Kobayashi-Maskawa Institute
for the Origin of Particles and the Universe

NAGOYA UNIVERSITY

WIMP tracking with cryogenic nuclear emulsion

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Motivation

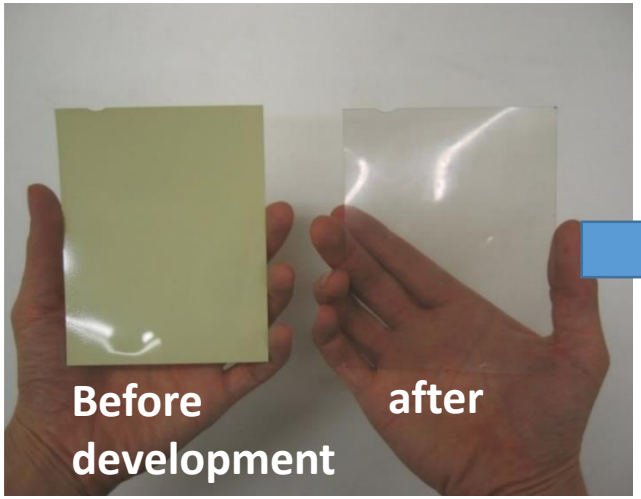
- Dark matter has yet to be observed experimentally
  - The DAMA/LIBRA claims the direct detection of WIMP by observing annual modulation signature
  - some other experiments found no signal
- Directional measurement can solve the problem
  - use signal's forward-backward asymmetry
    - different with annual modulation
  - need to detect a recoil nucleus as a track

Requirements for a detector

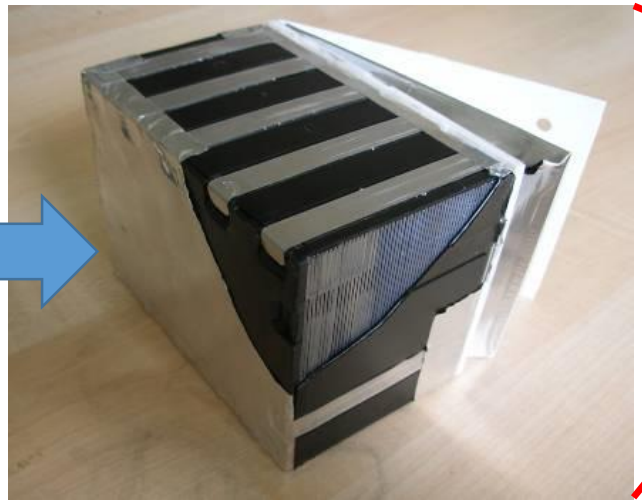
- Detector needs mass scalability
  - expected event rate: < 0.01 kg^{-1} day^{-1}
  - detector mass requires O(10 – 100) kg
- Solid-type tracking detector has the mass scalability
  - recoil energy is expected to be O(10) keV
    - track length will be O(0.1) μm
  - need nanometric position resolution
- Nuclear emulsion is one of the candidates

Nuclear emulsion

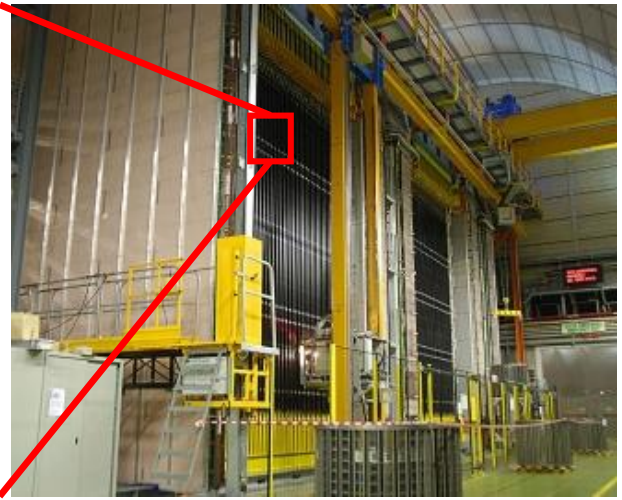
- Photographic film with sensitivity to a charged particle
  - position resolution: around 1 μm
  - mass scalability: up to tons scale
  - no time resolution



Nuclear emulsion films
for the OPERA experiment



Emulsion Cloud Chamber (sandwich of
57 emulsion films and 56 lead plates)



The OPERA detector
(Use 30 tons emulsion)

Detection principle

A silver bromide crystal is an extremely small sensor

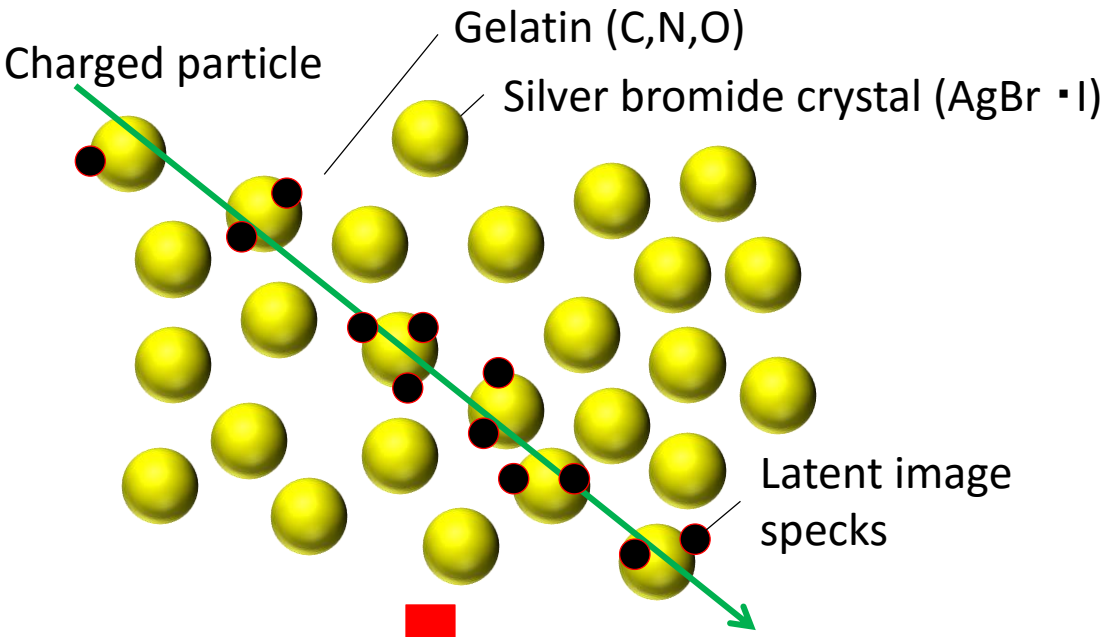
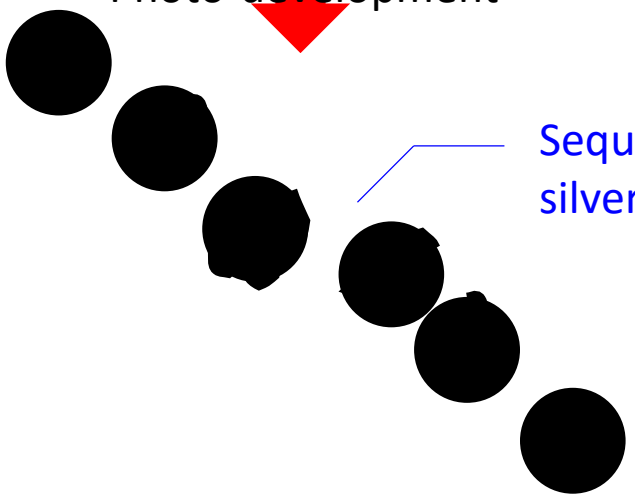
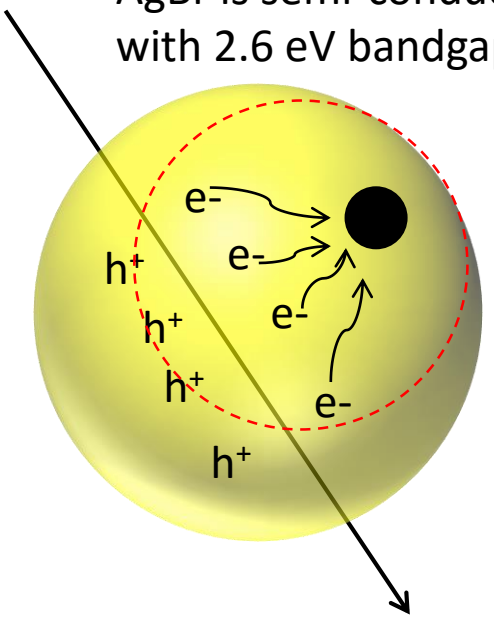


Photo-development



AgBr is semi-conductor with 2.6 eV bandgap



Ag^+ (interstitial silver ion) + e^- → Ag_1

$Ag_1 + Ag^+ + e^-$ → Ag_2 ・ ・ ・ ・ → Ag_n

⇩

Grow the "latent image specks" Ag_n ($n > 4$) in photo-development by a catalytic effect

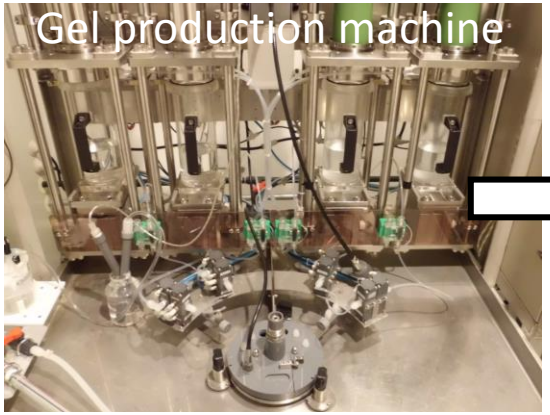
⇩

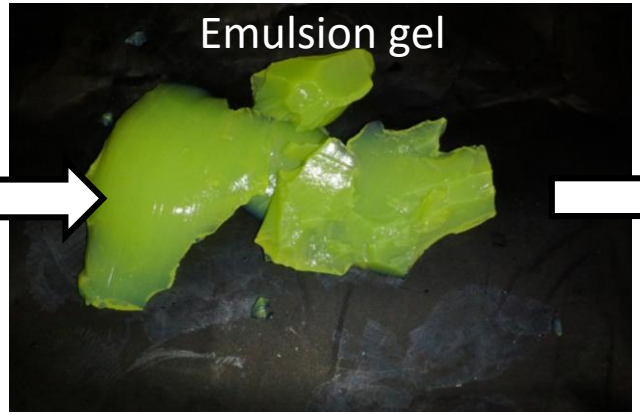
Visualize a track as a sequence of silver grains

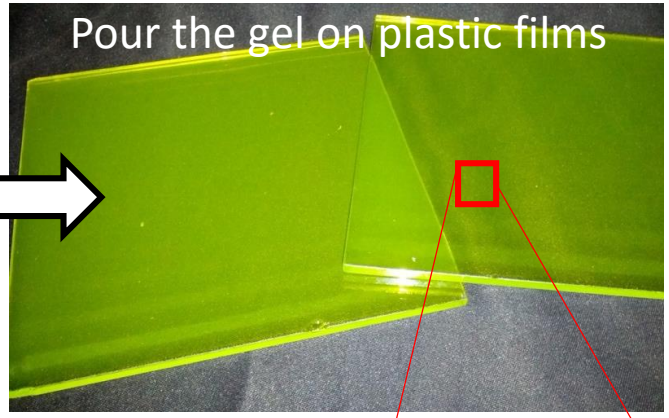
Fine-grained nuclear emulsion

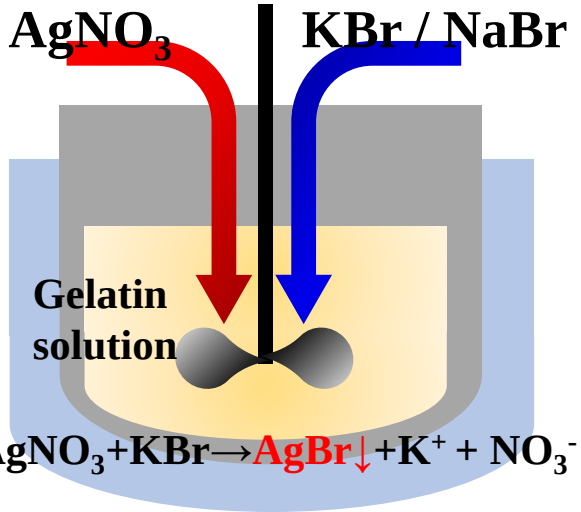
- Fine-grained emulsion can detect an extremely short track
- Nagoya University introduced the emulsion production machine

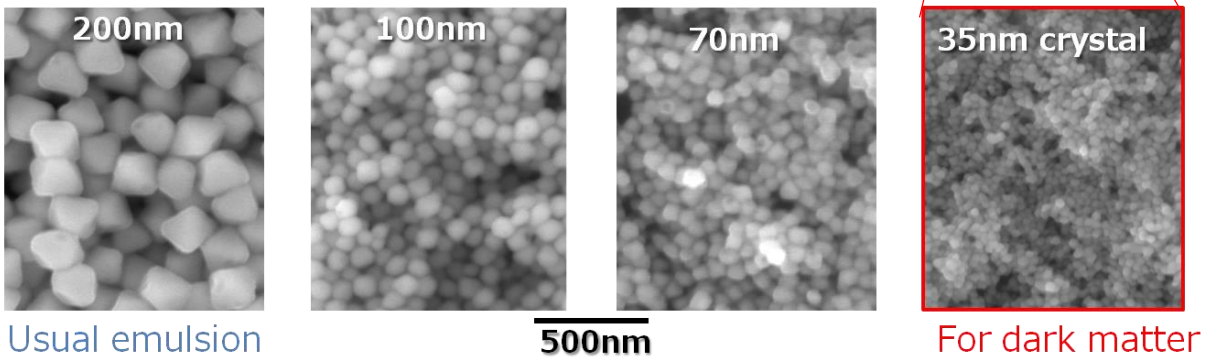
T. Asada *et al.*, Journal of Physics: Conference Series 469 (2013) 012010







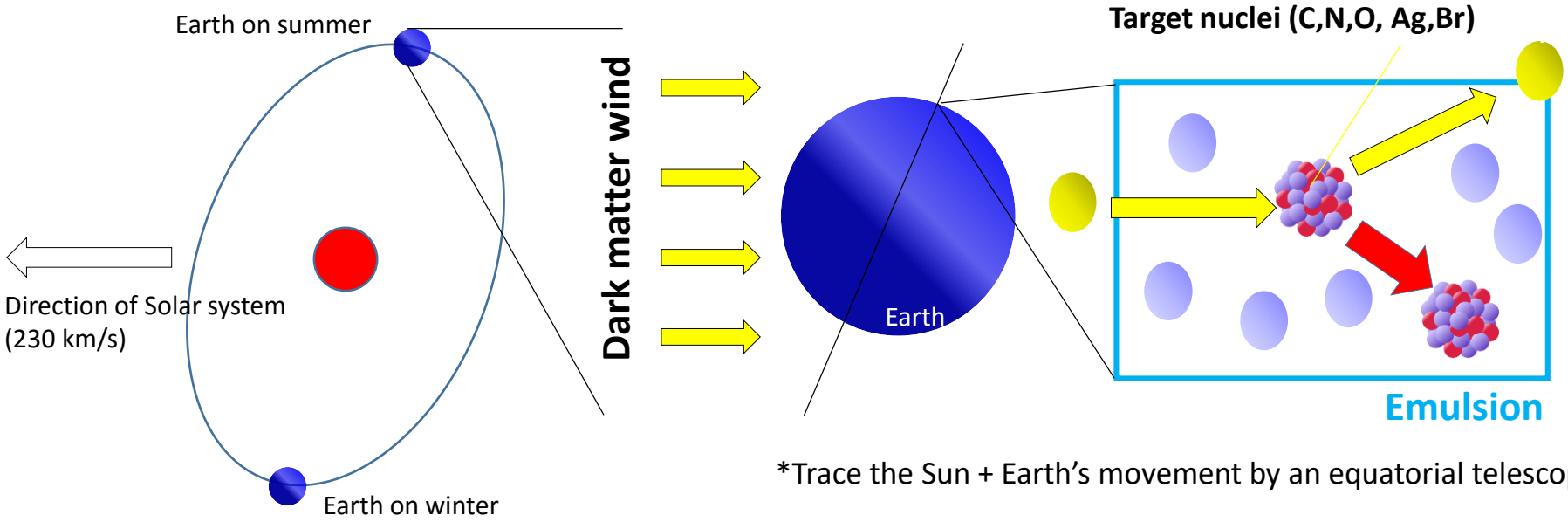




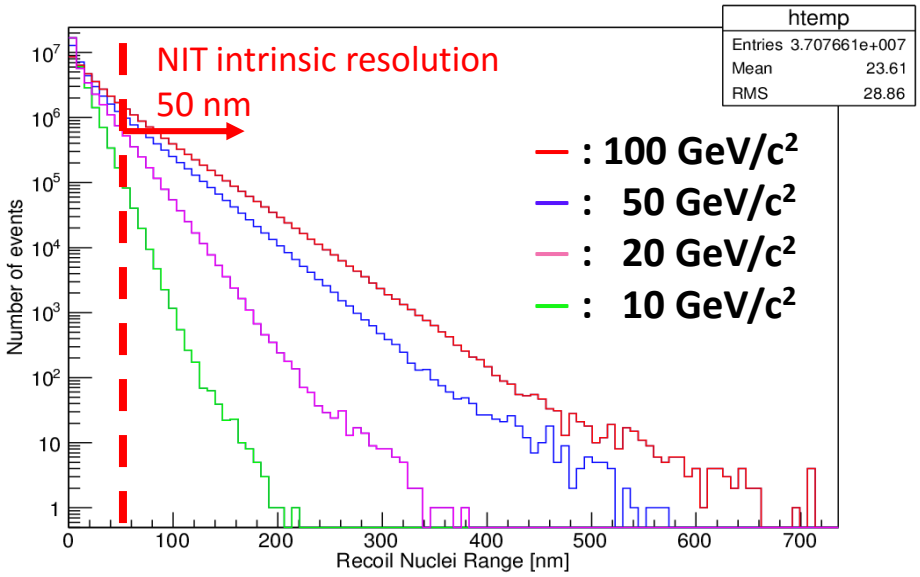
Usual emulsion: 2.4 crystals/μm

For DM ("Nano Imaging Tracker: NIT"): 11 crystals/μm

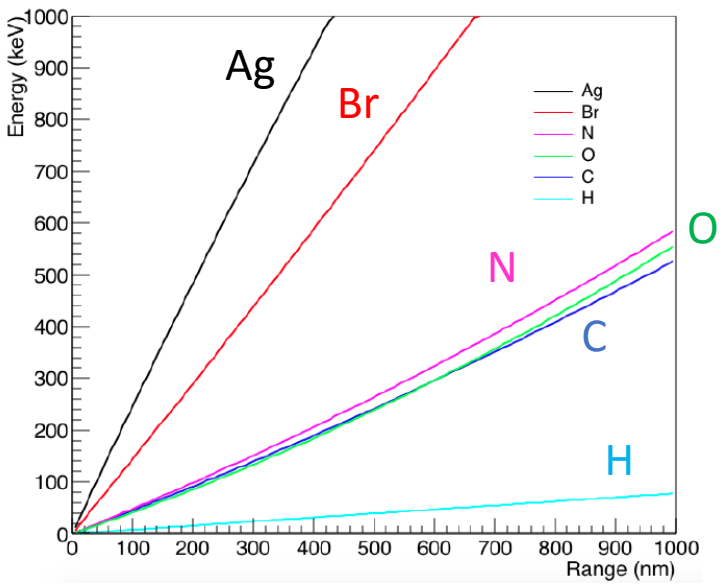
Directional Dark Matter Search with Nuclear Emulsion



*Trace the Sun + Earth's movement by an equatorial telescope



Track length

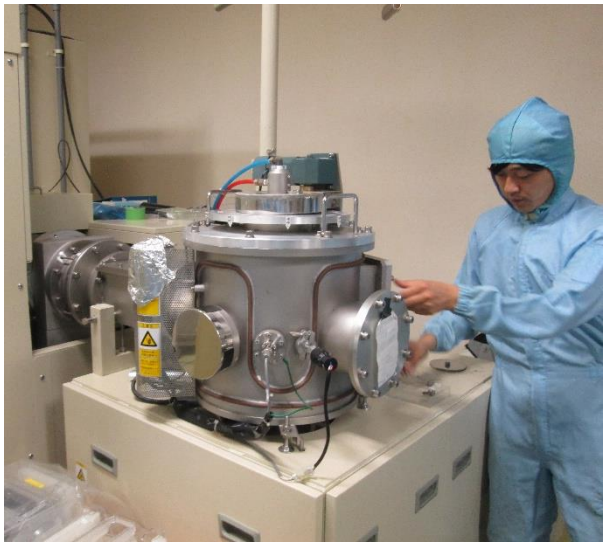


Kinetic energy and track length

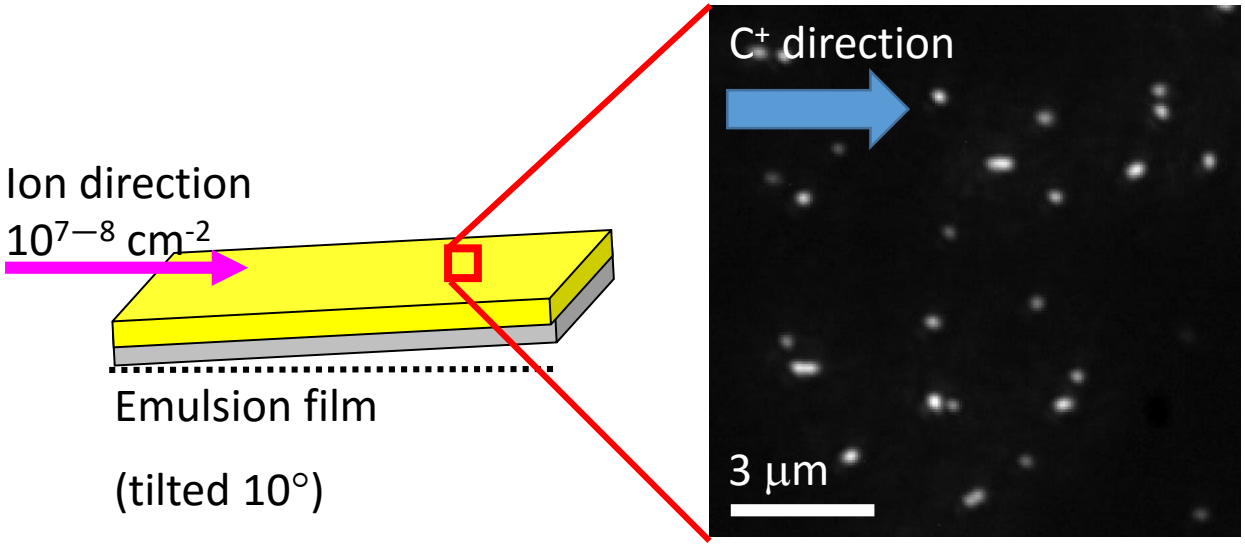
Performance check

- Demonstrated WIMP signal detection by using low velocity ions were supplied by an ion implant system
- The detection sensitivities to C^+, Kr^+ are consistent with 100% at room temperature

M. Natsume *et al.*, Nucl Inst. Meth. A. 575 (2007)439



The ion implant system at Nagoya University can supply with C^+ and Kr^+ with up to 200 keV



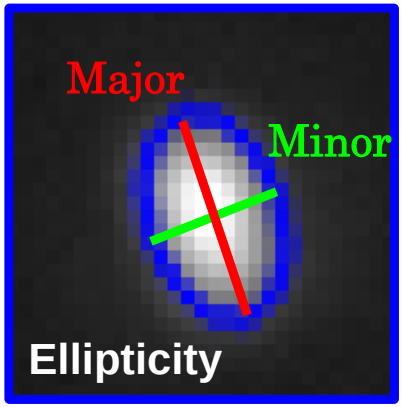
Epi-elluminated microscopic view of 80 keV C^+ (track length ~ 240 nm)

Signal selection and track reconstruction

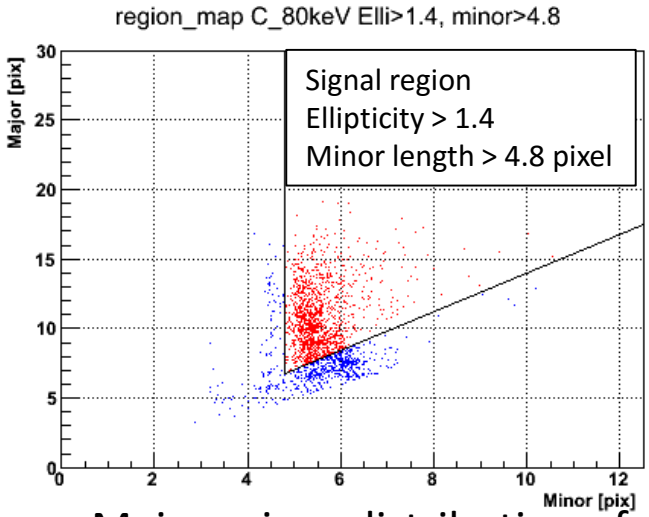
- Extract signal candidates by using shape recognition based on ellipse fitting
- Observed anisotropy of low speed ions

  - consistent with beam incident direction

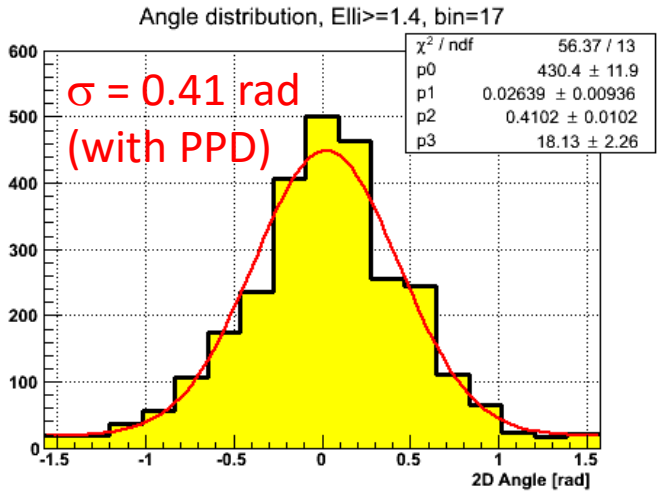
M. Kimura and T. Naka., Nucl. Inst. Meth. A. 680 (2012) 12-17



Extracted parameters by optical analysis



Major-minor distribution of 80 keV C^+ ions in NIT

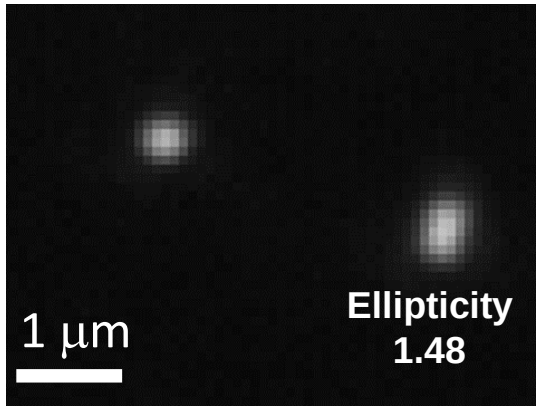


Angular distribution for the events in the signal region

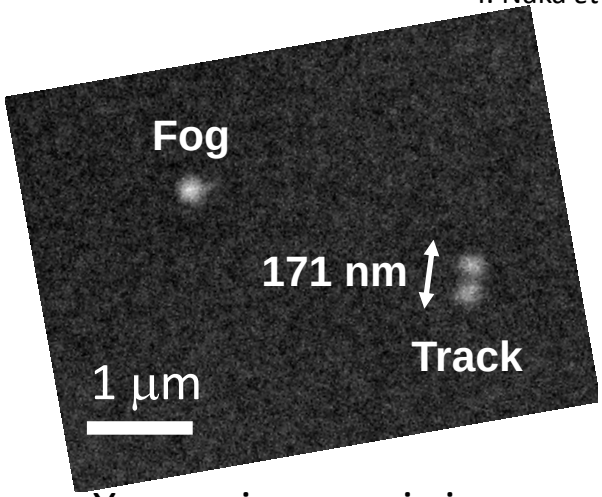
Signal confirmation

- X-ray microscope confirms the candidates
  - resolve the candidates into its components
    - signal is detected as a line of two or more grains
    - a single grain does not form a track (“fog”)

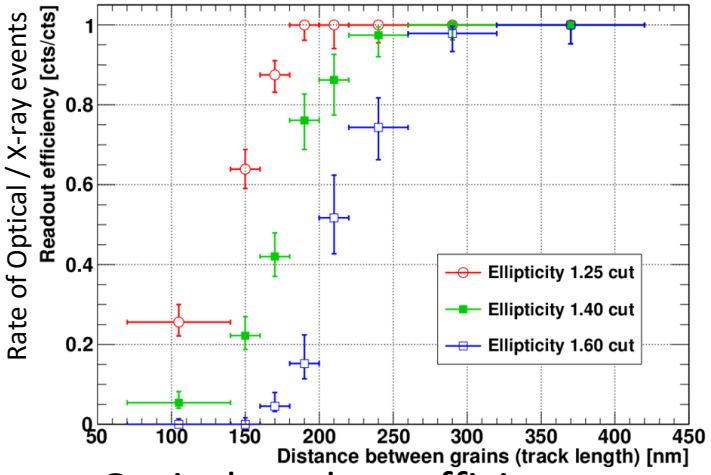
T. Naka *et al*., Review of Scientific Instruments 86, 073701 (2015)



Optical image for Kr^+ ions



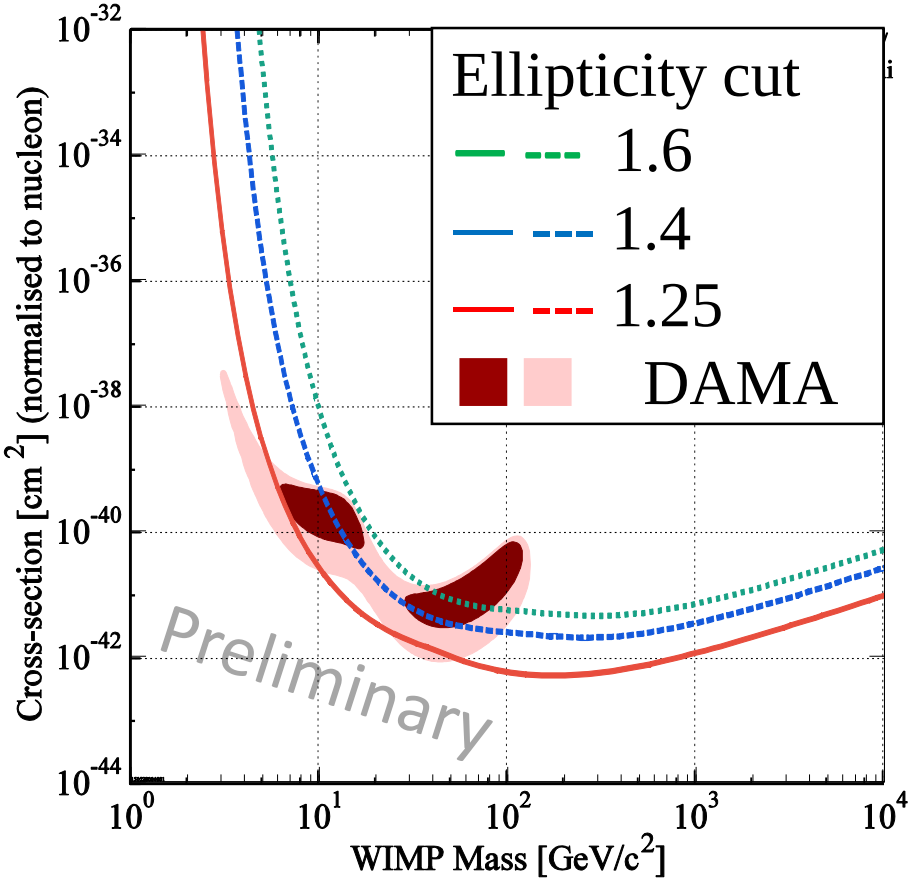
X-ray microscopic image
(using Spring-8, Japan)



Optical readout efficiency
as function of track length

Ideal sensitivity

- Need O(10) kg detector to investigate the DAMA region



Cross Section Limit (Zero background, 25 kg·year, 90% C.L.)

Background sources

- External components
  - neutron due to cosmic rays
  - radiation from radioactivity in bedrock → Underground Shield
- Internal
  - dusts in gelatin binder → Gelatin filtration
  - radioactivity in emulsion
    - U, Th series → Gelatin purification
    - ^{40}K → Replace KBr with NaBr
    - ^{14}C

$^{14}C \rightarrow {}^{14}N + \bar{\nu}_e + \beta$ (E_{max} = 154 keV)

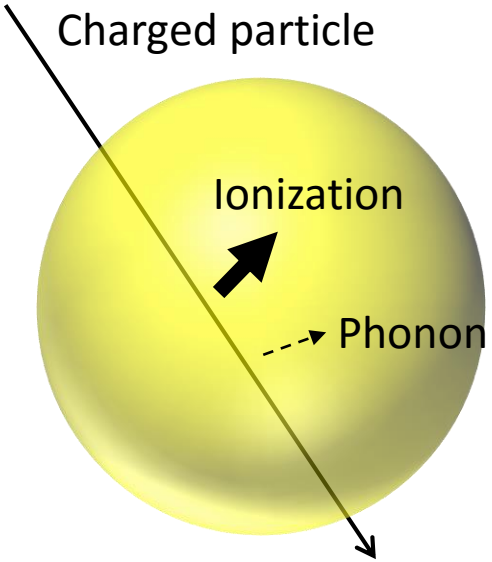
^{14}C in gelatin: 2×10^{6} $kg^{-1}day^{-1}$ (by AMS measurement)

→ (1) Use low activity polymer (PVA: < 3×10^{-3} $kg^{-1}day^{-1}$)

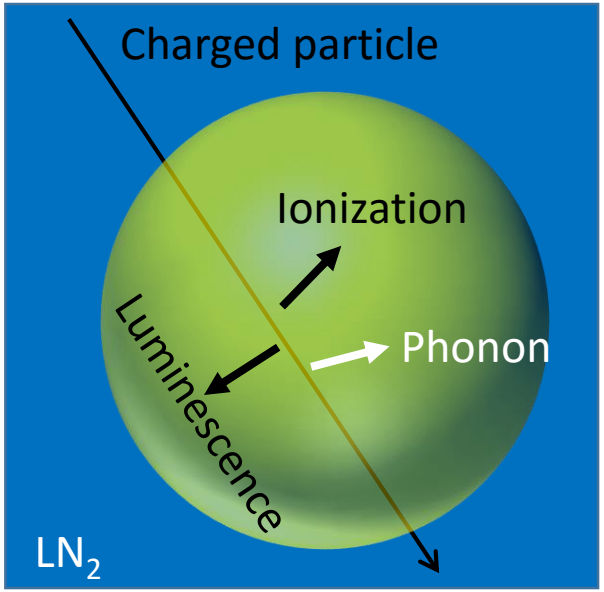
(2) Remove electron tracks by cryogenic approach

Concept of background rejection

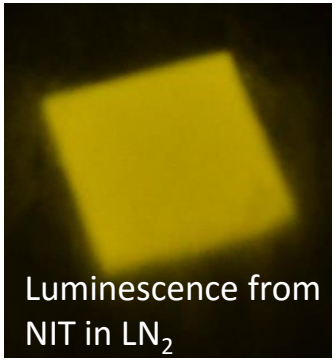
- Need electron rejection power of at least 10^{-9} to start a 10 kg experiment
- Cryogenic approach can elicit deep responses from a silver bromide crystal

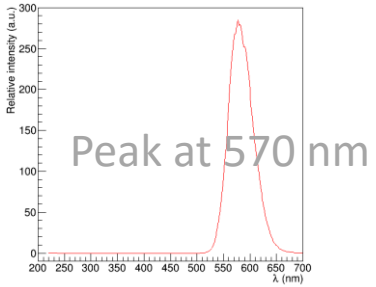


AgBr crystal in room temperature



In cryogenic temperature

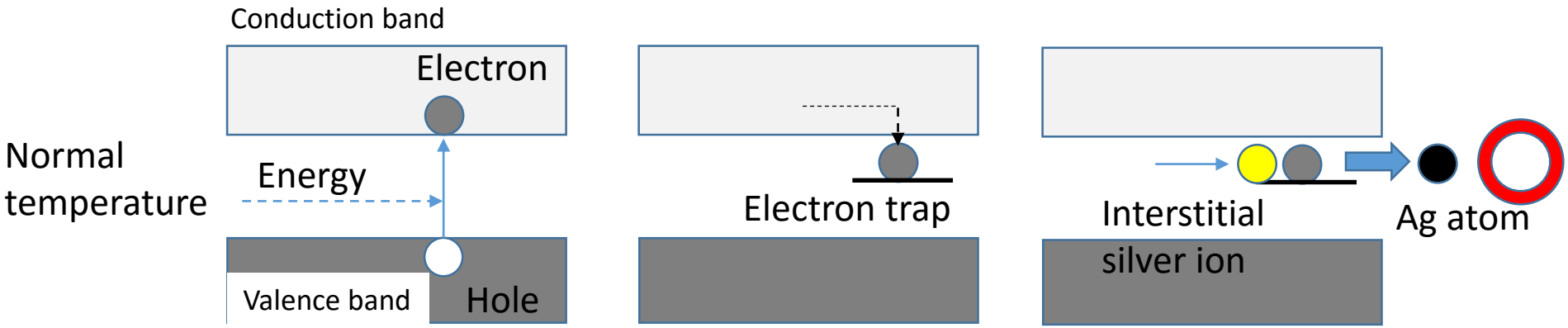




*W. Smart *et al*, Acta Phys.Polon. B17 (1986) 41

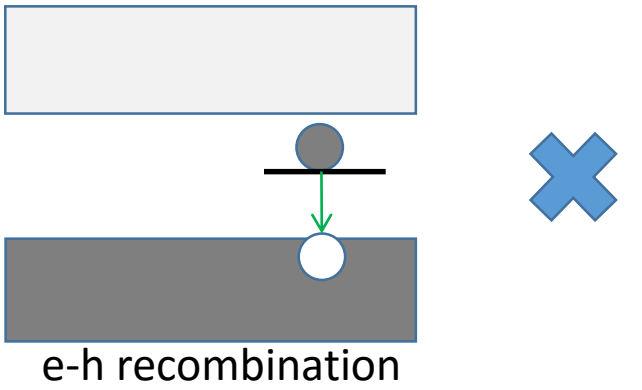
Emulsion sensitivity to electron at cryogenic temperature

- The sensitivity to electrons reduces with decreasing temperature



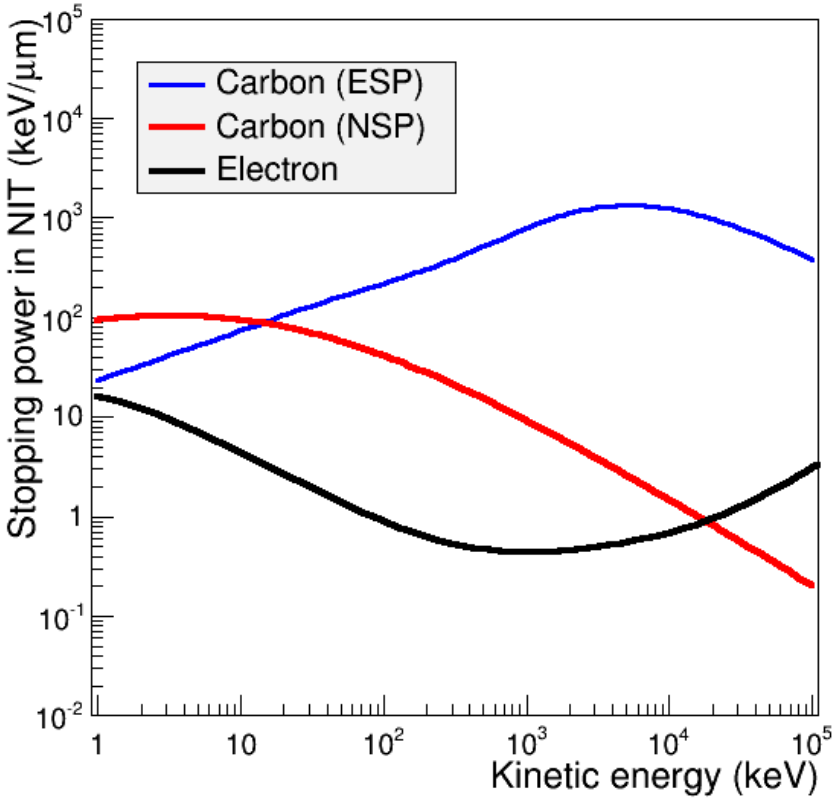
Cryogenic temperature

*Interstitial silver ions do not work at cryogenic temperature



Nuclear recoil track

- Nuclear recoil tracks have large stopping power



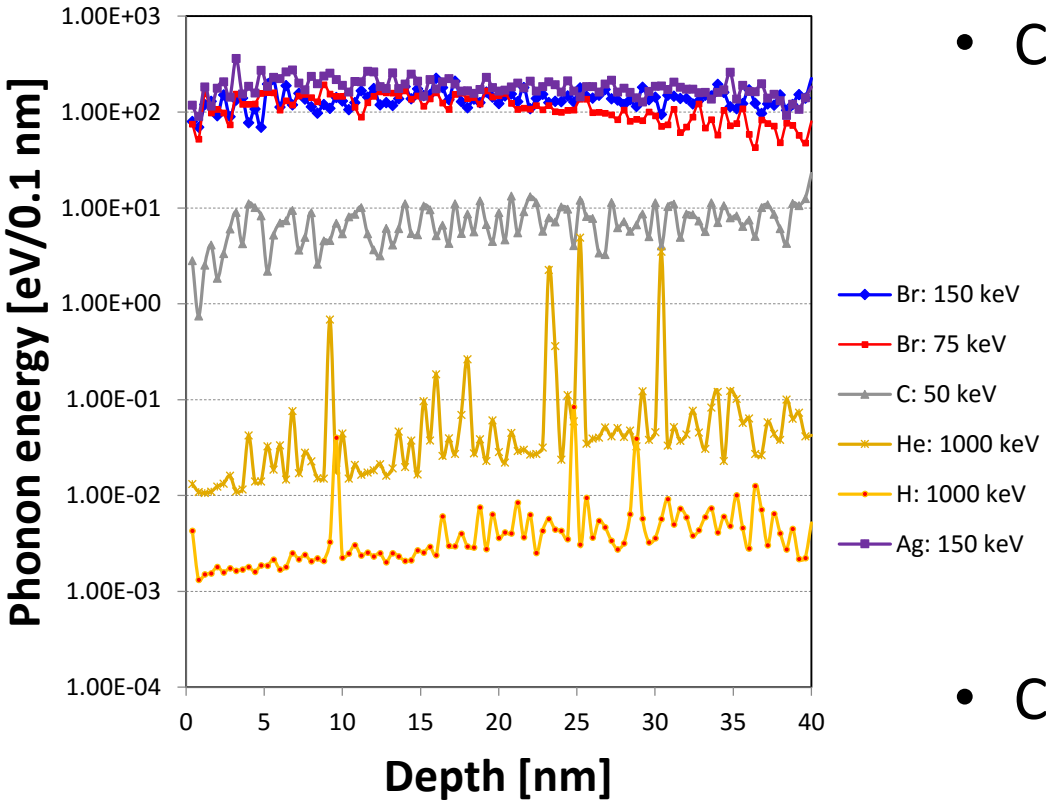
Stopping powers of C^{+} and electrons in NIT according to SRIM and ESTAR (NIST)

Total stopping power
= Electron stopping power (ESP)
+ Nuclear stopping power (NSP)

- Electron stopping power (ESP)
  - collision with electrons
    - ionization
- Nuclear stopping power (NSP)
  - collision with atoms
    - phonon
      - crystal temperature rise
    - lattice defect production

Temperature rise due to phonon effect

- Local temperature rise can recover sensitivity loss



Average phonon energy in 40 nm AgBr layer by various particles (simulated by SRIM)

- Case 1: Uniform temperature rise

	Total phonon energy in 40 nm [eV]	δT for 40 nm AgBr [K]
Ag (150 keV)	18600	58
Br (150 KeV)	13800	43
C (50 keV)	734	2.3
He (1000 keV)	15.9	0.050
H (1000 keV)	0.54	0.0017

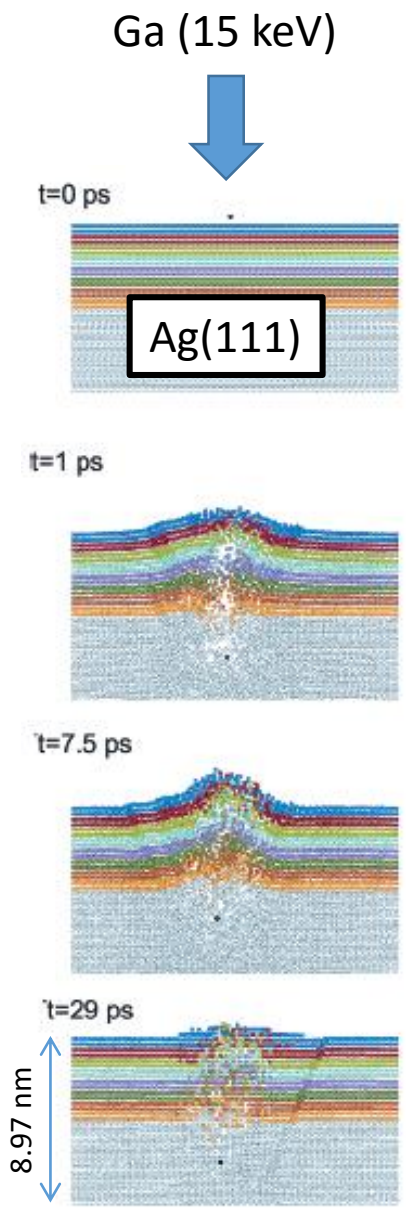
- Case 2: Local temperature rise

$\Delta T = 10^4$ K for 10^{-11} sec due to thermal spike*

*J.A. Brinkman, Journal of Applied Physics **25**, 961 (1954)

Lattice defect production

- Nuclear stopping power induces atomic displacement
  - produce lattice defect in a crystal*
  - the defect acts as a site of latent image formation
  - the site forms latent image specks efficiently and recover sensitivity



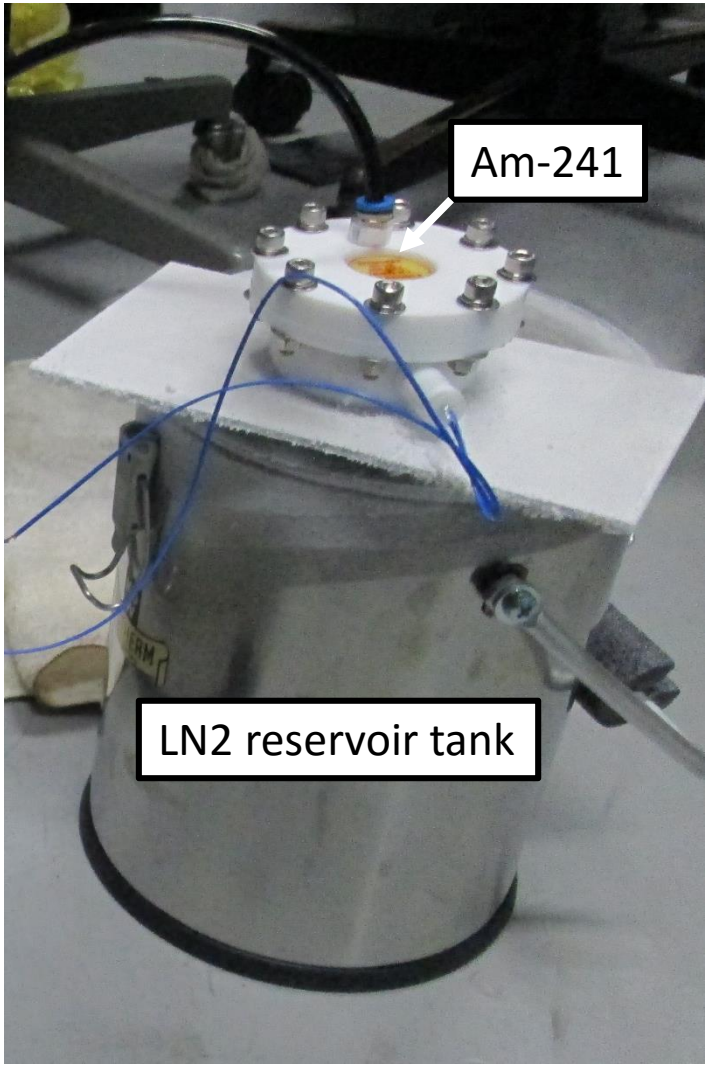
Atomic displacement by a Ga ion on molecule dynamics simulation
J. Phys. Chem. B 2004,108, 7831

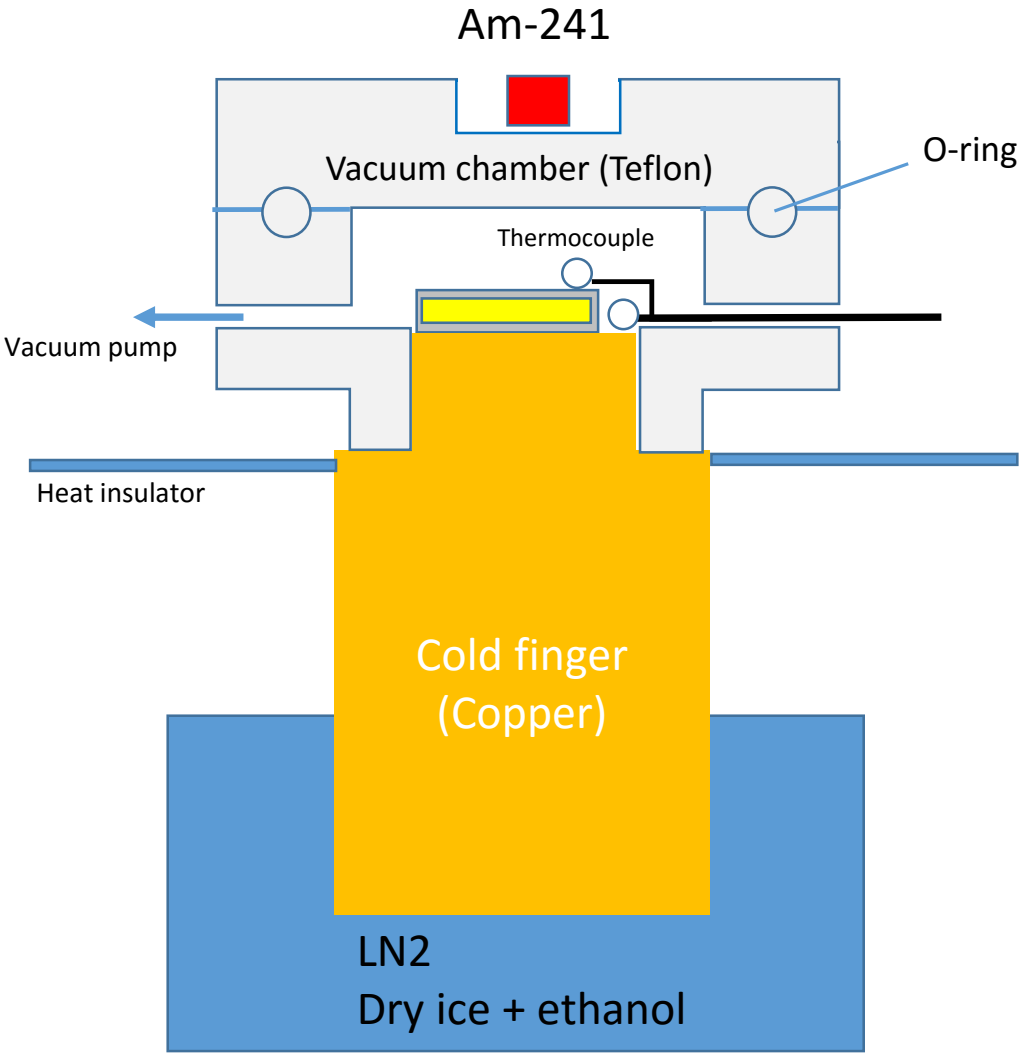
*T. Naka *et al.*, Jpn. J. Appl. Phys. 52 (2013) 112601

Test for sensitivity measurement

- Aim to quantify the effect of low temperature on the sensitivity to electron
- Experimental condition
  - Emulsion (with halogen accepter sensitization)
    - Nano Imaging Tracker (NIT) : 40 nm size AgBr crystal
  - Temperature : 77 – 293 K
  - Vacuum : less than 0.02 atm (water vapor pressure)
    - remove the fading effect
    - avoid accumulating frost on the surface
  - Radiation rays :
    - ^{241}Am(2.9 MBq) : 20 and 60 keV γ

Experimental arrangement

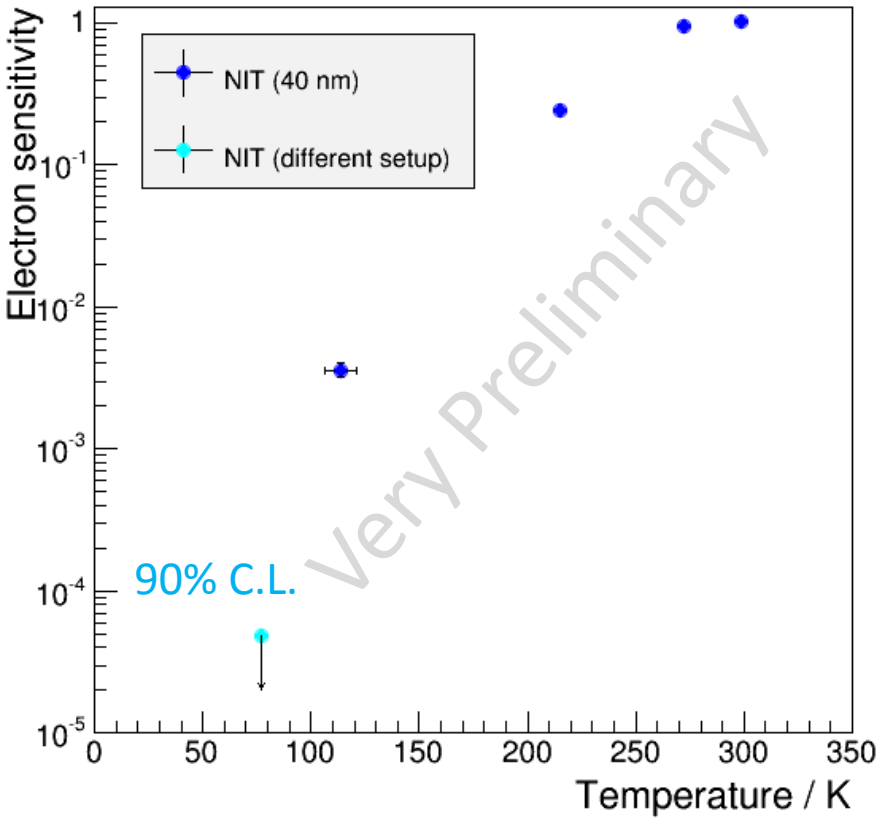




Cross section view of the cryostat

Sensitivity to electron

No sensitivity to electron(ESP 15 keV/μm) at LN_2 temperature



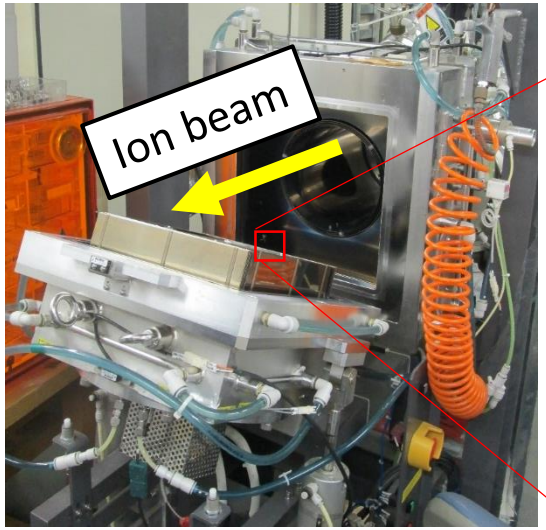
- Development condition
  - MAA 5 °C 10 min
  - Without post-fixed physical development (PPD)
- Evaluation method
  - Count the number of grains in 1000 μm^3 by visual inspection
  - Calculate ratio to the expected number of electrons per 1000 μm^3

Electron rejection power will be roughly the squared sensitivity

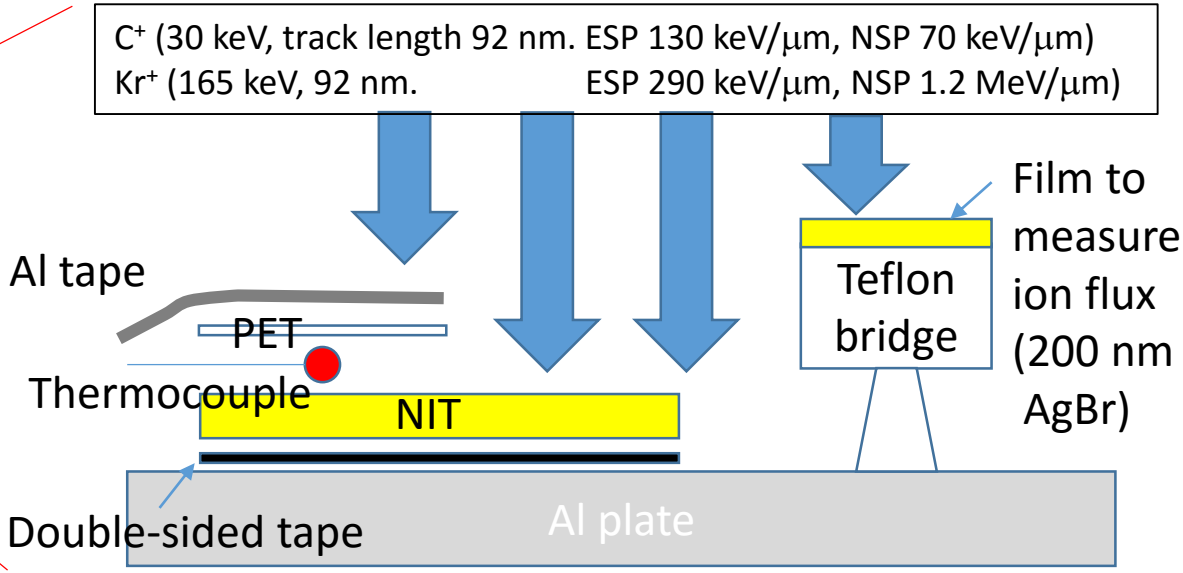
$< (5 \times 10^{-5})^2 = 3 \times 10^{-9}$ at 77 K.

Sensitivity measurement for ions

- Aim to measure the sensitivity to light and heavy ions at cryogenic temperature
- Use an ion implant system at Kanagawa University
  - Emulsion temperature reaches to 93 K (-180 °C)



Ion implant system
at Kanagawa University



Cross section view of setup

Sensitivity to ions

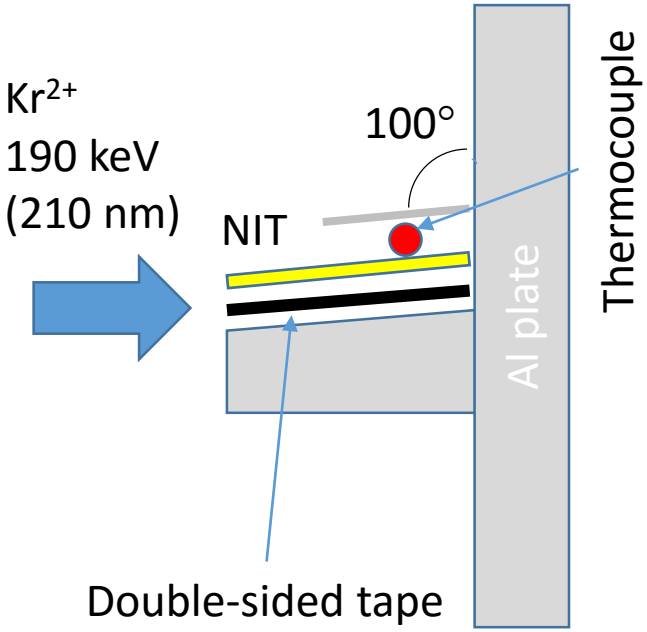
- Prepare treated PPD- and untreated PPD samples
  - PPD increases the size of grains to be easily observed
    - indicates intrinsic detection efficiency
- Measure the number of grains per cm^2 by eye

Kr^+ 165 keV	Measured (cm^{-2})	Detection efficiency
Flux monitor	$(11.0 \pm 0.3) \times 10^7$	-
Without PPD	$(1.31 \pm 0.08) \times 10^7$	0.119 ± 0.008
With PPD	$(3.0 \pm 0.2) \times 10^7$	0.28 ± 0.02

C^+ 30 keV	Measured (cm^{-2})	Detection efficiency
Flux monitor	$(9.9 \pm 0.3) \times 10^7$	-
Without PPD	$(0.71 \pm 0.04) \times 10^7$	0.072 ± 0.005
With PPD	$(1.29 \pm 0.09) \times 10^7$	0.13 ± 0.01

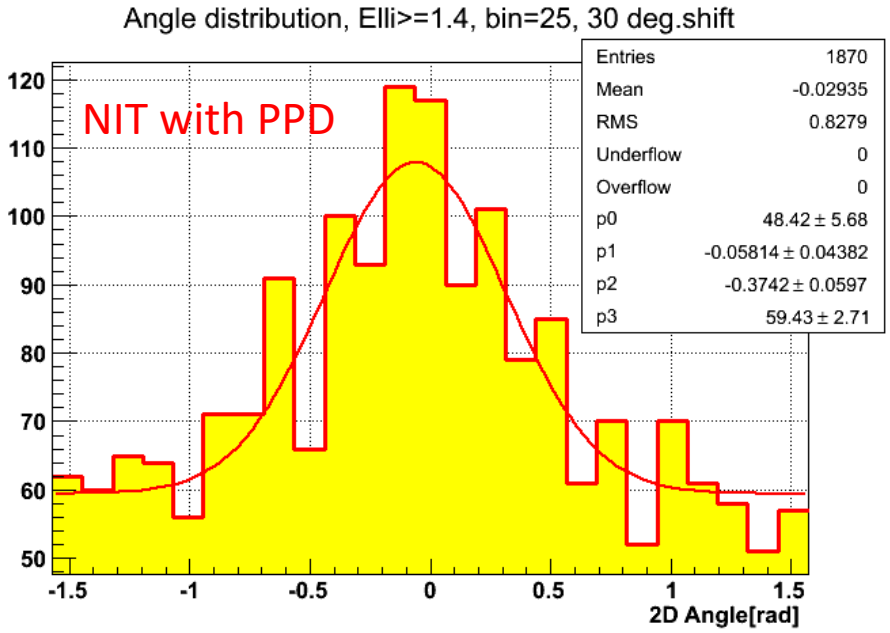
Ion tracking with cryogenic nuclear emulsion

- Aim to measure angular distribution at cryogenic temperature
- Exposure condition
  - Emulsion temperature: 95 K (-178 °C)
  - Ion type: Kr^{2+} with 190 keV
    (track length = 210 nm)
  - Exposure density: 1 x 10^9 cm^{-2}



Angular distribution in NIT

- Treated PPD
- Scan the sample by the automatic scanning system
- Enable to measure track angle at cryogenic temperature



Temperature	Beam	Angular resolution
293 K	C^{+} 80 keV (expected range 240 nm)	0.41 ± 0.01 rad
95 K	Kr^{2+} 190 keV (210 nm)	0.37 ± 0.06 rad

* Both samples are treated PPD

Conclusions

- Fine-grained nuclear emulsion is a promising detector for directional dark matter search
- We propose cryogenic approach to remove electron background events coming from ^{14}C decays
- For proof of principle we irradiated NIT with γ rays and ions at LN_2 temperature

  - no sensitivity to electron

  - NIT has sensitivity to low speed ions (C^+, Kr^+)

    - not concordant with the simplest hypothesis (uniform temperature rise)

  - track angle can be measured

Future prospects

- Preparation of emulsion dark matter experiment is under way at LNGS underground

  - a 1 kg experiment will start from Oct. 2018

- We will measure emulsion properties to propose introducing the cryogenic approach

  - tracking efficiency as function of energy

  - long term stability at cryogenic temperature

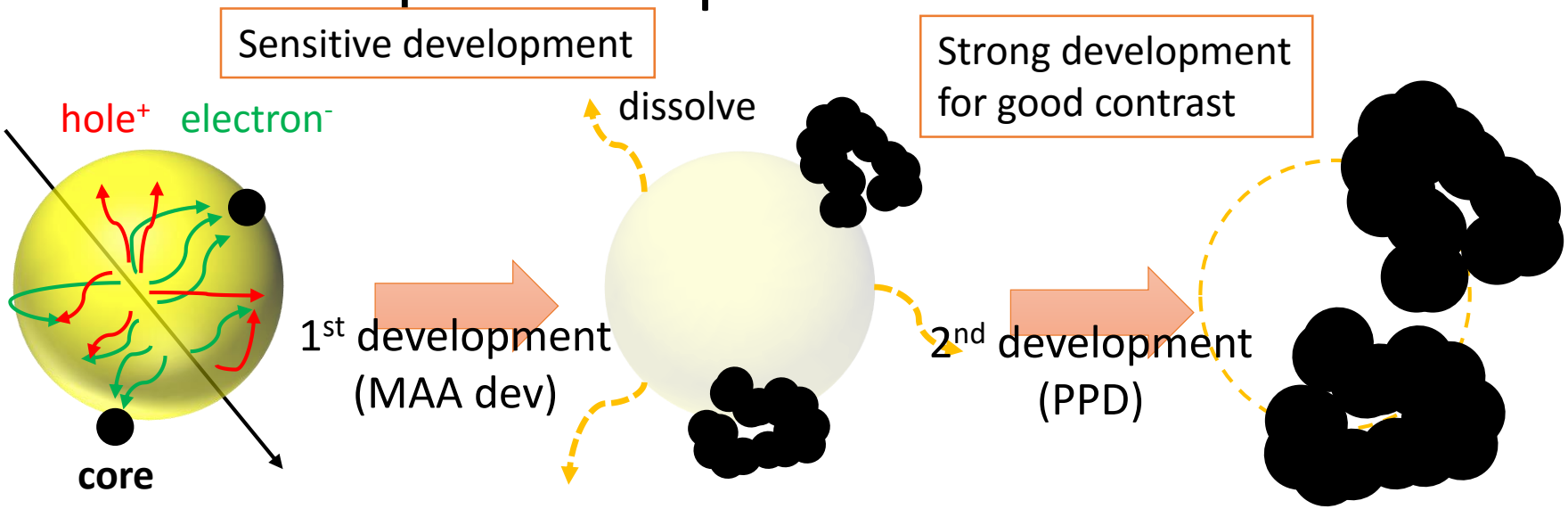
    (mechanical stress, sensitivity, fog noise …)

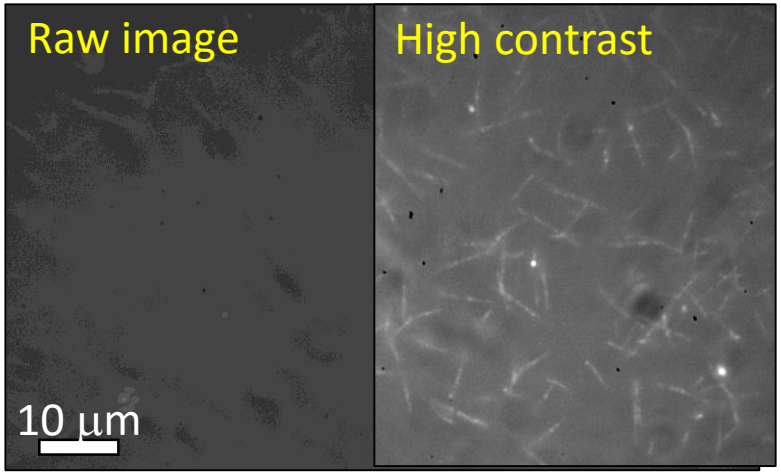
  - study cooling method for a 1 kg emulsion

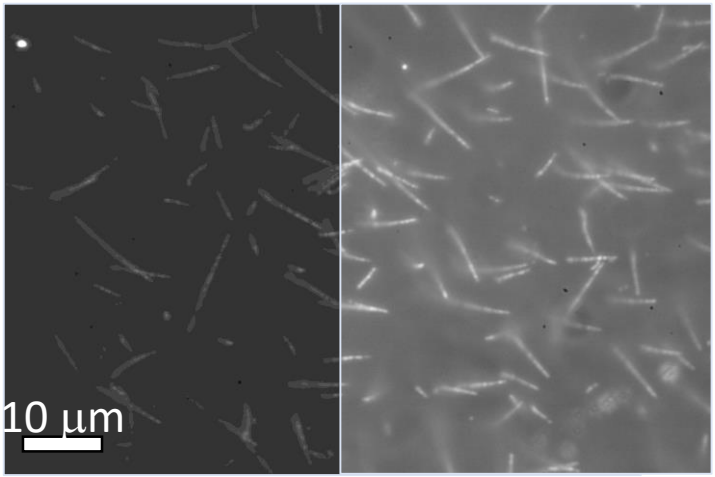
Acknowledgement

- We would like to thank Prof. Dr. Nakata and his students at Kanagawa University for the ion exposures
- We appreciate helpful discussions with Dr. Tani and Prof. Dr. Kuge

Development process

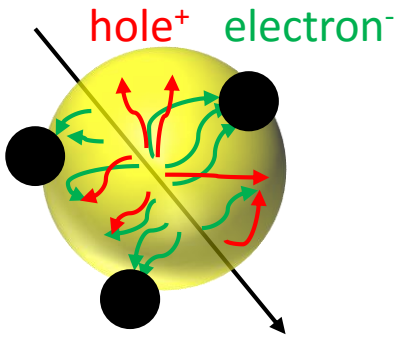




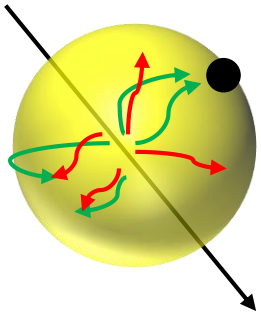


α tracks from Am-241

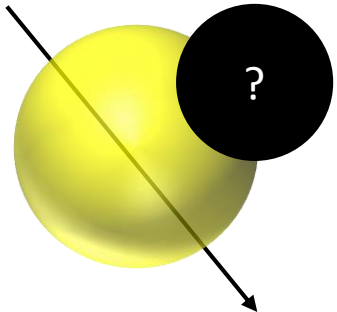
Type of event sources



- Signal events (recoil nuclei)
  - dE/dx : 100 – 1000 keV/μm
  - Many e-h pairs → strong signal



- Background event (electron)
  - dE/dx : 1 – 10 keV/μm
  - A few e-h pairs → weak signal



- Noise event (thermal excitation, dust)
  - Thermal excitation: random single grain
  - Dust: strange shape (not round)

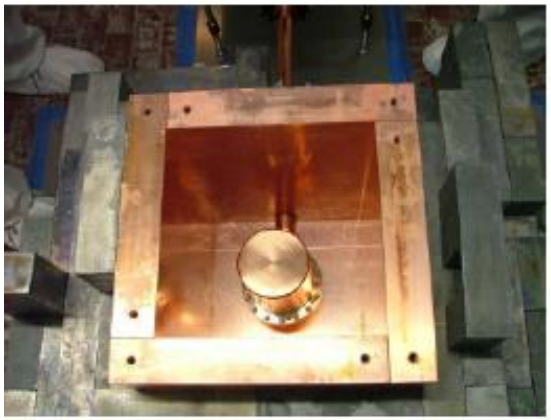
Radioactivity measurement @ LNGS

1. ICP-MS
   - ✓ HR-ICP-MS
   - ✓ ICP-QMS

Concentration of Th, U for AgBr▪I, gelatin, PVA and polystilen

2. Ge detector

		Total and peak background count rate [/day]			
Detector	Volume (cm^3)	60-2700 keV	352 keV	583 keV	1461 keV
GePv	363	951	5.6	3.7	6.4
GeCris	468	221	<0.9	<0.6	2.9
GeMPI	413	70	<0.3	<0.2	0.7



C. Arpesella et al., Astropart. Phys. 18 (2002) 1-25

Supported by S. Nisi (LNGS) , C. Galbiati (Darkside)

electron background

Ge spectroscopy in LNGS (Italy)

Type	gelatin	AgBr crystal
^{228}Ra (mBq/kg)	< 1.3	< 12
^{228}Th (mBq/kg)	20 ± 2	< 5.5
^{226}Ra (mBq/kg)	2.4 ± 0.6	< 8.9
^{234}Th (mBq/kg)	< 79	< 220
^{234m}Pa (mBq/kg)	< 44	< 590
^{235}U (mBq/kg)	< 1.8	< 9.2
^{40}K (Bq/kg)	< 0.0087	0.05 ± 0.02
^{137}Cs (mBq/kg)	2.2 ± 0.5	< 6.3
^{60}Co (mBq/kg)	-	-
^{108m}Ag (mBq/kg)	-	49.3 ± 3.9
^{110m}Ag (Bq/kg)	-	2.96 ± 0.15

^{228}Ra, ^{40}K	$(0.4 - 6.2) \times 10^4$ /kg/day
^{110}Ag	2.5×10^5 /kg/day
^{14}C	1.7×10^6 /kg/day (NA)

10^{-6} rejection power for electrons is required

neutron background

Neutron from inside

Process	SOURCES simulation $[n \cdot kg^{-1} \cdot y^{-1}]$
(α, n) from ^{232}Th chain	0.11±0.03
(α, n) from ^{238}U chain	0.24±0.07
Spontaneous fission	0.75±0.22
Total flux	1.10±0.32

Nuclear recoil induced by neutrons
(> 100 nm tracks)
⇒ 0.065 $kg^{-1}year^{-1}$

Environmental neutron

Studies of the flux measurement and shielding plan are in progress

Other neutron sources

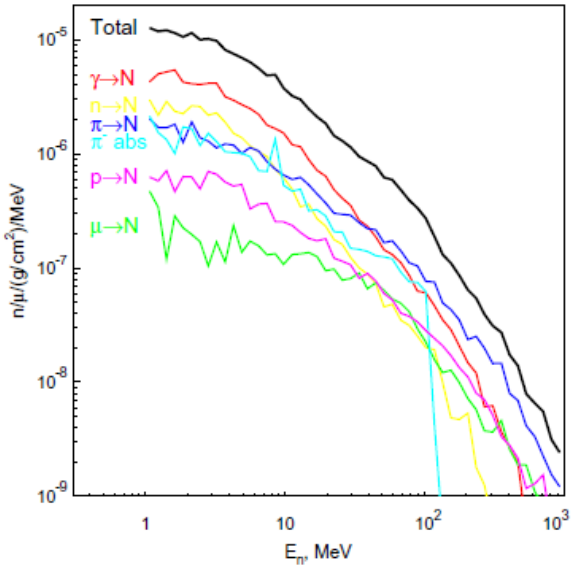
- Neutrons from enviromental radioactivity

Should be reduced to a negligible level with appropriate shielding; to be studied.

- Cosmic muon-induced neutrons

Under evaluation; in underground sites is expected be less than the one from intrinsic radioactive contamination (preliminary rough estimation)

Differential energy spectrum of neutrons produced by 280 GeV muons



Plot from A. Lindote et al., Astroparticle Phys.31 (2009) 366

Approximations and assumptions:

Neutron differential spectrum: 10^{-5} n/μ/g/cm^2/MeV

Material used in the simulation is C_nH_{2n}

20 kg of emulsions

Muon flux: 1/m^2/h

Neutron flux: 0.18 n/y/MeV → 0.009 n/kg/y/MeV

With a rough integration from 0 to 10 MeV → about 0.05 n/kg/y

Emulsion composition

Element	Mass fraction	Atom fraction
Ag	0.46302	0.1227
Br	0.3388	0.1216
I	0.0112	0.0025
C	0.0722	0.1706
O	0.0724	0.1283
N	0.0281	0.0569
H	0.014	0.3970
S	0.00031	0.0003

Costituent	Mass fraction
AgBrI	0.813
Gelatin	0.1253
PVA	0.0617

Weighting by mass fractions (Polystyrene is negligible)

Total contamination from ^{238}U: 1.75 ppb (21.6 mBq/kg)

Total contamination from ^{232}Th: 1.18 ppb (4.8 mBq/Kg)

Purification

- K-40

Main source : $AgNO_3$ + **KBr** → AgBr + K^+ + NO_3^-

⇩

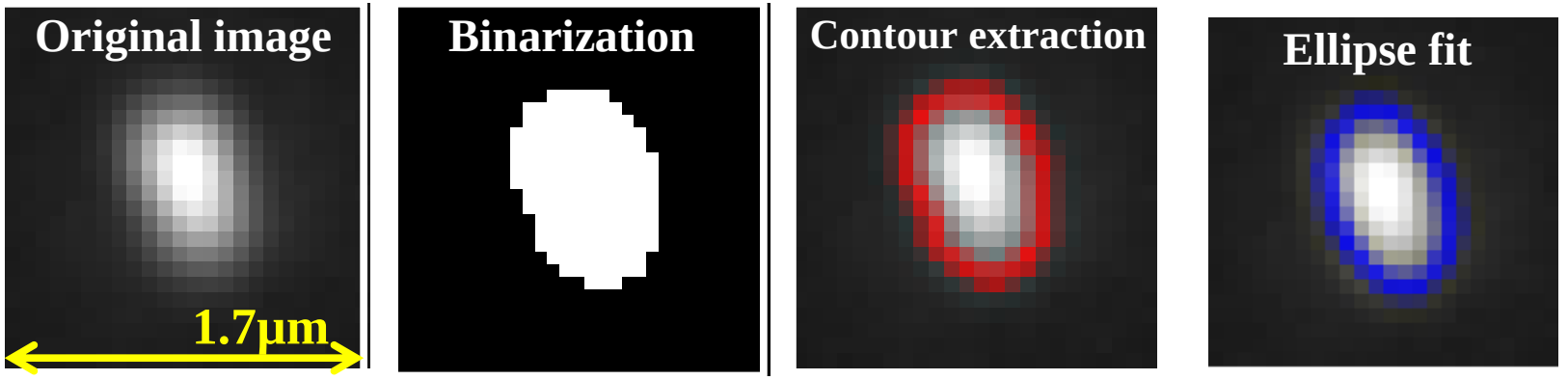
$AgNO_3$ + **NaBr** → AgBr + Na^+ + NO_3^-

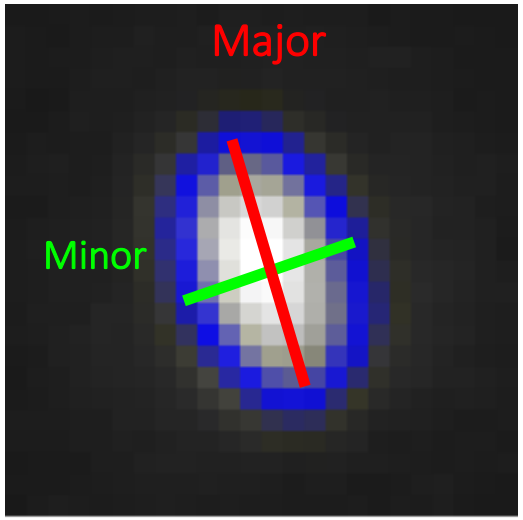
- pure-gelatin (Highly deionized gelatin)

→ remove cation and anion

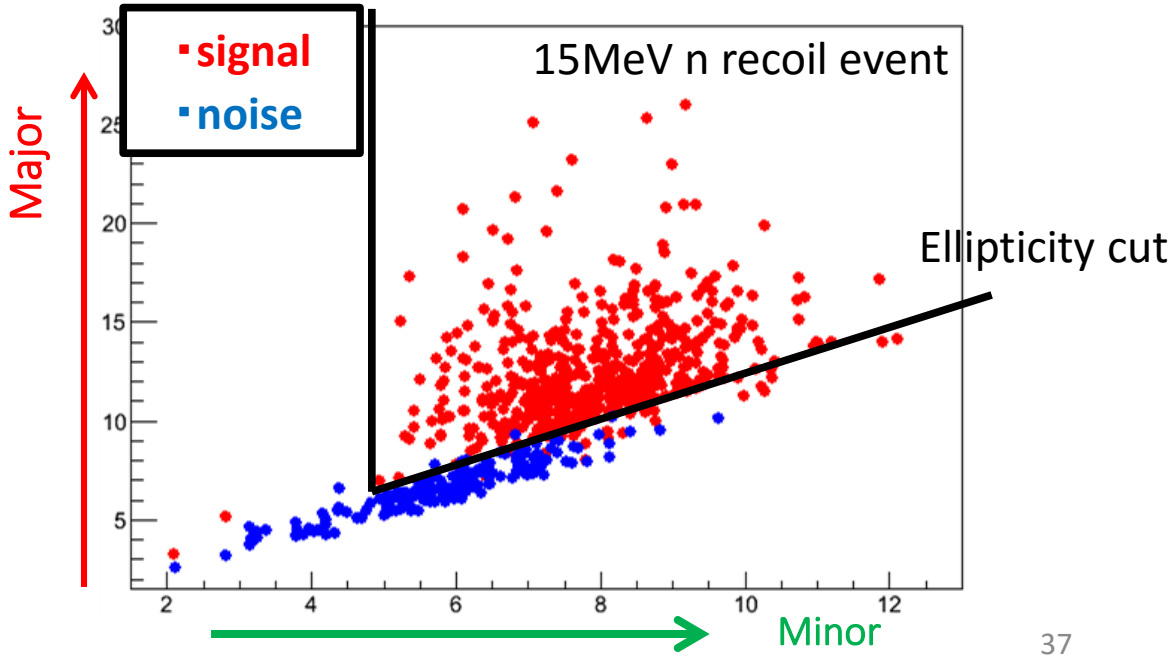
	Ca	Cl	Fe	Mn	Pb	Zn	NO_2	SO_4	NO_3
イナートゼラチン(Crushed Bone)	2800	530	5.0	0	—	1.0	0	360	0
〃 (Green Bone)	3600	2630	5.0	0	—	1.0	0	370	50
脱イオンゼラチン(Green Bone)	0.6	9	2.6	0	0	0	0	4	0

1st selection : Contour Recognition





Ellipticity = Major / Minor



Specific heat of silver bromine (bulk type)

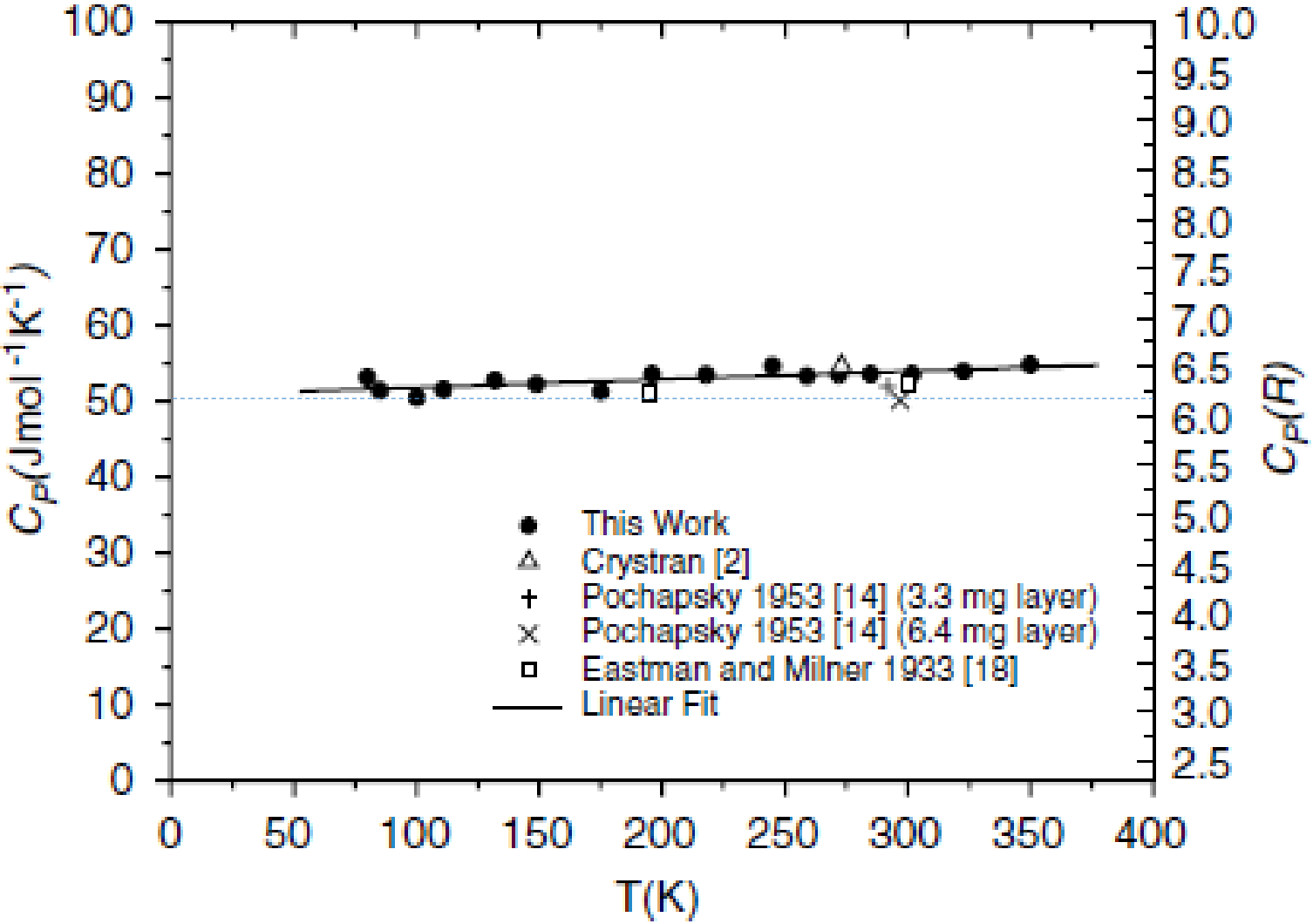


Figure 2. Heat capacity at constant pressure (C_P) of AgBr as a function of temperature ($R = 8.314\,\mathrm{J\,mol^{-1}\,K^{-1}}$) along with the reported data.

* K. Kamran *et al.*, J. Phys. D : Appl. Phys. 40(2007)869-873

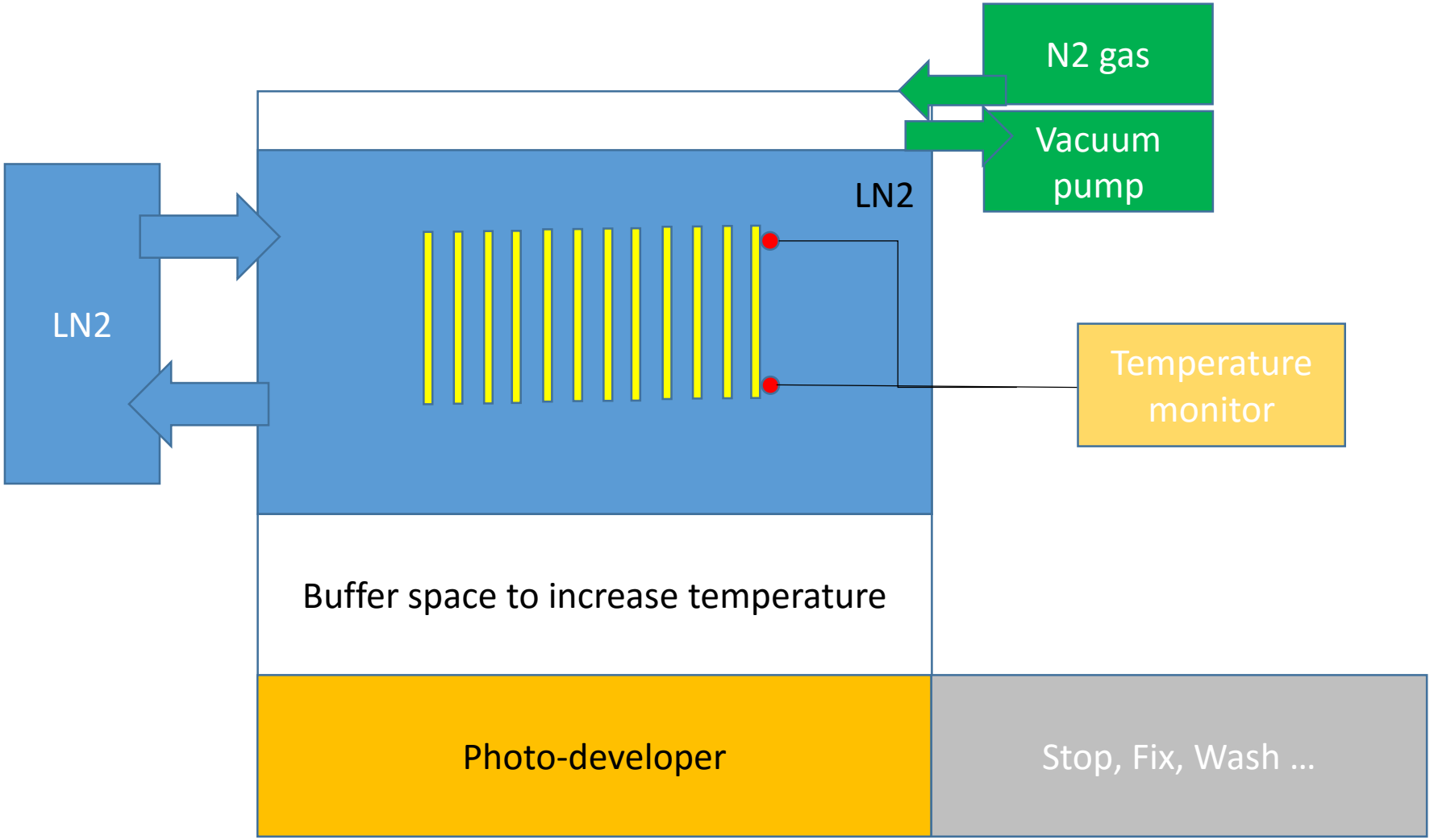
Applications of luminescence

(To be investigated fundamental properties)

- For DM
  - position trigger for large size emulsion detector
  - nuclide identification
- For other experiments
  - time resolution ($\rightarrow$ the AEgIS experiment)
  - fluorescence emission solid-type tracking detector
    + super resolution technique (e.g. STORM)

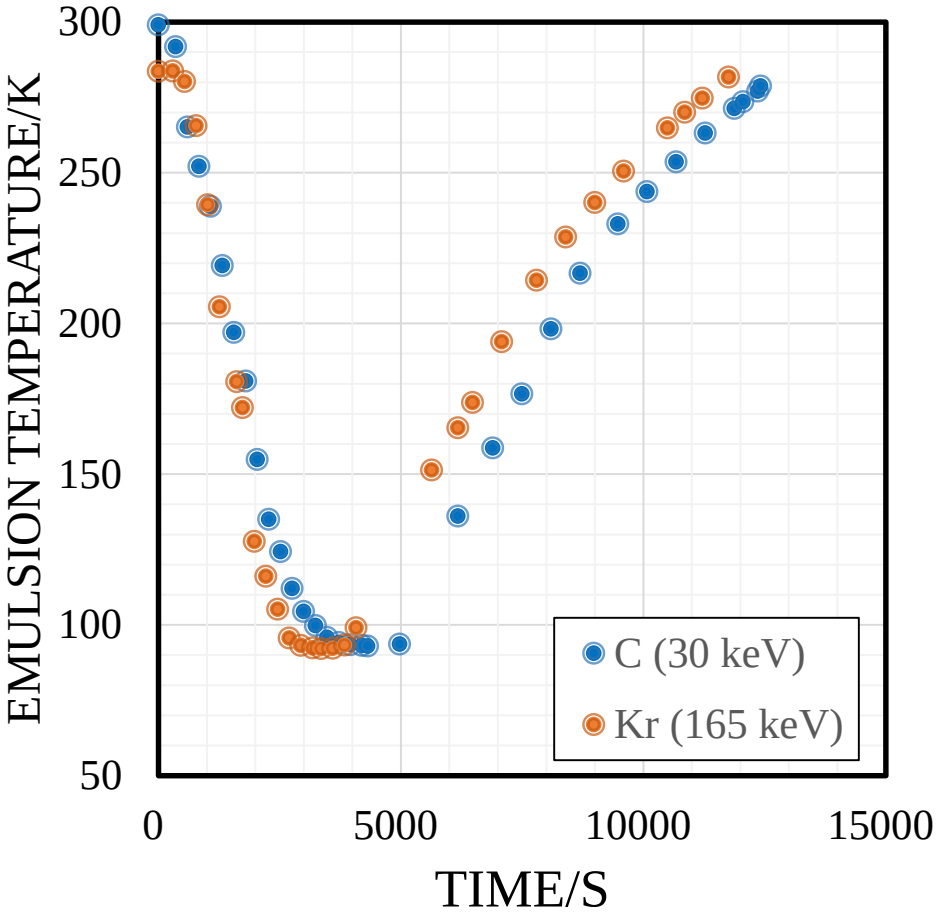
Possible design

Soak emulsion films in LN2 directly → good mass scalability



Emulsion temperature

- Temperature reaches to 93 K (-180 °C)



1 hour to cool down
3 hours to warm up