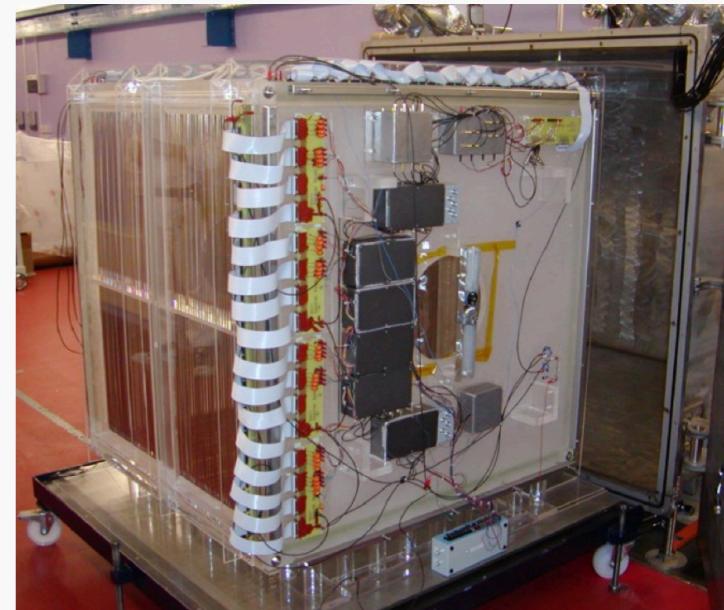
# Direction-sensitive search methods

- **Particle tracking** is necessary to scattering angle from Cygnus direction
  - Need to measure < 10 keV nuclear recoil (**VERY short track!**)
- To achieve < 10 keV nuclear recoil track reconstruction, ...
  - ultra-fine granularity detector (NEWSdm: next talk by T.Naka)
  - use **low pressure gas** to extend trajectory



“DRIFT”  
pioneer of DM search  
using gaseous TPC

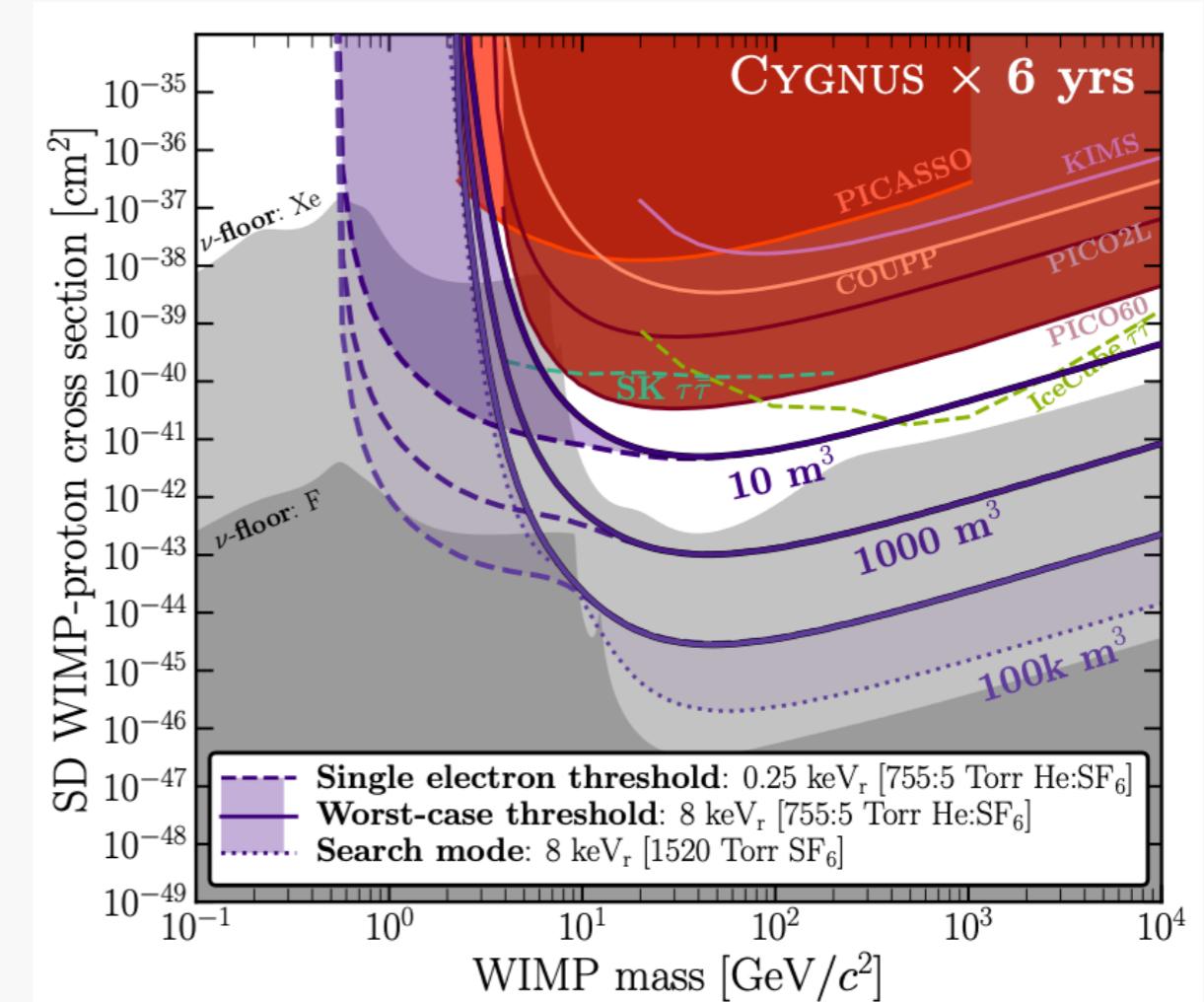
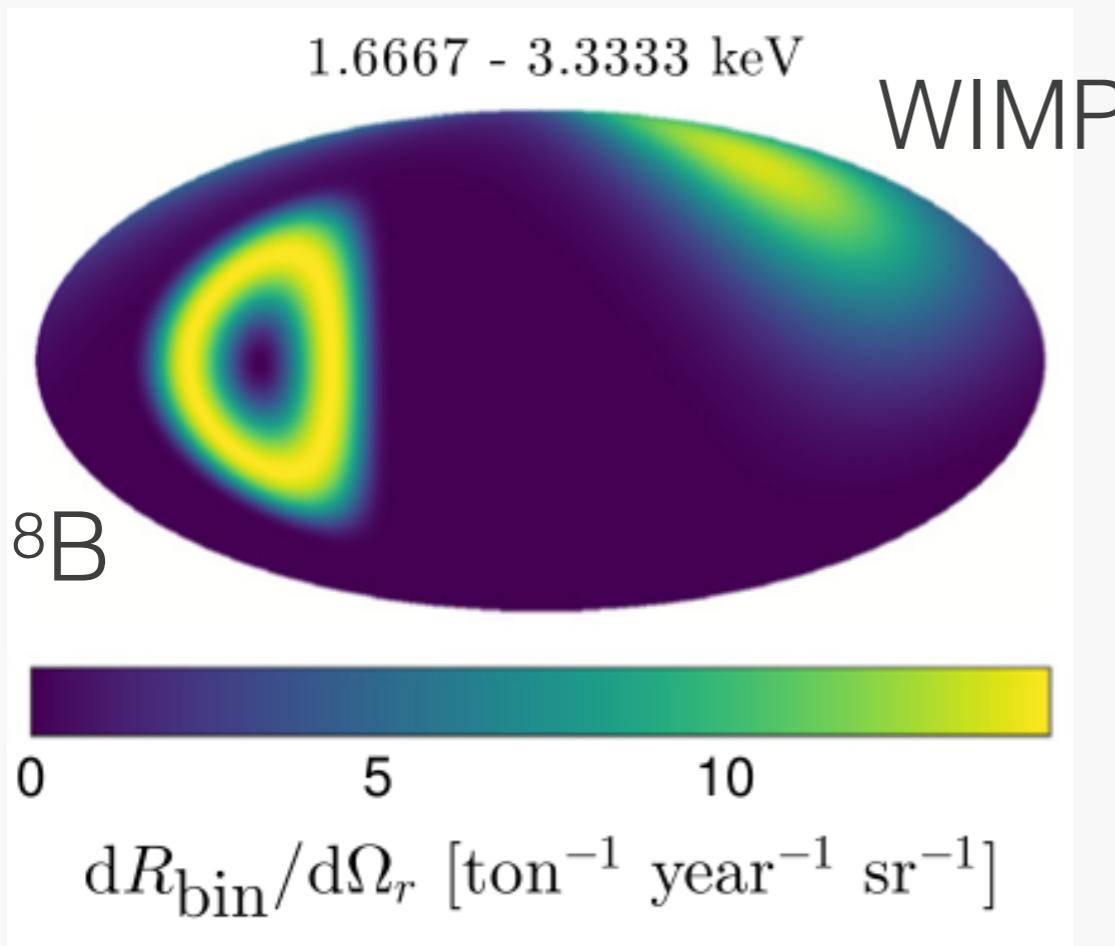
Large volume, Low-BG,  
Underground experiment



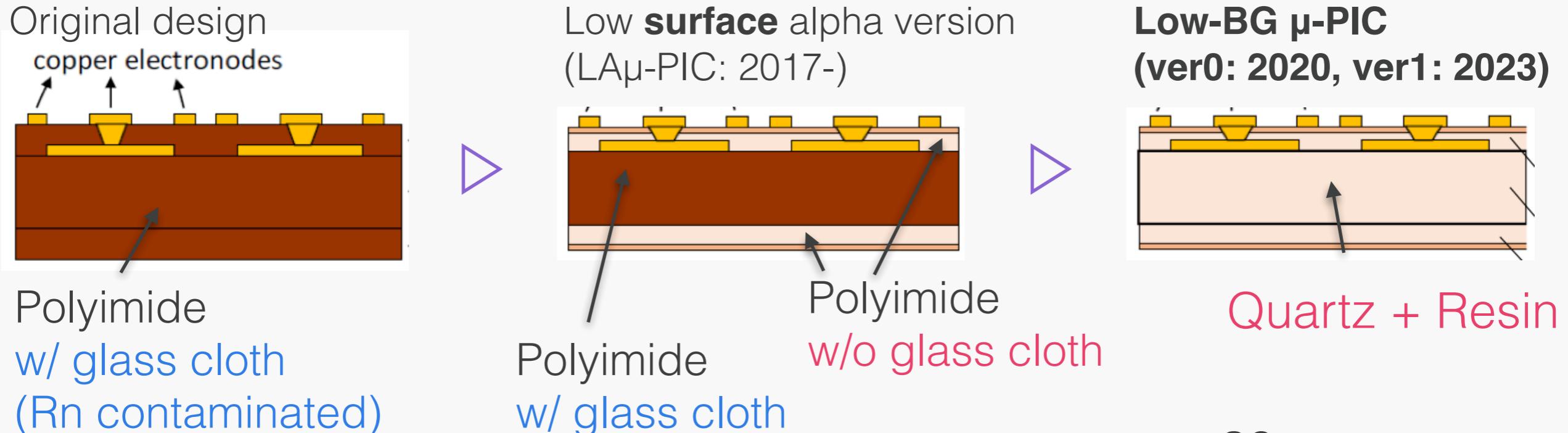
...and larger scale gaseous chambers  
widely studying by CYGNUS community

# Benefits

- Strong signature of WIMP (CDM)
- Kinematics of DM (isotropic or non-isotropic?)
- ${}^8\text{B}$   $\nu$  rejection allows to explore “neutrino floor”
  - Neutrino-nucleus coherent scattering will be irreducible BG without directionality



# Development of “clean” detector

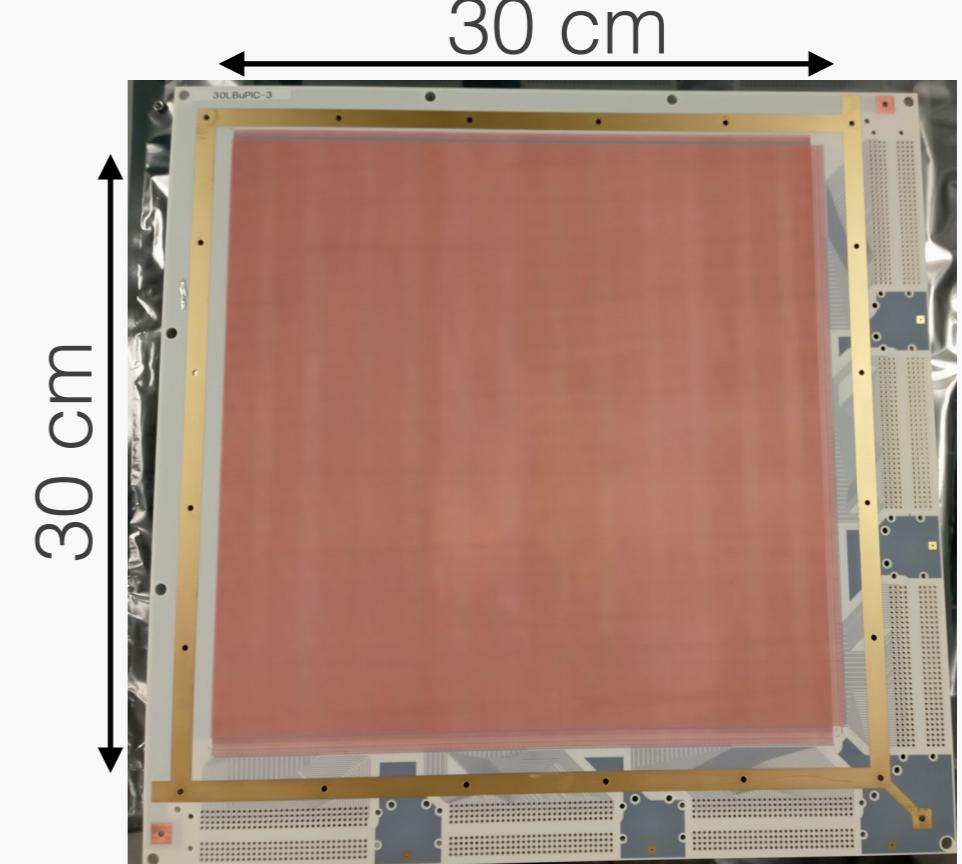


Radon emanation measurement:  
LA $\mu$ -PIC: **2.3 ± 0.5** [mBq /  $\mu$ -PIC]

LBG $\mu$ -PIC: <0.03 [mBq /  $\mu$ -PIC]  
(90% C.L.)

paper in preparation  
(see poster P05 by R. Namai)

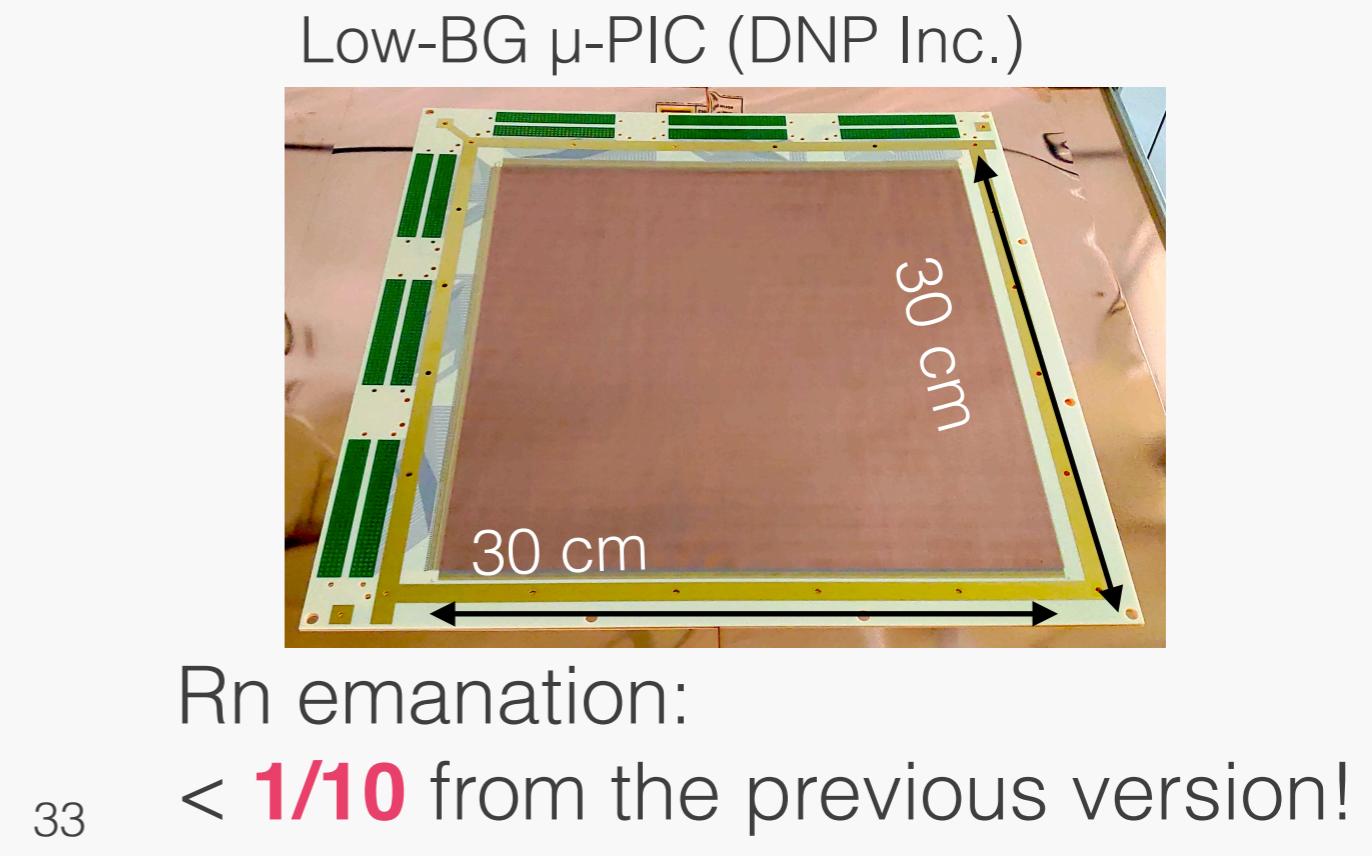
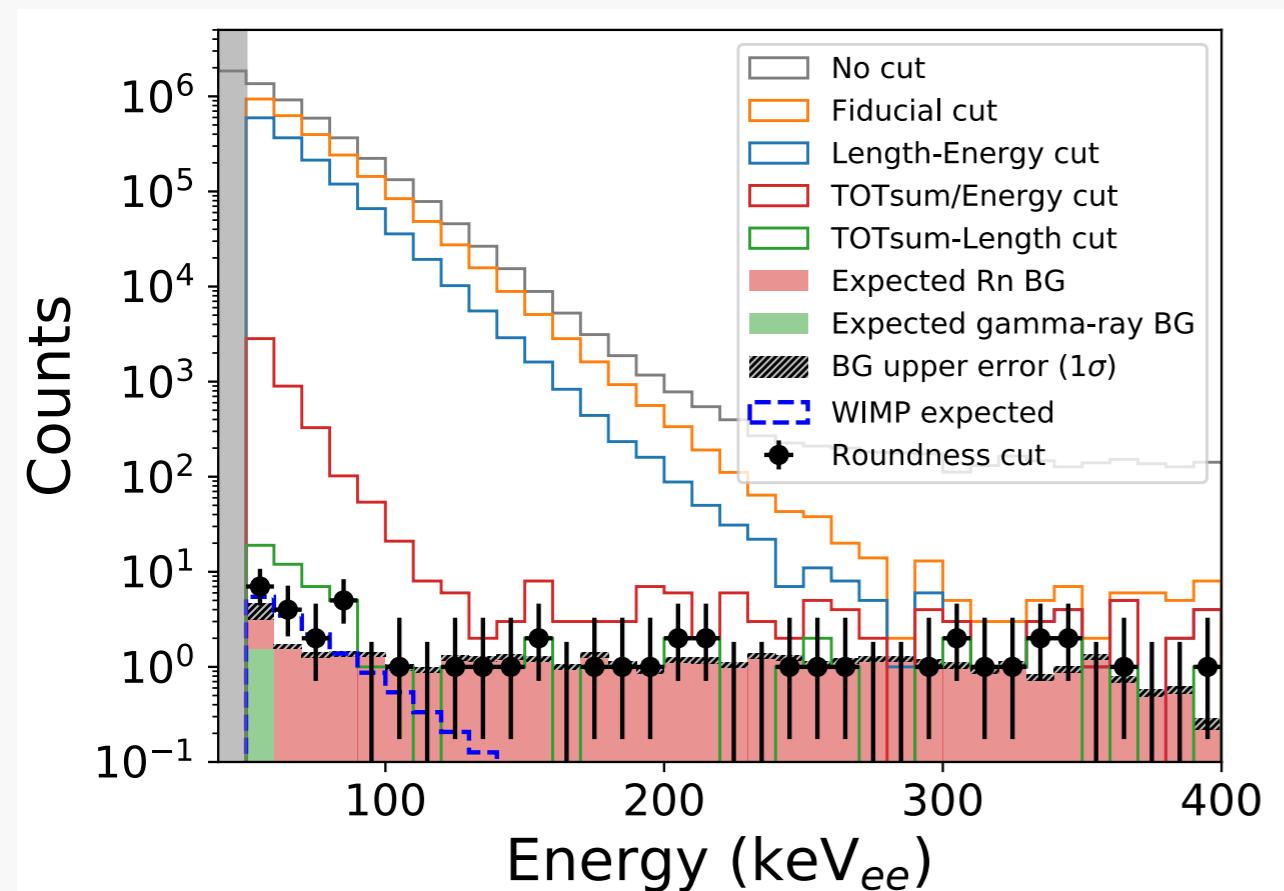
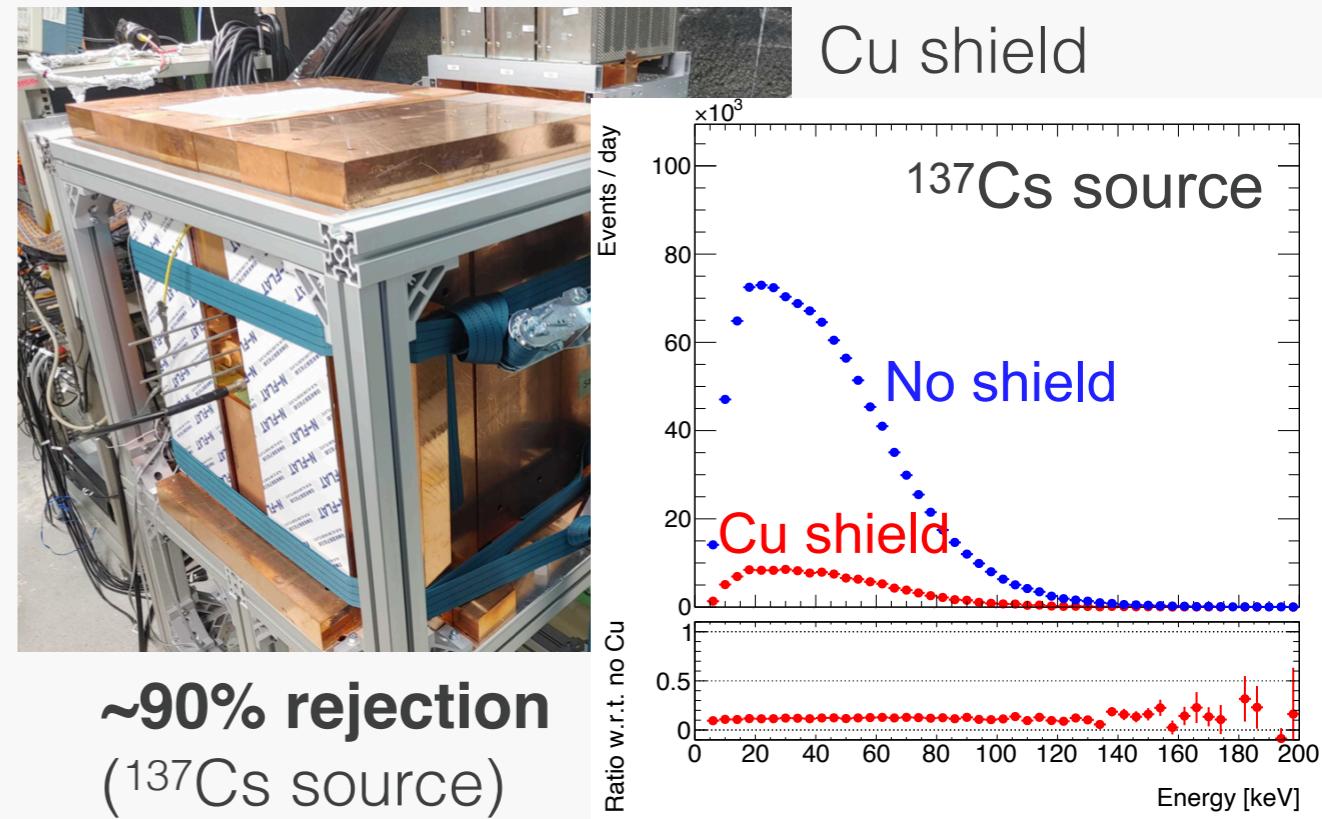
32



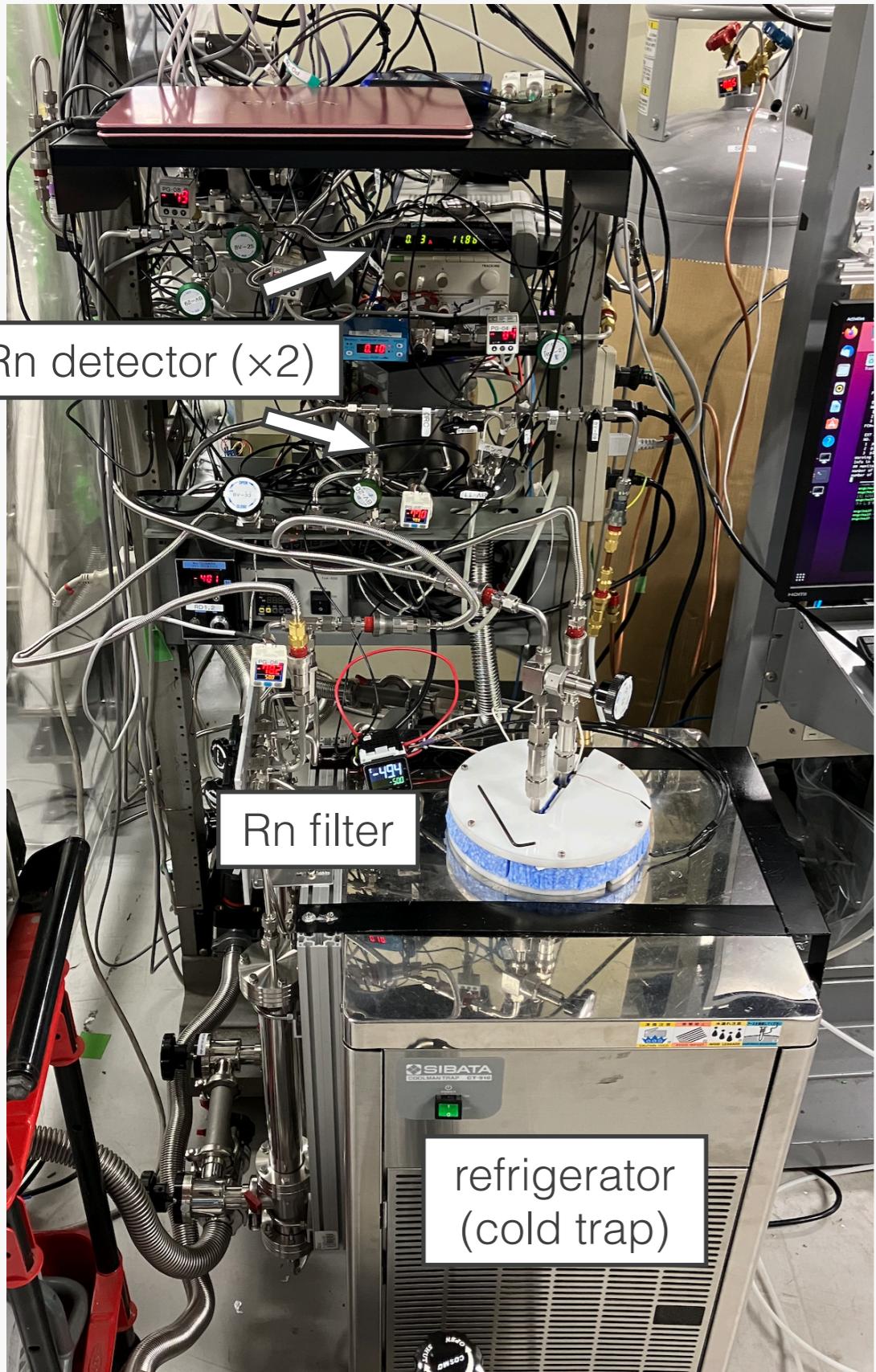
LBG $\mu$ -PIC ver1 (DNP)

# Backgrounds

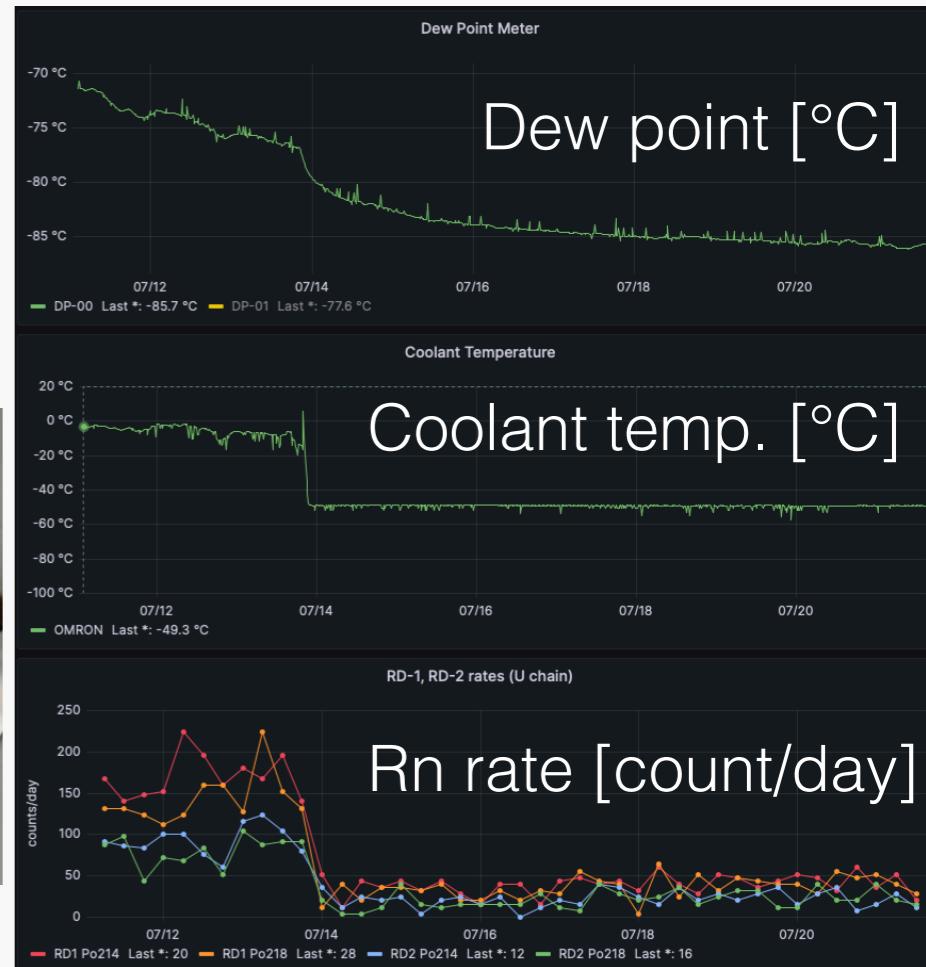
- Ambient gamma (external source)
  - Cu shield installed
  - Measurement ongoing
- Alpha from Rn progenies (internal source)
  - Emanation from the detector
  - “Clean” detector developed



# Detector infrastructure



- Gas circulation system is ready
  - Rn filter installed
    - ▶ low-BG zeolite (Nihon Univ.)



low-BG zeolite (xxxg)

**Ready for a surface run operation!**

# C/N-1.0 sensitivity

