Toho University

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

Dark Matter Search Experiments with High-Resolution Nuclear Emulsion Tracker for Ultra-Short Tracks and Recent Application Developments

Takashi Asada

Toho University

On behalf of NEWSdm collaboration

The NEWSdm experiment

NEWSdm

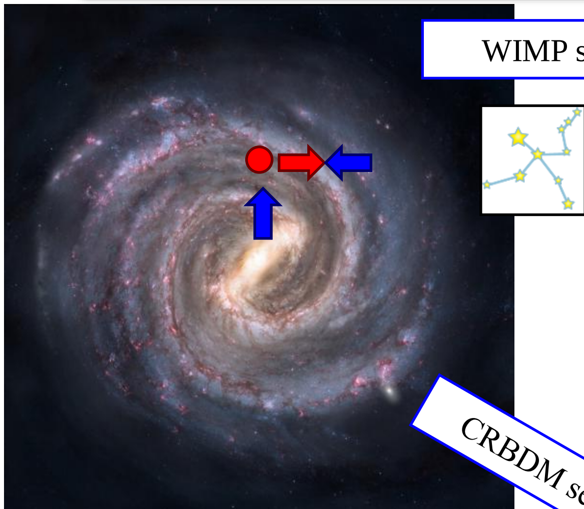
Nuclear Emulsions for WIMP Search with Directional Measurement

Website:
news-dm.lngs.infn.it

Letter of intent:
https://arxiv.org/pdf/1604.04199.pdf

- Direct dark matter search with **directionality**
- Target: **nuclear emulsion film**
- Combination of **high-speed** scanning / **high-precision** scanning
- Current status: analysis of pilot run and system update toward scale up
- Goal
  - 10 kg·year → DAMA region
  - 10–100 ton·year → neutrino floor

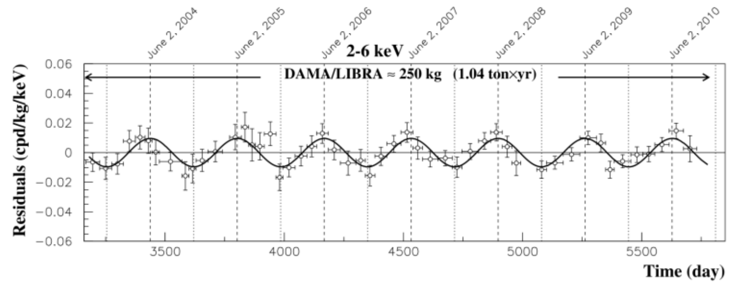
Direct Dark Matter search and directionality



WIMP search

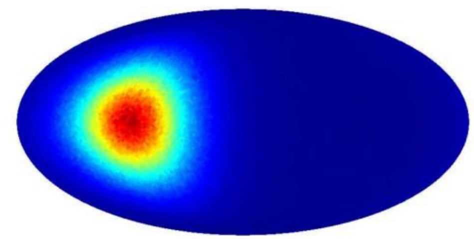
CRBDM search

Annual modulation



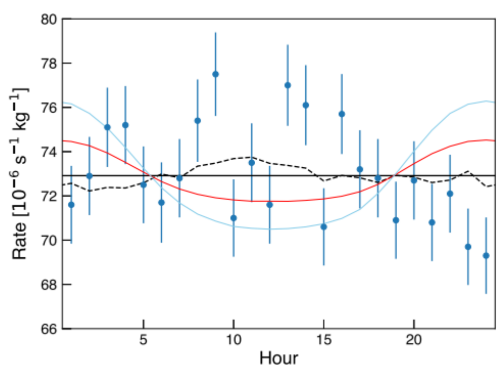
DAMA/LIBRA
R. Bernabei et al., Eur. Phys. J. C (2013) 73:2648

CYGNUS anisotropy



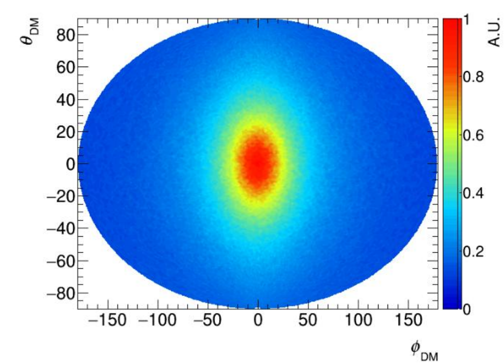
(J. Billard et al.(2010))

Diurnal modulation



PROSPECT
M. Andriamirado *et al.* Phys. Rev. D **104**, 012009 (2021)

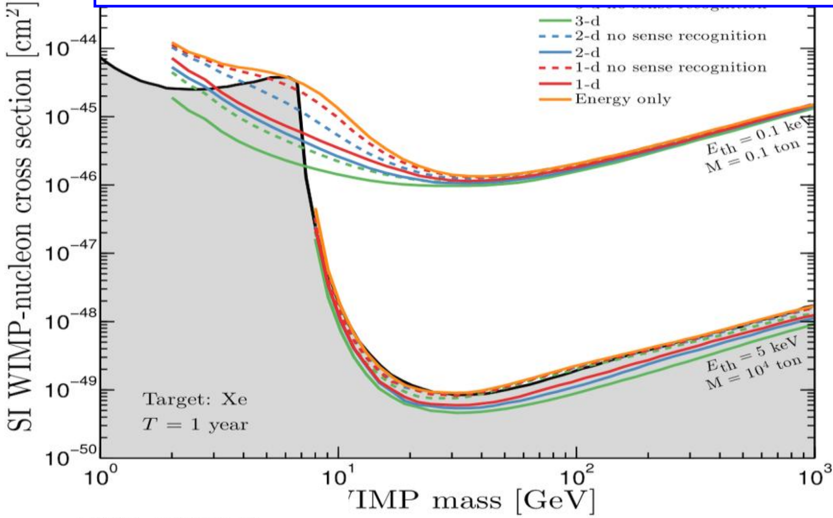
GC anisotropy

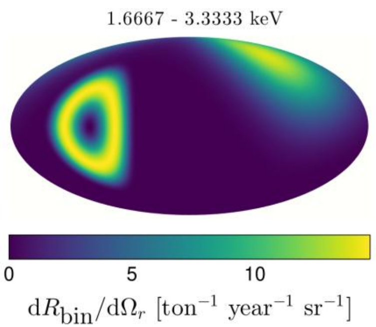


Keiko I. Nagao *et al* JCAP07(2023)061

The Advantage of Directionality for dark matter search

Overcoming the Neutrino Floor

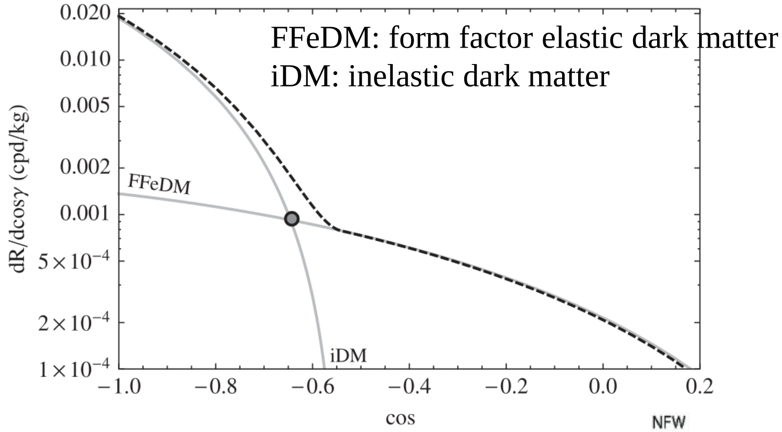




1602.03781(2016)

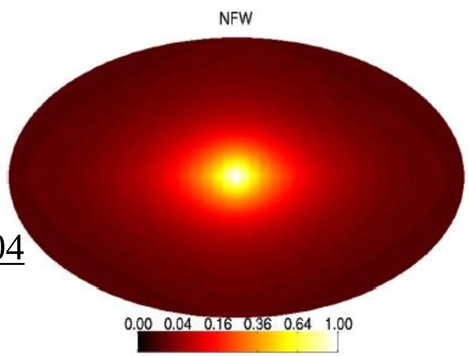
Directional property

PHYSICAL REVIEW D **81,** 096005 (2010)



Boosted dark matter

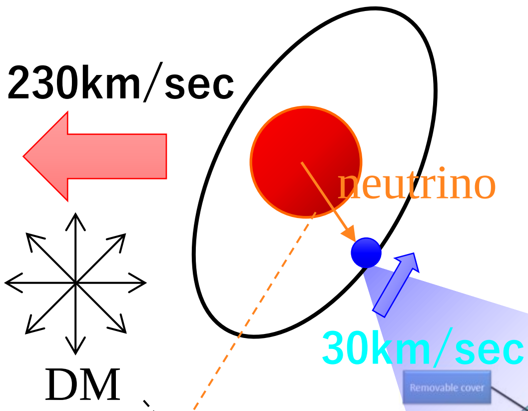
10.1103/PhysRevLett.126.091804

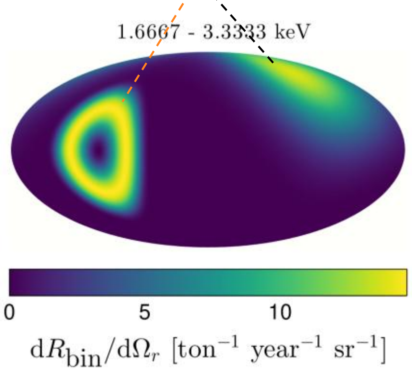


- Unique possibility to overcome the "neutrino floor", where coherent neutrino scattering creates an irreducible background
- Directional information is helpful in understanding the DM model

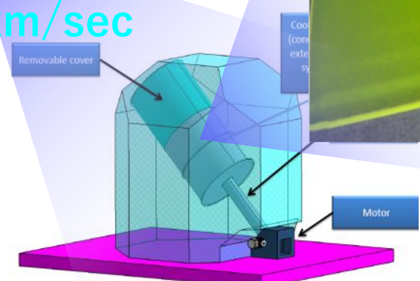
NEWSdm

Nuclear **E**mulsions for **W**IMP **S**earch -**d**irectional **m**easurement

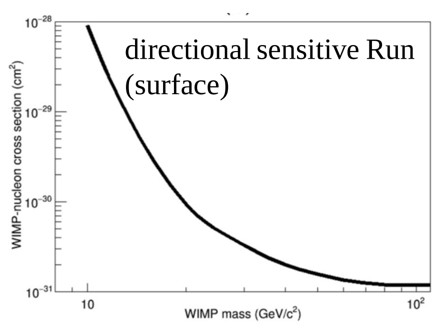




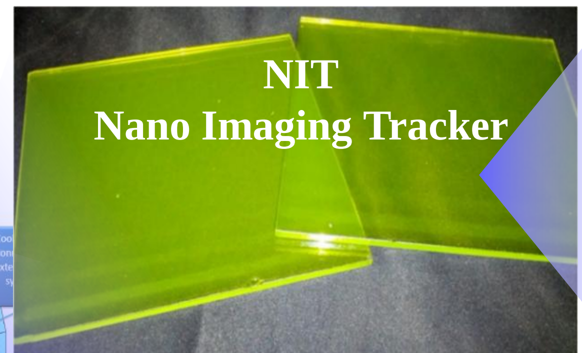
1602.03781(2016)

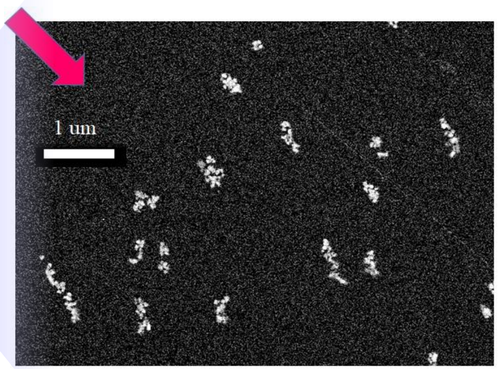


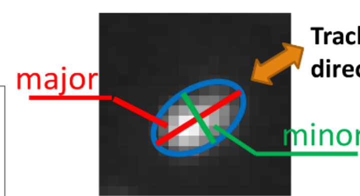
Equatorial mount



Super-resolution nuclear emulsion and sub-micron tracking







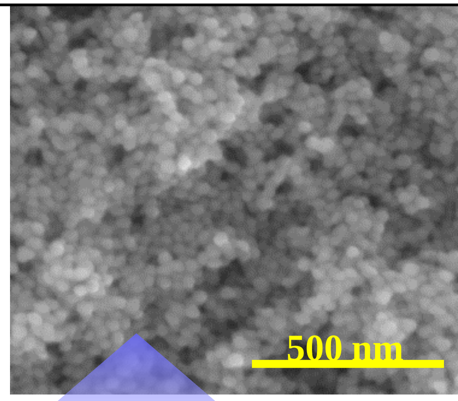
Ellipticity = $\frac{major}{minor}$

high speed & high resolution readout System by optical microscope

Direct dark matter search with directional sensitivity

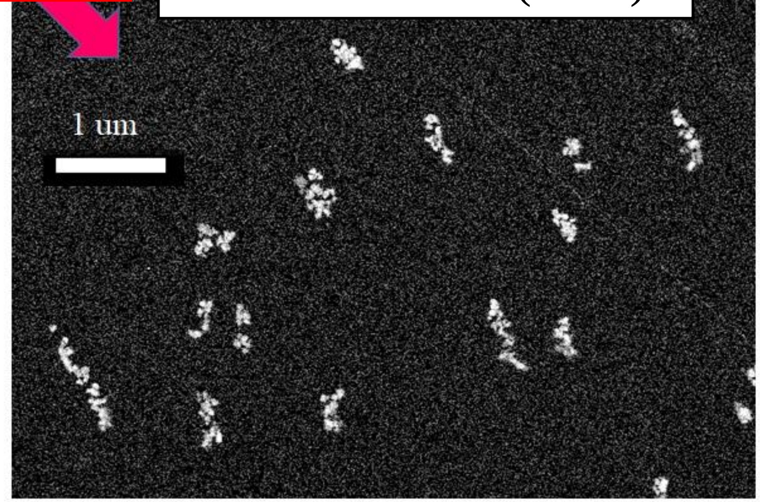
Nuclear emulsion

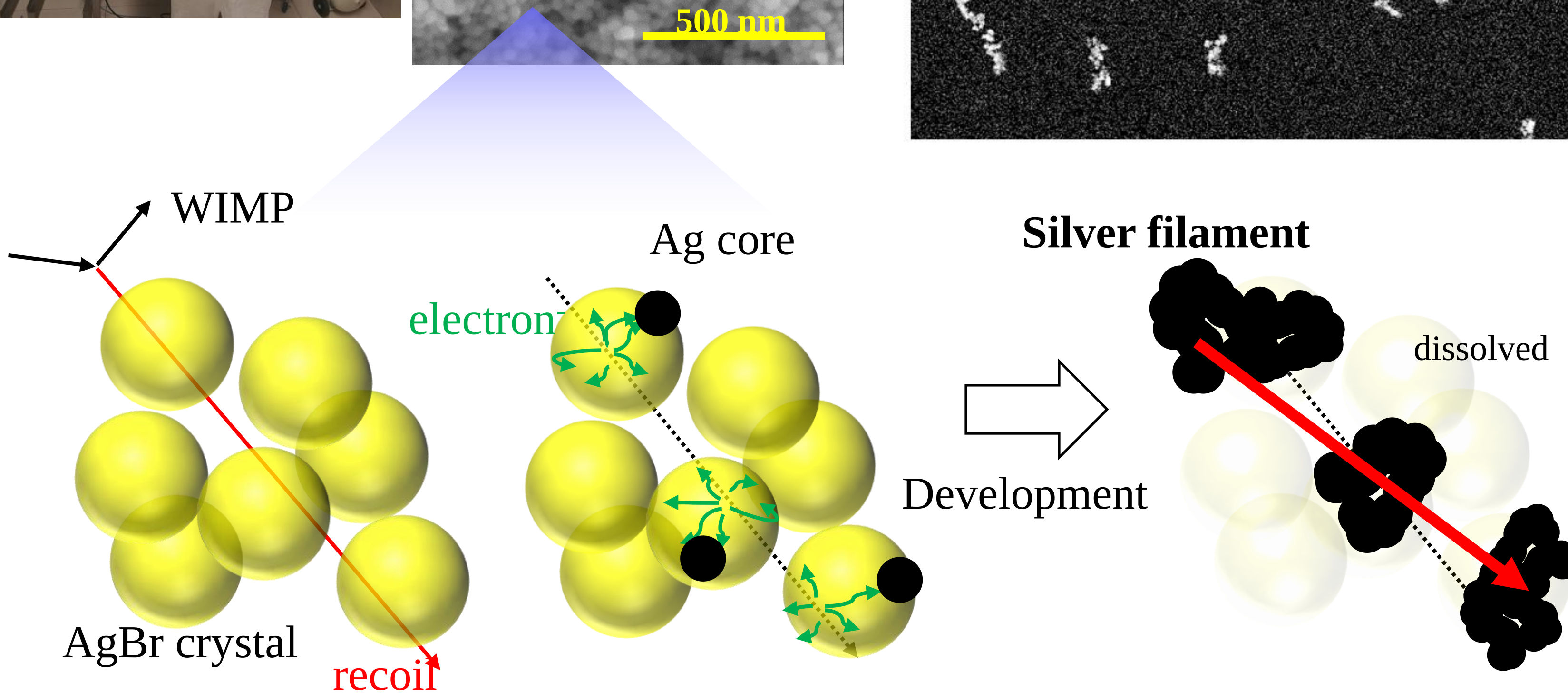
AgBr(I) Crystals (SEM)



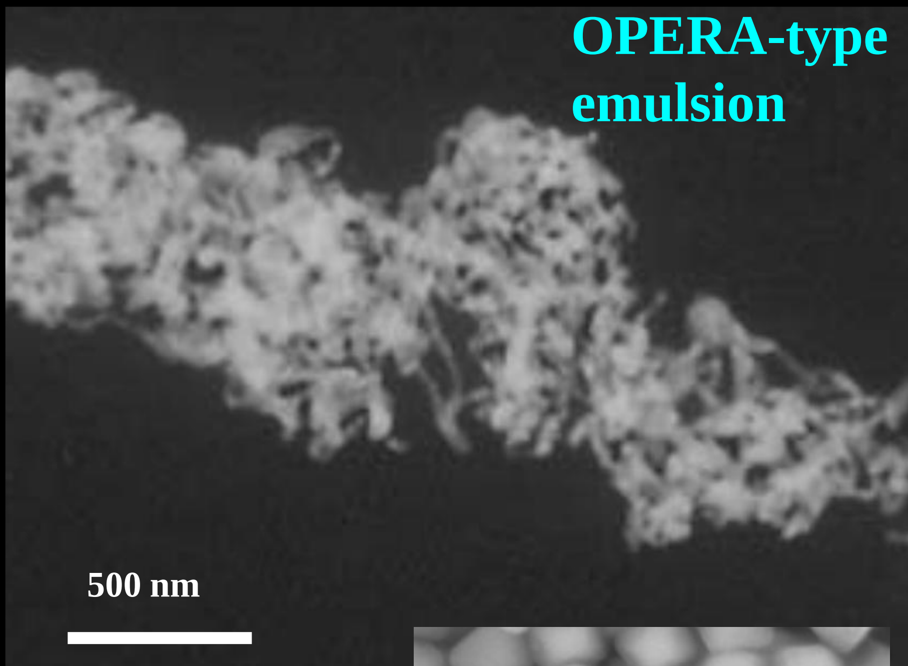
^{12}C ion

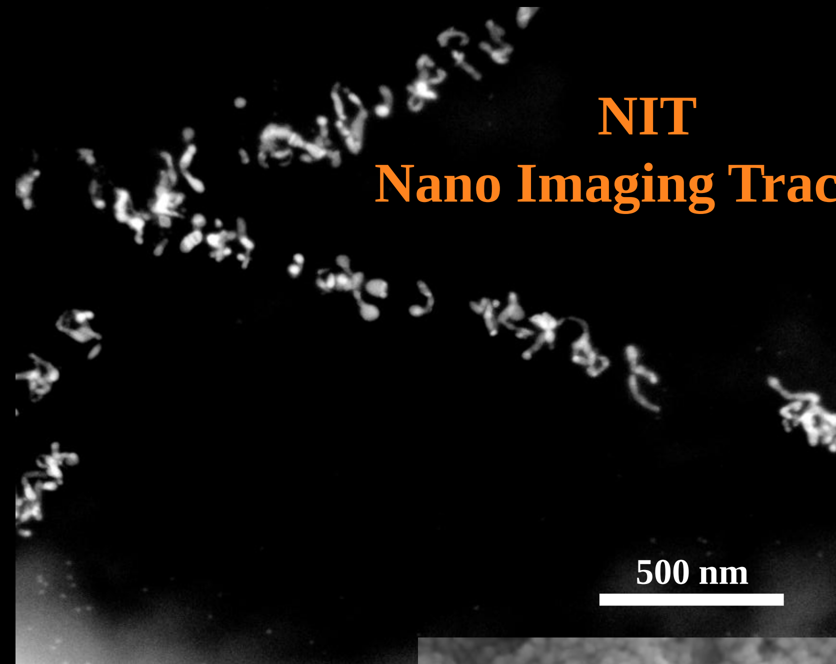
Detected tracks (SEM)



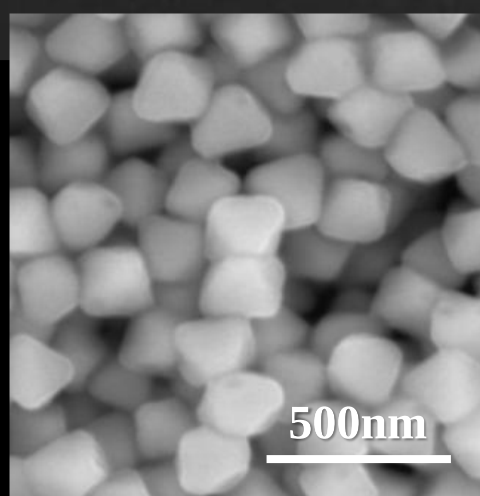


Electron microscope image (α-ray, crystal)

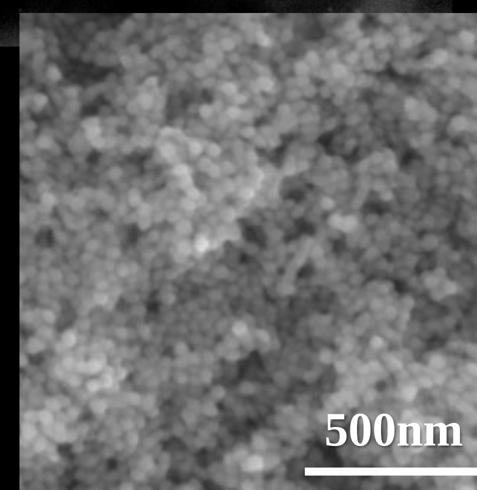




200nm crystal



35nm crystal



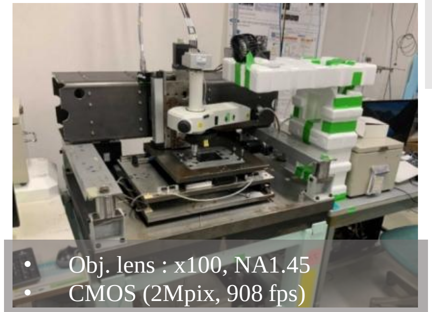
TN et al., NIM A Nucl. Inst. Meth. A 718 (2013) 519-521
T. Asada, TN et al., , PTEP (2017)063H01

Readout System by Optical Microscope

PTS-2 @ Kanagawa U.

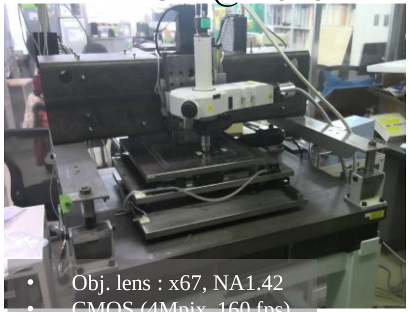
Just started operating

PTS-3 @ Nagoya



- Obj. lens : x100, NA1.45
- CMOS (2Mpix, 908 fps)
- Blue LED (455 nm)

PTS-4 @ Toho

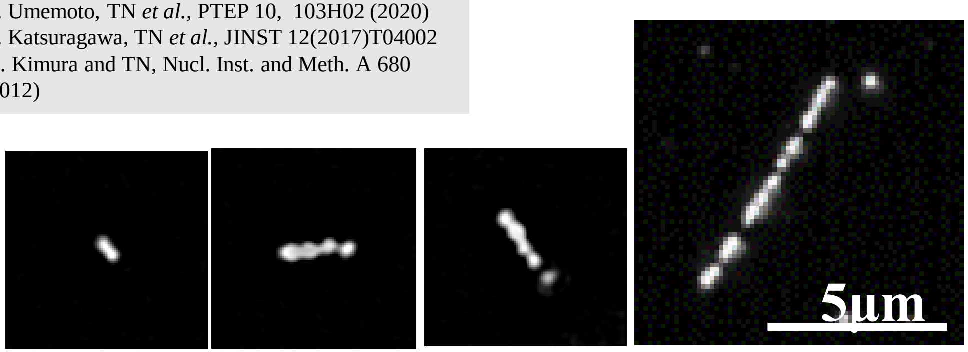


- Obj. lens : x67, NA1.42
- CMOS (4Mpix, 160 fps)
- Blue LED (455 nm)

PTS-5 @ Nagoya

Under commissioning

T. Shiraishi, TN *et al.*, PTEP, 4, 043H01 (2021)
A. Umemoto, TN *et al.*, PTEP 10, 103H02 (2020)
Y. Katsuragawa, TN *et al.*, JINST 12(2017)T04002
M. Kimura and TN, Nucl. Inst. and Meth. A 680 (2012)



WIMP signal

Higher energy signal e.g., boosted DM

Proton recoil or alpha

10 keV@proton (30 keV@C)

500 keV@proton

2D reconstructed

3D reconstructed

~ 0.4 kg/year/machine (100 times improved from pilot machine)

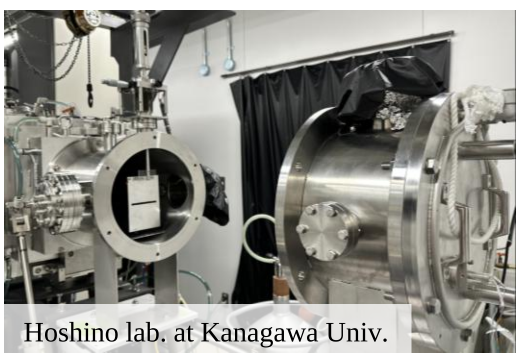
~ 1.2 kg/year/machine

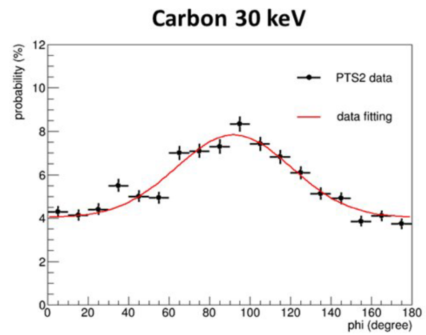
- high resolution and wide range is detectable
- kg scale capability

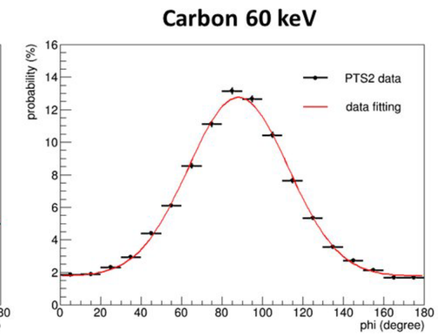
Direction sensitivity calibration (2D)

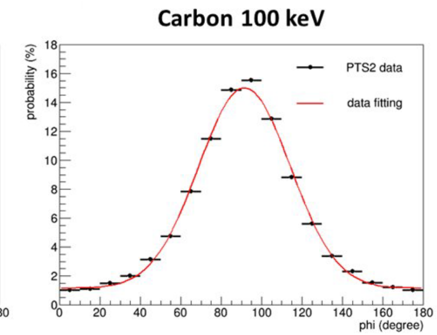
■ Ion-implantation

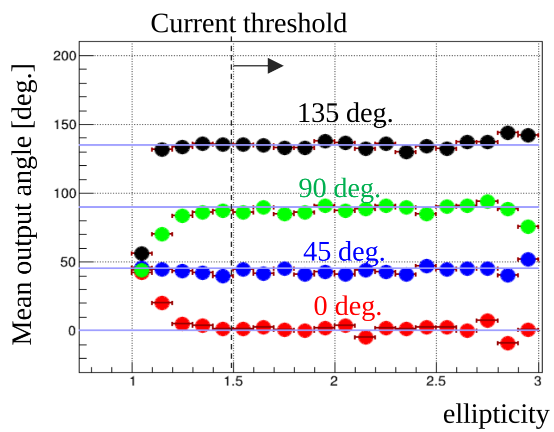

IMASS at Nagoya Univ.


Hoshino lab. at Kanagawa Univ.







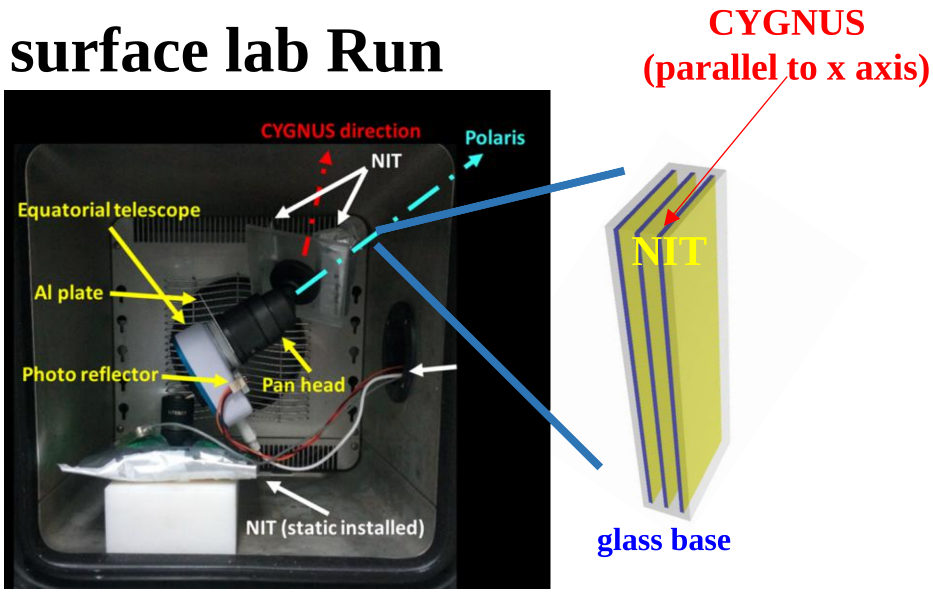


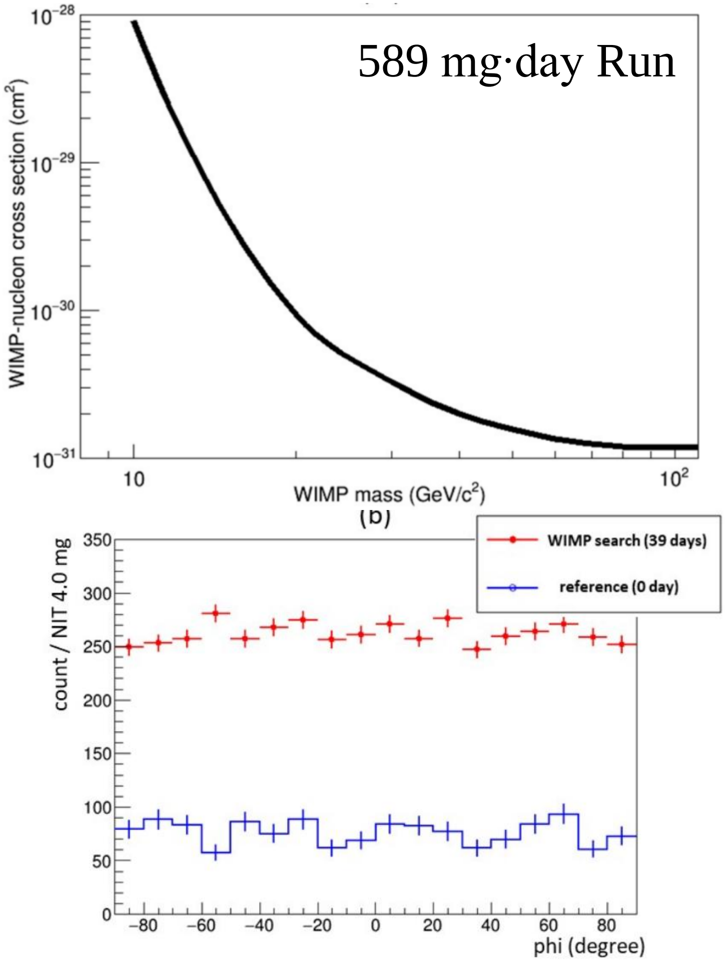
Energy of Carbon	Angular resolution [deg.]
100 keV	32 +- 3
60 keV	35 +- 3
30 keV	59 +- 2

First Directional Sensitive search for DM

A. Umemoto et al JCAP02(2025)012

surface lab Run



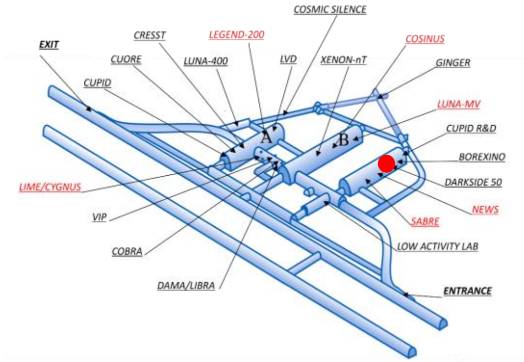


Source	Activity/Flux	background event rate (/mg/day)
^{14}C in NIT	21 ± 6 Bq/kg	0.11 ± 0.04
^{40}K in slide glass	1.5 ± 0.2 Bq/kg	0.09 ± 0.04
^{238}U chain in slide glass	3.0 ± 1.0 Bq/kg	0.53 ± 0.21
^{232}Th chain in slide glass	0.9 ± 0.1 Bq/kg	0.21 ± 0.09
environmental γ ray	$\mathcal{O}(0.01)$ /s/cm^2	0.21 - 0.55
cosmic-ray ($\mu^{\pm}$)	$\mathcal{O}(0.01)$ /s/cm^2	2.35 ± 0.70
Total		3.50 ± 0.92

muon limit at surface lab

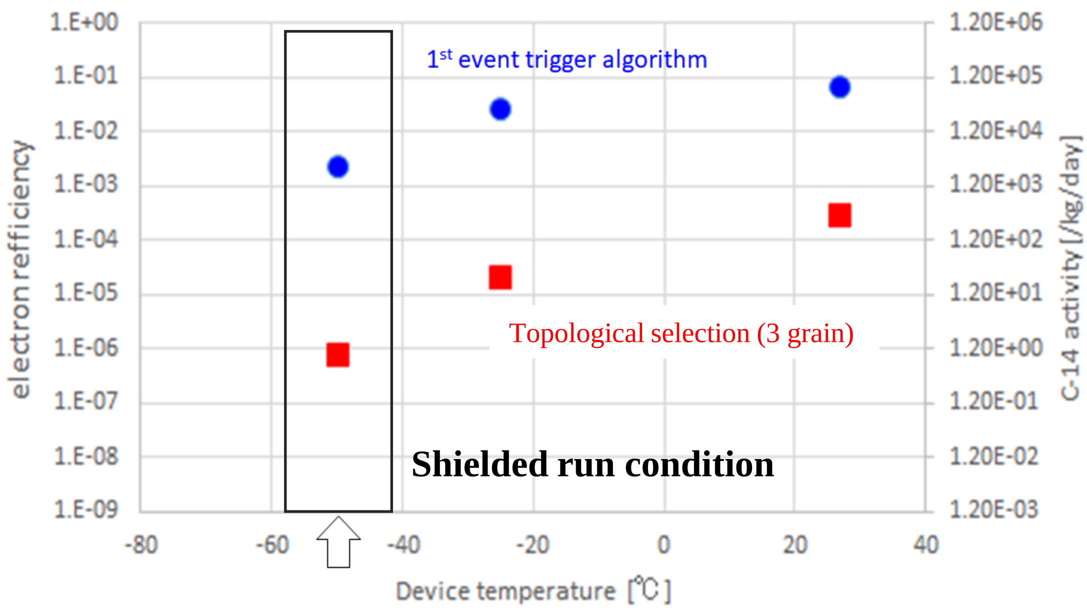
consistent with flat background

Shielded Run in LNGS underground lab



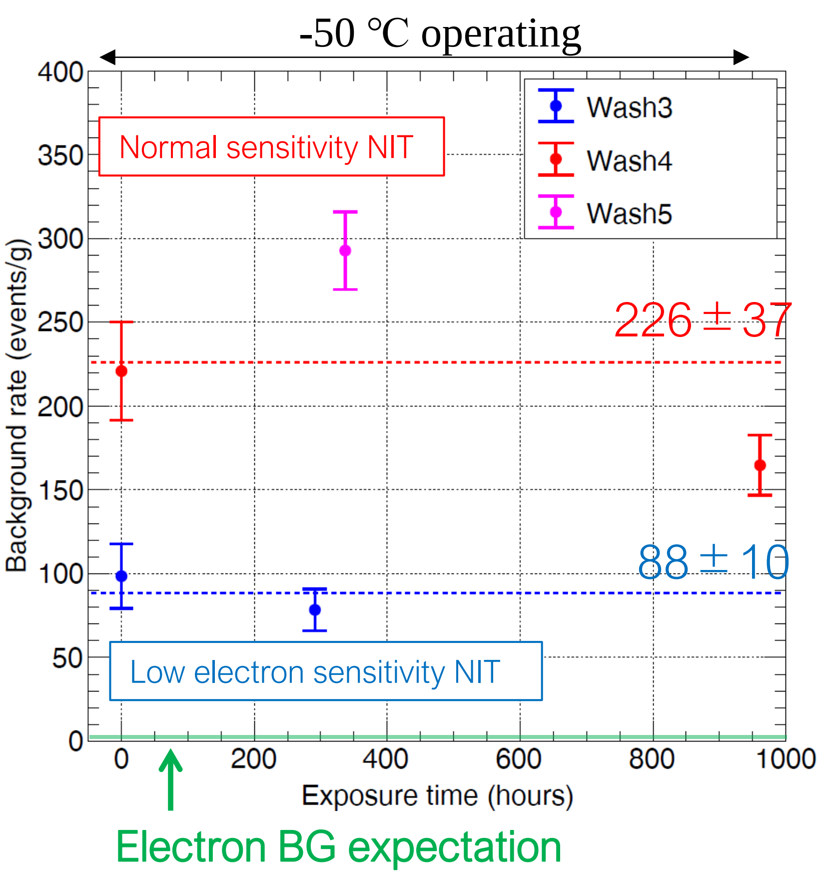
concept: shielding and low temperature operation to suppress known BG

Temperature dependence for electron efficiency

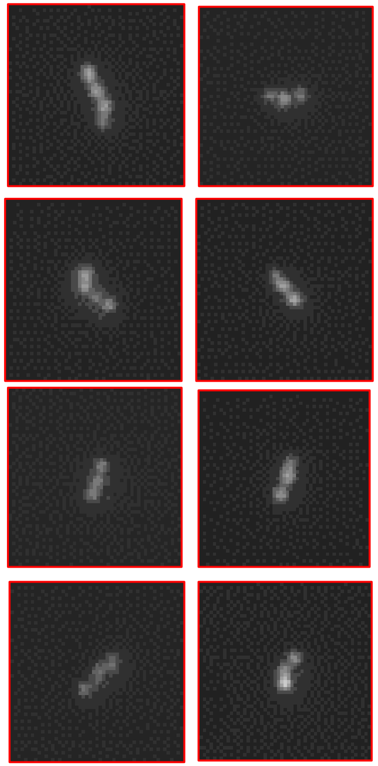


	Flux @ underground	Event rate for current selection condition [/kg/day] outside the shield	Event rate for current selection condition [/kg/day] w/ shield
μ	~10^{-8} /cm^2/s	< 1 × 10^{-2}	< 1 × 10^{-2}
Environment γ-ray	0.38 /cm^2/s	**~ 1.8 × 10^5**	< 100
C-14 (intrinsic)		~100	**~100**
Neutron	~10^{-6} /cm^2/s	< 0.1	< 10^{-3}

First BG Run result (Run3-6, 2021)

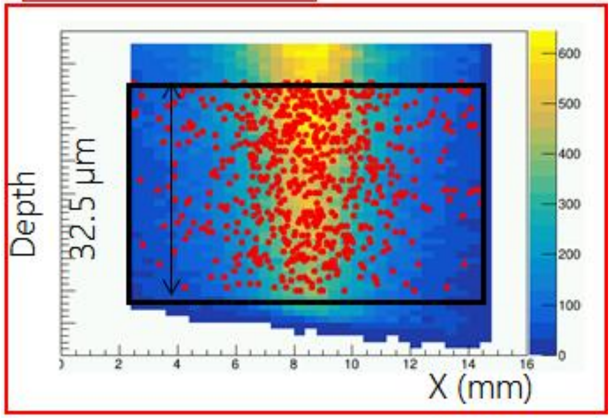


Found candidates

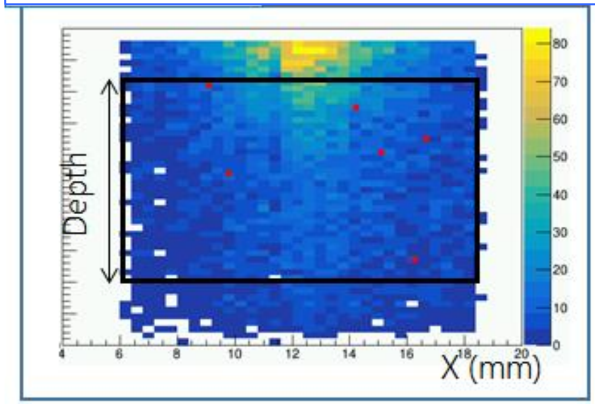


Am-γ test

Standard emulsion



Low sensitivity emulsion

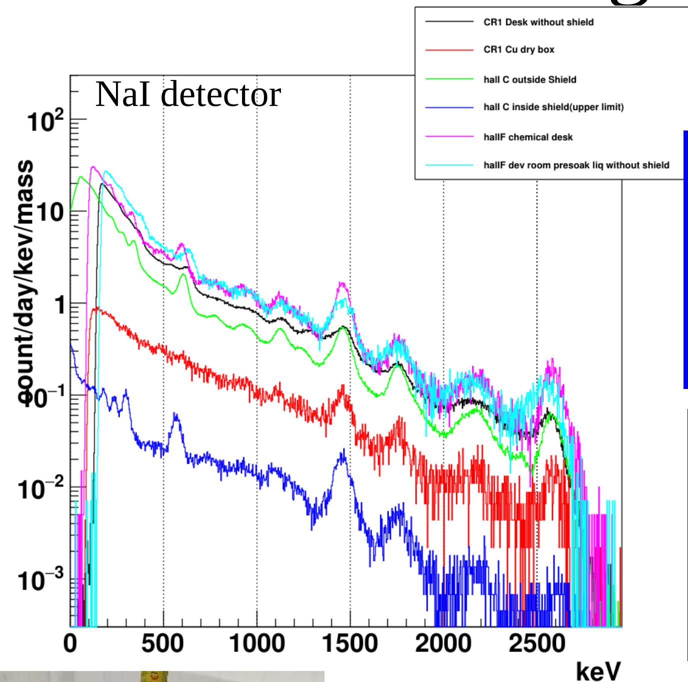


<u>× 2.6 times difference for BG</u>

→Not electron like

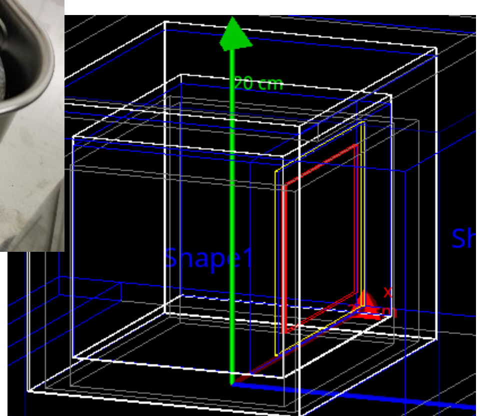
<u>× 130 times difference for gamma</u>

Simulation of gamma-electron background



Electron produced in emulsion (/d/plate(2g))	Hall F Film making	Hall F Development	Hall C transportation	Hall C shielding	CR1 Drying shielding
From Lead	-	3150	-	2400	<100
From environmental gamma	456360	60310	257140 (Hall C) 422650 (CR1)	13	10540

Counts (/d/plate(2g))	Drying shielding (100% dry case)	Drying shielding (50% dry case)	Drying shielding (0% dry case)
Electrons produced in emulsion	10540	53800	106900
Gamma-rays entering emulsion	136500	138050	140100

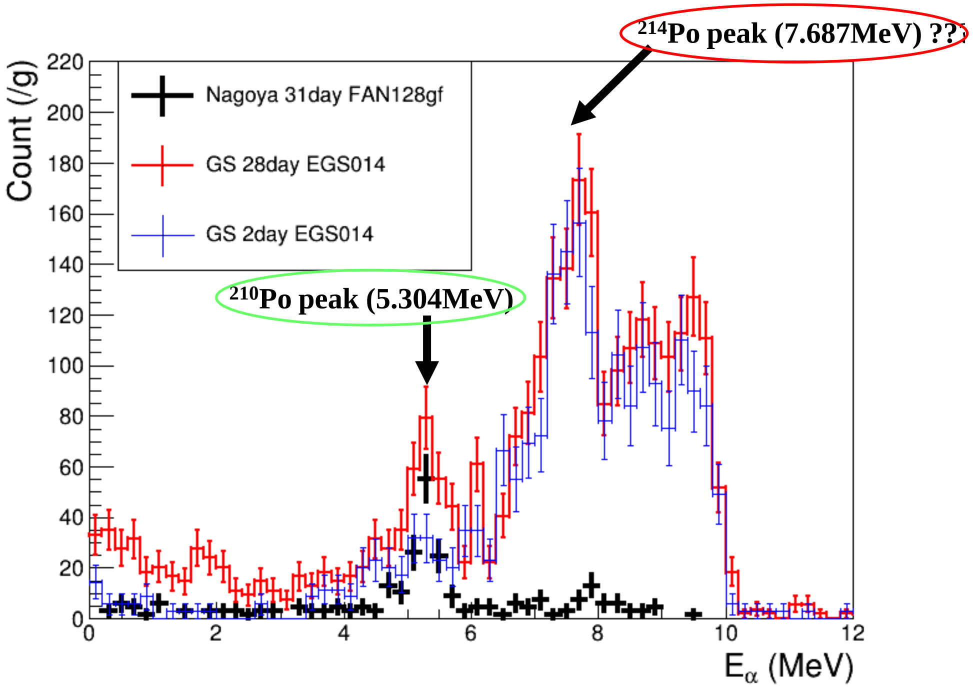


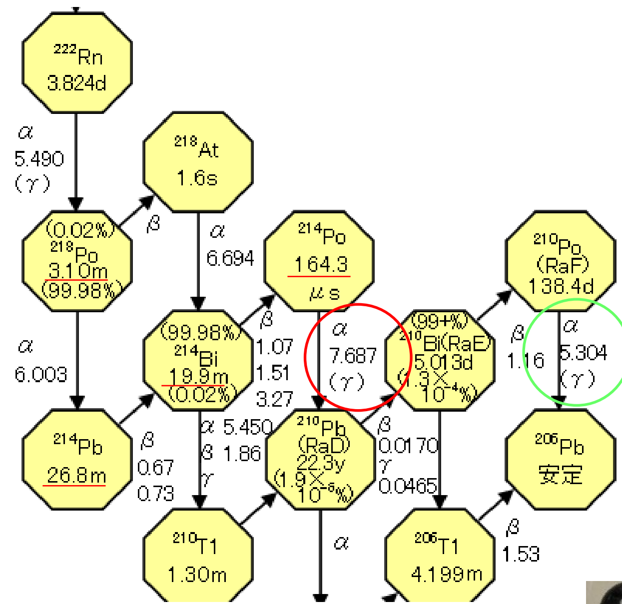
Run5

situation	time (h)	selection efficiency	Electron (/g/day)	wet factor	gamma TSL (/g)	^{14}C TSL (/g)
set	1.5	1.7×10^{-4}	2313745	0.003	0.072	5.7×10^{-5}
pre-dry	21.2	1.7×10^{-4}	1163718	0.010	1.745	2.7×10^{-3}
dry	19.38	1.7×10^{-4}	1207	1 (–0.01)	<0.166	$<2.5\times10^{-1}$
exposure	961.12	5.7×10^{-7}	1207	1	0.027	4.1×10^{-2}
extraction	0.3	5.7×10^{-7}	128570	1	0.001	1.4×10^{-5}
develop	0.20	1.7×10^{-4}	228180	1	0.323	2.6×10^{-3}
				total events	< **2.17**	<**0.30**

electron contribution will be very small

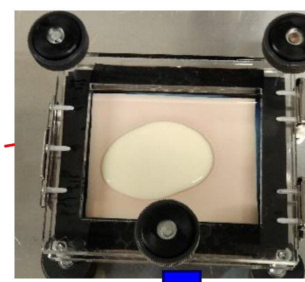
Radon (daughter) contamination at film production



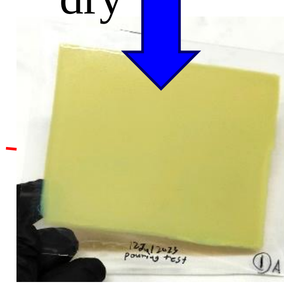


new test in radon free room

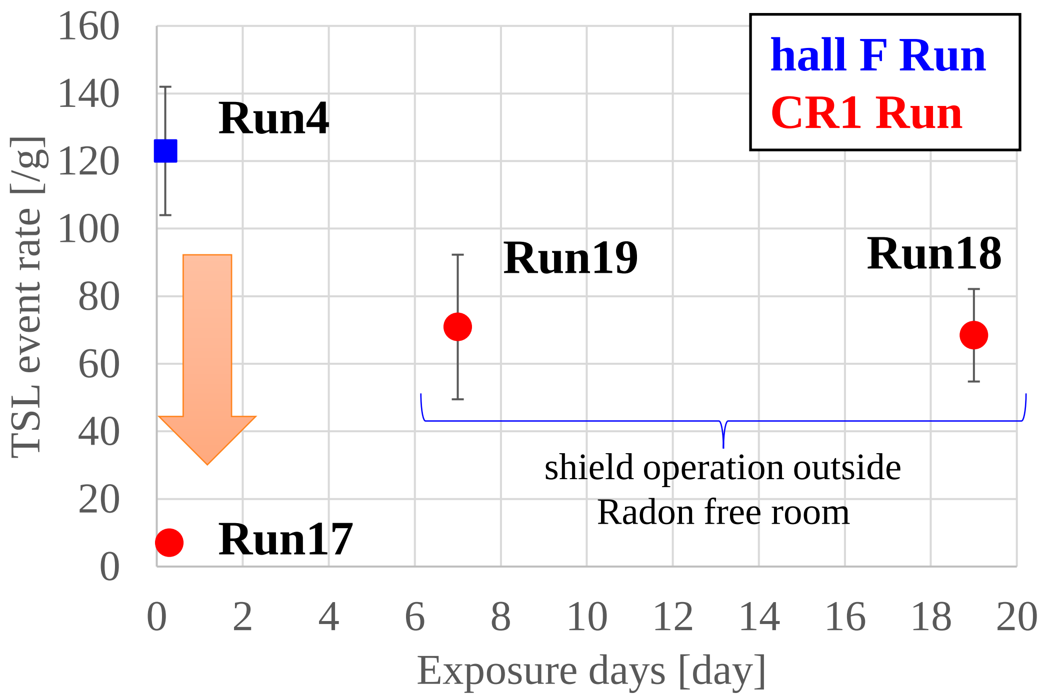
place	Radon Bq/m³	temperature℃	humidity %
hallF prod.room	72.5	20.7	44.8
hallF dev.room desk	87	17.2	53.5
hallF corridor air	73.8	17.1	46
hallC	46.9	14.5	45.3
hallC compressed air (drying in shield)	163.1	15.1	11
hallC N2 (exposure in shield)	2.3	15.1	7.8
hallB air (source of room air)	18.6	14.5	46
CR1 (druing Run19)	3.7	17.1	11.5



dry



Run with Radon Free Room



Run18

situation	time (h)	selection efficiency	Electron (/g/day)	wet factor	gamma TSL (/g)	^{14}C TSL (/g)
Set	0.5	1.0E-05	<2142836	0.003	<0.0014	1.2E-06
Dry	21.6	1.0E-05	5270	1 (–0.01)	<0.0473	0.0163
Exposure	454.0	3.3E-08	1207	1	0.0008	0.0011
Extraction	0.42	3.3E-08	128570	1	0.0001	1.0E-06
Develop	0.4	1.0E-05	31730	1	0.0056	3.2E-04
no shield	0.6	1.0E-05	128570	1	0.0296	4.2E-04
				total events	**<0.085**	0.018

Total non-shielded time in operation is suppressed to ~30min!

- Radon free room
- film production in small shield

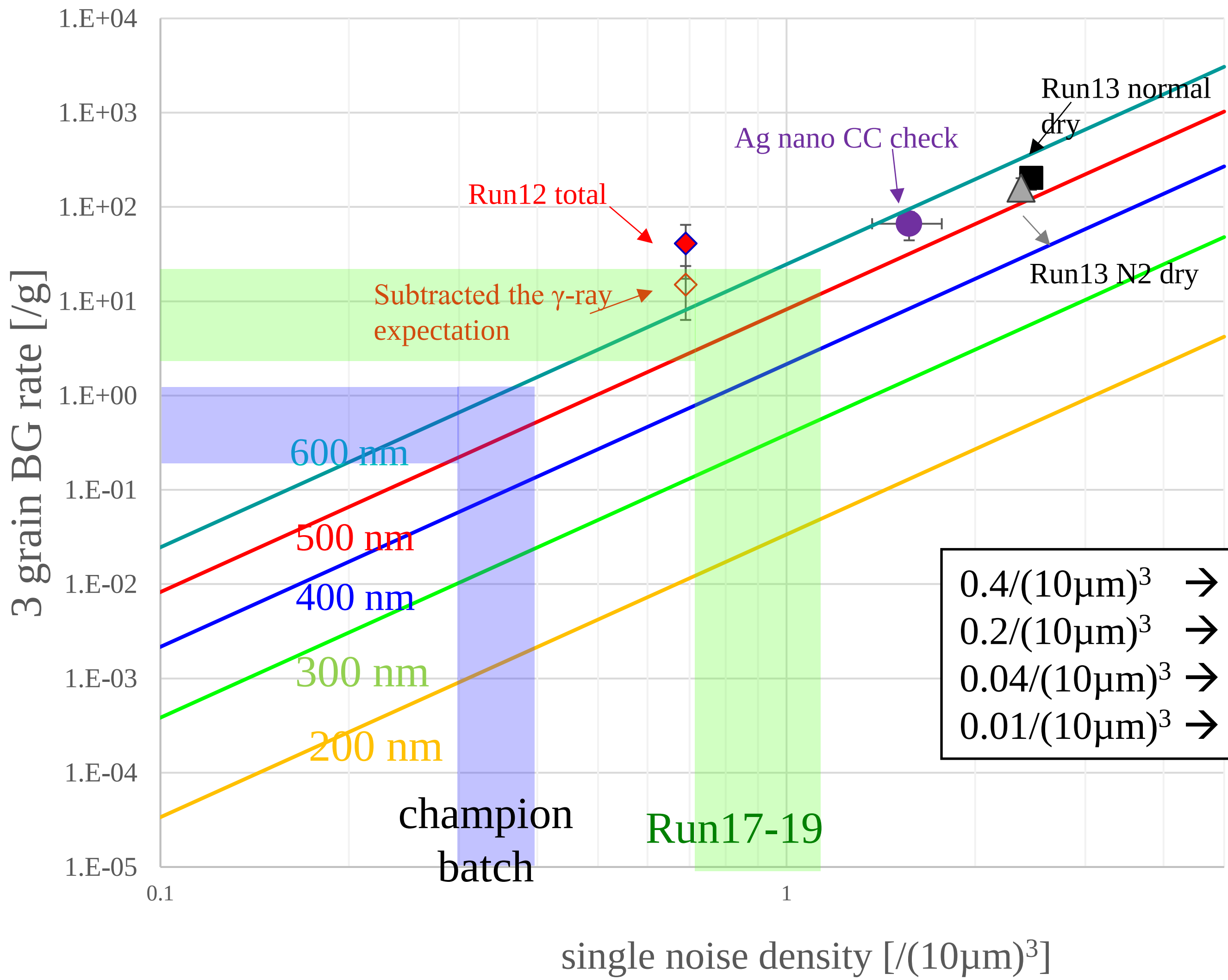
0 day (non-exposed) events was greatly suppressed!

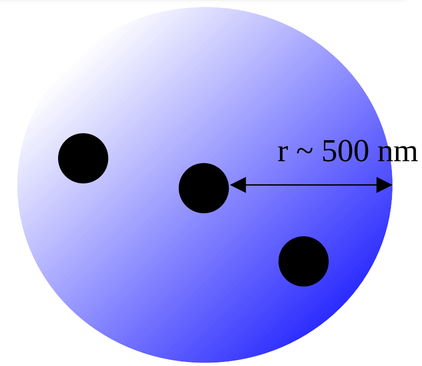
However, exposed events has some constant jump
→ Unexpected source in shield?

Still 0 day has O(1-10) events while gamma estimation is O(0.1)

chance coincidence of single grain may start to limit

rough estimation of Fog Chance Coincidence





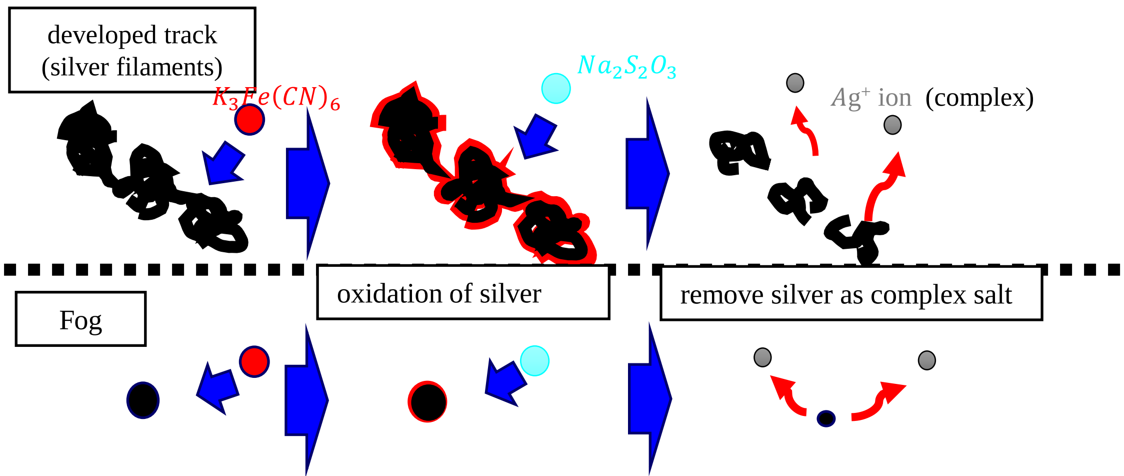
accidental track formation
by random single noise
→ ∝ (noise density)^3

$0.4/(10\mu m)^3$ → 1ev/1g	↕	Current level (induced by development)
$0.2/(10\mu m)^3$ → 1ev/10g		
$0.04/(10\mu m)^3$ → 1ev/1kg		Gelatin limit
$0.01/(10\mu m)^3$ → 1ev/100kg		PVA limit

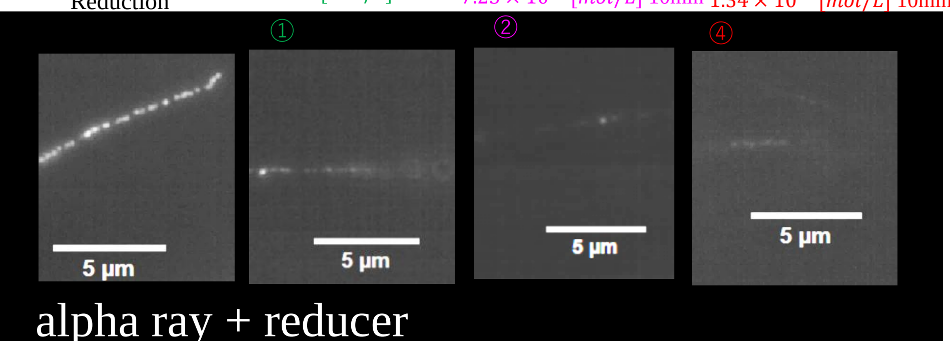
Chemical elimination of single noises

Farmer's Reducer

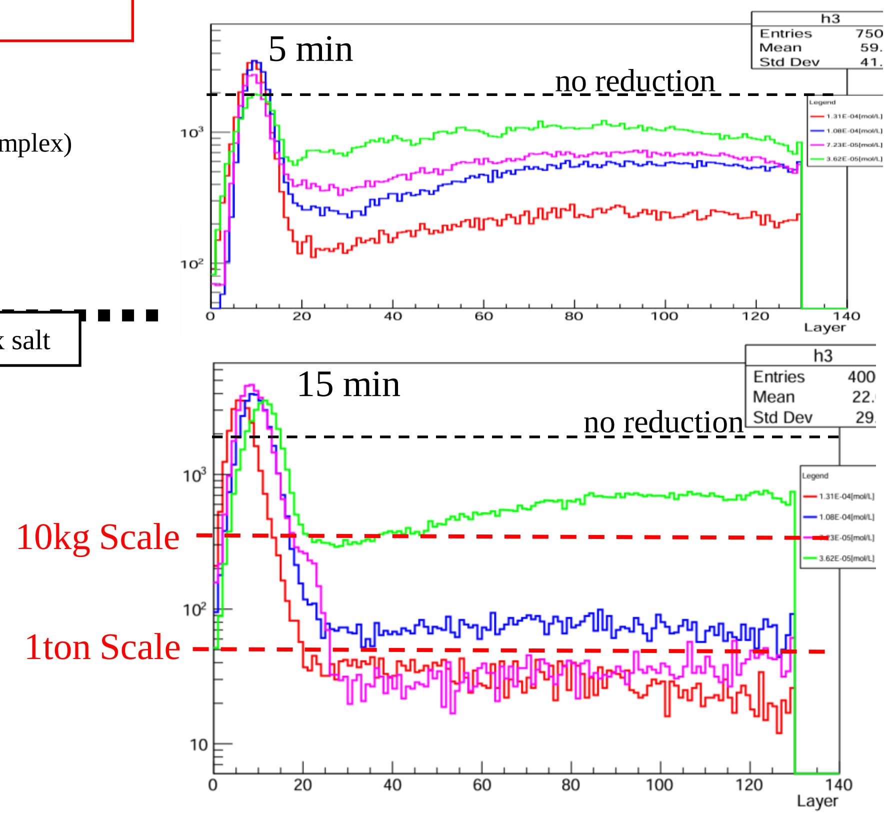
$$4Ag + 4K_3Fe(CN)_6 + 6Na_2S_2O_3$$
$$\rightarrow 2Ag_2S_2O_3 \cdot 2Na_2S_2O_3 + 3K_4Fe(CN)_6 + Na_4Fe(CN)_6$$



No Reduction | $3.62 \times 10^{-5}[mol/L]$ 10min | $7.23 \times 10^{-5}[mol/L]$ 10min | $1.34 \times 10^{-4}[mol/L]$ 10min



noise distribution for emulsion Z



--- no reduction
$3.62 \times 10^{-5}[mol/L]$
$7.23 \times 10^{-5}[mol/L]$
$1.08 \times 10^{-4}[mol/L]$
$1.31 \times 10^{-4}[mol/L]$

Single noise is reduced to ton-scale and the signal survives!

low-radioactive emulsion for ton scale

intrinsic radioactivity

	U-238	Th232	K-40	Ag-108	C-14
Highly deionized gelatin +NaBr	~27	~6	35	~50	24000

[mBq/kg]

gelatin:
2.00×10^6 /kg/day

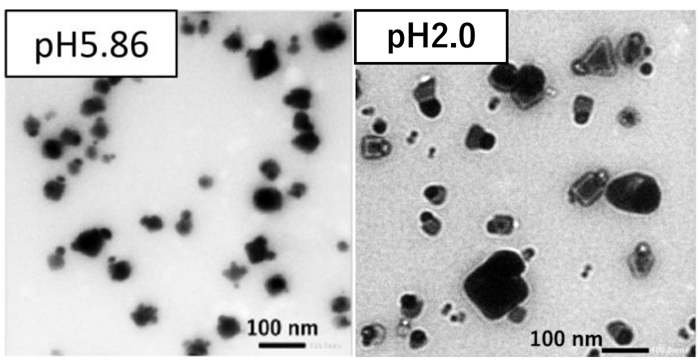
PVA:
< 2899 /kg/day

TSL (current sensitivity, -50℃)

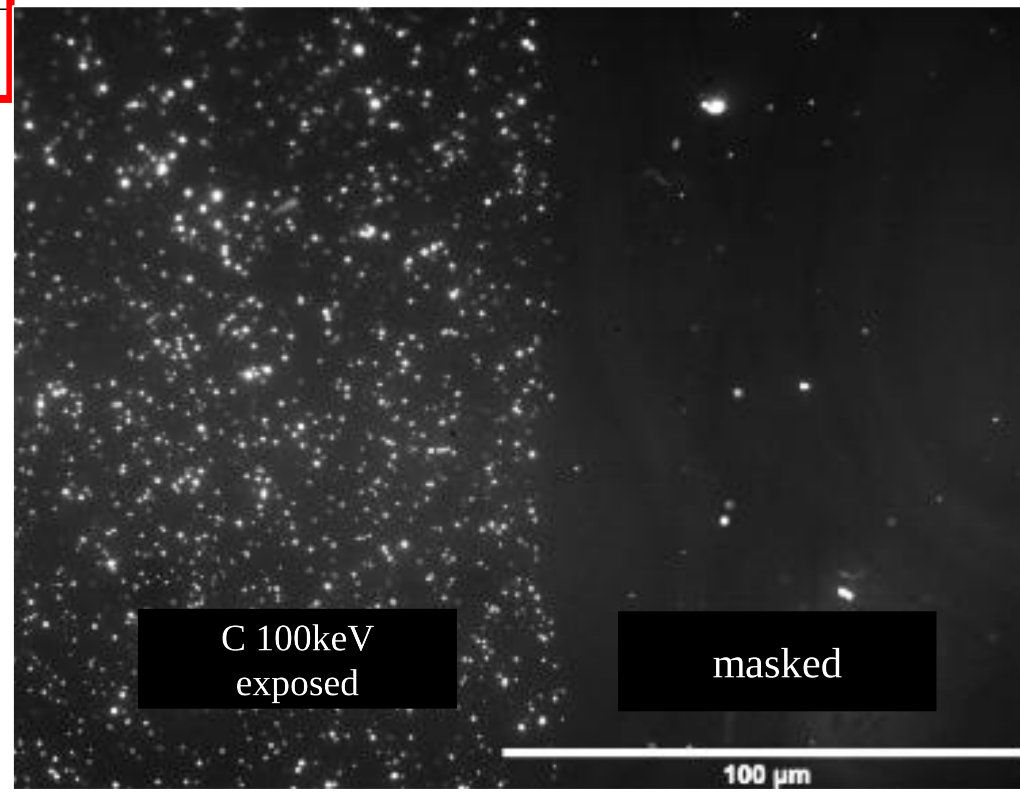
O(1) events/kg/day

O(1) events/ton/day

<u>essential update for ton scale</u>



Mechanical properties very different from gelatin
New size control method by pH is applied

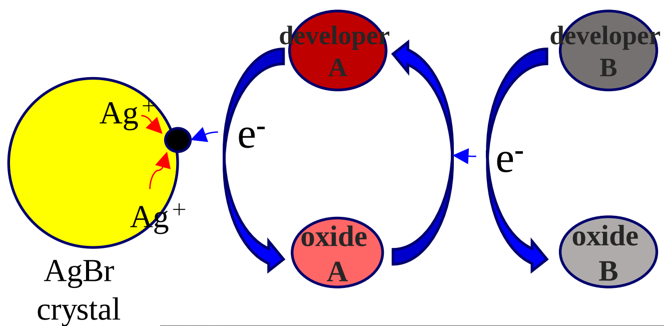


Carbon ion → first confirmation of DM detection potential

Sensitivity upgrade study

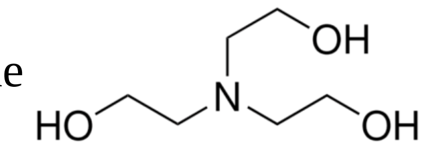
low temperature, reducer, PVA… sensitivity improvement is needed

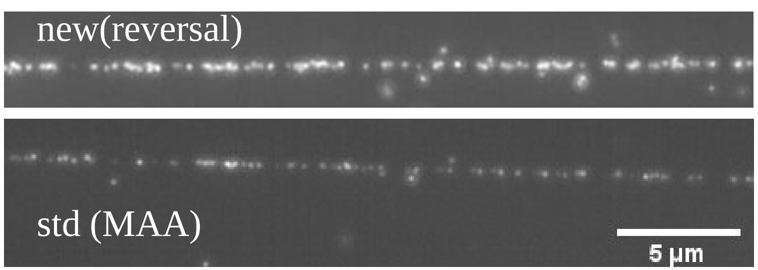
Superadditive developers

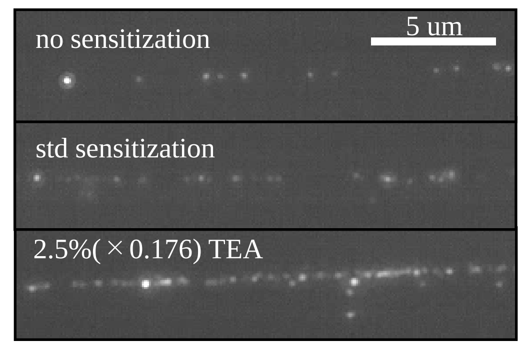


Reversal developer
A: phenidone
B: hydroquinone

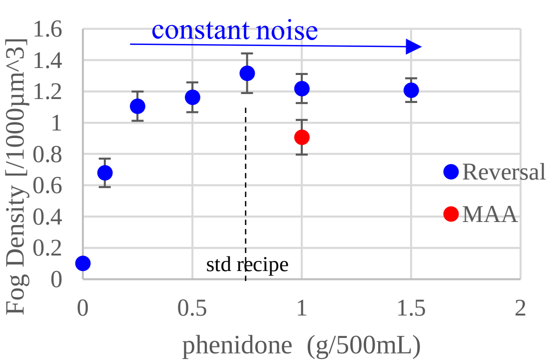
new sensitizer:
Triethanolamine



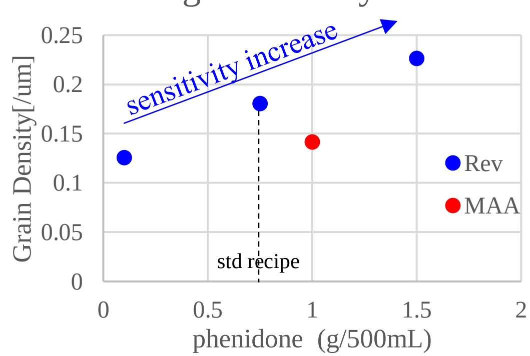


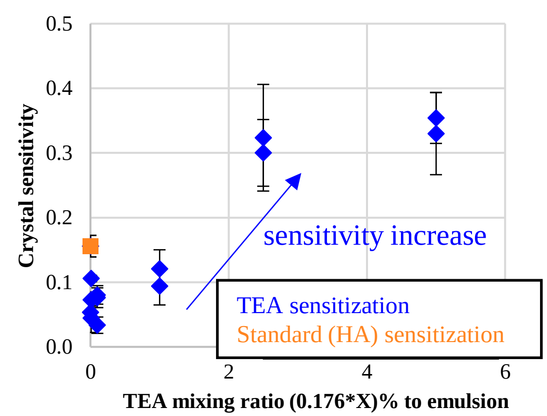


noise ratio



grain density

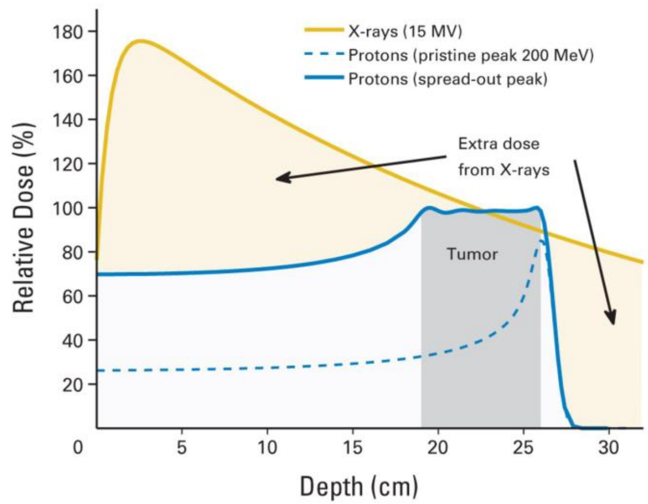




The FOOT (FragmentatiOn Of Target) experiment

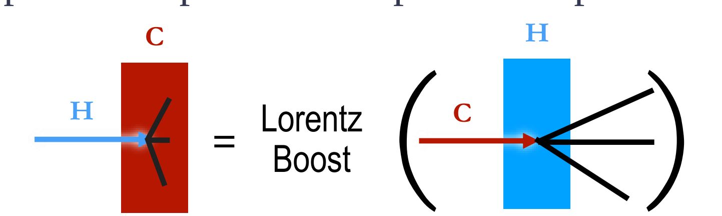
Charged Particle Therapy: Cancer treatment by radiation using Bragg peak of ion beam (~200 MeV proton etc.)
Nuclear fragmentation of the target (and beam) particles is an issue.

- case of proton, heavy ions (C,N,O) from the target are too short (~um) but significant contribution for dose



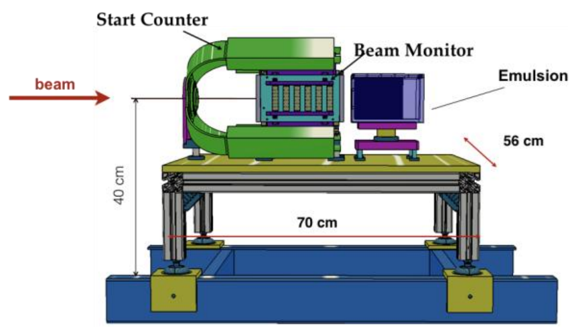
FOOT aims at measuring nuclear fragmentation cross sections to improve Treatment Planning Systems for proton and ion therapy

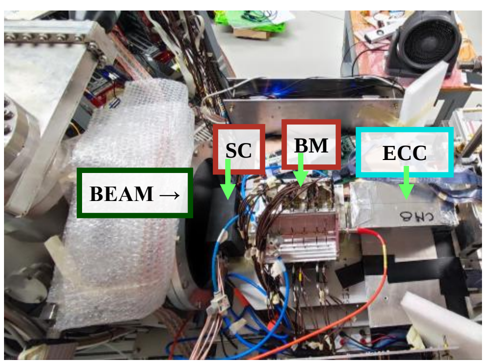
Inverse kinematic approach



fragments with low energy and short range

fragments with higher energy and longer range

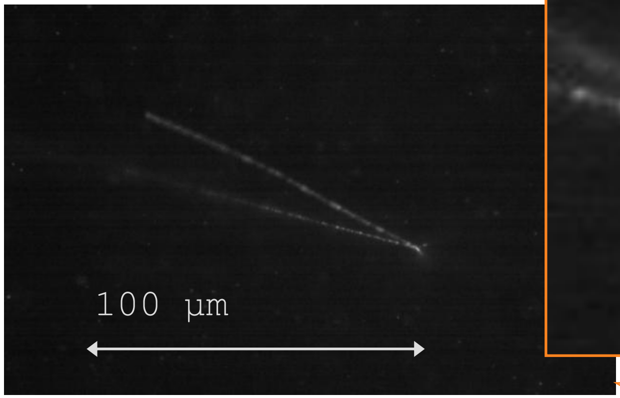


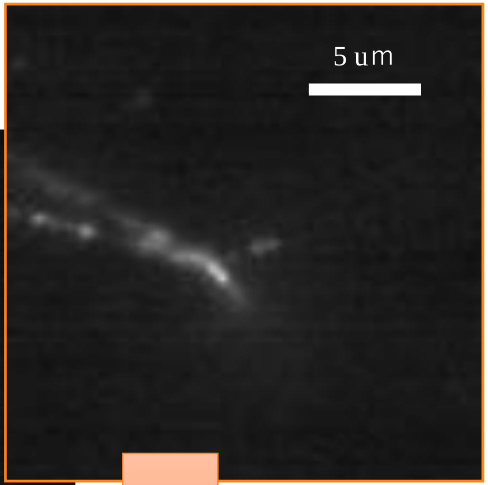


beam exposure at CNAO (Pavia, Italy)

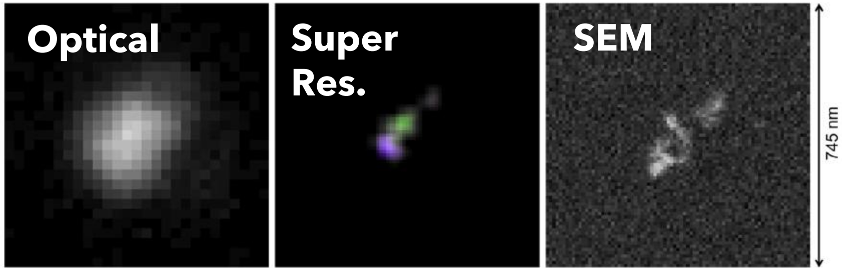
FOOT / DAMON (Direct meAsureMent of target fragmentatiON)

not inversed kinematics but direct measurement of ~um fragmentations
→ NIT as target and detector
→ super resolution analysis





further analysis



problem: induced and fragmented protons were low sensitivity

new development, new sensitization application are ongoing

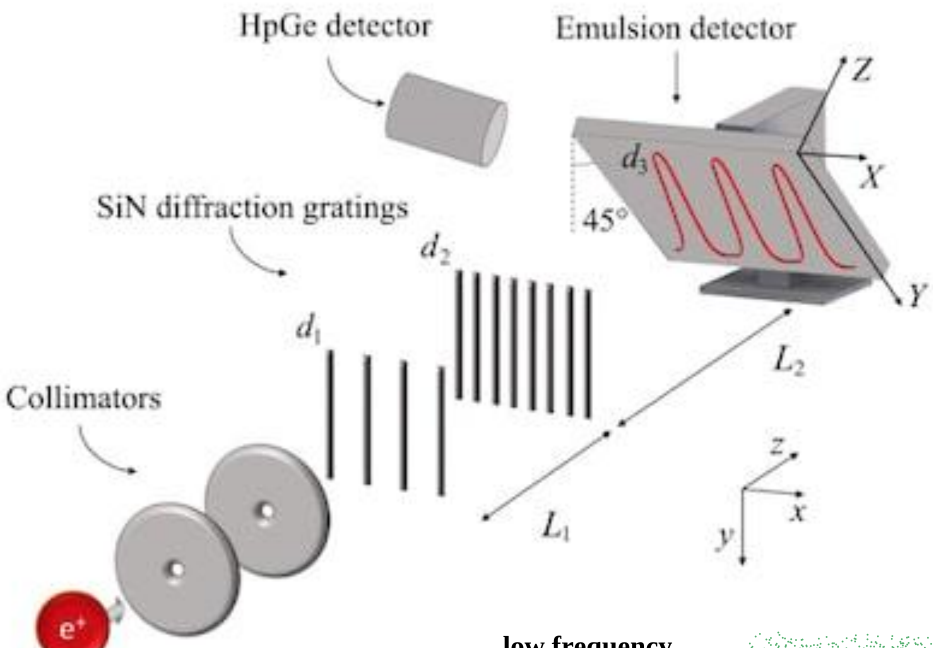
exposure at Nagoya proton therapy center

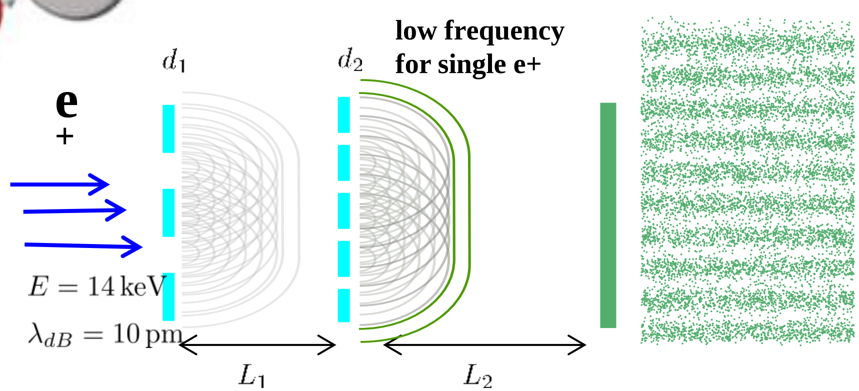
QUPLAS experiment

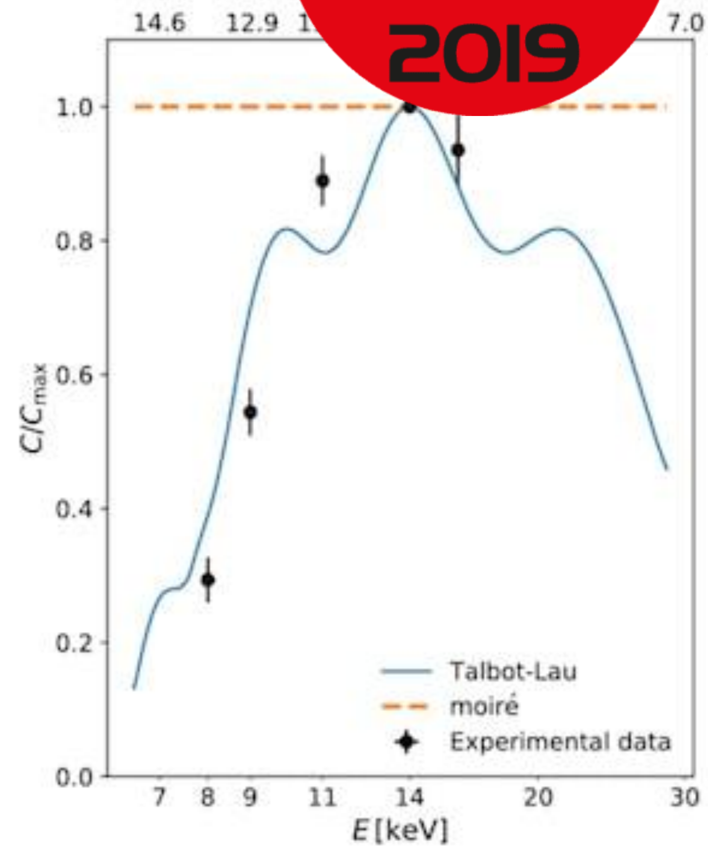
(**QU**antum interferometry and gravity with **P**ositrons and **LAS**ers)

physicsworld TOP 10 BREAKTHROUGH 2019

first antimatter interferometry





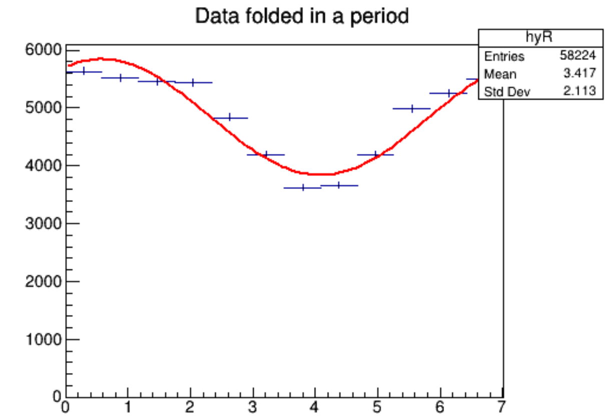


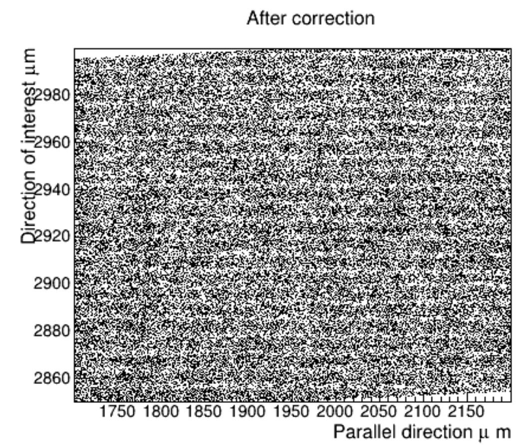
from positron to positronium ($e^- + e^+$)

next phase upgrade for AB effect, gravity(WEP) measurement

10keV positron + NIT
(resolution confirmation by single grating)

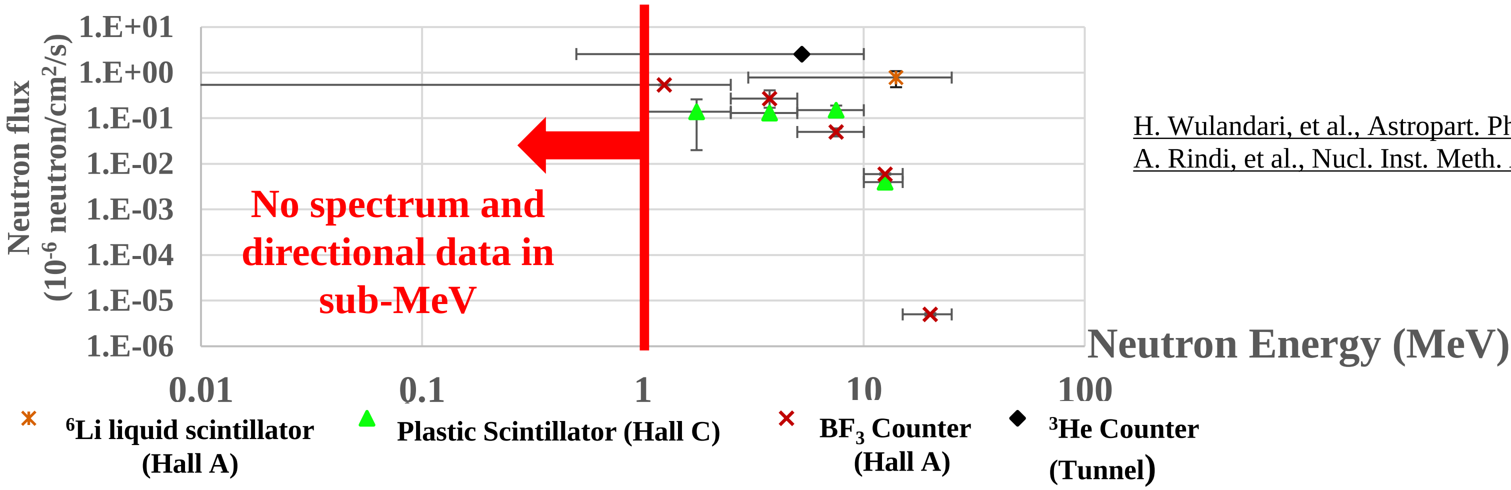
- 1um order resolution → NIT can achieve (6um pattern is well visible)
- positronium will have half energy of positron for same interference. Further lower energy threshold is needed.
    - stop in the gelatin layer can be problem. Fine grain can reduce that effect?





Unfortunately beam source caused trouble and suspended.
However, a byproduct study: Antiproton Interferometry and the Aharonov-Bohm Effect (AIABE) is organizing now.

Environmental Neutron Measurement @LNGS

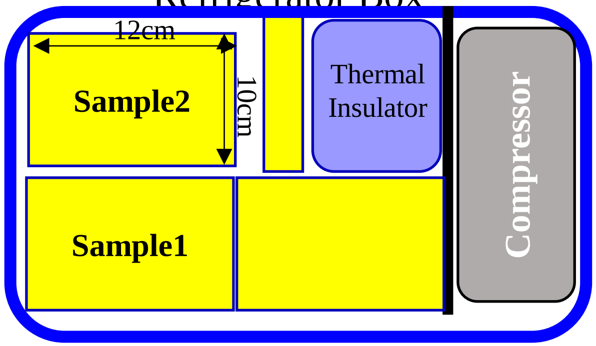


H. Wulandari, et al., Astropart. Phys. **22** (2004) 313.
A. Rindi, et al., Nucl. Inst. Meth. A, **272** (1988) 871.

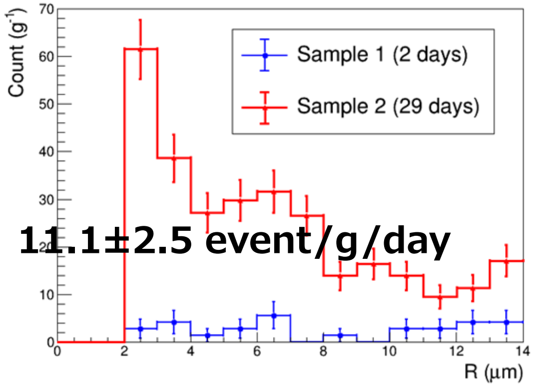
Neutron Detector	Energy Range	γ-ray rejection power	Energy Resolution	Directionality
Liquid Scintillator	1MeV – 100MeV	Bad	Good	None
BF_3, ^{3}He Proportional Counter	Thermal – 20MeV	Good	None	None
Proton-recoil Proportional Counter	10keV – 2MeV	Bad	Good	None
Nano Imaging Tracker (NIT)	Thermal & 100 keV –	Good	Good	Good

Neutrons can be significant noise that cannot be removed
Direct measurement at each experimental site is important

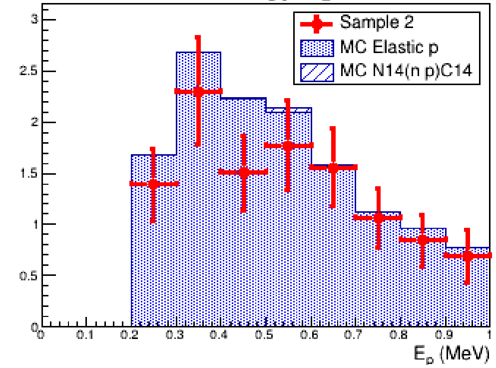
Demonstration of environment neutron measurement on the surface lab. at LNGS



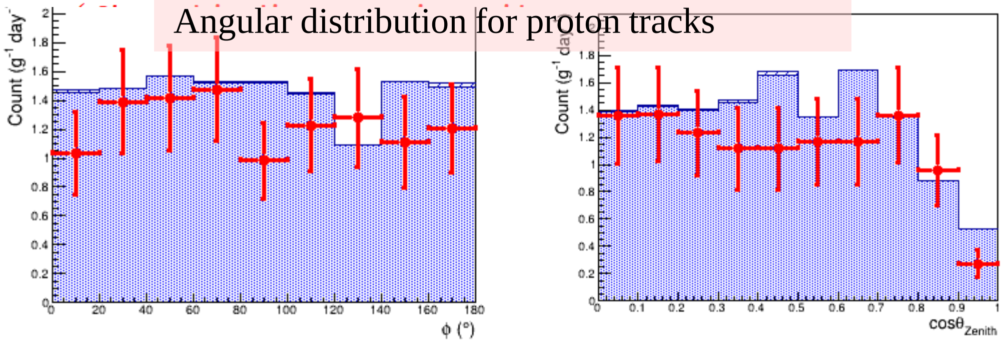
Proton range spectrum



Proton energy spectrum



Angular distribution for proton tracks



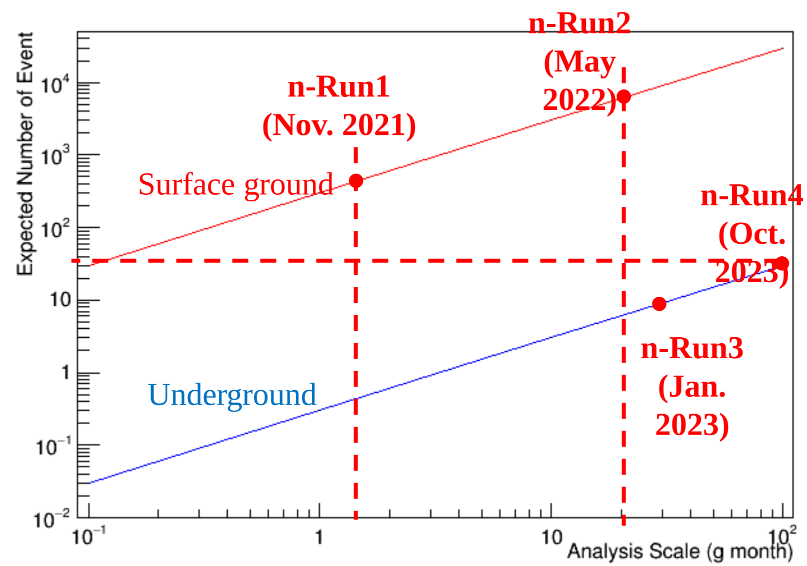
<u>Neutron Flux @0.25-10 MeV :</u>
$(7.6 \pm 1.7) \times 10^{-3}$n cm^{-2} s^{-1}

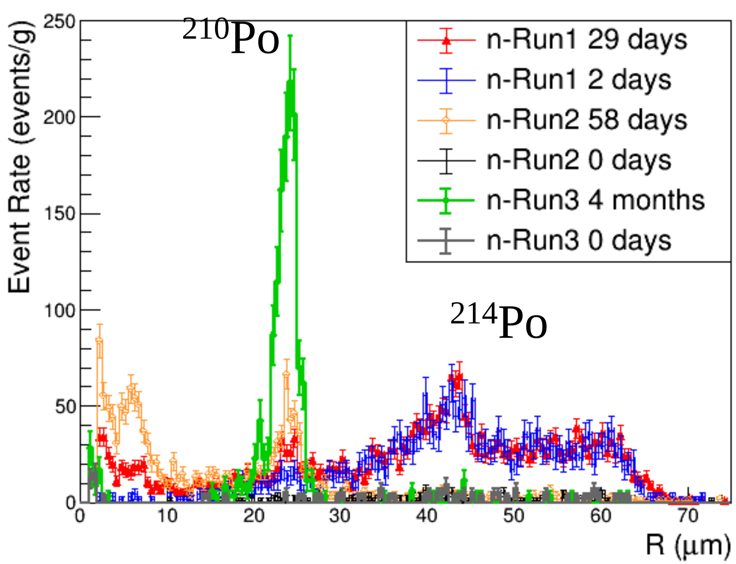
First measurement of sub-MeV neutron with direction information

Phys. Rev. C 107, 014608 (2023)

Radon daughter problems and scale up

	Installed Place	^{214}Po contamination (/g)	Experimental Scale (g*month)
n-Run1 (Nov. 2021 -)	Surface ground	O(1000)	2
n-Run2 (May 2022 -)	Surface ground	O(100)	20
n-Run3 (Jan. 2023 -)	Underground Hall C & F	O(100)	30
n-Run4 (Nov. 2023 -)	Underground Hall C	O(1) (CR1)	100





non time-dependent tracks induced by Radon daughters were problem.
Neutron measurement also get benefit of radon free room operation and background greatly reduced.

Run 5 (>100g scale) needs operation scale upgrade and now studying.

Conclusion

- Directionality is interesting and promising property for direct dark mater search.
- NIT (Nano imaging tracker) is fine-grained nuclear emulsion which can detects nano-scale track with directionality and even can applicated wide range experiment.
- Many test run were performed at Gran Sasso National Laboratory (LNGS) and we have tried to understand our background. Feeding back the result, new technology have been studied.
- Recently application use of NIT detector is spreading to wide field.