DIRECTIONAL DARK MATTER SEARCHES WITH THE NEWSdm EXPERIMENT

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15th International Workshop on the Identification of Dark Matter 2024 (IDM 2024), Jul 8-12 2024 L'Aquila (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

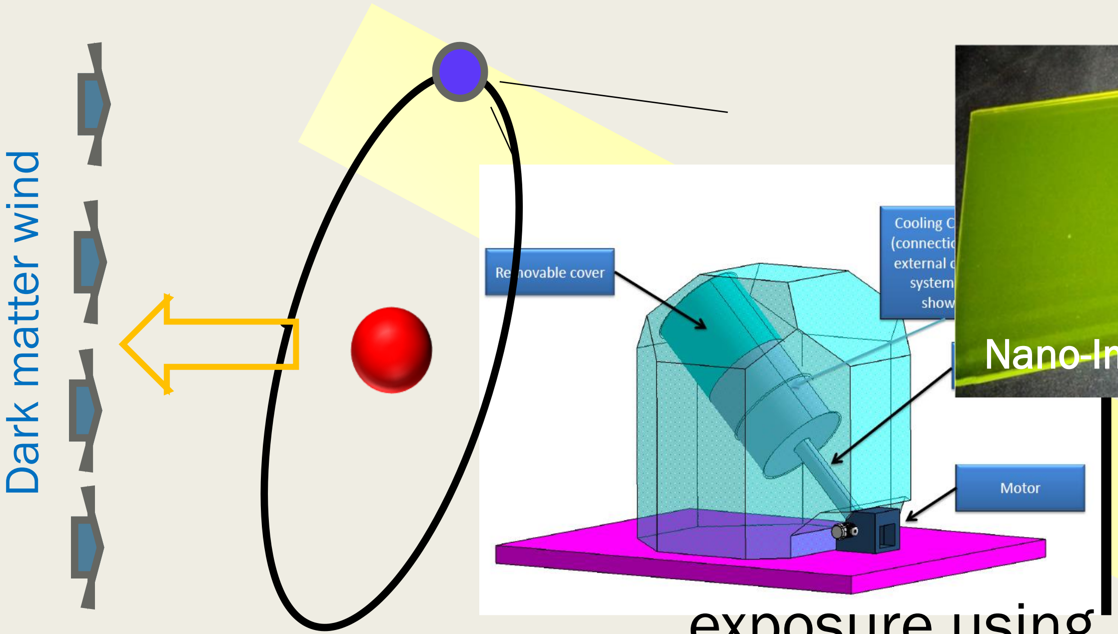
SOUTH KOREA
Gyeongsang University

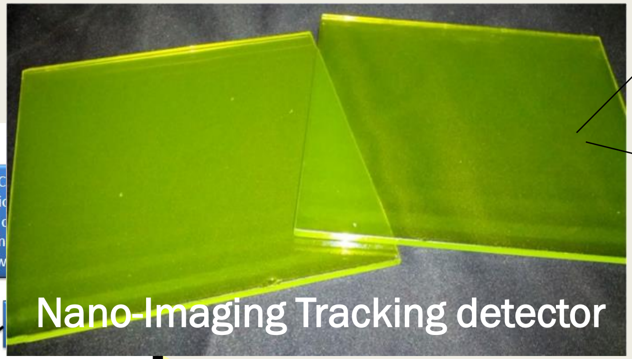
TURKEY
METU Ankara

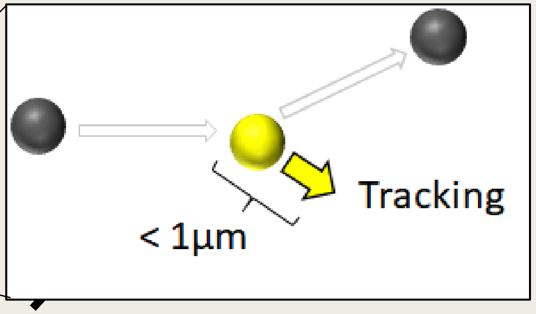
Website: news-dm.lngs.infn.it
Letter of intent: https://arxiv.org/pdf/1604.04199.pdf

NEWSdm experiment concept

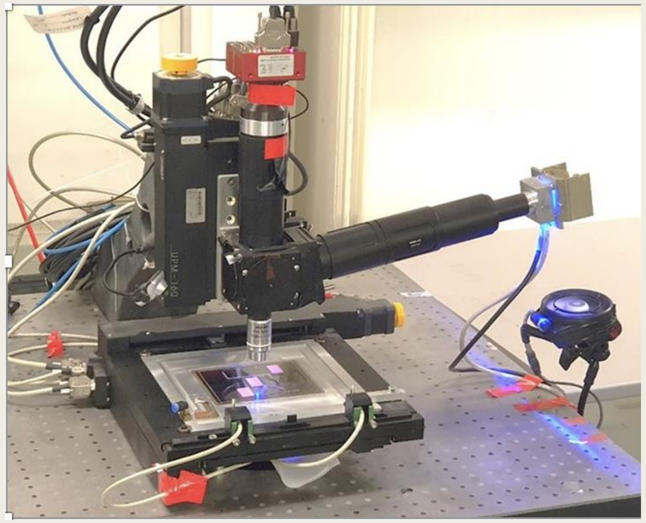
Direction sensitive dark matter search with nano-tracking technologies for super resolution nuclear emulsion







Optical image readout

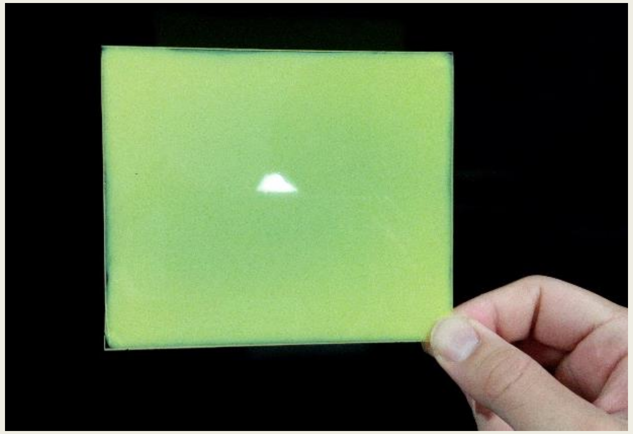


exposure using
an equatorial telescope

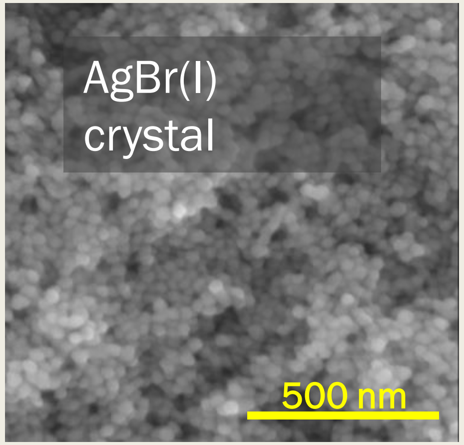
Underground laboratory
Gran Sasso (LNGS)

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

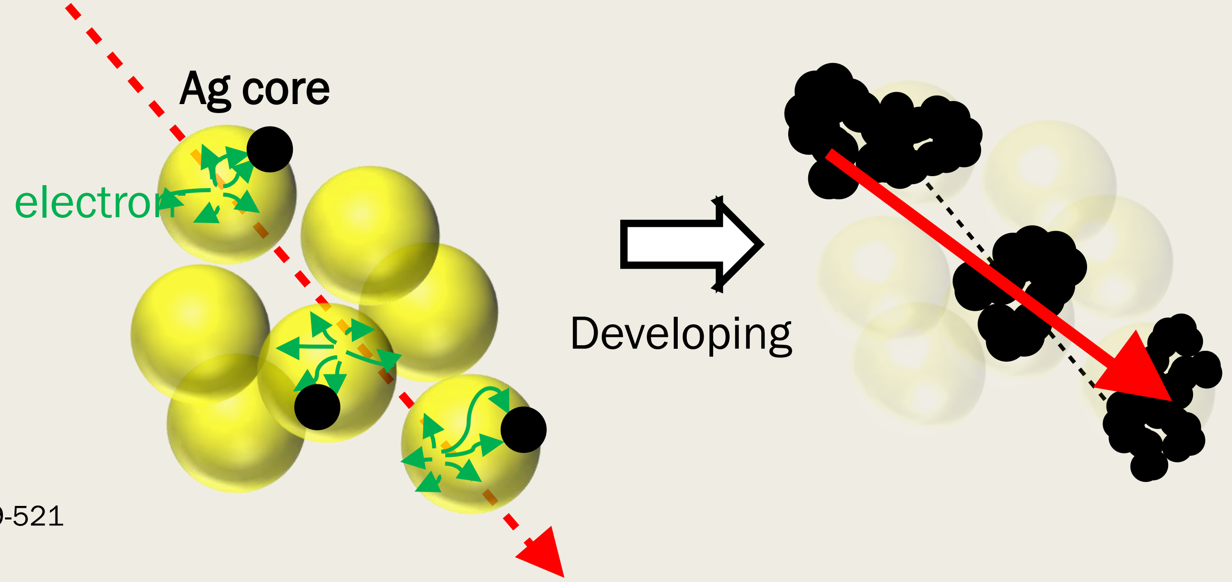
Nano Imaging Tracker (NIT) developed for NEWSdm



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



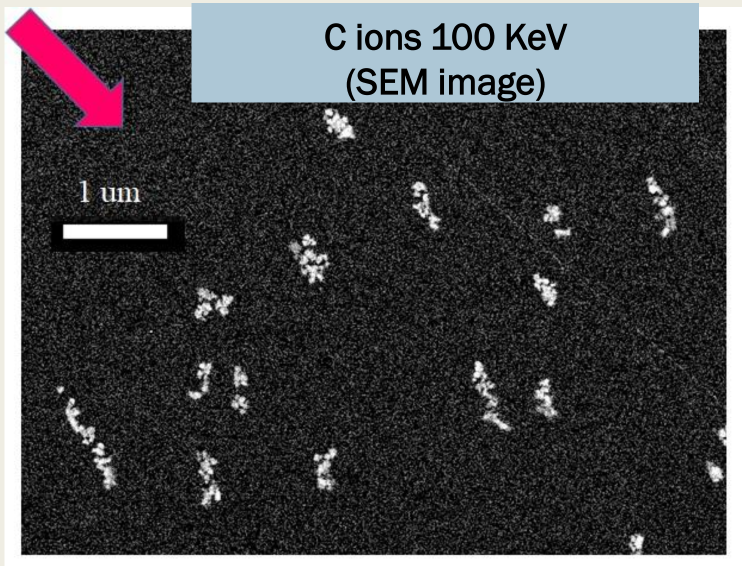
NIM A Nucl. Inst. Meth. A 718 (2013) 519-521
PTEP (2017)063H01



		Mass fraction	Atomic Fraction
Heavier DM	Ag	0.44	0.10
	Br	0.32	0.10
	I	0.019	0.004
Lighter DM	C	0.101	0.214
	O	0.074	0.118
	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

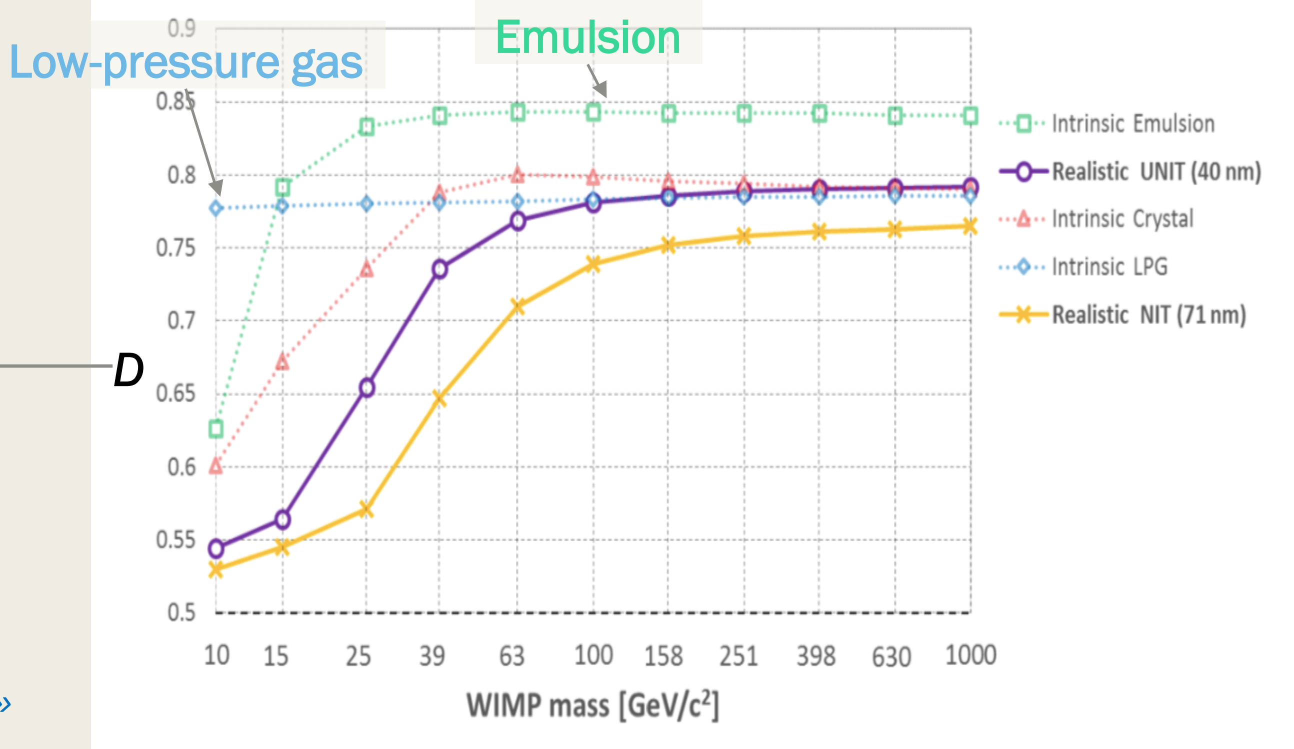


Directionality preservation of nuclear recoils

- 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:

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

Proposed in JCAP01(2017)027

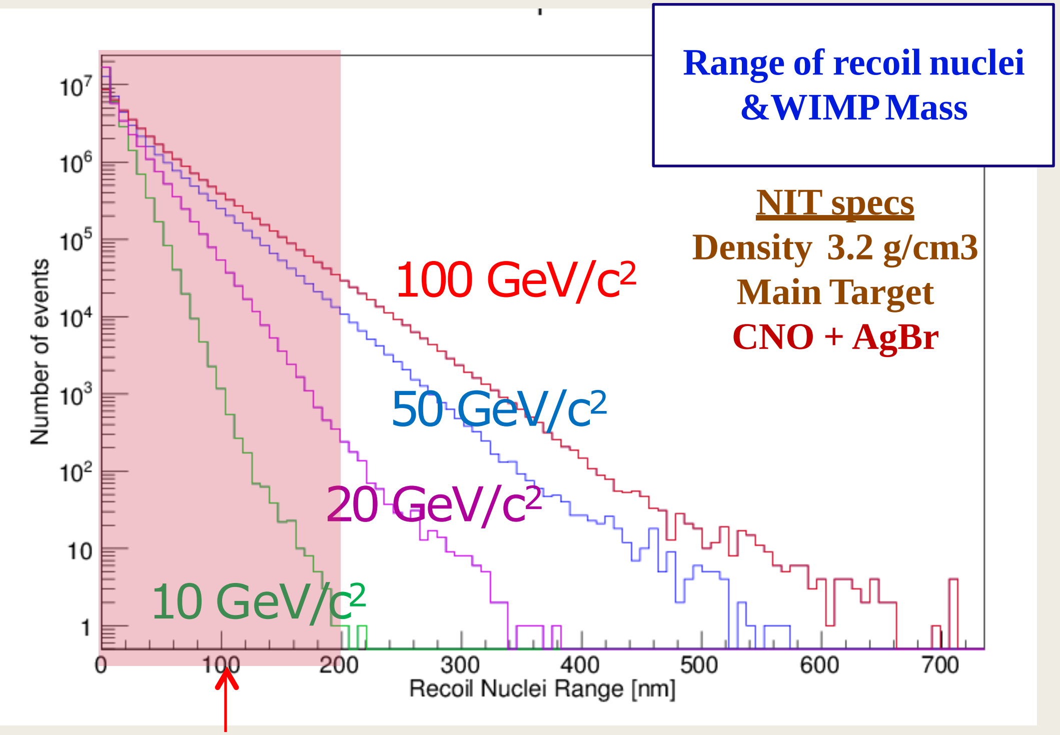


Realistic distribution of mean values of weighted-cosϑ for NIT and U-NIT, compared with other detectors

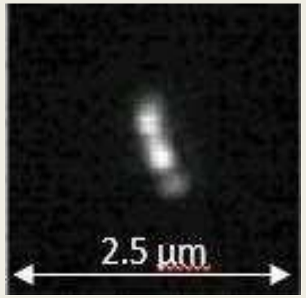
A. Alexandrov, et al,
«Directionality preservation of nuclear recoils in an emulsion detector for directional dark matter search»
JCAP 04 (2021) 047

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!)



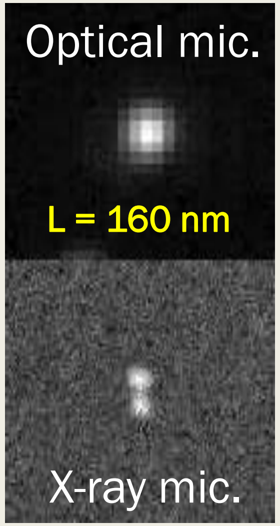
Inaccessible due to diffraction limit



E~100keV

Carbon ions

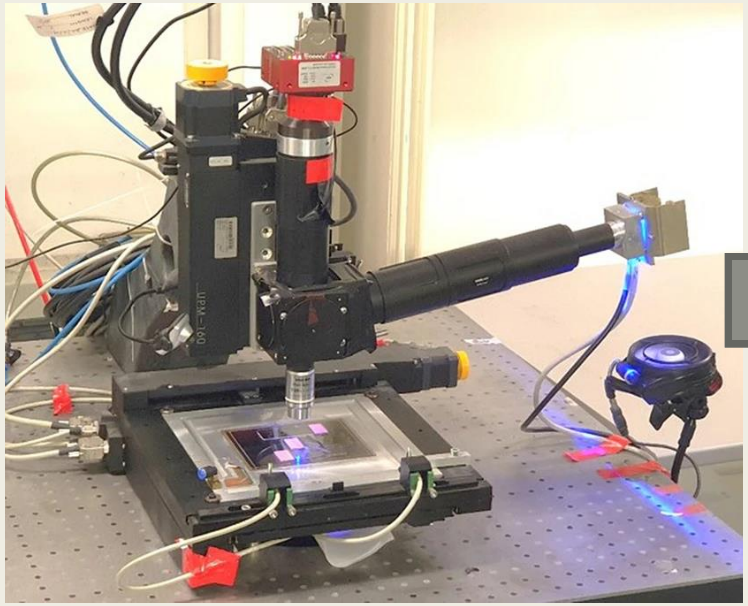
E<100 keV

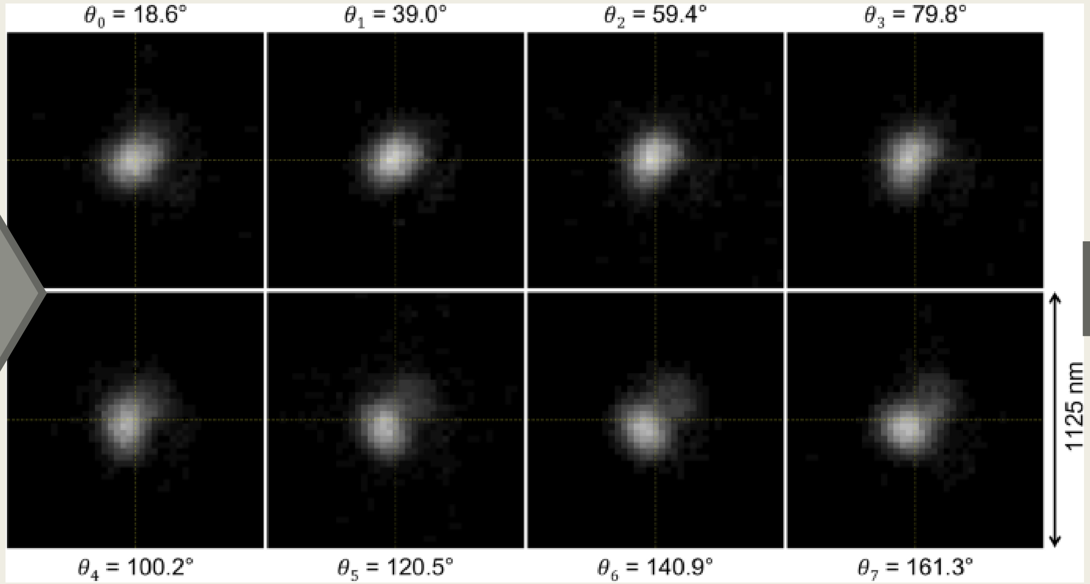


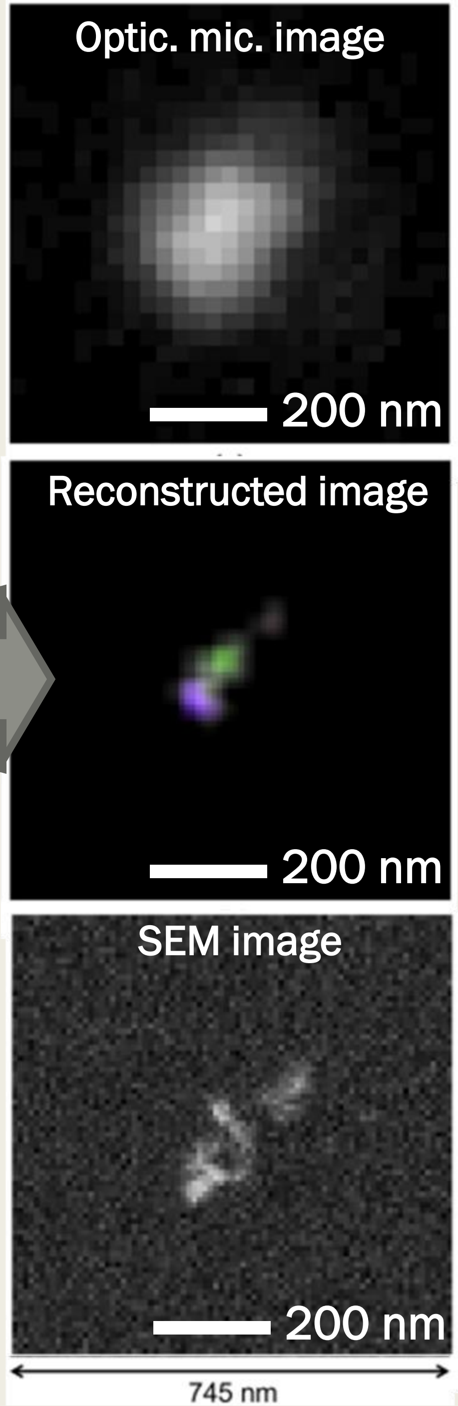
LSPR-based super-resolution imaging

100 keV Carbon ion in NIT

Optical mic images (8 polarizations)

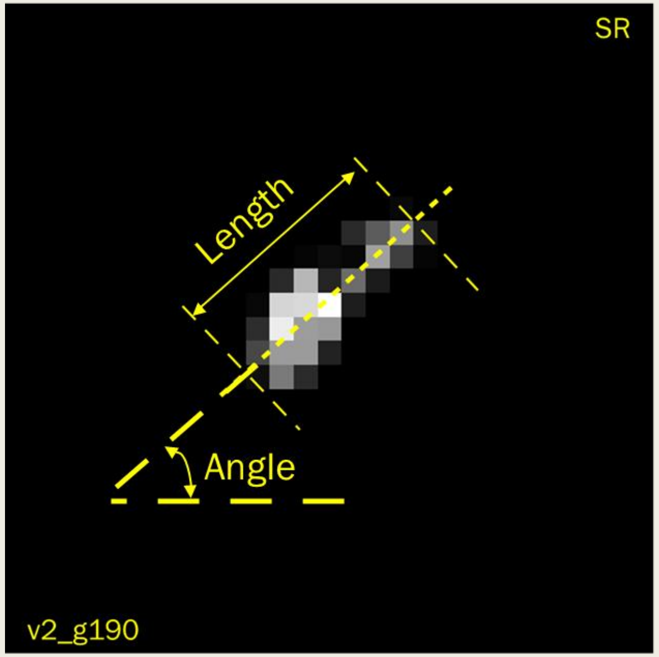


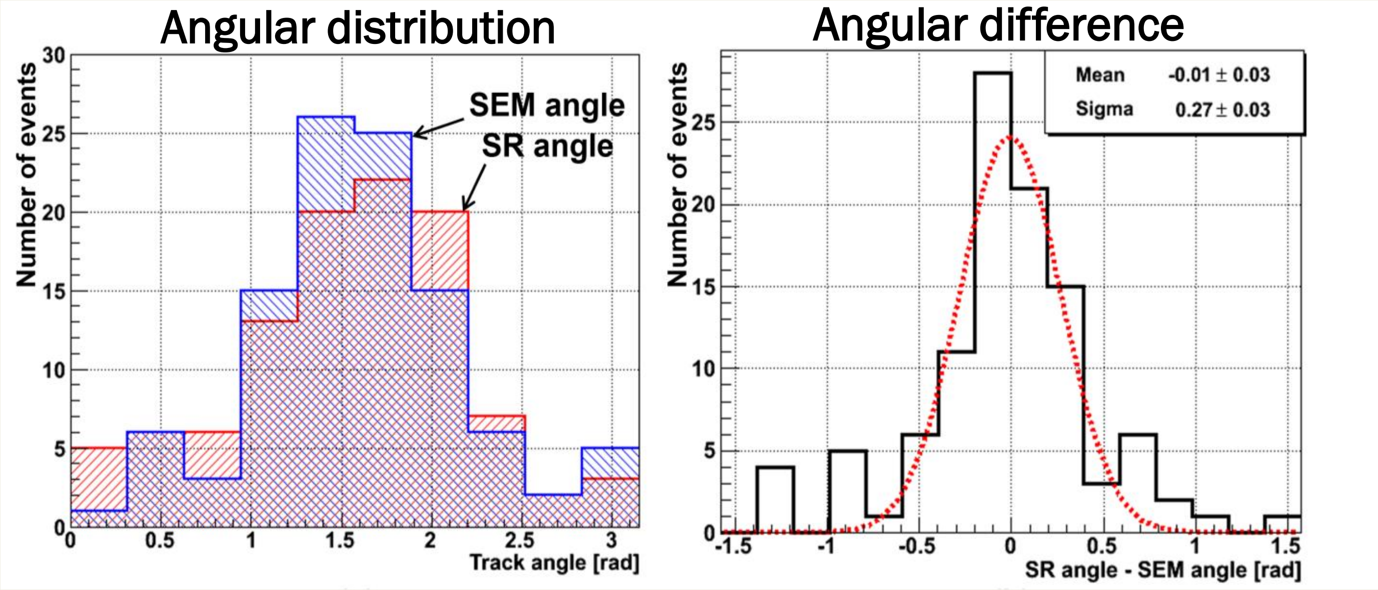


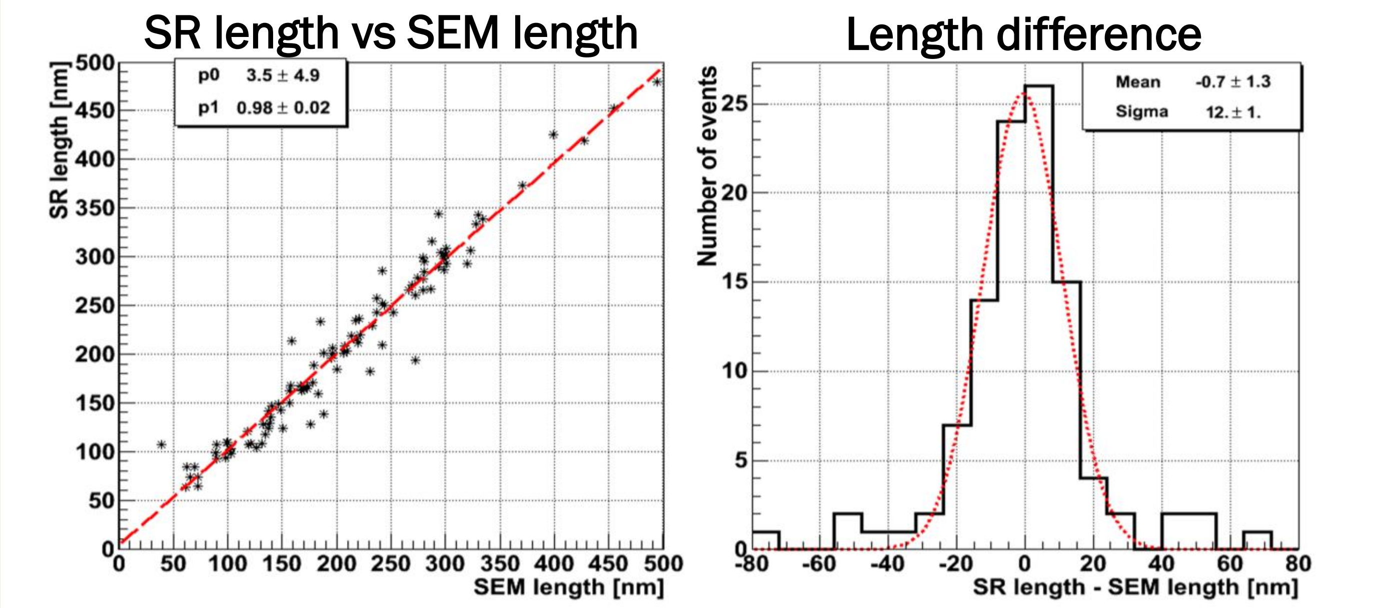


Alexandrov, A., et al.
"Super-resolution high-speed optical microscopy for fully automated readout of metallic nanoparticles and nanostructures."
Sci Rep 10, 18773 (2020). https://doi.org/10.1038/s41598-020-75883-z

LSPR-based super-resolution imaging







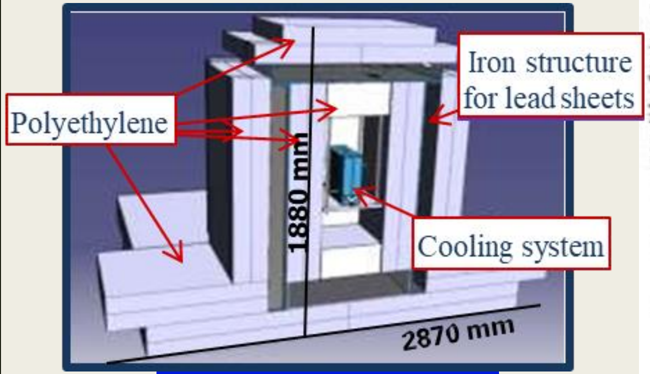
Angular resolution: 270 ± 30 mrad
Length accuracy: 12 ± 1 nm
Spatial resolution: ~ 50 nm
NIT granularity: 71 nm

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

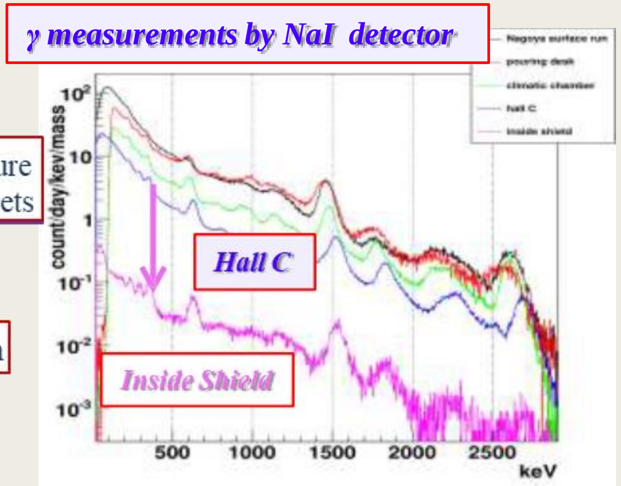
Backgrounds

Environmental

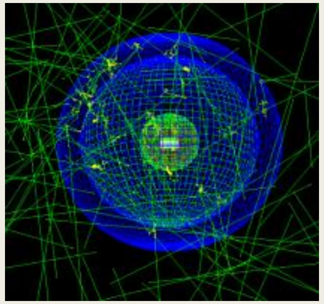
Current shield



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.)



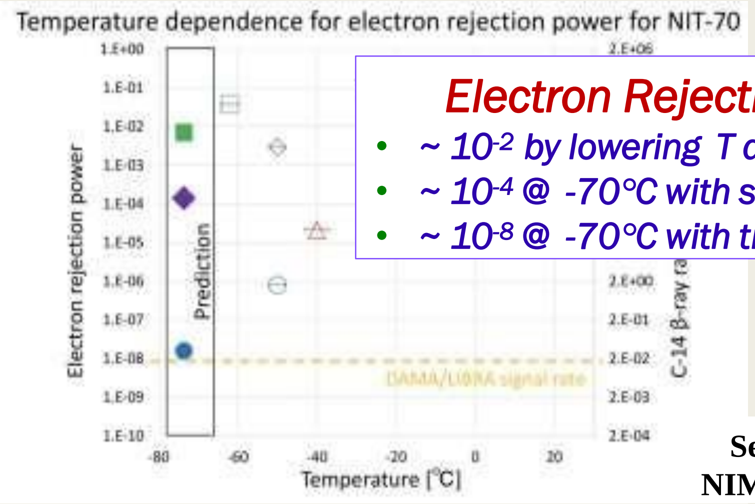
10 kg detector shield (1 m HDPE @LNGS)

Source	Rate $[10\,\mathrm{kg} \times \mathrm{y}]^{-1}$
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 $[\mathrm{g} \times \mathrm{month}]^{-1}$	Rate $[\mathrm{kg} \times \mathrm{year}]^{-1}$
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

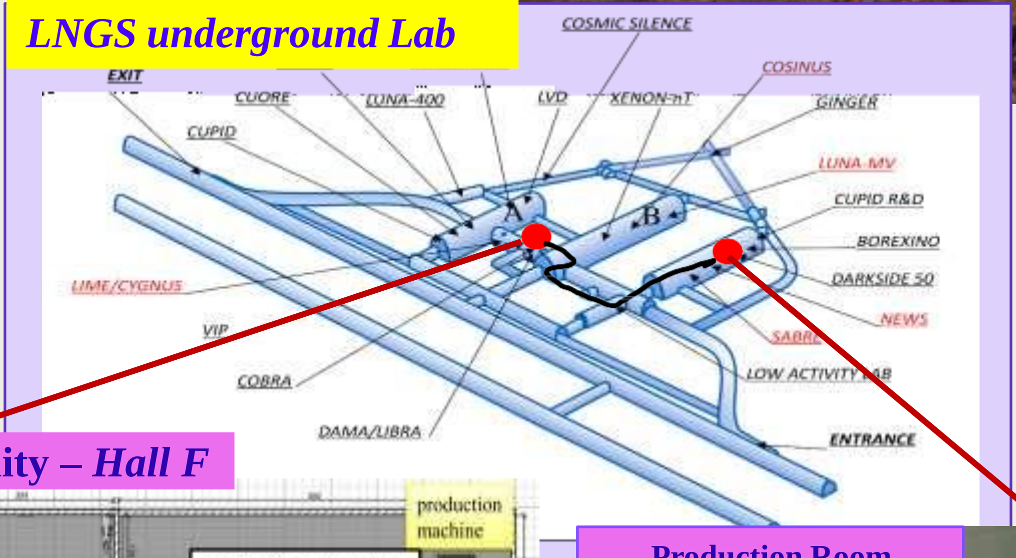
Experimental Activity @ LNGS

Neutron flux @ surface Lab

LNGS surface Lab

Development Room
Clean Room ISO 7

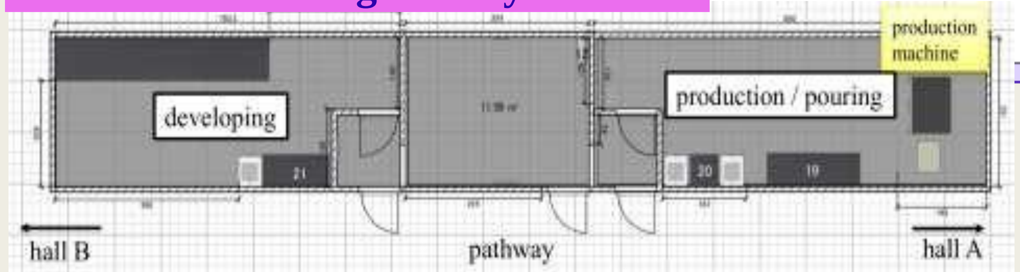
LNGS underground Lab



Cooling Box for Target

Target insertion by crane

Emulsion Handling Facility – *Hall F*



Shielded Exposure set-up – *Hall C*

Lead shield : 5.6 cm
Polyethilene : 31.5 cm

Production Room
Clean Room ISO 6
Capability ~100 g /day

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

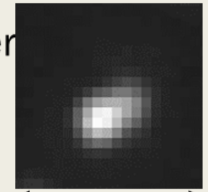
First underground exposure inside shield

Automatic readout
1^{st} trigger

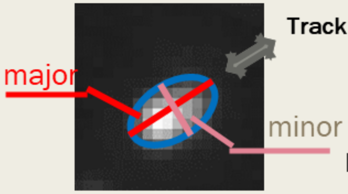
Elliptical shape trigger

Requirement

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



1 um



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

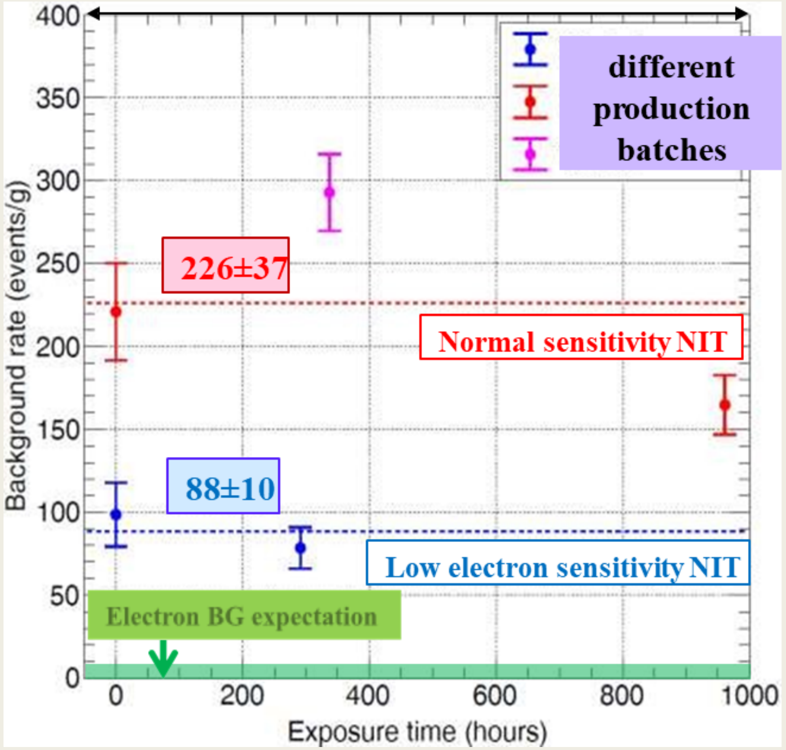
Training sample :
neutron induce recoil nuclei @AIST
(880keV, -50℃)

Manual check

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

Current Selection

-50 ℃ exposures, 10g , up to 40 days

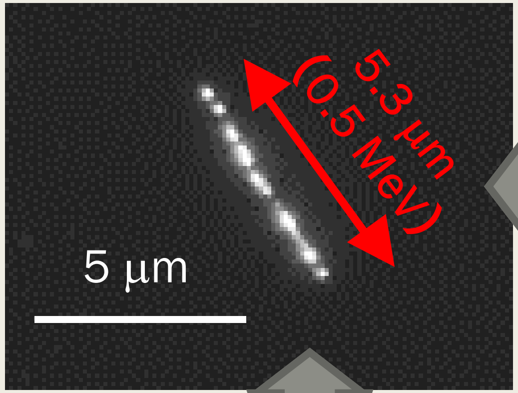


Results:

- *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*

NIT as a Neutron Detector

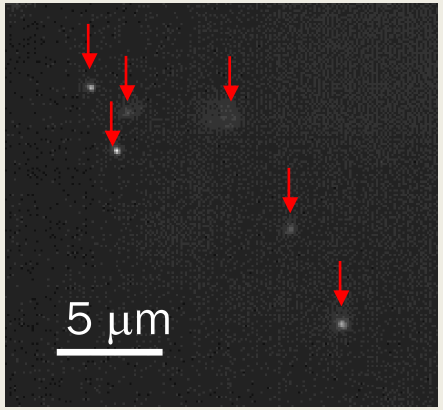
Recoil proton signal



Topological or Range cut

Clearly distinguishable

γ-ray (β-ray)

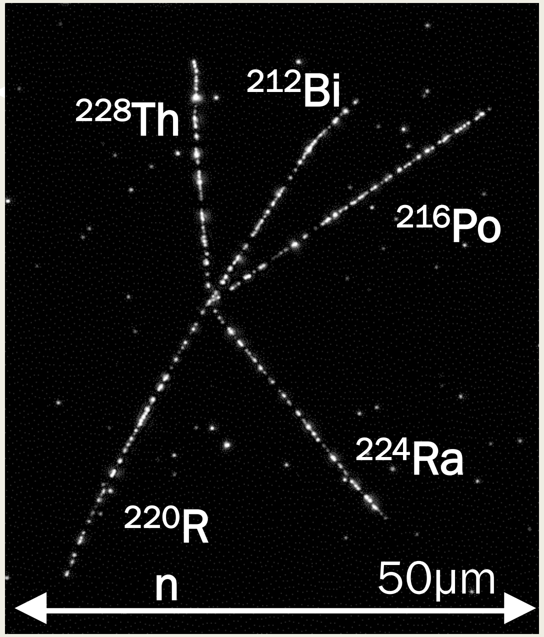


Exposed 5x10^7 γ-ray/cm^2 from ^{241}Am (5 years accumulation of environmental γ-ray)

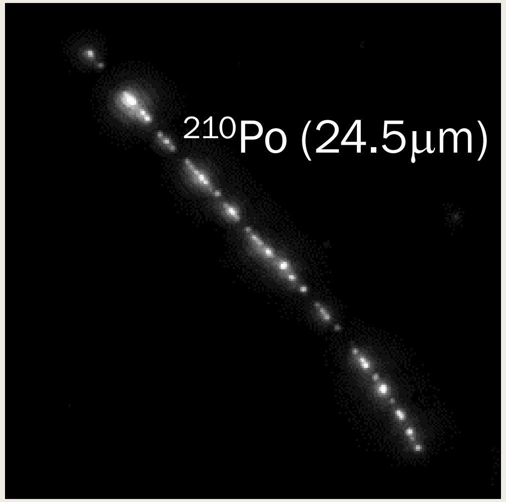
✓ Environmental γ-rays cannot become background

α-ray

Th star (^{228}Th → ^{208}Pb)



Single-α in U series



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

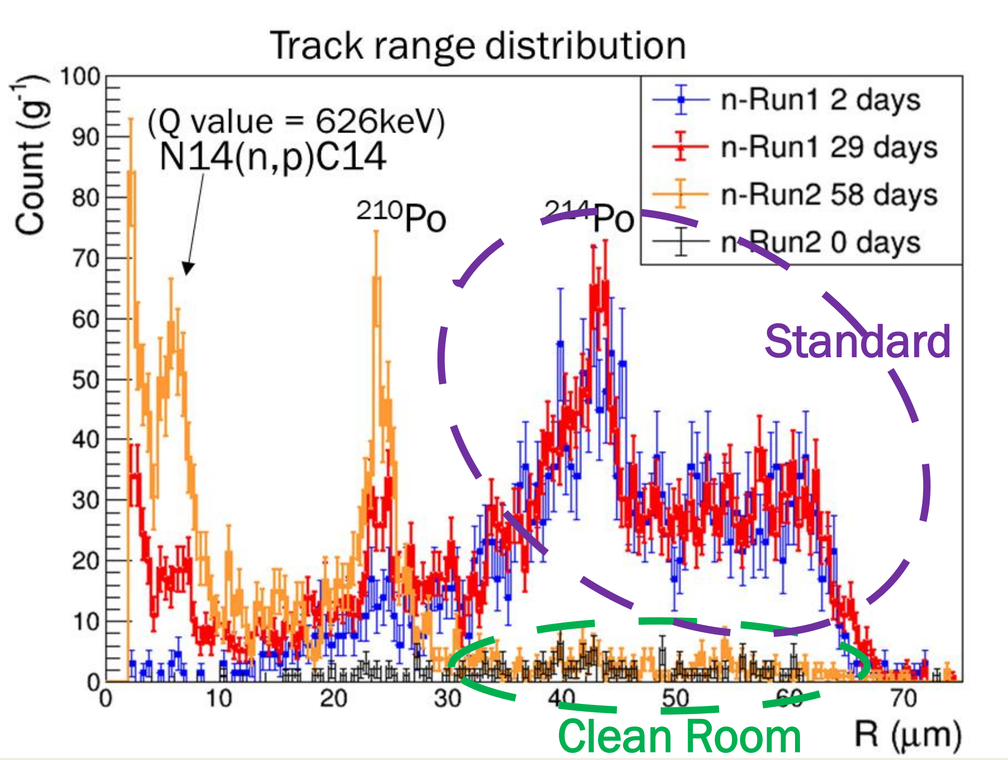
✓ MeV region can be analyzed excluding single-α (especially ^{210}Po peak around 24μm)

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 @ surface lab

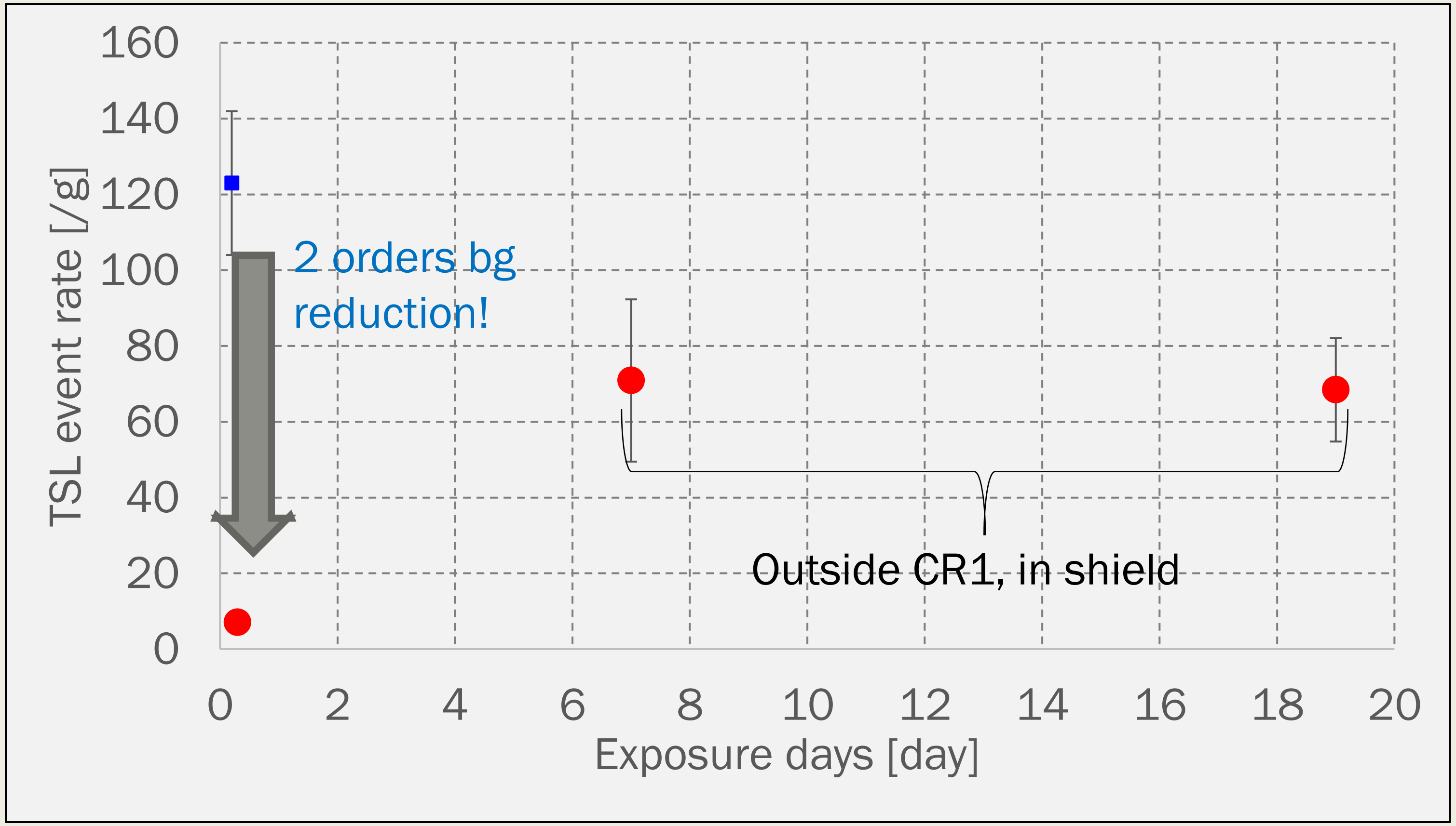
$$ {}^{222}_{86}\mathrm{Rn} \xrightarrow[3.8235\ \mathrm{d}]{\alpha\ 5.59\ \mathrm{MeV}} {}^{218}_{84}\mathrm{Po} \xrightarrow[3.05\ \mathrm{min}]{\alpha\ 6.11\ \mathrm{MeV}} {}^{214}_{82}\mathrm{Pb} \xrightarrow[26.8\ \mathrm{min}]{\beta^-} {}^{214}_{83}\mathrm{Bi} \xrightarrow[19.9\ \mathrm{min}]{\beta^-}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

- 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 <u>disappeared</u> in the clean one!



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

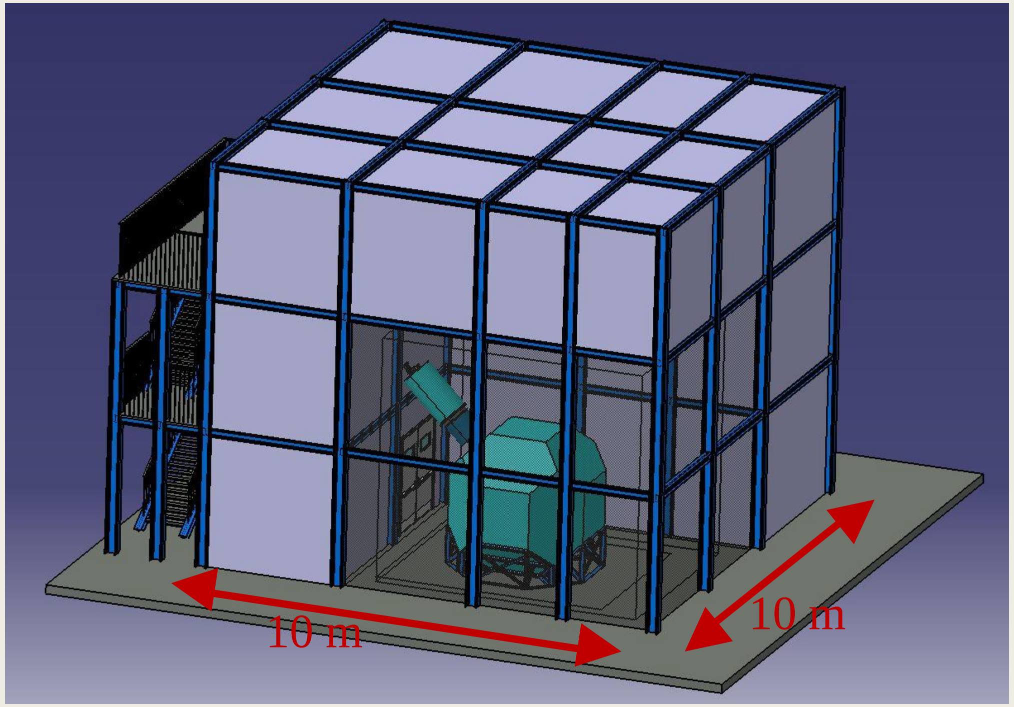
Measurements using “Rn-free” NIT emulsion

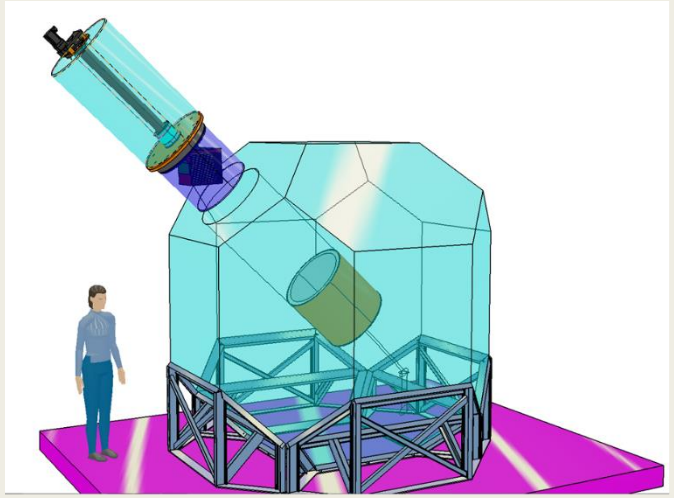


- Important confirmation of the α as the source of the offset background, down to the expected level!
- Results compatible with no increase of the background inside the shield as expected
- Increase of the background while moving away from CR1
- To make a shielded tests in CR1

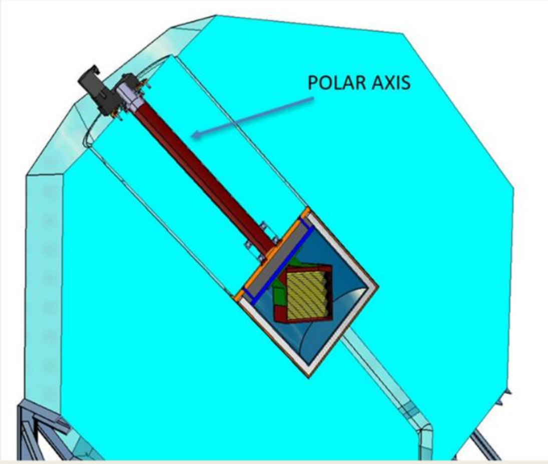
Future facility for NEWSdm: 10kg and beyond

Emulsion facility and shielding with an equatorial telescope

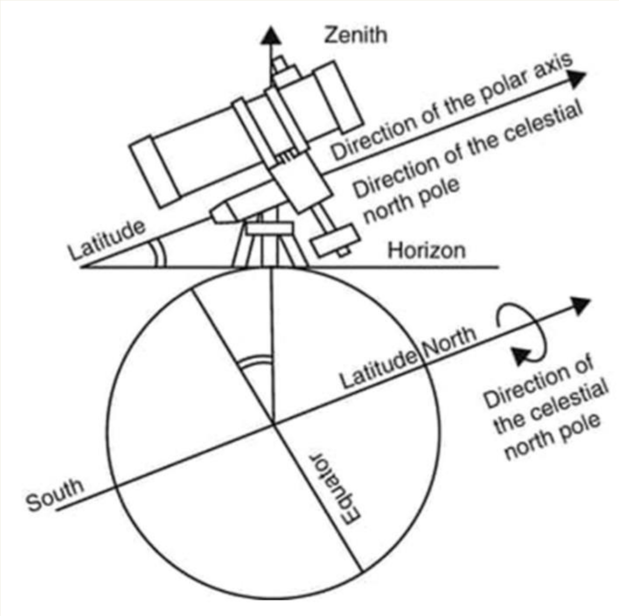


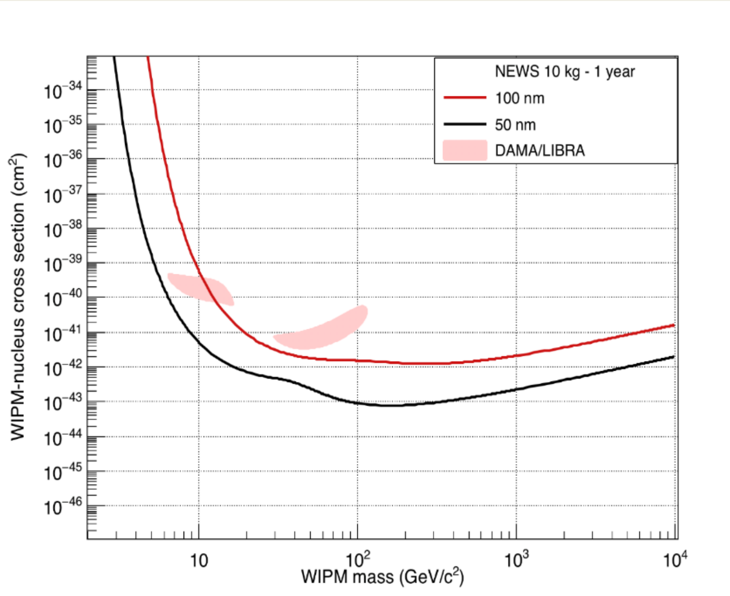


(a)

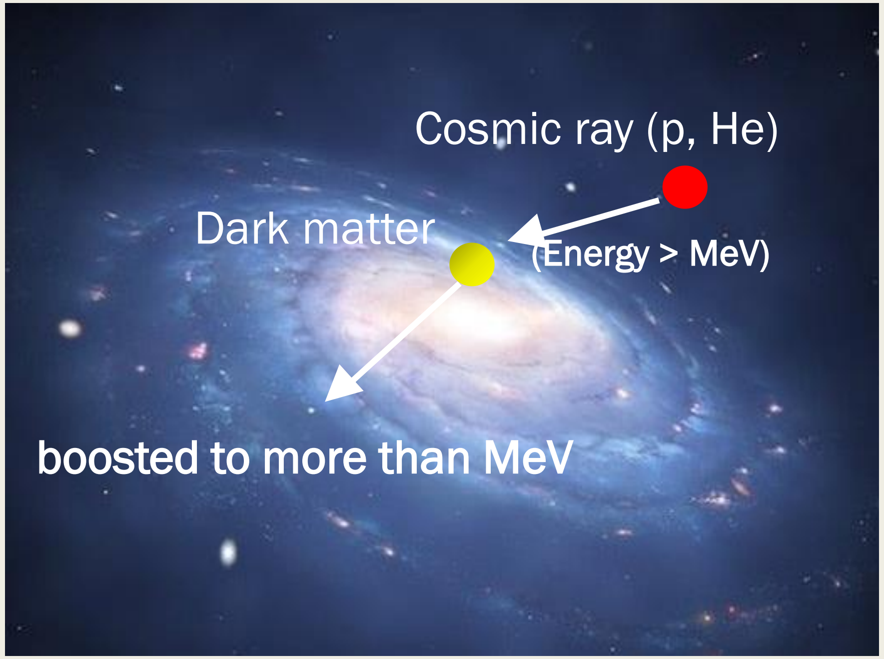


(b)

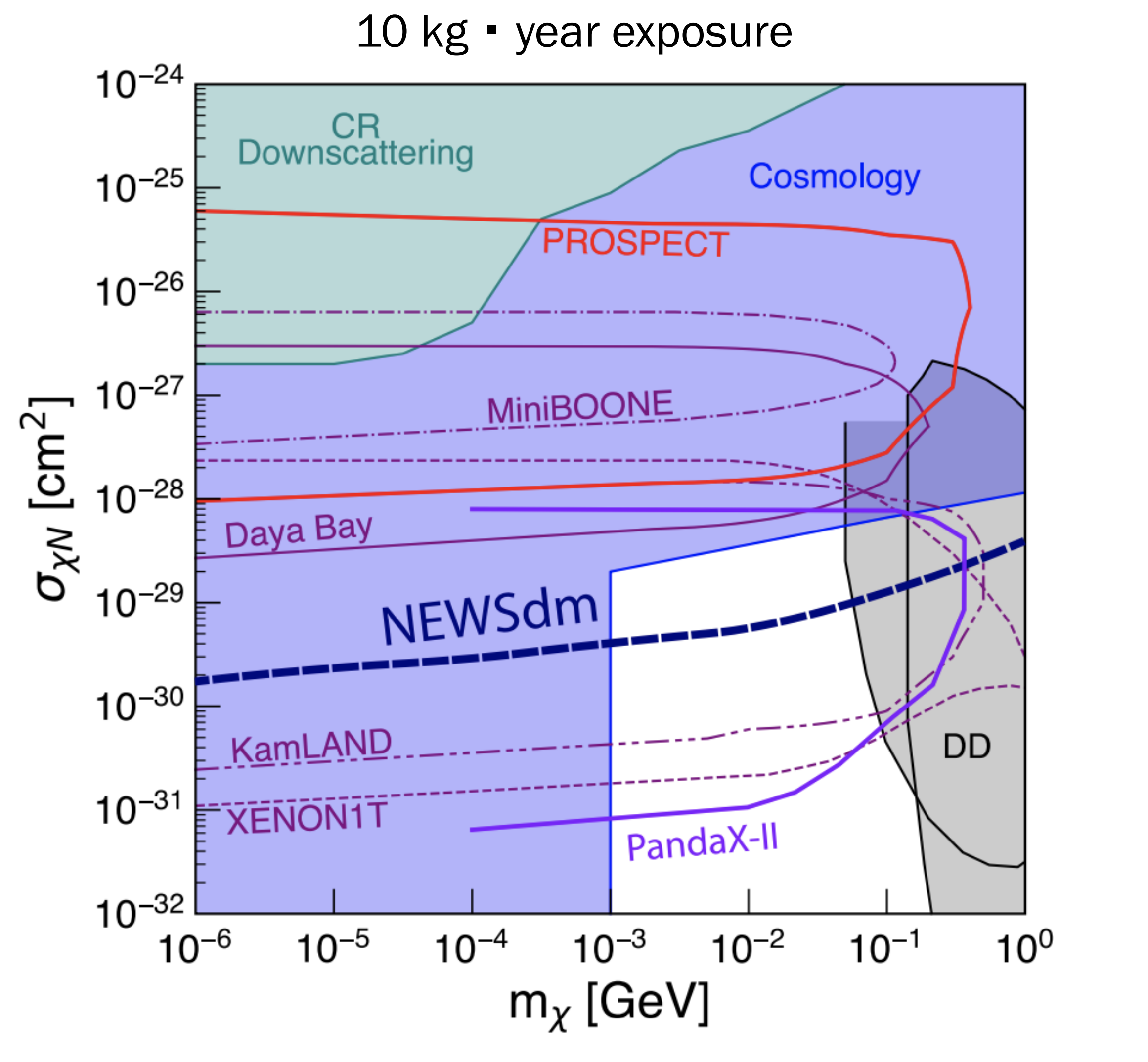




Boosted DM scenario

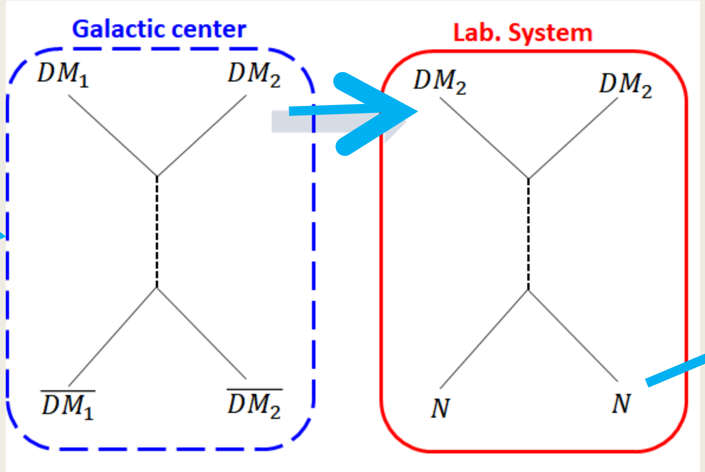


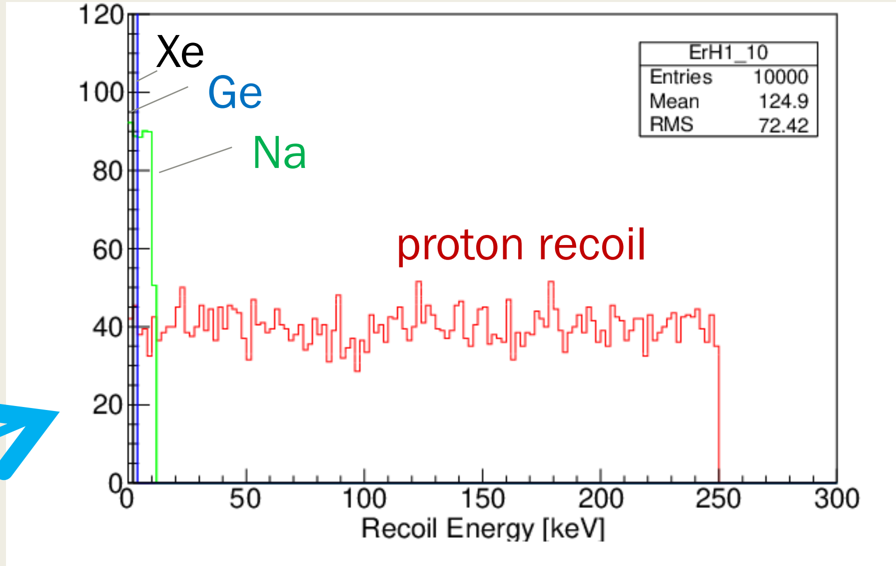
Sensitivity curves of the 10 kg NEWSdm detector for 1 year of exposure at the surface (Assergi) level and exclusion plot from PROSPECT surface experiment. The boundaries go through the dots corresponding to three H and CNO recoil events with track lengths of more than 70 nm.



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

Multi-component DM scenario

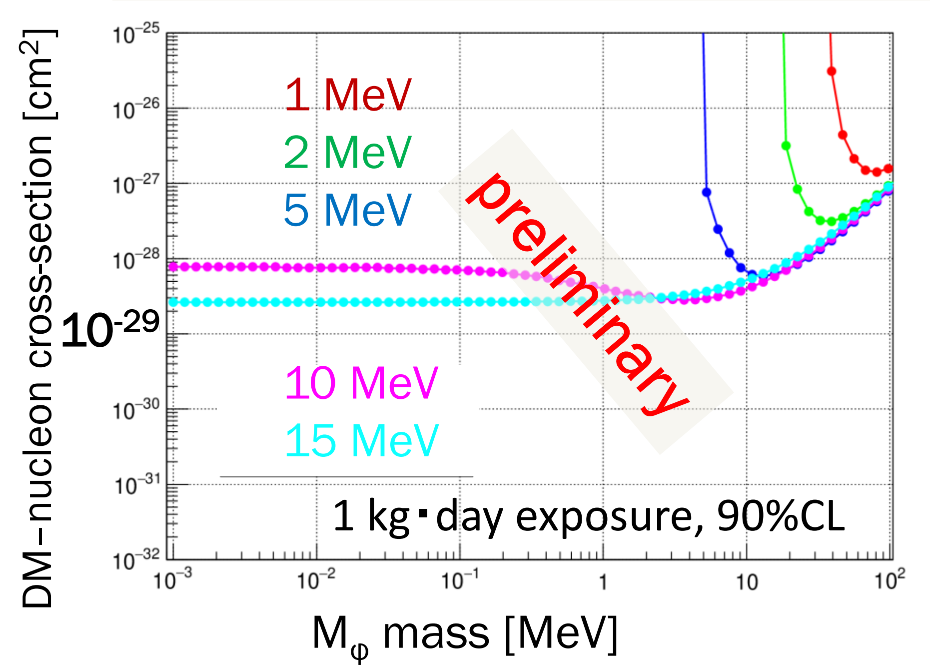




$DM_1 > DM_2$

Mass difference is kinetic energy of DM_2

Expected sensitivity limit for DM–nucleon cross-section



Expected flux on the Earth

$$\phi \sim 1.6\ cm^{-2}s^{-1}\left(\frac{<\sigma v>}{5\times10^{-26}\ cm^3/s}\right)\left(\frac{5\ MeV/c^2}{M_1}\right)^2$$

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

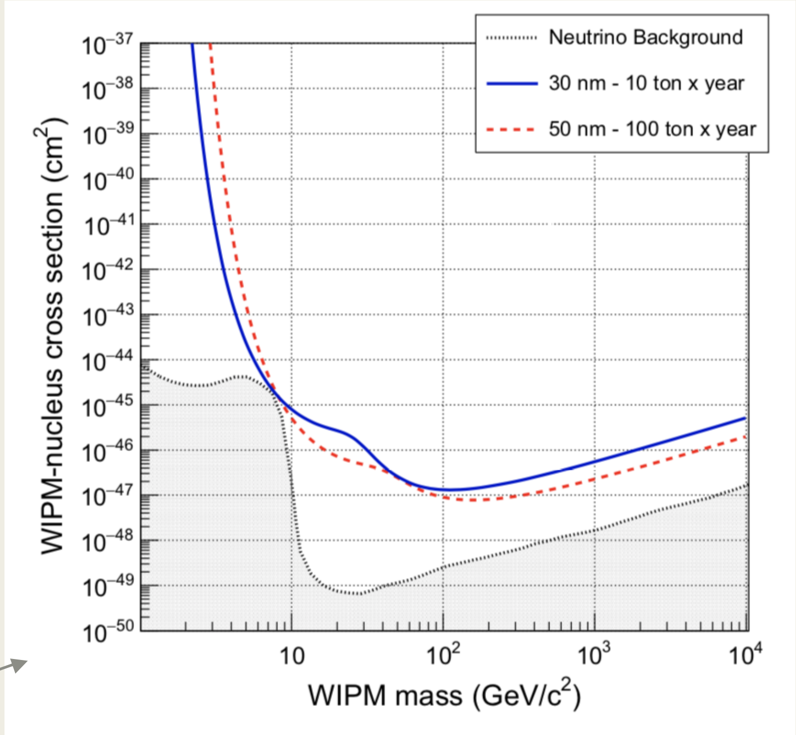
Assumption:

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

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 @ Gran Sasso Underground
- Background studies in progress with 10g scale in shielding at -50 C°
- Directional measurements of sub-MeV neutron flux at 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*
- CDR with all supporting measurements is submitted in July 2023

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

THANK YOU FOR ATTENTION!

Andrey ALEXANDROV (on behalf of the NEWSdm collaboration)

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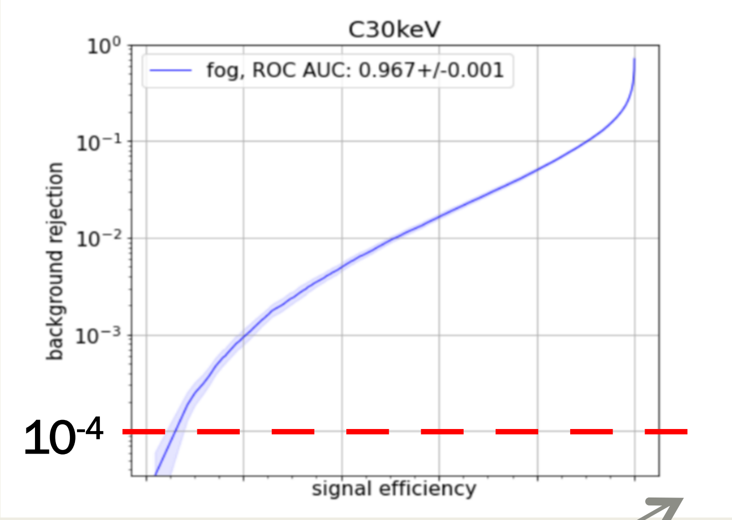
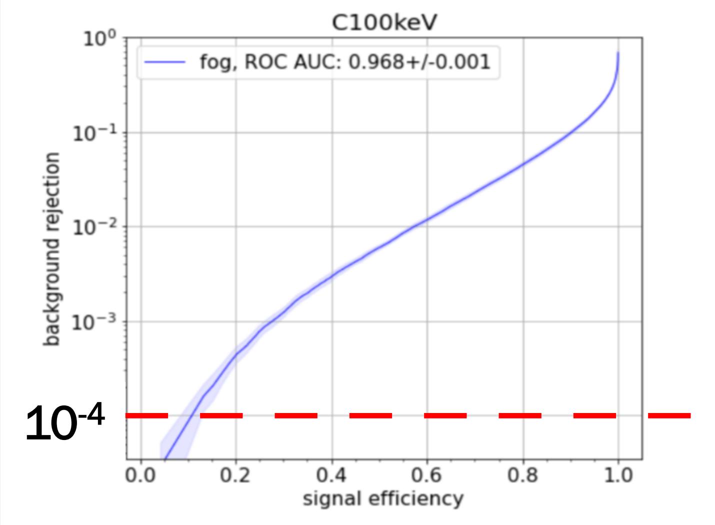
BACKUP SLIDES

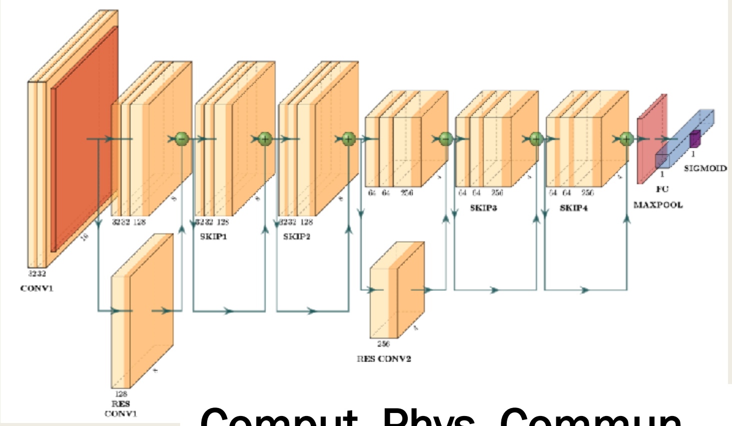
Background reduction: Machine Learning approach





Only polarization data

Schematic view of the CNN architecture



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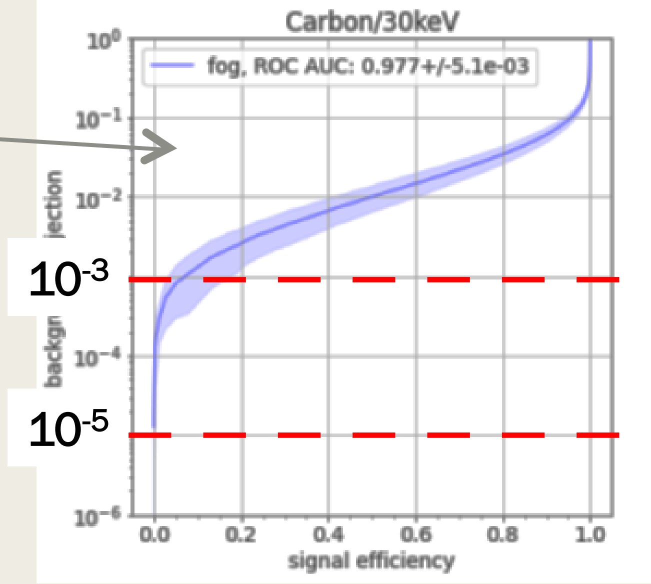
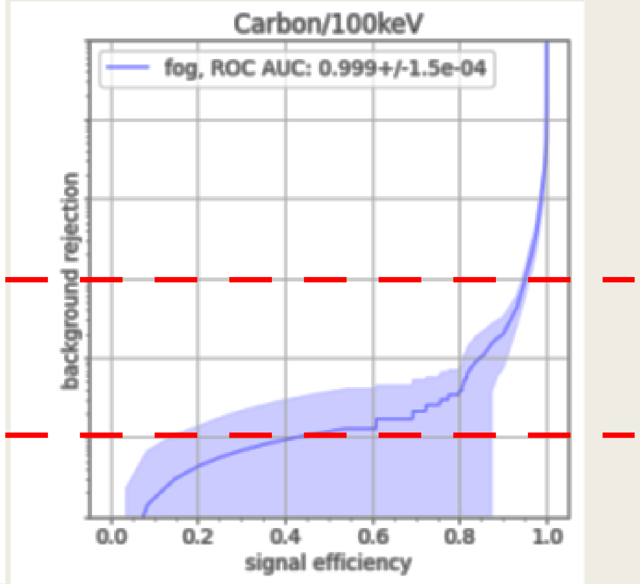
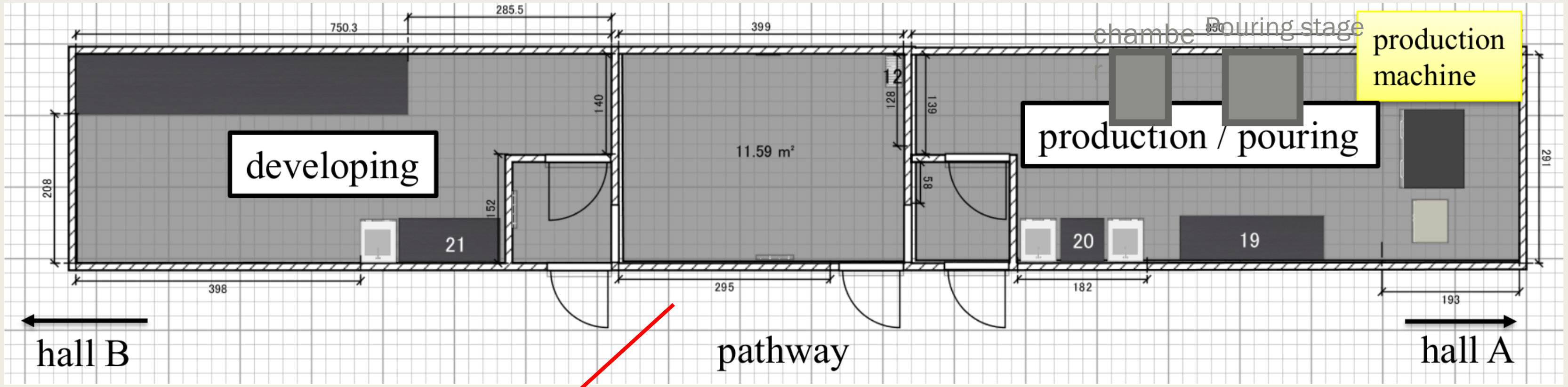
Only colour data



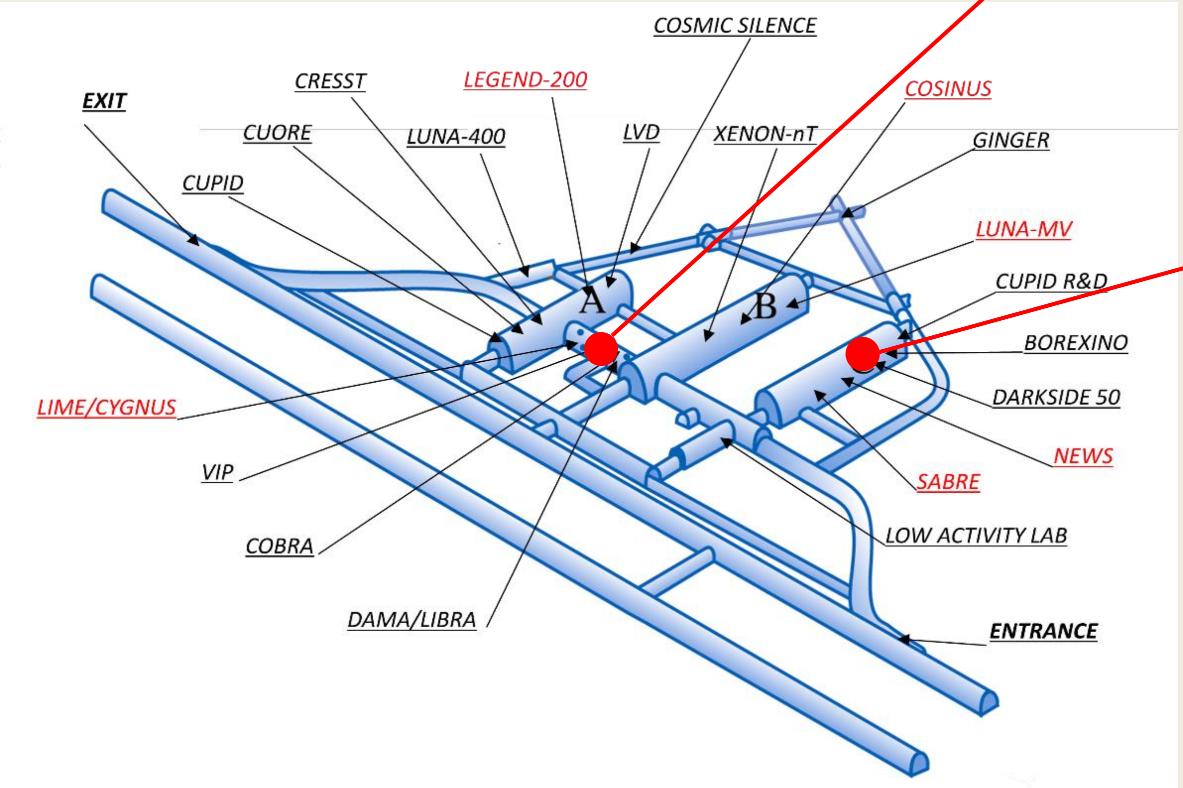


Background reduction factor and efficiency for different thresholds on ML probability-like output on **validation** data

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

Gel production room

Development room

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

Neutron spectrum measurement @ LNGS Surface Lab

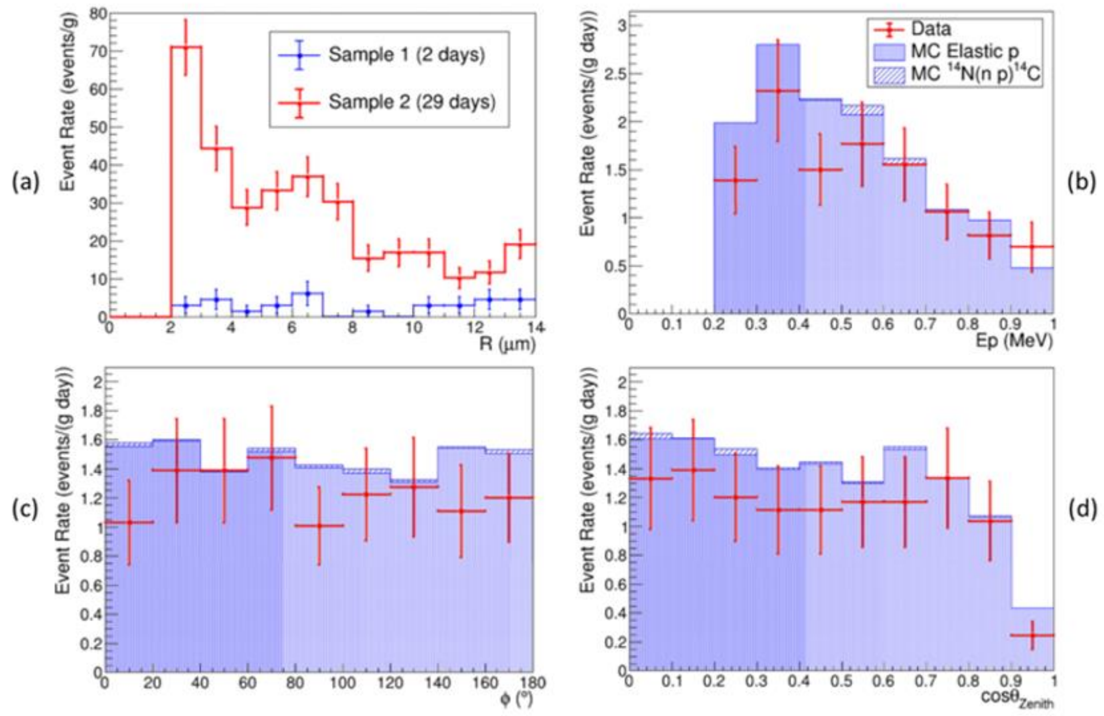


Figure 3.(a) Range distribution of recoil protons in the sub-MeV region for Sample 1 (2 days, blue) and Sample 2 (29 days, red) at LNGS. (b-d) Sub-MeV neutron measurement results after subtracting the data of Sample 1 from Sample 2 for an equivalent exposure of 27 days. For the MC simulation, neutron 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.

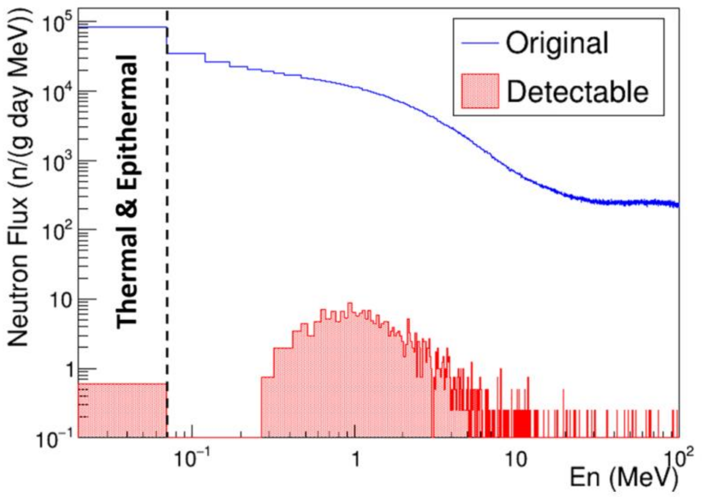
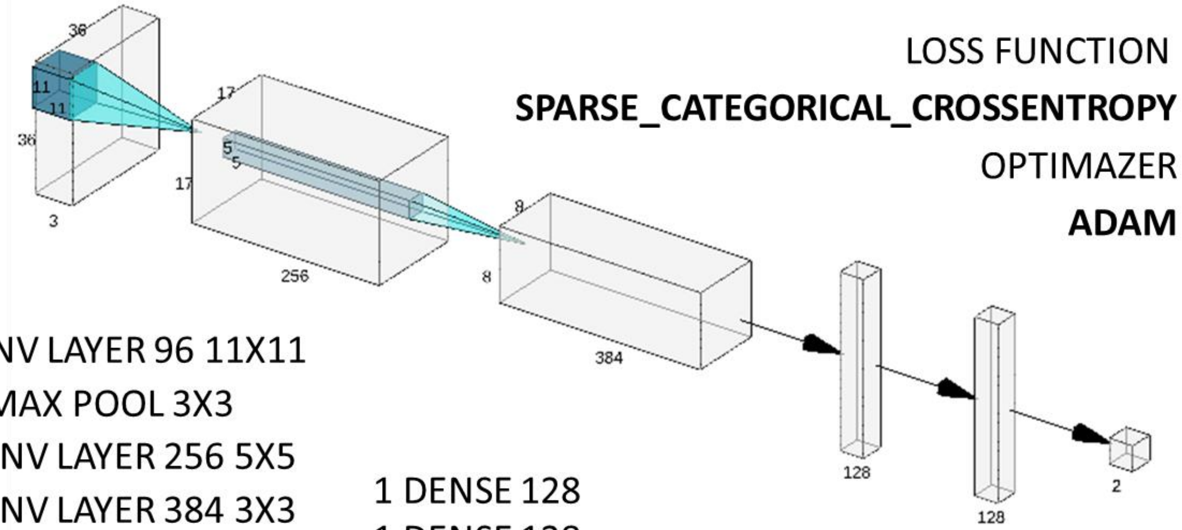


FIG. 9. Detectable neutron spectrum in NIT with 1 (g day) exposure at LNGS surface laboratory estimated by a MC simulation based on GEANT4. The blue line is the original energy of the incident neutrons, and the red filled histogram is the neutron spectrum accounting for the selection and the detection 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)

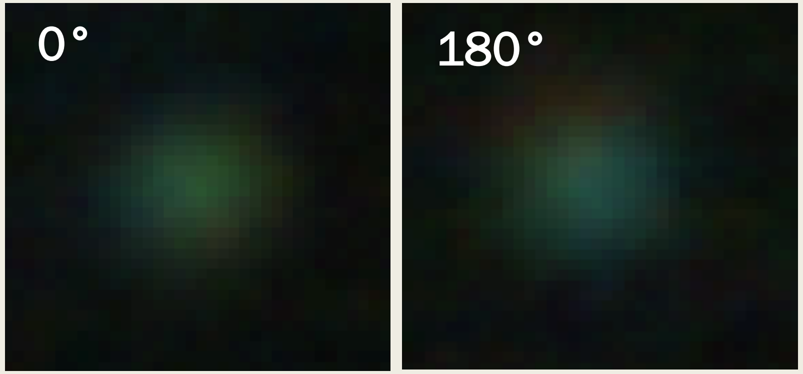
Sense recognition with color
Machine Learning approach



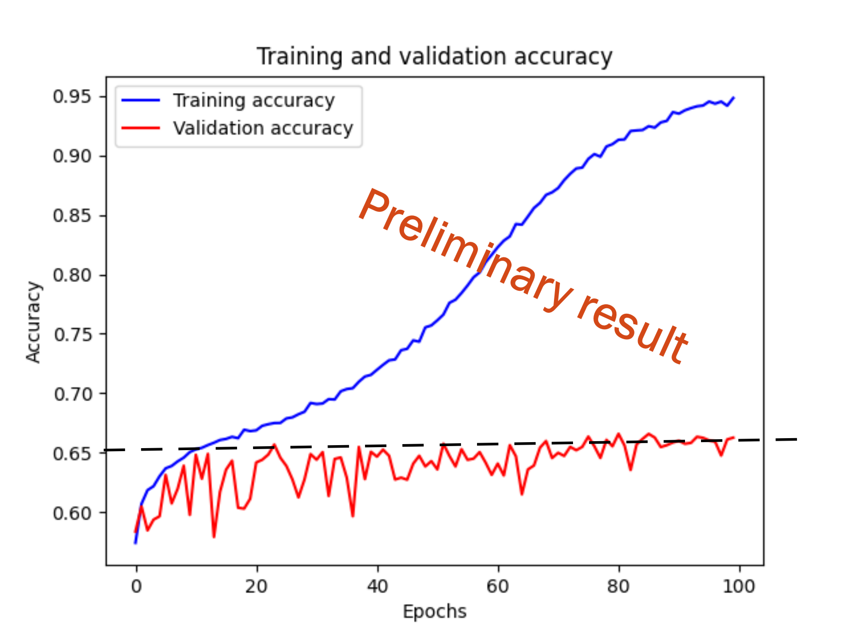
LOSS FUNCTION
SPARSE_CATEGORICAL_CROSSENTROPY
OPTIMAZER
ADAM

1 CONV LAYER 96 11X11
MAX POOL 3X3
2 CONV LAYER 256 5X5
3 CONV LAYER 384 3X3
MAX POOL 3X3

1 DENSE 128
1 DENSE 128
1 DENSE 2



Carbon ion 100 keV



Sense prediction accuracy = 65%