Direction Sensitive Direct Dark Matter Search with Super-High Resolution Nuclear Emulsions

KMI, Nagoya University

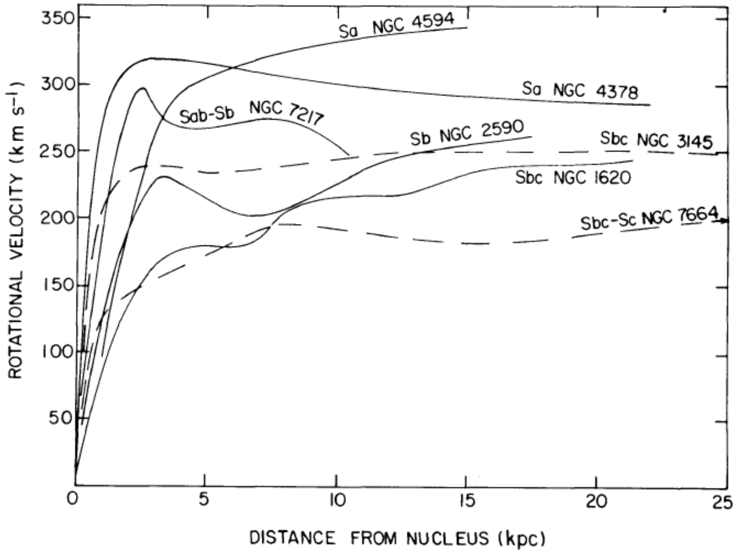
Tatsuhiro NAKA

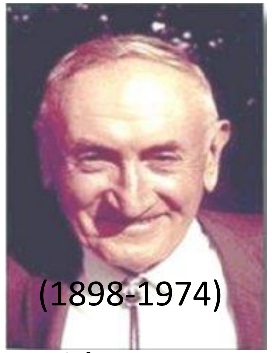
on behalf of the NEWSdm collaboration

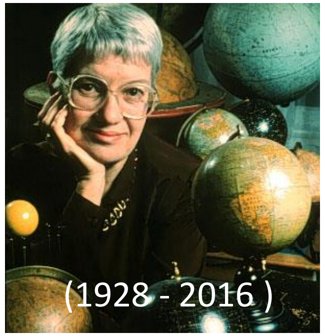
KMI2017, 5-7 Jan., 2017 (presentation : 6th, Jan.) @ ES hall, Nagoya University

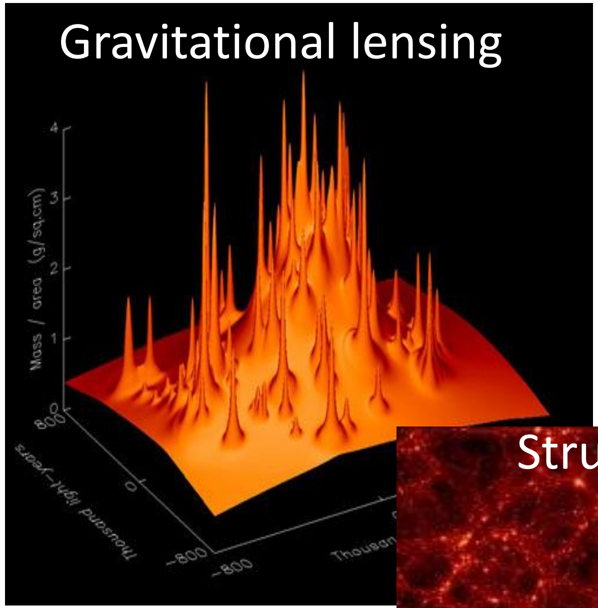
Dark matter problem for various scale of universe

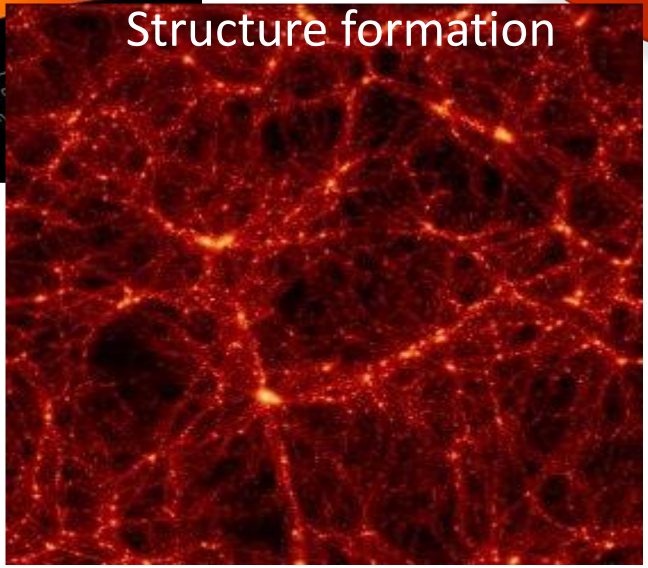
Local scale — Global scale

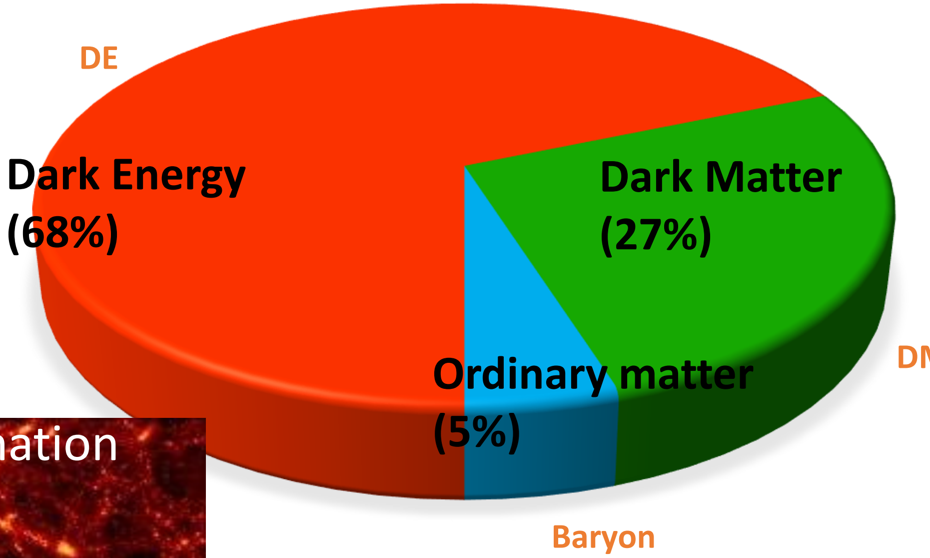












Planck 2013 results

High precision CMB measurement (WMAP, Planck) and related cosmology

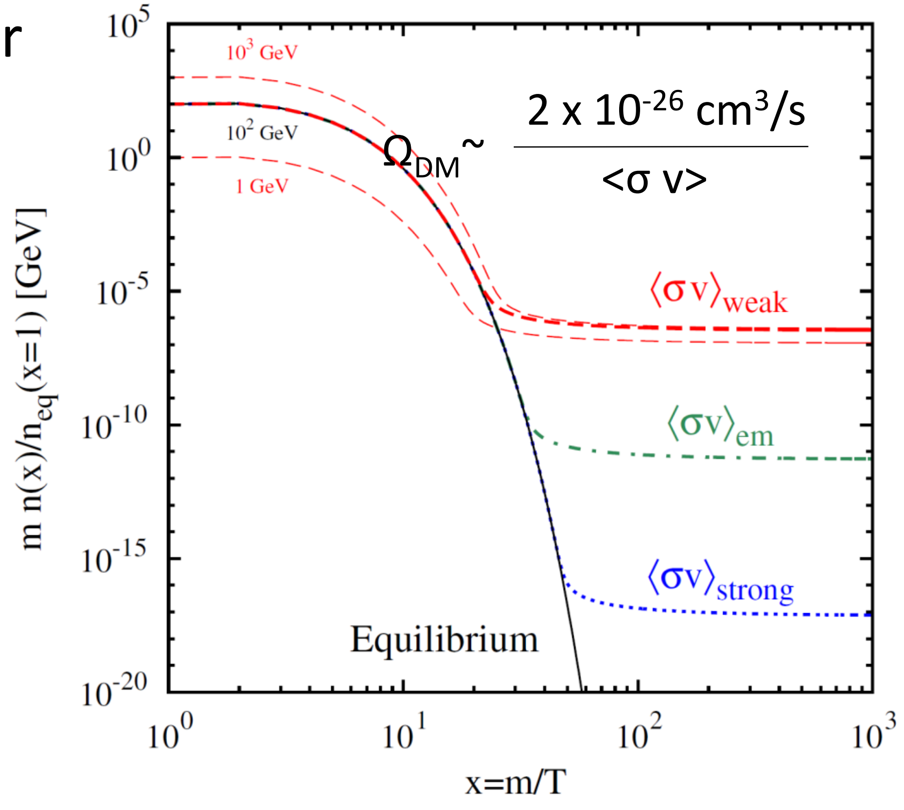
Fritz Zwicky

Zwicky, F. (1933), Helvetica Physica Acta 6: 110127, Bibcode:1933AcHPh...6..110Z

Vera C. Rubin et al., Asro.phys. J., 225:L107-111, 1978t

Dark matter property

- **Thermal process**
  - ☑ weak coupling and the massscale ⇒ WIMP dark matter
    e.g., SUSY, KK ・・
  - ☑ Difference of structure formation of galaxy
    between observation and simulation
    ⇒ warm dark matter (sterile neutrino ?), SIMP dark matter



Phys. Rev. D 86, 023506(2012)

- **Non-thermal process**
  - ☑ Axion
    ⇒ solution to "strong CP problem

✓Other discussion

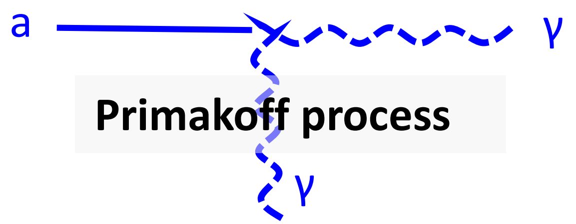
- ☑ self-interacting dark matter [e.g., Abell3827, MNRAS **449** (2015) 3393]
- ☑ AMS anomaly

Approach of Dark Matter Search

Axion dark matter

- Strong CP problem for QCD
- Axion is derived by "PQ symmetry" breaking

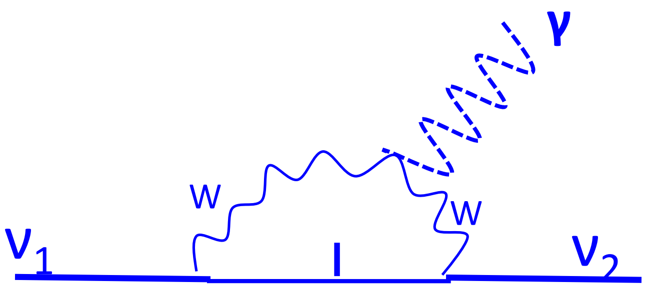
Expected Mass ~ 100 μeV/c²
- Lattice QCD [*Nature* **593** (2016) 69-71]
- Cosmology include topological defect [Kawasaki + , PRD **91**, 065014 (2015)]



warm dark matter

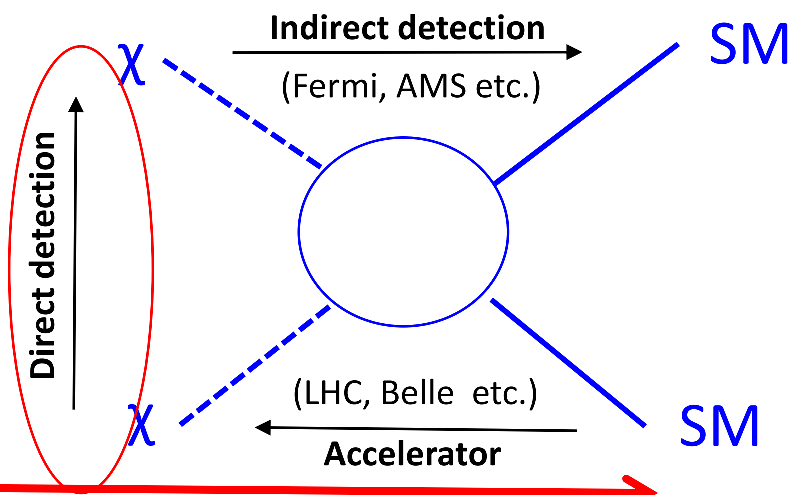
- Lighter mass particle with bit larger velocity dispersion e.g., sterile neutrino

Anomaly of short base-line experiment is incompatible from dark matter because of too high mixing angle



WIMP dark matter

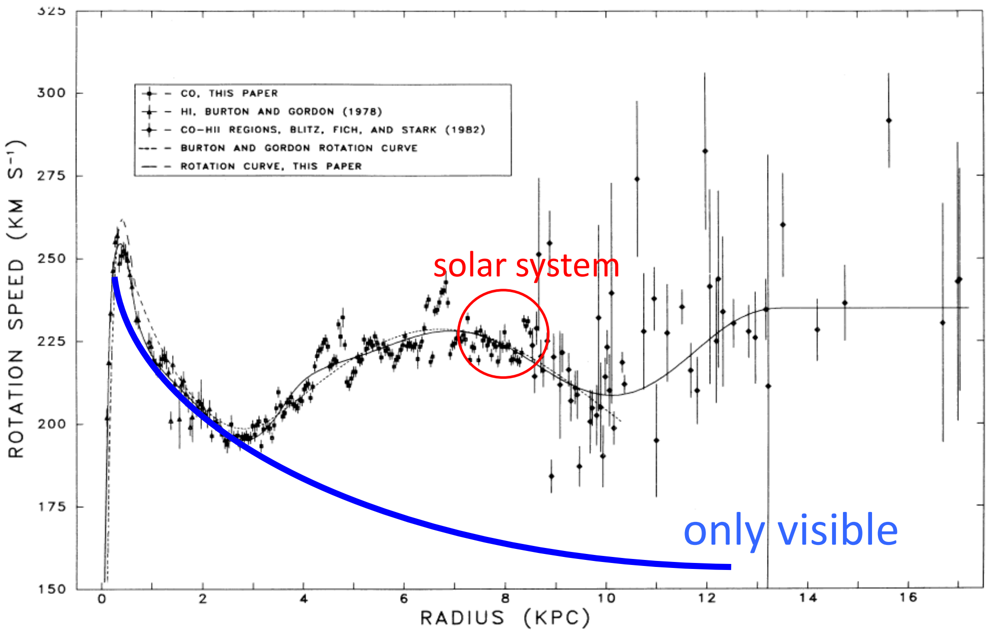
- Weak scale from thermal relic abundance
- Massive particle as cold dark matter
- Encourage from some beyond SM theory



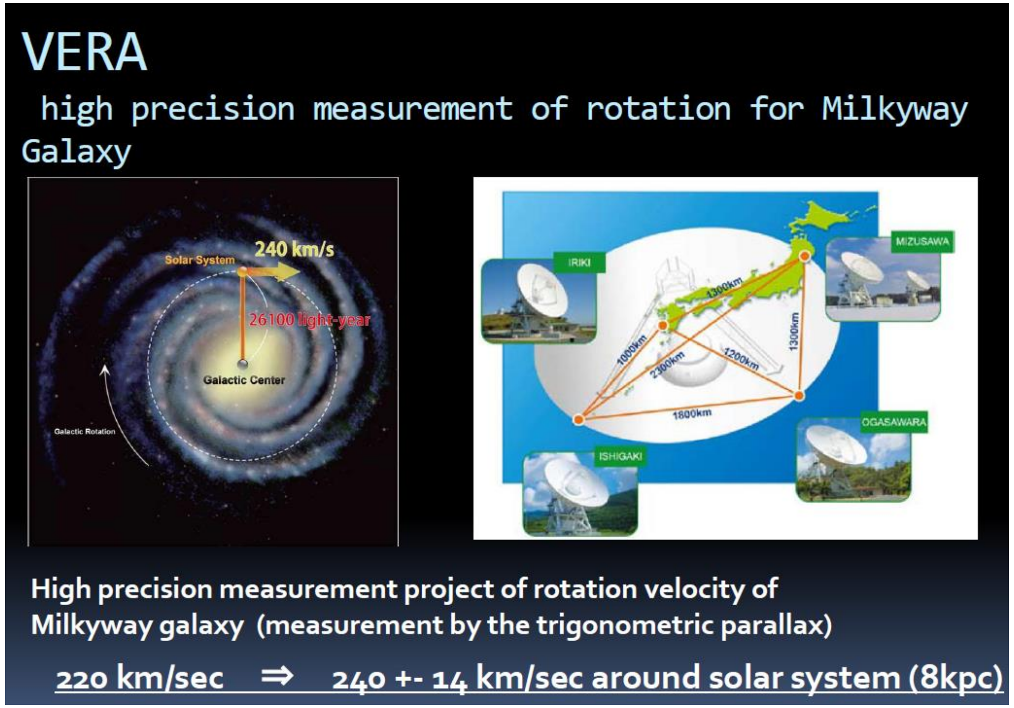
μeV/c² meV/c² keV/c² GeV/c² TeV/c²

Dark Matter mass

Dark Matter in the Milky Way galaxy



Astrophys. J. 295: 422-436, 1985

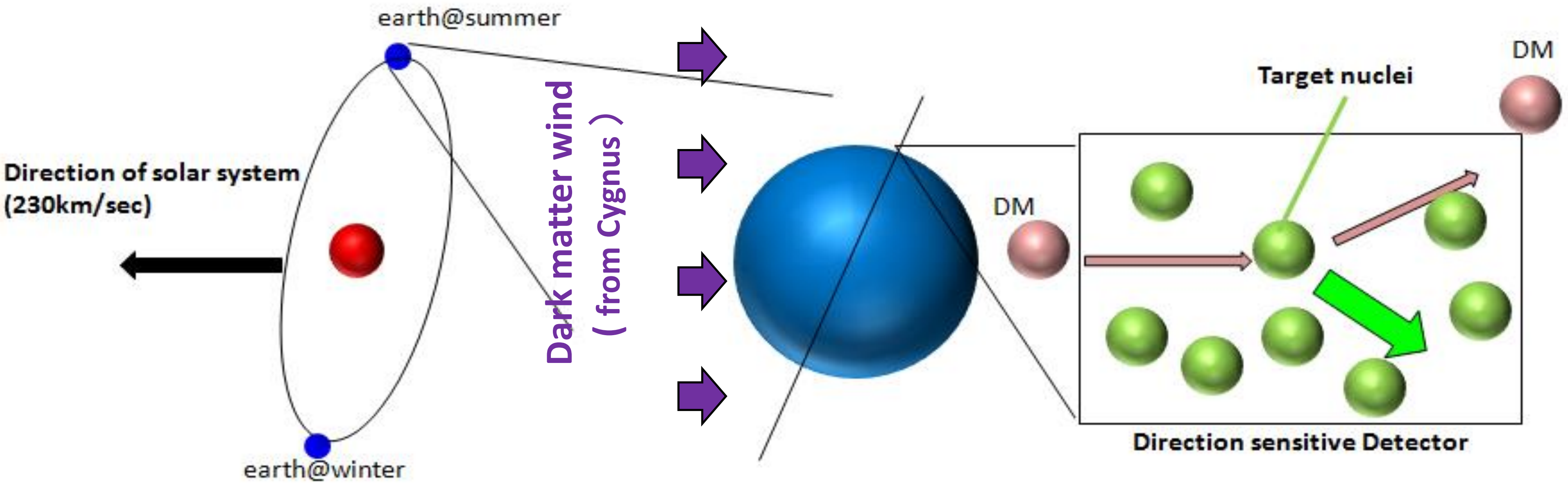


Local dark matter density : 0.3-0.5 GeV/cm^3

- ✓ **This value is independent on dark matter model**
- ✓ **Very much mount of DM is condensed in the halo because mean dark matter density in the universe is ~ 1.4 keV/cm^3 (27 % of critical density ratio)**

Dark matter flux on the earth ~ 100000 /cm^2/sec @ 100 GeV/c^2 dark matter

Detection principle



Annual Modulation

Diurnal Modulation

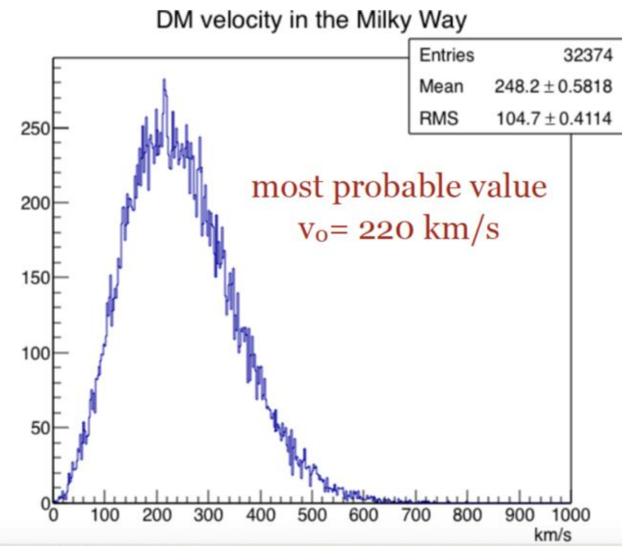
$$S(v_{lab}) \simeq S_k(v_s) + S_{Ann} cos\omega_{rev}(t - t_0) + S_d cos\omega_{rot}(t - t_d)$$

2 – 3 % variation

0.1 – 0.01 % variation

This is impossible for current technologies.

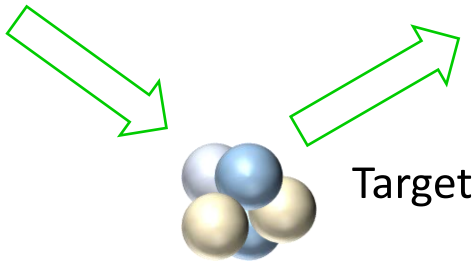
Kinematics of direct DM detection



WIMP dark matter detection

Dark matter

Dark matter



Target nuclei

keV scale energy

Nuclear recoil

Detection as
Ionization
Phonon
Light

Local dark matter density :
0.3-0.5 GeV/cm^3

Dark Matter halo distributio

Unknown parameter
And particle model dependenc

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\rho_\chi}{m_\chi} \int_{v_{min}}^{v_{max}} \mathrm{d}^3 v \; f(\vec{v}) v \frac{\mathrm{d}\sigma(\vec{v}, E_R)}{\mathrm{d}E_R}$$

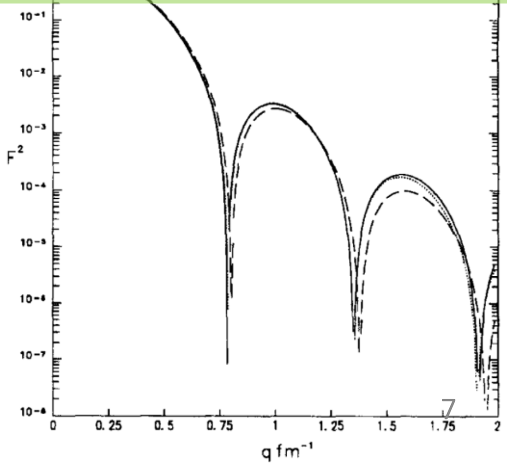
Unknown parameter

Target and detector dependence

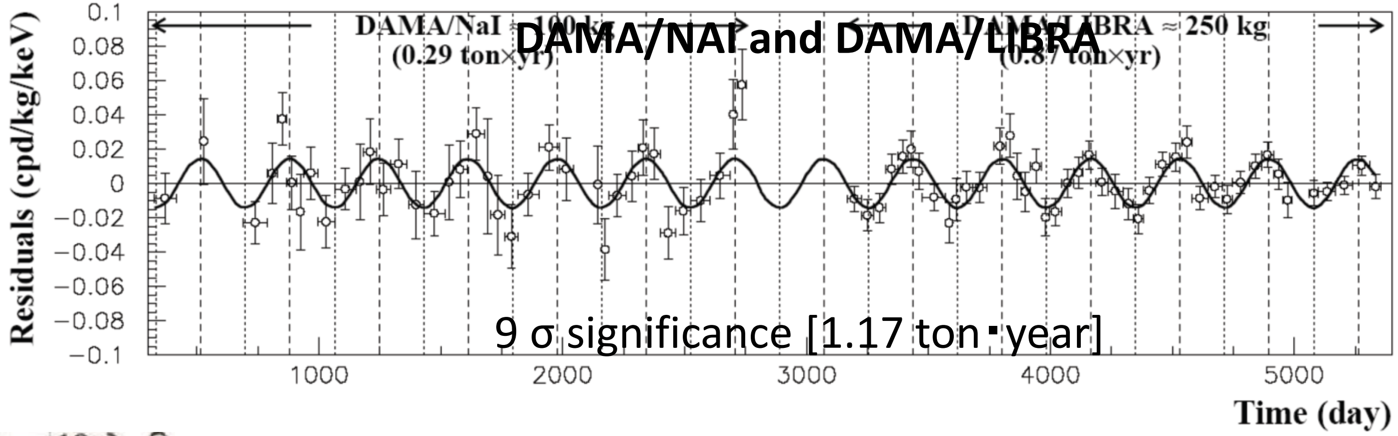
- ➢ Nuclear form factor
- ➢ Quenching factor

⇒ it's important for cross section and energy reconstruction

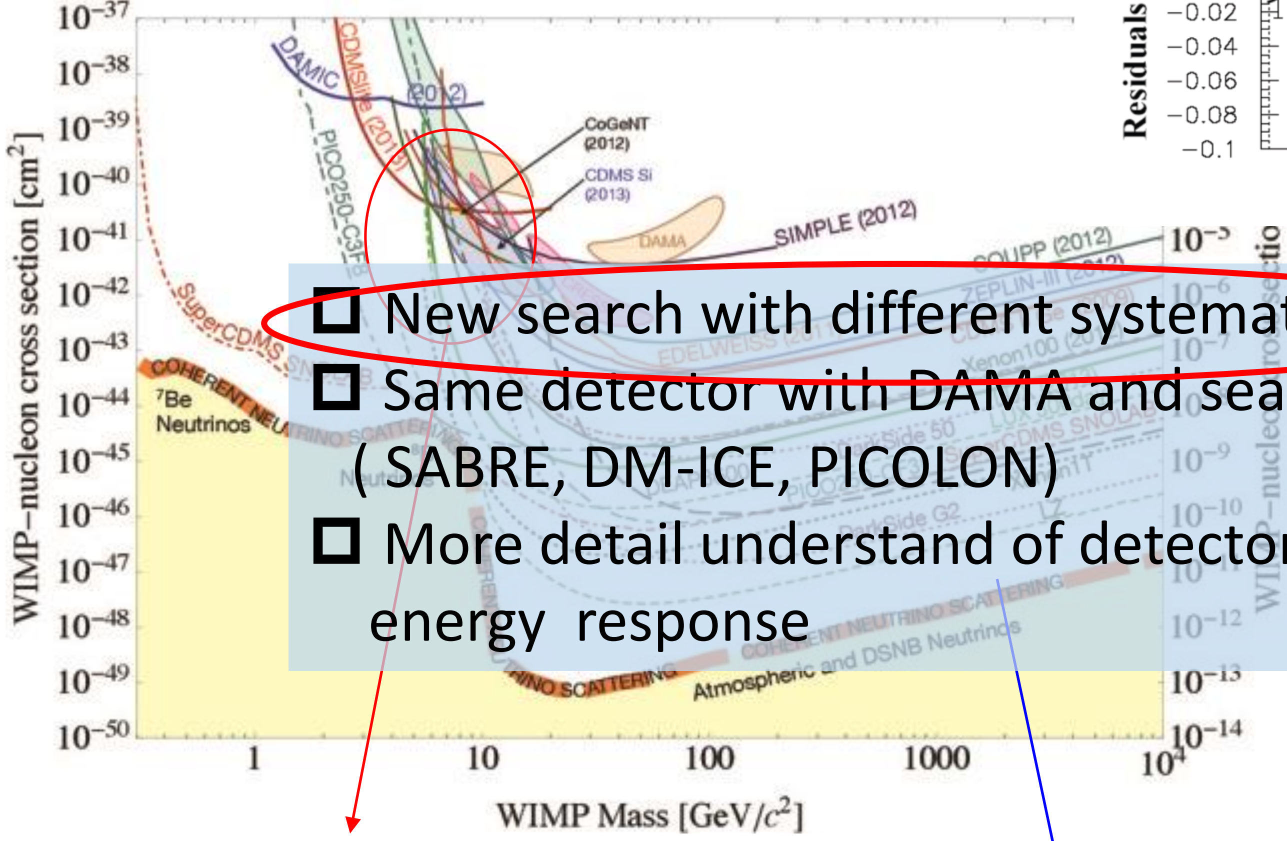
Form factor effect to momentum transfer



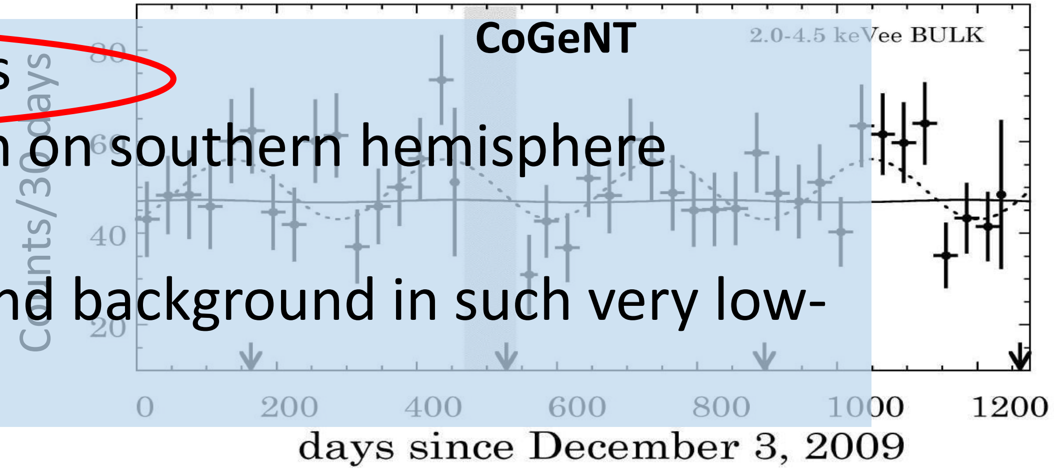
DAMA/NAI and DAMA/LIBRA



9 σ significance [1.17 ton·year]



CoGeNT



- ☐ New search with different systematics
- ☐ Same detector with DAMA and search on southern hemisphere (SABRE, DM-ICE, PICOLON)
- ☐ More detail understand of detector and background in such very low-energy response

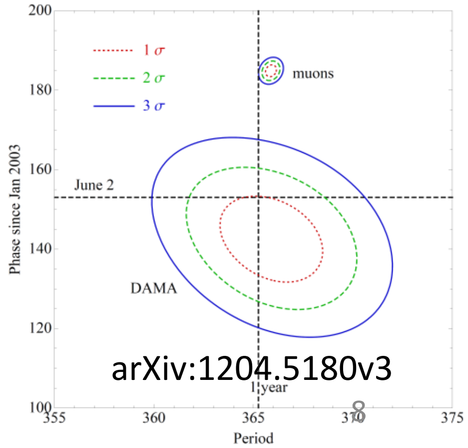
Around 10 GeV mass region is very chaotic, and other detectors are also just around energy threshold

Coherent scattering due to neutrino is final bound

DAMA : May 26th +- 7 days

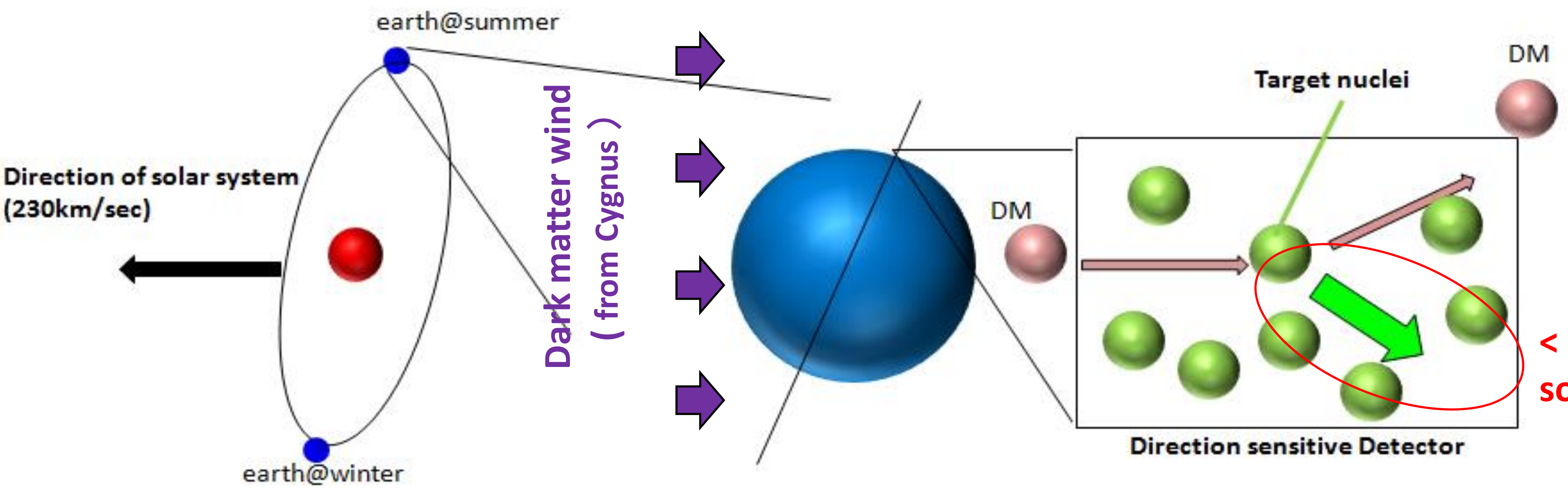
5.7 σ difference

Muon by BOREXINO
July 7 +- 6 days
(June 29 +- 6 days)



arXiv:1204.5180v3

Direction sensitive search



< 1 μm length in solid or liquid

Annual Modulation

Diurnal Modulation

$$S(v_{lab}) \simeq S_k(v_s) + S_{Ann} cos\omega_{rev}(t - t_0) + S_d cos\omega_{rot}(t - t_d)$$

2 – 3 % variation

0.1 – 0.01 % variation

⇩

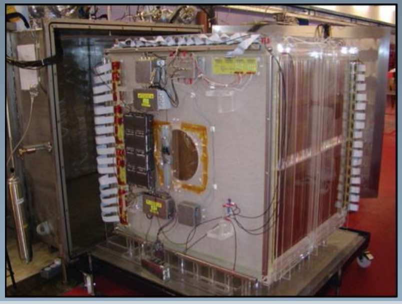
Directional detection
(= detection as track)

Direction Sensitive detector

CYGNUS community

Gaseous Detector

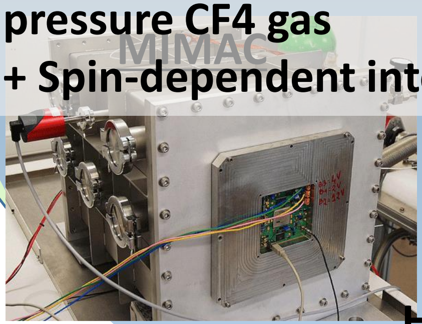
DRIFT



DMTPC

D³

Typically target mass scale ~ 10-100 g with low-pressure CF4 gas
+ Spin-dependent interaction search



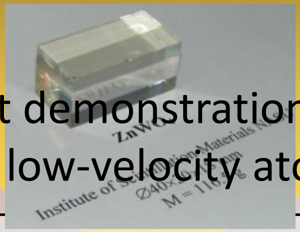
High pressure Xe gas

Solid detector

NEWSdm

Future project toward high scale + model-independent directional search

$ZnWO_4$



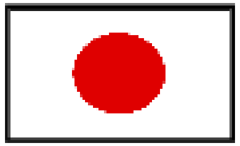
Not demonstration yet for low-velocity atom

- White paper : " The Case For a Directional Dark Matter Detector And Status of Current Experimental Efforts ", Int. Ann. Mod. Phys. A, Vol.25, No.1 (2010) 1-51
- Readout technology paper : "Readout technologies for directional WIMP Dark Matter detection ", Phys. Rep. Vol.662 (2016) 1-46

The NEWSdm Collaboration

[Nuclear Emulsions for WIMPs Search with directional measurement]

LNGS-LOI 48/15



Japan
Chiba
Nagoya

Russia
LPI RAS Moscow
JINR Dubna
SINP MSU Moscow

Italy
Bari
LNGS
Naples
Rome

Turkey
METU Ankara

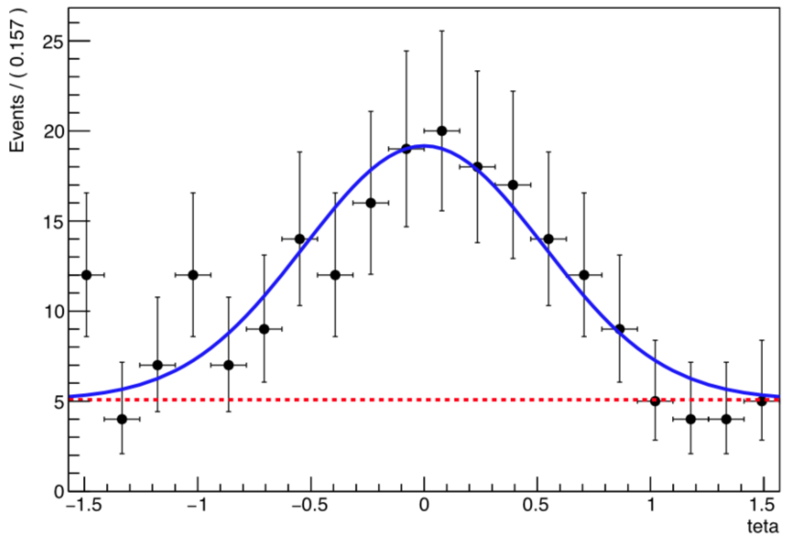
NEWS: Nuclear Emulsions for WIMP Search
Letter of Intent
(NEWS Collaboration)

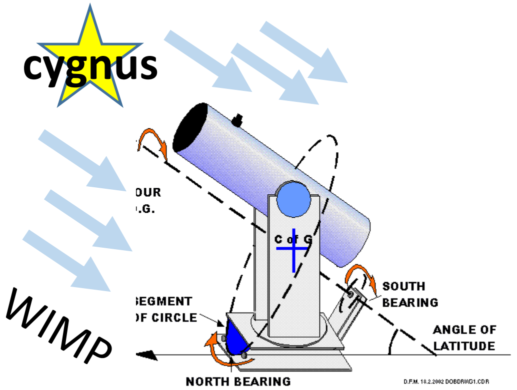
A. Aleksandrov[b], A. Anokhina[n], T. Asada[k], D. Bender[p], I. Bodnarchuk[m], A. Buonaura[b,h], S. Buontempo[b], M. Chernyavskii[o], A. Chukanov[m], L. Consiglio[b,h], N. D'Ambrosio[e], G. De Lellis[b,h], M. De Serio[a,g], A. Di Crescenzo[b,h], N. Di Marco[e], S. Dmitrievski[m], T. Dzhatdoev[n], R. A. Fini[a], S. Furuya[k], G. Galati[b,h], V. Gentile[b,h], S. Gorbunov[o], Y. Gornushkin[m], A. M. Guler[p], H. Ichiki[k], C. Kamiscioglu[p], M. Kamiscioglu[p], T. Katsuragawa[k], M. Kimura[k], N. Konovalova[o], K. Kuge[l], A. Lauria[b,h], P. Loverre[d,j], S. Machii[k], A. Managadze[n], P. Monacelli[d,j], M. C. Montesi[b,h], T. Naka[k], M. Nakamura[k], T. Nakano[k], A. Pastore[a,g], D. Podgrudkov[n], N. Polukhina[o], F. Pupilli[f], T. Roganova[n], G. Rosa[d,j], O. Sato[k], T. Shchedrina[o], S. Simone[a,g], C. Sirignano[c,i], A. Sotnikov[m], N. Starkov[o], P. Strolin[b,h], Y. Tawara[k], V. Tioukov[b], A. Umemoto[k], M. Vladymyrov[o], M. Yoshimoto[k], S. Zemskova[m]

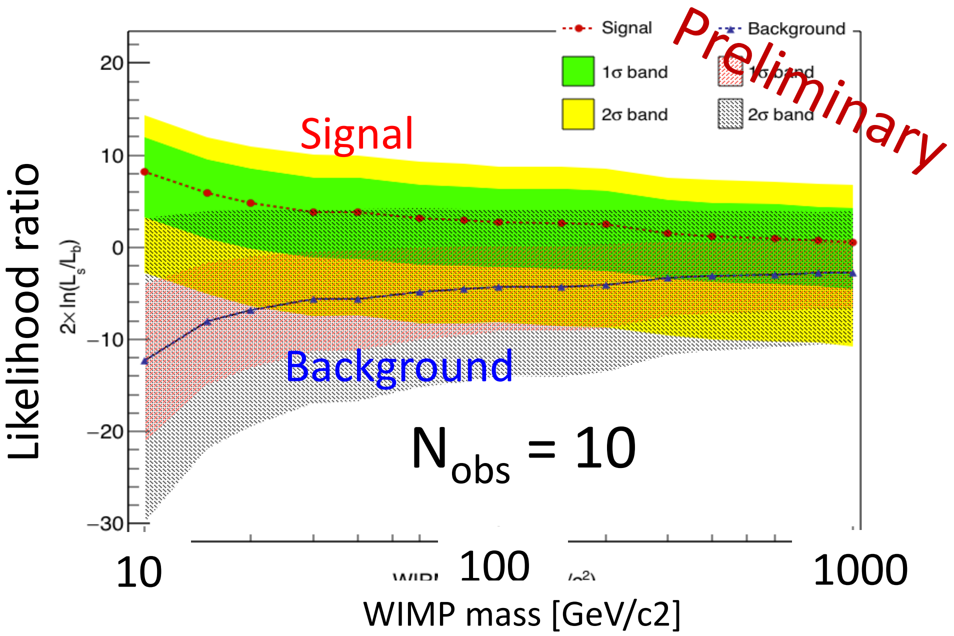
arxiv.org/pdf/1604.04199v1.pdf

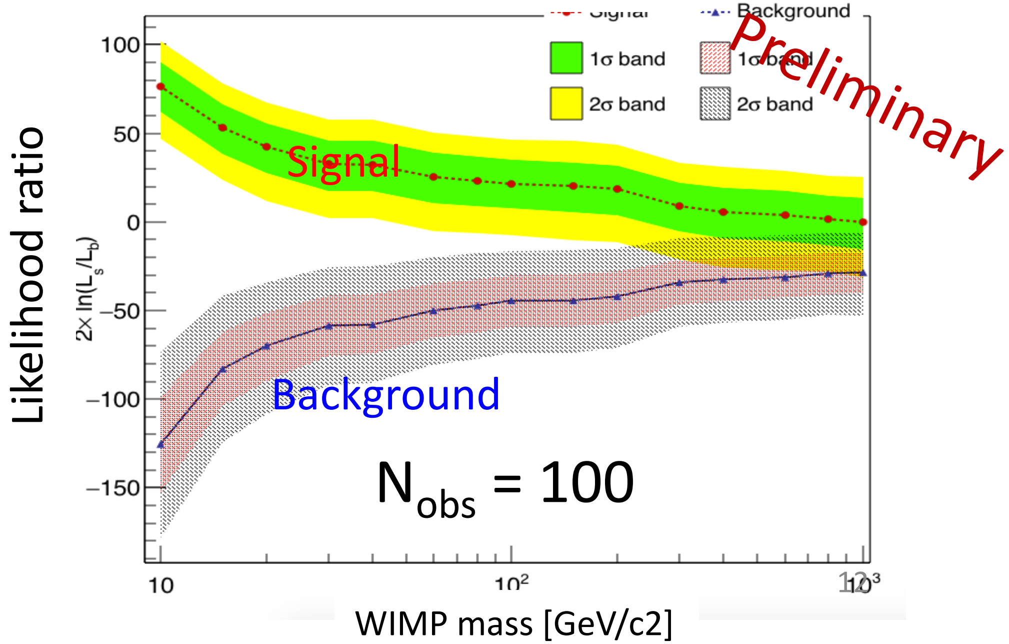
http://news-dm.lngs.infn.it

Potential of Directional Sensitive Search









Gaussian distribution   Flat distribution

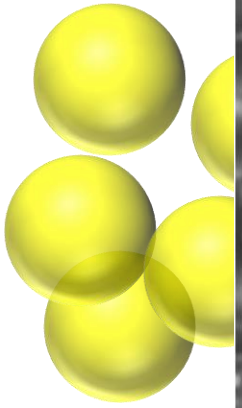
$$\mathscr{L} = \frac{(\mu_s+\mu_b)^N}{N!} e^{-(\mu_s+\mu_b)} \times \prod \left(\frac{\mu_s}{\mu_s+\mu_b} S(R_n) + \frac{\mu_b}{\mu_s+\mu_b} B(R_n) \right)$$

Direction information : Several 10 events

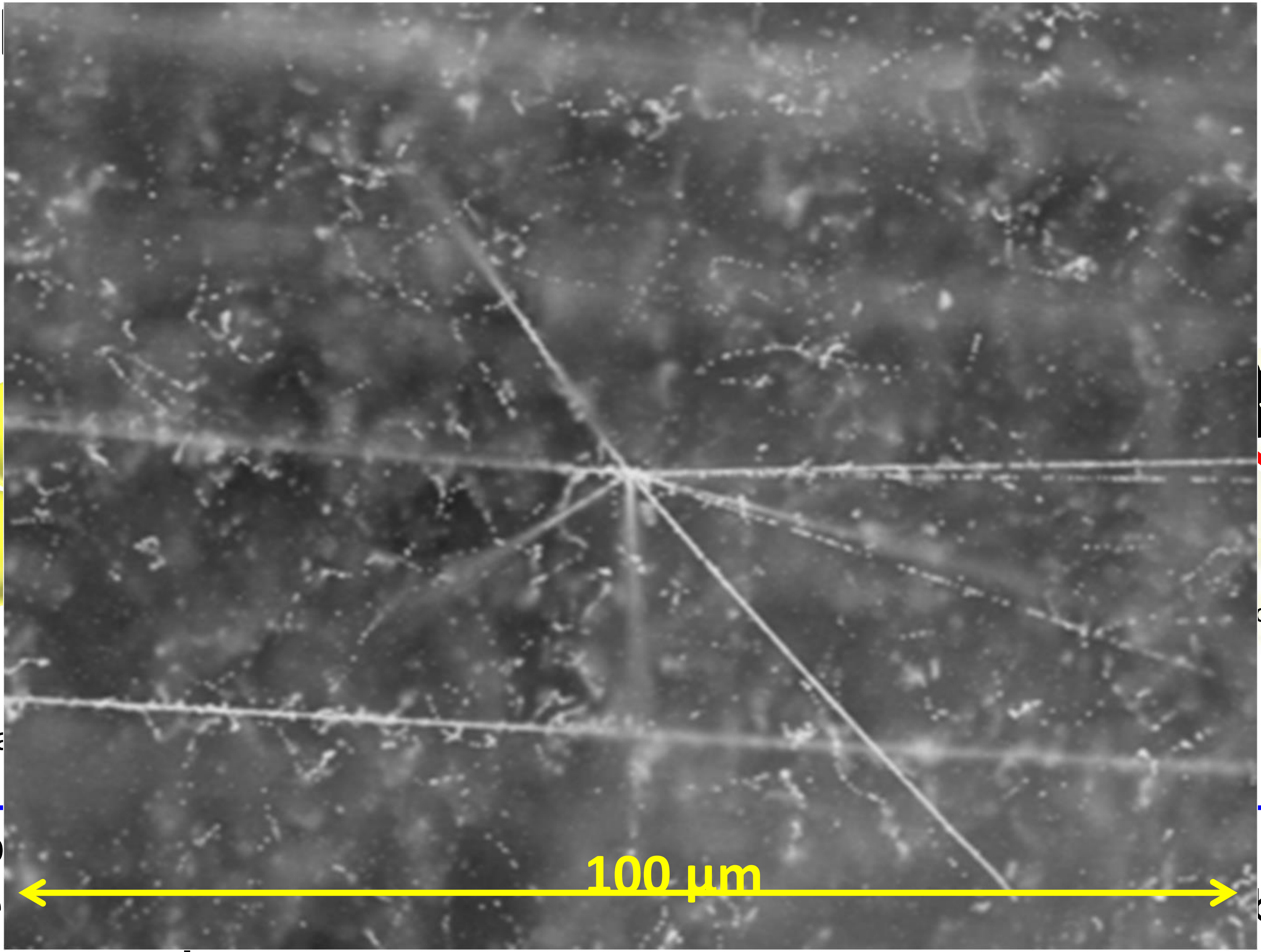
Gain of 100 times

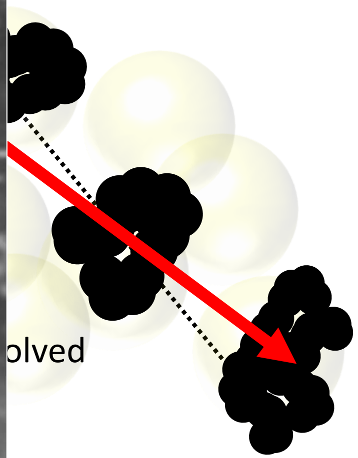
Annual modulation : Several 1000 events

Nuclear



Silver halide crysta

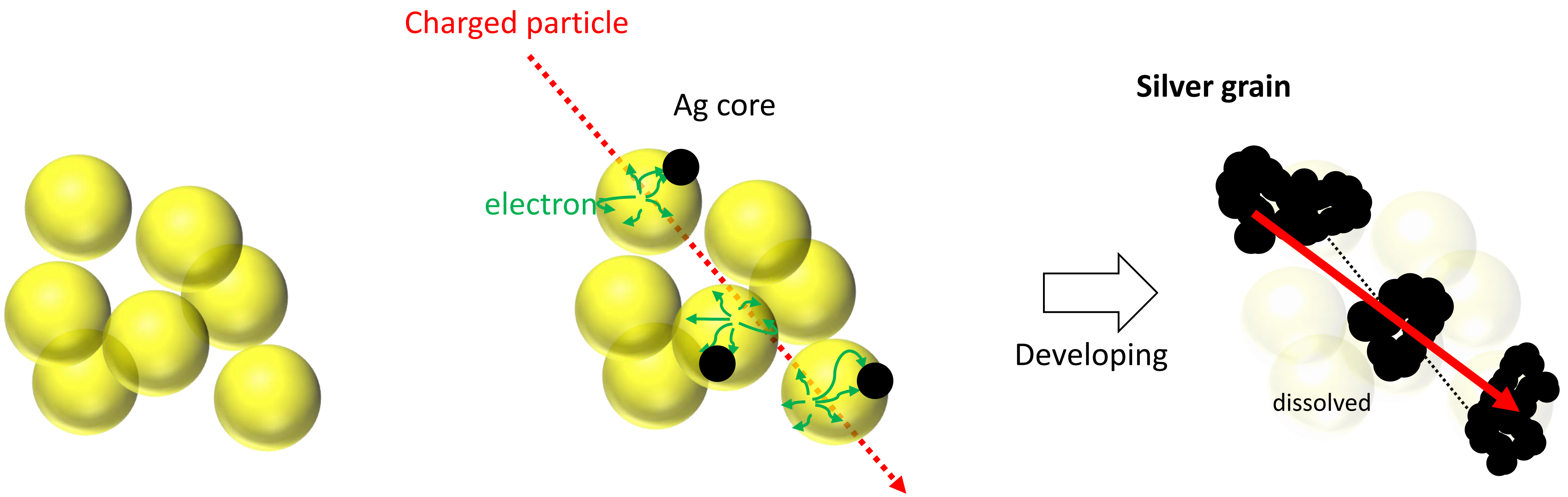




read out by microscope

- Sp
- Se bility of latent image specks

Nuclear Emulsion [detection principle]



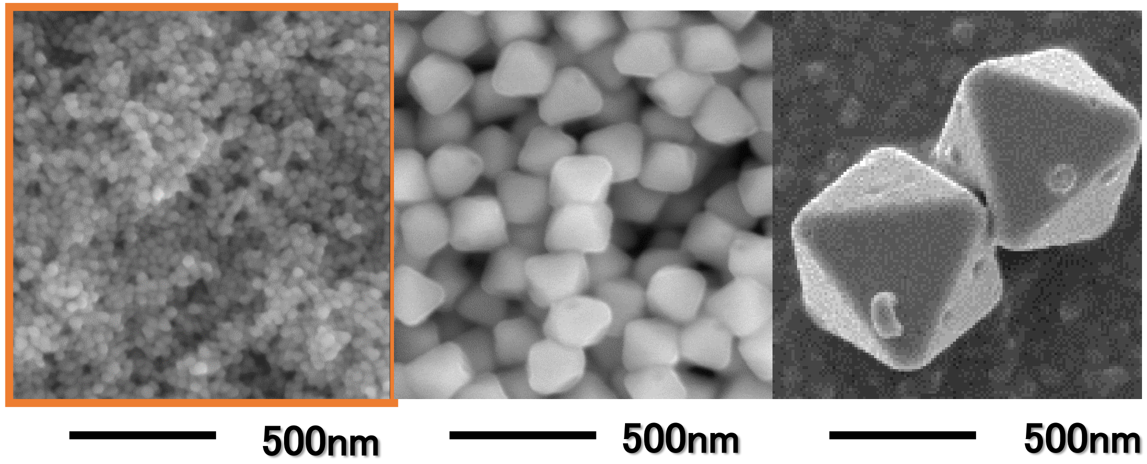
Silver halide crystal (AgBr・I) in the polymer (gelatin)

⇒Tracks are read out by microscope

- ☐ **Spatial resolution ⇒ crystal size and the density**
- ☐ **Sensitivity crystal ⇒ crystal size, deepness of electron traps, stability of latent image specks**

Nuclear emulsion [production]

- That have been started since 2010 by support of KMI
- Self-production of device by scientists
- Now, this place is operated as the center for nuclear emulsion users
- This project is pioneer of that.

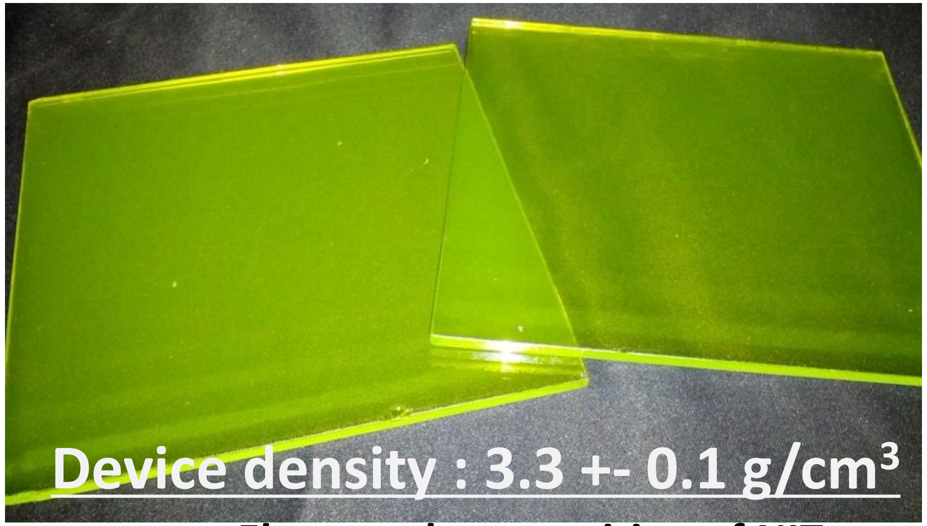


T. Naka et al., *Nucl. Inst. Meth.* A 718 (2013) 519-521

	x1 scale machine	x 3 scale machine
Install	2010	2014
one batch scale	~ 100 g device	~ 300 g device
Cost per batch	~ 10 K Yen	~ 30 k Yen
Purpose	R&D, DM search	Mass production

Kobe Univ., Toho Univ., Univ. of Tokyo, Bern Univ. and others for neutrino physics, cosmic-ray, muon tomography and other motivation

Fine-grained Nuclear Emulsion [Nano Imaging Tracker: NIT]

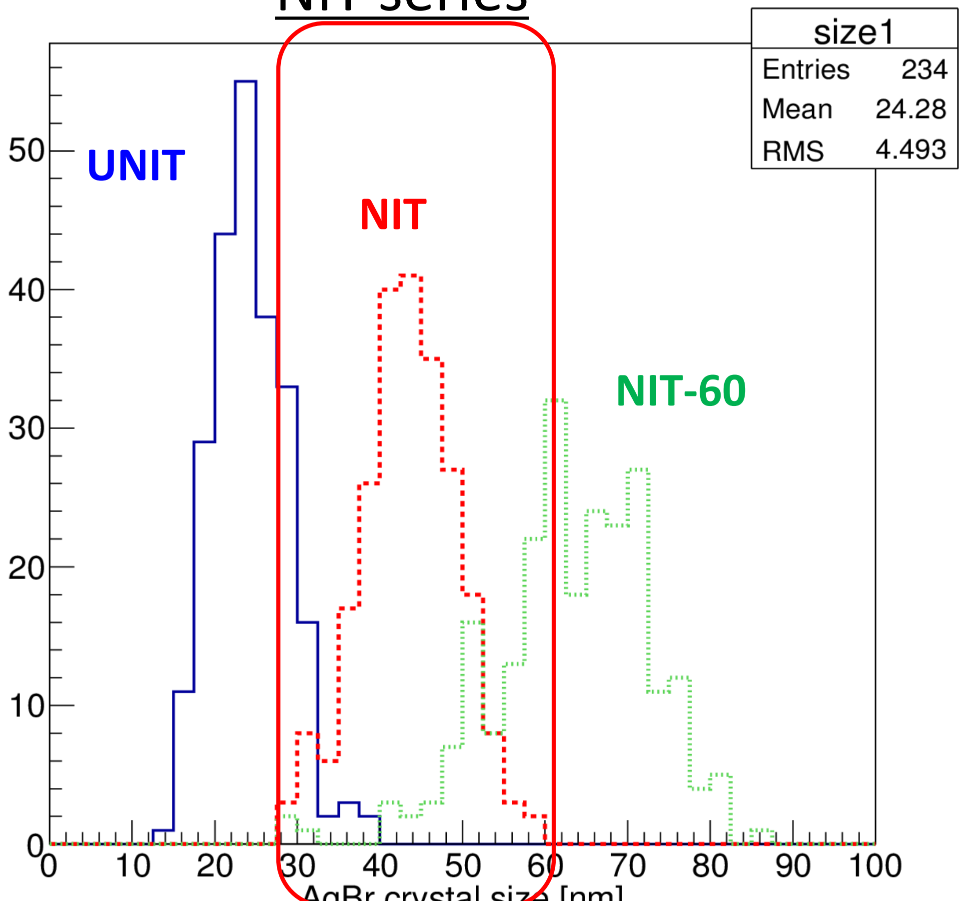


Elemental composition of NIT

	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	< 0.001	< 0.001

✓ Elemental analyze
✓ SEM-EDX
✓ content for added chemical

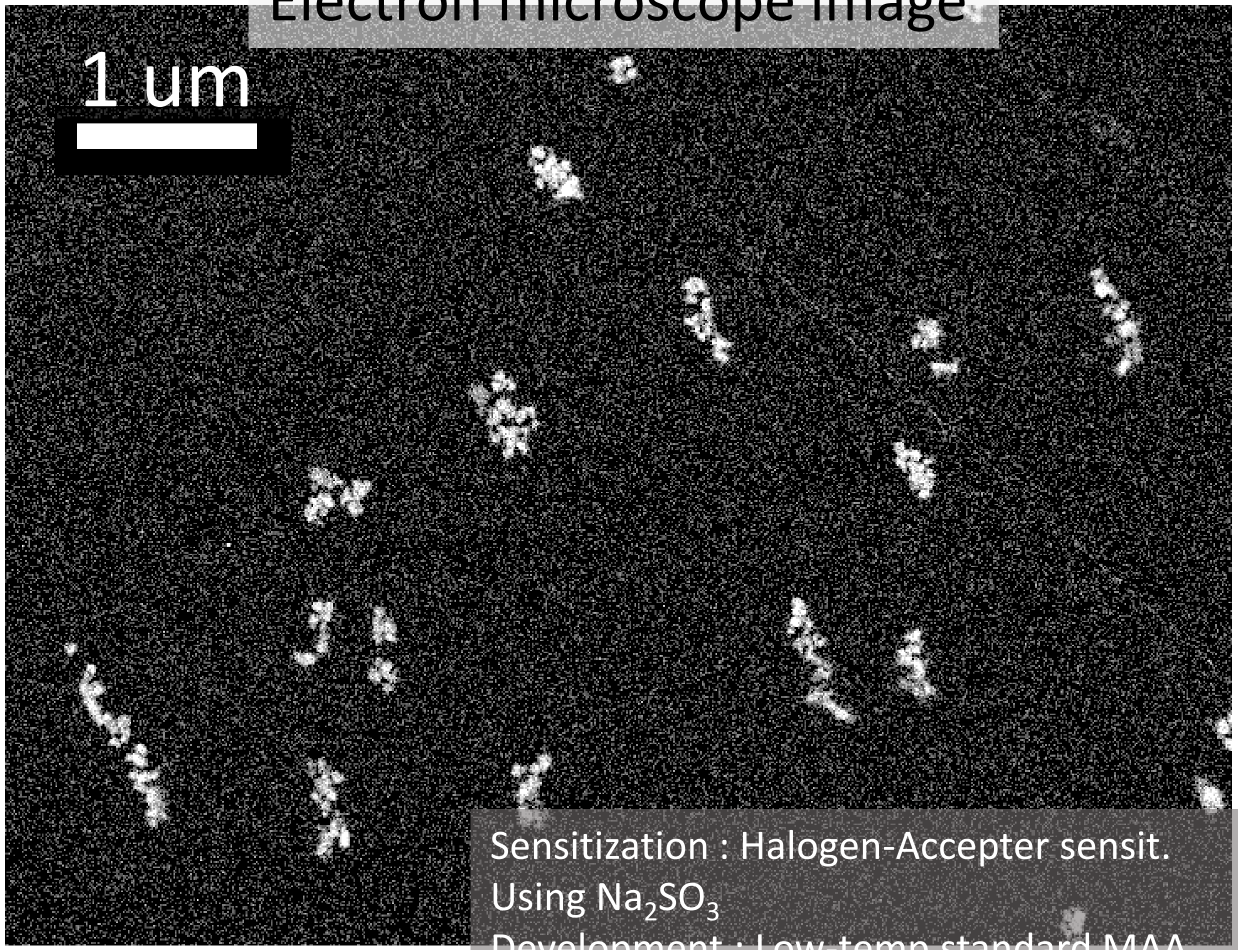
NIT series



AgBr crystal size [nm]

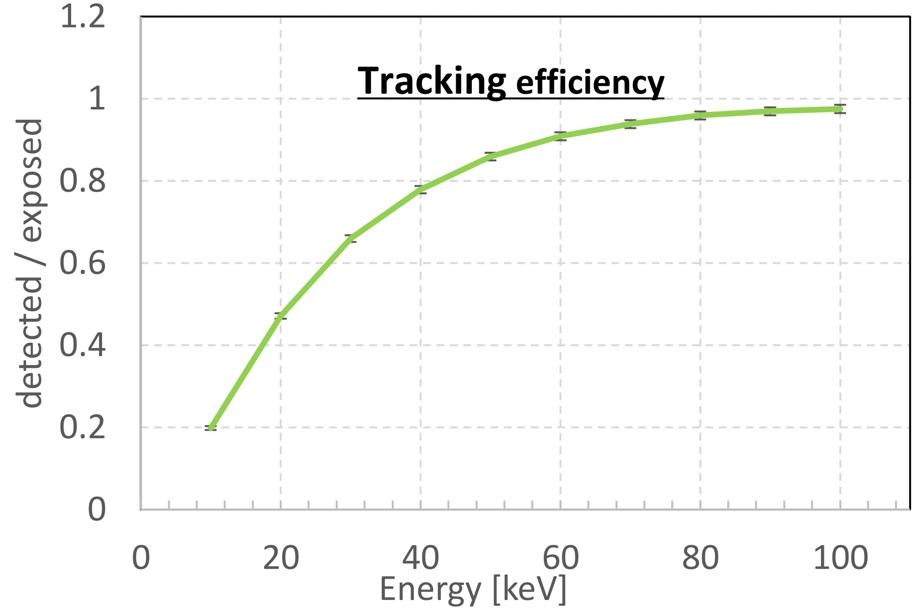
Low-velocity ions tracking for NIT device

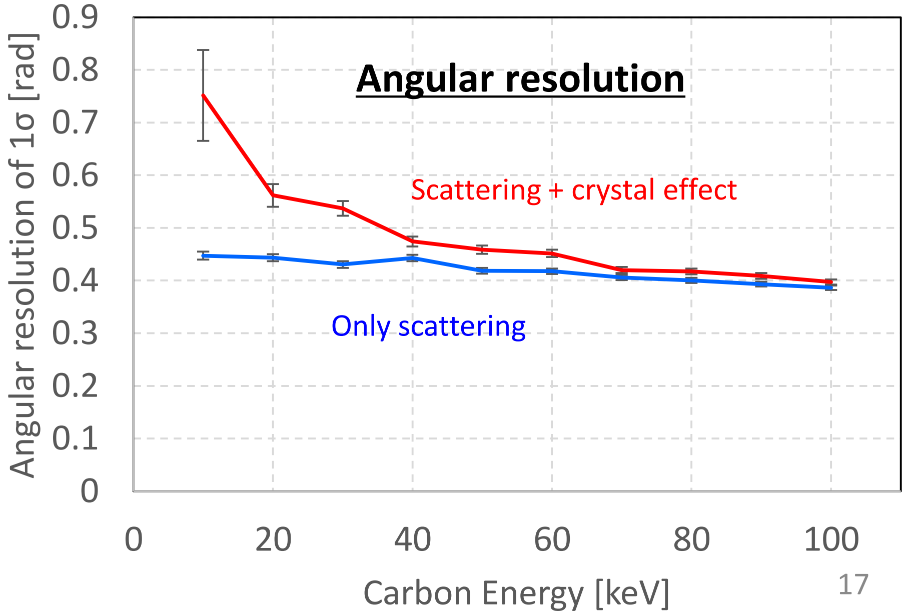
Electron microscope image



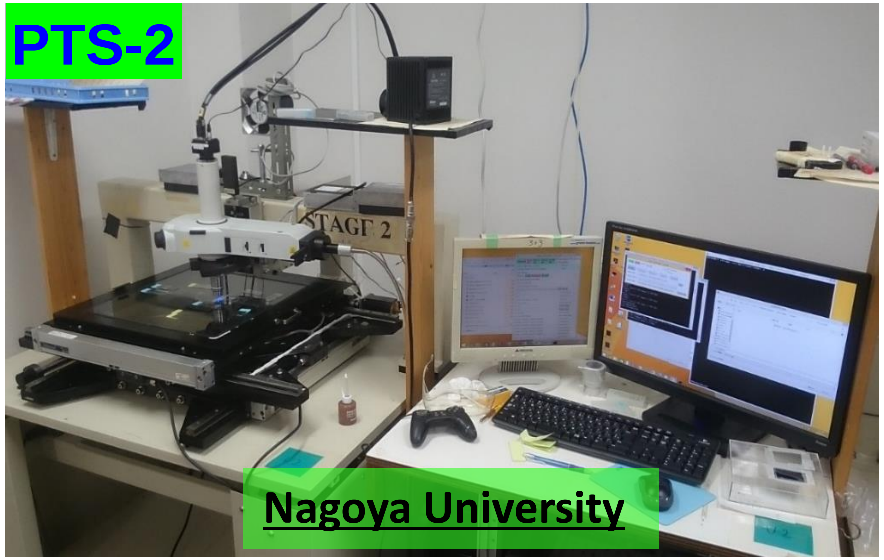
Sensitization : Halogen-Accepter sensit.
Using Na_2SO_3
Development : Low-temp standard MAA

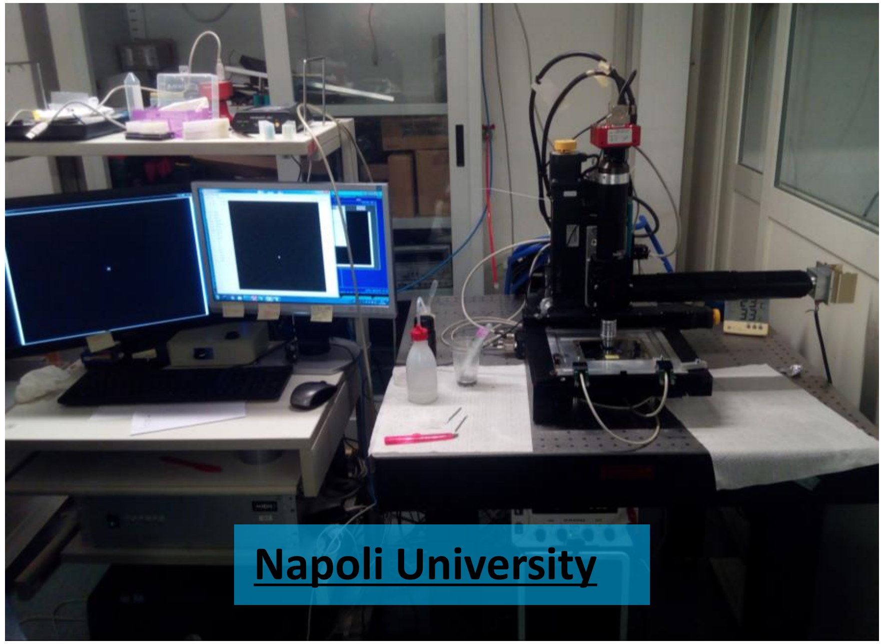
Intrinsic potential for NIT device

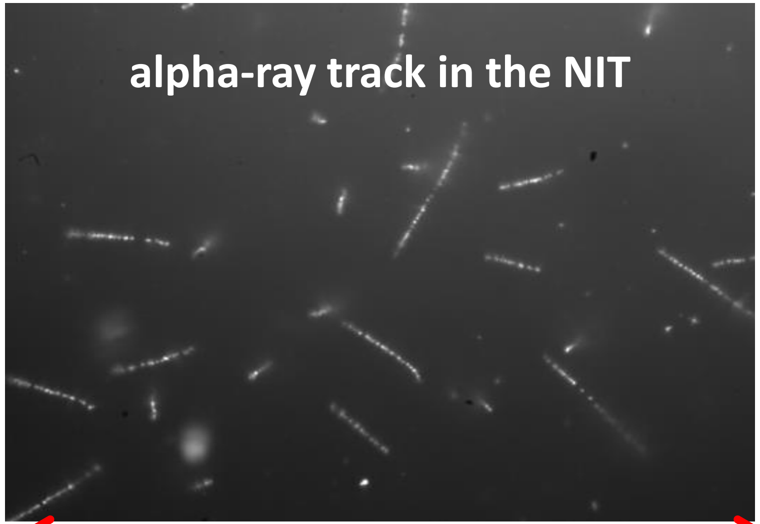




New scanning system for nano-imaging tracking



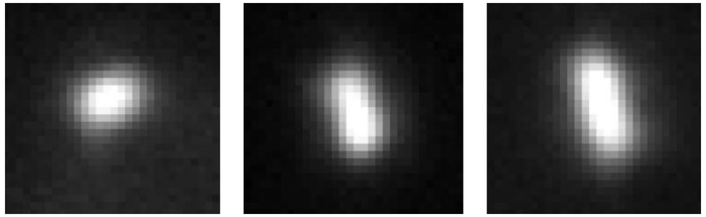


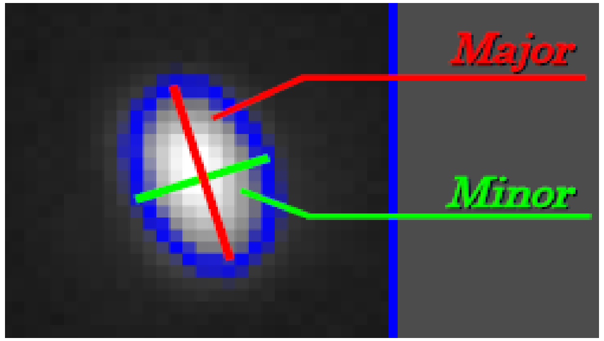


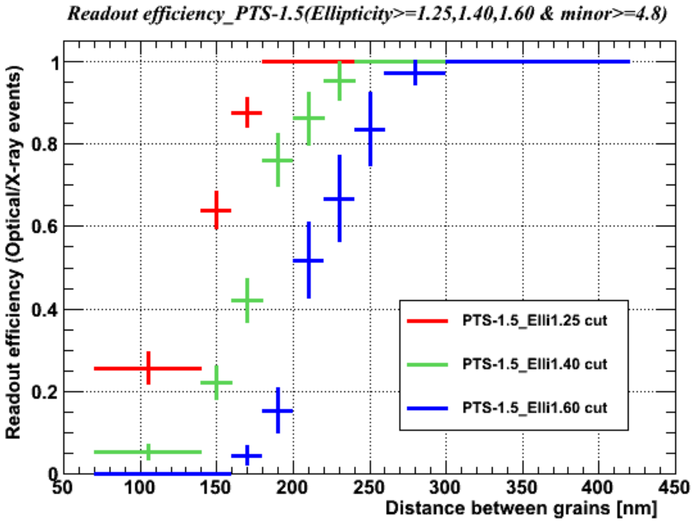
50 µm

First system with epi-illuminate optics

- High contrast image to small Ag grain
- New optical information such as Plasmon resonance







Algorism was proposed by
M. Kimura and T. Naka, NIMA 680 (2012) 12

Analysis Flow

1st scanning

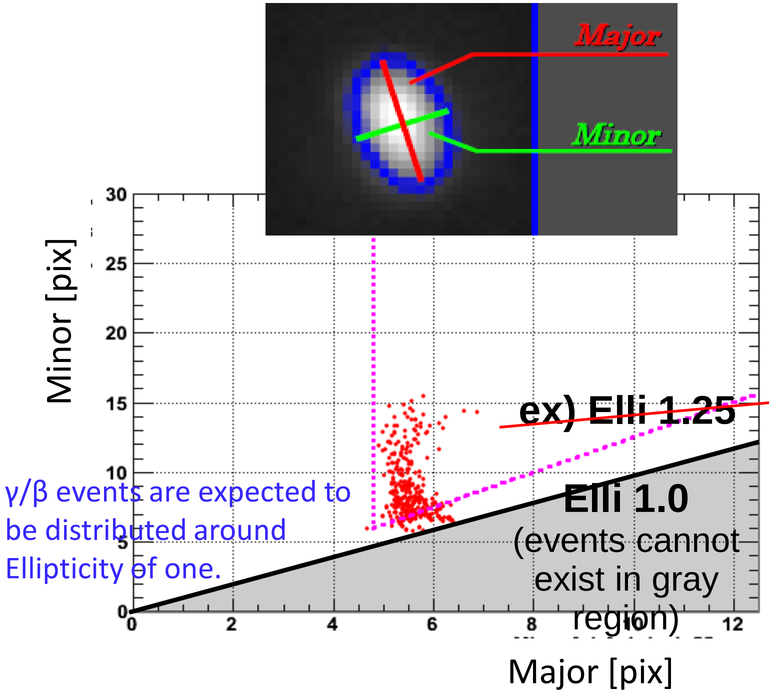
- High speed scanning
- Rough candidate events selection

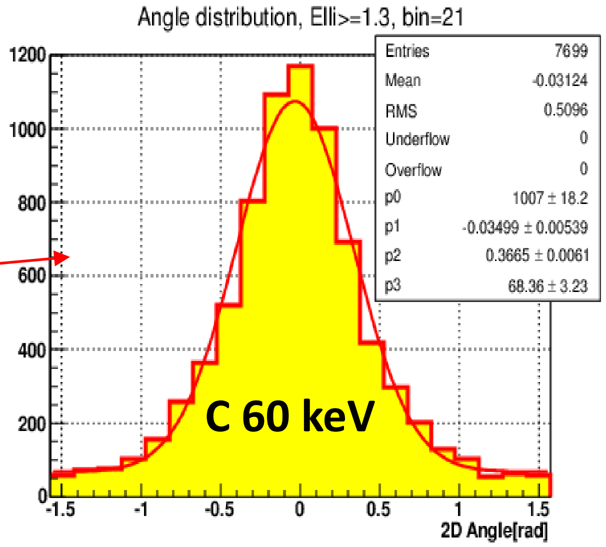
2nd scanning

- Pinpoint scanning
- Rejection of accidental leakage
- Contaminated dust rejection using image processing

3rd or more scanning

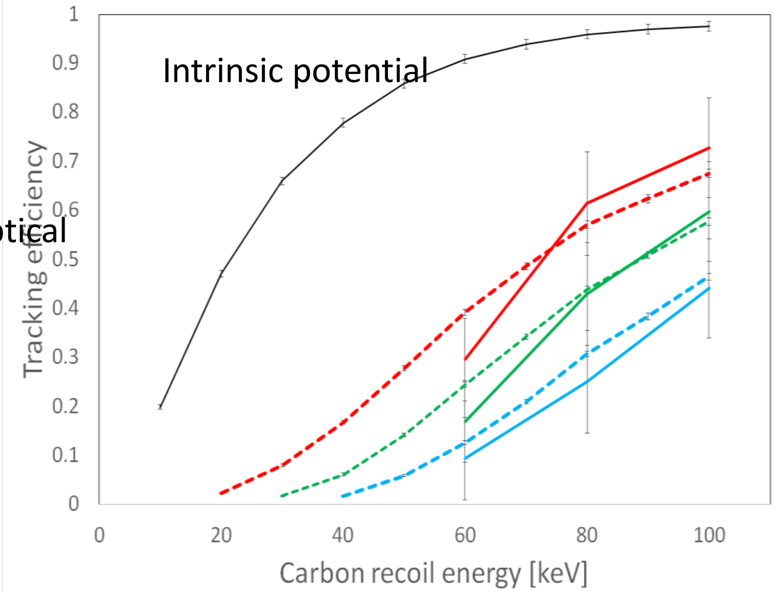
- High level analysis using cutting-edge technologies
- Plasmon analysis





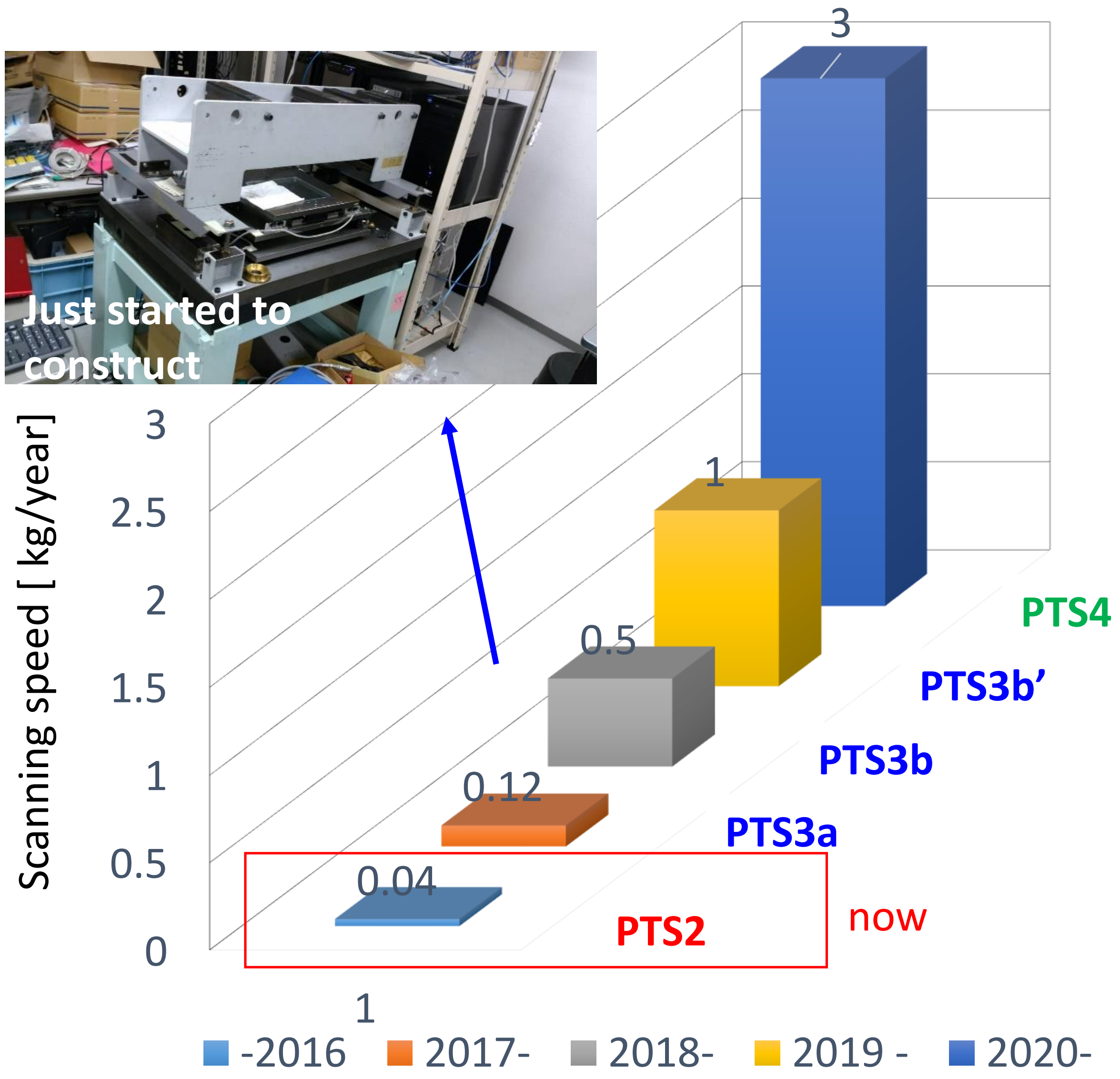
Direction sensitive efficiency :
~ 20-30 % @ 60 keV
⇒ further tuning is needed because it has dependence of chemical development and optical condition

Angular resolution :
~ 0.5 rad. @ 60 keV
⇒no so large dependence for energy



Accidental leakage event :
~ 1 % spherical noise ⇒ to be rejected in 2nd scanning

Roadmap of scanning system for nano-scale tracking



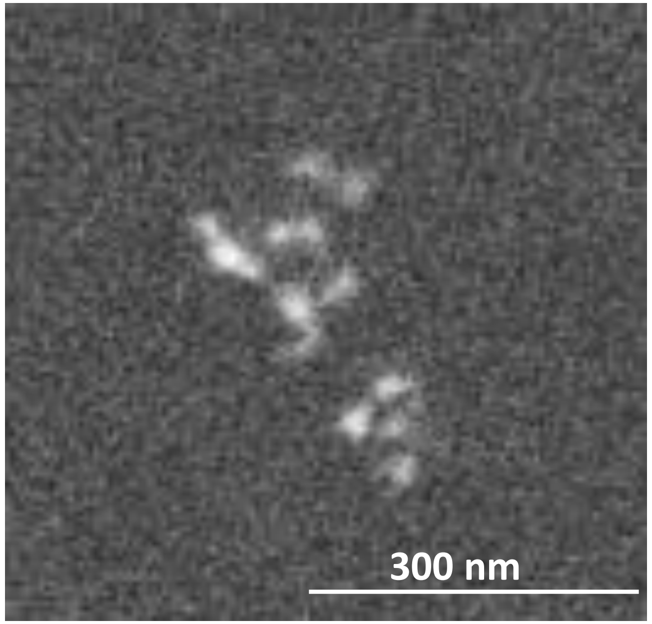
[PTS2] 40 g/y (current system)

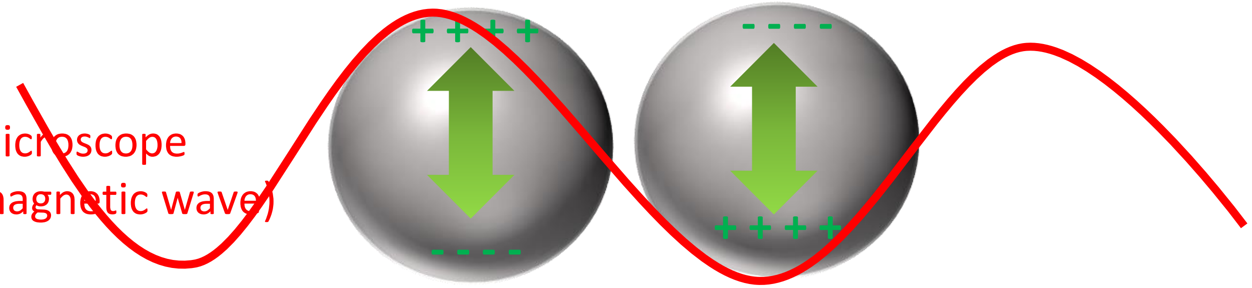
[PTS3a] 120 g/y expected (x 3 higher than PTS2])
⇒ Wider FOV due to higher vision camera

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

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

New Information for readout
⇒ Localized surface plasmon resonance





- Nuclear recoil tracks have very complicate structure with silver nano-particle
- This is very unique structure for that such as high dE/dx particles

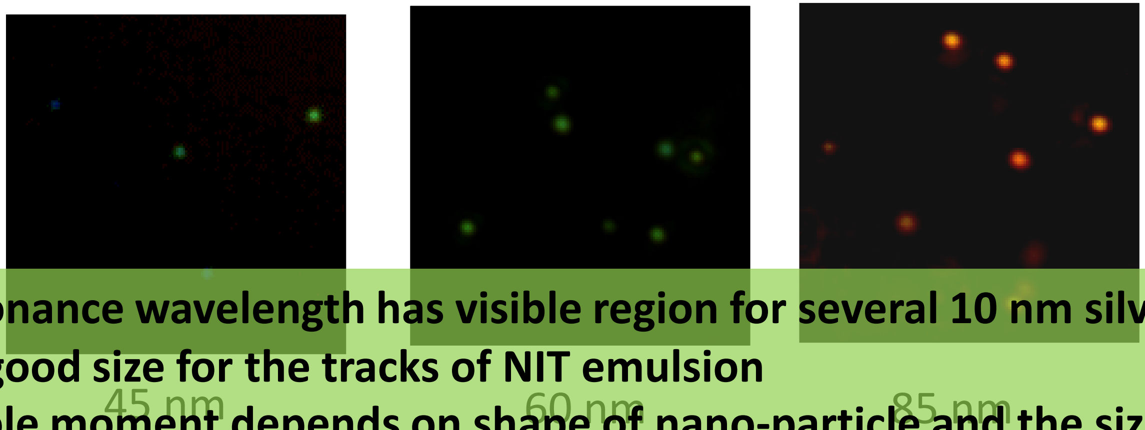
Dipole-moment of free electron in the nano metaric particle

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

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

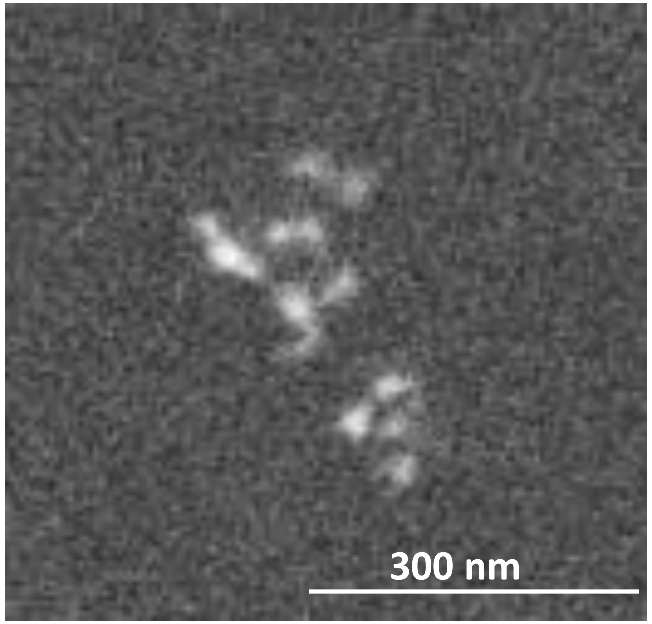
Information of nano-scale structure is extremely important for discrimination from various backgrounds

⇔ optical resolution : ~ 230 nm
⇔ electron microscope : not realistic for actual analysis by that strong limitation



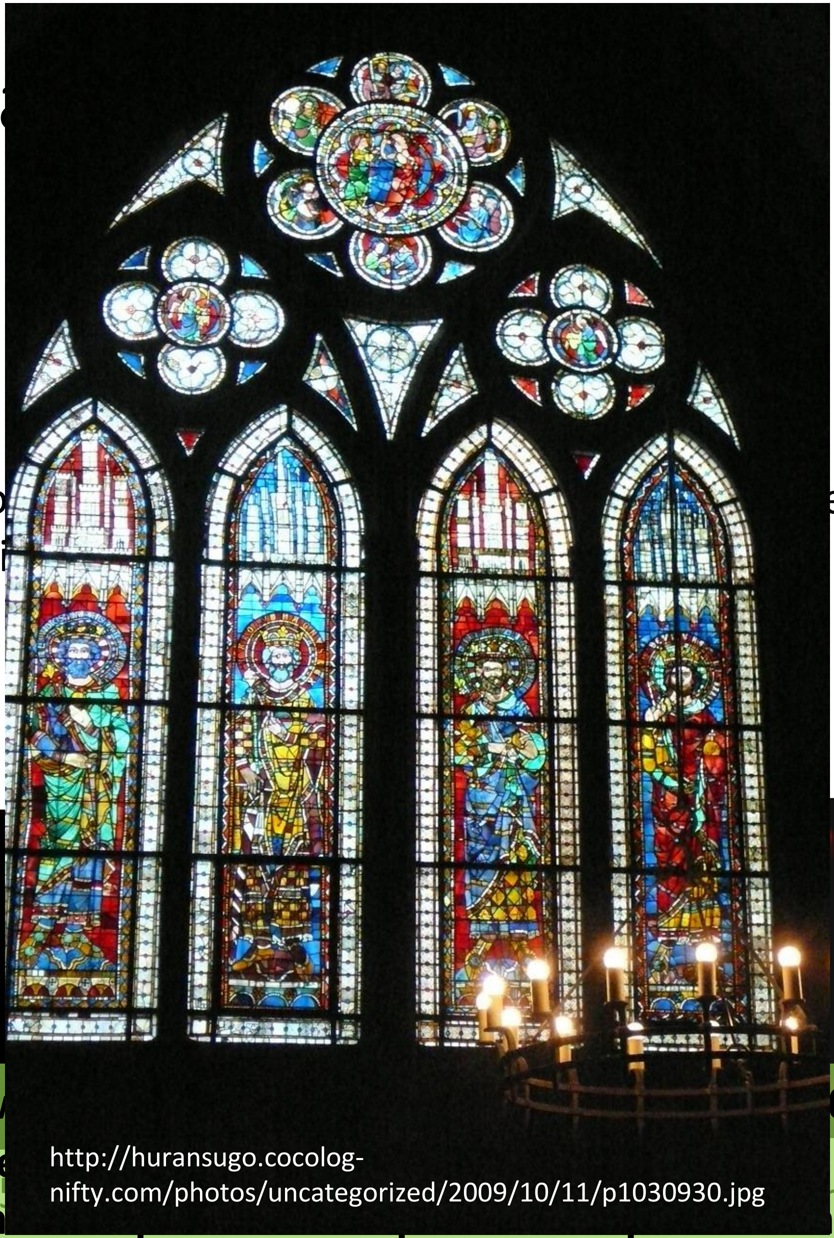
✓ Resonance wavelength has visible region for several 10 nm silver
⇒just good size for the tracks of NIT emulsion
✓ Dipole moment depends on shape of nano-particle and the size
⇒ strong dependence on resonance peak and polarization

New Information for readout
⇒ Localized surface plasmon resona



- Nuclear recoil tracks have very complicate structure with silver nano-particle
- This is very unique structure for that such as high dE/dx particles

Dipo … etaric
parti



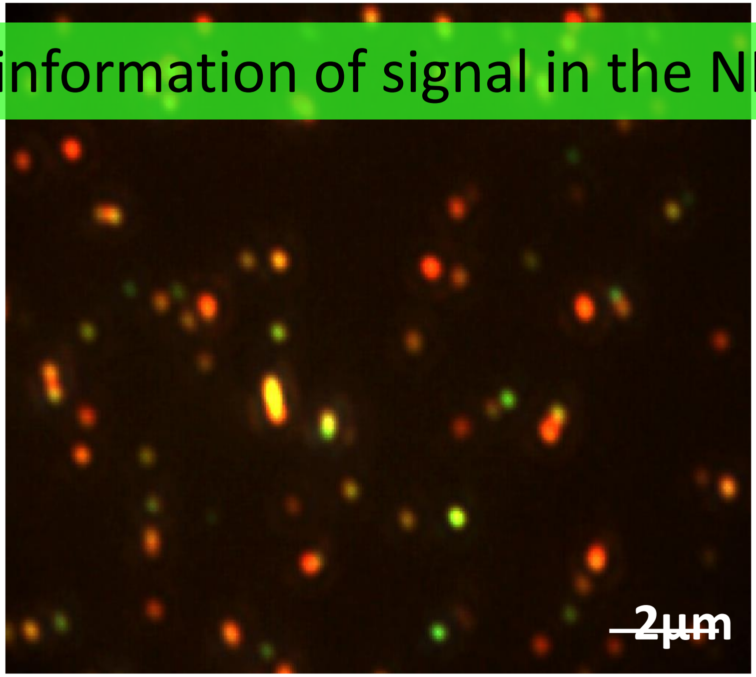
Information of nano-scale structure is extremely important for discrimination from various backgrounds

⇔ **optical resolution : ~ 230 nm**

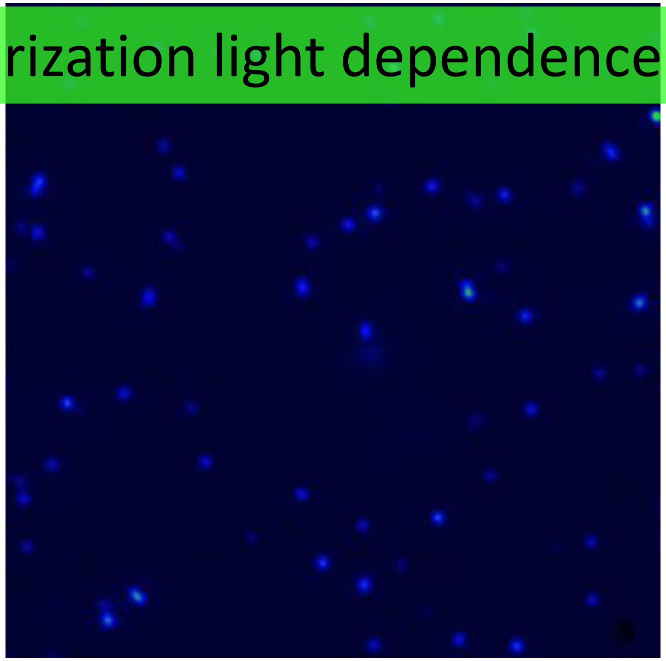
⇔ **electron microscope : not realistic for actual analysis by that strong limitation**

✓ **Resonance v … 0 nm silver**
⇒just good size … nm
✓ **Dipole mom … d the size**
⇒ strong dependence on resonance peak and polarization

Color information of signal in the NIT emulsion



Polarization light dependence



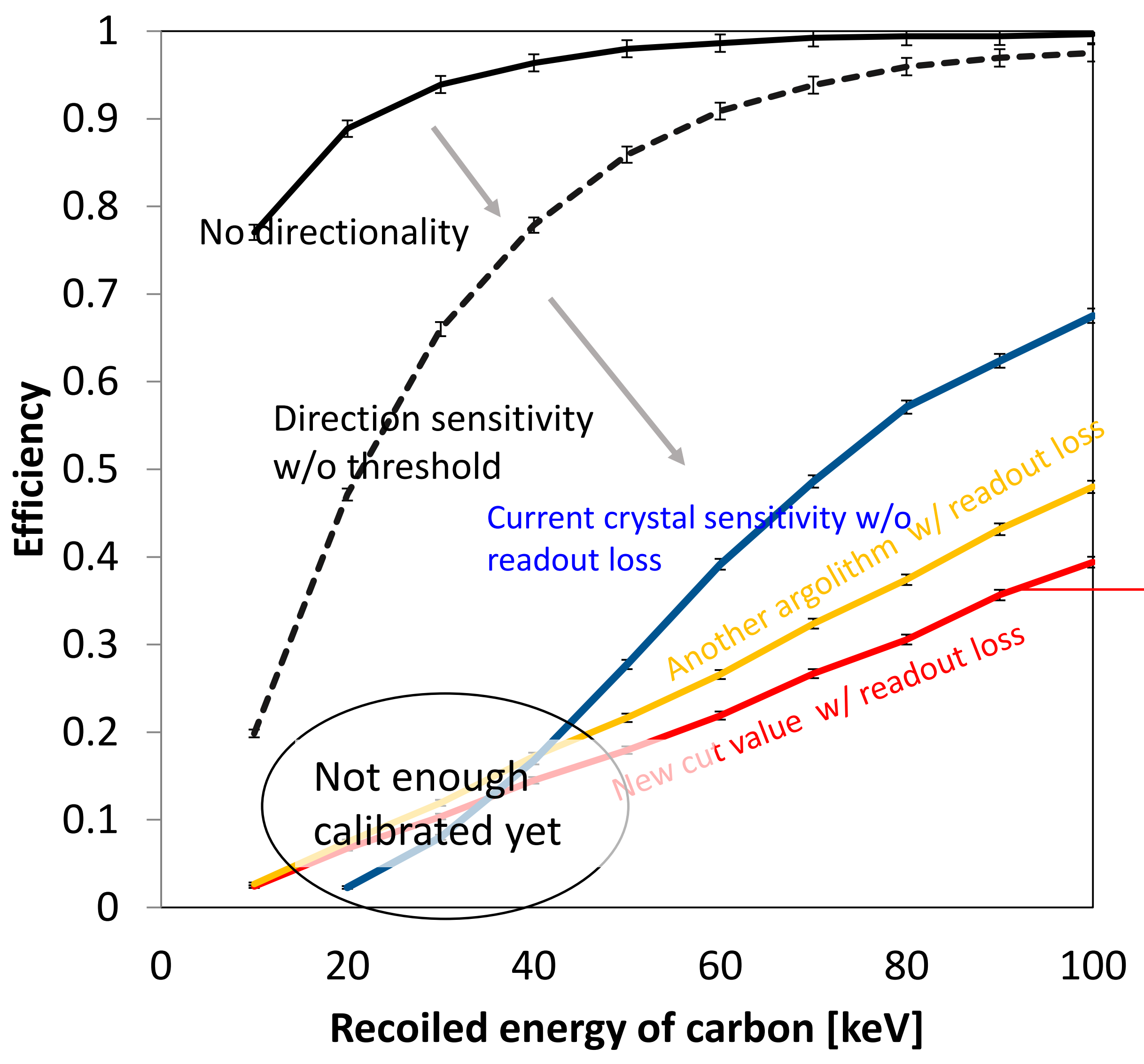
↔
Polarizer angle

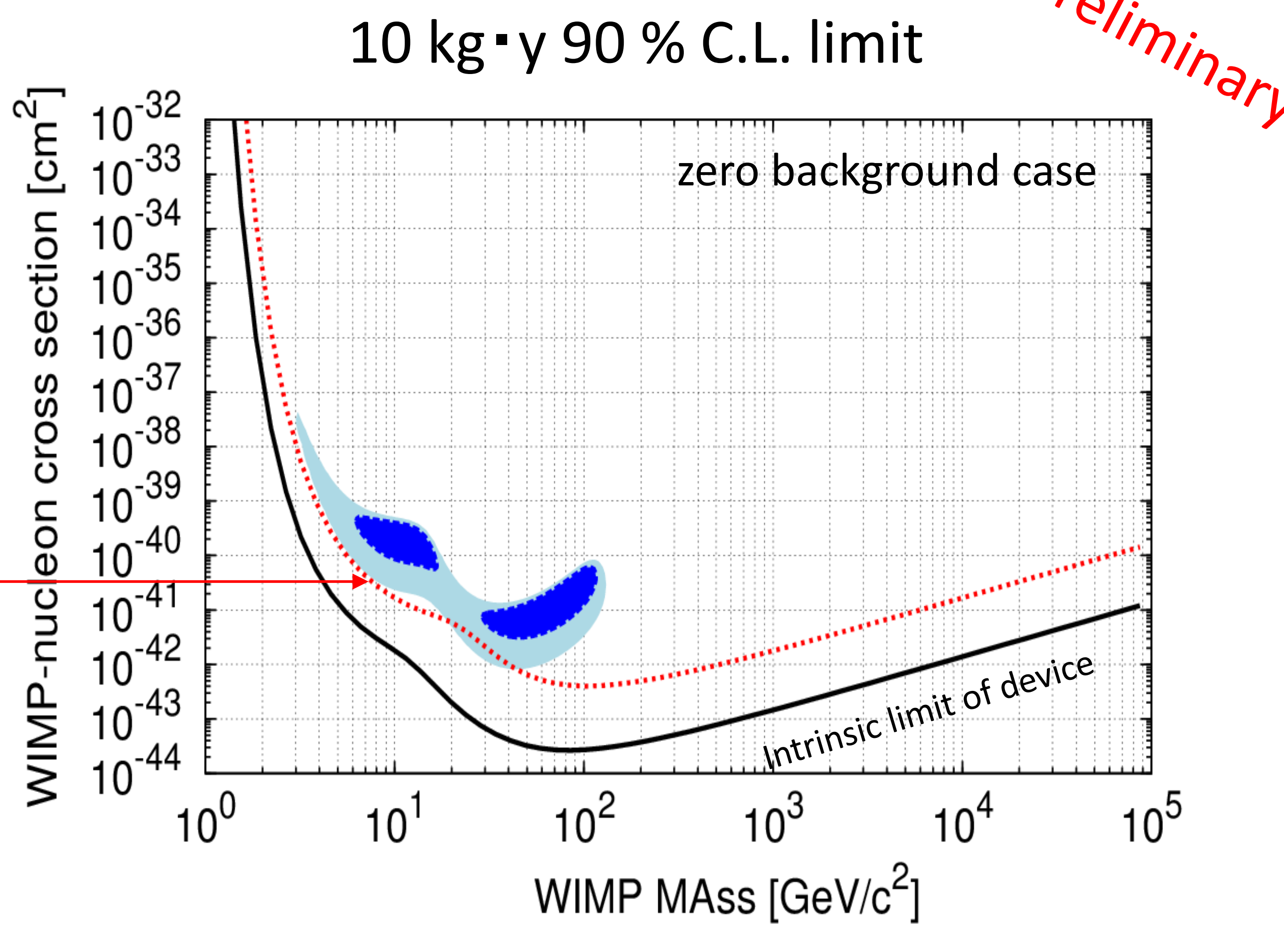
Next new readout information to confirm the signal

- Color information of recorded events
- polarization dependence information

➢ Particle ID (especially, electron and nuclear recoil)
➢ contaminated noise identification
➢ super-high resolution
⇒ improve the threshold (low-mass region search)
➢ Collaboration with computer scientist (Yandex in Russia)
⇒ cutting-edge technologies for computer science

Study for sensitivity with our detector





- ➢ **Sensitivity will be improved with direction information**
- ➢ **Readout loss will be improved by upgrade of optics**

Intrinsic Backgrounds

1. Intrinsic radioactivity

⇒ **mostly understand using mass-spectrometry and Ge detector**

	U-238	Th-232	K-40	Ag-110m	C-14
1st prototype device	27	6	69020	(~400)	24000
Current device	~27	~6	35	(~400)	24000
Ultra-low BG device	1-10	~ 1	< 35	(~400)	< 100

[mBq/kg]

2. Intrinsic Neutron emission

⇒ **Simulation using measured data of radioactivity in the current device**

Process	SOURCE simulation [/kg/y]
(α, n) from ^{232}Th chain	0.12 +- 0.04
(α, n) from ^{238}U chain	0.27 +- 0.09
Spontaneous fission	0.8 +- 0.3
Total flux	**1.2 +- 0.4**

Expected nuclear recoil tracks of > 100 nm + directionality

0.03- 0.05 /kg/y

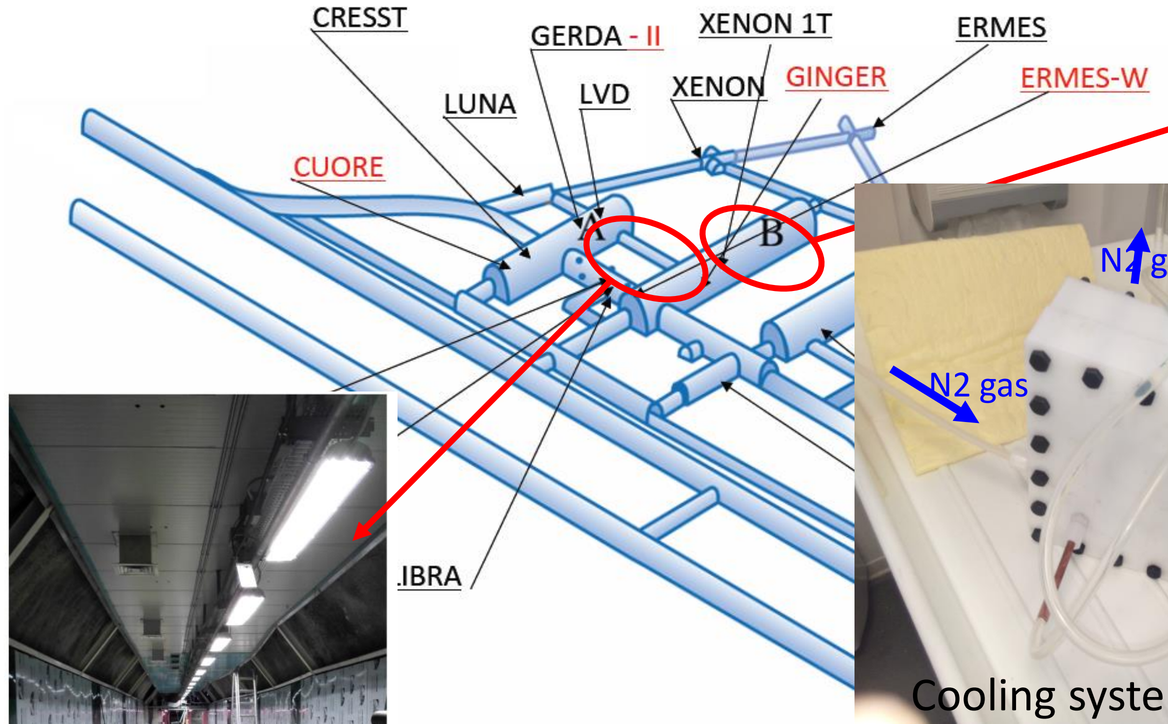
3. Dust contamination

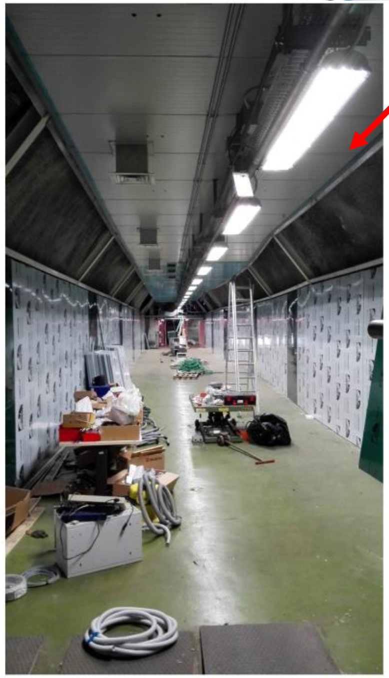
⇒ **need to understand the source, purification and discrimination by analysis**

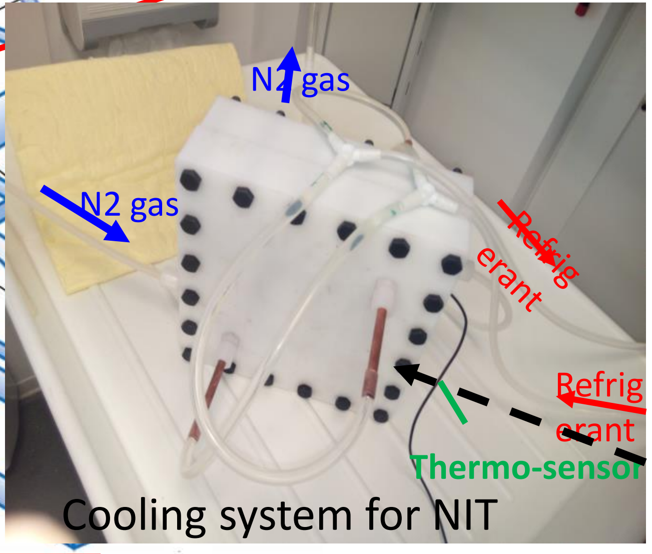
A. Alexandrov *et al.,* Astropart. Phys. 80 (2016)16-21

Pilot-run environment and shield

Gran Sasso underground laboratory, Italy





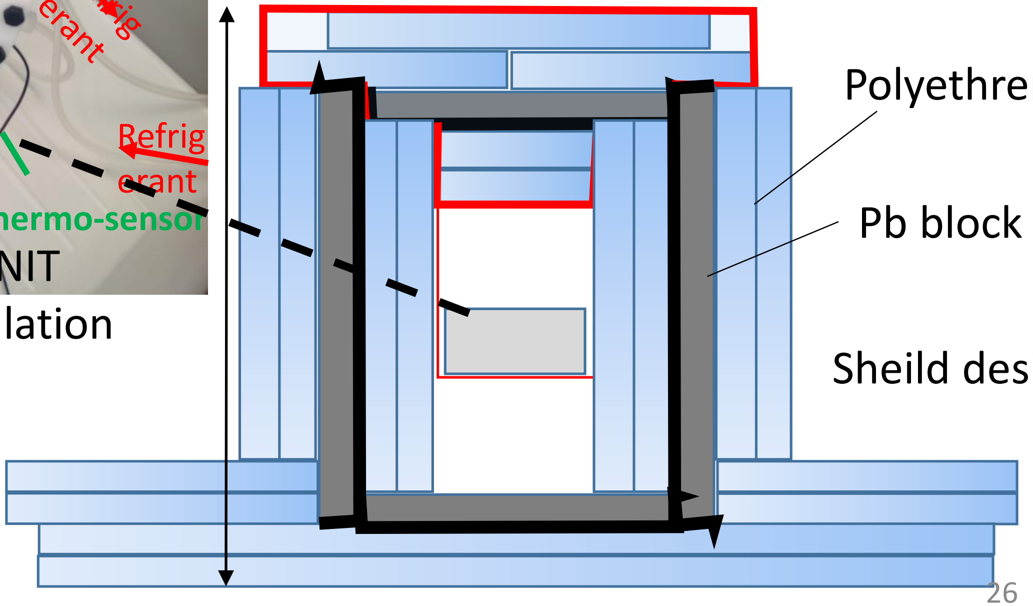


Cooling system for NIT emulsion film installation

New site :

- ☐ Detector making
- ☐ Chemical treatment
- ☐ Clean room

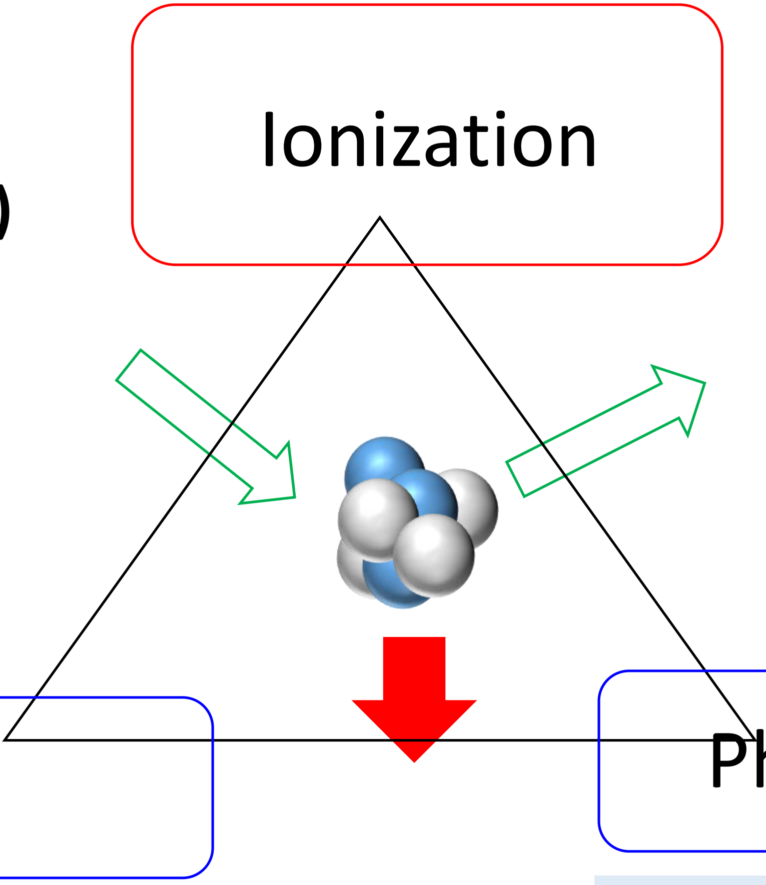
Now on construction

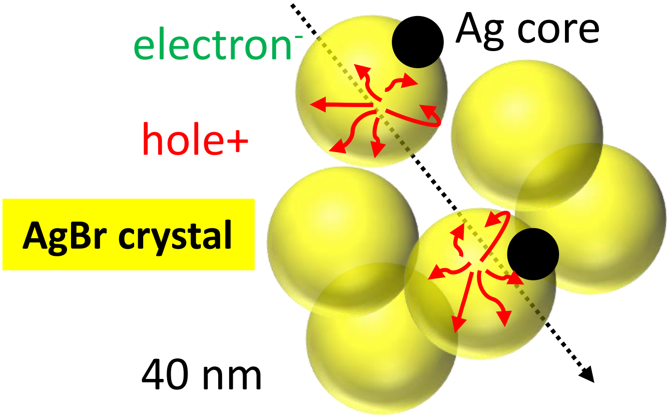


Sheild design

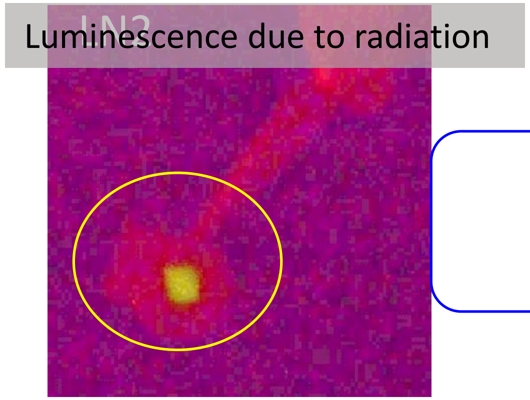
New potential of NIT detector toward large scale experiment [cryogenic NIT emulsion device]

New phenomena in cryogenic condition (around liquid N_2 temperature)





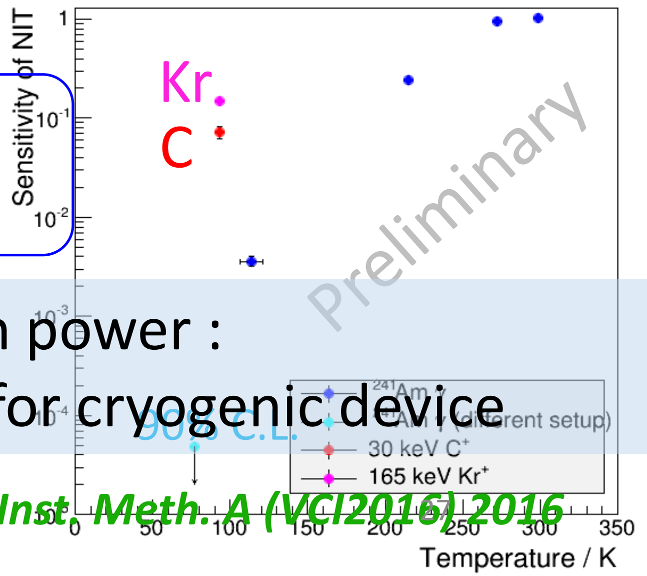
Usual detection mechanism is ionization



Photoluminescence

Time resolution and position self-trigger

Poster presentation at KMI2017 (no. 28) by Hiromasa Ichiki +



electron rejection power : better than 10^{-9} for cryogenic device

M. Kimura et al., Nucl. Inst. Meth. A (VCI2016) 2016

Summary and schedule

- We need new method, technologies and information to break through current dark matter search situation.
- Directional dark matter search is one of the promising method for that
- NEWSdm collaboration propose the experiment using super-high resolution nuclear emulsion (Nano Imaging Tracker: NIT) , and study toward large scale directional search.
- First demonstration about the capability of detecting the nuclear recoil as track by solid detector
- Now, we are studying to understand the background and that rejection

Main study

2016-2017

Understanding of background and the rejection

Readout system demonstration

New system for high-precision analysis

Preparation and test run for 1-10 g scale

2017- 2018

Detector upgrade

Low-background run

New readout system demonstration

Proposal for 1 kg scale experiment

2018 -

Scale-up of experiment

Upgrade for BG discrimination

Physics run for SI cross section with direction sensitivity