NEWSdm experiment

Directional dark matter search with super-high resolution nuclear emulsion

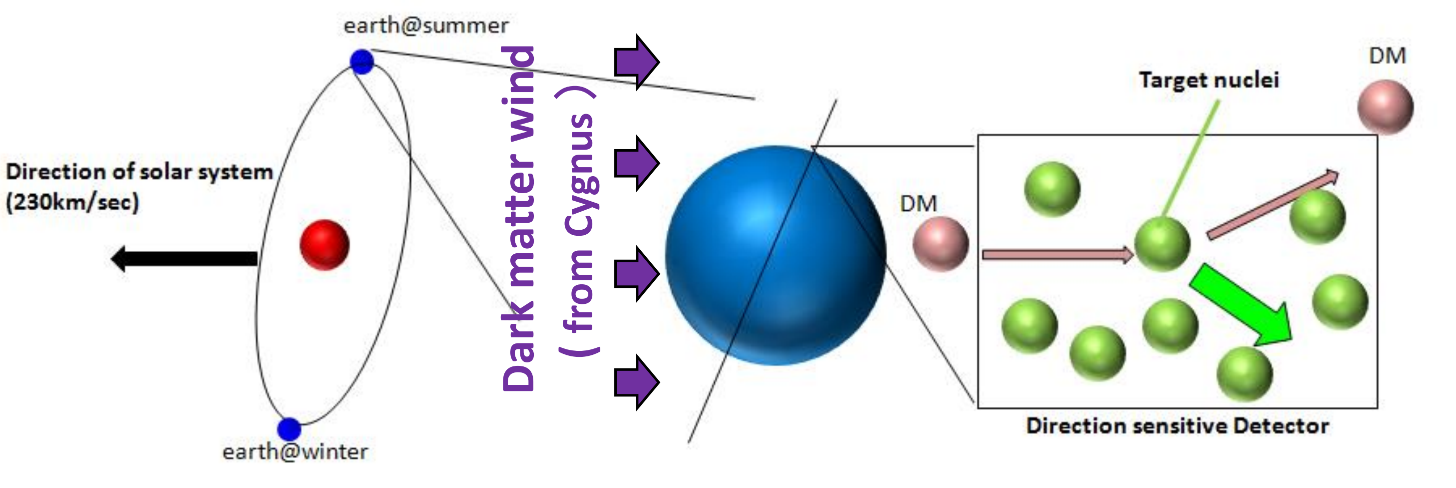
NAKA Tatsuhiro

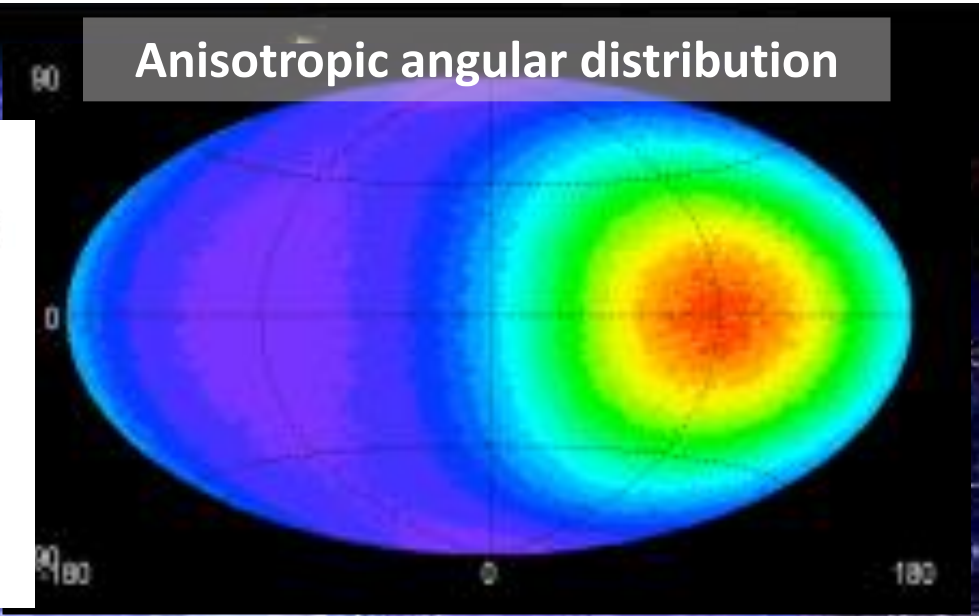
Toho University

on behalf of NEWSdm collaboration

The 2nd Dmnet international symposium 2022.9.13-15 (presentation on 15th)

Direct Dark Matter search and Directionality

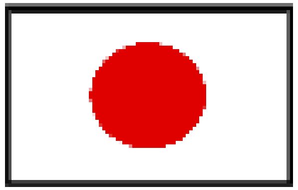




- Good discovery potential with lower statistics (several 10 events enough)
- High Background discrimination
- Dark matter astronomy

"Tracking" is finally very important to identify the DM

NEWSdm experiment
[Nuclear Emulsion for WIMPs Search – directional measurement]



Nagoya
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Roma,
Padova,
Potenza,
Benevento

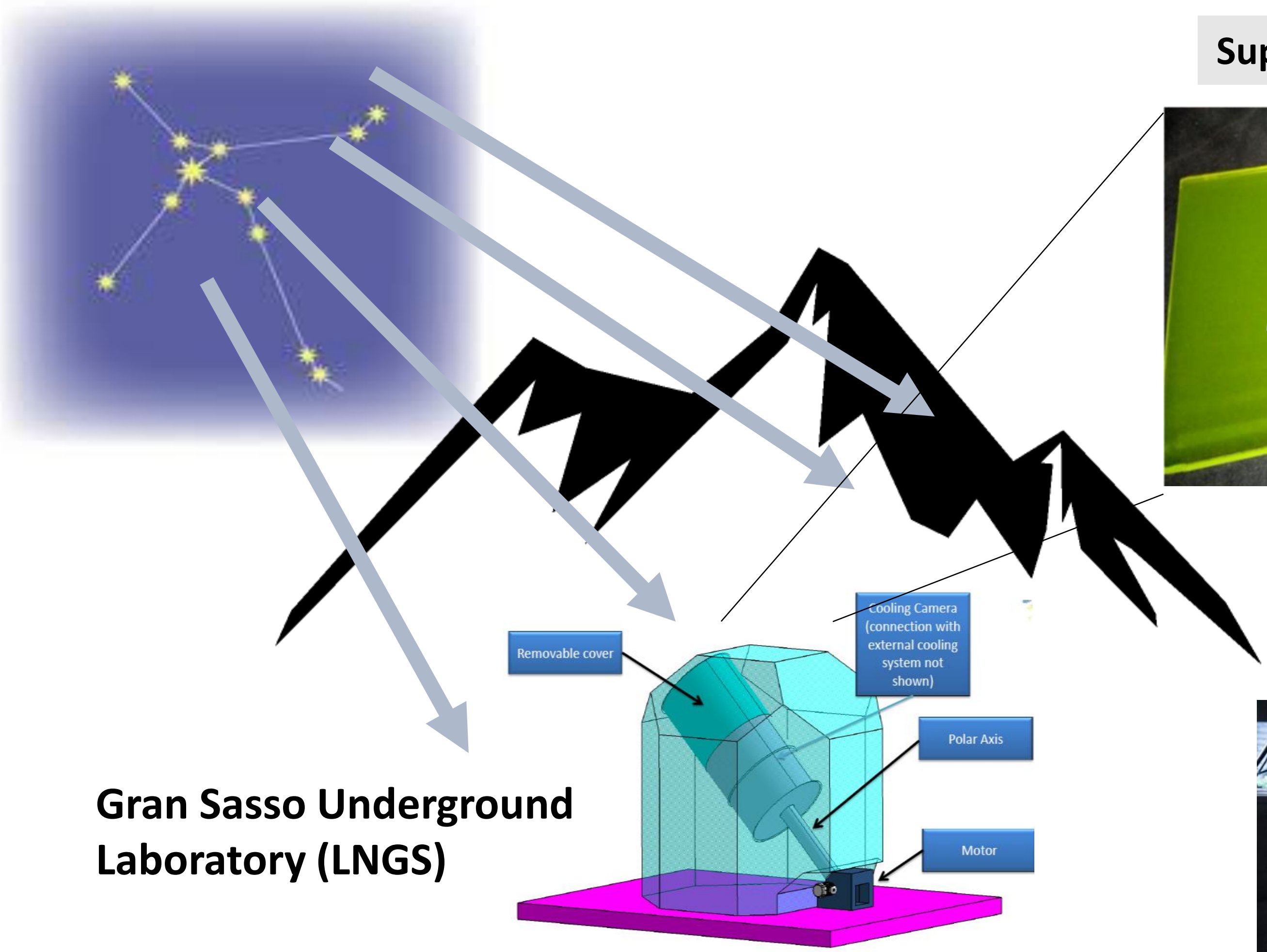
LPI RAS Moscow
JINR Dubna
SINP MSU Moscow
INR Moscow
Yandex School of Data Analysis

Gyeongsang

http://news-dm.lngs.infn.it

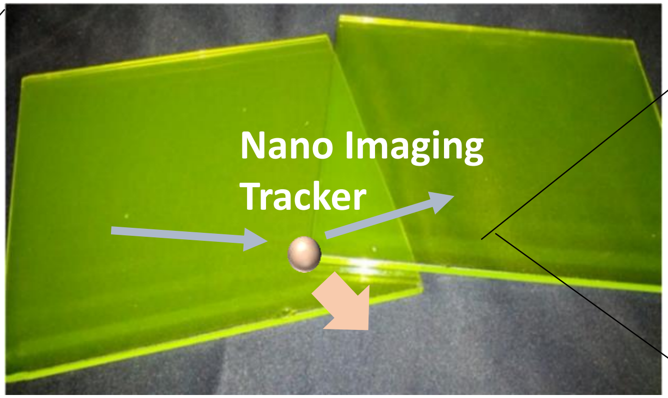
LOI under review by the LNGS science committee

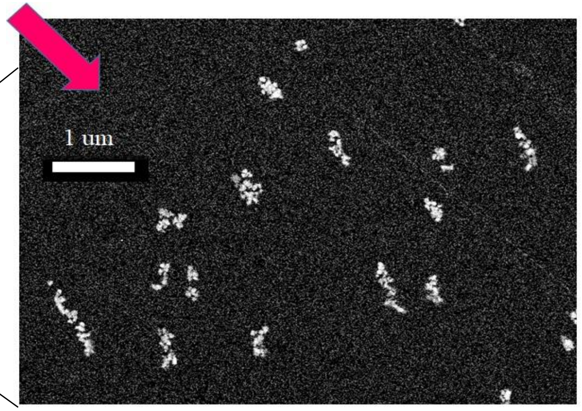
NEWSdm
[Nuclear Emulsion for WIMP search- directional measurement]



Gran Sasso Underground Laboratory (LNGS)

Super-resolution nuclear emulsion and sub-micron tracking

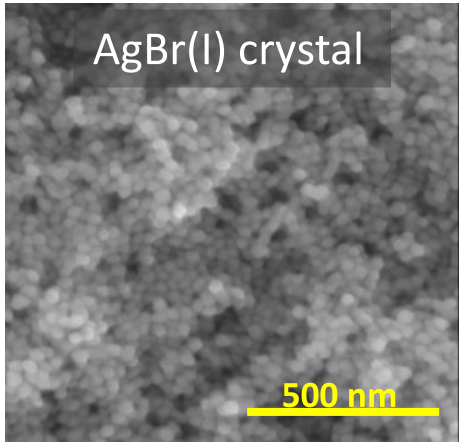




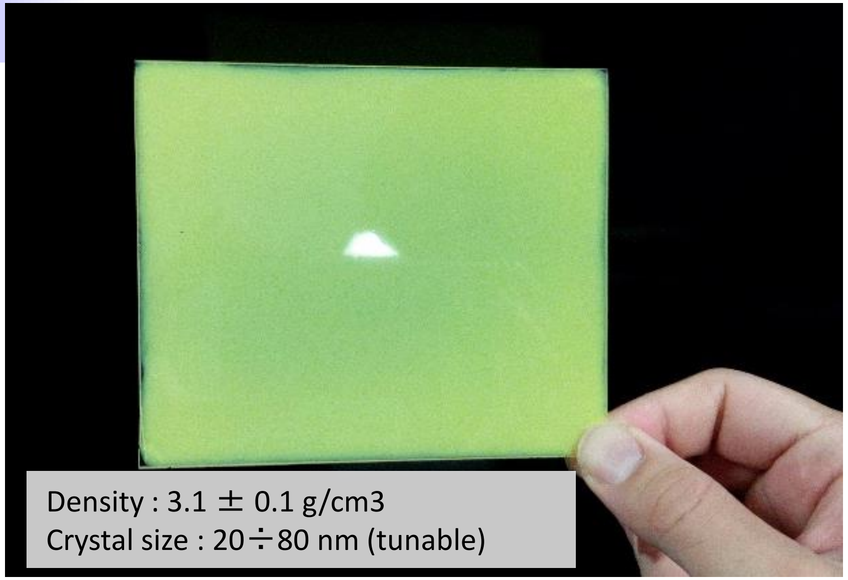
Readout by the optical system

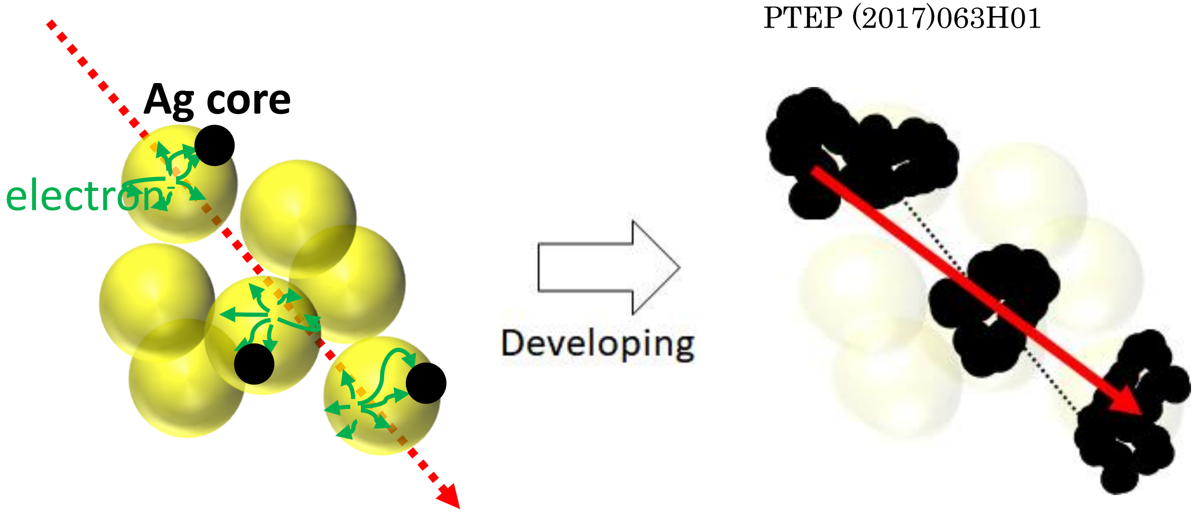
- Optical readout system
- Super-resolution analysis
- Directional and topological measurement

Nano Imaging Tracker (NIT) for NEWSdm

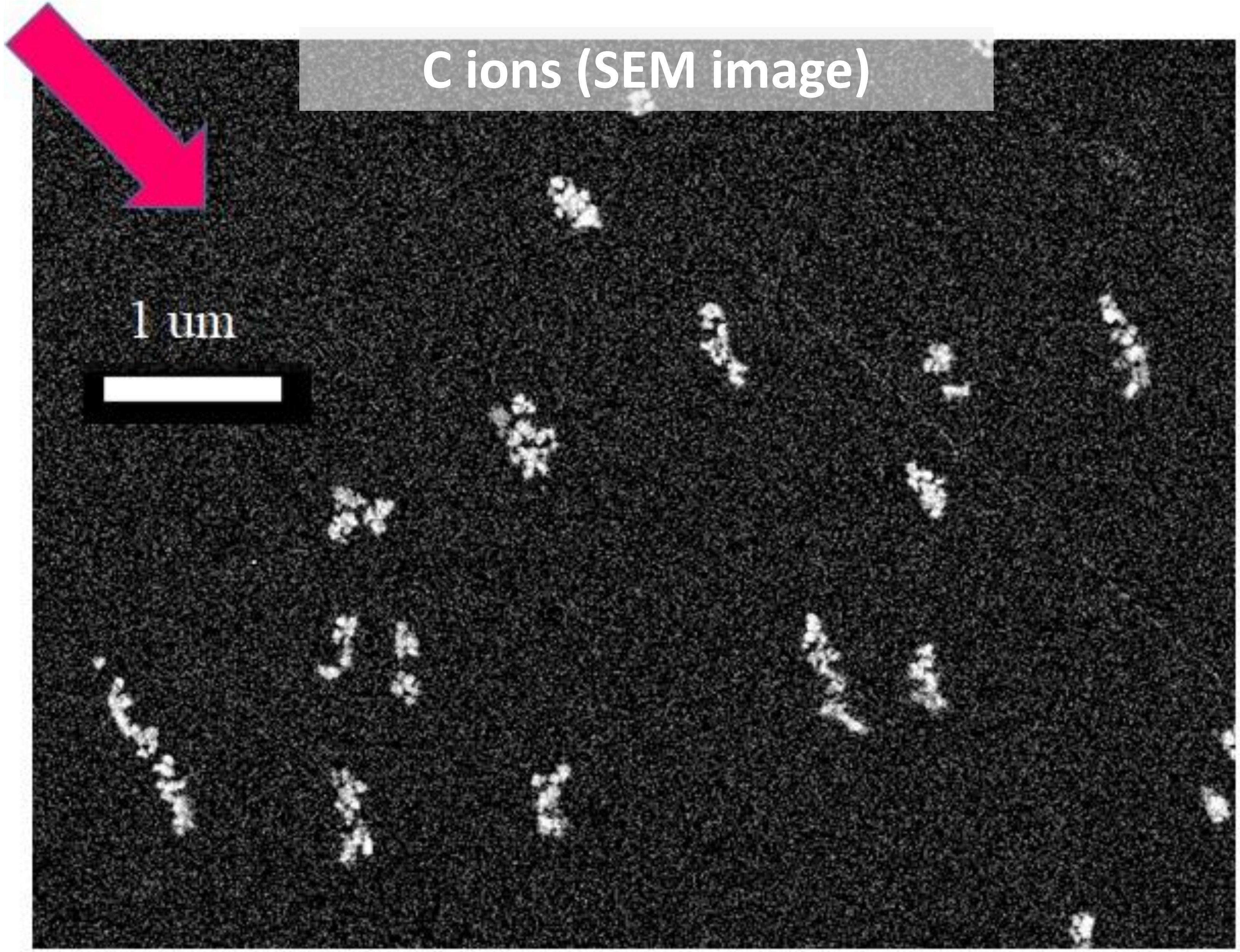


NIM A Nucl. Inst. Meth. A 718 (2013) 519-521
PTEP (2017)063H01

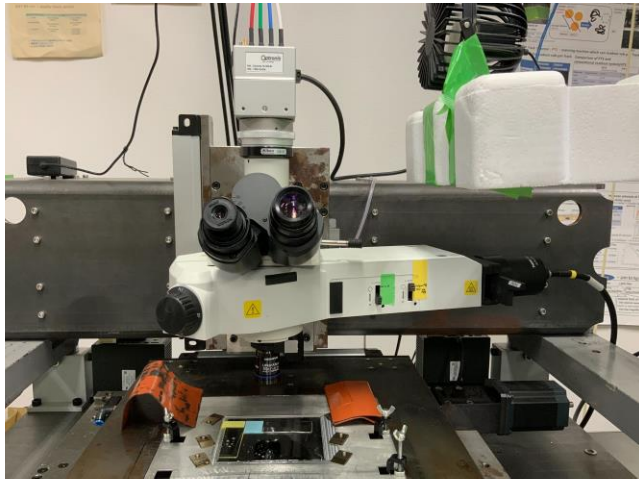




	Element	Mass fraction [%]	Atomic fraction [%]
Main target heavier DM	Ag	41.5	8.4
	Br	29.7	8.1
	I	1.9	0.3
Main target	C	12.3	22.7
	N	3.7	5.2
	O	9.2	12.5
Neutron, BDM	H	1.8	42.8
	S, Na + others	~0.1	0.1


C ions (SEM image)
1 um

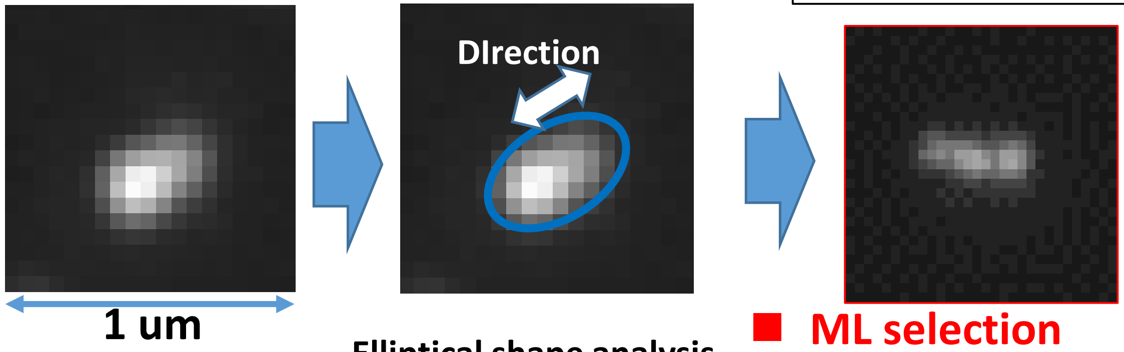
Readout technologies



Current set-up and performance

- Blue LED (450 nm λ)
  → 200 nm optical resolution
- CMOS camera image taking
- X100 objective lens

~ 0.1 kg/year/machine



Further selection

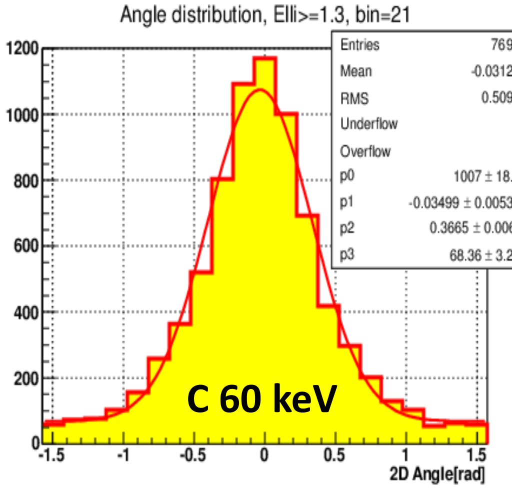
Elliptical shape analysis

PTEP. 103H02 (2020) 10

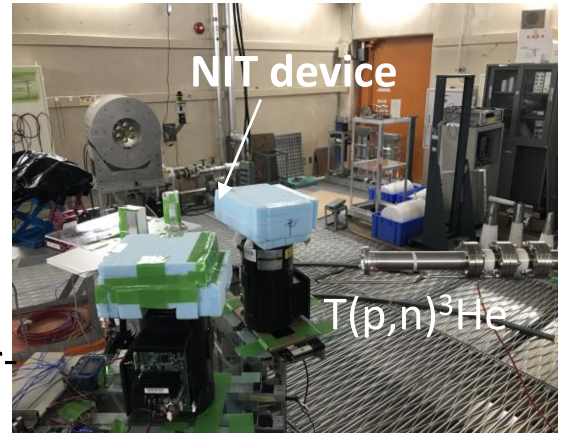
- **ML selection**
  ⇒ more likely track selection
- Plasmon analysis and super-resolution

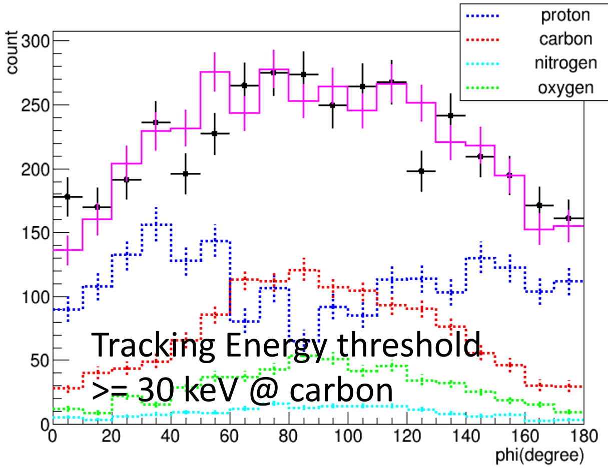
PTEP, 063H02,(2019) 6
Scientific Reports (2020) 10:18773

■ Ion-implantation



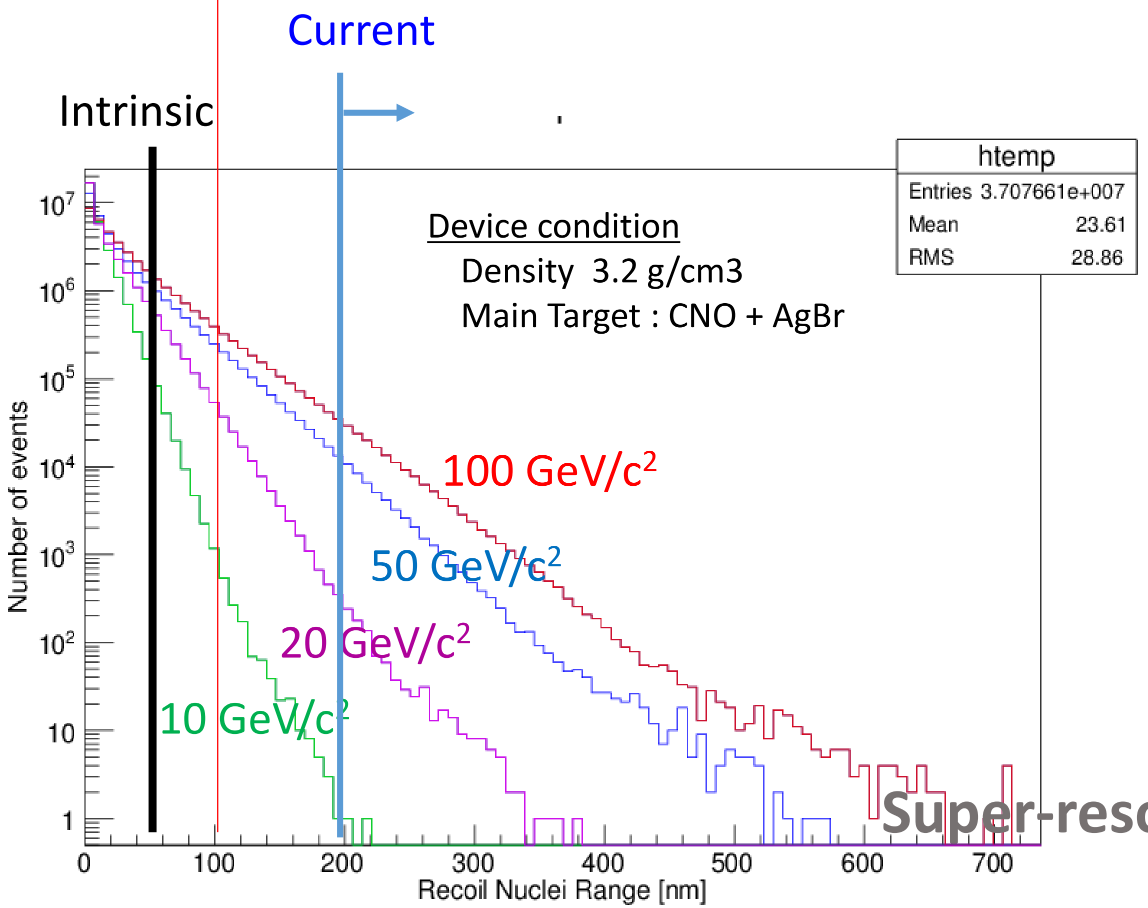
■ Nuclear recoil by neutron

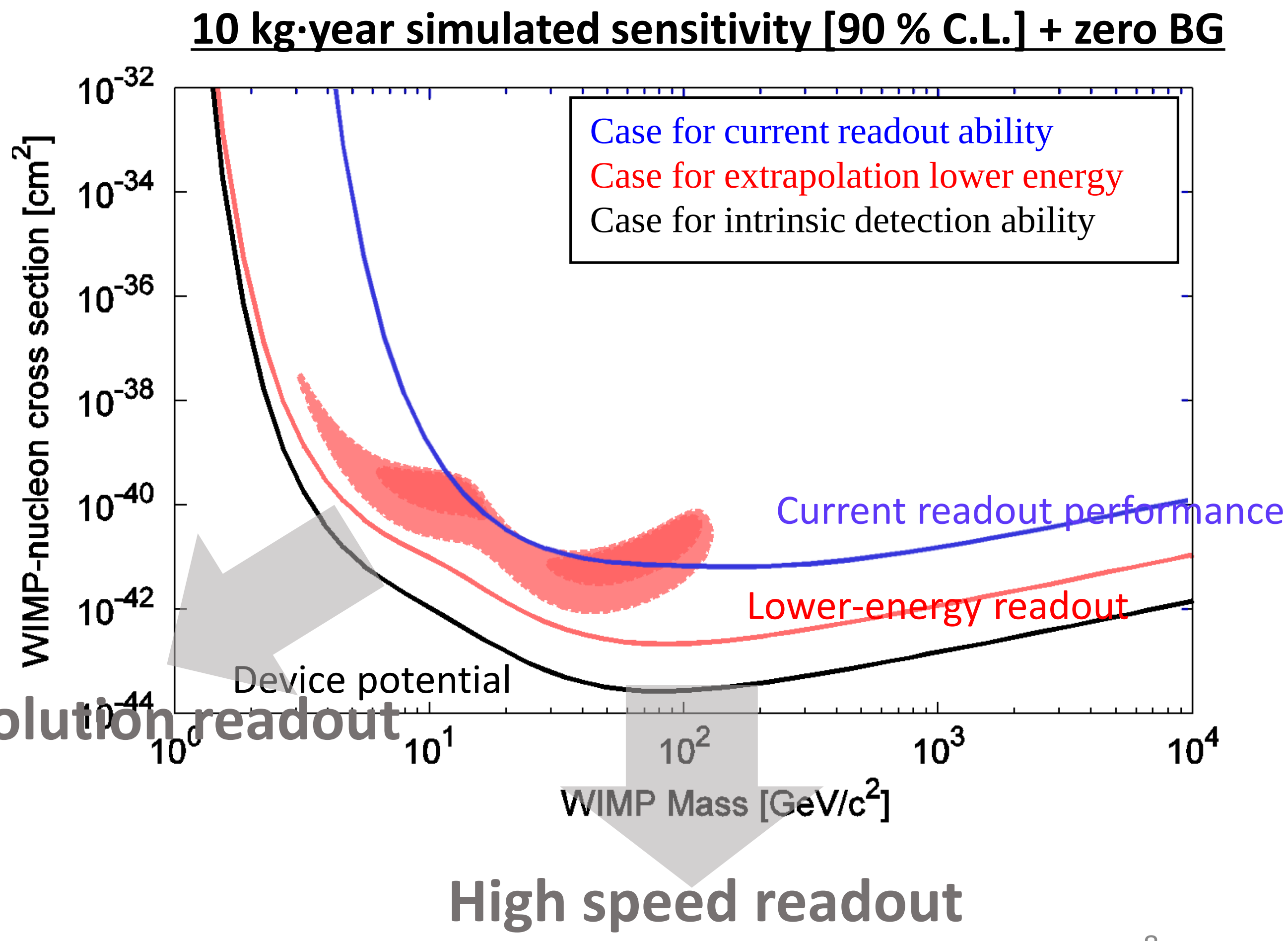




Dark matter sensitivity

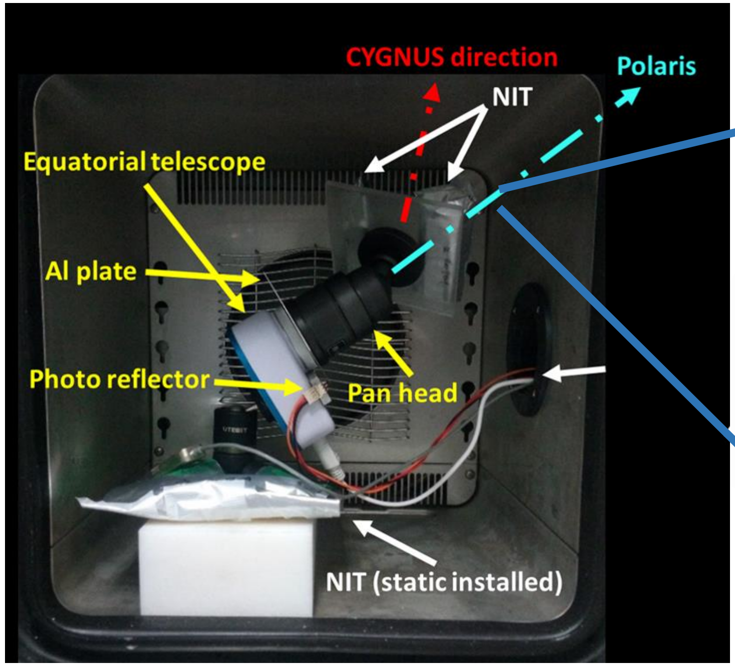
Demonstrated new tech.





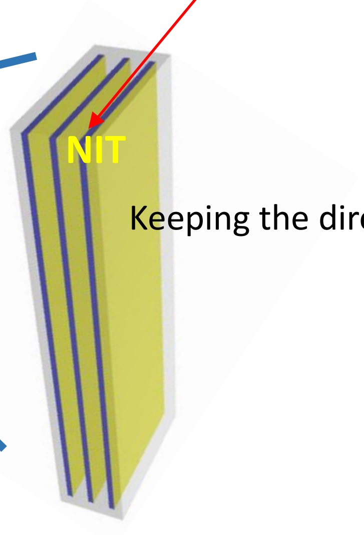
Demonstration of directional dark matter search [surface run @ Nagoya University]

Technical test at surface lab.

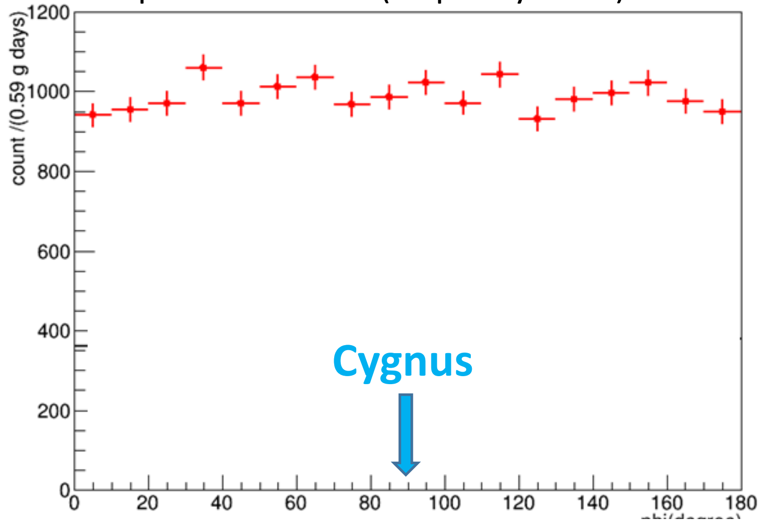


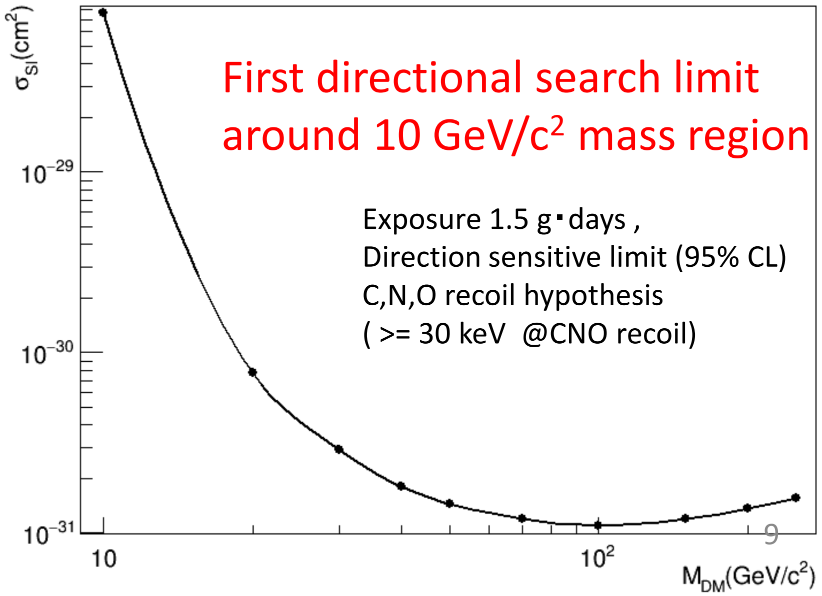
CYGNUS
(parallel to x axis)

glass base



Keeping the direction to the Cygnus



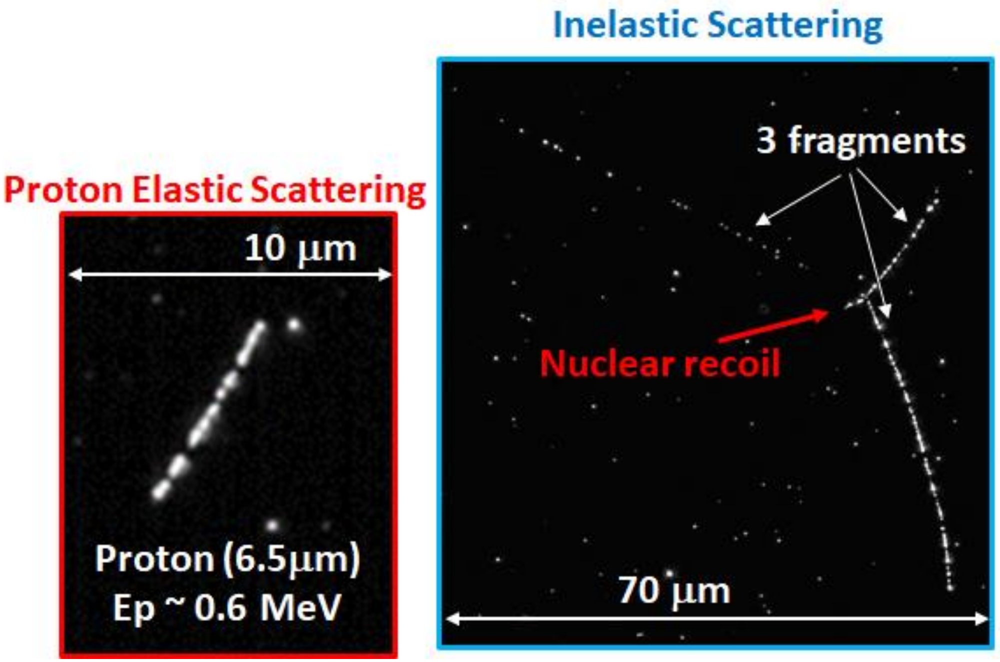


- **First demonstration of solid detector and directly tracking analysis**
- **Directional search around 10 GeV/c2 region is first in the world**

Proton recoil

Neutron Measurement

Sub-MeV or more energy neutron measurement by proton of > 100keV



Perfectly γ(or electron) background rejection by topological track information and crystal sensitivity

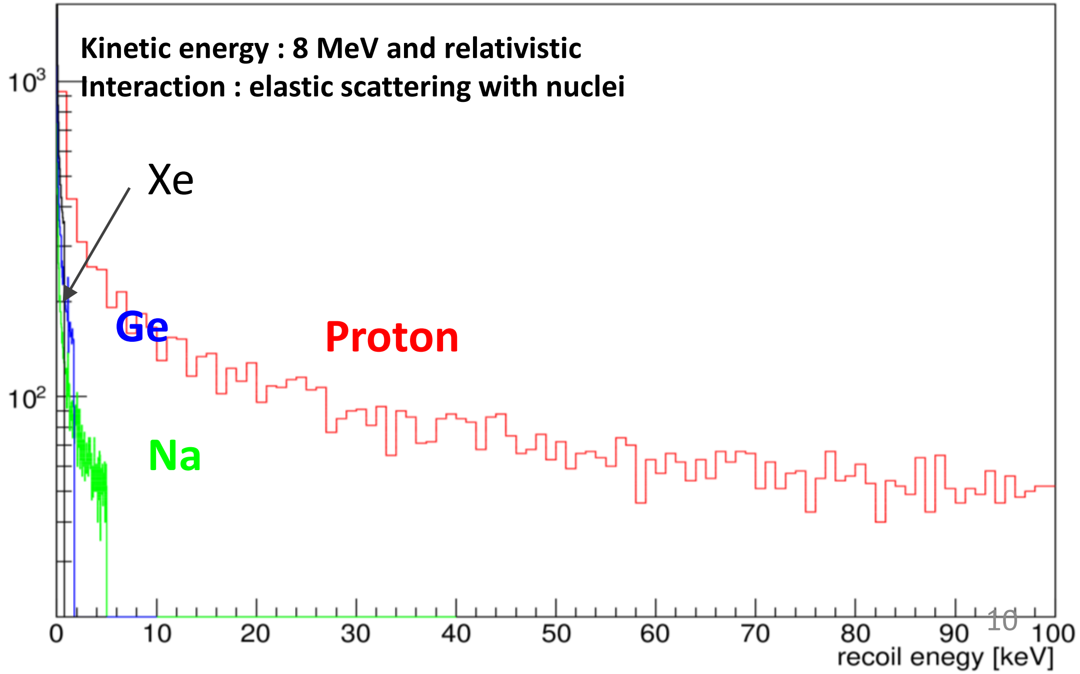
Boosted DM

- **Annihilation process of two-component DM in the GC**
- **MeV scale DM and baryon scattering**

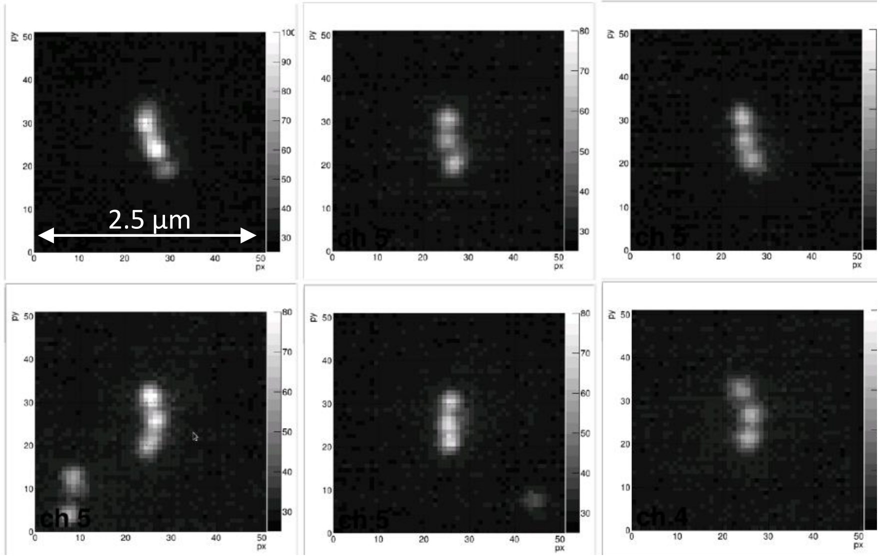
$\chi\chi \rightarrow XX$ [galactic center]

$\mathrm{X} + \mathrm{N} \rightarrow X + N$ **Test of baryon interaction**

BDM flux on the earth $\phi \sim 1.6\, cm^{-2} s^{-1} \left(\frac{<\sigma v>}{5 \times 10^{-26}\, cm^3/s} \right) \left(\frac{5\, MeV/c^2}{M_1} \right)^2$



Low-E Proton tracking

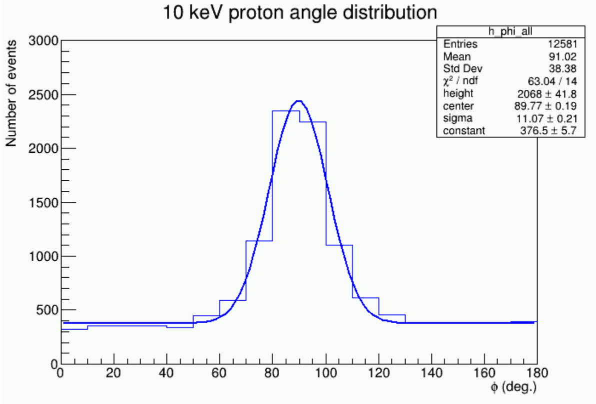


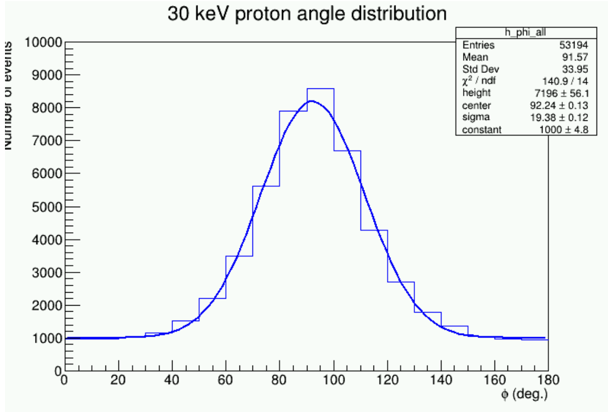
Low-energy proton beam by ion-implantation system

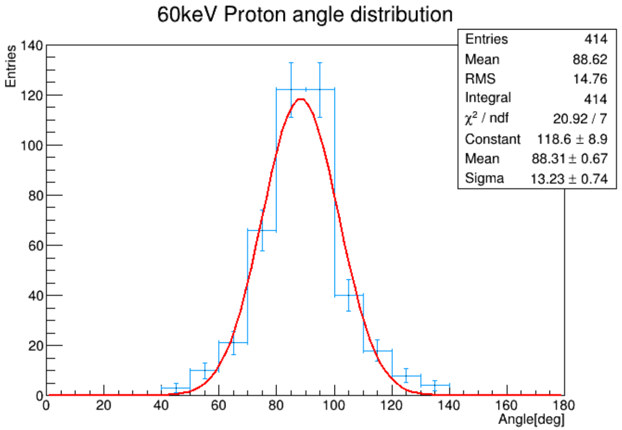
Setup condition :
- Horizontal exposure (~ 10°)
- NIT device : 70nm crystal + HA sensitization
- Data taking : PTS3 &4 analyzed

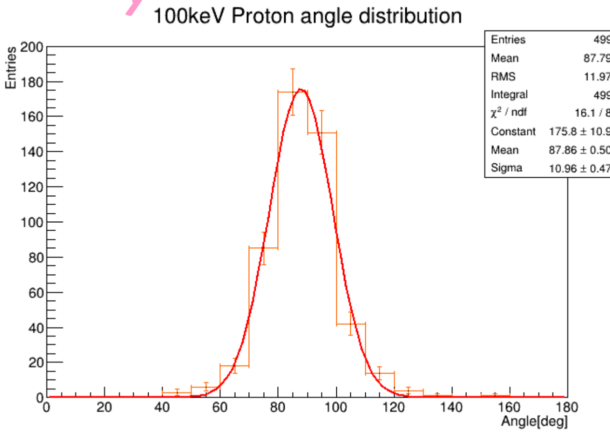
Angular distribution of proton induced by the ion-implantation system [10-100keV]

Preliminary









Proton recoil track of >10 keV was observed!!

Technical Application

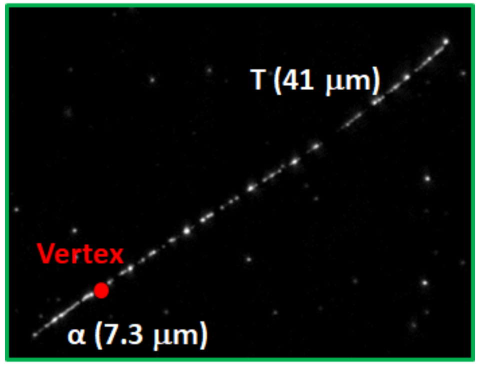
NIT device

Thermal & cold neutron imaging

■ Thermal & cold neutron imaging

① n + ^{10}B → α + ^{7}Li + 2.31MeV

② n + ^{6}Li → α + T + 4.78MeV

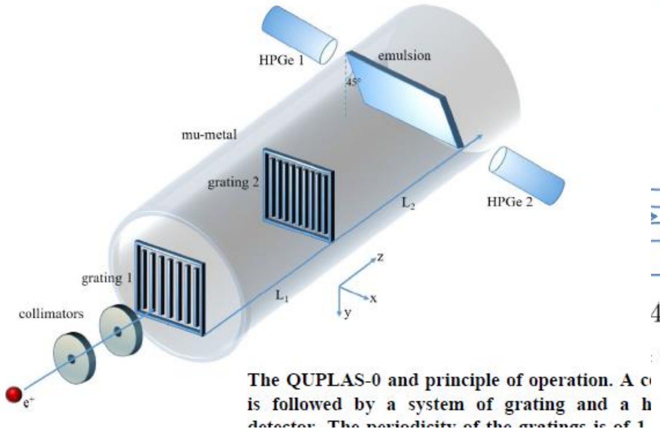


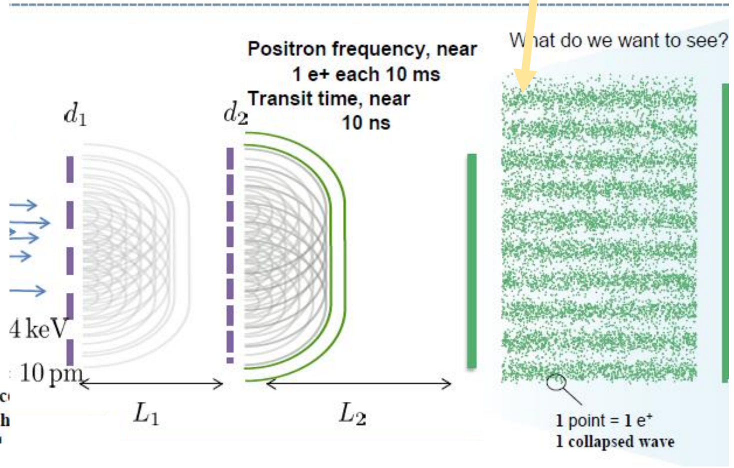
EPJ C vol.78, 959 (2018)

- Neutron radiography
- Gravitational effect by ultra-cold neutron

Etc.

Quantum effect for anti-particle [QUPLAS experiment]





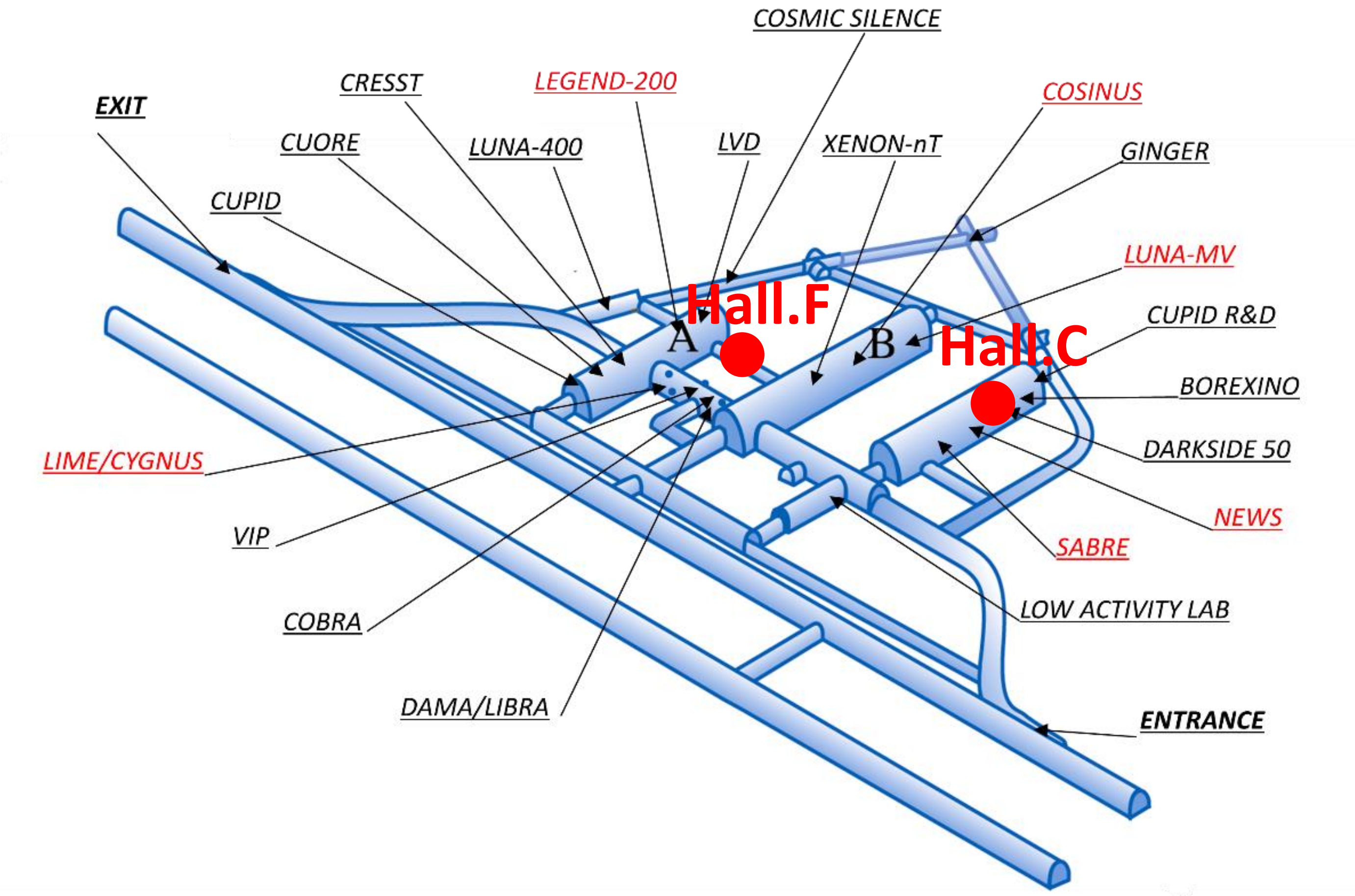
Scanning system → Paleo detector

- Heavy dark matter
- Q-ball
- Monopole

Galactic Archaeology!

Current LNGS activities

Underground facility @ LNGS



Underground facility @ LNGS

Device Production

~ 100 g /production/4 hour

(1 kg target production/week)

External background source	Shield power
Environmental γ-rays	$< 10^{-3}$
Environmental neutrons	$< 4.7 \times 10^{-2}$ (90 % C.L.)

Background expectation

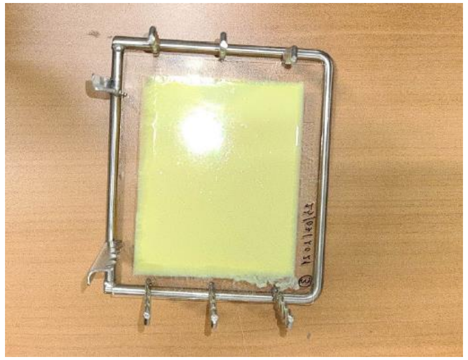
[Intrinsic radioactivity in the device]

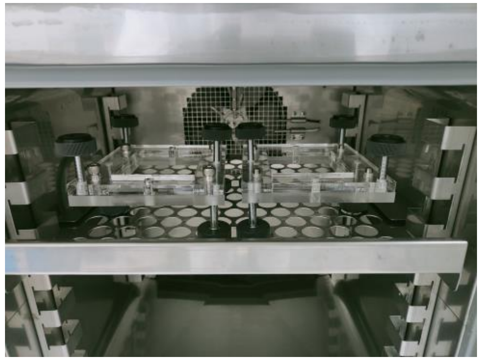
	Activity [mBq/kg]
U-238	42
Th-232	7-21
K-40	40-130
Ag-108m	50
C-14	24000

	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} /cm²/s	< 1 x 10^{-2}	< 1 x 10^{-2}
Environment γ-ray	0.38 /cm²/s	~ 1.8 x 10^{5}	< 100
C-14 (intrinsic)		~100	~100
Neutron	~10^{-6} /cm²/s	< 0.1	< 10^{-3}

Run operation

Pouring process — **Pre-dry process** — **Dry process** — **Run** — **Extraction + Development**





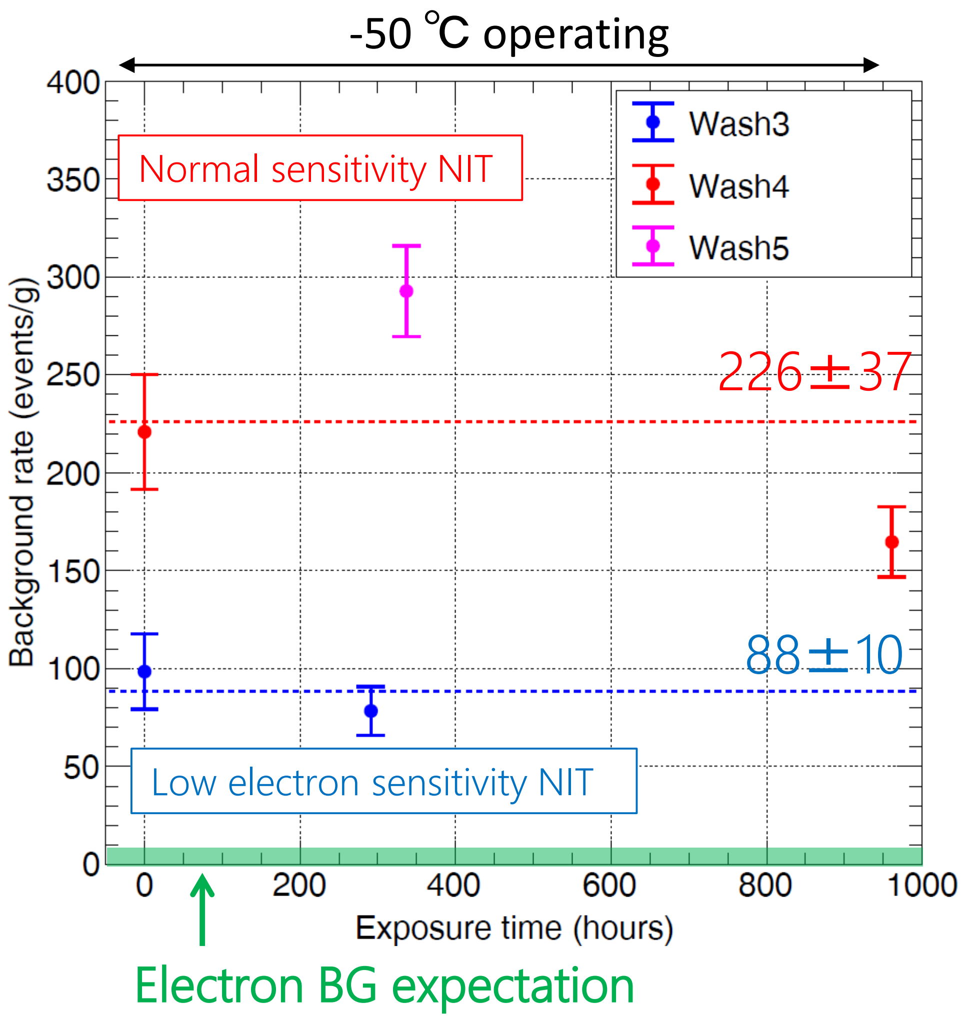
O(1) or less /g for electrons

~0.1 /g/day for electron (-50℃ operation)

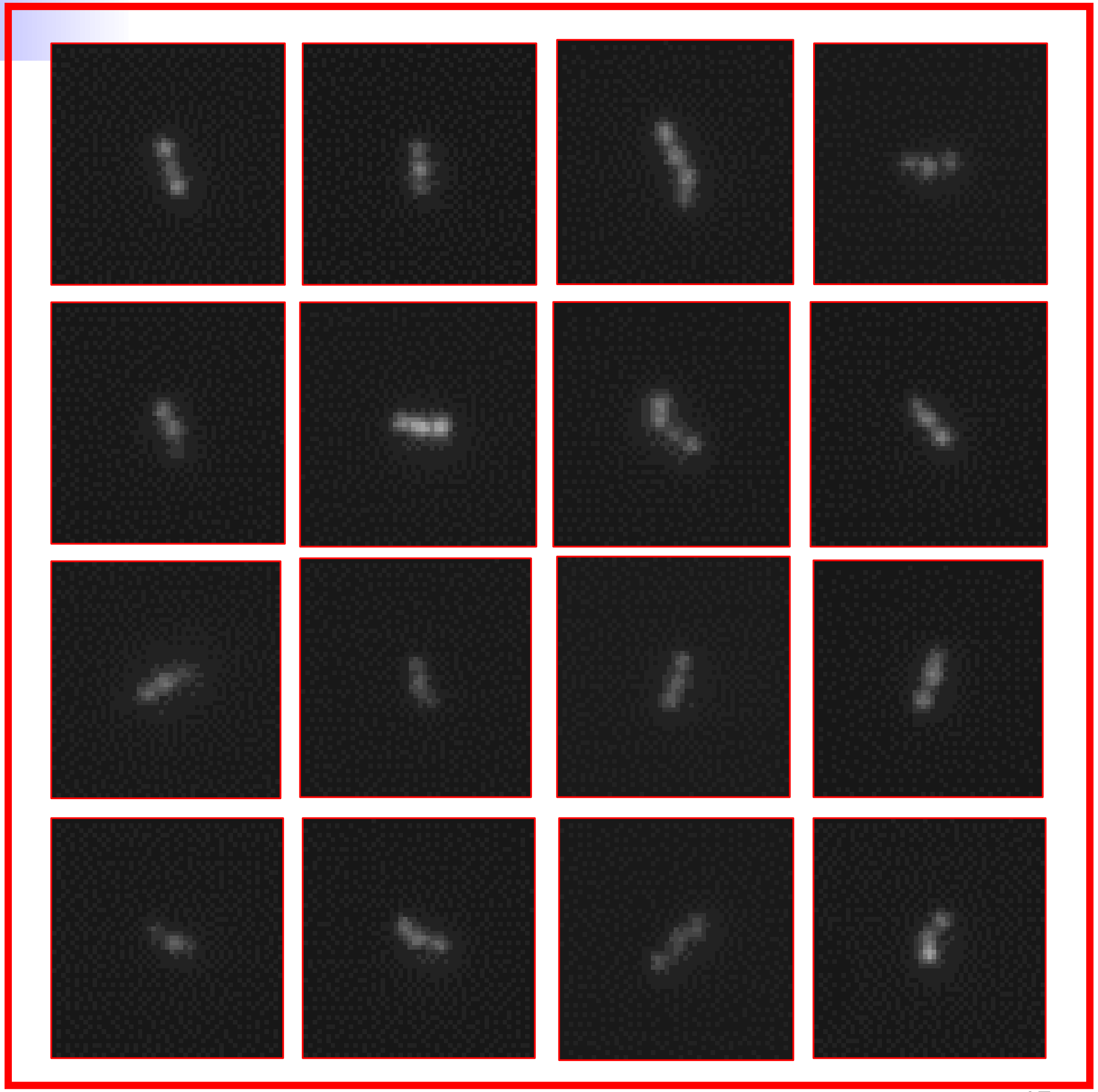
~ 5 /g for electrons

Integrated electron BG rate : 10 or less /g/month

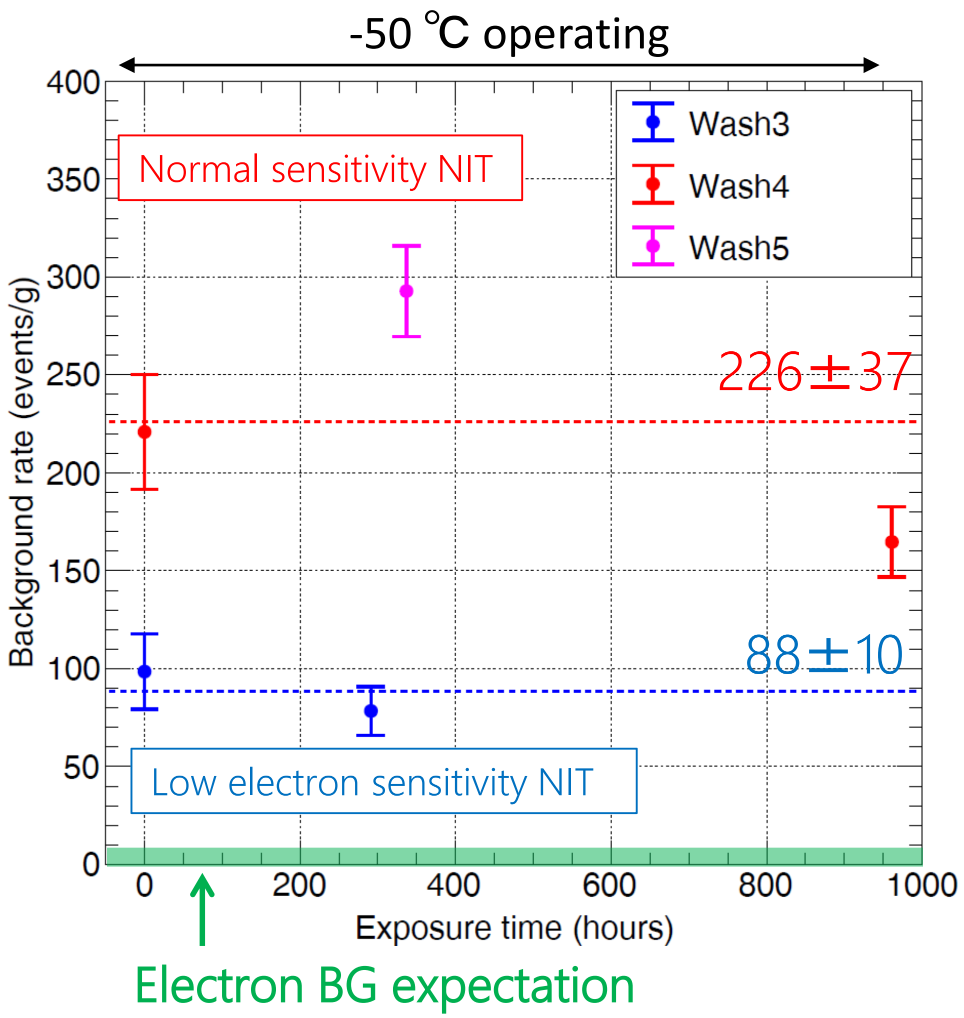
Underground BG run status

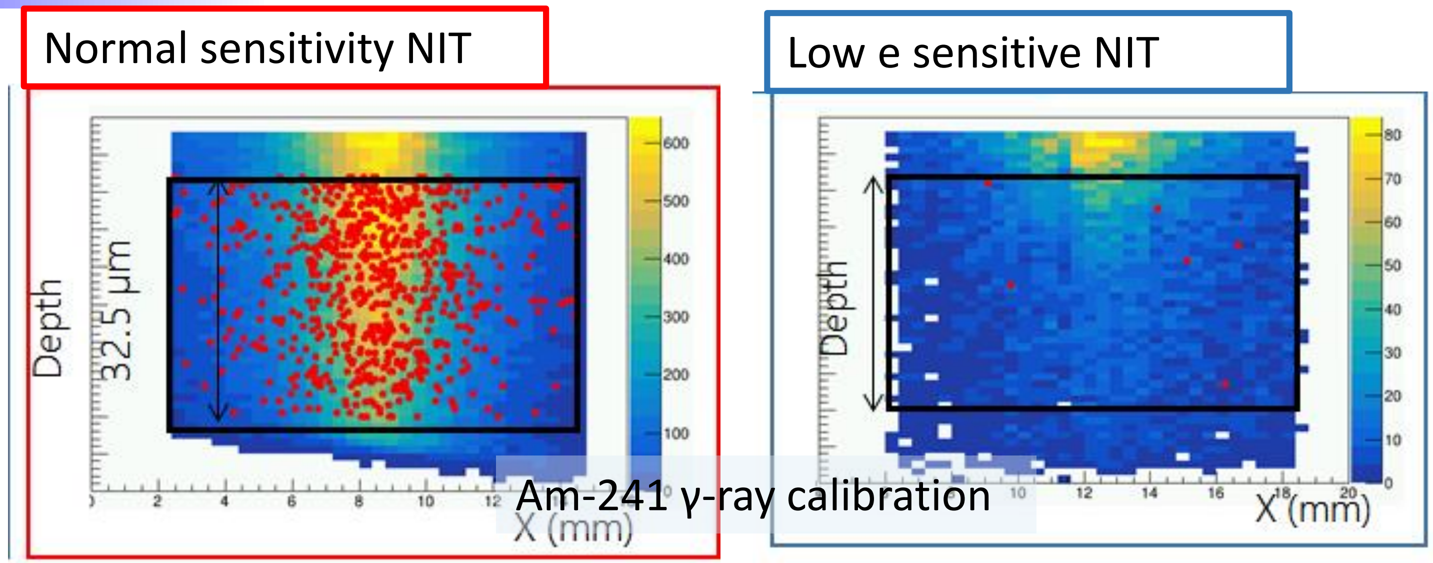


Example of Selected candidate events



Underground BG run status

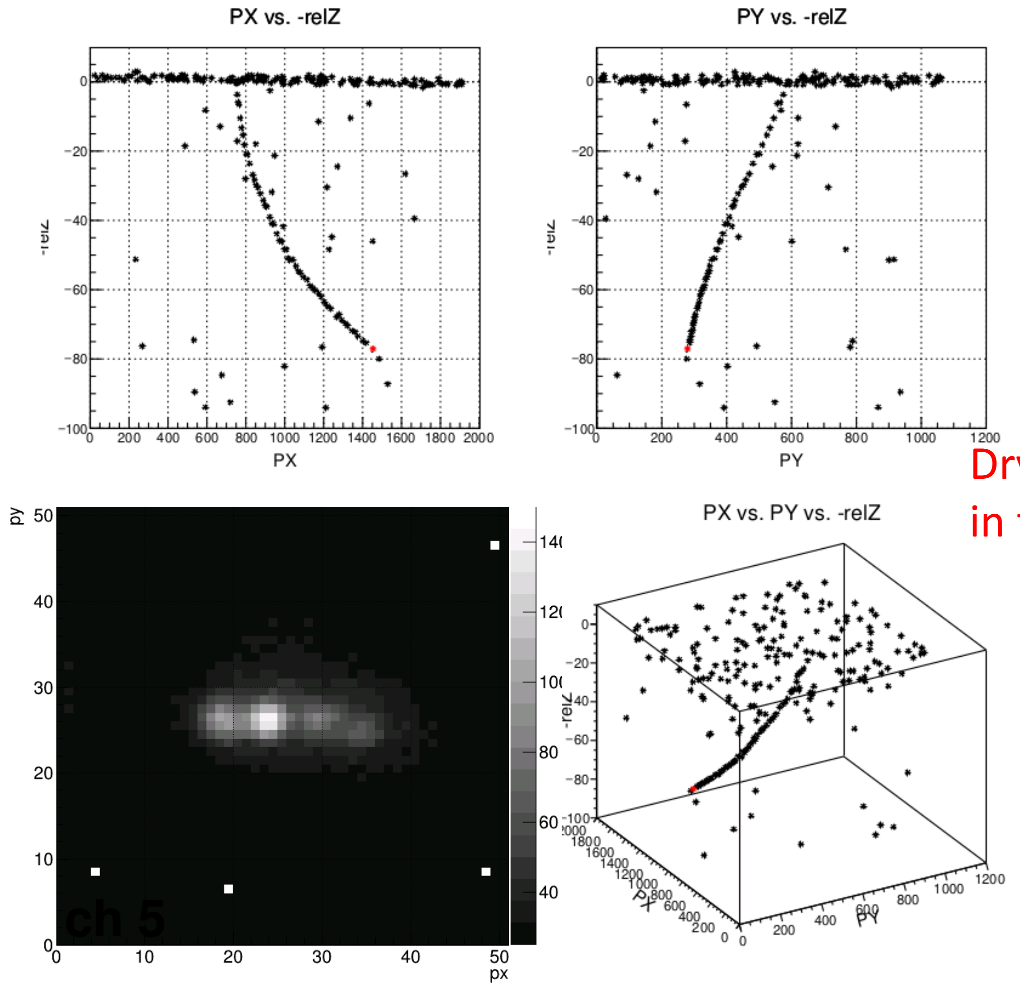




Electron efficiency is ×130 difference

- **Ruled out as electron BG**
  - **- Not so difference between two type NIT**
  - **- 10 times higher event rate than electron BG expectation**
  - **- track topology**
- **NO time dependency at -50℃**
  ⇒ Not CNO recoil
- **Unlikely accumulate outside the shield**

α-ray possibility



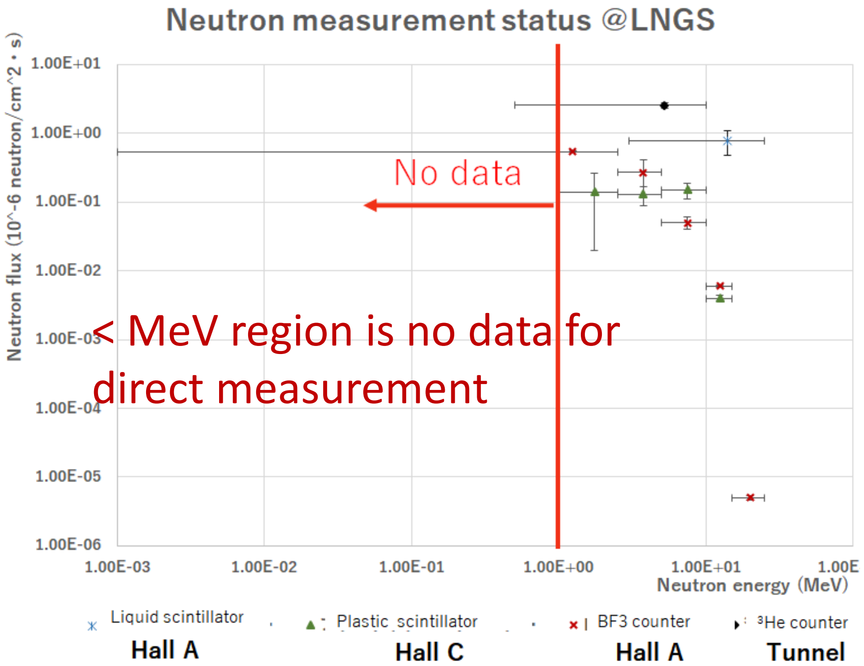
Rn measurement

		Bq/m^3	Sigma	℃	humid.	mbar
Hall. F	hallF prod.room chamber opened	**75.9**	15.3	12.1	82.4	917.8
Hall. F	hallF prod.room pouring desk	**72.5**	15.2	20.7	44.8	916.2
Hall. F	hallF prod.room fridge (wet gel)	**71.0**	9.1	8.4	52.6	912.6
Hall. F	hallF control room	**81.1**	16.7	17.5	44.5	907.4
Hall. F	hallF prod.room chem.desk	**89.2**	16.1	19.5	39.6	909.8
Dry process in the shield	hallC compressed air	**163.1**	14.3	15.1	11.0	915.7
Dry process in the shield	hallC N2 20L/h	**2.3**	2.6	15.1	7.8	921.3
Dry process in the shield	hallC top of shield air	**46.9**	9.6	14.5	45.3	914.8
	hallF dev.room desk	**87.0**	16.4	17.2	53.5	907.1
	hallF corridor air	**73.8**	19.8	17.1	46.0	907.1
	hallB air (source of room air)	**18.6**	6.3	14.5	46.0	909.3

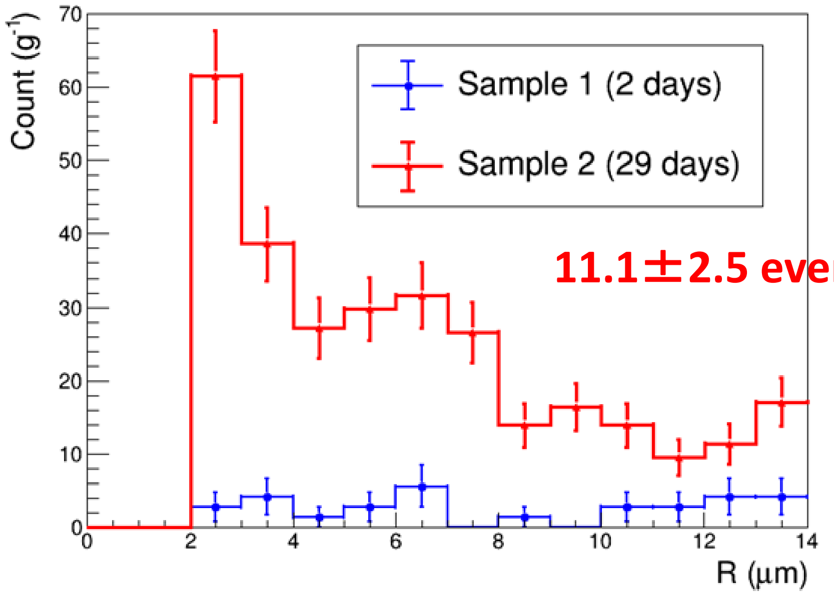
*average from 8h to end

2 times higher alpha-ray source (Rn) was contaminated in the drying air

Sub-MeV neutron measurement at LNGS

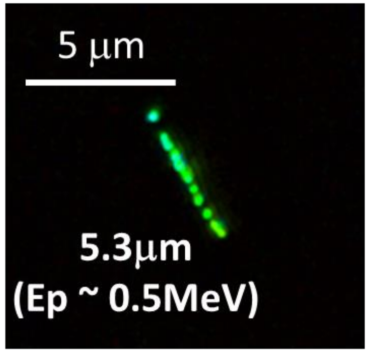


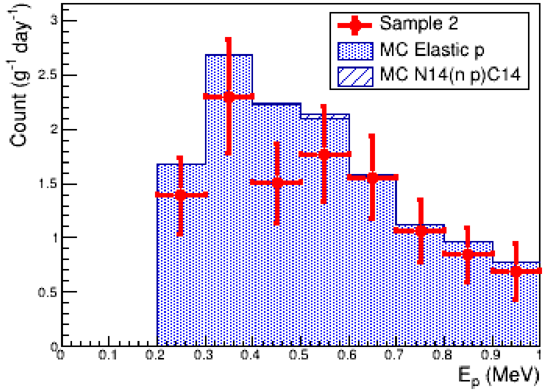
Range spectrum of Single-prong signal

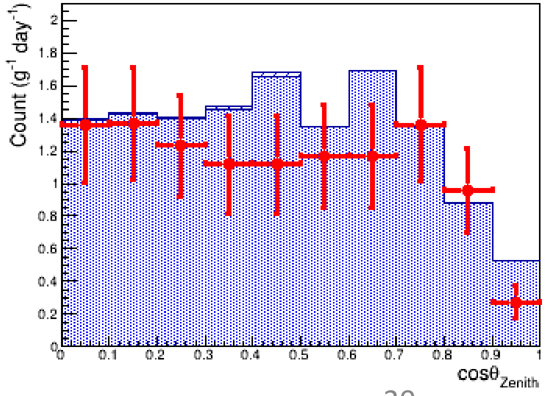


11.1±2.5 event/g/day

Neutron elastic scattering







✓ **Observed signal increase consistent with environmental neutron signal**

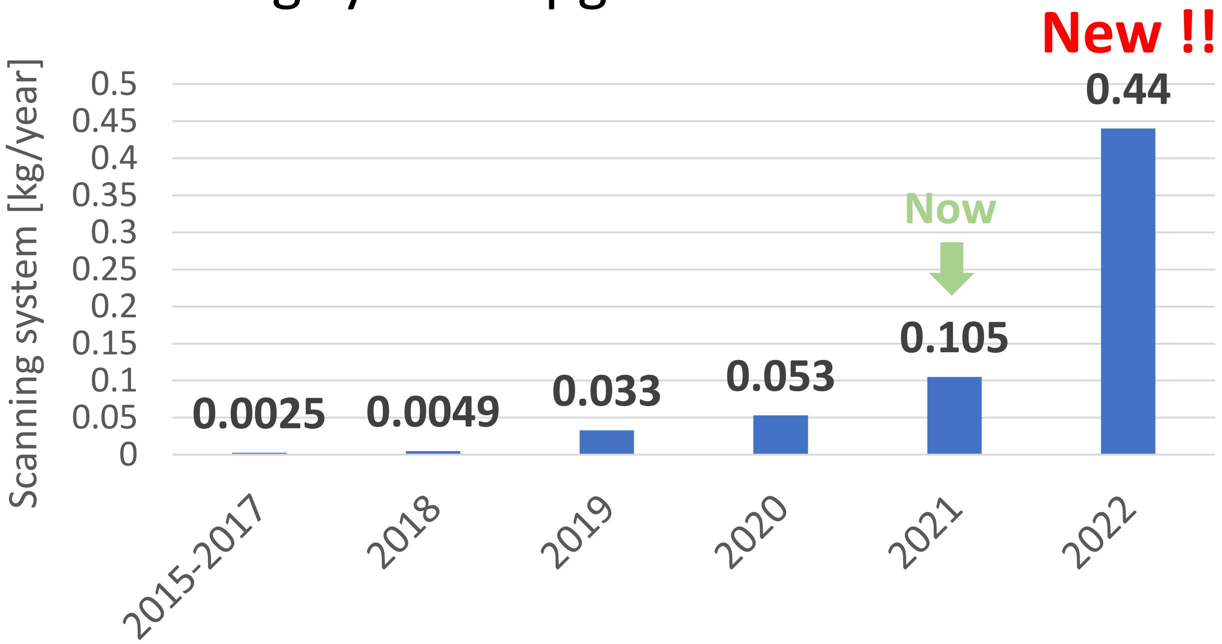
Flux @0.25-10 MeV :(5.9±1.2) x 10^{-3} cm^{-2} s^{-1}

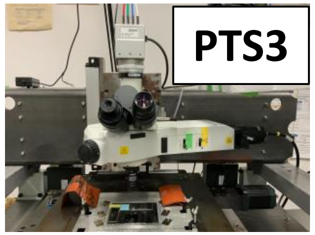
arXiv:2208.13366 (2022)

Next: underground measurement

Prospect

■ Scanning system upgrade





+1

Current speed : 0.1kg/year/mothine
→ 0.44 kg/y/machine x 5 machine ~ 2.0 kg/y scanning [2022-2023

Additional upgrade study is also on going
~ 2.0 kg/y scanning ⇒ > 50 kg/y [2024-]
* multi camera and wide view image taking
* 10 machine operation

■ Underground and surface run [2022-2023 task]

- Improvement to lower background condition and scale up
- Proton recoil tracking to search the BDM both surface and underground run
- Neutron measurement at underground lab

And, continue to various upgrade study for the device and data analysis

Conclusion

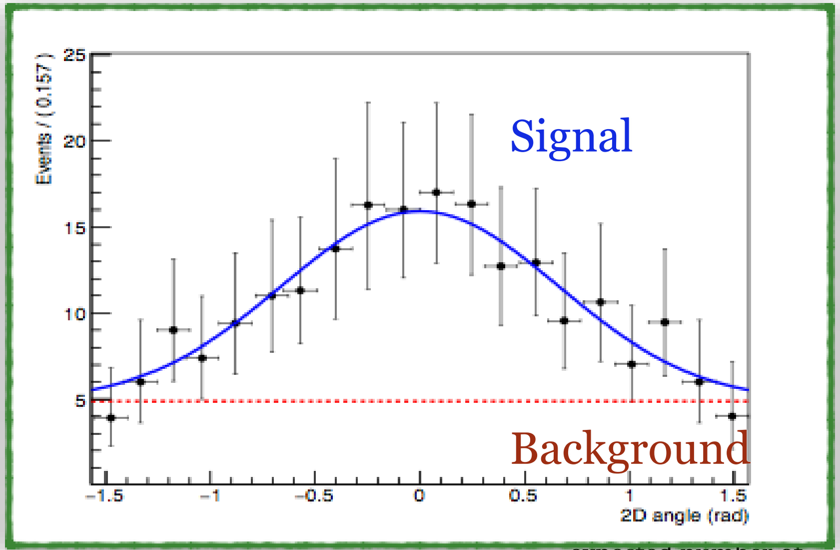
- NEWSdm is motivated by the directional dark matter search, and sub-micron length tracking by the Nano Imaging Tracker (NIT) based on the fine-grained nuclear emulsion
- Tracking ability for the nuclear recoil of O(10) keV was demonstrated by the ion-implantation system and neutron recoil
- Directional search was also demonstrated at the surface lab. using the telescope, and got the first limit with directional information
- Device facility at hall.F, LNGS was constructed, and all handling from device production is possible.
- Now, underground run at LNGS is promoting, and observed the higher level BG to our expectation

⇒ they are expected to be BG attributed to alpha-ray contaminated in dry process

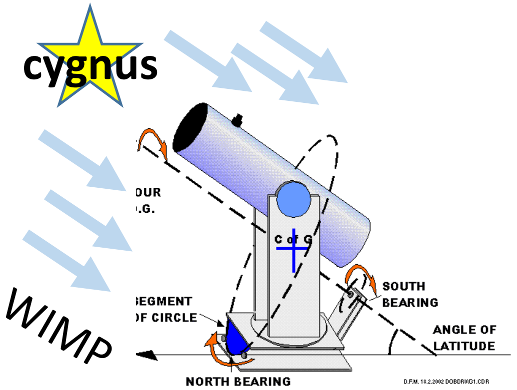
- Sub-MeV neutron measurement on surface lab. at LNGS was succeeded , and go to underground measurement as next.

Back up

Potential of Directional Sensitive Search



N. Agfanova *et al.* (NEWSdm collaboration)
Eur. Phys. J. C (2018) 78: 578



expected number of WIMP events

expected number of background events

signal pdf

background pdf

$$\mathscr{L}(\sigma_{\chi-n}, R_b) = \frac{e^{-(\mu_\chi+\mu_b)}}{N!} \times \prod_{i=1}^{N} [\mu_\chi f_\chi(\vec{q}_i;t_i) + \mu_b f_b(\vec{q}_i)]$$

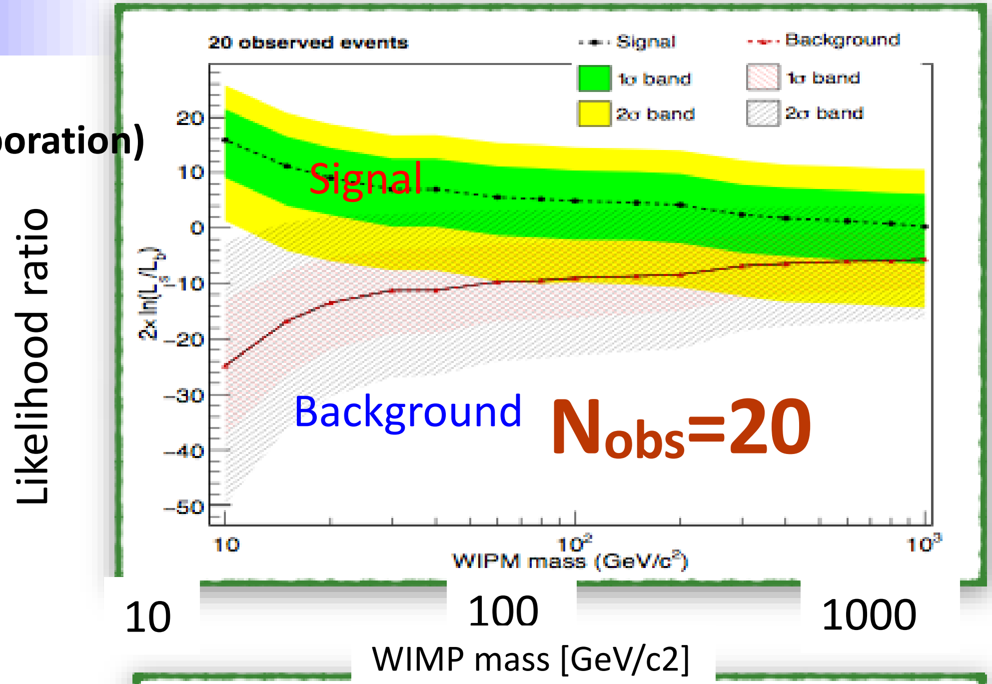
total number of observed events

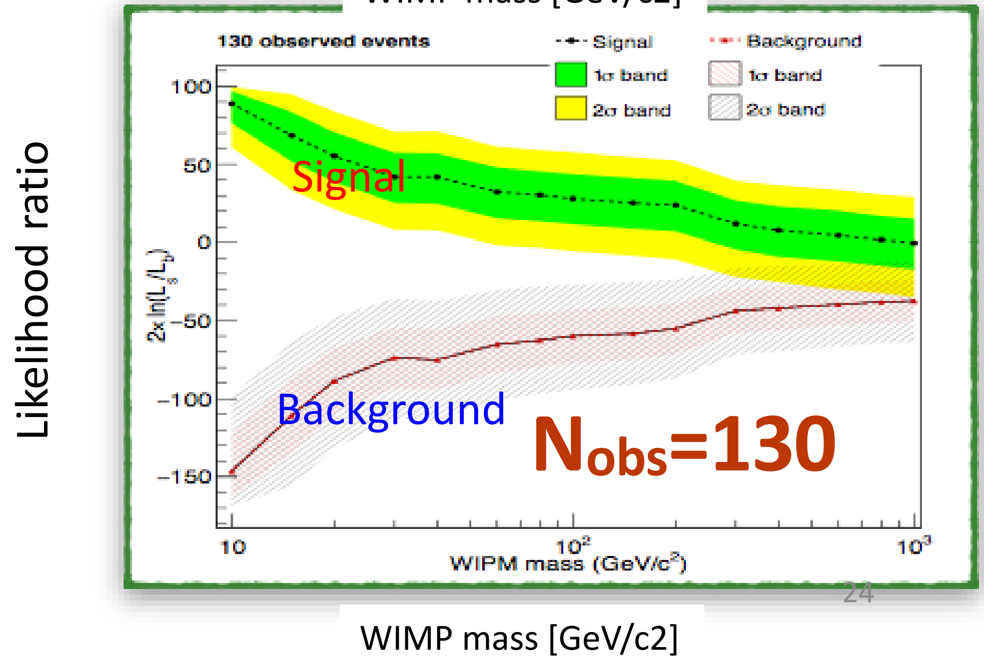
set of observables

<u>Annual modulation : O(1000) events</u>

Gain of 100 times

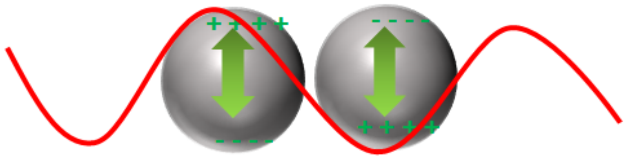
<u>Direction information : O(10) events</u>





Super-resolution system with localized surface plasmon resonance(LSPR) response

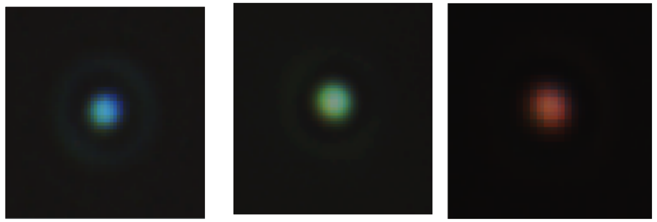
LSPR

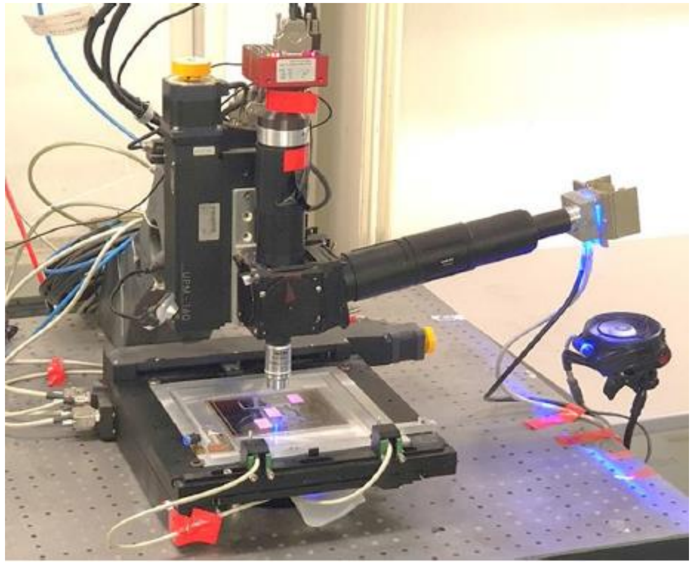


Dipole-moment of free electron in the nano metaric particle

$$p = 4\pi\varepsilon_m a^3 \frac{\varepsilon_1(\lambda) - \varepsilon_m(\lambda)}{\varepsilon_1(\lambda) + 2\varepsilon_m(\lambda)} E_0$$

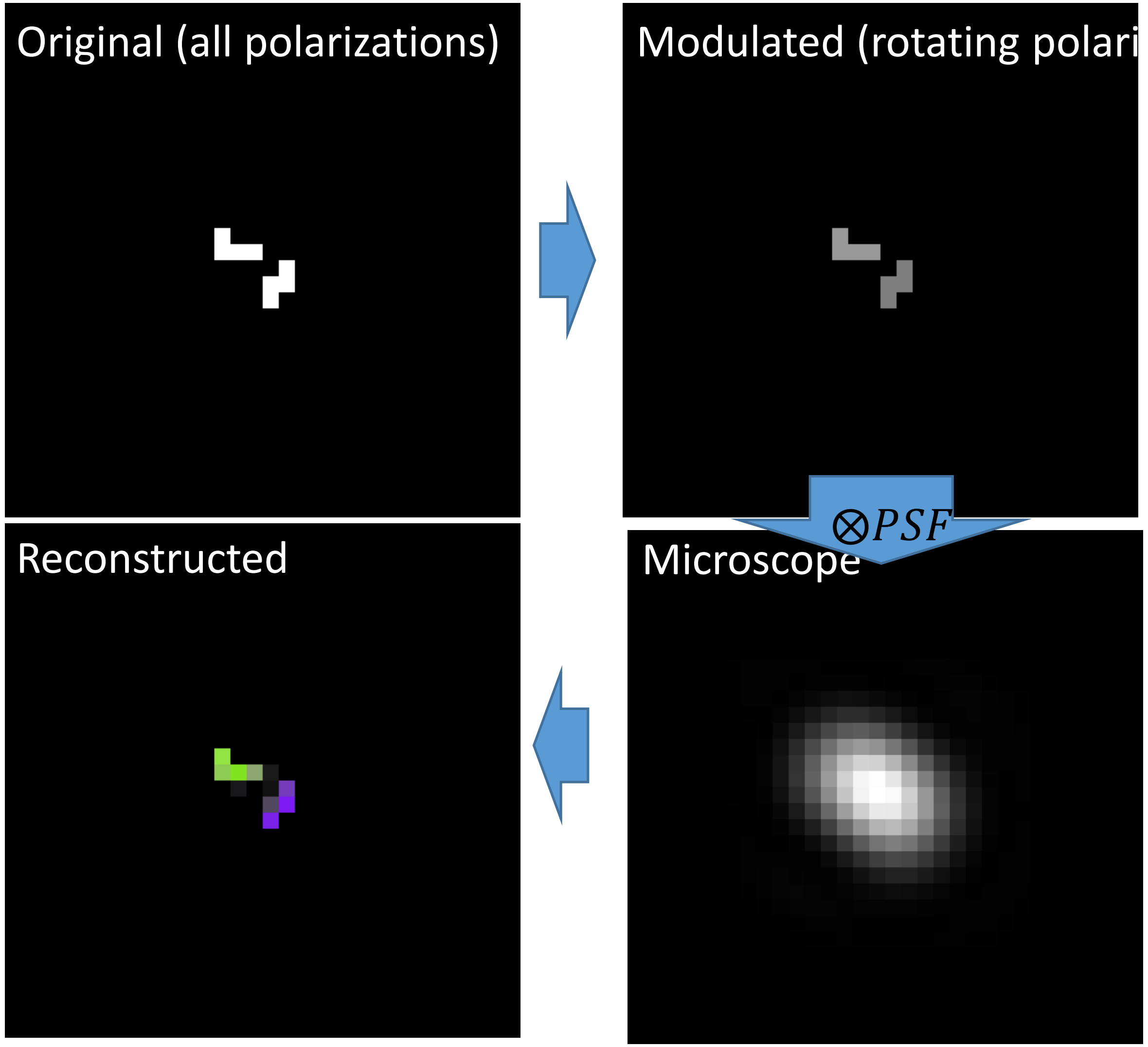
$$\varepsilon_1(\lambda_l) + 2\varepsilon_m(\lambda_l) \approx 0$$





PTEP, 063H02,(2019) 6 https://doi.org/10.1093/ptep/ptz033

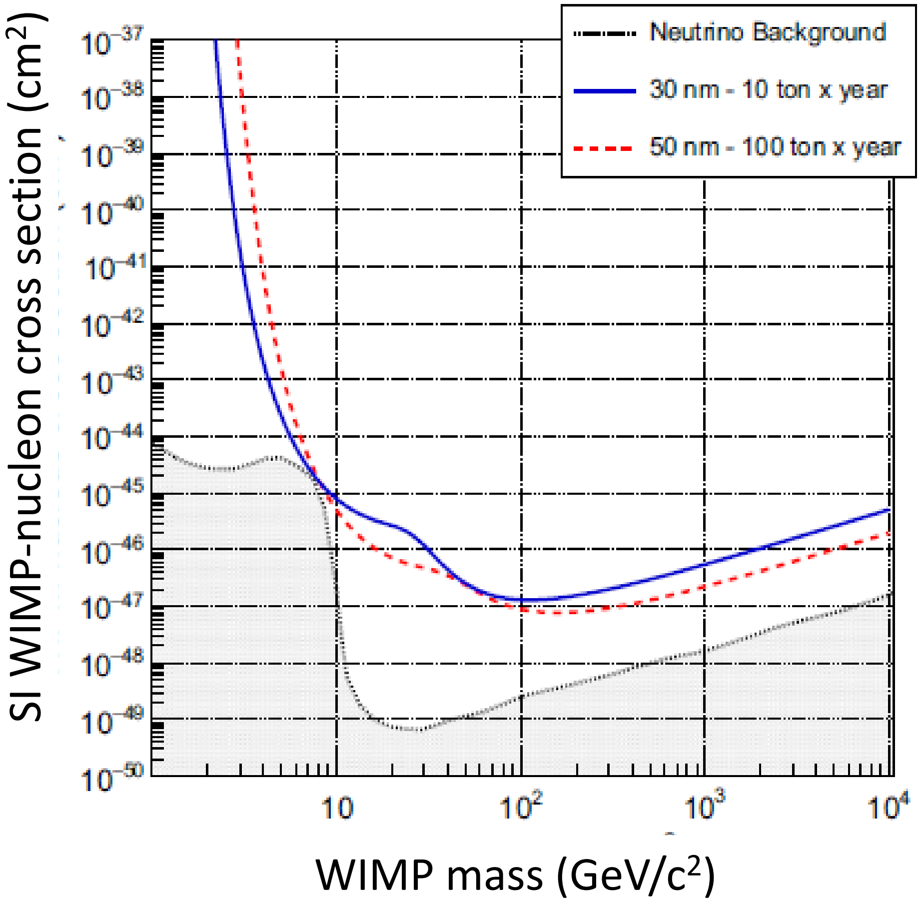
Scientific Reports (2020) 10:18773



Modulate the intensity of each pixel in the image: $I_\theta = a\cos[2(\theta - \varphi)] + b$

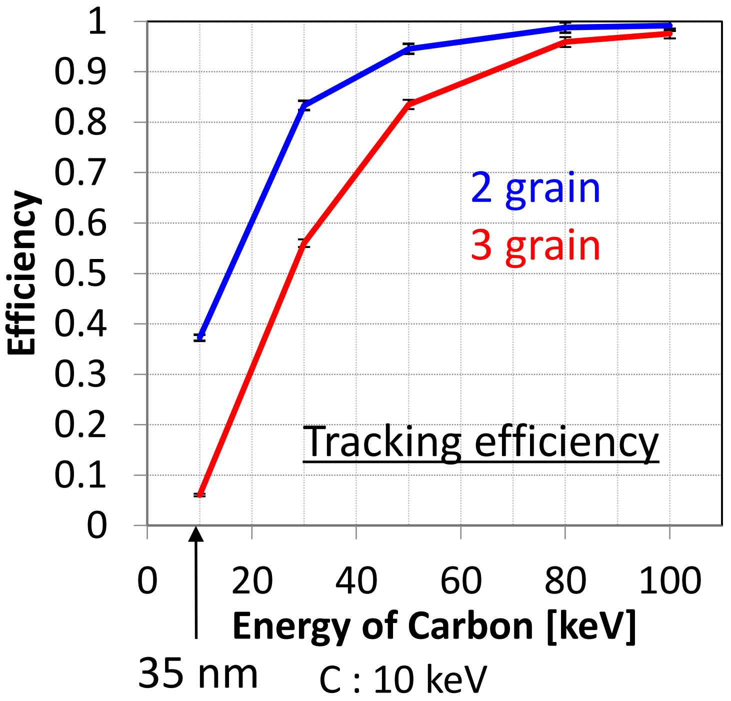
θ – polarization angle
φ – pixel "phase",
b – pixel brightness mean,
a – pixel brightness change amplitude

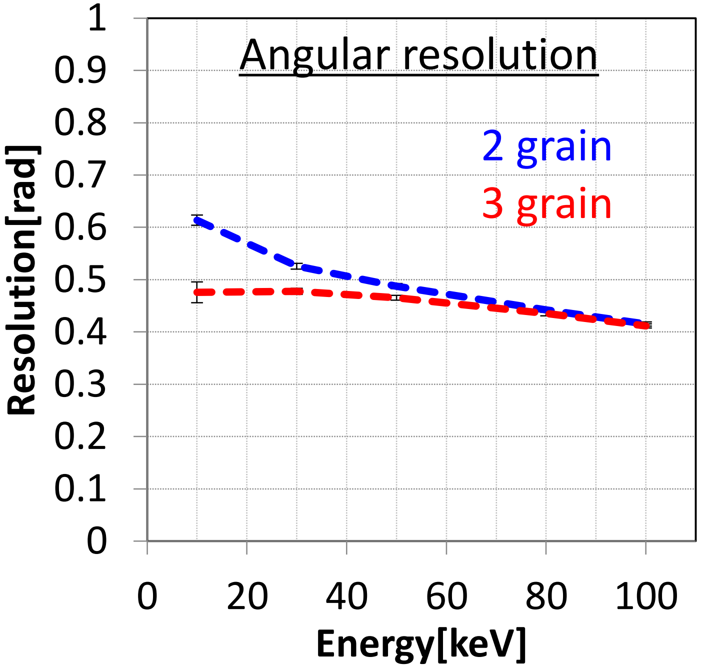
Device potential toward neutrino



NEWSdm collaboration Eur. Phys. J. C 78 (2018) 578 DOI: 10.1140/epjc/s10052-018-6060-1

Simulation for NIT device intrinsic potential





C : 10 keV
Br : 45 keV
Ag : 55 keV

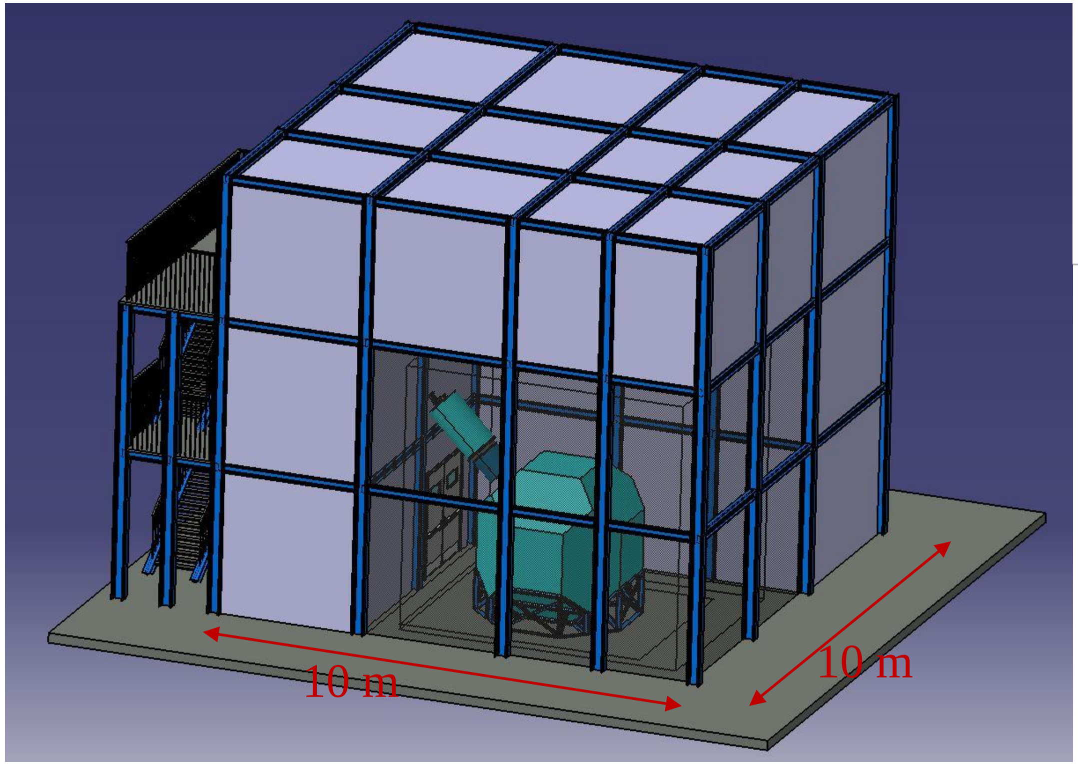
☑ 10 ton production : special machine optimized this device is required (more simple system : current machine is over speck)

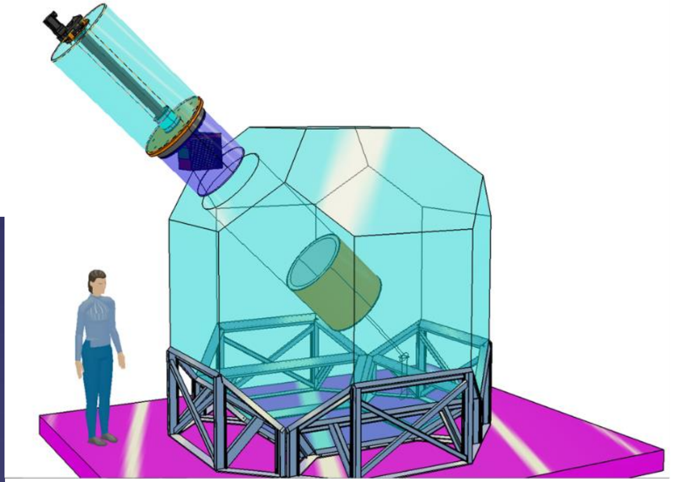
☑ High scanning speed machine is needed (current highest machine in the nuclear emulsion field is ~1 ton/month)

☑ under studying about light emission from NIT as event trigger

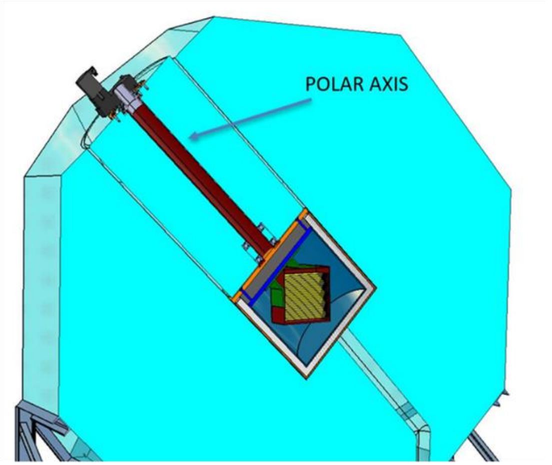
Future facility for NEWSdm: 10kg and beyond

Emulsion facility and shielding with an equatorial telescope





(a)



(b)