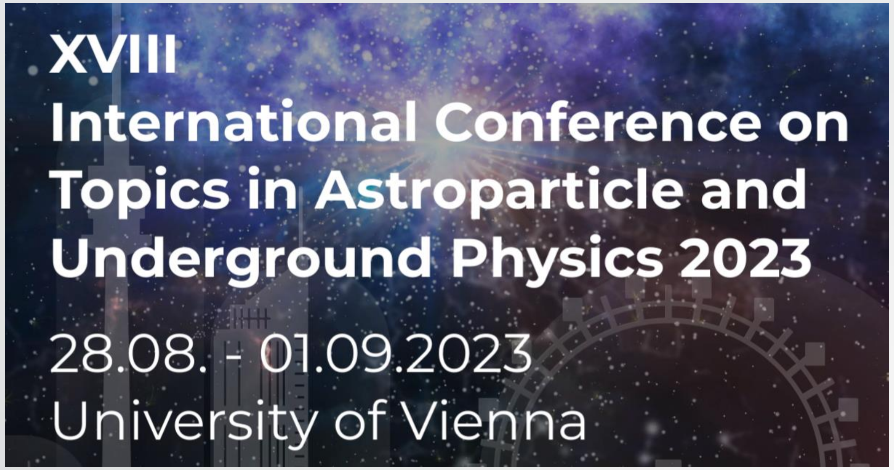


Directional dark matter search with nuclear emulsions

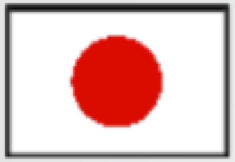
Valeri Tioukov

INFN Napoli

NEWSdm collaboration

NEWSdm COLLABORATION

81 physicists
23 Institutes



JAPAN
Chiba, Nagoya, Toho

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

ITALY
LNGS,
INFN: Napoli, Roma, Padova
Univ.: Napoli, Roma, Padova,
Potenza, Benevento

SOUTH KOREA
Gyeongsang University

TURKEY
METU Ankara

Website: *news-dm.lngs.infn.it*

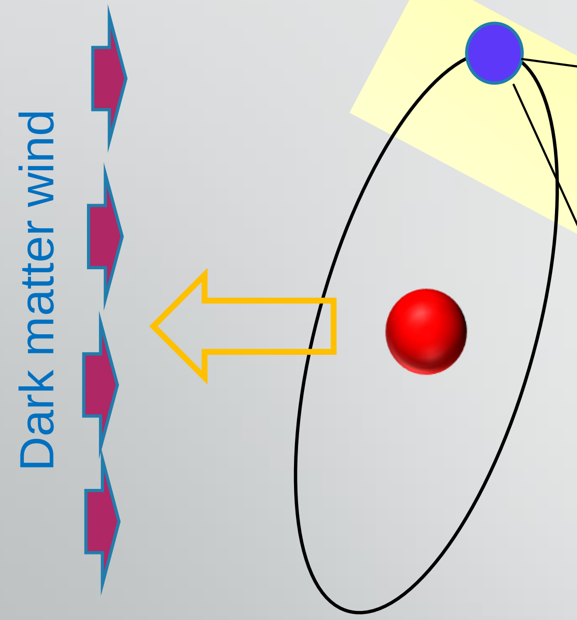
Letter of intent: *https://arxiv.org/pdf/1604.04199.pdf*

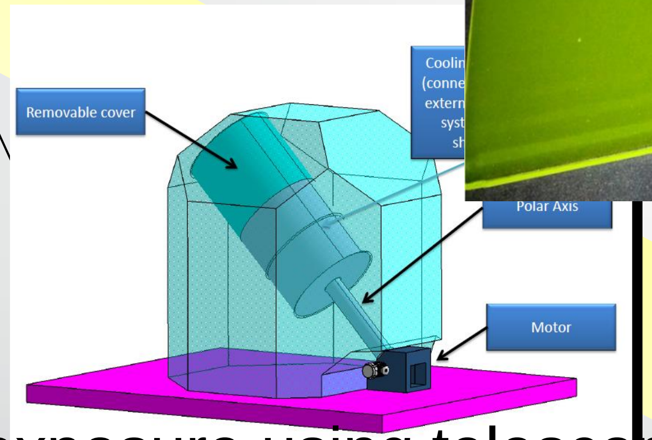
Outlook

- Physical concept: directional WIMP recoils search
- Technology advances as part of NEWS R&D
- Ongoing activity at LNGS
- Prospects and potential at LNGS
  - News as DM search experiment
    - Conventional DM
    - Boosted DM
  - Different NIT and emulsion technology applications

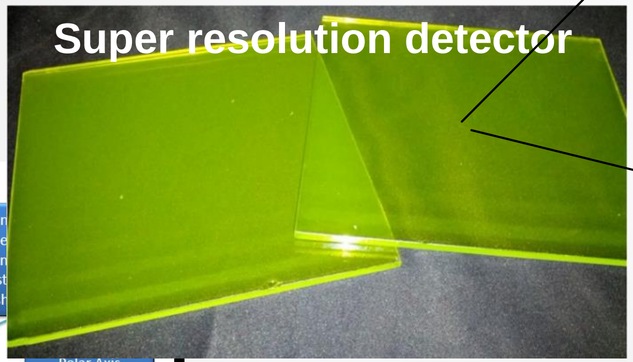
NEWSdm experiment concept

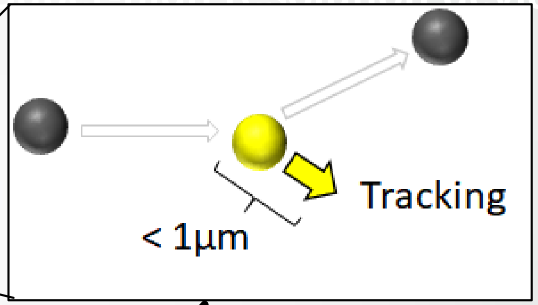
Direction sensitive dark matter search with nano-tracking technologies for super resolution nuclear emulsion



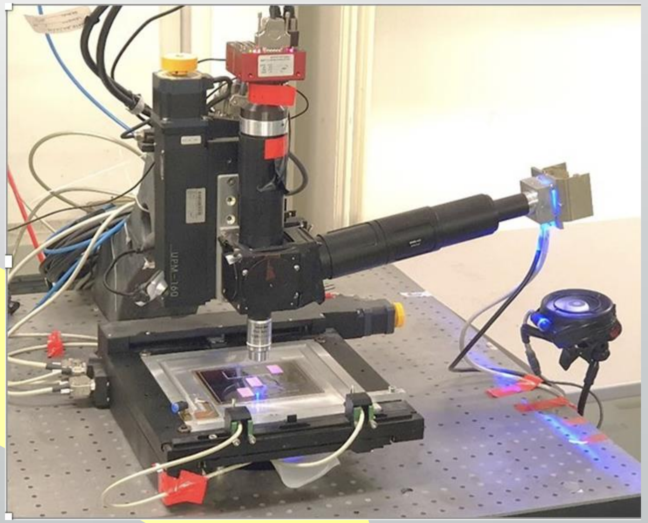


exposure using telescope





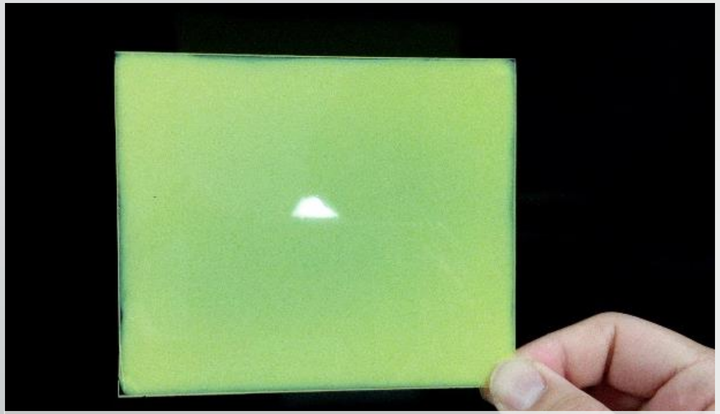
Optical image readout



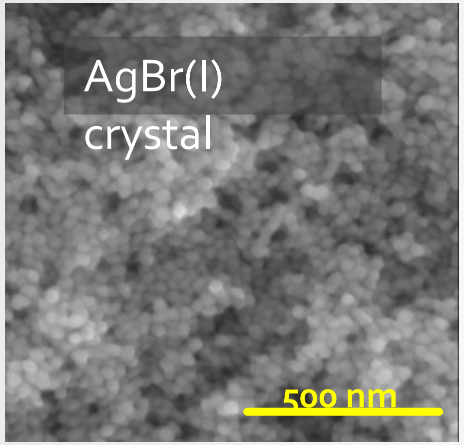
Underground laboratory
Gran Sasso (LNGS)

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

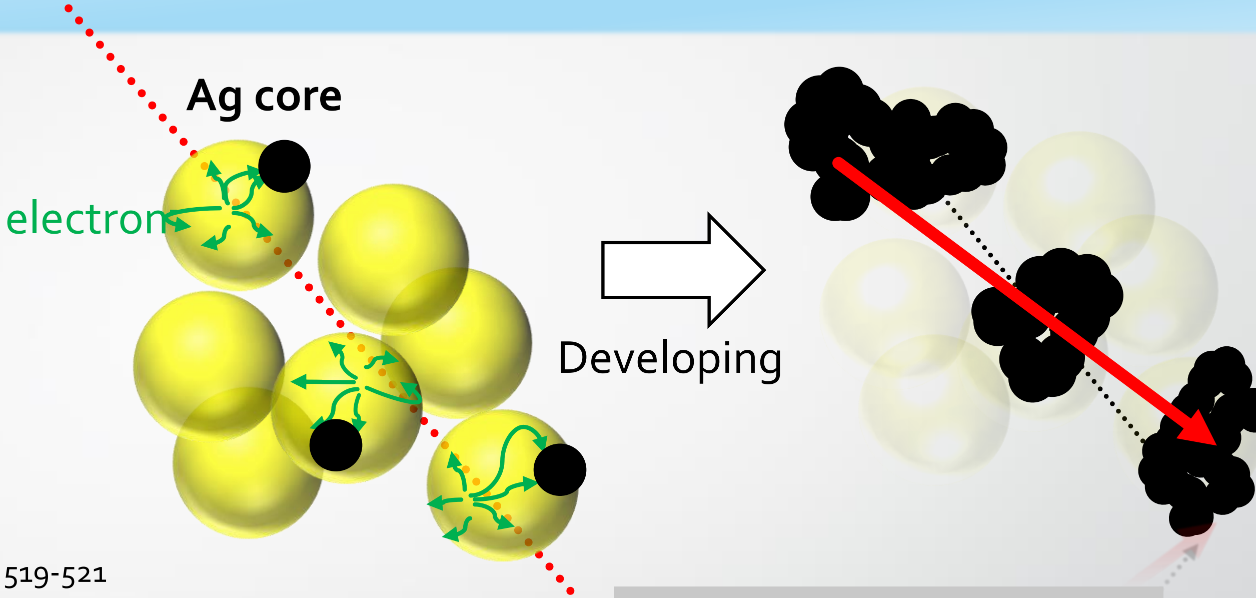
Nano Imaging Tracker (NIT) developed for NEWSdm



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



Heavier DM: Ag, Br, I
Lighter DM: C, O, N
neutron: H

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

Solid-state detector
Density: 3.1 g/cm³

High-speed volume analysis for nanometric tracks is required

C ions 100 KeV (SEM image)

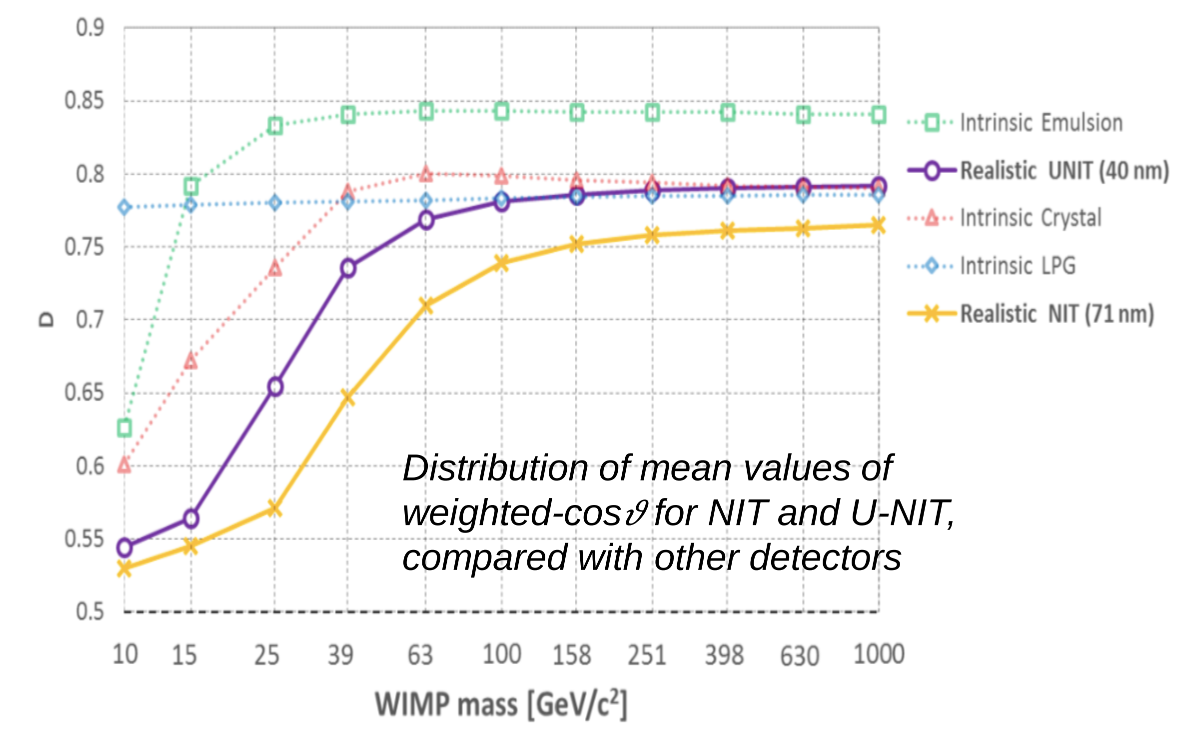
Directionality preservation of nuclear recoils

- 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

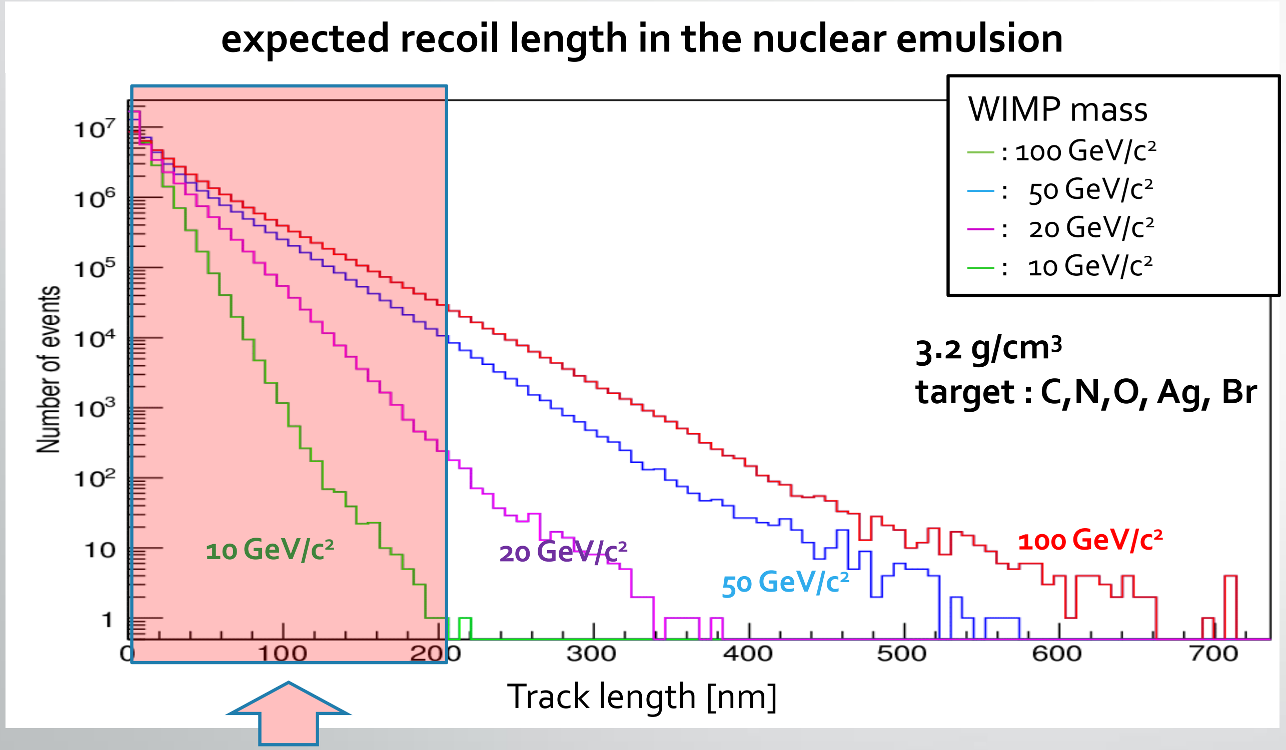
A. Alexandrov, G. De Lellis, A. Di Crescenzo, A. Golovatiuk and V. Tioukov,
«Directionality preservation of nuclear recoils in an emulsion detector for directional dark matter search»
JCAP 04 (2021) 047



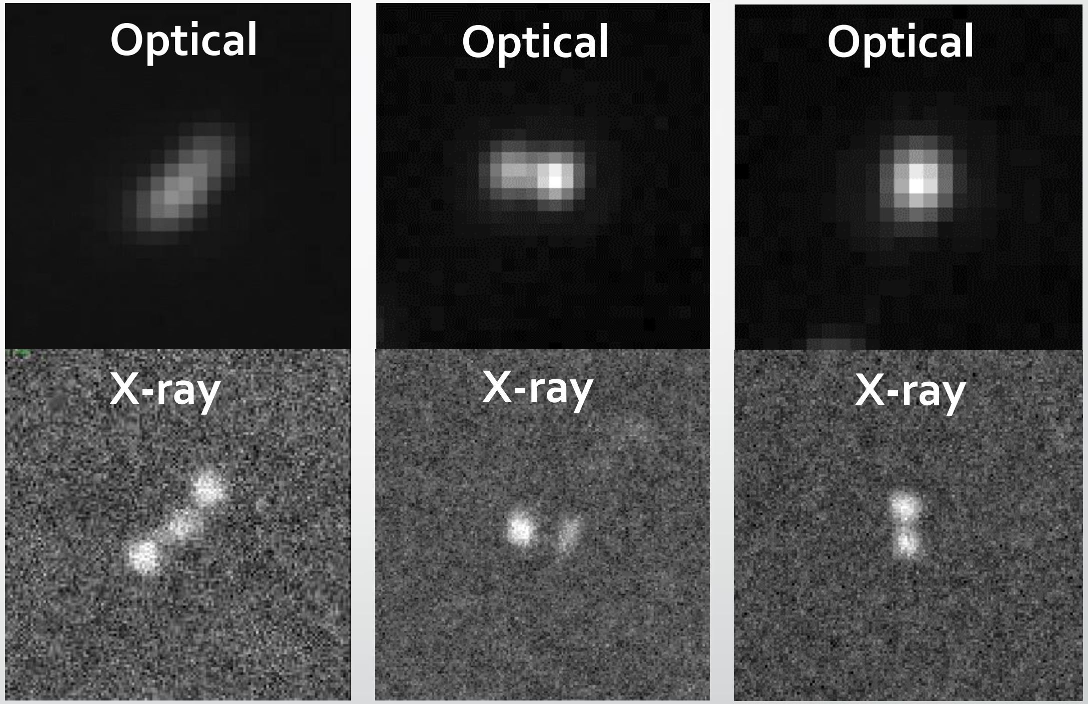
Distribution of mean values of weighted-cosϑ for NIT and U-NIT, compared with other detectors

here
“Intrinsic” – do not consider the detector or readout granularity
“Realistic” – take into account all detector-related effects (granularity, thresholds, etc)

Direction detection challenge



Optical diffraction limit

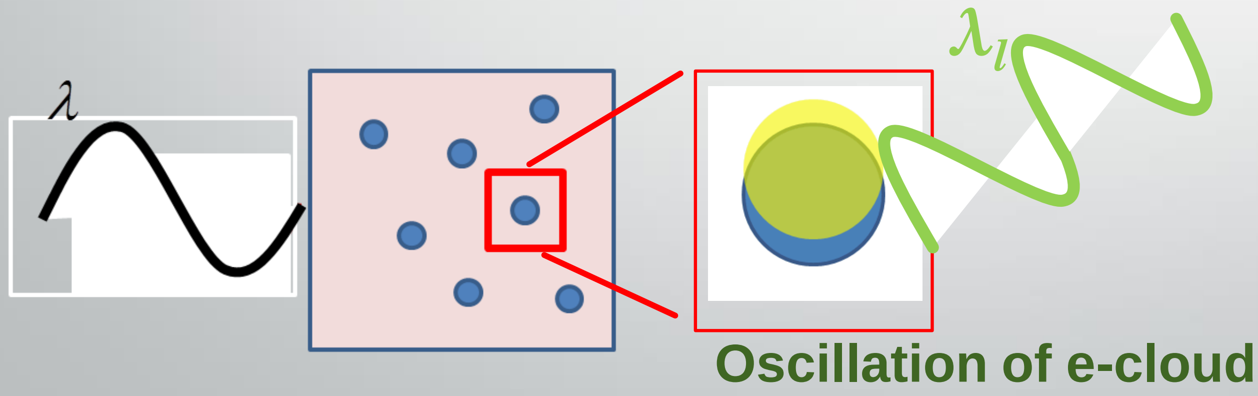


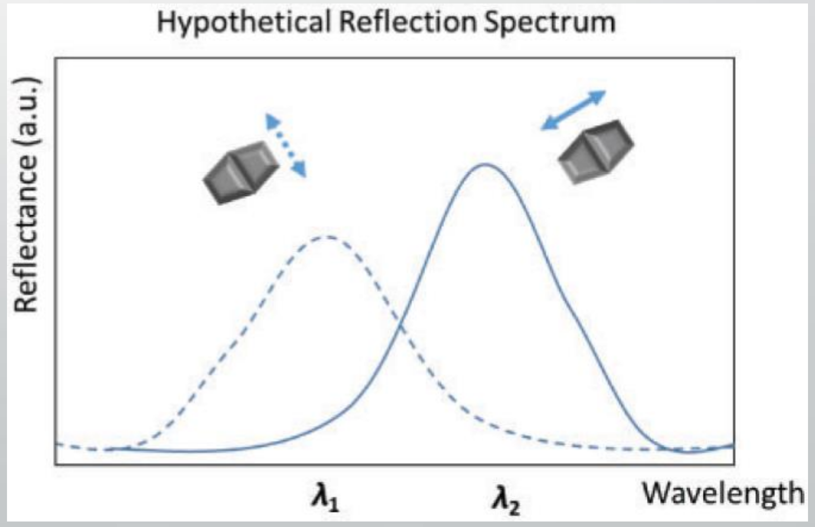
L = 380 nm L = 265 nm L = 160 nm

Need super-resolution to measure tracks shorter than 200 nm

Optical readout beyond the diffraction limit

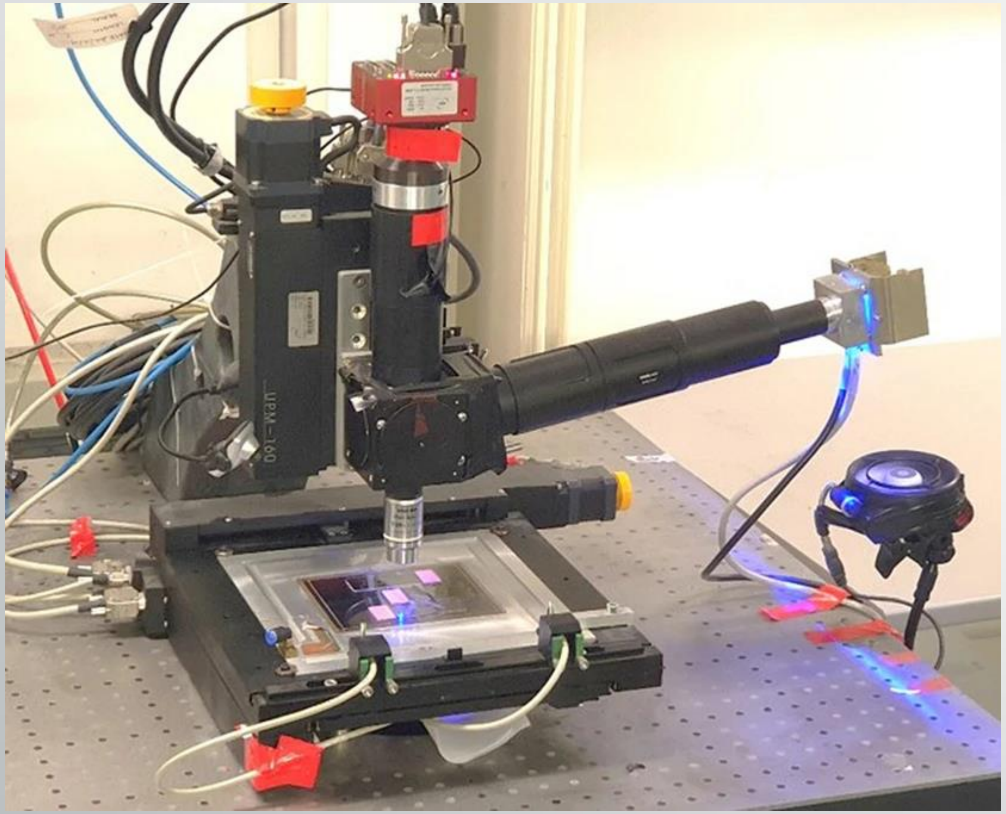
- Super-resolution idea: use the **plasmon resonance** effect to overcome the diffraction limit:
  - generated by a light wave trapped within conductive nanoparticles smaller than the wavelength of light
  - resonant frequency strongly depends on the composition, size, geometry, dielectric environment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

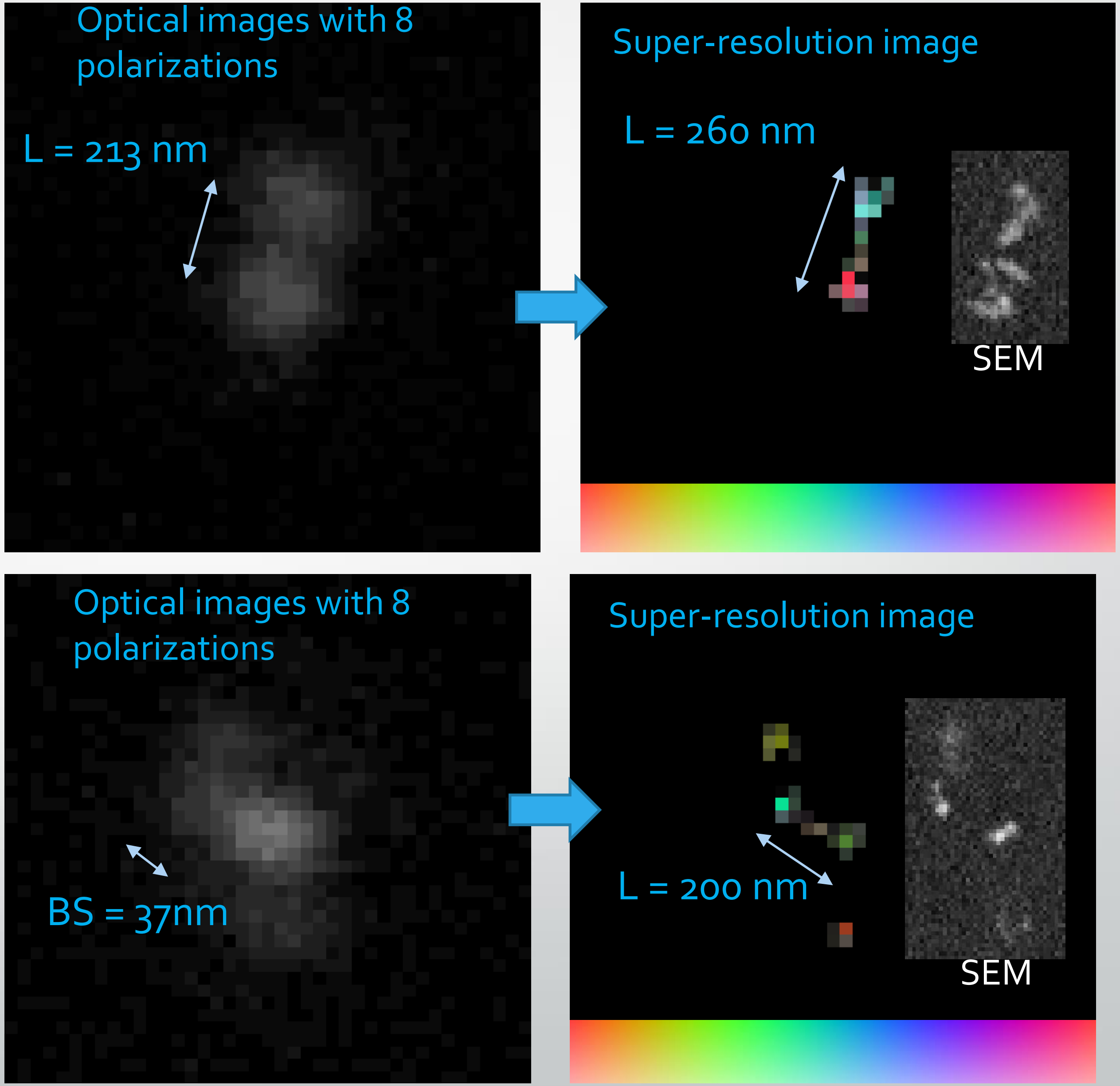




PTEP, Vol. 2019 Issue 62019, 063H02

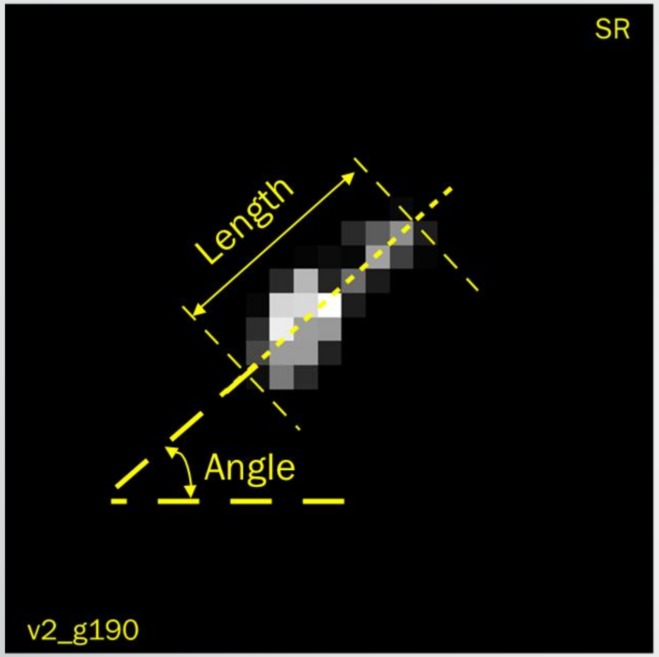
LSPR-based super-resolution imaging based on join deconvolution set of 8 polarized images

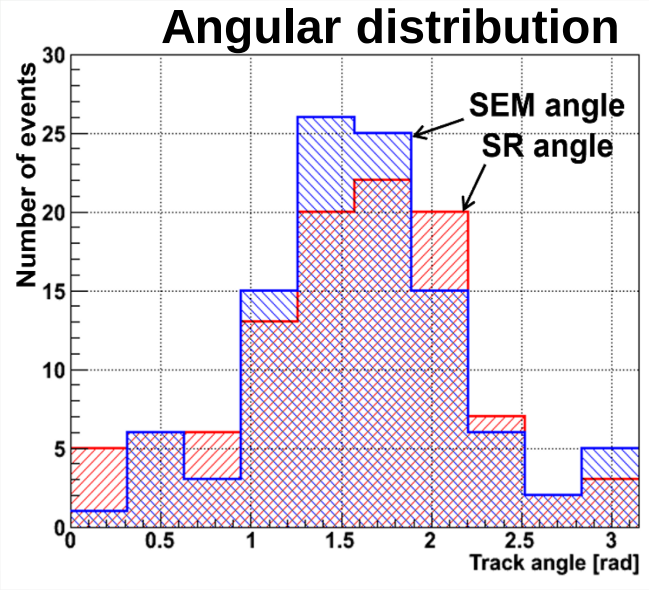


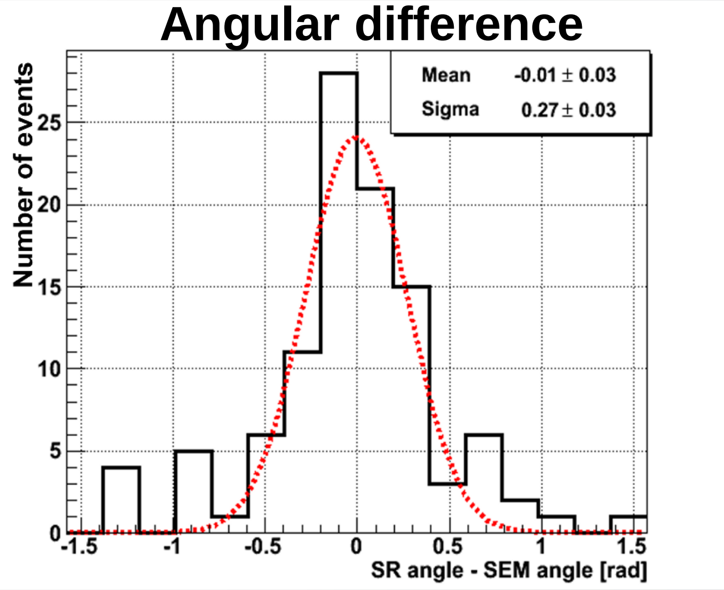


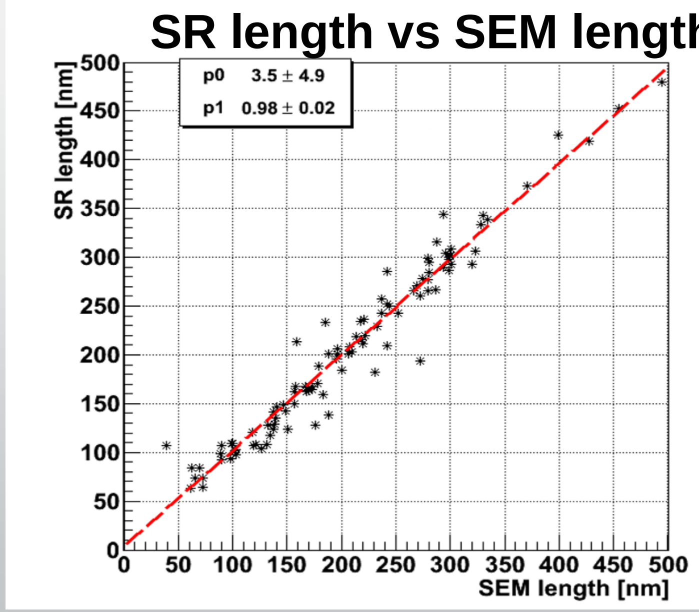
Alexandrov, A., *et al.* Super-resolution high-speed optical microscopy for fully automated readout of metallic nanoparticles and nanostructures. *Sci Rep* 10, 18773 (2020). https://doi.org/10.1038/s41598-020-75883-z

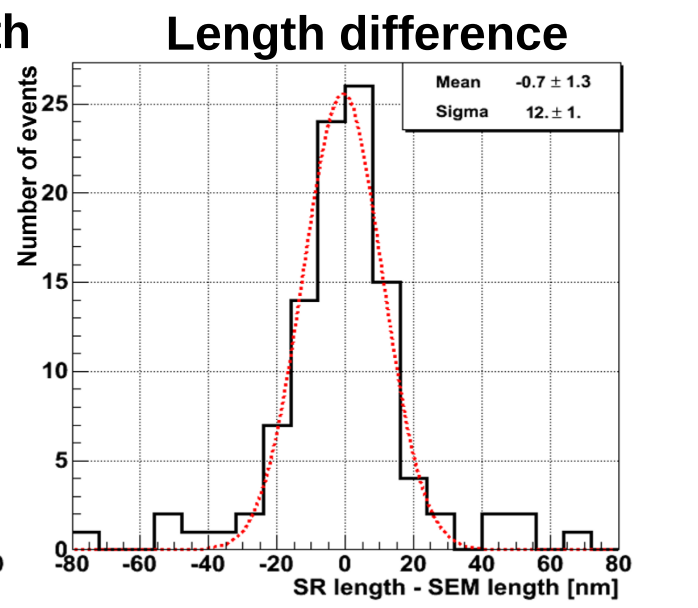
Joint Image Deconvolution - Comparison with SEM











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

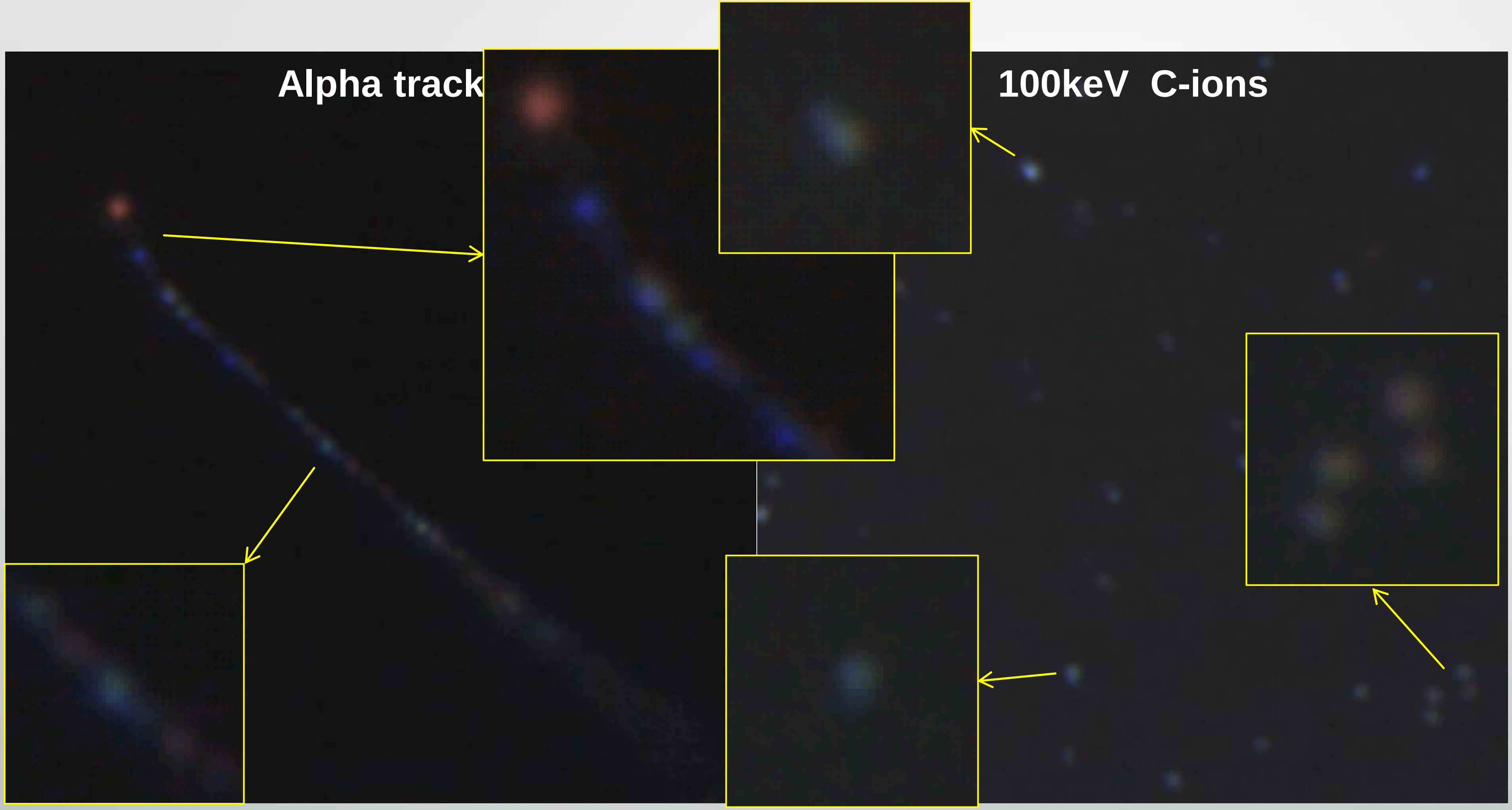


Image size 15 µm x 15 µm

Image size 15 µm x 15 µm

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

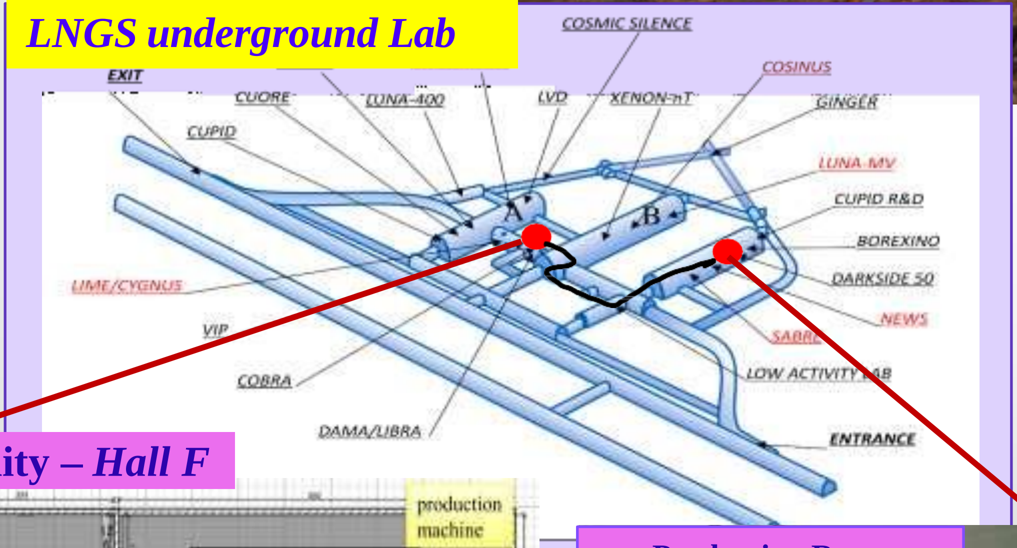
Experimental Activity @ Gran Sasso Lab (ITALY)

Neutron flux @ surface Lab

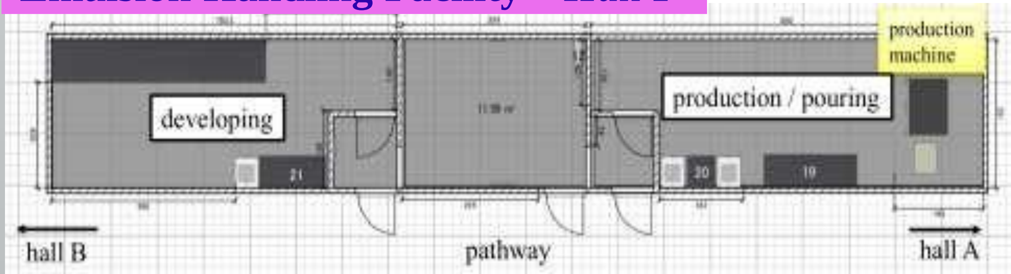
LNGS surface Lab

Development Room
Clean Room ISO 7

LNGS underground Lab



Emulsion Handling Facility – *Hall F*



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

Cooling Box for Target

Target insertion by crane

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

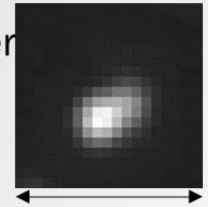
First underground exposure inside shield

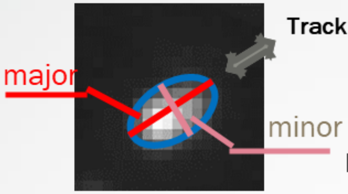
Automatic readout
1st trigger

Elliptical shape trigger

Requirement

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





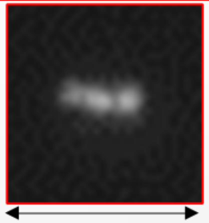
CNO : > 30 keV

Electron efficiency: 0.05

CNN
(machine learning)

≧ 3 grain track recognition

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

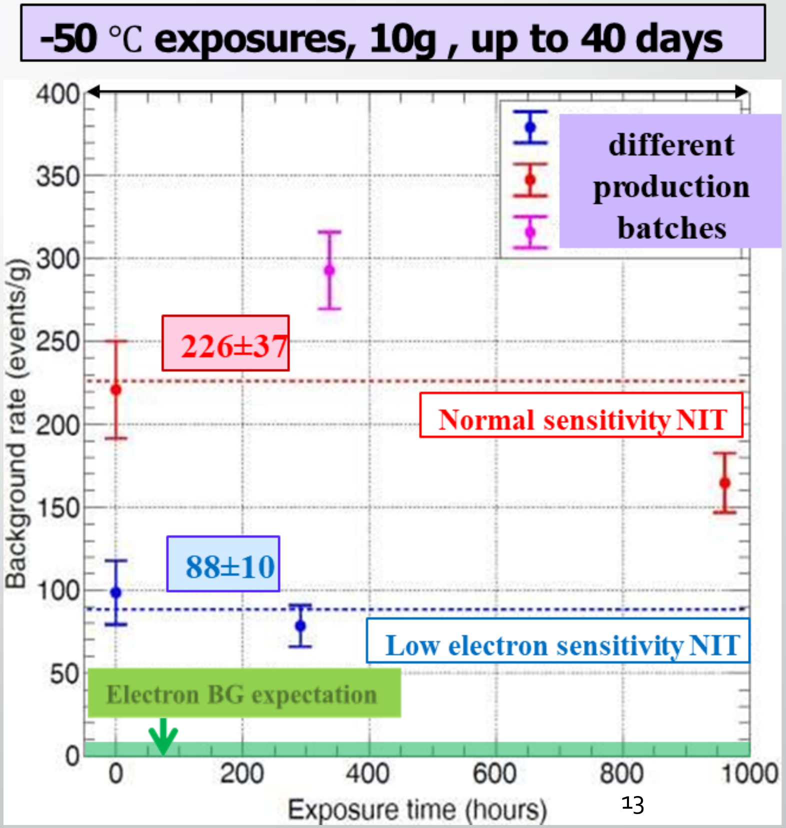


Training sample :
neutron induce recoil nuclei @AIST
(880keV, -50℃)

Manual check

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

Current Selection

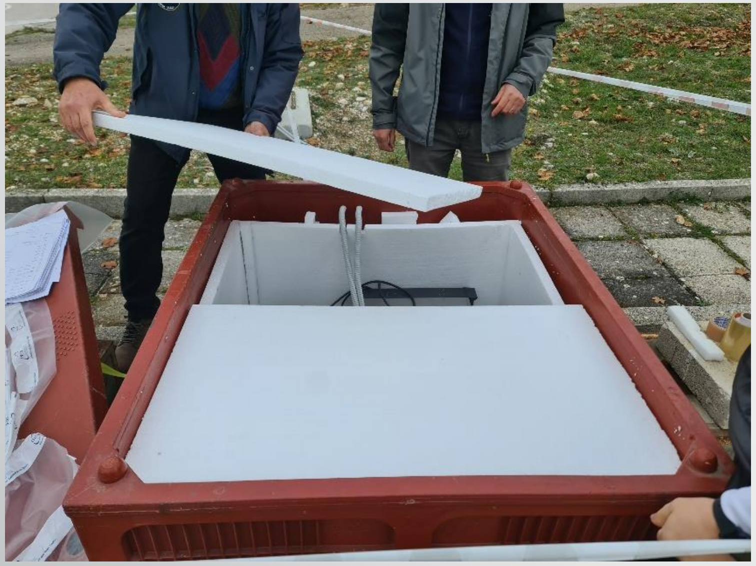


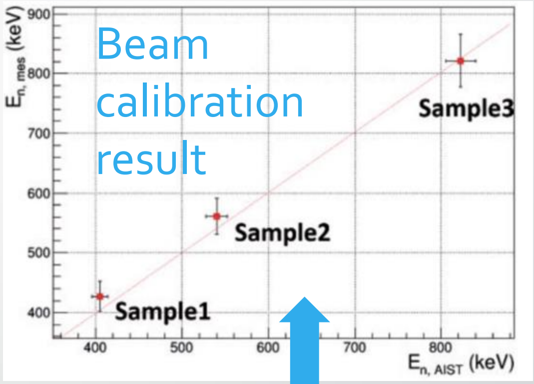
Results:

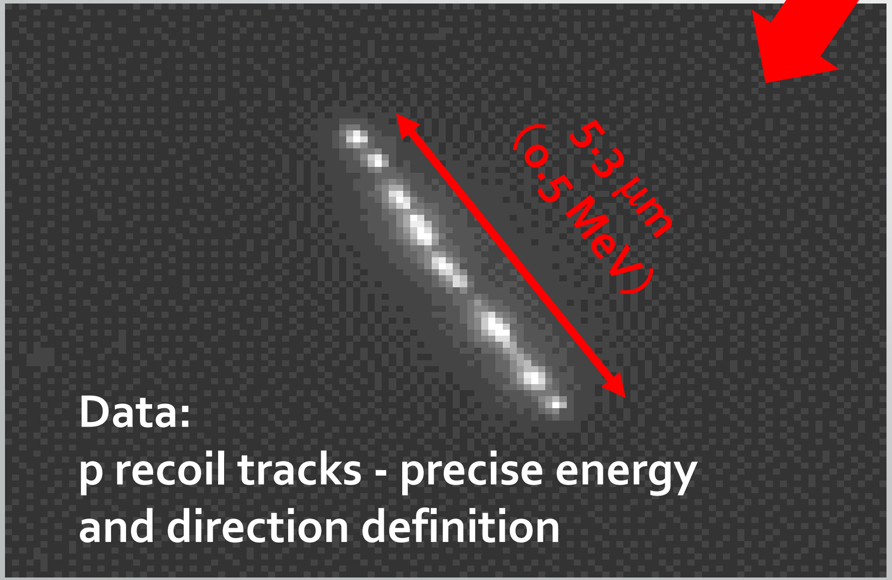
- ***Too many candidates ($x10^2$ more than expected e)***
- ***Signal not increasing with in-shield exposure time***
- ***Using NIT with reduced sensitivity to e ➔ not enough***

Neutron bg study at LNGS (external and underground)

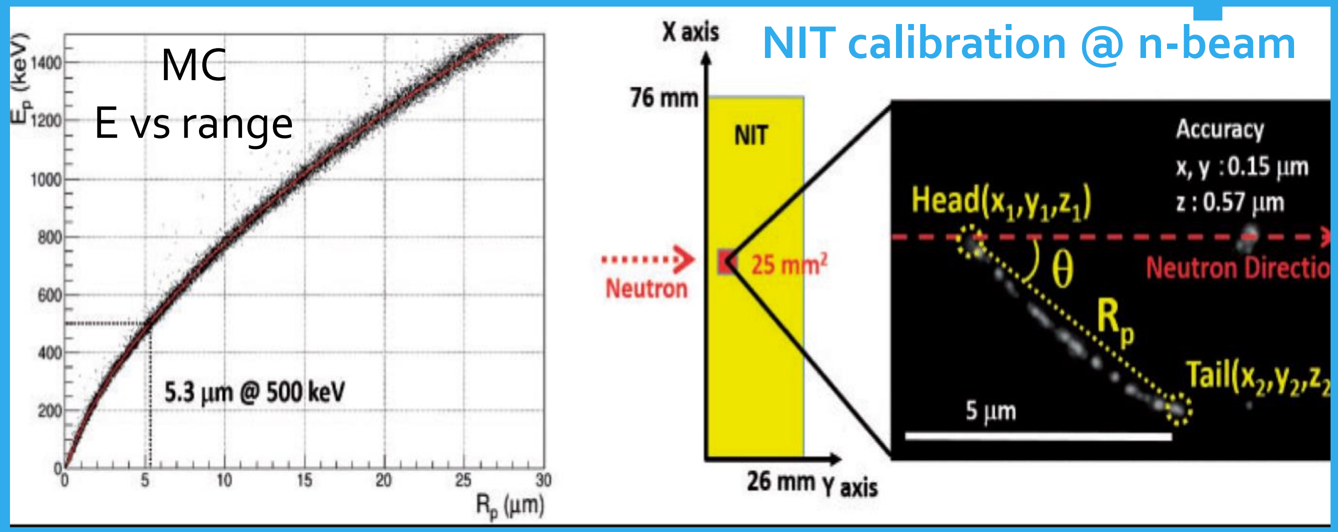
first sub-MeV energy & direction n-spectrum measurement





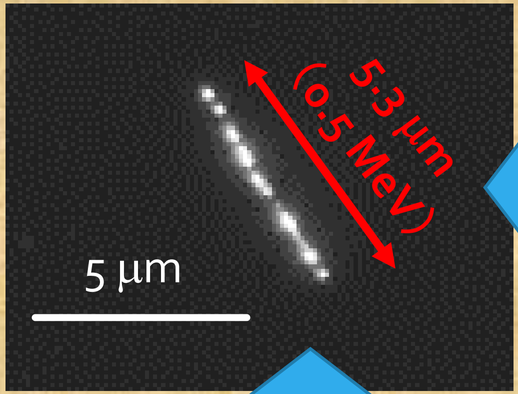


NIT calibration @ n-beam



NIT as a Neutron Detector

Recoil proton signal

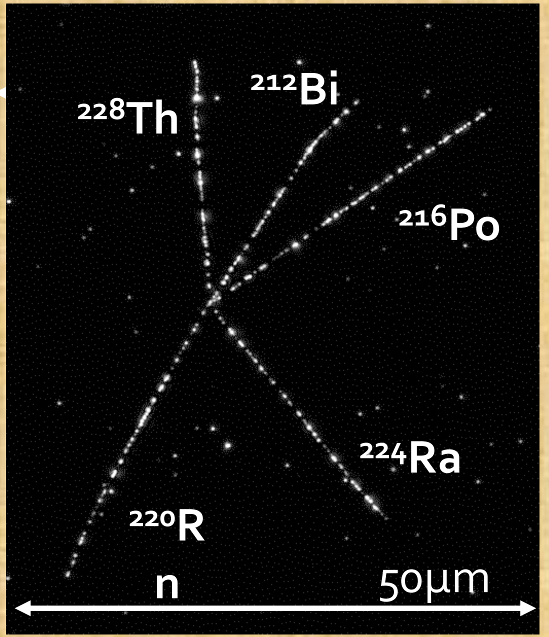


Topological or Range cut

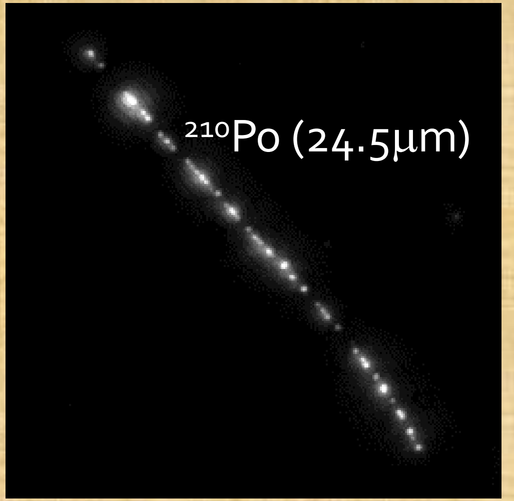
Clearly distinguishable

α-ray

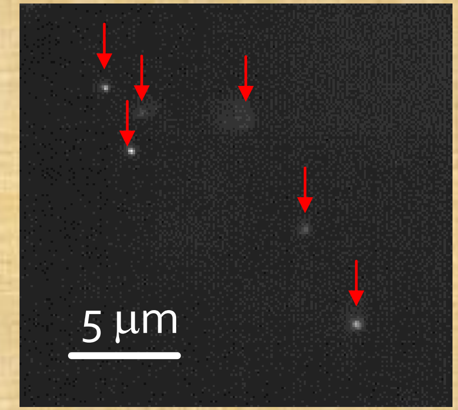
Th star ($^{228}Th \rightarrow {}^{208}Pb$)



Single-α in U series



γ-ray (β-ray)



Exposed 5×10^7 γ-ray/cm^2 from ^{241}Am (5 years accumulation of environmental γ-ray)

✓ **Environmental γ-rays cannot become background**

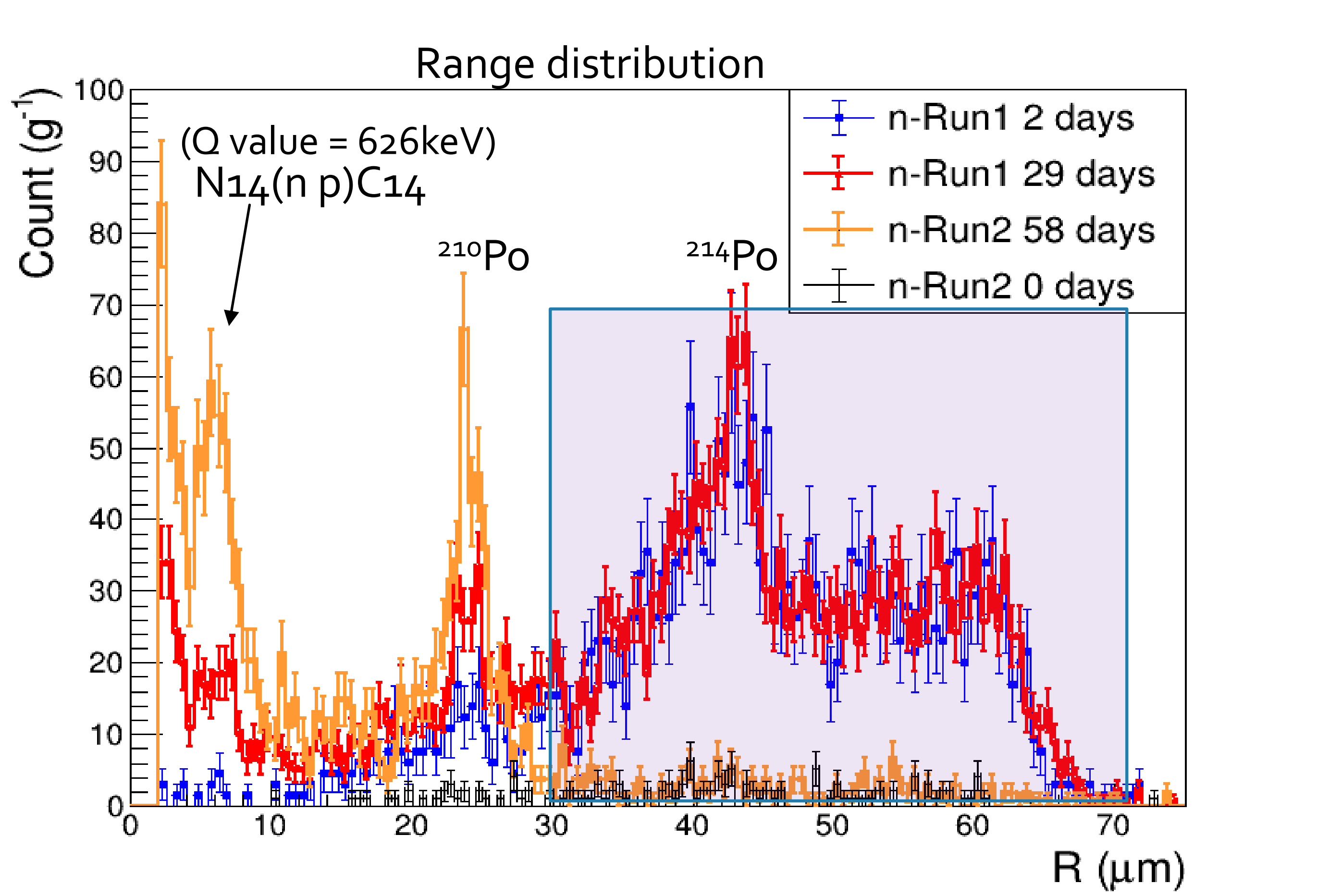
✓ **There is no background in sub-MeV region (2 ~ 14 μm → 0.25 ~ 1 MeV in proton energy)**

✓ **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

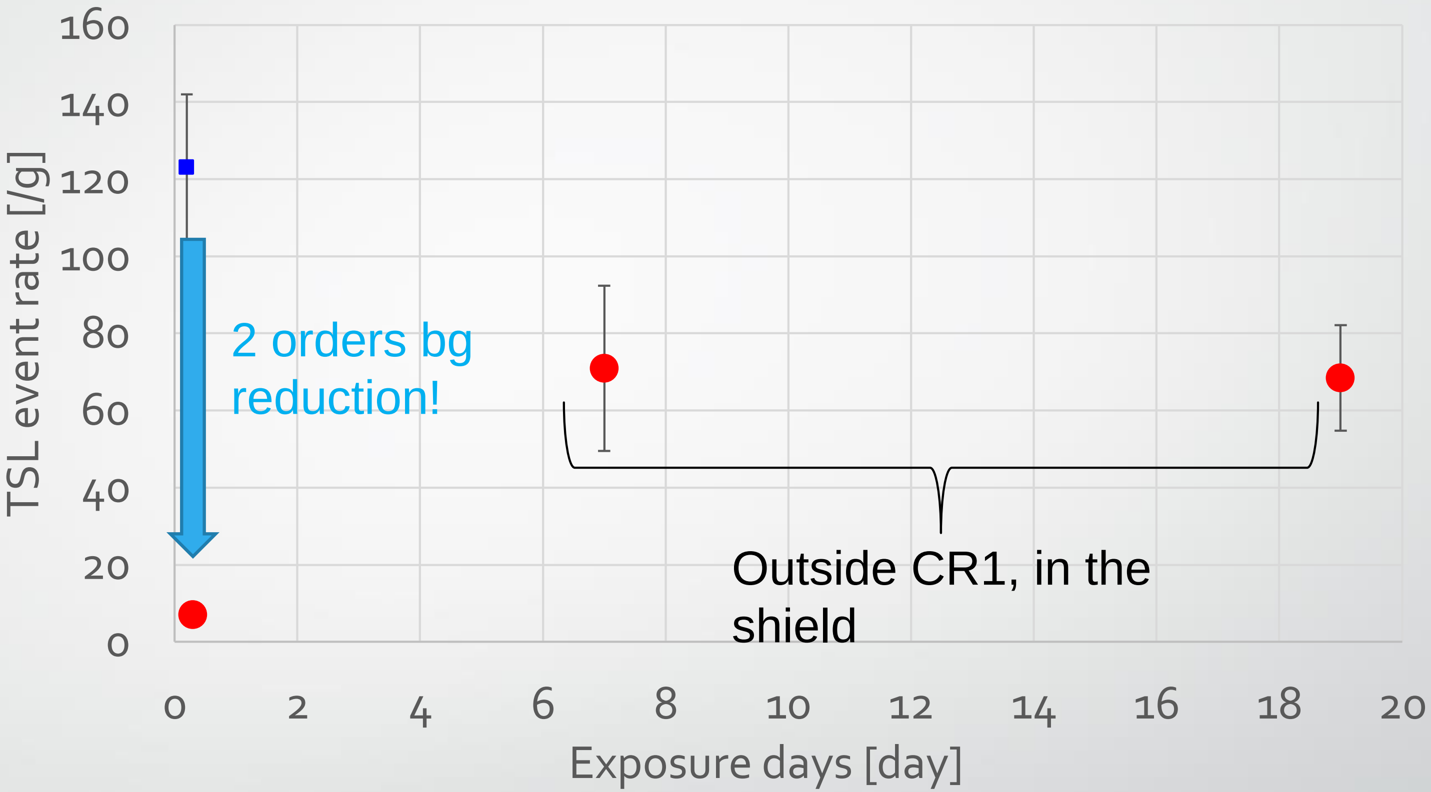
Time independent Alpha tail associated with emulsion production phase

- 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 conditions, has <u>disappeared</u> in the clean one!**



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

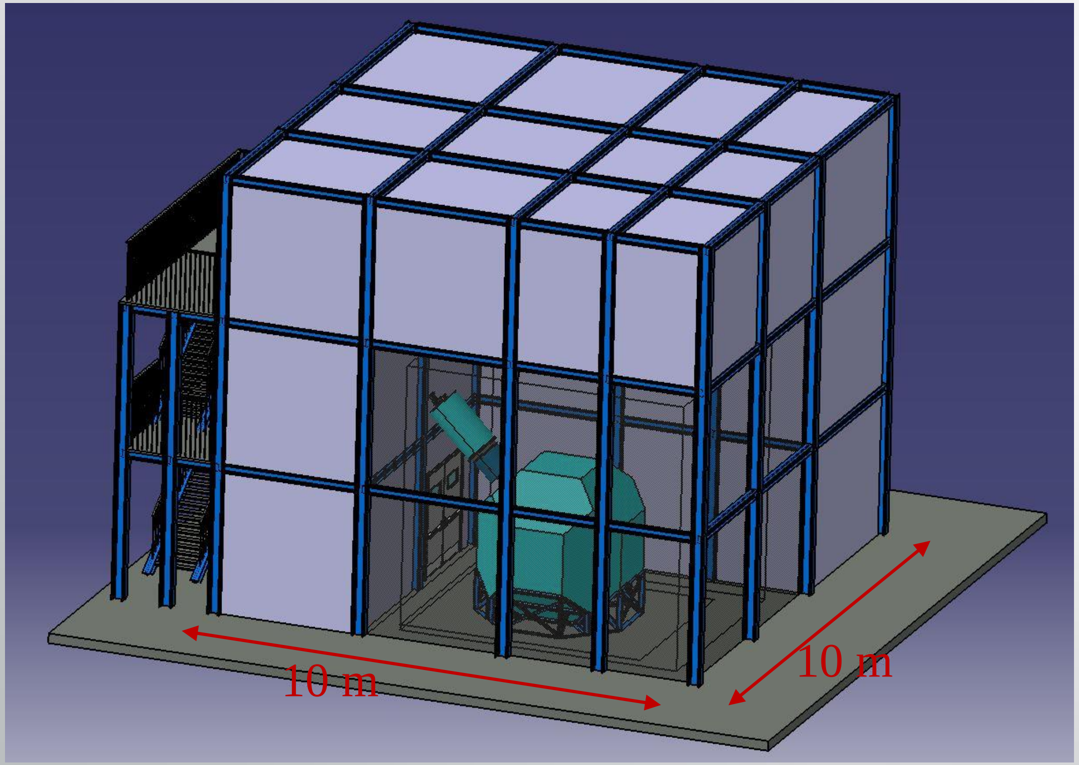
Measurements in 2023 using Rn-free condition

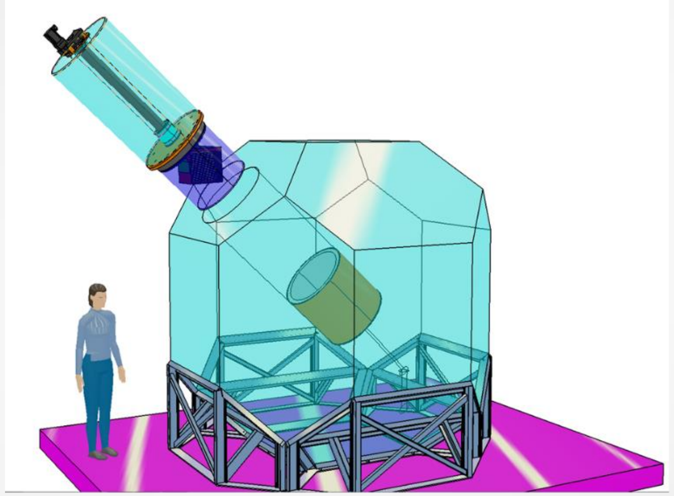


Important confirmation of the α as the source of the offset background, down to the expected level!
Results compatible with no increase of the background inside the shield as expected
Increase of the background while moving away from CR1
To make a shielded tests in CR1

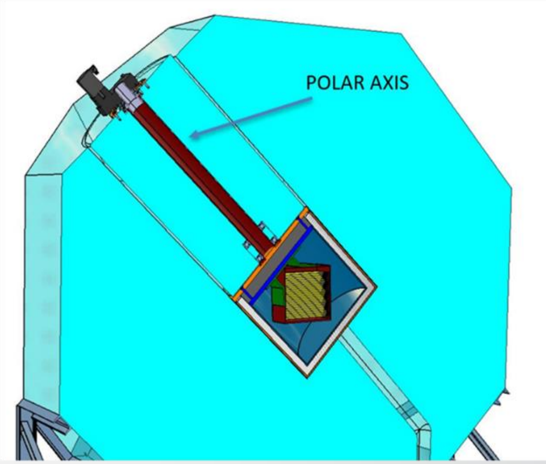
Future facility for NEWSdm: 10kg and beyond

Emulsion facility and shielding with an equatorial telescope

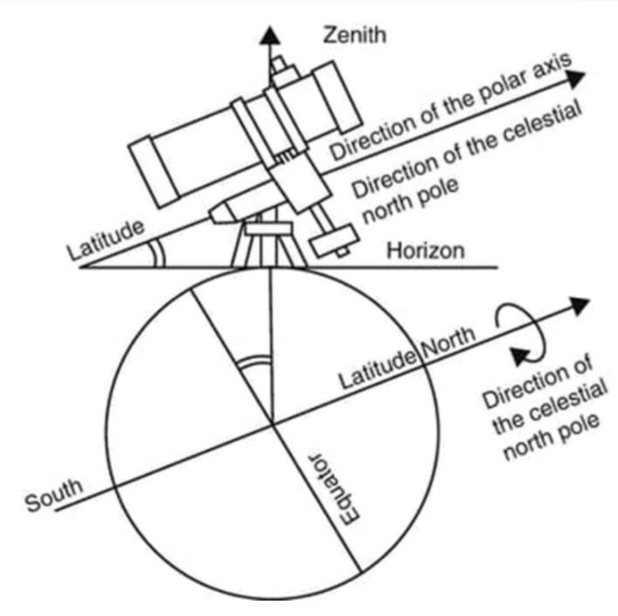


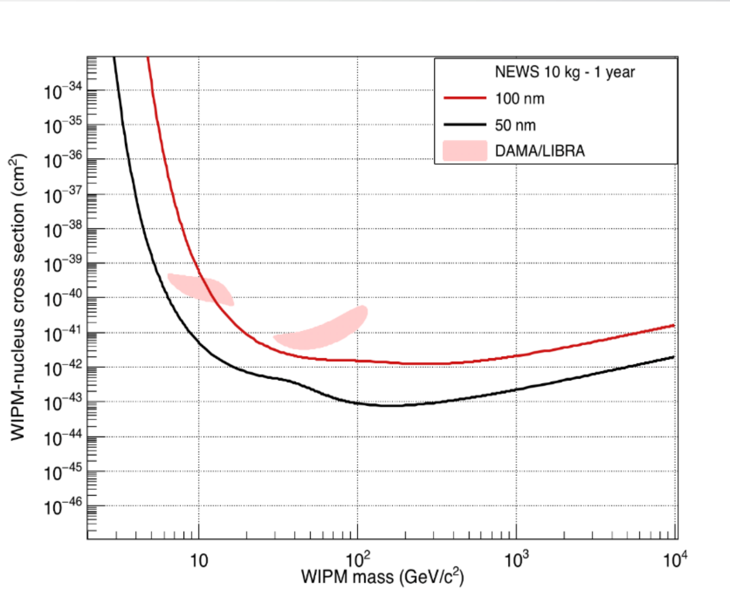


(a)



(b)

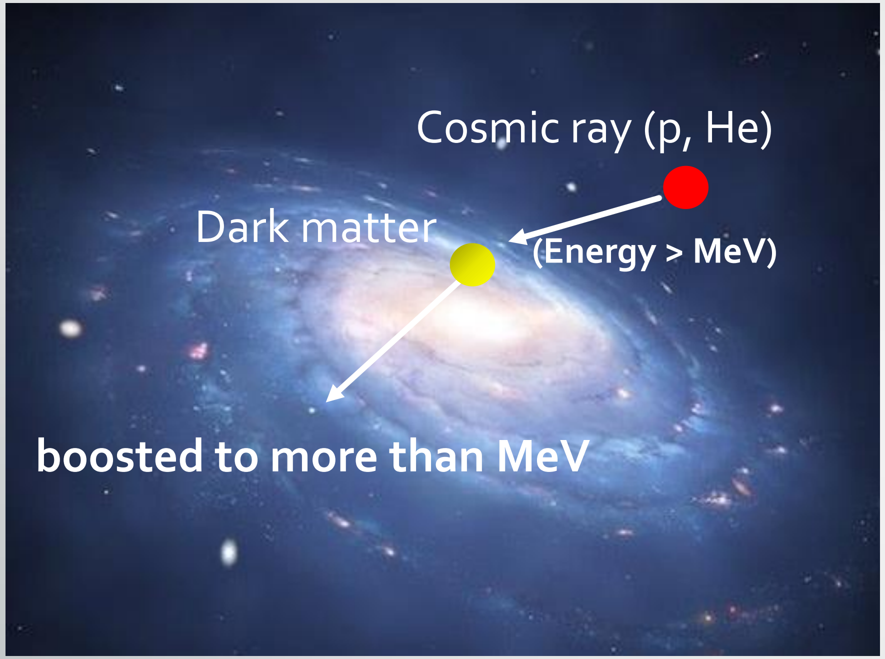


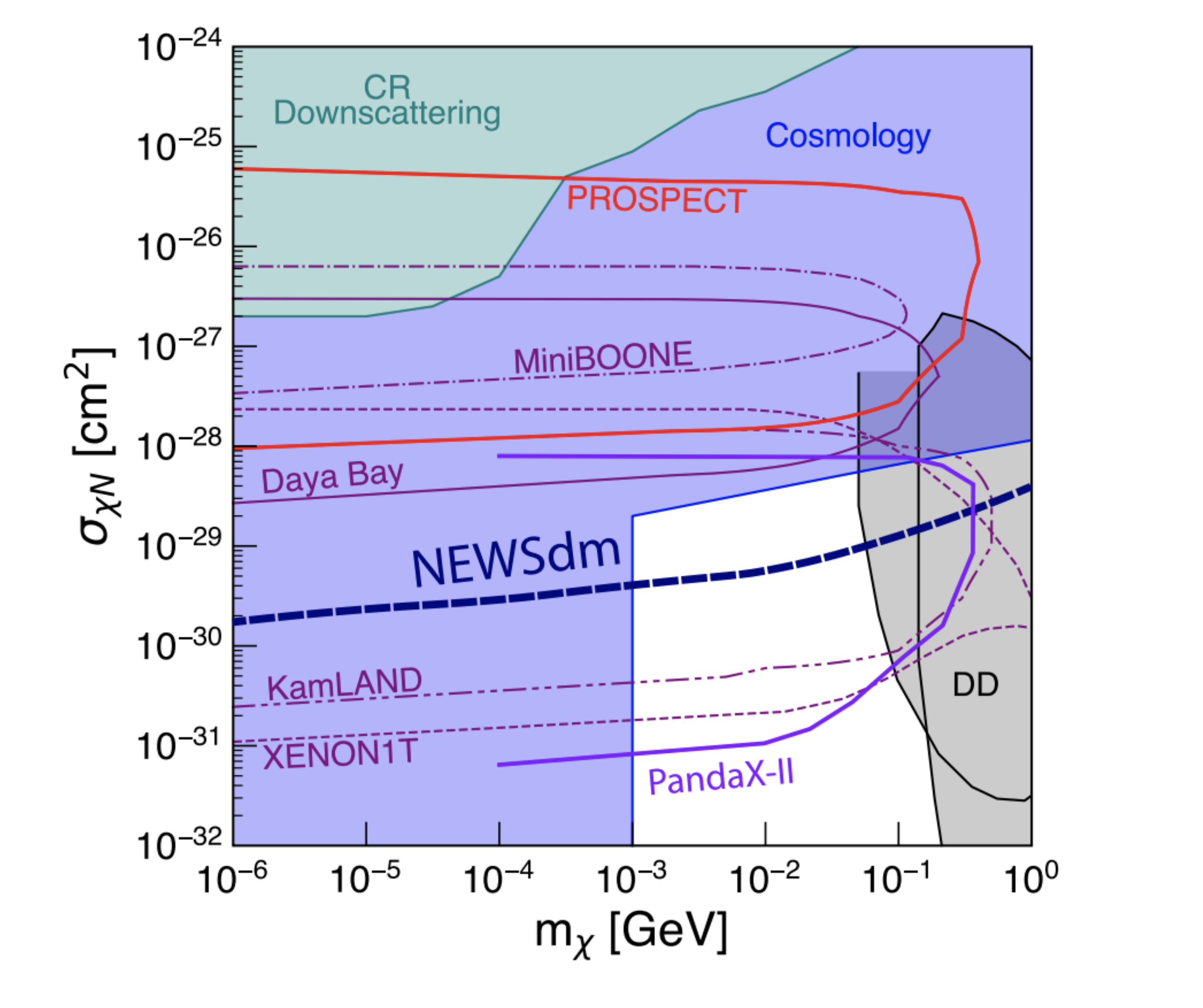


- Distributed setup with re-use of the existing facilities is possible and under consideration
- CDR in submission phase

10 kg emulsion detector sensitivity to boosted DM

https://iopscience.iop.org/article/10.1088/1475-7516/2023/07/067/pdf





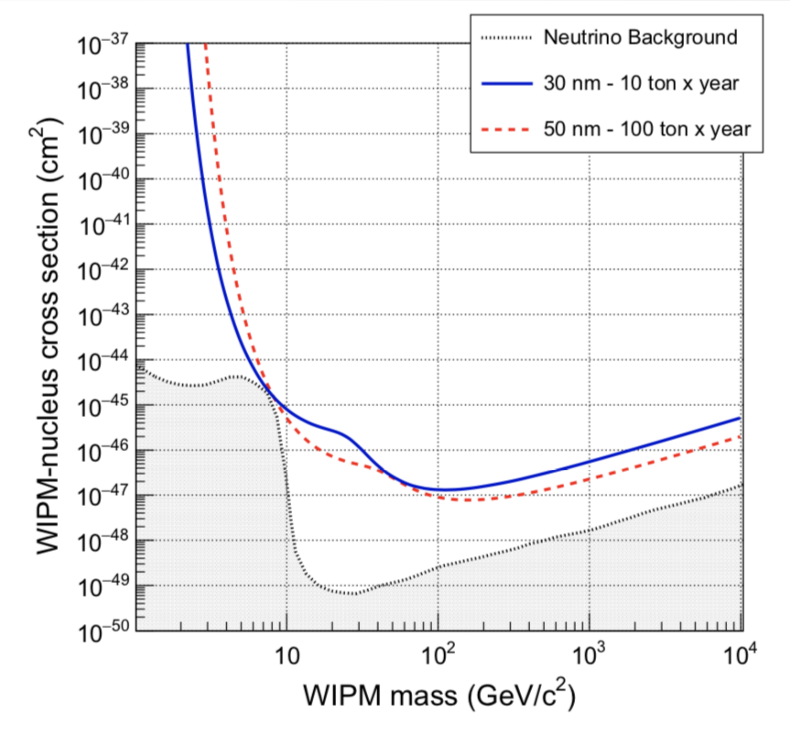
Sensitivity curves of the 10 kg NEWSdm detector for 1 year of exposure at the surface (Assergi) in comparison to other experiments. The boundaries corresponding to three H and CNO recoil events with track lengths of more than 70 nm.

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

Conclusion

- 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 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!

Backup

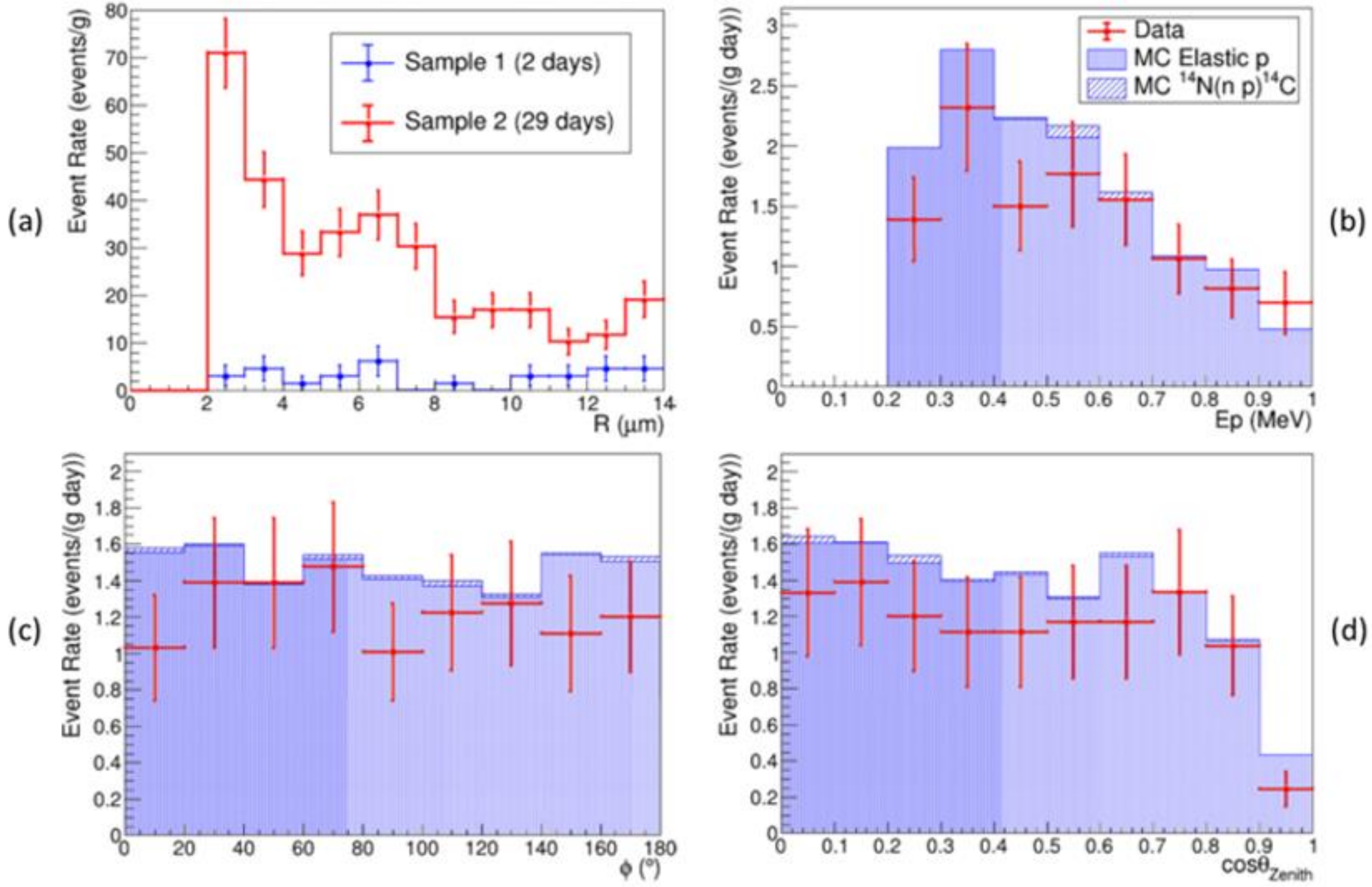


Figure 3.(a) Range distribution of recoil protons in the sub-MeV region for Sample 1 (2 days, blue) and Sample 2 (29 days, red) at LNGS. (b-d) Sub-MeV neutron measurement results after subtracting the data of Sample 1 from Sample 2 for an equivalent exposure of 27 days. For the MC simulation, neutron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

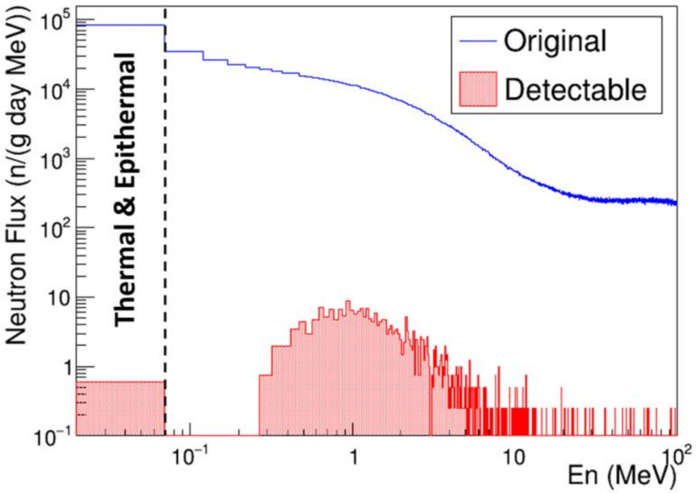
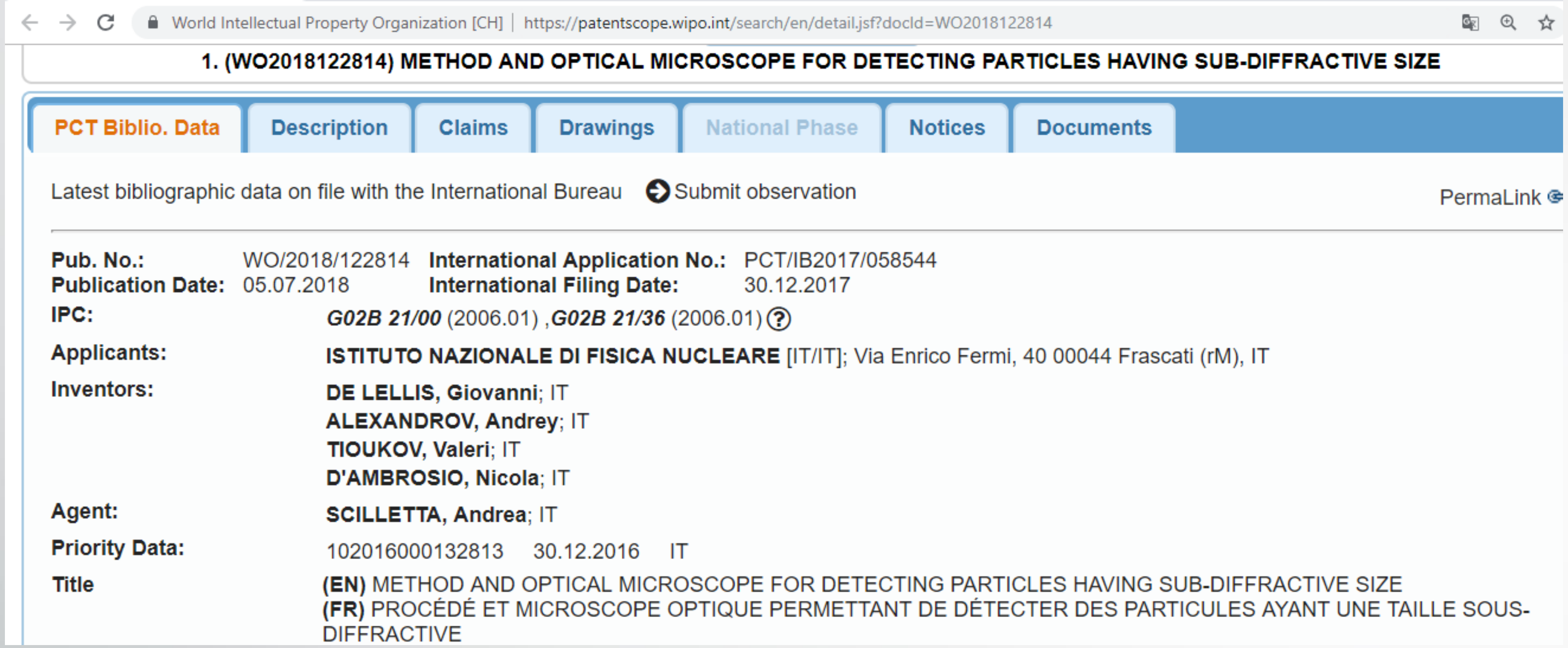


FIG. 9. Detectable neutron spectrum in NIT with 1 (g day) exposure at LNGS surface laboratory estimated by a MC simulation based on GEANT4. The blue line is the original energy of the incident neutrons, and the red filled histogram is the neutron spectrum accounting for the selection and the detection 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) Environmental sub-MeV neutron measurement at the Gran Sasso surface laboratory with a super-fine-grained nuclear emulsion detector

Super resolution: 3-dimensions!



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

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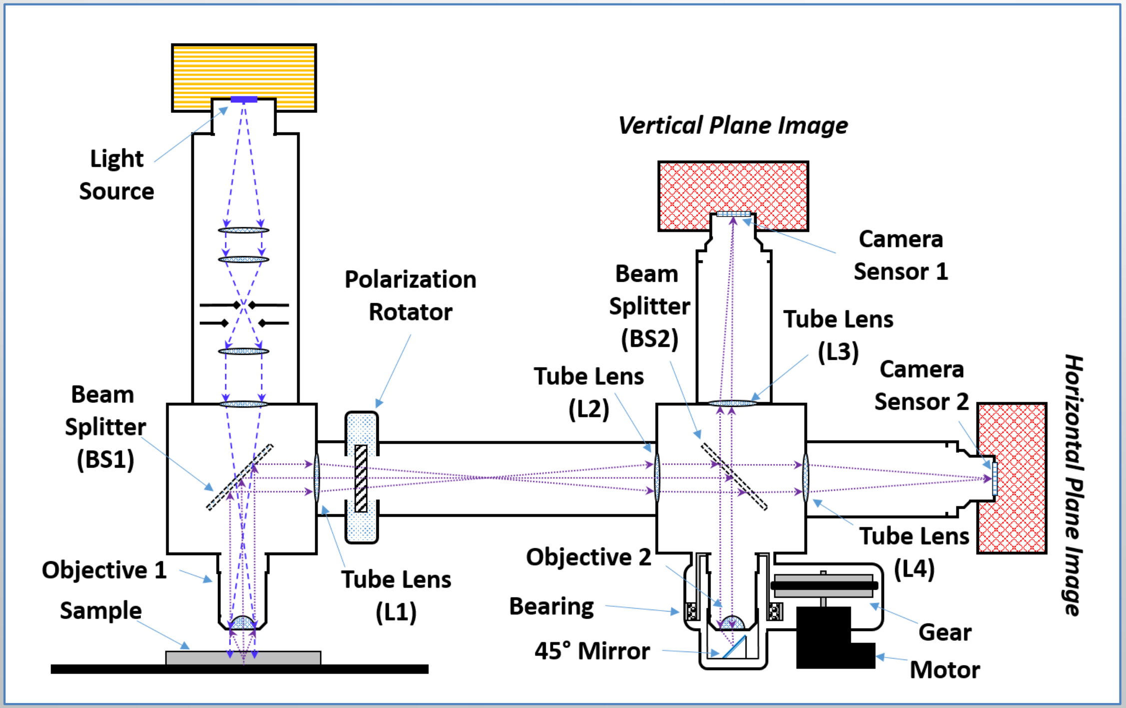
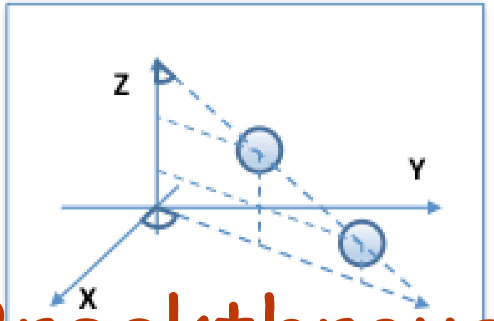
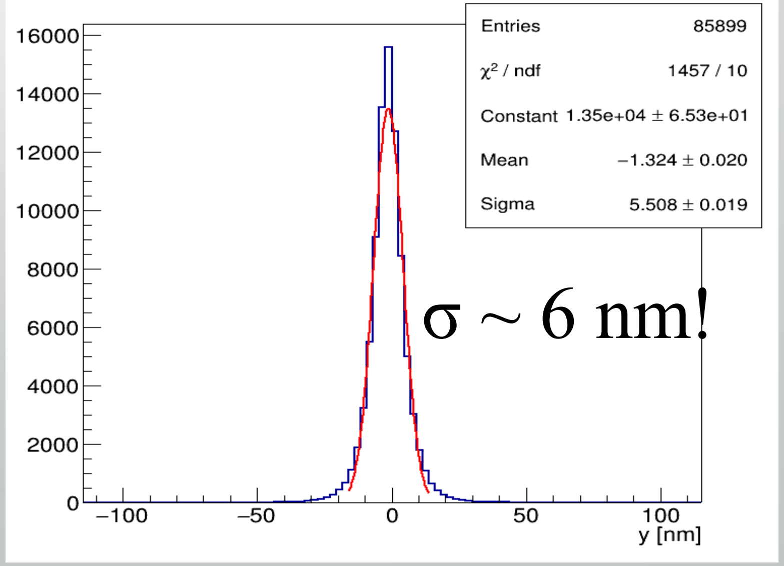
Title **(EN)** METHOD AND OPTICAL MICROSCOPE FOR DETECTING PARTICLES HAVING SUB-DIFFRACTIVE SIZE
(FR) PROCÉDÉ ET MICROSCOPE OPTIQUE PERMETTANT DE DÉTECTER DES PARTICULES AYANT UNE TAILLE SOUS-DIFFRACTIVE



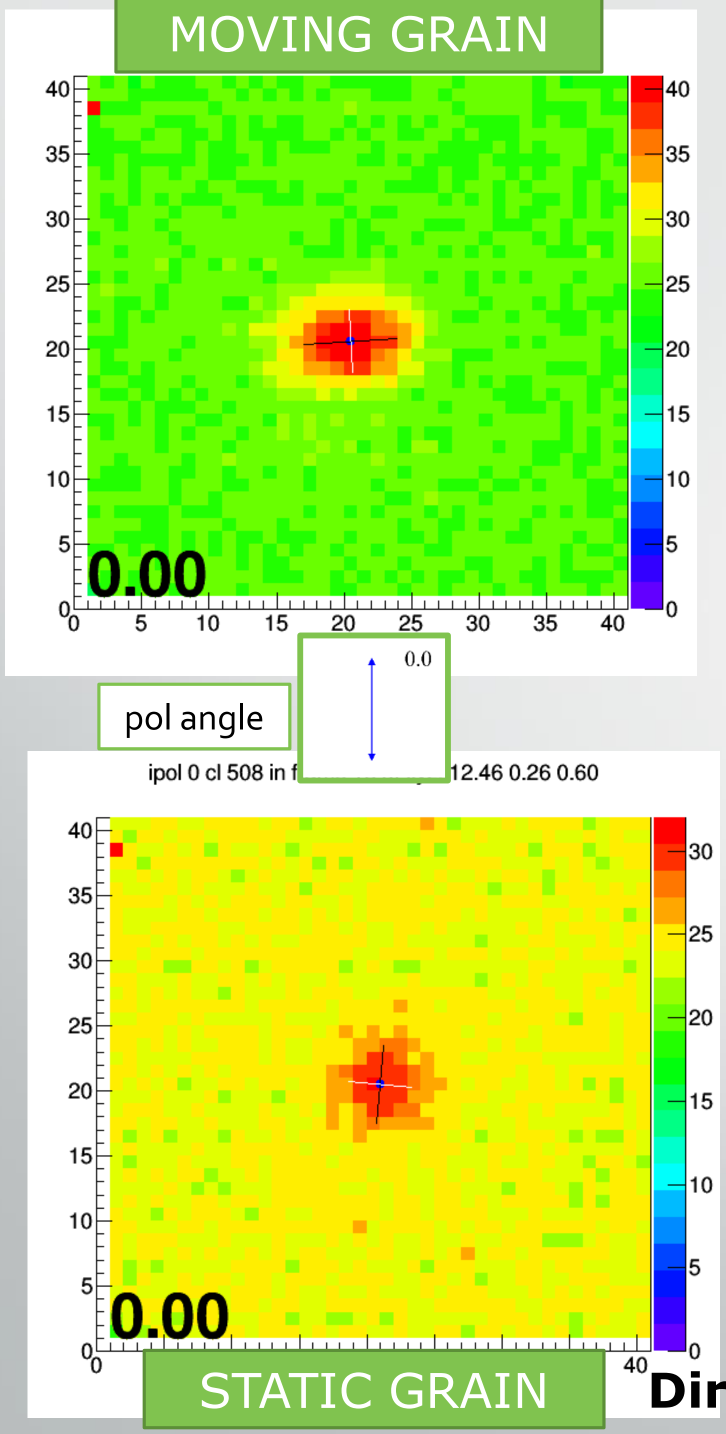


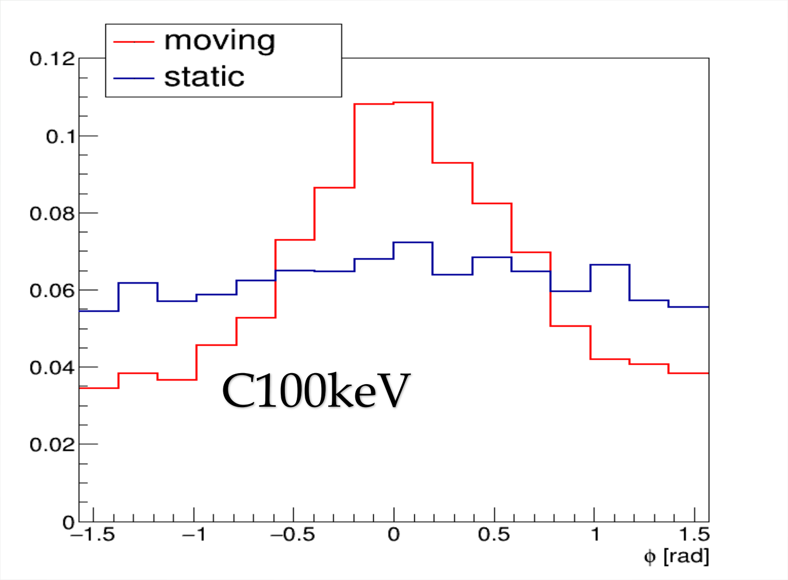
Breakthrough

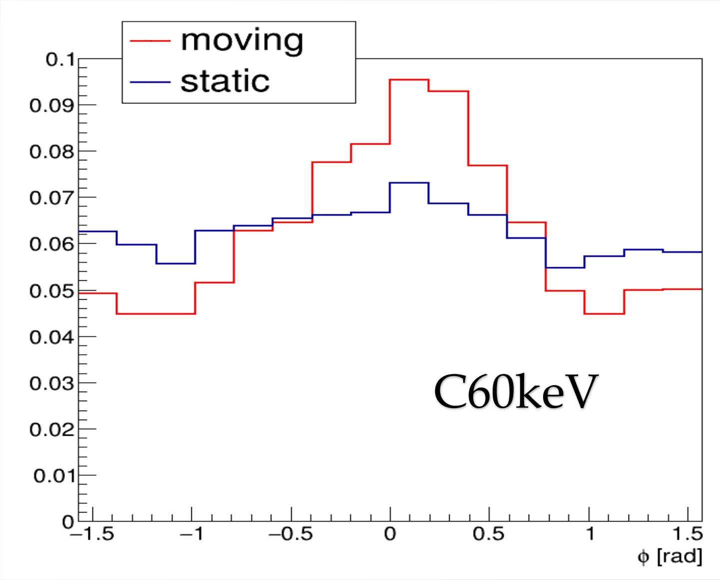


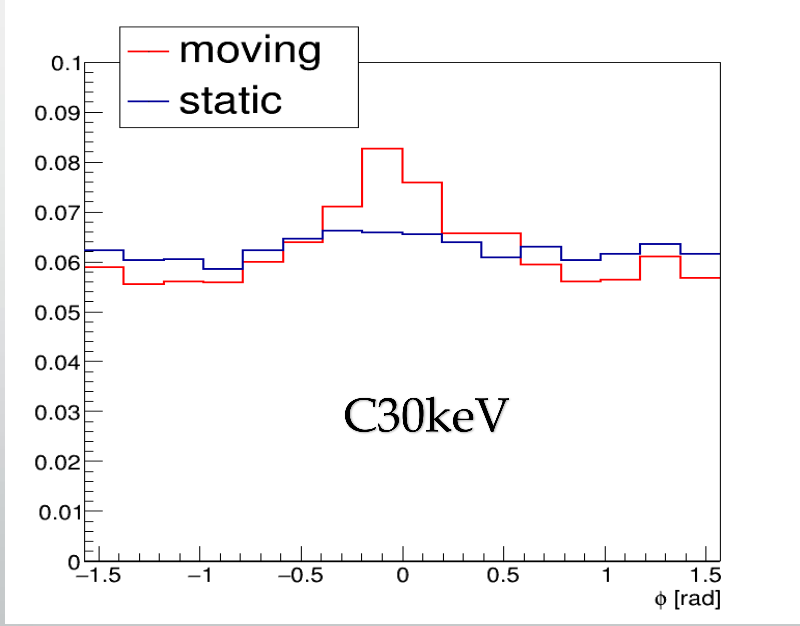
$\sigma \sim 6$ nm!

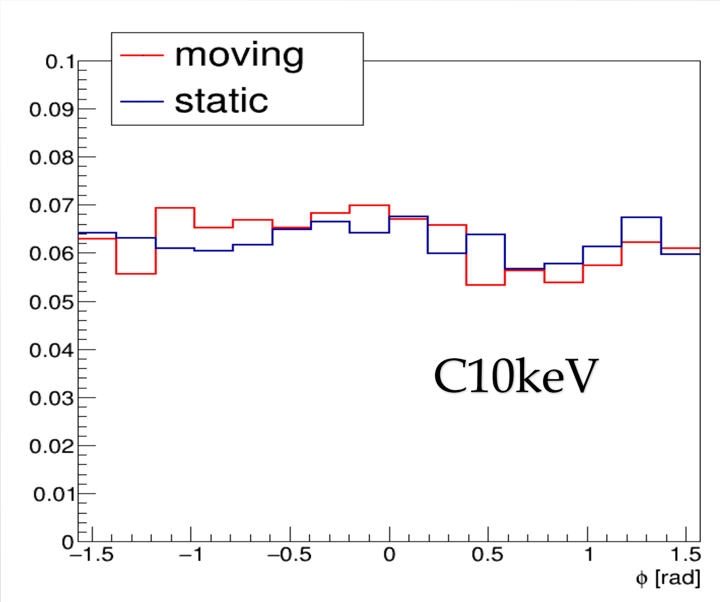
Plasmon analysis of isolated grains







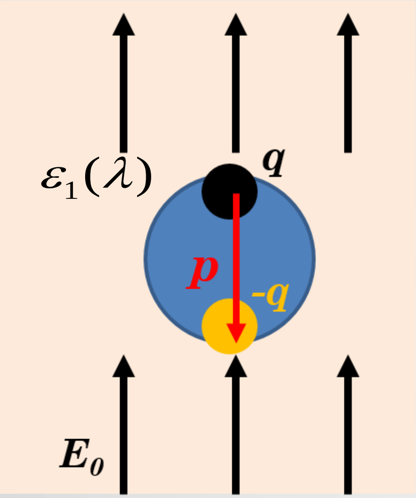




Directionality demonstrated with Carbon ions down to 30 keV

LSP (Localized Surface Plasmon) resonance

Annu. Rev. Phys. Chem. 58 (2007) 267-297



dipole in metallic particle

dipole moment

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

resonance

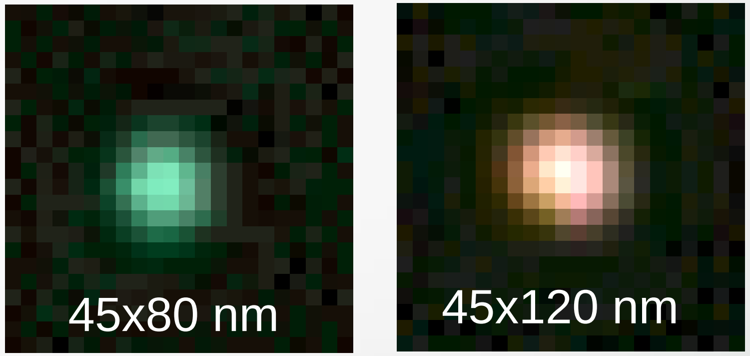
$$\varepsilon_1(\lambda_l) + 2\varepsilon_m(\lambda_l) \approx 0$$

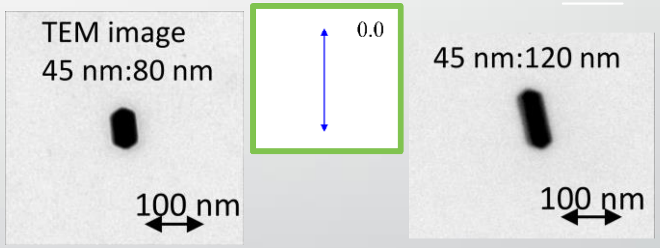
Appl. Phys. Lett. **80**, 1826 (2002)

Ag grain size → resonance wavelength

Colored optical image of silver rod

*polarization rotating





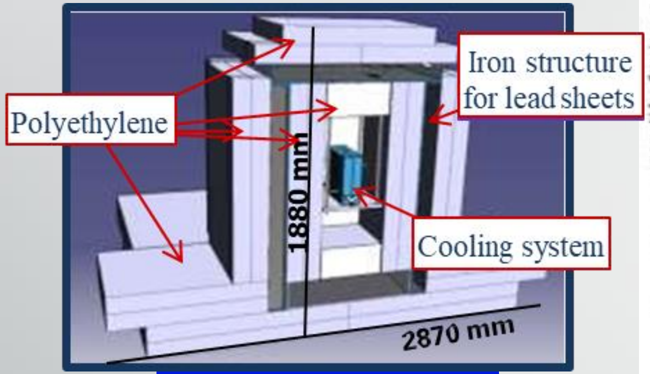
~45 nm : blue
~80 nm : green

~45 nm : blue
~120 nm :orange–red

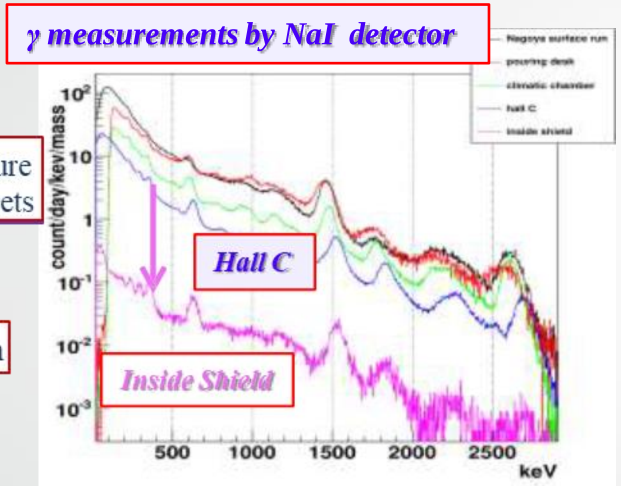
Backgrounds

Environmental

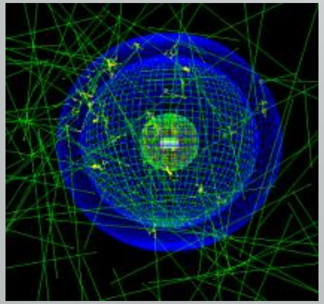
Current shield



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.)



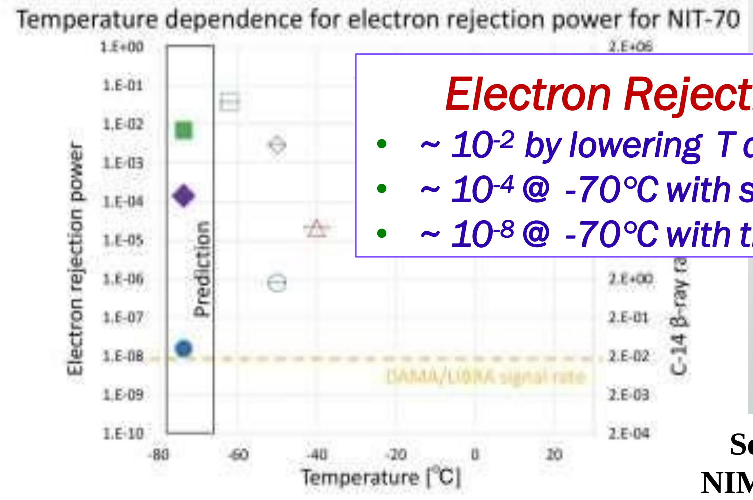
10 kg detector shield (1 m HDPE @LNGS)

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 [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

Other (not DM) applications for NIT and emulsion technology

- Neutron directional measurements in sub-MeV region
- Microscopy and fast scanning systems development
- Neutrino physics: SND@LHC experiment ongoing at CERN
- Medical physics: FOOT (Fragmentation On Target) project
- QUPLAS for antimatter gravitation study
- Muon radiography