NUCLEAR EMULSIONS FOR WIMP SEARCH
directional measurement

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on behalf of the NEWSdm Collaboration

29th Rencontres de Blois
May 28 - June 2, 2017

LETTER OF INTENT

- Submitted to Gran Sasso Scientific Committee at the end of 2015

LNGS-LOI 48/15

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

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https://arxiv.org/pdf/1604.04199.pdf

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
LPI RAS Moscow, JINR Dubna
SINP MSU Moscow, INR Moscow
Yandex School of Data Analysis

SOUTH KOREA
Gyeongsang

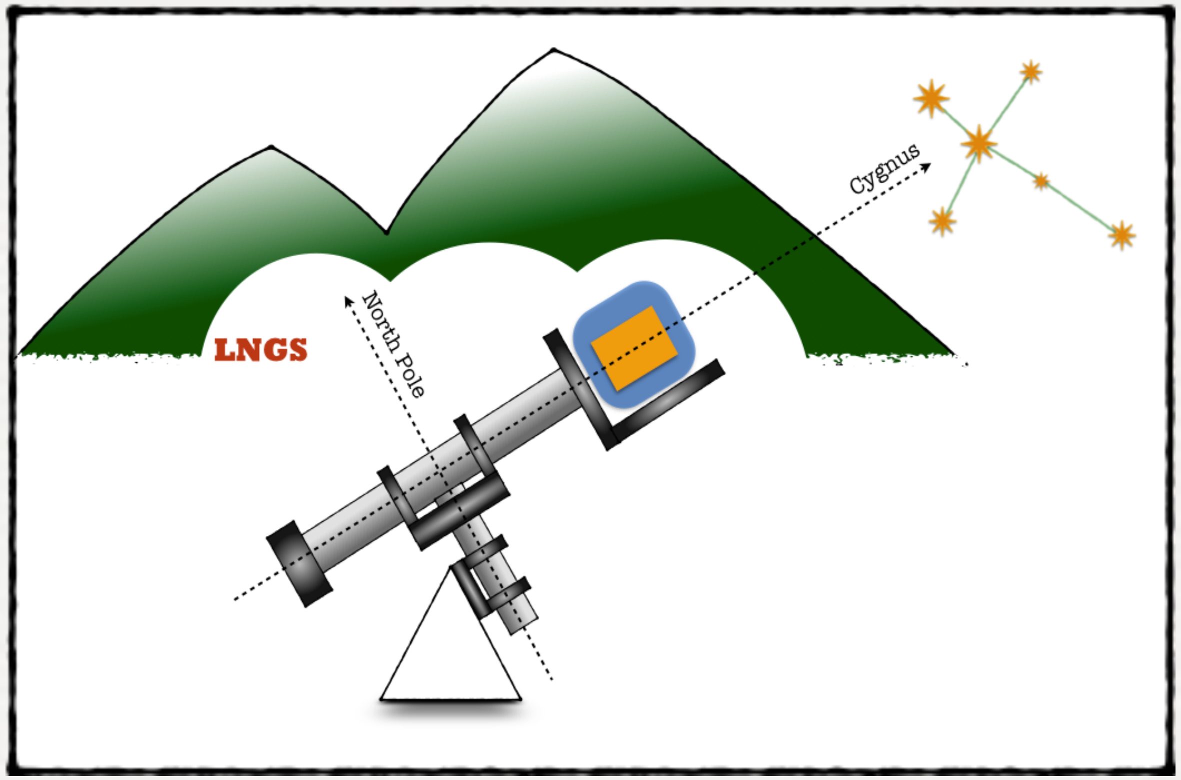
TURKEY
METU Ankara

news-dm.lngs.infn.it

OUTLINE

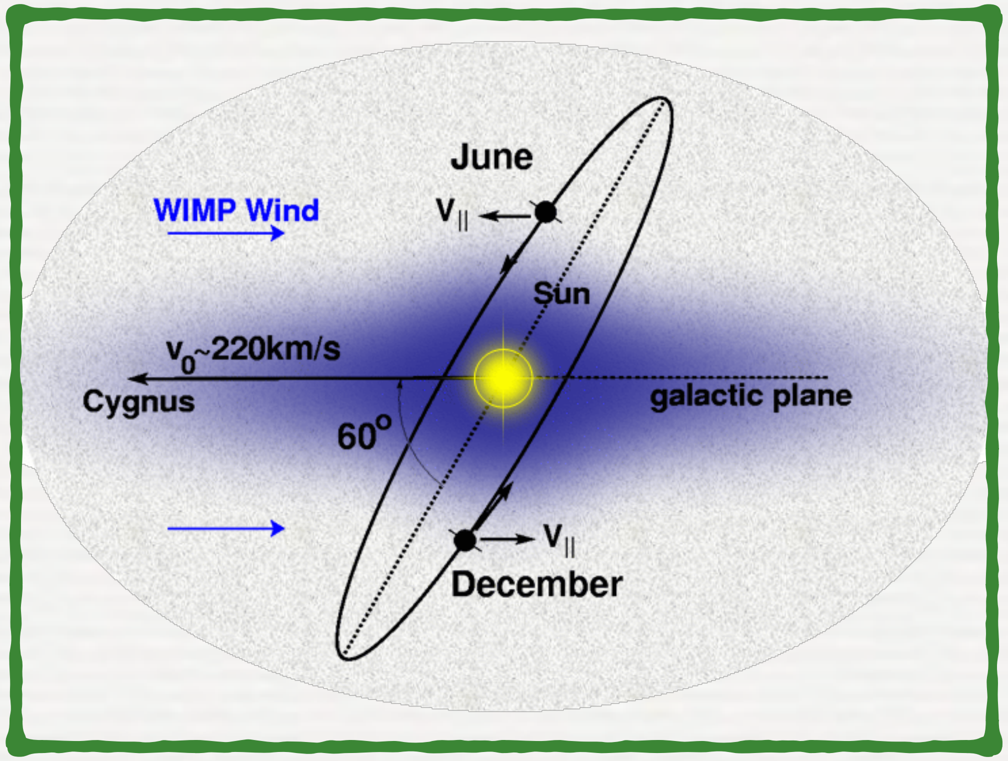
- The NEWSdm idea:

  a novel approach to ***directional*** detection of Dark Matter
- High Resolution Nuclear Emulsions: NIT
- Detection principle
- Background studies
- Sensitivity
- Current status of the experiment
- Conclusions and perpectives



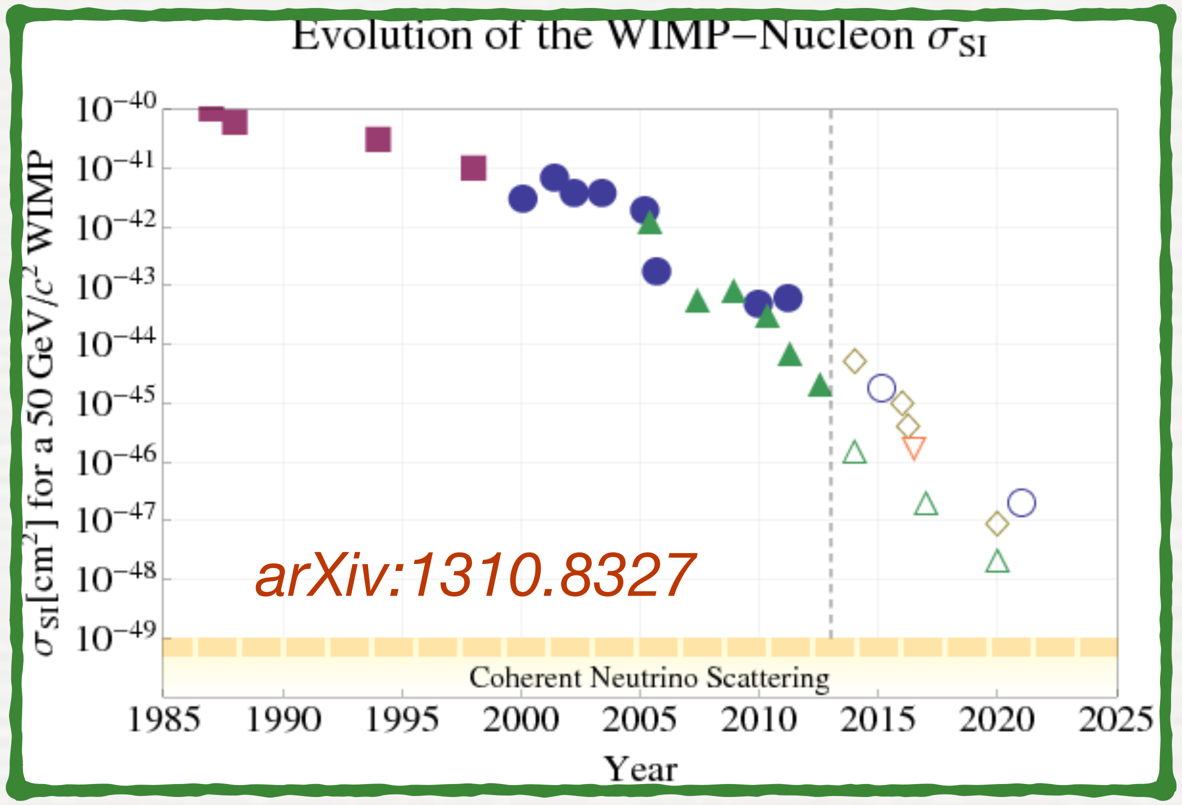
POWER OF DIRECTIONALITY

- Impinging direction of DM particle is (preferentially) opposite to the velocity of the Sun in the Galaxy, i. e. from Cygnus Constellation



- Unambiguous proof of the galactic origin of Dark Matter

- Unique possibility to overcome the "neutrino floor", where coherent neutrino scattering creates an irreducible background



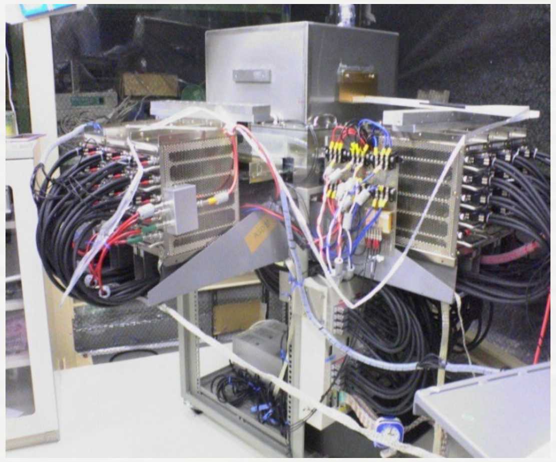
DIRECTIONAL DARK MATTER SEARCHES

Current approach:

low pressure gaseous detector

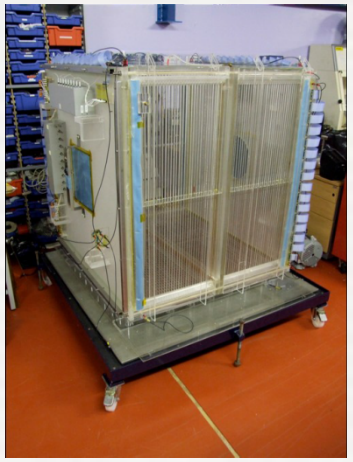
- Targets: CF_4, CF_4+CS_2, $CF_4 + CHF_3$
- Recoil track length O(mm)
- Small achievable detector mass due to the low gas density

$\Rightarrow$Sensitivity limited to spin-dependent interaction

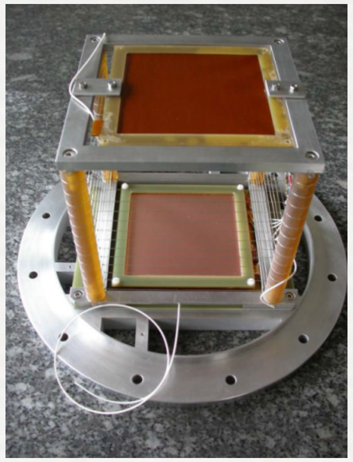


NEWAGE@ Japan

DM-TPC@ USA



DRIFT @ UK



MIMAC@ France

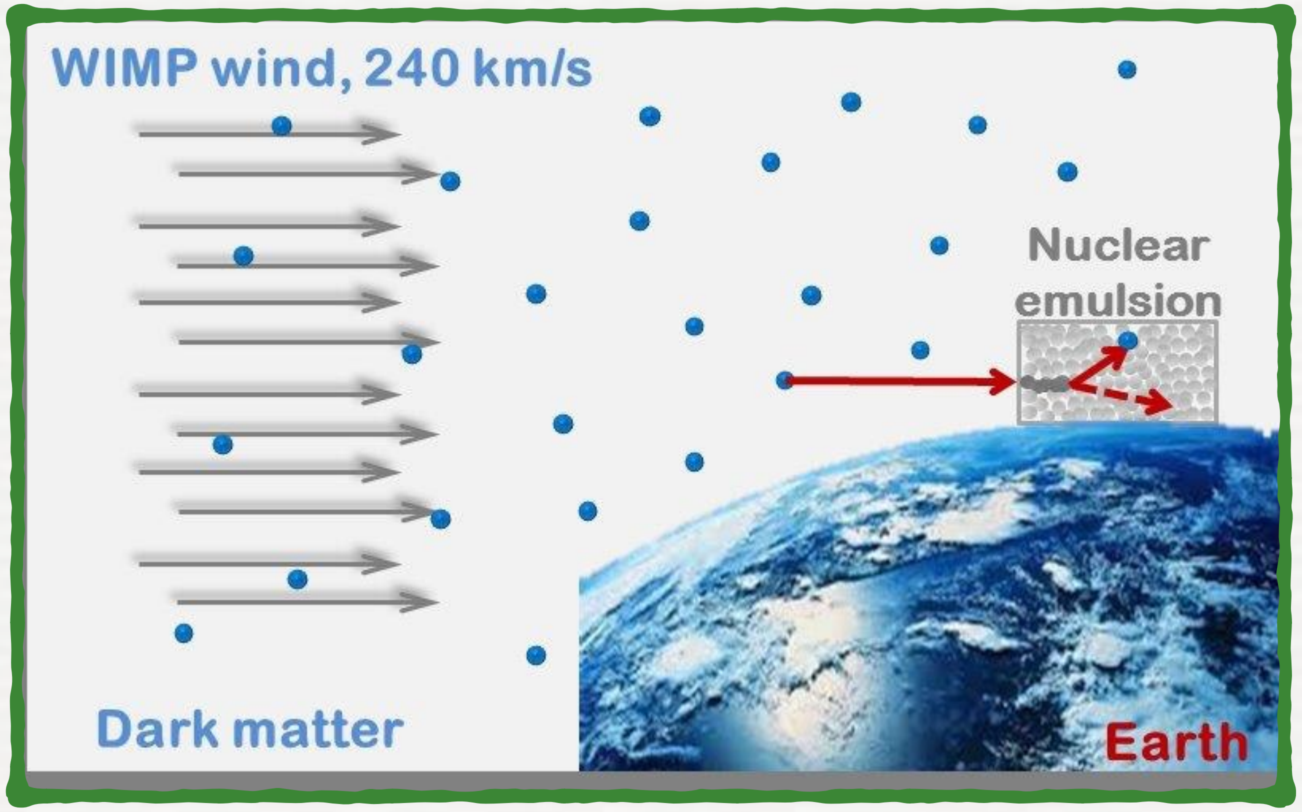
DIRECTIONAL APPROACH

Use solid target:

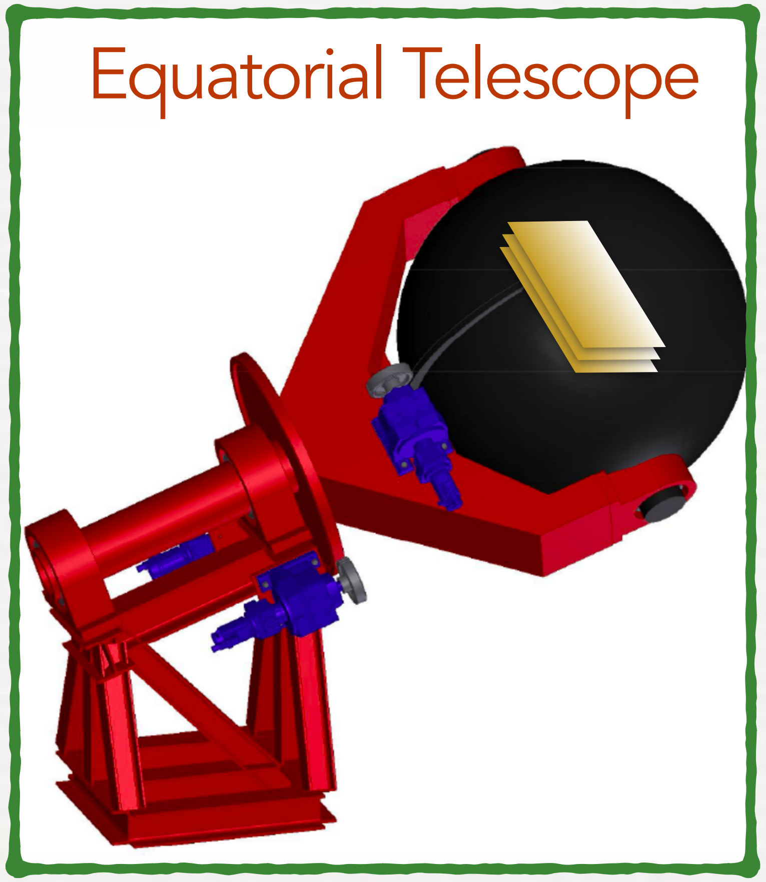
- Large detector mass
- Smaller recoil track length O(100 nm)

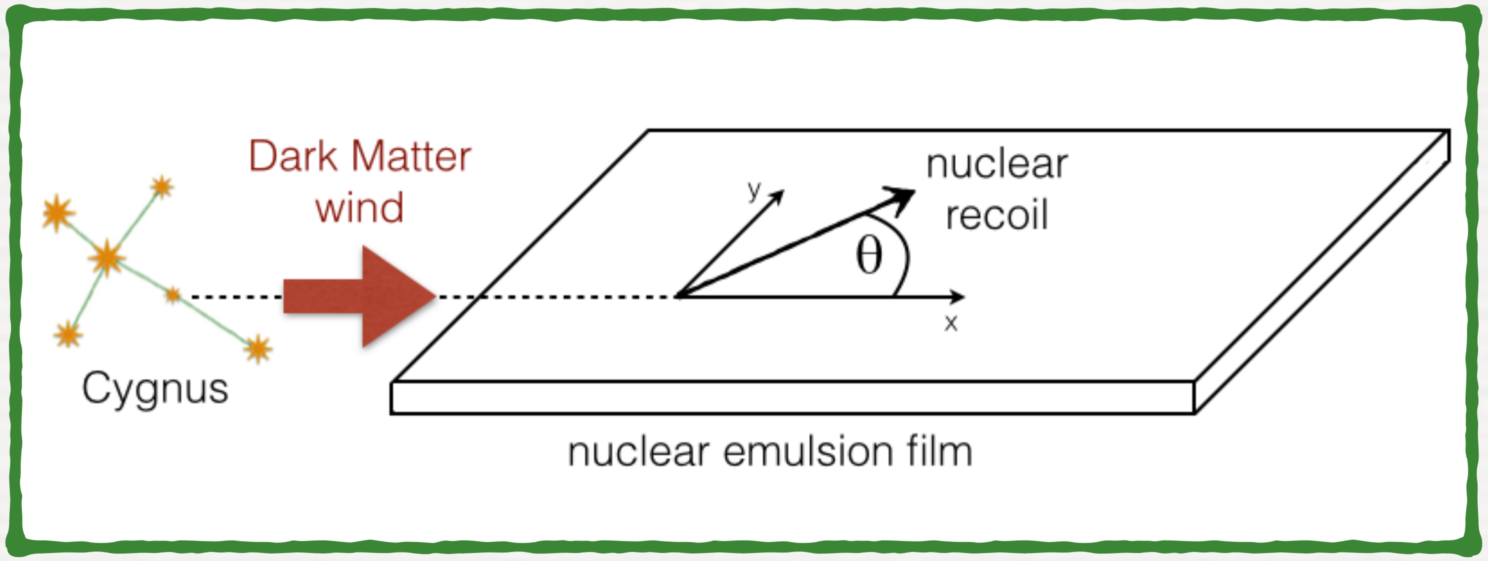
→ very high resolution tracking detector

Nuclear Emulsion based detector acting both as target and tracking device



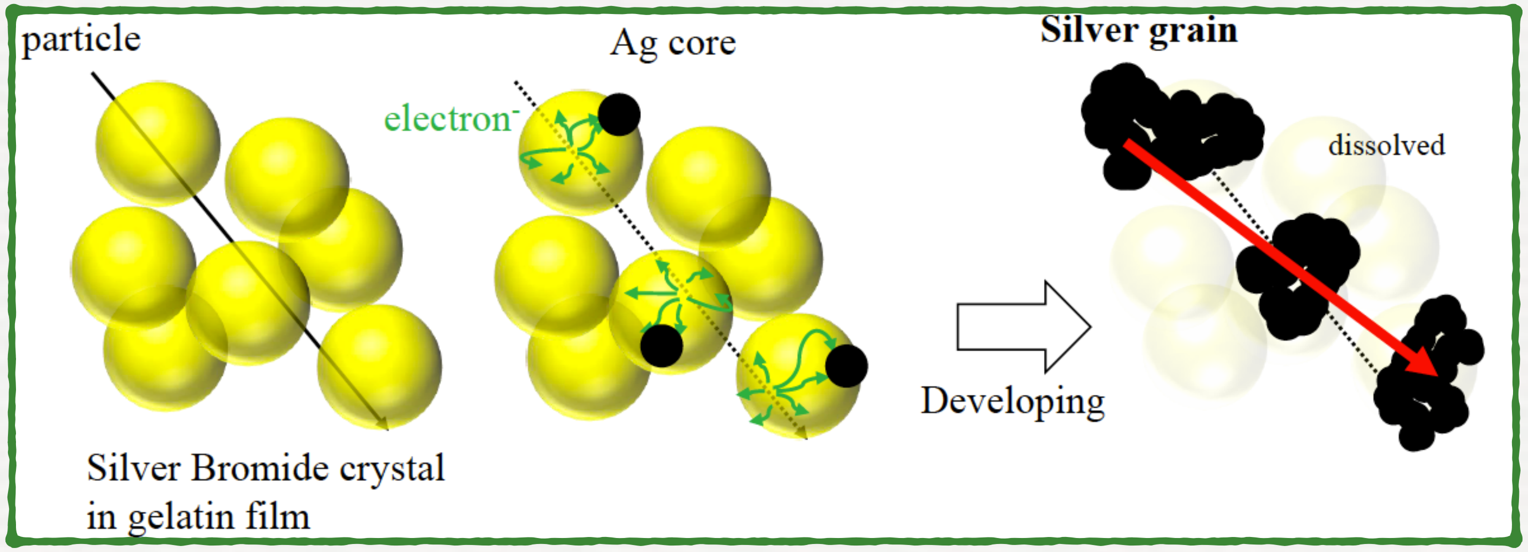
THE NEWSdm PRINCIPLE





- **Aim**: detect the direction of **nuclear recoils** produced in WIMP interactions
- **Target**: nanometric nuclear emulsions acting both as target and tracking detector
- **Background reduction:** neutron **shied** surrounding the target
- **Fixed pointing**: target mounted on **equatorial telescope** constantly pointing to the Cygnus Constellation
- **Location**: Underground Gran Sasso Laboratory

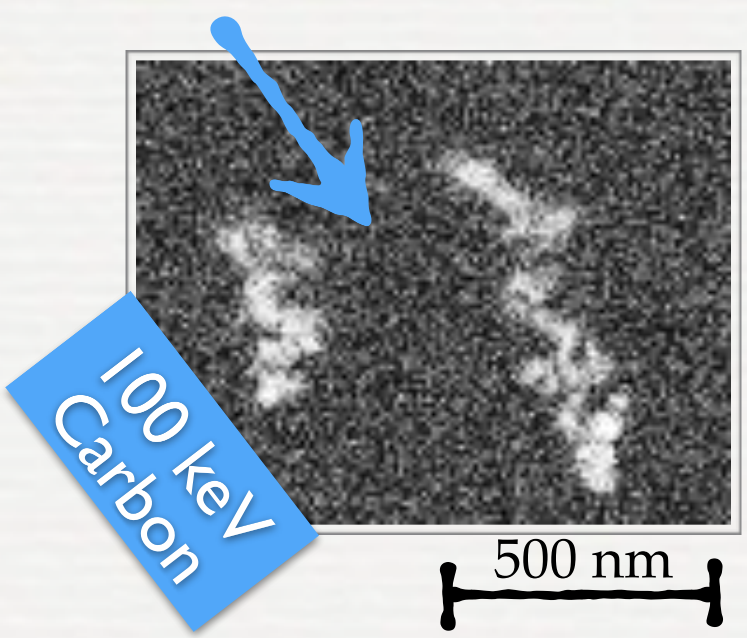
NIT: Nano emulsion Imaging Trackers

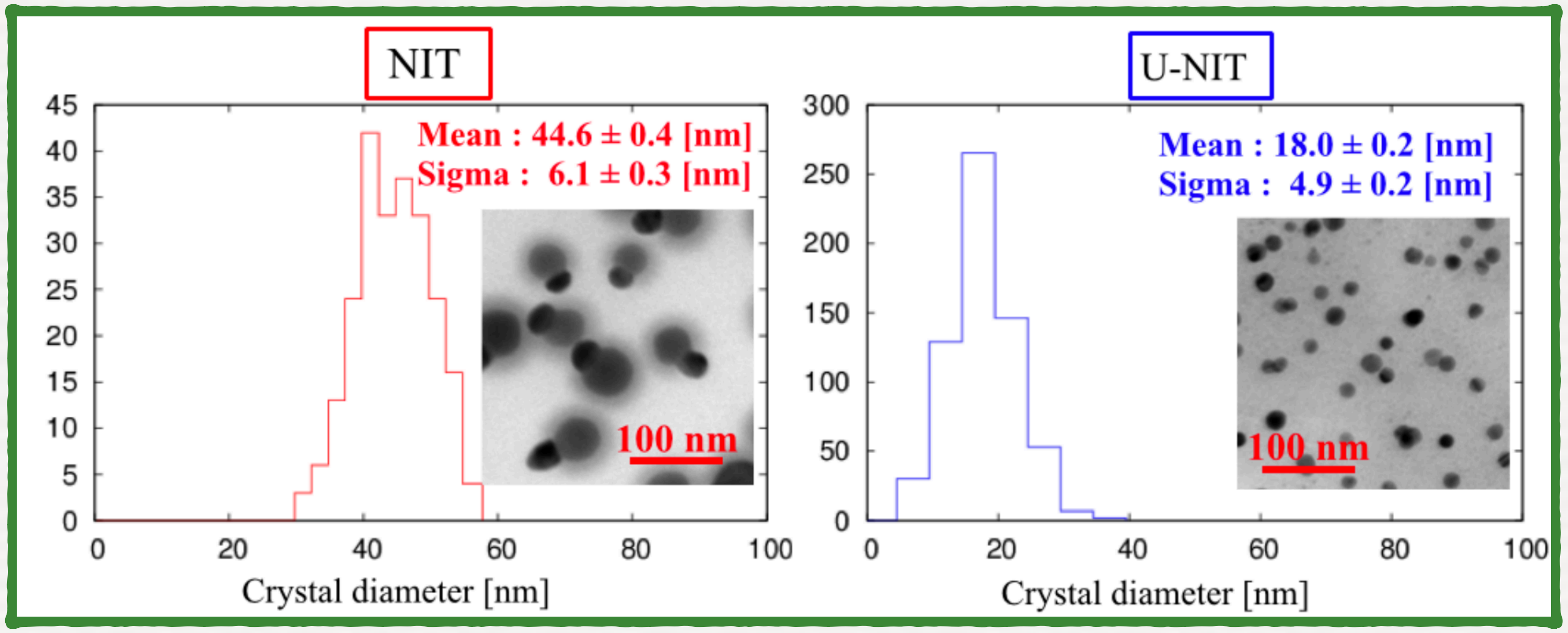


A long history, from the discovery of the **Pion (1947)** to the discovery of $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode (**OPERA, 2015**)

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

- New kind of emulsion for DM search
- Smaller crystal size





NIT EMULSIONS

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

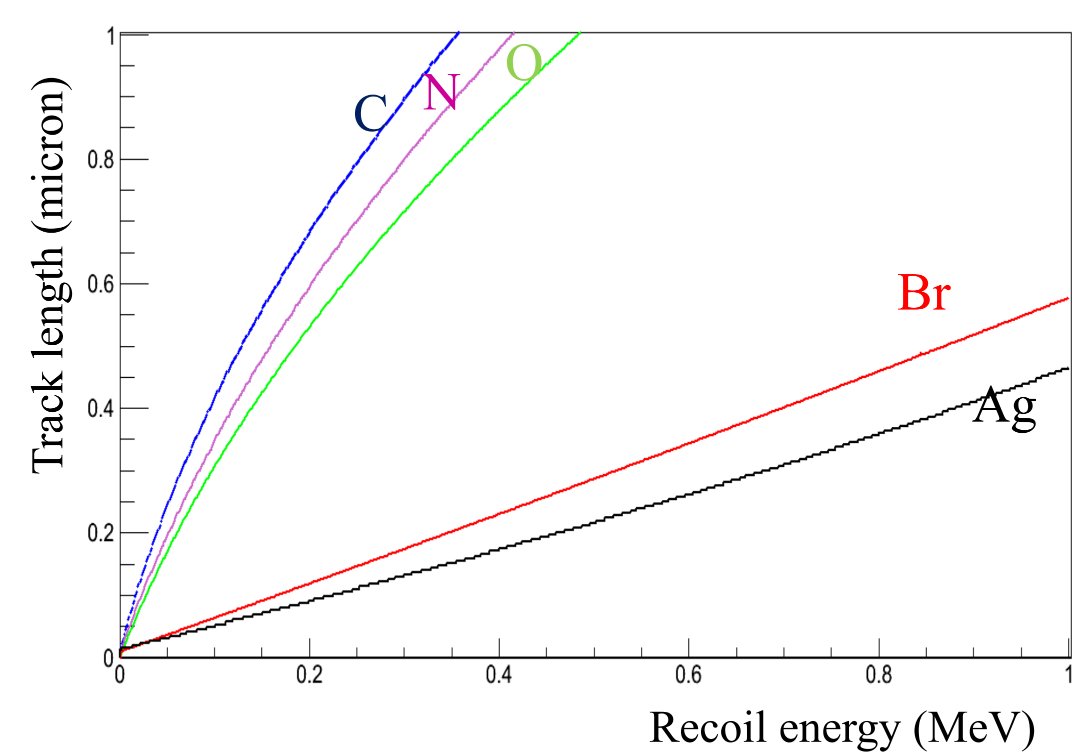
(b) Elemental composition

heavy nuclei

light nuclei

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

Each nucleus gives a different contribution to the overall sensitivity



Lighter nuclei
(longer range at same recoil energy)

↓

Sensitivity to low WIMP mass

Readout Technology

TRACK IDENTIFICATION

- Challenge: detect tracks with lengths comparable/shorter than optical resolution
- Strategy: two-steps approach

STEP 1 **CANDIDATE IDENTIFICATION WITH OPTICAL MICROSCOPES**

Pros: Fast scanning profiting of the improvements driven by the OPERA experiment, dedicated measurement stations in each lab

Limit: Resolution with standard technologies ~ 200 nm

STEP 2 **CANDIDATE VALIDATION**

X-ray microscope

Pros: High resolution ~ 50 nm or better

Cons: extremely slow and not convenient (need an external lab)

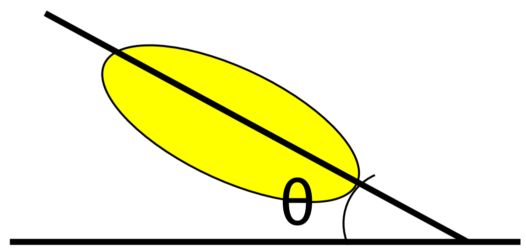
New technology with optical microscopes

READOUT STRATEGY

STEP 1: CANDIDATE IDENTIFICATION

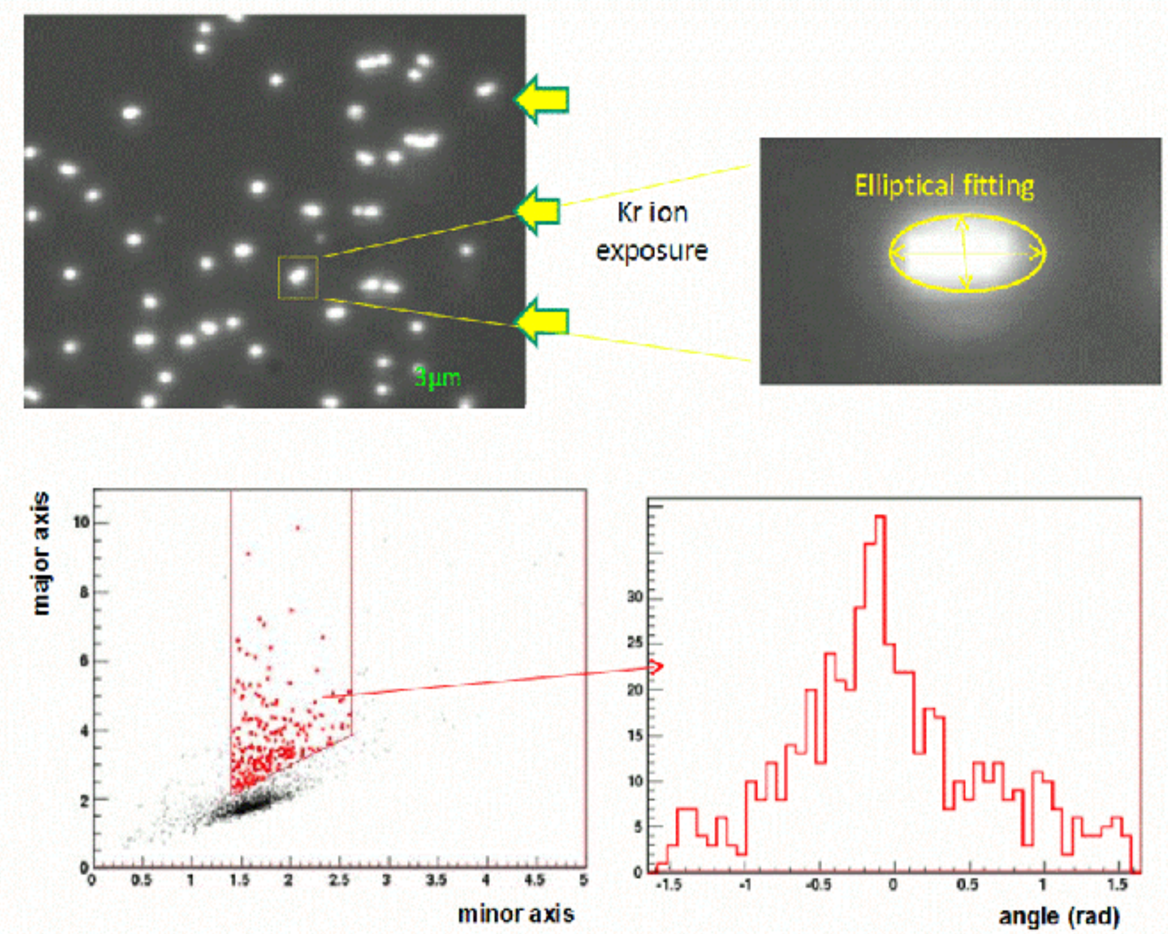
- Scanning with **optical microscope** and **shape recognition analysis**
- Automatic selection of candidate signals by optical microscopy
- Selection of clusters with elliptical shape: major axis along track direction
- Background: spherical cluster
- Resolution 200 nm (one order of magnitude better than the OPERA scanning system), scanning speed 20 cm^2/h

Test using 400 keV Kr ions



Direction detected!

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



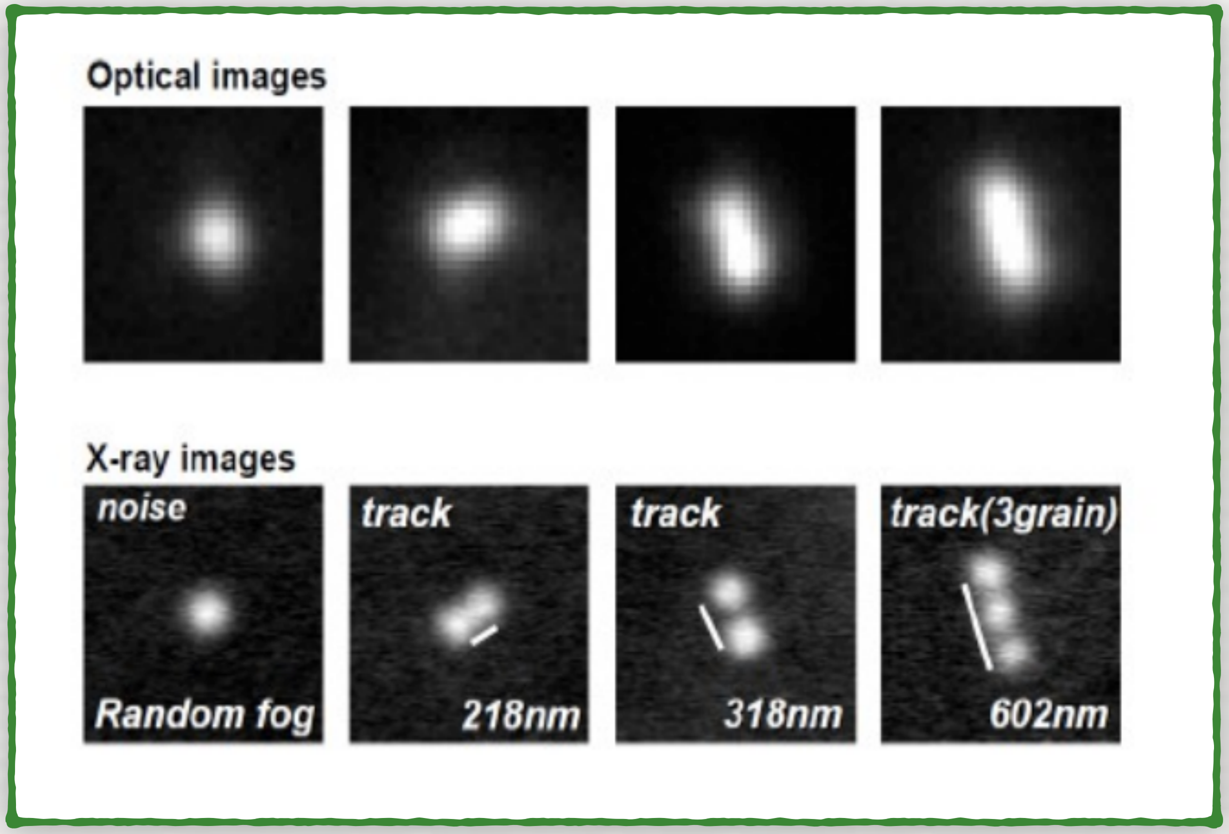
OVERALL ANGULAR RESOLUTION

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

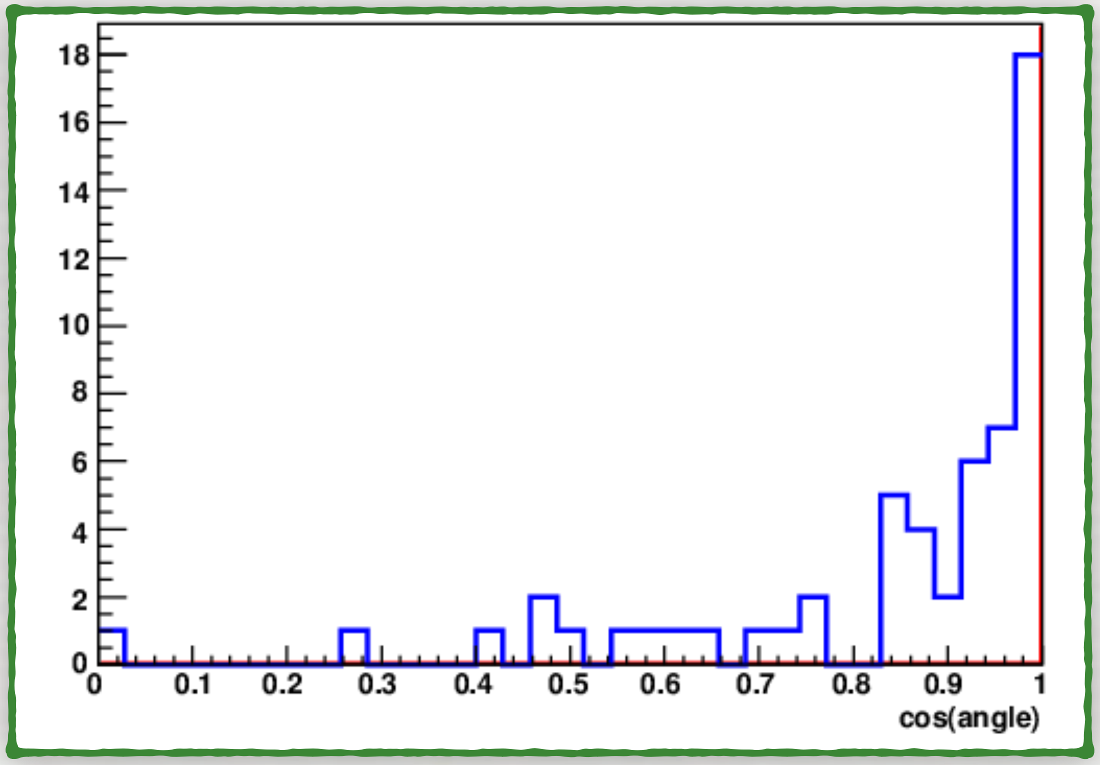
$$\sigma = 360 \text{ mrad}$$

READOUT STRATEGY
STEP 2: CANDIDATE VALIDATION

- 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



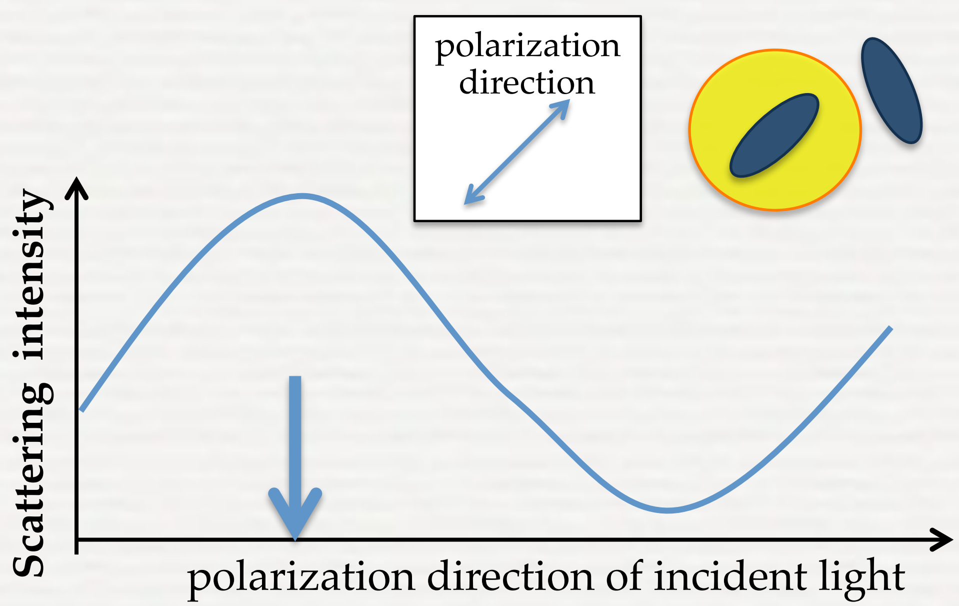
Matching Efficiency
99%
(572/579)

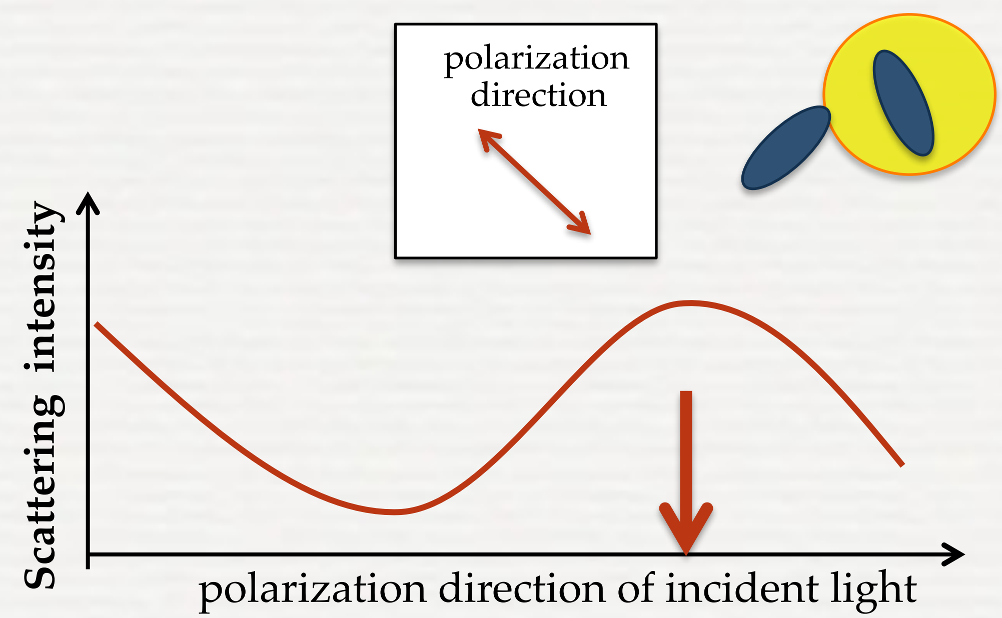


- Slow analysis speed
- Need of external X-ray guns

Resonant Light Scattering

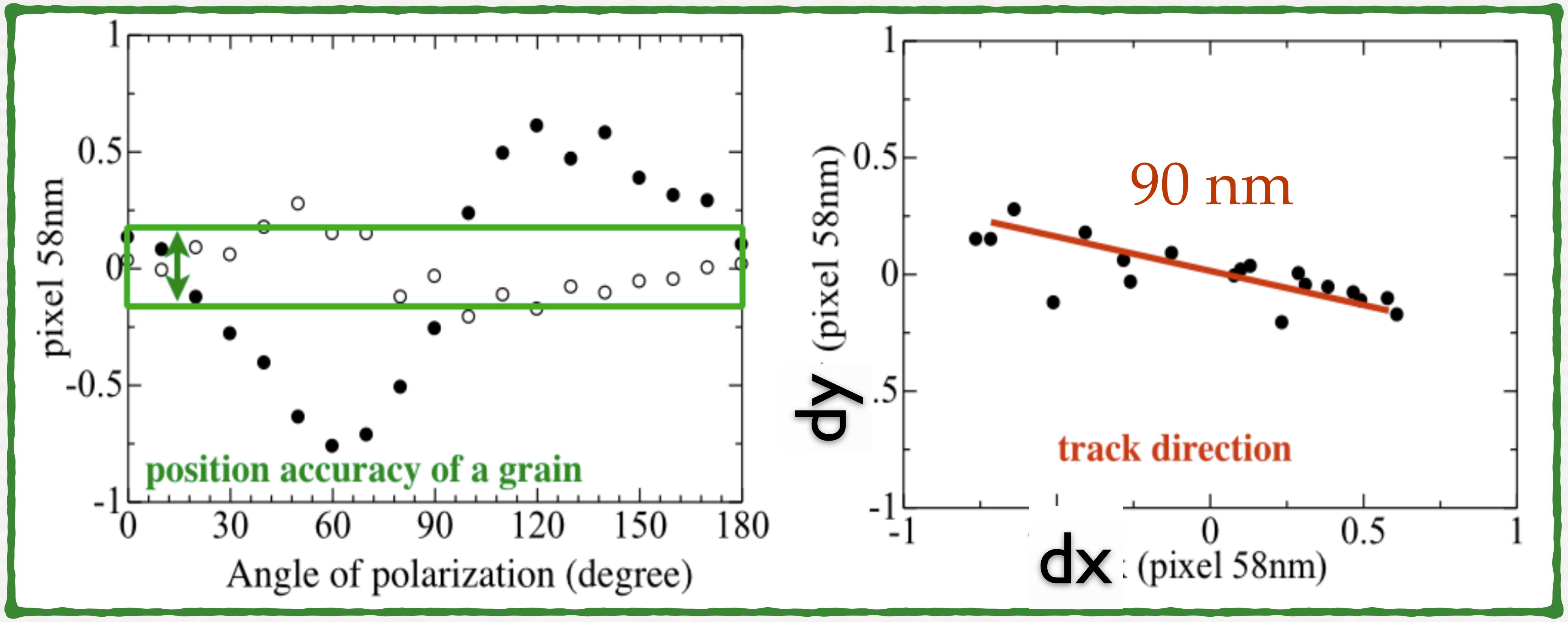
- Occurring when the light is scattering off a nanometric metallic (silver) grains are dispersed in a dielectric medium *(Applied Phys Letters 80 (2002) 1826)*
- Sensitive to the shape of nanometric grains: when silver grains are **not spherical**, the resonant response depends on the polarization of the incident light.
- Each grain is emphasized at different polarization values





Nanometric Track Reconstruction

- Taking multiple measurements over the whole polarization range produces a displacement of the barycenter of the cluster
- Application of resonant light scattering to an elliptical cluster
- Measure the displacement of cluster barycentre as a function of polarization angle (dx, dy)

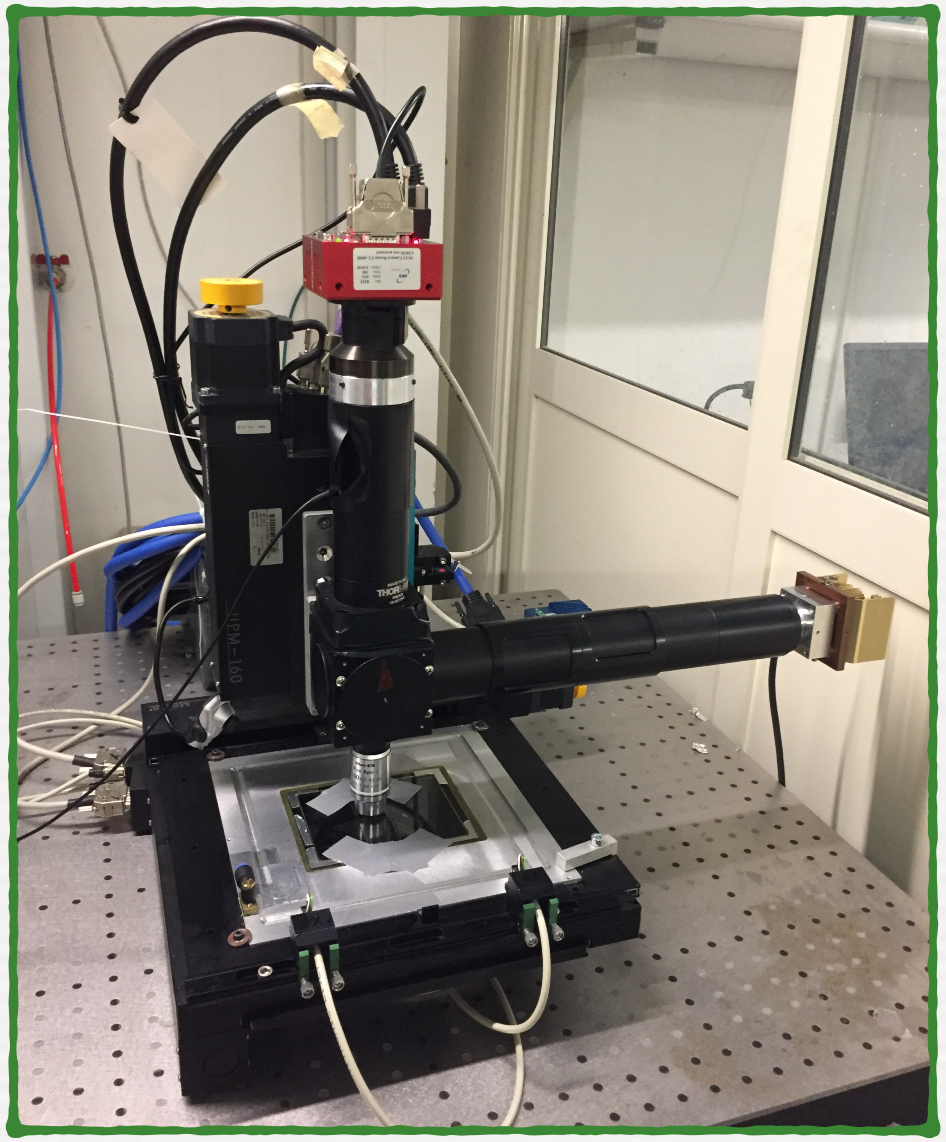


- **Measurement of track slope and length**

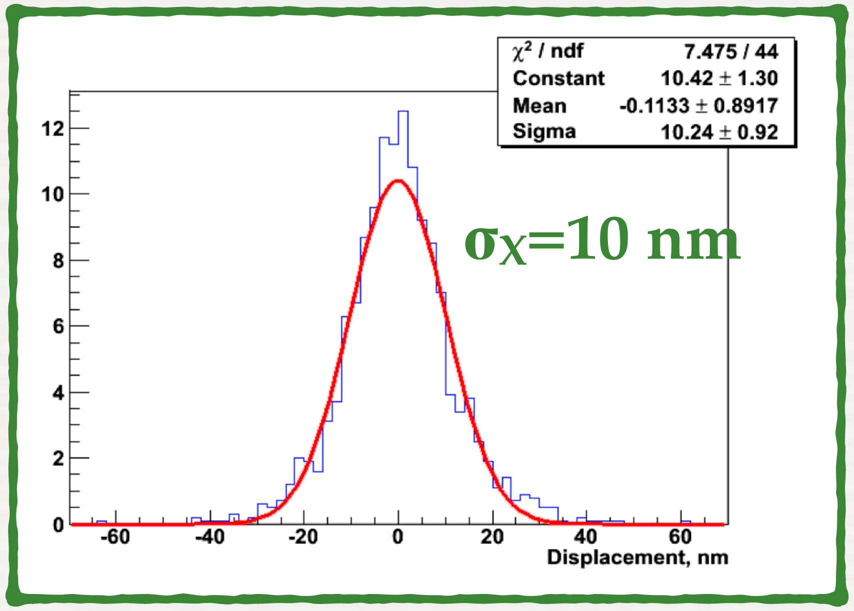
beyond **optical resolution**

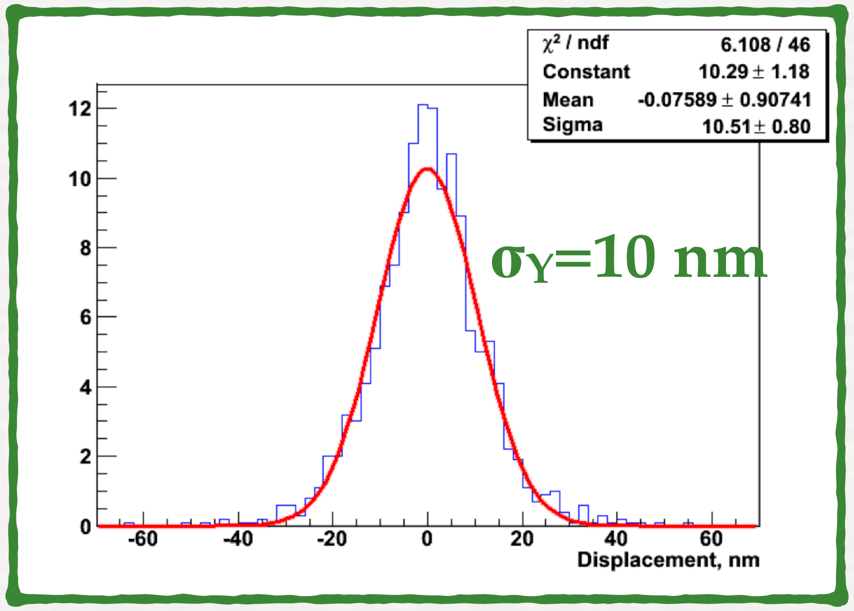
Position Accuracy

- Optical microscope assembled



- Exploiting resonant light effect





Unprecedented accuracy of **10 nm** achieved on both coordinates

Breakthrough

Background Studies

Background Studies

- Measurement of intrinsic radioactivity: neutrons

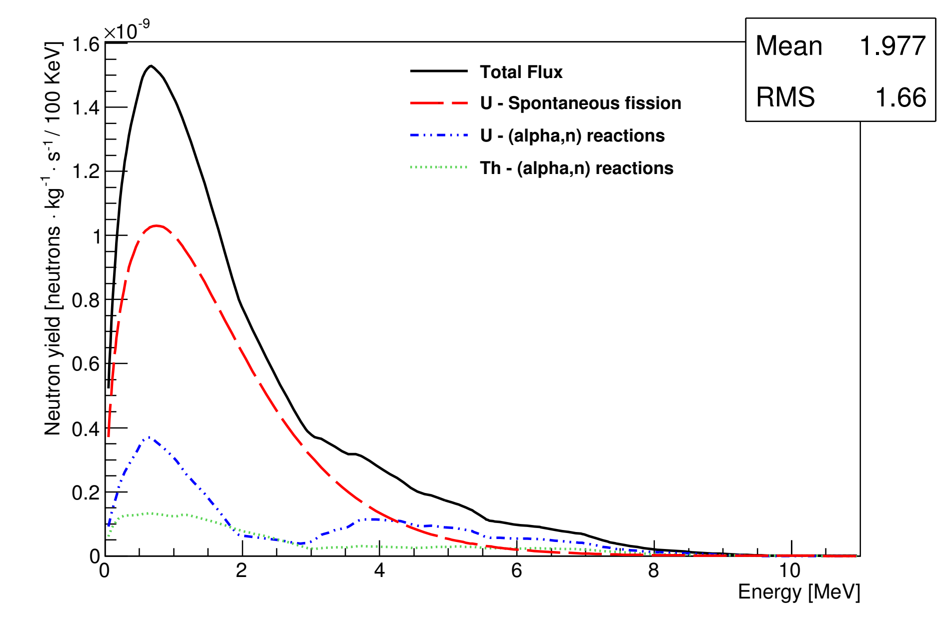
Nuclide	Contamination [ppb]	Activity [mBq/Kg]
	Gelatine	
^{232}Th	2.7	11.0
^{238}U	3.9	48.1
	PVA	
^{232}Th	< 0.5	< 2.0
^{238}U	< 0.7	< 8.6
	AgBr-I	
^{232}Th	1.0	4.1
^{238}U	1.5	18.5

^{238}U: 1.87 ppb (23.1 mBq/kg)

^{232}Th: 1.26 ppb (5.1 mBq/Kg)

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

Process	SOURCES simulation $[n \cdot kg^{-1} \cdot y^{-1}]$	Semi-analytical calculation $[n \cdot kg^{-1} \cdot y^{-1}]$
$(\alpha$, n) from ^{232}Th chain	0.12±0.04	0.10±0.03
$(\alpha$, n) from ^{238}U chain	0.27±0.08	0.26±0.08
Spontaneous fission	0.79±0.24	0.82±0.24
Total flux	1.18±0.35	1.18±0.35



From simulation: detectable neutron induced background

$\varepsilon \sim 1\% \rightarrow \sim 0.01$ n/kg year

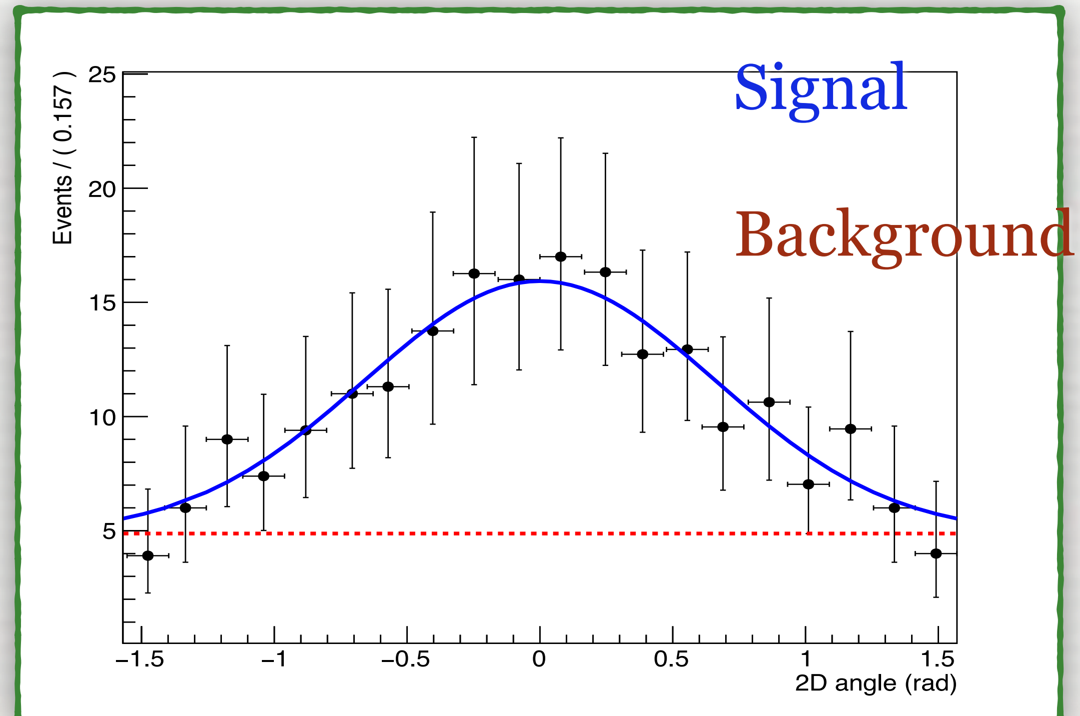
NEWSdm Collaboration
Astroparticle Physics 80 (2016) 16

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

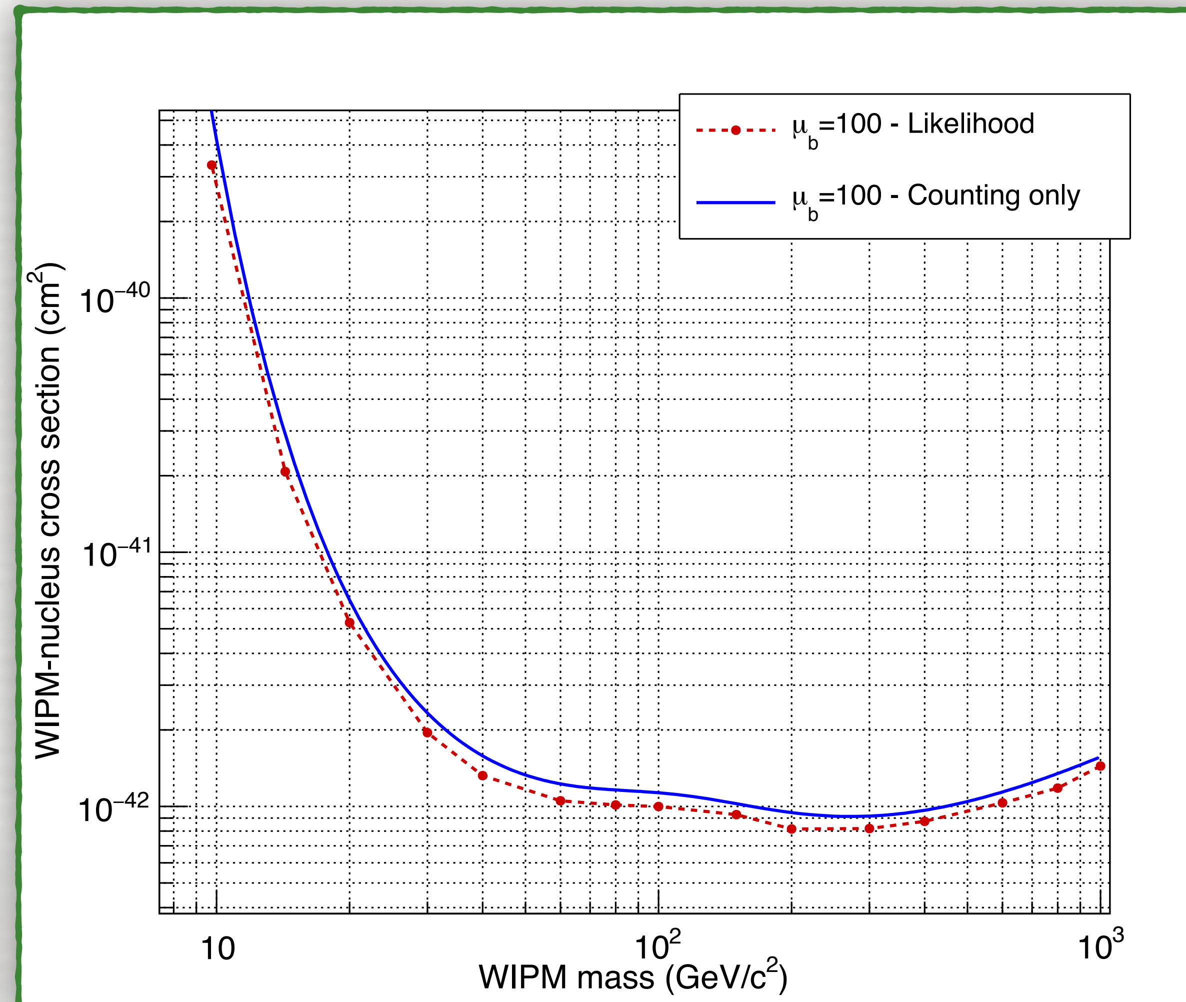
NEWSdm
SENSITIVITY

EXPLOIT DIRECTIONALITY

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



- Mass= 10 kg
- Exposure time = 10 years
- $N_{background}$ = 100
- Threshold = 100 nm



- Likelihood function

expected number of WIMP events

expected number of background events

signal pdf

background pdf

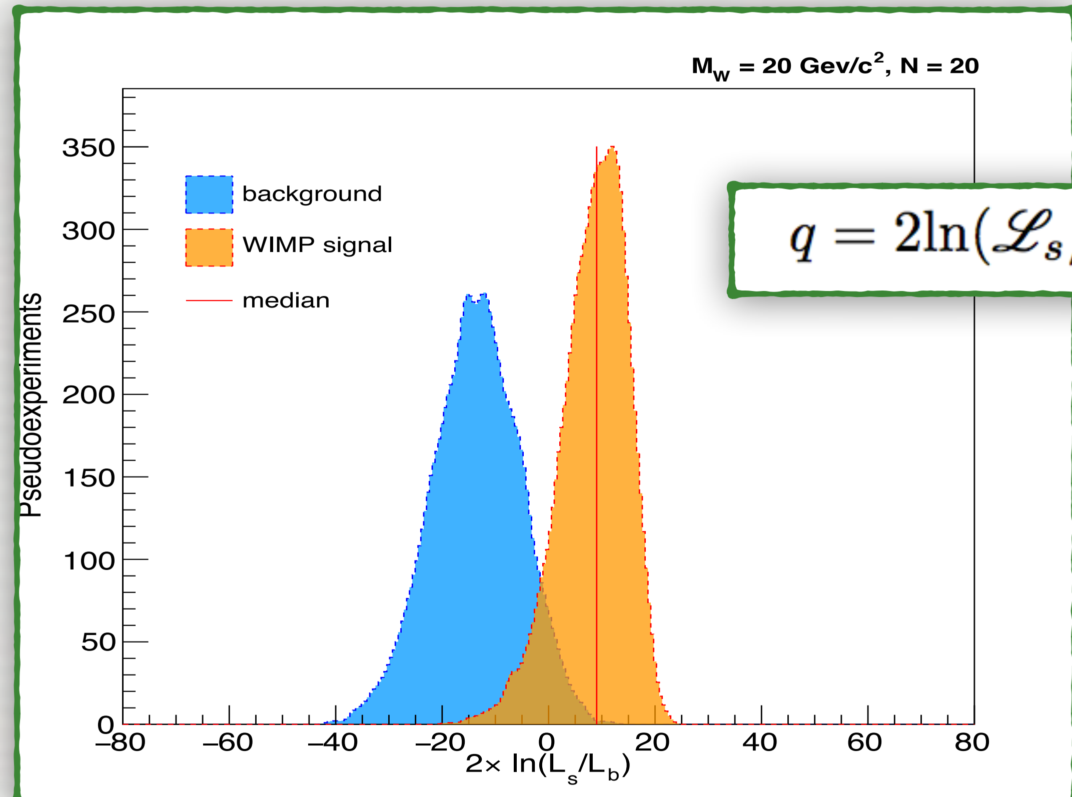
$$\mathcal{L}(\sigma_{\chi-n}, R_b) = \frac{e^{-(\mu_\chi+\mu_b)}}{N!} \times \prod_{i=1}^{N} [\mu_\chi f_\chi(\vec{q}_i; t_i) + \mu_b f_b(\vec{q}_i)]$$

total number of observed events

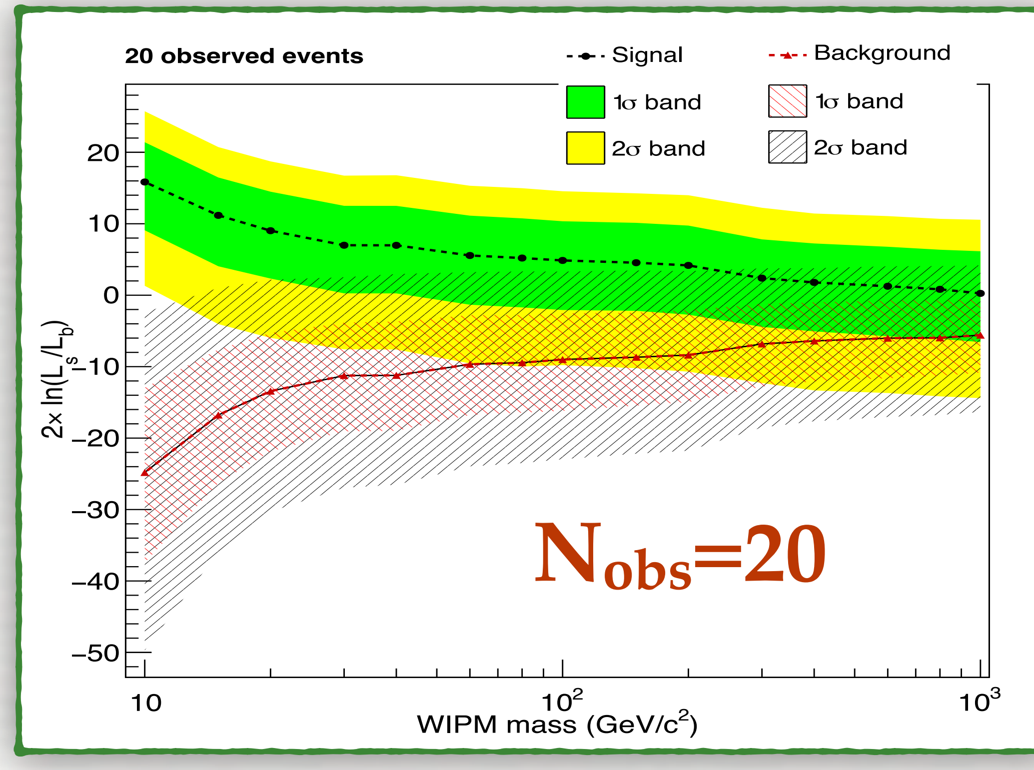
set of observables

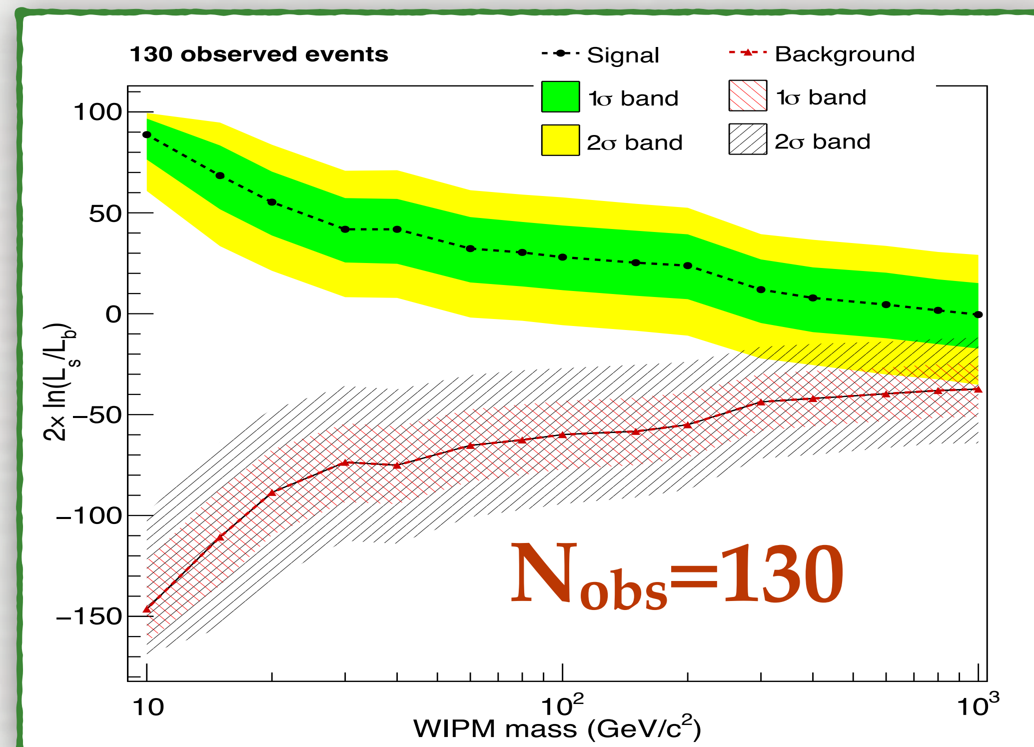
WIMP Signal Identification

- Test anisotropy of observed signal
- Unambiguous proof of WIMP origin of recoil signal
- Signal/background hypothesis separation



$$q = 2\ln(\mathscr{L}_s/\mathscr{L}_b)$$



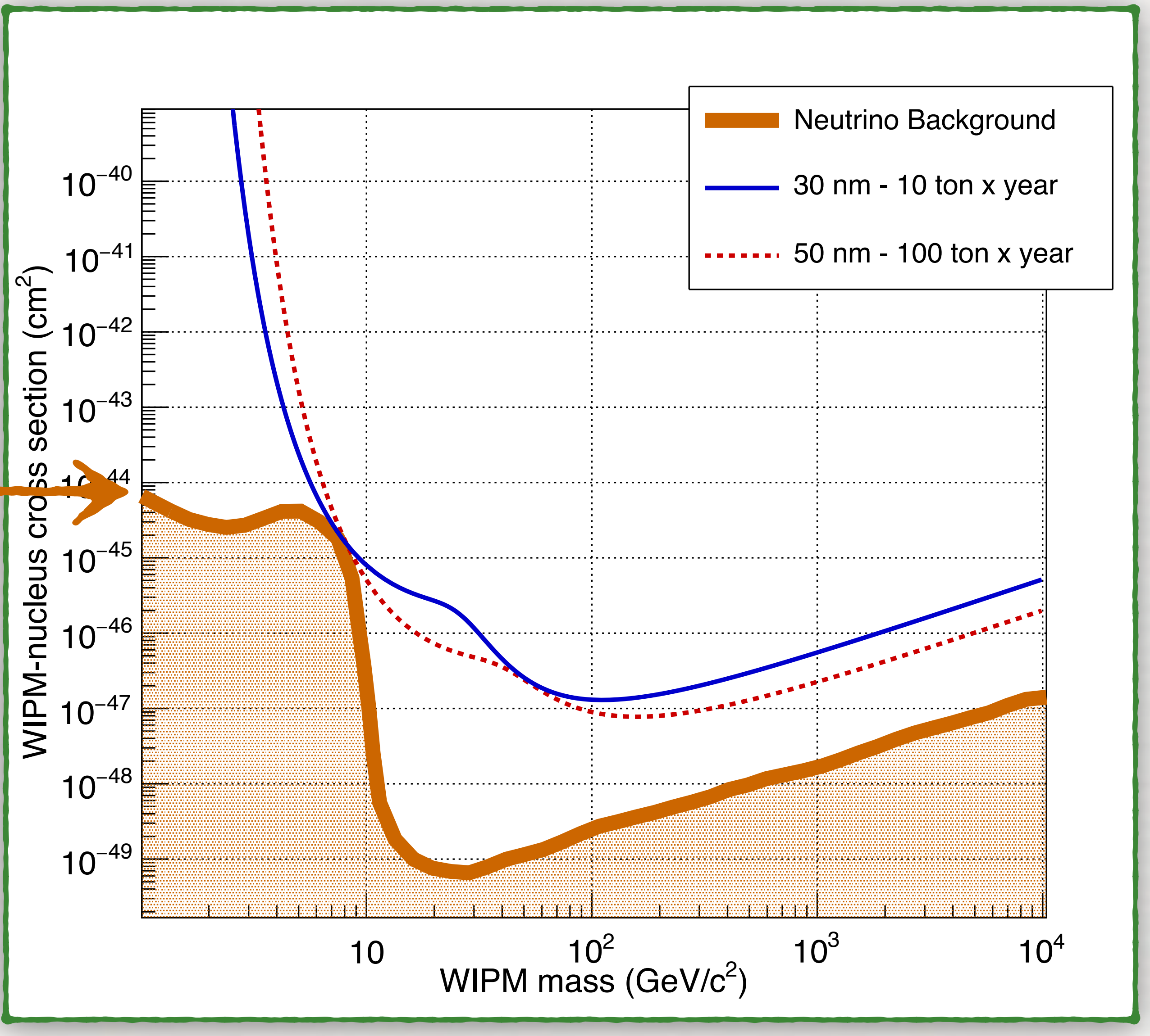


- 20 events required to prove that data are not compatible with background at 3σ CL for M_W<20 GeV/c^2
- 130 events give 3σ CL in the whole WIMP mass range

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)



REQUIREMENTS

- Larger mass scale detector
- Reduction of track length threshold

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

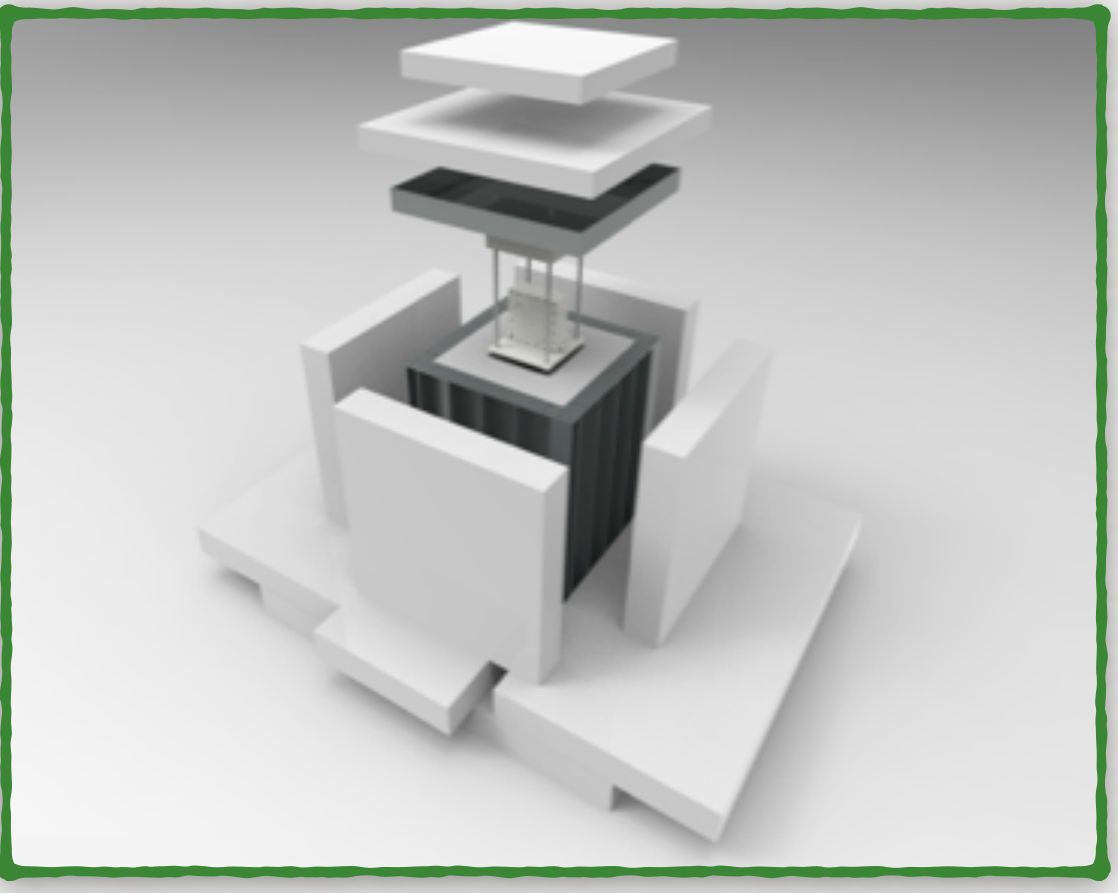
Current Status Of The Experiment

Technical Test

- **Aim**: measure the detectable background from environmental and intrinsic sources and validate estimates from simulations
- Confirmation of a negligible background will pave the way for the construction of a **pilot experiment** with an exposure on the **kg year** scale
- Pilot experiment will act as a **demonstrator** to further extend the mass range

- **Experimental setup:**
- shield from environmental background
- cooling system to ensure required temperature to NIT emulsions

Polyethylene slabs 40 cm-thick - absorb environmental and cosmogenic neutrons
Lead bricks 10 cm-thick - absorb environmental photons



Technical Test

- Installed in Underground Gran Sasso INFN Laboratories in March 2017

CONCLUSIONS

- A novel approach for **directional Dark Matter searches** is proposed in NEWSdm
- Use of fine-grained **nuclear emulsion** as target and tracking system
- Breakthrough in readout technologies to go beyond optical resolution
- Neutron background from intrinsic radioactivity negligible up to ~10 kg year
- Prepare a kg scale (pilot) experiment as a demonstrator of the technology
- Aim: large mass scale detector to go beyond "neutrino floor"
- Status:
  - Letter of Intent submitted to LNGSC in 2015
  - First technical test performed in March 2017
  - TDR in preparation

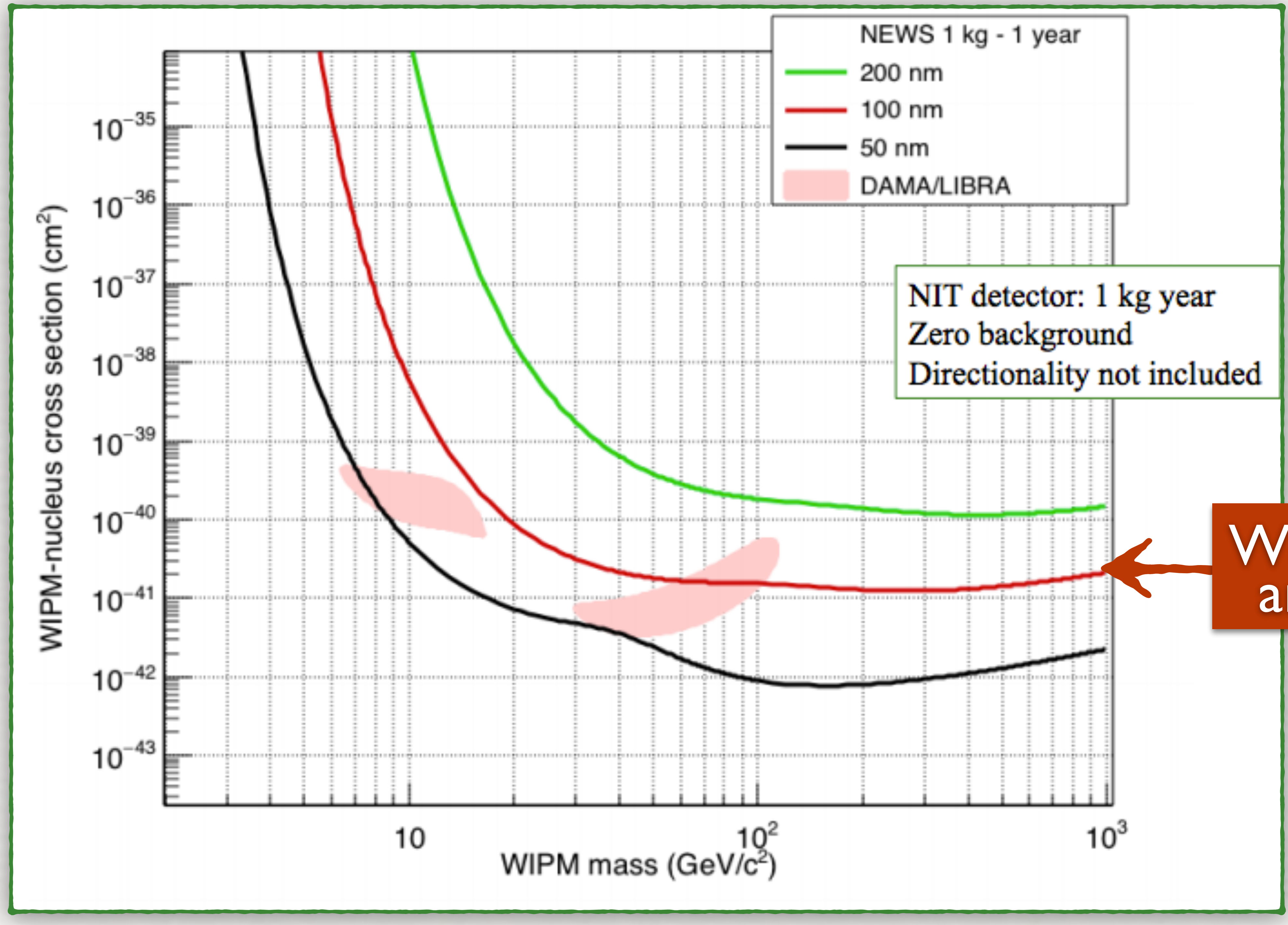
*part of the Collaboration when test started in LNGS

THANK YOU FOR YOUR ATTENTION

Backup Slides

EXCLUSION PLOT

- Pilot experiment: 1 kg year



Where we are now

BEYOND OPTICAL RESOLUTION

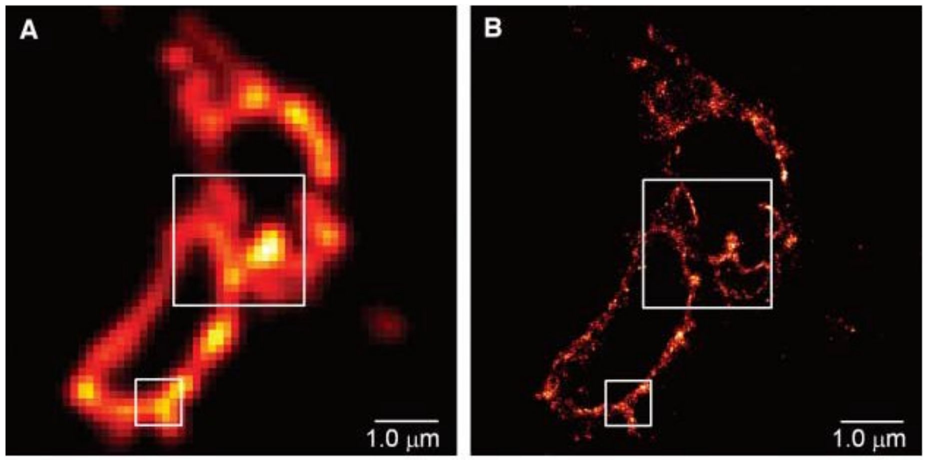
OPTICAL MICROSCOPES

- New technologies

Imaging beyond the optical resolution

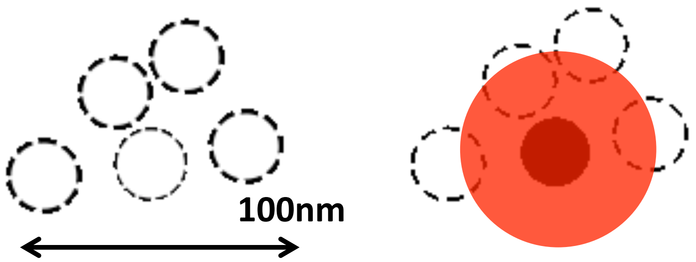
2014 Nobel Prize in Chemistry

COS-7 cell optical images



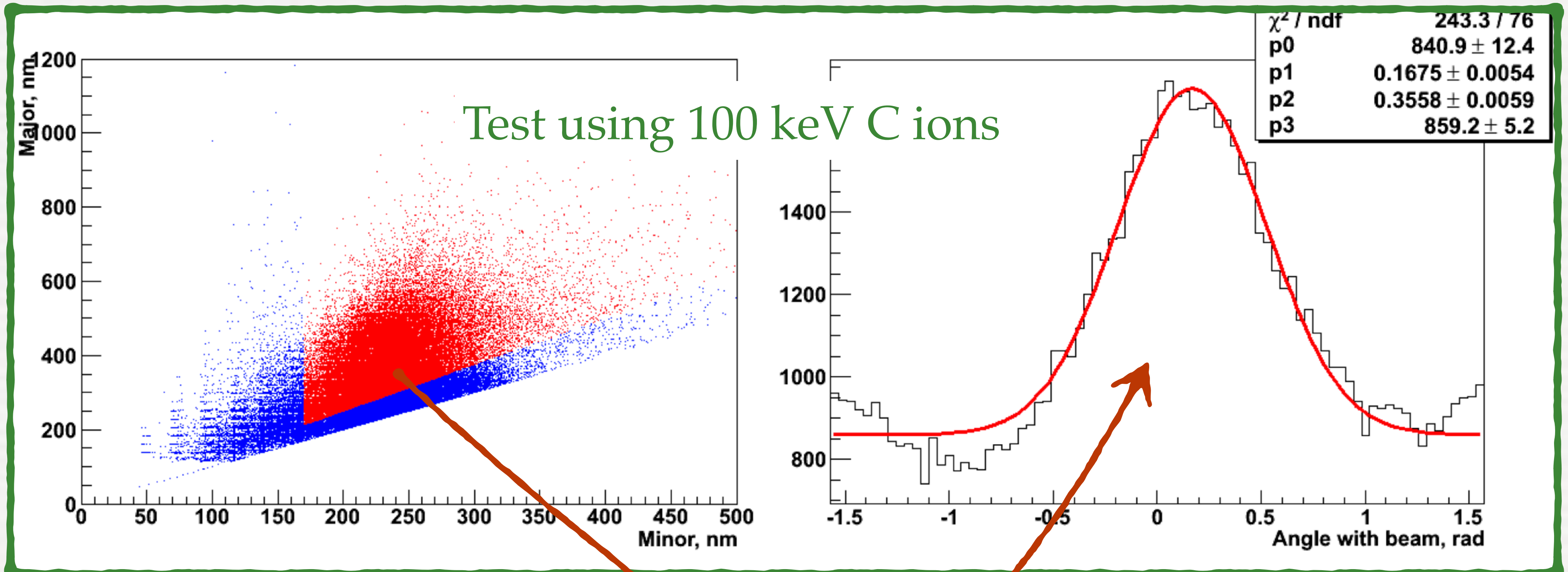
Fluorescent molecule

Eric Betzig *et al.*, Science 313, 1642 (2006)



Using fluorescence

SELECTION OF TRACKS
WITH SHAPE ANALYSIS



SIGNAL SELECTION

- Major axis/minor axis > 1.25
- minor axis > 170 nm

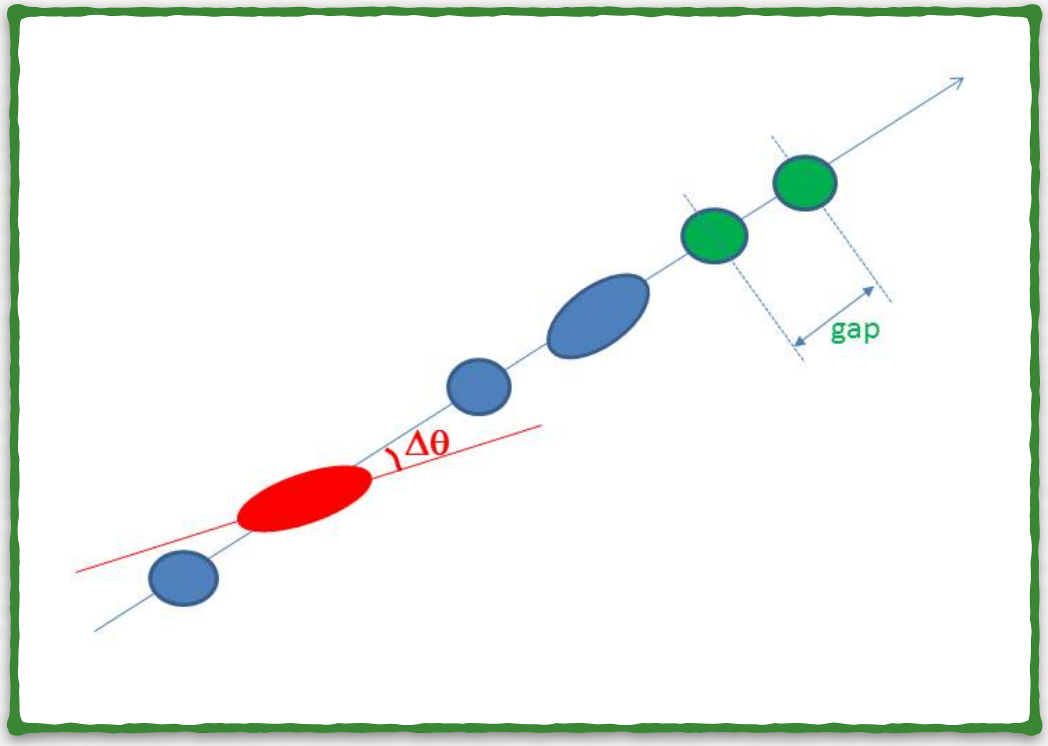
OVERALL ANGULAR RESOLUTION

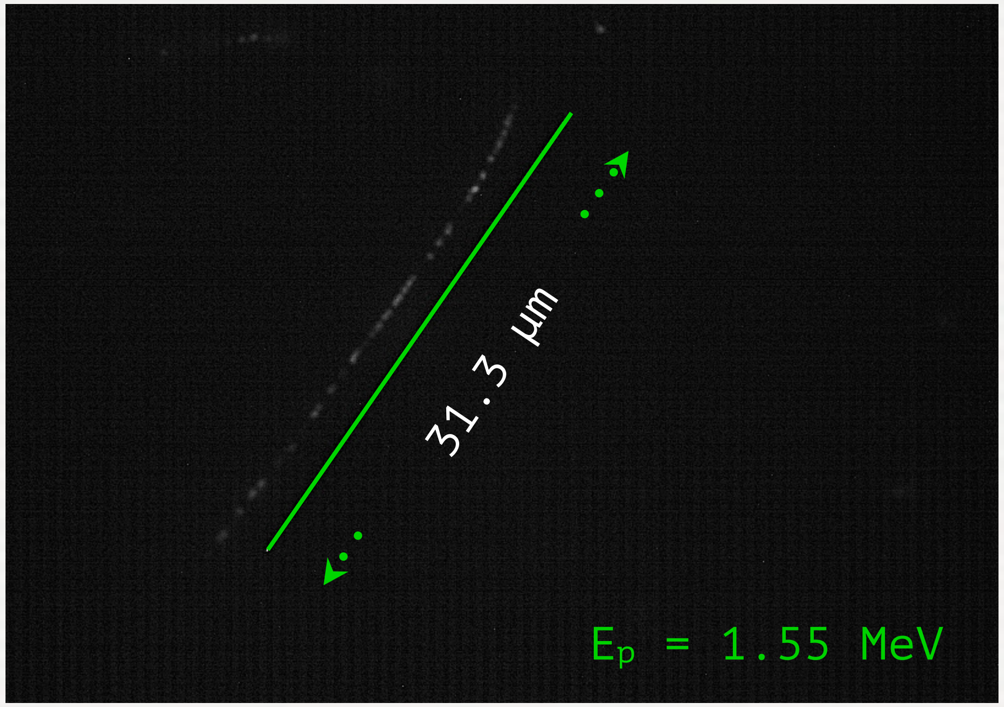
$$\sigma^2 = \sigma^2_{\text{intrinsic}} + \sigma^2_{\text{scattering}}$$

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

Intrinsic Angular Resolution

- Neutron test beam sample: exposure at FNS (Japan)
- Compare clusters with elliptical (e > 1.1) shape with the proton recoil direction
- Scattering contribution negligible





INTRINSIC ANGULAR RESOLUTION

σ = 235 mrad = 13°