# Nuclear Emulsion Based Detector for Directional Dark Mater Search

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On behalf of the NEWSdm Collaboration

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# What are properties of DM?

- No colour charge
- No electric charge
- No strong self-interaction
- Stable, or very long-lived

- Not a particle in the Standard Model of particle physics

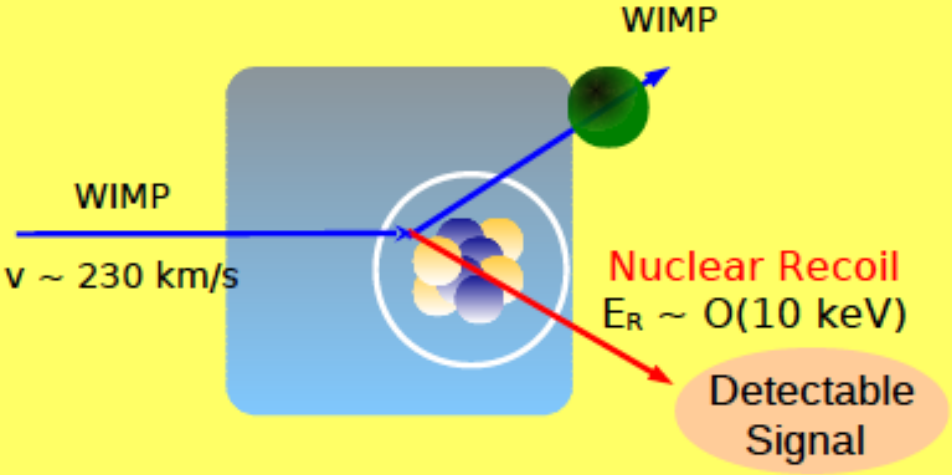
- It possesses gravitational interactions
- No other long range interaction is allowed. Otherwise it would have formed "atoms" and , hence, stars etc.
- It may posses some very weak interaction.

**Many DM candidates:**

- **WIMPS**
- **Axions**
- **Gravitinos**
- **Kaluza-Klein states**
- **…..**

# Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
➡ nuclear recoil




- Recoil Energy

$$E_r = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1-\cos\theta) \sim \mathcal{O}(10\ \mathrm{keV})$$

- Event rate

$$R \propto N \frac{\rho_\chi}{m_\chi}\langle\sigma_{\chi-N}\rangle$$

N ➔ number of target nuclei

$\rho_\chi/m_\chi$ ➔ local WIMP number density

$\langle\sigma\rangle$ ➔ velocity-averaged scattering cross section

# Experimental Challenges

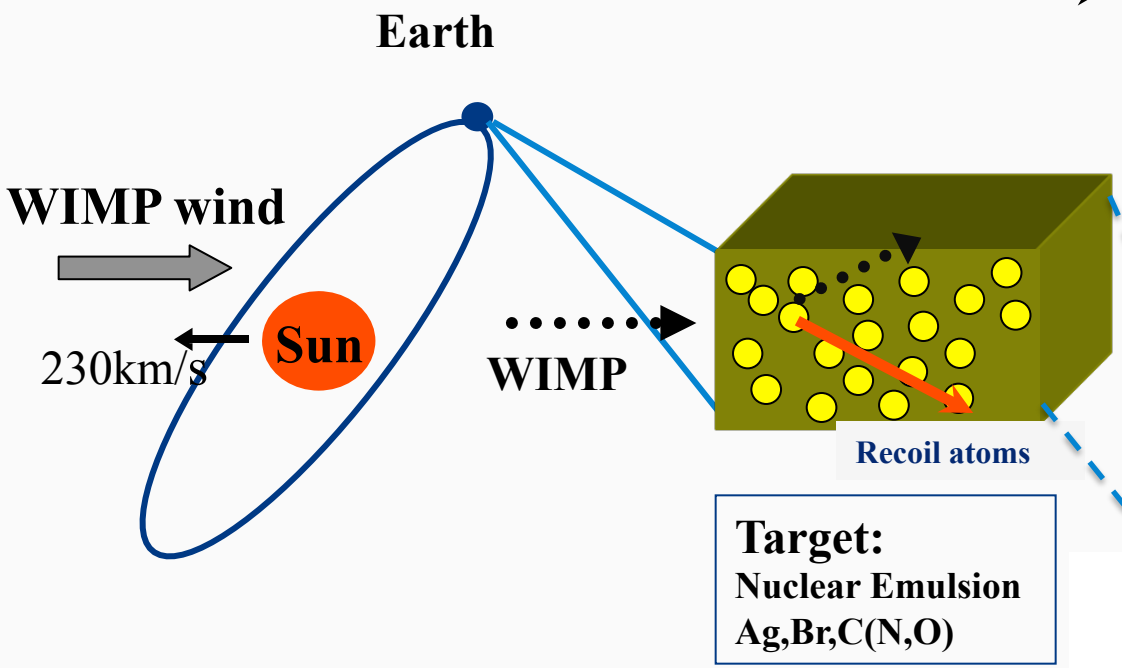
**WIMPs: Extremely small scattering rate, small energy of the recoiling nucleus, and subtle signatures…**

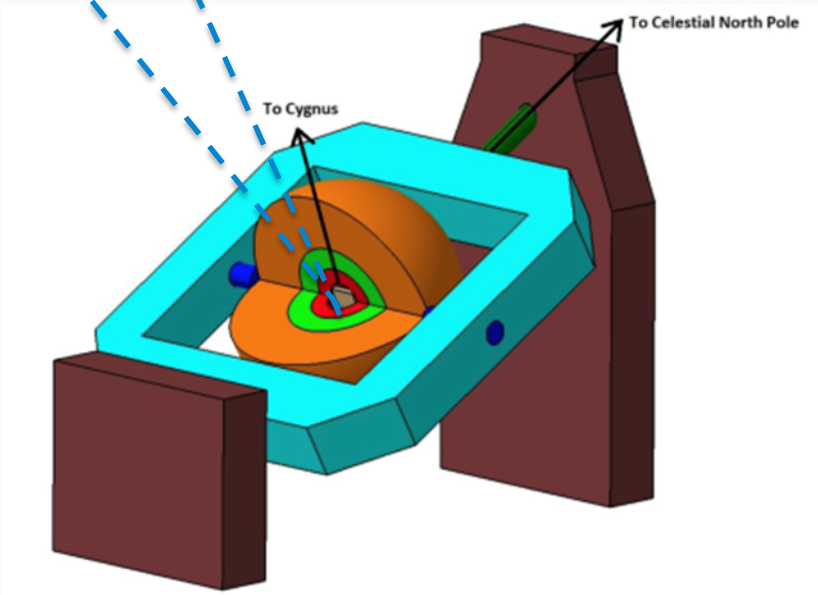
**Requirements:**

- **Low (keV) energy threshold**
- **Large target mass**
- **Suppression of backgrounds from radioactivity and cosmic rays ($\alpha$,$\beta$,$\gamma$, neutrons)**
  - **Deep sites**
  - **Passive/active shielding**
- **Discrimination of residual background**
  - **Use WIMPS signatures :**
    - **Nuclear recoils**
    - **Absence of multiple scattering**
    - **Annual modulation**
    - **Directionality**

# NEWSdm Design Concept

- Directional dark matter search with solid tracking detector (3～4 g/cm$^3$), spin independent search.



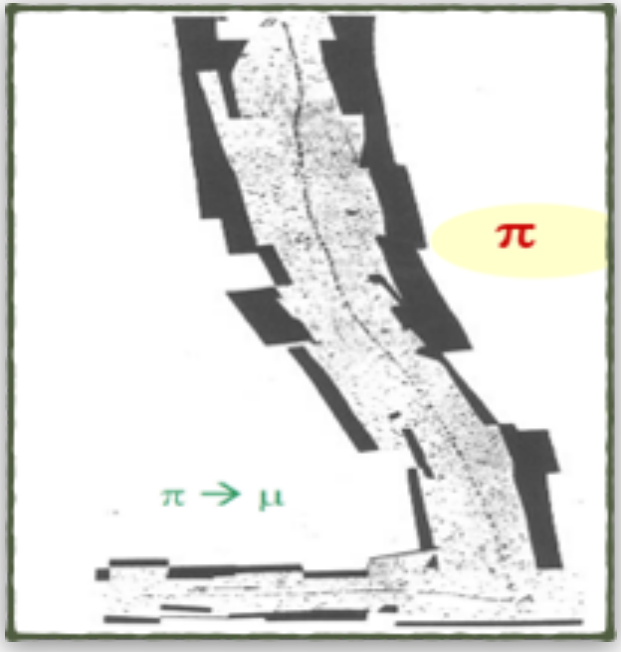




- Mount on equatorial telescope; keep target pointed to DM wind (Cygnus constellation)
- **Ultra pure components, underground, shielding; background control**

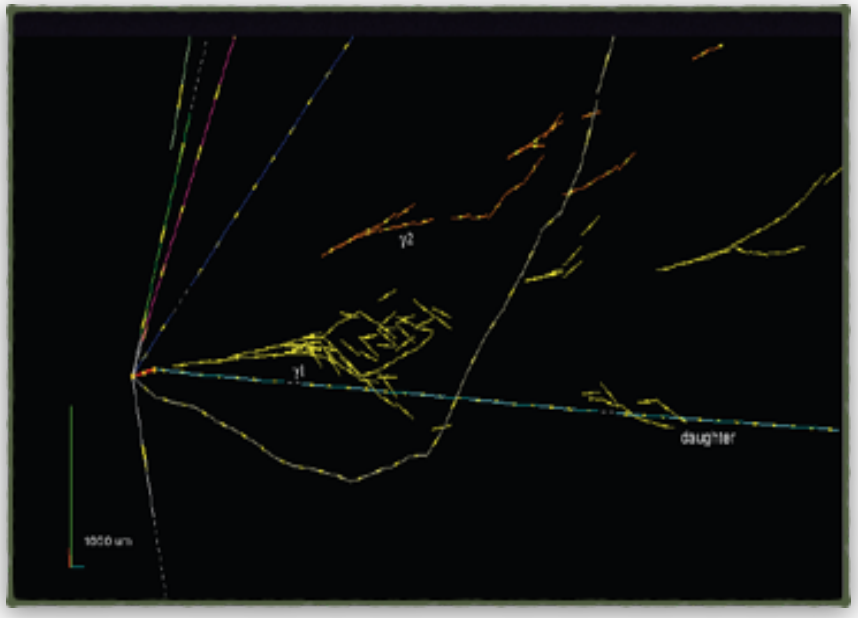
# Nuclear Emulsion

- 3D tracking detector with an excellent spatial resolution
- Flexible size and configuration
- Low detector cost ( 100kg ~ $50K )
- No time resolution

A long history,
The discovery of the Pion (1947)

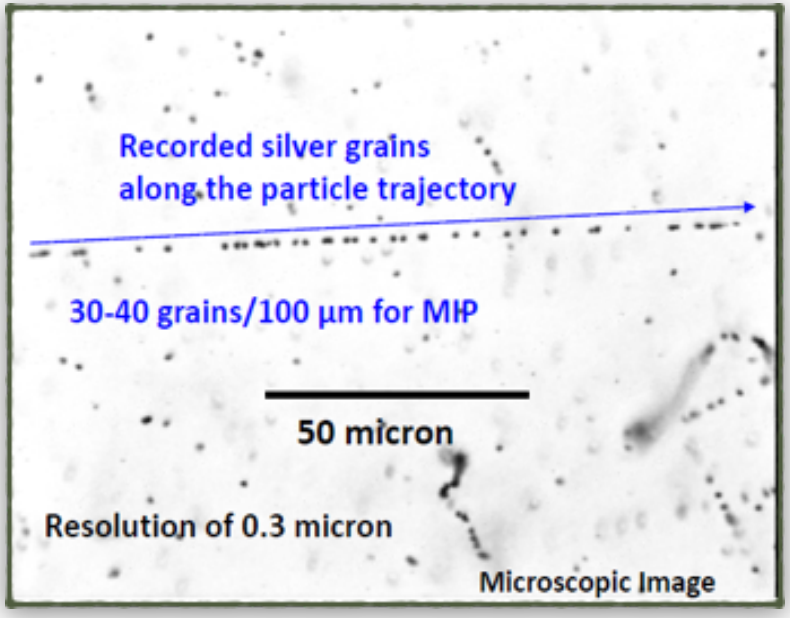


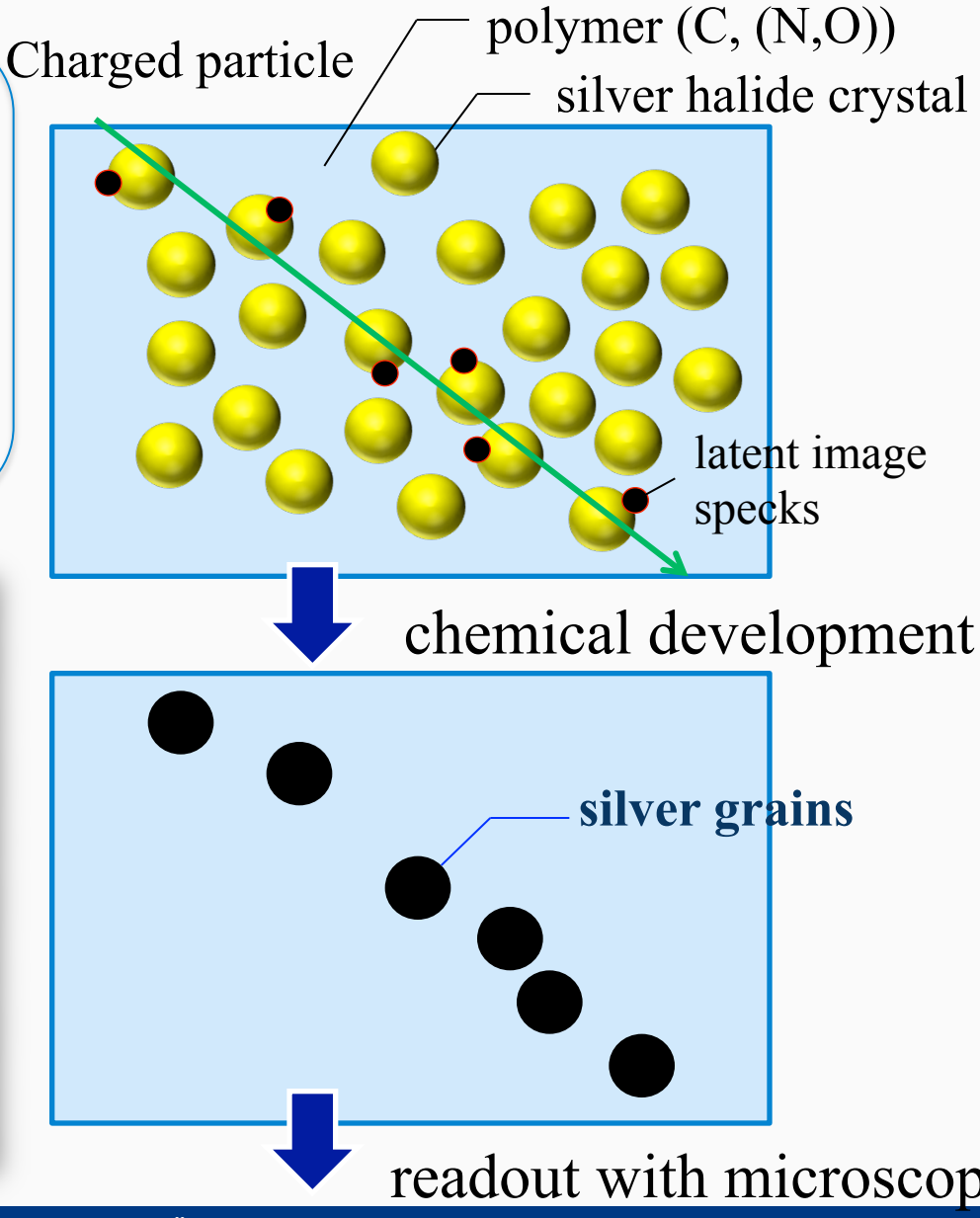

OPERA $\nu_\tau$ event (2015)



# Nuclear Emulsion based DM detector

- Nuclear emulsions: AgBr crystals in organic gelatine
- Passage of charged particle produce latent image
- Chemical treatment make Ag grains visible

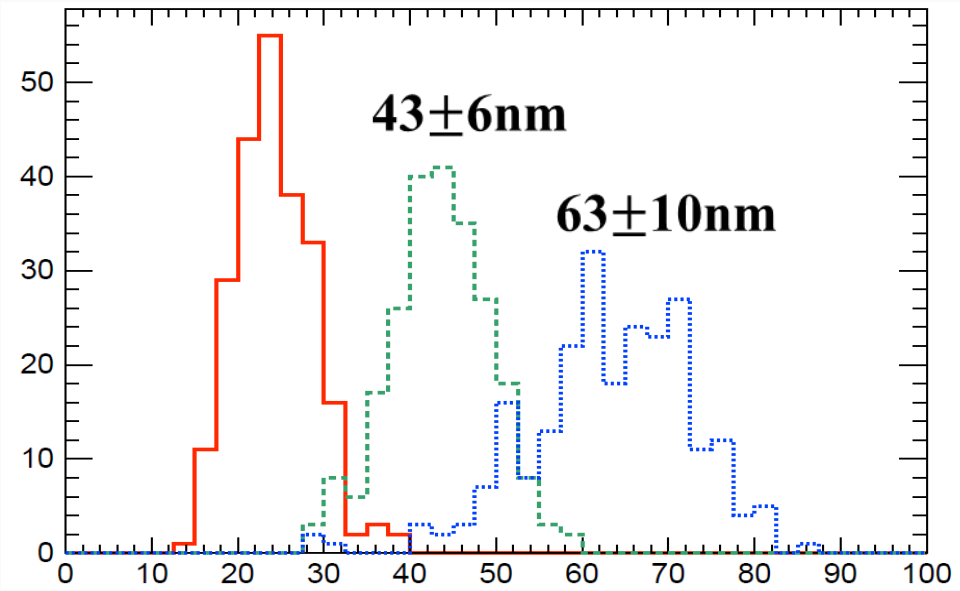


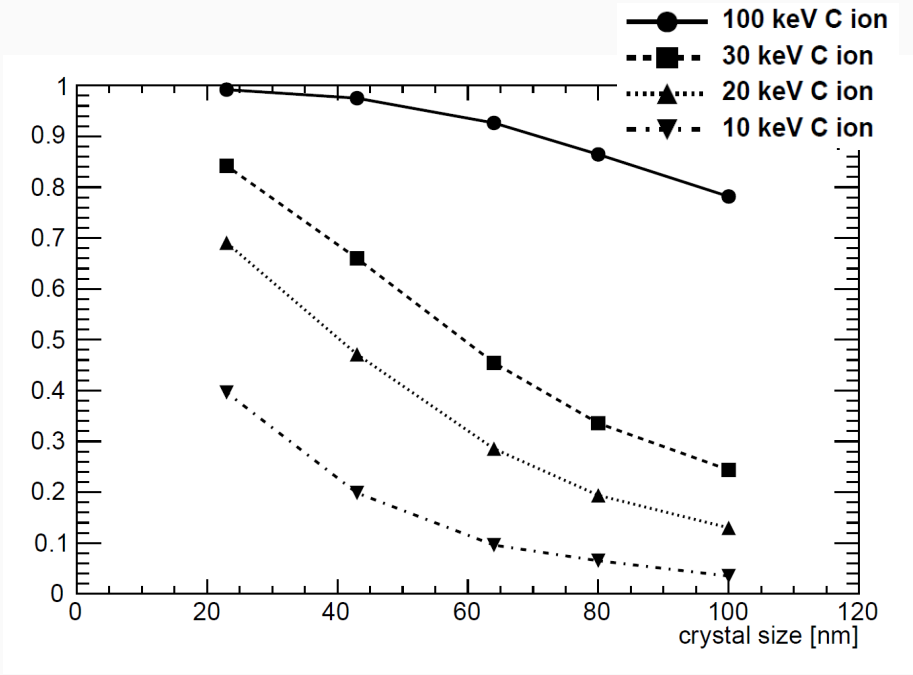
# Fine Grained Nuclear Emulsion

- Silver halide crystal size has been controllable
  - 20 – 60 nm (NIT type)
    -WIMP induced recoil length O(10-200 nm)
  - not sensitive to MIP

**24±4nm** crystal size




Probability of penetrating two grains

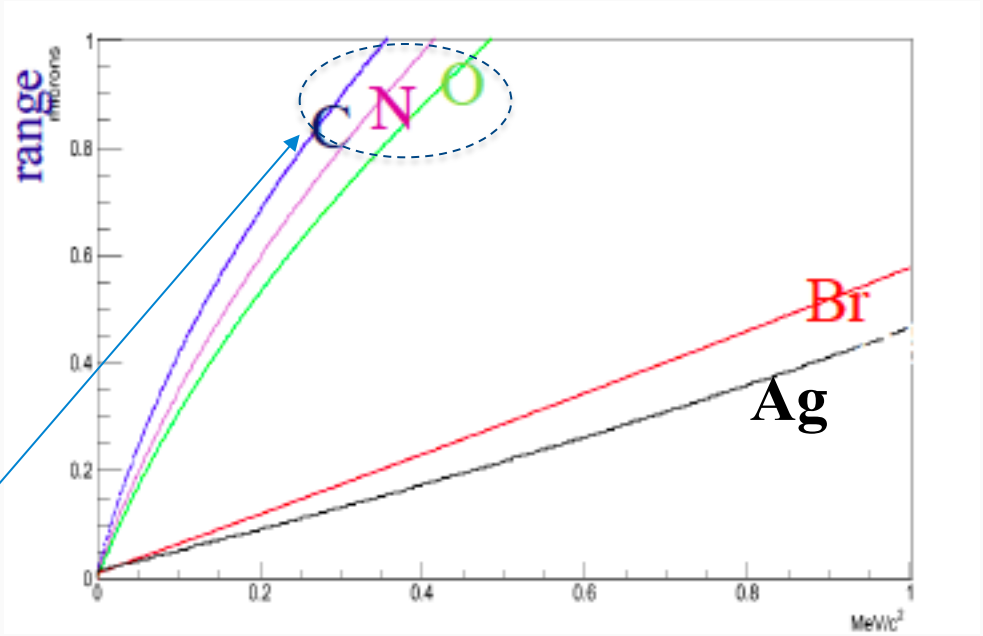


# Fine Grained Nuclear Emulsion

| Constituent | Mass Fraction |
|---|---|
| AgBr-I | 0.78 |
| Gelatin | 0.17 |
| PVA | 0.05 |

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

| Element | 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 | 0.003 | 0.003 |




- Light nuclei sensitive to low mass WIMP

Each nucleus gives a different contribution to the overall sensitivity

# Readout System

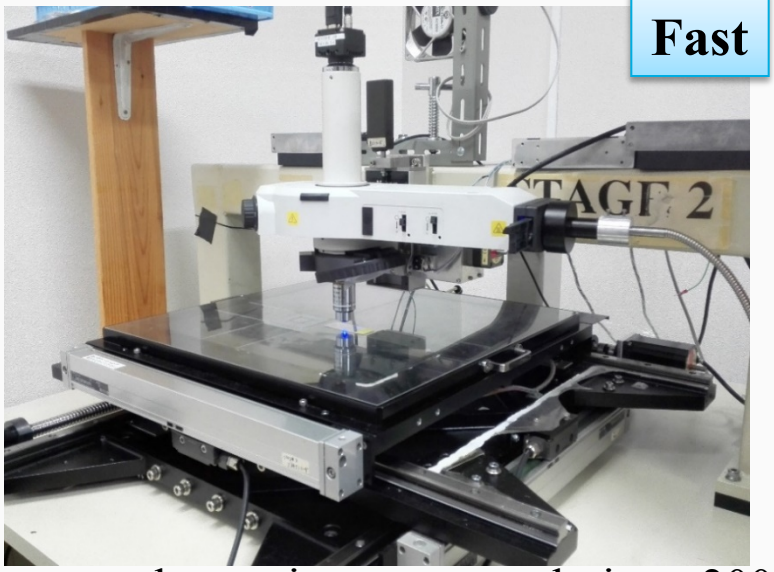
- The read-out is performed in two Phases:

**1. Fast pre-selection of the candidate signal tracks**

- optical microscope

**2. Signal Confirmation; event by event scanning with higher resolution optics**

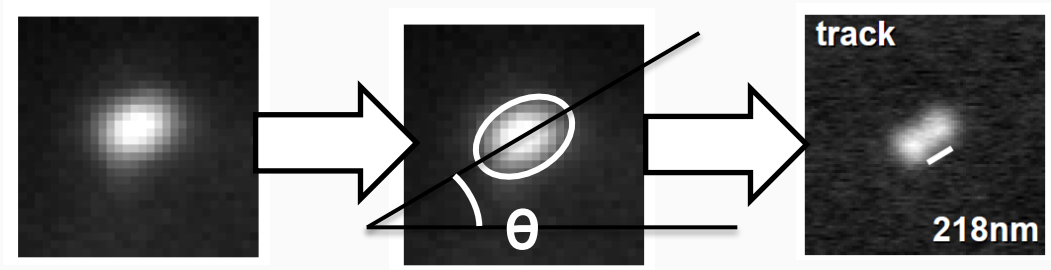
- X-ray microscope
- optical microscope with polarized light




Automated scanning stage resolution ~200 nm

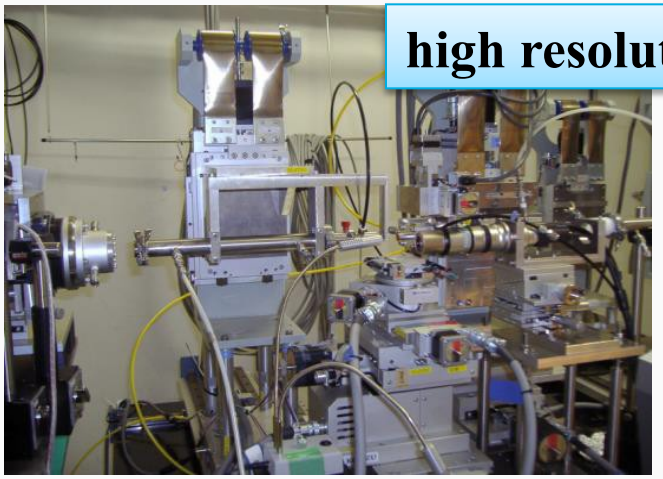
@ NIT-40

Fitting an ellipse




optical

X-ray

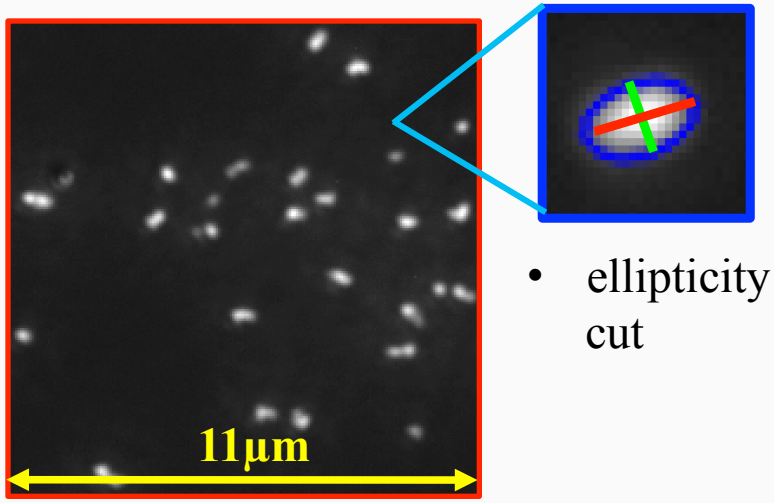



X-ray microscope resolution 30 nm

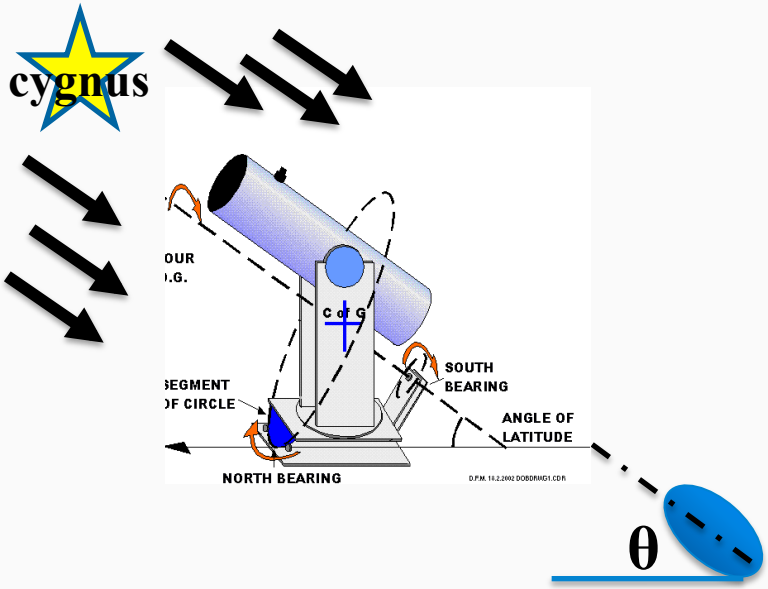
# Readout System: Optical Microscope

## 1st step : Candidate Identification

- Scanning with optical microscope and shape recognition analysis
- Selection of clusters with elliptical shape: major axis along track direction
- Background: spherical cluster
- Resolution 200 nm (one order of magnitude better than the OPERA scanning system).

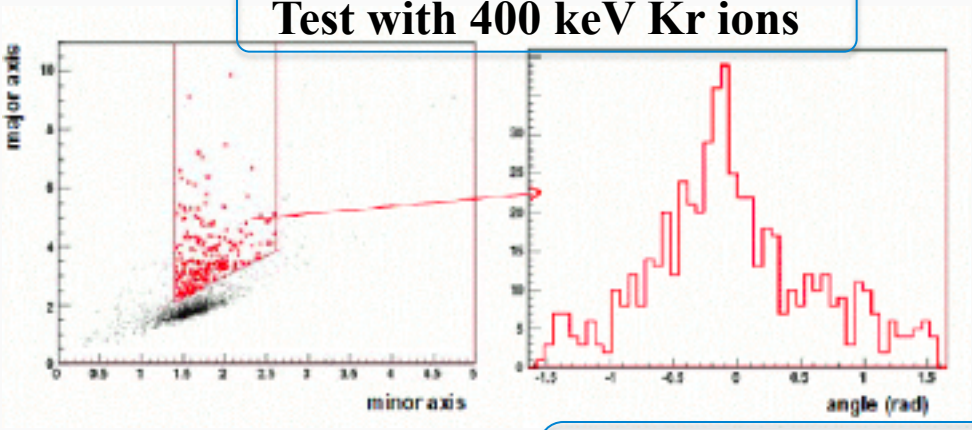



- ellipticity cut




Direction measurement

**Test with 400 keV Kr ions**



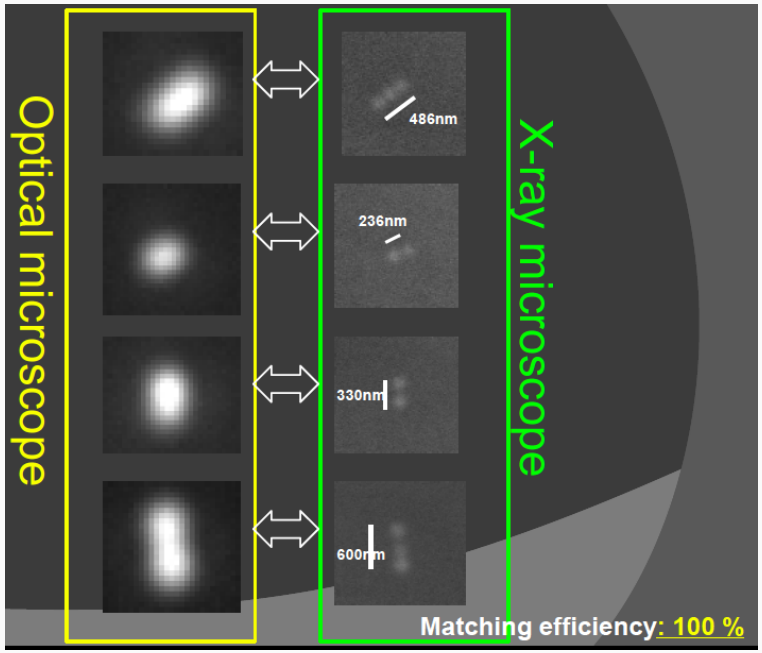

$\sigma^2 = \sigma^2_{int} + \sigma^2_{scatt}$

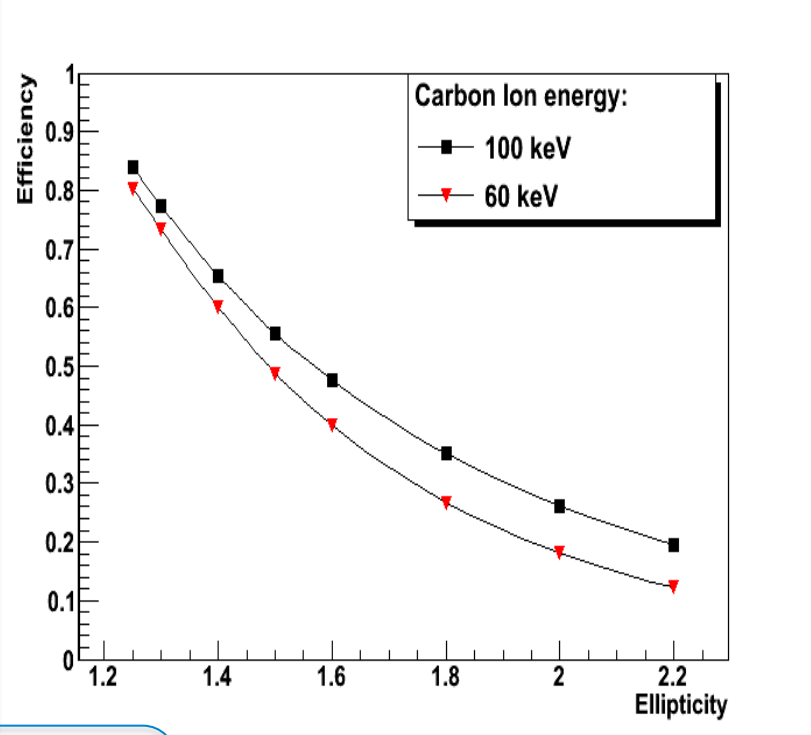
$\sigma = 360$ mrad

# Readout System: X-ray Microscope

**2nd step :Candidate Confirmation**

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

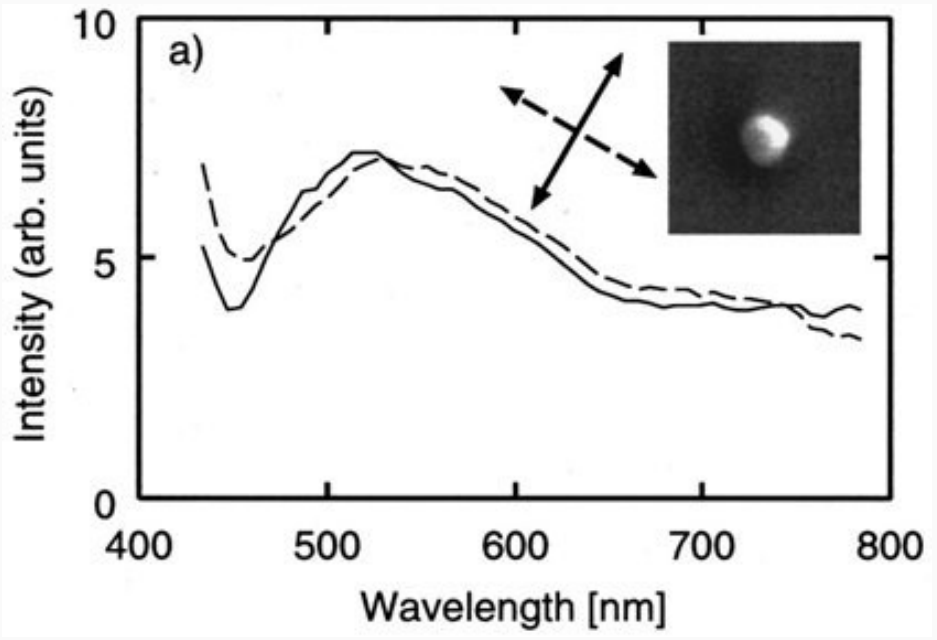


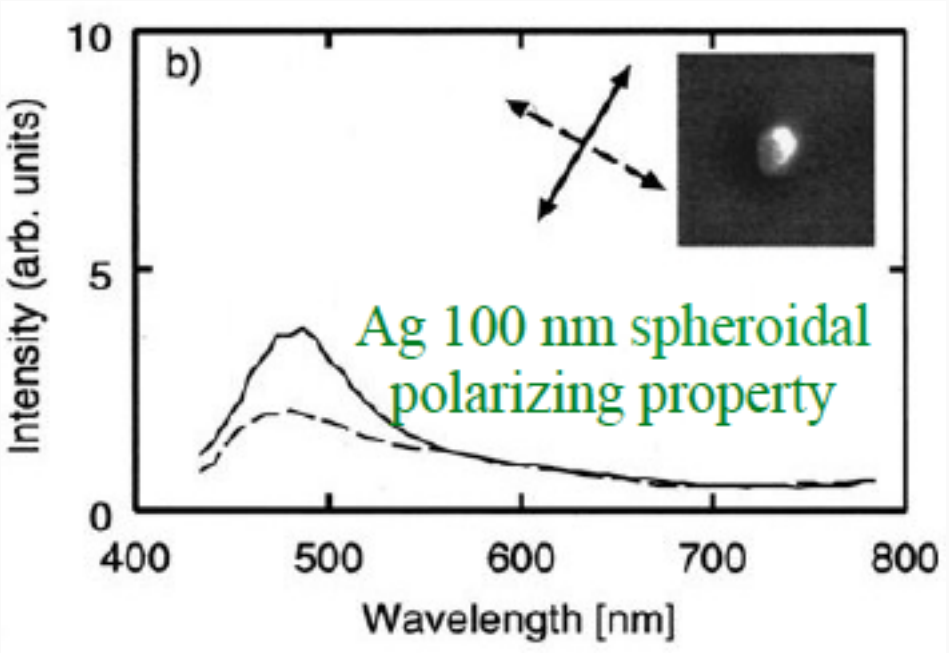




- Slow analysis speed;
  - The analysis of a few hundred $\mu m^2$ takes about 100 s.
- Need of external X-ray guns

# Readout System: Resonant Light Scattering

- Occurring when the light is scattering off a nanometric metallic (silver) grains are dispersed in a dielectric medium
- Scattering spectrum depends on the light polarization and on the grain shape (Applied Phys Letters 80 (2002) 1826)



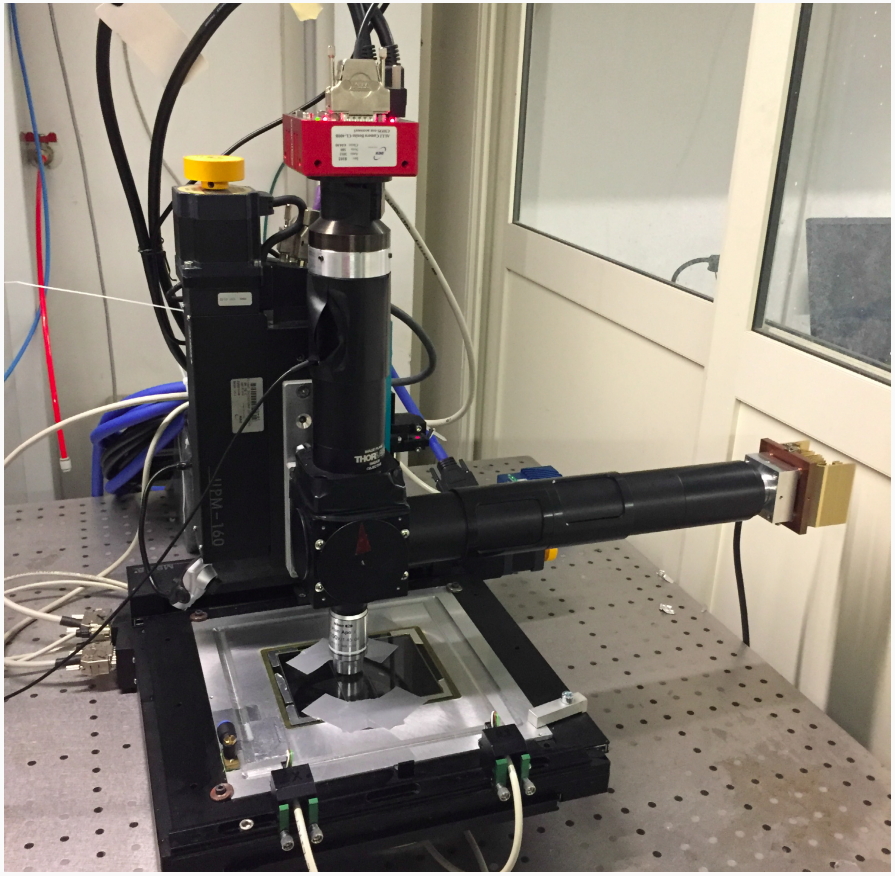



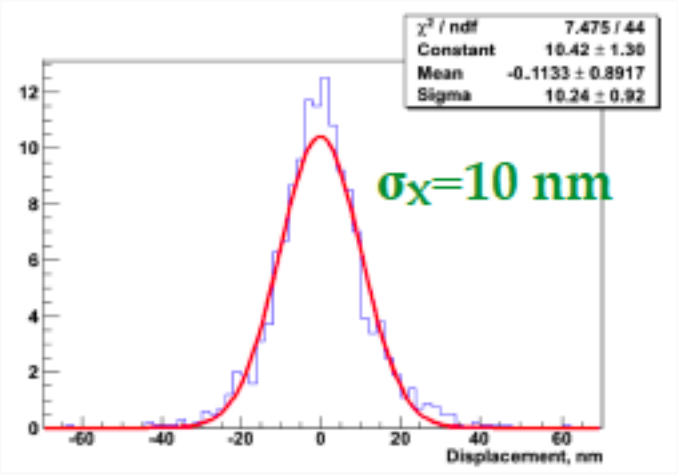

- The polarization dependence of the resonance frequencies strongly reflects the shape anisotropy.

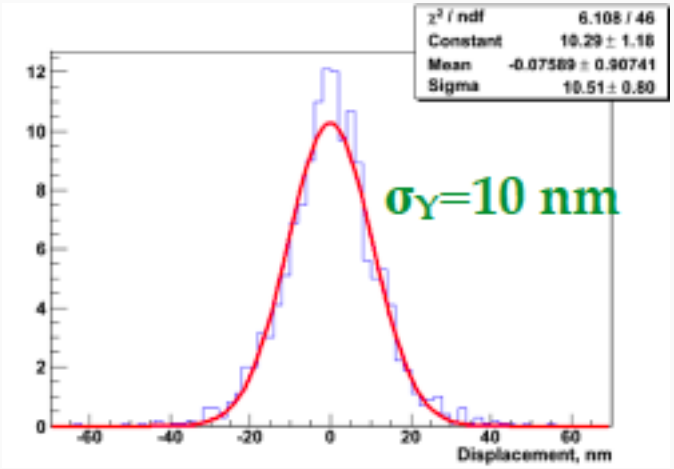
# Readout System: Resonant Light Scattering

- Optical microscope assembled

- An accuracy of 10 nm achieved on **both** coordinates !



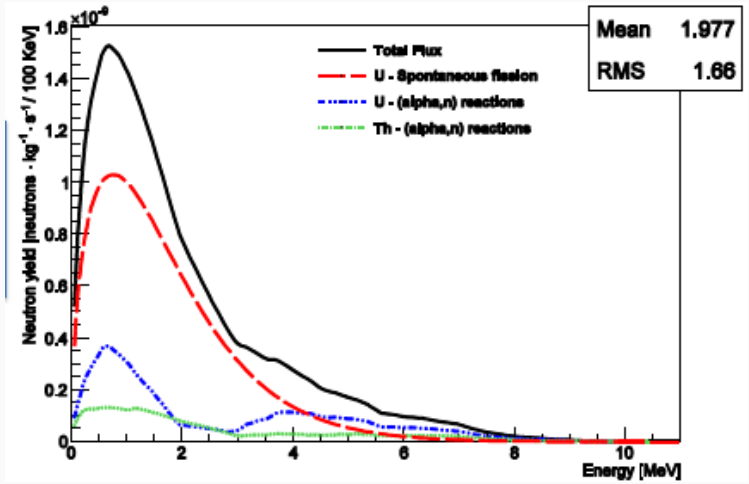


# Background Study

- Two main categories have to be taken into account:
  - the environmental or external background
    - can be significantly reduced by placing the detector underground, and designing an appropriate shield against the natural radioactivity.
  - the intrinsic one
    - is an irreducible source of radiation: it is therefore crucial to control the radioactivity of the materials used for the construction of both the detector and the structure of the apparatus.

| 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 |



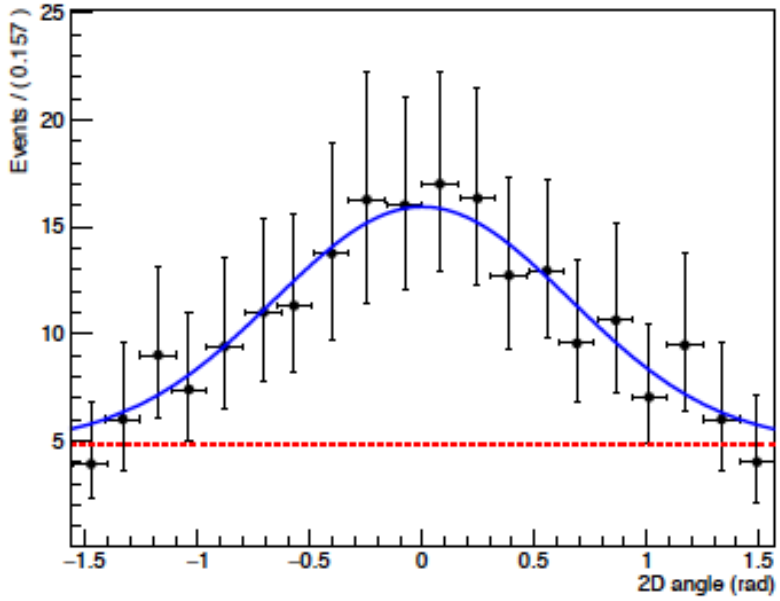

Background yield from the intrinsic radioactive contamination of NIT: ~1.2 n/kg.year

Neutron background from intrinsic radioactivity negligible up to ≈10 kg year

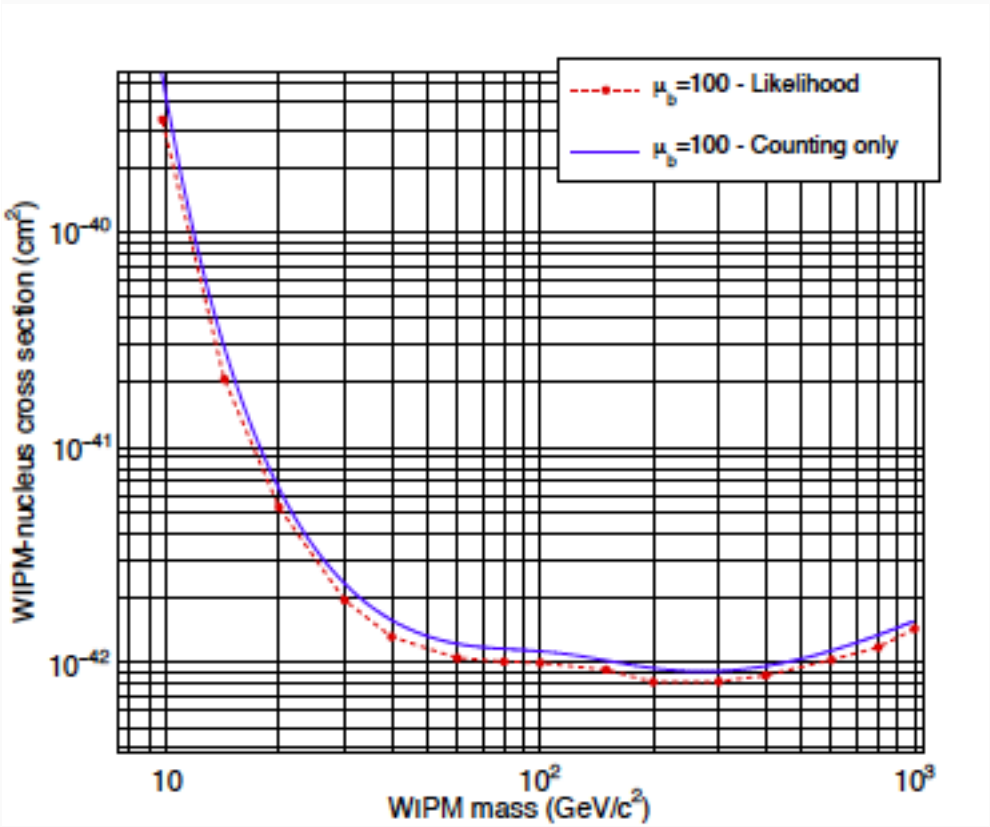
# Sensitivity

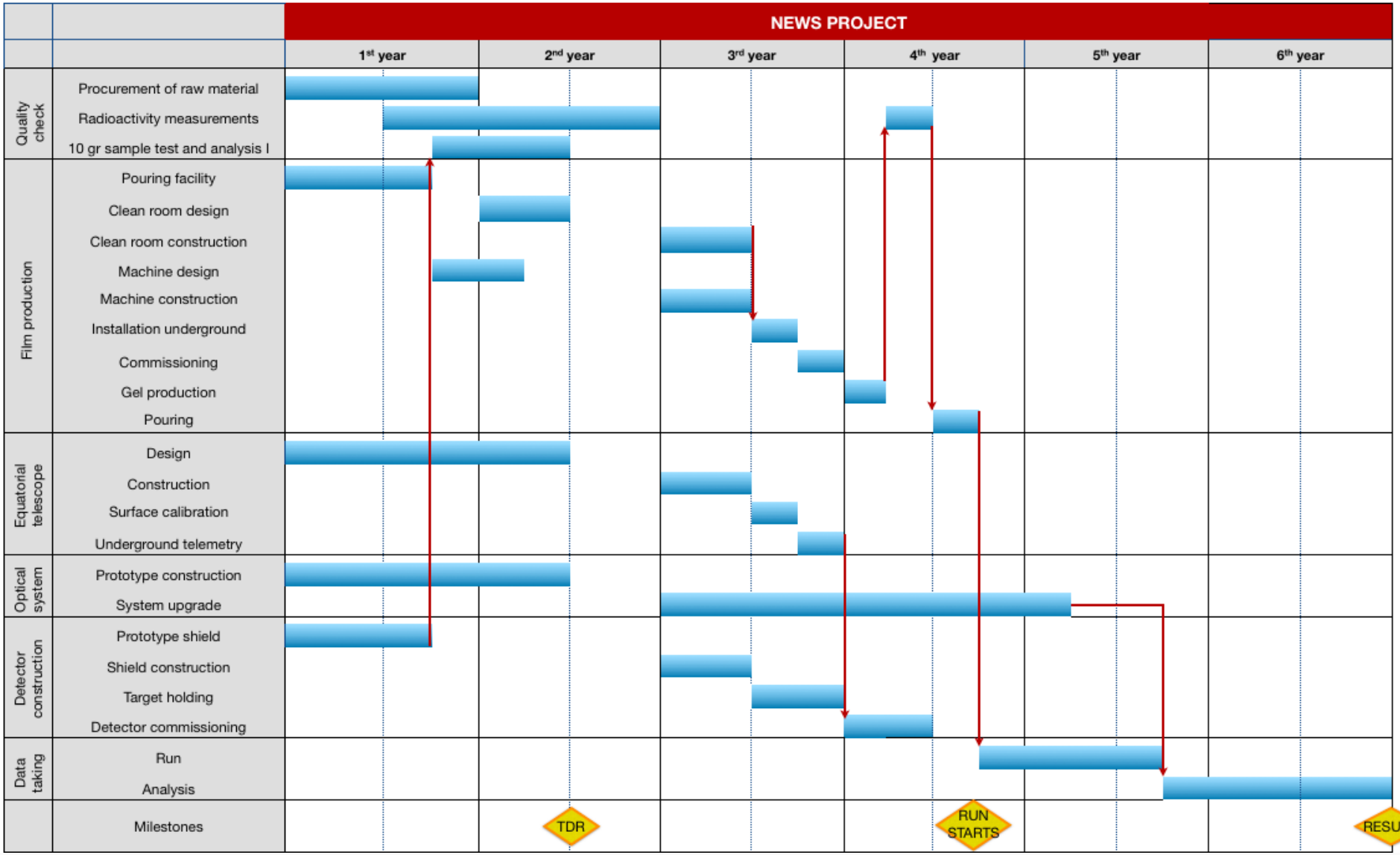
Evaluation of upper limit and sensitivity based on the profile likelihood ratio test

Mass= 10 kg
- Exposure time = 10 years
- Nbackground = 100
- Threshold = 100 nm




2D angular distribution of 100 WIMP-induced recoils and 100 background events.






**2016-2017 R&D TDR**

**Kg scale experiment 2018-**

# Current Status

- Measure the detectable background from environmental and intrinsic sources and validate estimates from simulations.

# NEWSdm Collaboration



LNGS-LOI 48/15

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

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**~70 physicists**

**https://arxiv.org/abs/1604.04199**

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- INFN e Univ. Roma
- GSSI Institute

## Japan
- Nagoya University
- Chiba University

## Russia
- LPIRAS Moscow
- JINR Dubna
- SINP MSU Moscow
- INR Moscow
- Yandex School of Data Analysis

## S. Korea
- Gyeongsang

## Turkey
- METU

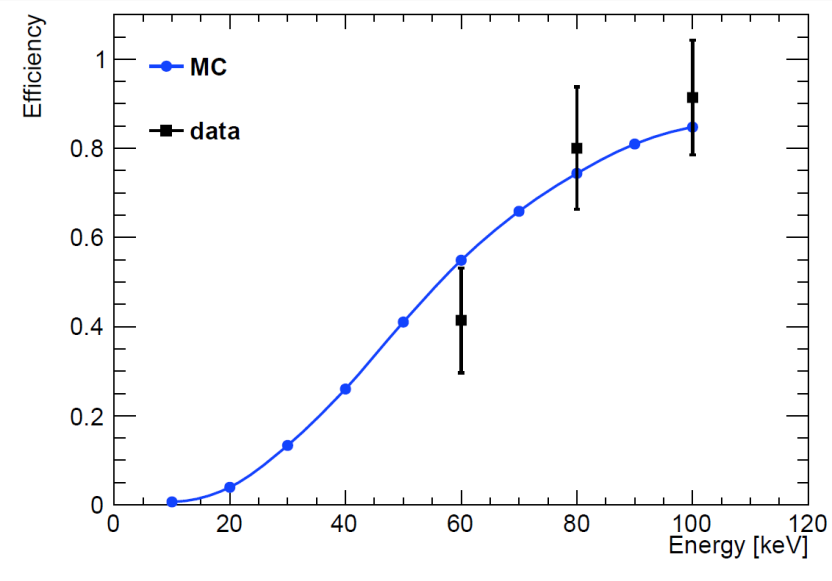
# Conclusion

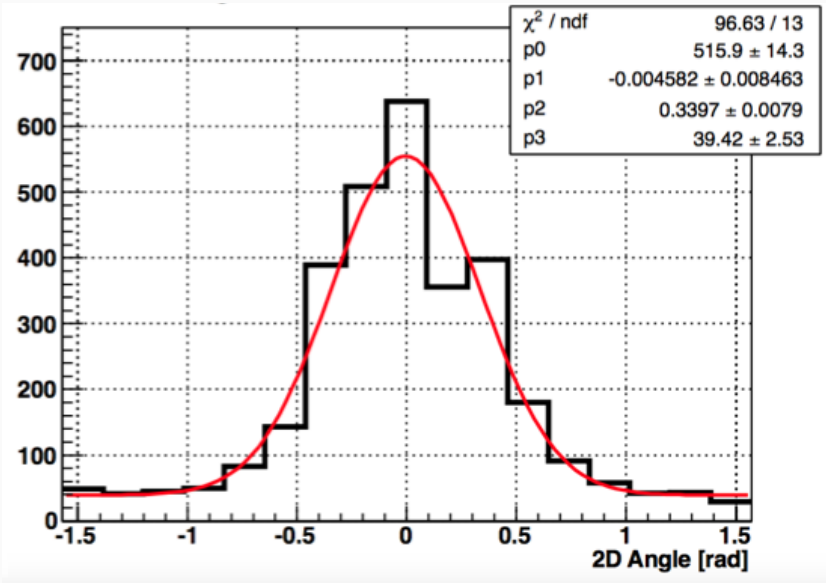
- NEWSdm experiment: a novel approach for directional dark matter searches.
- Concept a solid detector would allow to explore spin-independent 10 – 1000 GeV/$c^2$ WIMP mass region.
- NIT emulsion 20 – 60 nm crystal size emulsion is available.
- **R&D phase (2016-2017) funded in view of the pilot experiment**
- **Prepare a kg scale experiment as a demonstrator of the technology and the first spin-independent search of this kind.**
- TDR in preparation

# Back up

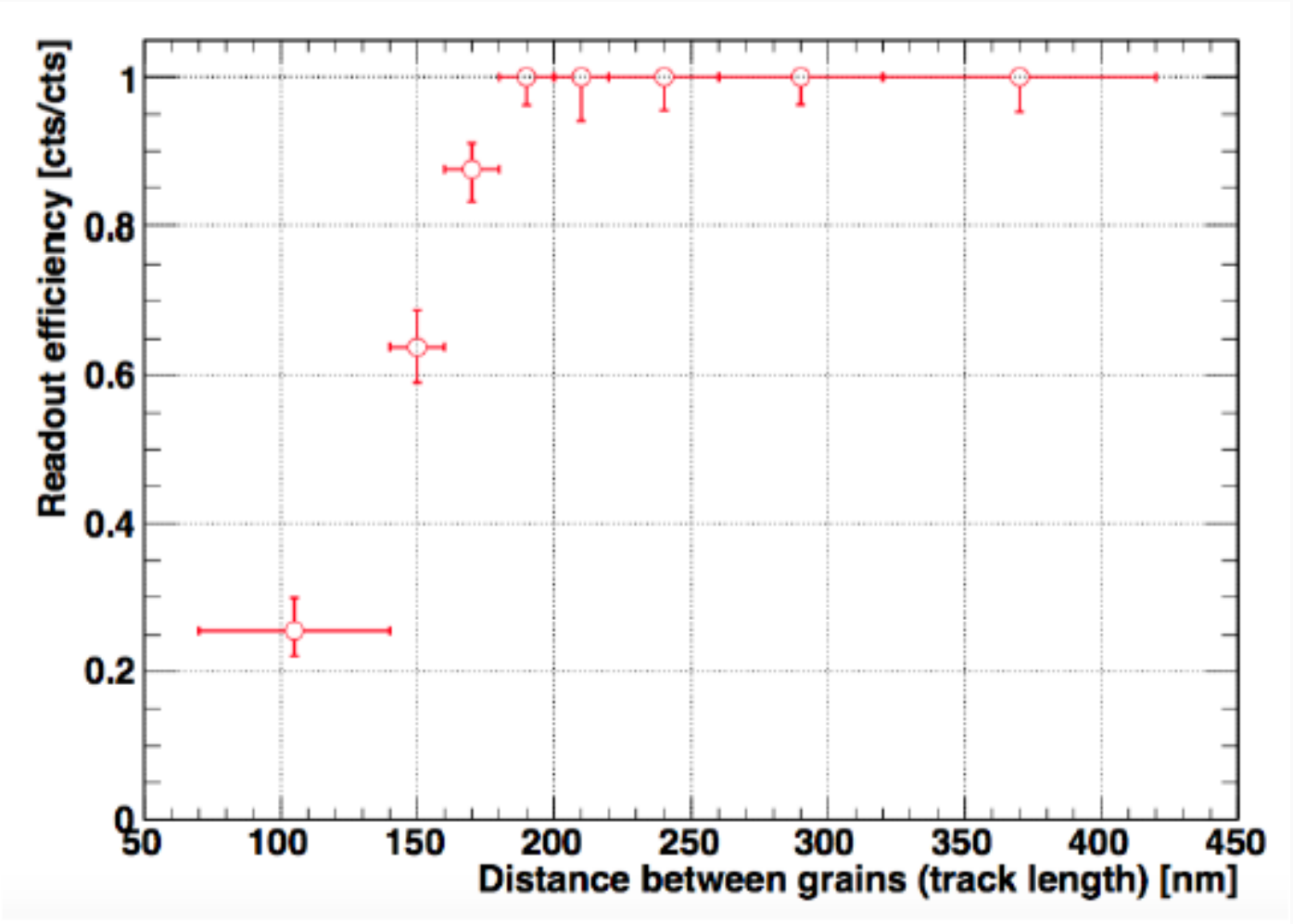
# Efficiency & Angular Resolution

- Low energy **60 – 100 keV carbon** exposure test using NIT-40
- Ellipticity cut > 1.25
- 80% tracking efficiency @80 keV
- 340 mrad (**20 degree**) angular resolution@ 80 keV



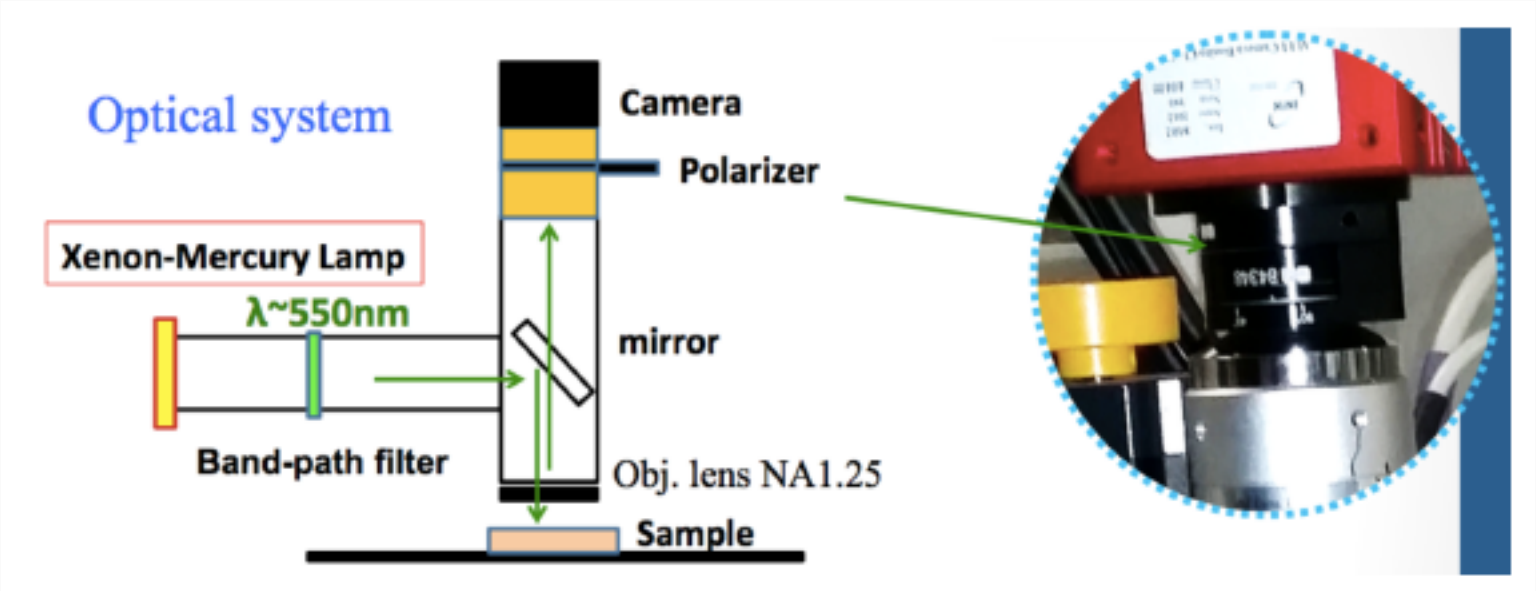



# Efficiency




Efficiency of the elliptical fit analysis versus the track length when an ellipticity of 1.25 is used as a threshold.

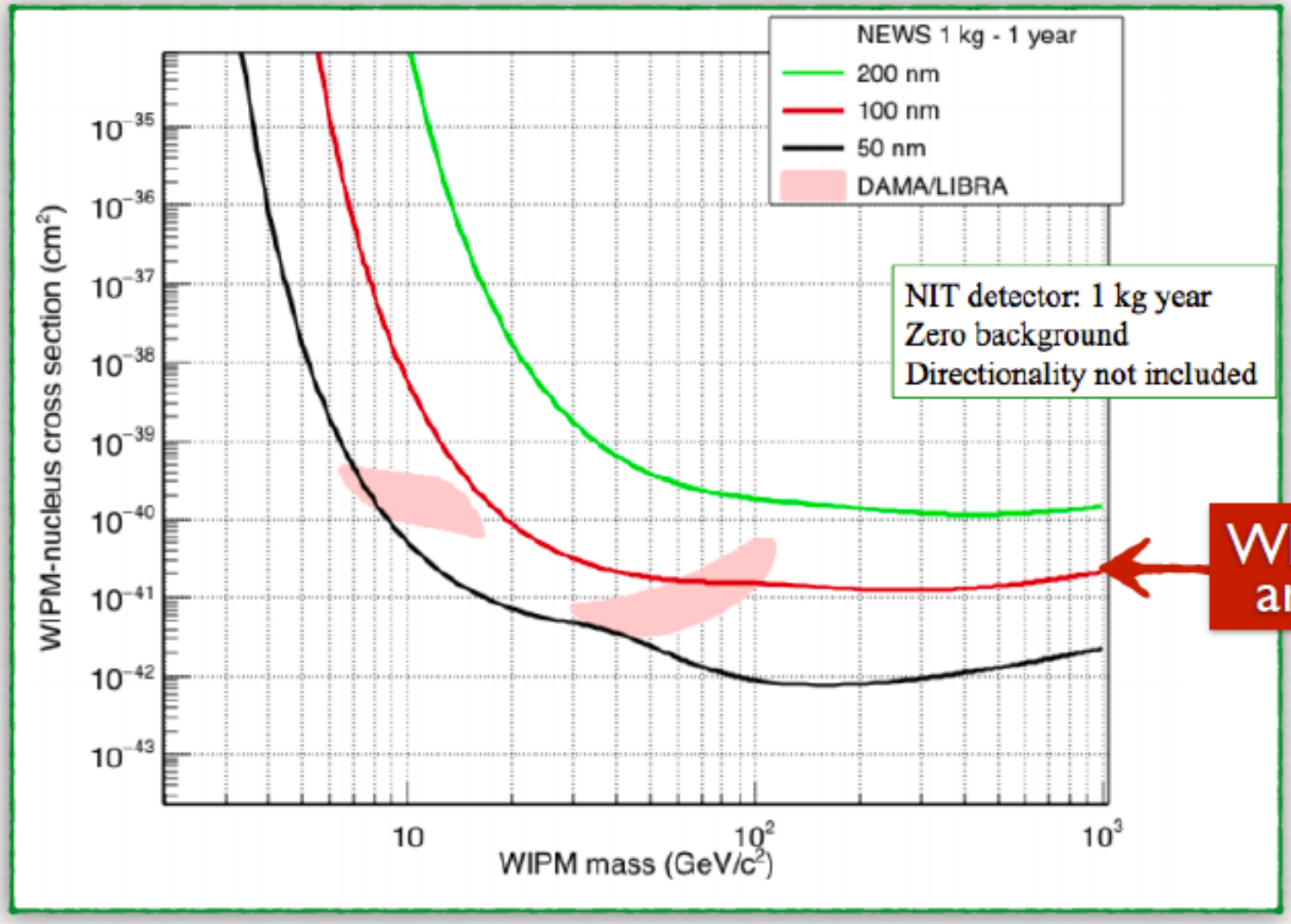
# Resonant Light Scattering




Optical microscopes have been equipped with a polarization filter. The polarization direction can be changed by rotating the polariser. The rotation is at the moment done by hand while its automation is being designed.

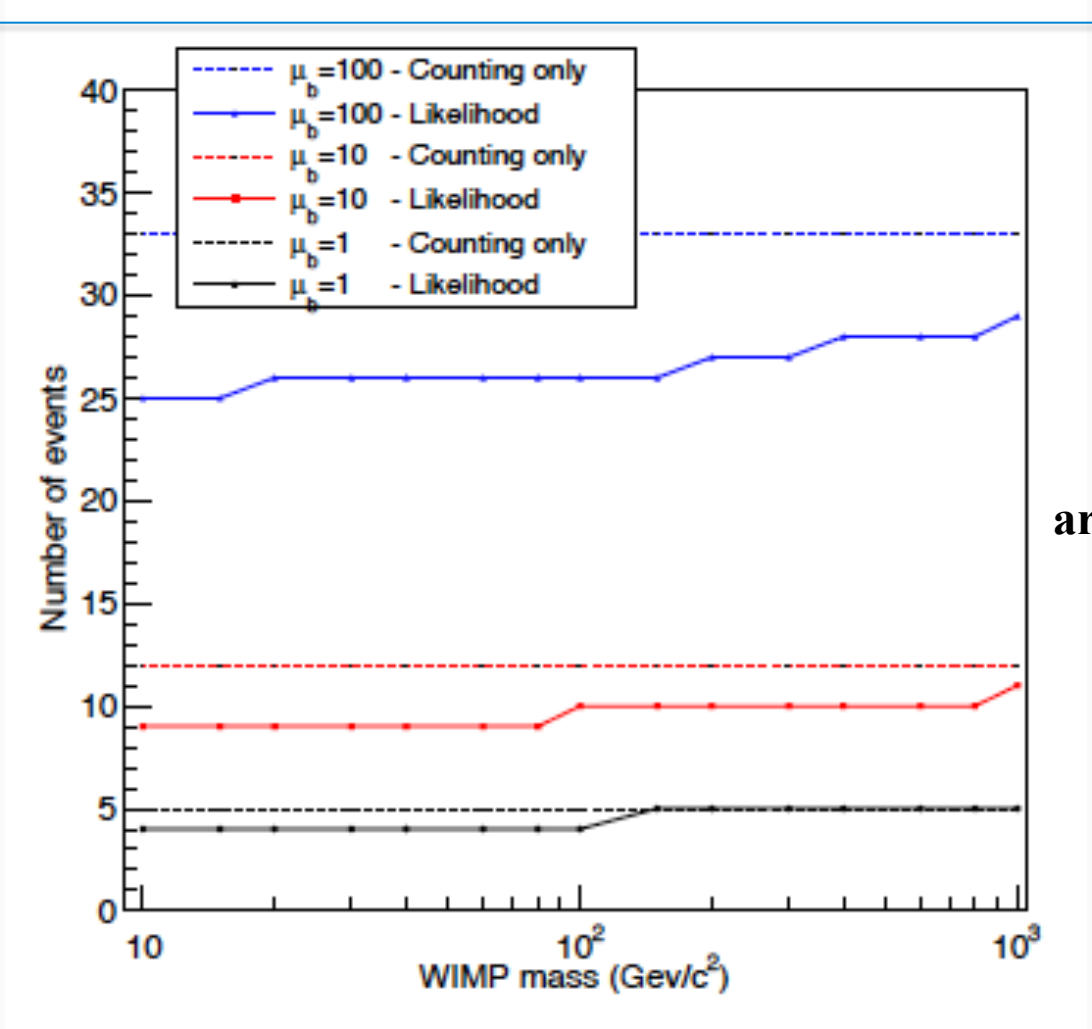
# Physics Goals

- Pilot experiment: 1 kg year



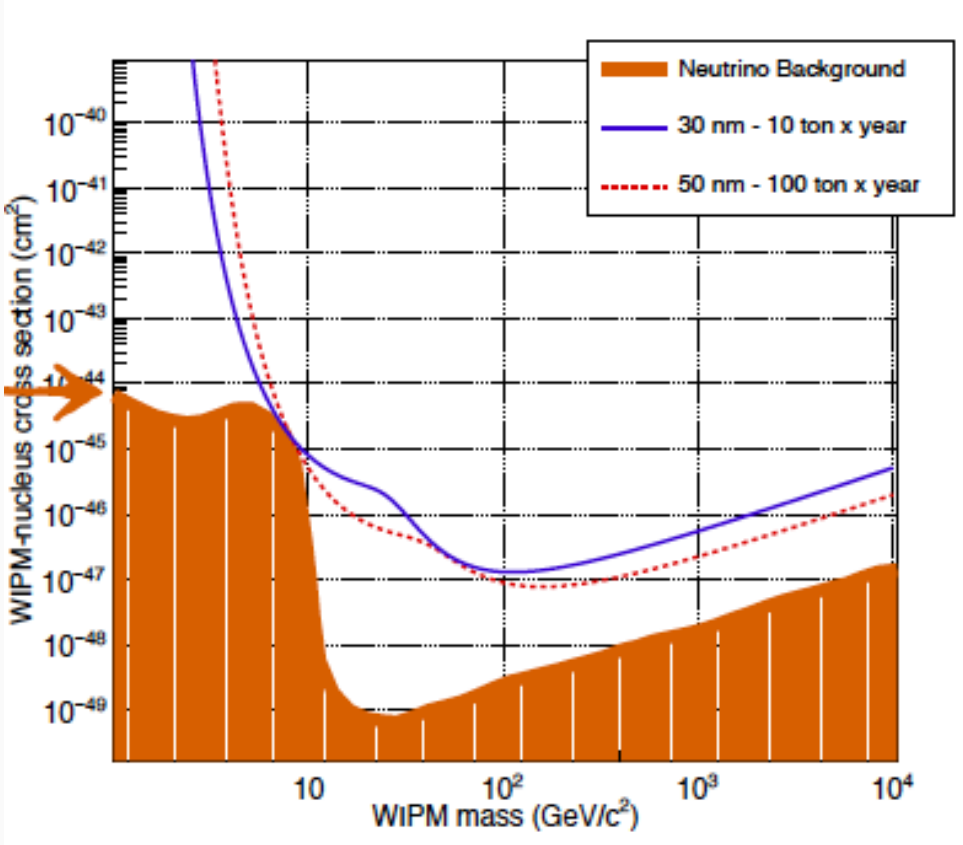
# Sensitivity

Minimum number of signal events required to get a 3σ evidence as a function of the WIMP mass.




**arXiv:1705.00613**

# Neutrino Floor




The neutrino bound is reached with:

➡10 ton x year exposure if 30 nm threshold

➡100 ton x year exposure if 50 nm threshold

# Target Design