NEWS: Nuclear Emulsion Wimp Search

G. De Lellis on behalf of

Bari, Gran Sasso, Nagoya (Japan), Napoli

Outline

- Directional Dark Matter Searches
- The NEWS idea:

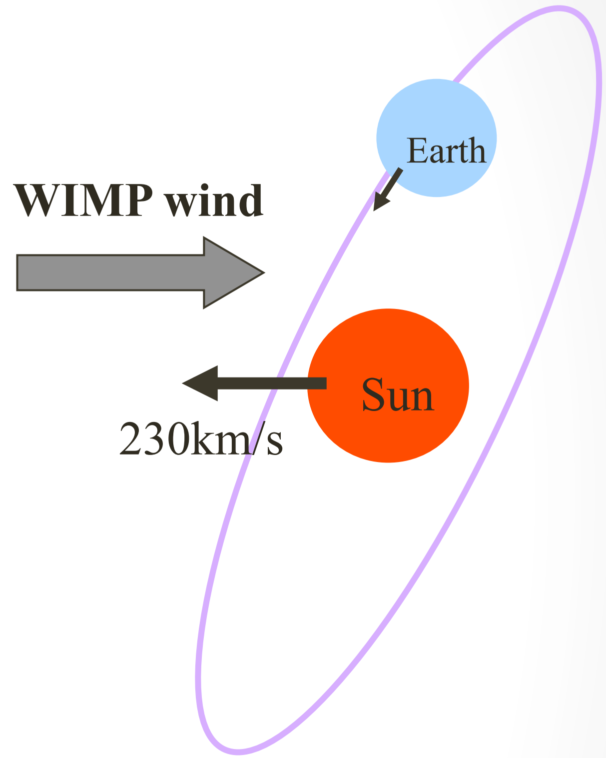
  a novel approach to directional detection of DM
- High Resolution Nuclear Emulsions: NIT
- Detection Principle
- NEWS R&D actvity
- Sensitivity goal

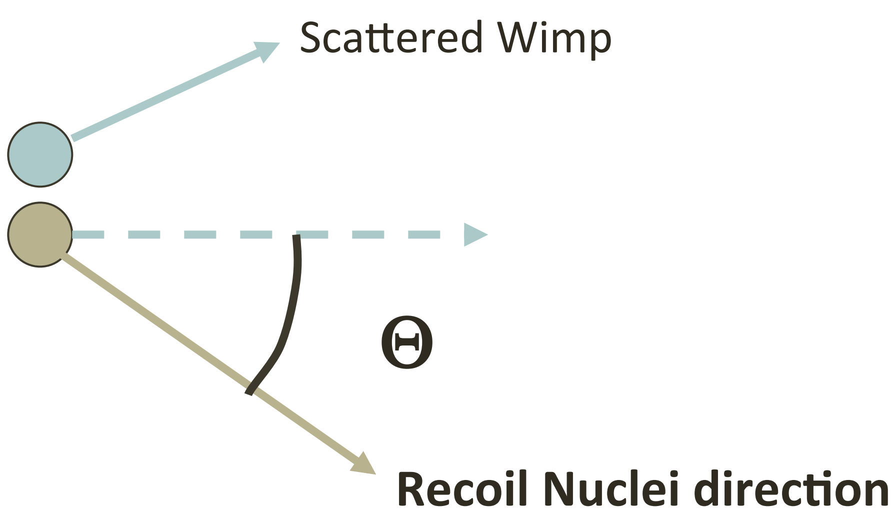
Directional Dark Matter Searches

Earth revolution gives seasonal modulation

Due to solar system movement in the galaxy, the WIMP Flux is expected to be not isotropic @earth.

A directional measurement would provide a strong signature and an unambiguous proof of the galactic origin of DM





WIMP cross-section with nuclei $\propto A^2$

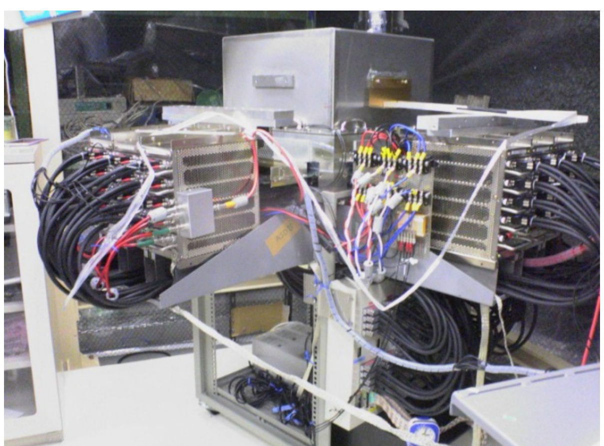
Directional Dark Matter Searches

Current approach:

low pressure gaseous detector

- Targets: CF4, CF4+CS2, CF4 + CHF3
- Recoil track length O(mm)
- Small achievable detector mass due to the low gas density

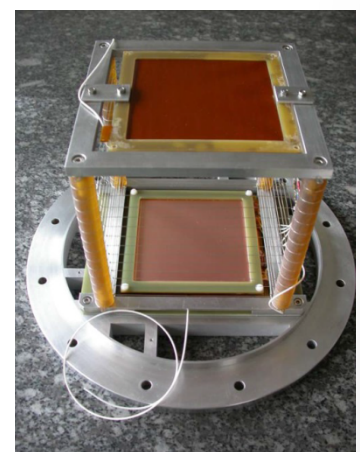
⇒Sensitivity limited to spin-dependent interaction



NEWAGE@ Japan

DM-TPC@ USA

DRIFT @ UK



MIMAC@ France

Directional Dark Matter Searches

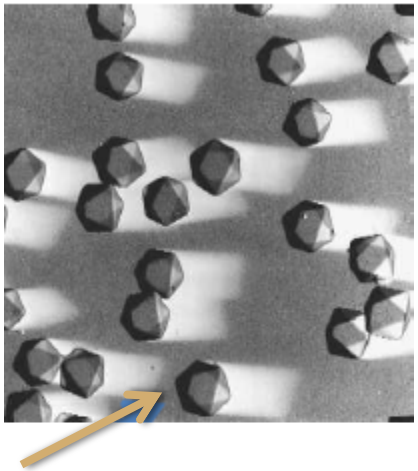
Use solid targets:

- Large detector mass
- Smaller recoil track lenght O(100 nm) → very high resolution tracking detector

Nuclear Emulsion based detector acting both as target and tracking device

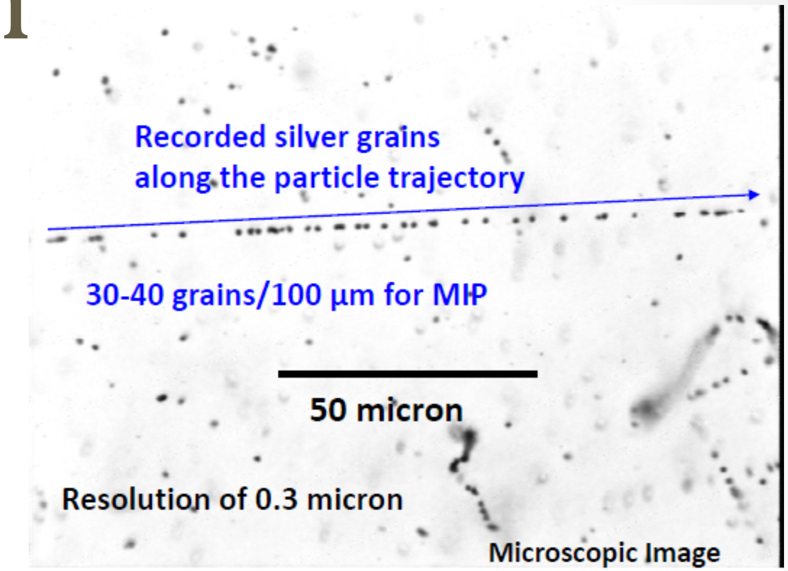
NEWS: Nuclear Emulsion WIMP search

Nuclear Emulsion

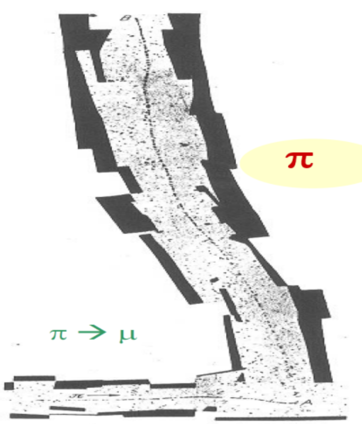


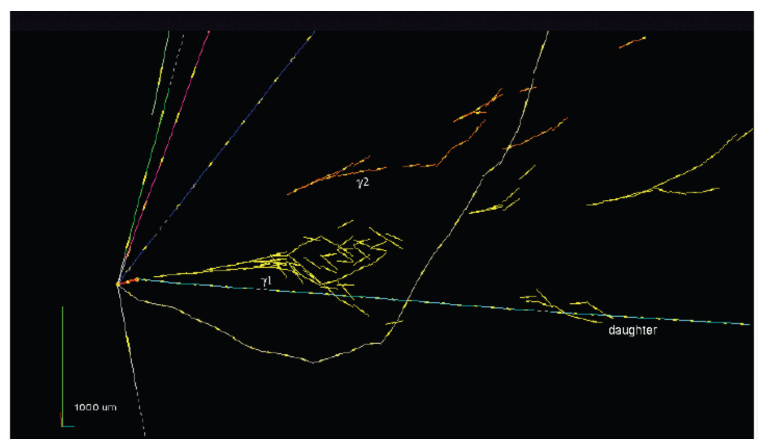
AgBr crystal
size 0.2-0.3 μm

After the passage of charged particles through the emulsion,
a latent image is produced
The emulsion chemical development makes Ag grains visible
with an optical microscope



A long history, from the discovery of the Pion (1947) to the evidence of $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode (OPERA, 2013)

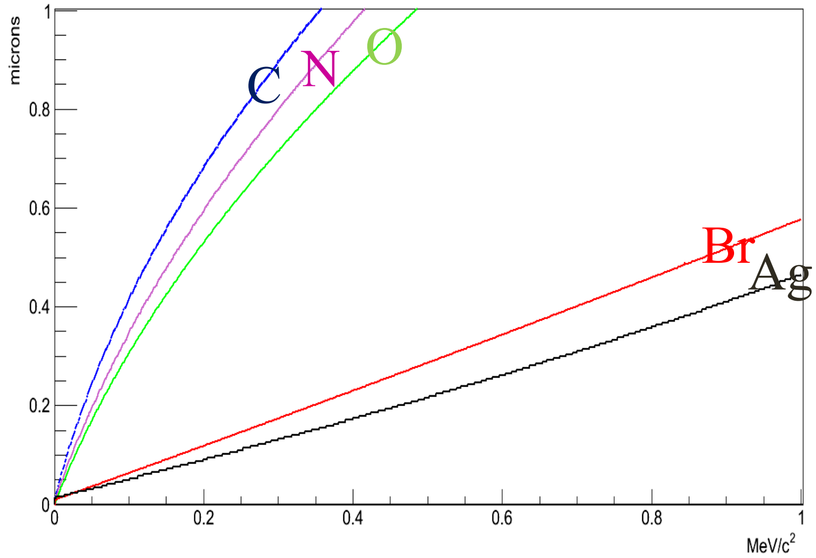




Nuclear Emulsion

Chemical composition of nuclear emulsions

	A	% Weight
I	126.9	0.8
Ag	107.9	28.5
Br	79.9	20.7
S	32.1	1.3
O	16.0	13.7
N	14.0	8.6
C	12.0	23.6
H	1.0	2.9



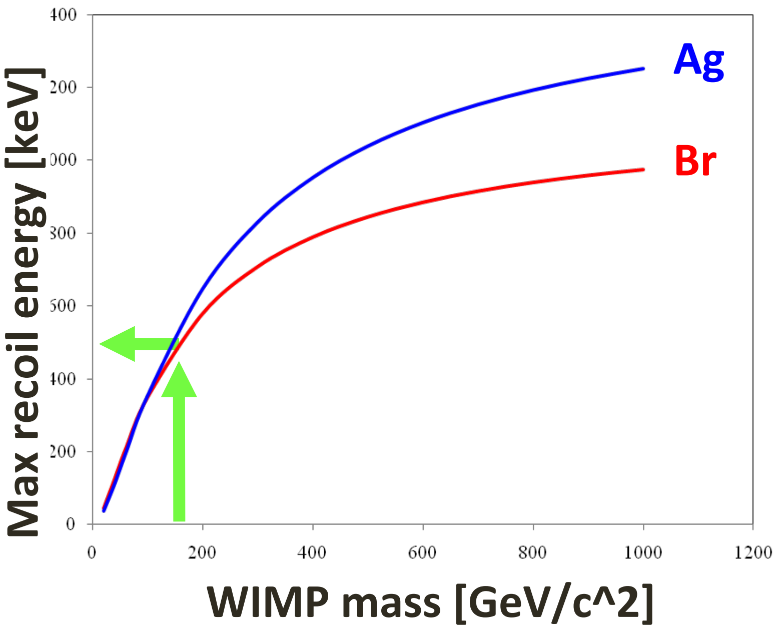
Lighter nuclei

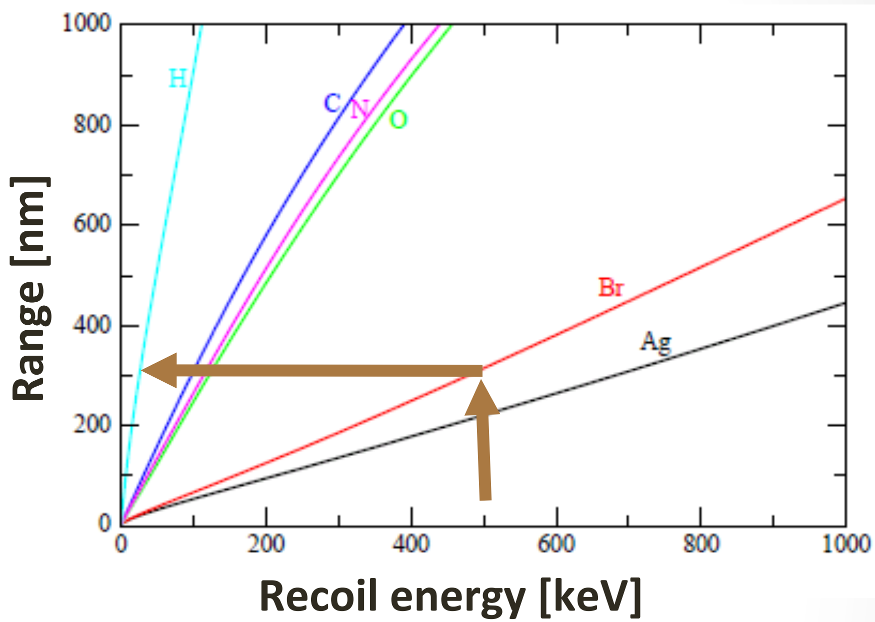
(longer range at same recoil energy)

↓

Sensitivity to low WIMP mass

Nuclear Emulsion





WIMP velocity < 800 km/sec

Take e.g. M_{WIMP} ~ **150 GeV/c²**

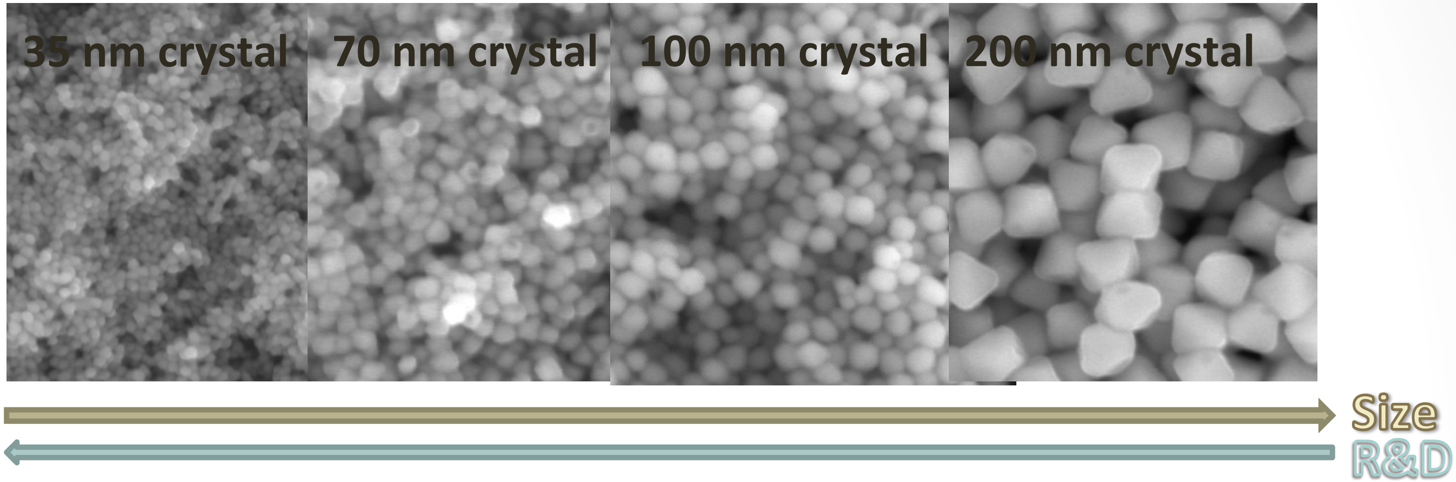
Recoil energy < 500 keV

Br range < 300 nm

OPERA emulsion films:

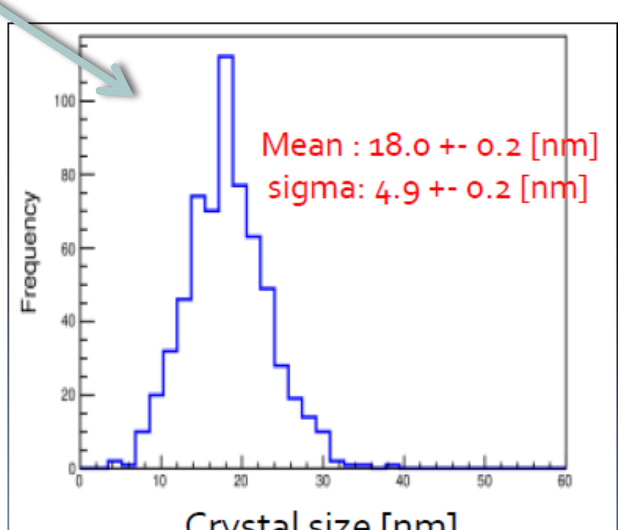
Silver grain size ~ 200 nm → too large to record nanometric nuclear recoils

NIT emulsion films: Nano Imaging Trackers

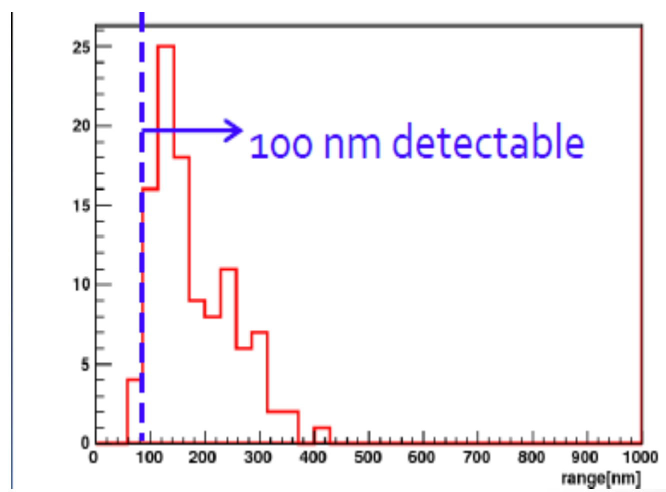


Natsume et al, NIM A575 (2007) 439

Recent developments

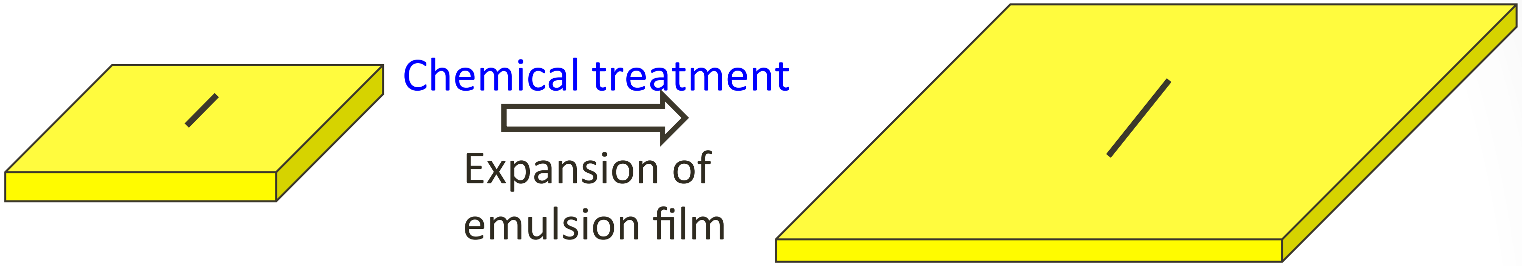


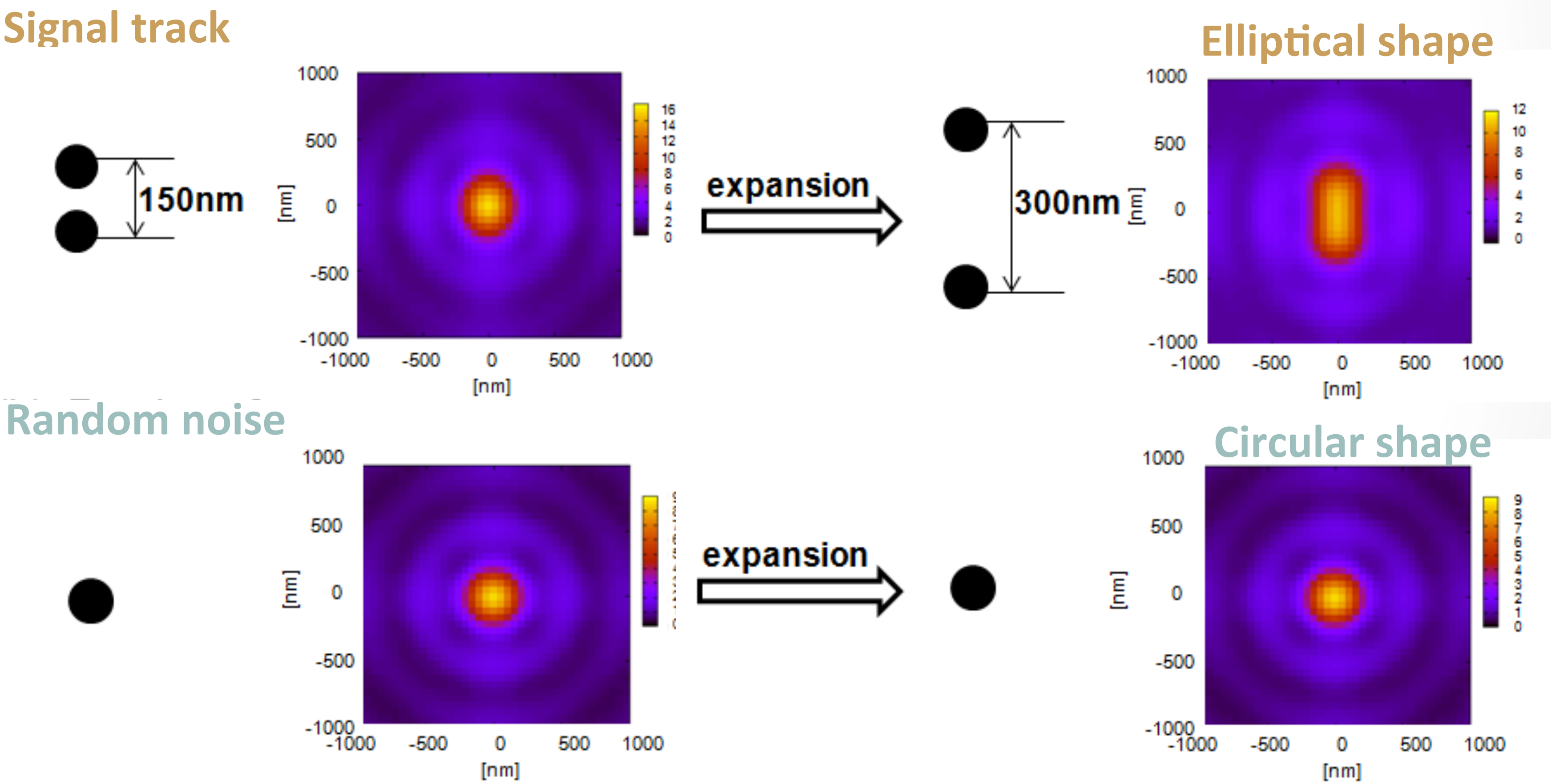
Range distribution [nm]



Concept of readout: film expansion

T. Naka et al., NIMA581 (2007) 761



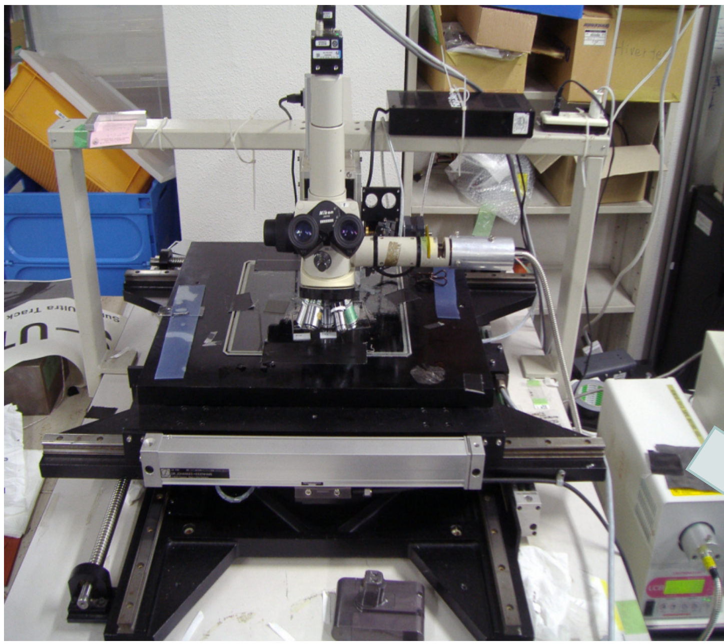


Concept of readout: scanning system

Two-step read-out:

i. Pre-selection of candidate signal tracks with the optical microscopes

ii. Final confirmation of signal with X-ray microscopy

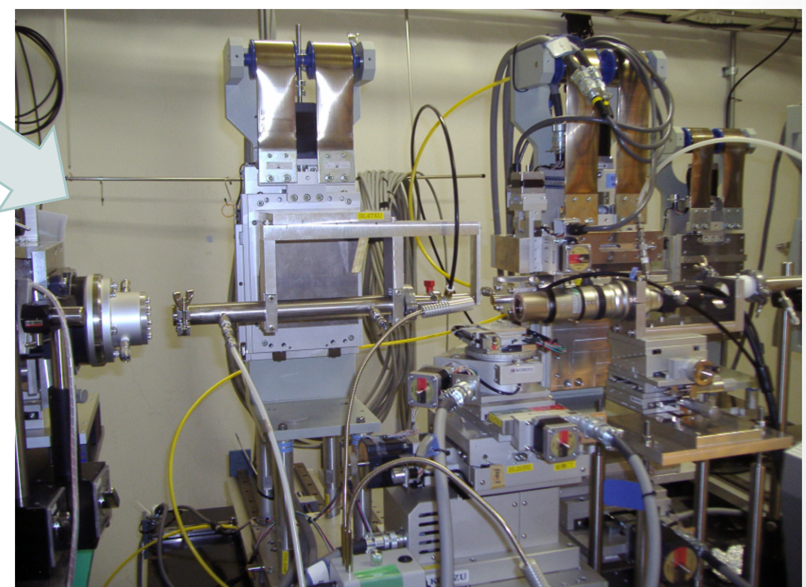


Optical Readout

Automatic selection of candidate signals by optical microscopy. Full area scan. Resolution 200 nm, scanning speed 20 cm^2/h

X-ray Readout

Pin-point check at X-ray microscope of candidate signals selected by optical readout . Resolution ~ 30 nm

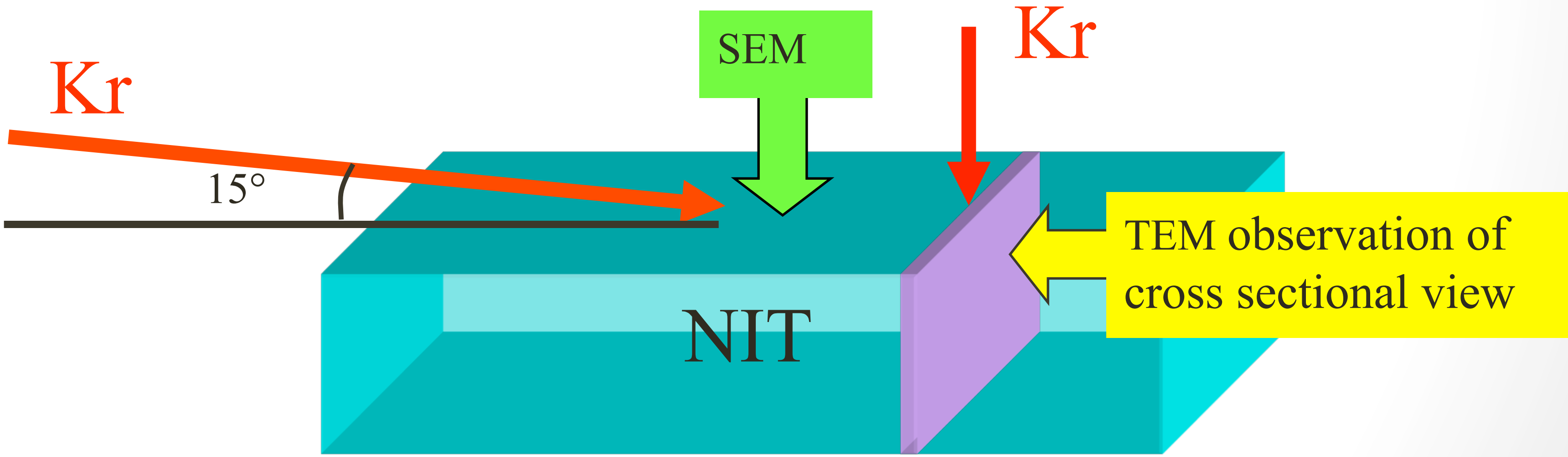


Concept of readout

What about WIMP recoil nuclei ?

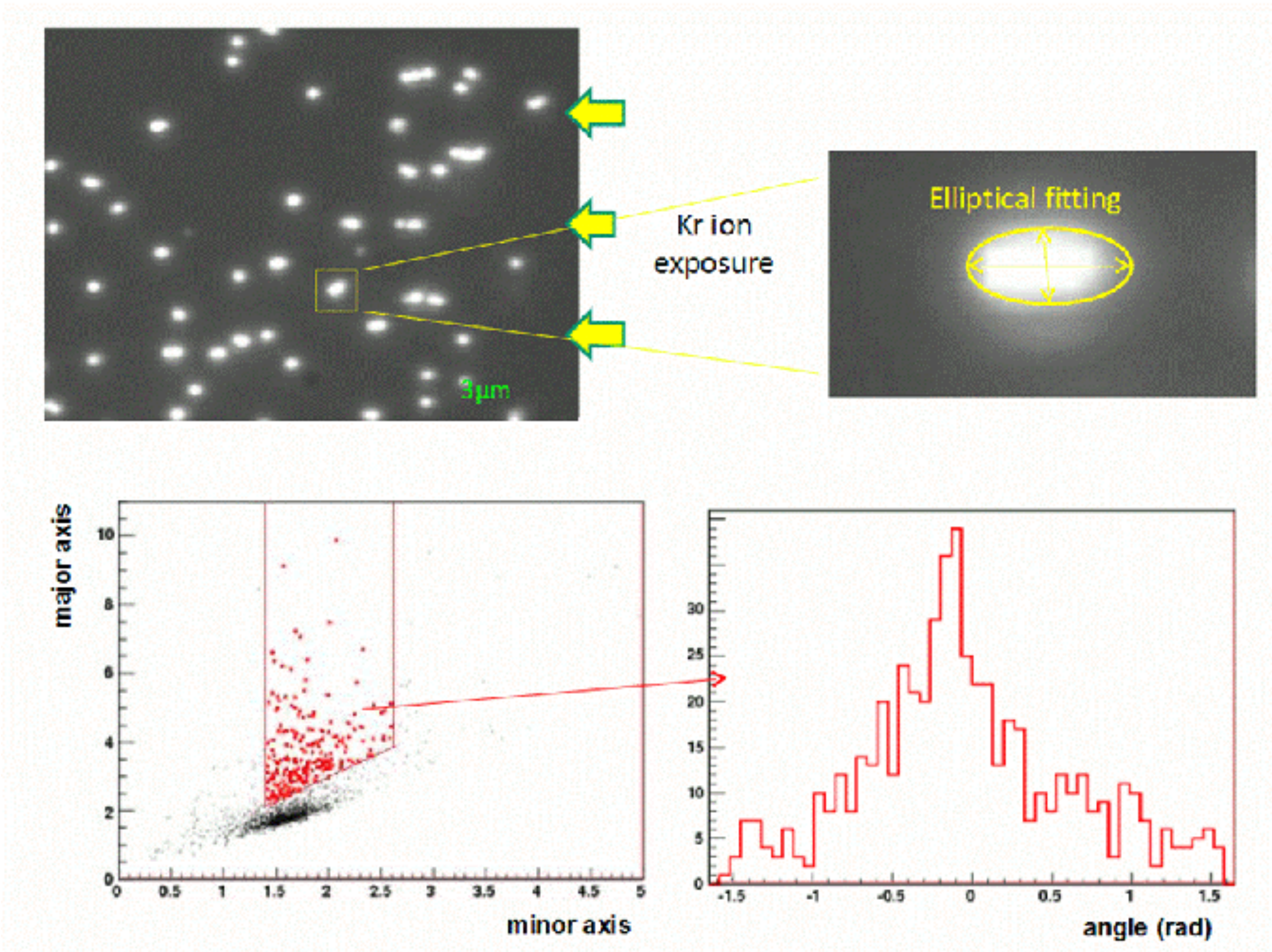
"Simulation" of Br recoils: implantation of Kr ions in NIT emulsion films

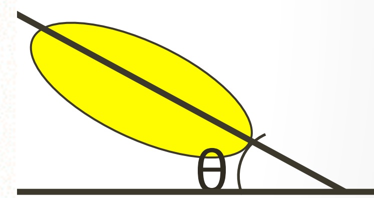
Low velocity ion created by an ion implantation system



Concept of readout:
step I, shape recognition

Test using 400 keV Kr ions





Direction detected!

Concept of readout: step I, shape recognition

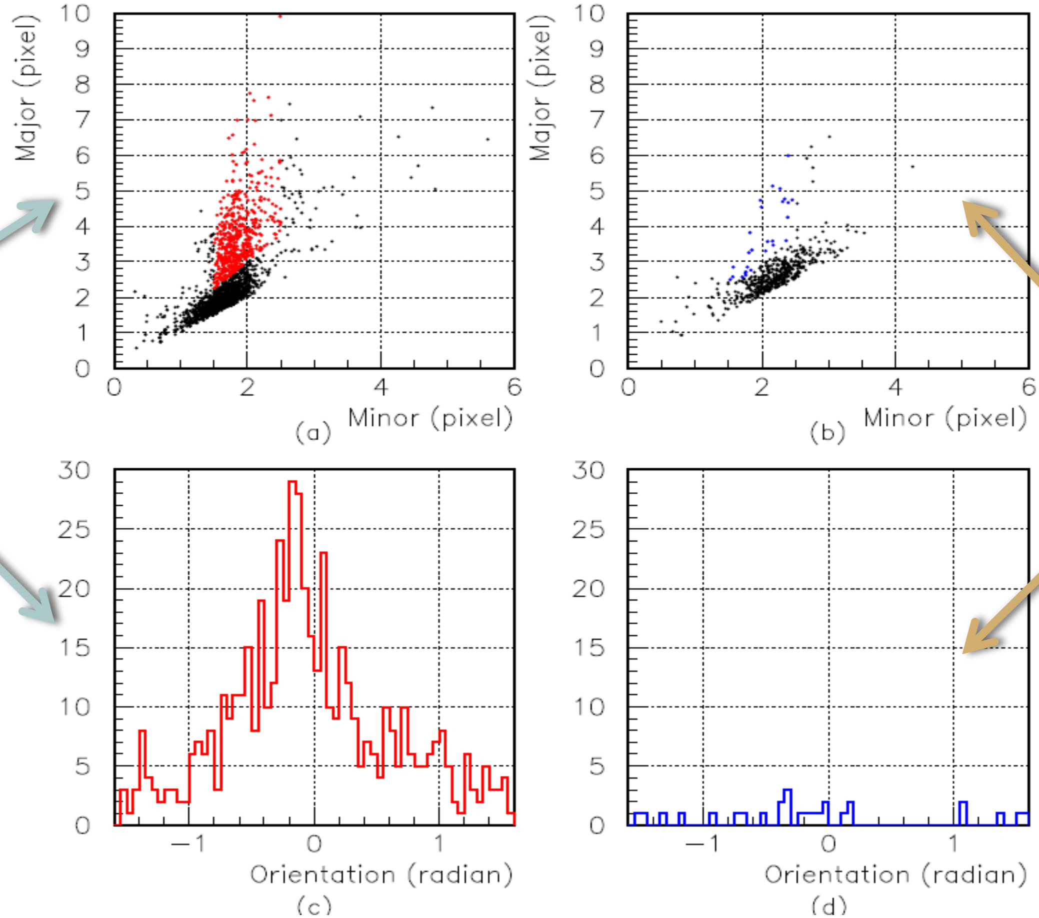
Image analysis: selection of Kr ion tracks elliptical fit (minor and major axis)

Major/minor>1.5

1.4<minor <2.6

pixel > 40

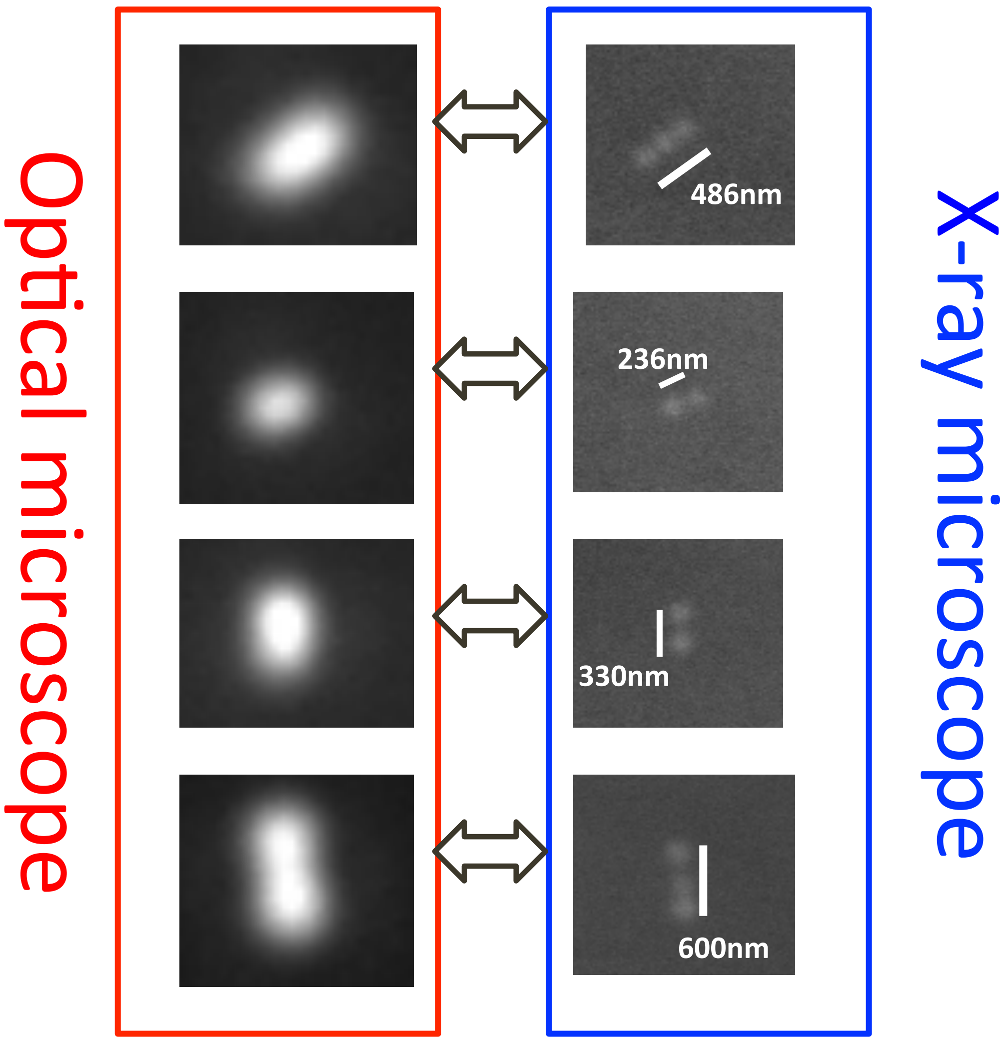
Film exposed to Kr ions



Reference film (unexposed)

Nucl.Instrum.Meth. A680 (2012) 12-17

Concept of readout:
step II, X-ray microscopy

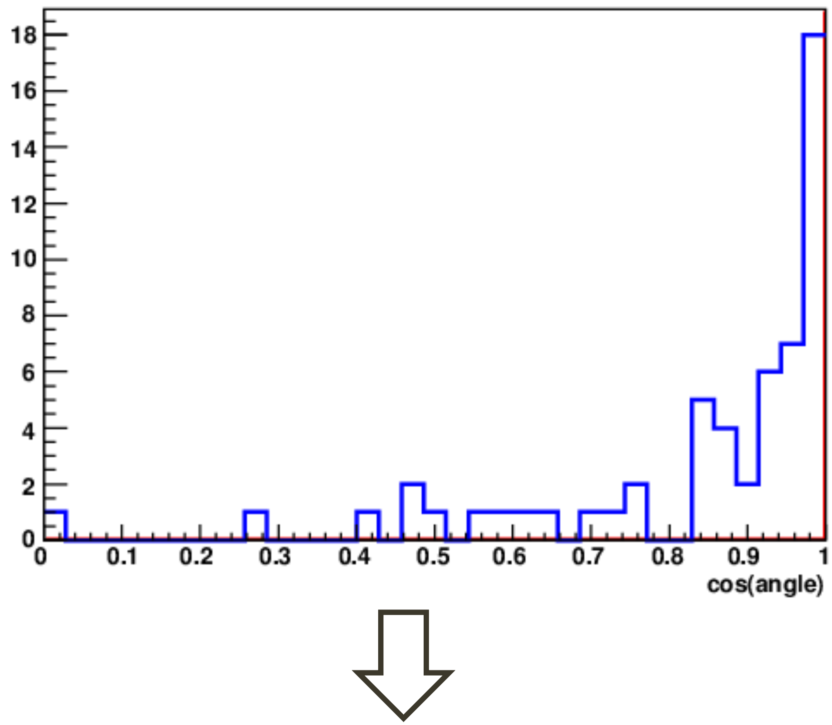


Matching of recoiled tracks between Optical and X-ray microscope

Success rate of matching

572/579=99%

Concept of readout:
step II, X-ray microscopy



	angular resolution [degrees]
optical microscope	31.4 +- 4.7 degree @original range: 150-250nm
X-ray microscope	16.8+-2.9 degree @original range: 150-250nm

R&D activity

- NIT technology
- Optical and X-ray read-out system
- Intrinsic background measurement
- Angular resolution measurement, neutron test beam
- Full MC simulation

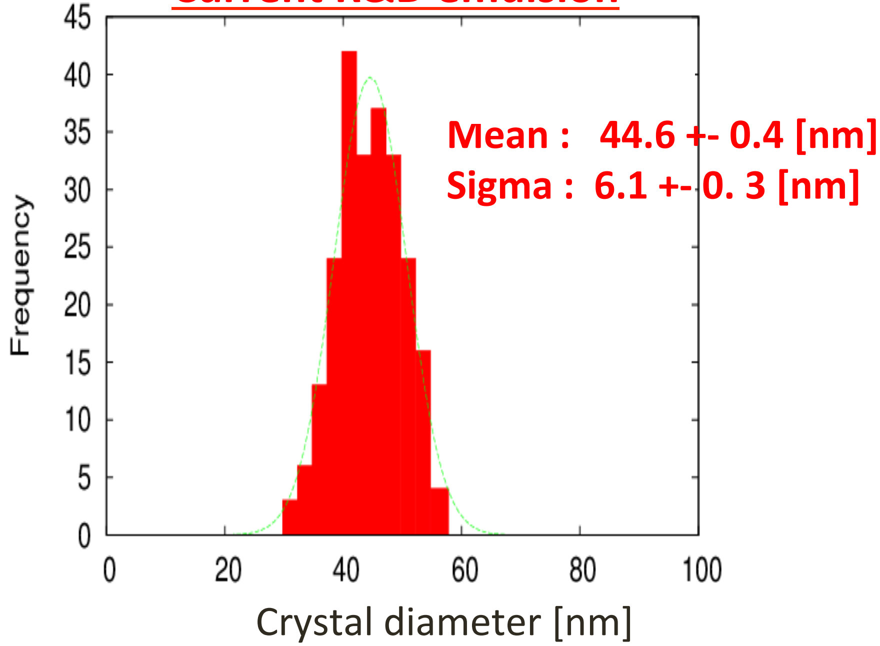
R&D activity

- NIT technology
- Optical and X-ray read-out system
- Intrinsic background measurement
- Angular resolution measurement, neutron test beam
- Full MC simulation

Nano Imaging Tracker

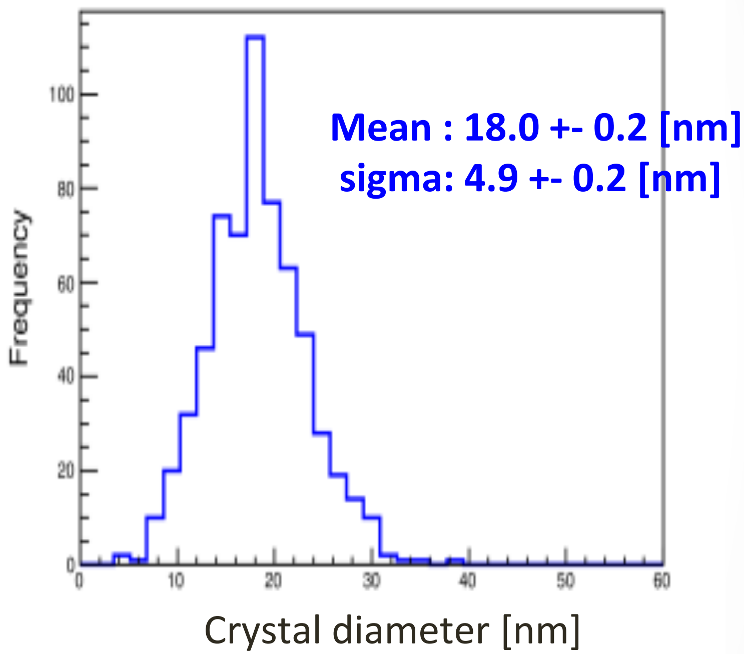
NIT

Current R&D emulsion



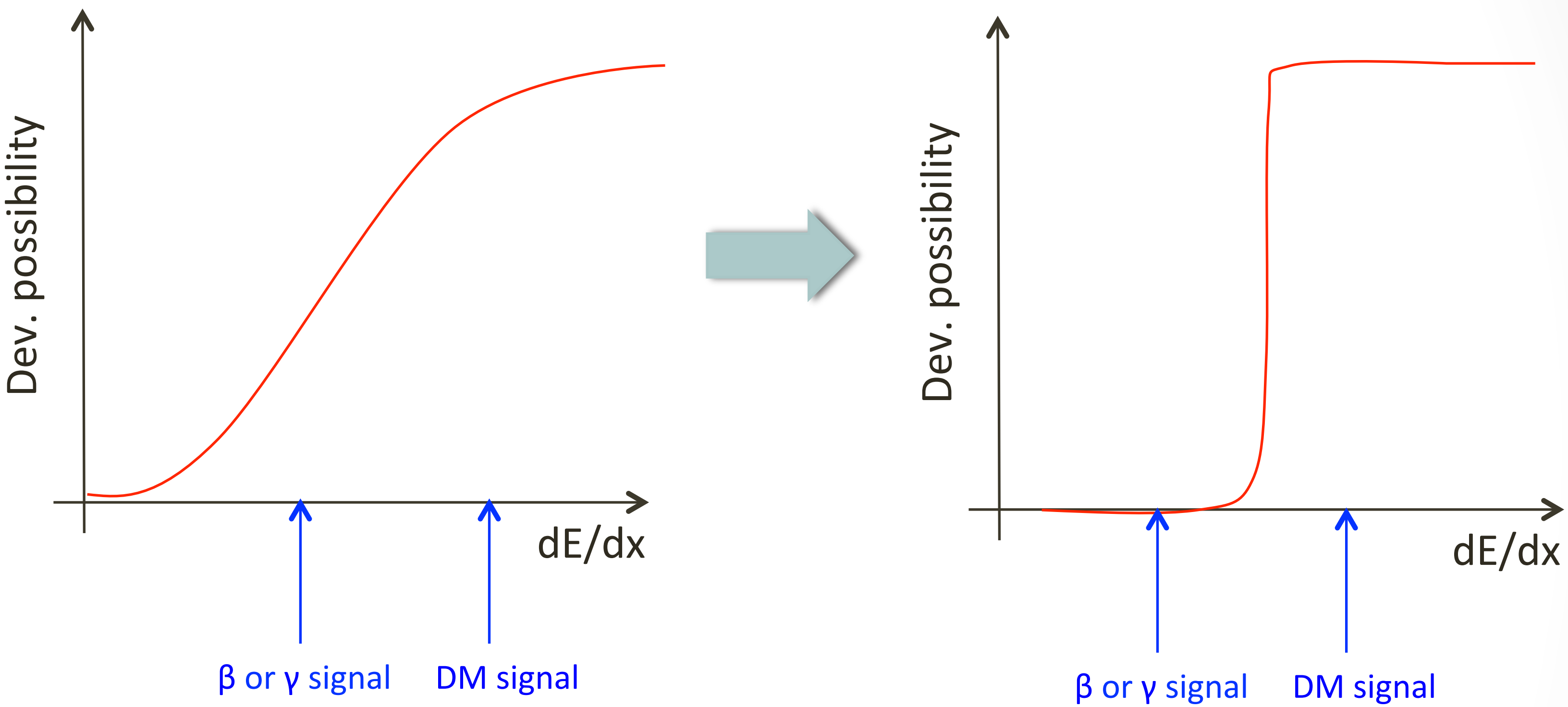
U-NIT

Finest grain emulsion



	NIT	U-NIT
AgBr density	12 AgBr/μm	29 AgBr/μm
Detectable range	> 200 nm	> 100 nm
Tracking E threshold	> 80 keV@C	> ~ 30 keV@C

Nano Imaging Tracker: sensitivity control



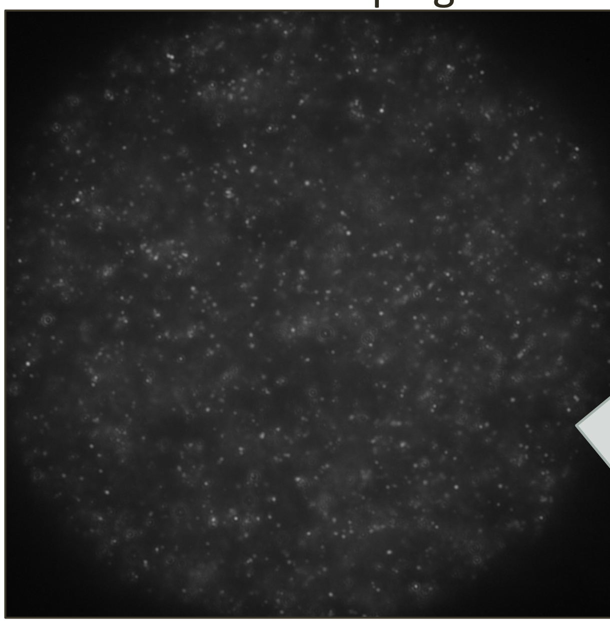
Formation efficiency of latent image speck to be maximized.

By doping of electron capture (e.g. Rh, Ir) in a crystal, sharpness of sensitivity dependence with dE/dx should be improved.

Nano Imaging Tracker: sensitivity control

241-Am γ source. 2.909±0.0970 MBq

Without Rh doping



~ 60 µm

Preliminary results

With Rh doping (~ 50 Rh/AgBr)

~ 60 µm

We need more tuning of doping quantity and sensitivity control, but it shows a good response ⇨ **in Progress**

R&D activity

- NIT technology
- Optical and X-ray read-out system
- Intrinsic background measurement
- Angular resolution measurement, neutron test beam
- Full MC simulation

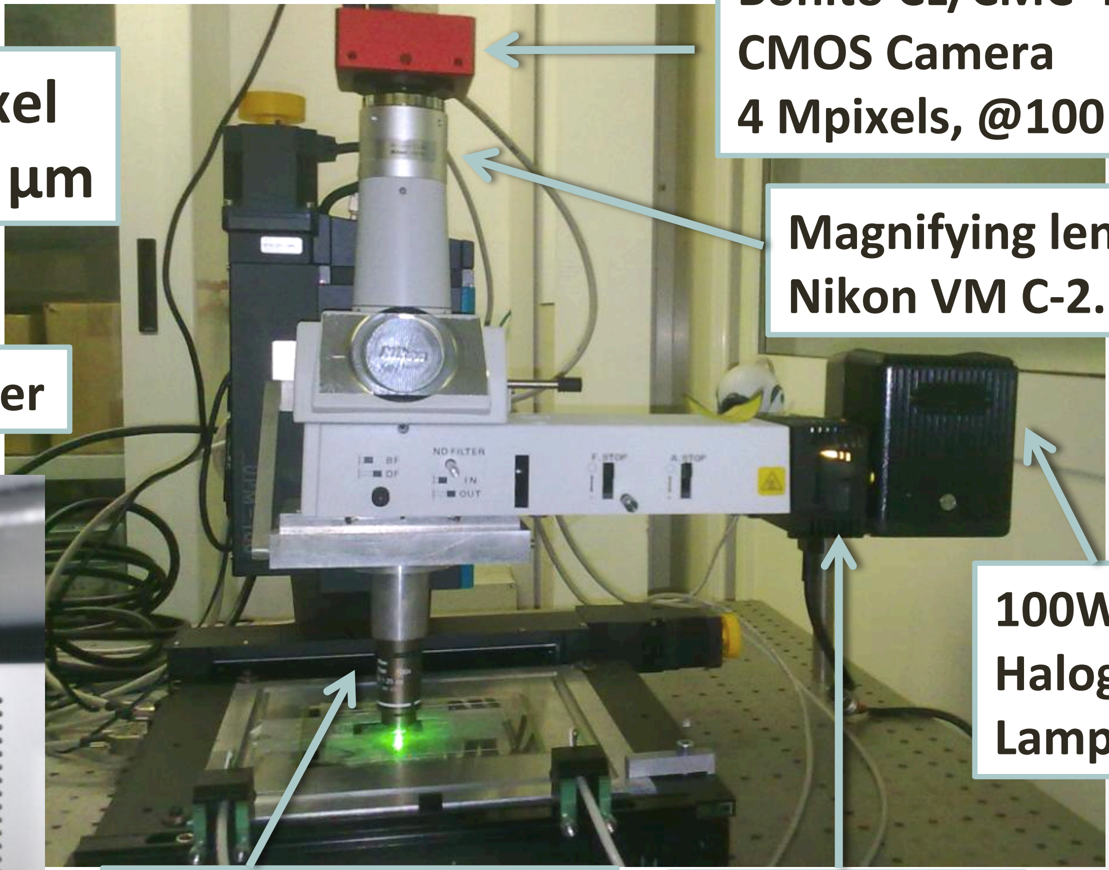
Optical Scanning System: current prototype

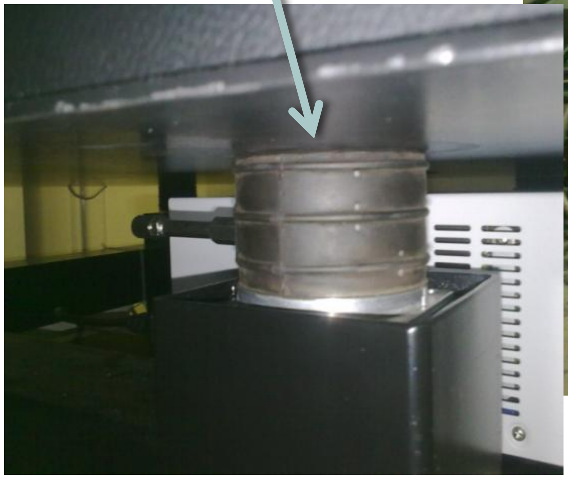
Resolution: 28 nm/pixel
View Size: 65.2 x 48.3 µm

Bonito CL/CMC-4000
CMOS Camera
4 Mpixels, @100 fps

Magnifying lens,
Nikon VM C-2.5x

Pneumatic Vibration Dumper





100W
Halogen
Lamp

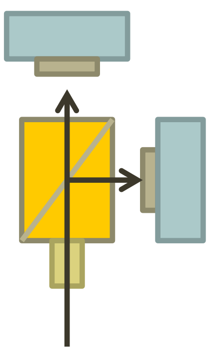
Nikon Oil Objective
100x, 1.25 N.A., Plan

Green Optical
Filter

Optical Scanning System: final prototype

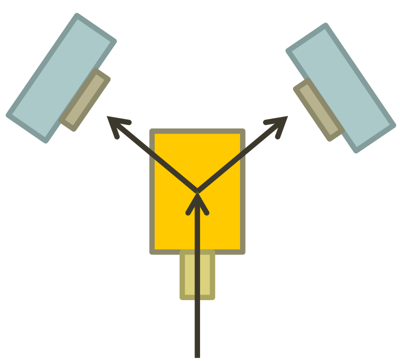
Final goal: 200 nm resolution. 20 cm^2/h scanning speed.

- Use of piezoelectric-driven objective
- New CMOS/ CCD image sensor with a resolution of 4 to 12 megapixel and an acquisition rate of about 400 frames /second
- A more powerful computing system (based on Graphical Processing Unit, GPU) to process and manage the data resulting from image acquisition and analysis
- Multiple camera to analyze the same emulsion sheet at same time or different sheets using the same mechanics. Using same Z stage and piezo-drive system for each camera to normalize the position of the plane focus on all cameras

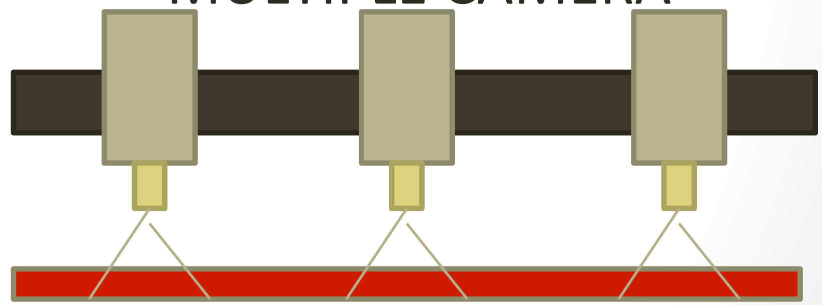


Using two cameras to focus different layers

Using two or more sensors to acquire different portion of the images

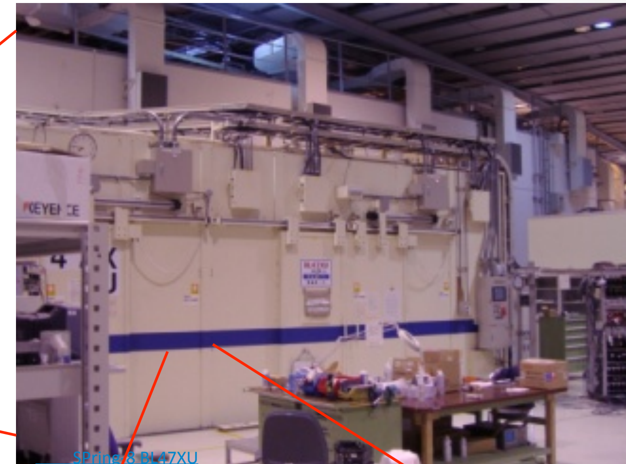


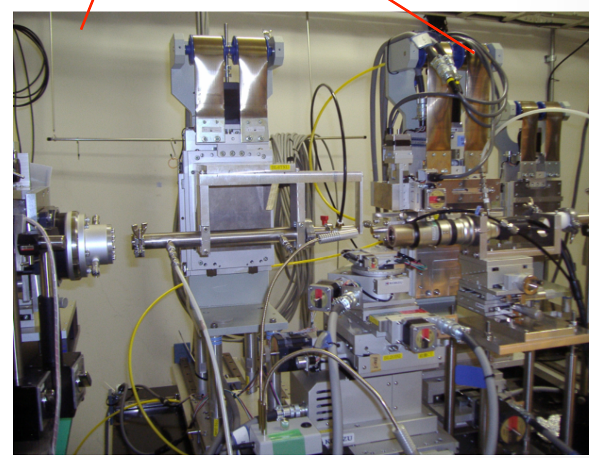
MULTIPLE CAMERA



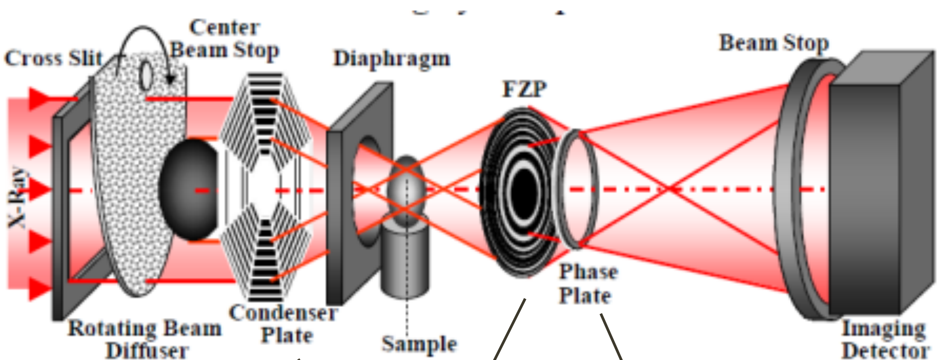
X-ray Scanning System

SPring-8 @ Japan





8keV X-ray

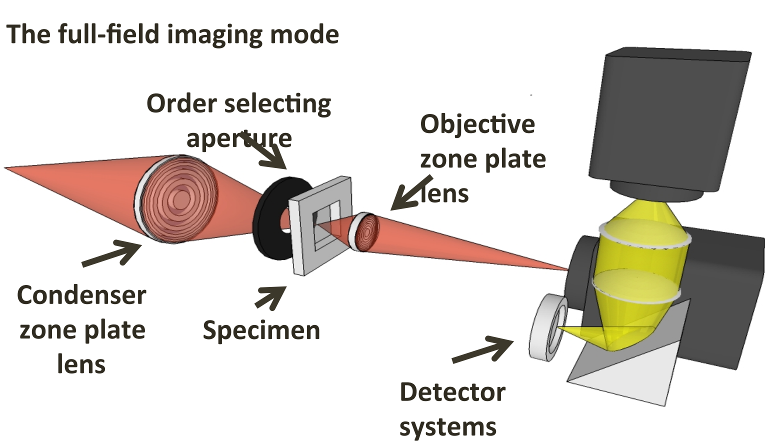


Zone plate Zernike phase plate

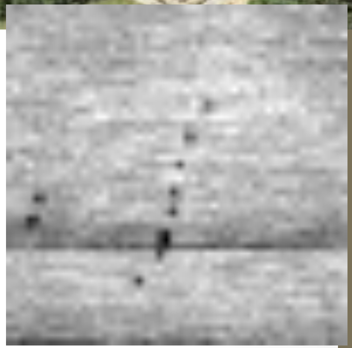
-Thickness of film : 100μm
-Focal depth : 70μm
-Type of optics: phase contrast
-X-ray Energy : 8keV

X-ray Scanning System

TwinMic X-ray source at Elettra (Trieste)



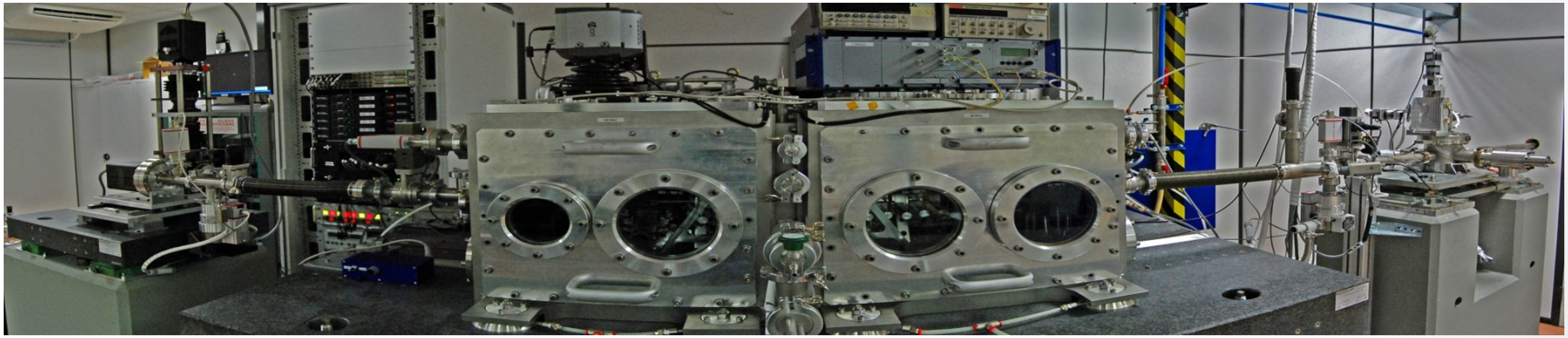
E = 1.14 keV



C recoil track

200nm spot size

- Energy up to 2 keV
- Analysis of morphology in transmission
- Fast imaging, dynamics, micro-tomography
- Spatial resolution < 50 nm



X-ray Scanning System

R&D activity:

- Development of an inter-calibration between the two read-out systems in order to measure only pre-selected zones
- Automation of the scanning procedure

R&D activity

- NIT technology assessment
- Optical read-out system
- *X-ray read-out system*
- Intrinsic background measurement
- Angular resolution measurement, Neutron test beam
- Full MC simulation

Intrinsic background measurement

α from ^{238}U and ^{232}Th chains are responsible of neutron emission through (α,n) reactions

Parent	Daughter	Decay Mode	Energy [MeV]	Half Life
^{238}U	^{234}Th	α	**4.27**	4.47×10^{9} yr
^{234}Th	^{234}Pa	β	0.273	24.1 d
^{234}Pa	^{234}U	β	2.20	6.70 hr
^{234}U	^{230}Th	α	**4.86**	2.45×10^{5} yr
^{230}Th	^{226}Ra	α	**4.77**	7.54×10^{4} yr
^{226}Ra	^{222}Rn	α	**4.87**	1.60×10^{3} yr
^{222}Rn	^{218}Po	α	**5.59**	3.82 d
^{218}Po	^{214}Pb	α	**6.12**	3.10 min
^{214}Pb	^{214}Bi	β	1.02	26.8 min
^{214}Bi	^{214}Po	β	3.27	19.9 min
^{214}Po	^{210}Pb	α	**7.88**	0.164 ms
^{210}Pb	^{210}Bi	β	0.0635	22.3 yr
^{210}Bi	^{210}Po	β	1.43	5.01 d
^{210}Po	^{206}Pb	α	**5.41**	138 d
^{206}Pb				stable

Parent	Daughter	Decay Mode	Energy [MeV]	Half Life
^{232}Th	^{228}Ra	α	**4.08**	1.41×10^{10} yr
^{228}Ra	^{228}Ac	β	0.0459	5.75 yr
^{228}Ac	^{228}Th	β	2.12	6.25 hr
^{228}Th	^{224}Ra	α	**5.52**	1.91 yr
^{224}Ra	^{220}Rn	α	**5.79**	3.63 d
^{220}Rn	^{216}Po	α	**6.40**	55.6 s
^{216}Po	^{212}Pb	α	**6.91**	0.145 s
^{212}Pb	^{212}Bi	β	0.570	10.6 hr
^{212}Bi	^{212}Po	β 64.06%	2.25	60.6 min
	^{208}Tl	α 35.94%	**6.21**	
^{212}Po	^{208}Pb	α	**8.96**	299 ns
^{208}Tl	^{208}Pb	β	5.00	3.05 min
^{208}Pb				stable

In nature, Thorium and Uranium chains are in secular equilibrium which implies that the activity is the same for all the species in the chain.

Human intervention during the production phase of materials can alter this equilibrium by artificially introducing some species of the chain

Mass spectrometry sensitive only to first elements of the chains
Gamma spectroscopy is sensitive to elements in the chain (through γ emitted by excited states)

Mass spectrometry: preliminary results

Gelatin sample	**Contamination [ppb]**	**Activity [mBQ/kg]**
Th	2.7	11
U	3.9	48

PVA	**Contamination [ppb]**	**Activity [mBQ/kg]**
Th	<0.5	<2
U	<0.7	<9

AgBrI	**Contamination [ppb]**	**Activity [mBQ/kg]**
Th	1	4
U	1.5	18

Polystyrene	**Contamination [ppb]**	**Activity [mBQ/kg]**
Th	0.019	0.08
U	0.009	0.11

Uncertainty on contamination : 30%

Conversion factors: 1 Bq/Kg(^{232}Th) = 246 ppb(^{232}Th) ; 1 Bq/Kg(^{238}U) = 81 ppb(^{238}U)

Gamma spectrometry: preliminary results

sample: **AgBr-I powder**, production 14-AUG-2013, OPERA
weight: 148.9 g
live time: 825660 s
detector: GeMPI2

radionuclide concentrations:

Th-232:			
Ra-228:	< 52 mBq/kg	<==>	< 1.3 E-8 g/g
Th-228:	< 3.8 mBq/kg	<==>	< 9.4 E-10 g/g
U-238:			
Ra-226	< 25 mBq/kg	<==>	< 2.0 E-9 g/g
Th-234	< 3.3 Bq/kg	<==>	< 2.7 E-7 g/g
Pa-234m	< 2.0 Bq/kg	<==>	< 1.6 E-7 g/g
U-235:	< 35 mBq/kg	<==>	< 6.1 E-8 g/g
K-40:	(98 +- 9) Bq/kg<==>	(3.2 +- 0.3) E-3 g/g	
Cs-137:	< 22 mBq/kg		
Co-60:	< 22 mBq/kg	@ start of measurement: 05-NOV-2013	
Ag-108m:	(67 +- 9) mBq/kg	@ start of measurement: 05-NOV-2013	
Ag-110m:	(4.54 +- 0.23) Bq/kg	@ start of measurement: 05-NOV-2013	

From ICP-MS
Th-232: (4±1) mBq/Kg

From ICP-MS
U-238: (18±5) mBq/Kg

The high potassium contamination spoils the measurement of other radionuclides, reducing the sensitivity

upper limits with k=1.645,
uncertainties are given with k=1 (approx. 68% CL);

Ra-228 from Ac-228;
Th-228 from Pb-212 & Bi-212 & Tl-208;
Ra-226 from Pb-214 & Bi-214;
U-235 from U-235 & Ra-226/Pb-214/Bi-214

Gamma spectrometry: preliminary results

sample:	**Gelatin, pure**, 2013/8/19, OPERA		
weight:	49.7 g		
live time:	1187626 s		
detector:	GePV		

radionuclide concentrations:

Th-232:			
Ra-228:	< 26 mBq/kg	<==>	< 6.5 E-9 g/g
Th-228:	(0.04 +-0.01) Bq/kg	<==>	(9 +- 2) E-9 g/g
U-238:			
Ra-226	< 21 mBq/kg	<==>	< 1.7 E-9 g/g
Th-234	< 0.44 Bq/kg	<==>	< 3.6 E-8 g/g
Pa-234m	< 0.52 Bq/kg	<==>	< 4.2 E-8 g/g
U-235:	< 15 mBq/kg	<==>	< 2.7 E-8 g/g
K-40:	< 0.30 Bq/kg	<==>	< 9.7 E-6 g/g
Cs-137:	< 6.1 mBq/kg		
Co-60:	< 4.6 mBq/kg	@ start of measurement: 25-OCT-2013	

Potassium contamination seems lower

upper limits with k=1.645,
uncertainties are given with k=1 (approx. 68% CL);

Sample too small to give a significant result

Ra-228 from Ac-228;
Th-228 from Pb-212 & Bi-212 & Tl-208;
Ra-226 from Pb-214 & Bi-214;
U-235 from U-235 & Ra-226/Pb-214/Bi-214

Intrinsic background measurement

New measurements with
^{40}K-free samples of:

Pure Gelatin

AgBrI

PVA

R&D activity

- NIT technology assessment
- Optical read-out system
- *X-ray read-out system*
- Intrinsic background measurement
- Angular resolution measurement, Neutron test beam
- Full MC simulation

Angular resolution measurement

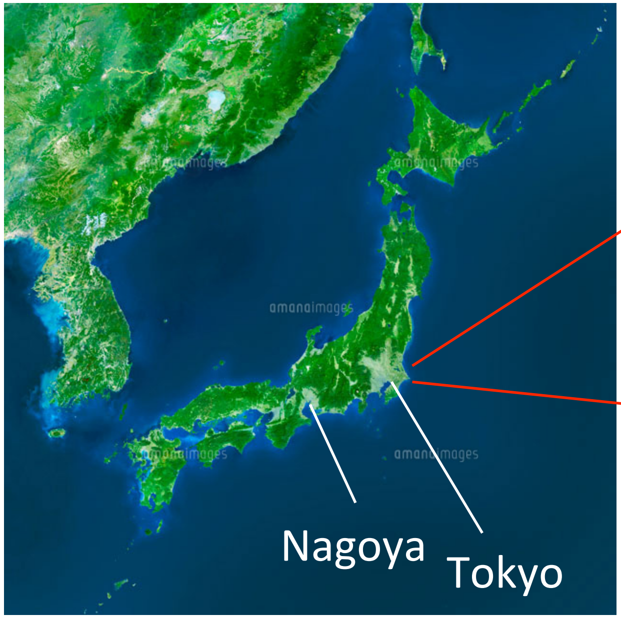
- The discovery potential of a directional experiment depends also on the tracking resolution (~ 20 degrees enough because dominated by the intrinsic spread)

→ implantation of slow ions in NIT samples, in order to simulate WIMP-induced nuclear recoils, and test beam with neutron sources to study the background rejection power.

- The analysis of NIT samples used for such test beams to test the prototype of the new read-out system and perform the optimization and fine-tuning of the scanning software and of the tracking algorithms
- The expected result is to reach a tracking threshold of 100nm and an angular resolution of about 30 degrees (twice better with X-ray microscopy)

Neutron Test Beam

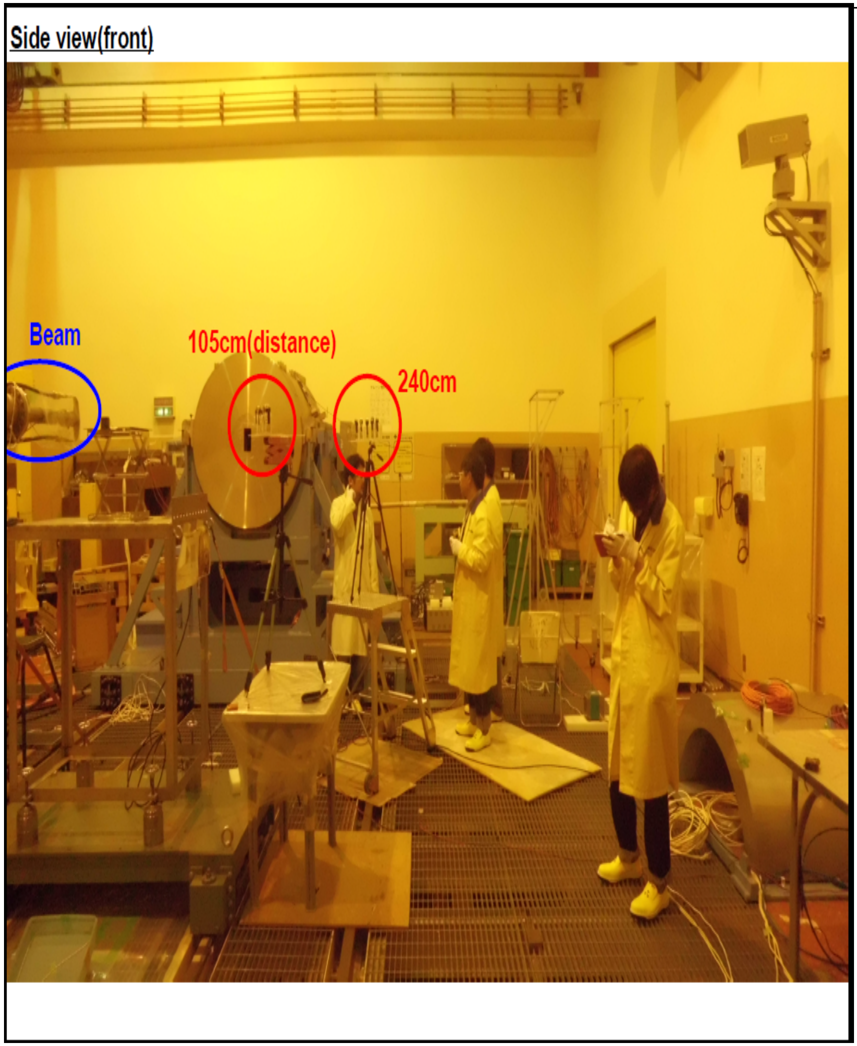
FNS (Fusion Neutron Source) at JAERI

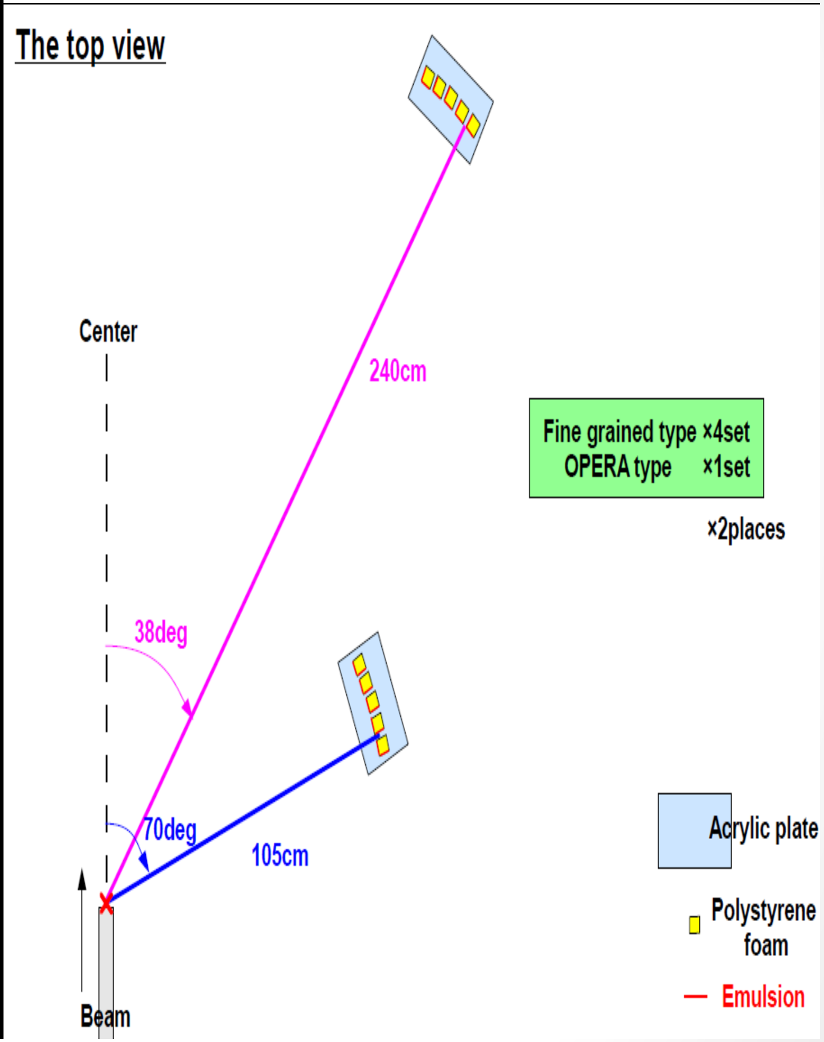


$$D + D \begin{cases} \xrightarrow{50\ \%} {}^{3}He + \mathbf{n}\ (2.45\ \text{MeV}) \\ \xrightarrow{50\ \%} T + p\ (3.45\ \text{MeV}) \end{cases}$$

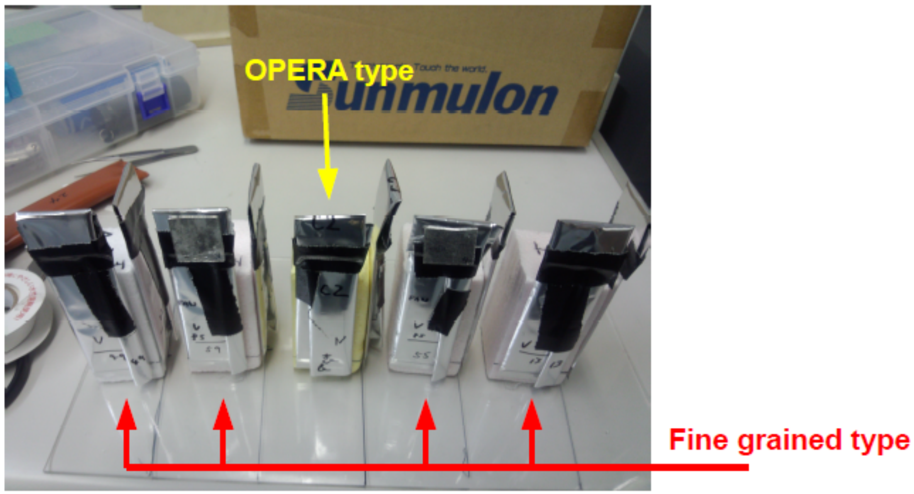
Study of NIT response to neutrons

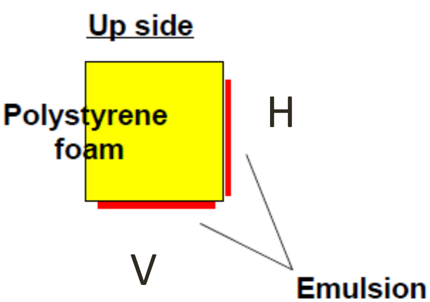
Neutron Test Beam





Neutron Test Beam





NIT (40 nm crystal size) : no Rh + HA sensitized emulsion

Fine grained type :main sample

- **carbon recoiled**
- **Angular distribution**

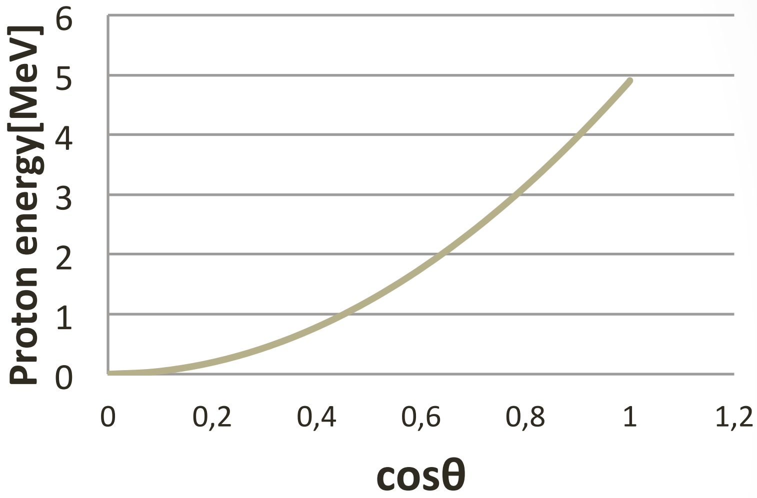
(OPERA type : Proton recoiled)

※ no sensitized OPERA like emulsion

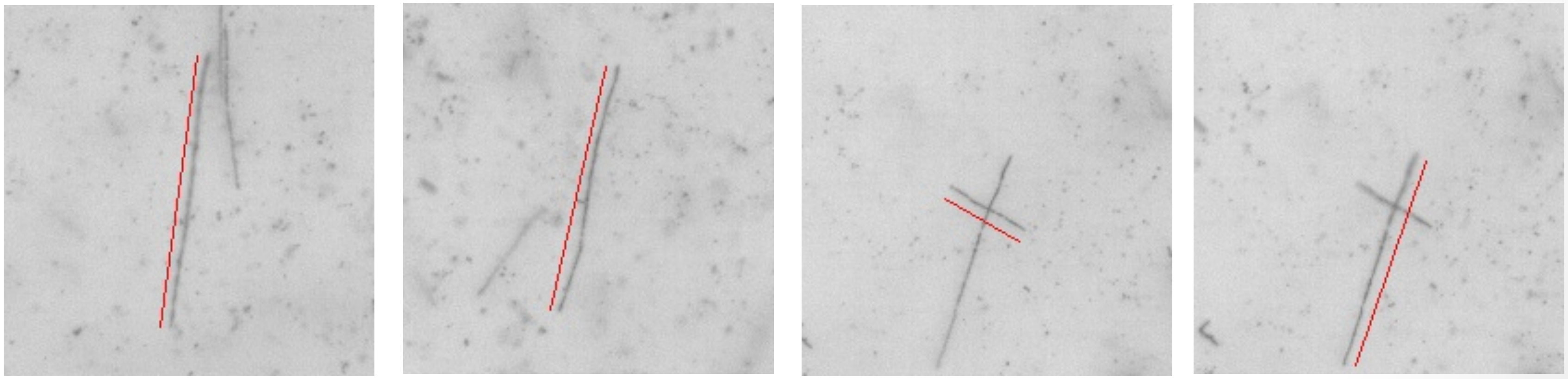
Neutron Test Beam

From proton energy to neutron energy

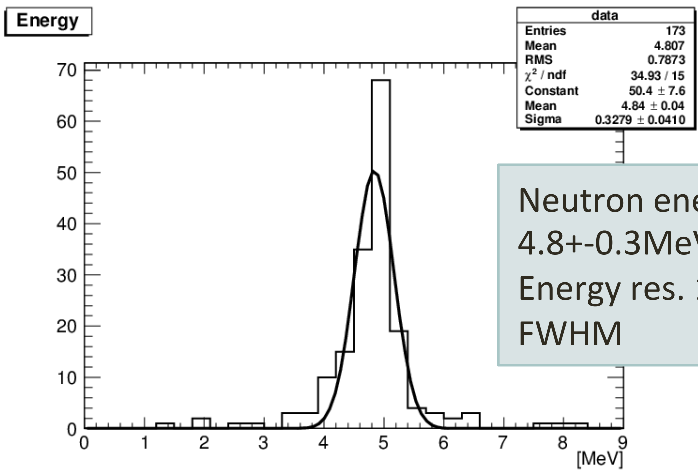
- $E_p = E_n \times \cos^2\theta$
  (elastic scattering formula)
- $E_n = E_p / \cos^2\theta$



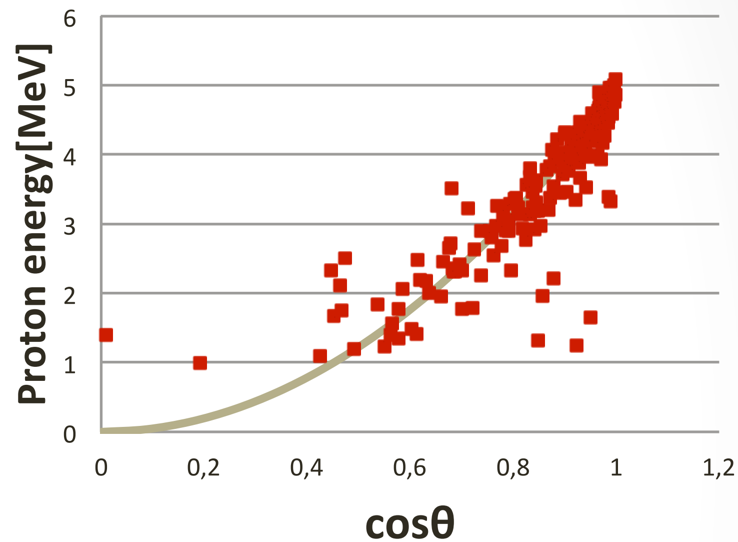
Proton recoil track images



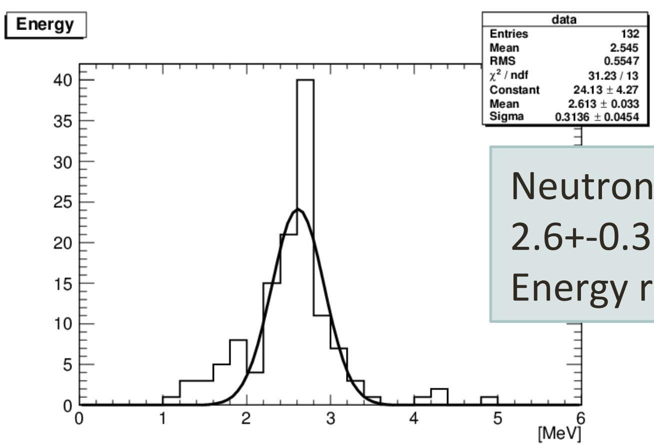
Neutron Test Beam



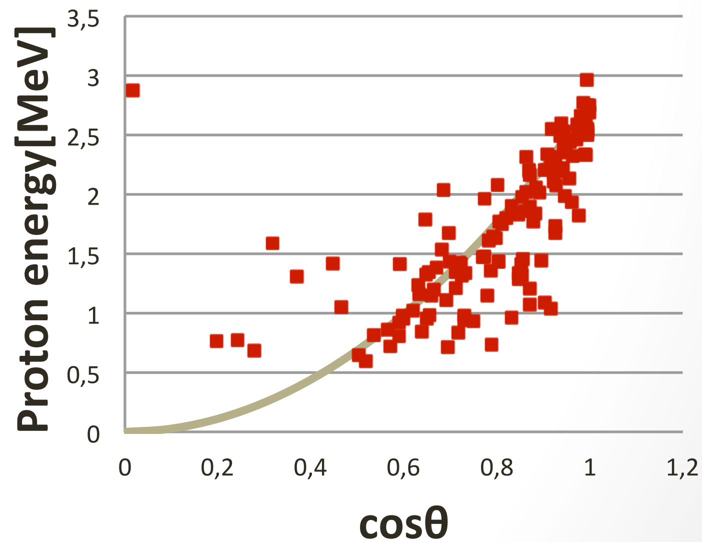
Neutron energy
4.8+-0.3MeV
Energy res. 14% as FWHM



Preliminary

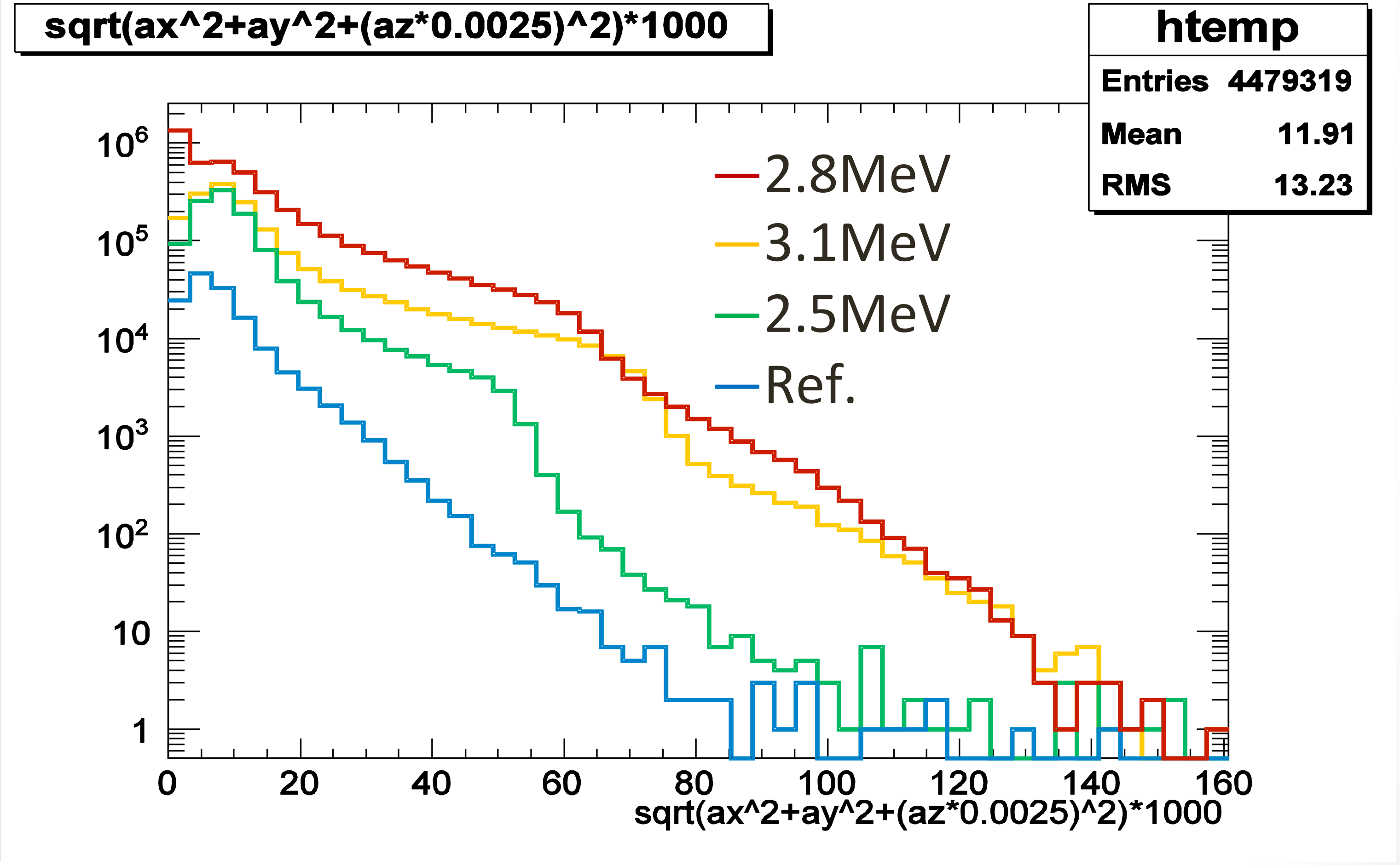


Neutron energy
2.6+-0.3MeV
Energy res. 24%



Neutron Test Beam

Preliminary result of the automatic scanning:



R&D activity

- NIT technology assessment
- Optical read-out system
- *X-ray read-out system*
- Intrinsic background measurement
- Angular resolution measurement, Neutron test beam
- Full MC simulation

Full MC simulation

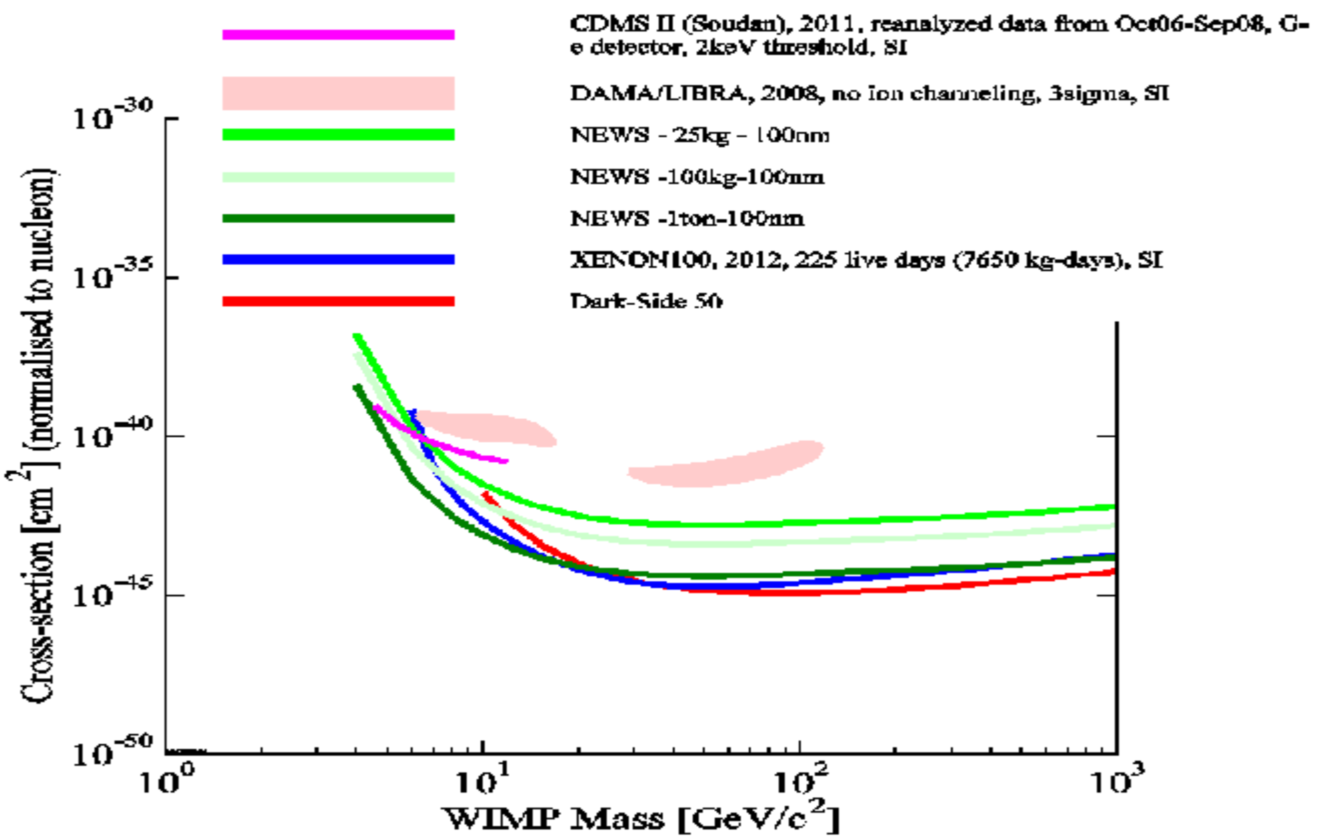
- SOURCES-based simulation to study neutron yield from spontaneus fission and (α,n) reactions

- Geant4 full MC simulation including intrinsic and external background, angular resolution, tracking threshold and efficiency.

… in progress

Sensitivity goal

- Zero-background hypothesis
- 90% C.L.
- 100 nm tracking threshold
- directionality information not included (it will improve)



NEWS Gantt Chart