Status of NEWS:
Nuclear Emulsions for Wimp Search

Giovanni Rosa
Sapienza University and INFN Rome – Italy
on behalf of the NEWS Collaboration

Contents

- Detection principle
- Experimental tests
- Nano-imaging with optical microscopes
- Background study
- Sensitivity
- Towards a demonstrator

The NEWS Collaboration

Italy
Bari
GSSI
LNGS
Naples
Rome

Japan
Chiba
Nagoya

Russia
LPI RAS Moscow
JINR Dubna
SINP MSU Moscow

Turkey
METU Ankara

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

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

A. Aleksandrov[b,h], A. Anokhina[n], T. Asada[k], I.Bodnarchuk[m], A. Buonaura[b,h], M. Chernyavskii[o], A. Chukanov[m], L. Consiglio[e], 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,g], S. Furuya[k], G. Galati[b,h], V. Gentile[b,h], S. Gorbunov[o], Y. Gornushkin[m], M. Guler[p], H. Ichiki[k], 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,h], A. Umemoto[k], M. Vladymyrov[o], M. Yoshimoto[k], S. Zemskova[m]

[a]*INFN Sezione di Bari, Bari, Italy*
[b]*INFN Sezione di Napoli, Napoli, Italy*
[c]*INFN Sezione di Padova, Padova, Italy*
[d]*INFN Sezione di Roma, Roma, Italy*
[e]*INFN-Laboratori Nazionali del Gran Sasso, Assergi (L'Aquila), Italy*
[f]*INFN-Laboratori Nazionali di Frascati, Frascati (Roma), Italy*
[g]*Dipartimento di Fisica dell'Università di Bari, Italy*
[h]*Dipartimento di Fisica dell'Università Federico II di Napoli, Napoli, Italy*
[i]*Dipartimento di Fisica e Astronomia dell'Università di Padova, Padova, Italy*
[j]*Dipartimento di Fisica dell'Università di Roma, Rome, Italy*
[k]*Nagoya University and KM Institute, Nagoya, Japan*
[l]*Chiba University, Chiba, Japan*
[m]*JINR-Joint Institute for Nuclear Research, Dubna, Russia*
[n]*SINP MSU-Skobeltsyn Institute of Nuclear Physics of Moscow State University, Russia*
[o]*LPI-Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia*
[p]*METU-Middle East Technical University, Ankara, Turkey*

LNGS-LOI 48/15

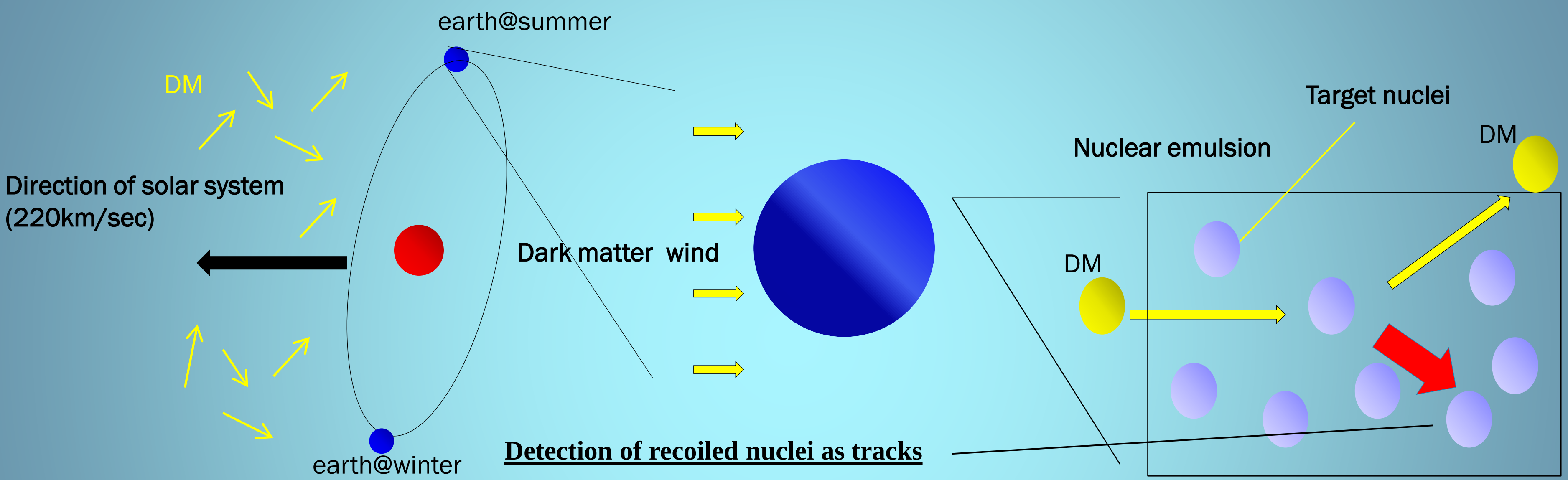
TO THE LNGS SCIENTIFIC COMMITTEE

~60 physicists

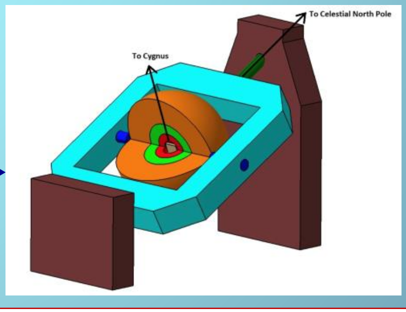
https://arxiv.org/abs/1604.04199

Experimental concept:

- The direct WIMP search paradigm - detect nuclear recoil ➔ **tracking**
- In nuclear emulsion (a solid state detector) sub-μm recoil track lenghts ➔ **nano-imaging**
- For the galactic DM a ***non-isotropic WIMP flux*** is expected on Earth…



- …***Directionality*** as a strong signature
  ➔ **keep target pointed to DM wind (Cygnus)**
  by an equatorial telescope, e.g.



- However (as for everybody…) beware of each and every type of ***Background***
  ➔ **Instrumental, intrinsic radioactivity, environmental, cosmogenic**
  (ultrapure components, underground, shielding…)

A brief reminder about Nuclear Emulsions
I – Atomic composition, R vs. E

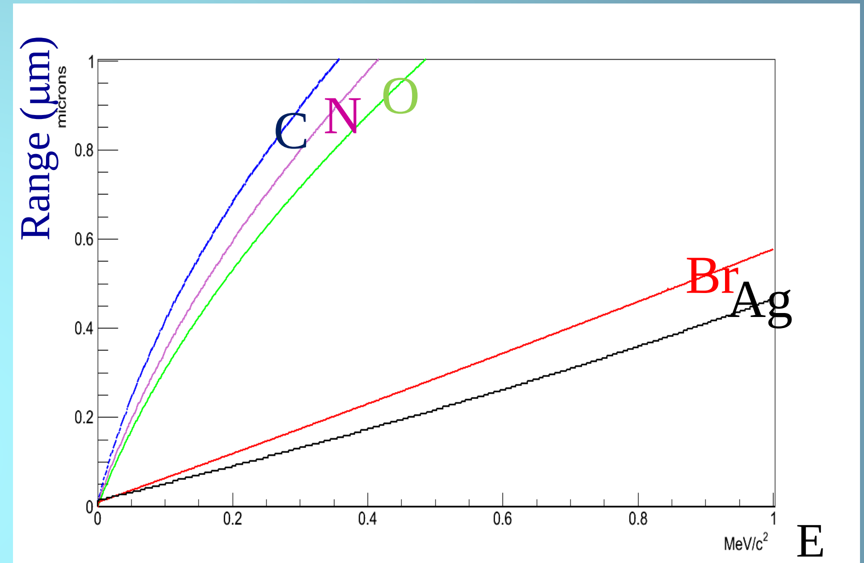
AgBr-I: sensitive elements
Organic gelatine: retaining structure
PVA to stabilise the crystal growth

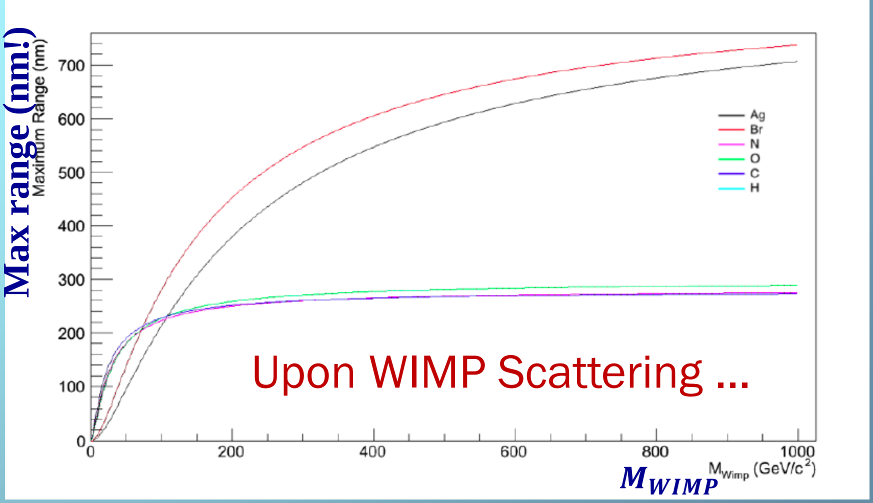
Constituent	Mass Fraction
AgBr-I	0.78
Gelatin	0.17
PVA	0.05

(a) Constituents of nuclear emulsion

Element	Mass Fraction	Atomic Fraction
Ag	0.44	0.12
Br	0.32	0.12
I	0.019	0.003
C	0.101	0.172
O	0.074	0.129
N	0.027	0.057
H	0.016	0.396
S	0.003	0.003

(b) Elemental composition

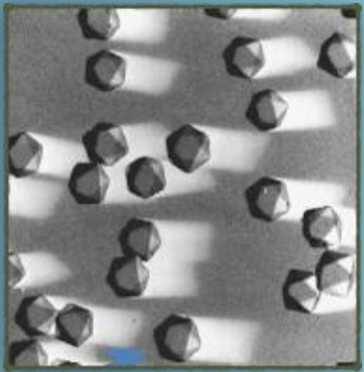




Both light and heavy nuclei

A brief reminder about Nuclear Emulsions – II a particle detector

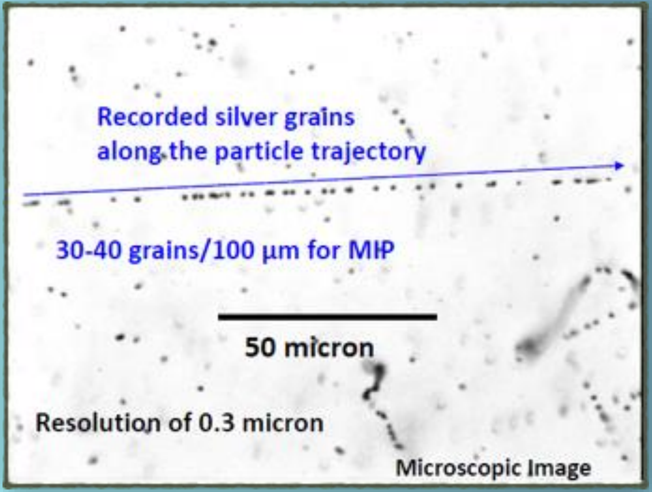
- A last-century, "venerable" detector of any ionizing particle with still unrivalled spatial resolution
- Know-how transmitted through generations of experimentalists
- Big improvements from early CR records on mountain or balloon to neutrino oscillations at accelerator

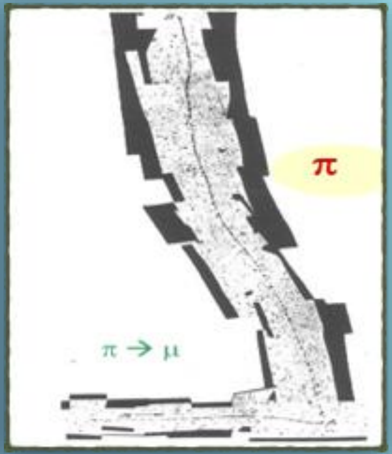


AgBr crystal size 0.2-0.3 μm

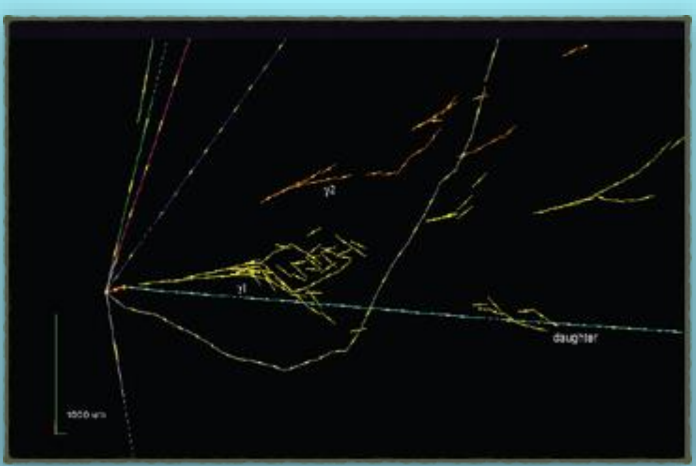
After the passage of charged particles through the emulsion, a latent image is produced.

The emulsion chemical development makes Ag grains visible with an optical microscope





The discovery of the **Pion (1947)...**



...the 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

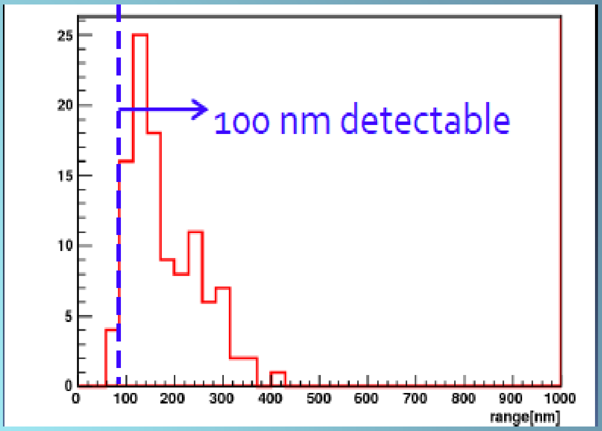
→ intense (and succesfull!) ***R&D*** in progress...

Recipe for nuclear emulsions dedicated to DM detection

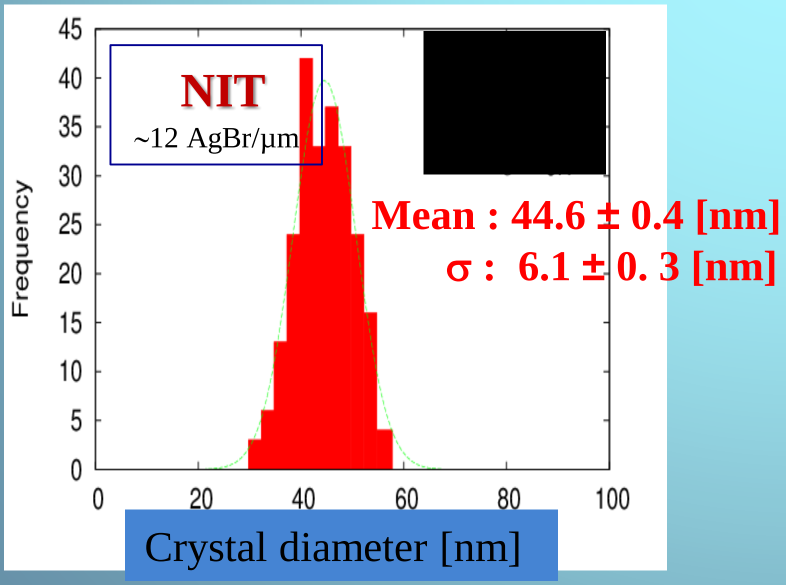
1 - reduce sensitive crystal size wrt OPERA-type
   ➔ a Nano Imaging Tracker (**NIT**)
2 - make gel/tune development to be insensitive to mip
3 - select/purify components to reduce “fog noise”
4 – sensitize the target on-site (underground)
5 – keep it at low temperature to reduce random noise
6 – etc…

Dectable range threshold
(a key parameter)
Is determined mainly by
crystal size

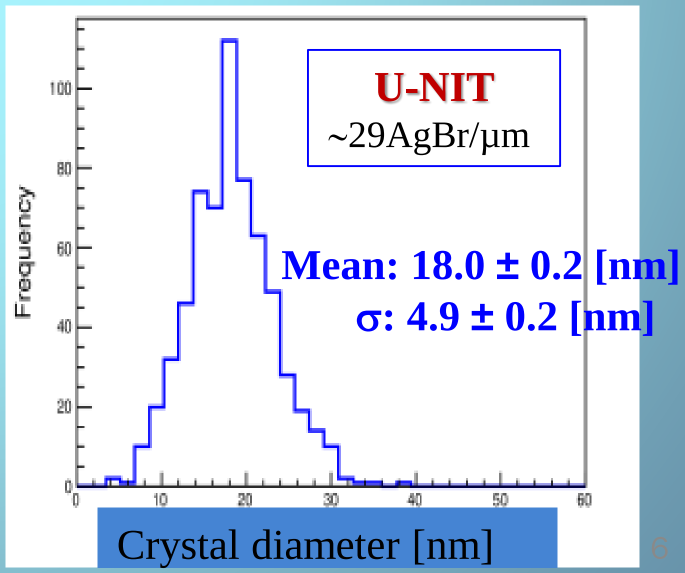
Range threshold	Carbon Energy
200 nm	75 keV
100 nm	35 keV
50 nm	15 keV



Baseline emulsion sample



Finest grain emulsion



Challenge after NIT production: **detect** (measure) **tracks** when their lengths become comparable/**shorter** than the **optical resolution** **(with "standard" technologies ~ 200 nm)**

Experimental campaign
study of nuclear recoil-like tracks in NIT

(Ion implantation, source exposures, neutron irradiations…)

- **A two-step scanning strategy defined and applied:**
  1. **Candidate selection** by fast optical scanning (à la OPERA) looking for ellipsoidal shapes
  2. **Nuclear track confirmation / background rejection** with a higher resolution scanning

     (**initial approach: X-ray microscopy** – but extremely slow & needing outside resources…)

- **Significant upgrade of dedicated microscopes (hardware & software)**

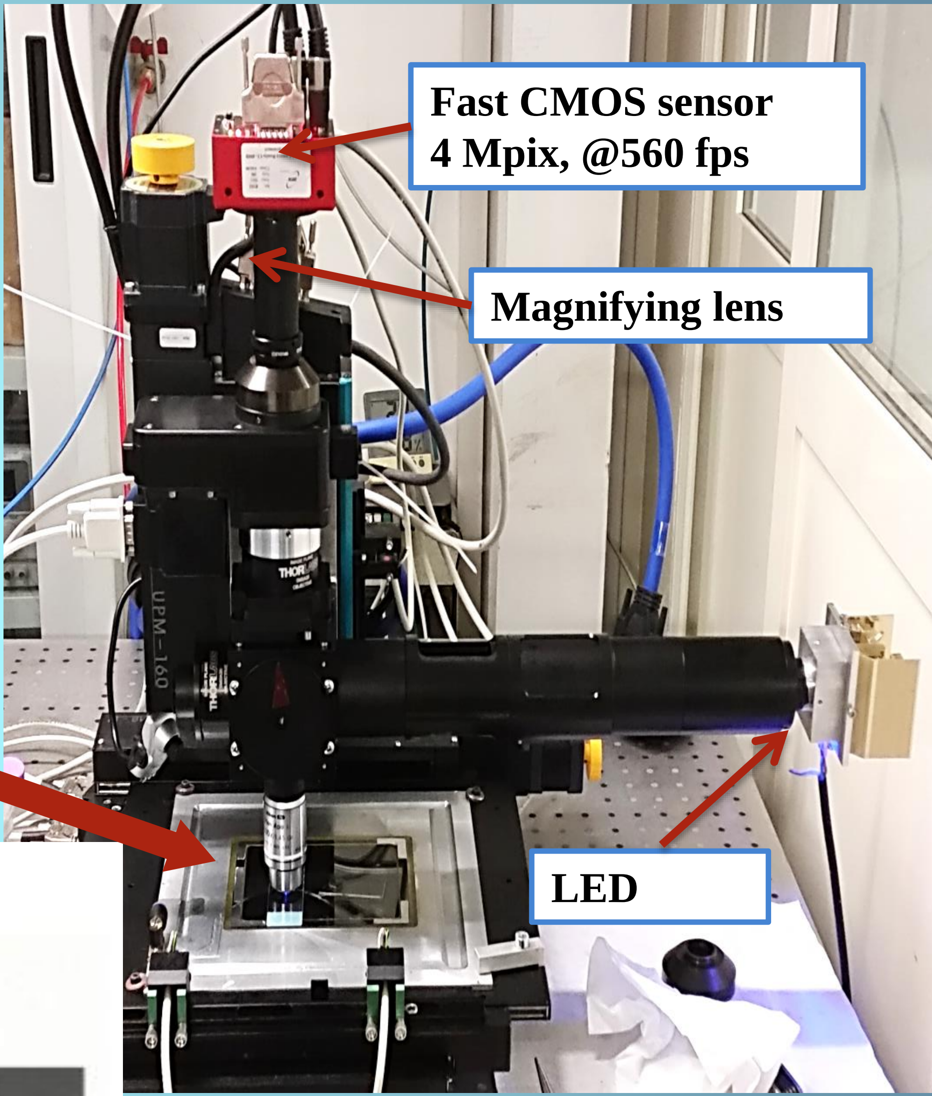
- **Selection efficiency studies of the first step as a function of track length threshold & quality cuts**

- **Assessment of angular resolution in view of directionality**

Optical Microscope Read-out: Step 1

100x objective lens with high N.A.

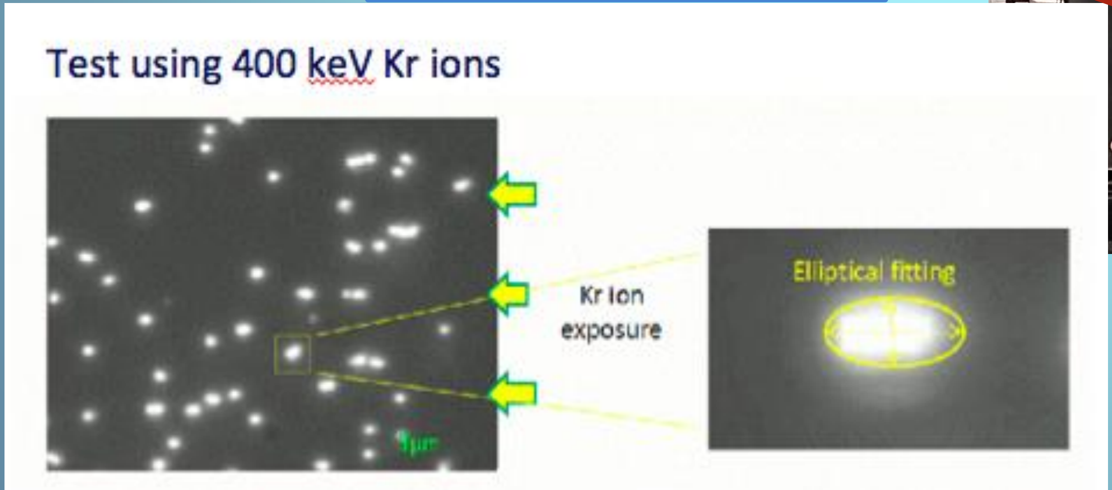
Resolution: 30 nm/pixel
View Size: 65 x 50 μm^2



Fast CMOS sensor
4 Mpix, @560 fps

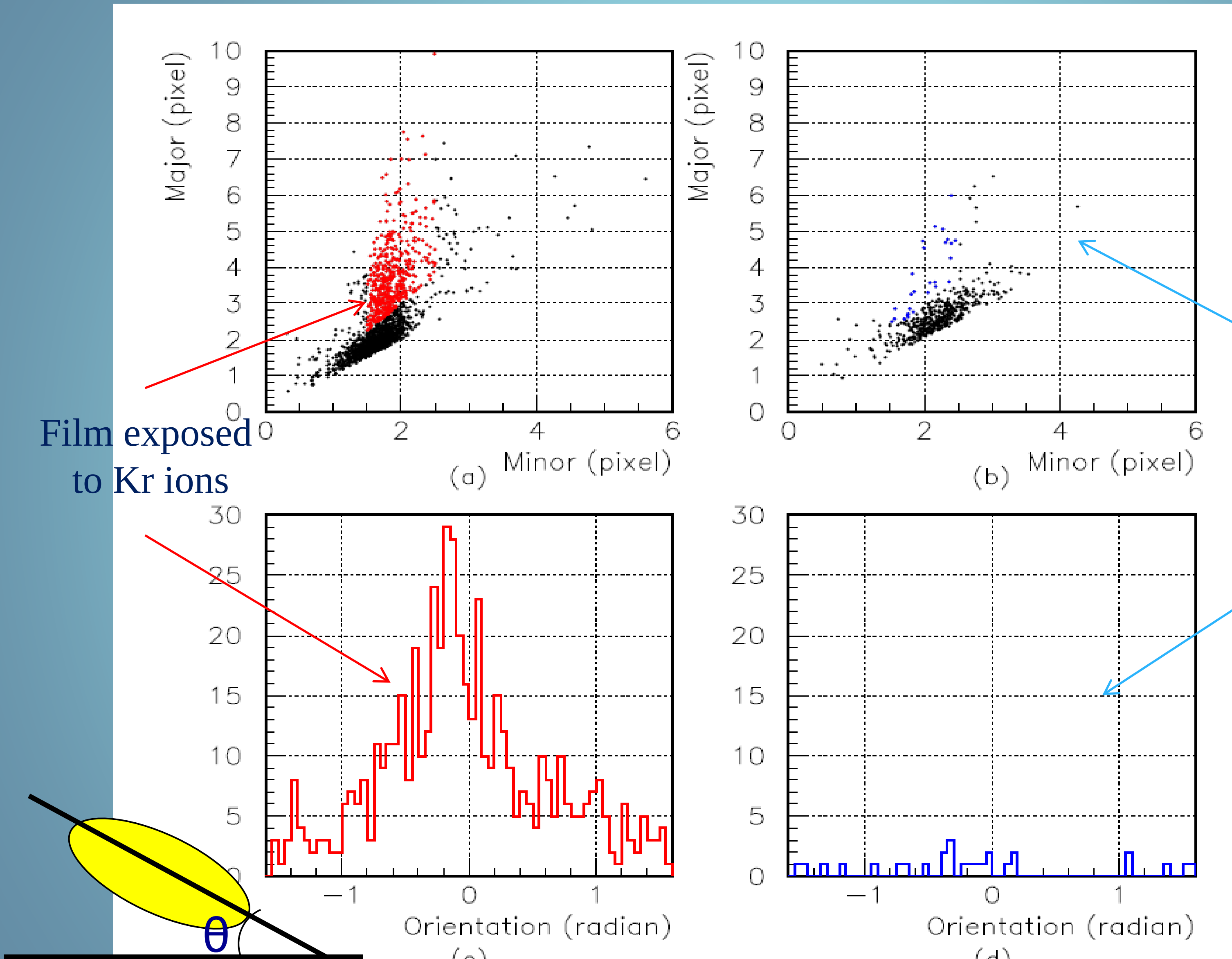
Magnifying lens

LED



Scanning with **optical microscope** and **shape recognition analysis**

Selection of Kr ion tracks with shape analysis



Film exposed to Kr ions

Reference film (unexposed)

Major/minor>1.5

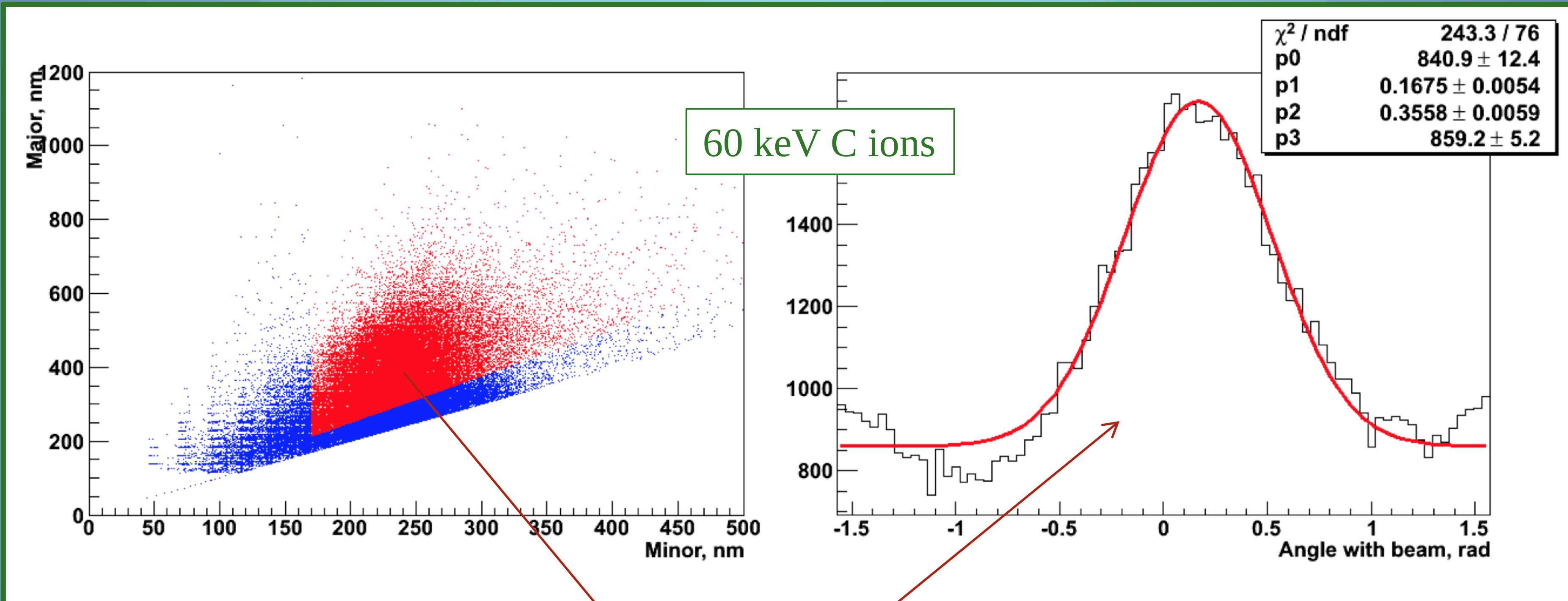
1.4<minor <2.6

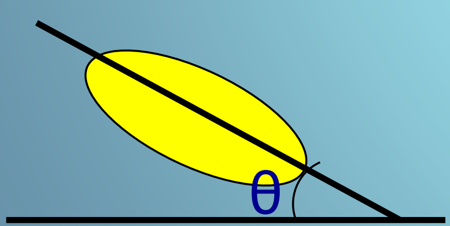
pixel > 40

Direction detected!

NIM A680 (2012) 12-17

Selection of C ion tracks with shape analysis





Direction detected!

Signal selection:

- Major/minor>1.25
- minor > 170 nm

$$\sigma^2 = \sigma^2_{intrinsic} + \sigma^2_{scattering}$$

$$\sigma = 360 \text{ mrad}$$

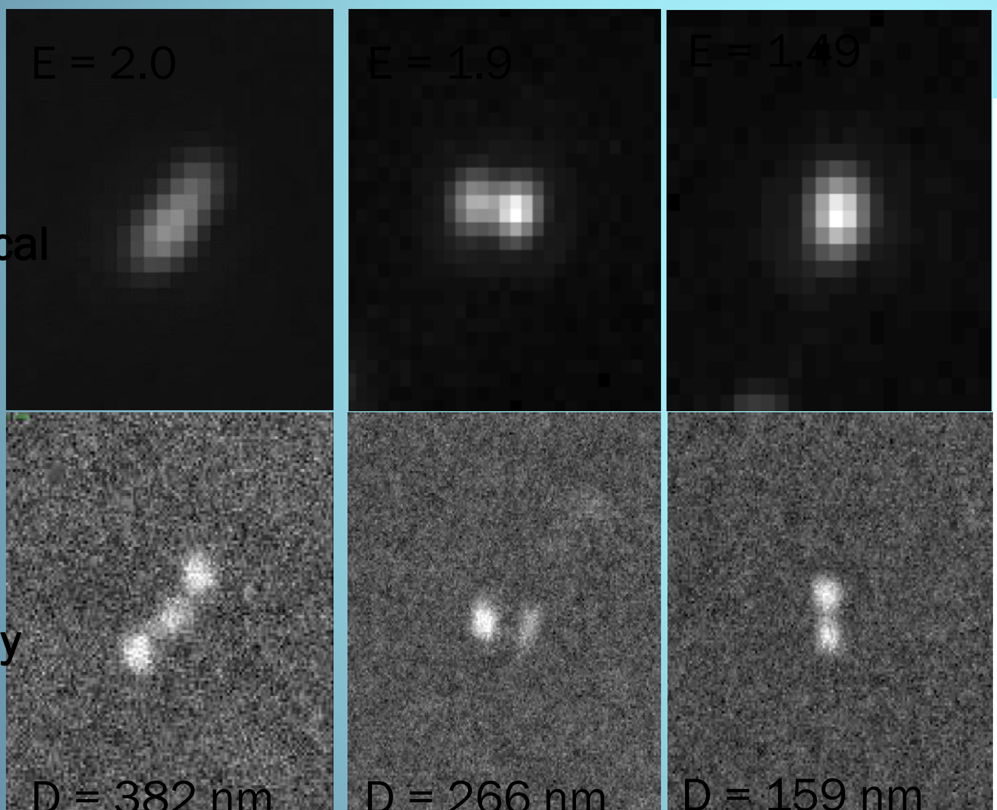
EFFICIENCY EVALUATION

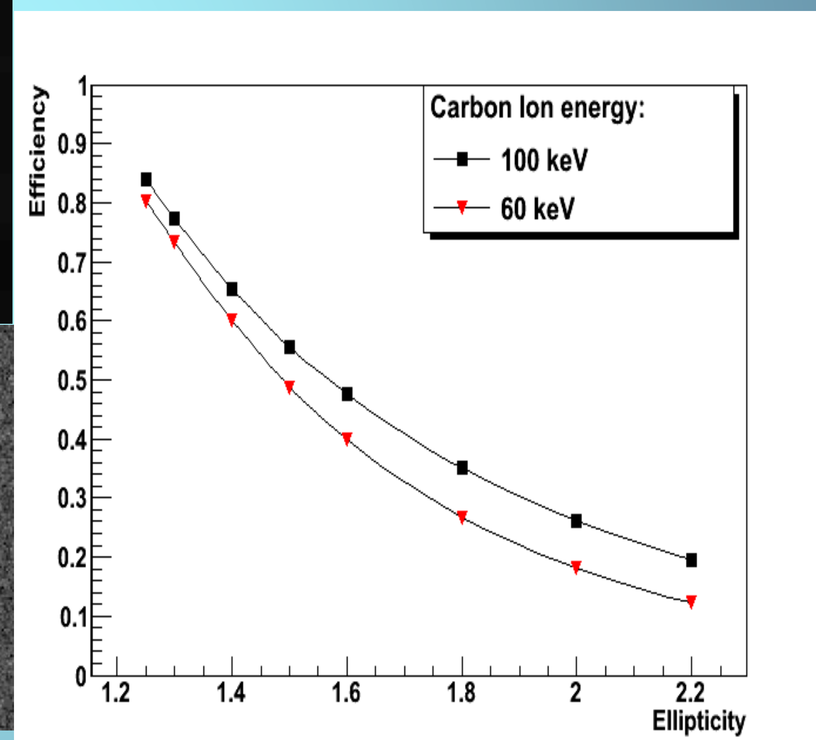
- Implantation: 60÷100 keV C-ions
- Emulsion sample: 40nm-crystal
- Scan with X-ray microscope & select candidates
- Scan with Optical microscope by a pin-point check & Elliptical fit

X-ray MS
- 10.83nm / pix
- 2048 x 2048 pix CCD

Optical

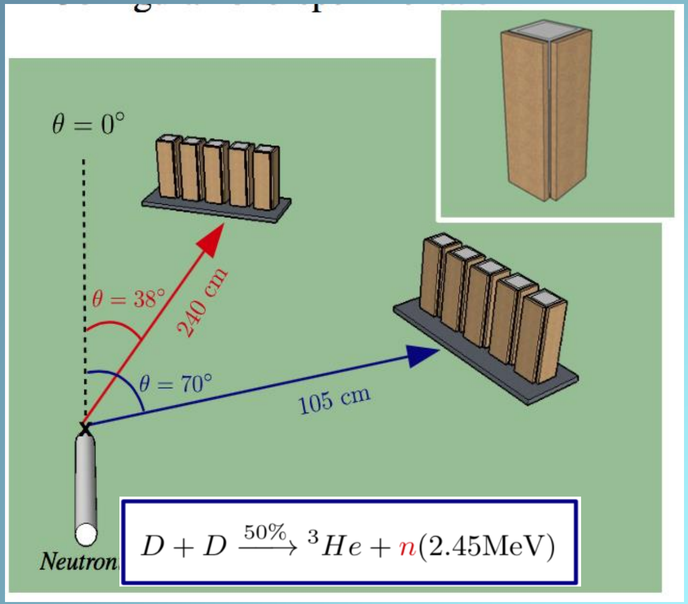
X-Ray

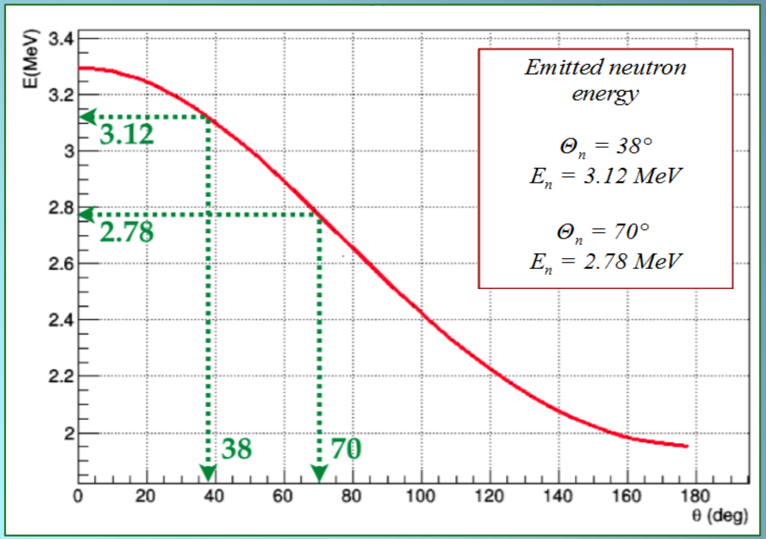




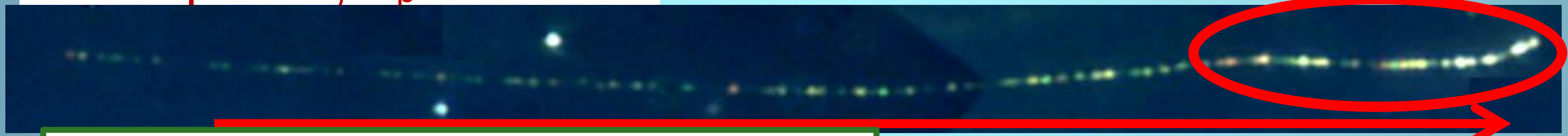
X-ray microscope: ~50 nm resolution and readout speed ~ $(200\mu m)^2$/100 s

Neutron Test Beam @ FNS (Japan)



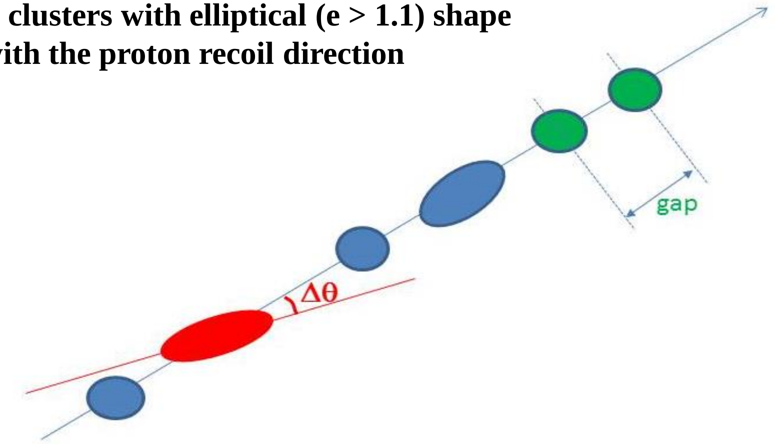


Recoil proton, $E_p = 1.55$ MeV

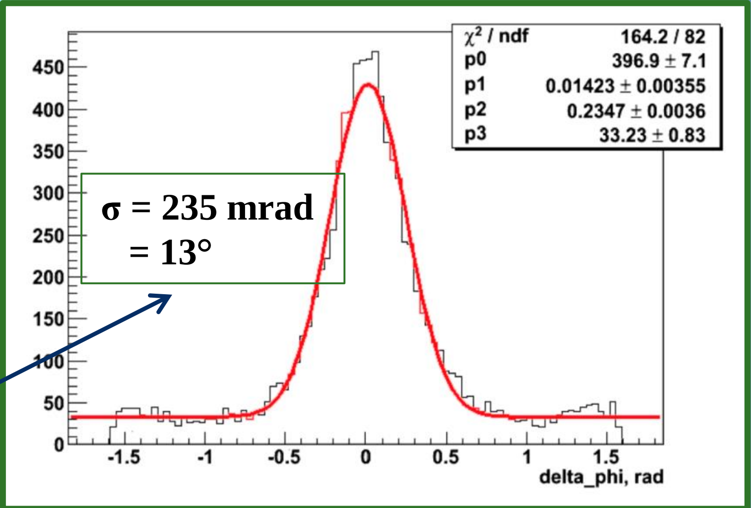


dE/dx

Compare clusters with elliptical (e > 1.1) shape with the proton recoil direction



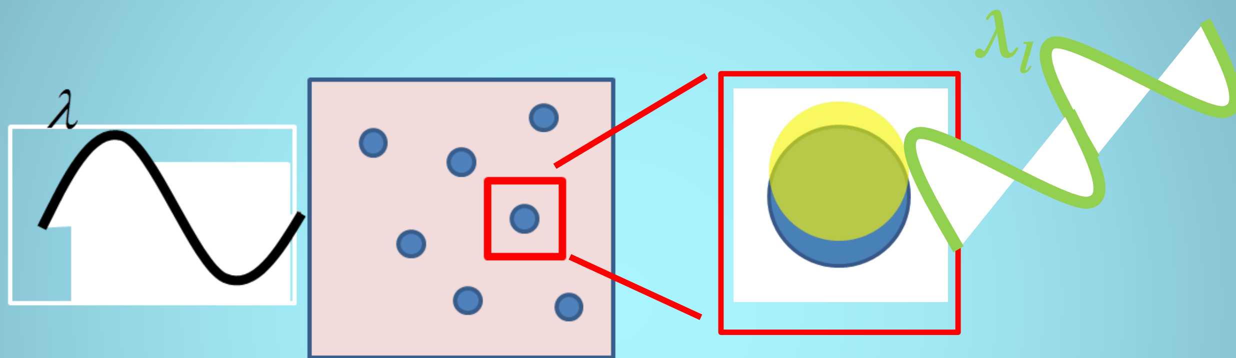
Intrinsic Angular Resolution



So far so good, but second step with X-ray is extremely uncomfortable, and too slow (scaling up to large target mass out of reach)
➔ Compelling reasons to go ***beyond optical resolution***

Exploiting Resonant Light Scattering

by Ag nanoparticles (spheroidal shape of single/multiple clusters)

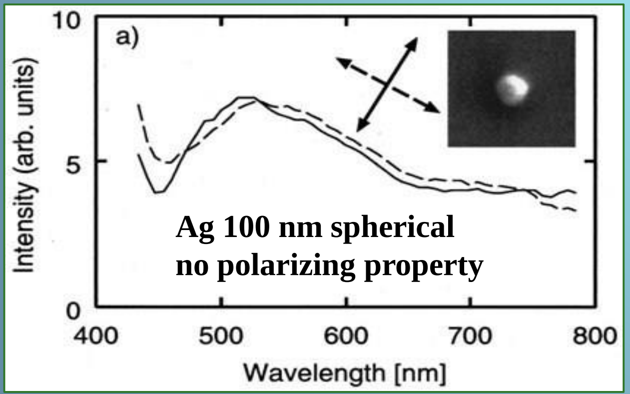


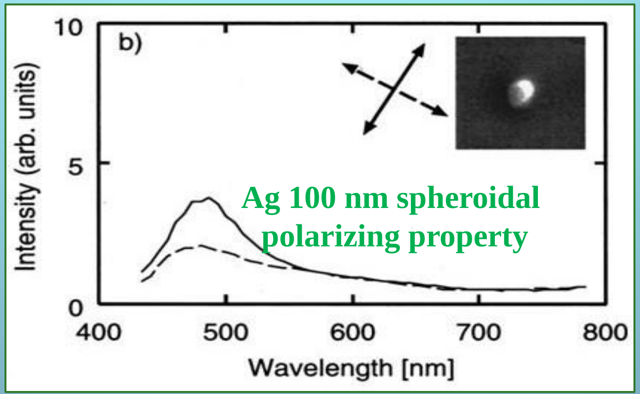
Nano-metal in dielectric medium

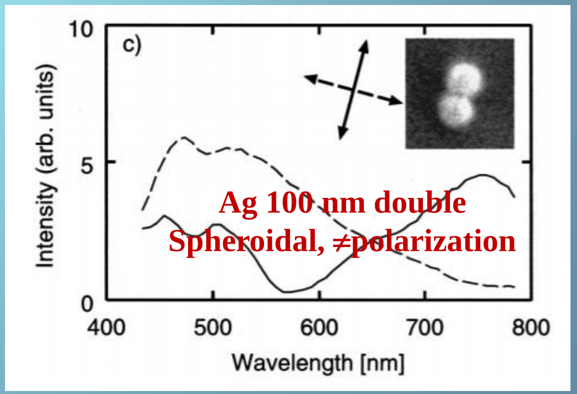
Plasma oscillation of e-cloud

Response spectrum depends on the light polarization and on the grain shape

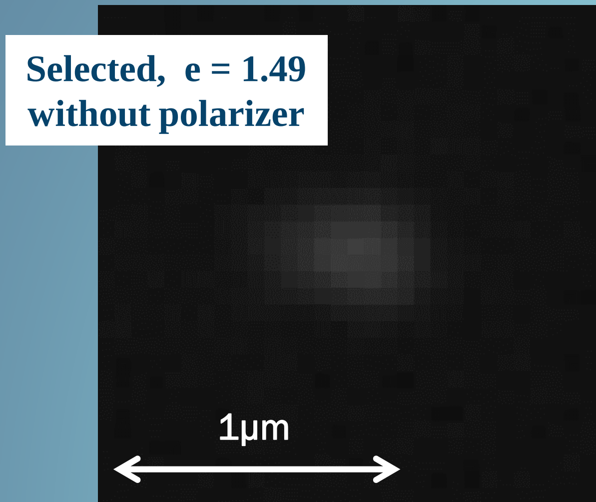
See e.g. ***H.Tamaru et al., Applied Phys Letters 80, 1826 (2002) - …and Nobel Prize for Chemistry 2014***

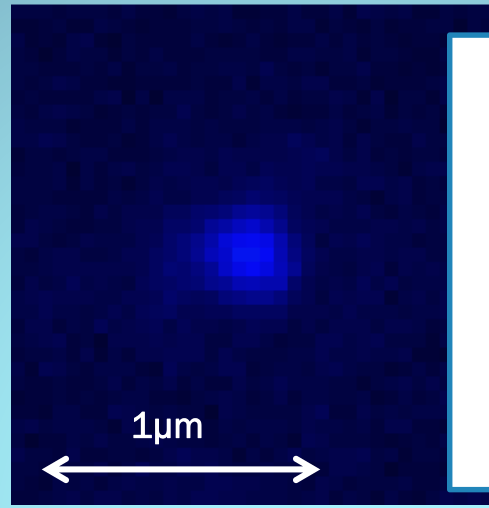


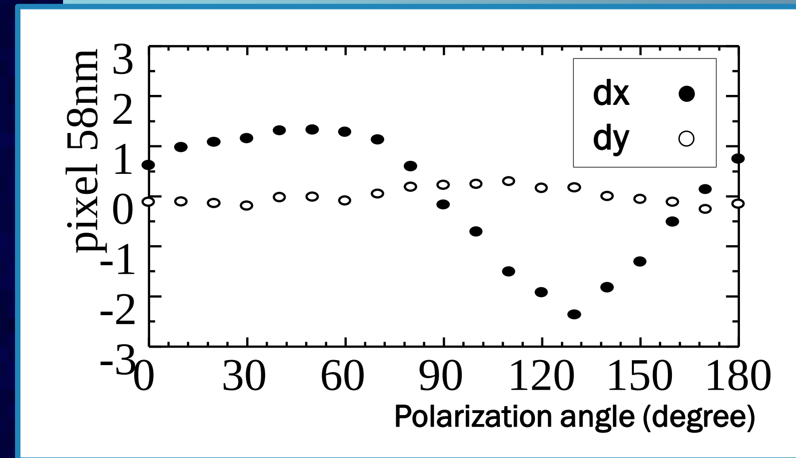




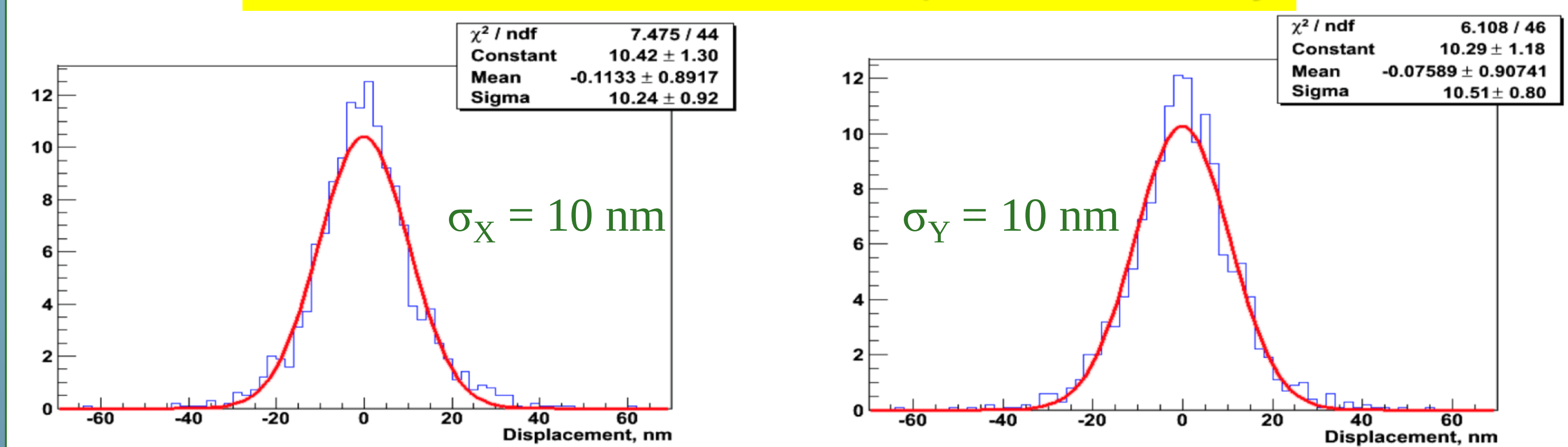
Step-wise polarization implemented on NEWS microscopes
Resonant light scattering method applied to NIT







It works ! ➔ striking enhancement of the ***position accuracy***



(pixel size 28 nm)

Unprecedented position accuracy of 10 nm achieved on both in-plane coordinates

A breakthrough in the technology - Second step of scanning transferred to optical microscopes

Can do better ? Of course yes, e.g. 3D exploitation under test!

Physics background study – 1. Intrinsic

Measurement of intrinsic radioactivity - Neutrons

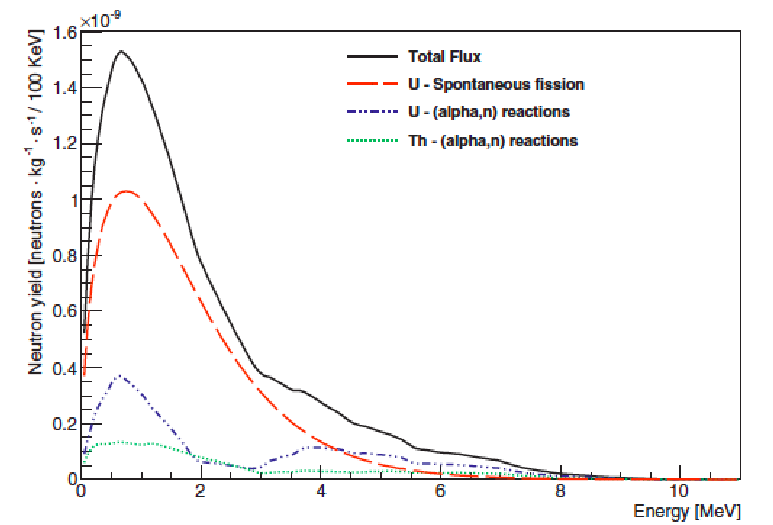
Nuclide	Contamination [ppb]	Activity [mBq/Kg]
Gelatine		
^{232}Th	2.7	11.0
^{238}U	3.9	48.1
PVA		
^{232}Th	< 0.5	< 2.0
^{238}U	< 0.7	< 8.6
AgBr-I		
^{232}Th	1.0	4.1
^{238}U	1.5	18.5

Constituent	Mass Fraction
AgBr-I	0.78
Gelatin	0.17
PVA	0.05

(a) Constituents of nuclear emulsion

^{238}U: 1.87 ppb (23.1 mBq/kg)
^{232}Th: 1.26 ppb (5.1 mBq/Kg)

Process	SOURCES simulation [kg^{-1} y^{-1}]	Semi-analytical calculation [kg^{-1} y^{-1}]
(α, n) from ^{232}Th chain	0.12 ± 0.04	0.11 ± 0.03
(α, n) from ^{238}U chain	0.27 ± 0.09	0.26 ± 0.08
Spontaneous fission	0.8 ± 0.3	0.8 ± 0.3
Total flux	1.2 ± 0.4	1.2 ± 0.4



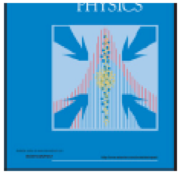
Astroparticle Physics 80 (2016) 16–21

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropartphys

ELSEVIER



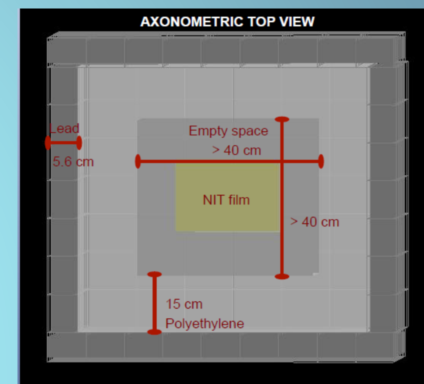
Intrinsic neutron background of nuclear emulsions for directional Dark Matter searches

CrossMark

Physics background study
2. Environmental ➔ Shielding

Entering the battle field of the underground Lab (LNGS)
Old OPERA facility adapted, new Lab in preparation (ready 2017)
A test exposure of about 10g×1y will start by next November

DarkSide-10 shield

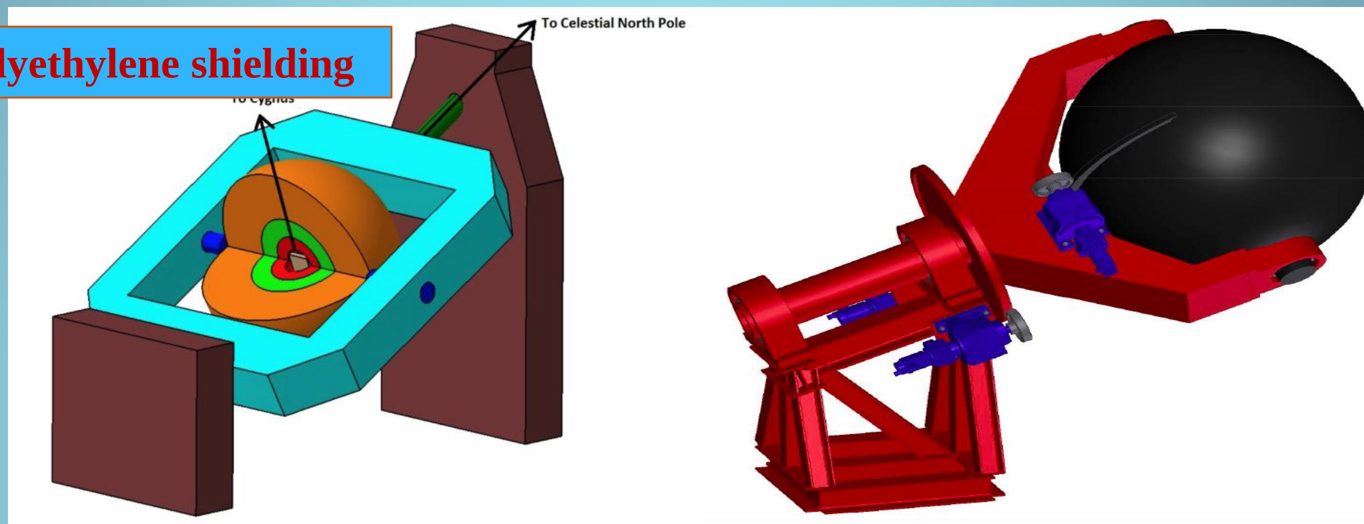


Lead shield

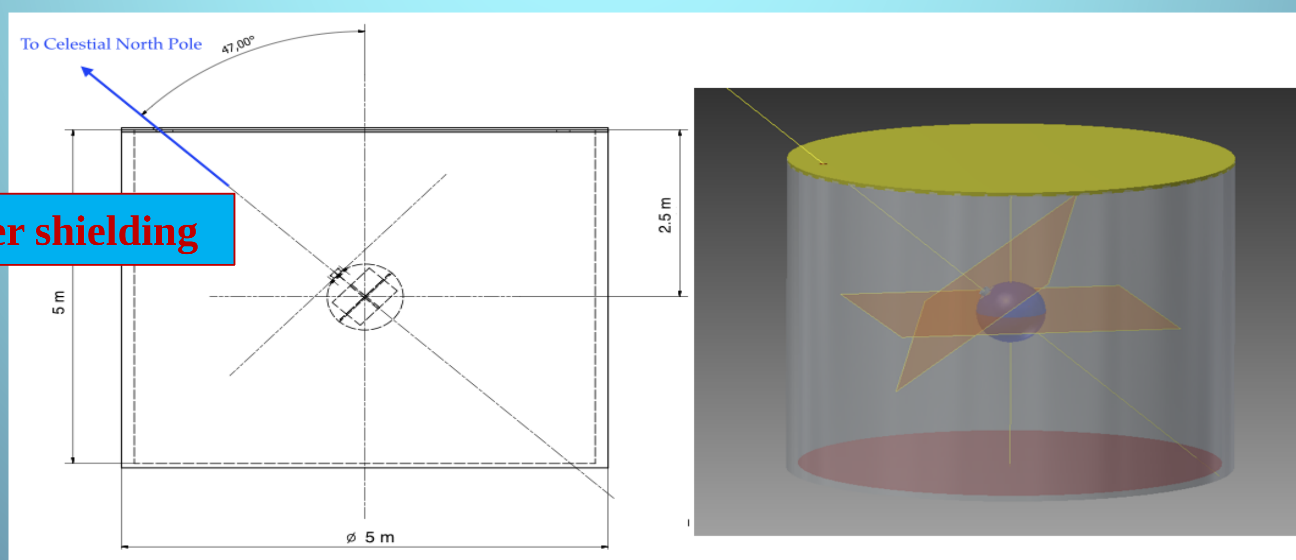
- **Geant4 simulation under tuning for 10 g NIT and two shielding options:**
  1. Water shield, e.g. reusing DarkSide_10 tanks ➔ turned out to be not available for a long exposure
  2. Pb shield (arranging about 300 OPERA bricks…) with inner Polyethylene
- **Muons, cosmogenic neutrons, environmental neutrons and γ considered**
  - Neutron background expected to be negligible for the test
  - Electrons from environmental γ expected to be less than from intrinsic C^{14}
- **On-site sensitizitazion of ultrapure NIT gel produced in Japan: tested, ok**
- **Cooling system: ready (~ *-20 C°*)**

In view of the Demonstrator scale (≥ 1kg×1y, 2018- …):
Study in progress for an equatorial telescope ➔ directionality

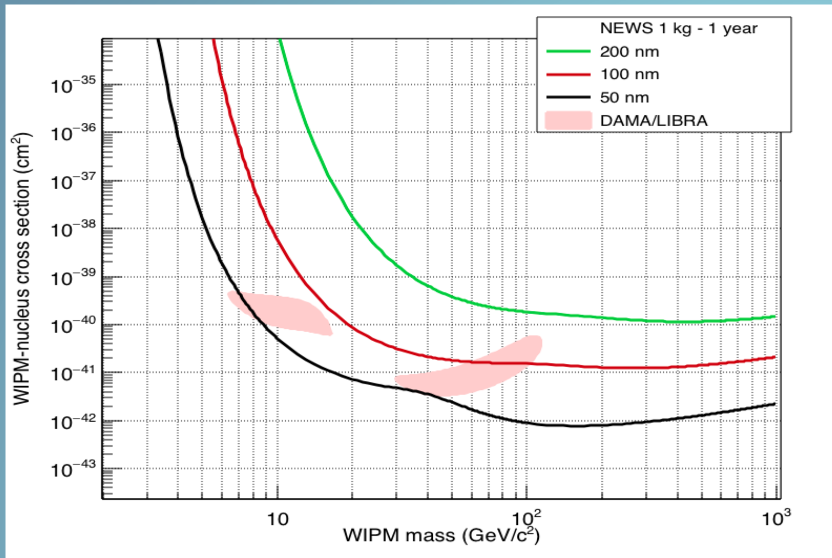
OPTION 1: polyethylene shielding



OPTION 2: water shielding



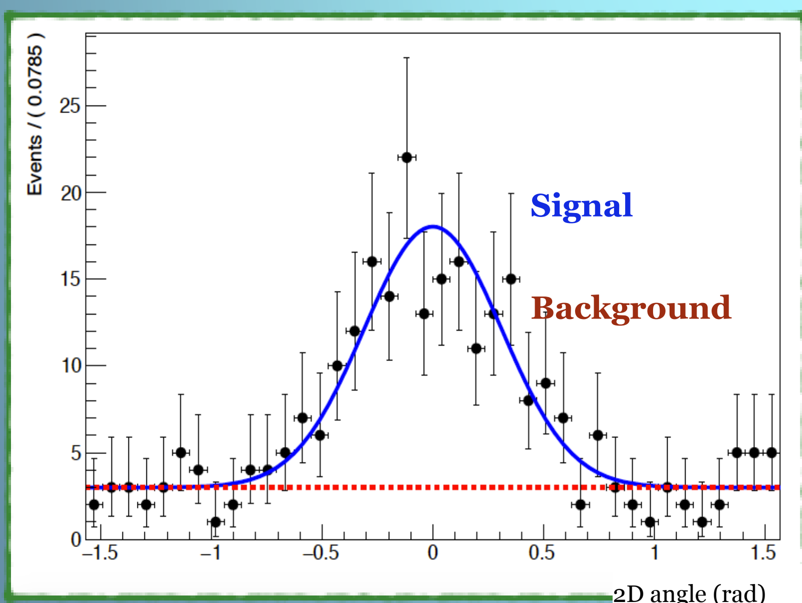
Basic ingredients are there for a first evaluation of *SENSITIVITY*

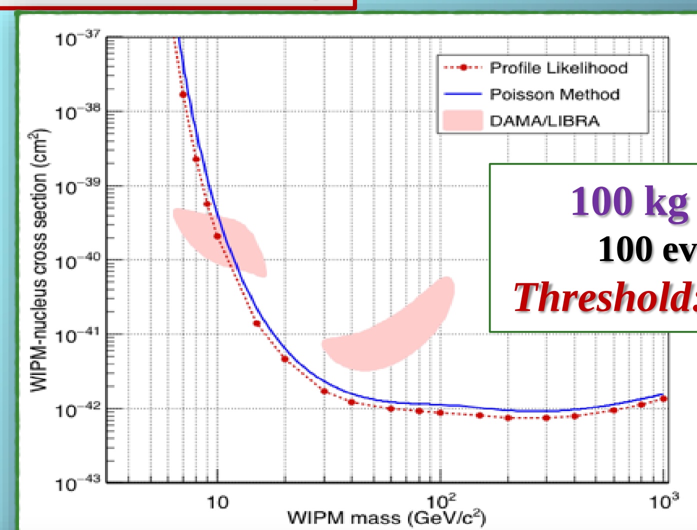


NIT detector: 1 kg year
Zero background
Directionality not included

Crucial parameter:
Minimal range detectable
(100 nm safe, ➔ 50 nm at reach)

…the added value of Directionality





100 kg year
100 events
Threshold: 100 nm

Likelihood for N events, μ_χ WIMPs and μ_b background

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

Conclusions and outlook

- **Nuclear emulsions with nanometric grains open the way for a directional dark matter search with high sensitivity**

  (compact detector, modular, scalable to high mass)

- **Breakthrough in readout technologies for optical microscopes**
  - **No need for X-ray confirmation (much faster and convenient)**
  - **Push the track length threshold down (higher sensitivity)**

- **Neutron background from intrinsic radioactivity negligible**

  up to ~ 10 kg year

- **R&D phase (2016-2017) funded in view of the pilot experiment**

- **test exposure (~10 g, 1 y) at LNGS about to start**

- **Prepare a kg scale experiment as a demonstrator of the technology and the first spin-independent search of this kind**

Hope we'll deliver good NEWS next time…

… it would be a pitty the no NEWS case