DIRECTIONAL DARK MATTER SEARCH with *NEWSdm*

International Conference on Neutrinos and Dark Matter (NuDM-2022)

25-28 September 2022
Sharm El-Sheikh, Egypt

Giovanni ROSA

National Institute for Nuclear Physics (INFN)

Roma (Italy)

On behalf of the NEWSdm Collaboration

The NEWSdm COLLABORATION

81 physicists
19 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
Univ.: Napoli, Roma,
Potenza, Benevento

SOUTH KOREA
Gyeongsang University

TURKEY
METU Ankara

The NEWSdm Experiment

Nuclear **E**mulsions for **W**IMP **S**earch
with **d**irectional **m**easurement

Website:
news-dm.lngs.infn.it

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

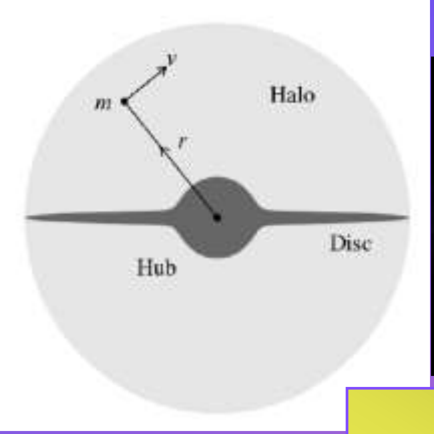
- Direct **dark matter** search with **directionality**
- Target: **nuclear emulsion film**
- **Nanometric** granularity in solid state
- Unprecedented **position resolution**
- **High-speed** scanning

- Physics goal at reach
  - 10 kg·year → **DAMA region**
  - Boosted Dark Matter scenarios
- Scalability and discovery potential
  - 10–100 ton·year → **neutrino floor**

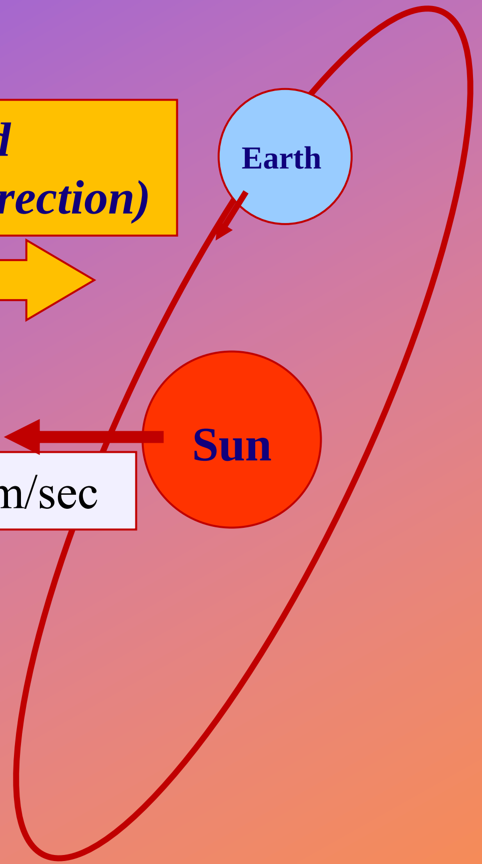
"The" Physics case

Standard Halo WIMP paradigm

- **Mass range GeV – TeV**
- **Flux @ 100 GeV/c^2 ~ 10^5 / cm^2 · sec**
- **Local energy density ~ 0.4 GeV/cm^3**
- **Maxwellian velocity < escape 600 Km/s**
- **Weak coupling cross section < 10^{-40} cm^2 per nucleon**



WIMP wind (Cygnus Direction)



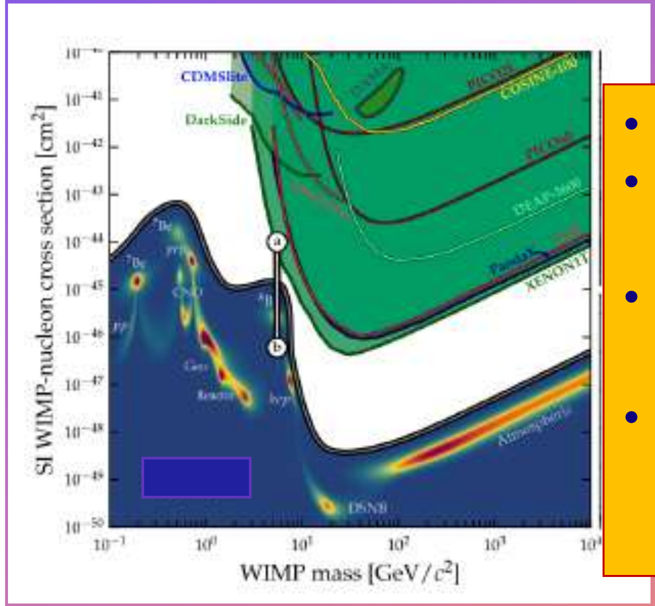
~250km/sec

@ A terrestrial detector

The WIMP velocity combines with:

a) Sun velocity wrt halo
➔ ***non-isotropic flux***

b) Earth velocity in the solar system
➔ ***seasonal modulation***



- *Widely explored experimental region*
- *Challenge: scale-up detector mass keeping negligible background*
- *Challenge: detection threshold for lower WIMP mass*
- *Ultimate limitation: **neutrino "fog"** (isotropic, already indistinguishable background)*

Unique way out:

Exploit the signature of

Directionality

Phy. Rev. D 81, 096005 (2010)
Phys. Rep. 627 (2016) 1

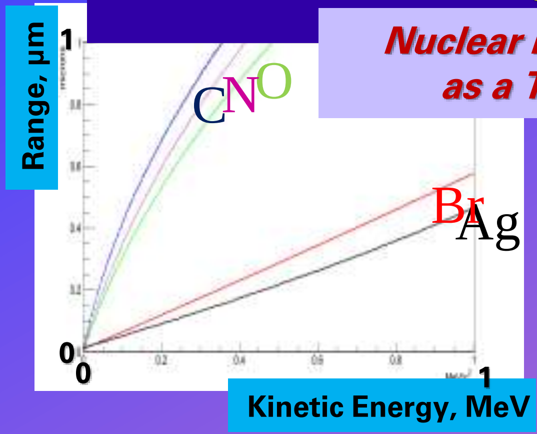
Detection Principle

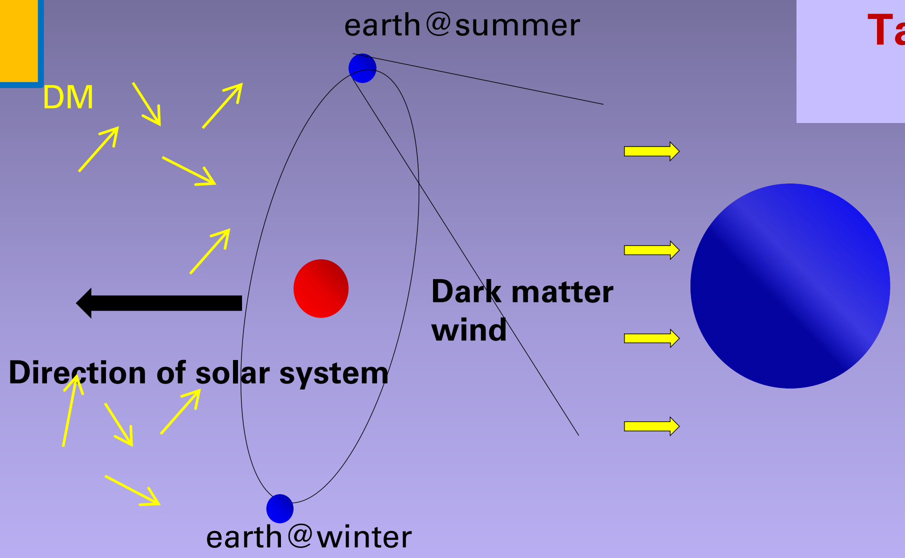
Advantage of solid state:
"small", **compact target**

Challenge of **"lighter"** (sub-TeV) **DM**:
sub-MeV kinetic energy of recoil nuclei

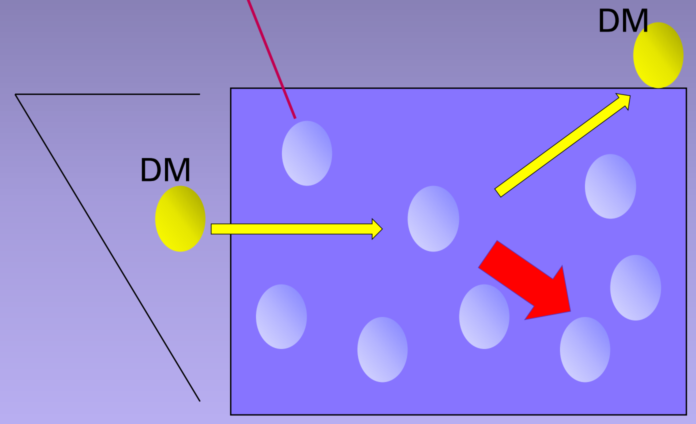
➔ ***sub-micron track length !***

Nuclear Emulsion as a Target





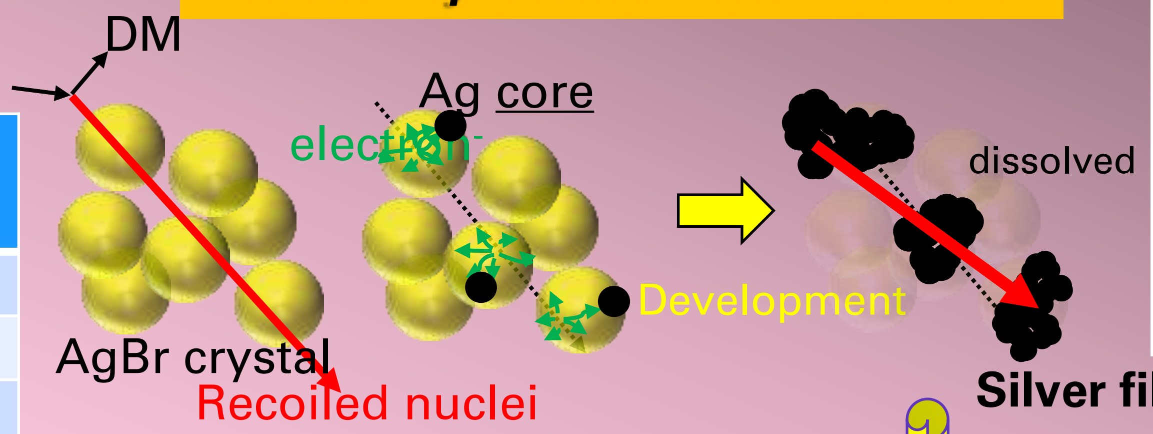
Target nuclei, any medium (gas,liquid,solid state)

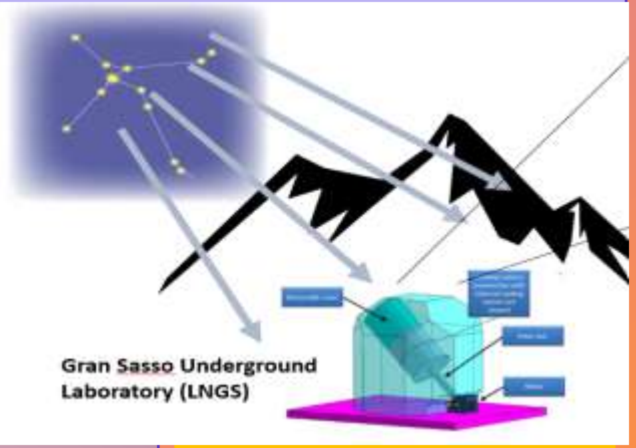


Element	Mass fract. [%]	Atomic fract. [%]
Ag	41.5	8.4
Br	29.7	8.1
I	1.9	0.3
C	12.3	22.7
N	3.7	5.2
O	9.2	12.5
H	1.8	42.8

heavier DM (Ag, Br, I); Main target (C, N, O); Neutron BDM (H)

Detection of recoiled nuclei as tracks





Looking for Dark Matter
In a Photographic Dark Room

Continuous sensitivity (no time stamp):

➔ keep the Target "pointed to Cygnus" by a rotating telescope

History and evolution of Nuclear Emulsion

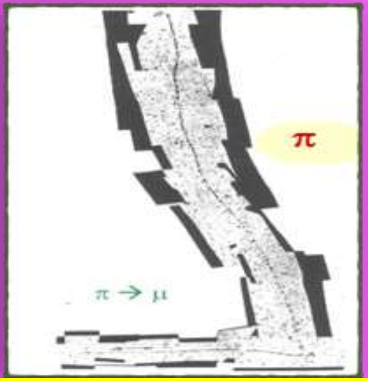
- A last-century, "venerable" detector, with still unrivalled spatial resolution
- Big improvements from early CR records to neutrino oscillations at accelerator

...In Ancient Epoch Slaves called "undergraduate students"

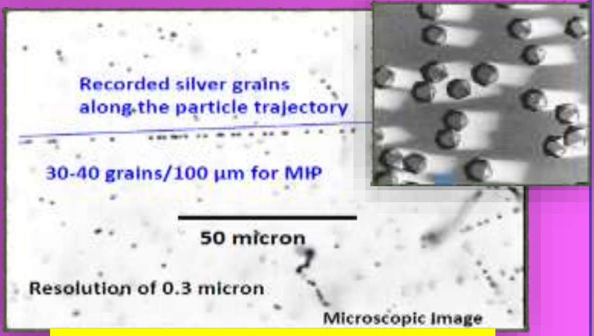
Performed eye-scan and recorded data by hand

But under a New Dinasty...

Microscopes were automated and driven by computers



Discovery of the **Pion (1947)...**



AgBr crystal size 0.2-0.3 μm

.Discovery of $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode (OPERA, 2015)

"traditional" detector & the ultrafast optical scanning adopted for OPERA

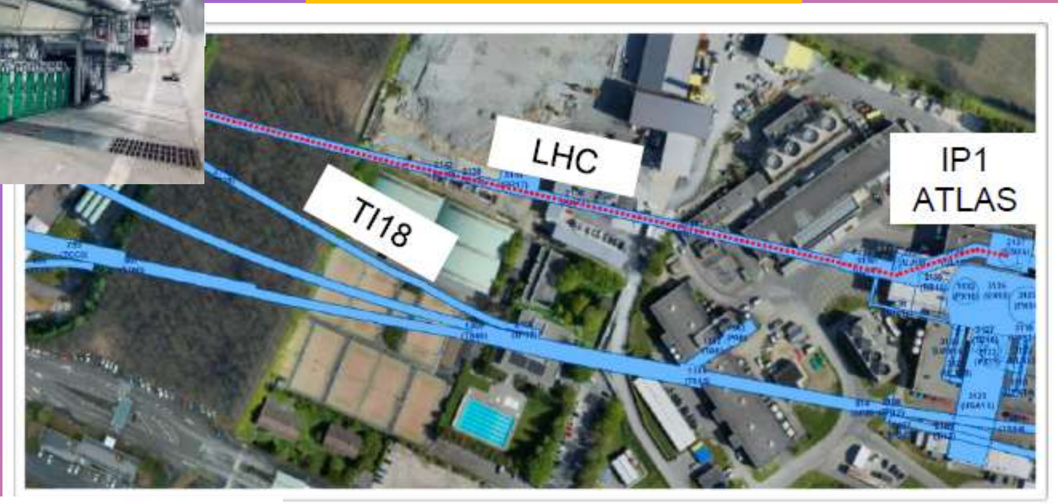
suitable for fixed-target Search for Hidden Particles (SHiP)@CERN and Neutrino study

➔ Futher *R&D* in progress...

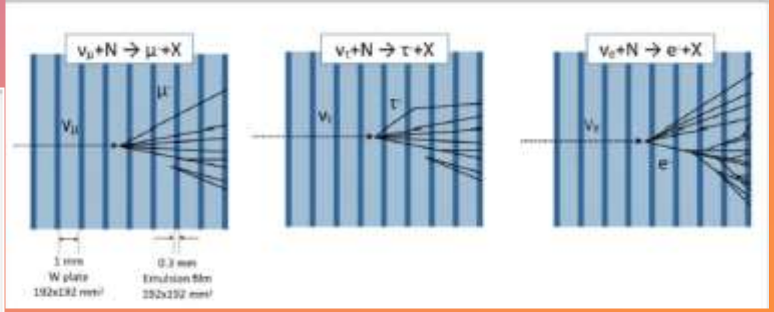
Scattering and Neutrino Detector SND@LHC

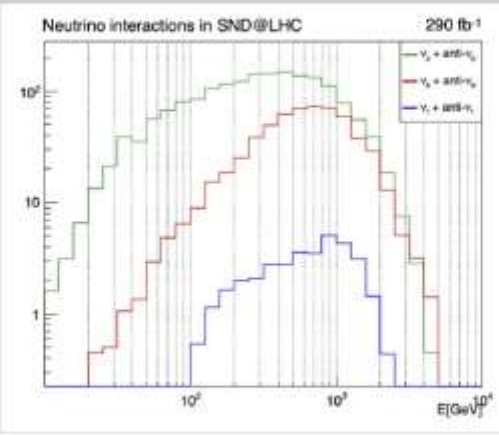
Website: https://snd-lhc.web.cern.ch/

Located in TI18 transfer tunnel



Target: *ECC "bricks" Tungsten/Emulsion*, 830 Kg
Acceptance: 7.2 < η < 8.4, slightly off-axis





Run3 Data taking 2022-2025 just started!

- *Aiming to collect ~2000 ν events @290 fb^{-1}*
- *ν cross-section & charm production @High E*
- *Explore BSM scenarios for hidden sector*

A Novel Type of Emulsion: NIT

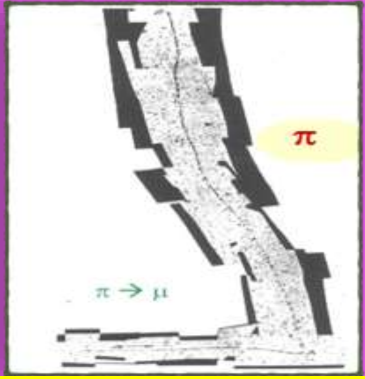
- A last-century, "venerable" detector, with still unrivalled spatial resolution
- Big improvements from early CR records to neutrino oscillations at accelerator

...In Ancient Epoch Slaves called "undergraduate students"

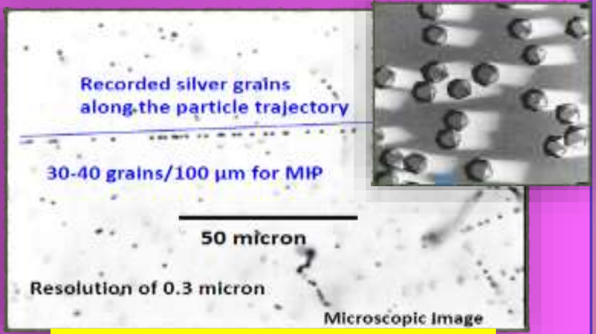
Performed eye-scan and recorded data by hand

But under a New Dinasty...

Microscopes were automated and driven by computers



Discovery of the Pion (1947)...



AgBr crystal size 0.2-0.3 μm

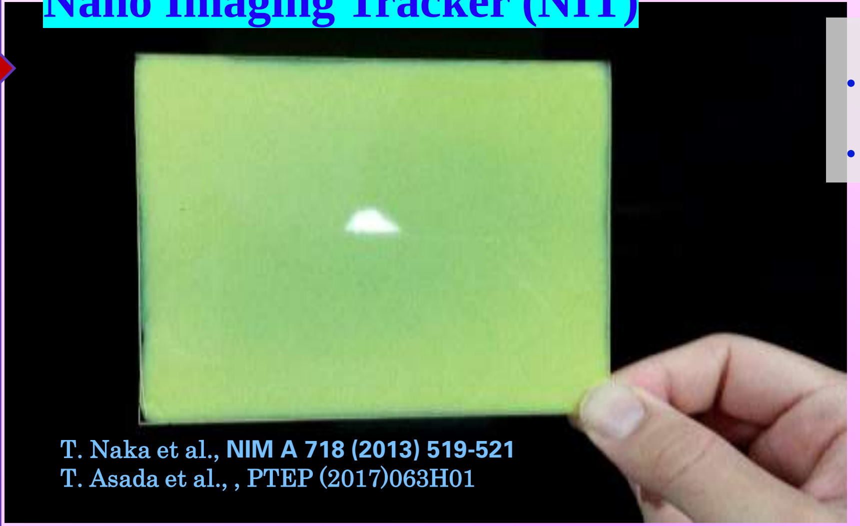
.Discovery of $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode (OPERA, 2015)

"traditional" detector & even the ultrafast optical scanning adopted for OPERA

not suitable/not enough for DM detection

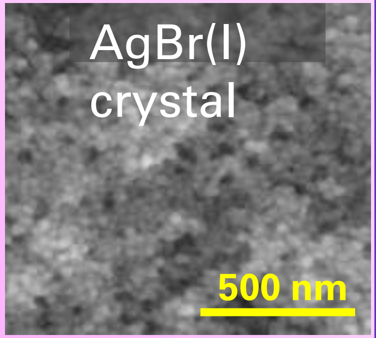
➔ intense (and succesfull!) *R&D*, still in progress...

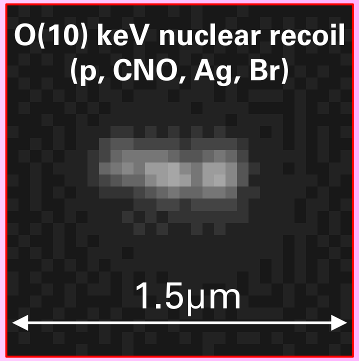
Nano Imaging Tracker (NIT)

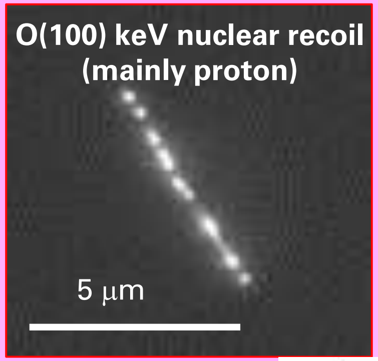


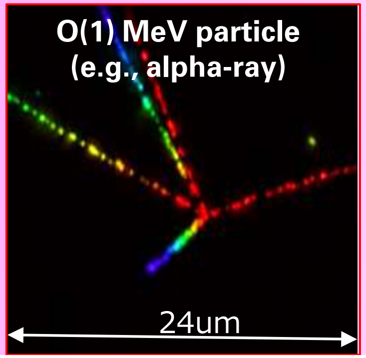
Properties

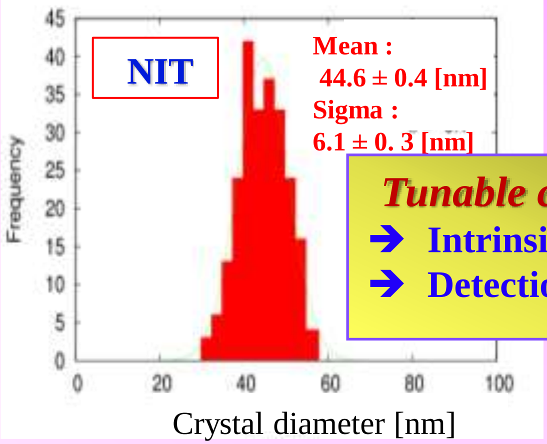
- AgBr(I) Crystal size: ~ 70 nm (σ ~ 8 nm)
- Density : 3.1 g/cm3







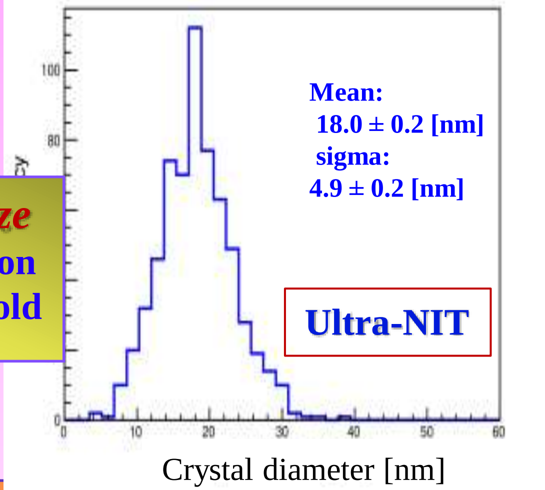




Tunable crystal size

➔ Intrinsic resolution

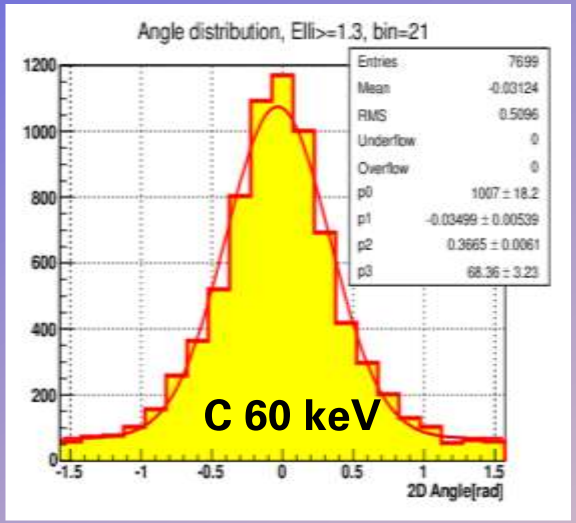
➔ Detection threshold



Nuclear recoil signal in NIT

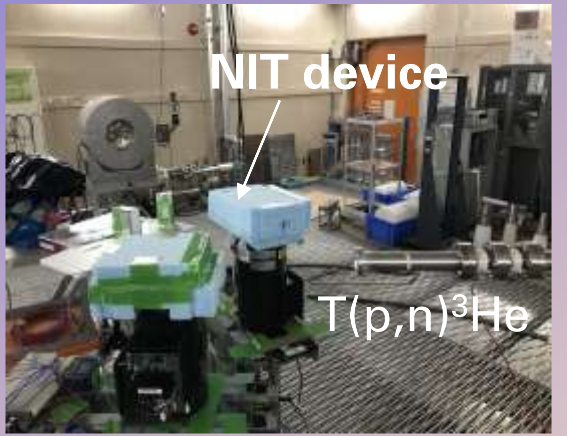
Demonstration of the Detection principle

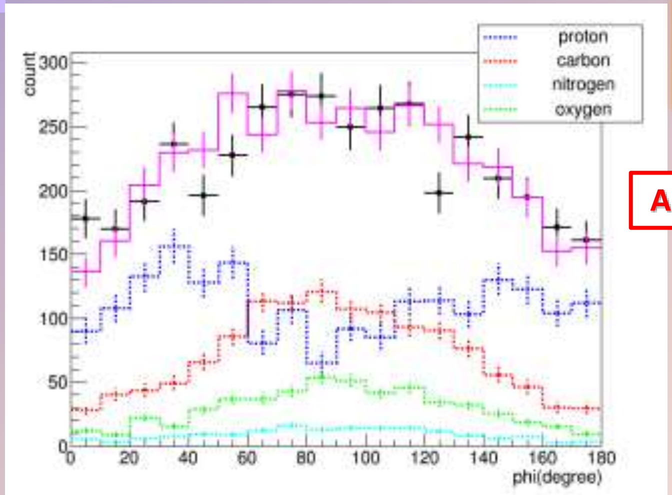
Ion-implantation

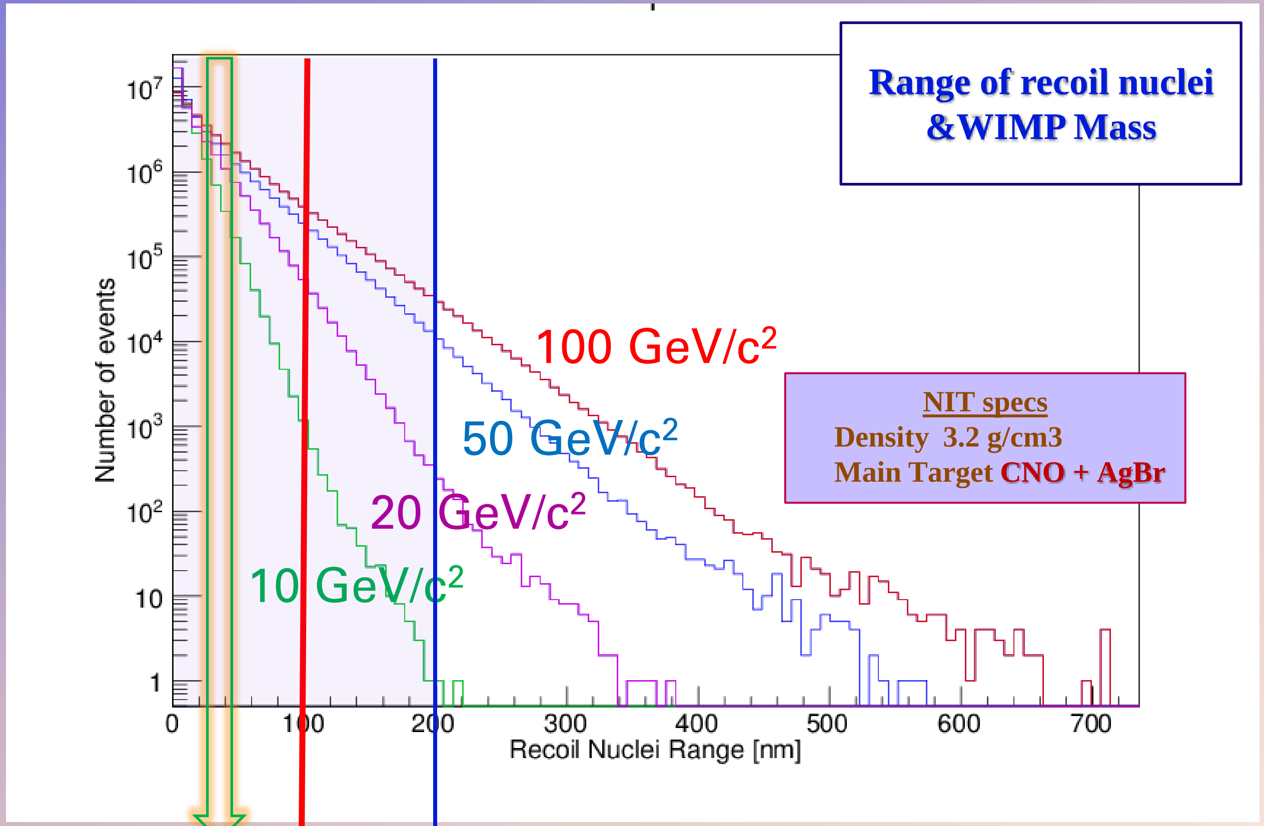


○

Nuclear recoil by neutron







NIT specs
Density 3.2 g/cm3
Main Target CNO + AgBr

Intrinsic resolution limit ~ crystal size

Normal limit of Optical Resolution

Achieved detection threshold

Tracking @ nanometric scale is challenging:

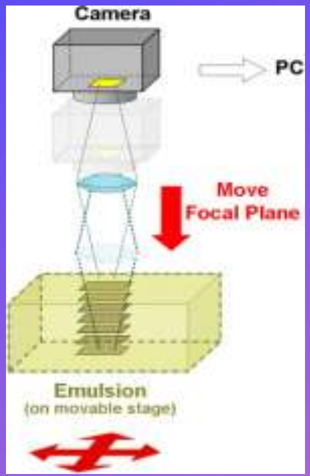
- **Tracks are made of 3-D aligned clusters of "bright" pixels**
- **Brightness in proportion of local energy deposit by ionizing particles**
- **Detection of very short (1÷3 clusters) tracks requires high rejection power of background**

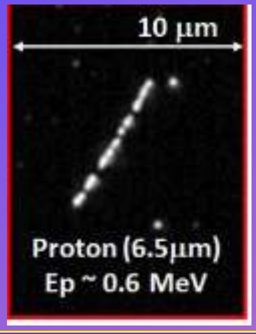
Signal and noise in NIT

3-D fast automated scanning ≡ High resolution tomography

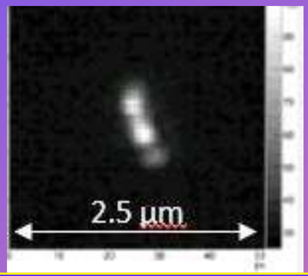
- ***Signal:*** Ionization path ↔ aligned clusters of bright pixels *(NIT not sensitive to m.i.p.!)*
- ***Noise:*** Dust, impurities, thermal noise ↔ random clusters of bright pixels
  + physics by local energy loss (e.g. electrons!)

➢ 2-D Image analysis based on grey-level, size & shape
➢ 3-D Track finding + Likelihood

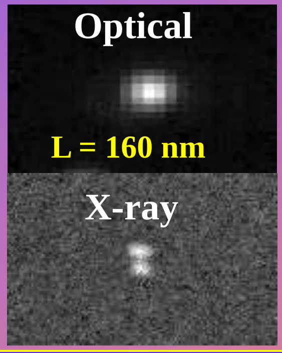




Long proton: easy



<100 keV C,N,O: difficult

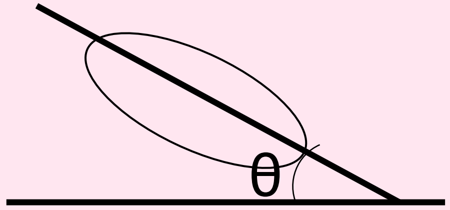


2 unresolved clusters: very hard!

Efficiency →	Resolution, Detection Threshold, Sensitivity
← ***Purity***	Rejection of Background (Instrumental & Physics)

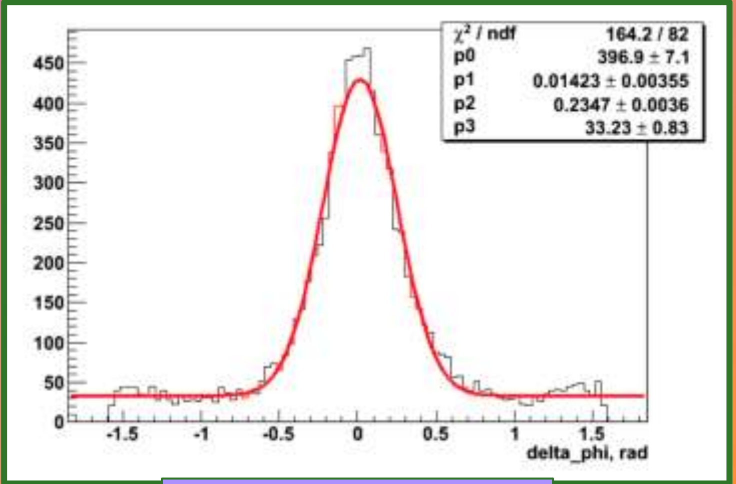
1 µm

Elliptical shape analysis



Direction detected!

dE/dx

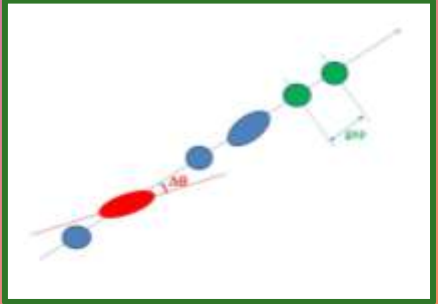


σ = 235 mrad = 13°

Demonstration of the Directionality

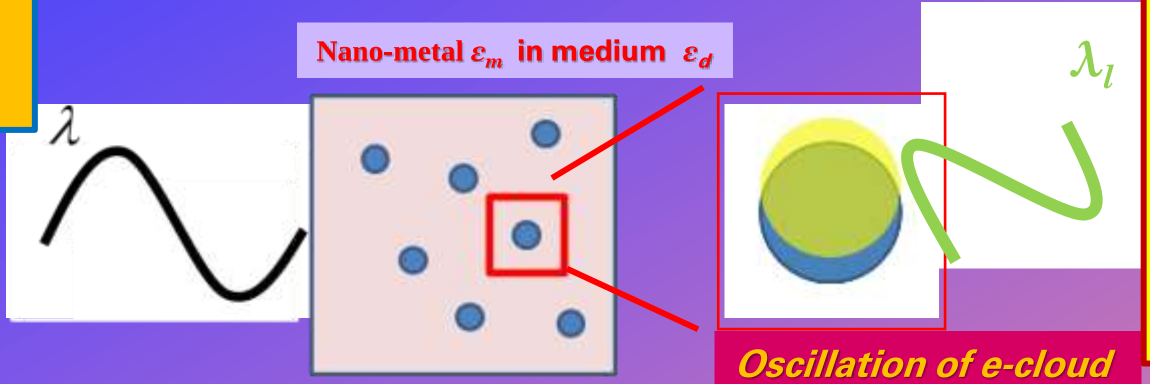
Assessment of angular resolution

- Neutron test Beam sample (FNS exposure)
- Compare clusters with elliptical (e > 1.1) shape with the proton recoil direction
- Scattering contribution negligible



From microscopy to nanoscopy
Localized Surface Plasmon Resonance

H.Tamaru et al ., Appl. Phys Lett. 80, 1826 (2002)
E. Betzig et al., Science 313, 1642 (2006)
Nobel Prize for Chemistry 2014

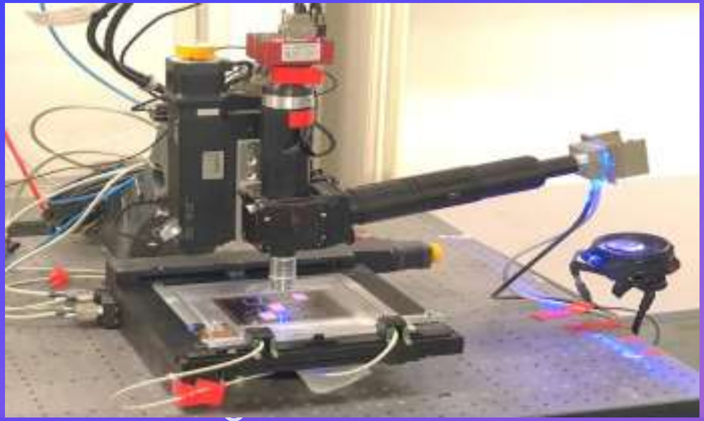


- ***E_l* intensity of inside metal**

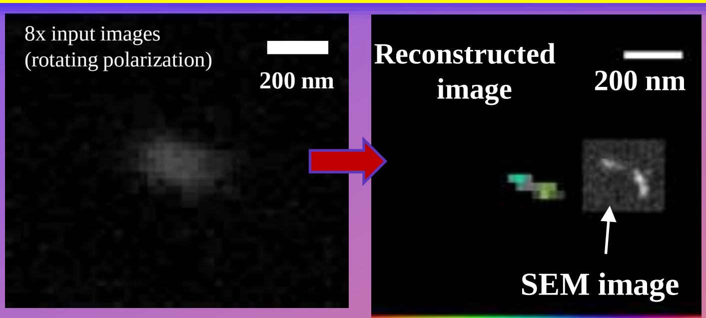
$$E_l = \frac{3\varepsilon_d(\lambda)}{\varepsilon_m(\lambda)+2\varepsilon_d(\lambda)} E_0$$

- **Depends on polarization, wavelength and metal shape**
- **Resonance-enhanced for**

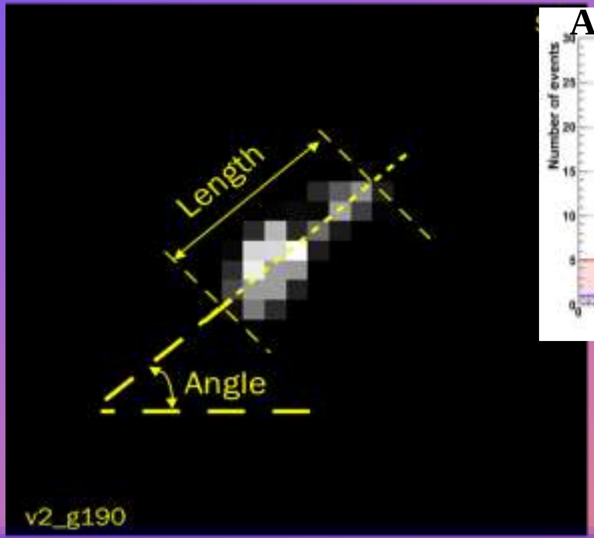
$$\varepsilon_m(\lambda_l)+2\varepsilon_d(\lambda_l)\approx 0$$

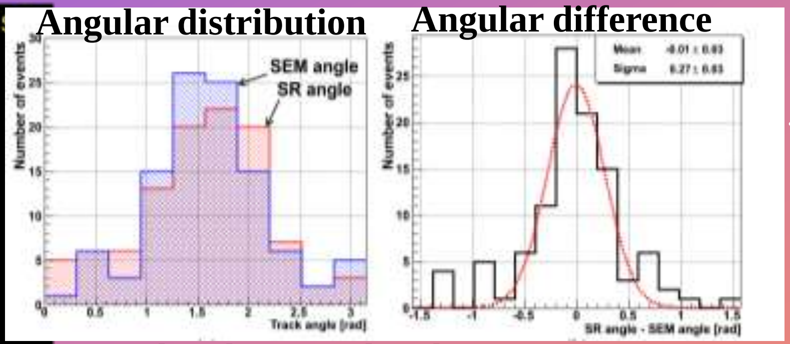


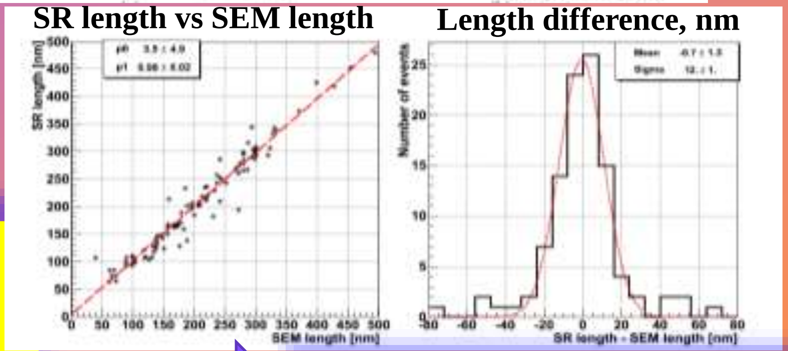
LSPR-BASED SUPER-RESOLUTION IMAGING BASED ON DECONVOLUTION OF A SET OF 8 POLARIZED IMAGES



100 keV Carbon ion in NIT







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

Direction + Sense

Scientific Reports 10 (2020) 18773

Promising R&D in progress:
polarization + colour
➔ *Head/Tail* discrimination
Under development:
Machine Learning, CNN approach

Comp. Phys. Comm. 275 (2022) 108312

Experimental Activity @ Gran Sasso Lab (ITALY)

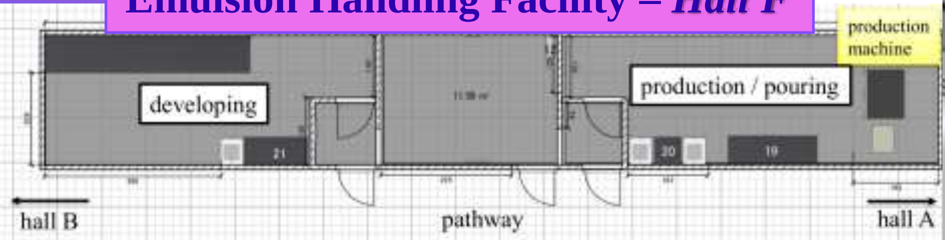
Neutron flux @ surface Lab

LNGS surface Lab

LNGS underground Lab

Development Room
Clean Room ISO 7

Emulsion Handling Facility – *Hall F*



Emulsion production & test runs:
19 production batches for 3162 g
>350 film samples
13 shield Runs + 2 neutron measurement Runs + many tests
>40 development batches

Jan. 2021 – to date

3162 g NIT produced

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

Background

Instrumental

Extremely short paths as a signal in a hand-made detector

➔ Each and every cluster of bright-enough pixels could be a background
- Dust
- Fog by impurities, thermal fluctuations
- Local energy deposit…

➔ Avoid/reduce noise during production, exposure, development
- ➢ Purity of components, clean handling in a clean Lab
- ➢ Fine tuning of chemical treatments

➔ Correct/reject optical scanning artifacts
- ➢ Aberration, field distortion, contrast…

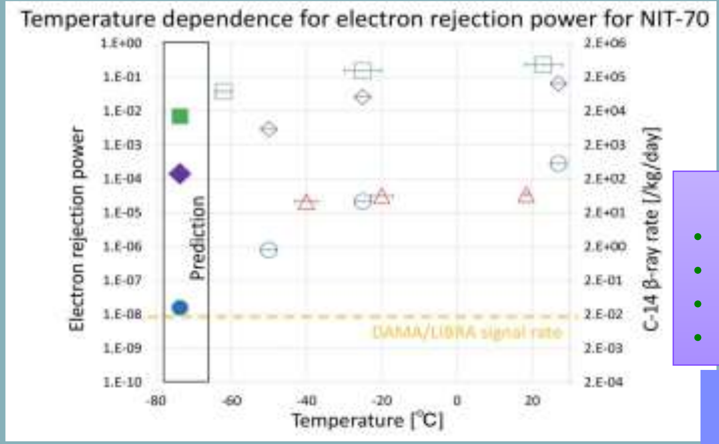
➔ Image analysis, super-resolution, pattern recognition

Intrinsic

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	$(4.04 \pm 0.02) \times 10^{6}$

Astropart. Phys.. 80 (2016) 16–21

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

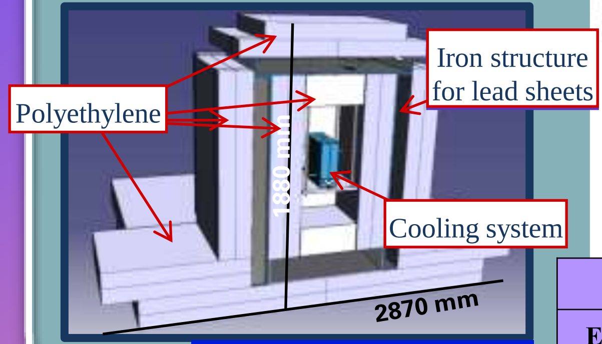


Electron Rejection power
- *~ 10^{-2} by lowering T down to -70°C*
- *~ 10^{-4} @ -70°C with shape analysis*
- *~ 10^{-8} @ -70°C with track likelihood*
- *Can be improved by low-sensitization*

Sensitivity vs. T:
NIM A845 (2017) 373

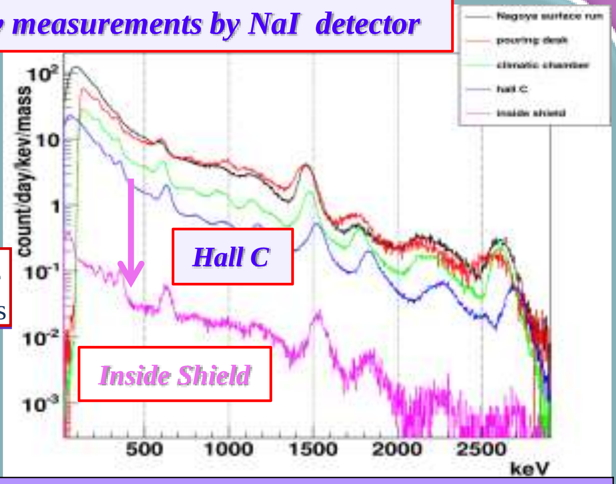
Environmental

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



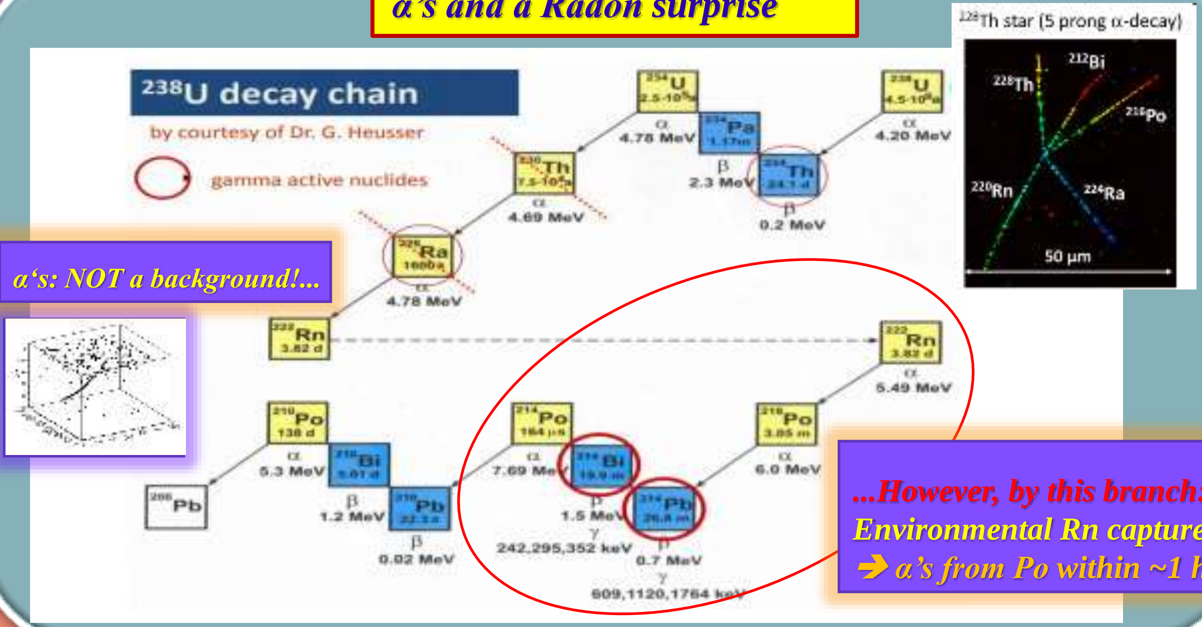
Lead shield : 5.6 cm
Polyethilene : 31.5 cm

γ measurements by NaI detector



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

α's and a Radon surprise

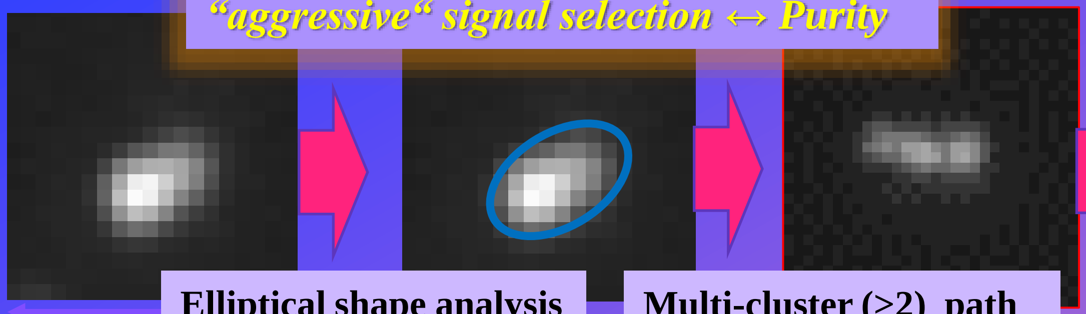


α's: NOT a background!...

...However, by this branch:
Environmental Rn captured
➔ α's from Po within ~1 h

Underground exposures inside shielding

"aggressive" signal selection ↔ Purity

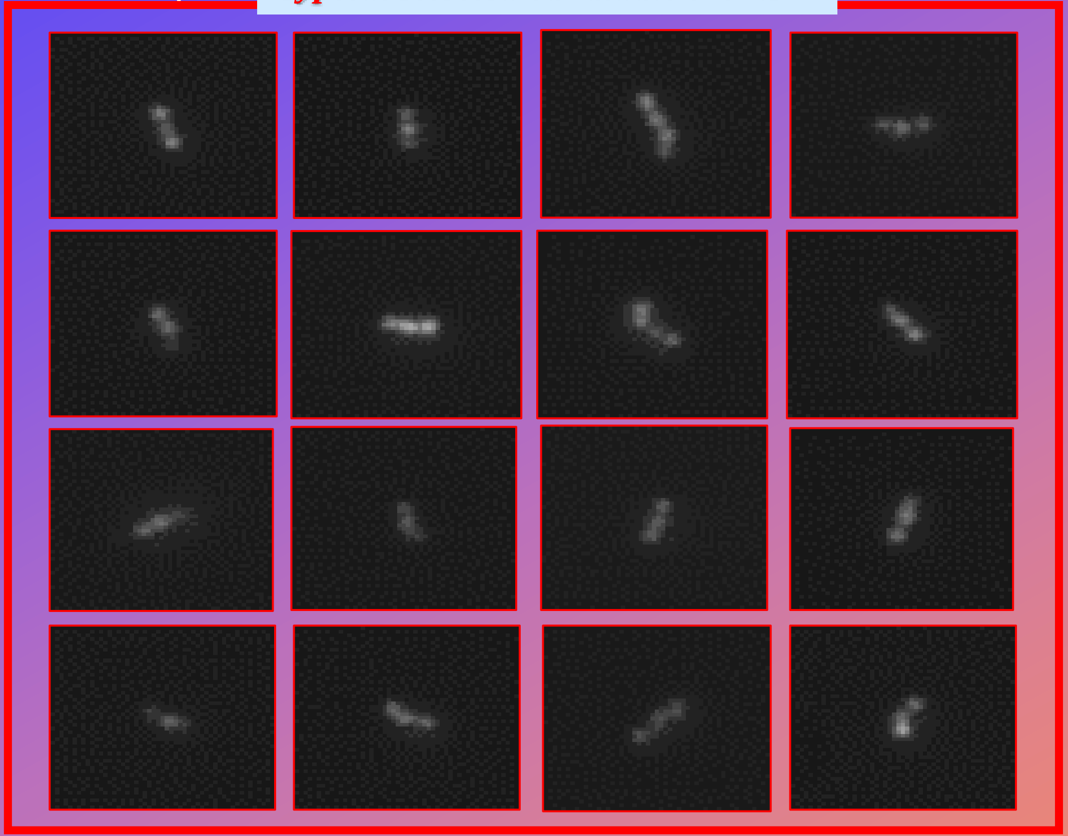


Elliptical shape analysis

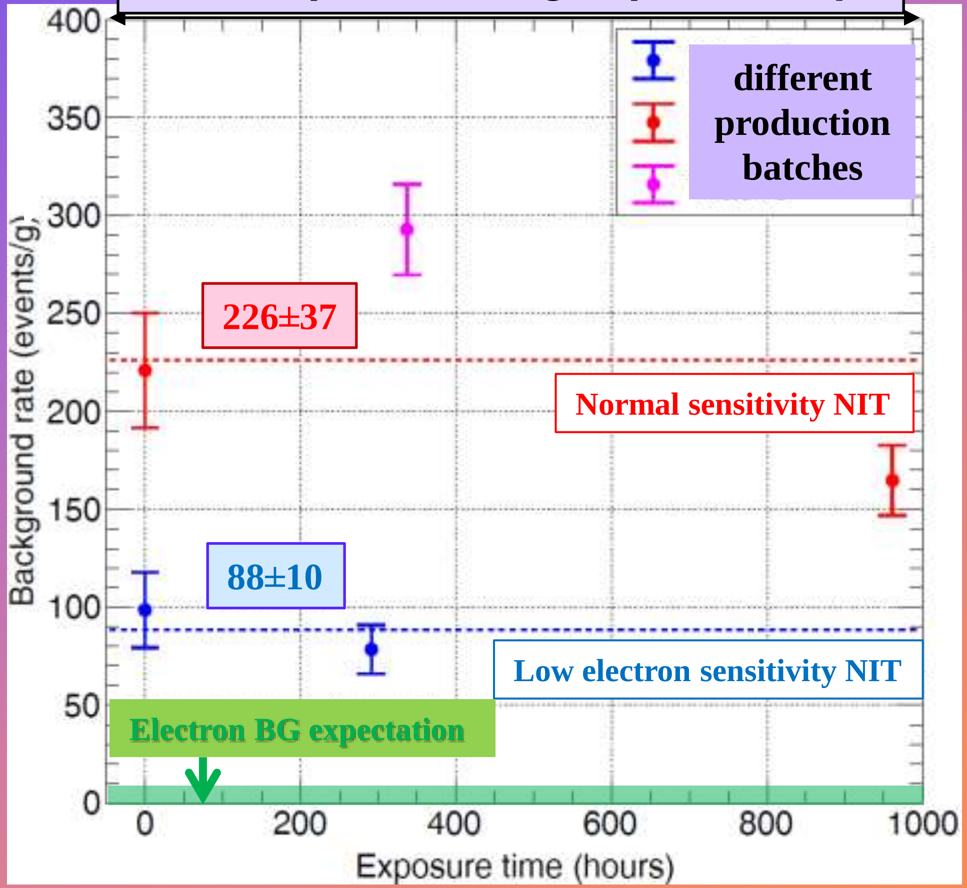
Multi-cluster (>2) path

Further selection:
Likelihood
Recoil-like vs. β-like

\+ *Typical selected candidate events*



-50 ℃ exposures, 10g , up to 40 days



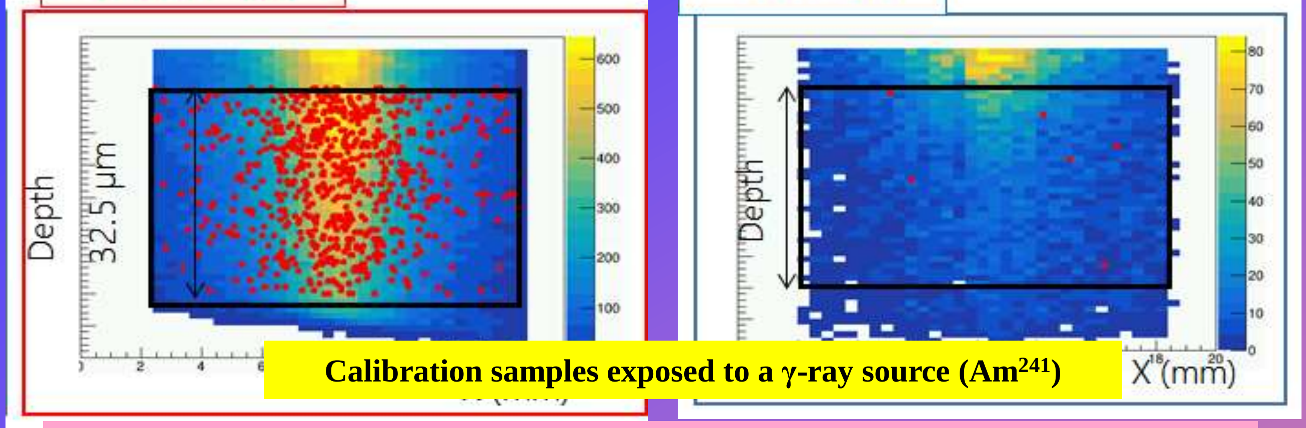
Results:

- *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*

Underground exposures inside shielding: about the excess of >2 clusters…

About e
Comparing batches of different sensitivity

Standard | ×130 times reduction | Low sensitivity for *e*



Calibration samples exposed to a γ-ray source (Am^{241})

➔ ***Same NIT types as in shield, completely different response***
➔ ***Consistently ruling out the hypothesis of electrons***

- The observed “prompt” and “constant” excess must come from some early stage of plate handling, and from environment
- Rn is known to be unevenly distributed in the underground Lab, due to air exchange and ventilation
- Rn can be trapped in liquids, and diffused in aerosol
- “Normal” α tracks are NOT a background, but…

➔ Current hypothesis (under check):

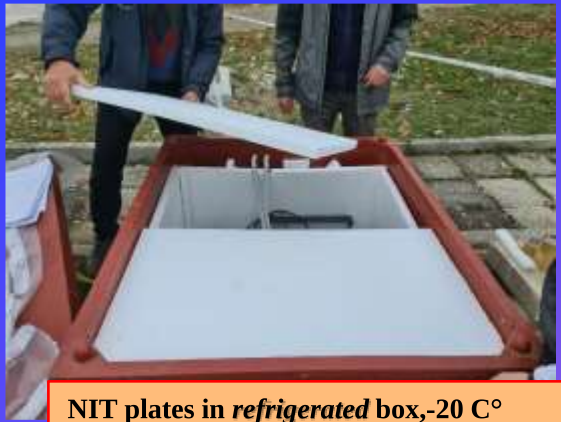
“In early stages of gel sensitization and plate pouring, when the emulsion is still in a liquid/wet state, the combined effect of crystal mobility and fading may produce track fragments in the form of short sequences of clusters, surviving after setting”

➔ The first hour, beginning of Po branch!

About Rn
a campaign to check level @ any step of handling and exposure

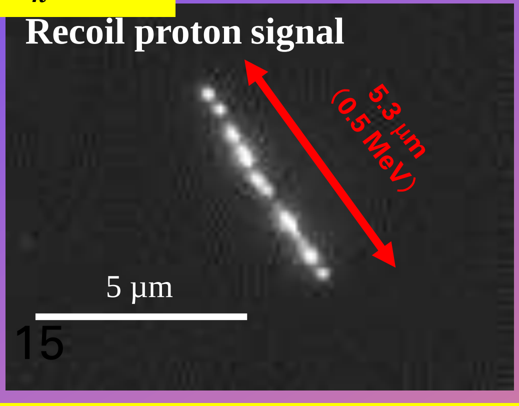
	Rn measurements	Bq/m^3	Sigma	℃	humid.	mbar
Hall F	hallF prod.room chamber opened	**75.9**	15.3	12.1	82.4	917.8
Hall F	hallF prod.room pouring desk	**72.5**	15.2	20.7	44.8	916.2
Hall F	hallF prod.room fridge (wet gel)	**71.0**	9.1	8.4	52.6	912.6
Hall F	hallF control room	**81.1**	16.7	17.5	44.5	907.4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

Neutron flux measurement at Surface Lab



NIT plates in ***refrigerated*** box,-20 C°

$E_p = E_n \cos^2\theta$

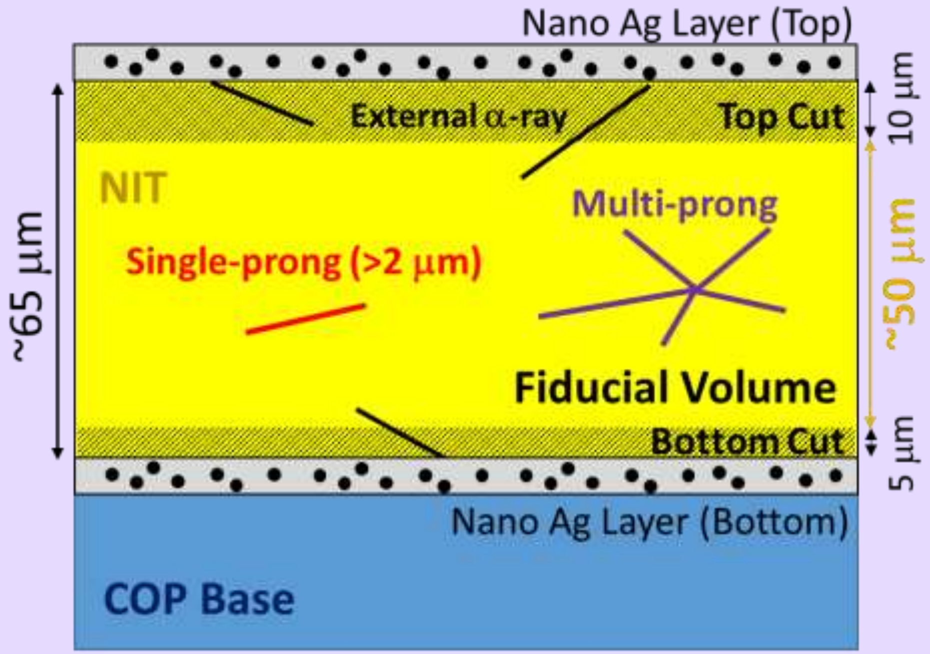


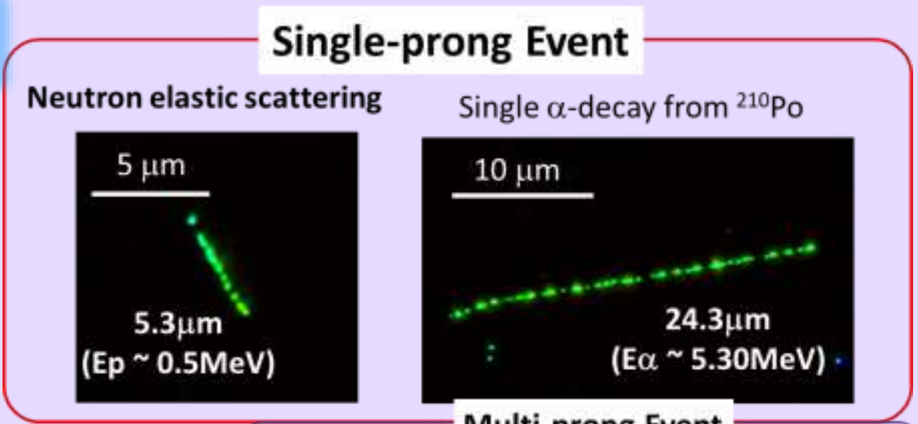
NIT calibration

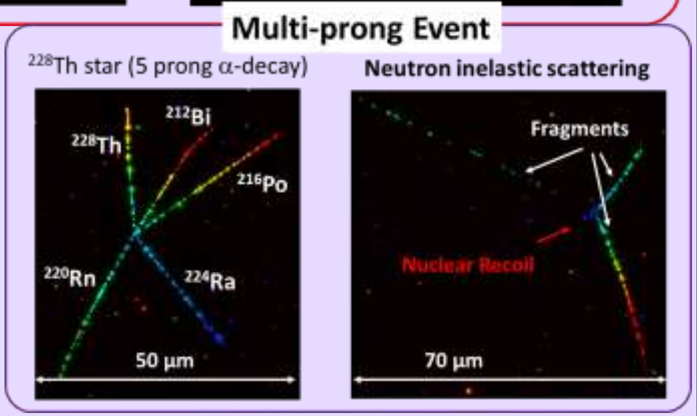
Monochromatic 880 keV neutron exposure

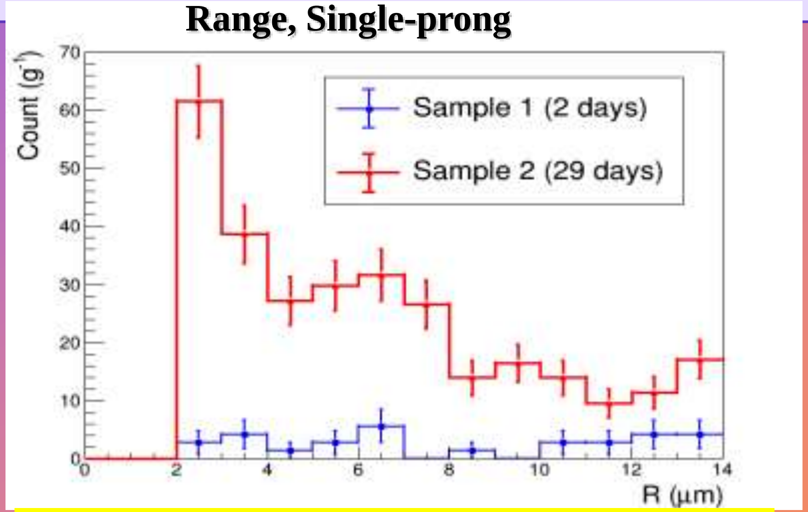
T(p n)^{3}He reaction at AIST (Japan)

Event classification









No background in sub-MeV region

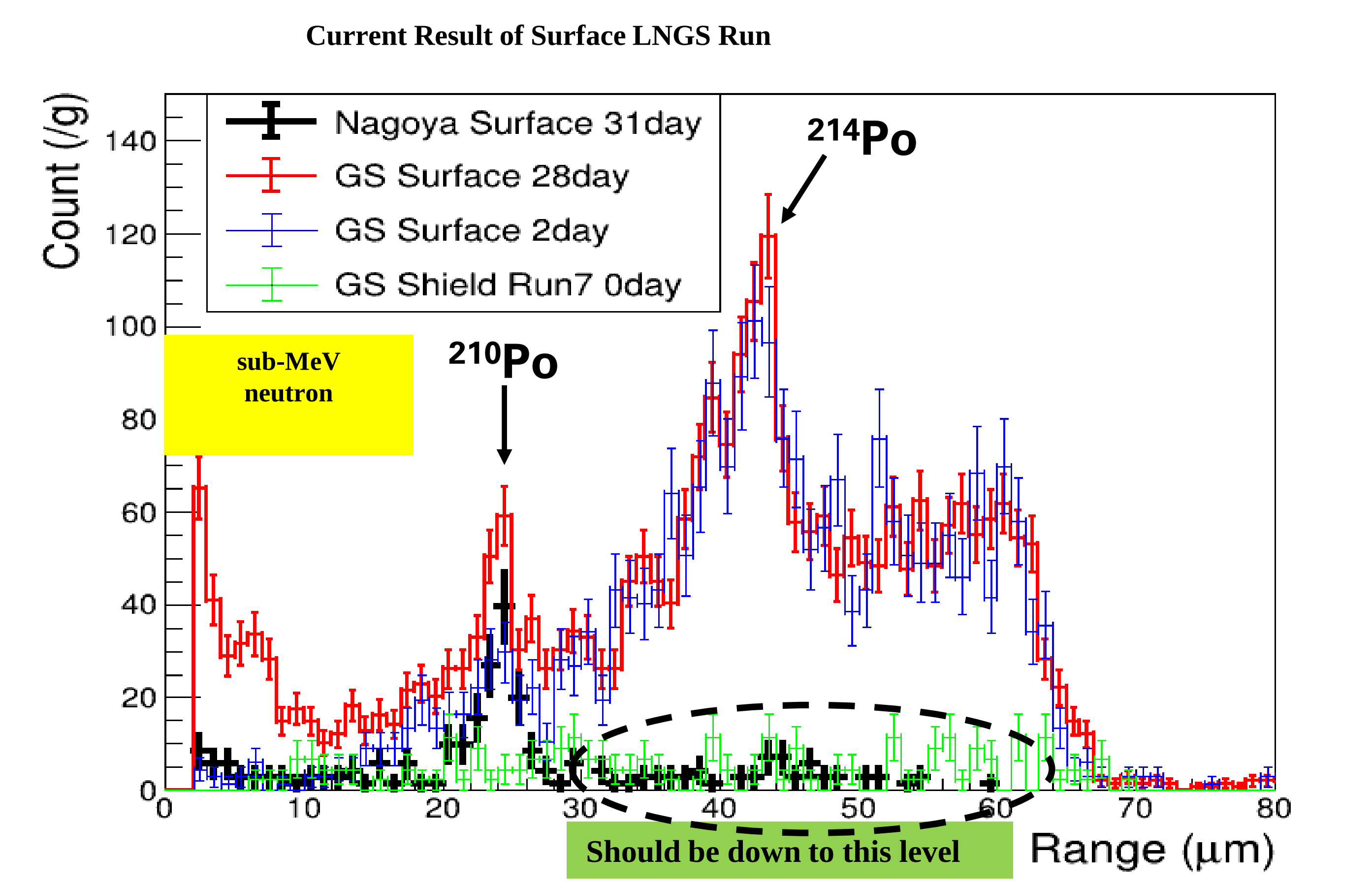
(2 ~ 14 μm → 0.25 ~ 1 MeV in proton energy)

Measured Neutron flux :

(7.4±1.7) ·10^{-3} cm^{-2} s^{-1}

T. Shiraishi et al.
https://doi.org/10.48550/arXiv.2208.13366
Submitted to Phys. Rev. C on Sep. 22nd

The issue of Rn & α's at Surface Lab



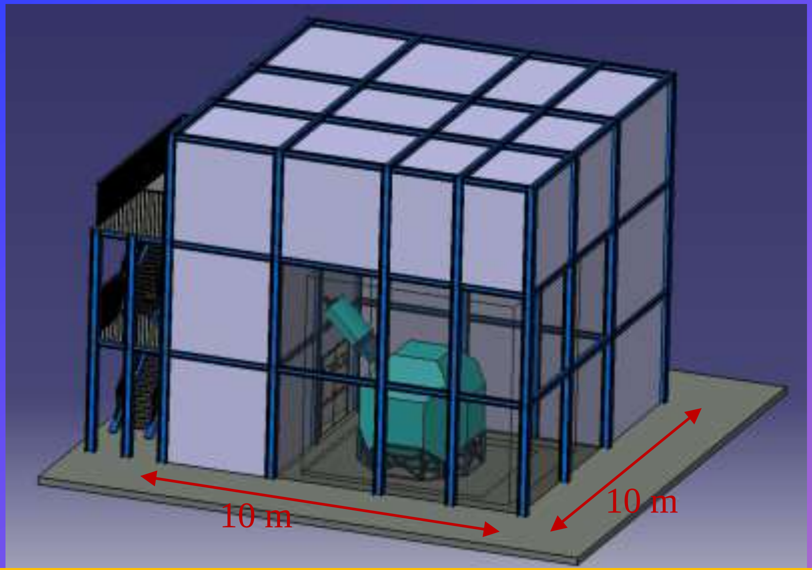
Range > 15 μm, mostly α tracks

- Po peaks clearly visible (Rn chain)
- Compared to a surface run in Japan, too many tracks
- In contrast with neutron-induced tracks, no time dependence ("prompt" contamination at production stage underground)
- In a recent test, after this exposure, plates were produced under "Rn free" nitrogen fluxed coverage

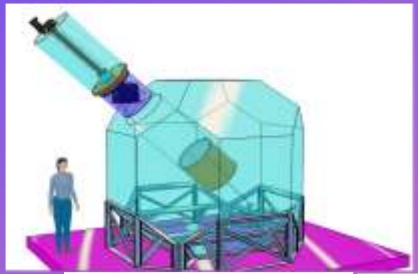
➔ *α excess disappeared!*

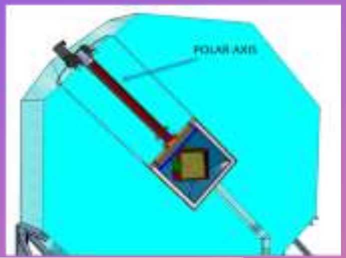
Under implementation:
Plate pouring & drying in a Glove box fluxed with nitrogen, almost Rn-free

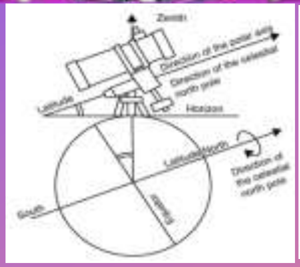
Towards a 10 kg·year Detector (and beyond)

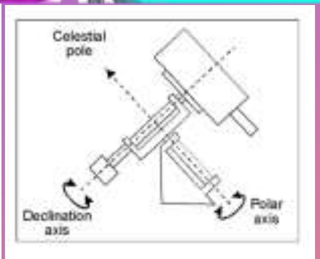


Emulsion facility and shielding with an equatorial telescope

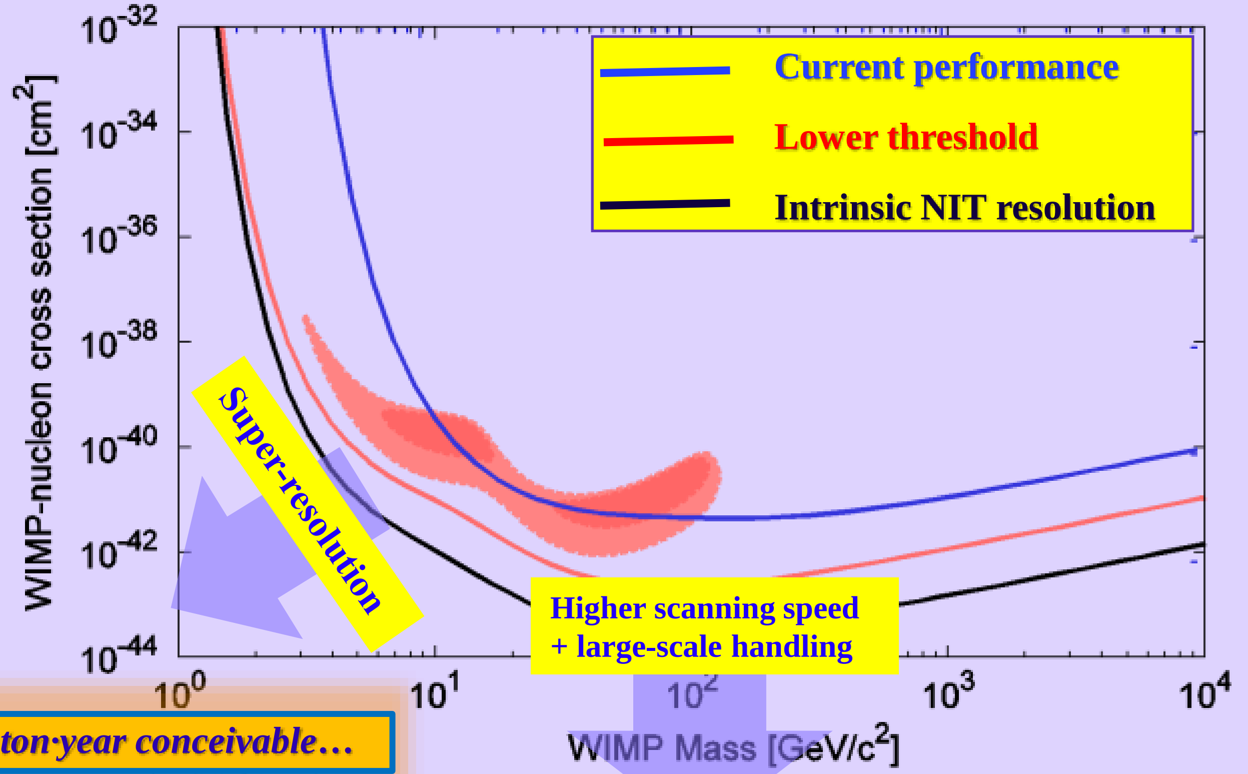




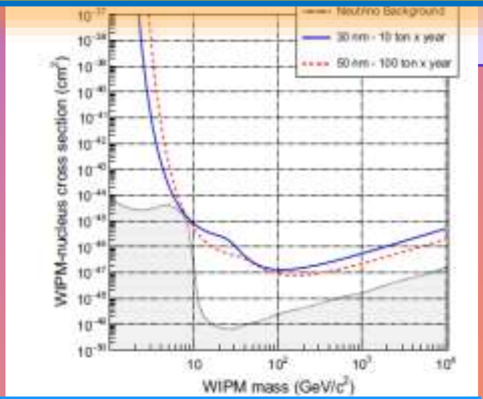




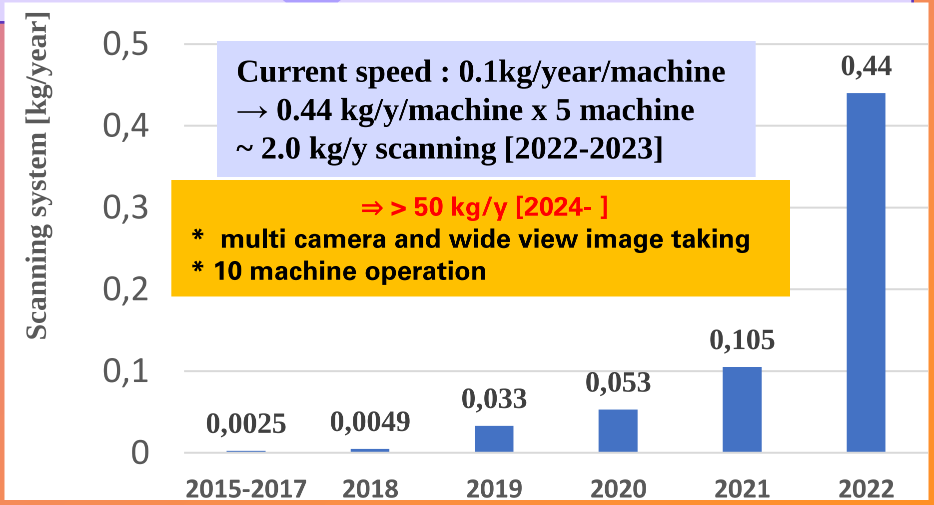
10 kg·year simulated sensitivity [90 % C.L.] + zero BG



Scale-up to 10 ton·year conceivable…

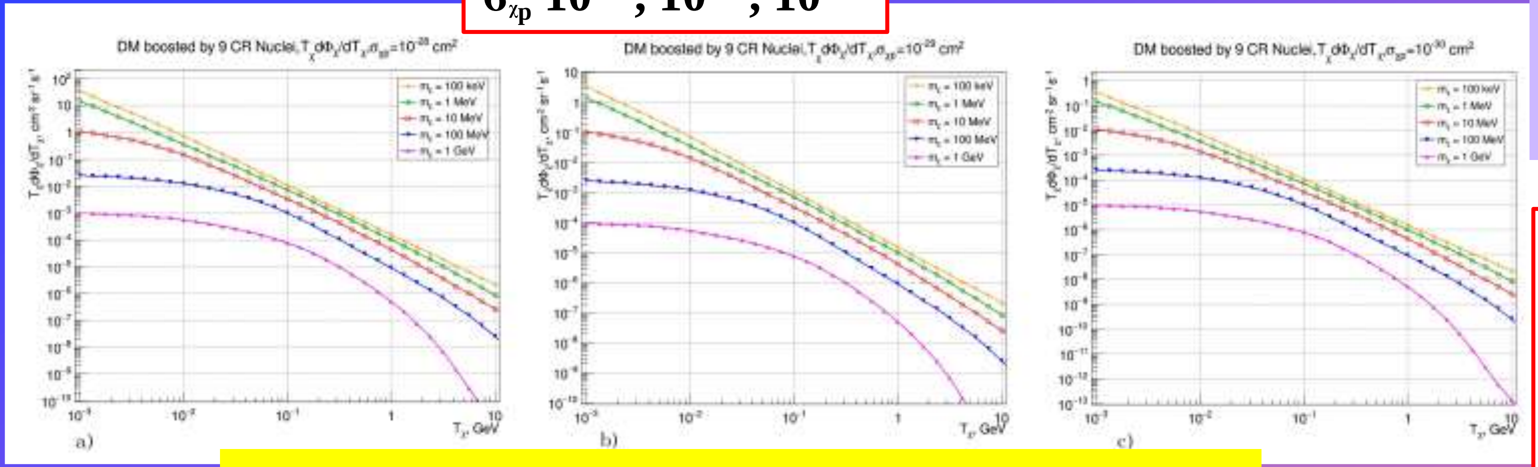


NEWSdm, Eur. Phys. J. C 78 (2018) 578

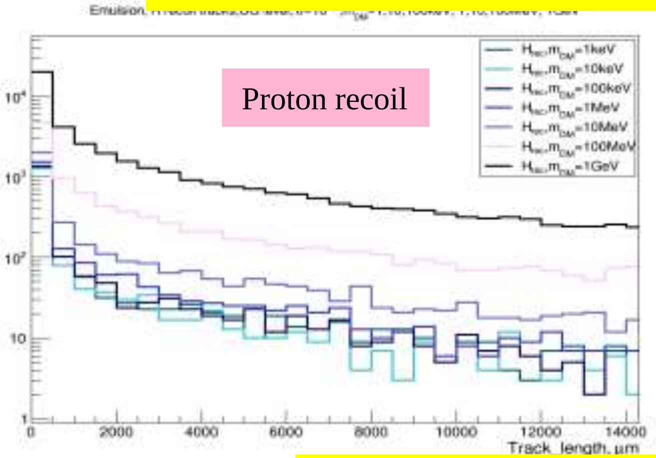


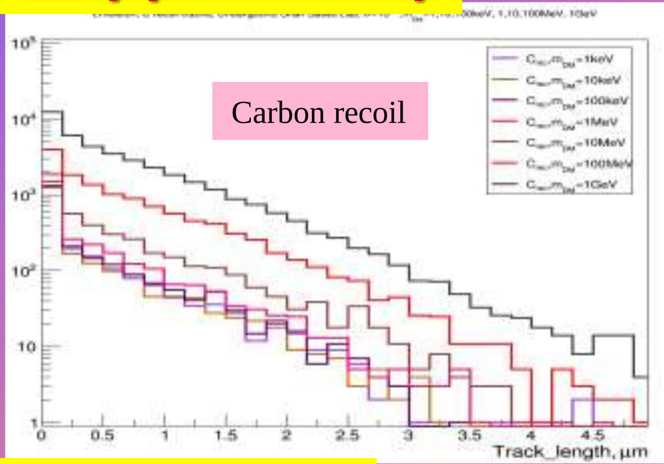
Boosted Dark Matter

$\sigma_{\chi p}$ 10^{-28}, 10^{-29}, 10^{-30}



Under investigation, MC, *very preliminary*





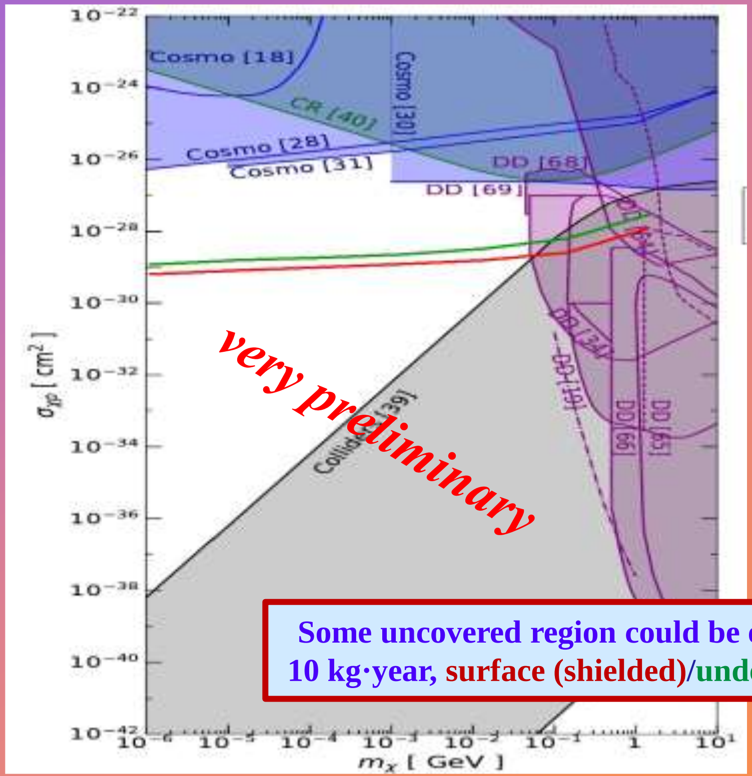
Track lenght for proton recoil and Carbon recoil, µm

Case 0 e.g. 10.1103/PhysRevLett.126.091804

Cosmic-ray boost ↔ the other way around of nuclear recoil!

"a subdominant, highly energetic, component of DM must be generated through collisions with cosmic rays"

m_χ 100 keV up to GeV



Some uncovered region could be explored
10 kg·year, surface (shielded)/underground

Detection threshold anyway relevant
…and *Directionality*
this time pointing to the Galactic center

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

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**
- ***We plan to submit in Spring 2023 a CDR with all supporting measurements***