Directional dark matter search with nuclear emulsion

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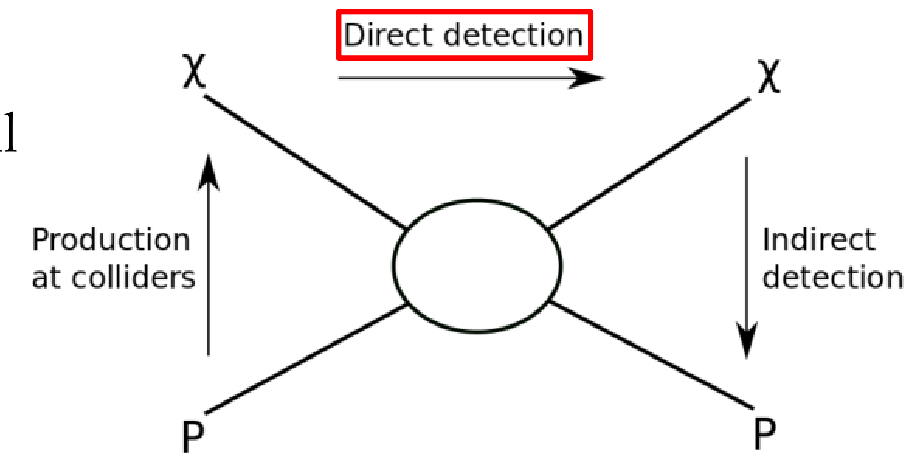
University of Naples/LNGS/JSPS

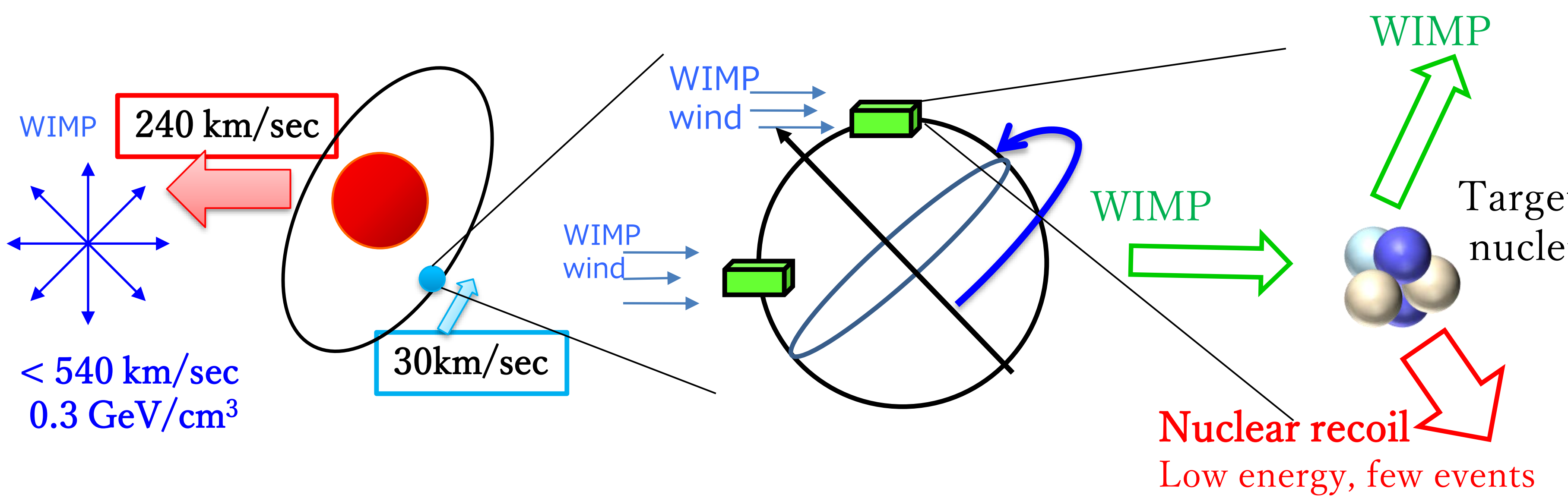
On behalf of NEWSdm collaboration

Direct Dark Matter Search

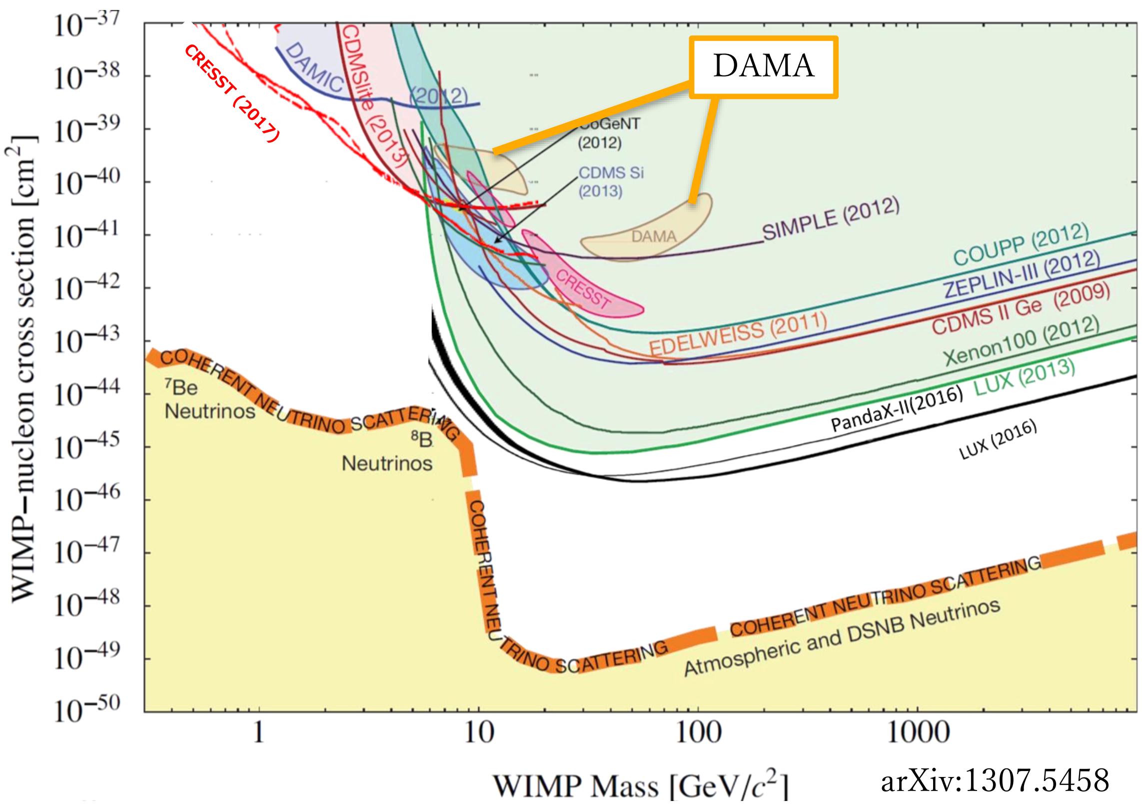
The aim is the detection of nuclear recoil come from WIMP interaction

WIMP wind is good feature to proof the detection and the galactic origin





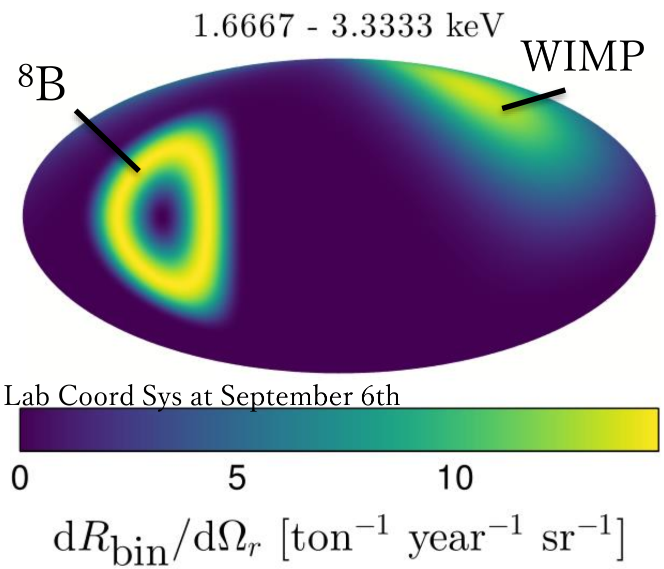
Recent Direct Dark Matter Searches

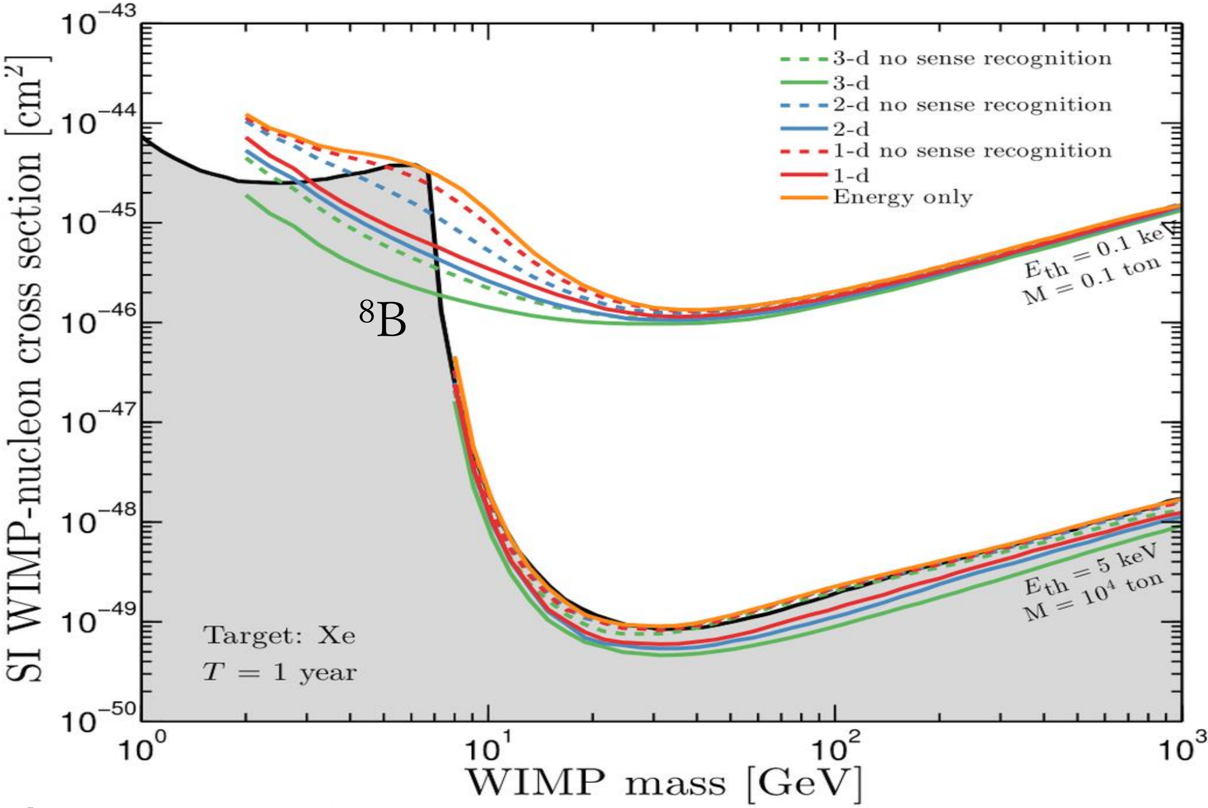


arXiv:1307.5458
+ IDM2016 reports
+ ICNFP2017

The direct detection is approaching to neutrino floor

The Advantage of Directionality





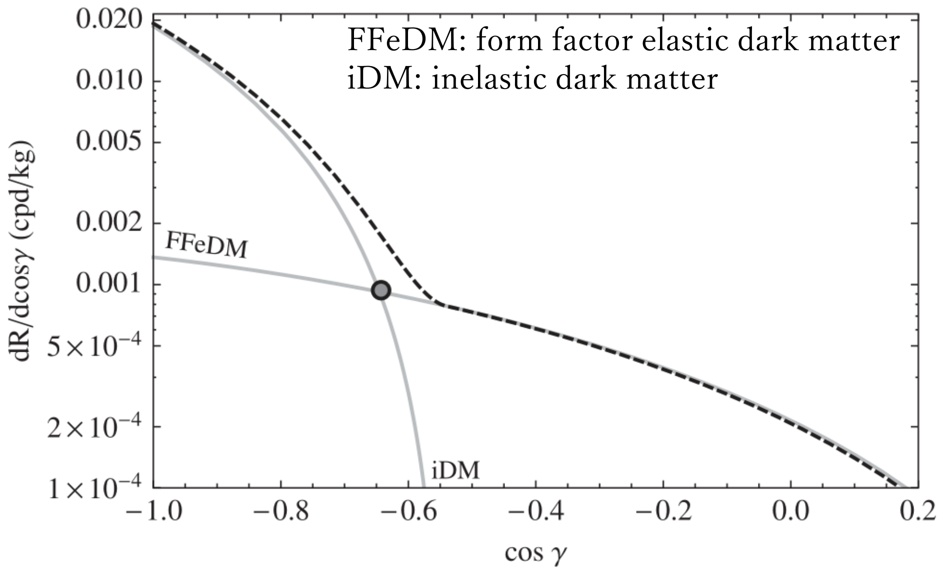
F. Mayet *et al.*, Physics Reports 627 (2016) 1

Directional detection will overcome the neutrino floor

The Advantage of Directionality

inelastic dark matter

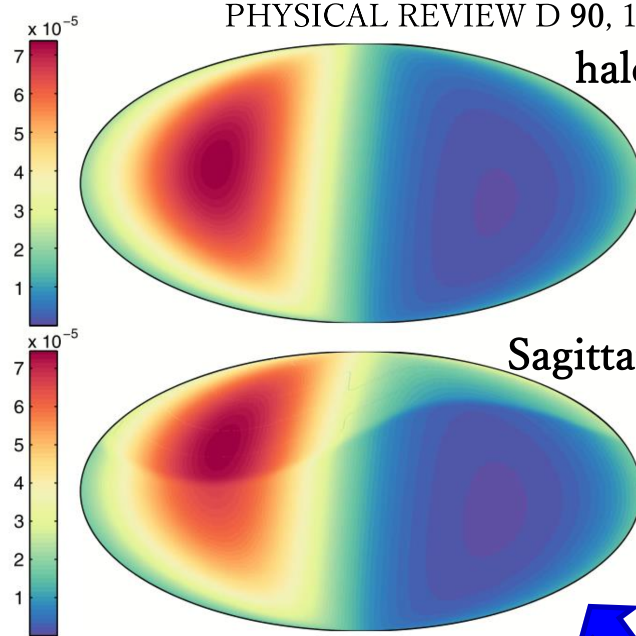
PHYSICAL REVIEW D **81**, 096005 (2010)

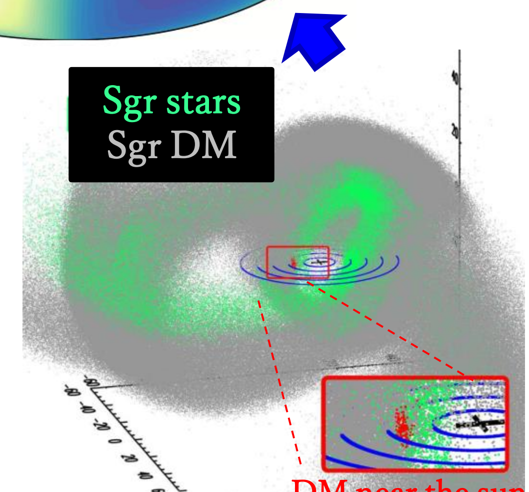


this effect is emphasized with heavier target!

dark matter streams

PHYSICAL REVIEW D **90**, 123511 (2014)





C. W. Purcell et al., JCAP 08, 027 (2012)

And other anisotropic DM velocity models…
(cf. Nagao's talk, 22 Aug)

Directionality will contribute for the physics of WIMP

NEWSdm collaboration

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

http://news-dm.lngs.infn.it

LoI under review by
the LNGS Scientific Committee

https://arxiv.org/abs/1604.04199

NEWSdm Collaboration
70 physicists, 14 institutes

ITALY
INFN e Univ. Bari,
LNGS, INFN e Univ. Napoli,
INFN e Univ. Roma
GSSI Institute

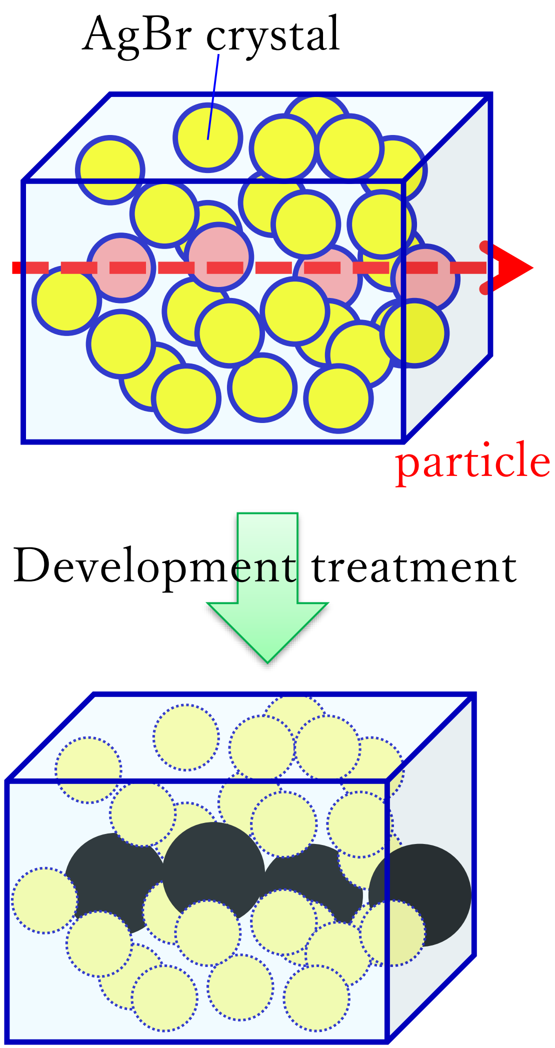
JAPAN
Chiba, Nagoya

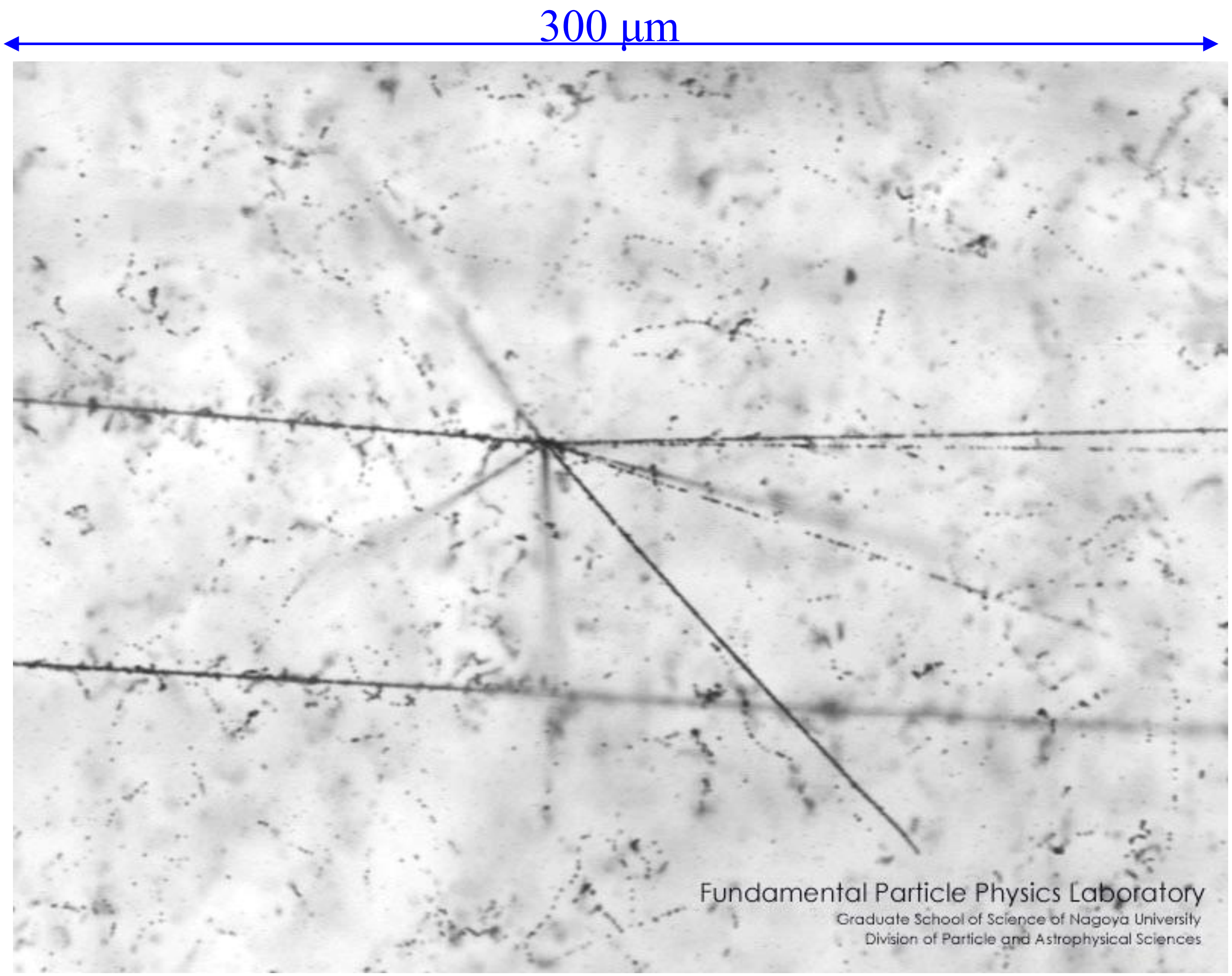
RUSSIA
LPIRAS Moscow, JINR Dubna
SINP MSU Moscow, INR Moscow
Yandex School of Data Analysis

SOUTH KOREA
Gyeongsang

TURKEY
METU Ankara

Nuclear Emulsion

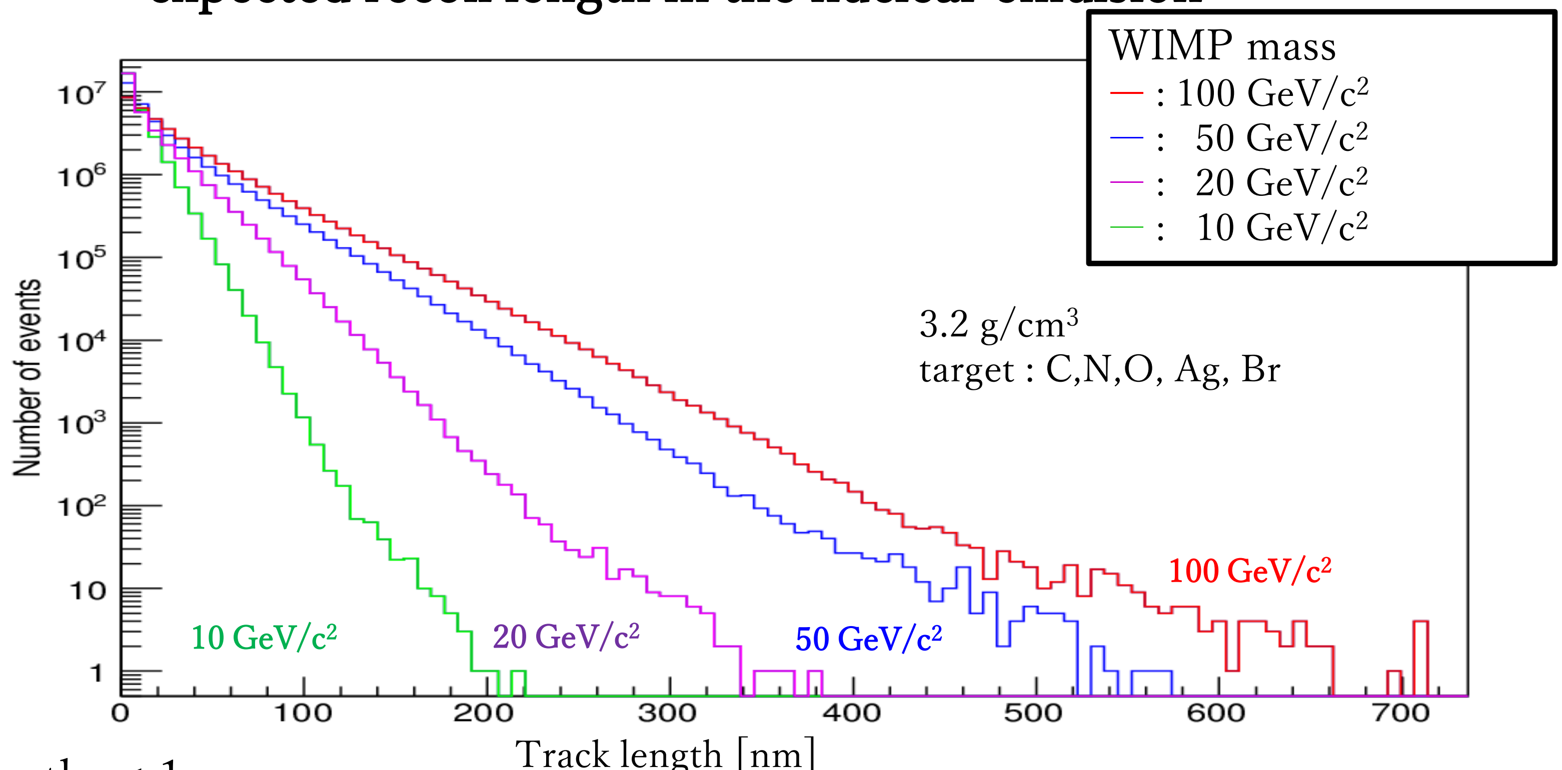




3 dimensional tracking with high spatial resolution

The challenge of NEWSdm

expected recoil length in the nuclear emulsion



recoil length < 1 um

Angular dispersion due to straggling ~ 25 deg

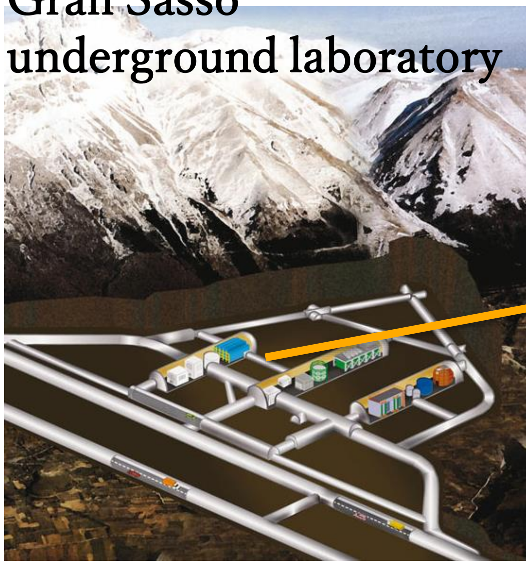
low background

scalability

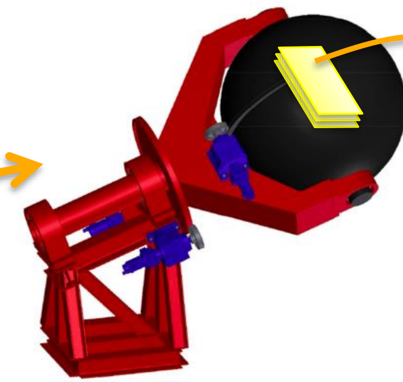
→ new technologies both detector and analysis

NEWSdm Experiment

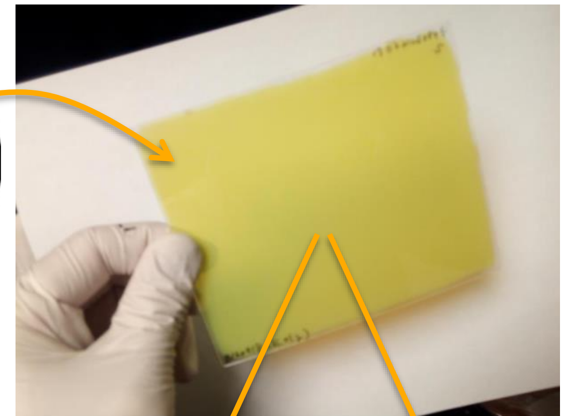
Gran Sasso underground laboratory



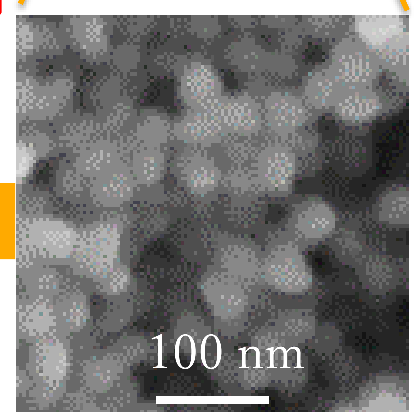
Equatorial Telescope

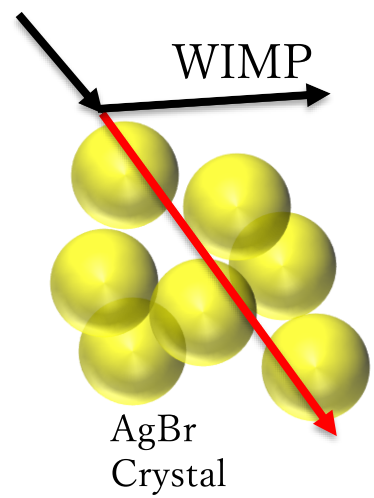


Emulsion film

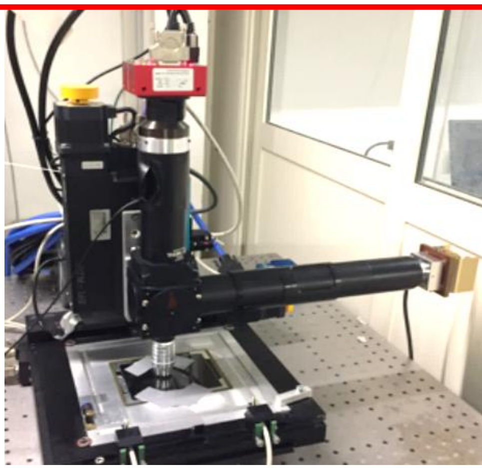


Super-high resolution device



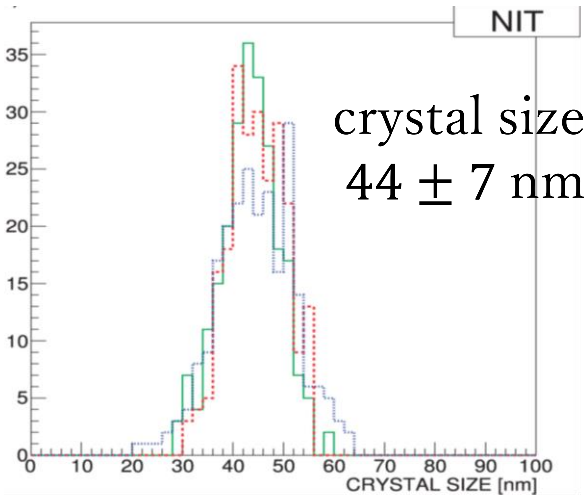


multiple analysis(high-speed/high-precision)

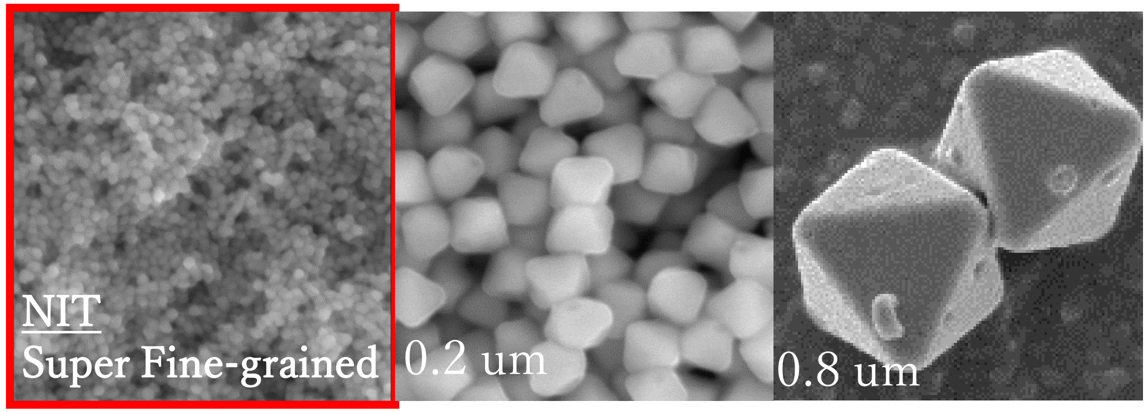


Super Fine-grained Nuclear Emulsion : NIT

NIT(Nano Imaging Tracker) PTEP (2017) 063H01



crystal size
44 ± 7 nm



500nm 500nm 500nm

Smaller crystals give higher resolution

theoretical resolution
(average crystal distance)
→ 71 nm !

Self production facility in Japan

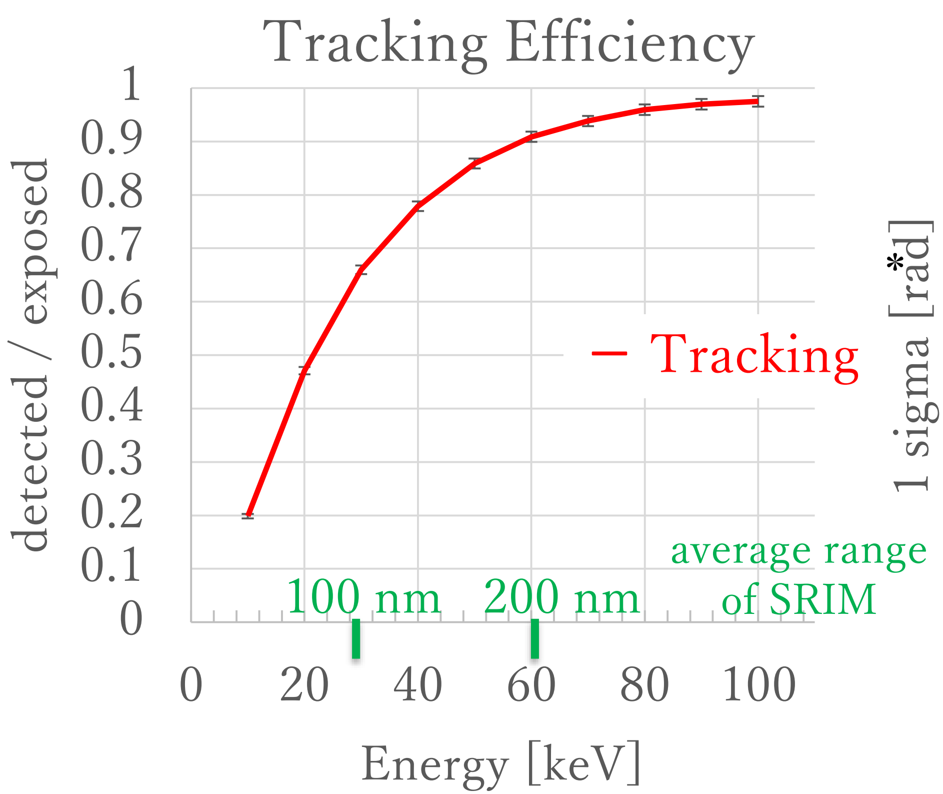
Production time : 4–5 hours /batch
Production amount : ~ 100 g (+ 300 g)
(2nd machine)

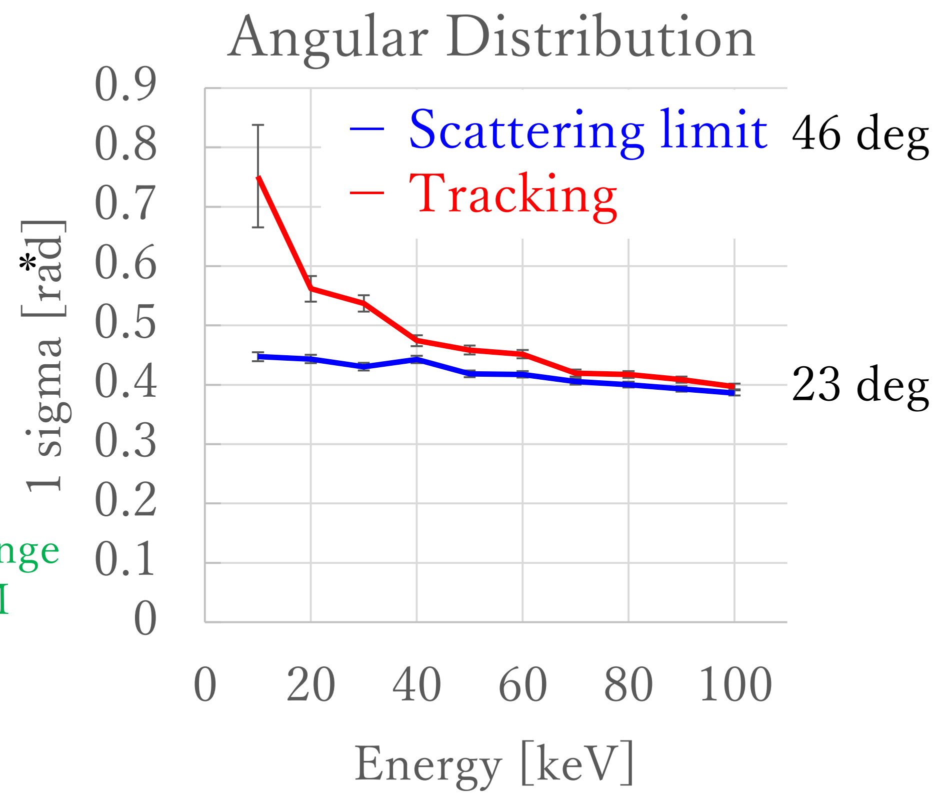
large mass easily achievable!

Potential of NIT

MC of scattering (SRIM) and crystal size of NIT

*case of ^{12}C in emulsion





tracking : at least 2 crystal

high angular resolution for low energy track

Readout strategy

overall scan : 1st selection

trigger of signal candidates
- high speed scanning
- minimum selection for next analysis

Higher level selection 1

Higher level selection 2

Higher level selection 3

⋮

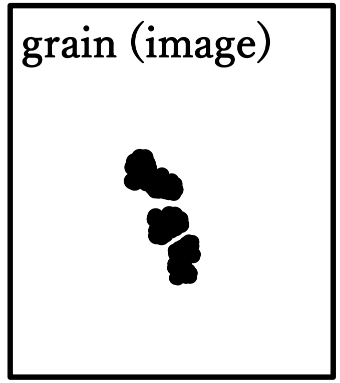
multiple scanning for higher precision
- complex software analysis
- repeat scanning
- analysis by other imaging system
  - plasmon effect
  - 3 dimensional readout

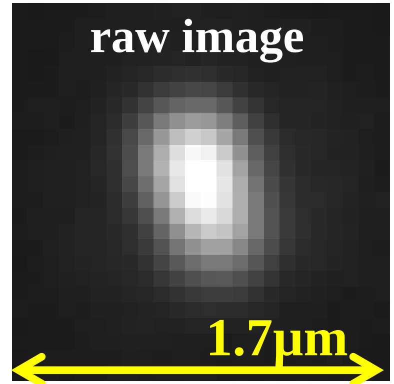
signal confirmation

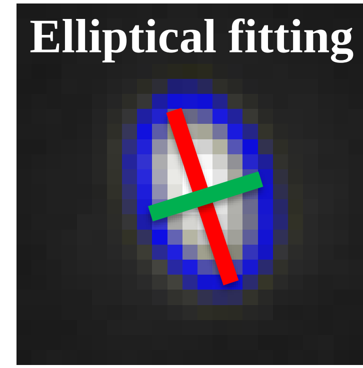
1st selection : shape analysis

Optical Microscope PTS-2

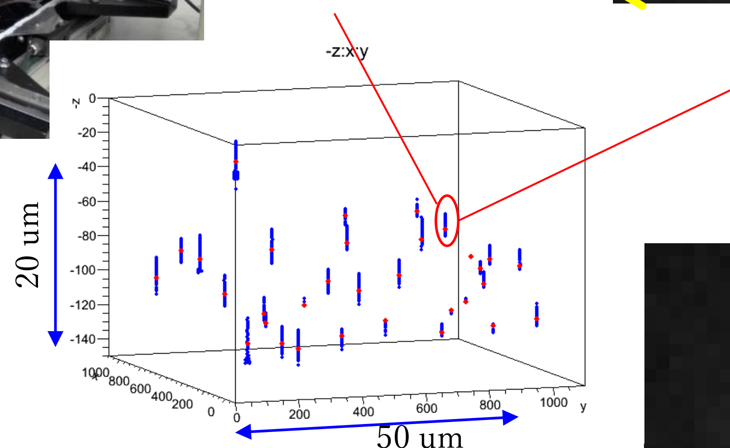
[JINST 12 (2017) T04002]

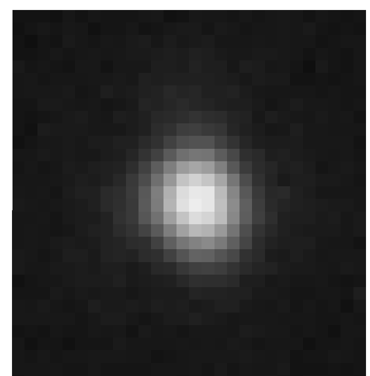






ellipticity = major / minor





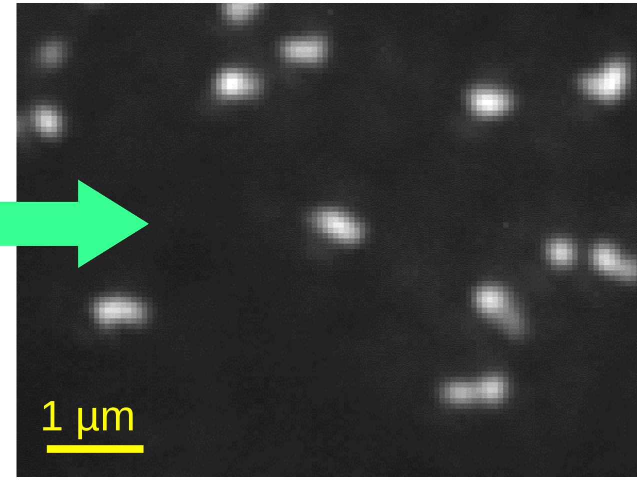
- high speed scanning
- 3D positioning for each events
- minimum amount selection for next analysis

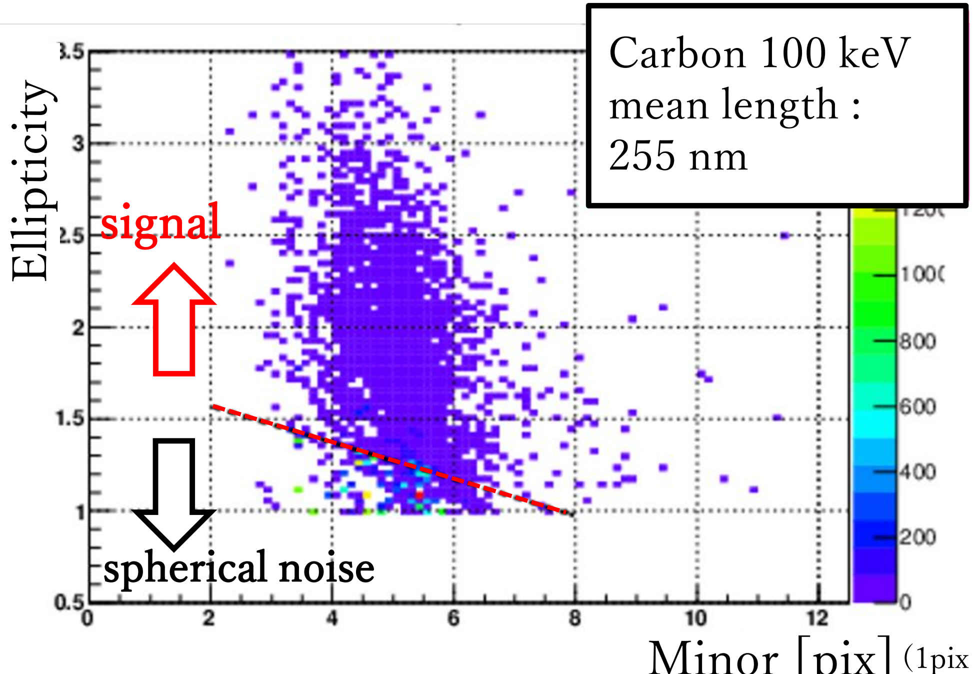
dominant noise (spherical shape)

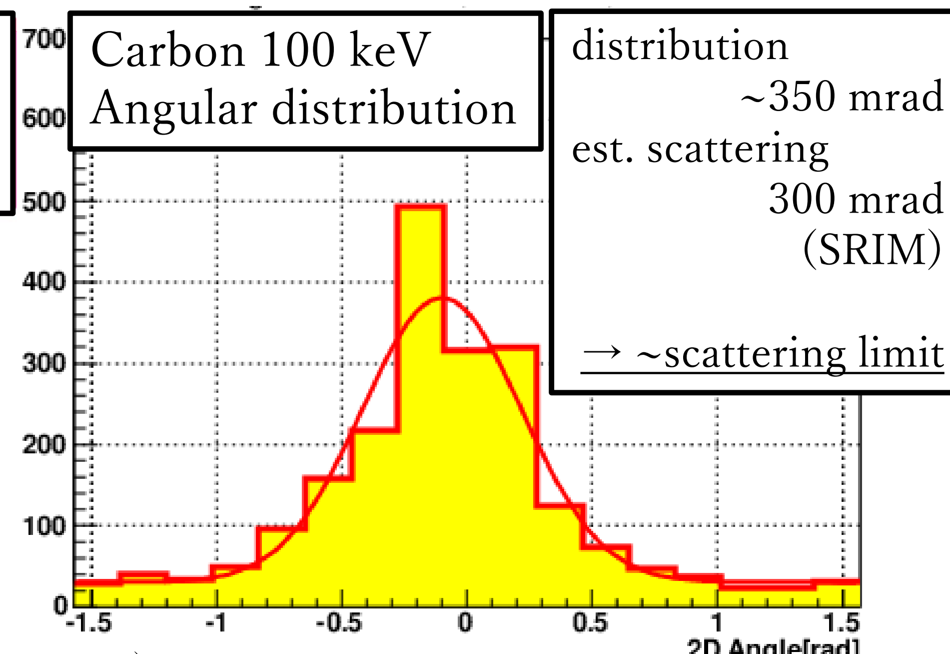
- unexpected developing crystal
- tiny dust from material

Detection of low energy tracks

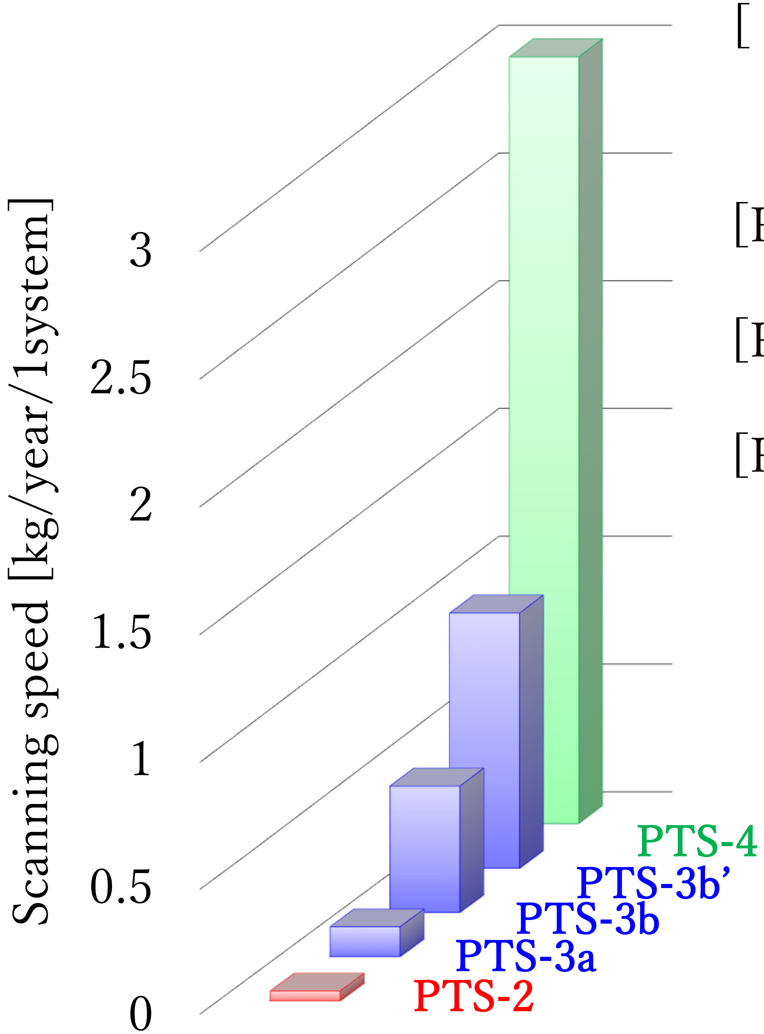
Ion implantation system @Nagoya Univ.







Roadmap of 1st selection system



[PTS2] **40 g/y** (current system)

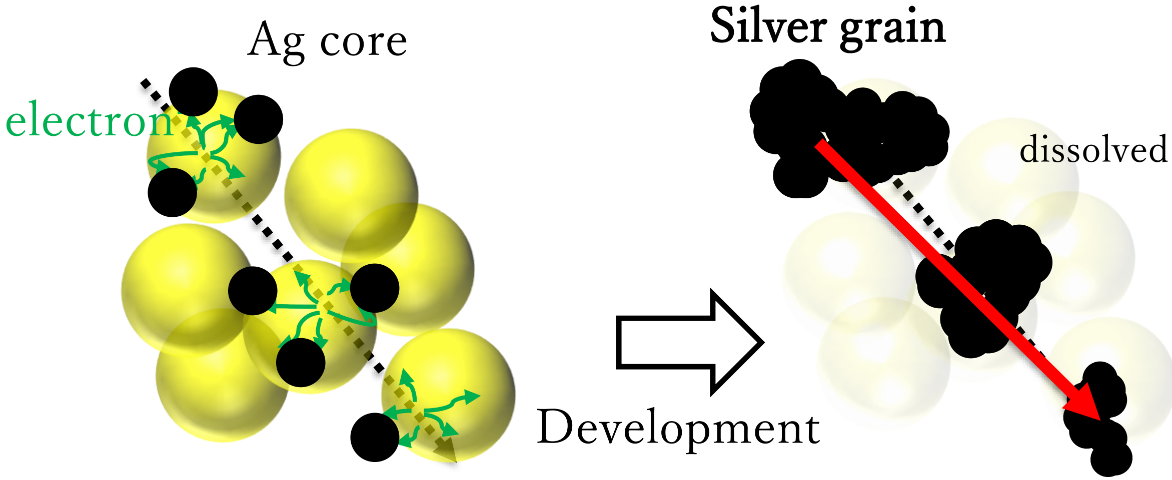
[PTS3a] **120 g/y** expected (x 3 higher than PTS2])
Wider FOV due to higher vision camera

[PTS3b] **500 g/y** expected
PTS3a + large DOF system

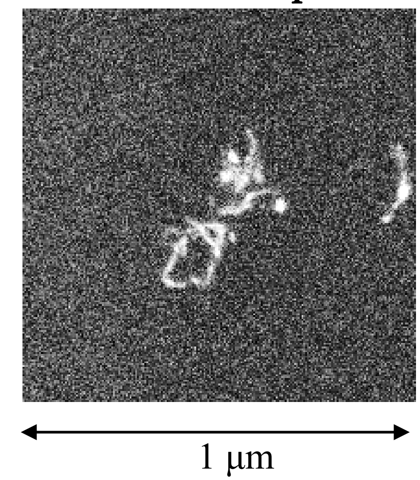
[PTS3b', PTS4] **1000 - 3000 g/y** expected
PTS3b + custom special lens, high framerate

scan-sharing with multi-laboratory/multi-systems

Higher Level Analysis



Electron microscopic image



Purpose :

- signal confirmation and BG separation
- accurate measurement of track details (angle, length···)

characteristic nano-structure of silver grain is not negligible
→ super-resolution

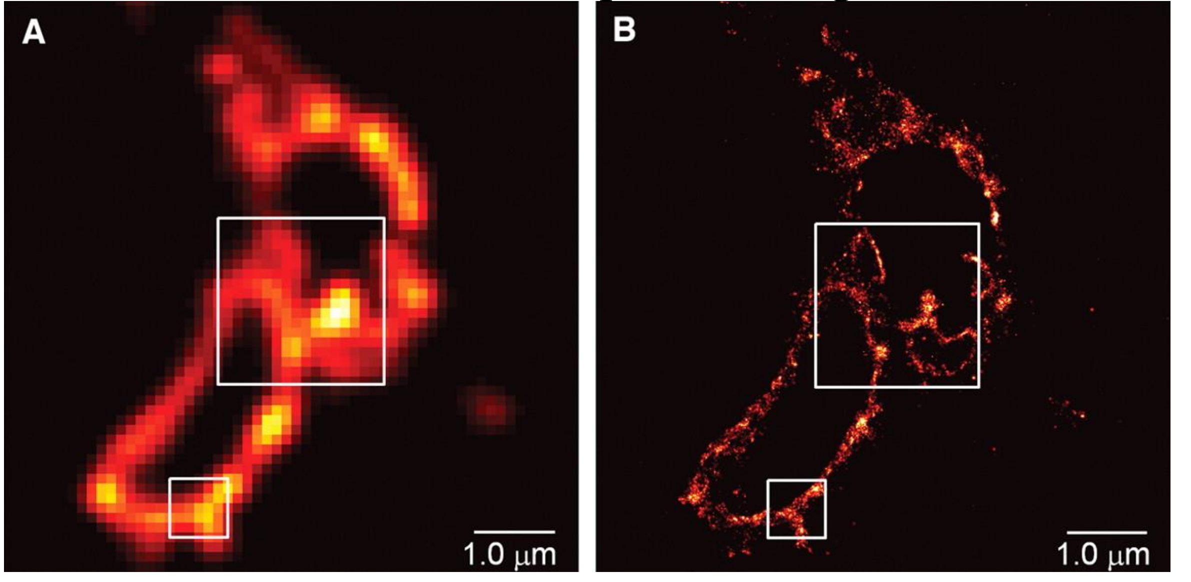
Imaging beyond the optical resolution

The position accuracy is superior than the optical resolution

each fluorescence molecular can be observed

→ super resolution

COS-7 cell optical images

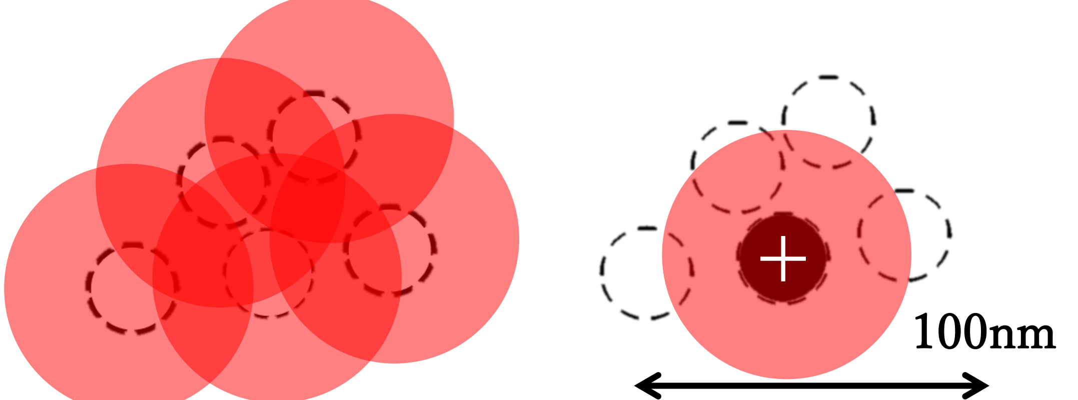


Eric Betzig *et al.*, Science 313, 1642 (2006)
2014 Nobel Prize in Chemistry

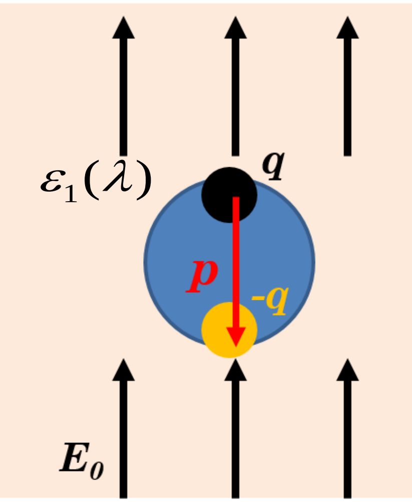
How our case is?

Silver (metal) structure

→ <u>Local Surface Plasmon</u>



LSP (Localized Surface Plasmon resonance)



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

dipole in metalic particle

dipole moment

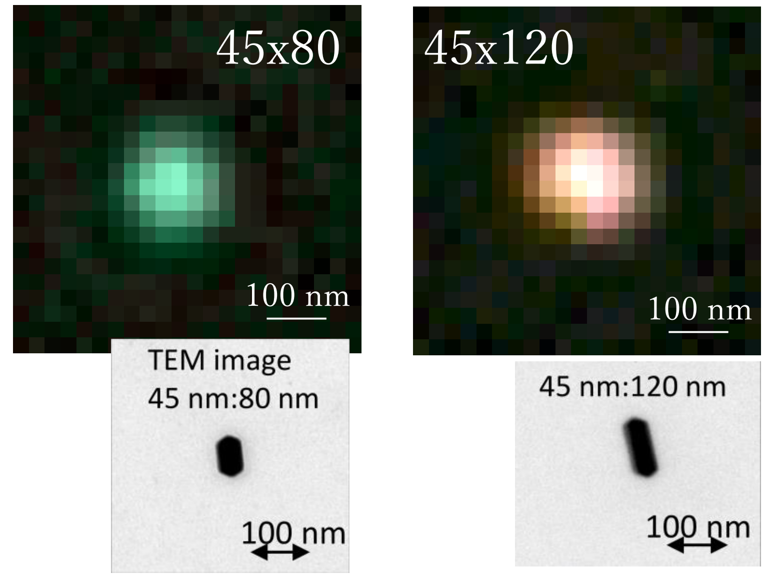
$$p = 4\pi\varepsilon_m a^3 \frac{\varepsilon_1(\lambda) - \varepsilon_m(\lambda)}{\varepsilon_1(\lambda) + 2\varepsilon_m(\lambda)} E_0$$

resonance

$$\boxed{\varepsilon_1(\lambda_l) + 2\varepsilon_m(\lambda_l) \approx 0}$$

Colored optical image of silver rod

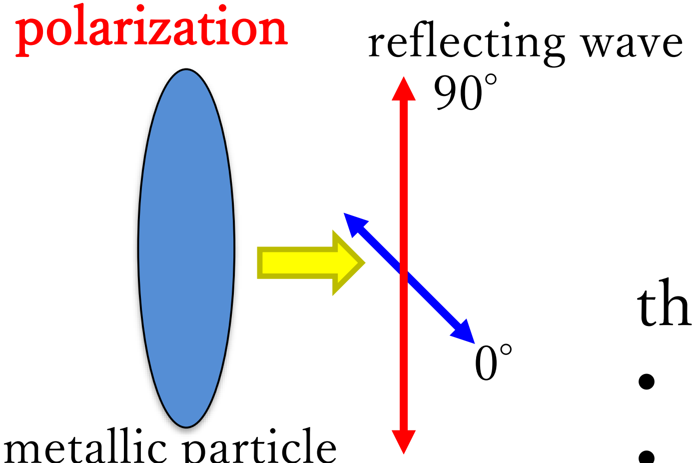
*polarization rotating



~45 nm : blue
~80 nm : green

~45 nm : blue
~120 nm :orang–red

polarization



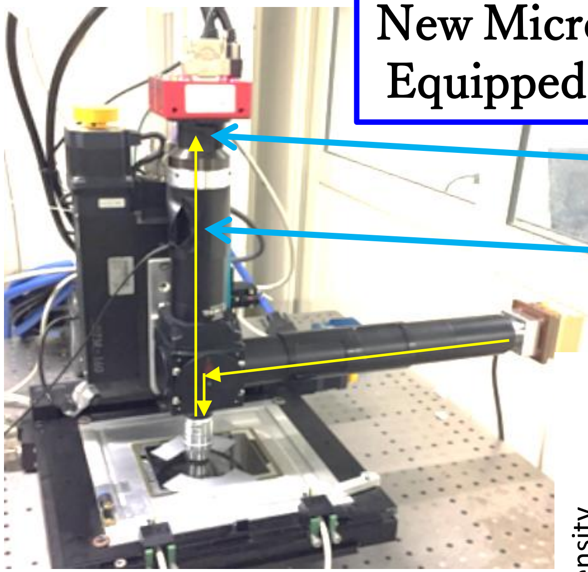
Appl. Phys. Lett. **80**, 1826 (2002)

the shape of particle affect to resonance

- particle direction → resonance pol angle
- particle length → resonance wavelength

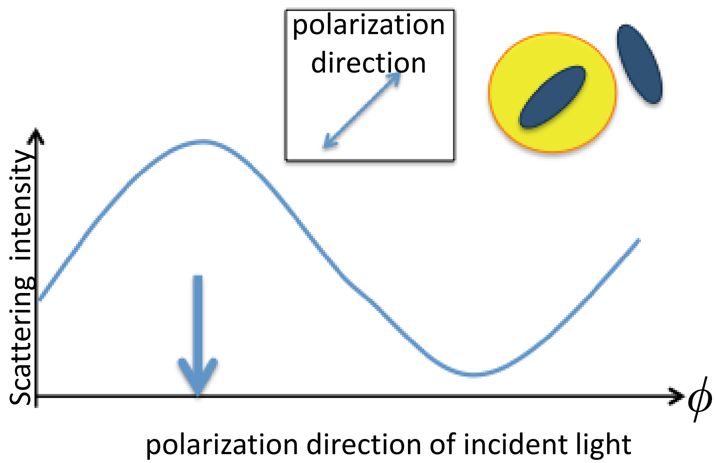
Super resolution analysis with LSP polarization

New Microscope
Equipped with liquid crystal polarizer

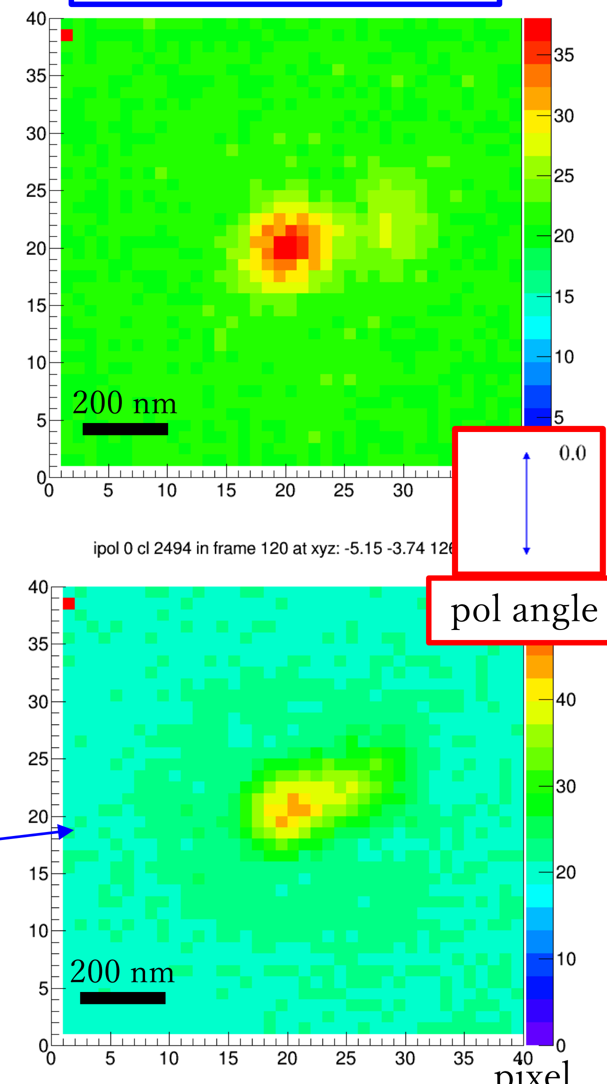


Exit polarizer plate

LC Polarization Rotator



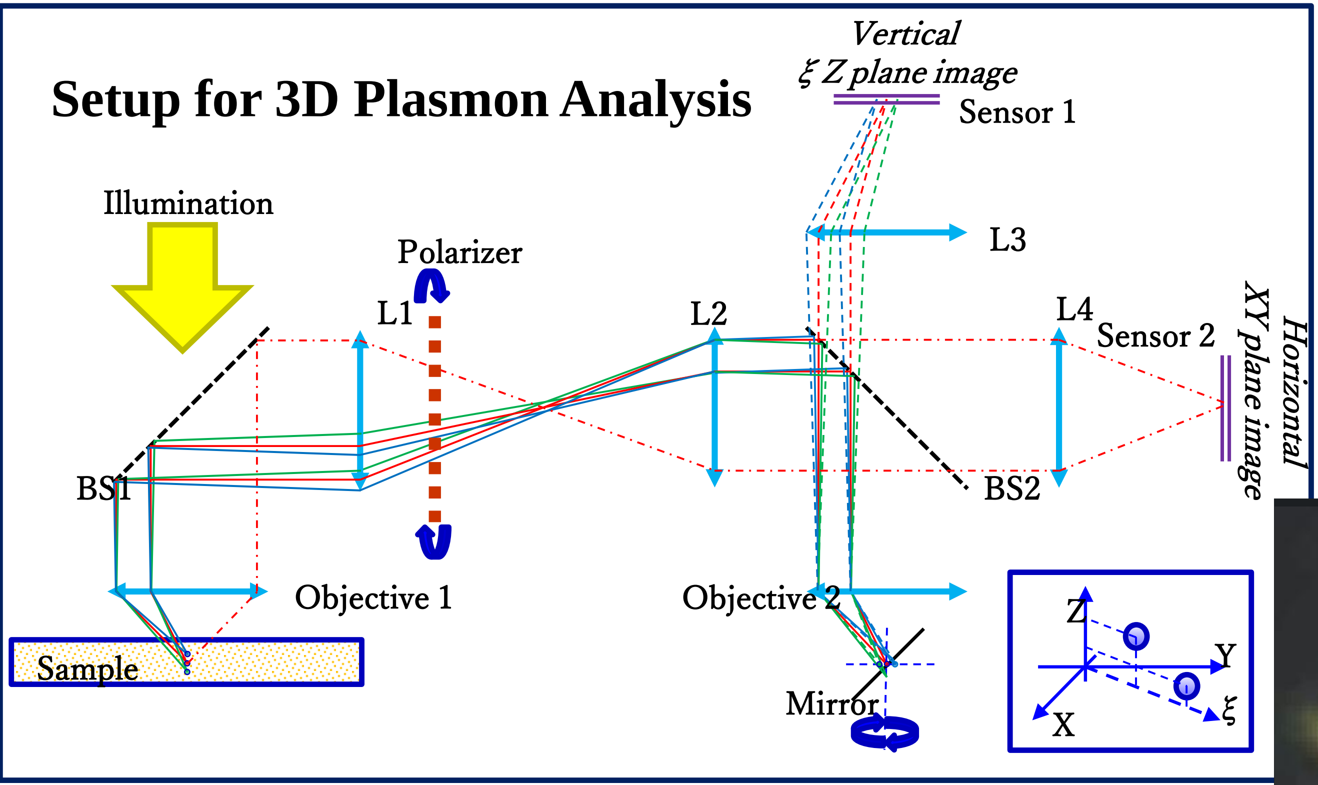
100 keV Carbon track



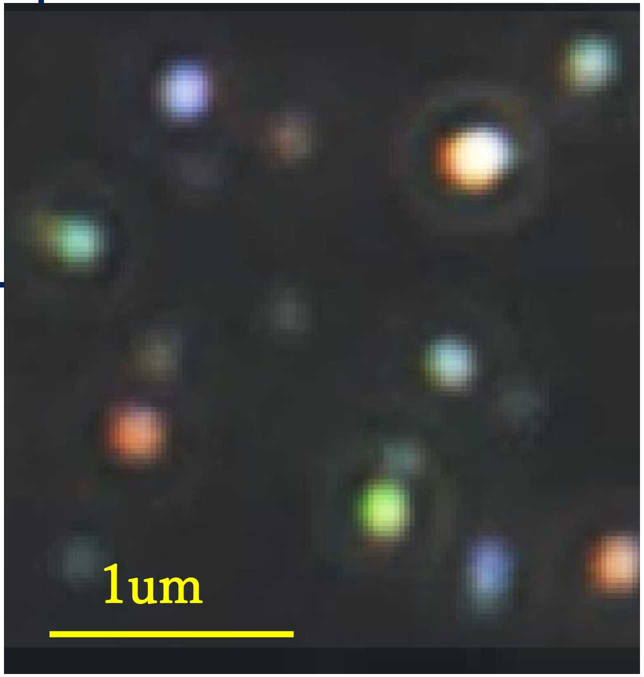
The positions of indistinguishable silver grains can be measured as barycenter moving

We are evaluating this new system now

R&D of further analysis



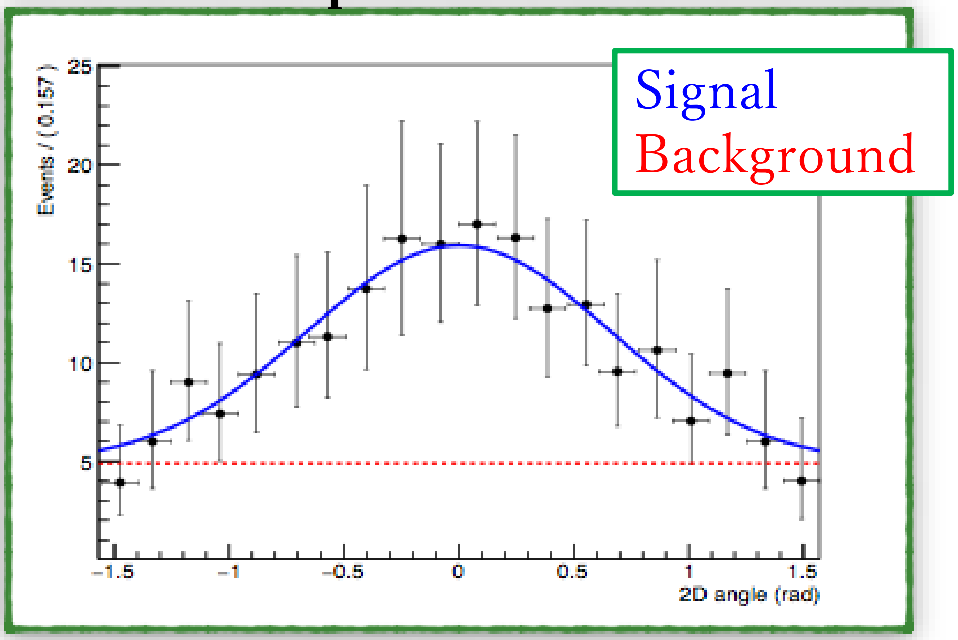
color camera image of carbon tracks

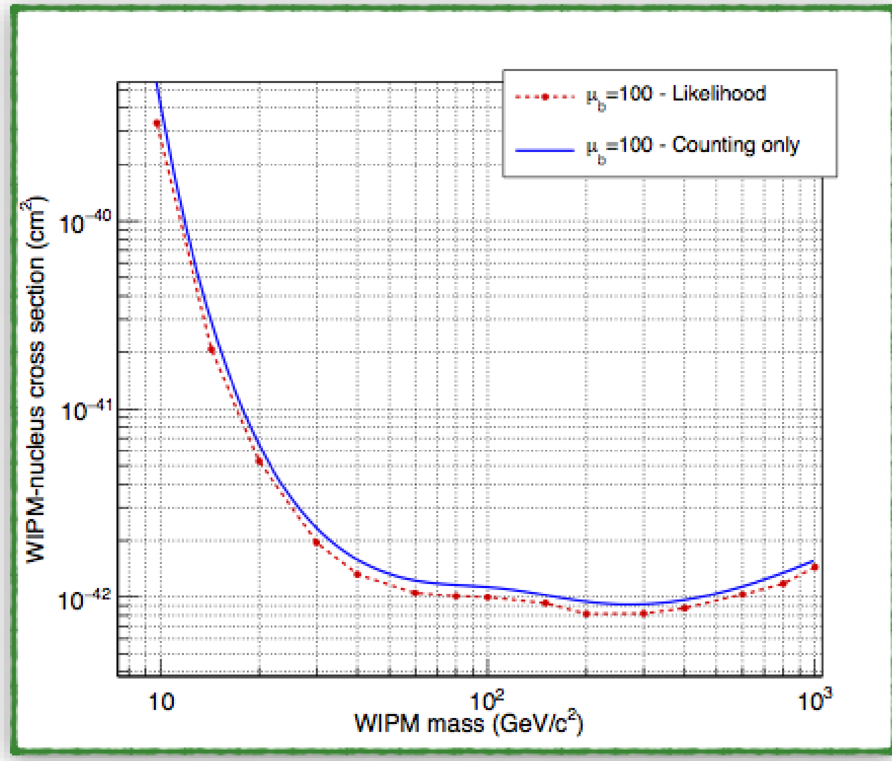


- 3D reconstruction
  - super-resolved analysis with LSP of z axis
- multi-wavelength analysis
  - super-resolution by color difference
  - dE/dx information by grain length

Exploit Directionality

Evaluation of upper limit and sensitivity based on the profile likelihood ratio test





Likelihood function

expected number of WIMP events — expected number of BG events — signal pdf — background pdf

$$\mathscr{L}(\sigma_{\chi-n}, R_b) = \frac{e^{-(\mu_\chi+\mu_b)}}{N!} \times \prod_{i=1}^{N} [\mu_\chi f_\chi(\vec{q}_i; t_i) + \mu_b f_b(\vec{q}_i)]$$

total number of observed events — set of observables

- Threshold = 100 nm
- Straggling estimated by TRIM
- Exposure= 100 kg years
- $N_{background}$ = 100

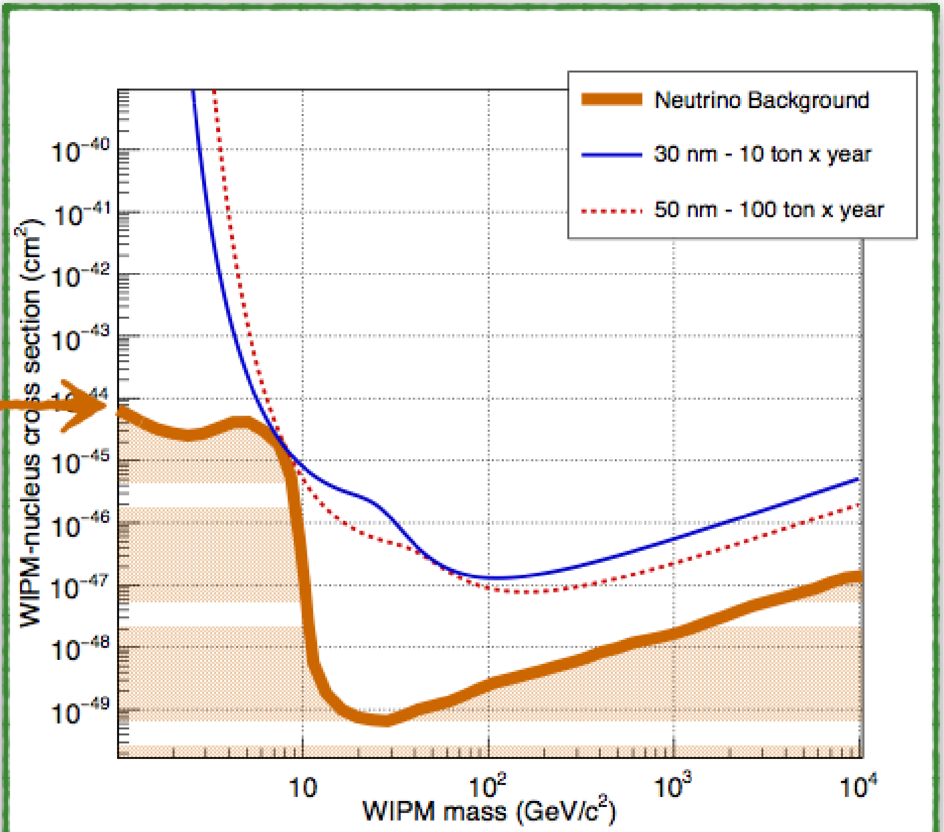
[arXiv:1705.00613]

Towards Neutrino Floor

- Discrimination based on measurement of recoil direction
- Unique possibility to search for WIMP signal beyond "neutrino floor"

Neutrino coherent scattering indistinguishable from WIMP interactions

Phys.Rev.D89 (2014) no.2, 023524 (Xe/Ge target)



The neutrino bound is reached with:
➡10 ton x year exposure if 30 nm threshold
➡100 ton x year exposure if 50 nm threshold

REQUIREMENTS

Reduction of track length threshold

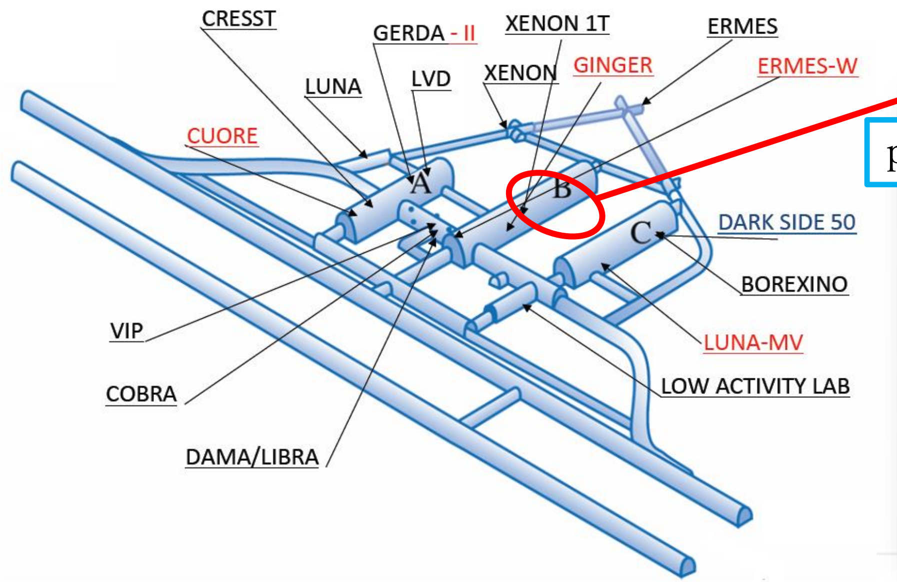
- Ultra-NIT (25nm crystal) has 40 nm theoretical resolution
- high resolution analysis with LSP

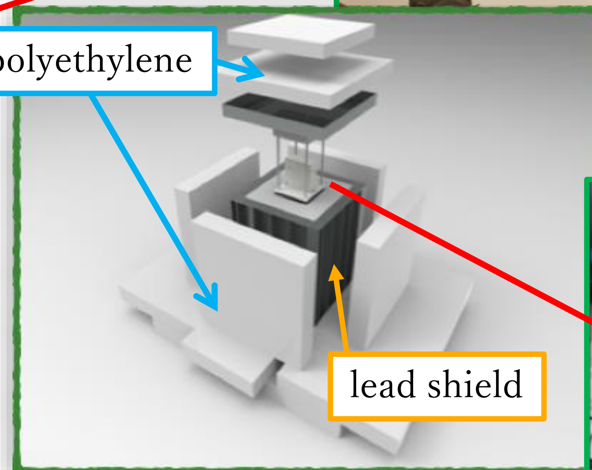
Larger mass scale detector

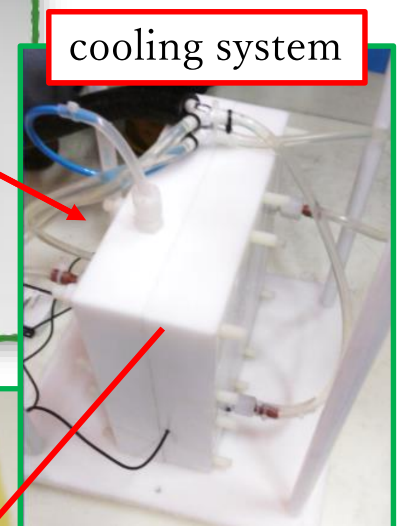
- further high speed scanning system
- extreme low BG detector

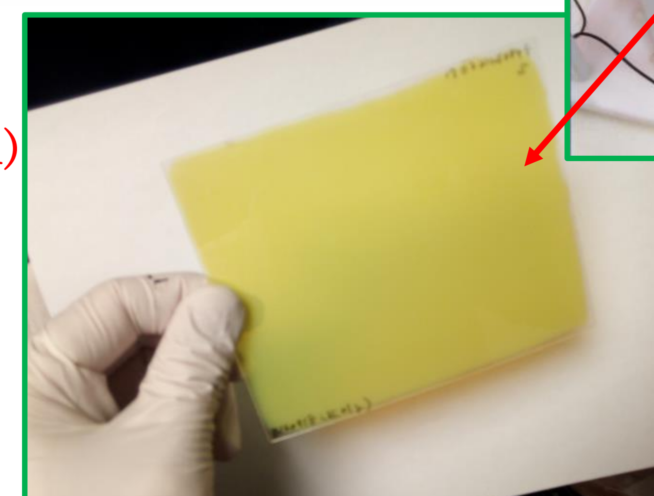
pilot-run

Gran Sasso underground laboratory, Italy





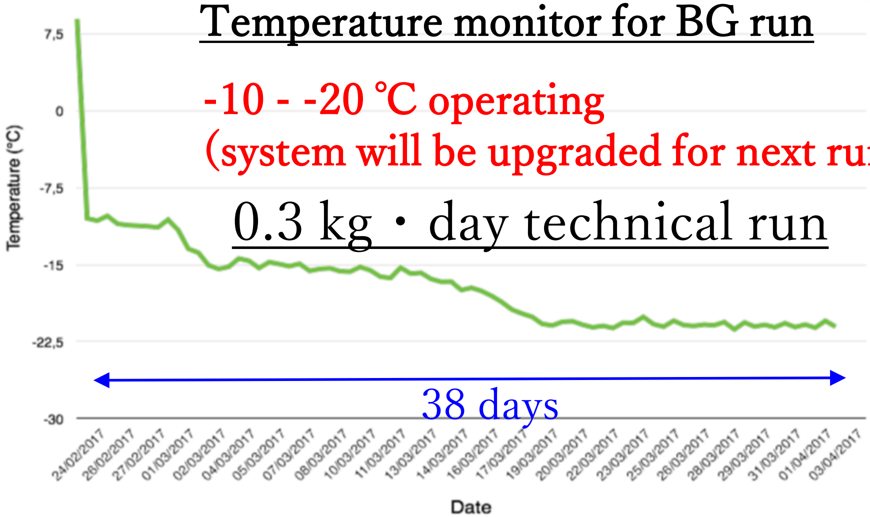




Temperature monitor for BG run

-10 - -20 ℃ operating
(system will be upgraded for next run)

0.3 kg・day technical run



summary

- Directionality is good parameter to discover WIMP
- NEWSdm is directional dark matter search experiment using many new techniques
  - super-high resolution detector of nuclear emulsion
  - multiple readout with high-speed/high-precision
- We are now R&D status and performed pilot run at Gran Sasso in 2017 and analyzing it now
- We plan to start physics run of kg·year scale exposure in 2019