Neutrinoless Double-Beta Decay
and
Xe Gas TPC Development

S. Obara
for the AXEL Collaboration
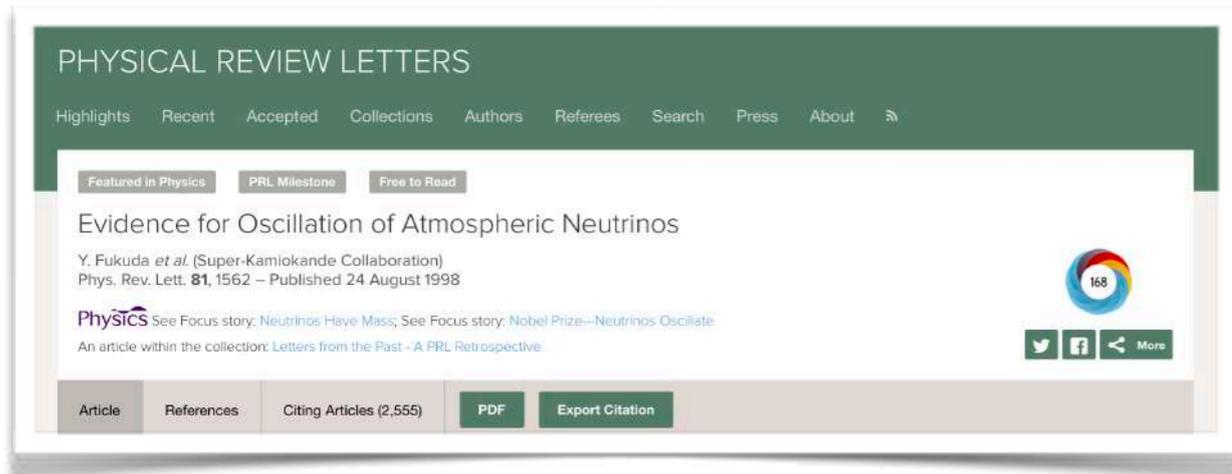
Outline

- INTRODUCTION;
    - Double-Beta Decay and Majorana Neutrinos
    - Recent 0v2b Search Experiments
    - Importance for Future Detectors

- AXEL EXPERIMENT;
    - Conceptual Design of AXEL
    - Results from Xe Gas 10L size prototype (HP10L)
    - Overview of Recent Study in Xe Gas 180L size prototype (HP180L)
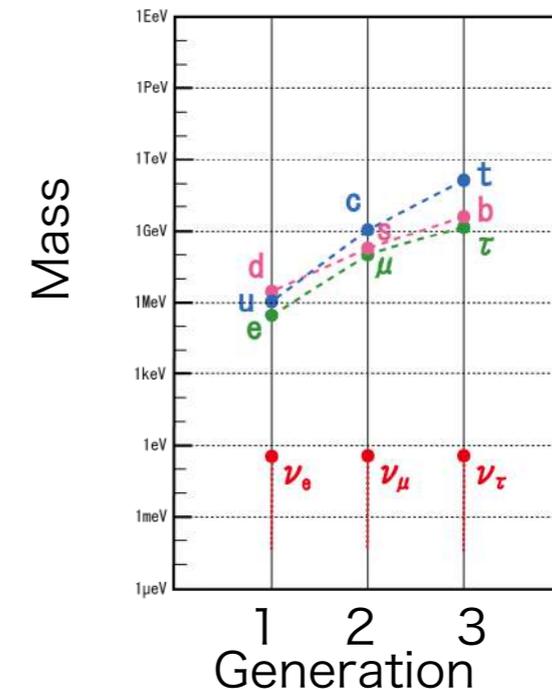
- SUMMARY

Neutrino Mysteries

PHYSICAL REVIEW LETTERS

Evidence for Oscillation of Atmospheric Neutrinos

Y. Fukuda *et al.* (Super-Kamiokande Collaboration)
Phys. Rev. Lett. **81**, 1562 – Published 24 August 1998

We know $m_\nu \neq 0$

via v-oscillation

However, we still have some neutrino mysteries…

- Mass Hierarchy ?

- Majorana ? Dirac ?

- Why so small mass ?

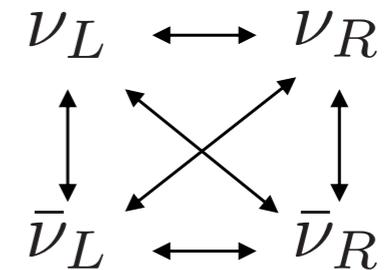and also CP-phase, sterile, absolute mass, …

Neutrino is Dirac ? Majorana ?

Dirac
$\nu \neq \bar{\nu}$

Majorana
$\nu = \bar{\nu}$

$$\nu_L \longleftrightarrow \nu_R$$
$$\bar{\nu}_L \longleftrightarrow \bar{\nu}_R$$

$$\mathcal{L}_{D+M} = m_D \left(\bar{\psi}_L \psi_R + \bar{\psi}_L^c \psi_R^c \right) + \underline{m_L \bar{\psi}_L^c \psi_L^c + m_R \bar{\psi}_R^c \psi_R^c} + h.c.$$
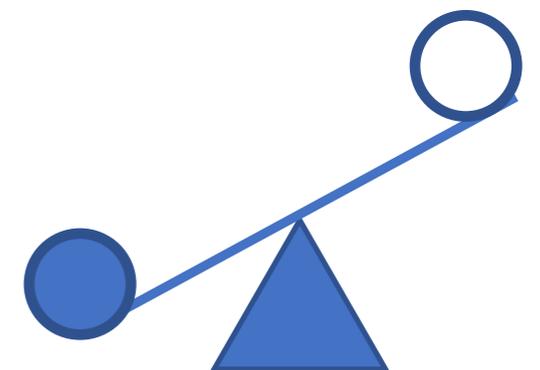
Majorana mass term

In Majorana case,,,

See-Saw mechanism[1-3] explain why so small mass

$$m_\nu \sim \frac{m_D^2}{m_R}$$

$$\mathcal{L}_{D+M} = \begin{pmatrix} \bar{\nu} & \bar{N} \end{pmatrix} \begin{pmatrix} m_\nu & 0 \\ 0 & m_N \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix} \longrightarrow \begin{pmatrix} \bar{\nu} & \bar{N} \end{pmatrix} \begin{pmatrix} \frac{m_D^2}{m_R} & 0 \\ 0 & m_R \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix}$$
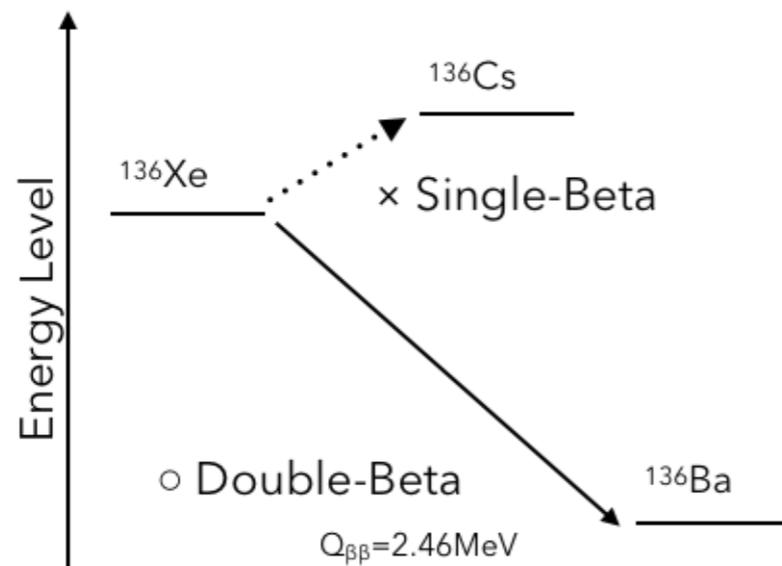
[1] Yanagida 1979,
[2] Gell-Mann, Ramond and Slansky 1979,
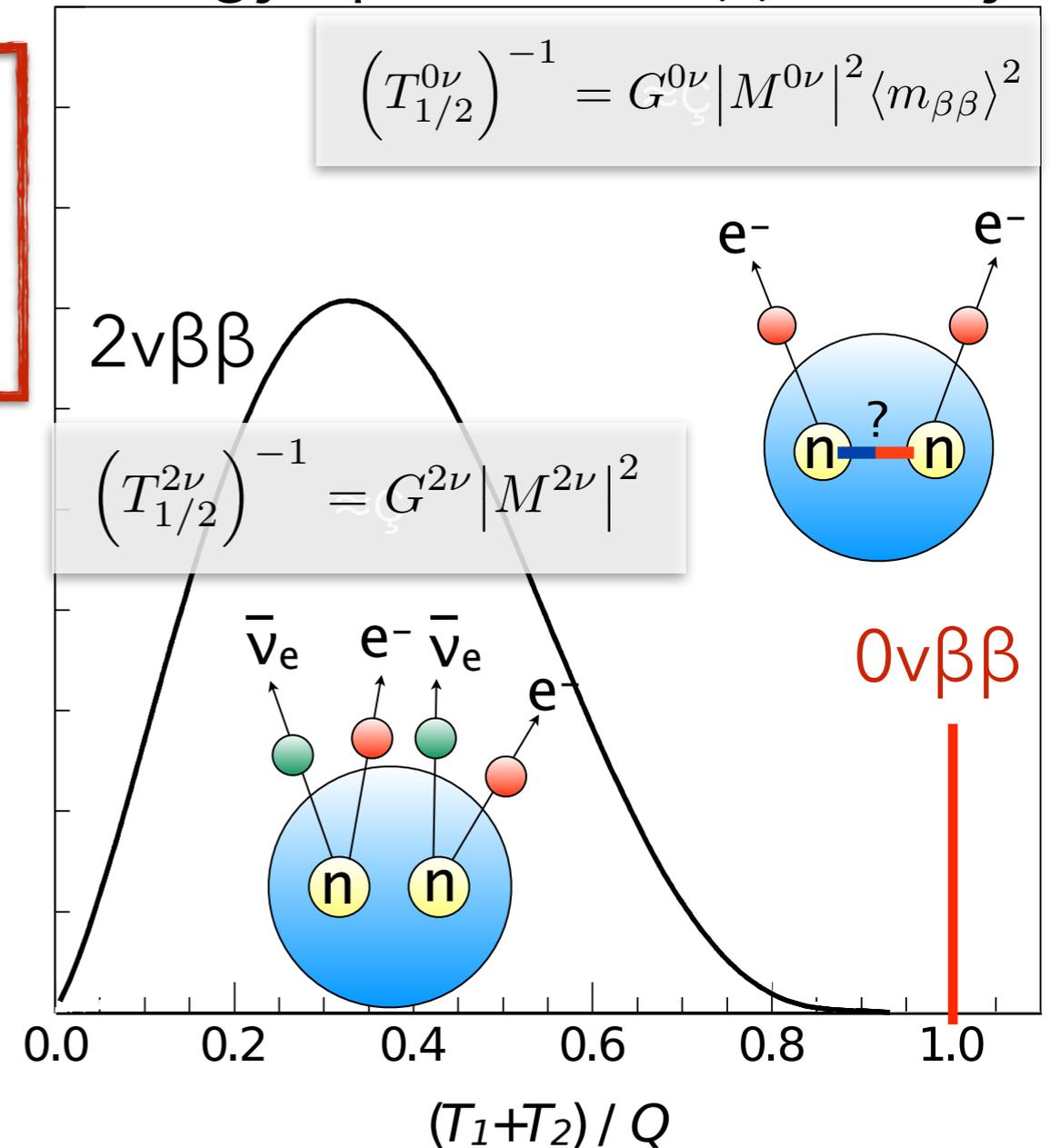[3] Minkowski 1977

What's the double-beta decay ?

Neutrinoless Double-Beta Decay is …

- ・ Two beta-rays only emission
- ・ Monochromatic energy @ Q-value
- ・ Evidence of Majorana Neutrino

For some nuclei, single-beta decay is prohibited
by the energy level
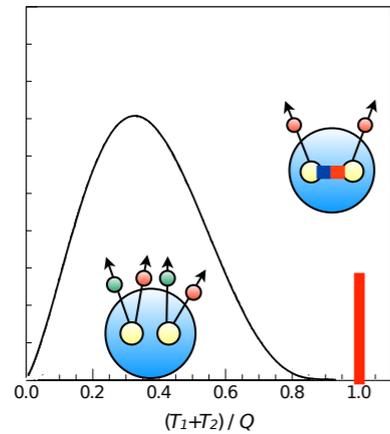but simultaneously double-beta is allowed

Energy spectra for ββ decay

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

$$\left(T_{1/2}^{2\nu}\right)^{-1} = G^{2\nu}\left|M^{2\nu}\right|^2$$

2νββ

0νββ

$\bar{\nu}_e$ e^- $\bar{\nu}_e$ e^-

$(T_1 + T_2) / Q$

Nucl	Q [keV]	Nat. [%]	Cost* [M$/ton]	$T^{2\nu}_{1/2}$ [yr]	Merit 😆	Demerit 😢	Experiments
^{48}Ca	4271	0.187	> 1000	4.4×10^{19}	Largest Q-value	Low NA, Difficult enrich	CANDLES
^{76}Ge	2040	7.7	~80	1.6×10^{21}	Long T2v		GERDA, MAJOARANA, (LEGEND)
^{82}Se	2995	9.2	~120	9.6×10^{19}			NEMO-3, (Super-NEMO)
^{96}Zr	3350	2.8		2.4×10^{19}	Large Q-value		(ZICOS)
^{100}Mo	3034	9.6	~80	7.1×10^{18}	Large Q-value	Short T2v	AMoRE, NEMO-3
^{116}Cd	2802	7.5	~180	2.8×10^{19}			COBRA
^{130}Te	2533	34.5	20	7.0×10^{20}	High NA		CUORE, (SNO+), (CUPID)
^{136}Xe	**2457**	**8.9**	**5~10**	**2.3×10^{21}**	**Long T2v, Easy enrich**		**KamLAND-Zen, PANDAX-III, EXO, NEXT, AXEL, and etc…**
^{150}Nd	3367	5.6	> 300	9.1×10^{18}	Large Q-value	ShortT2v, Difficult enrich	DCBA, NEMO

Recent 0v2b search

Searching the monochromatic ββ signal...

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

[PhaseSpace] [NME] [EffectiveMass]

$$\langle m_{\beta\beta}\rangle = \left|\left|U_{e1}^L\right|^2 m_1 + \left|U_{e2}^L\right|^2 m_2 e^{i\phi_2} + \left|U_{e3}^L\right|^2 m_3 e^{i\phi_3}\right|$$

taken from PDG2019

KamLAND-Zen (Liq.Scintillator)

$T_{1/2} > 1.07 \times 10^{26}$ yr (90%C.L.)
$|m_{\beta\beta}| < 61\text{-}165$ meV (90%C.L.)
Thanks to their
large volume and **low radioactivity**

GERDA (Germanium)

$T_{1/2} > 8.0 \times 10^{25}$ yr (90%C.L.)
$|m_{\beta\beta}| < 120\text{-}260$ meV (90%C.L.)
Thanks to their
good energy resolution and **background-free in ROI**

Neutrino Hierarchy is Normal ? or Inverted ?

Sear

We have to explore 0.01~0.001 meV region !!

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

QD

KamLAND-Zen

IH

0.01

0.001

NH

$|\langle m\rangle|$ [eV]

10^{-4}

0.0001   0.001   0.01   0.1   1

m_{MIN} [eV]

PDG2019

KamLAND-Zen   (Liq.Scintillator)

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for Future 0v2b Detectors

Gaseous Xenon TPC has three advantages !!

High-Pressure Gas
- 90% enrich ^{136}Xe
- Smaller than Super-K even if 1-ton Xe

Xenon Gas
- Small W-value
- Electroluminescence process

Tracking
- Identify two-electrons

Large Mass

Good Energy Resolution

BG-Free Technique

AXEL

(**A X**enon **E**lectro**L**uminescence detector)

Cockcroft-Walton
Voltage multiplier
for HV supply

ELCC
for energy & tracking

E

Drift Electron

Scintillation

- ^{136}Xe for 0ν2β
- 1ton xenon gas
- 6-8 bar

VUV PMTs
for T$_0$ signal

Drift Field Cage

AXEL

(**A X**enon **E**lectro**L**uminescence detector)

Pure Xenon Gas TPC

- ○ ^{136}Xe = 0v2b nuclei
- ○ Ionization W = 21eV
- ✗ Easy to discharge

Energy resolution of the Xenon Ion chamber
A. Bolotnikov, B. Ramsey Nucl. Instr. And Meth. A396(1997) 360

AXEL (**A X**enon **E**lectro**L**uminescence detector)

T$_0$ Timing

Tracking Plane

Drift Field Cage

^{136}Xe~1ton

γ

e

scintillation

E

PMT

ELCC

Scintillation & PMTs

- λ_{Xe} ~ 178 nm
- Use VUV-sensitive & 1MPa tolerable PMTs by Hamamatsu Photonics K.K.

- Obtain T$_0$ of 0v2b signal
- → Used to reconstruct Z position from ionization signal

AXEL   (**A X**enon **E**lectro**L**uminescence detector)

Use ***ElectroLuminescence Process***
for the ionization electrons tracking

$^{136}Xe \sim 1ton$

PMT

γ

e

ELCC

E

Drift Field Cage

$\vec{E}$

e   Xe   Xe   Xe

EL photon

→ Linear Amplification
→ Good Energy Resolution

cf1; NEXT also uses EL-process but with mesh plane
cf2; PandaX-III uses MM for tracking readout

ELCC (**E**lectroluminescence **L**ight **C**ollection **C**ell)

Cell-Type Tracking Plane

e⁻

10mm-pitch

- Drift anode electrode
- PTFE w/ holes
- Mesh electrode
- MPPC (photon sensor) array

EL area
(~2.5kV/cm/bar)

Drift area
(~0.1kV/cm/bar)

MPPC

MPPC

MPPC

e⁻

e⁻

e⁻

e⁻

E_{EL}

E_{Drift}

- Collect the drift electrons into cells
- Linear Amp. via EL-process
- Detect EL-photons by MPPCs

ELCC (**E**lectroluminescence **L**ight **C**ollection **C**ell)

- Optimize Parameter; hole-size, hole-pitch
- Max; Electron collection efficiency with ΔE
- Use; Finite Element Method
- Gmsh, ElmerSolver, and Garfield++
- => Φ5.5mm, 10mm-pitch

1.0cm 1.0cm

E_{drift}=100v/cm/atm

E_{anode}=2.5kV/cm/atm

2cm

0.6cm

0.5cm

0.58cm

gmsh

elmer

electric field of ELCC (at y=0)

z[cm]

x[cm]

kV/cm/atm

AXEL prototypes & Future prospects

2015   2018   202?   20??

10L - size (10g xenon)

- Establish ELCC
- Basic R&Ds
- Check ΔE

L 9 cm

Φ 10 cm

3000L - size
(100 kg xenon)

- Underground

Large - size

180L - size (8.6kg xenon)

- Evaluate ΔE @ Q-value
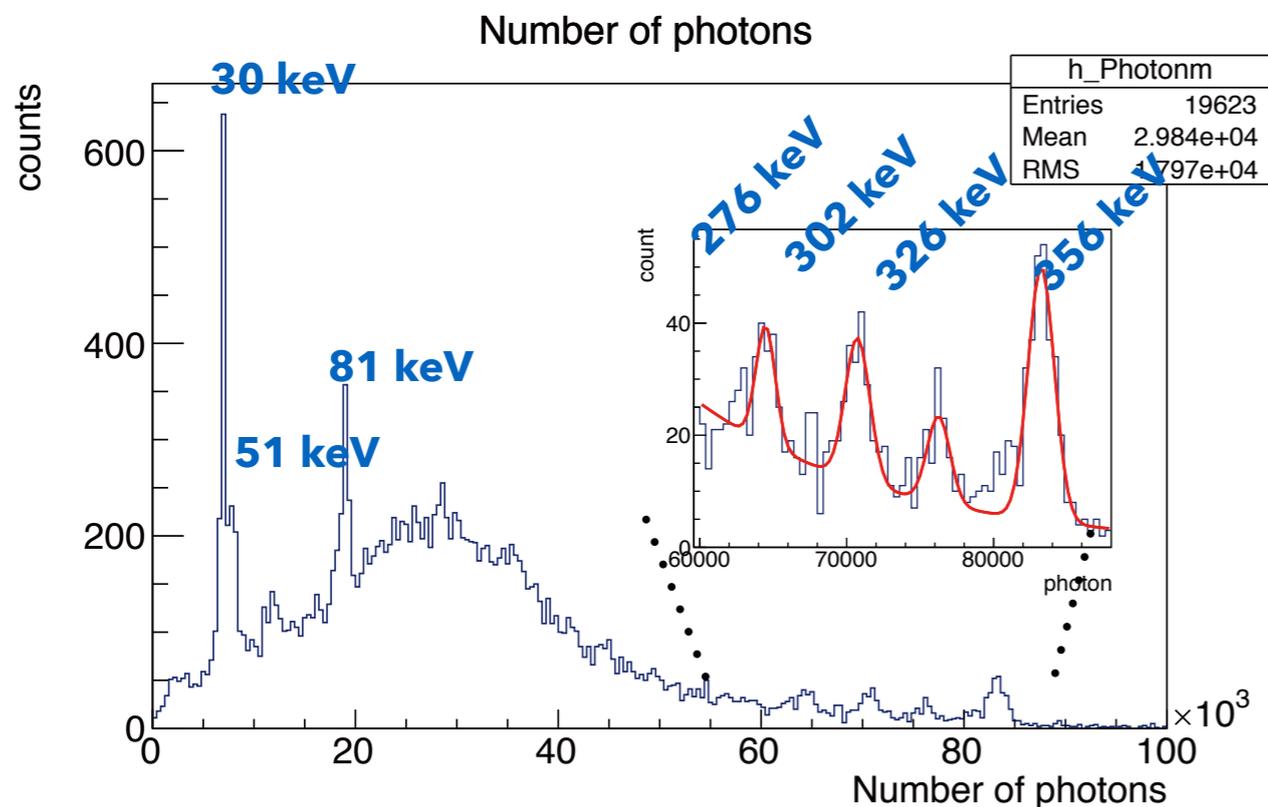- Estimate Radioactivity, Backgrounds
- Now constructing …

Φ 55 cm   L 83 cm

10L-prototype

9cm

5mm

φ10cm

AXEL HP10L prototype

VUV-PMT

2cm

MPPC array

7.5mm

10L-prototype

L 9 cm
Φ 10 cm

- Using ^{57}Co, ^{133}Ba source for ΔE evaluation
- Q-value (2.46MeV) β-ray is not fully contained
  in this small size
- Estimate with extrapolation; 0.8~1.8% FWHM @ Q-value

  ※ This worse ΔE is caused by ELCC design
  ※ Not so 100% efficiency for EL-photon collection
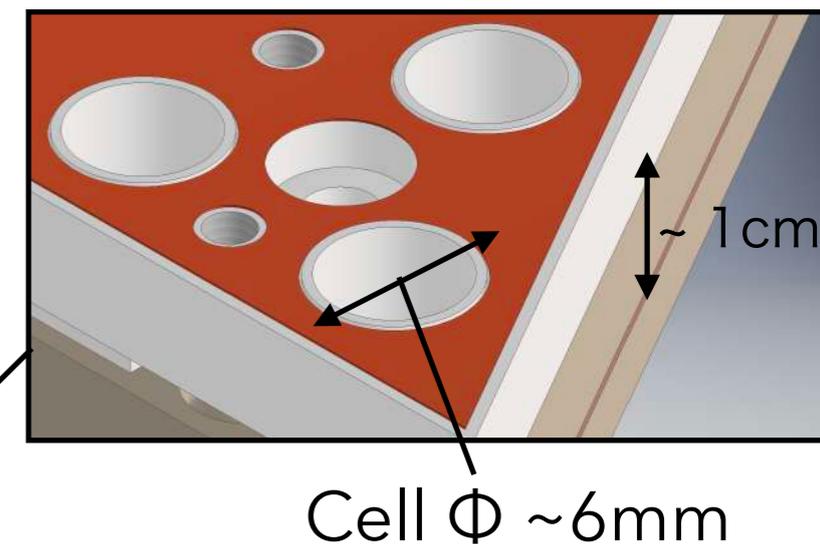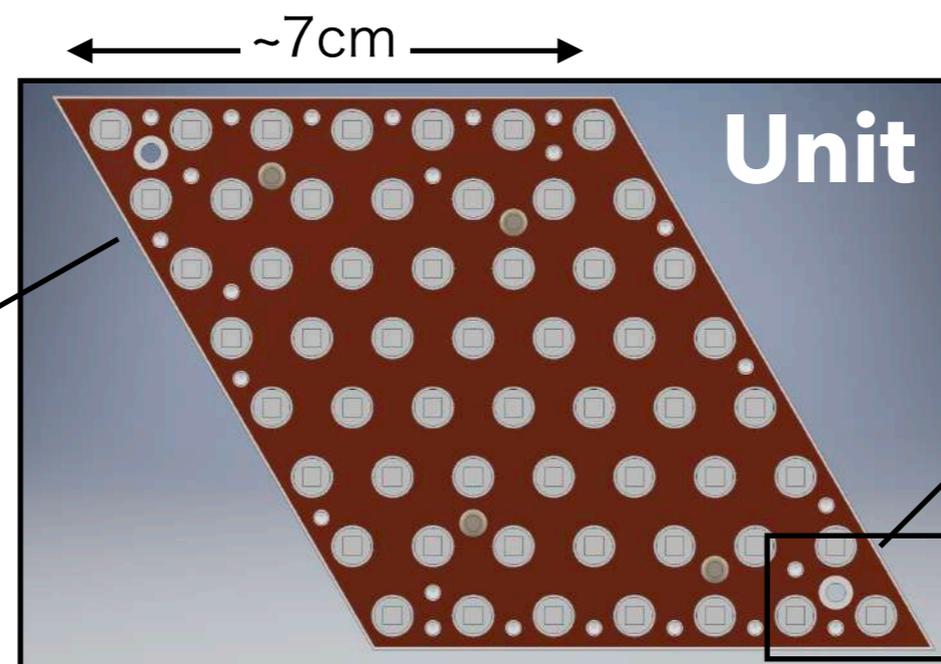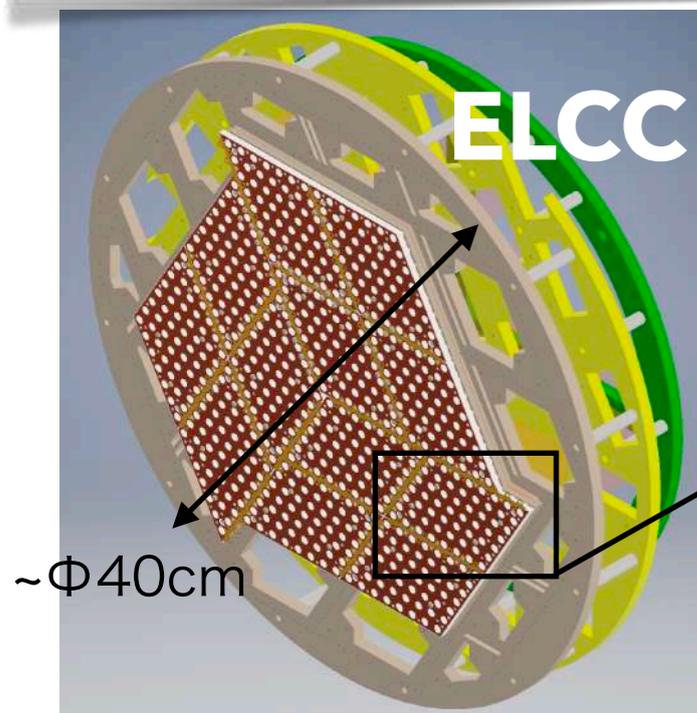 ※ Next HP180L prototype has the fixed ELCC

Number of photons

30 keV
51 keV
81 keV
276 keV
302 keV
326 keV
356 keV

h_Photonm	
Entries	19623
Mean	2.984e+04
RMS	1.797e+04

Extrapolate to Q-value
- 1.74% FWHM w/ $A\sqrt{E + BE^2}$
- 0.82% FWHM w/ $A\sqrt{E}$

Target: 0.5% FWHM

Q-val.

180L prototype detector

10 VUT-PMTs & LED for calibration

56×27 = 1,512 MPPCs on ELCC tracking plane with each 56 ch

Φ 55 cm

SUS304

Input AC-HV Generate DC-HV with Cockcroft-Walton circuit

Dynamic range; 1~10^4p.e. Also HV supply

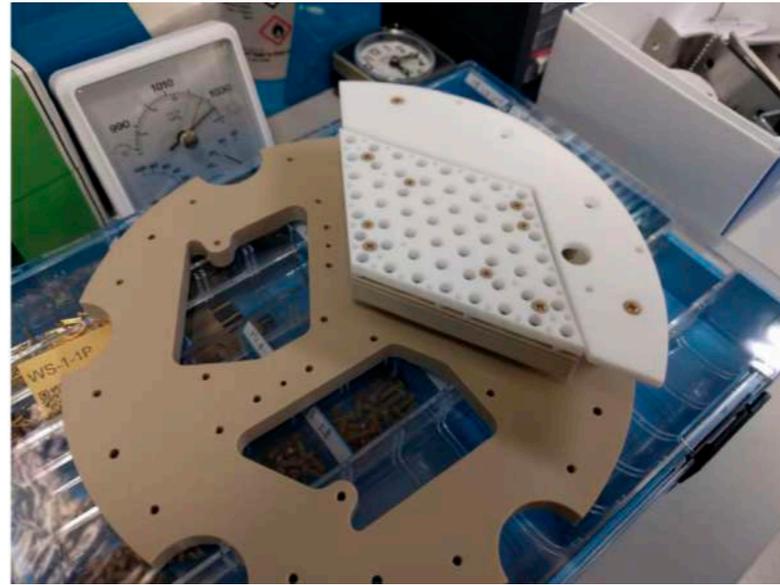Ring field cage

HV-Feedthrough

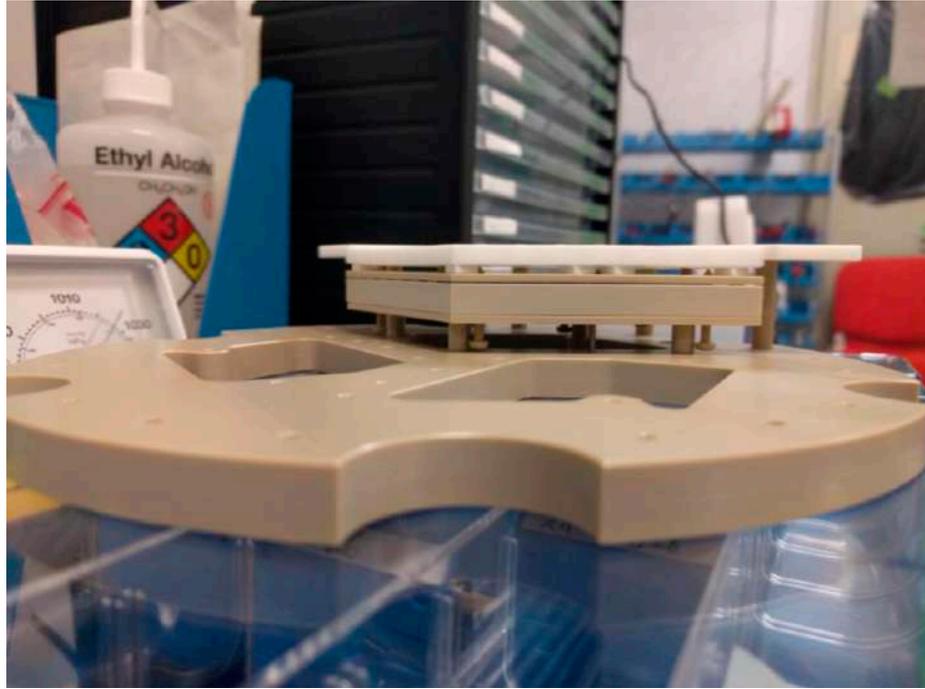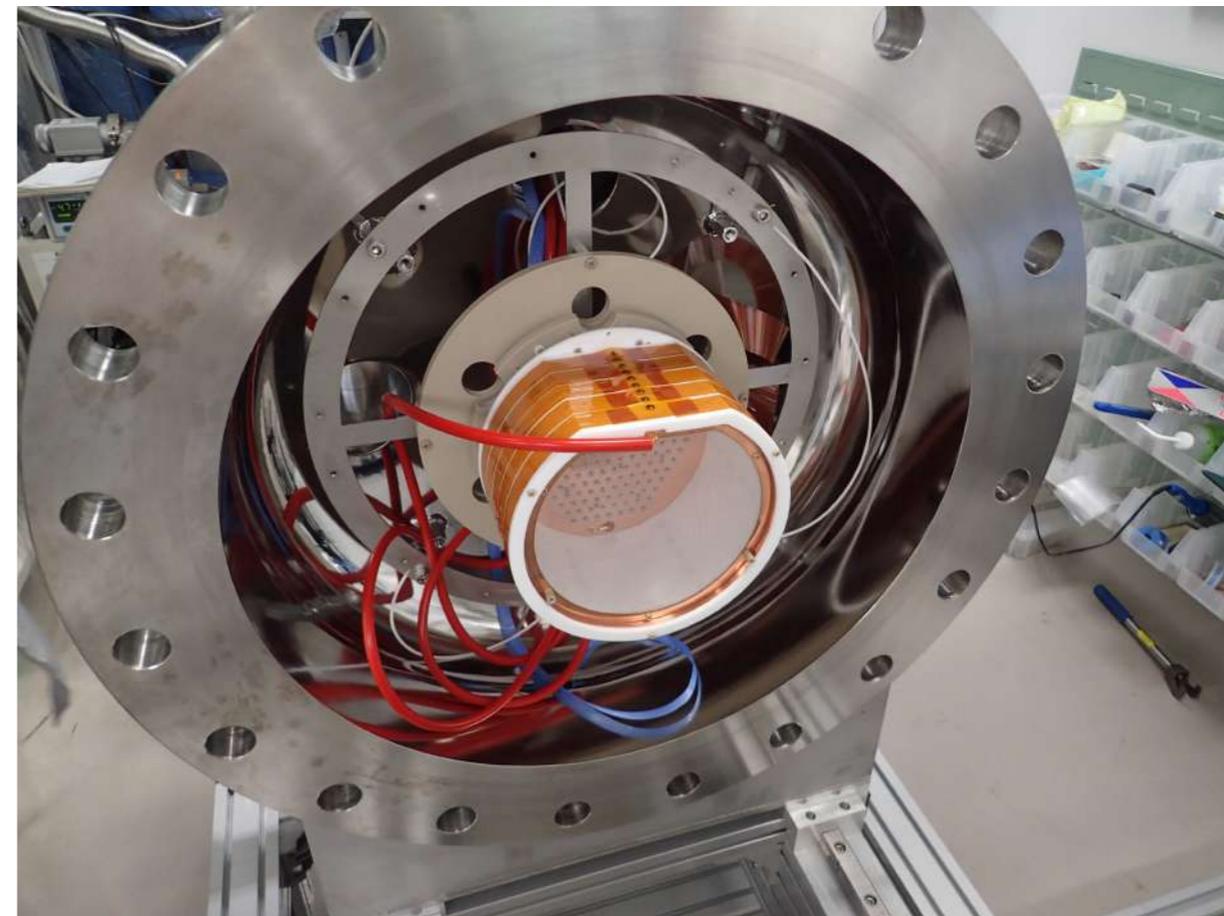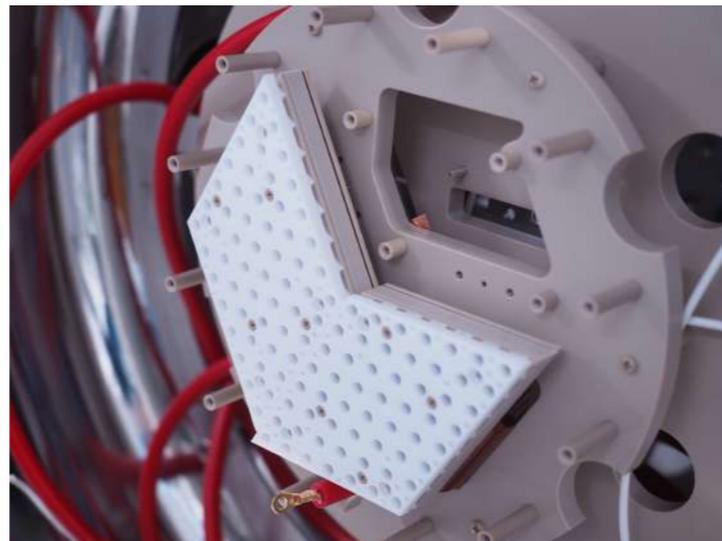Readout & Bias-HV supply via long FPC cable

L 83 cm

10-times larger size

- Evaluate Energy Resolution at Q-value
- Establish the Scalability for larger detector
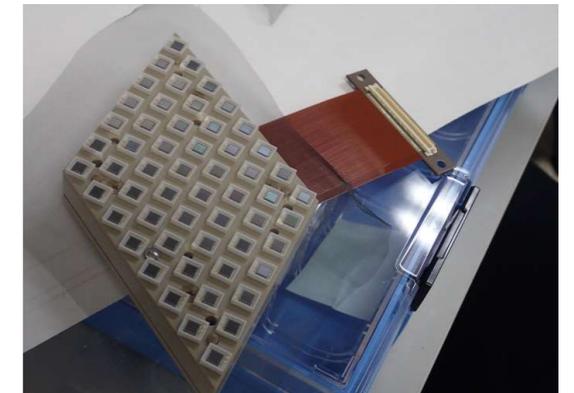- Now Constructing …
  (*Fin. 3unit/27unit=10%*)

ELCC

~Φ40cm

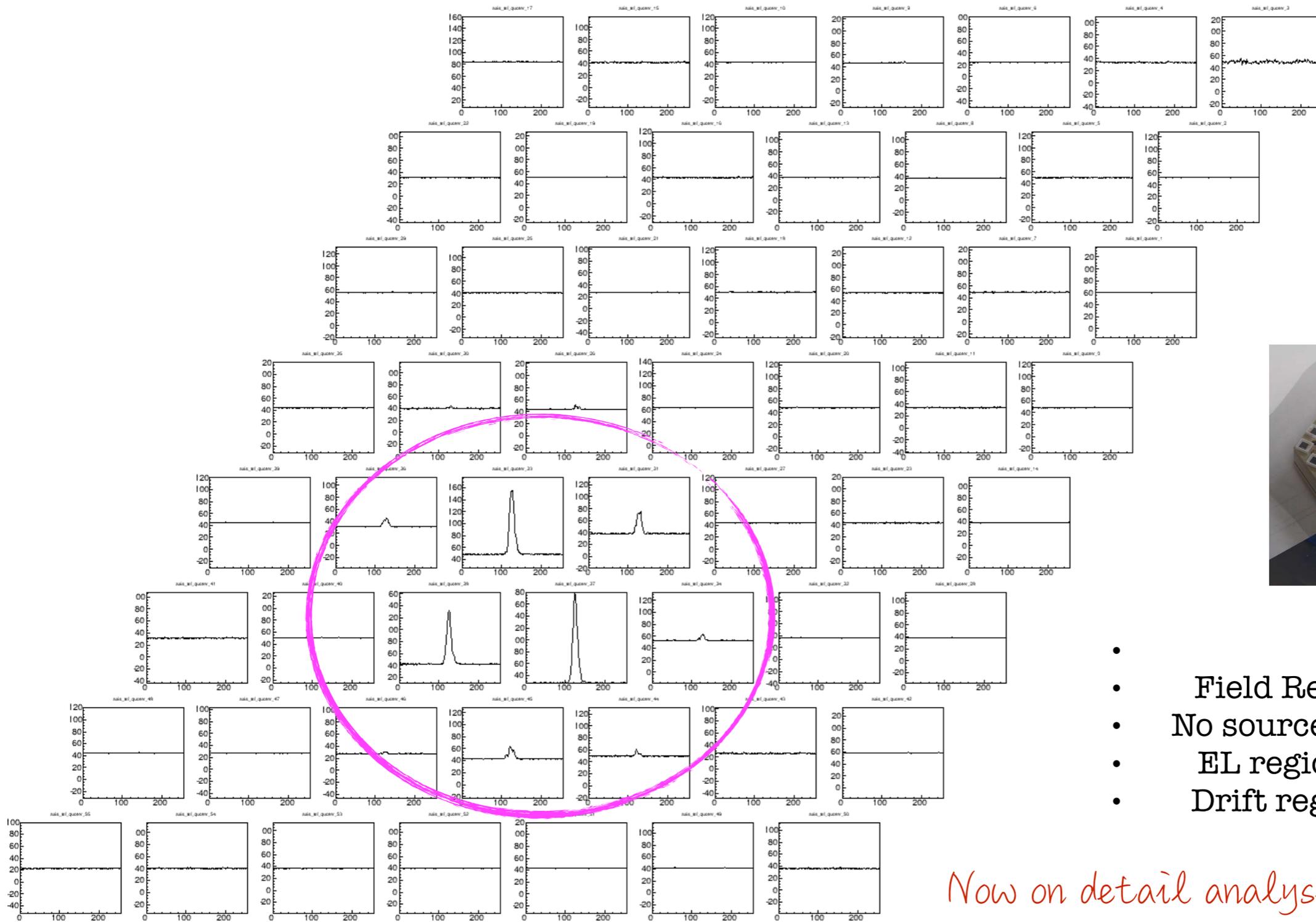

~7cm

Unit

~ 1cm

Cell Φ ~6mm

ELCC-Unit, FieldCage

Firstly, we start with
3-Units

First Light in HP180L !!!!!!!!!!!!!!
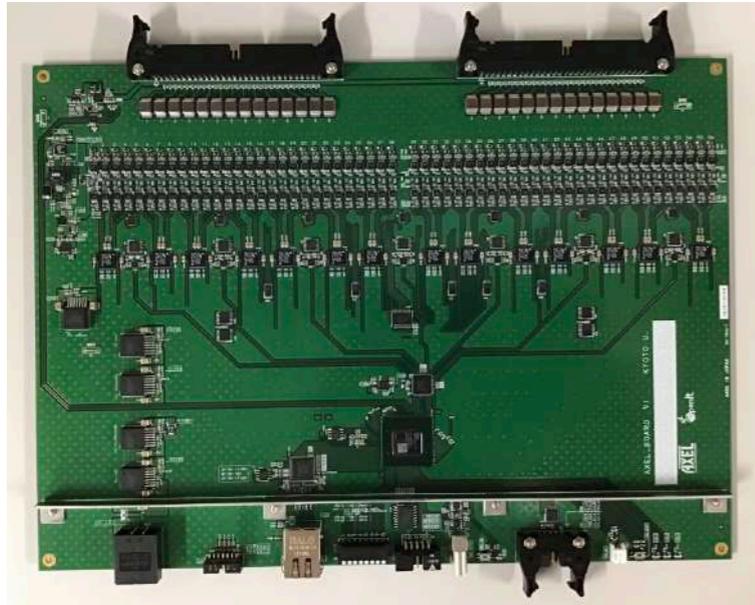
An environmental-γ event in a ELCC-Unit (56ch)

- Xe 1atm
- Field Region Φ15cm×10cm
- No source (Environmental-γ)
- EL region; 3.0 kV/cm/atm
- Drift region; 100V/cm/atm

Now on detail analysis with source-run

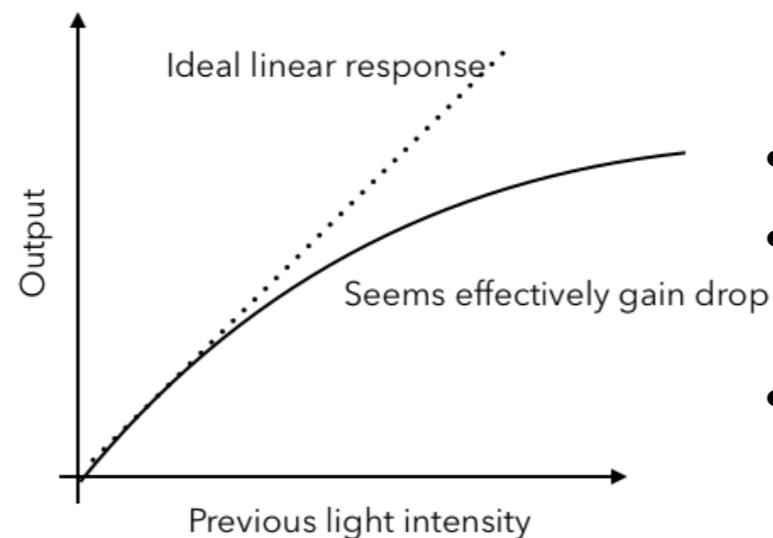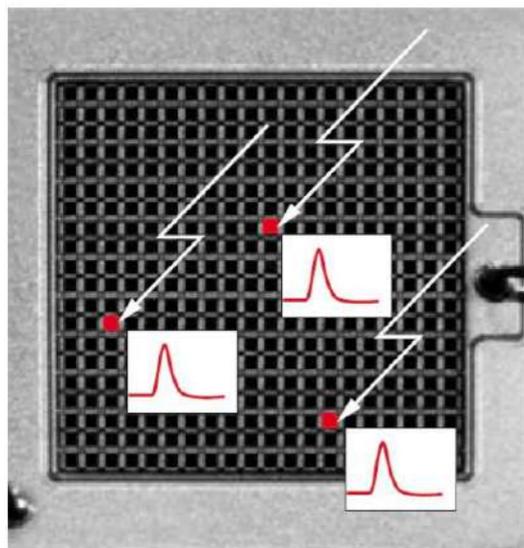# Electronics board & MPPC gain correction

New boards for HP180L

- Waveform readout from MPPCs; 56ch/board
- Dynamics range of Flash ADC; 1-10^{4}p.e./μsec (~2.5MeV)
- Monitor & Adjust the gain with feedback logic
- HV-supply to each MPPC (in the 0.2mV)
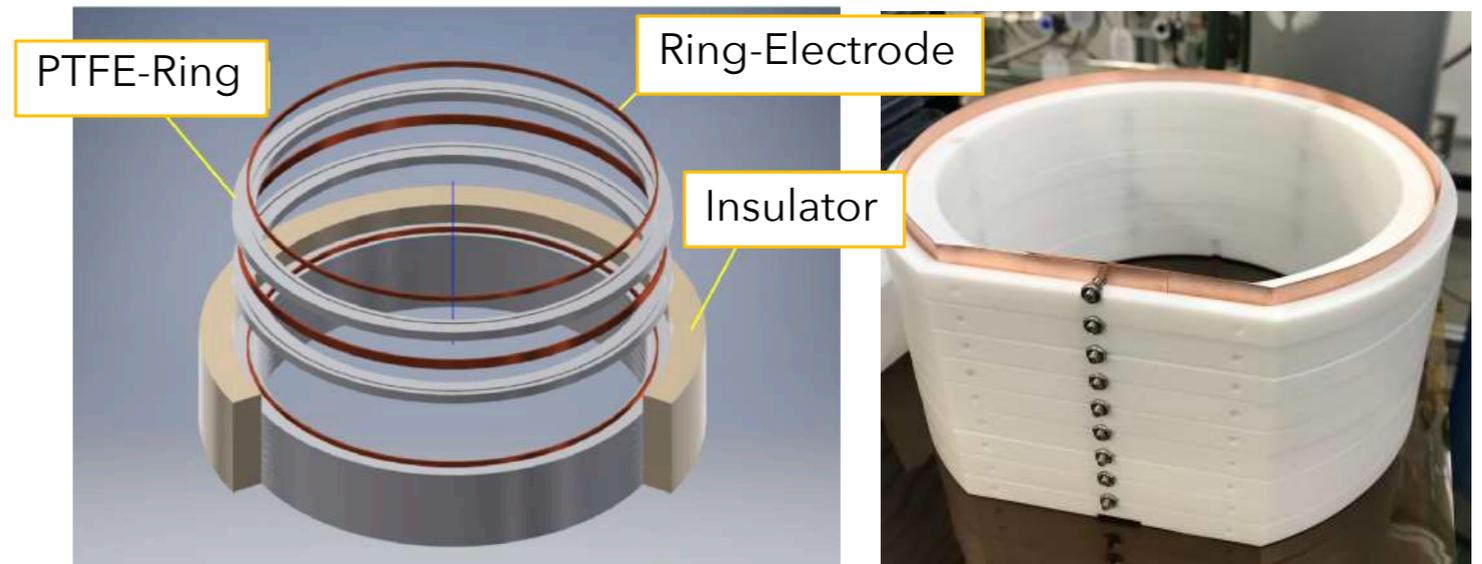
MPPC gain correction

Talk by Nakamura

- Non linearity after large light intensity
- We need the correction factor of saturation curve
- Measure with LED

FieldCage and Cockcroft-Walton Circuit for Drift Electric Field Supply

Develop "non-discharge field cage"

- Pure Xenon gas is easy to discharge
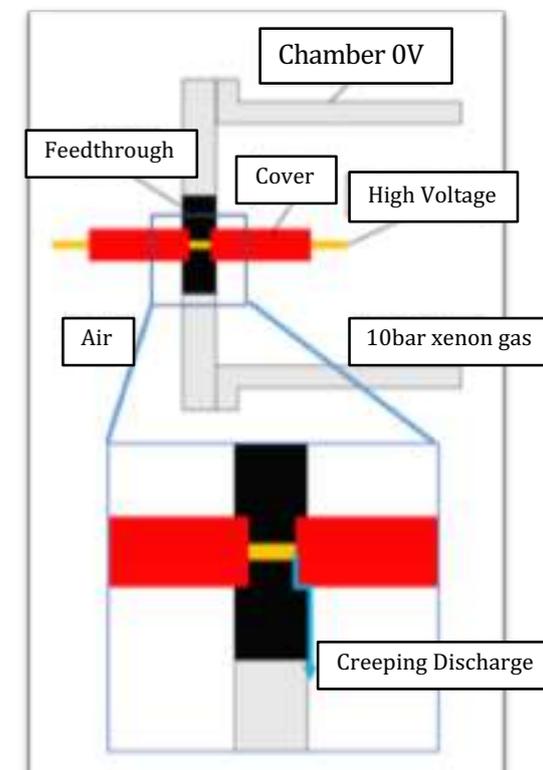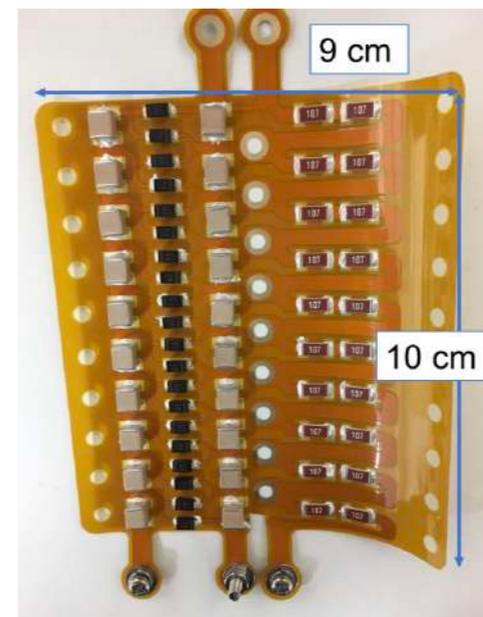- Block the electric path

Talk by Yoshida

PTFE-Ring

Ring-Electrode

Insulator

Develop "CW circuit for E$_{dfirt}$"

- Prevent to discharge at feedthrough
- HV is generated in the Chamber with Cockcroft-Walton Circuit

Prototype CW circuit

9 cm

10 cm

Chamber 0V

Feedthrough

Cover

High Voltage

Air

10bar xenon gas

Creeping Discharge

BG for 0v2β

Even if we achieve good ΔE = 0.5%-FWHM,

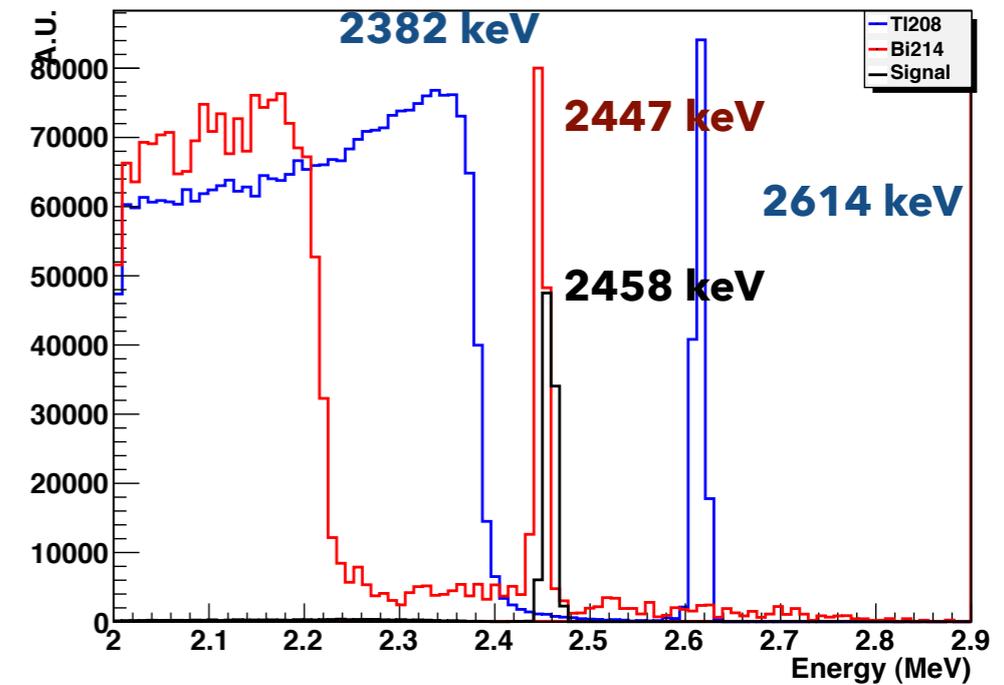**^{214}Bi γ-ray 2,447keV**

is dominant BG fo **^{136}Xe-0v2b (2,458keV)**

Topology identification !!
By DeepLearning; 75evt/yr ⇒ 0.8evt/yr
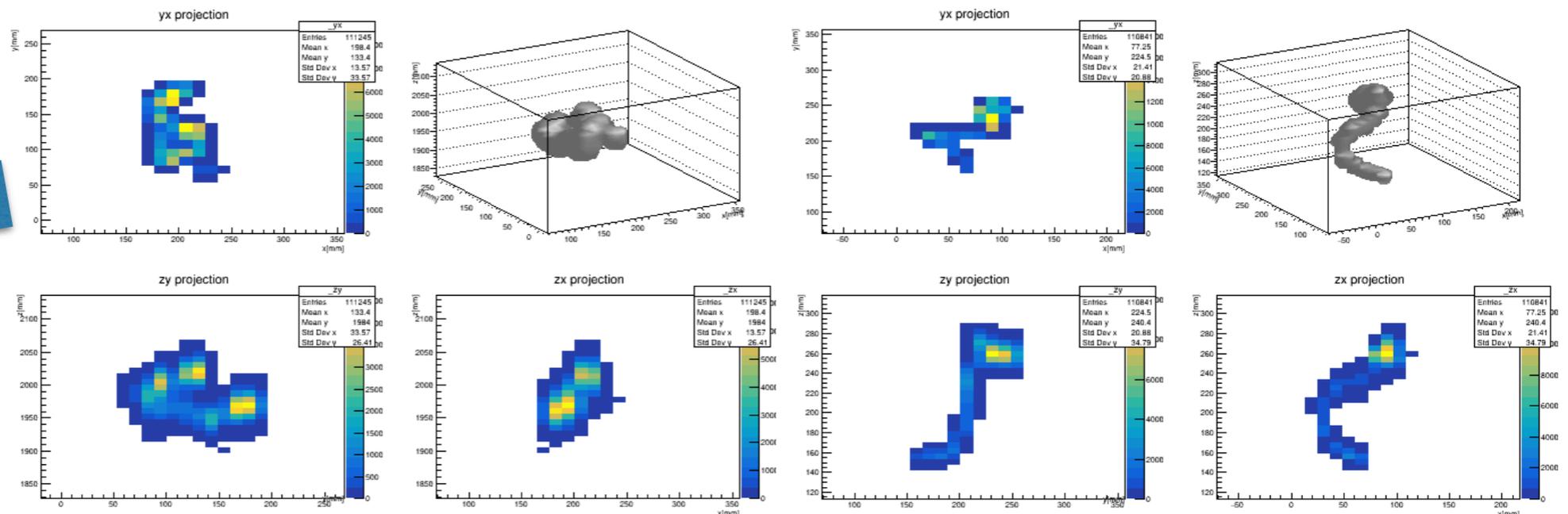
arXiv:1106.3630v1 [physics.ins-det] from NEXT paper

Positive Ion maybe useful for topology used BG rejection

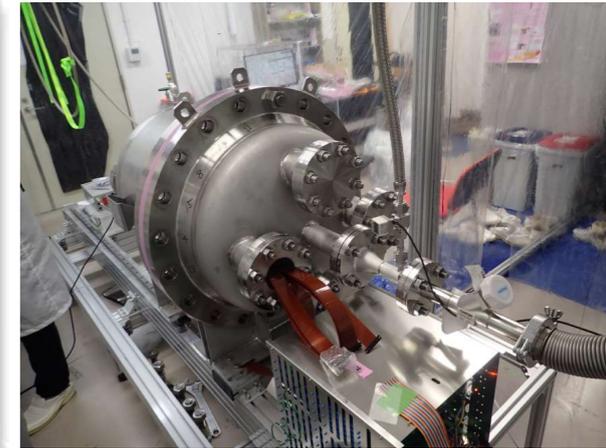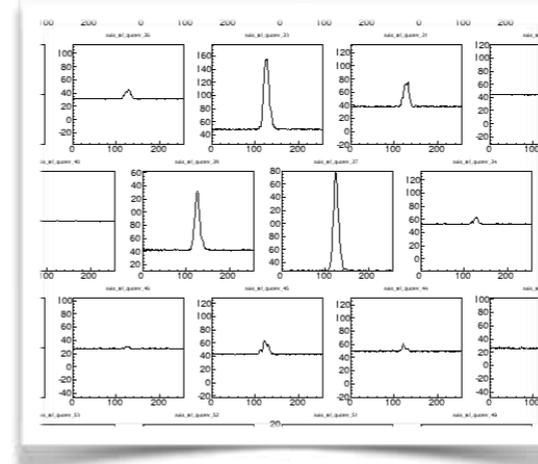Talk by Nakamura

0v2β (double-β)

^{214}Bi (gamma-ray)

Very Recent Status (1-good, 3-bad)

😆 **First Light Observation & Well-working New Components**

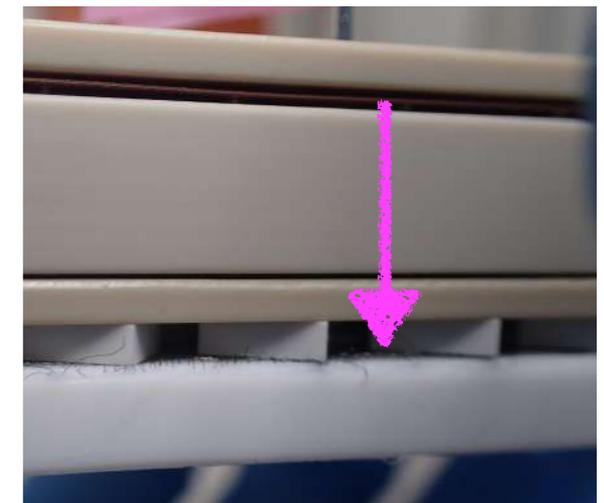- Successfully worked !!
- New ELCC, New ReadoutFPC, New Electronics, …

😢 **Discharge** ; ELCC-anode to GND-mesh

- Now investigating
- Find the electric path of discharge

😢 **Dead** Circulation **Pump** !!

- Not working, now being repaired

Anode plate to GND mesh through between the Units ?

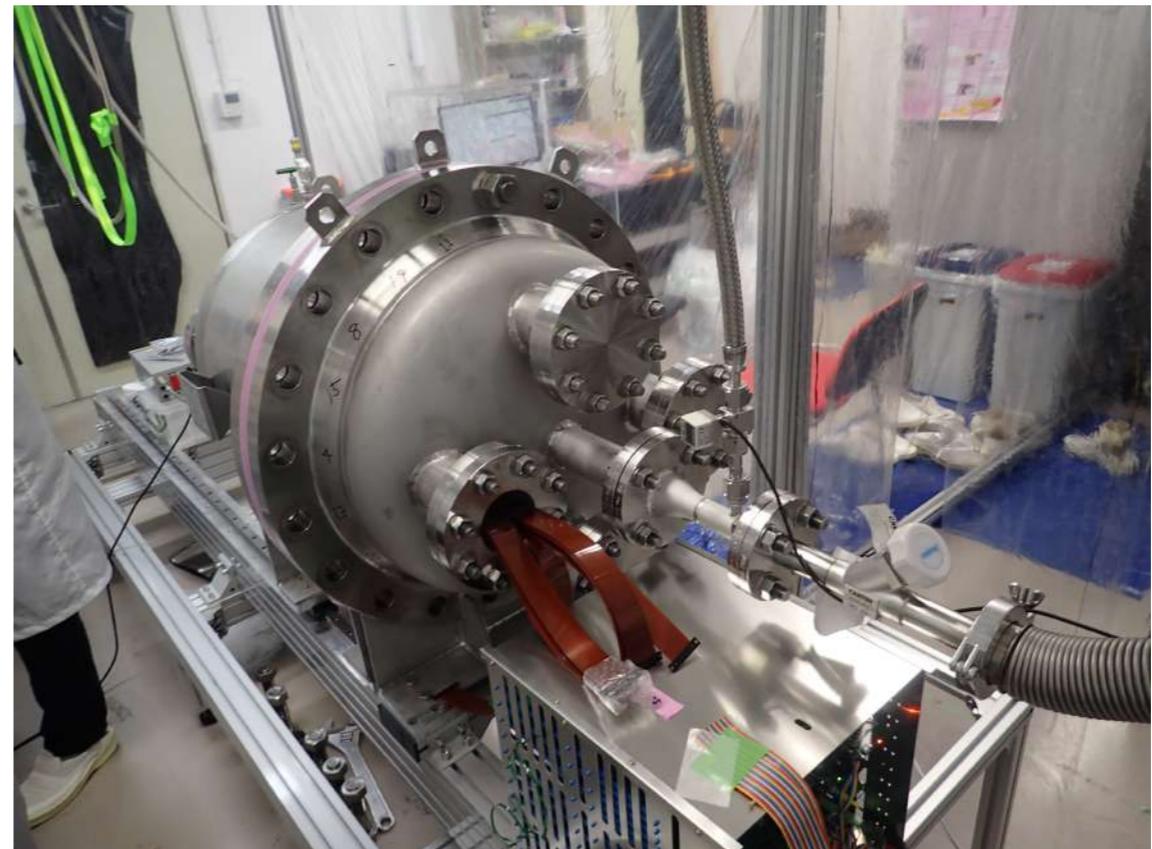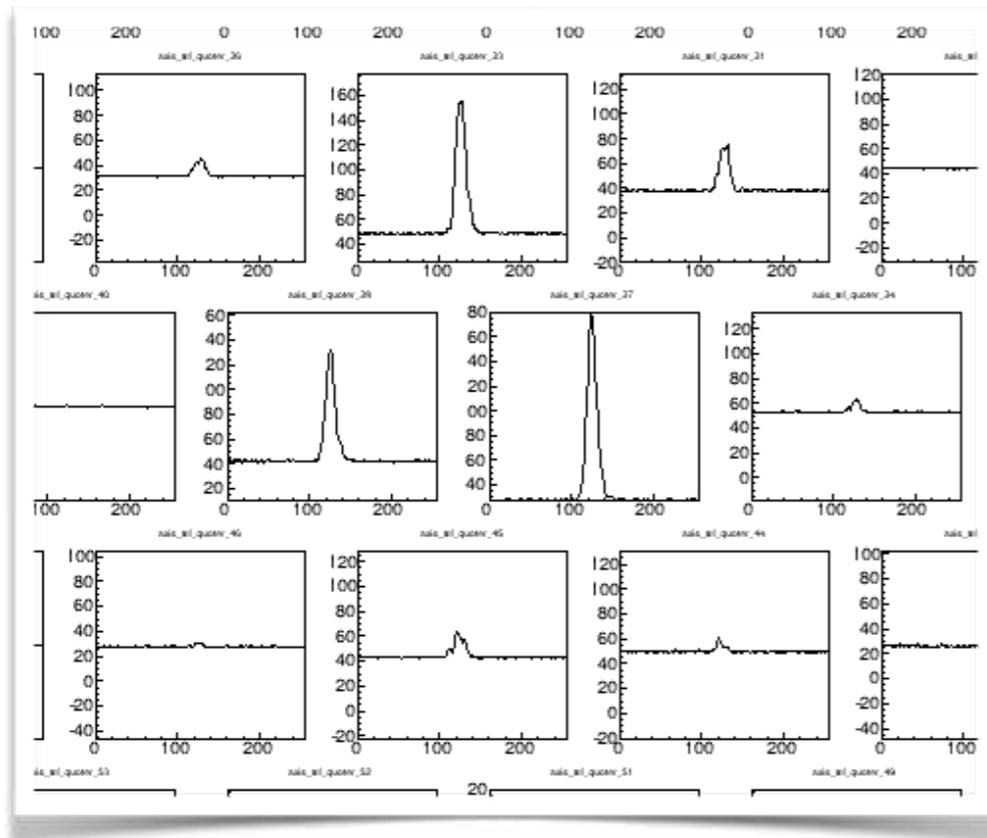😢 **Aeration** by Booster Pump Trouble

- Another pump (booster pump) has also trouble and Aeration !!
- How to purify our Xenon ?

Very Recent Status

😆 **First Light Observation & Well-working New Components**

- Successfully worked !!
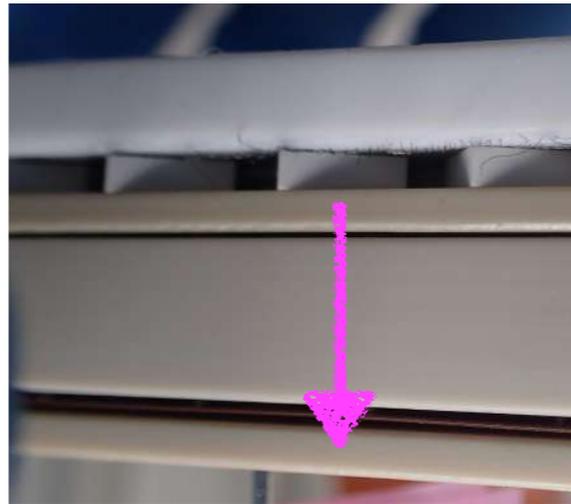- New ELCC, New ReadoutFPC, New Electronics, ⋯

Very Recent Status
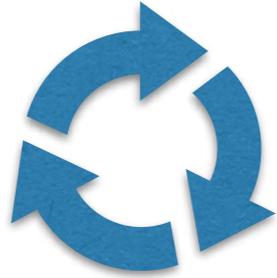
😢 **Discharge** ; New ELCC-anode to GND-mesh

- Now investigating
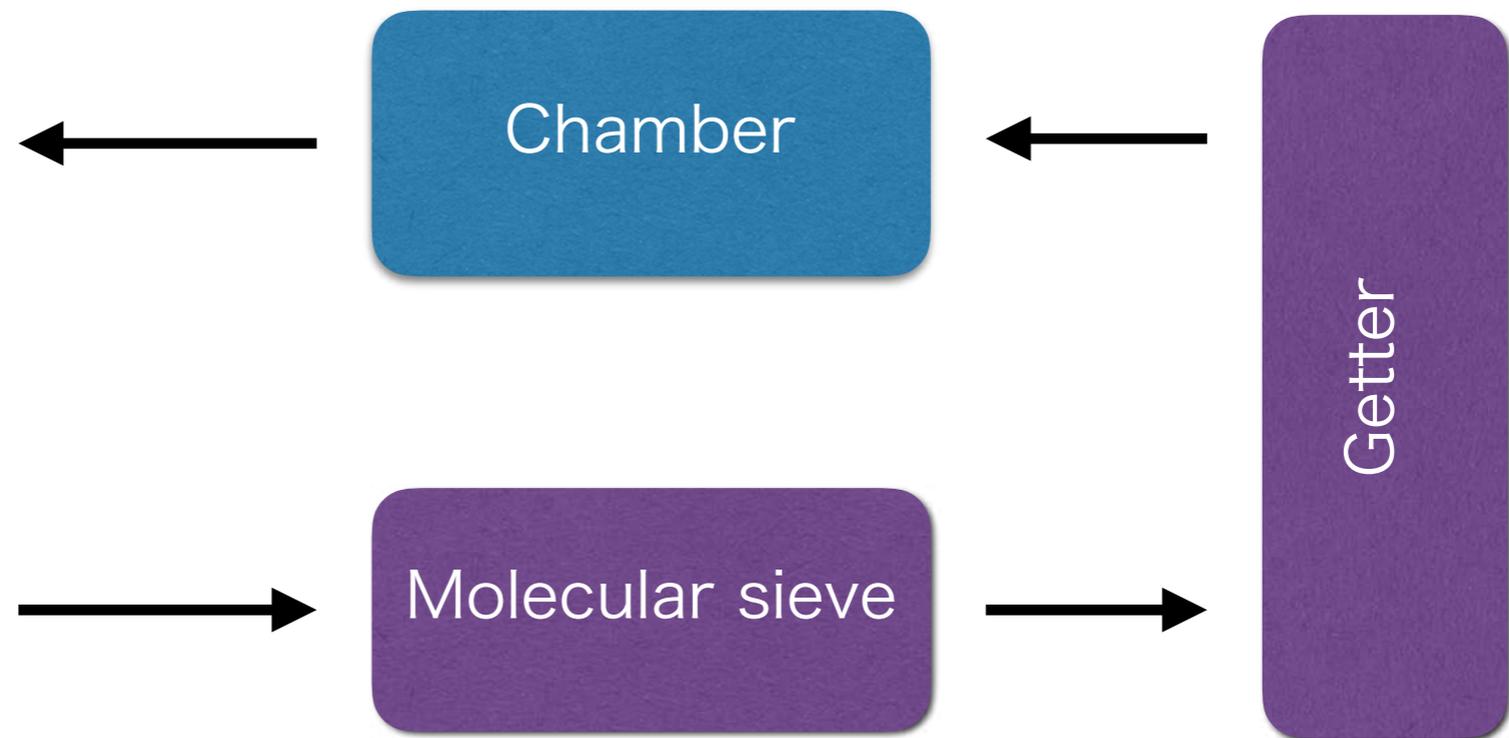- Find the electric path of discharge

Talk by Yoshida

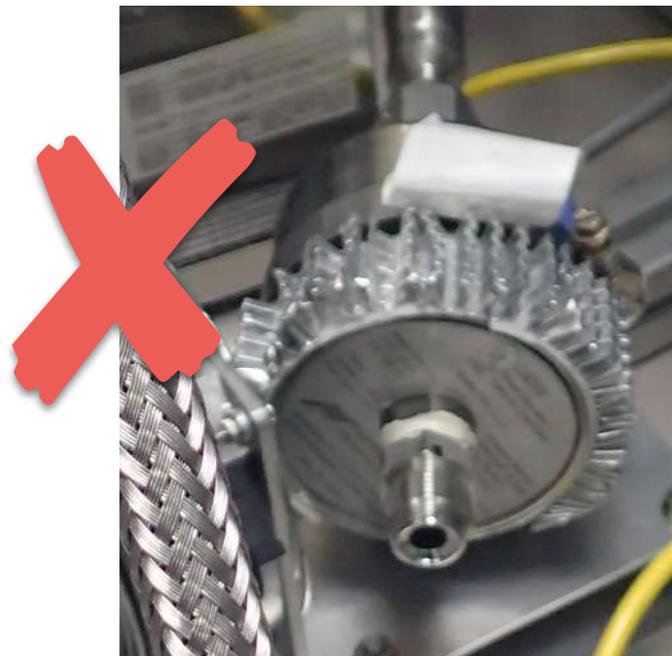Anode plate to GND mesh
through between the Units ?

Very Recent Status

😢 **Dead** Circulation **Pump** !!

Chamber → (left arrow)

Getter → Chamber
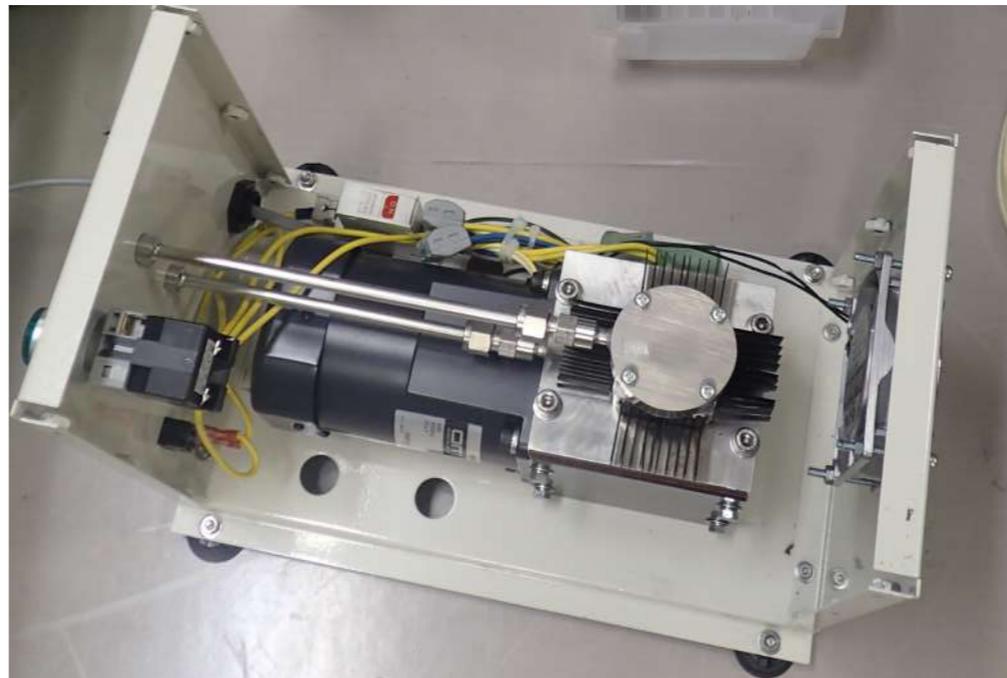
Molecular sieve → Getter

- Not working, now being repaired

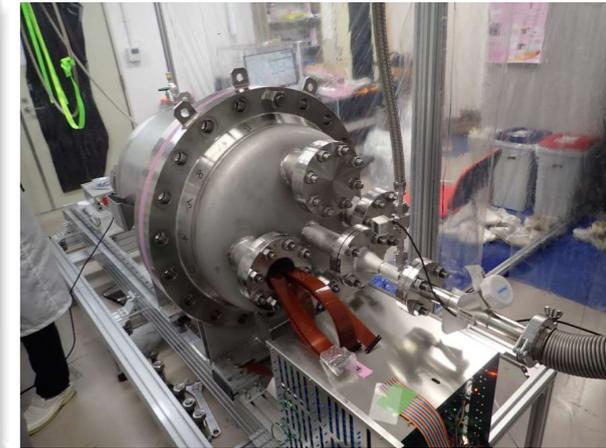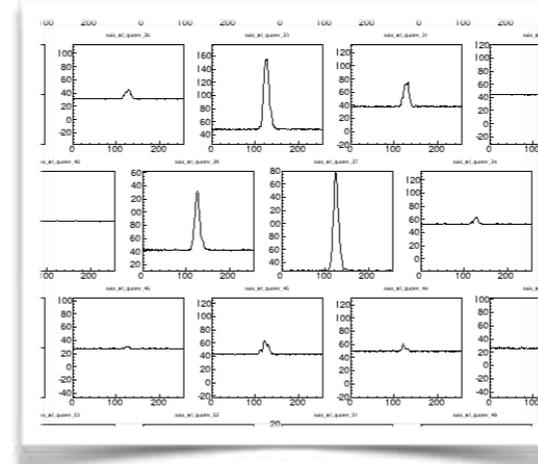# Very Recent Status

😢 **Aeration** by Booster Pump Trouble

- Another pump (booster pump) has also trouble and Aeration !!
- No any scintillation light nor EL light
- Found High H_2O contamination by dew-point meter
- **How to purify our Xenon** ?

Very Recent Status (1-good, 3-bad)

😆 **First Light Observation & Well-working New Components**

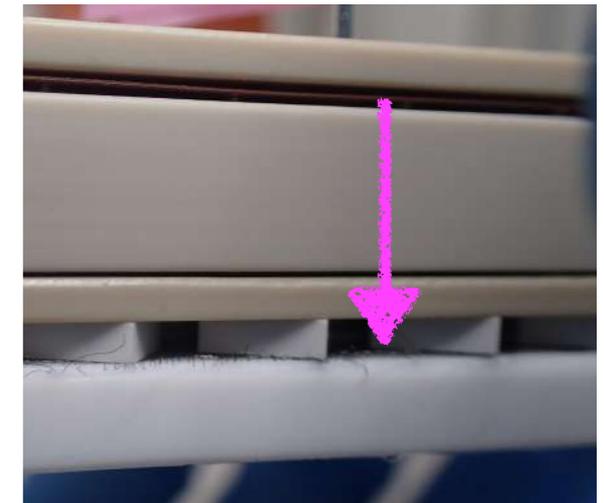- Successfully worked !!
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- Not working, now being repaired

😢 **Aeration by Booster Pump Trouble**

- Another pump (booster pump) has also trouble and Aeration !!
- How to purify our Xenon ?

SUMMARY

- 0v2b search is important to reveal the **Majorana nature of Neutrinos**

- For future double-beta decay search experiments (towards NH),
    - Large Target Mass, High Energy Resolution, Topology Tracking
    - Xe Gas TPC satisfy above !!

- **AXEL** detector
    - 1ton High-Pressure Xenon TPC
    - Unique readout system "**ELCC**" using electroluminescence process
    - **Constructing HP180L prototype**
    - Now some pump troubles …

- Various R&Ds
    - Optimization of ELCC design
    - Non-discharge Field cage & Cockcroft-Walton circuit
    - Topology Identification w/ Deep Learning & Positive-Ion detection
    - (Xenon gas purification)

Talk by Yoshida

Talk by Nakamura