NEWSdm : DIRECTIONAL DARK MATTER SEARCHES WITH NUCLEAR EMULTION

Zhakypbek SADYKOV (on behalf of the NEWSdm collaboration)

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

University of Naples “Federico II”, Naples, Italy

Table of contents

NEWSdm COLLABORATION

Nuclear Emulsion WIMP Search directional measurement

ITALY

LNGS
INFN: Napoli, Roma, Bologna, Bari, Padova

Univ.: Napoli, Roma, Partenope, Basilicata, Potenza, Sannio

JAPAN

Chiba, Nagoya, Toho, Tsukuba

RUSSIA

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

TURKEY

METU Ankara

SOUTH KOREA

Gyeongsang University

84 physicists
24 institutes

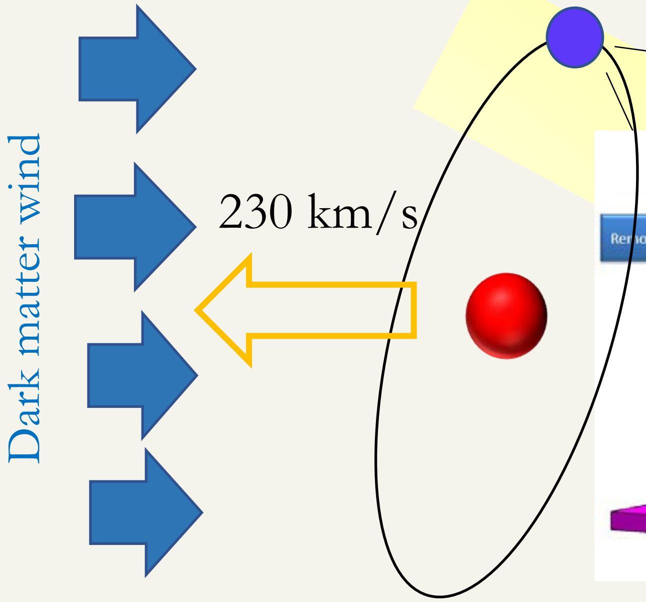
Website: news-dm.lngs.infn.it

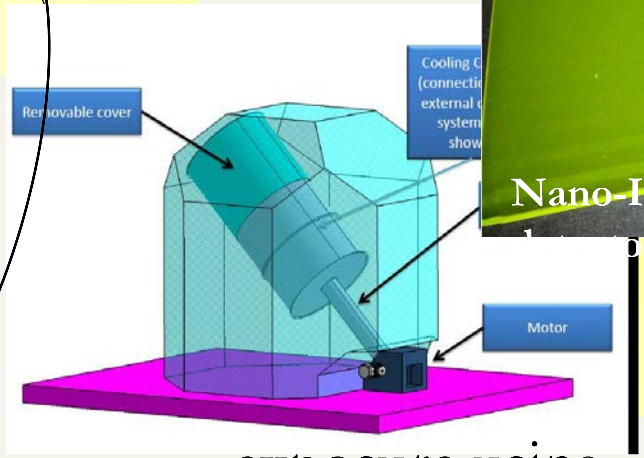
Letter of intent: https://arxiv.org/pdf/1604.04199.pdf

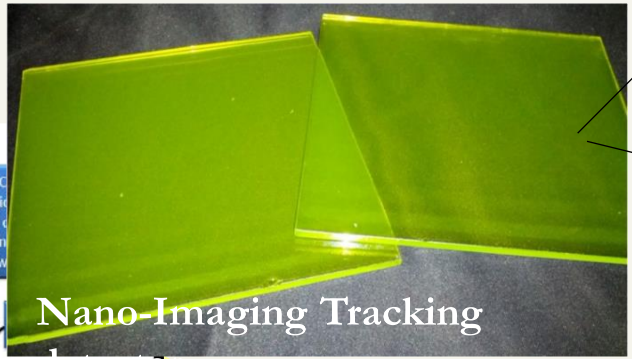
01

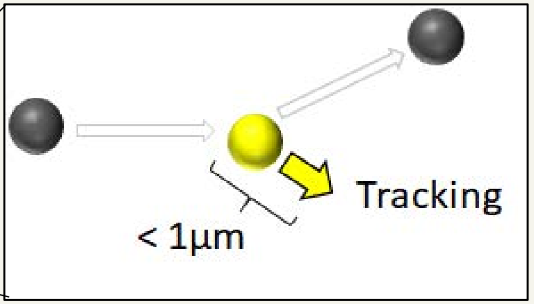
CONCEPT

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



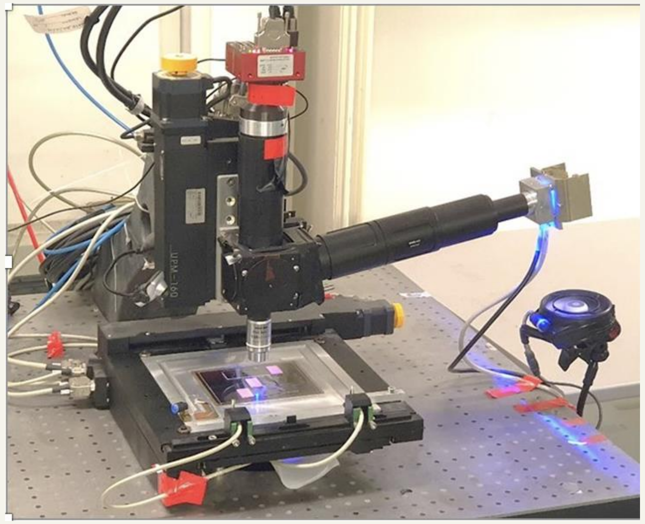






exposure using
an equatorial telescope

Optical image readout

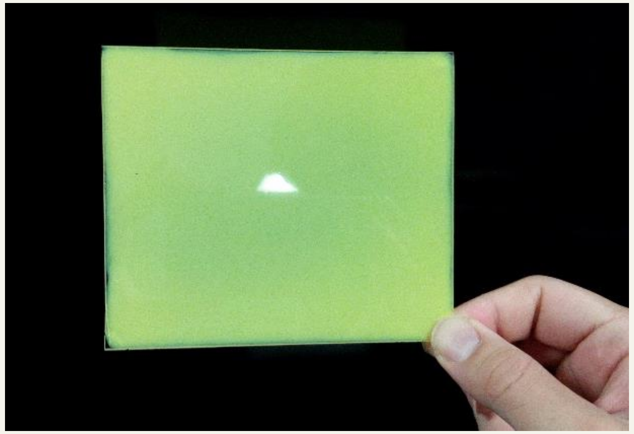


Underground laboratory
Gran Sasso (LNGS)

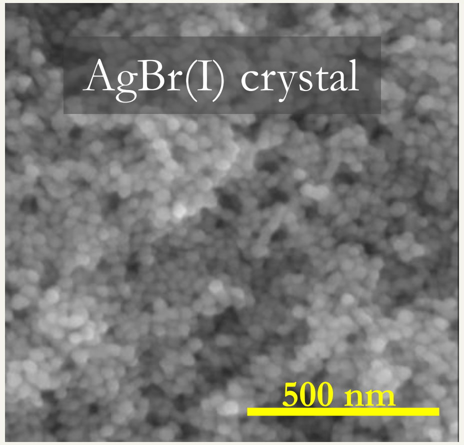
- Unique possibility to overcome the "neutrino floor", where coherent neutrino scattering creates an irreducible background
- Directional information is helpful in understanding the DM model

02

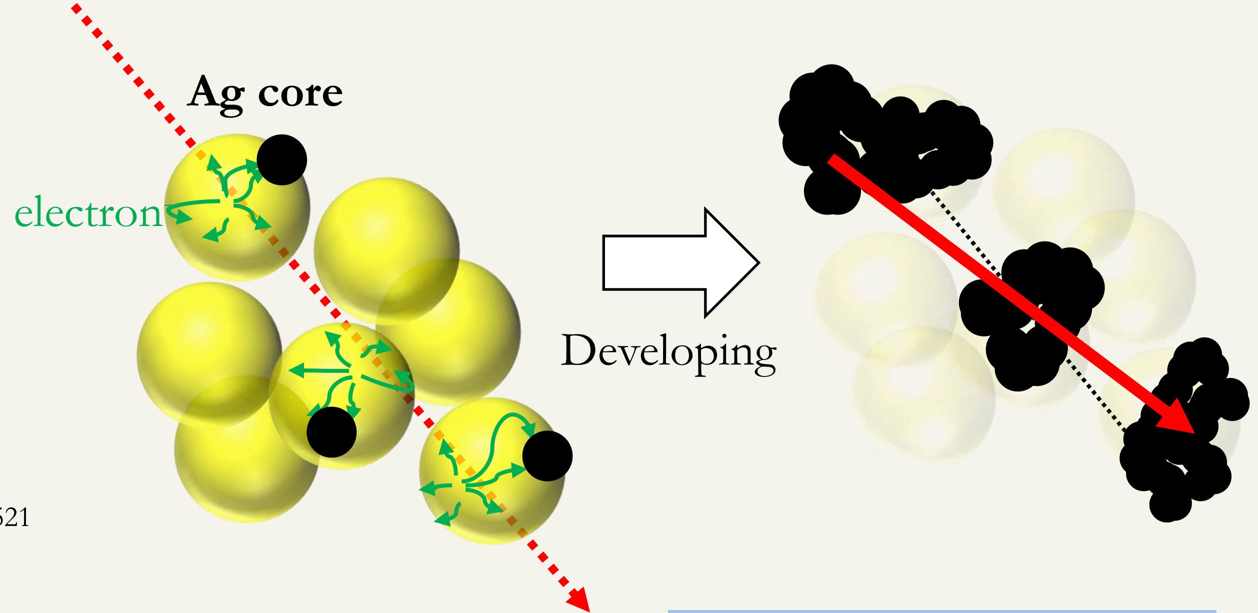
NANO IMAGING TRACKER



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



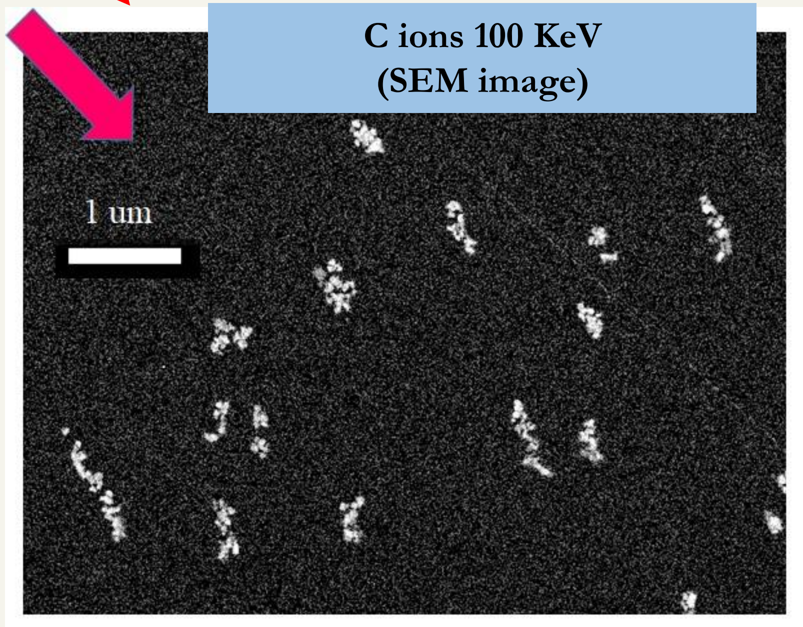
NIM A Nucl. Inst. Meth. A 718 (2013) 519-521
PTEP (2017)063H01



		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
Lighter DM / 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



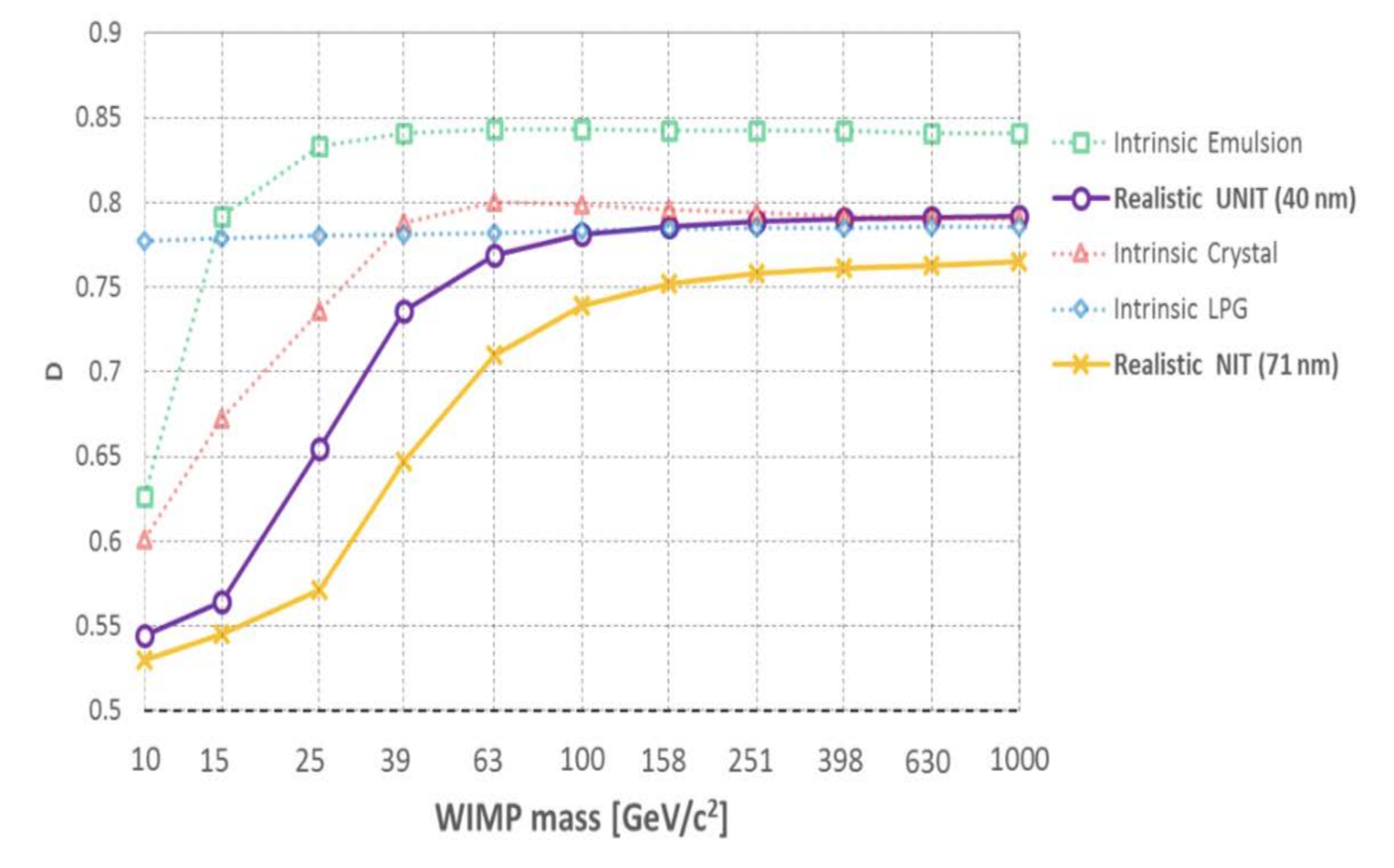
- Performance in the measurement of the recoil direction and comparison with other techniques

- 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:

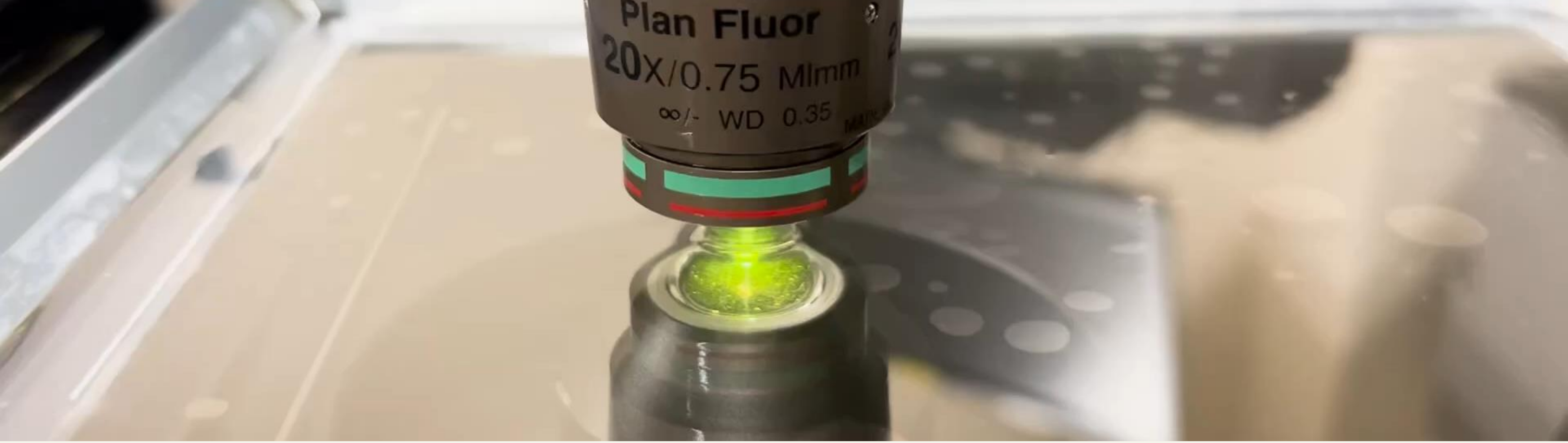
$$D = \frac{\sum_{i=0}^{N_{collisions}} \Delta E_i \cos\theta_i}{\sum_{i=0}^{N_{collisions}} \Delta E_i} = \frac{\langle \Delta E \cos\theta \rangle_{track}}{\langle \Delta E \rangle_{track}}$$

Proposed in JCAP01(2017)027



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

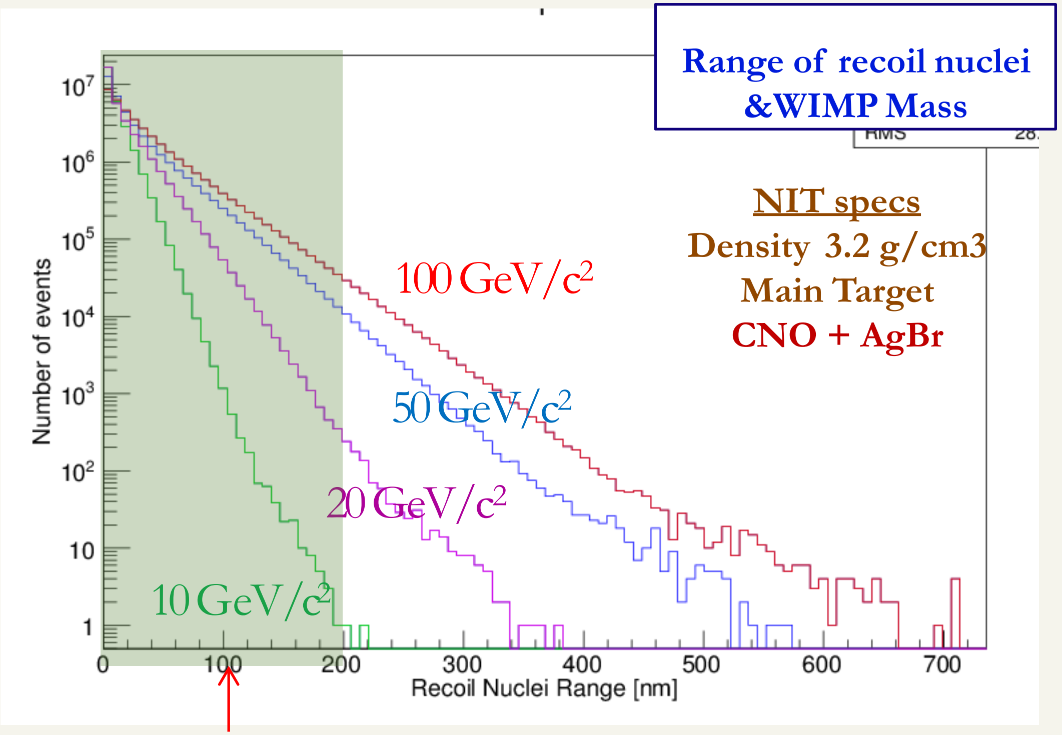
A. Alexandrov, G. De Lellis, A. Di Crescenzo, A. Golovatiuk and V. Tioukov,
«Directionality preservation of nuclear recoils in an emulsion detector for directional dark matter search» JCAP 04 (2021) 047



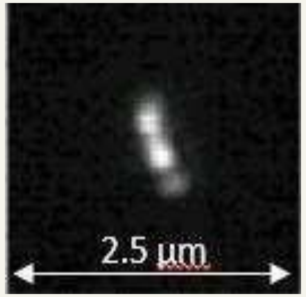
03

DATA COLLECTION AND ANALYSIS

- 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!)



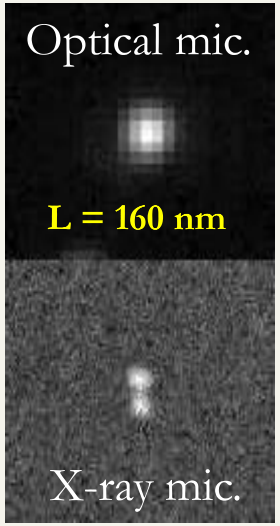
Inaccessible due to diffraction limit



E~100keV

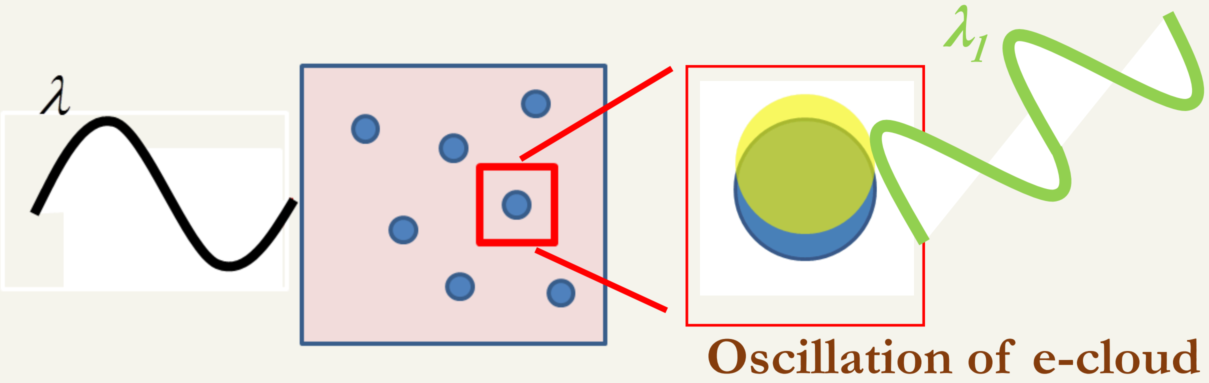
Carbon ions

E<100 keV

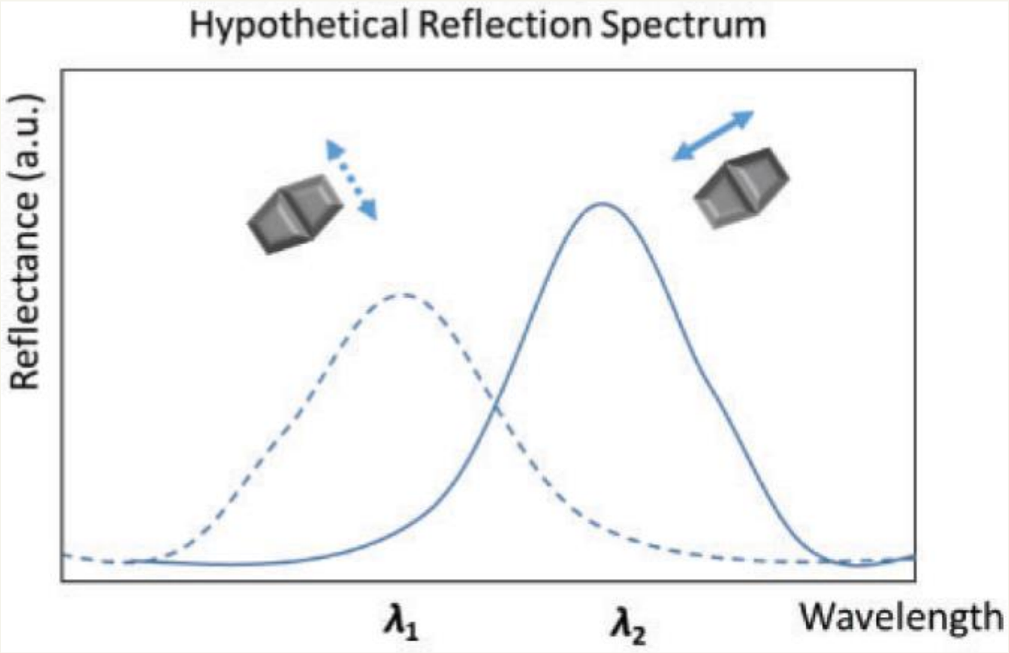


Optical readout beyond the diffraction limit

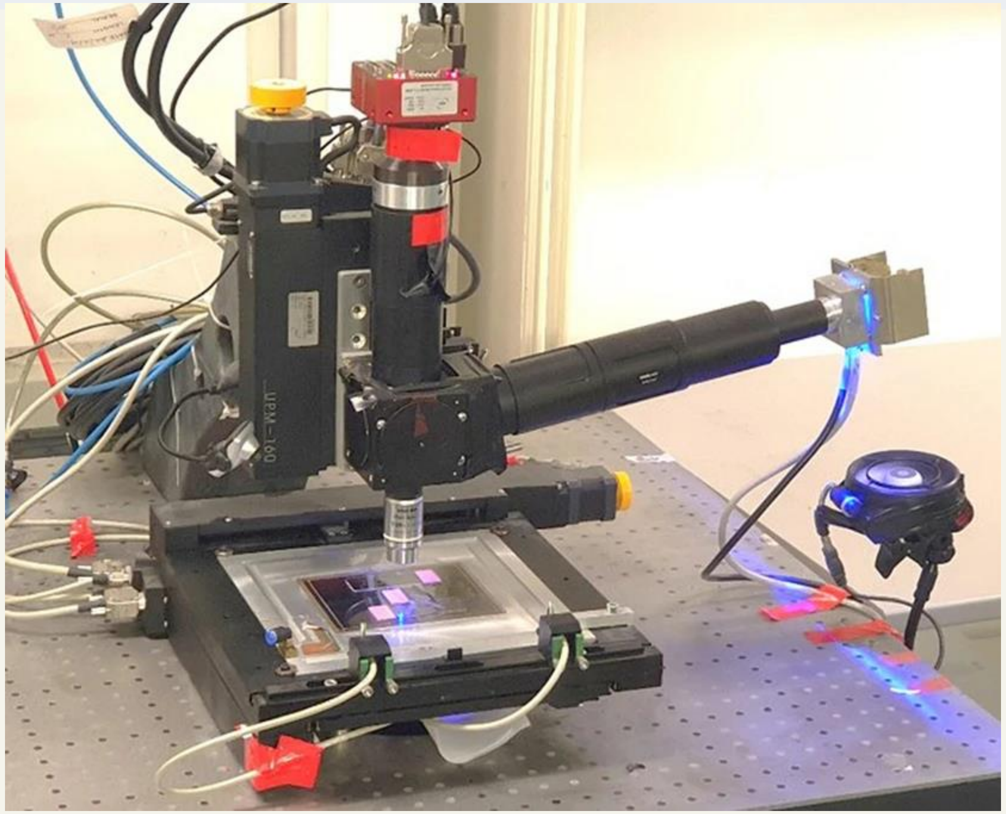
- Super-resolution idea: use the **plasmon resonance** effect to overcome the diffraction limit:
  - generated by a light wave trapped within conductive nanoparticles smaller than the wavelength of light
  - resonant frequency strongly depends on the composition, size, geometry, dielectric environment and distance between nanoparticles
  - occurs in the visible region for Ag and Au nanoparticles!
  - improve resolution by analyzing scattered light **polarization** and **spectrum**

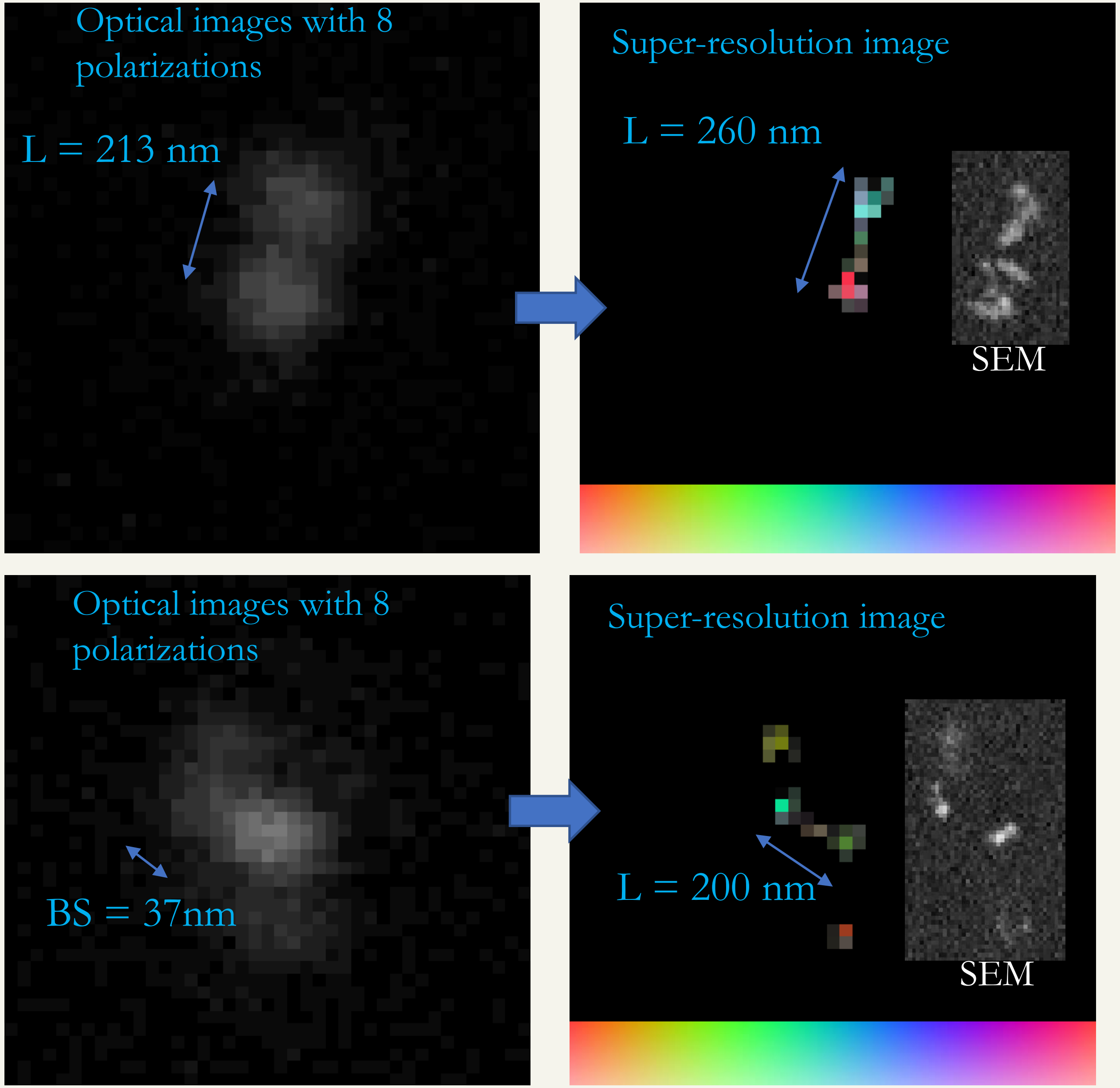


PTEP, Vol. 2019 Issue 62019, 063H02

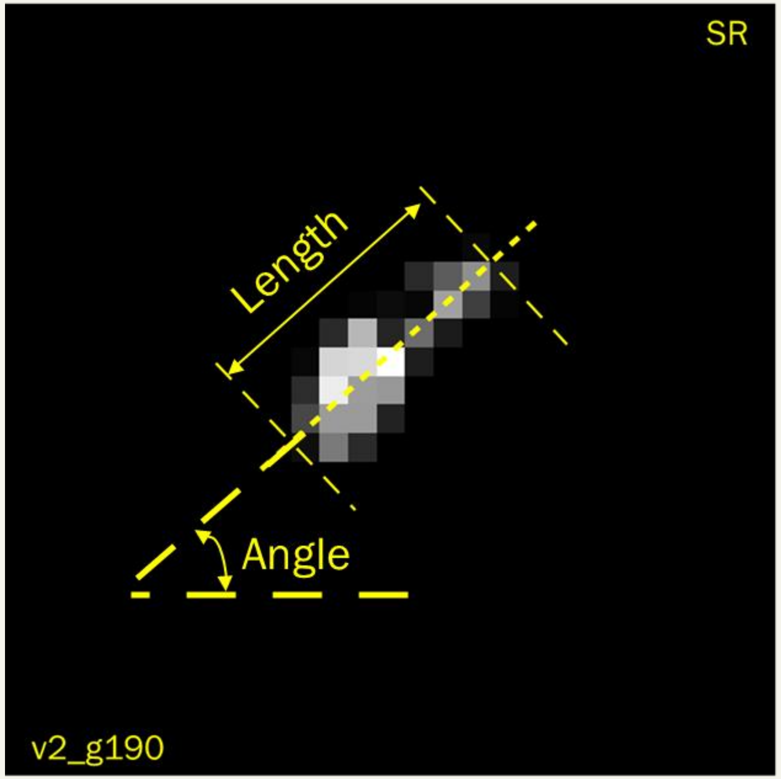


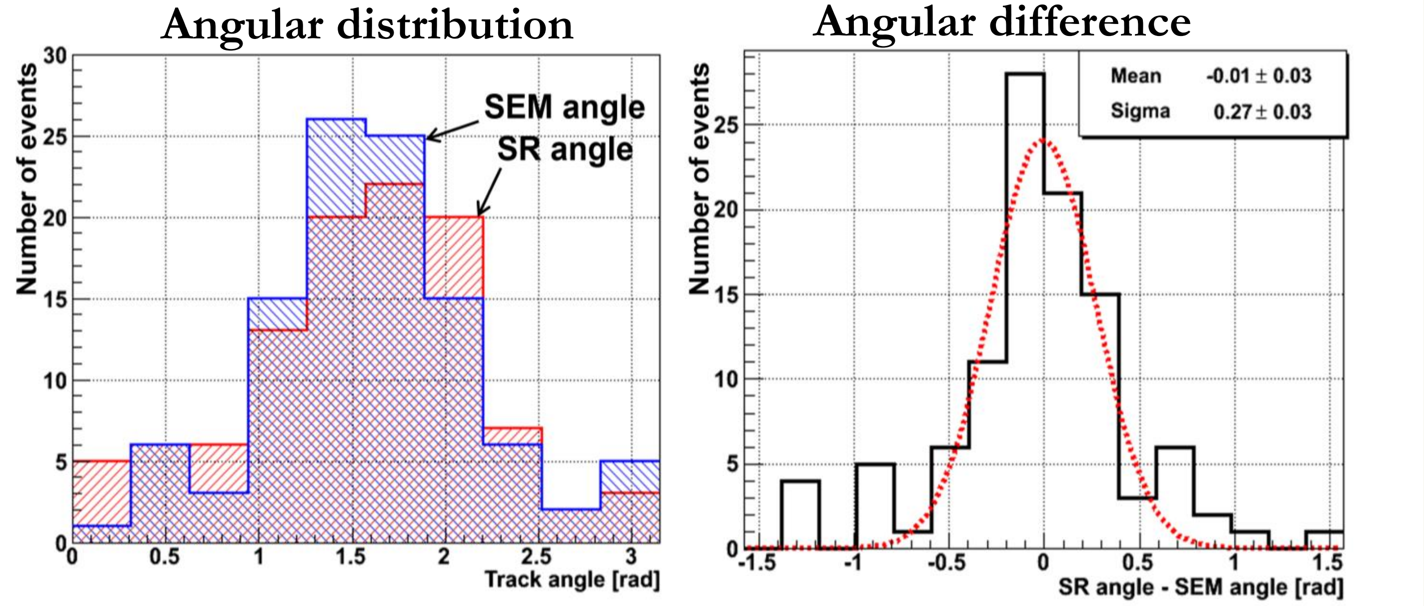
LSPR-based super-resolution imaging based on join deconvolution set of 8 polarized images

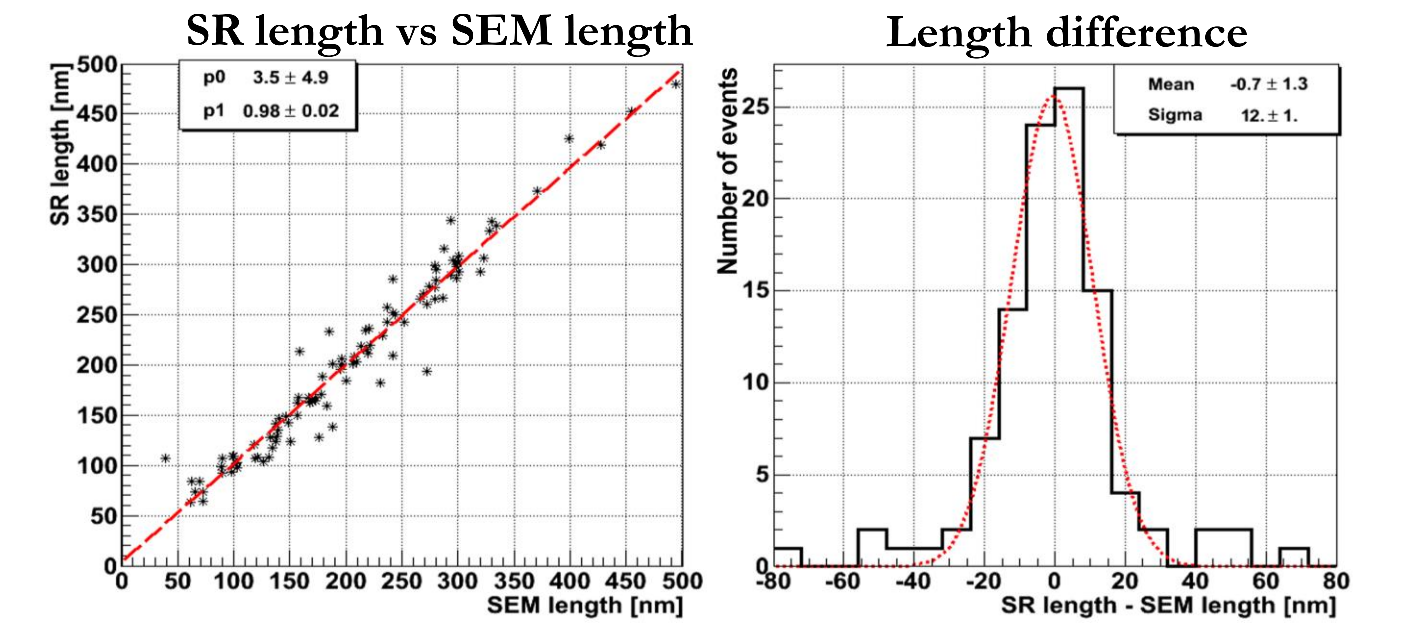




Alexandrov, A., *et al.* Super-resolution high-speed optical microscopy for fully automated readout of metallic nanoparticles and nanostructures. *Sci Rep* 10, 18773 (2020). https://doi.org/10.1038/s41598-020-75883-z







Angular resolution: 270 ± 30 mrad
Length accuracy: 12 ± 1 nm
Spatial resolution: ~ 60 nm
NIT granularity: 71 nm

https://doi.org/10.48550/arXiv.2304.03645
Submitted to Sci. Rep.

LSP in the NIT emulsion

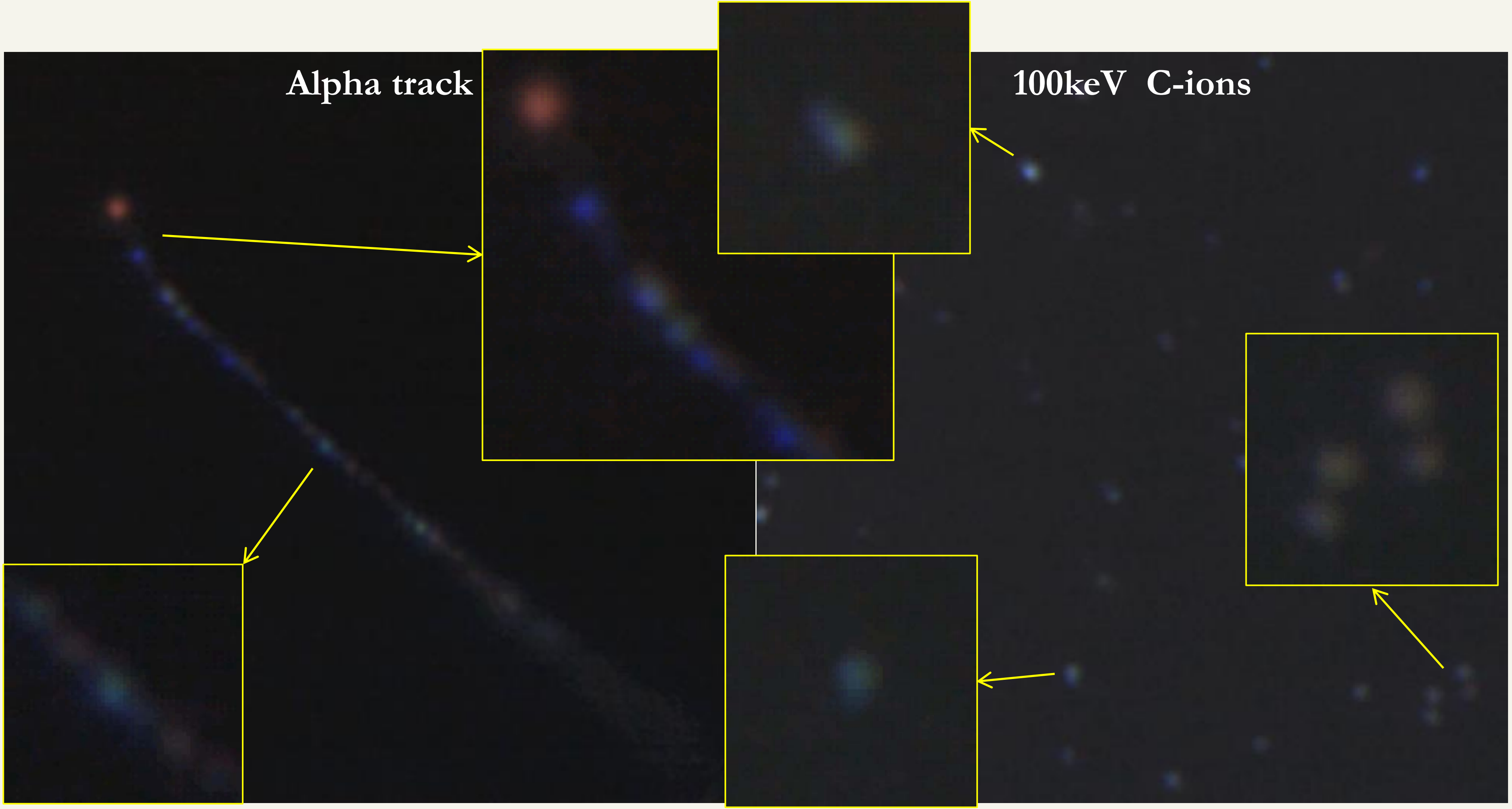


Image size 15 μm x 15 μm

Image size 15 μm x 15 μm

Head-tail discrimination possible! Integrated color&polarisation SR to be developed. ML approach looks most promising

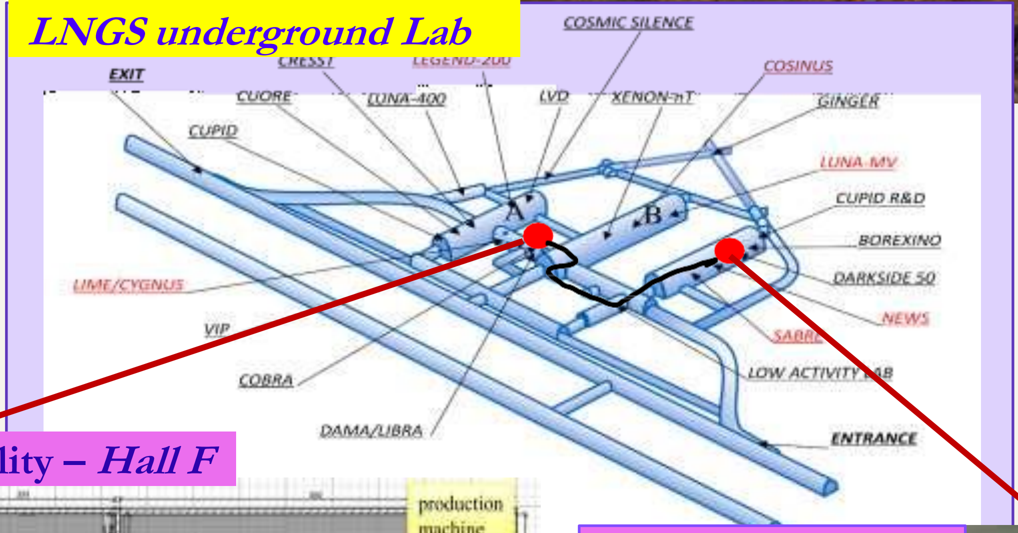
04

EXPERIMENTAL ACTIVITY

Neutron flux @ surface Lab

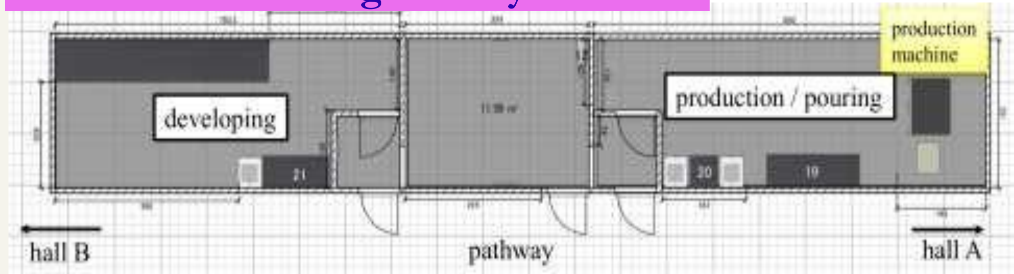
LNGS surface Lab

LNGS underground Lab



Development Room
Clean Room ISO 7

Emulsion Handling Facility – *Hall F*



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

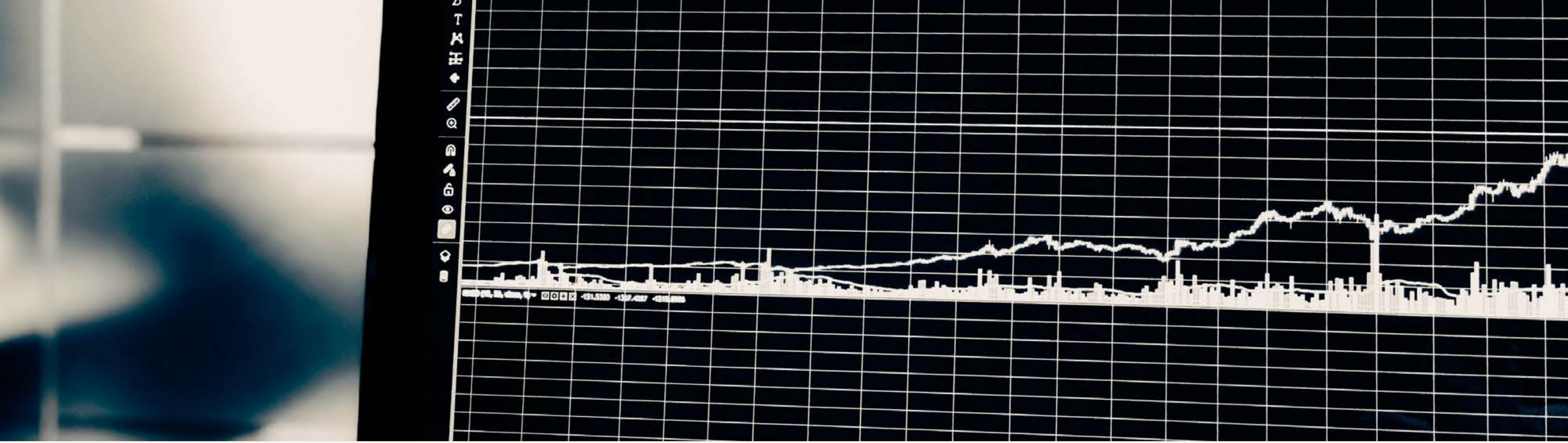
Cooling Box for Target

Target insertion by crane

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



05

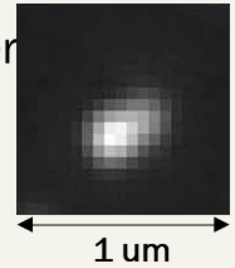
FIRST EXPERIMENTAL DATA

Automatic readout
1^{st} trigger

Elliptical shape trigger

Requirement

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

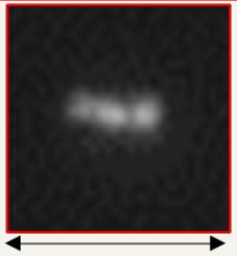


CNO : > 30 keV
Electron efficiency: 0.05

CNN
(machine learning)

≧ 3 grain track recognition

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



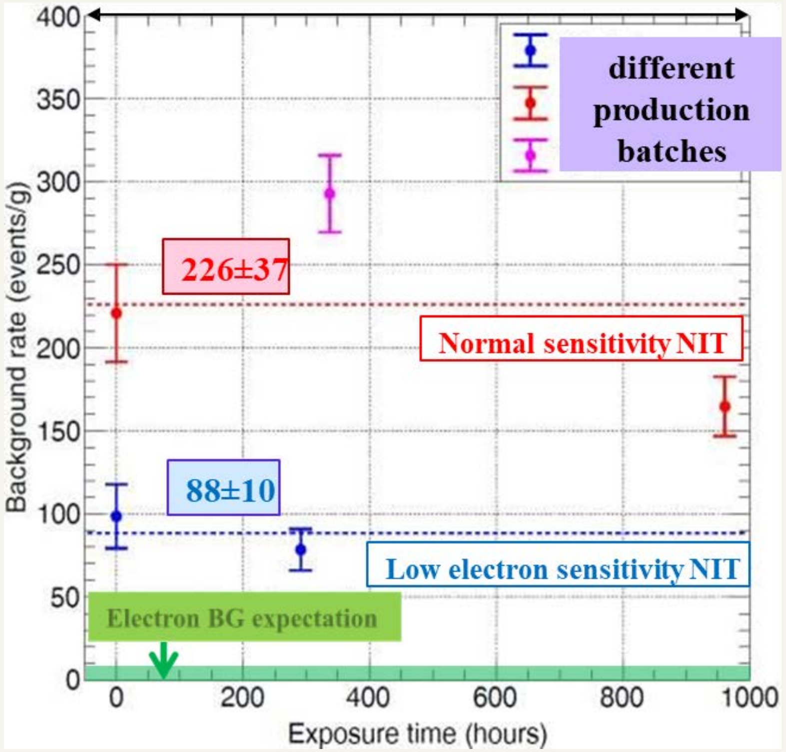
Training sample :
neutron induce recoil nuclei @AIST
(880keV, -50℃)

Manual check

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

Current Selection

-50 ℃ exposures, 10g , up to 40 days

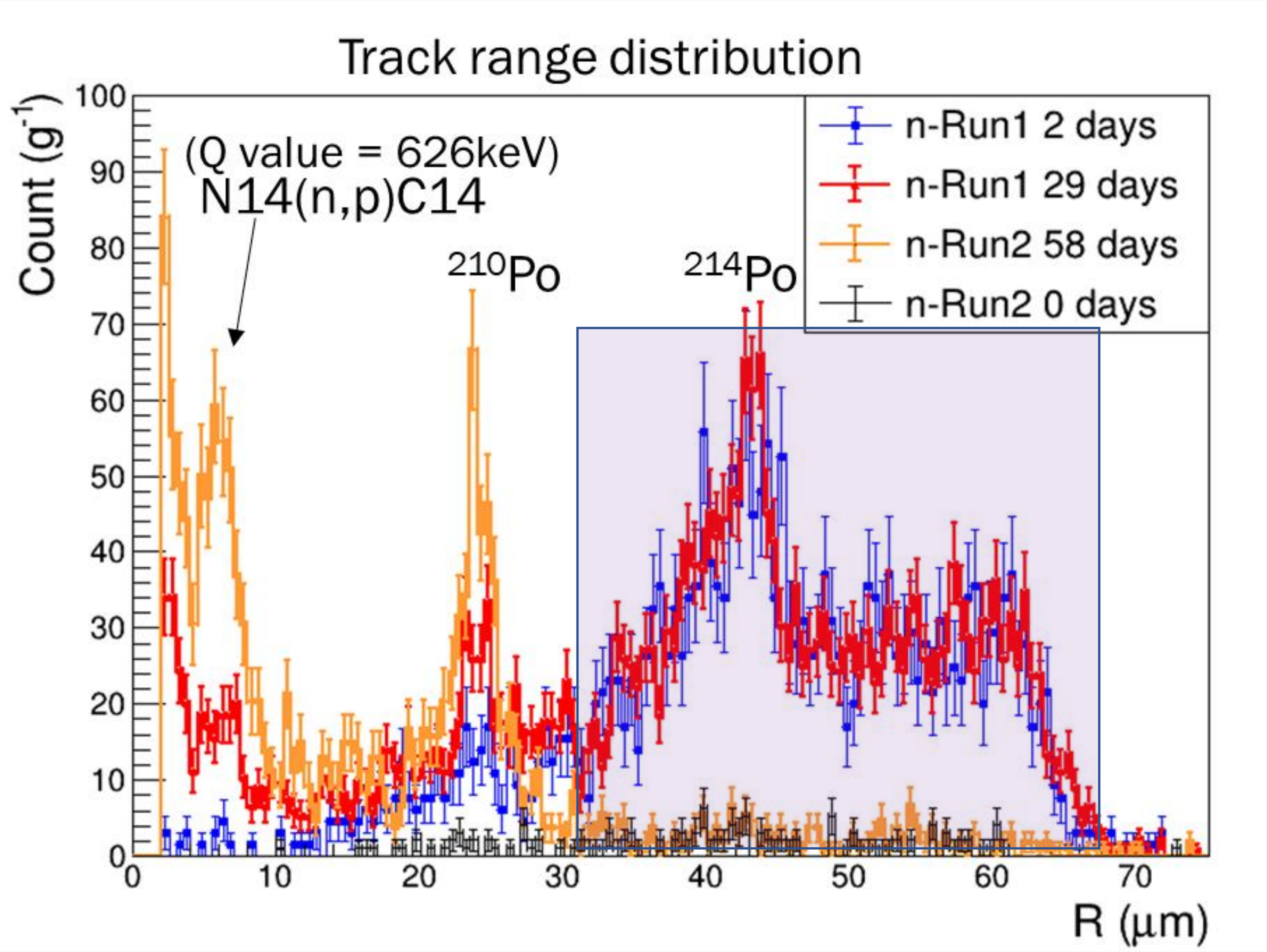


Results:

- *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*

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

- 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!**



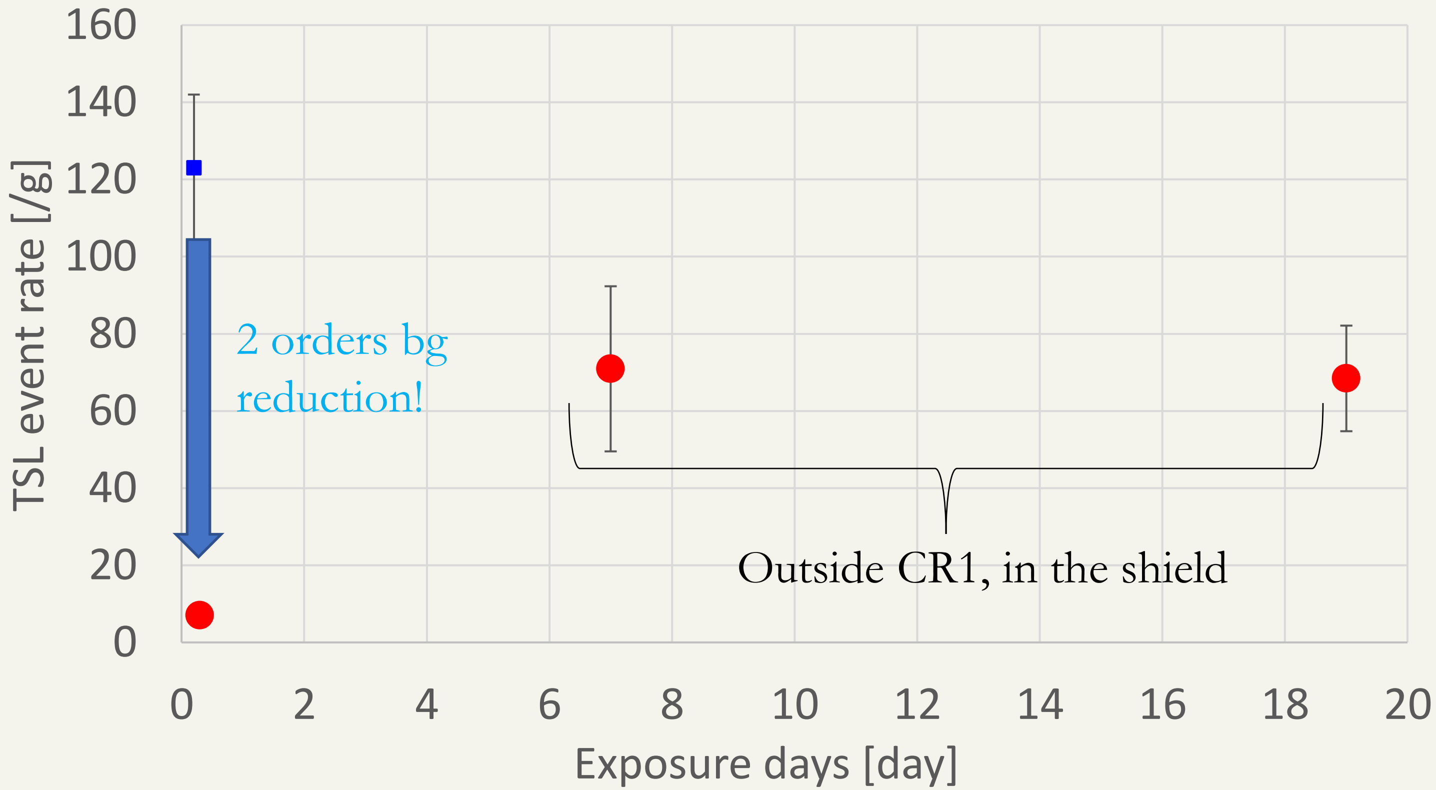
Production in standard conditions: >2000 ev/g, Rn-free: <5 ev/g

Neutron measument:

T. Shiraishi, et al., PTEP 2021 (2021) 4, 043H01

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

Measurements in 2023 using Rn-free condition

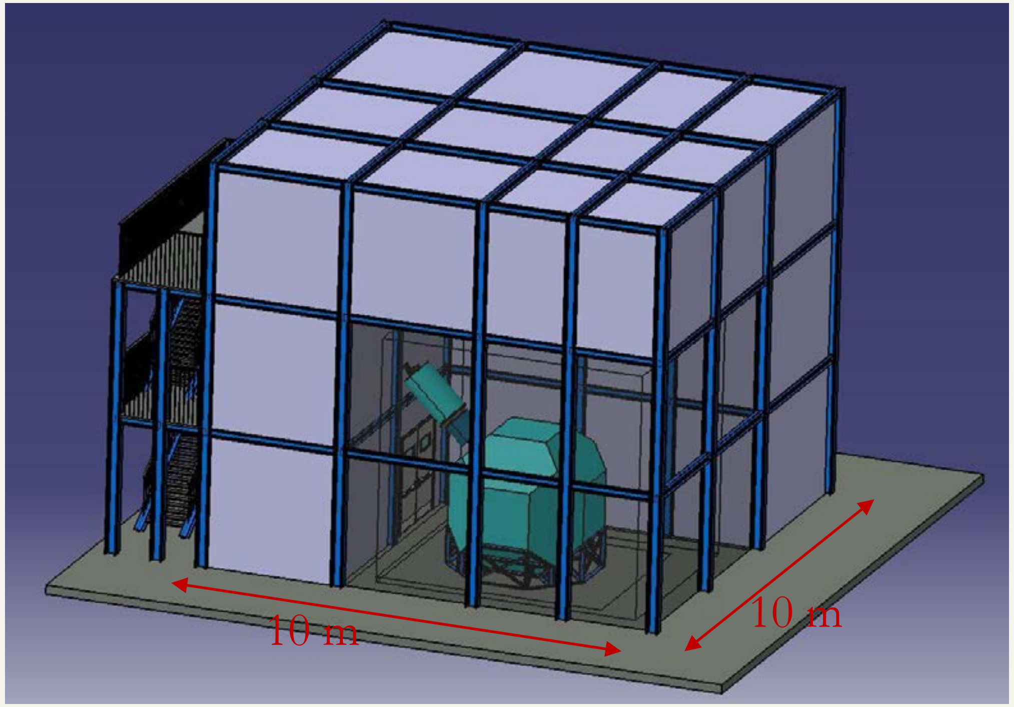


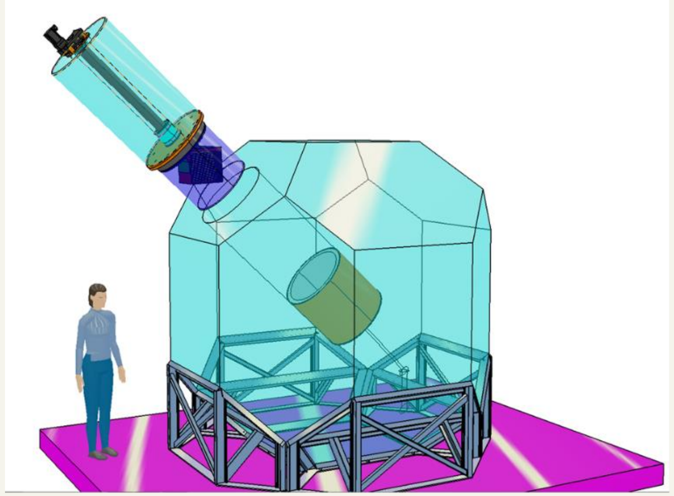
Important confirmation of the α as the source of the offset background, down to the expected level!
Results compatible with no increase of the background inside the shield as expected
Increase of the background while moving away from CR1
To make a shielded tests in CR1

06

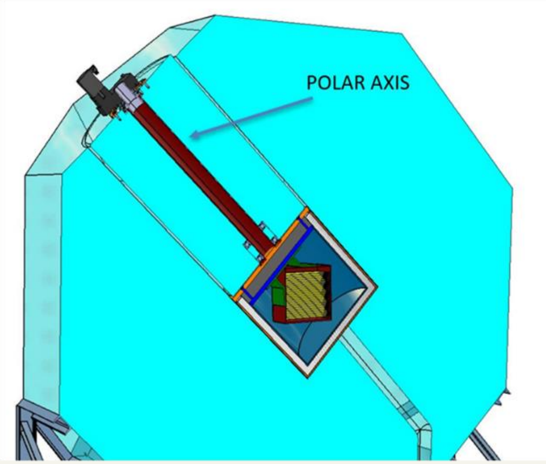
FUTURE FACILITY

Emulsion facility and shielding with an equatorial telescope

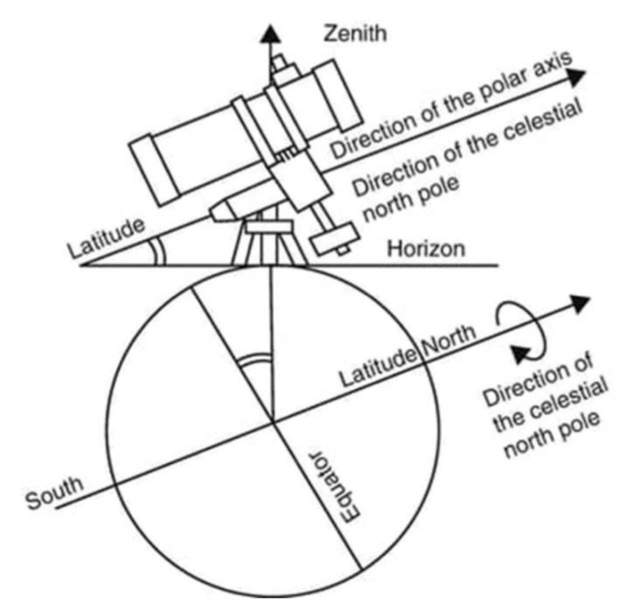


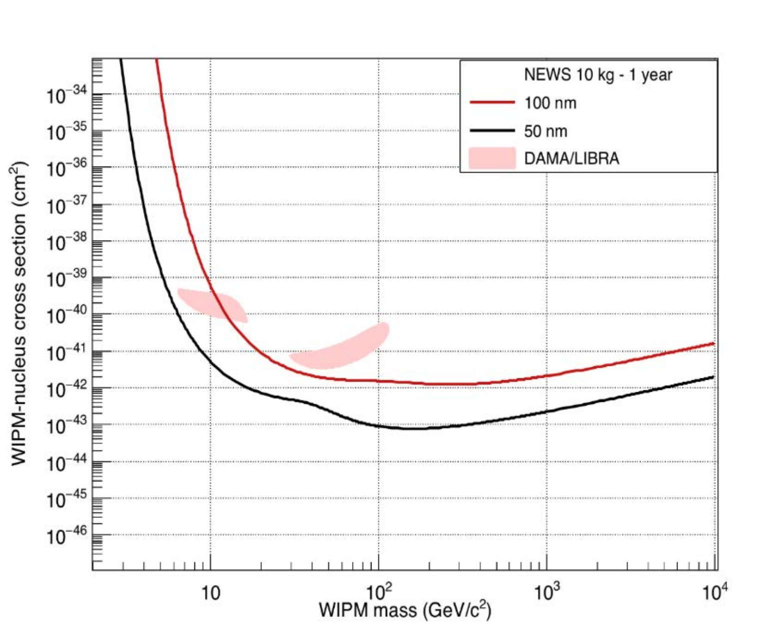


(a)

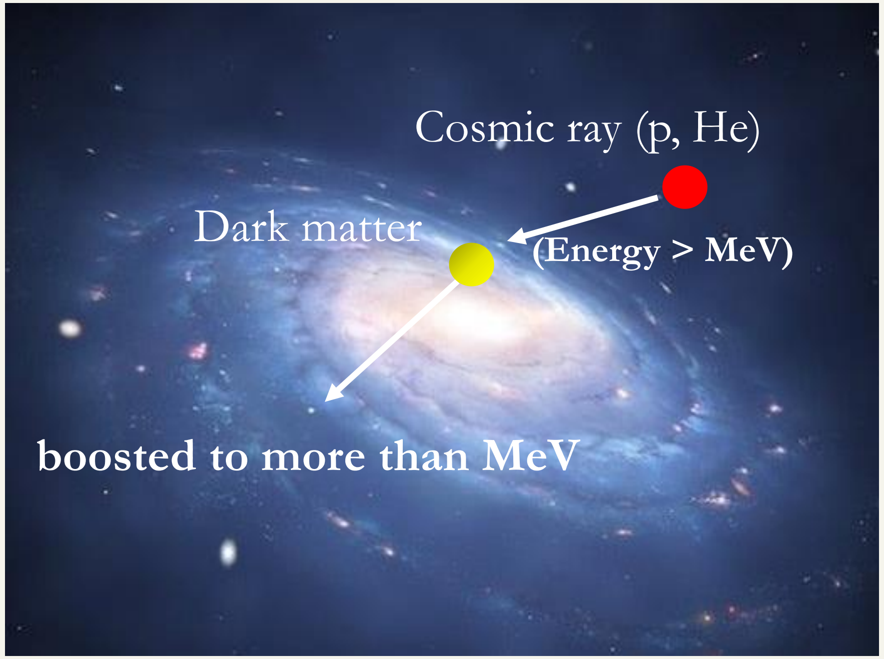


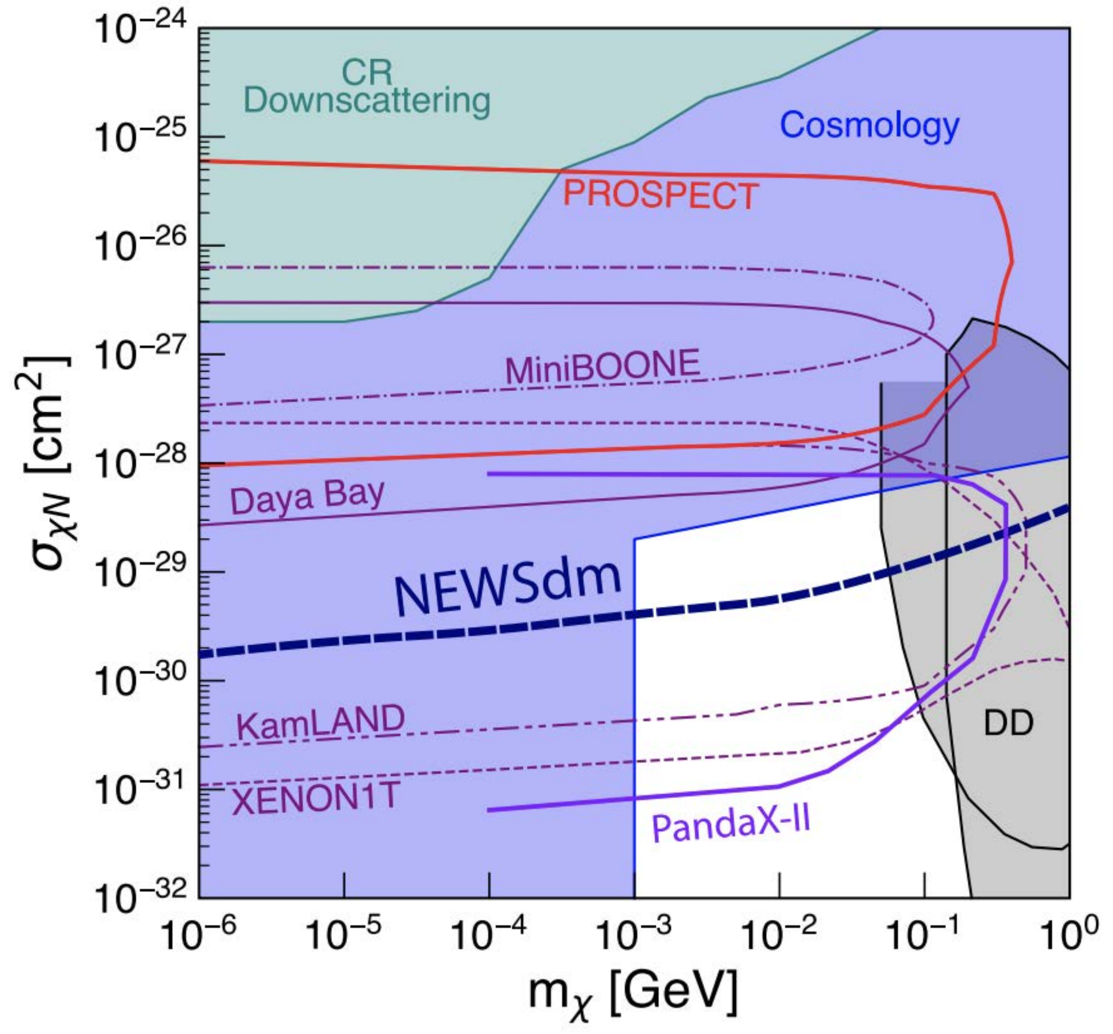
(b)





10 kg detector CDR submission in summer 2023





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.

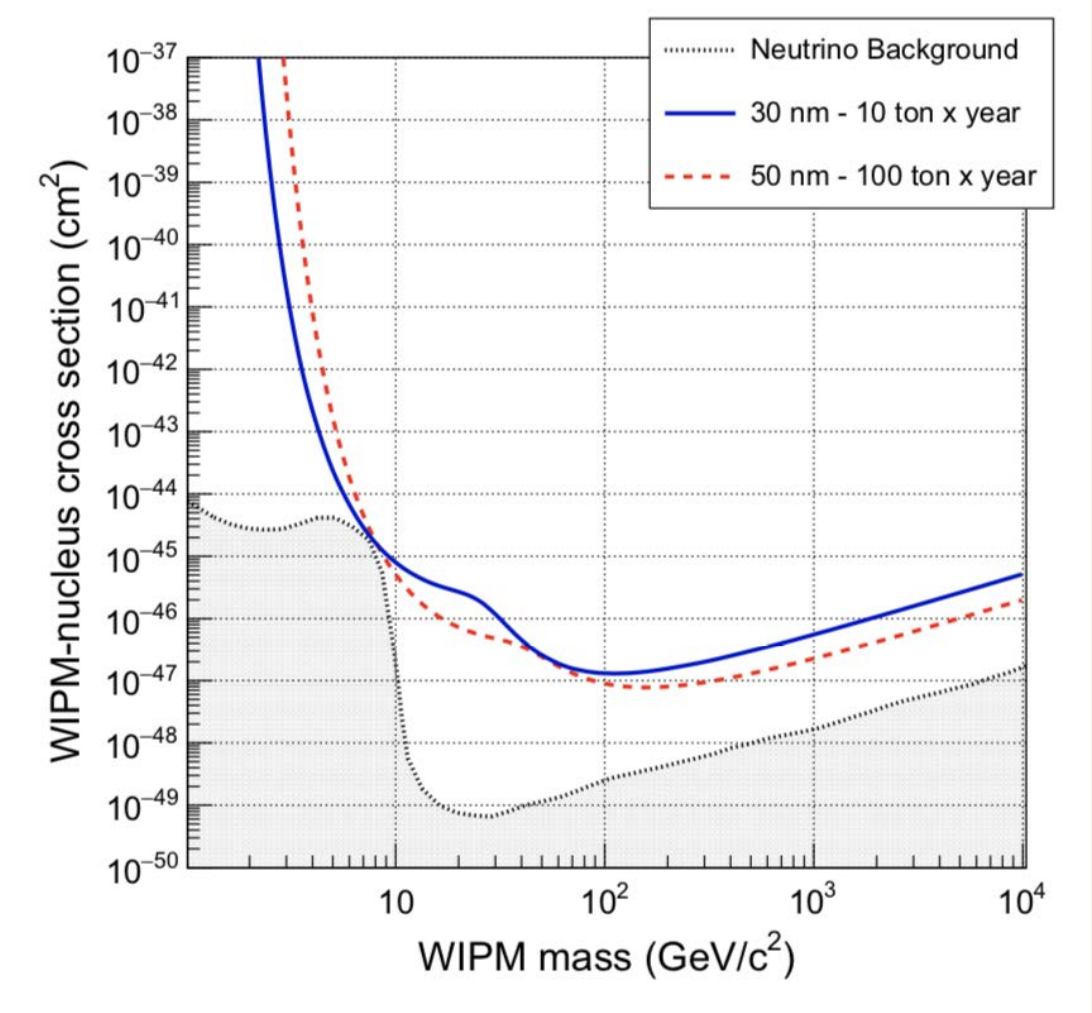
M. Andriamirado et al., Limits on sub-GeV dark matter from the PROSPECT reactor antineutrino experiment, Phys. Rev. D 104 (2021) 012009
e.g. 10.1103/PhysRevLett.126.091804

Other *boosting* scenarios are also under study
e.g. multi-component DM annihilation of MeV WIMPs producing keV hadrophilic DM

07 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°
- First-time directional measurement 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 scenarios
- Scalability and discovery potential (challenging background!)
  - 10–100 ton·year -> neutrino floor
- A CDR with all supporting measurements was presented in July 2023

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



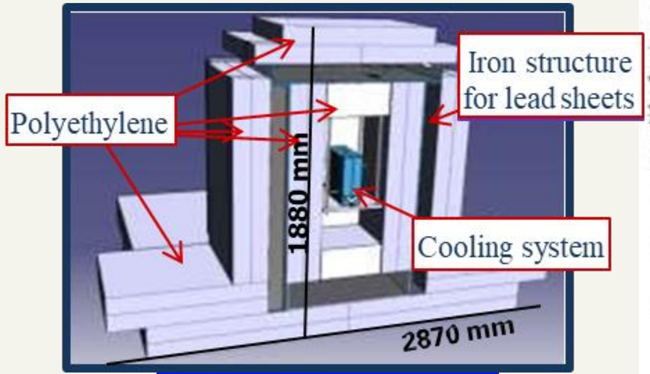
90% C.L. upper limits for the NEWSdm detector with exposures of 10 ton year (30 nm threshold) and 100 ton year (50 nm threshold) in the zero-background hypothesis

BACKUP

Environmental

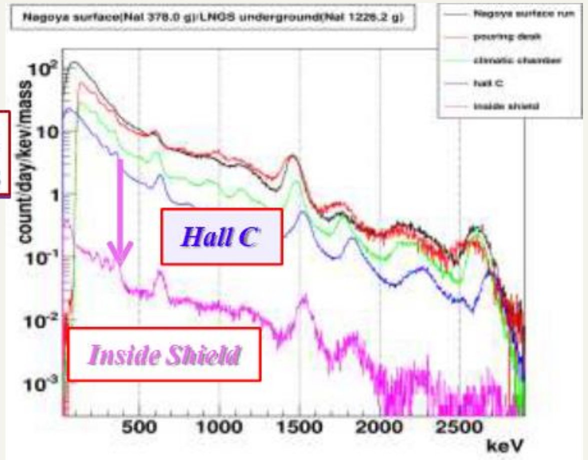
γ measurements by NaI detector

Current shield

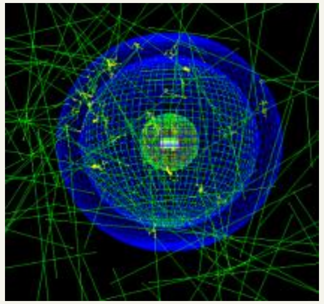


Lead shield : 5.6 cm
Polyethilene : 31.5 cm

γ measurements by NaI detector



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



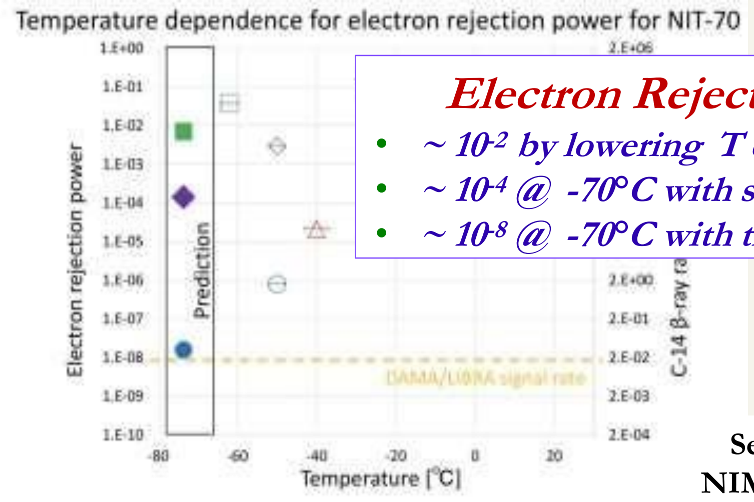
10 kg detector shield (1 m HDPE @LNGS)

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 [g × month]$^{-1}$	Rate [kg × 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

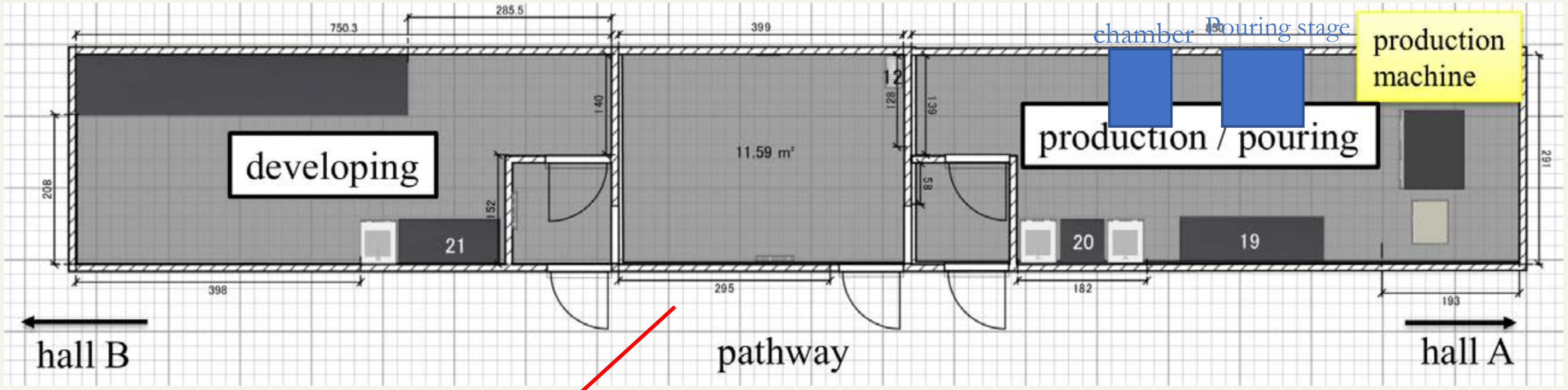
- *~ 10^{-2} by lowering T down to -70°C*
- *~ 10^{-4} @ -70°C with shape analysis*
- *~ 10^{-8} @ -70°C with track likelihood*

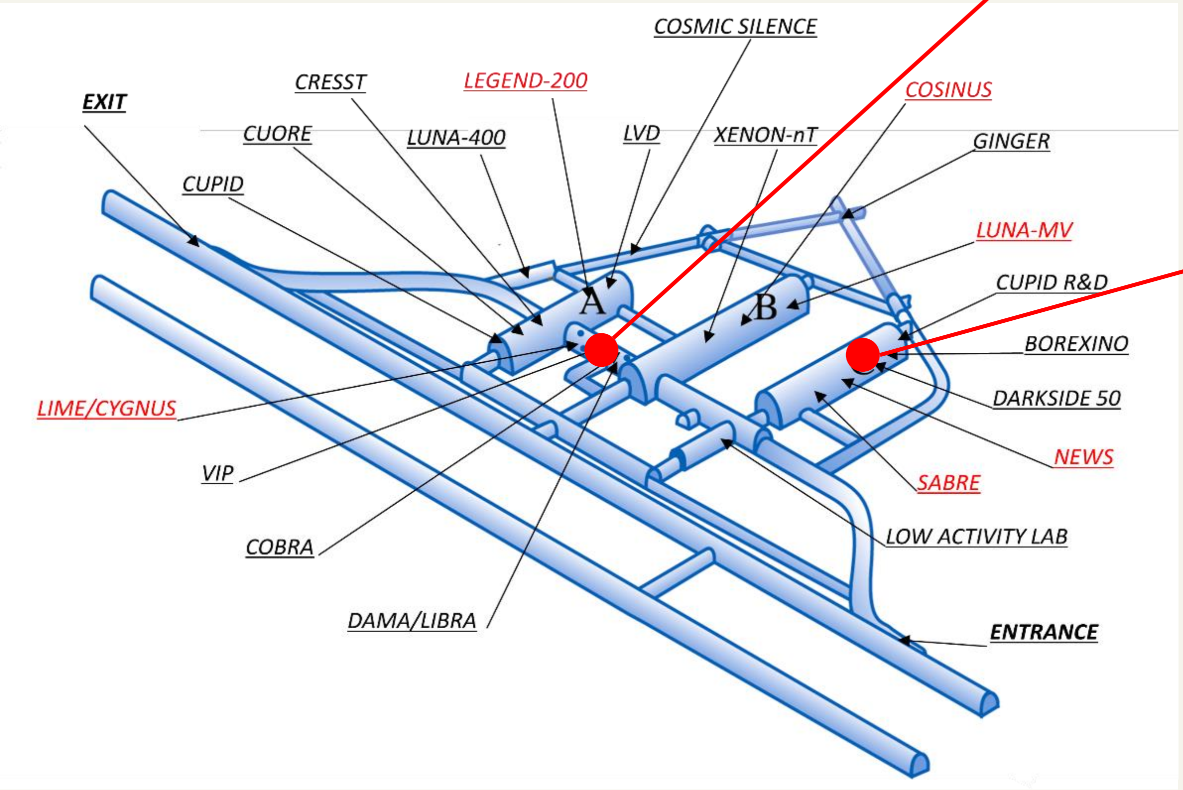
Sensitivity vs. T:
NIM A845 (2017) 373

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

NEWSdm underground facility and detector

Hall F





Hall C

Mass	Exposure	Temp.	Shield
~10g	40days	-50ºC	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 spectrum measurement @ LNGS Surface Lab

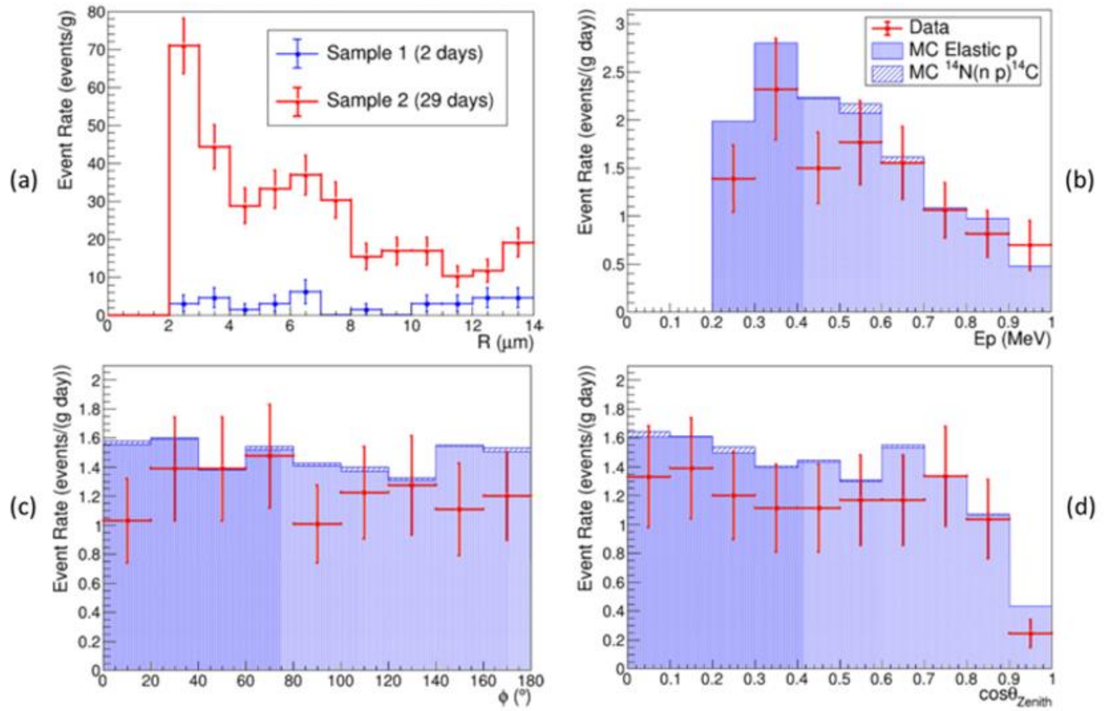


Figure 3.(a) Range distribution of recoil protons in the sub-MeV region for Sample 1 (2 days, blue) and Sample 2 (29 days, red) at LNGS. (b-d) Sub-MeV neutron measurement results after subtracting the data of Sample 1 from Sample 2 for an equivalent exposure of 27 days. For the MC simulation, neutron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

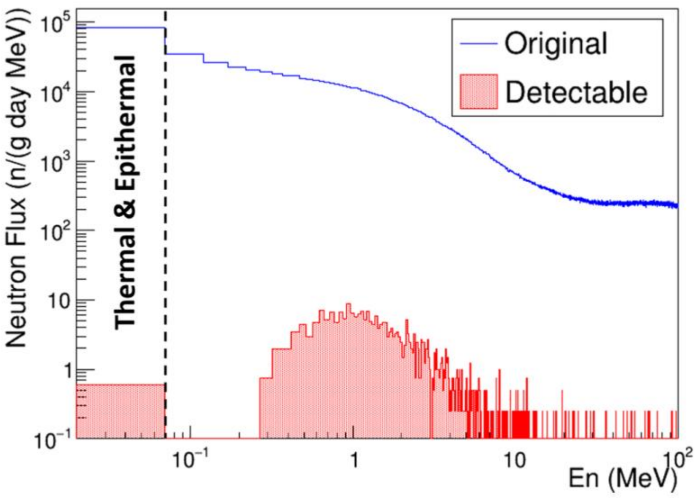
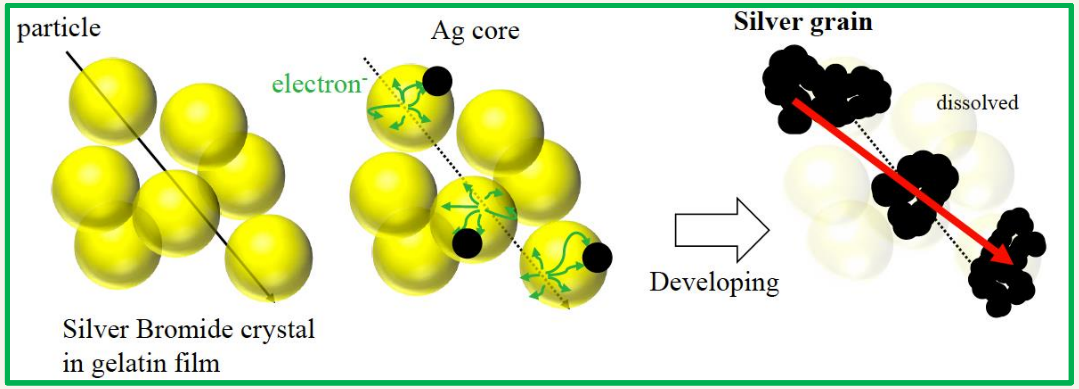


FIG. 9. Detectable neutron spectrum in NIT with 1 (g day) exposure at LNGS surface laboratory estimated by a MC simulation based on GEANT4. The blue line is the original energy of the incident neutrons, and the red filled histogram is the neutron spectrum accounting for the selection and the detection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

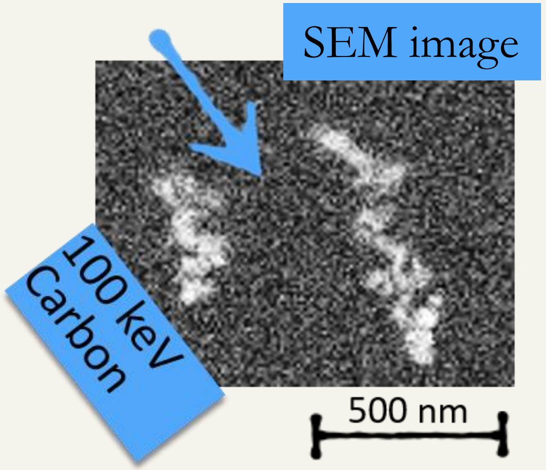
NIT: Nano emulsion Imaging Trackers

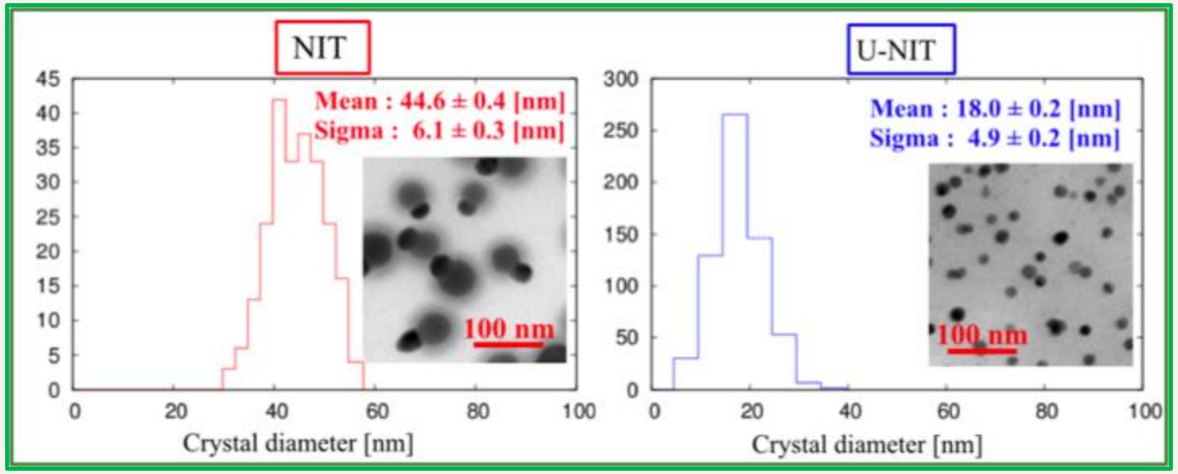


A long history, from the discovery of the **Pion (1947)** to the discovery of $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode (**OPERA, PRL 115 (2015) 121802**)

- Nuclear emulsions: AgBr crystals in organic gelatine
- Passage of charged particle produce *latent image*
- Chemical treatment make Ag grains visible

- New kind of emulsion for DM search
- Smaller crystal size





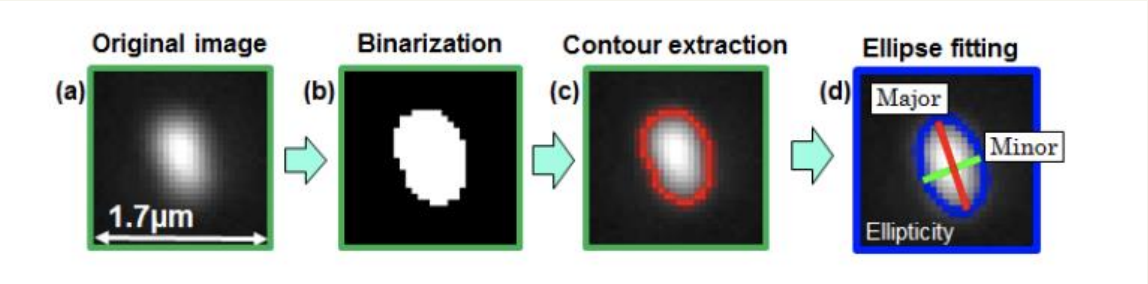
NIT granularity: 71 nm

U-NIT granularity: 40 nm

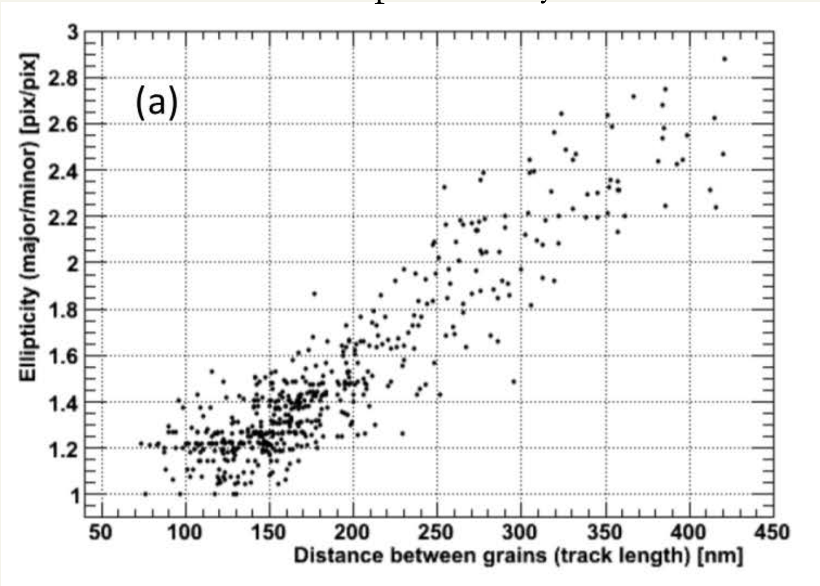
Shape analysis

PTEP (2019) 063H02

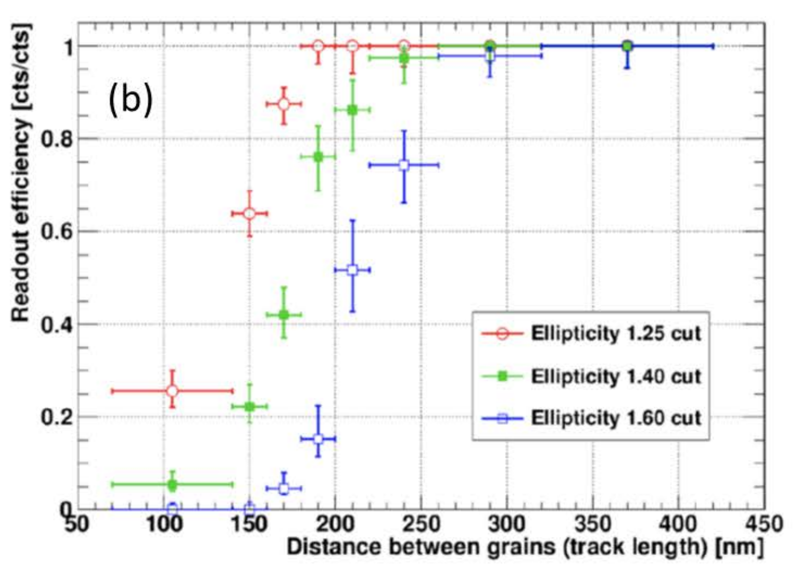
- Elliptical fit to measure the shape anisotropy



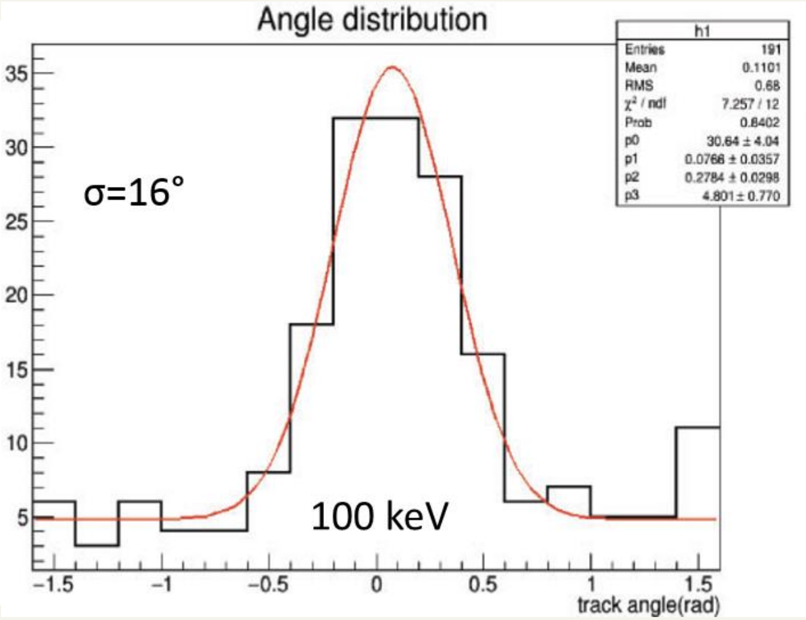
Correlation between track lengths measured by X-ray microscopy and ellipticity obtained with optical analysis



Correlation between readout efficiencies and track lengths for different ellipticity thresholds

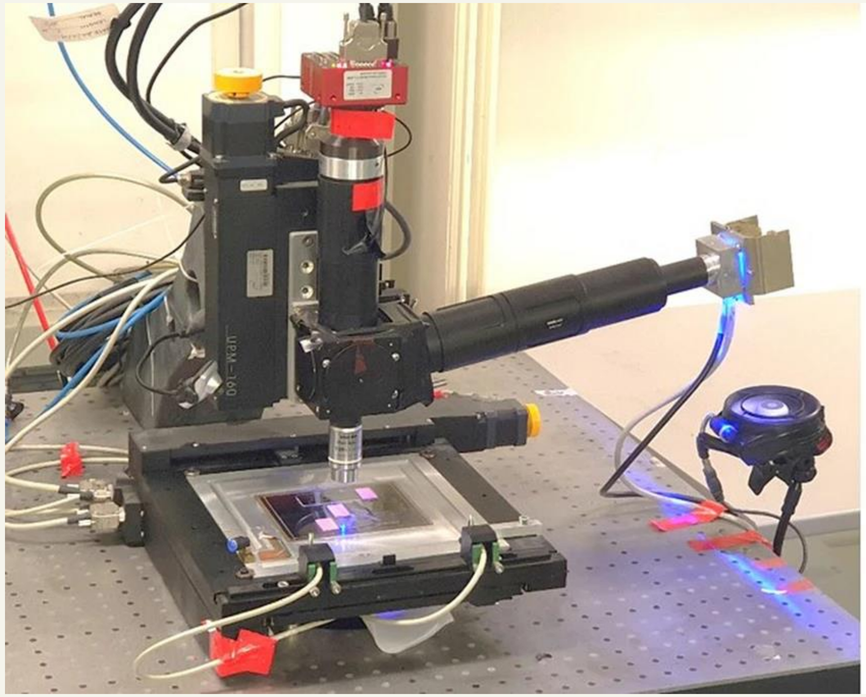


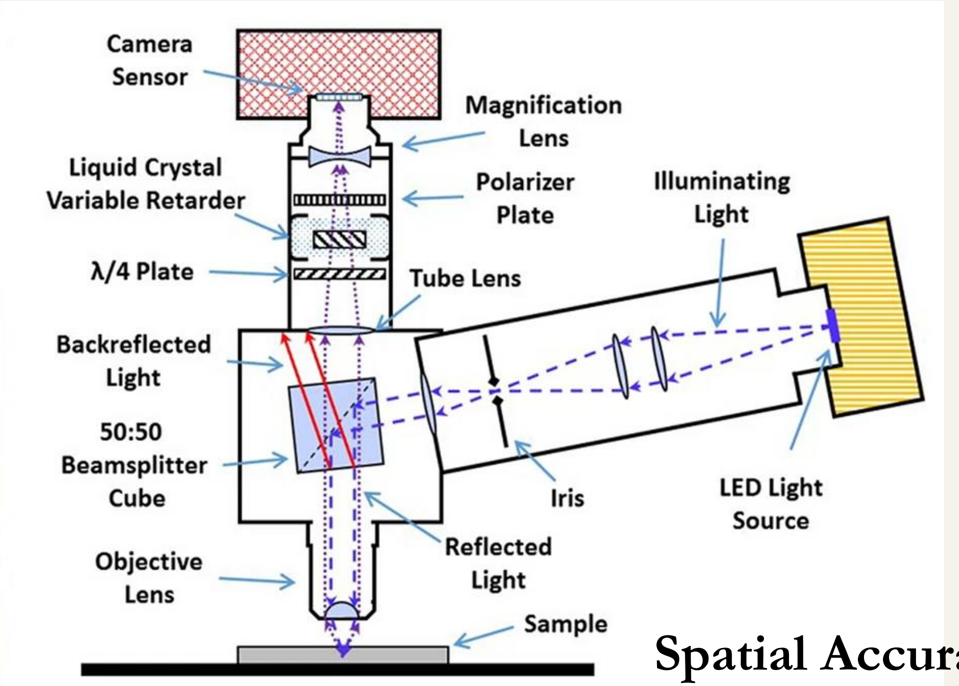
100 keV Carbon



Super-resolution microscope

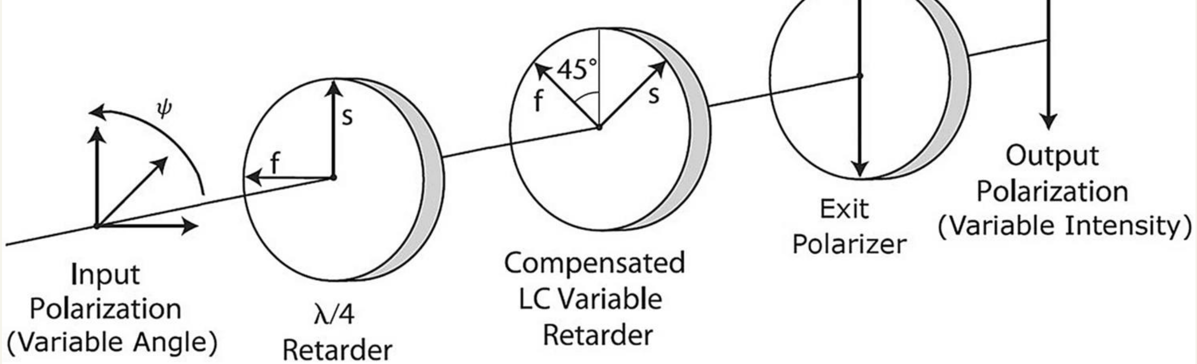
Sci. Rep. **10** (2020) 18773

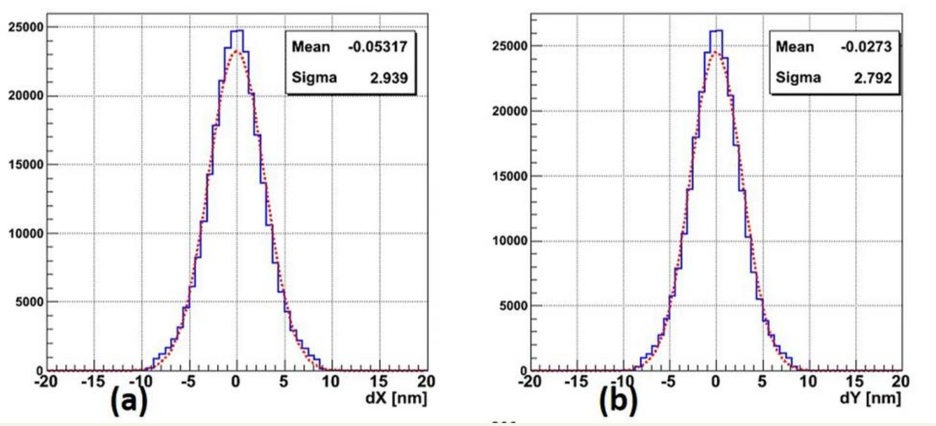




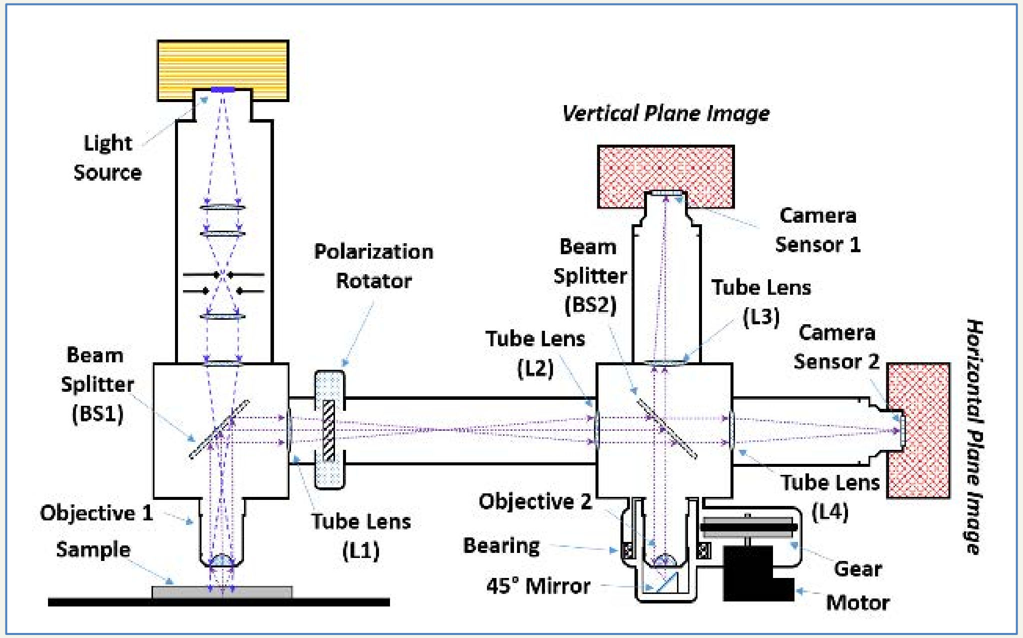
Spatial Accuracy = 3 nm

Liquid Crystal Polarization Analyzer

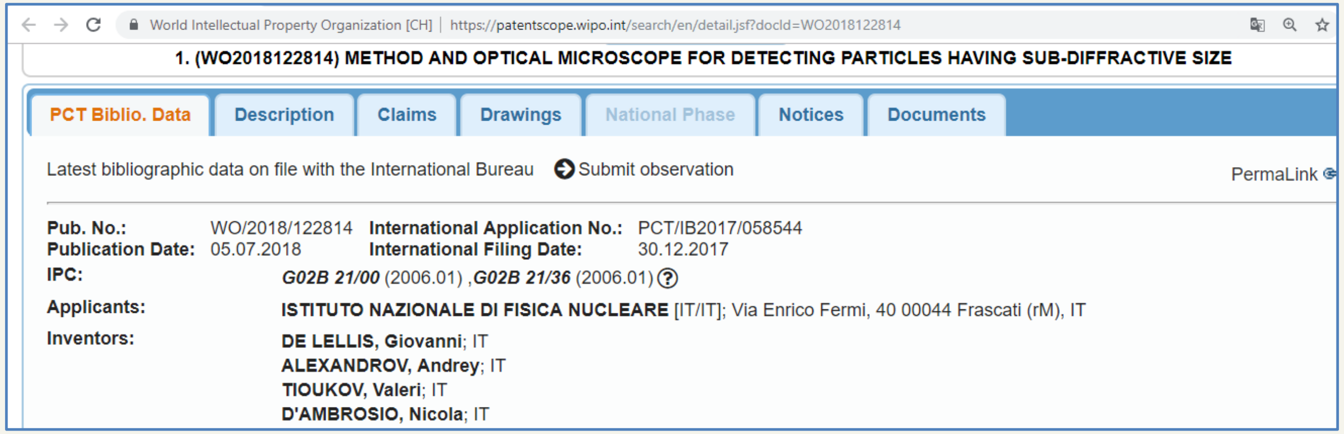




Measurement in 3D



International Patent No. WO/2018/122814



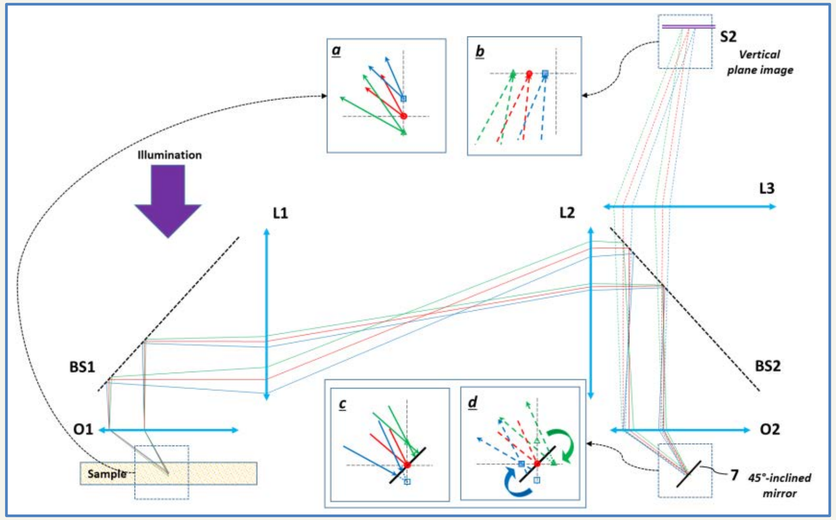
World Intellectual Property Organization [CH] | https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2018122814

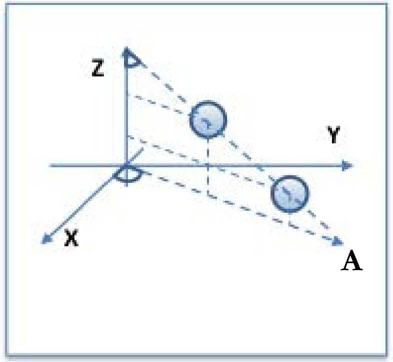
1. (WO2018122814) METHOD AND OPTICAL MICROSCOPE FOR DETECTING PARTICLES HAVING SUB-DIFFRACTIVE SIZE

PCT Biblio. Data | Description | Claims | Drawings | National Phase | Notices | Documents

Latest bibliographic data on file with the International Bureau   Submit observation   PermaLink

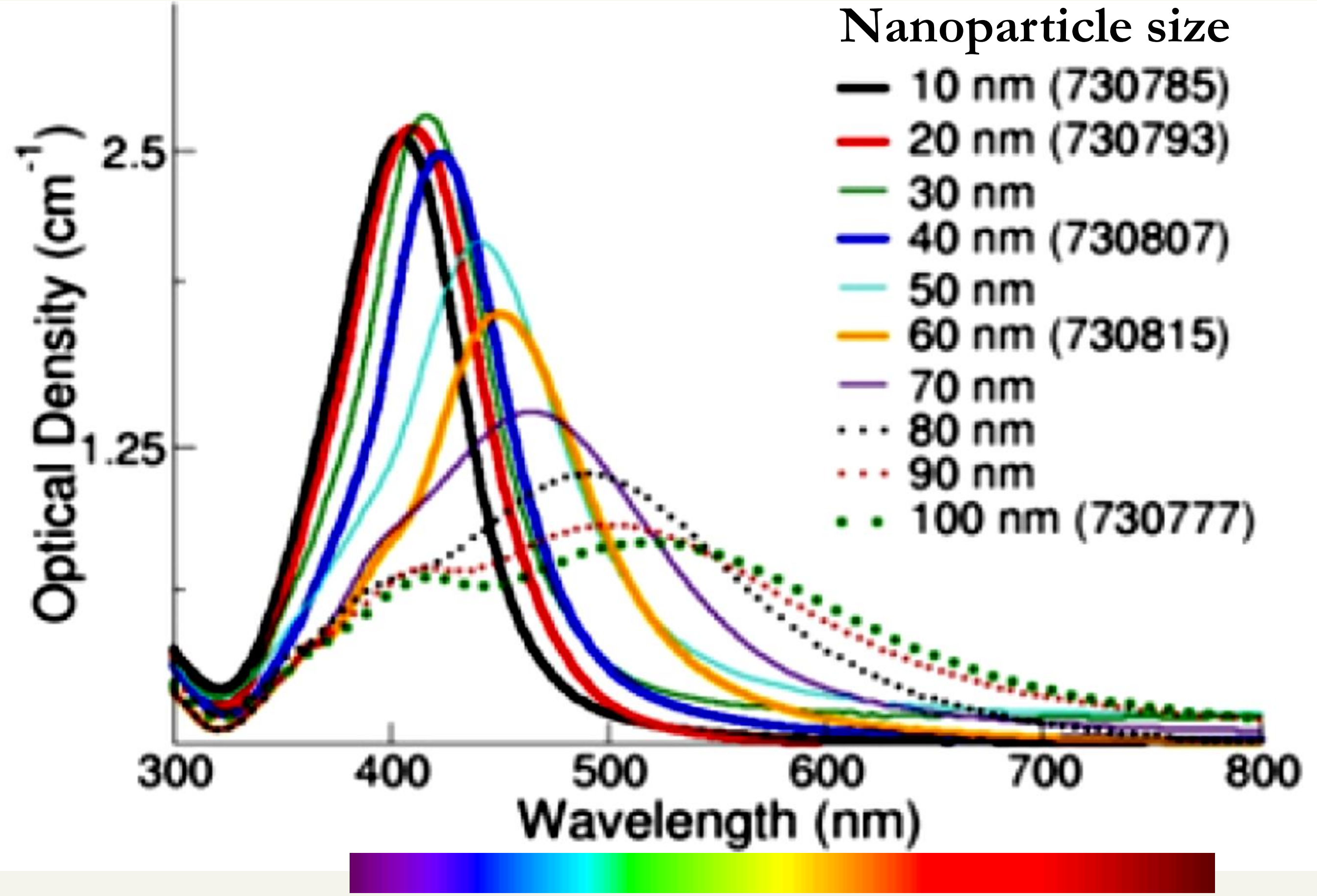
Pub. No.: WO/2018/122814   **International Application No.:** PCT/IB2017/058544
Publication Date: 05.07.2018   **International Filing Date:** 30.12.2017
IPC: *G02B 21/00* (2006.01) ,*G02B 21/36* (2006.01)
Applicants: **ISTITUTO NAZIONALE DI FISICA NUCLEARE** [IT/IT]; Via Enrico Fermi, 40 00044 Frascati (rM), IT
Inventors: **DE LELLIS, Giovanni**; IT
ALEXANDROV, Andrey; IT
TIOUKOV, Valeri; IT
D'AMBROSIO, Nicola; IT

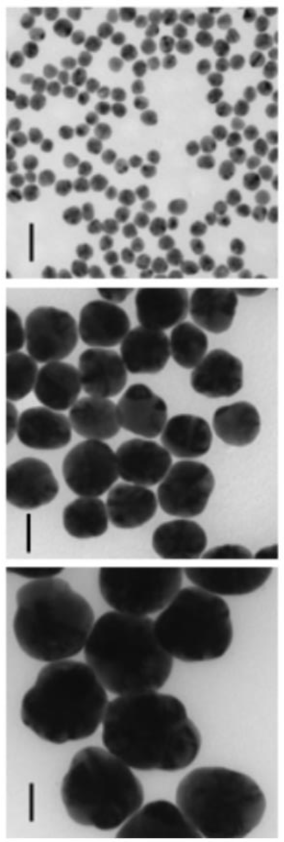




Two focal planes:
Horizontal: XY
Vertical: ZA

Plasmon resonance wavelength dependency



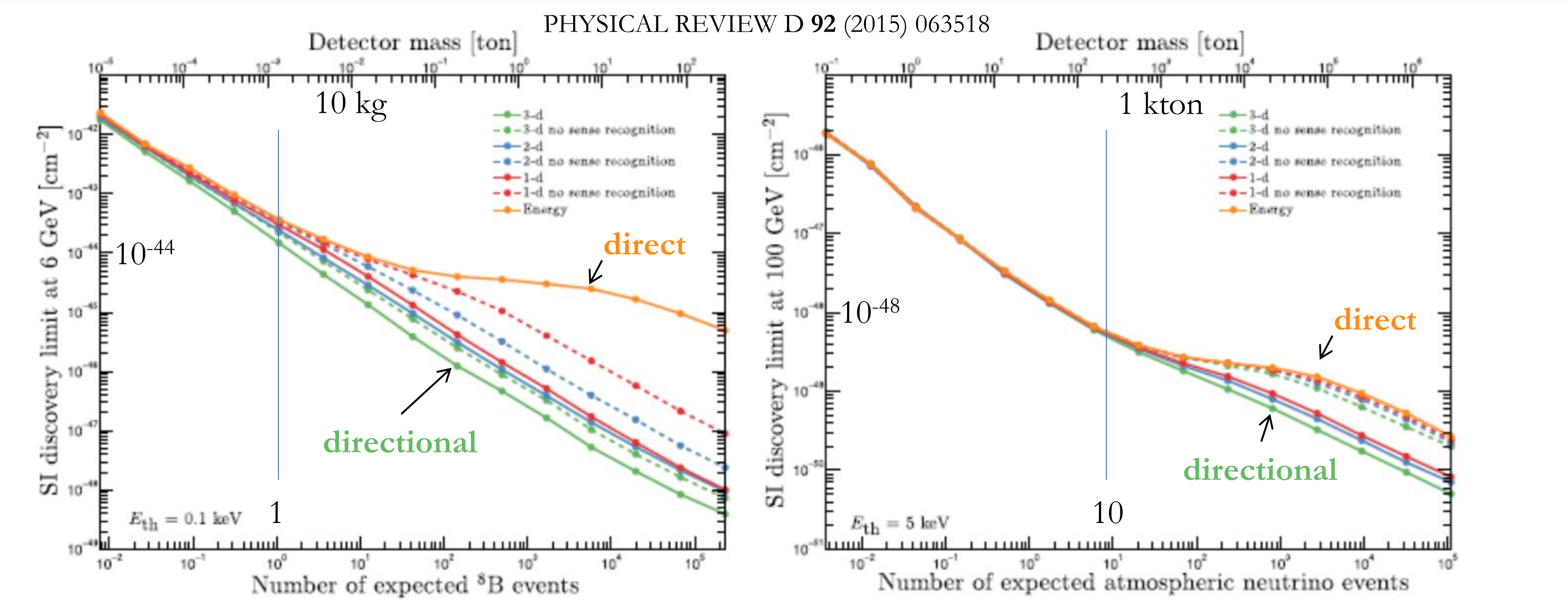


20 nm

60 nm

100 nm

Importance of the directional detection



Need 3D with sense recognition for best results!

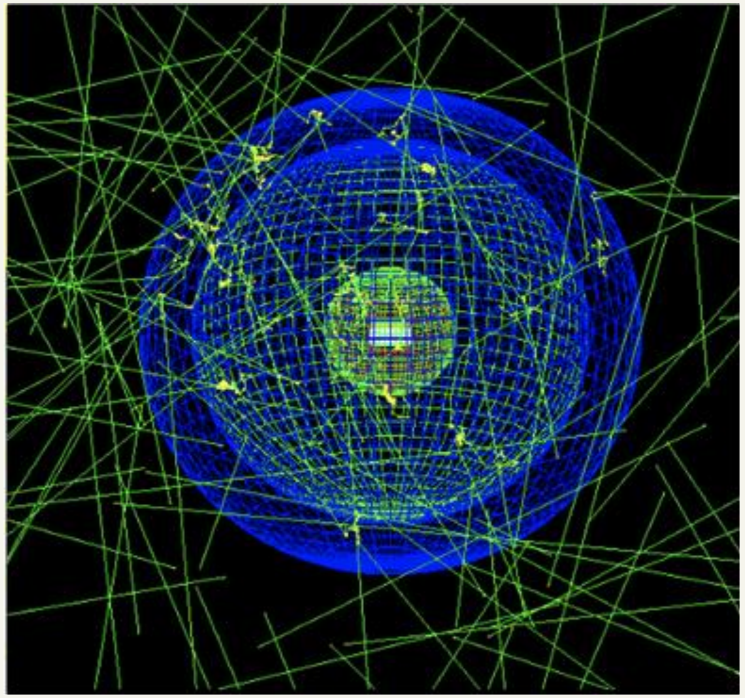
Shield simulation

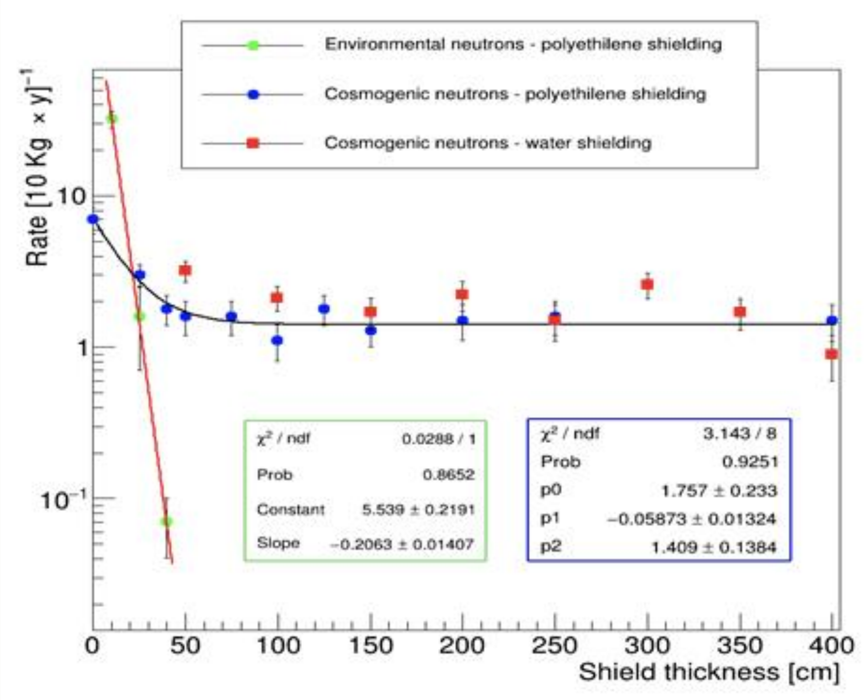
Optimisation of the shield with Geant4 simulation to reduce:

- neutrons from environmental radioactivity
- neutrons produced by cosmic muon spallation in the surrounding rock and in the shield itself
- Environmental gammas

Best configuration: 100 cm of polyethylene for a total neutron rate of ∽ 1.4 for an exposure of 10 kg year

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

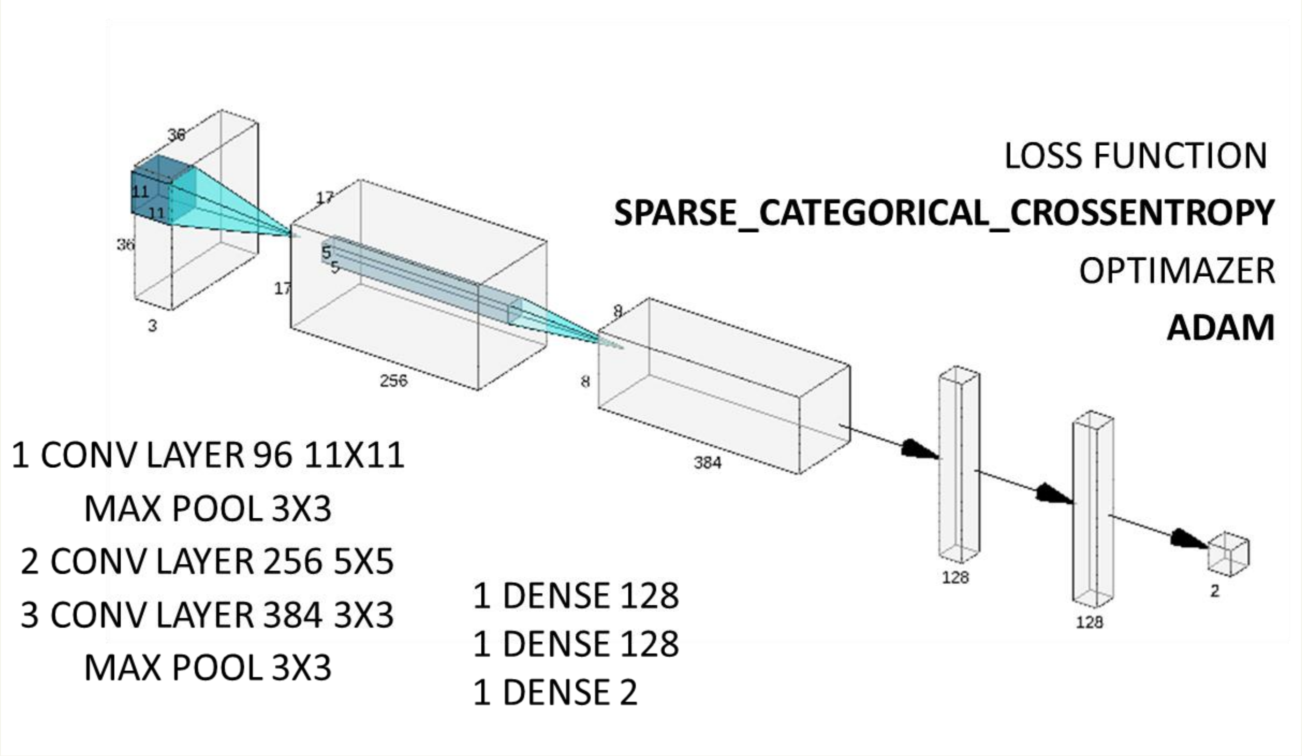


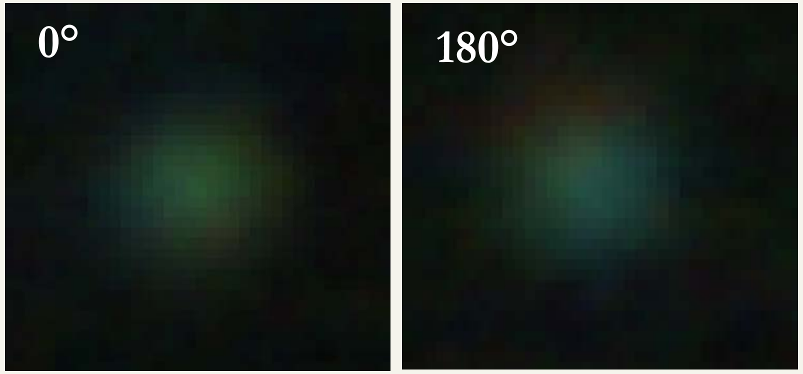


Astroparticle Physics 80 (2016) 16–21

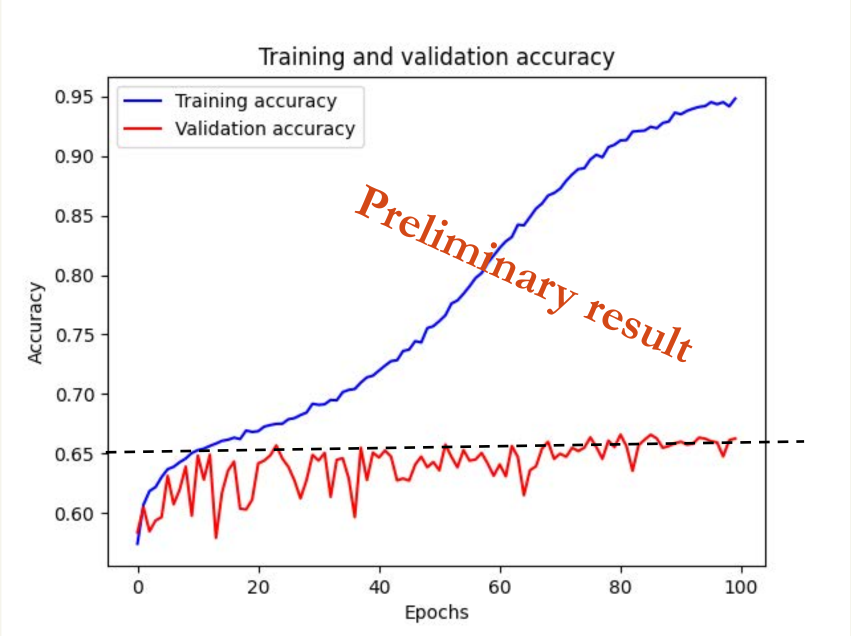
Intrinsic neutron background of nuclear emulsions for directional Dark Matter searches

Sense recognition with color
Machine Learning approach





Carbon ion 100 keV



Sense prediction accuracy = 65%