XIII International Conference
on New Frontiers in Physics
26 Aug - 4 Sep 2024, OAC, Kolymbari, Crete, Greece

DIRECTIONAL DARK MATTER SEARCHES WITH THE NEWSdm EXPERIMENT

Andrey ALEXANDROV (on behalf of the NEWSdm collaboration)

I.N.F.N. – National Institute for Nuclear Physics - Naples section, Italy

NEWSdm Collaboration

Nuclear Emulsion WIMP Search directional measurement

84 physicists
24 institutes

JAPAN
Chiba, Nagoya, Toho, Tsukuba

RUSSIA
LPI RAS Moscow
JINR Dubna
SINP MSU Moscow
INR RAS Moscow
NUST MISiS Moscow
NRU HSE Moscow

ITALY
LNGS
INFN: Napoli, Roma, Bologna, Bari, Padova
Univ.: Napoli, Roma, Partenope, Basilicata, Potenza, Sannio

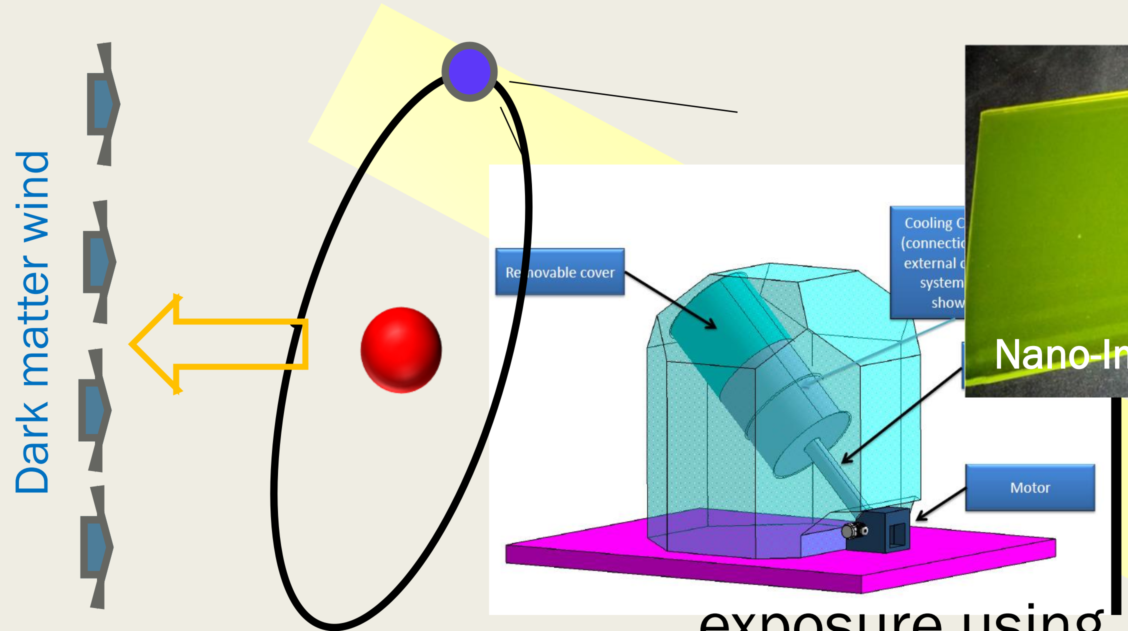
SOUTH KOREA
Gyeongsang University

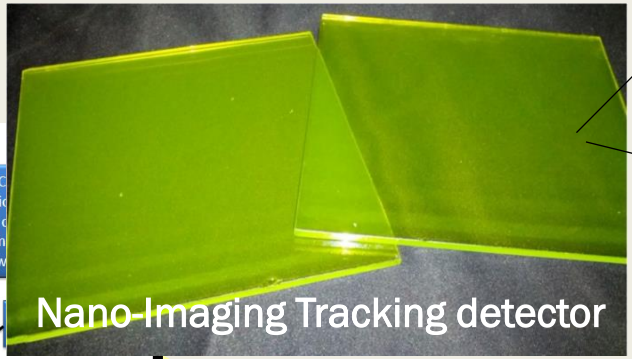
TURKEY
METU Ankara

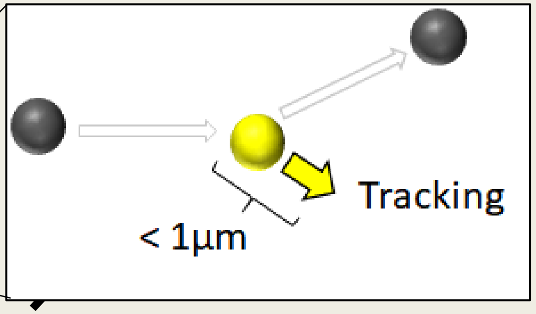
Website: news-dm.lngs.infn.it
Letter of intent: https://arxiv.org/pdf/1604.04199.pdf

NEWSdm experiment concept

Direction sensitive dark matter search with nano-tracking technologies for super resolution nuclear emulsion



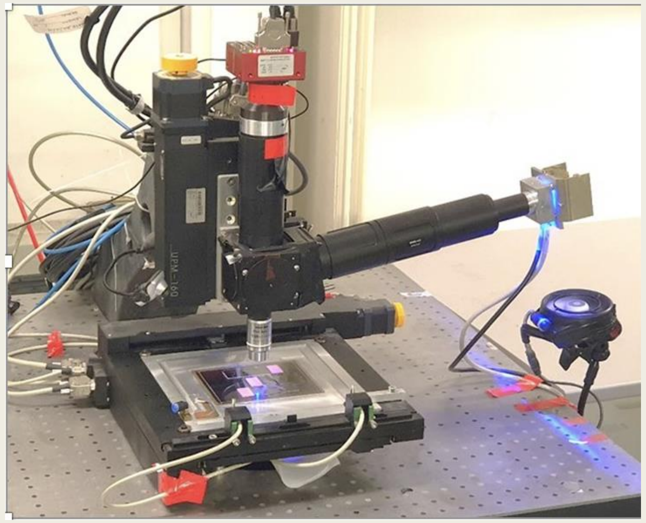




exposure using
an equatorial telescope

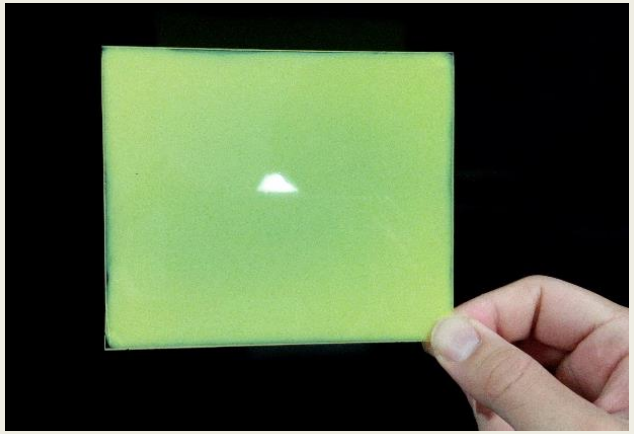
Underground laboratory
Gran Sasso (LNGS)

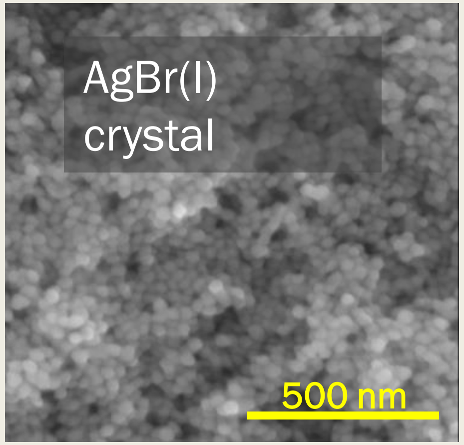
Optical image readout



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

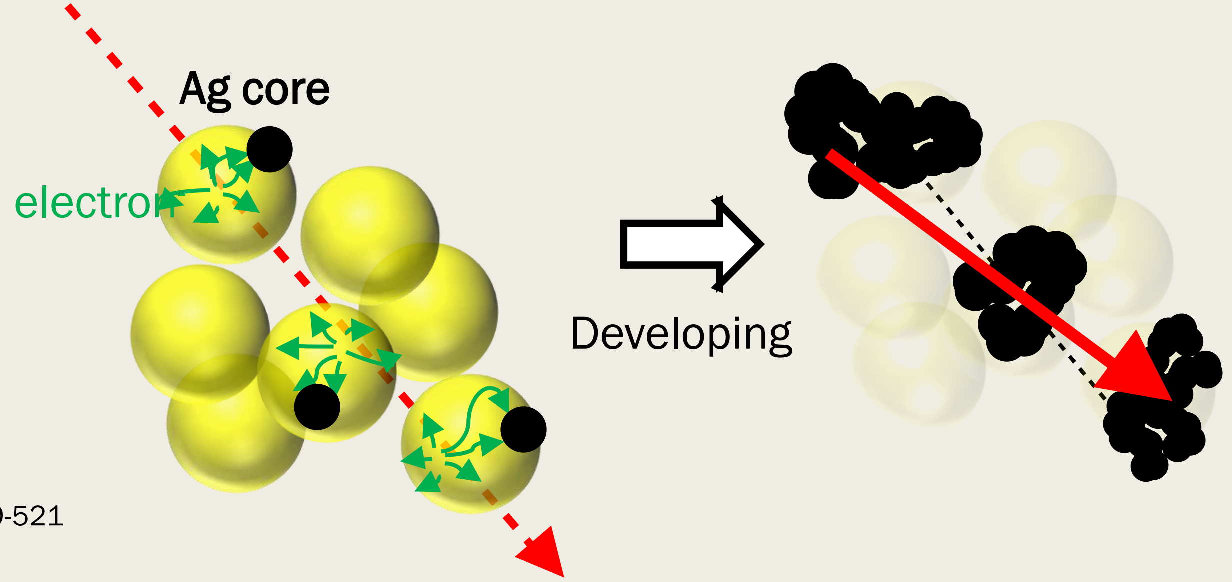
Nano Imaging Tracker (NIT) developed for NEWSdm





Density : 3.1 ± 0.1 g/cm3
Crystal size : 20÷80 nm (tunable)

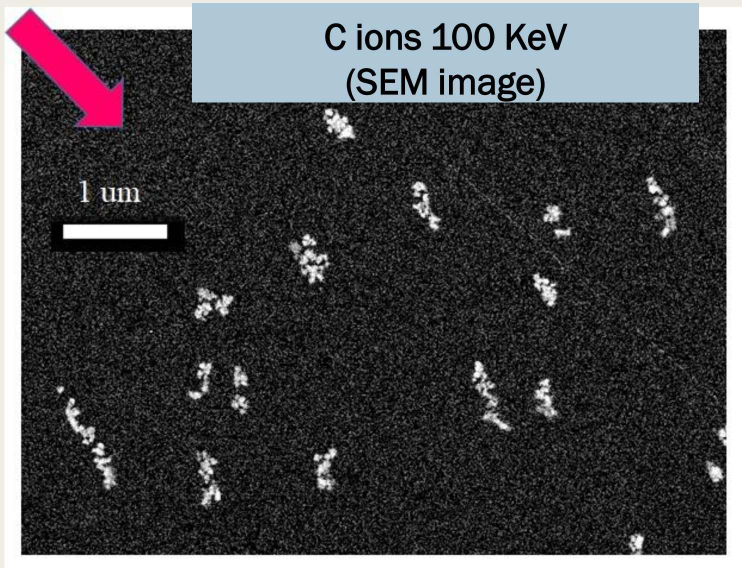
NIM A Nucl. Inst. Meth. A 718 (2013) 519-521
PTEP (2017)063H01



		Mass fraction	Atomic Fraction
Heavier DM	Ag	0.44	0.10
Heavier DM	Br	0.32	0.10
Heavier DM	I	0.019	0.004
Lighter DM	C	0.101	0.214
Lighter DM	O	0.074	0.118
Lighter DM	N	0.027	0.049
neutron	H	0.016	0.410
	S, Na + others	~ 0.001	~ 0.001

Solid-state detector
Density: 3.1 g/cm^3

High-speed volume analysis for nanometric tracks is required



Directionality preservation of nuclear recoils

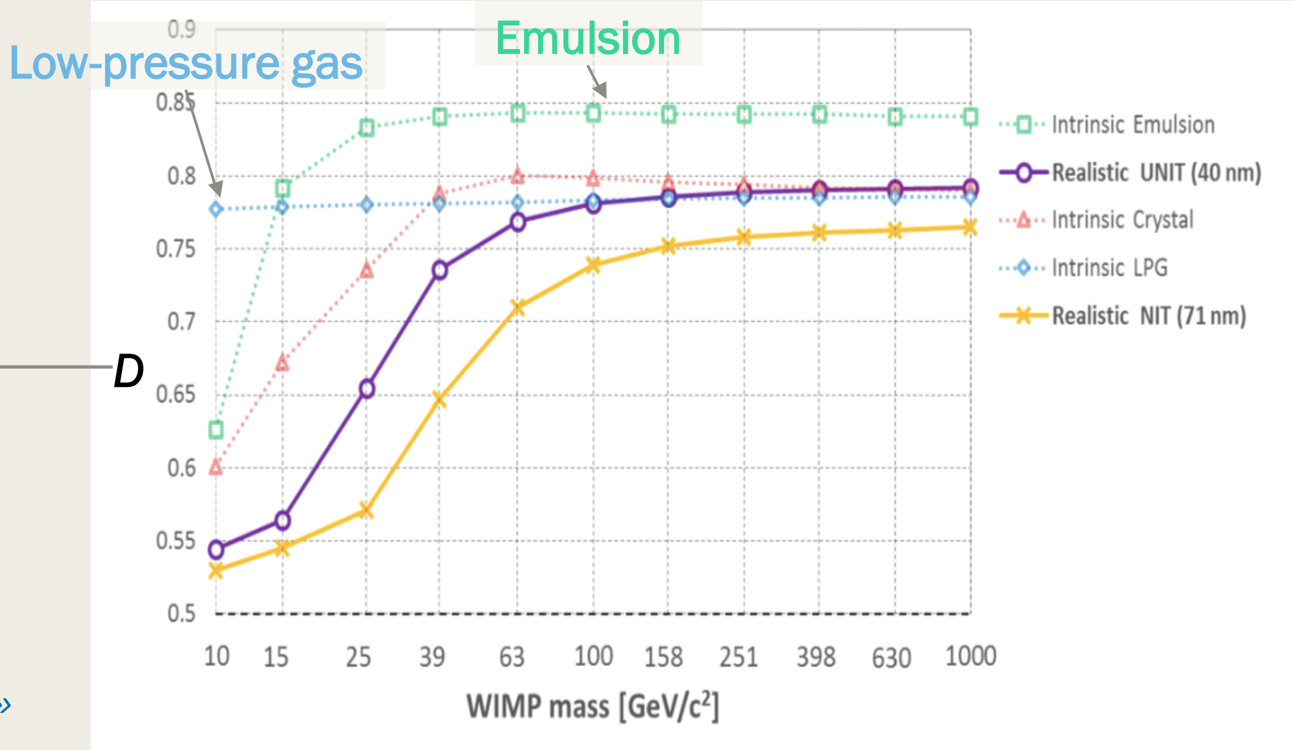
- Performance in the measurement of the recoil direction and comparison with other techniques

- Simulation of nuclear emulsion granularity: volume filled with AgBr crystals described as spheres of diameters 44±7 nm for NIT, 25±4 nm for U-NIT

- Evaluation of ***energy-weighted cosine*** distribution:

$$D = \frac{\sum_{i=0}^{N_{collisions}} \Delta E_i \cos\theta_i}{\sum_{i=0}^{N_{collisions}} \Delta E_i} = \frac{\langle \Delta E \cos\theta \rangle_{track}}{\langle \Delta E \rangle_{track}}$$

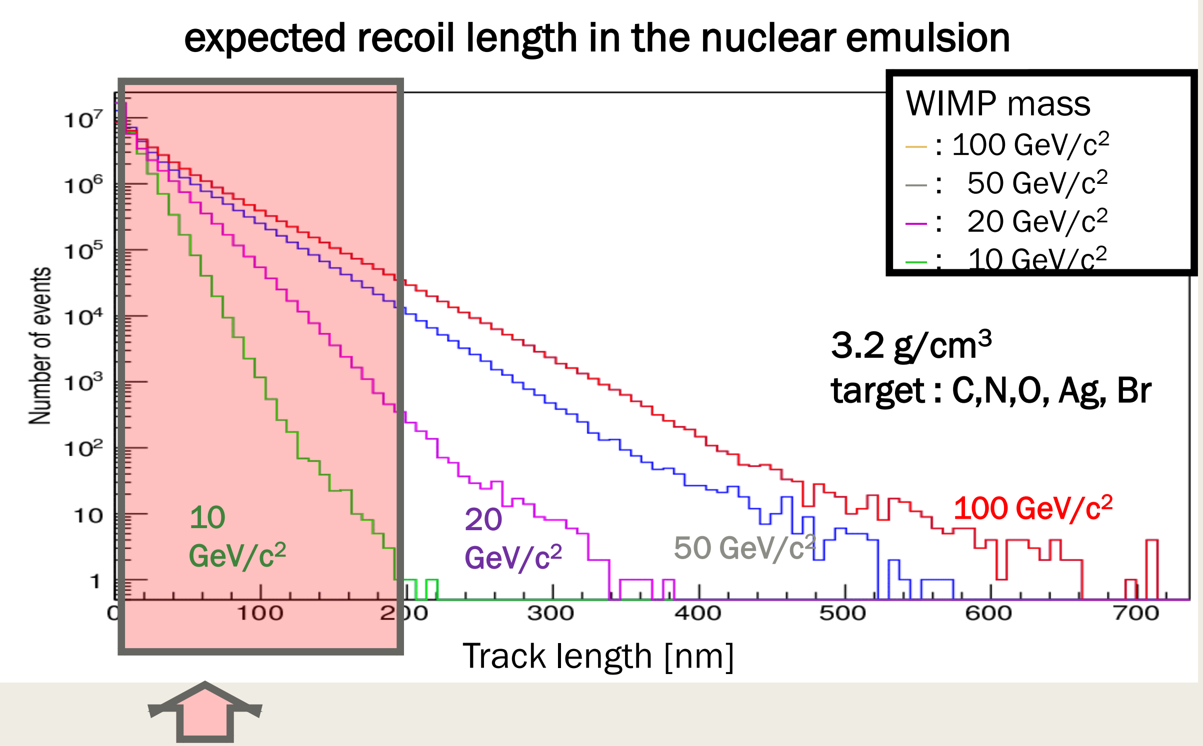
Introduced in JCAP01(2017)027



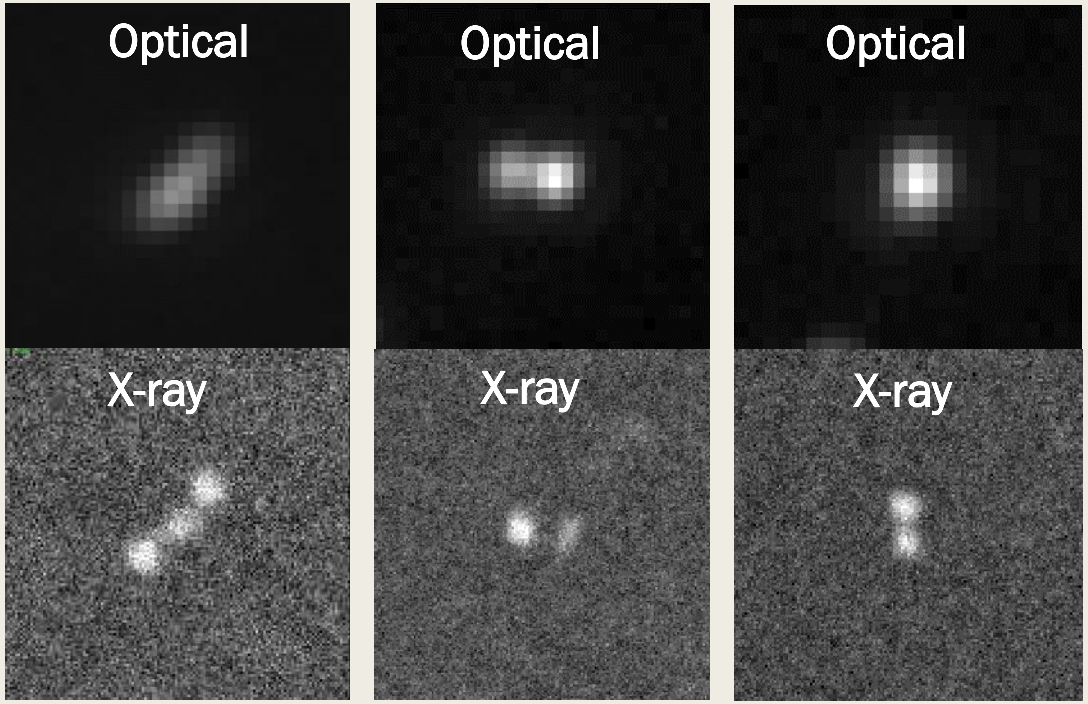
Realistic distribution of mean values of weighted-cosϑ for NIT and U-NIT, compared with other detectors

A. Alexandrov, et al,
«Directionality preservation of nuclear recoils in an emulsion detector for directional dark matter search»
JCAP 04 (2021) 047

Direction detection challenge



Inaccessible due to optical diffraction limit



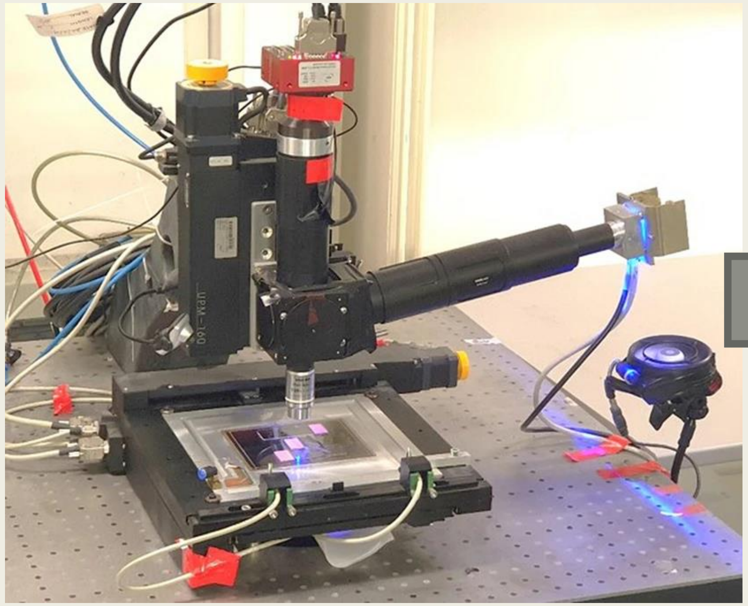
L = 380 nm L = 265 nm L = 160 nm

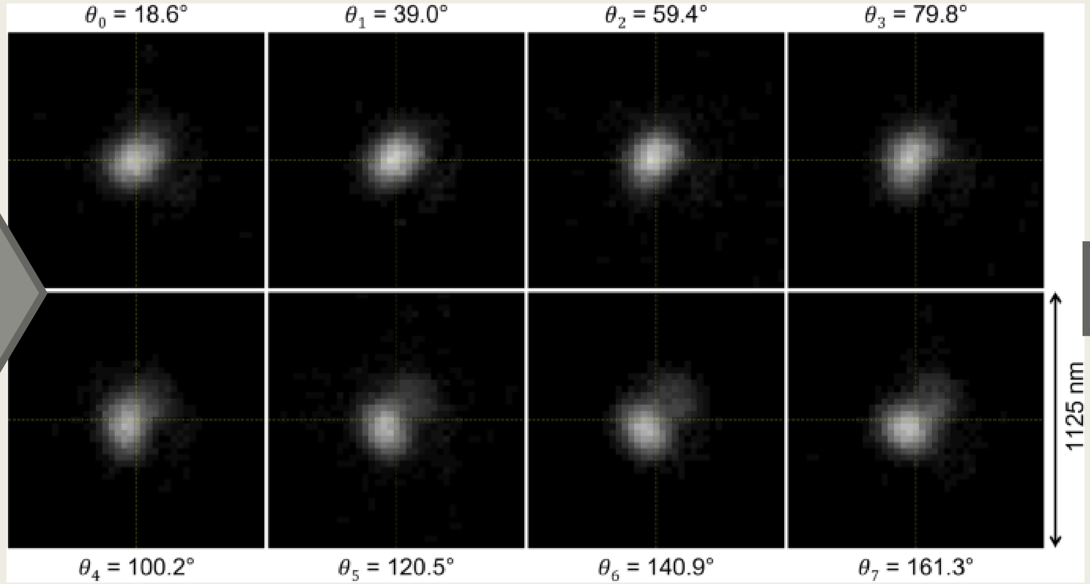
Need super-resolution to measure tracks shorter than 200 nm

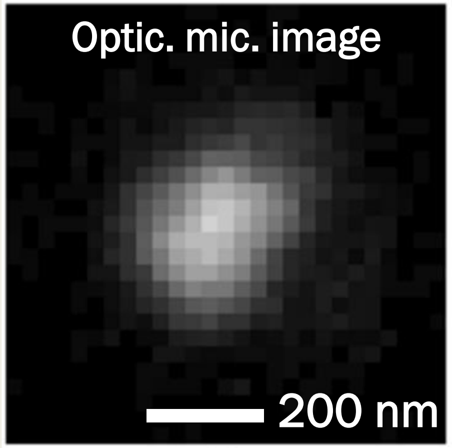
LSPR-based super-resolution imaging

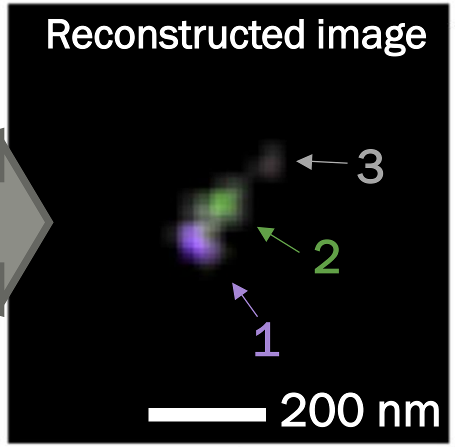
100 keV Carbon ion in NIT

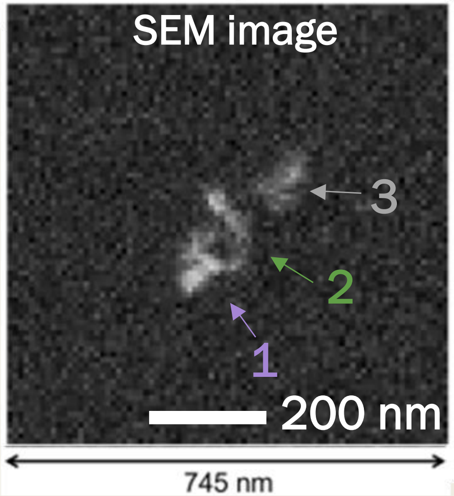
Optical mic images (8 polarizations)





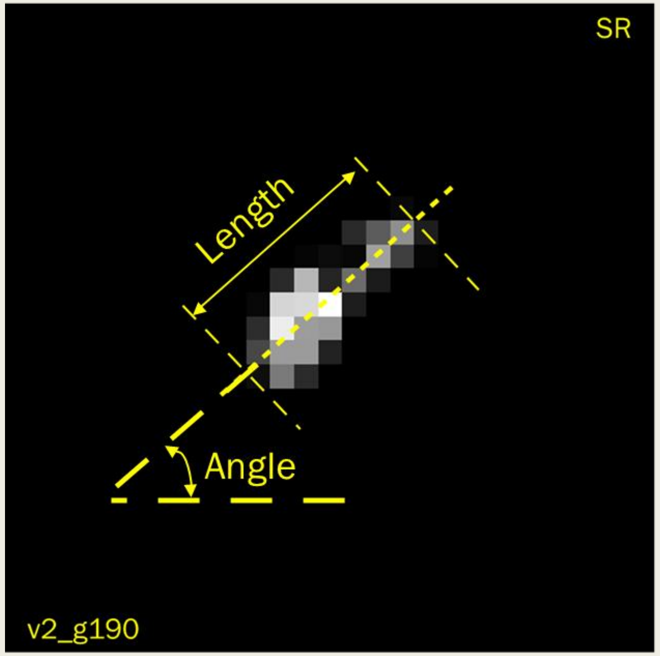


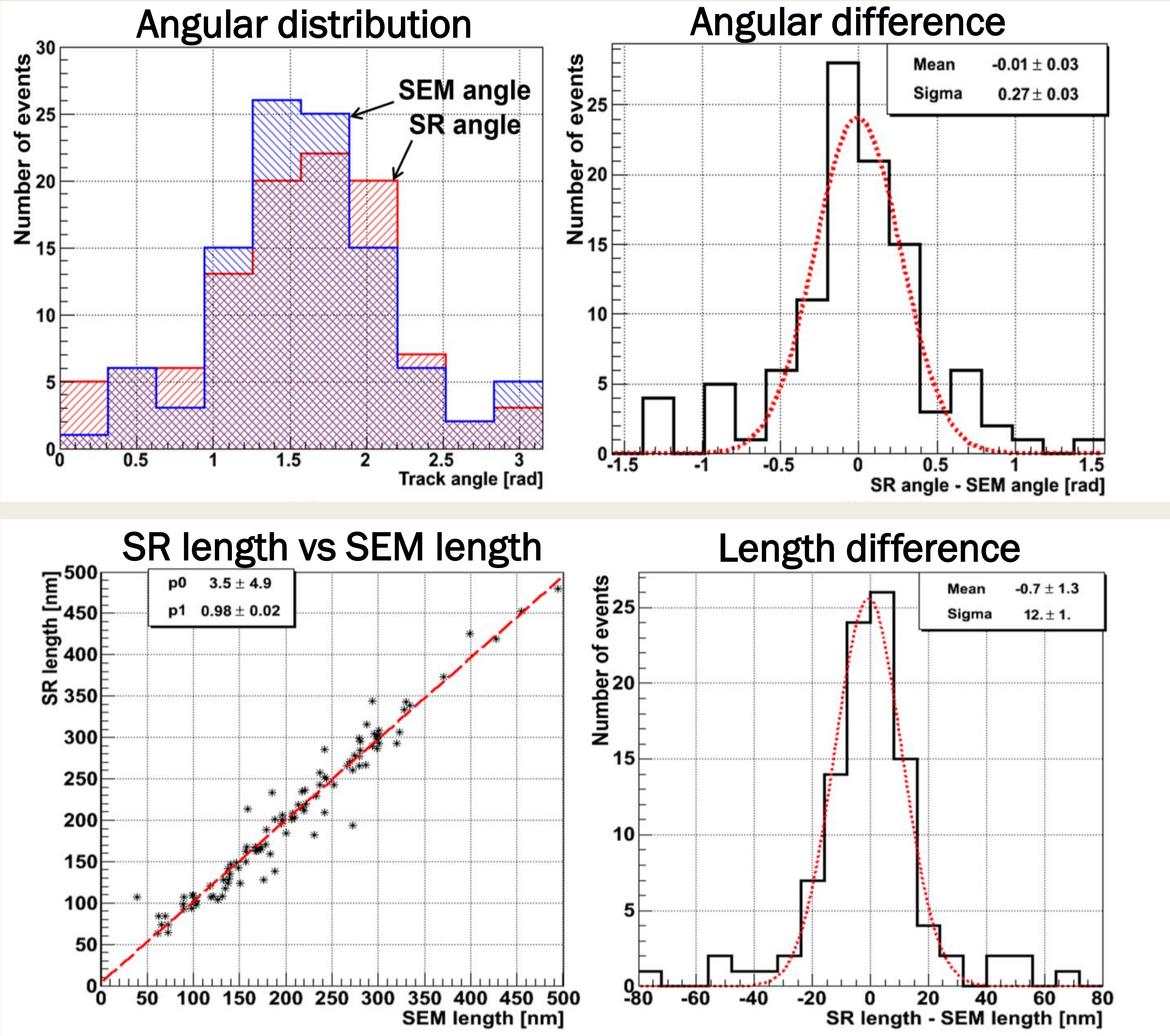




Alexandrov, A., et al.
“Super-resolution high-speed optical microscopy for fully automated readout of metallic nanoparticles and nanostructures.”
Sci Rep 10, 18773 (2020). https://doi.org/10.1038/s41598-020-75883-z

LSPR-based super-resolution imaging





Angular resolution: 270 ± 30 mrad
Length accuracy: 12 ± 1 nm
Spatial resolution: ~ 50 nm
NIT granularity: 71 nm

A. Alexandrov, et al
«Super-resolution imaging for the detection of low-energy ion tracks in fine-grained nuclear emulsions»
Sci Rep 13, 22813 (2023)
https://doi.org/10.1038/s41598-023-50208-y

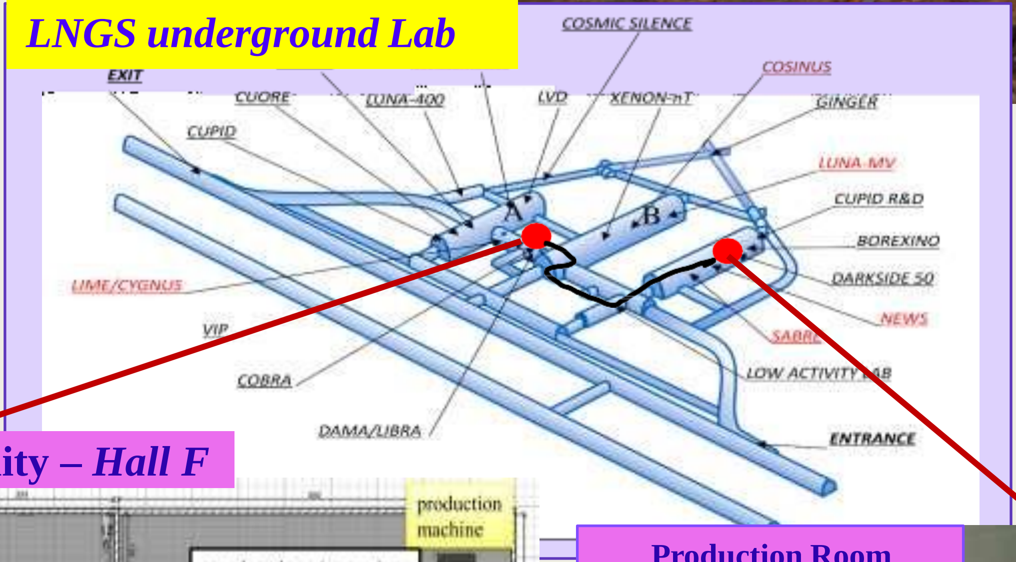
Experimental Activity @ LNGS

Neutron flux @ surface Lab

LNGS surface Lab

Development Room
Clean Room ISO 7

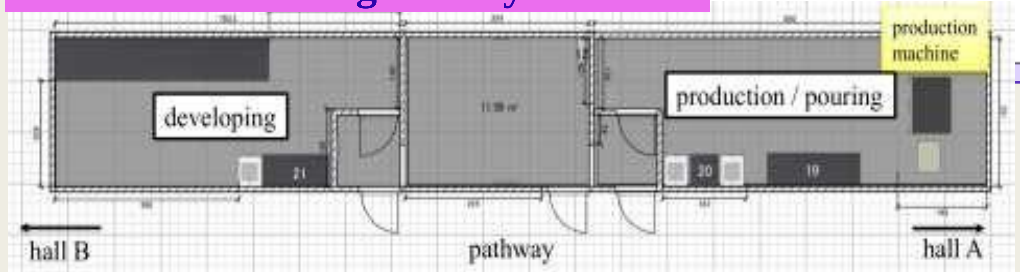
LNGS underground Lab



Cooling Box for Target

Target insertion by crane

Emulsion Handling Facility – *Hall F*



Production Room
Clean Room ISO 6
Capability ~1OO g /day

Shielded Exposure set-up – *Hall C*

Lead shield : 5.6 cm
Polyethilene : 31.5 cm

Jan. 2021 – to date
~1.1 kg of dry NIT produced
>75 developments done

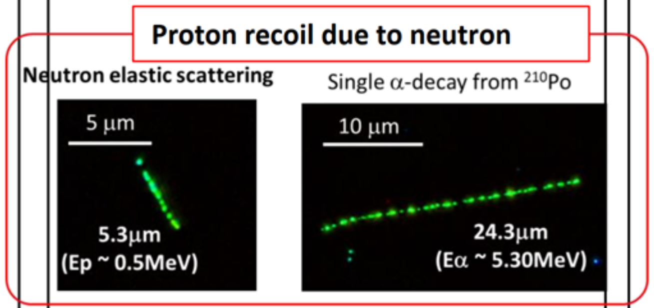
NIT technology applied now in several fields

Dark Matter Search

- WIMP search
- Non-standard DM search (e.g., low mass DM, multi-component DM)

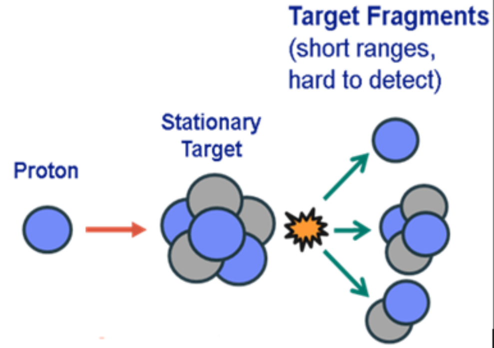
Neutron detection

- Environment neutron
- Cosmic-ray neutron
- Nuclear plant etc.



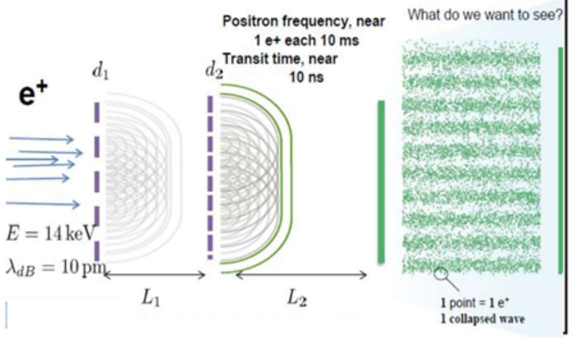
Ion-beam detection

- Ion-beam therapy
- Study for ion-beam
- properties



Quantum diffraction imaging

- Anti-particle quantum effect (e.g., QUPLAS)
- Cold-neutron detection



This talk

DAMON
Talk by N.D'Ambrosio, 3 Sep

QUPLAS
Talk by M.Giammarchi, 2 Sep

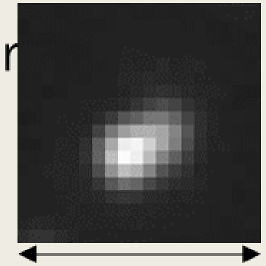
First underground exposure inside shield: Analysis chain

Automatic readout
1st trigger

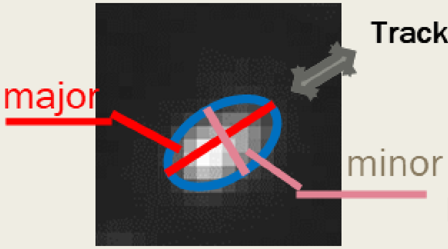
Elliptical shape trigger

Requirement

- High speed scanning
- Low energy threshold
- Single noise (fog) reduction



1 um



Track direction

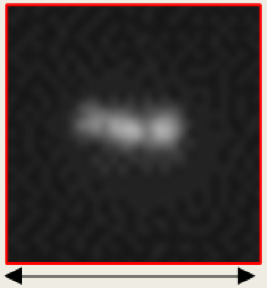
CNO : > 30 keV

Electron efficiency: 0.05

CNN (machine learning)

≧ 3 grain track recognition

- Candidate selection and narrow down the number of event
- Image feature extraction



1.5μm

Training sample :
neutron induce recoil nuclei @AIST
(880keV, -50℃)

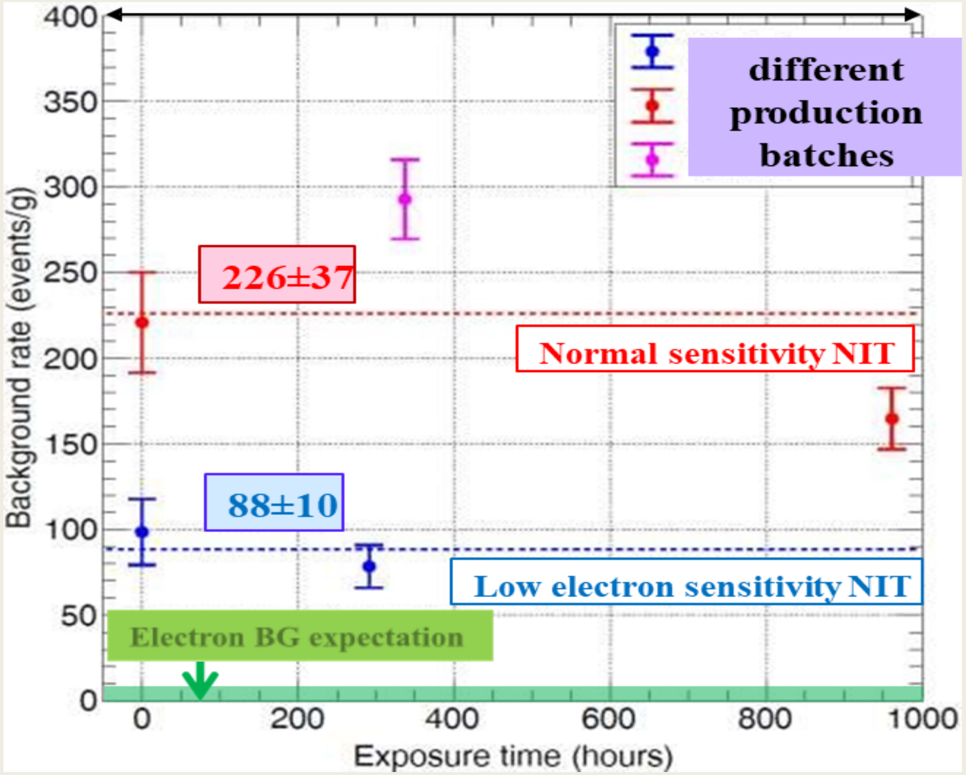
Manual check

Confirmation
Electron rejection power :
10^{-4} @ room temperature
10^{-6} @ -50℃

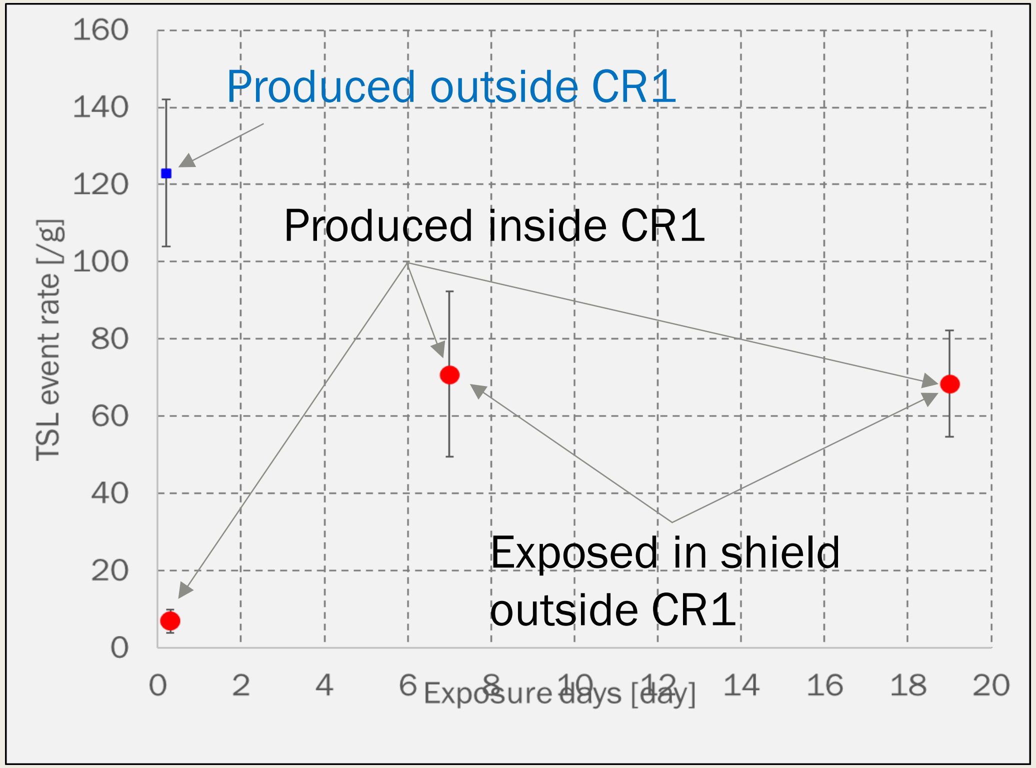
Current Selection

First underground exposure inside shield: Results

-50 °C exposures, 10g , up to 40 days



Emulsion production in Rn-free clean room



First exposure results:

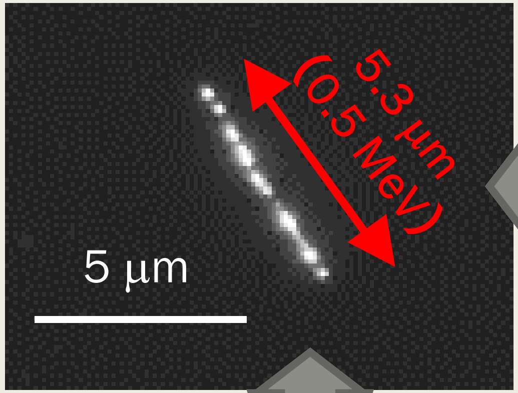
- Too many candidates (x10^2 more than expected e)
- Signal not increasing with in-shield exposure time
- Using NIT with reduced sensitivity to e ➔ not enough
- Definitely more CNO-like than e-like

Emulsion production in Rn-free environment:

- Important confirmation of the α as the source of the offset background, down to the expected level!
- Results compatible with no increase of the background inside the shield as expected
- Increase of the background while moving away from CR1
- To make a shielded tests in CR1

NIT as neutron detector

Recoil proton signal

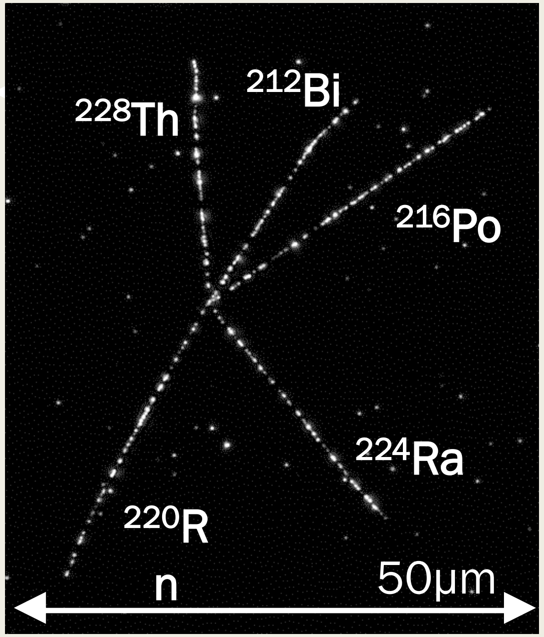


Topological or Range cut

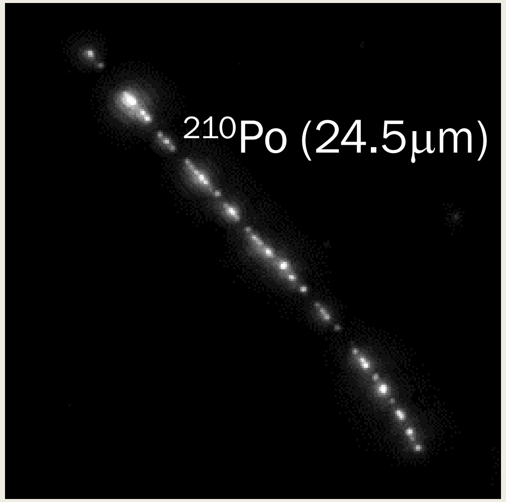
Clearly distinguishable

α-ray

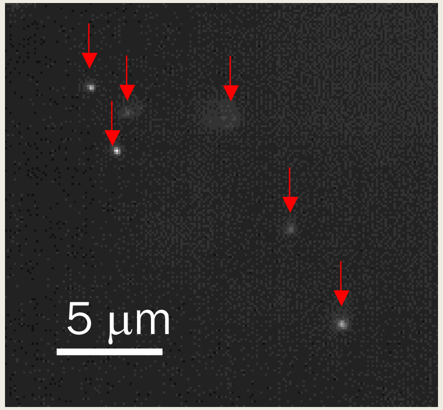
Th star (^{228}Th → ^{208}Pb)



Single-α in U series



γ-ray (β-ray)



Exposed 5x10^{7} γ-ray/cm^{2} from ^{241}Am
(5 years accumulation of environmental γ-ray)

✓ Environmental γ-rays cannot become background

✓ There is no background in sub-MeV region (2 ~ 14 μm → 0.25 ~ 1 MeV in proton energy)

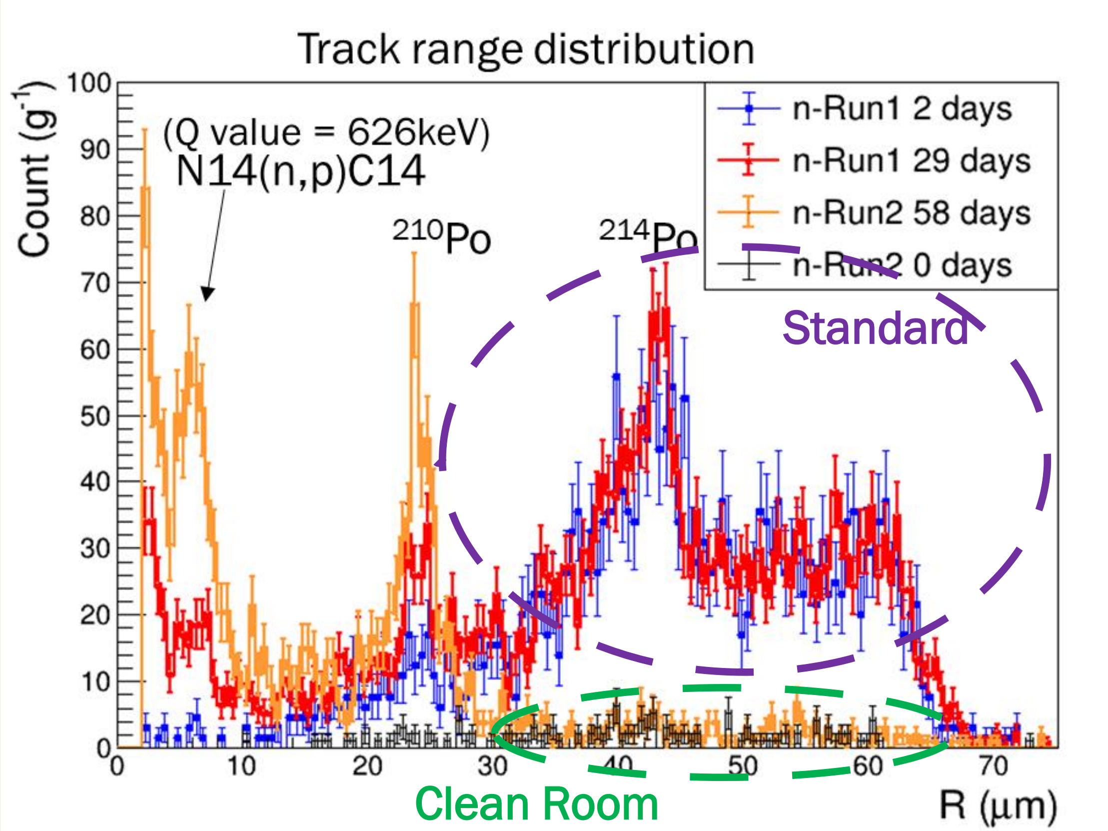
✓ MeV region can be analyzed excluding single-α (especially ^{210}Po peak around 24μm)

T. Shiraishi, *et al.*, Phys. Rev. C **107**, 014608 (2023) Environmental sub-MeV neutron measurement at the Gran Sasso surface laboratory with a super-fine-grained nuclear emulsion detector

Neutron spectrum measurement @ LNGS

$$^{222}_{86}\mathrm{Rn} \xrightarrow[3.8235\ \mathrm{d}]{\alpha\ 5.59\ \mathrm{MeV}} {}^{218}_{84}\mathrm{Po} \xrightarrow[3.05\ \mathrm{min}]{\alpha\ 6.11\ \mathrm{MeV}} {}^{214}_{82}\mathrm{Pb} \xrightarrow[26.8\ \mathrm{min}]{\beta^-} {}^{214}_{83}\mathrm{Bi} \xrightarrow[19.9\ \mathrm{min}]{\beta^-} {}^{214}_{84}\mathrm{Po} \xrightarrow[164.3\ \mu\mathrm{s}]{\alpha\ 7.83\ \mathrm{MeV}} {}^{210}_{82}\mathrm{Pb} \xrightarrow[22.26\ \mathrm{y}]{\beta^-} {}^{210}_{83}\mathrm{Bi} \xrightarrow[5.012\ \mathrm{d}]{\beta^-} {}^{210}_{84}\mathrm{Po} \xrightarrow[138.38\ \mathrm{d}]{\alpha\ 5.41\ \mathrm{MeV}} {}^{206}_{82}\mathrm{Pb}$$

- Excess hypothesis:
  - *Emulsion films are contaminated with radon and its products during the production phase*
  - *Emulsion becomes sensitive before the gel settles and remaining AgBr crystals mobility can lead to breaking of α tracks into smaller segments*
- Two NIT emulsion batches prepared:
  - *In standard conditions*
  - *In a Rn-free clean room*
- Time-independent (^{214}Po) peak, present in the standard emulsion, has disappeared in the clean one!



T. Shiraishi, et al., PTEP 2021 (2021) 4, 043H01
T. Shiraishi, et al., Phys. Rev. C 107, 014608 (2023)

Neutron spectrum measurement @ LNGS

Surface lab

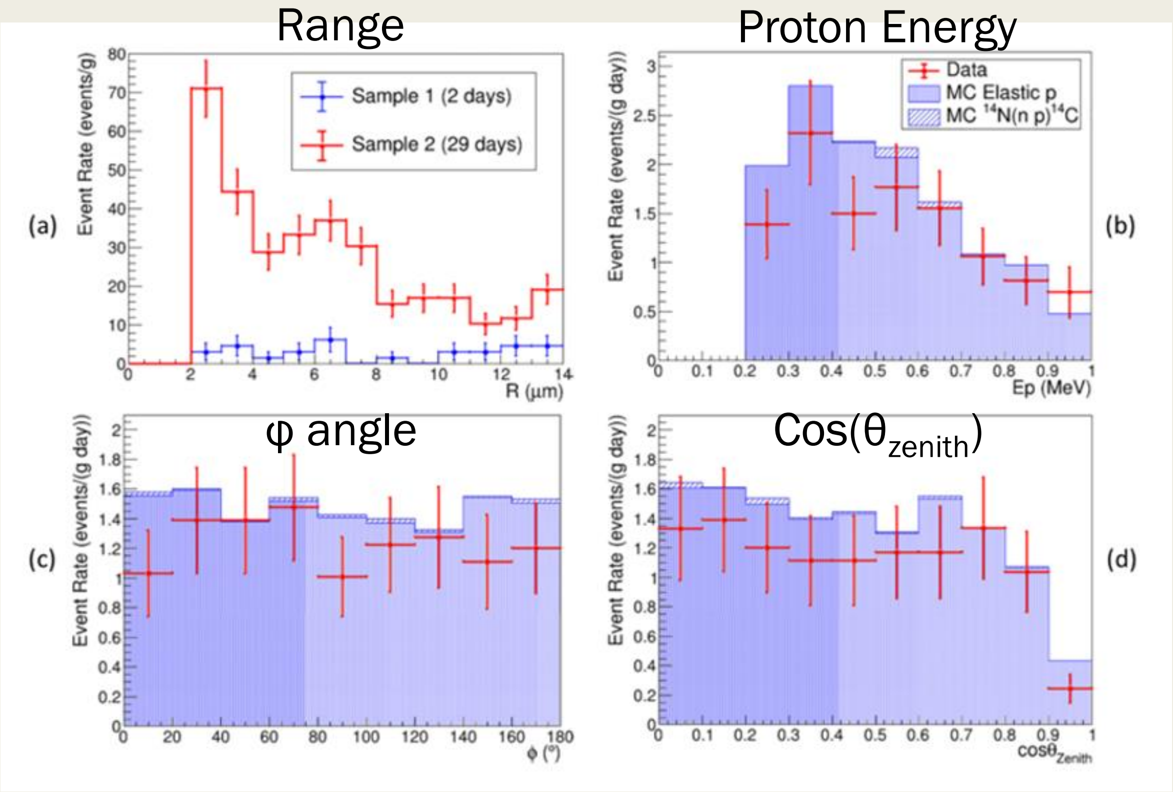
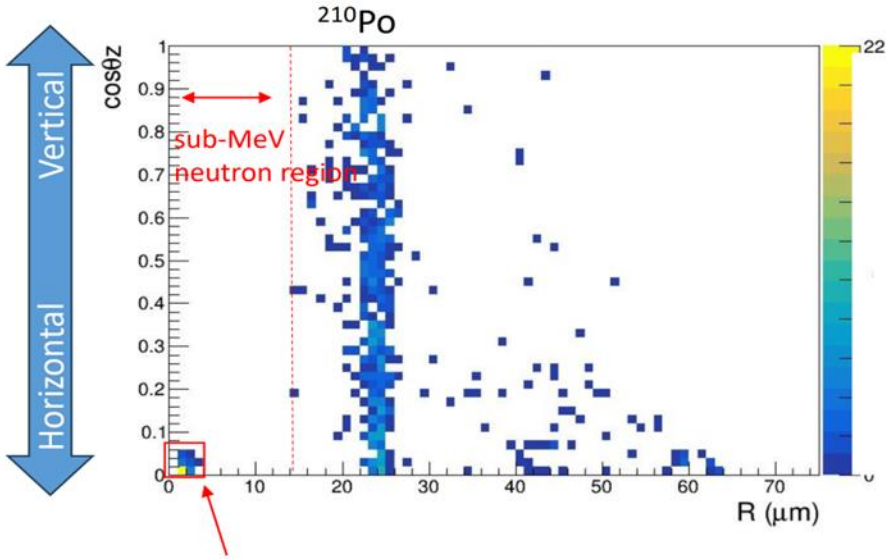


Figure 3.(a) Range distribution of recoil protons in the sub-MeV region for Sample 1 (2 days, blue) and Sample 2 (29 days, red) at LNGS. (b-d) Sub-MeV neutron measurement results after subtracting the data of Sample 1 from Sample 2 for an equivalent exposure of 27 days. For the MC simulation, neutron signals of elastic scattering and 14N(n, p)14C reaction are represented by blue filled and shaded histograms. Detection efficiency was accounted for in the MC simulation. (b) Proton energy spectrum, (c) plane angle, and (d) Zenith angle.

T. Shiraishi, et al., PTEP 2021 (2021) 4, 043H01
T. Shiraishi, et al., Phys. Rev. C 107, 014608 (2023)

Underground lab (Hall C)

~0.04 kg・day analyzed in the ~0.9 kg・day exposure device



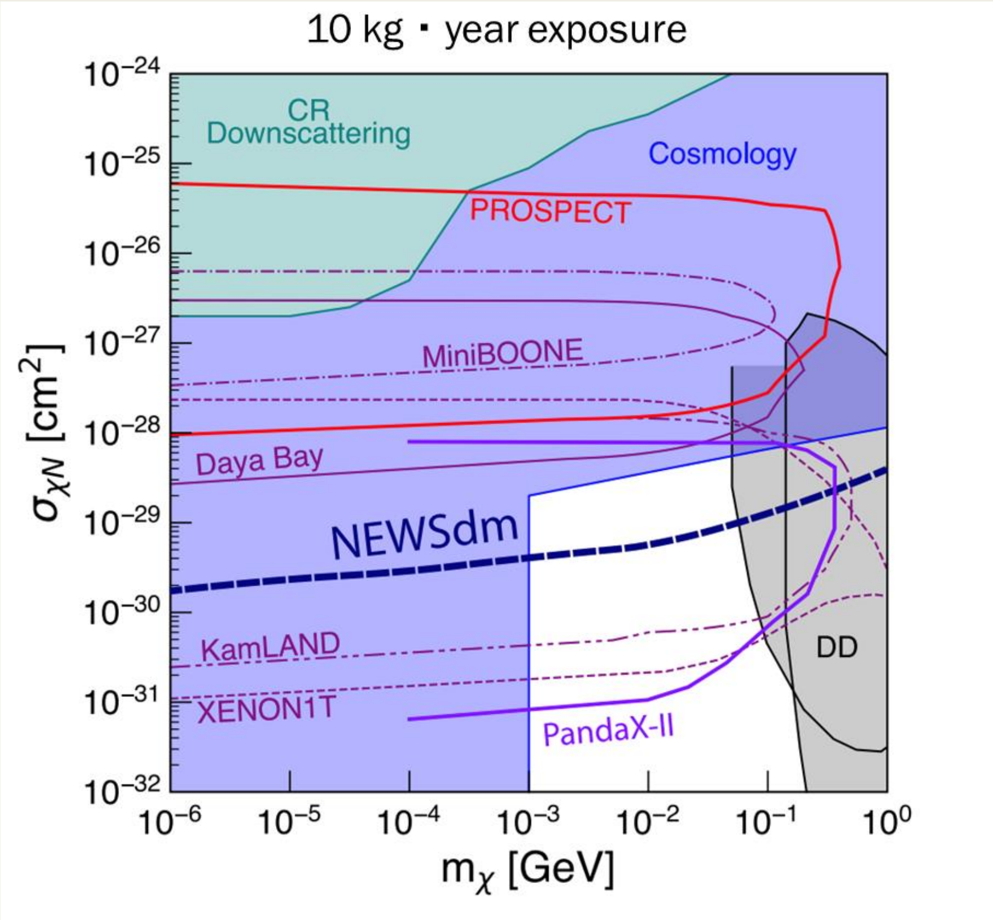
Mask cosθz < 0.05 && range < 3μm

Backgrounds from α-ray before drying process of emulsion plate are expected.
⇒ To be investigated more.

Current underground neutron flux upper limit
< 4.5 × 10^{-5} /cm²/sec (90%CL) *Very Preliminary

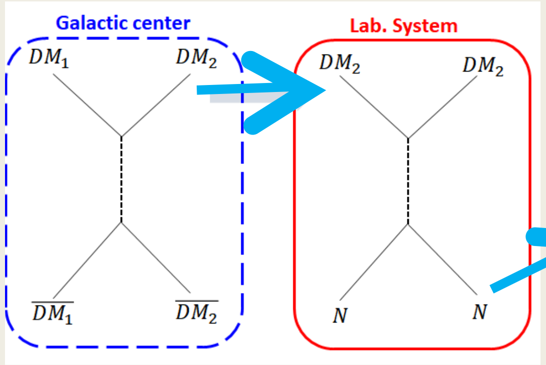
Data analysis is on going for 3 kg・day exposure

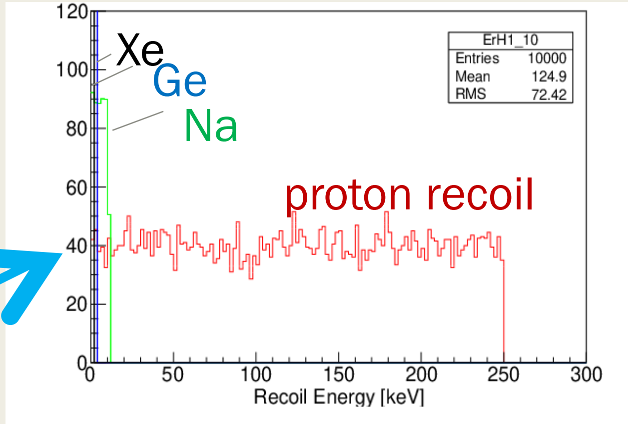
Boosted DM

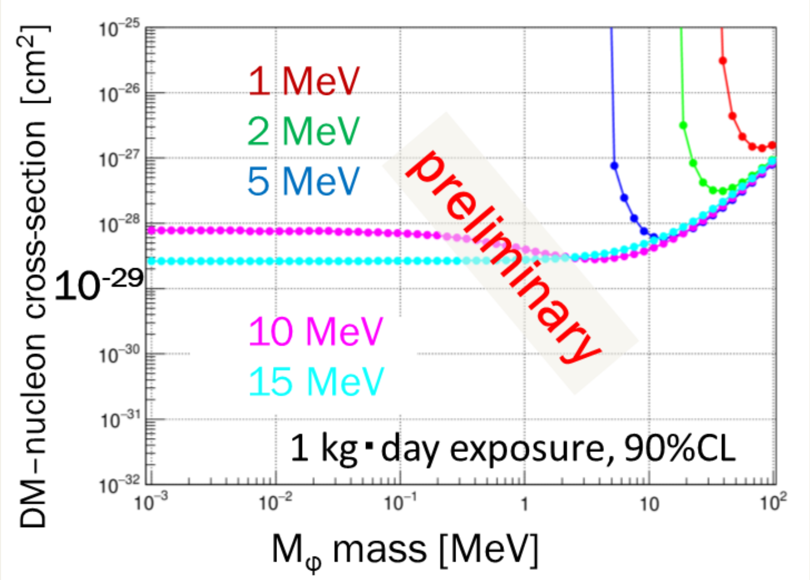


N.Y. Agafonova et al.,
«Directional sensitivity of the NEWSdm experiment to cosmic ray boosted dark matter",
JCAP07(2023)067

Multi-component DM







Expected sensitivity limit for DM−nucleon cross-section

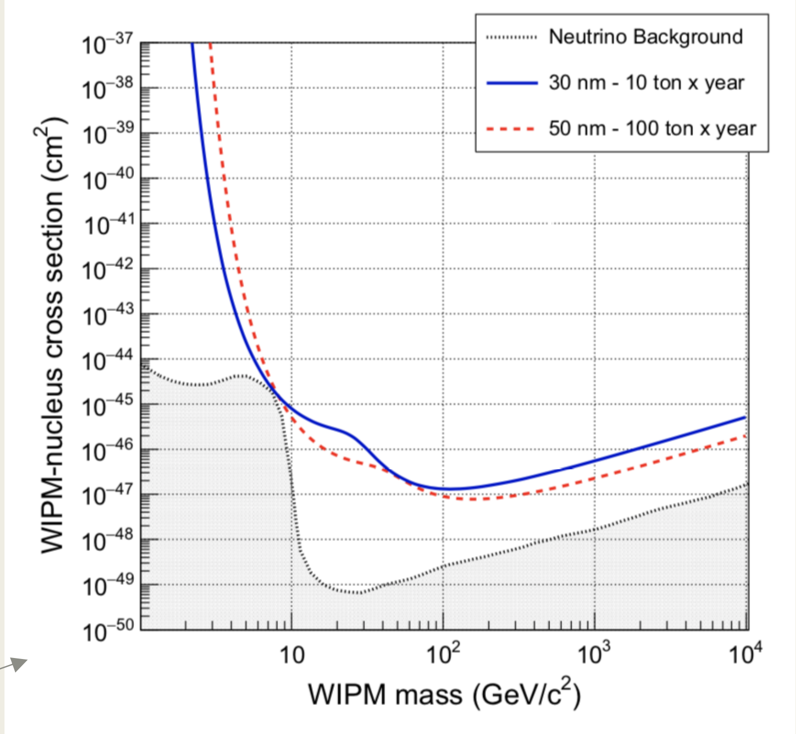
Assumption: DM1 > DM2

- DM1 is assumed to be the main component of DM halo
- DM2 has higher coupling with baryon than lepton

Summary

- NEWSdm a double break-through in the Nuclear Emulsion technology:
  - *Nanometric granularity with NIT*
  - *Super-resolution in optical domain by LSPR*
- Detection principle of WIMPs by nuclear recoil demonstrated
- Production & handling facility operational @ LNGS undergroung lab
- Background studies in progress with 10g scale in shielding at -50 C°
- First directional measurements of sub-MeV neutron flux at LNGS surface lab, will be extended to underground
- Physics goals at reach
  - *10 kg·year -> DAMA region*
  - *Boosted Dark Matter scenario*
  - *Multi-component DM scenario*
- Scalability and discovery potential (challenging background!)
  - *10–100 ton·year -> neutrino floor*
- NIT technology proved to be useful also for other fields where ultra-high position resolution required: medical physics (fragmentation study), antimatter gravity, etc

NEWSdm Collaboration
Eur.Phys.J. C78 (2018) no.7, 578



90% C.L. upper limits for the NEWSdm detector with exposures of 10 ton-year (30 nm threshold) and 100 ton-year (50 nm threshold) in the zero-background hypothesis

XIII International Conference on New Frontiers in Physics
26 Aug - 4 Sep 2024, OAC, Kolymbari, Crete, Greece

THANK YOU FOR ATTENTION!

Andrey ALEXANDROV (on behalf of the NEWSdm collaboration)

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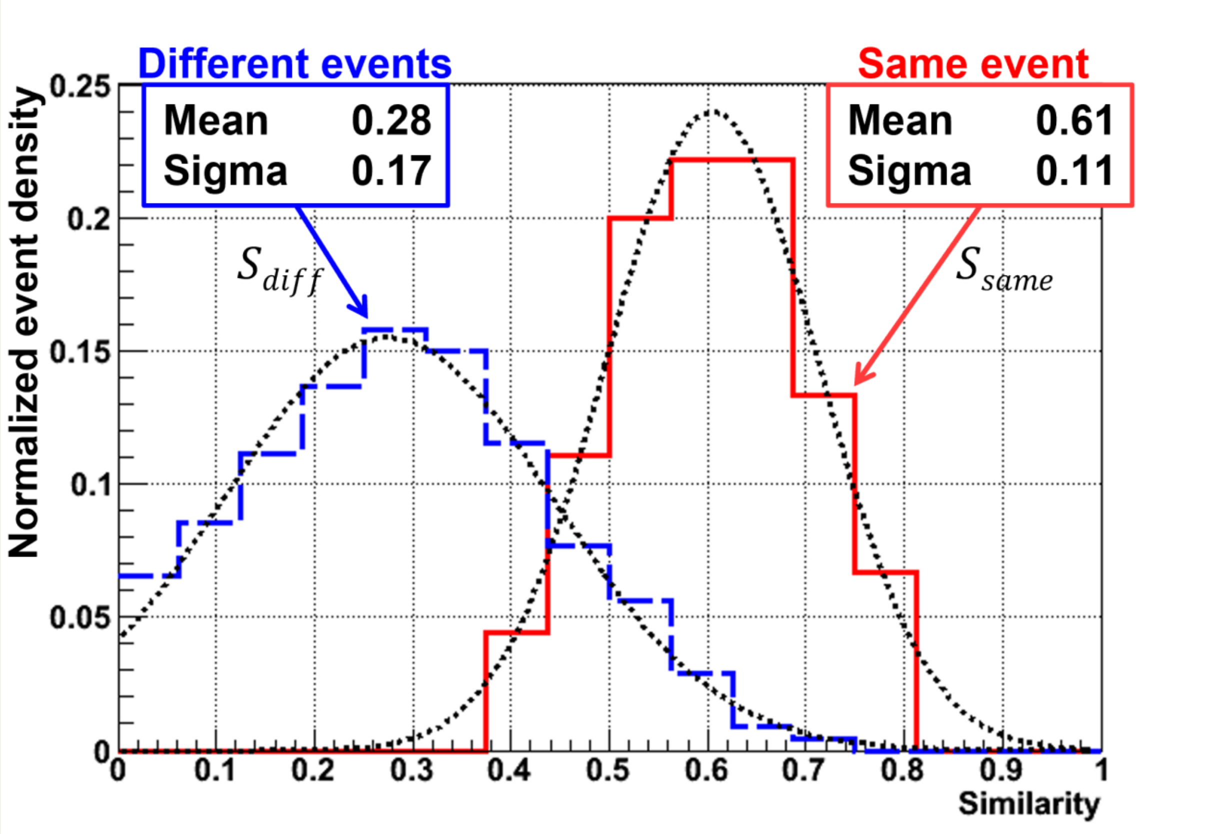
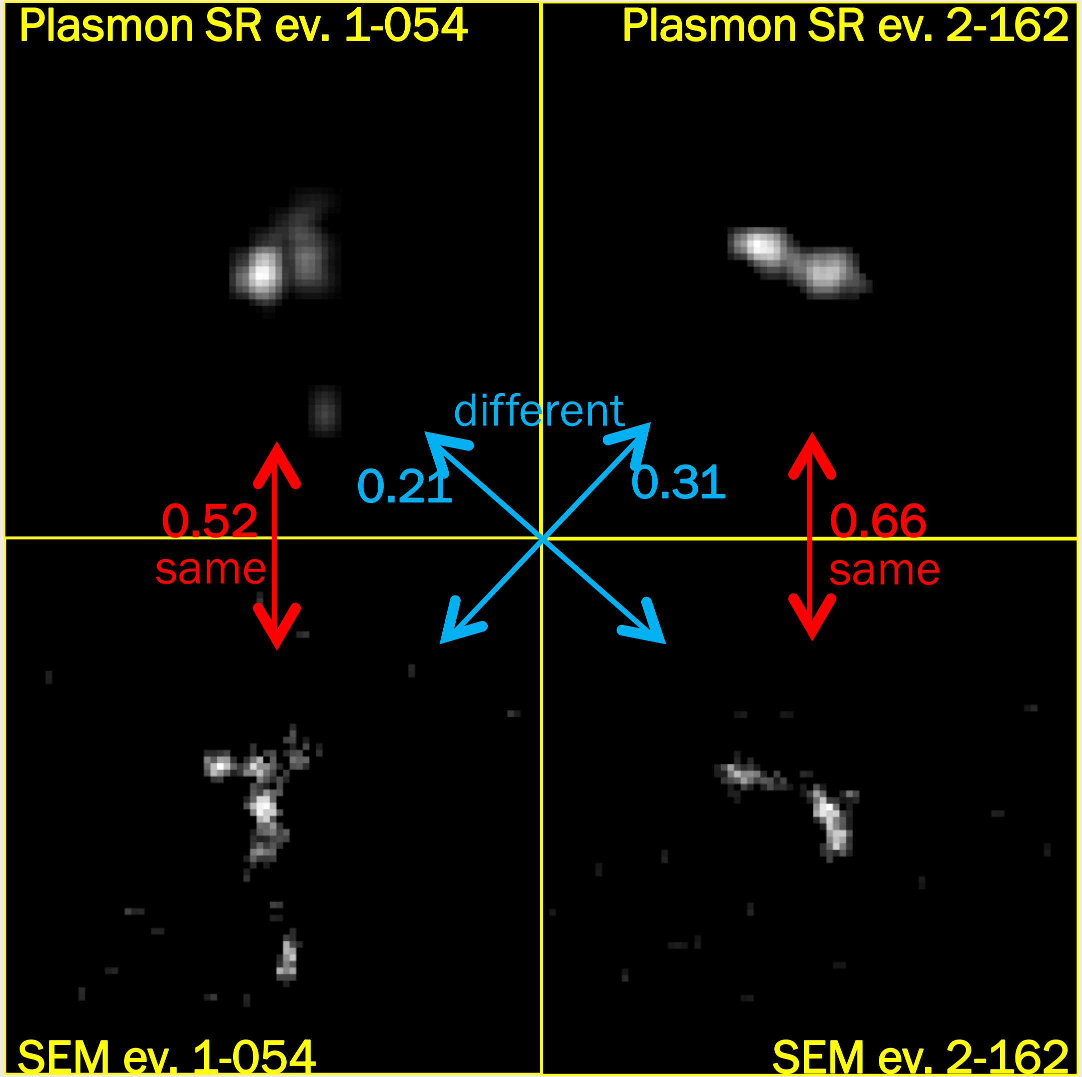
andrey.alexandrov@cern.ch

BACKUP SLIDES

Super-resolution imaging for the detection of low-energy ion tracks in fine-grained nuclear emulsions



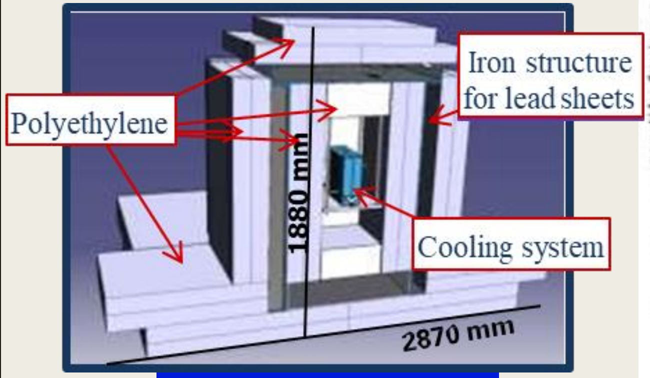


$$Similarity = \frac{\sum_i (SR_i - \overline{SR})(SEM_i - \overline{SEM})}{\sqrt{\sum_i (SR_i - \overline{SR})^2} \sqrt{\sum_i (SEM_i - \overline{SEM})^2}}$$

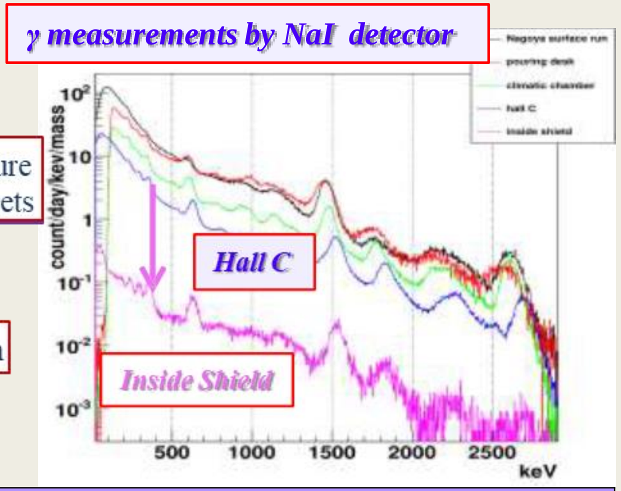
Backgrounds

Environmental

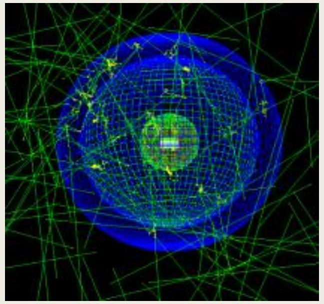
Current shield



Lead shield : 5.6 cm
Polyethilene : 31.5 cm



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



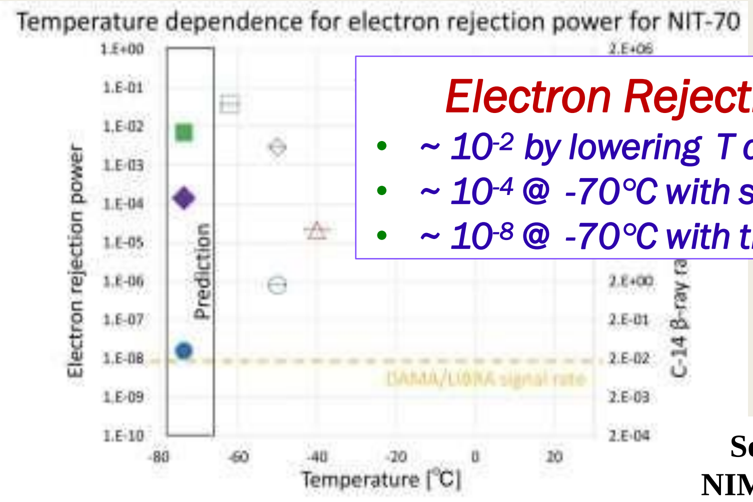
10 kg detector shield (1 m HDPE @LNGS)

Source	Rate $[10\ \text{kg} \times \text{y}]^{-1}$
Environmental gammas	$(1.97 \pm 0.17) \times 10^{4}$
Environmental neutrons	$\mathcal{O}(10^{-2})$
Cosmogenic neutrons	1.41 ± 0.14

Intrinsic

(Astropart. Phys.. 80 (2016) 16–21)

Intrinsic Radioactivity	Rate $[\text{g} \times \text{month}]^{-1}$	Rate $[\text{kg} \times \text{year}]^{-1}$
Radiogenic neutrons	$(5.0 \pm 1.7) \times 10^{-6}$	0.06 ± 0.02
Intrinsic ß	33.7 ± 1.8	$(4.04 \pm 0.02) \times 10^{6}$



Electron Rejection power

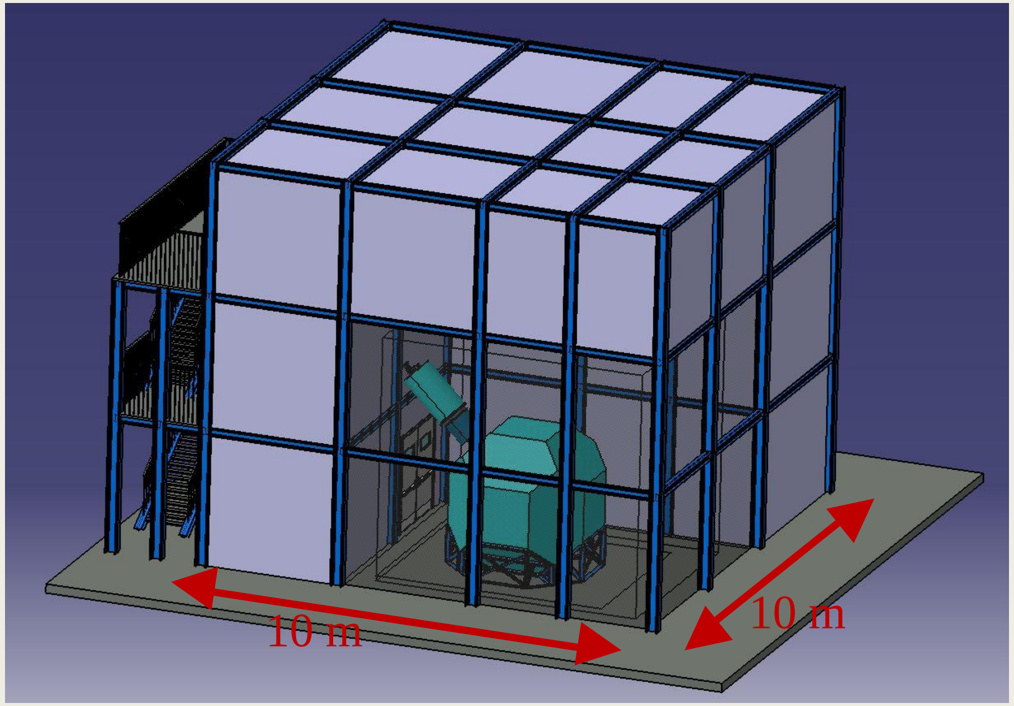
- *~ 10^{-2} by lowering T down to -70°C*
- *~ 10^{-4} @ -70°C with shape analysis*
- *~ 10^{-8} @ -70°C with track likelihood*

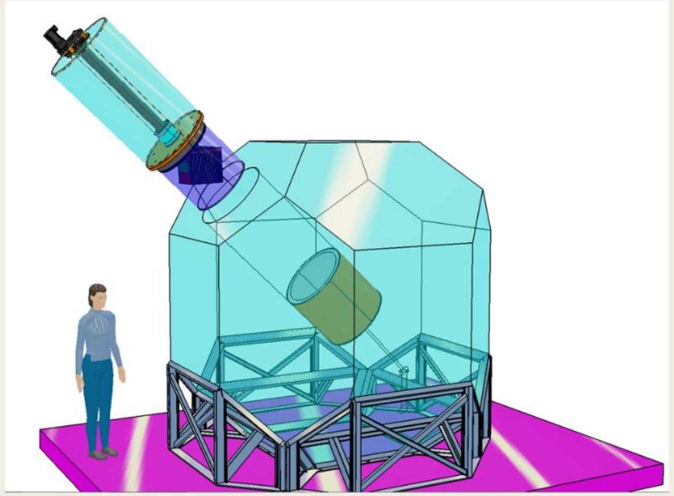
Sensitivity vs. T:
NIM A845 (2017) 373

Ultimate solution:
replace organic gelatin with a radio-pure polymer

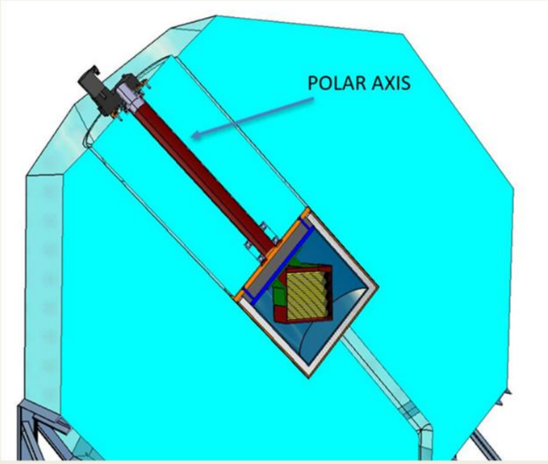
Future facility for NEWSdm: 10kg and beyond

Emulsion facility and shielding with an equatorial telescope

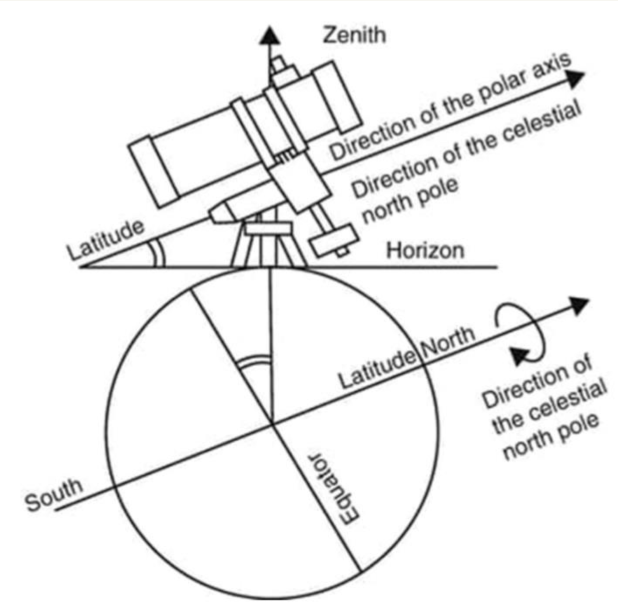


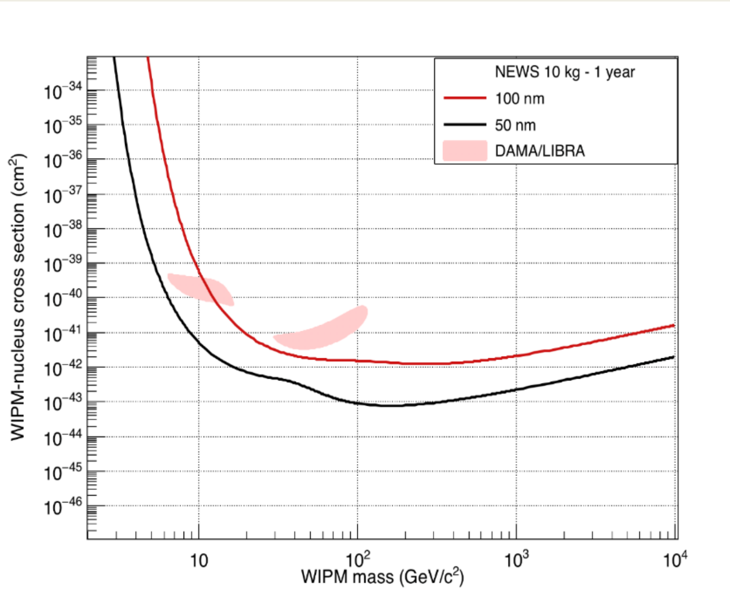


(a)



(b)





Nuclear Fragmentation in Proton Therapy

- In proton therapy only the target nuclei can undergo fragmentation
- Direct detection of target fragments is challenging: so far little data has been collected and only with inverse kinematics approaches
- The **DAMON** (Direct meAsureMent of target fragmentation, PRIN22) project aims at measuring for the first time proton-induced target fragmentation in **direct kinematics**

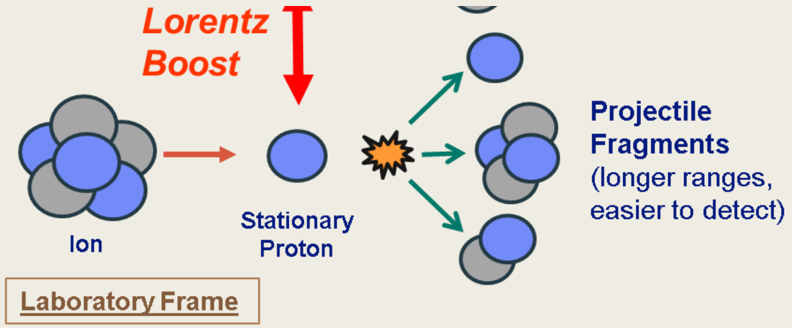
Expected Target Fragments' Ranges in H_2O

Fragment	E (MeV)	LET (keV/μm)	Range (μm)
^{15}O	1.0	983	2.3
^{15}N	1.0	925	2.5
^{14}N	2.0	1137	3.6
^{13}C	3.0	951	5.4
^{12}C	3.8	912	6.2
^{11}C	4.6	878	7.0
^{10}B	5.4	643	9.9
^{8}Be	6.4	400	15.7
^{6}Li	6.8	215	26.7
^{4}He	6.0	77	48.5
^{3}He	4.7	89	38.8
^{2}H	2.5	14	68.9

From: Tommasino F. and Durante *Cancers* **2015**, 7(1), 353-381;

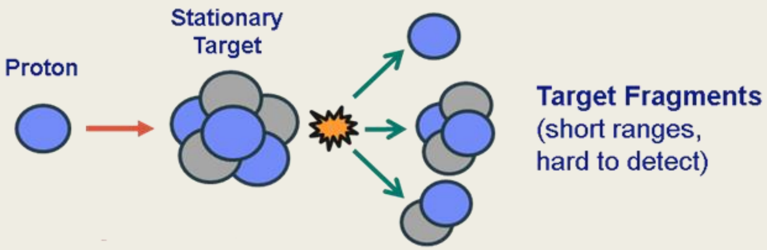
FOOT detector,
standard emulsions

Inverse kinematics



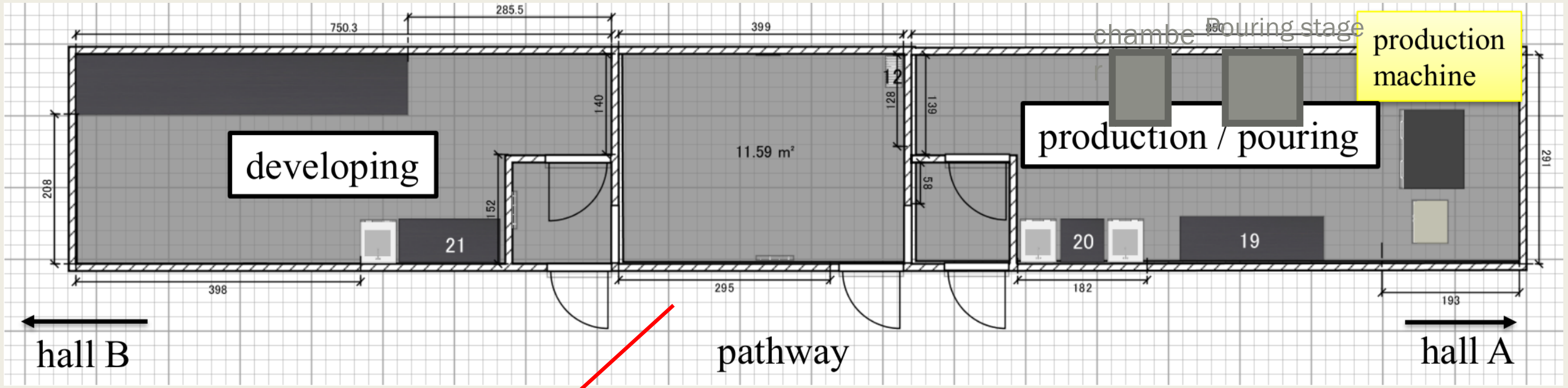
DAMON
NIT emulsions

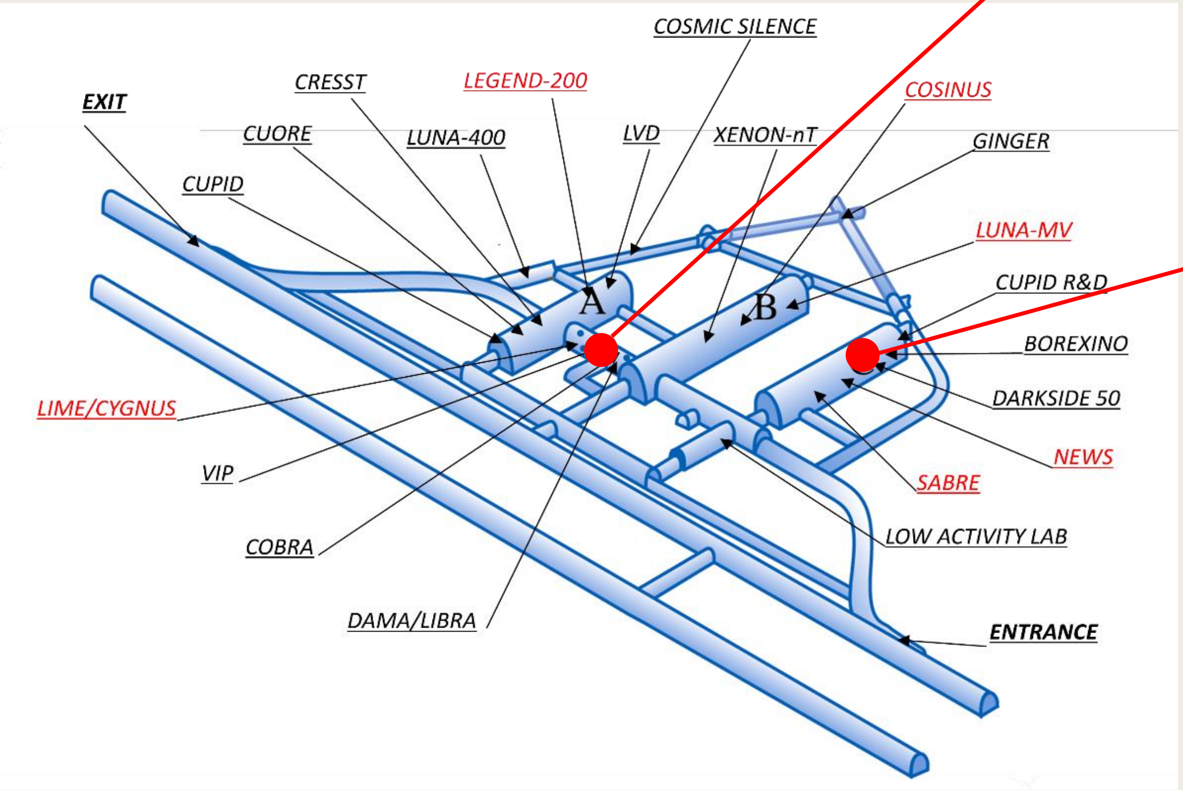
Direct kinematics



NEWSdm underground facility and detector

Hall F





Hall C

Mass	Exposure	Temp.	Shield
~10g	40days	-50°C	40cm PE + 10cm Pb

Emulsion facility at LNGS Hall F

- Work carried out in the facility:
  - Installation of containment vessels under the floor
  - Improvement of electric system
  - Installation of a thermostatic chamber
- Emulsion production machine
- Access to the emulsion facility since December 2020

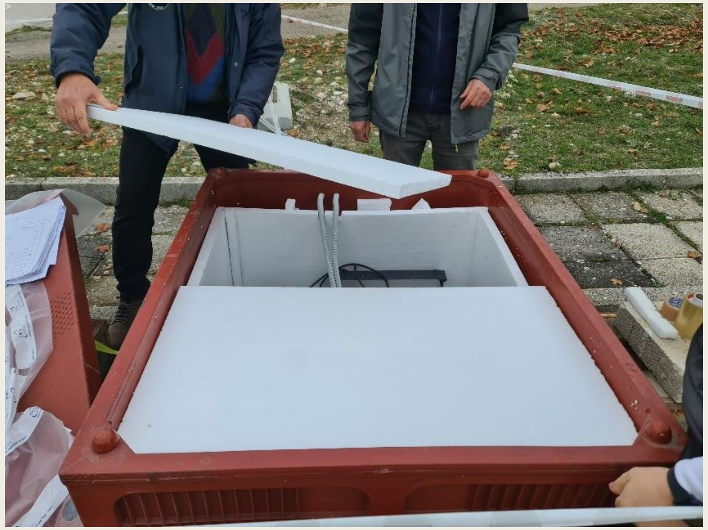
Development room

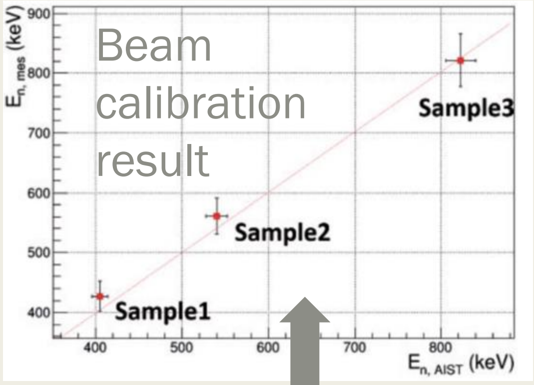
Gel production room

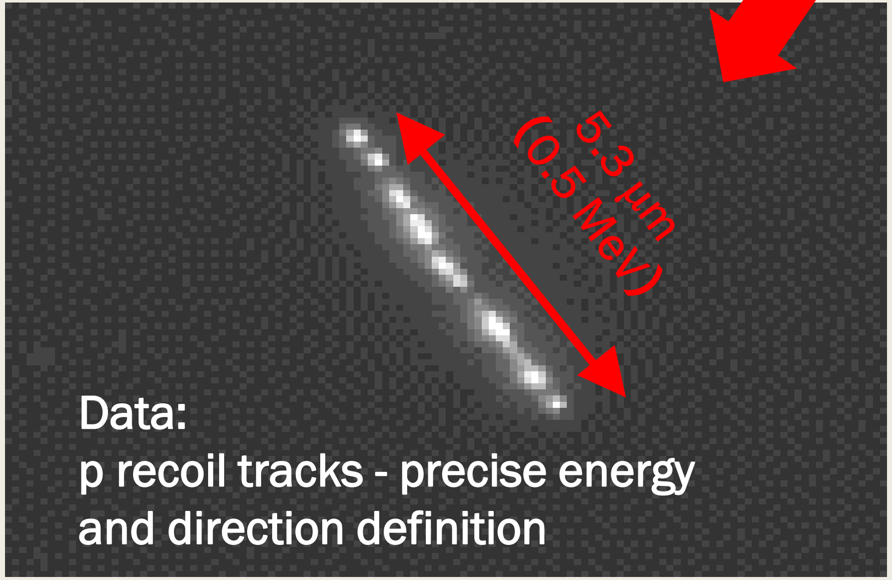
Gel production machine produced in Japan and certified compliant to EU safety

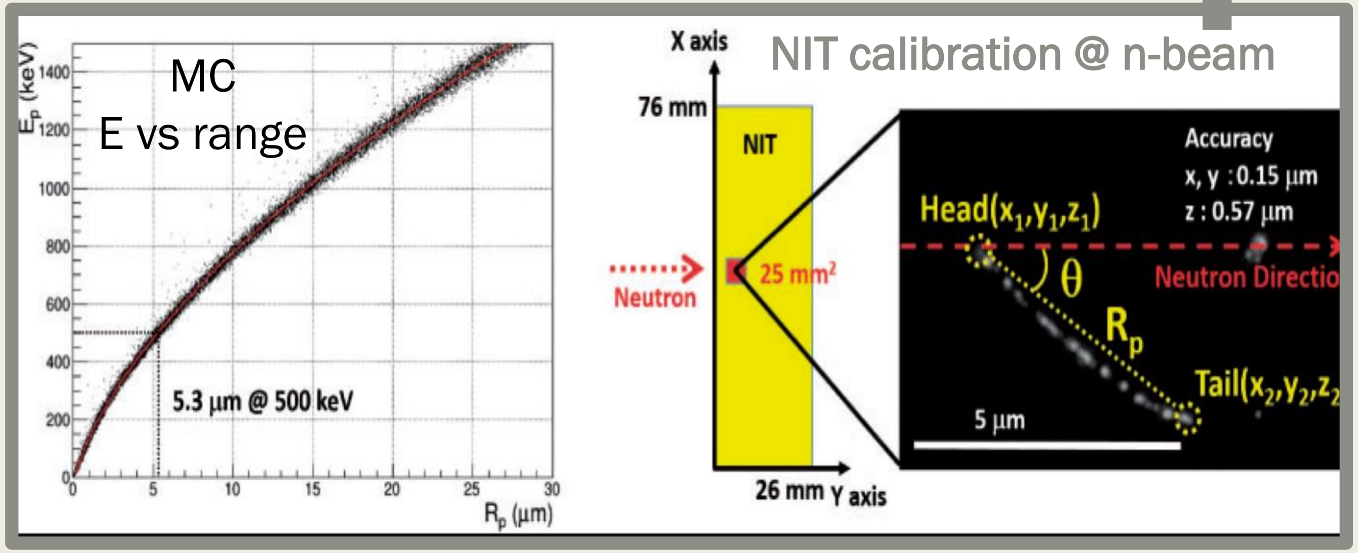
Neutron bg study at LNGS (external and underground)

first sub-MeV energy & direction n-spectrum measurement









Neutron spectrum measurement @ LNGS Surface Lab

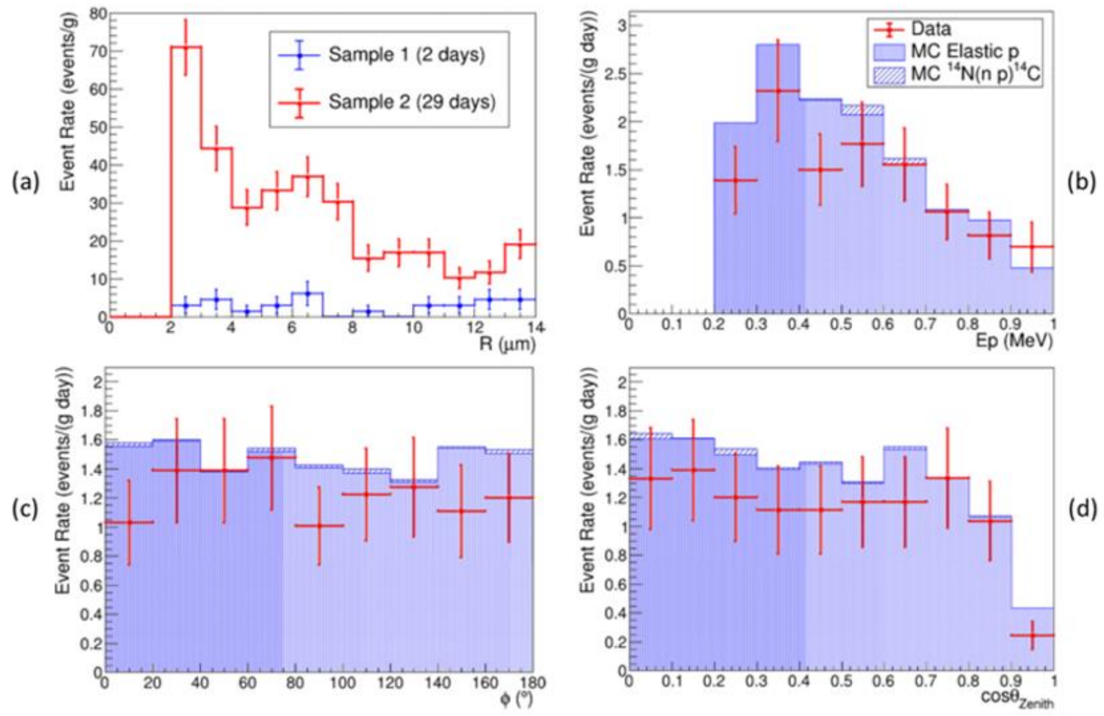


Figure 3.(a) Range distribution of recoil protons in the sub-MeV region for Sample 1 (2 days, blue) and Sample 2 (29 days, red) at LNGS. (b-d) Sub-MeV neutron measurement results after subtracting the data of Sample 1 from Sample 2 for an equivalent exposure of 27 days. For the MC simulation, neutron signals of elastic scattering and 14N(n, p)14C reaction are represented by blue filled and shaded histograms. Detection efficiency was accounted for in the MC simulation. (b) Proton energy spectrum, (c) plane angle, and (d) Zenith angle.

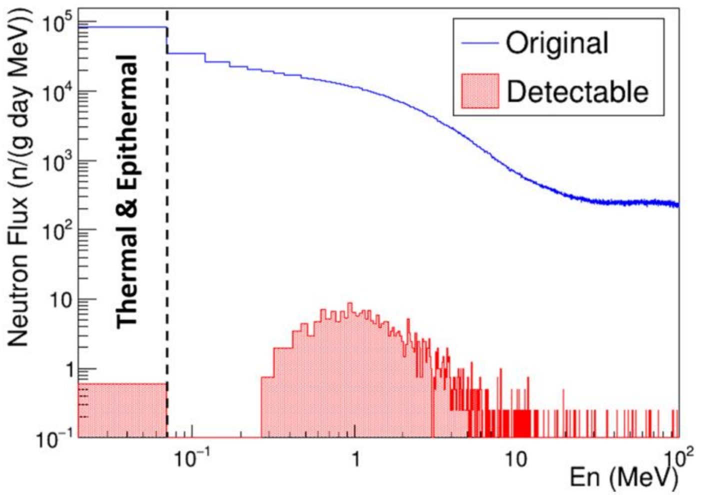
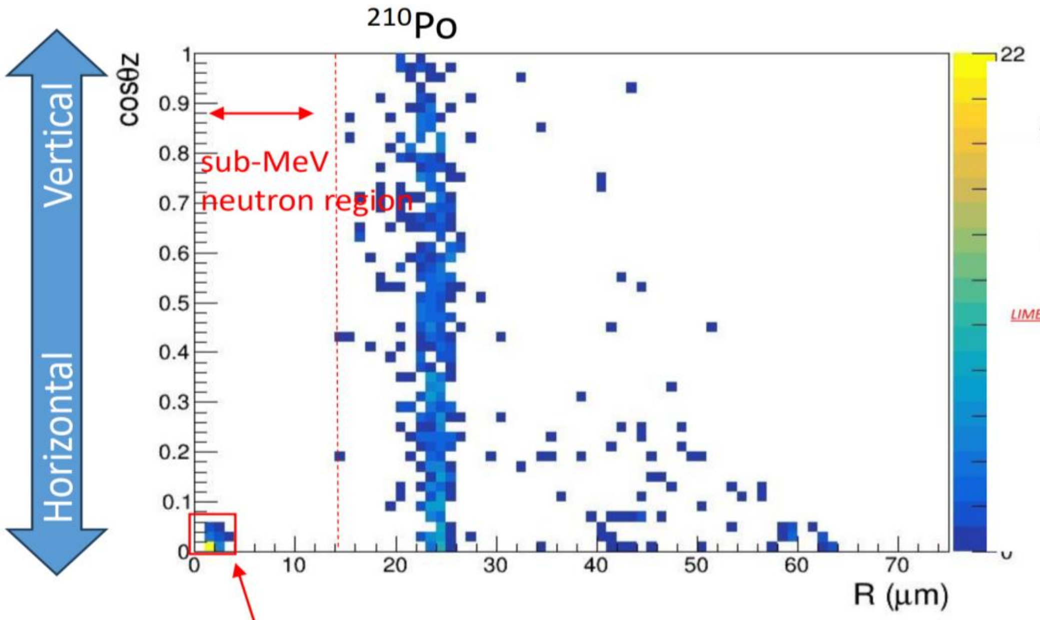


FIG. 9. Detectable neutron spectrum in NIT with 1 (g day) exposure at LNGS surface laboratory estimated by a MC simulation based on GEANT4. The blue line is the original energy of the incident neutrons, and the red filled histogram is the neutron spectrum accounting for the selection and the detection efficiency in this analysis. Below 100 keV is contribution from the $^{14}N(n, p)^{14}C$ reaction.

T. Shiraishi, *et al.*, Phys. Rev. C **107**, 014608 (2023)

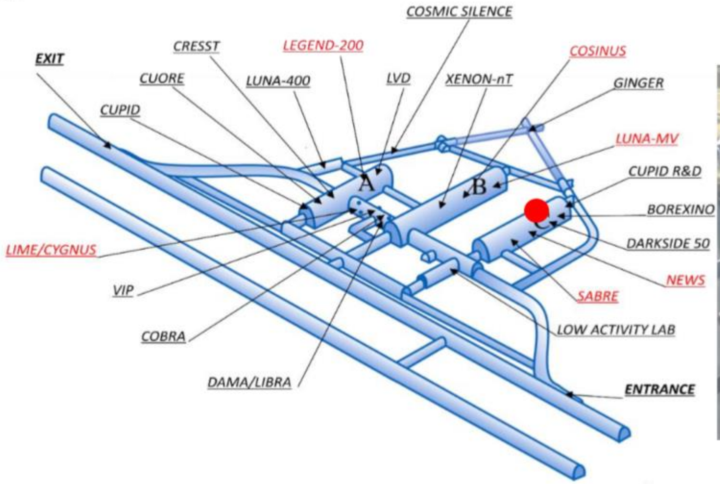
Underground neutron measurement

~0.04 kg・day analyzed in the ~0.9 kg・day exposure device



Mask cosθz < 0.05 && range < 3μm

Backgrounds from α-ray before drying process of emulsion plate are expected.
⇒ To be investigated more.

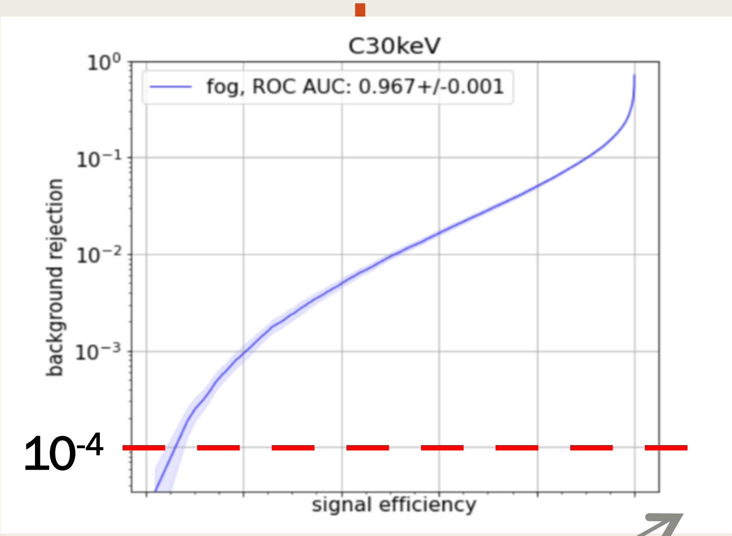


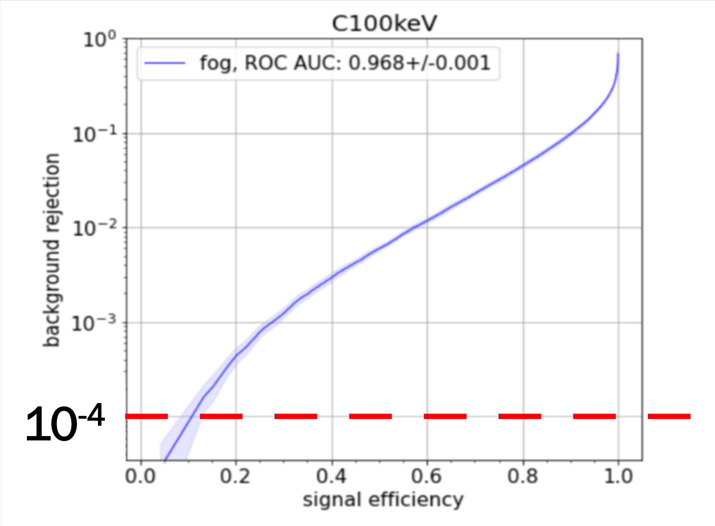
Hall.C exposure
[-15℃ operation]

Current underground neutron flux upper limit
< 4.5 × 10^{-5} /cm^2/sec (90%CL) *Very Preliminary

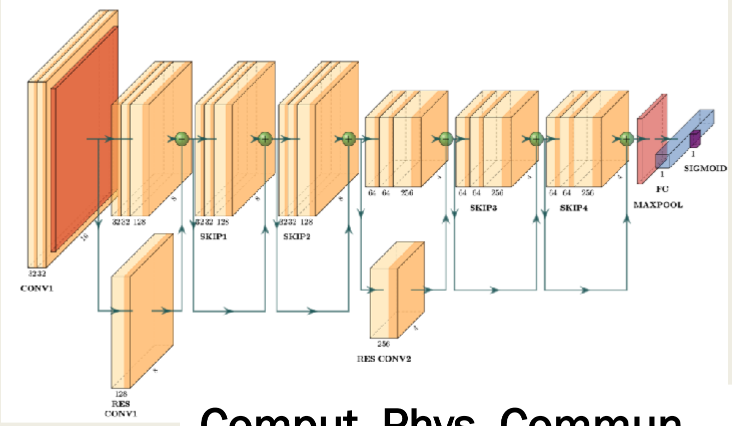
Data analysis is on going for 3 kg・day exposure

Background reduction: Machine Learning





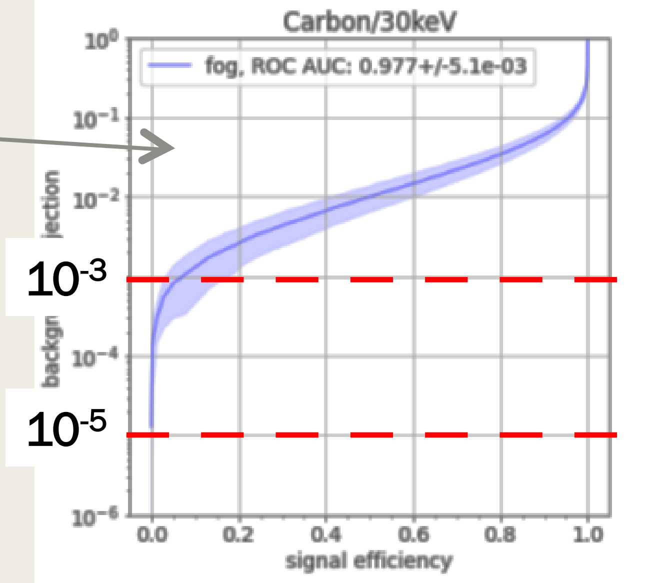
Schematic view of the CNN architecture

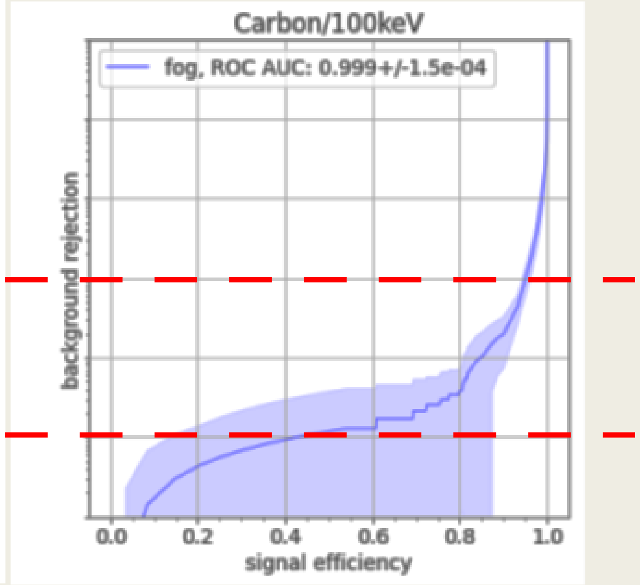


Comput. Phys. Commun. 275 (2022) 108312

Only polarization data

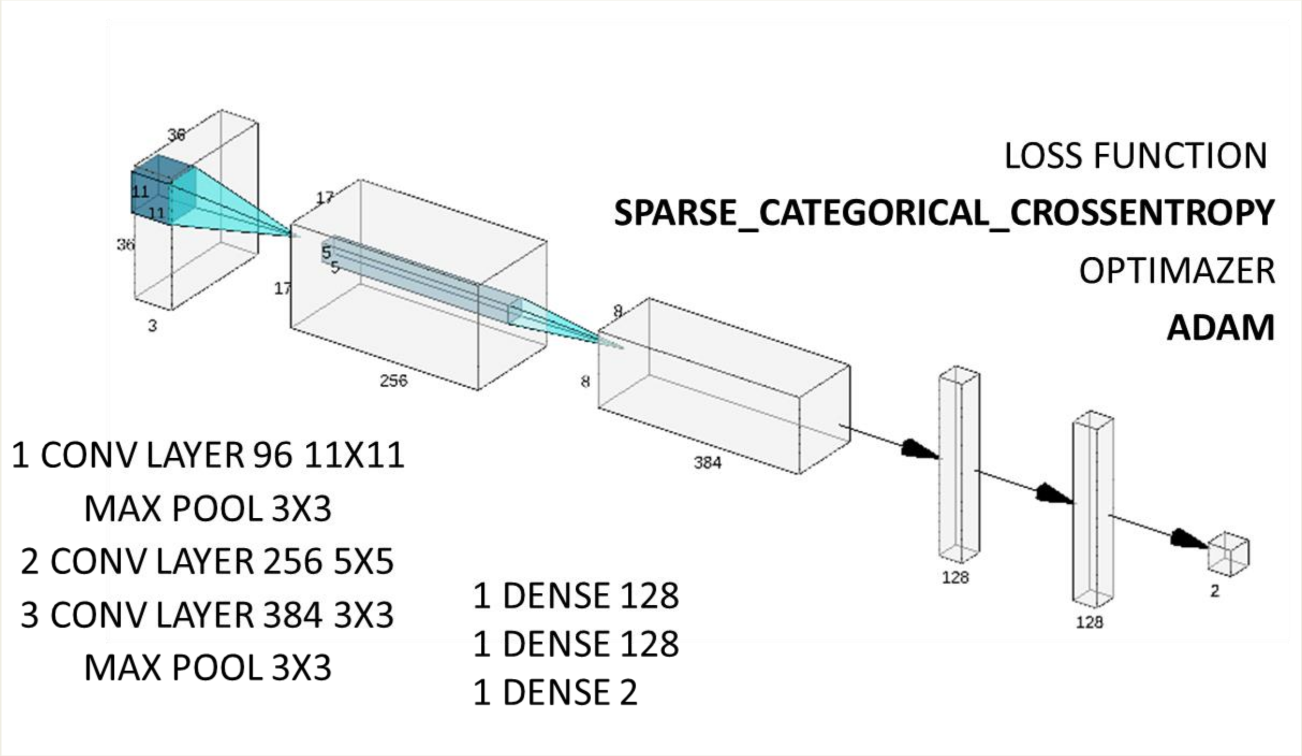
Only colour data

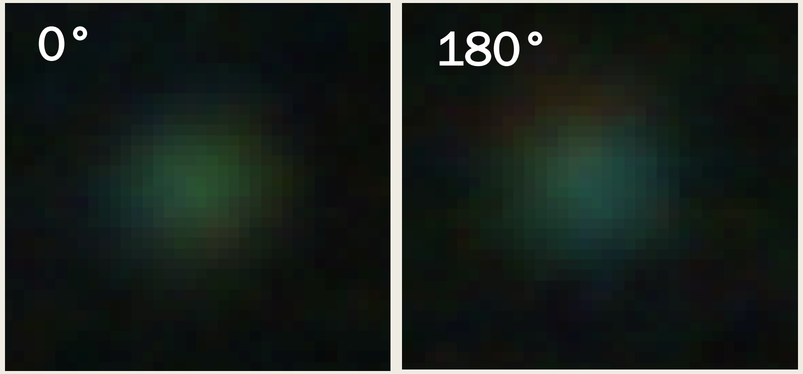




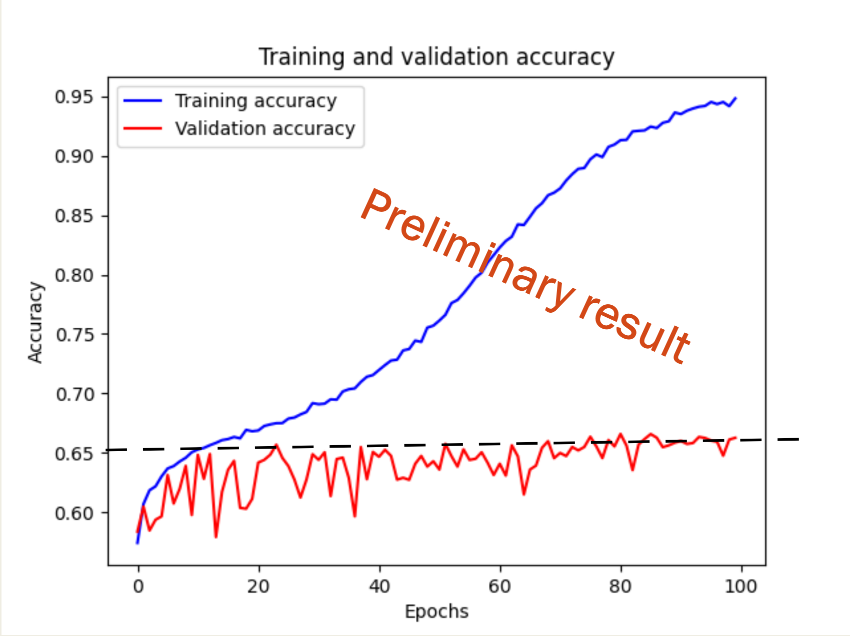
Background reduction factor and efficiency for different thresholds on ML probability-like output on **validation** data

Sense recognition with color
Machine Learning approach





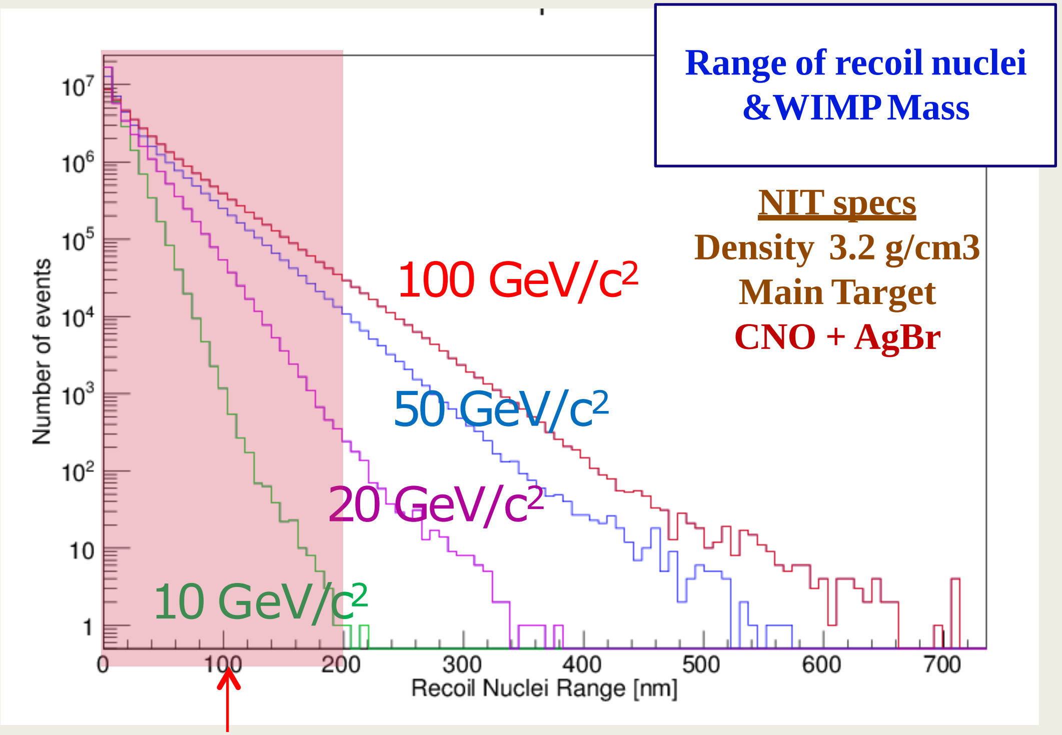
Carbon ion 100 keV



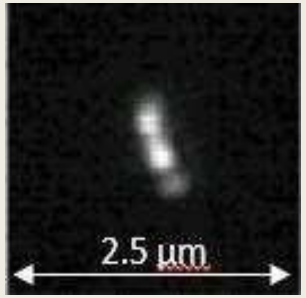
Sense prediction accuracy = 65%

Signal and noise in NIT

- Signal: Ionization path ↔ aligned clusters of bright pixels (NIT not sensitive to m.i.p.!)
- Noise: Dust, impurities, thermal noise ↔ random clusters of bright pixels + physics by local energy loss (e.g. electrons!)



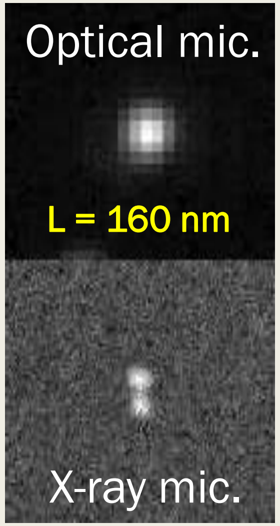
Inaccessible due to diffraction limit



E~100keV

Carbon ions

E<100 keV



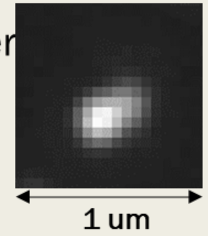
First underground exposure inside shield

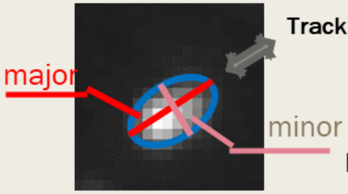
Automatic readout
1st trigger

Elliptical shape trigger

Requirement

- High speed scanning
- Low energy threshold
- Single noise (fog) reduction





CNO : > 30 keV
Electron efficiency: 0.05

CNO
(machine learning)

≧ 3 grain track recognition

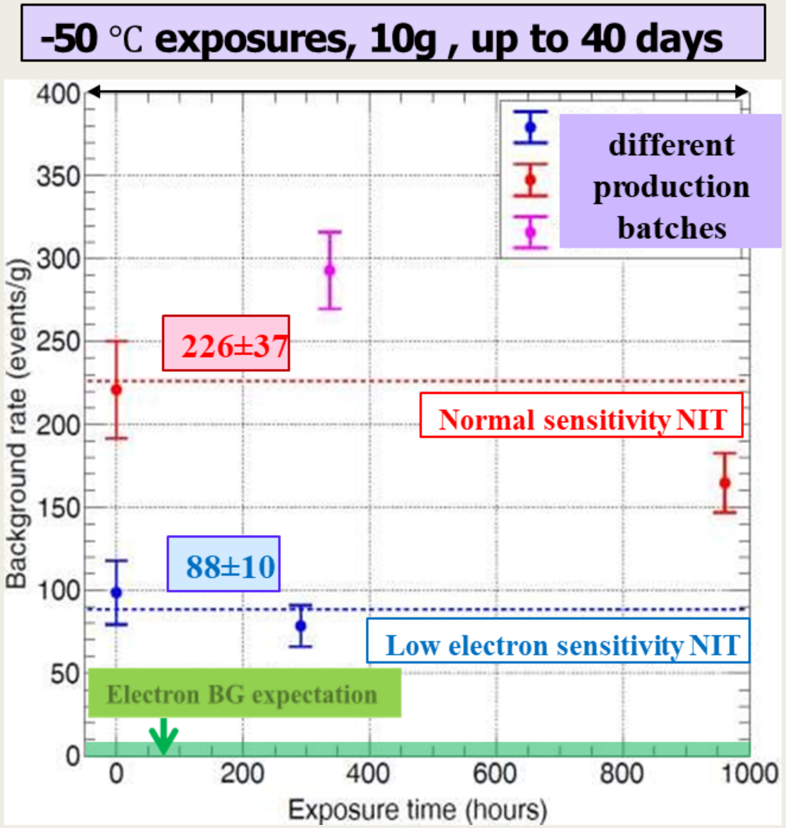
- Candidate selection and narrow down the number of event
- Image feature extraction

Training sample :
neutron induce recoil nuclei @AIST
(880keV, -50℃)

Manual check

Confirmation
Electron rejection power :
10^{-4} @ room temperature
10^{-6} @ -50℃

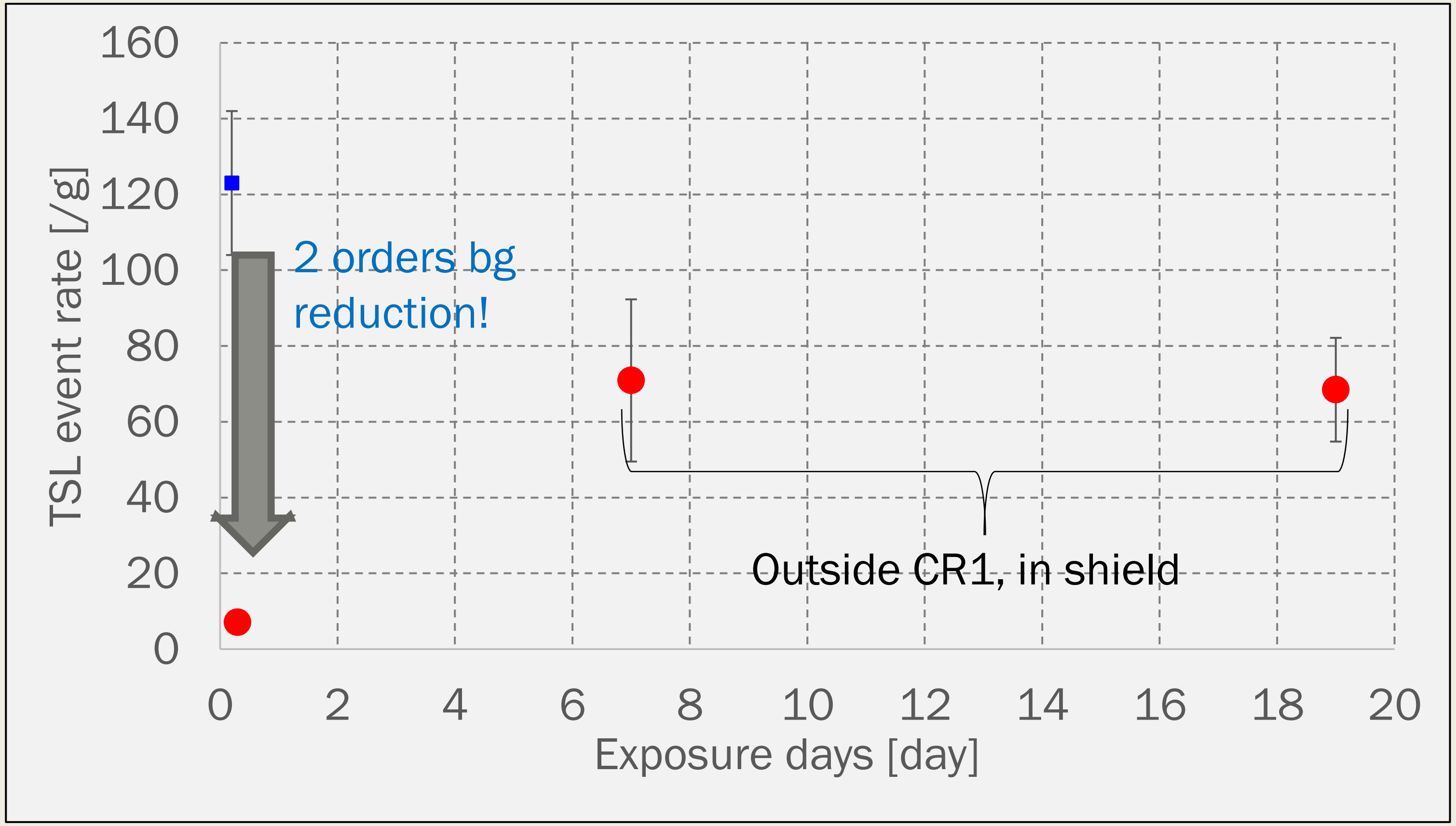
Current Selection



Results:

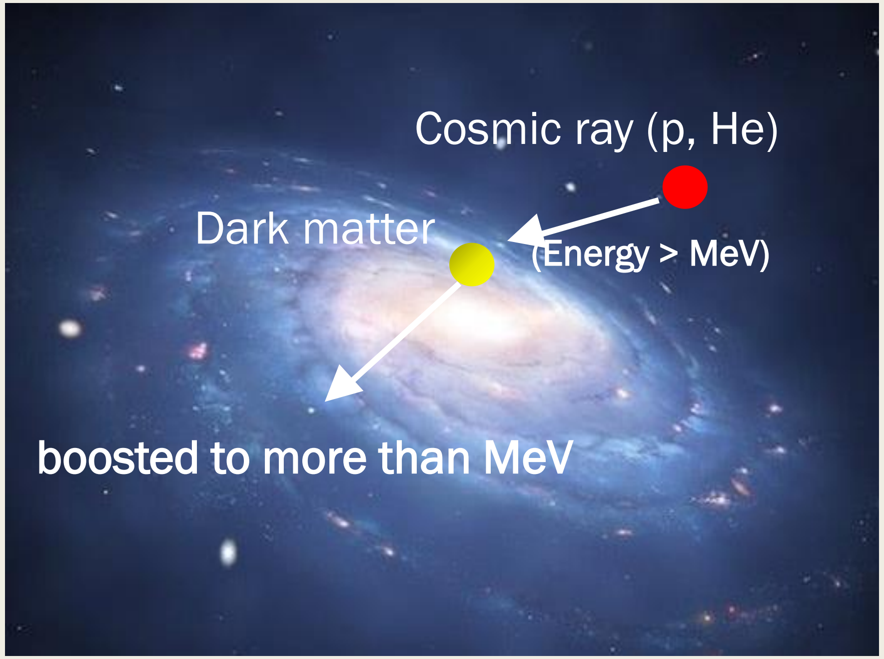
- *Too many candidates (x10^2 more than expected e)*
- *Signal not increasing with in-shield exposure time*
- *Using NIT with reduced sensitivity to e ➔ not enough*
- *Definitely more CNO-like than e-like*

Measurements using “Rn-free” NIT emulsion

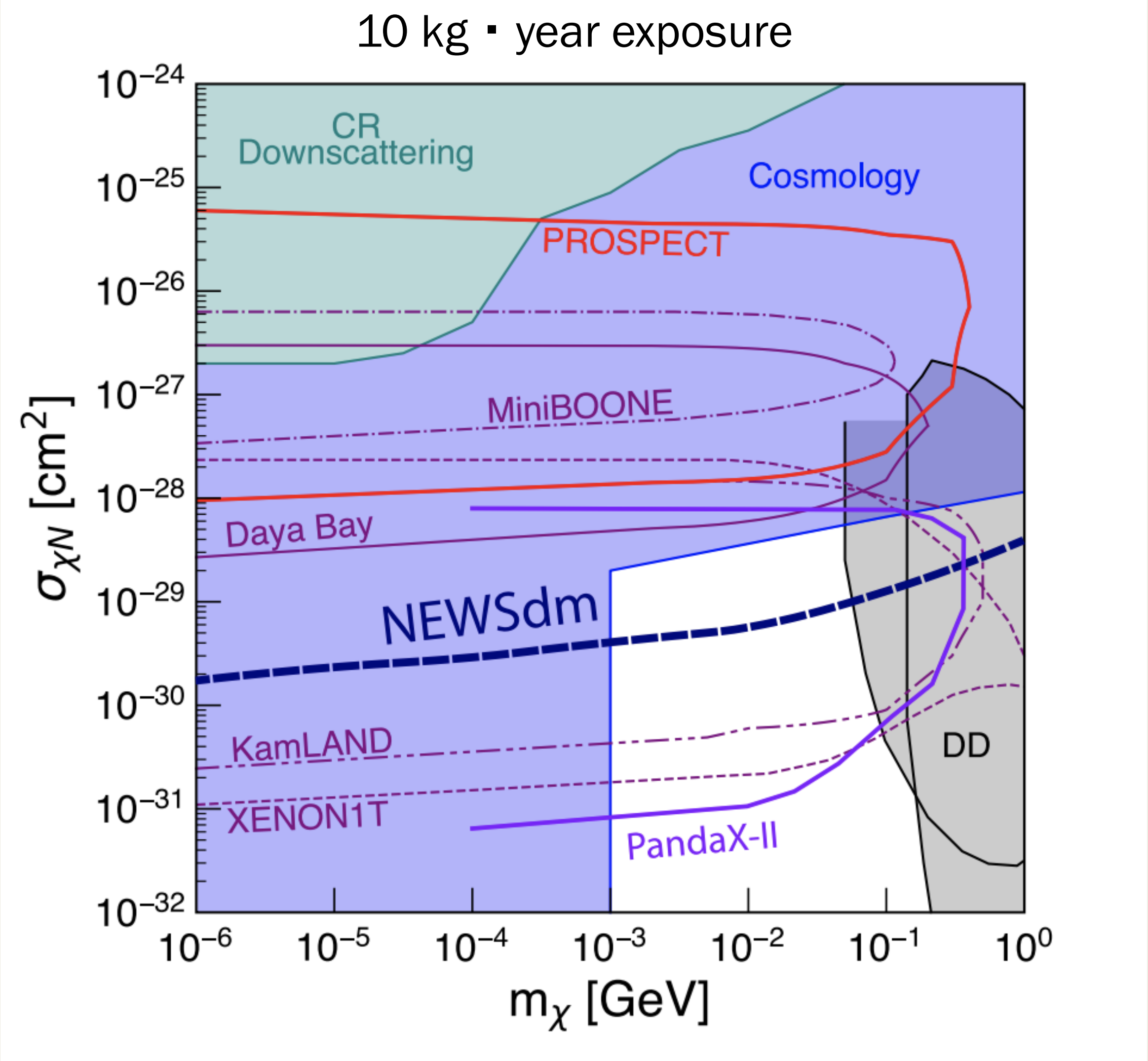


- Important confirmation of the α as the source of the offset background, down to the expected level!
- Results compatible with no increase of the background inside the shield as expected
- Increase of the background while moving away from CR1
- To make a shielded tests in CR1

Boosted DM scenario

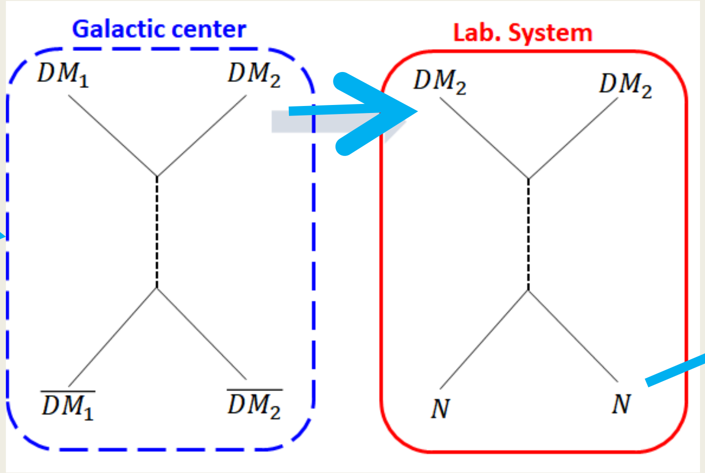


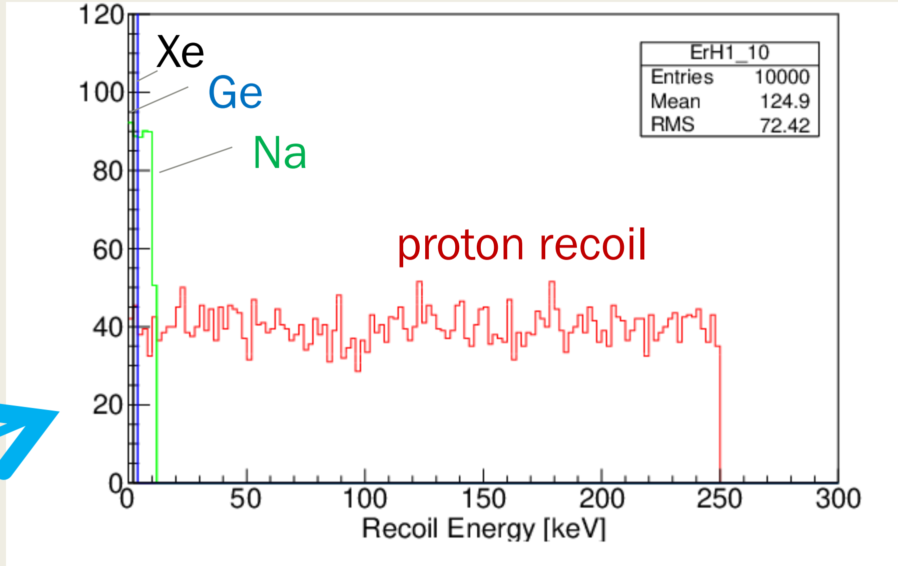
Sensitivity curves of the 10 kg NEWSdm detector for 1 year of exposure at the surface (Assergi) level and exclusion plot from PROSPECT surface experiment. The boundaries go through the dots corresponding to three H and CNO recoil events with track lengths of more than 70 nm.



N.Y. Agafonova et al., «Directional sensitivity of the NEWSdm experiment to cosmic ray boosted dark matter”, JCAP07(2023)067

Multi-component DM scenario

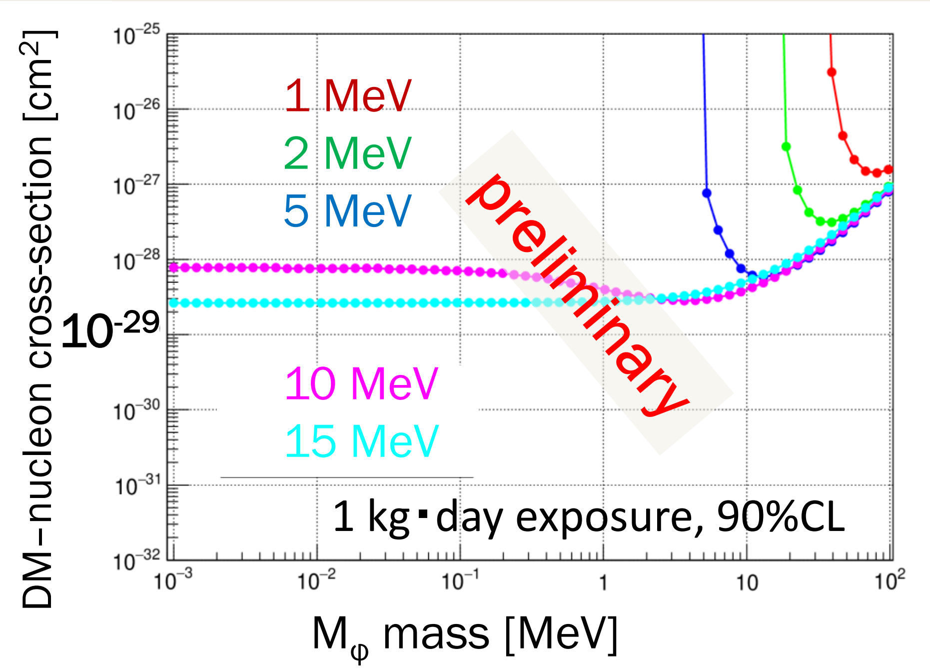




$DM_1 > DM_2$

Mass difference is kinetic energy of DM_2

Expected sensitivity limit for DM−nucleon cross-section



Expected flux on the Earth

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

https://arxiv.org/pdf/1405.7370.pdf

Assumption:

- DM1 is assumed to be the main component of DM halo
- DM2 has higher coupling with baryon than lepton