Development of negative-ion gaseous TPC using micro pattern readout for direction-sensitive dark matter search

Satoshi Higashino (Kobe University)

Kentaro Miuchi, Ayaka Nakayama, Mizuno Ofuji (Kobe University)
Tomonori Ikeda (Kyoto University)

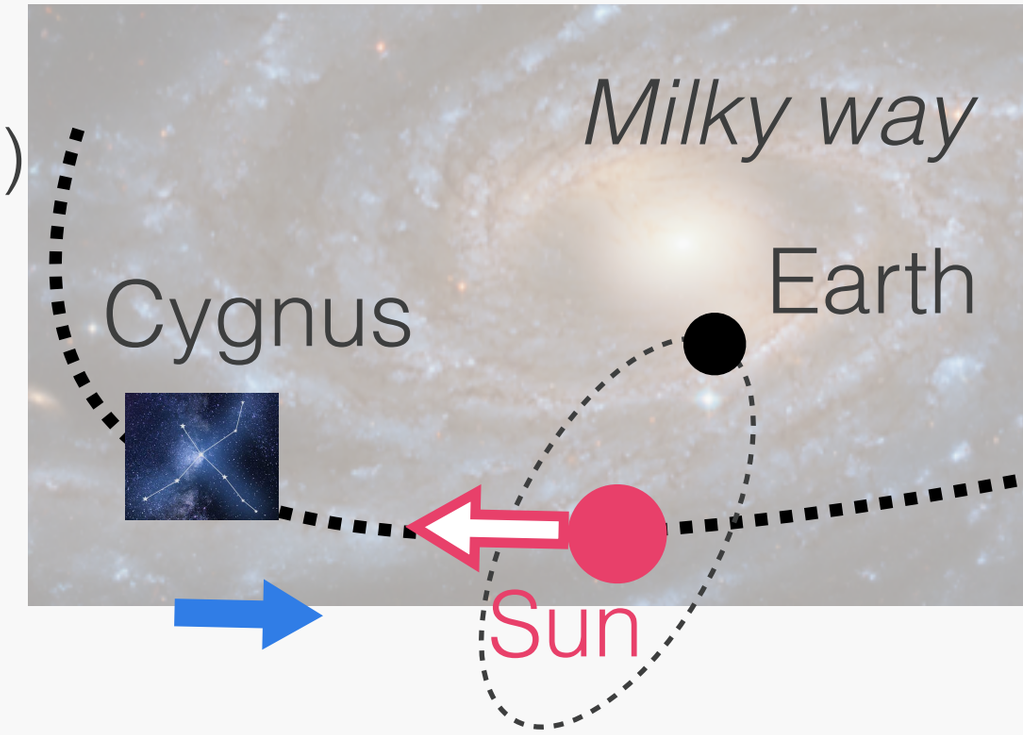
15 / 12 / 2022

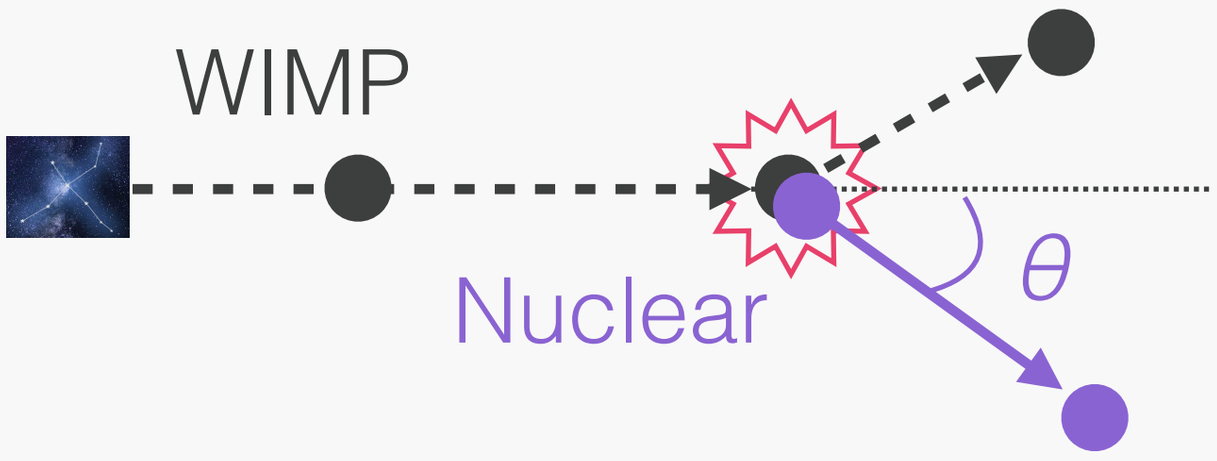
Introduction

Thank you for the good tour yesterday!

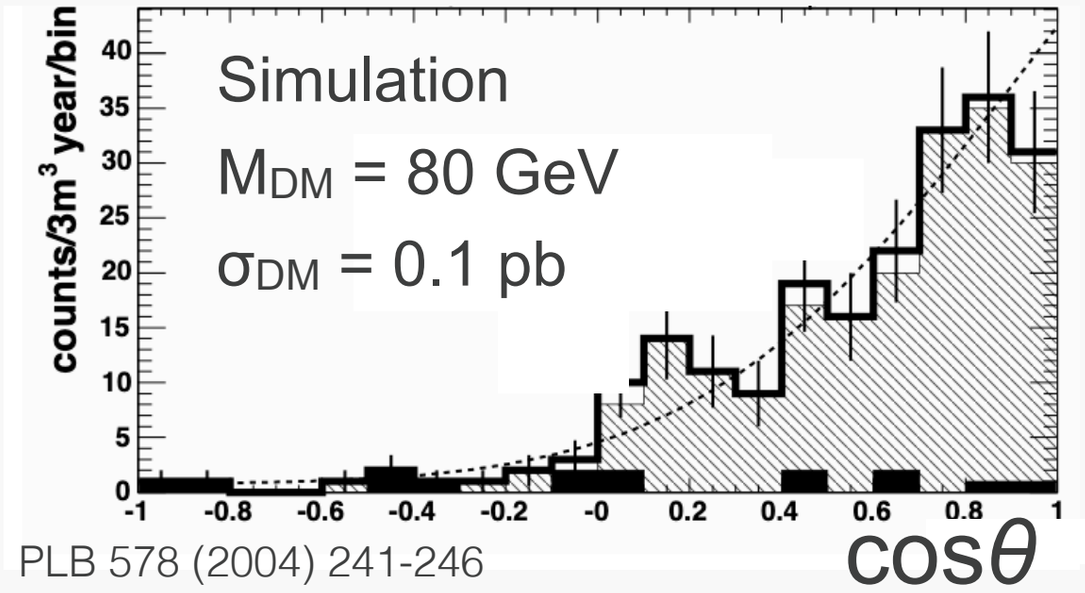
Direction-sensitive DM searches

- Detect scattering angle of nuclear recoils (NR) from the “Cygnus direction”
  - ➡ leads a strong signature of WIMP
  - ➡ allows to explore beyond the neutrino-floor

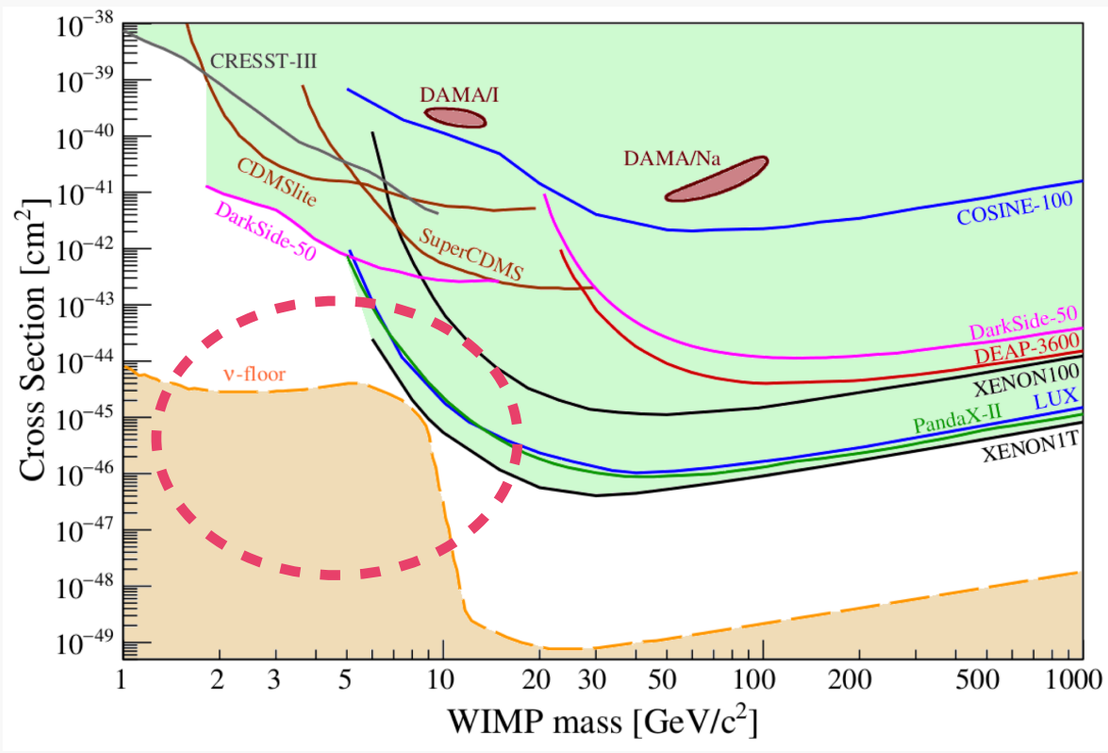




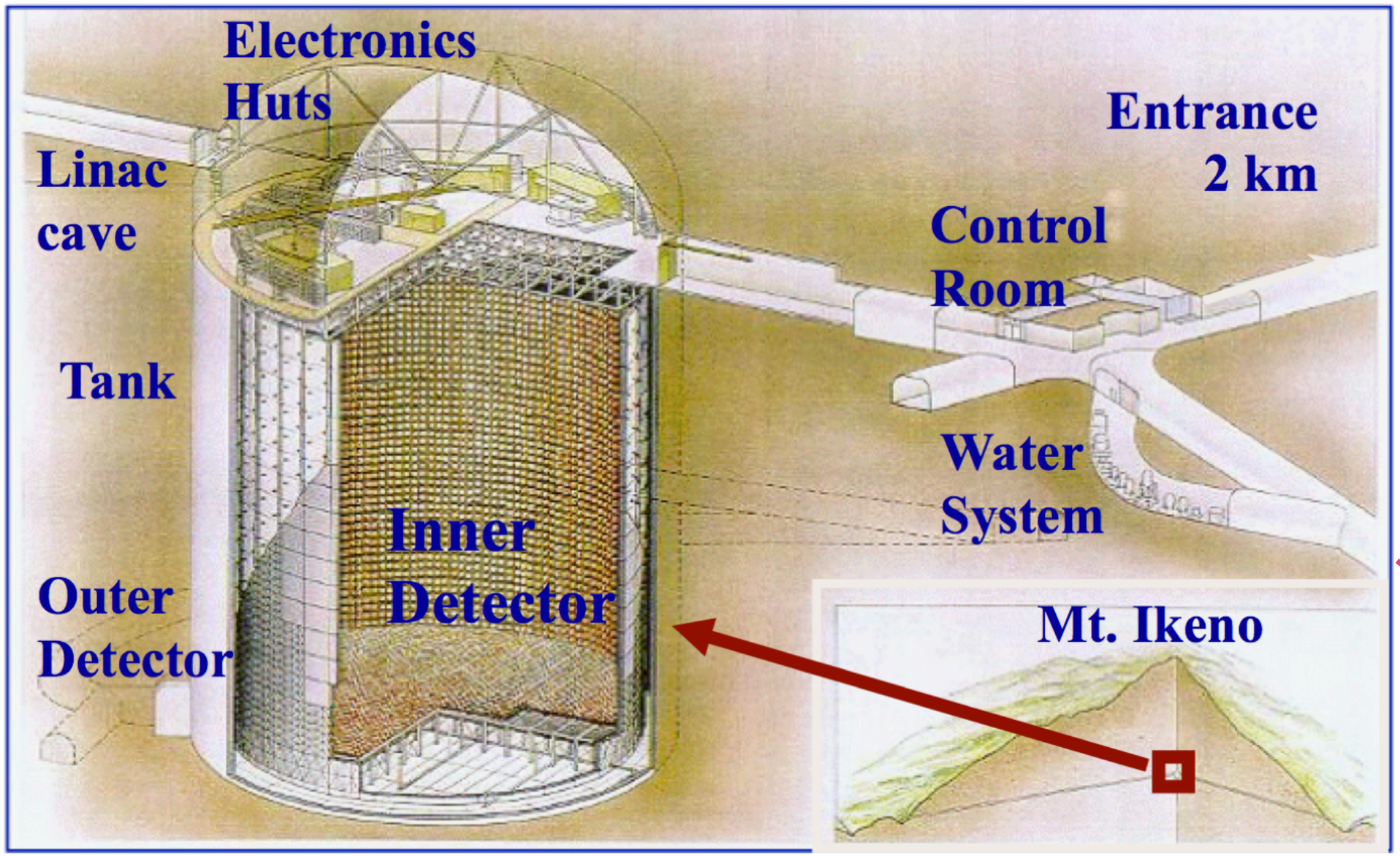
WIMP wind from Cygnus!



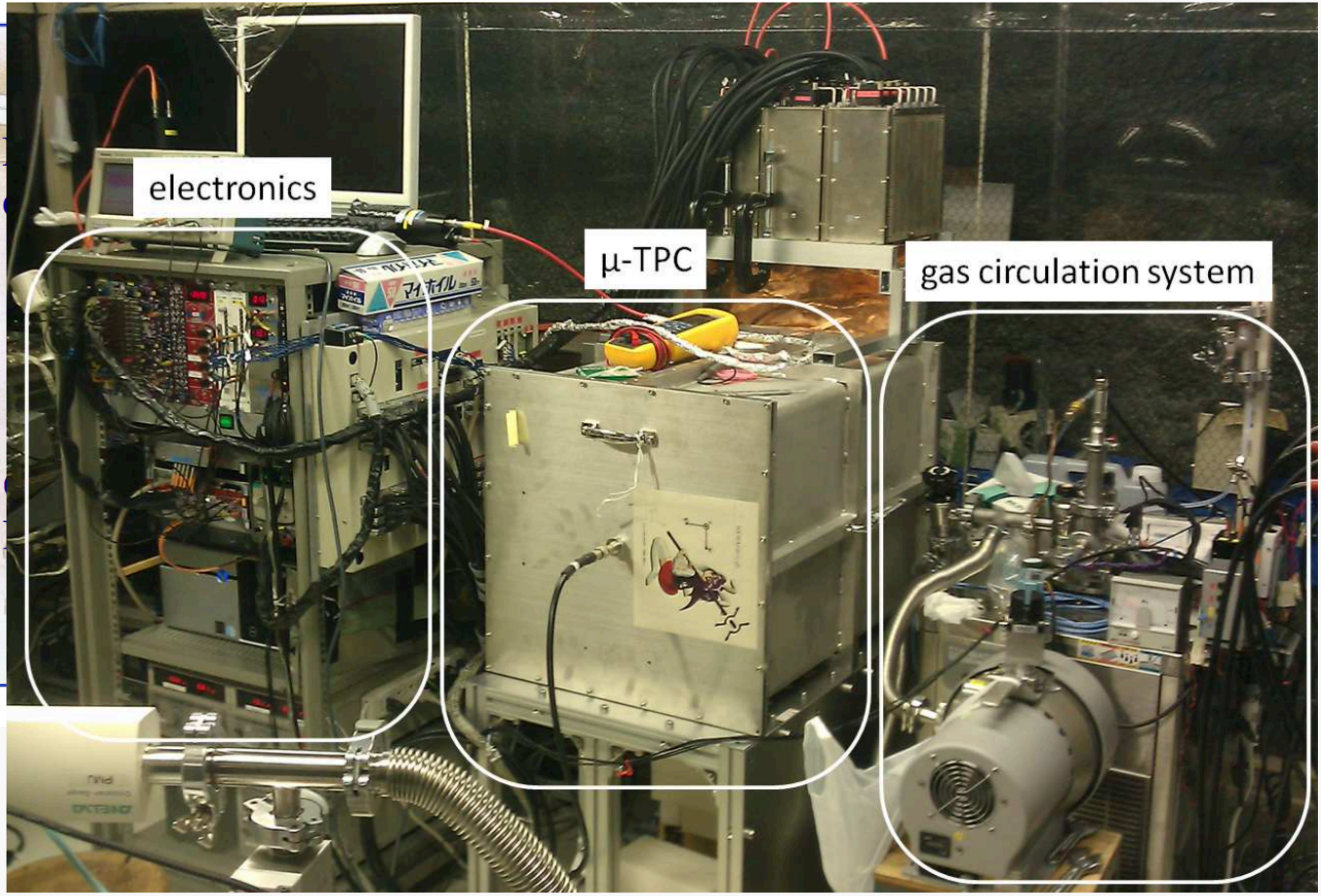
PLB 578 (2004) 241-246



NEWAGE

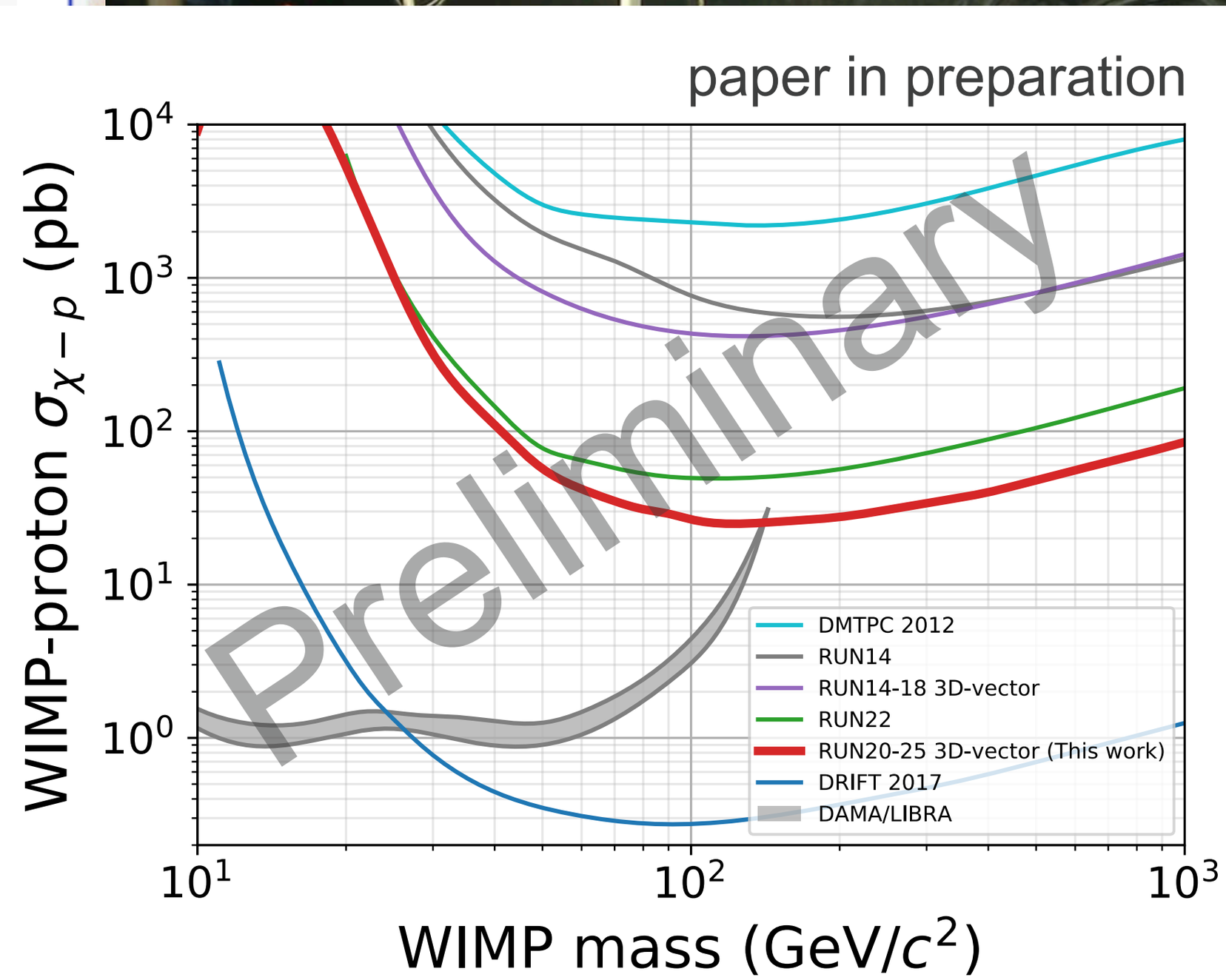

Electronics Huts
Linac cave
Tank
Outer Detector
Inner Detector
Entrance
2 km
Control Room
Water System
Mt. Ikeno
our Lab.

NEWAGE



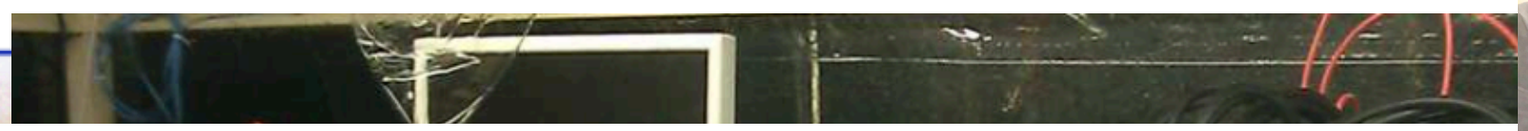
NEWAGE

paper in preparation

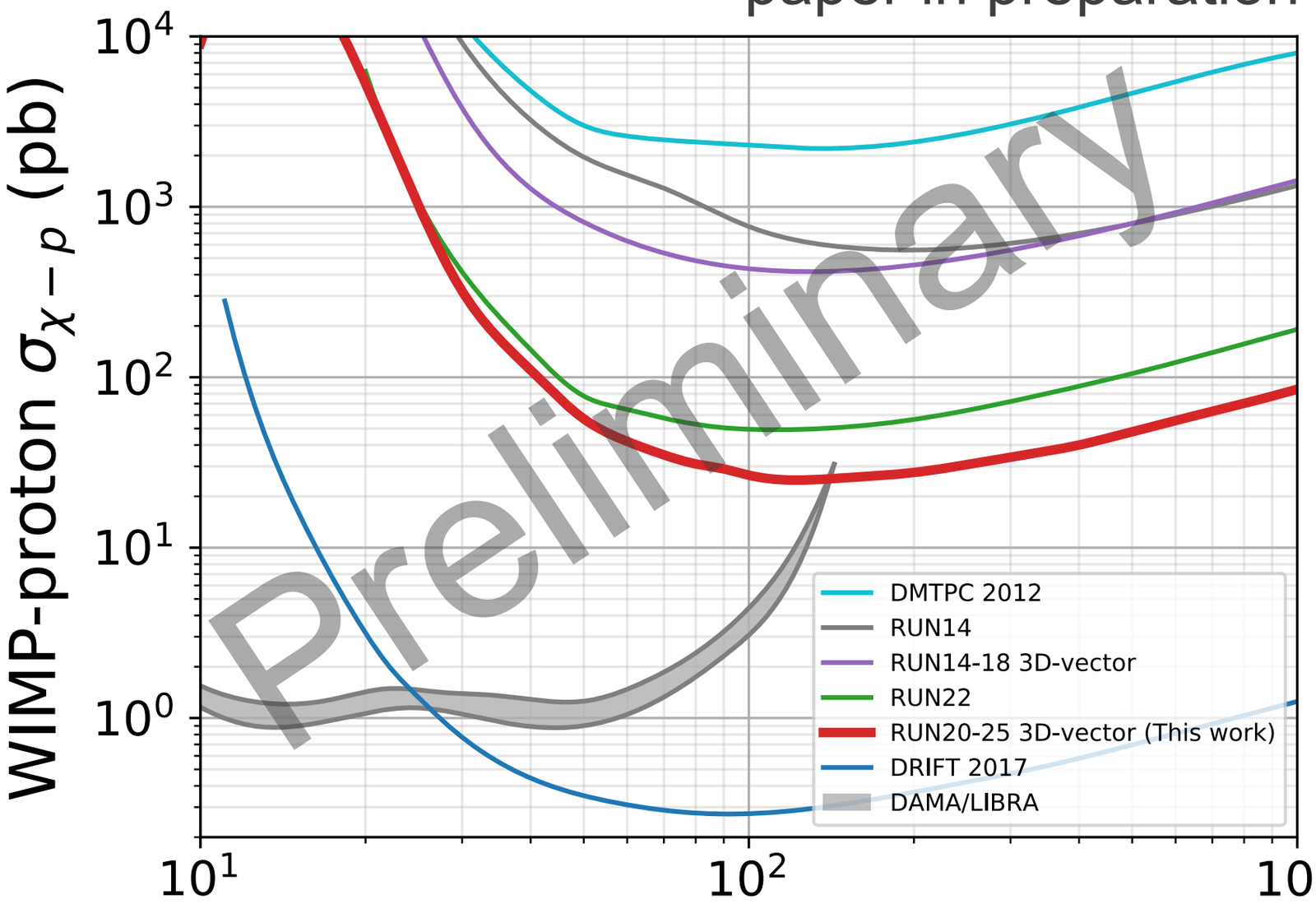


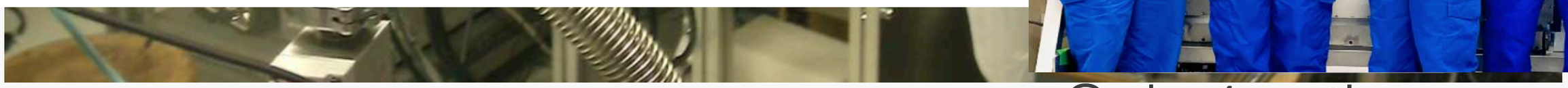
as circulation system

NEWAGE



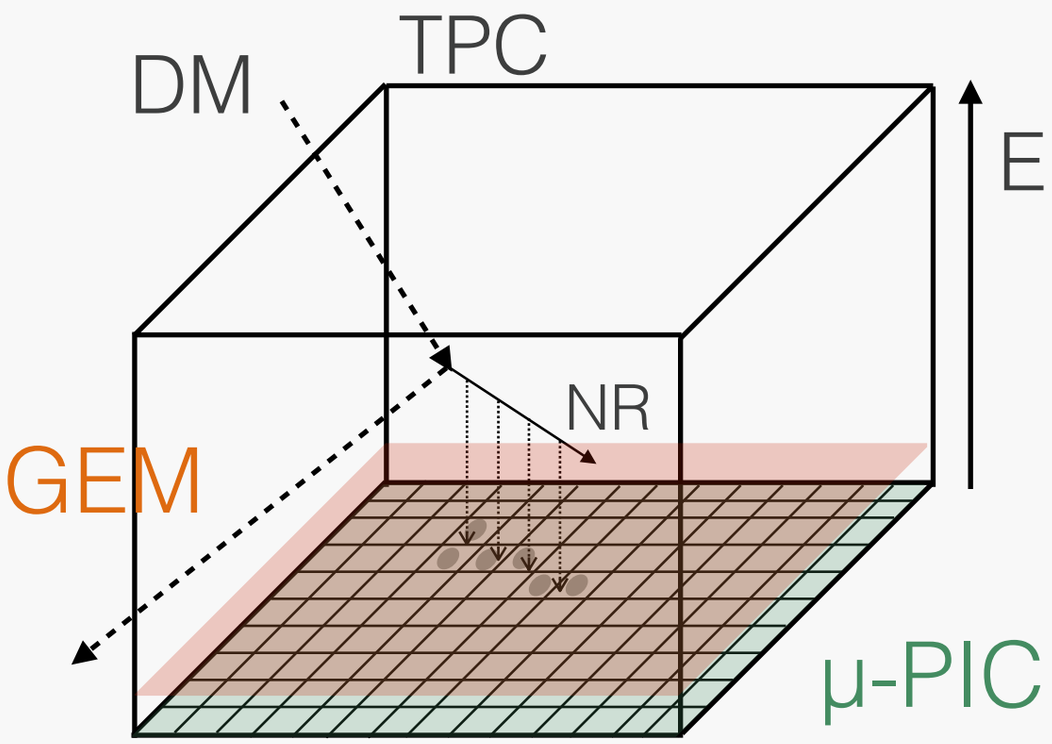
paper in preparation





Only 4 active people!

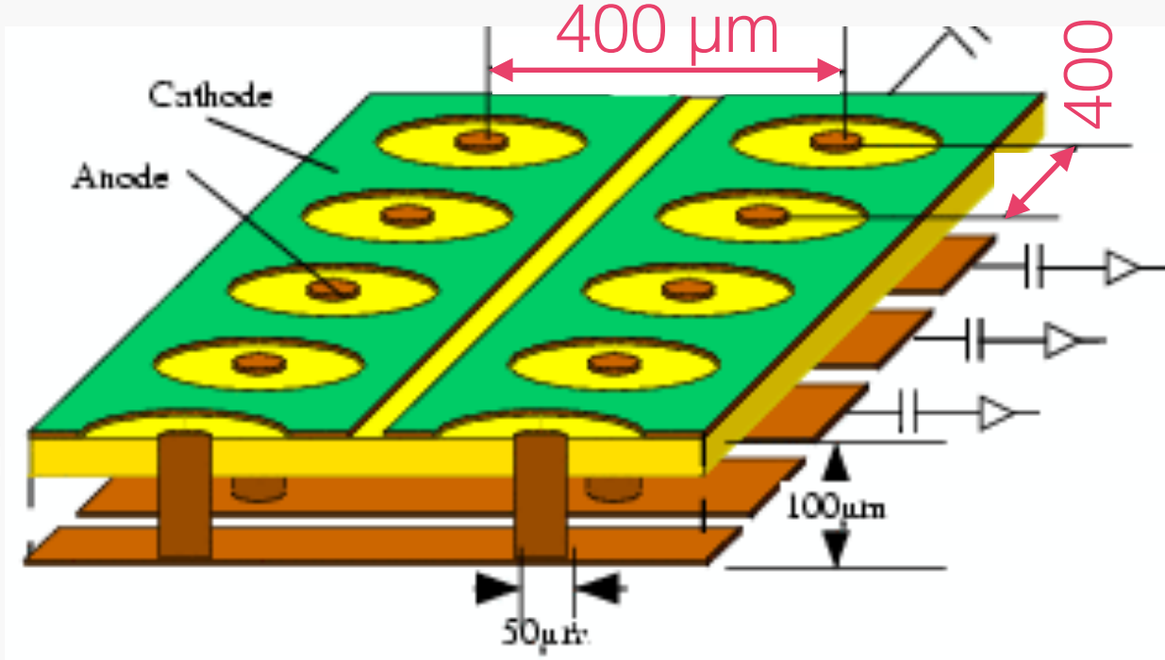
NEWAGE: 3D track detection with gaseous TPC



- TPC is filled with CF_4 gas (76 torr)
- Recoil angles can be measured by reconstructed tracks

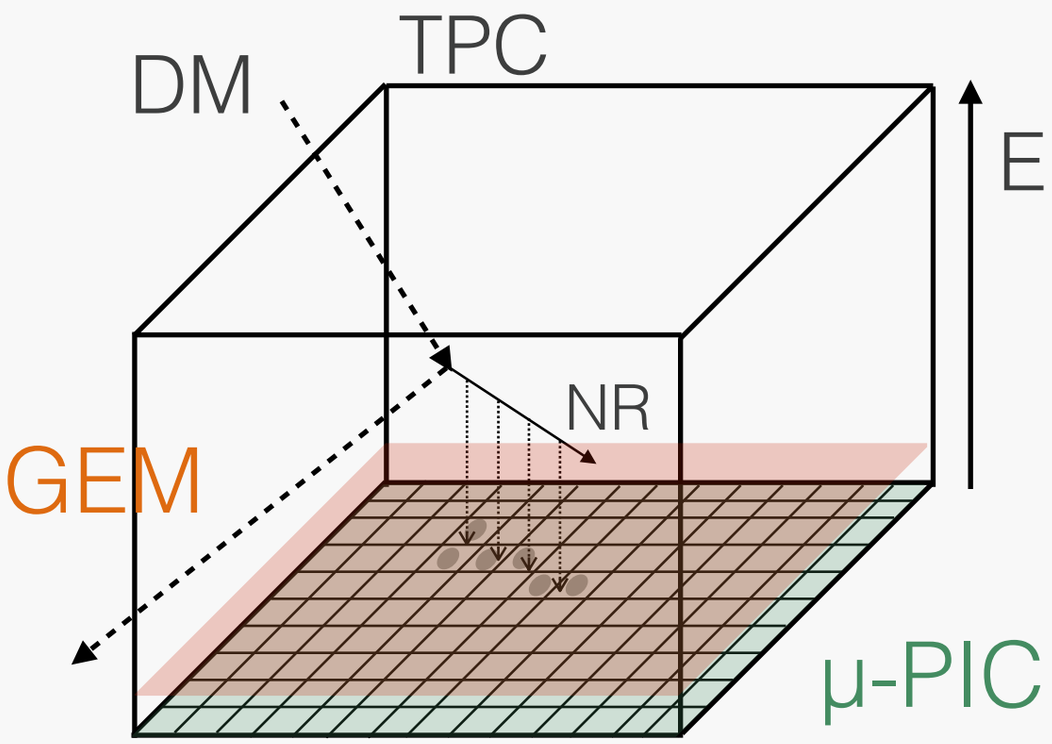
2D position + drift time
→WIMP search with 3D track

- μ-PIC readouts 2D position
  - ➡ **400 um pitch** 2D strip
  - ➡ also has capability of gas amplification
- GEM allows to cause further amplification



 μ-PIC: 2D strip readout + amplification

NEWAGE: 3D track detection with gaseous TPC



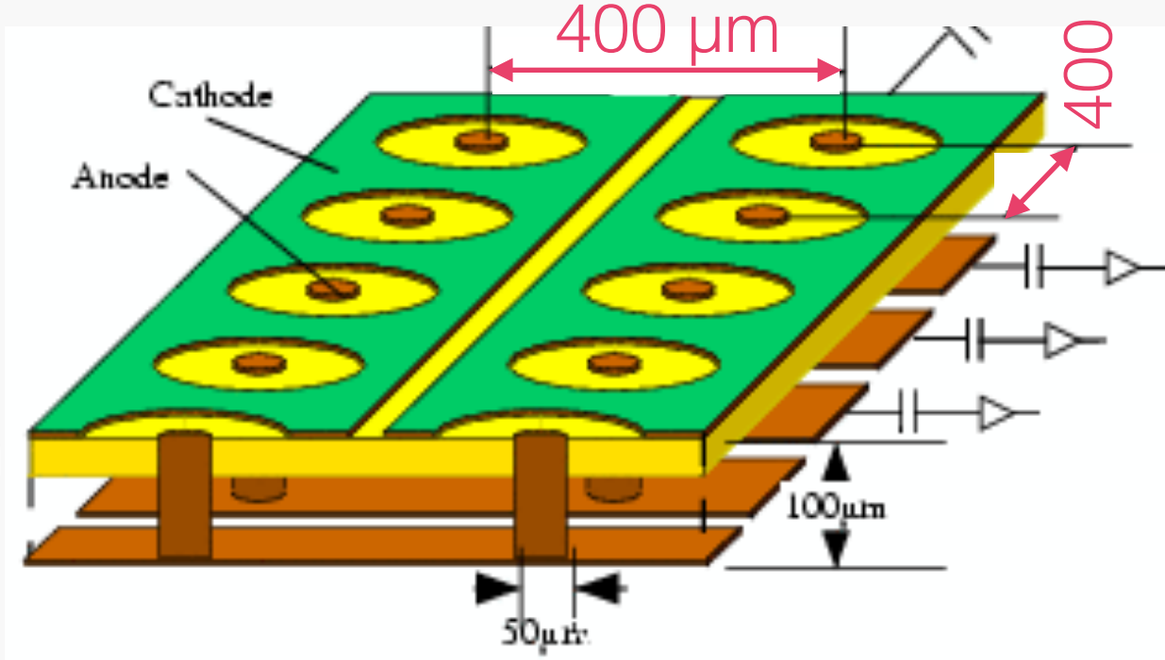
- TPC is filled with CF_4 gas (76 torr)
- Rec… by reco…

will be replaced to **SF_6** (negative-ion gas)

2D position + drift time

→WIMP search with 3D track

- μ-PIC readouts 2D position
  - ➡ **400 um pitch** 2D strip
  - ➡ also has capability of gas amplification
- GEM allows to cause further amplification



 μ-PIC: 2D strip readout + amplification

TPC using negative-ion gas: SF_6

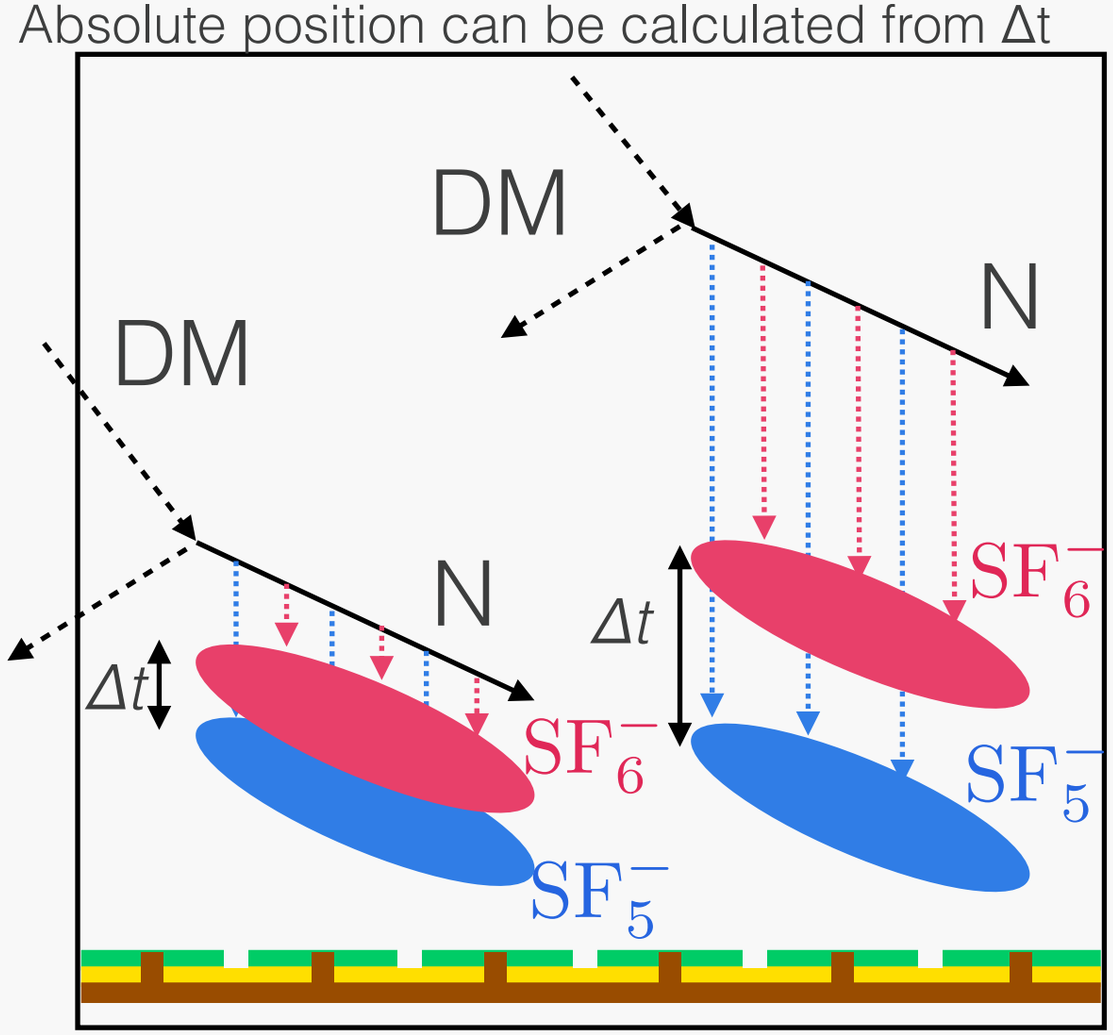
- Molecules capture ionized electrons and form 2 types of negative-ions

$$SF_6 + e^- \rightarrow SF_6^{-*}$$

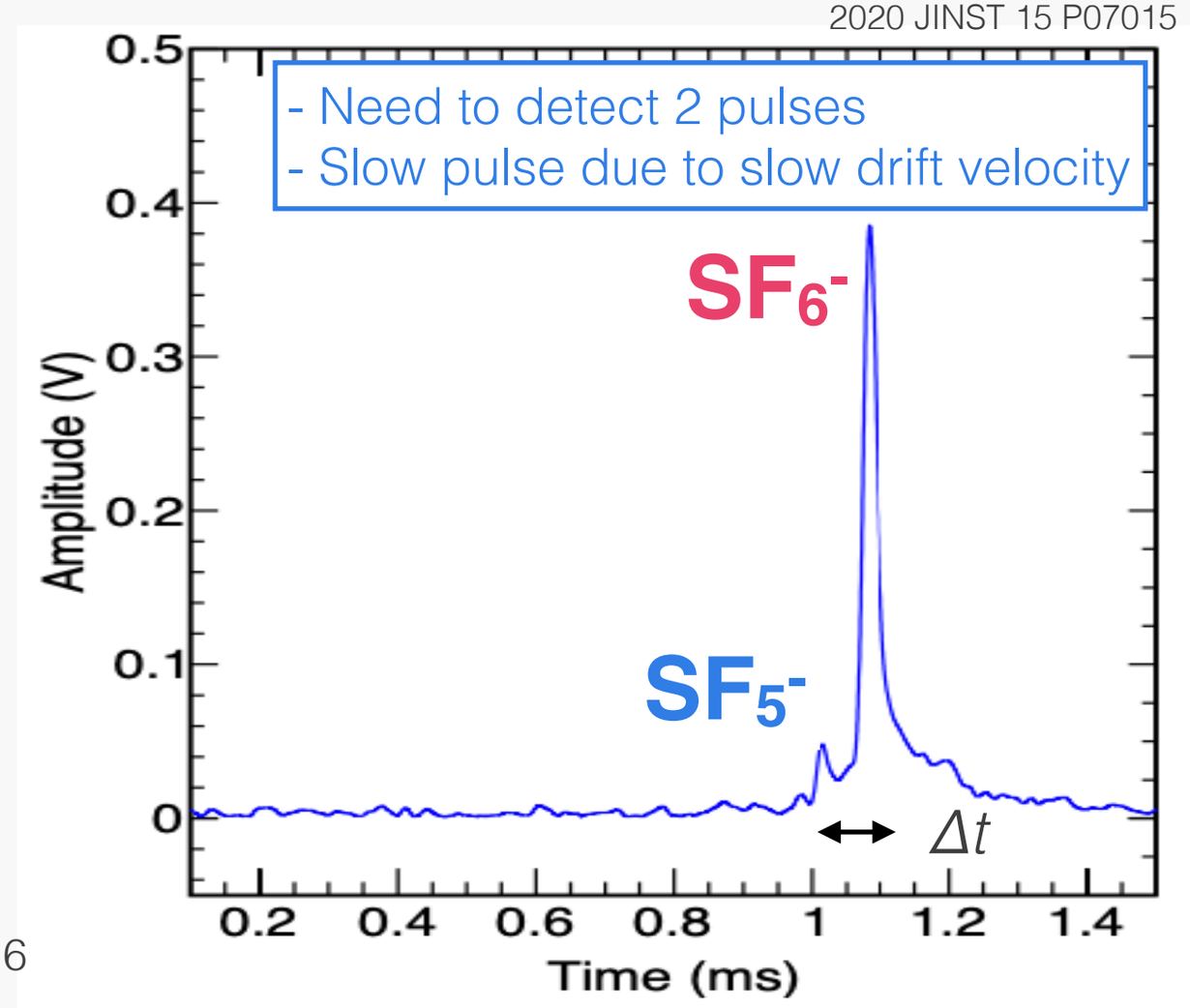
$$SF_6^{-*} + SF_6 \rightarrow \boxed{SF_6^-} + SF_6 \quad \text{(BR: ~97\%)}$$

$$SF_6^{-+} \rightarrow \boxed{SF_5^-} + F \quad \text{(BR: ~3\%)}$$

Absolute position can be calculated from Δt



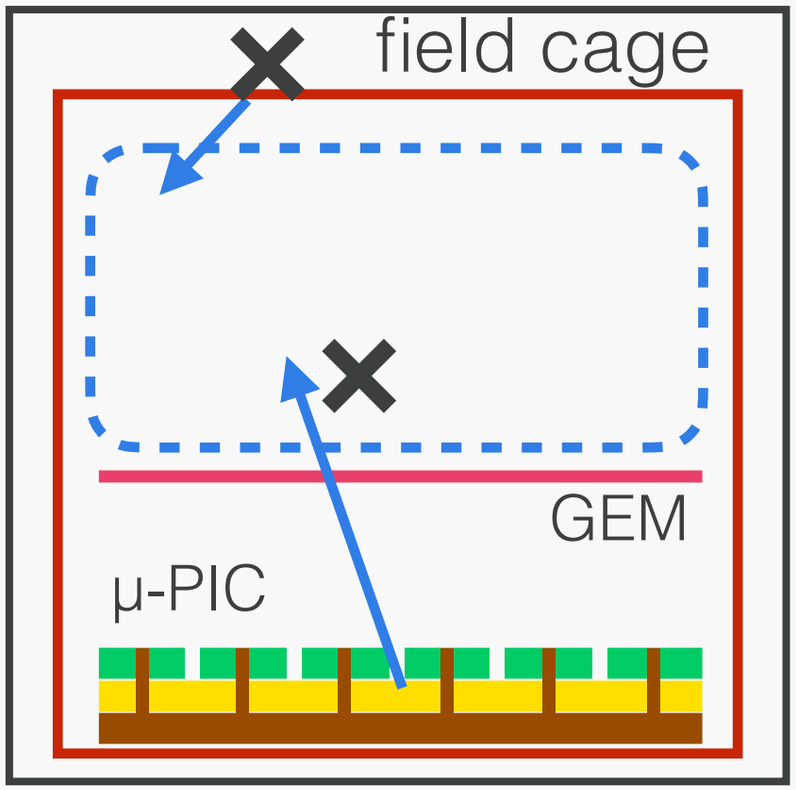
2020 JINST 15 P07015

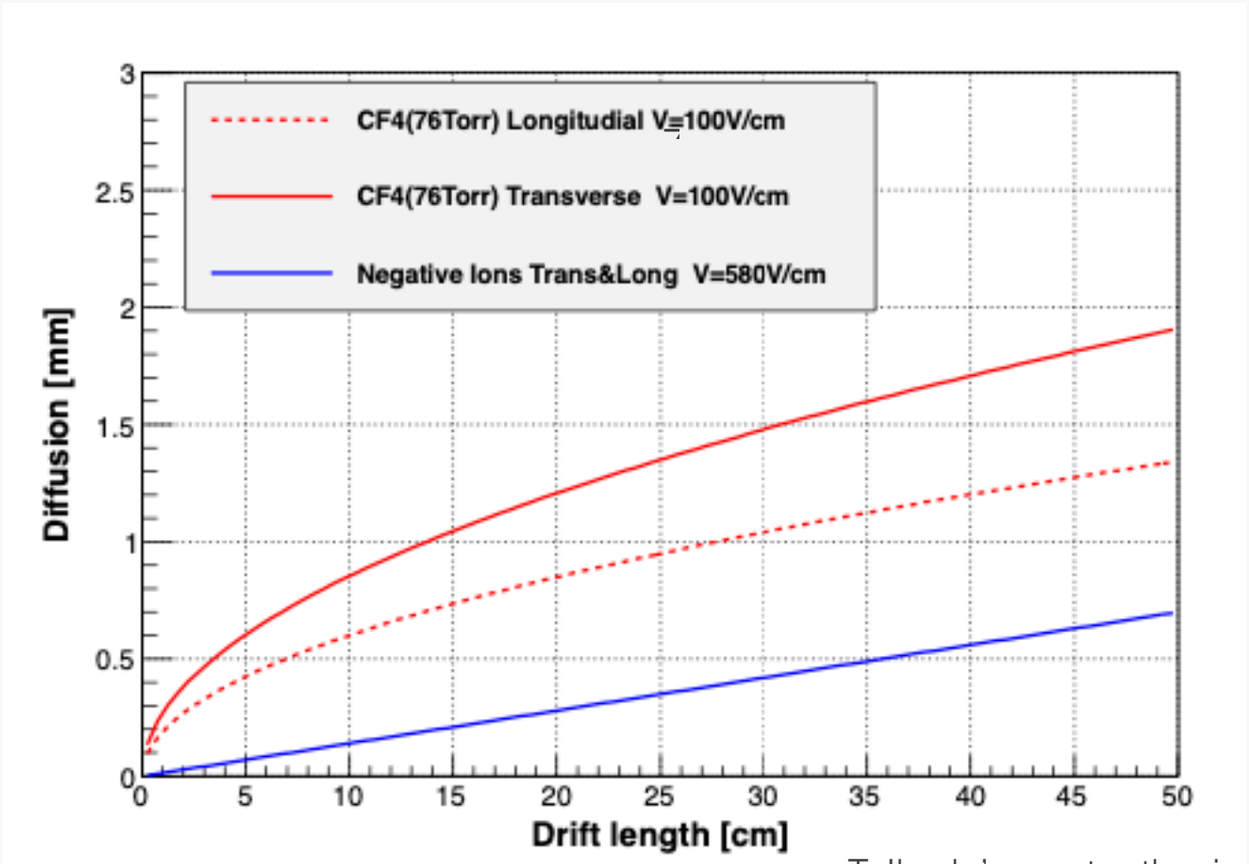


Benefit of negative-ion gas

- Reduce alpha ray backgrounds produced in material surface
  - ➡ detector and drift cathode
- lower diffusion improves precision of track reconstruction
  - ➡ allows to reconstruct short track
- more sensitive for low mass dark matter search

chamber





T. Ikeda's master thesis

Today's topics

- Test of prototype negative-ion TPC w/ μ-PIC

- Development of fine granularity
  pixel readout MPGD for negative-ion gas

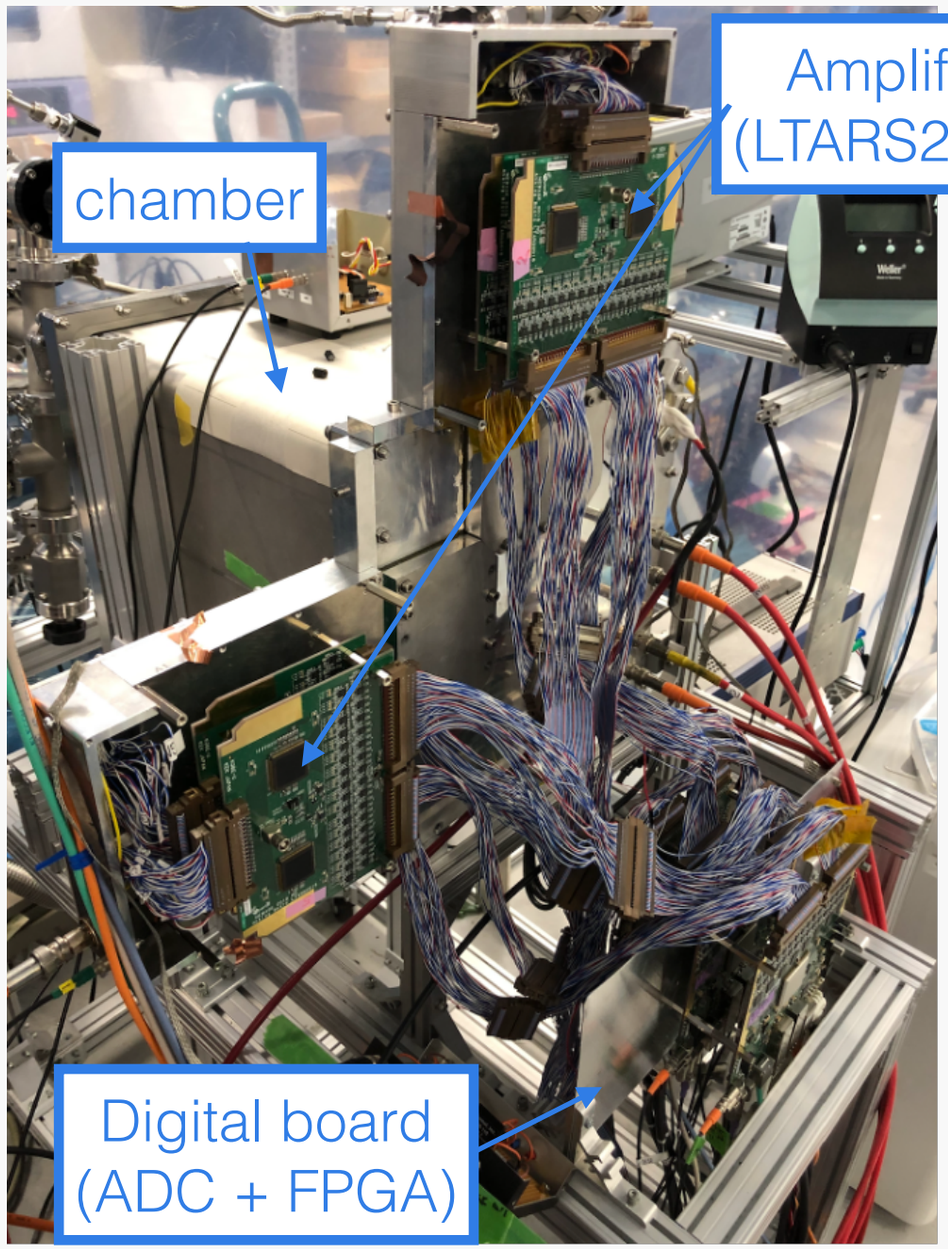
Today's topics

- Test of prototype negative-ion TPC w/ μ-PIC

- Development of fine granularity pixel readout MPGD for negative-ion gas

Prototype detector

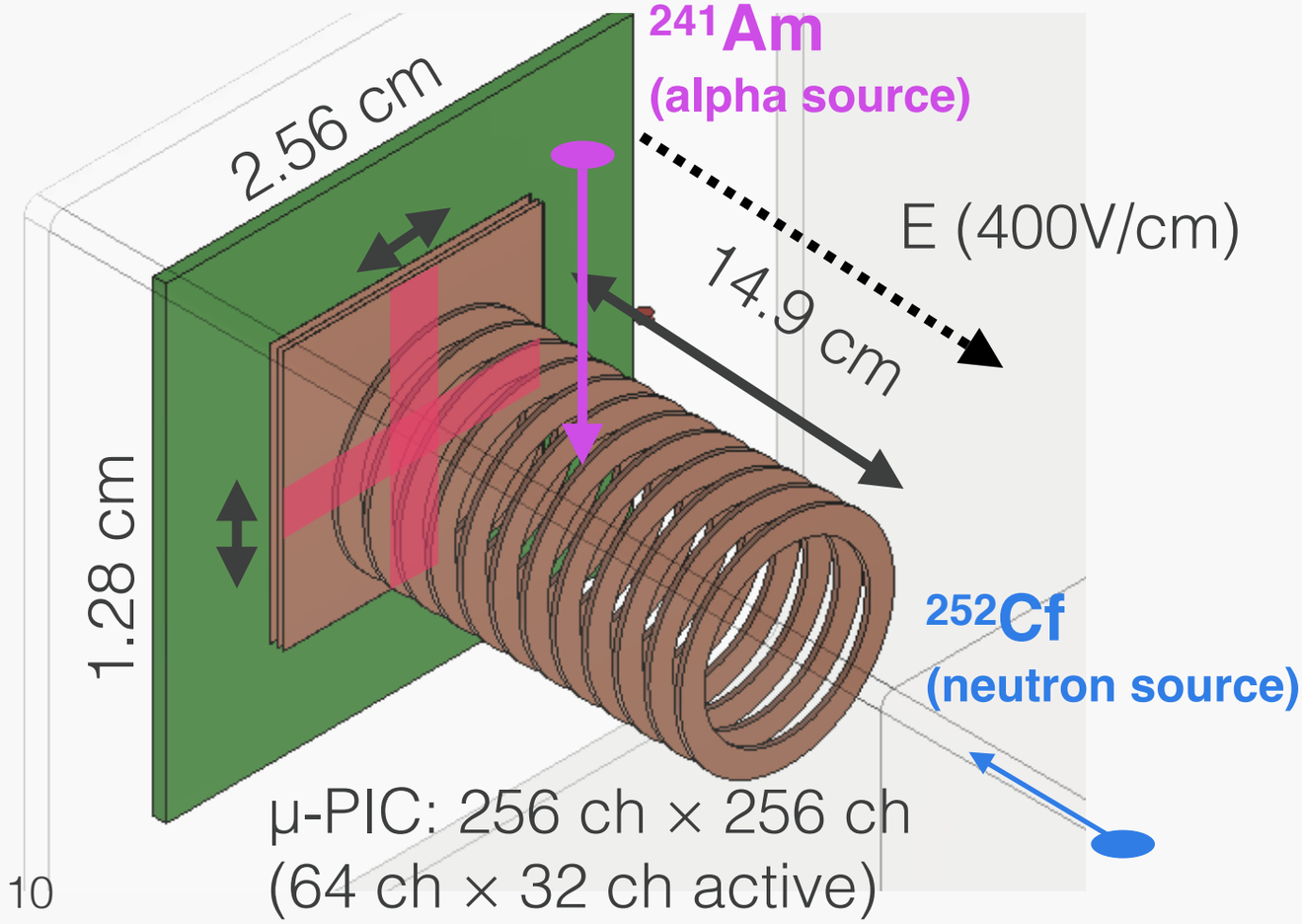
- 400 μm pitch μ-PIC readout + 2 GEMs amplification
- Dedicated electronics (LTARS2018 ASIC: T. Kishishita, et. al. 2020 JINST 15 T09009)



Filled with pure SF_6 gas (20 torr)

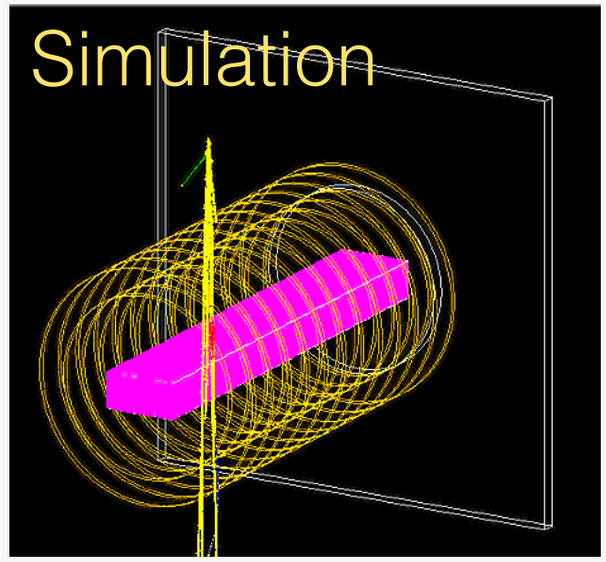
^{241}Am source (calibration)

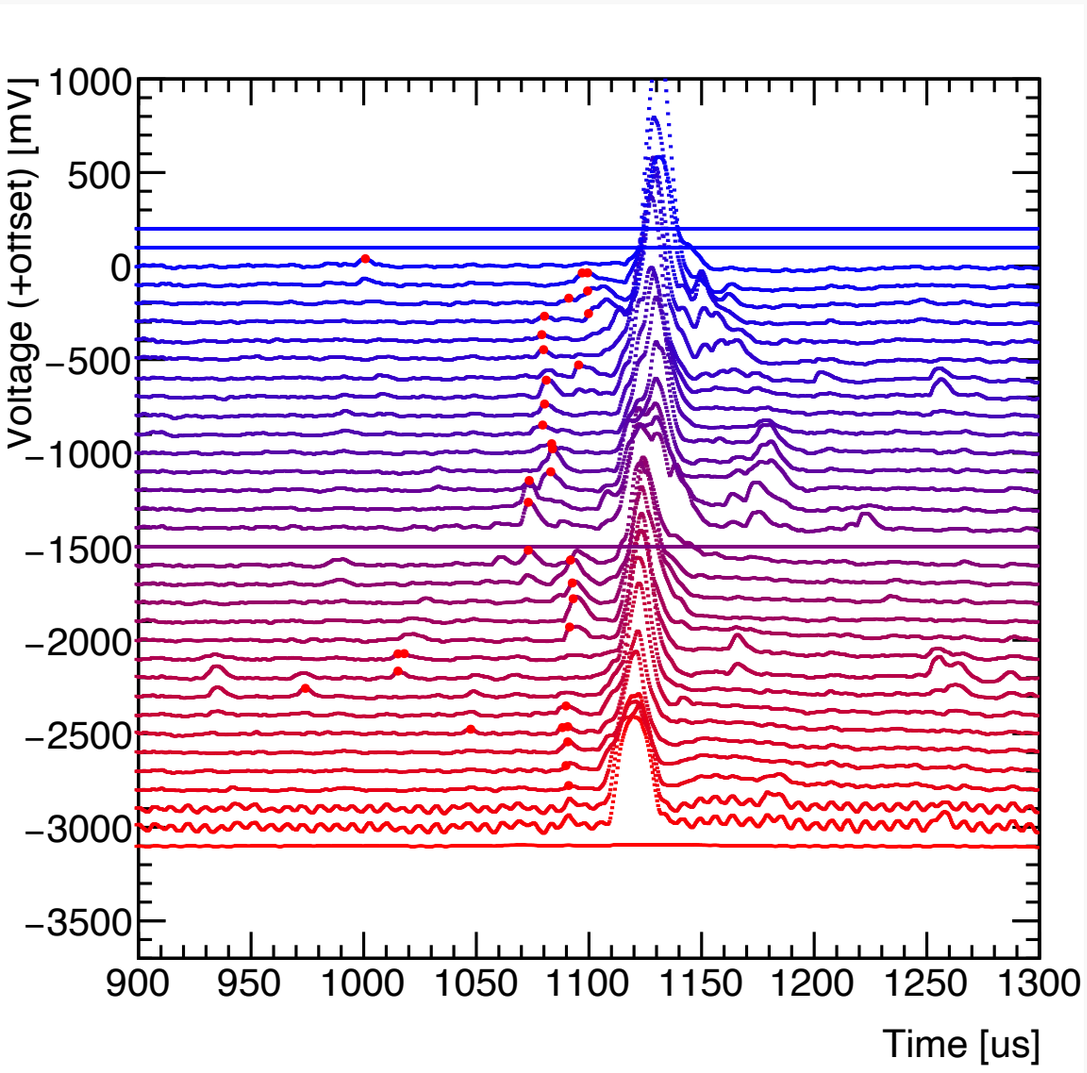
^{252}Cf source (NR measurement)

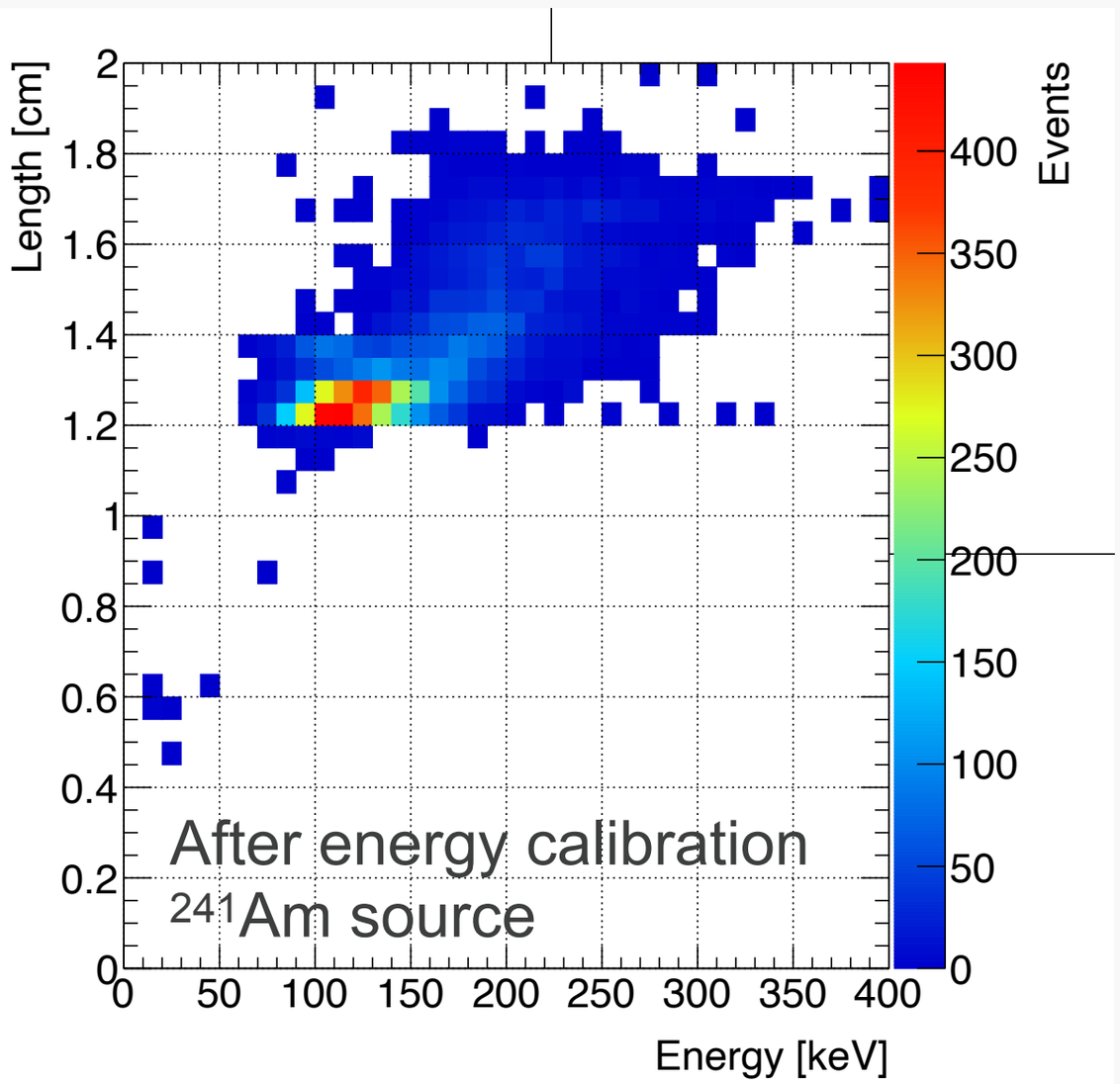


Demonstration using Alpha rays

- (Somehow) collimated ^{241}Am alpha source are placed
  - ➡ come across to the drift region
- Both SF_5^- and SF_6^- are clearly seen





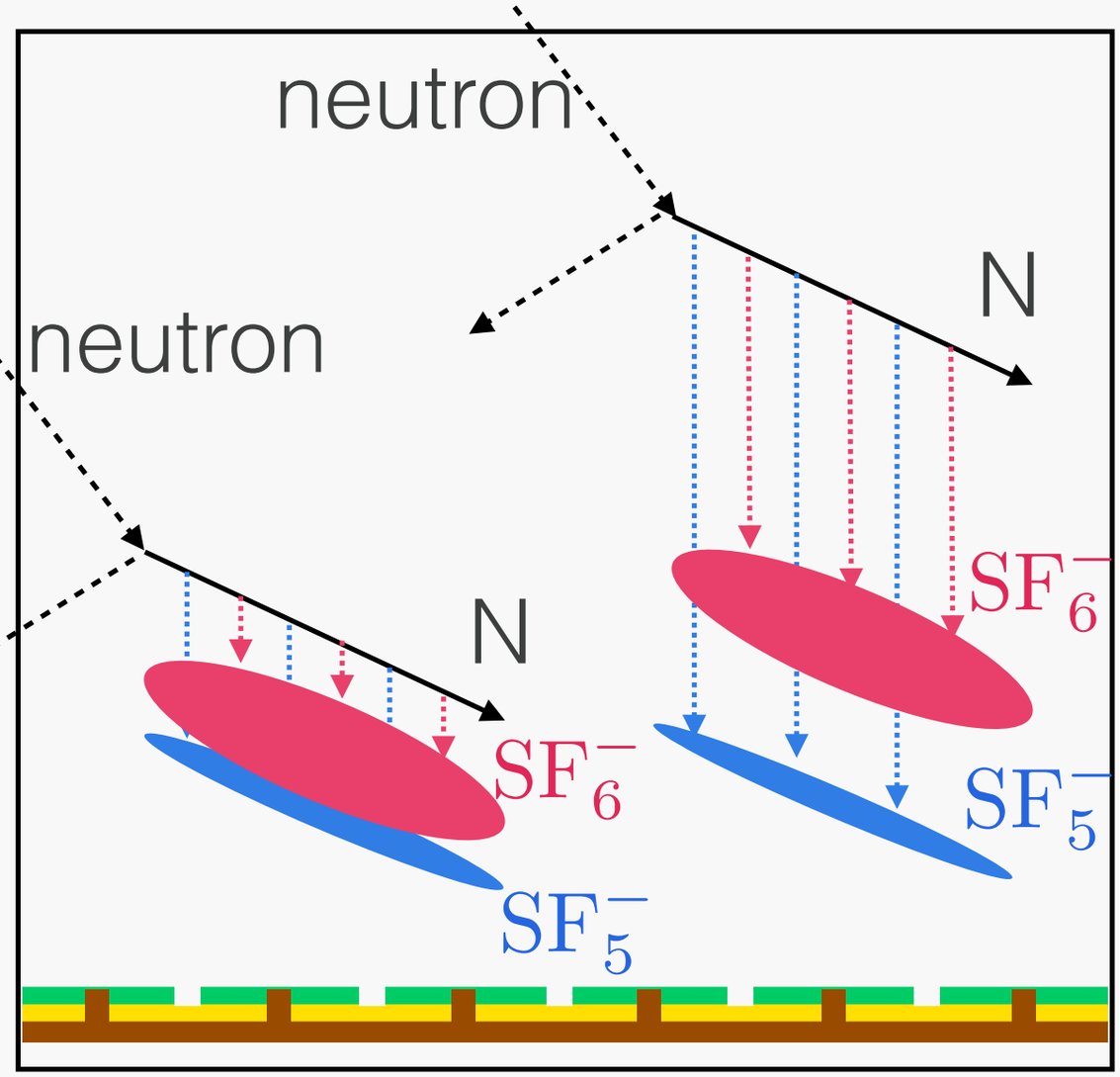


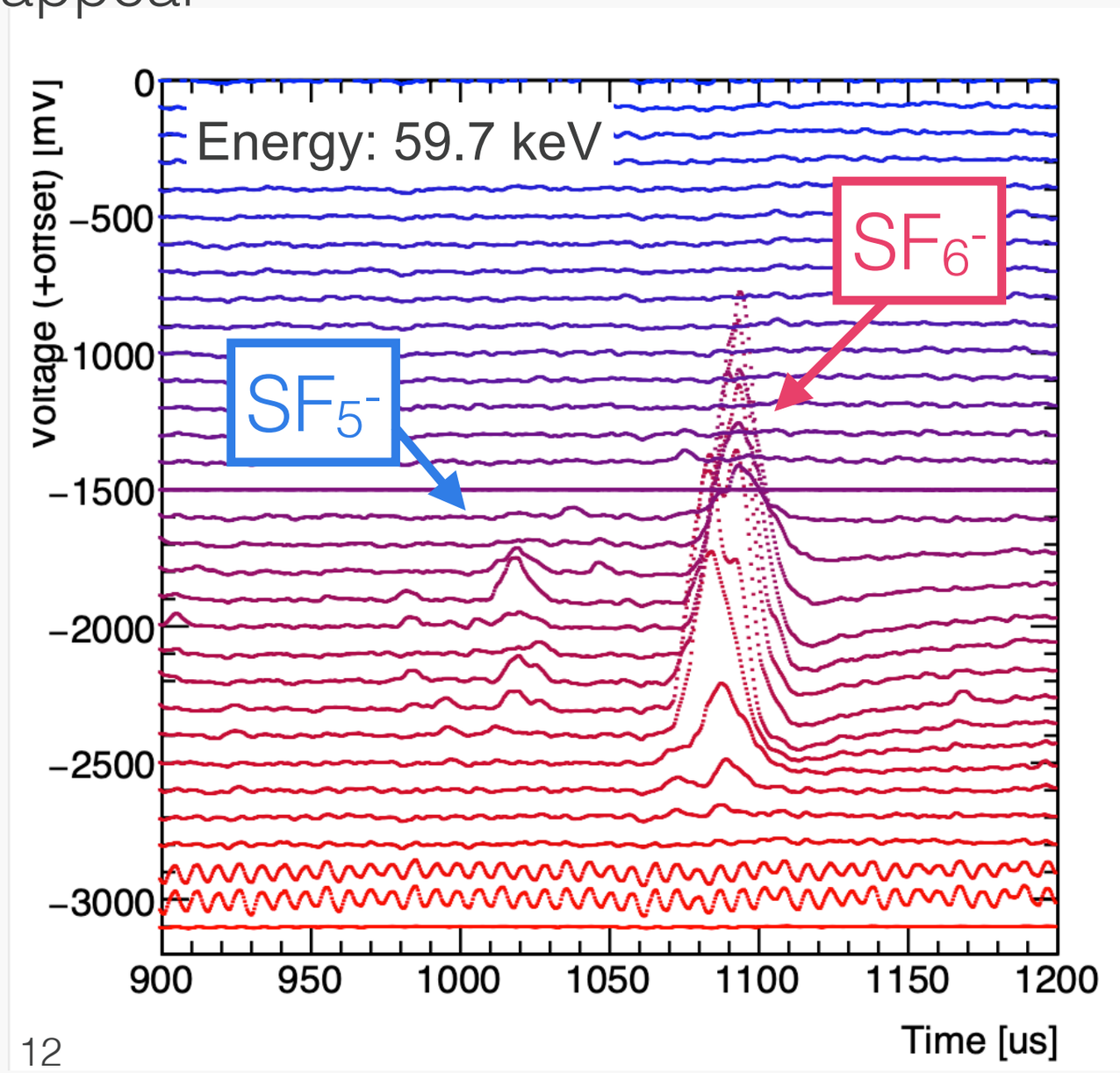
NR detection in neutron run (^{252}Cf)

- Detect NR: signals inside the fiducial region

  ➡ no signals at the corner of strips

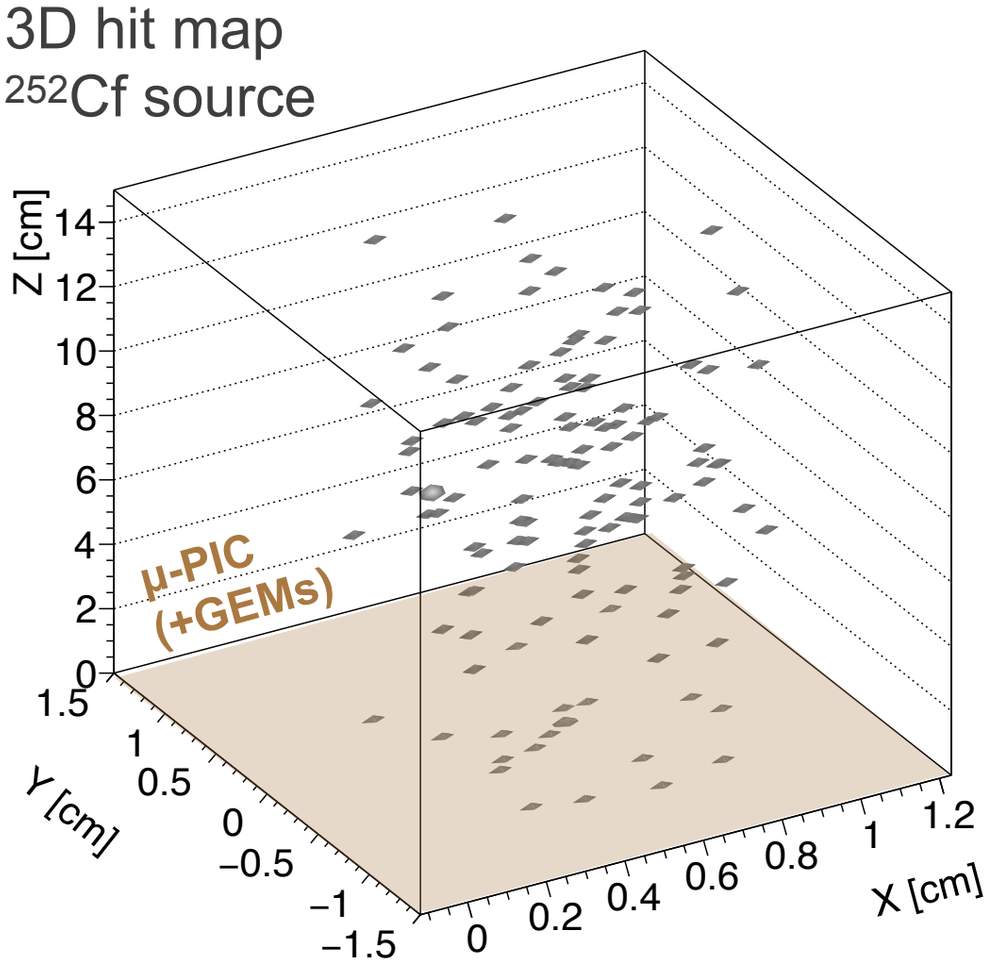
- Small SF_5^- signals are also clearly appear

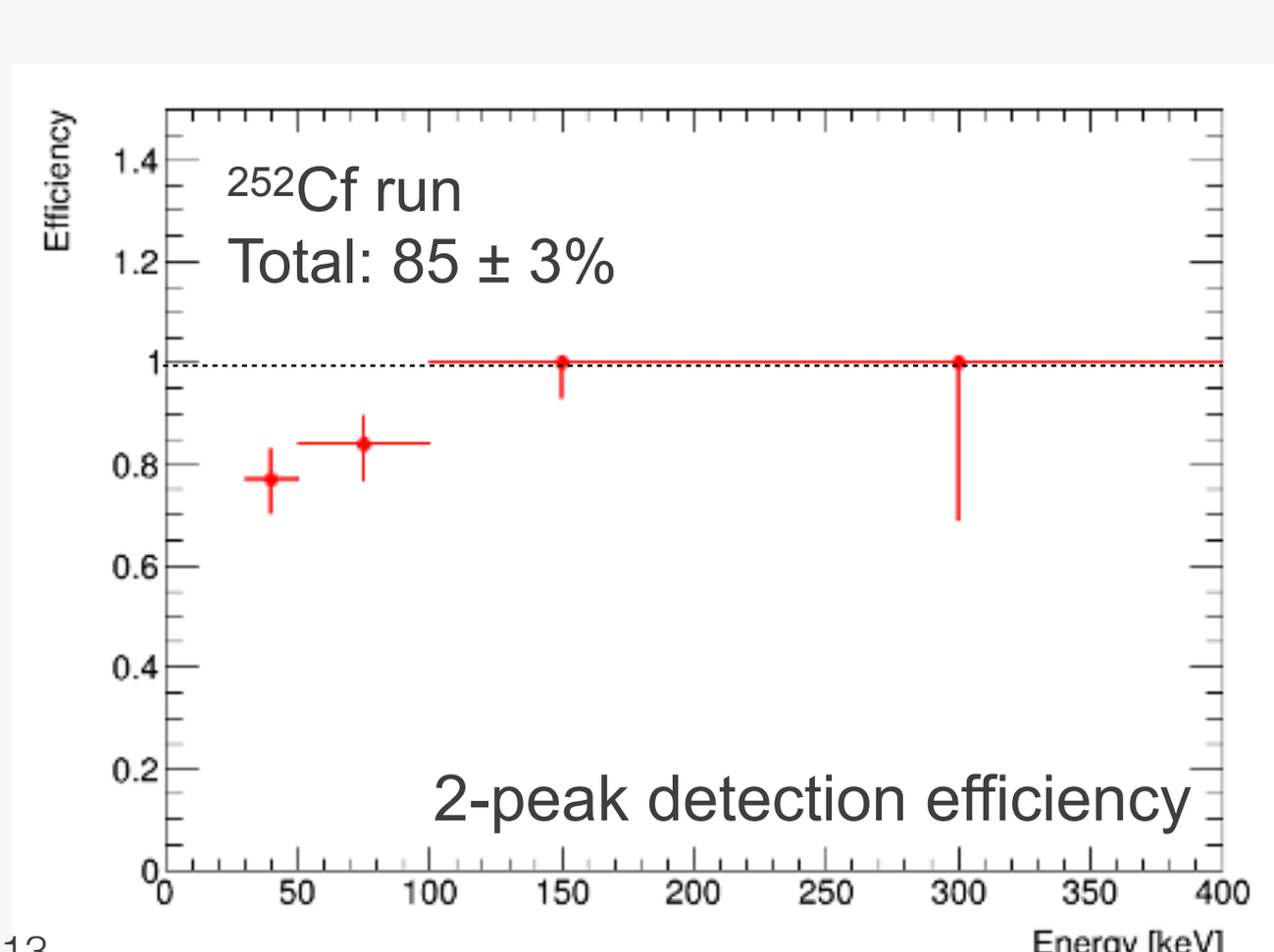




Absolute position reconstruction efficiency

- Absolute 3D position reconstruction successfully performed
- Good 2-peak detection efficiency
  - ➡ defined as "#events with SF_5^- peak / #NR evens"
- Ready to use for dark matter searches (directionality study is still ongoing)





The 7th International Conference on
Micro Pattern Gaseous Detectors 2022
Weizmann Institute of Science, Rehovot, Israel

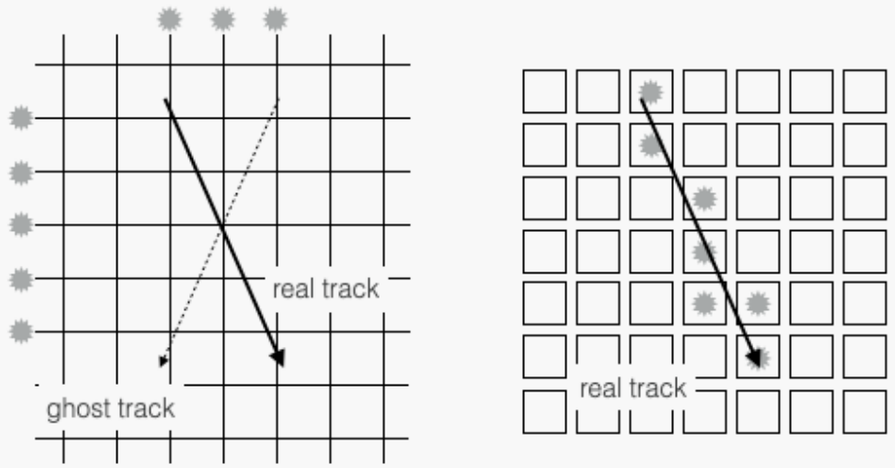
Today's topics

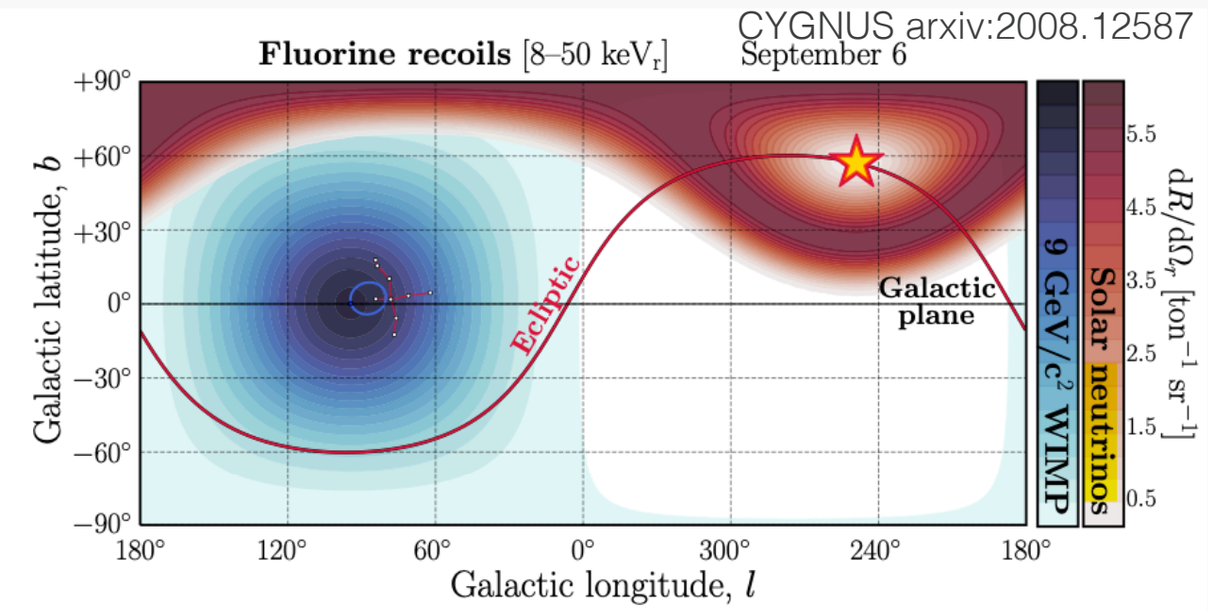
- Test of prototype negative-ion TPC w/ μ-PIC

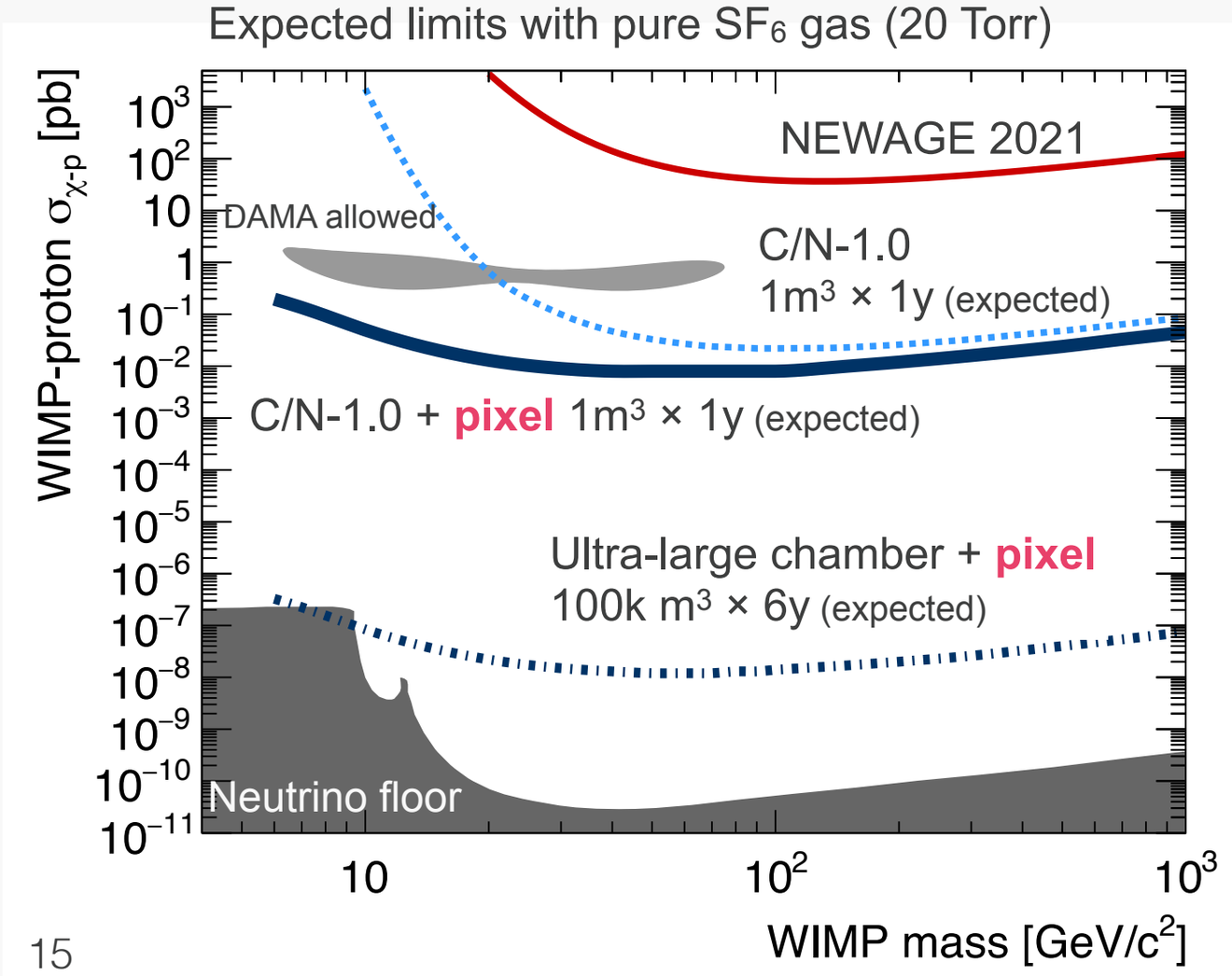
- Development of fine granularity pixel readout MPGD for negative-ion gas

100 μm pitch pixel readout

- Enable to achieve lower energy threshold
  - ➡ 100 keV_r (current: 400 μm pitch) → 10 keV_r (100 μm pitch + SF_6 20 torr)
  - ➡ allows to explore lower DM mass region
- Pixel readout can reduce ghost tracks





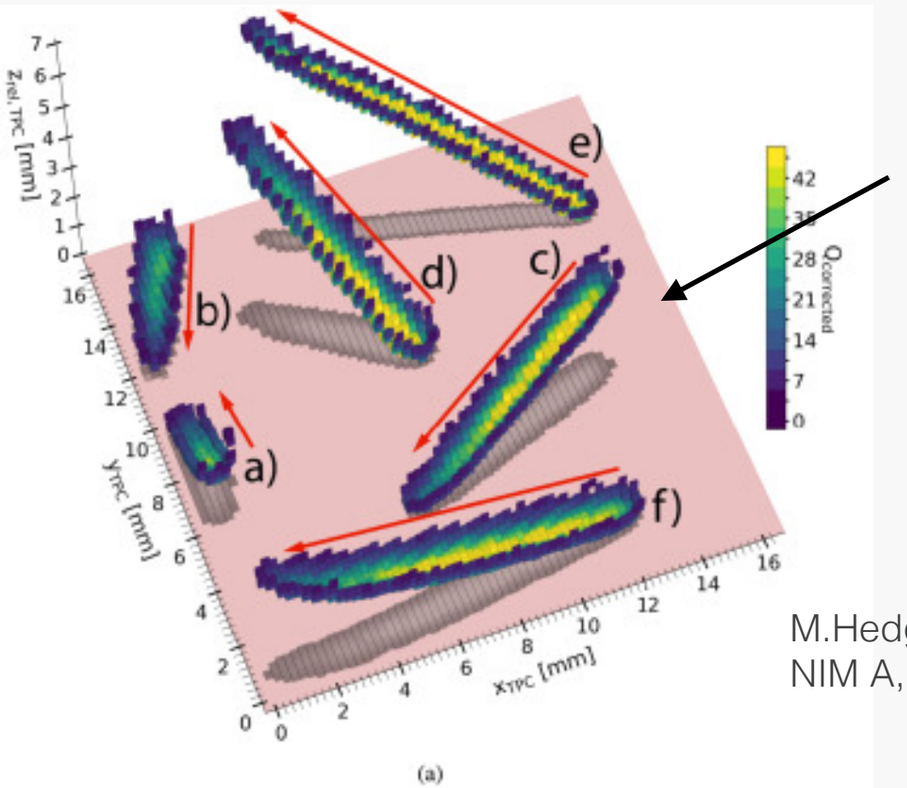


Pixel readout system for gaseous TPC

- Some excellent systems are already exist

  ➡ but we need to detect 2-peak events (**=multi hit readout for each trigger**)

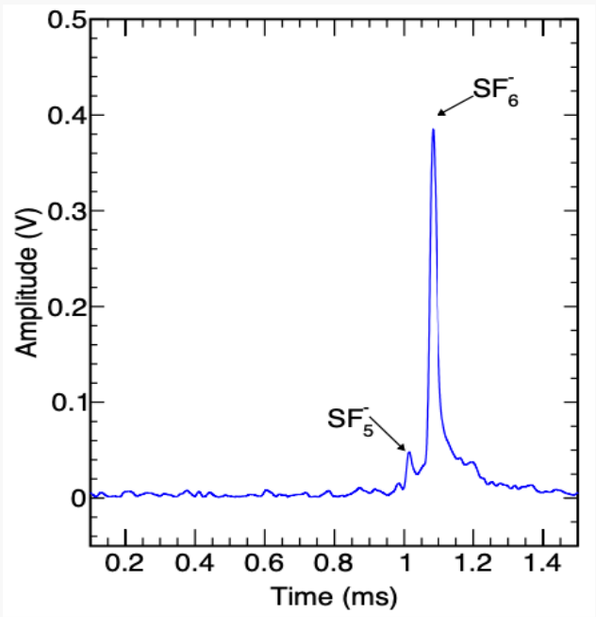
e.g.) ASIC	TimePix	FE-I4	LArPix	QPIX (by JP group)
Application	Gas TPC	Silicon (ATLAS) Gas TPC (SuperKEKB)	LAr TPC	Gas TPC
Digitization	Time over Threshold	Time over Threshold	Charge integral ADC	Charge integral ADC Time over Threshold
Pixel size	55 × 55 μm²	50 × 250 μm²	4 × 4 mm² (Pad)	200 × 200 μm² (ASIC) 400 × 400 μm² (Pad)



TPC @KEK (w/ FI-I4)

Excellent track reconstruction!

however…



M.Hedges, S.Vahsen, et. al.
NIM A, Volume 1026, 1 March 2022, 166066

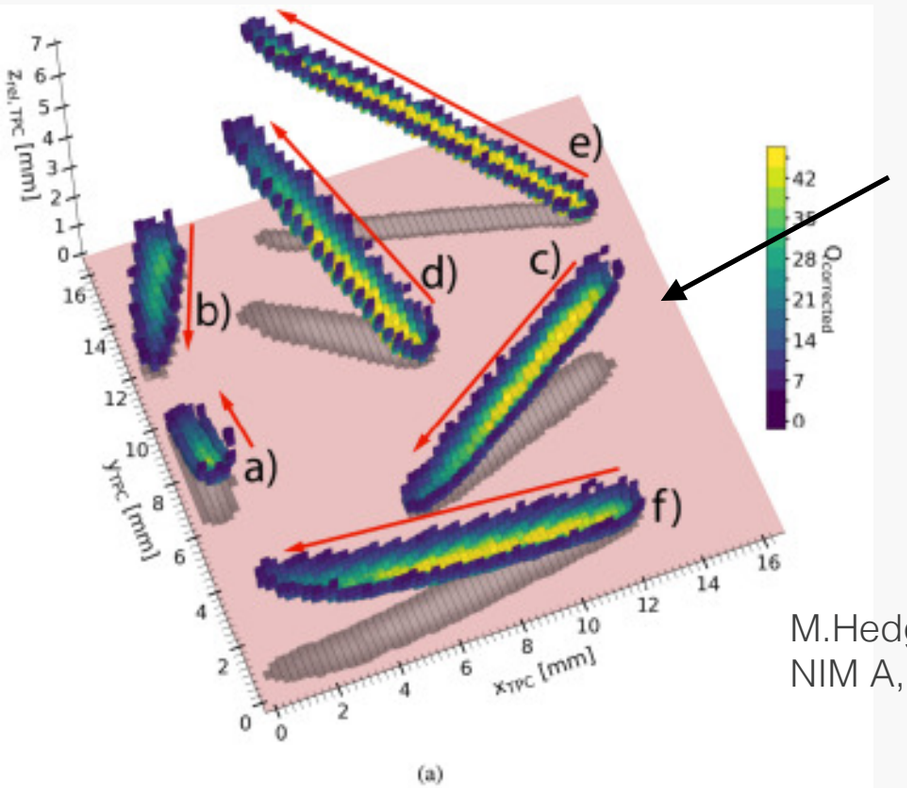
we need to produce dedicated ASIC for SF_6!

Pixel readout system for gaseous TPC

- Some excellent systems are already exist

  ➡ but we need to detect 2-peak events (**=multi hit readout for each trigger**)

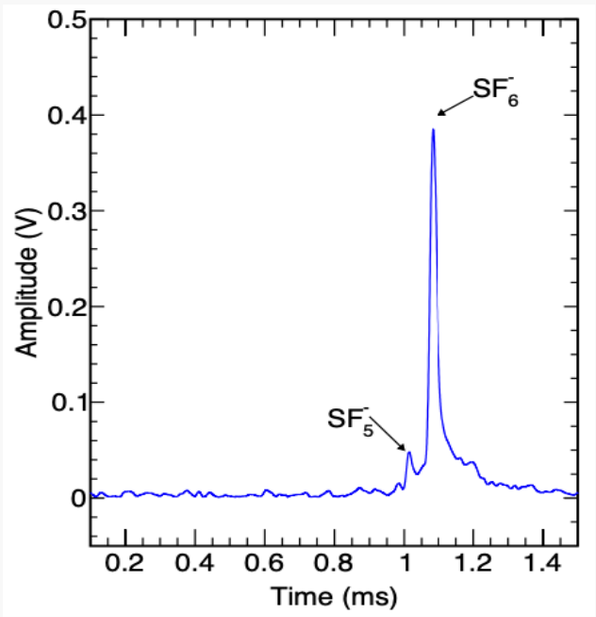
e.g.) ASIC	TimePix	FE-I4	LArPix	QPIX (by JP group)
Application	**GridPix!!!**	Silicon (ATLAS) Gas TPC (SuperKEKB)	LAr TPC	Gas TPC
Digitization	Time over Threshold	Time over Threshold	Charge integral ADC	Charge integral ADC Time over Threshold
Pixel size	55 × 55 μm²	50 × 250 μm²	4 × 4 mm² (Pad)	200 × 200 μm² (ASIC) 400 × 400 μm² (Pad)



TPC @KEK (w/ FI-I4)

Excellent track reconstruction!

however…



M.Hedges, S.Vahsen, et. al.
NIM A, Volume 1026, 1 March 2022, 166066

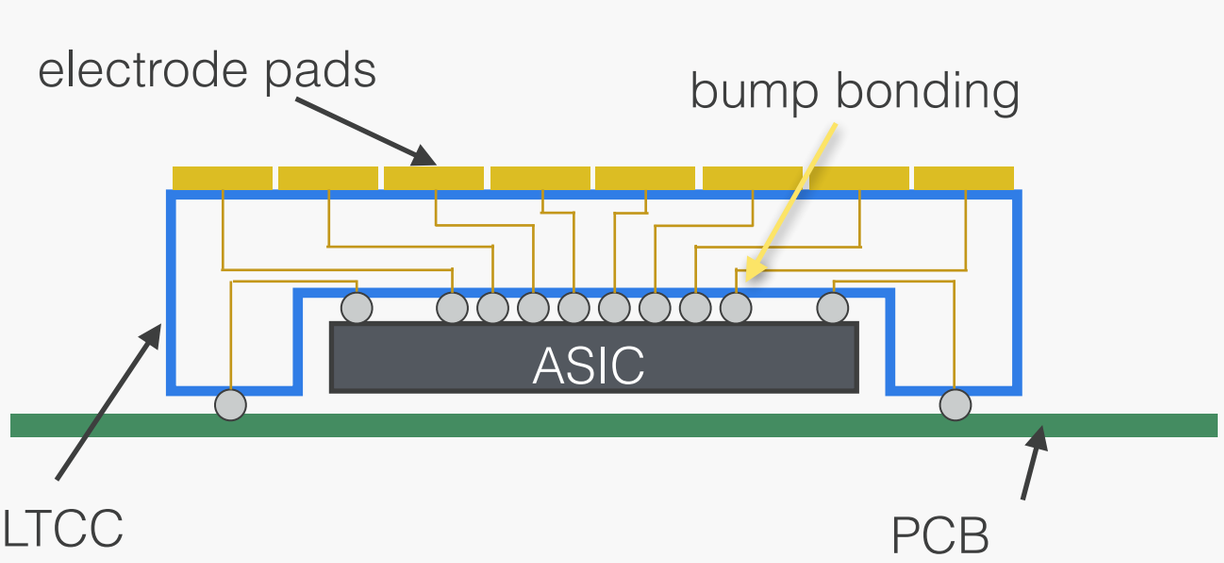
we need to produce dedicated ASIC for SF_6!

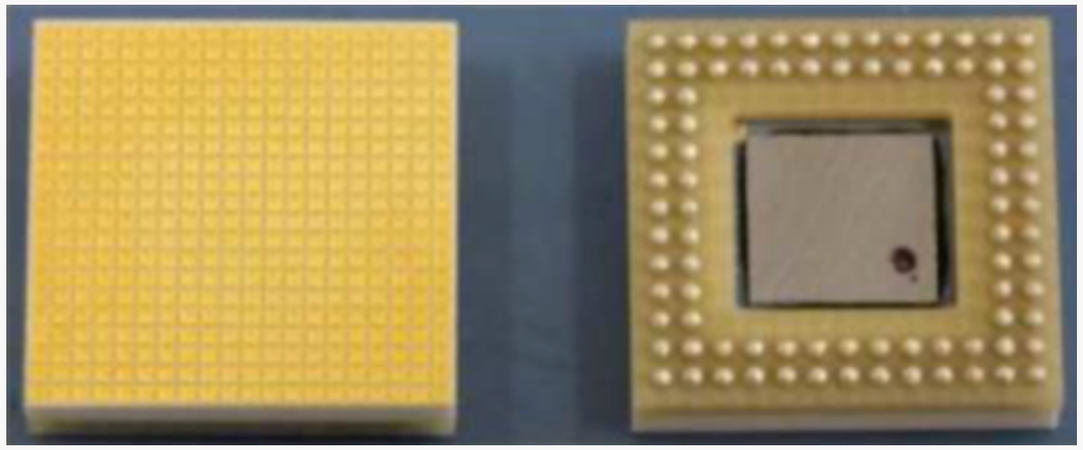
To achieve **100 μm** pixel readout, …

- Need bump bonding to connect to electrode pads
- Usually ASIC not only has pixelized region (e.g. I/O, digitization, …)

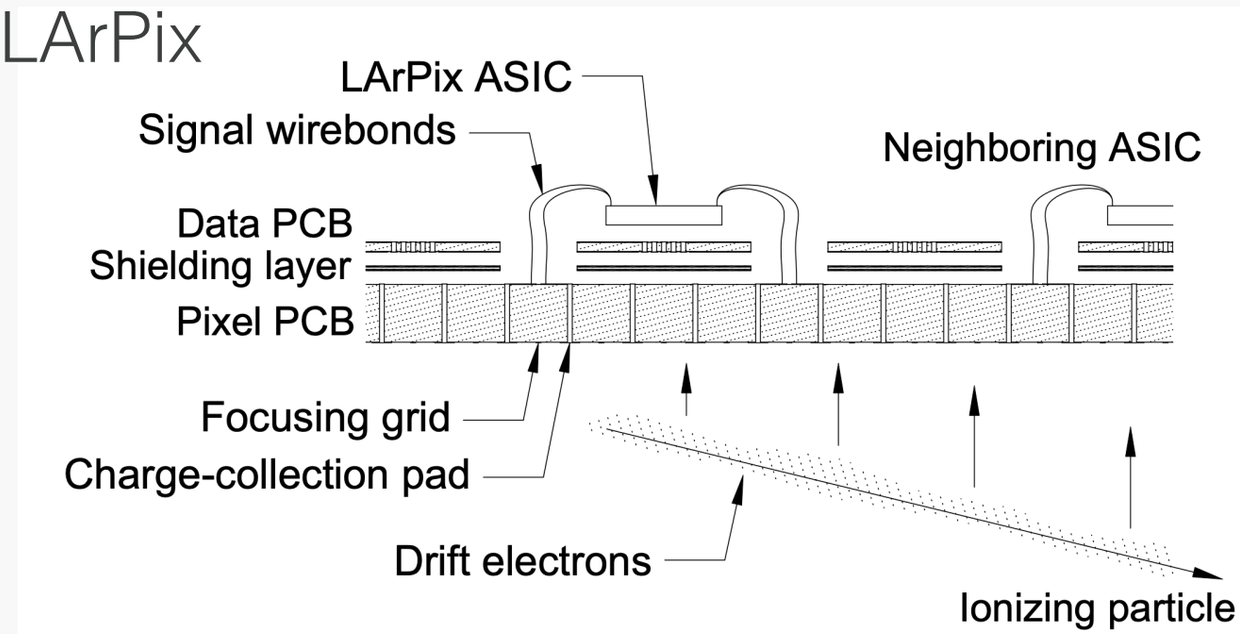
  ➡ need to prepare <100 μm pitch pixel region on ASIC

e.g. QPIX



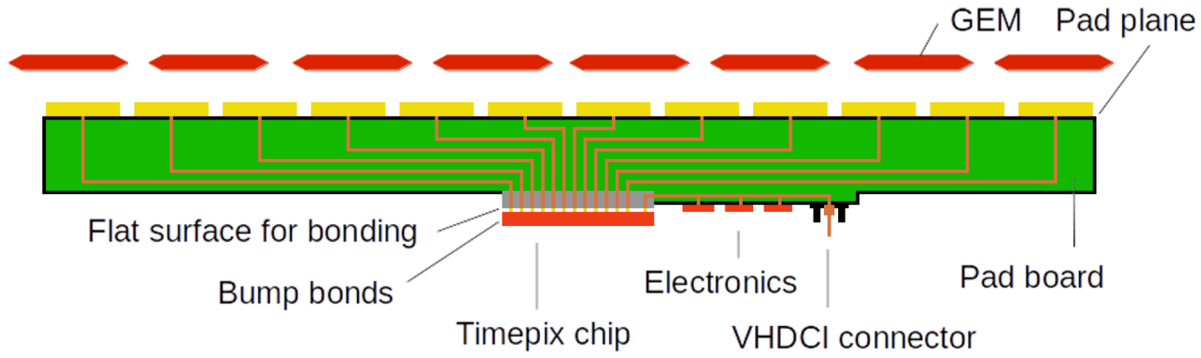


LArPix



2018 JINST 13 P10007

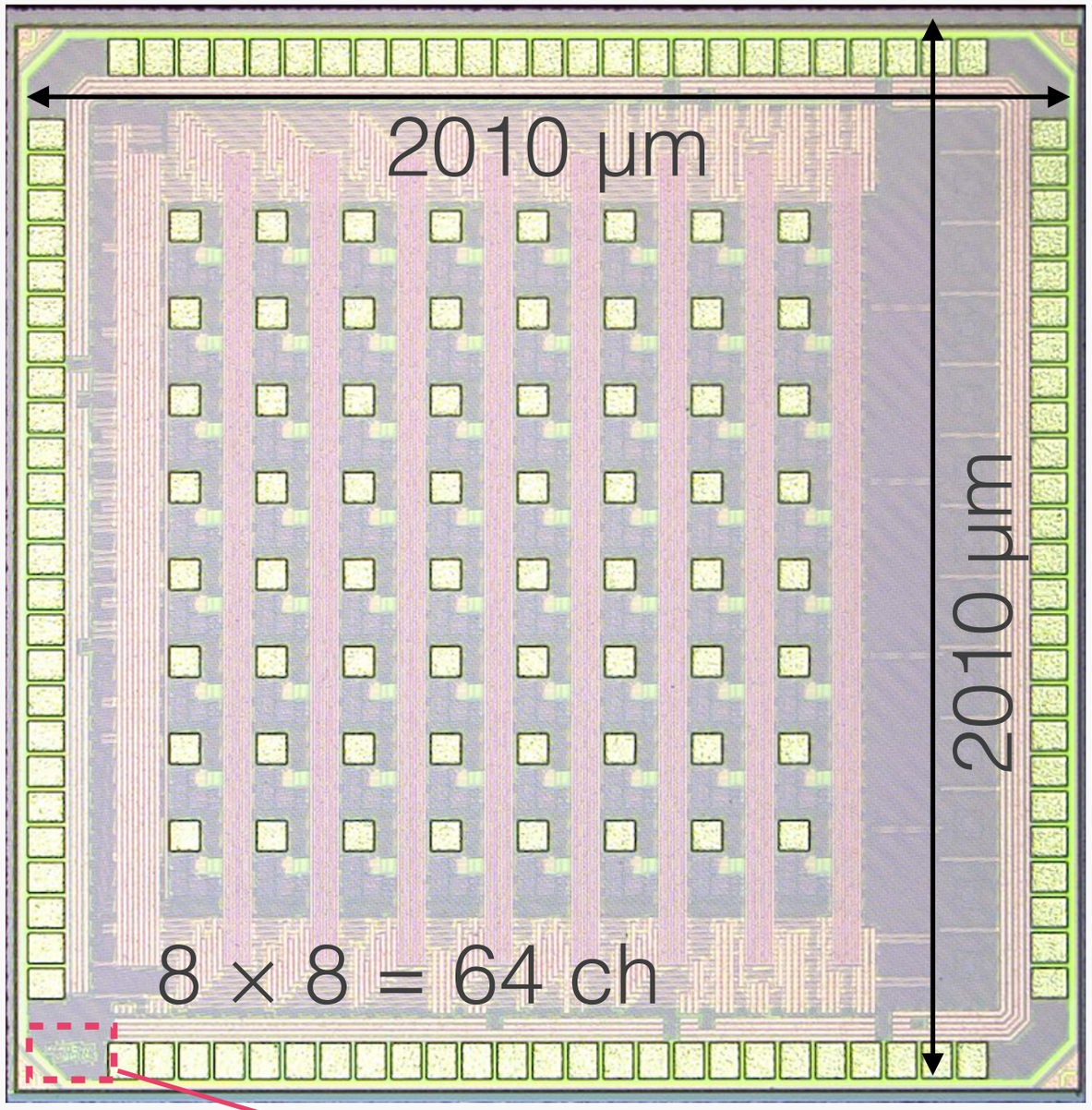
TimePix



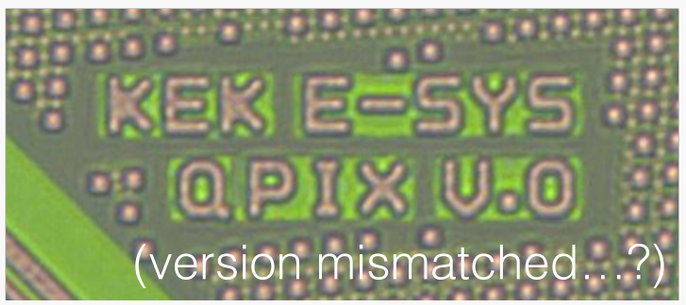
arXiv:1801.07178

QPIX NEO v1 prototype

Thanks to the electronics group in KEK



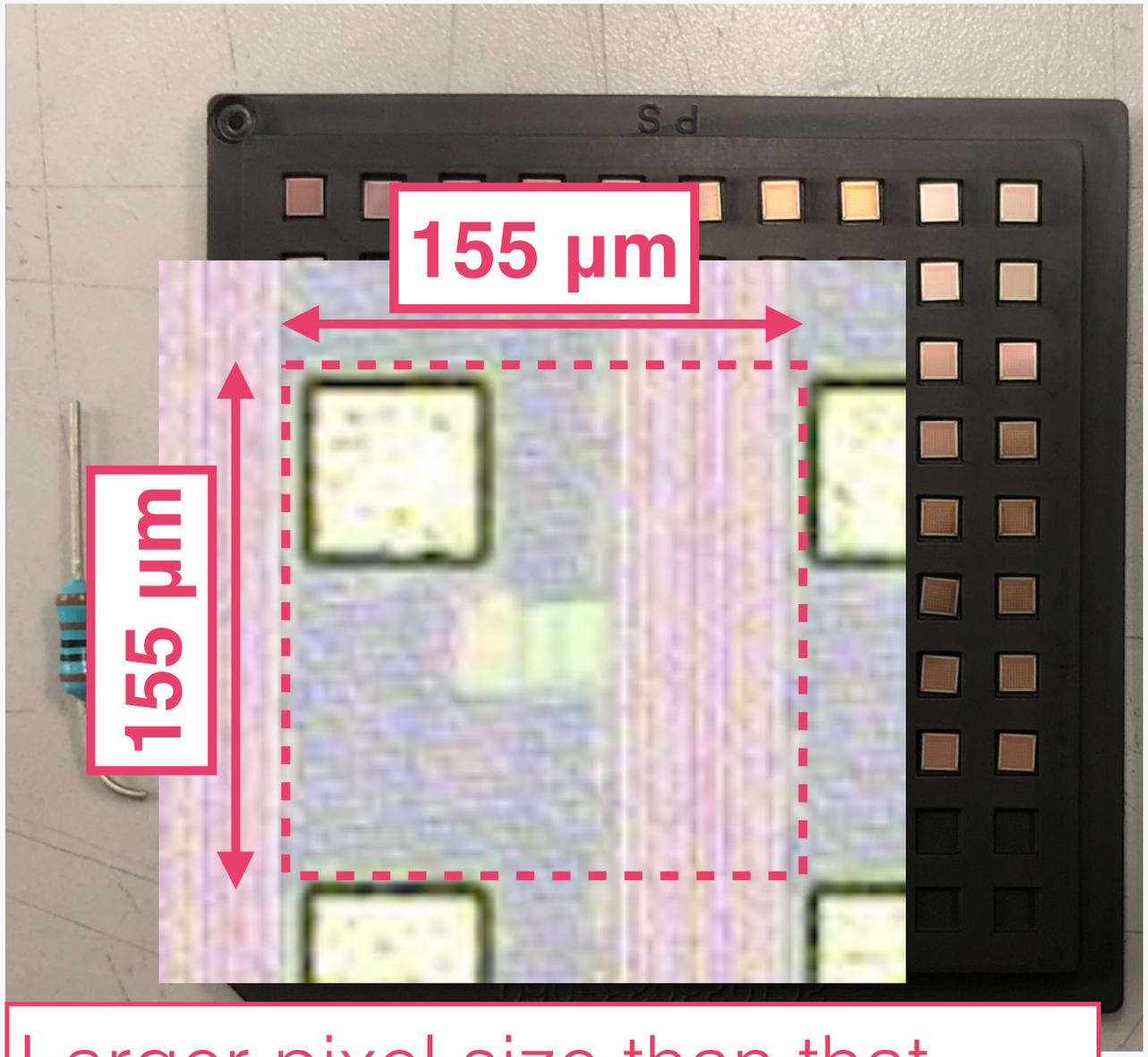
First production finished on Oct. 2022!

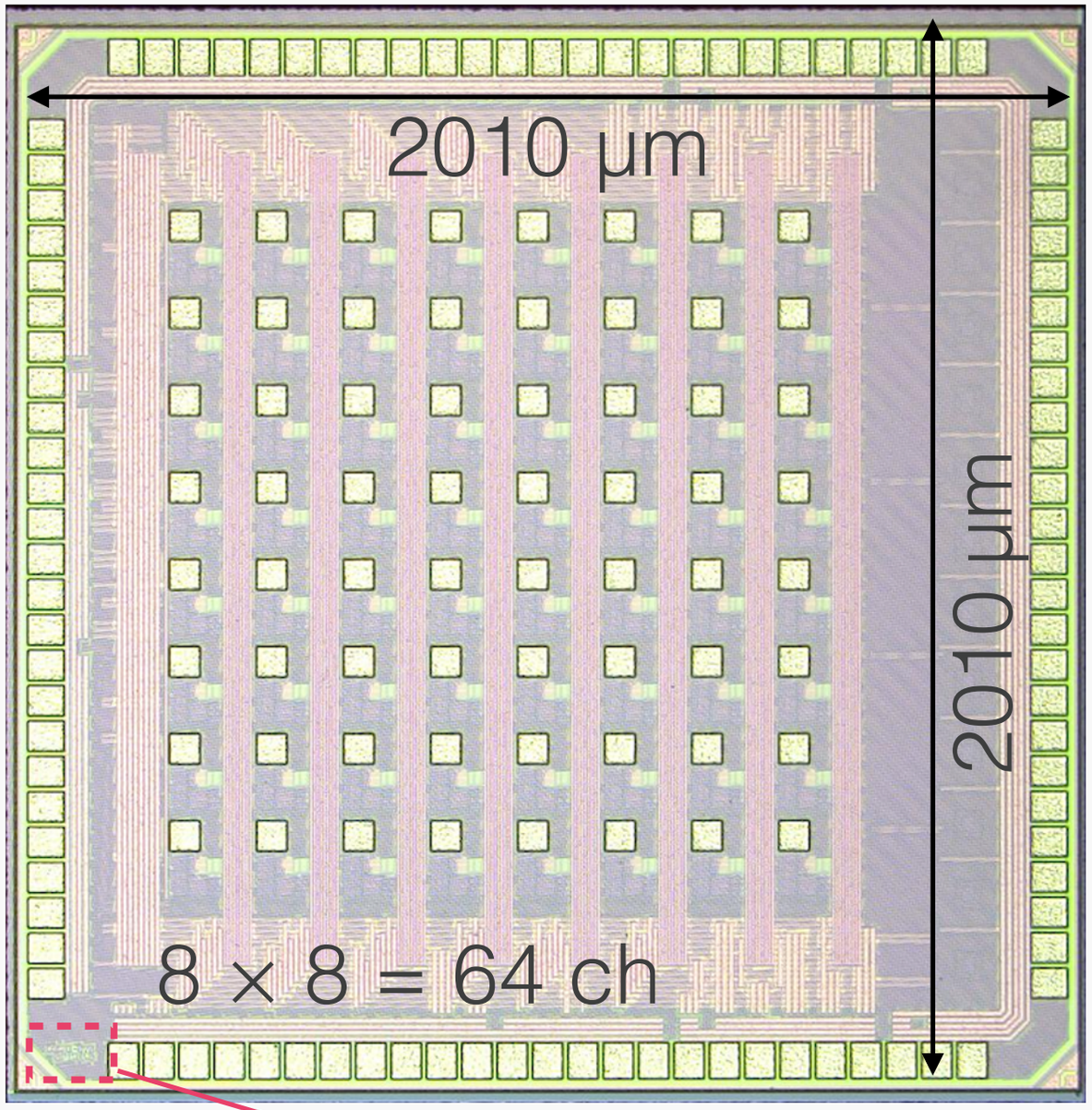


(version mismatched…?)

QPIX NEO v1 prototype

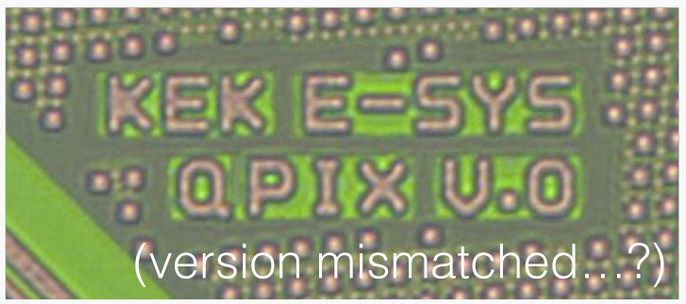
Thanks to the electronics group in KEK





Larger pixel size than that
in initial plan for some reasons

First production finished on Oct. 2022!

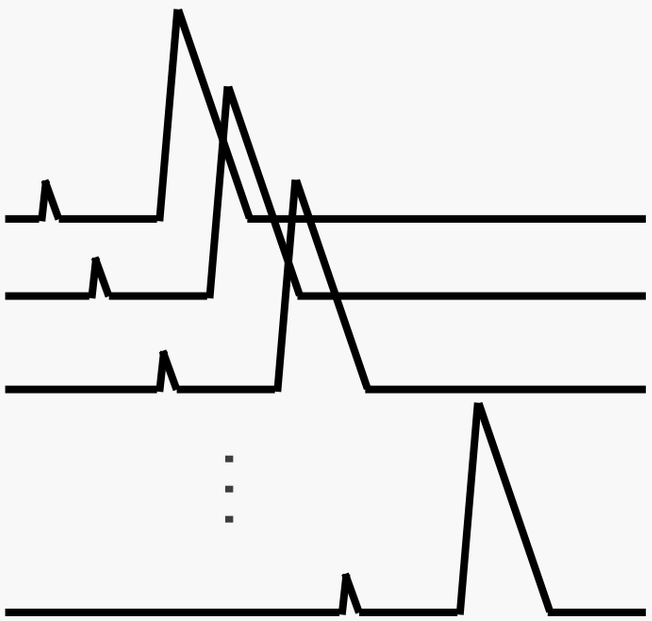


(version mismatched…?)

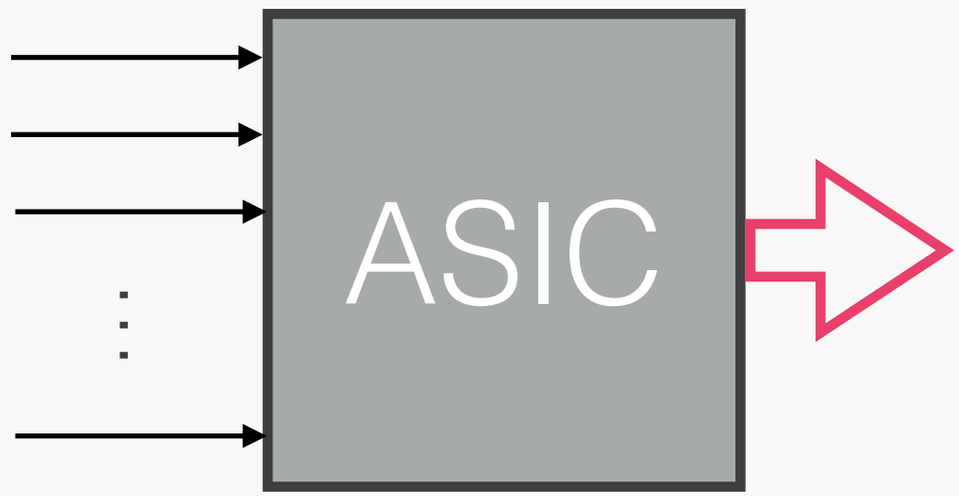
ASIC Specification

- 2 type output format prepared (waveform & ToT) just for tests

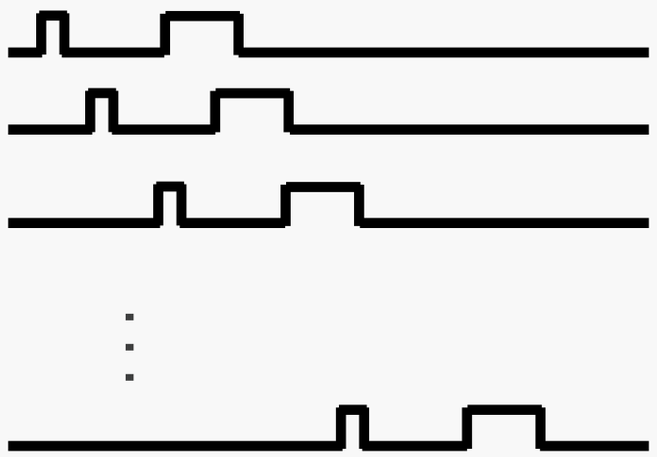
  ➡ ADC: main plan, ToT + time: backup plan



Analog pulses



ADC waveform

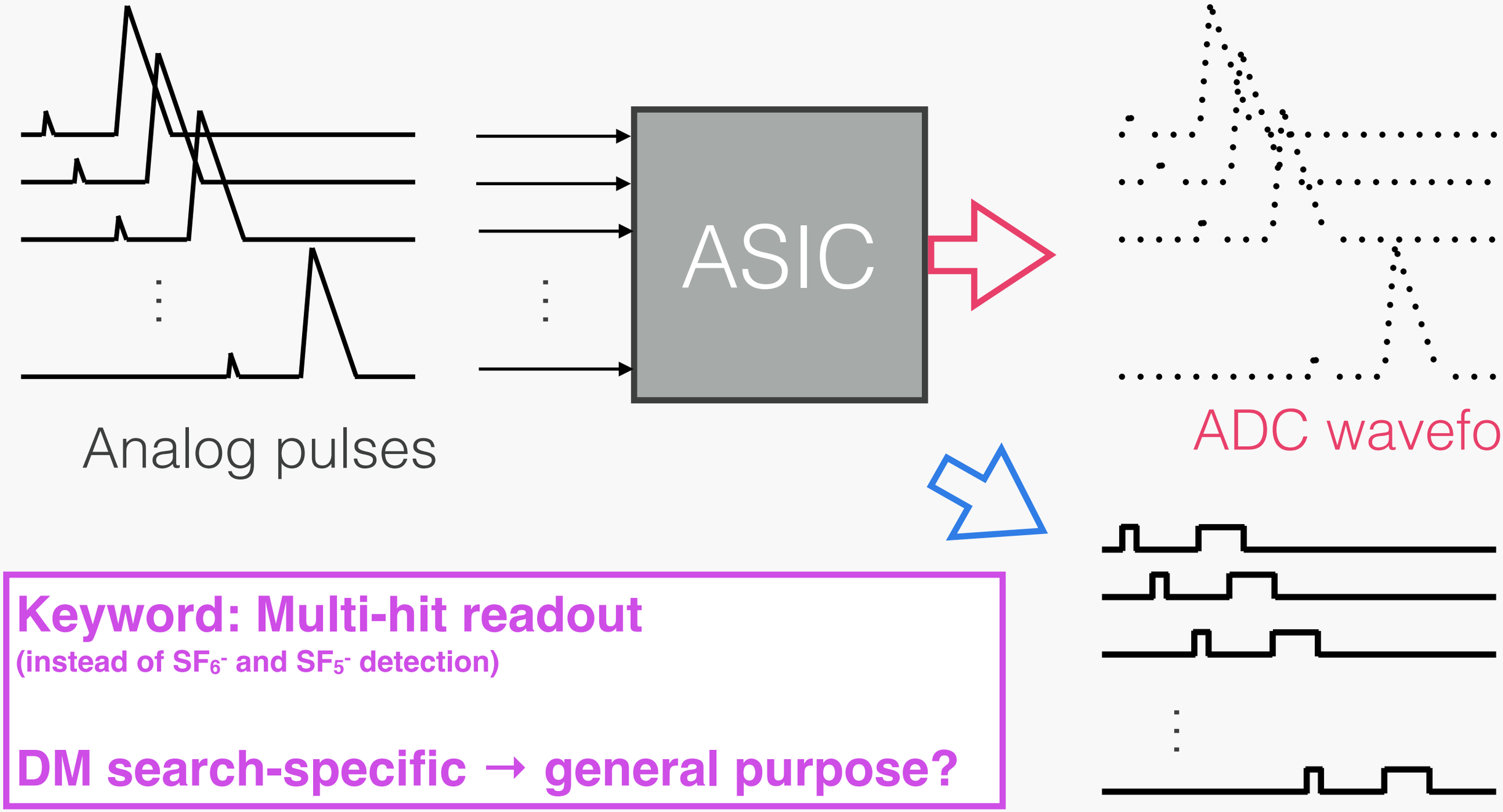


ToT + time (max 4 hits)

ASIC Specification

- 2 type output format prepared (waveform & ToT) just for tests

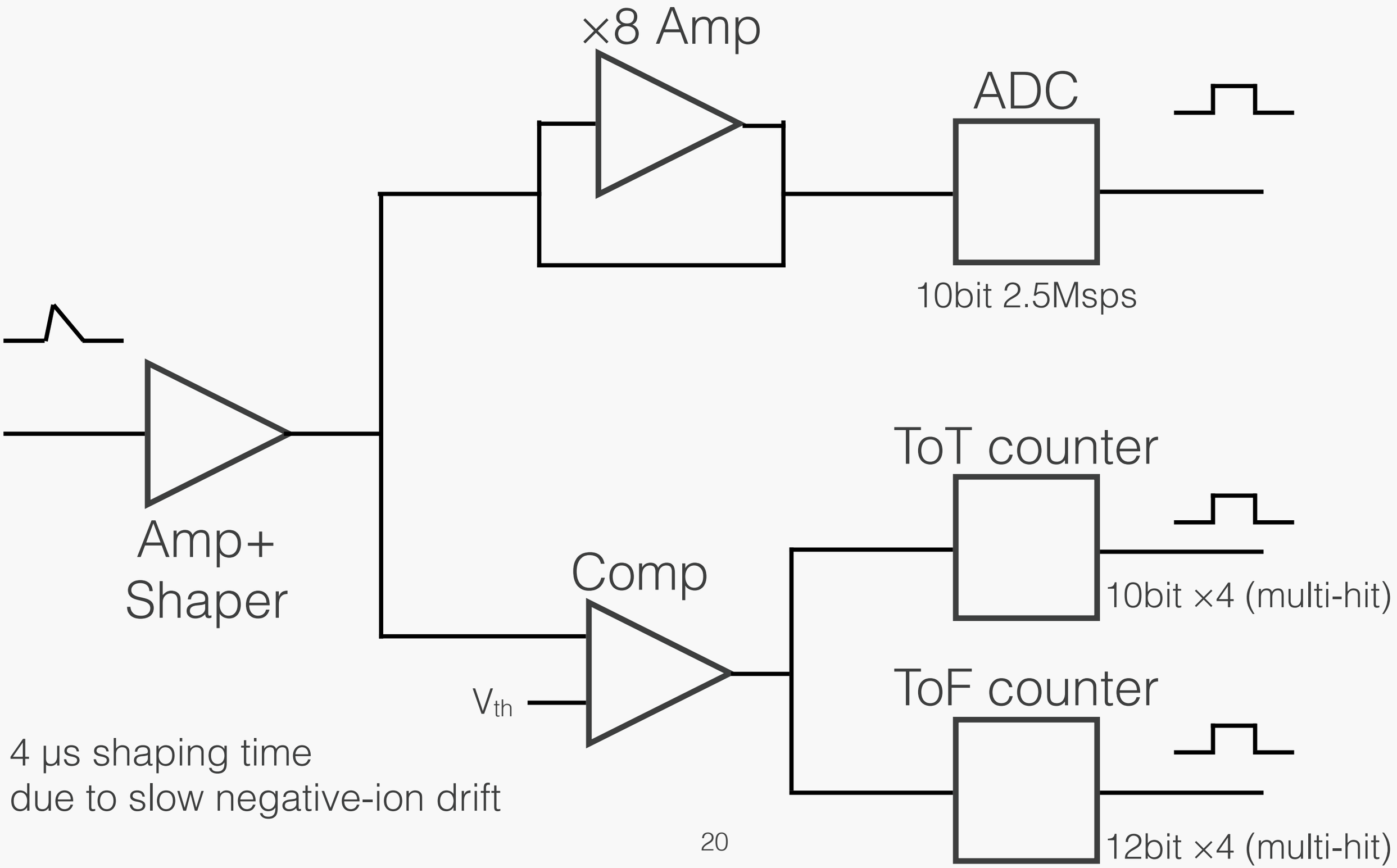
  ➡ ADC: main plan, ToT + time: backup plan



Keyword: Multi-hit readout
(instead of SF_6^- and SF_5^- detection)

DM search-specific → general purpose?

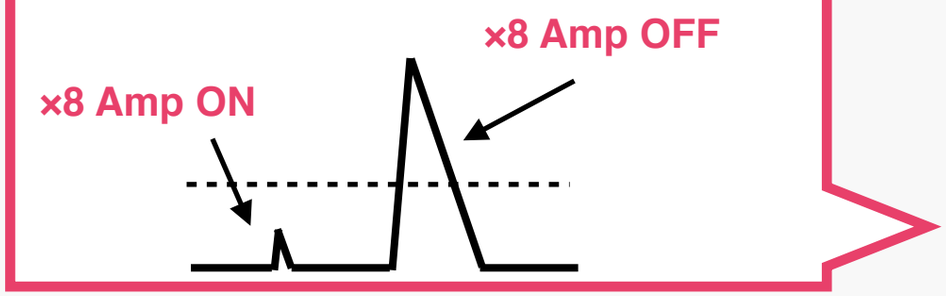
c.f. Eqivalent circuit for each channel



4 μs shaping time
due to slow negative-ion drift

c.f. Eqivalent circuit for each channel

Achieve large dynamic range



×8 Amp

ADC

10bit 2.5Msps

Amp+
Shaper

Comp

V_{th}

ToT counter

10bit ×4 (multi-hit)

ToF counter

12bit ×4 (multi-hit)

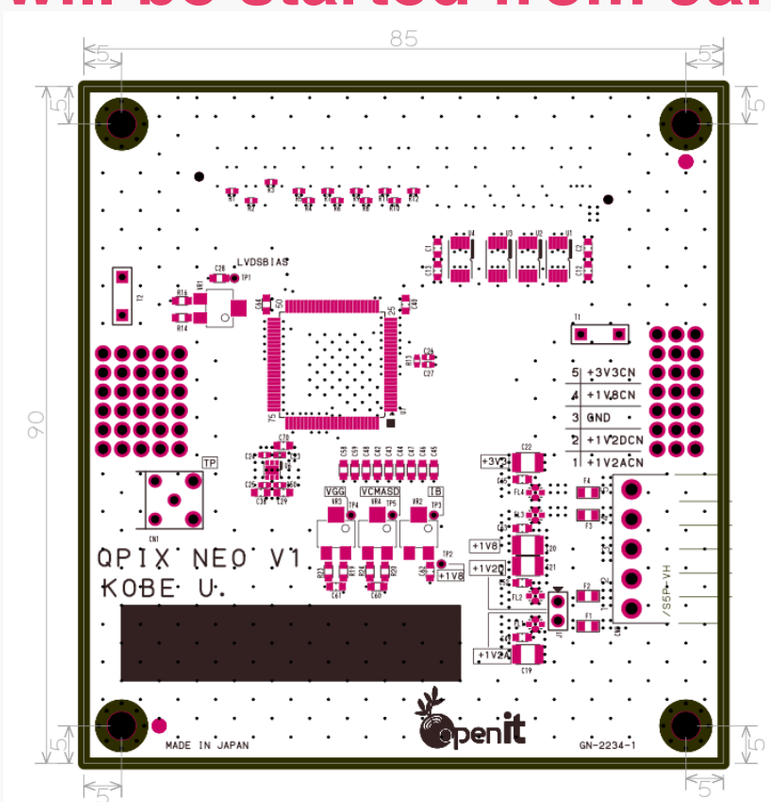
4 μs shaping time
due to slow negative-ion drift

PCB development

- First prototype electronics production ongoing
  - ➡ w/o chamber, electronics only
  - ➡ QPIX NEO is packaged
- ASIC board + ZYNQ evaluation board
  - ➡ **ASIC evaluation will be started from Jan. 2023. Stay tuned!**

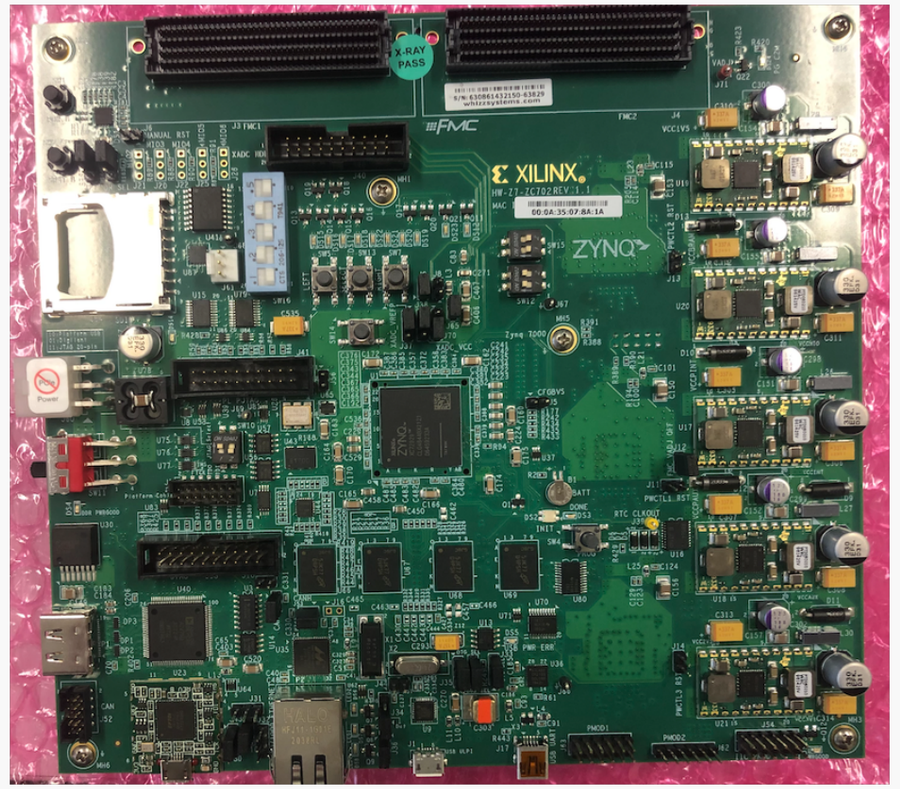
Packaged QPIX NEO

+



ASIC board
(will obtain on Jan. 2023)

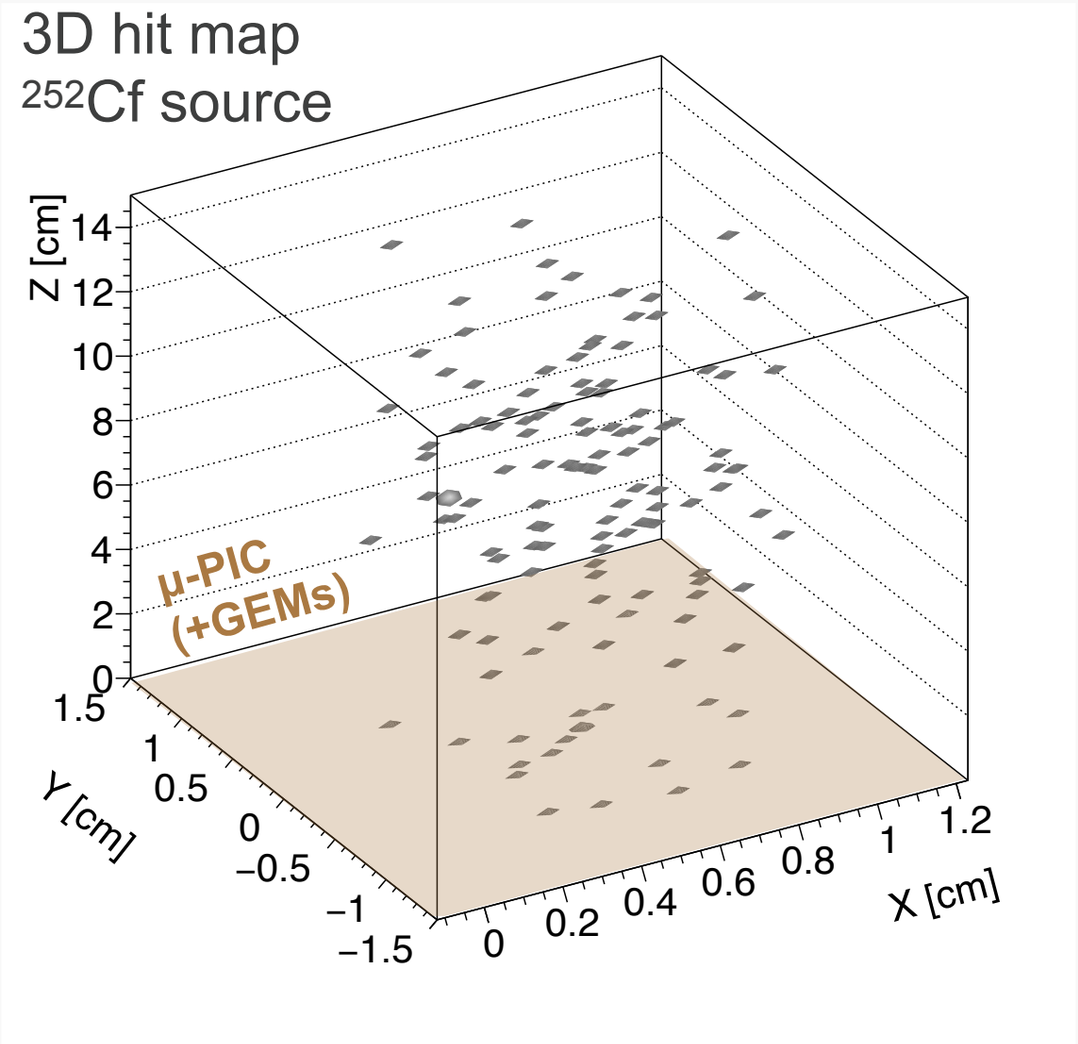
+

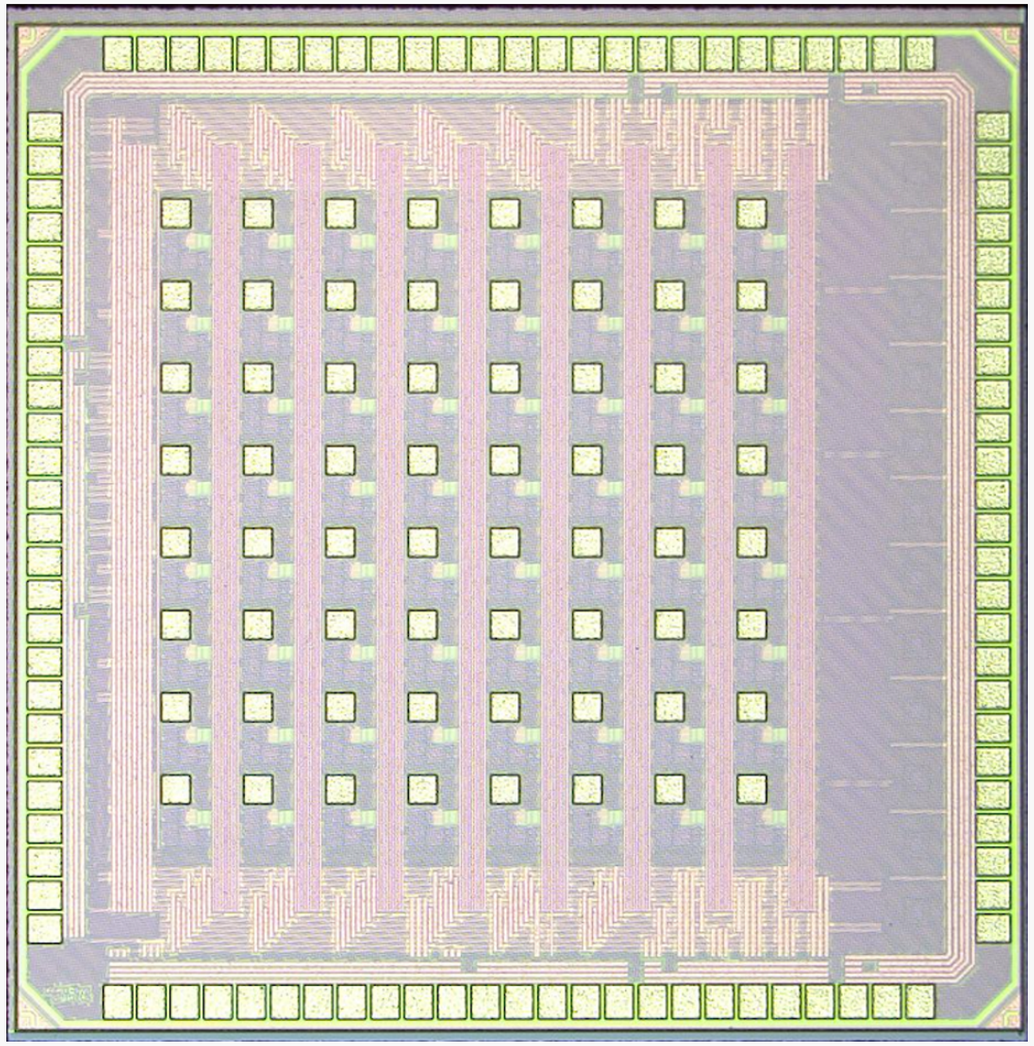


Xilinx ZC702 (ZYNQ board)

Conclusion

- Negative-ion TPC + MPGD has capability to improve sensitivity for direction-sensitive dark matter search
- First absolute 3D position reconstruction successfully worked using μ-PIC
- Development of high granularity readout electronics is started



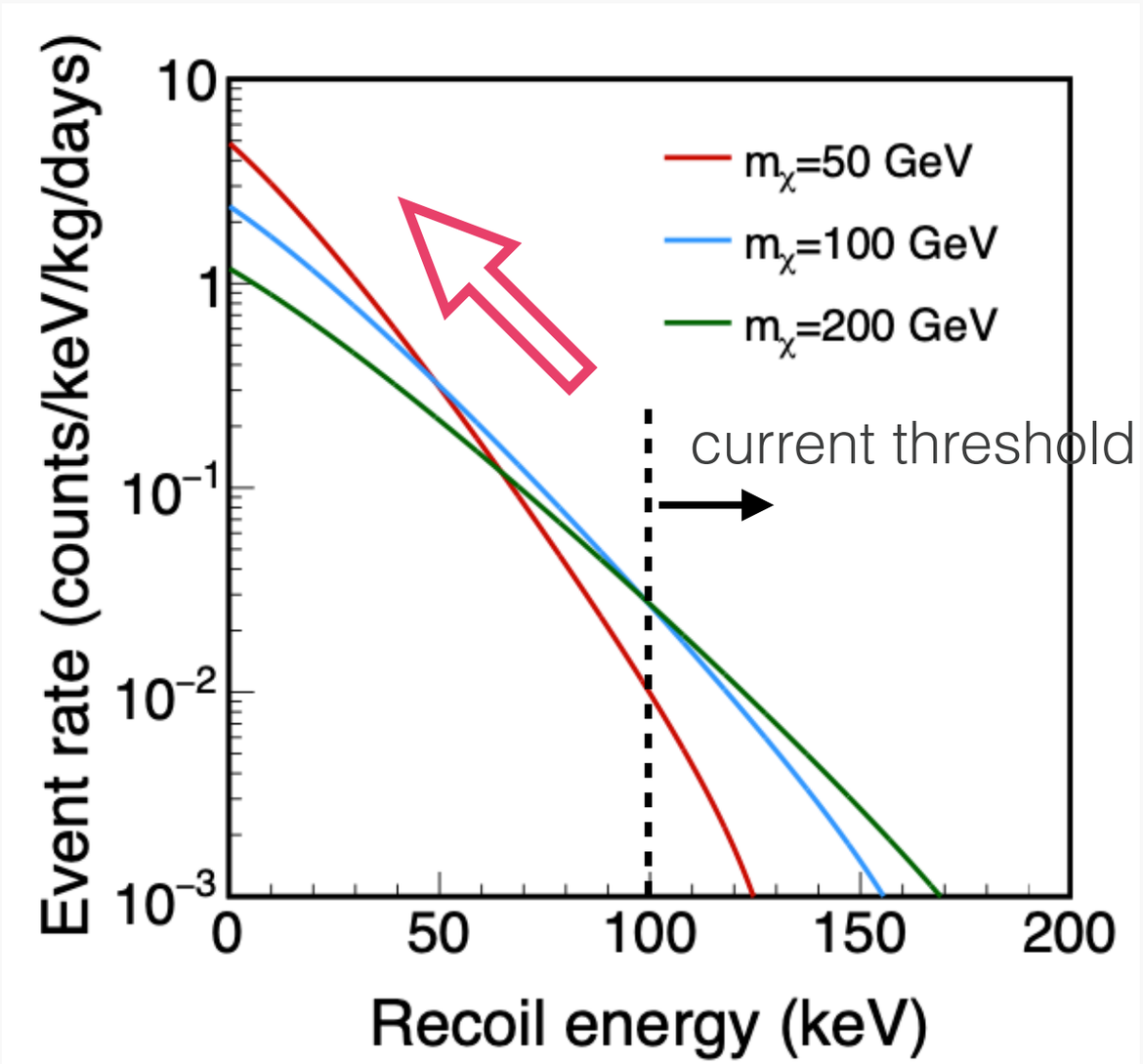


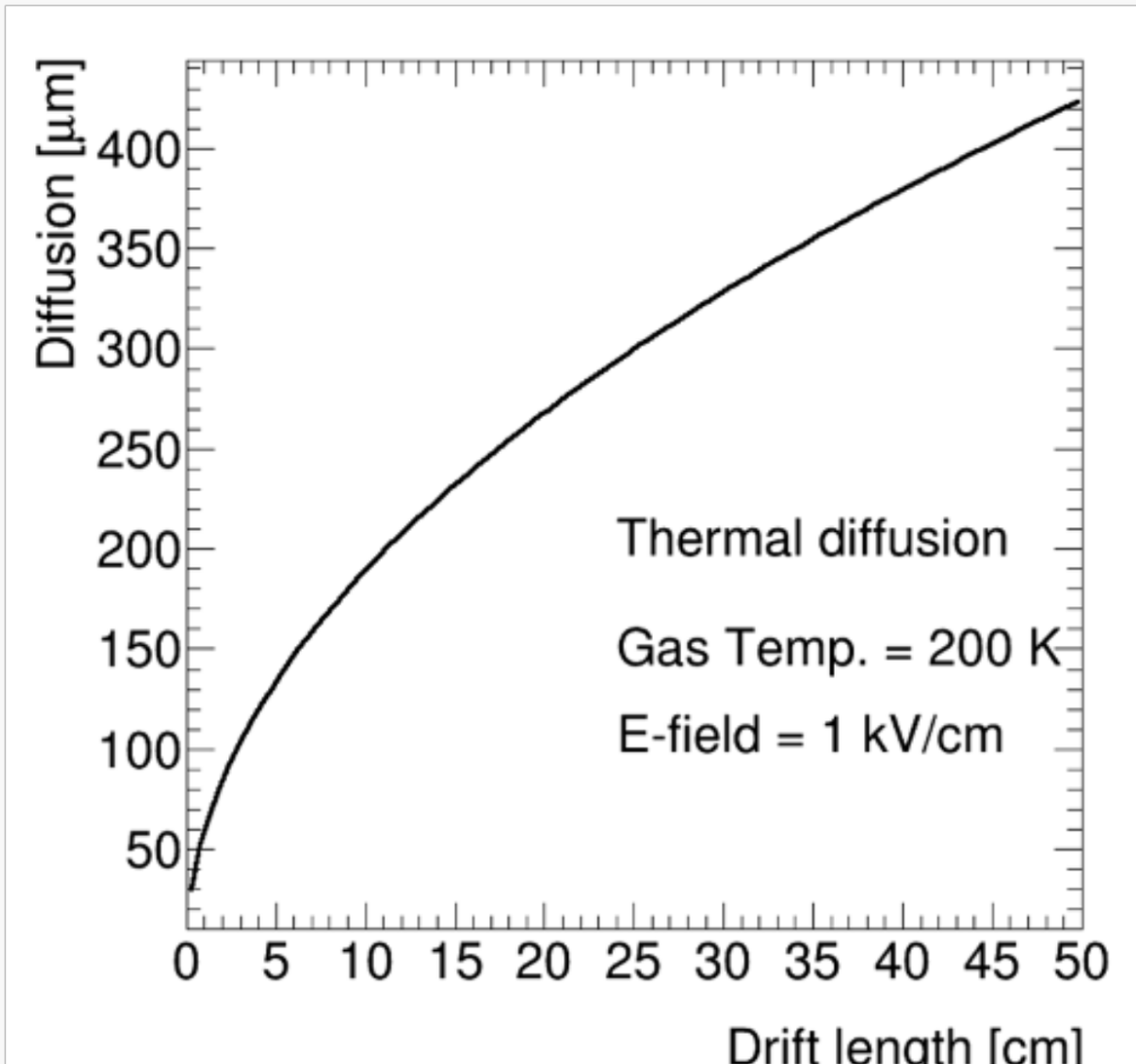
Thank you!

Backup

Drift diffusion

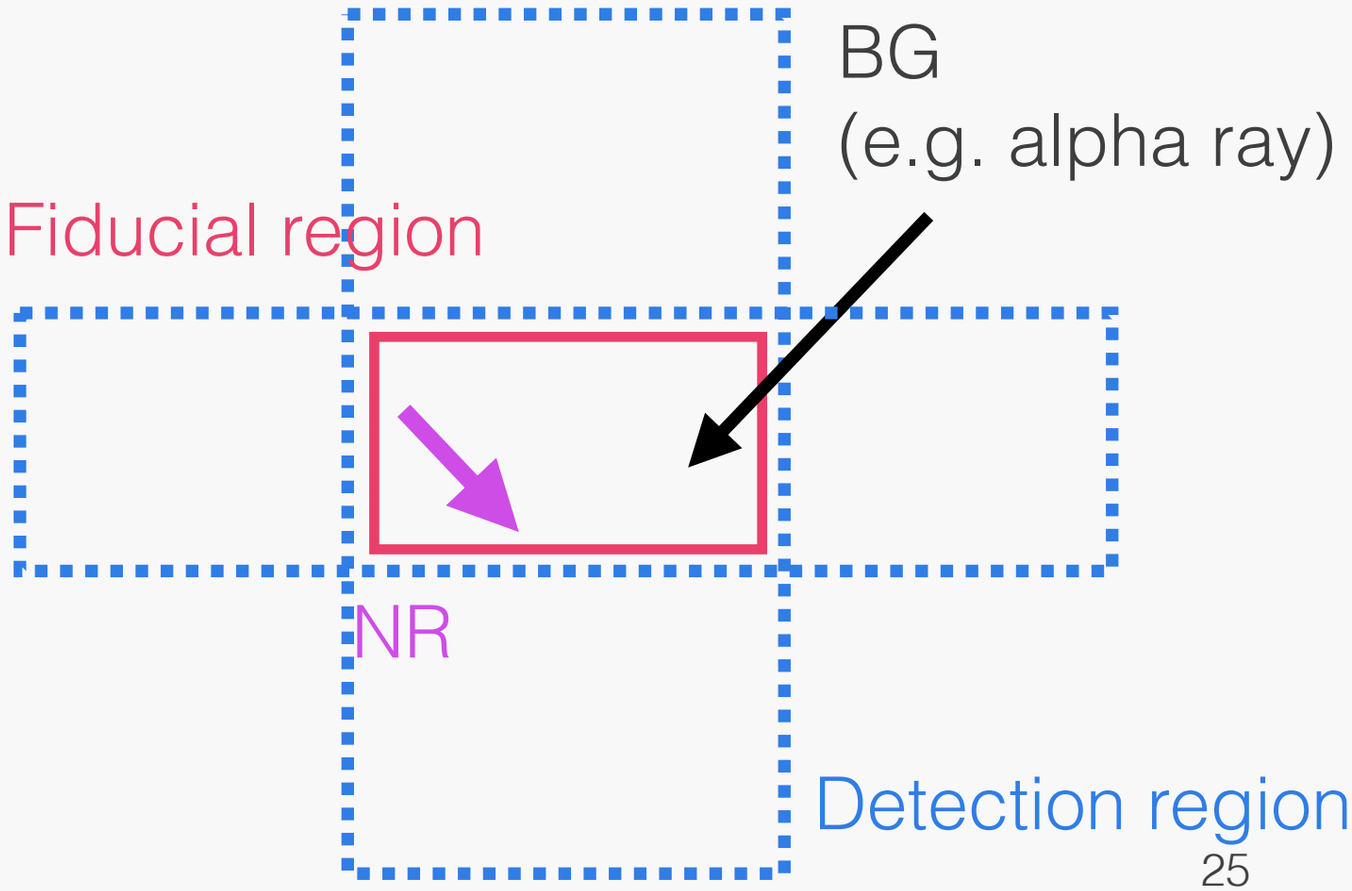
- In case of electron drifts, difficult to reconstruct <1 mm short tracks due to drift diffusion
  - ➡ Limited by readout pitch (400 μm for our μ-PIC)
- Negative ion drifts slowly and with small diffusion, which enable to explore low mass DM search
- **Need to readout with high granularity**

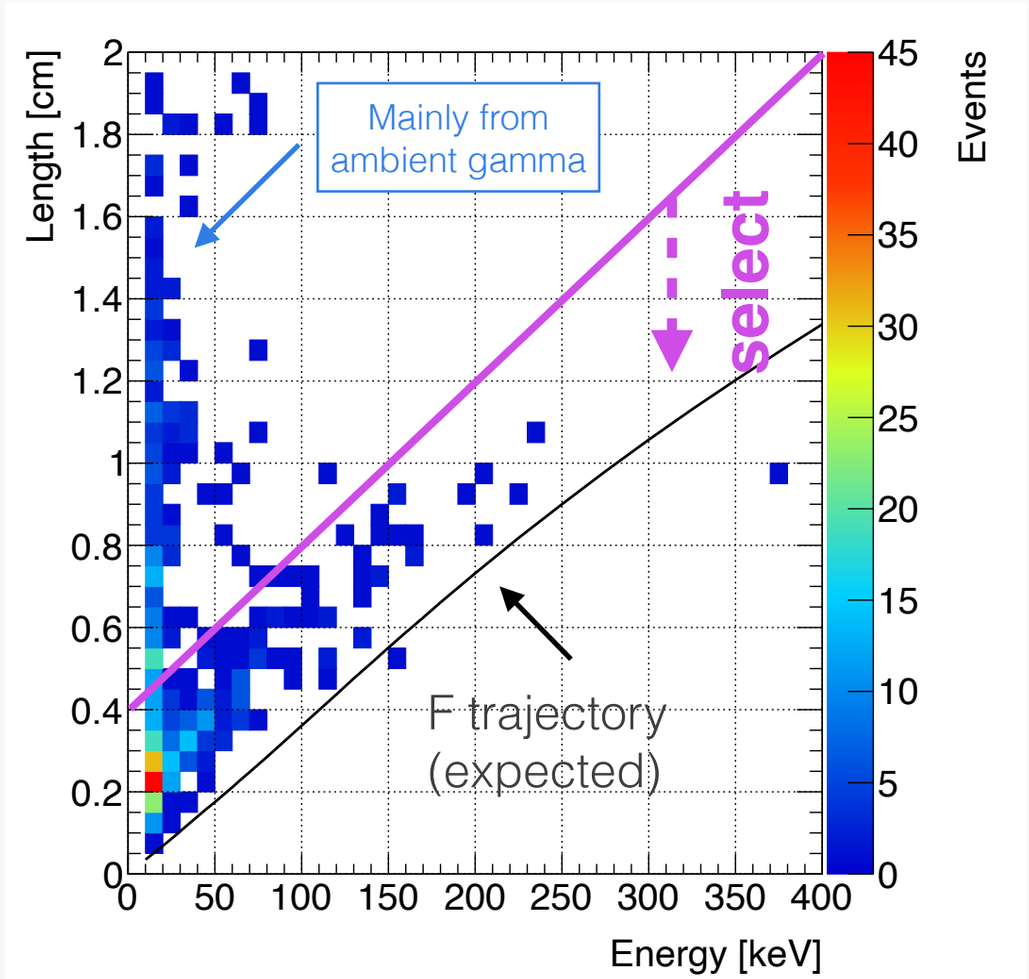




Event selection

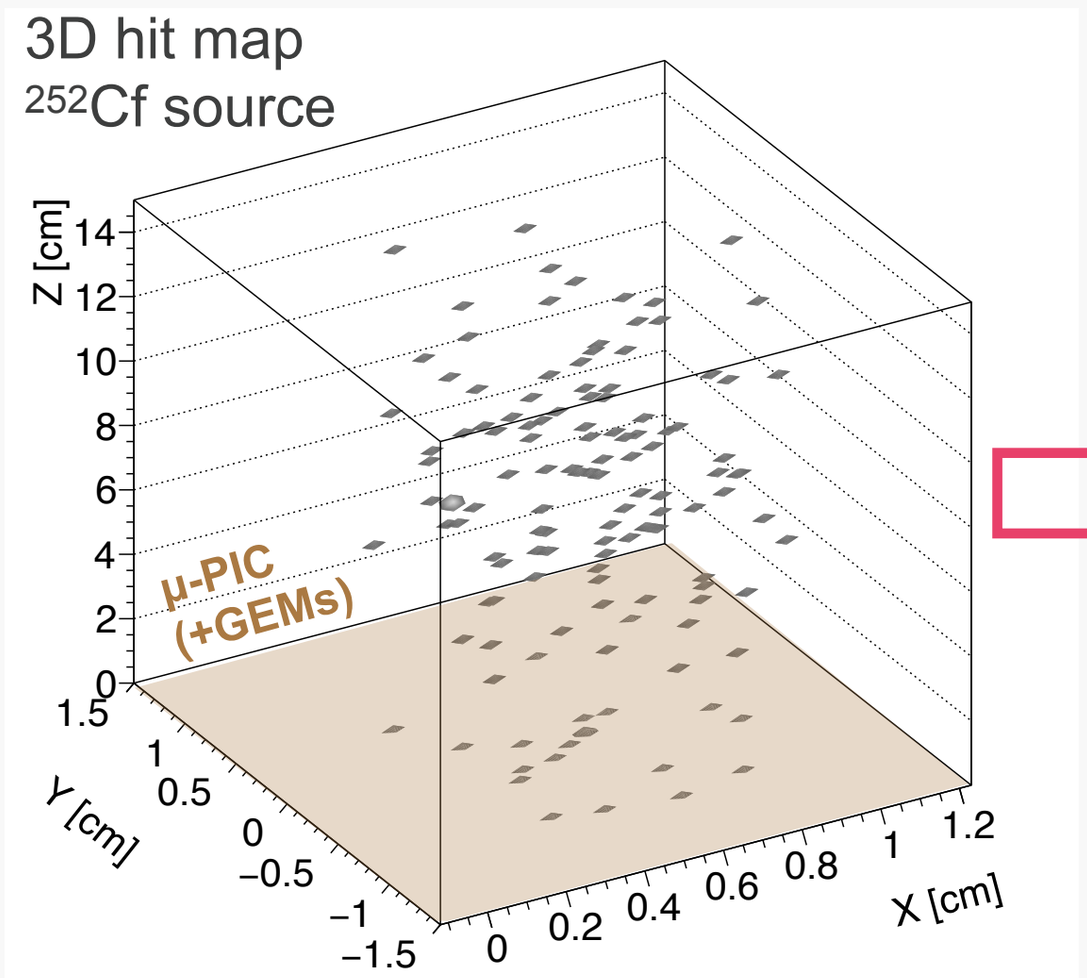
- Events which have no signals at the corners are selected
  - ➡ for alpha ray BG rejection
- Length - Energy cut is applied
  - ➡ for ambient gamma BG rejection

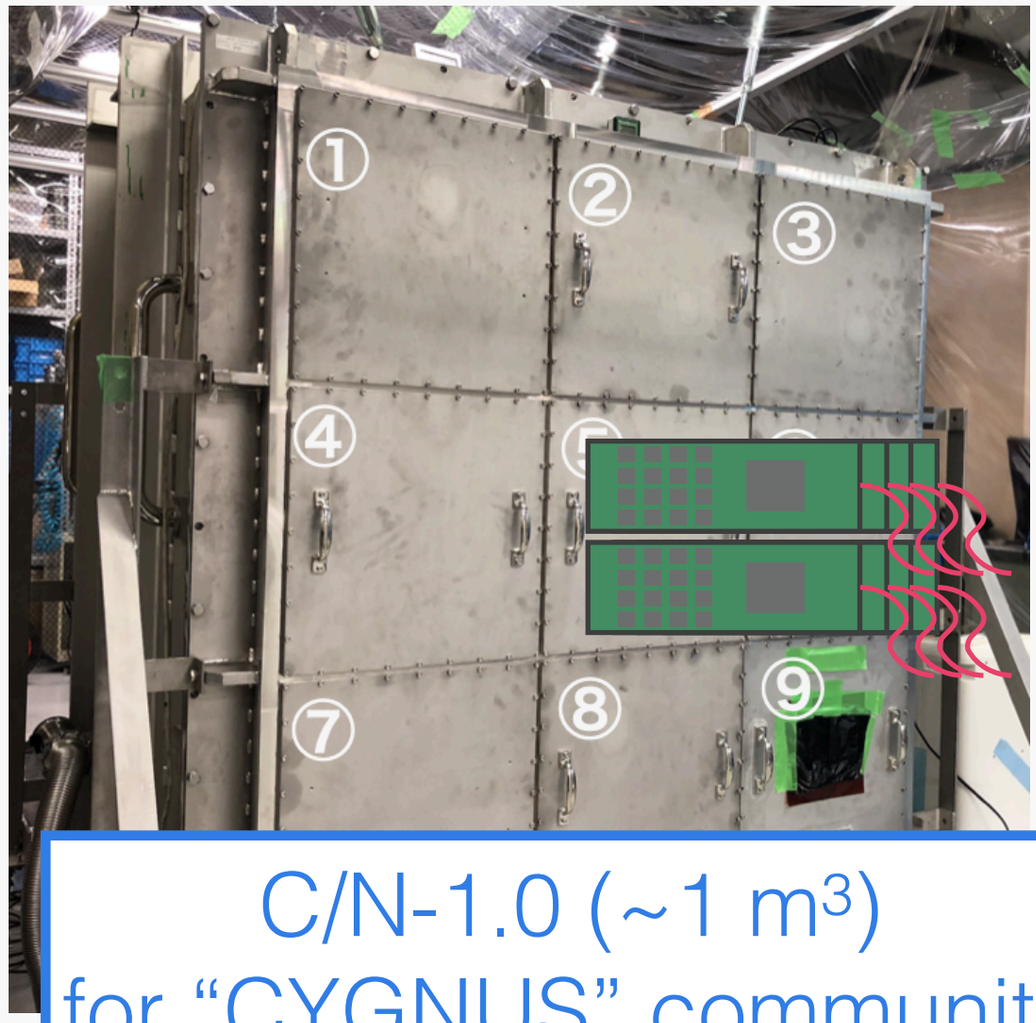




Future plans

- For directional dark matter searches, we need to …
  - ➡ measure angular resolution
  - ➡ increase the number of readout channels → electronics updating
  - ➡ increase detection volume → Large scale (~1 m^3) commissioning

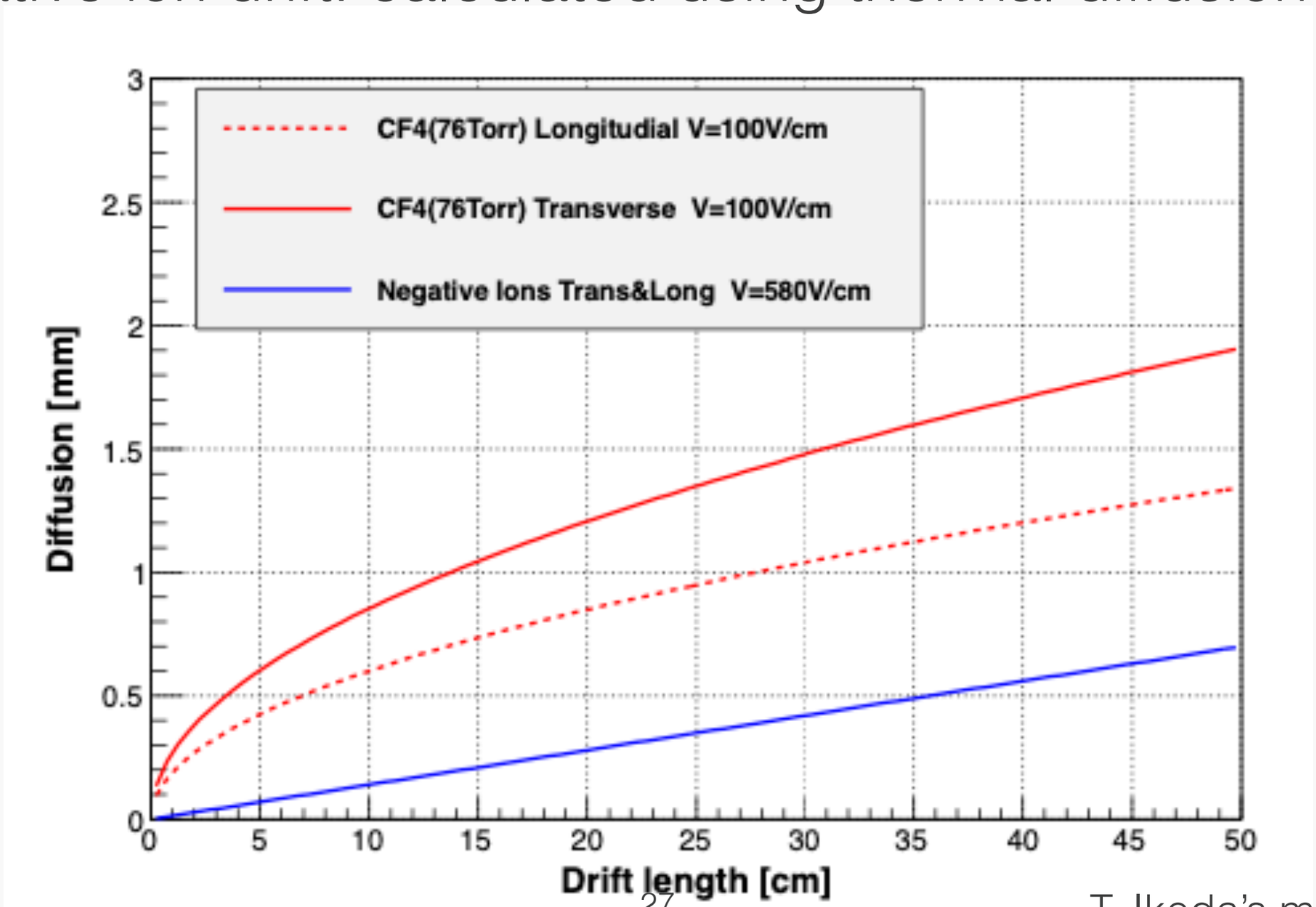




C/N-1.0 (~1 m^3)
for “CYGNUS” community

Diffusion of electron drifts

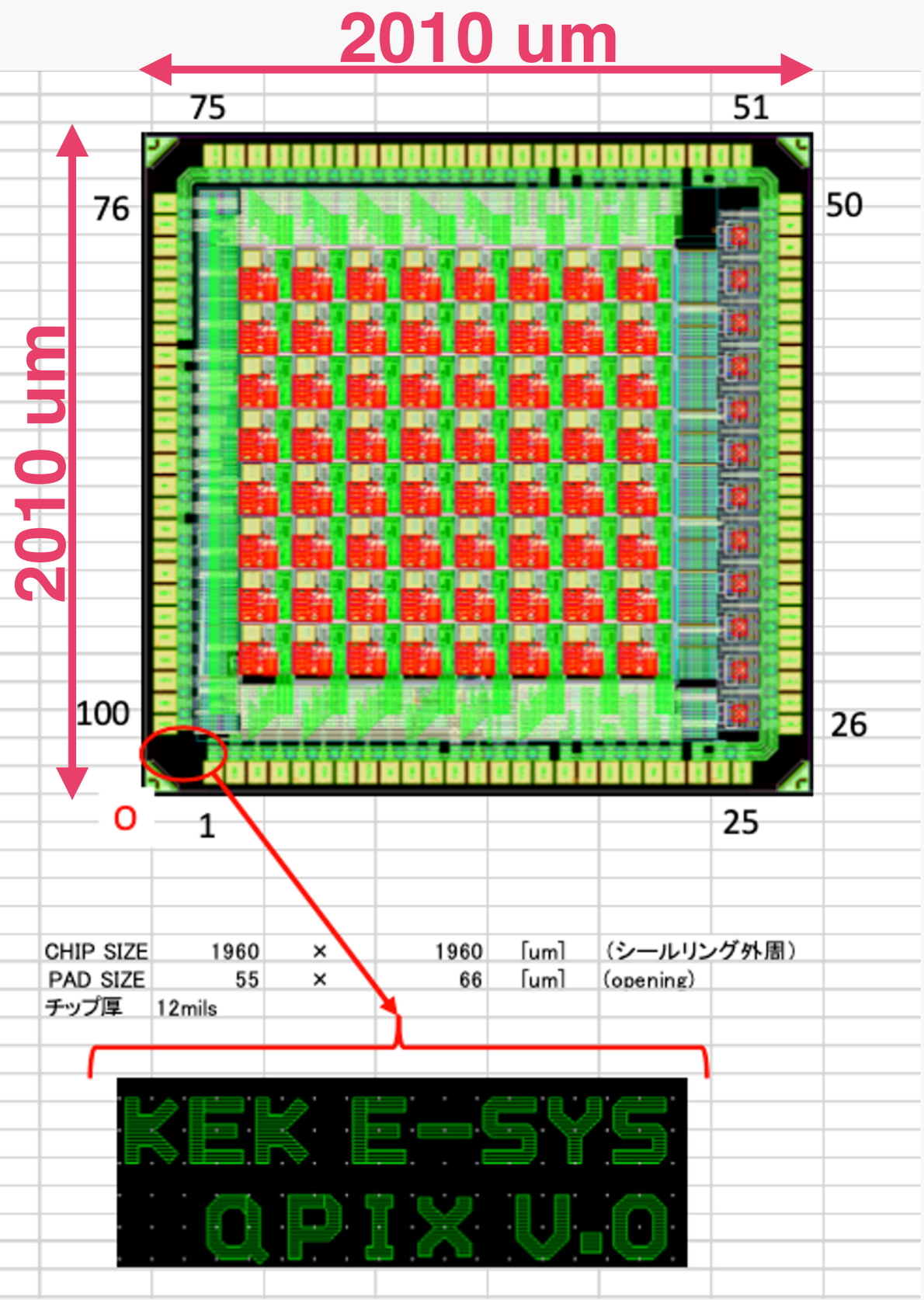
- Electron drift: calculated by MAGBOLZ
- Negative ion drift: calculated using thermal diffusion model



T. Ikeda's master thesis

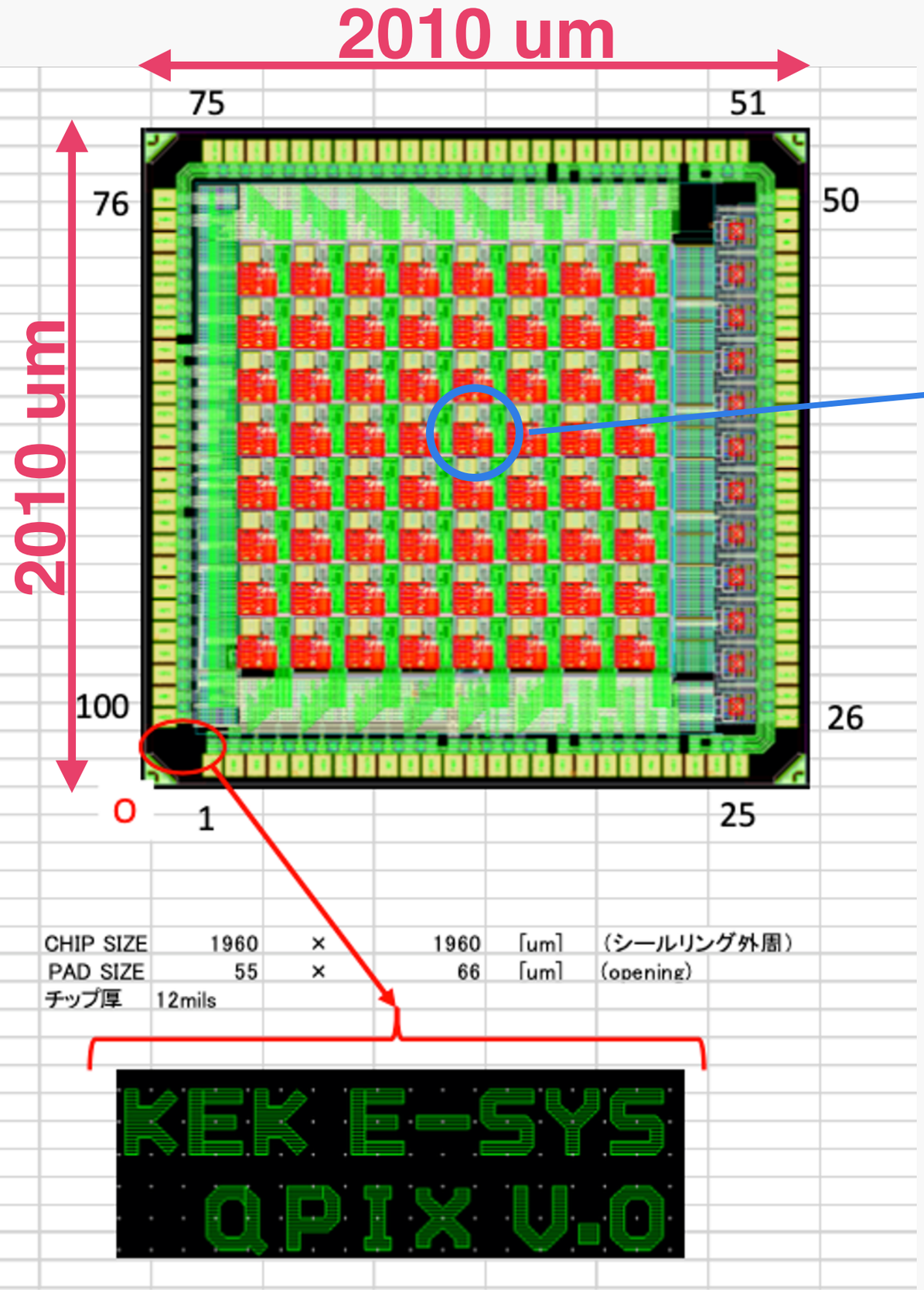
ASIC設計図

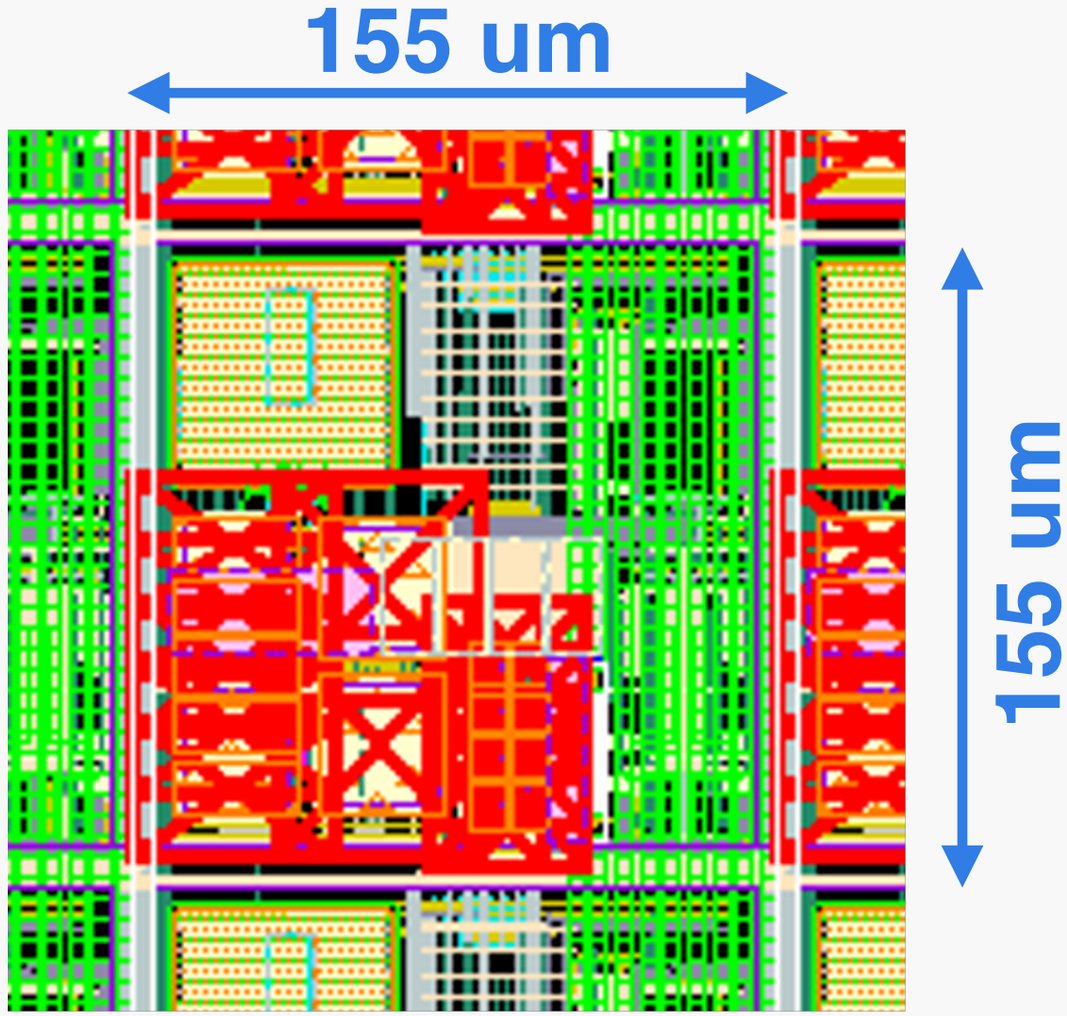
M. Miyahara (KEK)



ASIC設計図

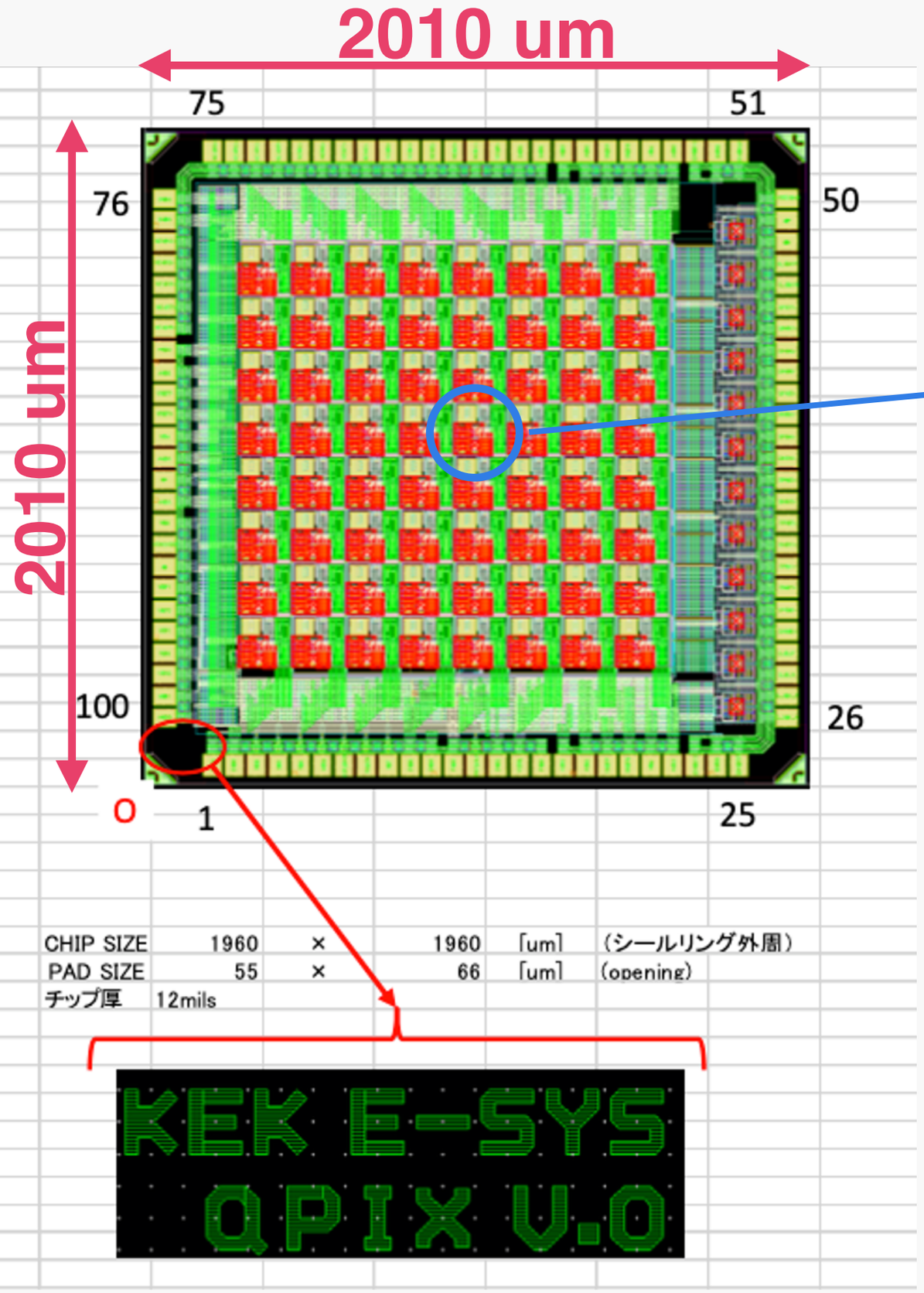
M. Miyahara (KEK)

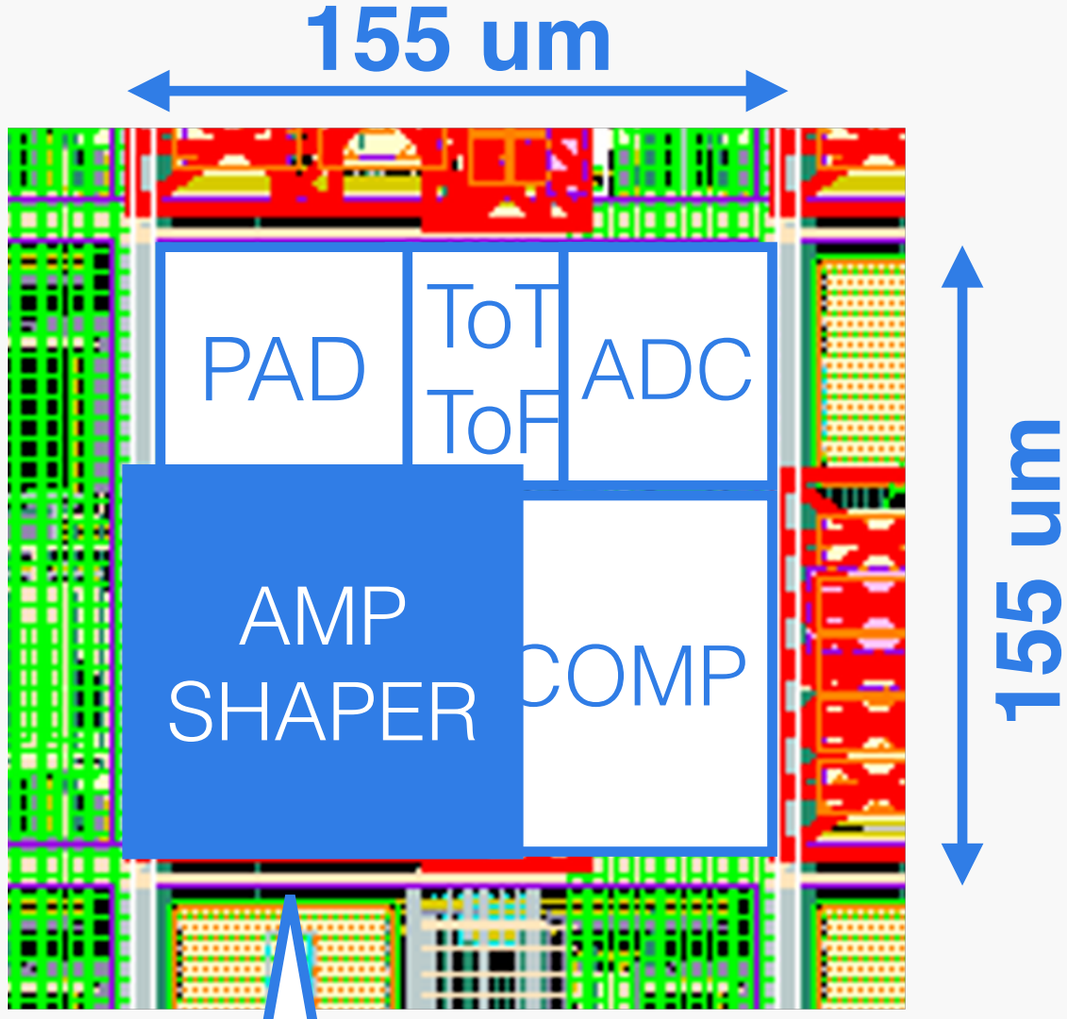




ASIC設計図

M. Miyahara (KEK)





Large analog circuit due to the large dynamic range (requires large capacitor)