Università di Roma
Tor Vergata

INFN

DM directionality approach using $ZnWO_4$ crystal scintillators

14th conference on the Identification of Dark Matter (IDM22)
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18-22, July 2022

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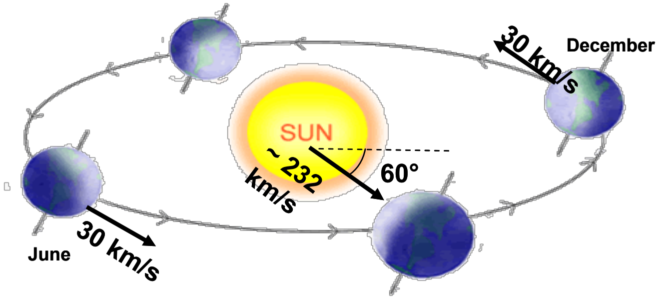
on behalf of the ADAMO Collaboration
University of Roma “Tor Vergata” and INFN

Signatures for direct detection experiments

In direct detection experiments to provide a Dark Matter signal identification with respect to the background, a model independent signature is needed



- Model independent annual modulation: annual variation of the interaction rate due to Earth motion around the Sun which is moving in the Galaxy

  at present the only feasible one, sensitive to many DM candidates and scenarios

  (successfully exploited by DAMA)

- Model independent diurnal modulation: due to the Earth revolution around its axis

  2nd order effect

See P. Belli
19/7/22, 5pm

- Diurnal variation: daily variation of the interaction rate due to the different Earth depth crossed by the Dark Matter particles

  only for high cross sections

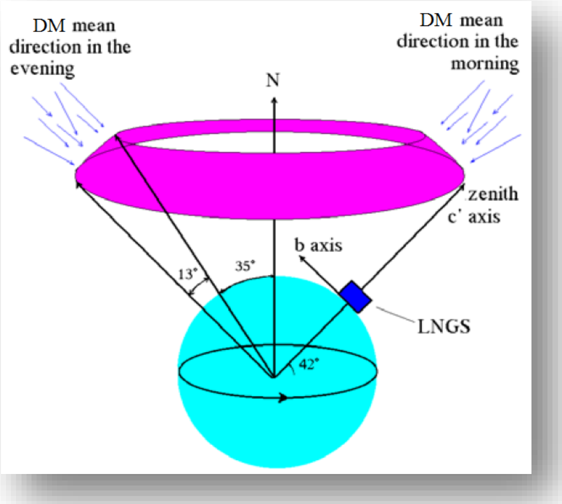
- **Directionality**: correlation of Dark Matter impinging direction with Earth's galactic motion

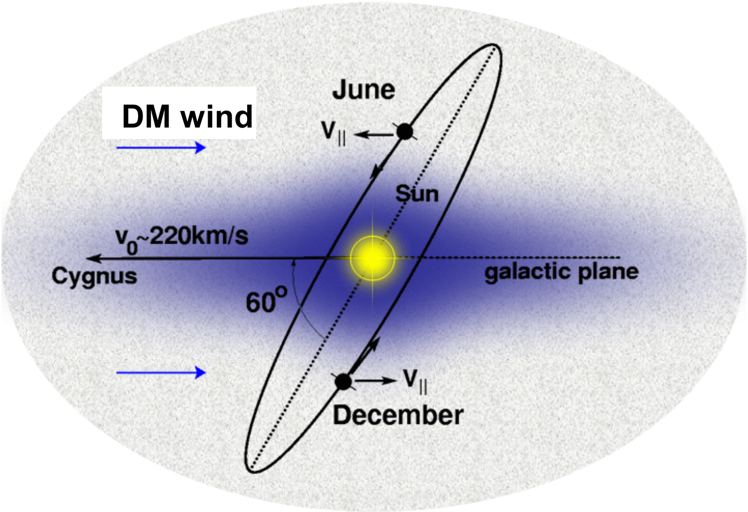
  only for DM candidate particle inducing recoils

What the directionality approach is?

Based on the study of the correlation between the arrival direction of those Dark Matter (DM) candidates able to induce a nuclear recoil and the Earth motion in the galactic frame

Impinging direction of DM particle is (preferentially) opposite to the velocity of the Sun in the Galaxy…





…and because of the Earth's rotation around its axis, the DM particles average direction with respect to an observer on the Earth changes with a period of a sidereal day

In case of DM candidate particles giving rise to nuclear recoils, the direction of the latter ones is expected to be strongly correlated with the direction of the impinging DM particle. Therefore, the observation of an anisotropy in the distribution of nuclear recoil direction could give further evidence and information for such candidates

A direction-sensitive detector is needed

Directionality techniques (R&D stage or Idea)

Detectors Strategies

In Low Pressure Time Projection Chamber the range of recoiling nuclei (energy depended) is of the order of mm while it is ~µm in solid detectors.

Tracking Detectors

High angular and spatial resolution is required at very low energy, low background techniques seem not mature, limitations on mass and stability.

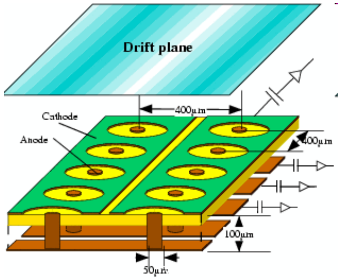
- **LP-TPC** (DRIFT, MIMAC, DMTTPC, NEWAGE, D3, NITEC, CYGNUS, INITIUM)
- **Nuclear Emulsions** (NEWSdm)
- **DNA**
- **Diamonds**

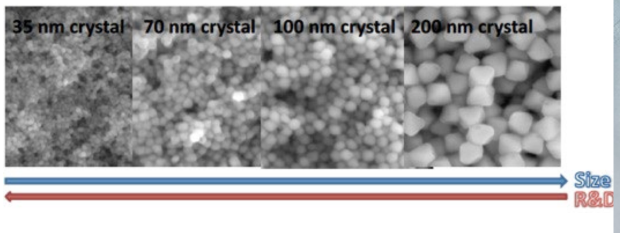
ideas

Detectors using Anisotropic Features

ideas

- **Anisotropic crystal scintillators** (ADAMO, Japanese group)
- **Carbon nanotubes-based detector** (ATRACT, PTOLEMY)
- **Columnar Recombination in LAr/LXe-TPC** (PRD 91 092007: no more data since 2015 with a small LAr-TPC: SCENE with a very weak indication of such an effect. Now RED)

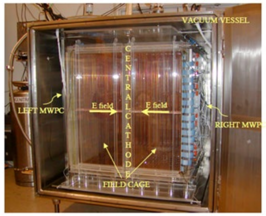




The DRIFT-IId detector in the Boulby Mine

The detector volume is divided by the central cathode, each half has its own multi-wire proportional chamber (MWPC) readout.

0.8 m^3 fiducial volume, 10/30 Torr CF_4/CS_2 --> 139 g



Dinesh Loomba

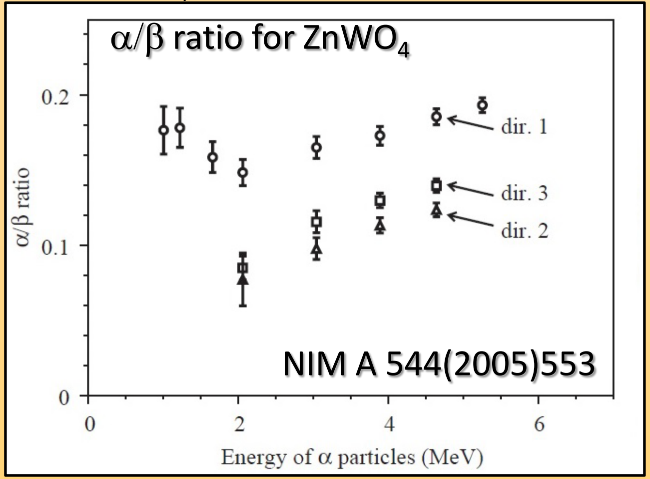
Directionality sensitive detectors: anisotropic scintillators

- **Why an Anisotropic Scintillator?** overcames practical limitations due to, e.g.,: (i) the low density of LP-TPC; (ii) the angular resolution; (iii) track reconstruction; (iv) the level of radiopurity; v) stability during the running conditions;

- The use of anisotropic scintillators to study the directionality signature proposed for the first time in refs. **[P. Belli et al., Il Nuovo Cim. C 15 (1992) 475**], where the case of anthracene was analysed; some preliminary activities have been carried out [N.J.C. Spooner et al, IDM1997 Workshop; Y. Shimizu et al., NIMA496(2003)347]: the idea was revisited in [**R. Bernabei et al., EPJC28(2003)203**]

- **What does Anisotropic Scintillator mean?**
  - **for heavy particles** the light output and the pulse shape depends on the particle impinging direction with respect to the crystal axes
  - **for γ/e** the light output and the pulse shape are isotropic

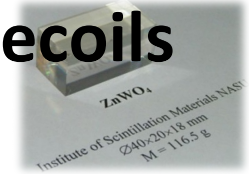
First indication of anisotropy properties for a $ZnWO_4$ crystal scintillator:



NIM A 544(2005)553

- **How can we profit of the Anisotropic Scintillators features?** Expected rate as a function of sidereal time and days of the year (see next slides)

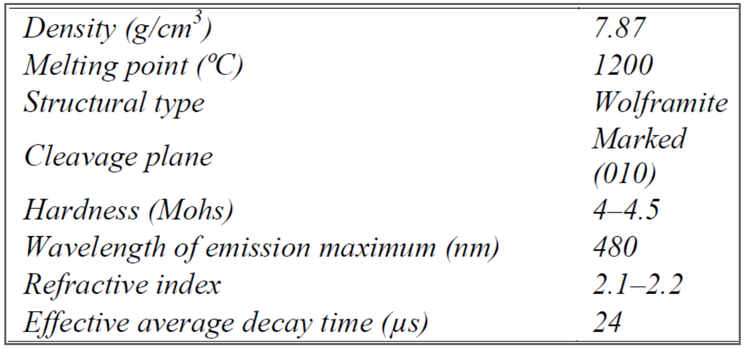
Study of the $ZnWO_4$ anisotropic response to nuclear recoils for the ADAMO project



Advantages of the $ZnWO_4$ crystal

- ✓ Very good anisotropic features
- ✓ High level of radio-purity
- ✓ High light output, that is low energy threshold feasible
- ✓ High stability in the running conditions
- ✓ Sensitivity to small and large mass DM candidate particles
- ✓ Detectors with ~ kg masses

NIMA544(2005)553, Eur. Phys. J. C 73 (2013) 2276



Density (g/cm^3)	*7.87*
Melting point (ºC)	*1200*
Structural type	*Wolframite*
Cleavage plane	*Marked (010)*
Hardness (Mohs)	*4–4.5*
Wavelength of emission maximum (nm)	*480*
Refractive index	*2.1–2.2*
Effective average decay time (μs)	*24*

Measurements of $ZnWO_4$ anisotropic response to nuclear recoils for the ADAMO project

In summer 2018 a campaign of measurements using a dedicated $ZnWO_4$ crystal to study the anisotropic features of the detector for low energy nuclear recoils started:

1. Preliminary measurements with a collimated α **source** have been performed

2. After α calibrations a campaign of measurements at ENEA-Casaccia with a **14 MeV neutron beam** has been carried out

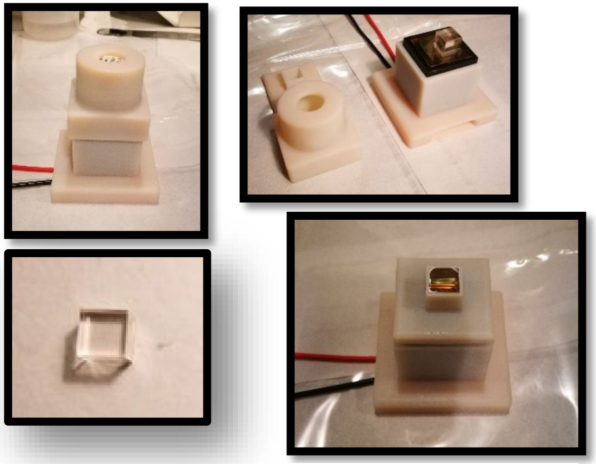
$ZnWO_4$ crystal = 10 x 10 x 10 mm^3 (detector of reduced dimensions to investigate neutron single-scattering)

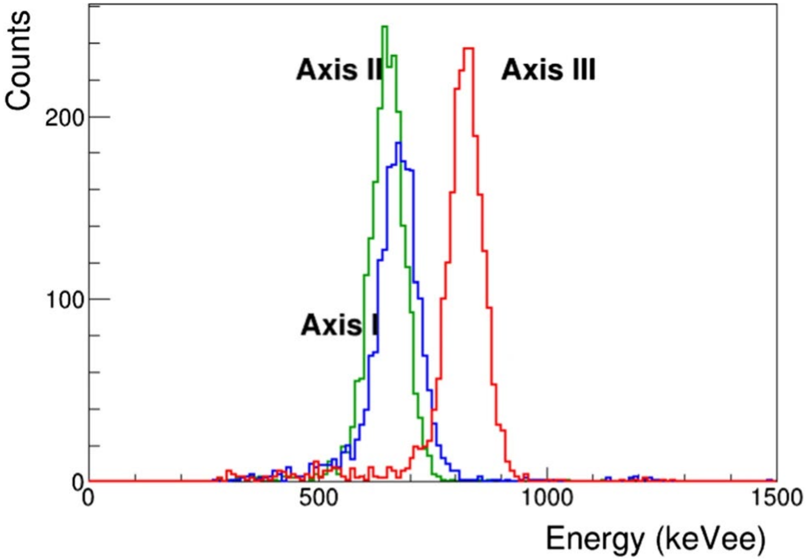
Eur.Phys.J.A 56 (2020) 83

Studying the response of the $ZnWO_4$ with ^{241}Am α source

Calibration set-up:

- PMT Hamamatsu H11934-200 (transit time ≈ 5 ns) + $ZnWO_4$
- LeCroy Oscilloscope 24Xs-A, 2.5 Gs/s, 200MHz bandwidth
- Pulse profiles acquired in a time window of 100 μs





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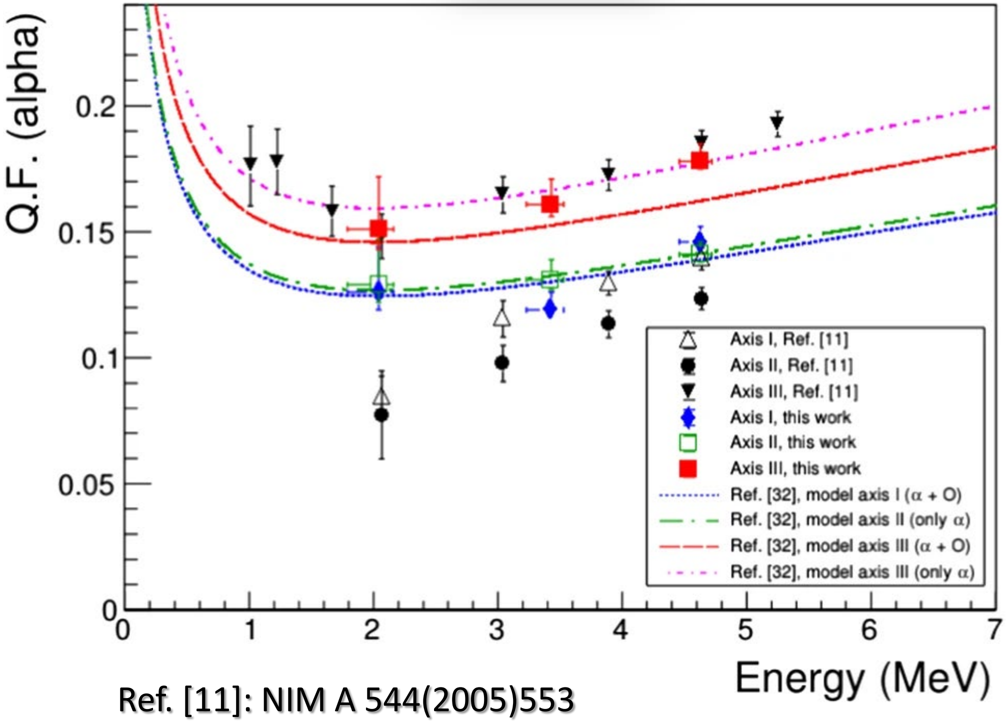
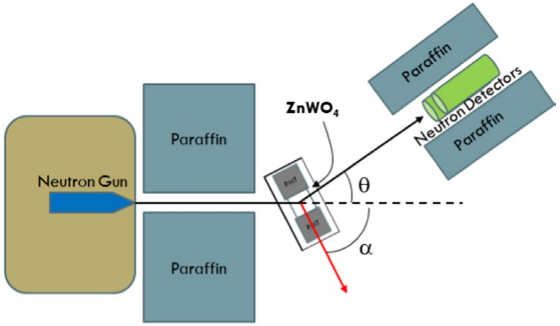


Ref. [11]: NIM A 544(2005)553

Studying the response of the ZnWO$_4$ with a neutron gun

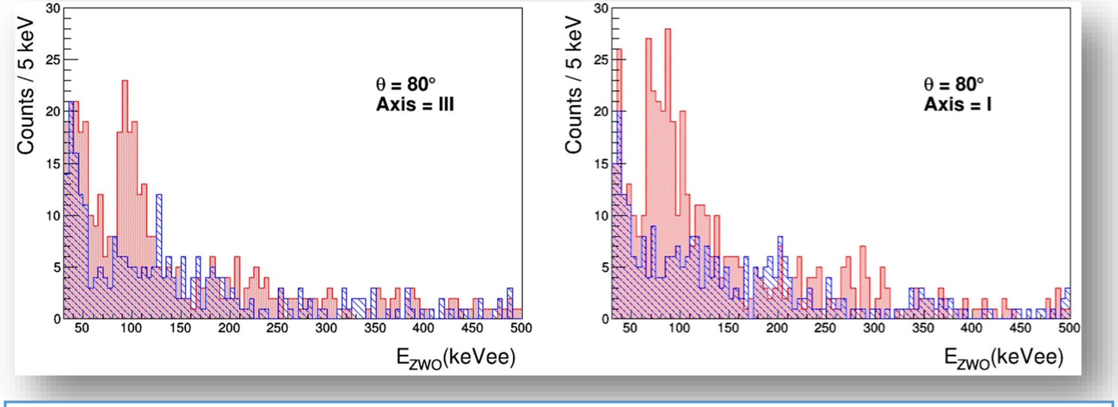
Eur.Phys.J.A 56 (2020) 83

- Set-up:
  - ✓ ZnWO$_4$ Crystal (10 x 10 x 10 mm^3)
  - ✓ Two Hamamatsu PMTs: HAMA-H11934-200
  - ✓ 2 Neutron detectors (Scionix EJ-309)
  - ✓ Neutron Gun, Thermo Scientific MP320: 14 MeV neutrons

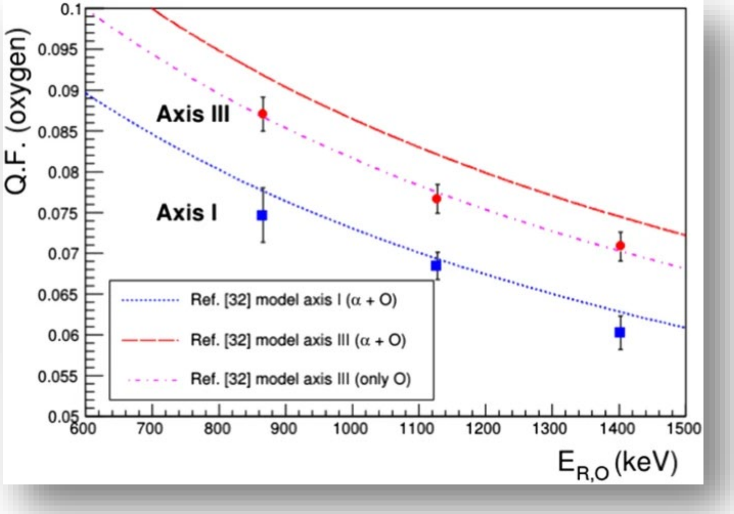


- Strategy: search for coincidence between a scattered neutron at a fixed angle and scintillation event in ZnWO$_4$ occurred in a well defined time window (ToF)
- Once fixed the θ angle, the recoil direction and energy are fixed
- Measurements performed at different θ angles

Energy distributions in ZnWO$_4$ for coincidence events when neutrons are identified in EJ-309 and two ToF windows are considered (θ=80°) to consider the **neutron induced recoils** and to characterize the **random coincidences**



First evidence at low energy



The anisotropy is significantly evident also for oxygen nuclear recoils in the energy region down to hundreds keV at **5.4 σ confidence level**.

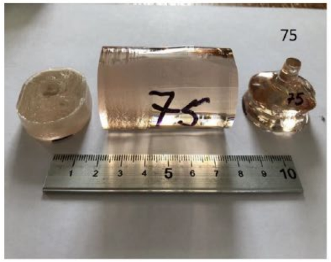
Optical and scintillation properties of advanced $ZnWO_4$ crystal scintillators

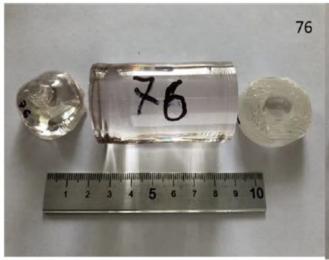
High optical and scintillation properties $ZnWO_4$ crystal scintillators were developed by using the **low-thermal gradient Czochralski technique** after an extended R&D that included variation of the compound stoichiometry, **using** of initial **WO_3** of **different producers** and **additionally purified**, utilization of **single** and **double crystallization with** and **without annealing** of the grown boules.

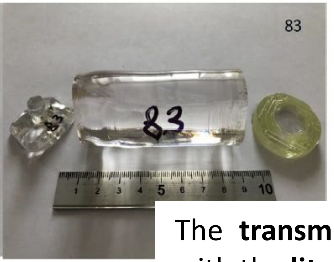
NIMA1029(2022)166400

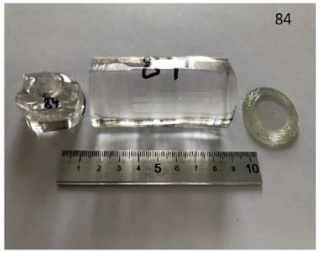
Table 1
The samples of $ZnWO_4$ crystals used in the present study and the boules of origin.

Crystal boule	Sample size (mm^3)	Number of crystallizations	WO_3 tungsten trioxide	Compound stoichiometry
No. 75	10 × 10 × 2 ⌀30 × 60	Double	NIIC II	+0.3% of WO_3
No. 76	10 × 10 × 2 ⌀30 × 60	Double	Nippon Tungsten Co., Ltd	+0.25% of ZnO
No. 83	10 × 10 × 2 ⌀30 × 60	Single, annealed	NIIC I	+0.15% of WO_3
No. 84	10 × 10 × 2 ⌀30 × 60	Single, annealed	NIIC I	Stoichiometric
No. 85	10 × 10 × 2 ⌀30 × 60	Single, annealed	Japan New Metals Co., Ltd	Stoichiometric
No. 91	⌀30 × 67	Single, annealed	NIIC I	Stoichiometric
No. 94	⌀30 × 31 ⌀30 × 32	Single, annealed	NIIC I	Stoichiometric





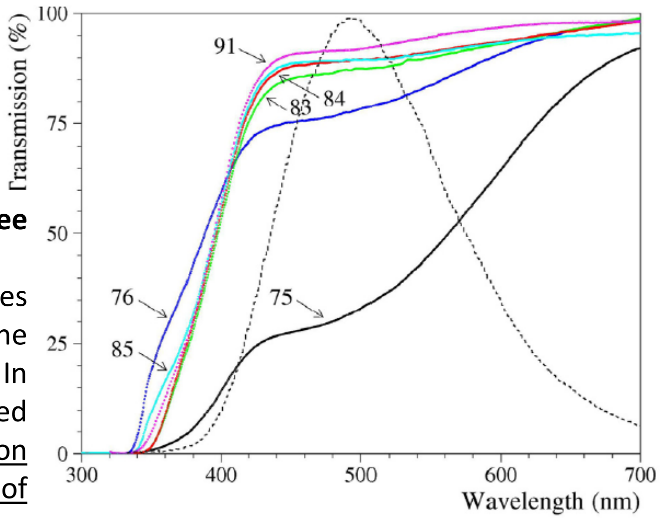




Several samples of tungsten oxide of different origin were utilized:

- **NIIC I**: synthesized at the NIIC (Nikolaev Institute of Inorganic Chemistry, Novosibirsk, Russia) with Si concentration <50 ppm and concentration of transition metals less than 1 ppm
- **NIIC II**: purified at the NIIC using an additional process of sublimation of tungsten chlorides;
- manufactured by **Nippon Tungsten** Co., Ltd. (Japan);
- manufactured by **Japan New Metals Co., Ltd** with a maximum Fe content <1 ppm and a maximum Mo content less than 10 ppm.

Optical transmission



The **transmission** spectra **agree** with the **literature** data.
However, the transmission varies substantially **depending** on the sample **production protocol**. In particular, the samples produced by double crystallization (samples 75, 76) are definitely of worse optical quality

Optical and scintillation properties of advanced $ZnWO_4$ crystal scintillators

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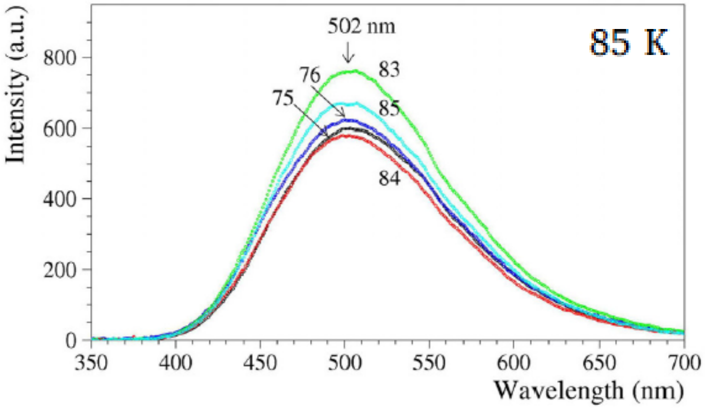
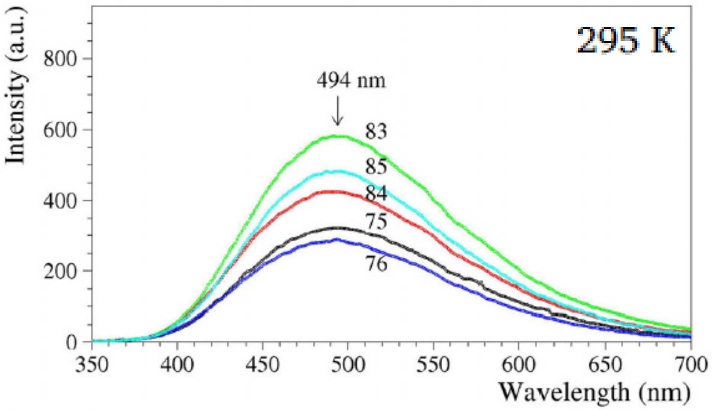
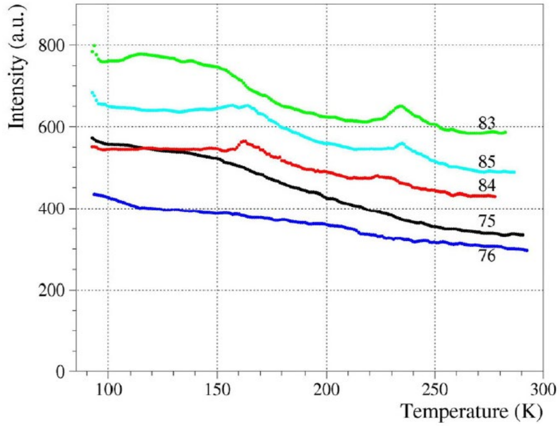
Luminescence under X-ray excitation and scintillation properties

Emission spectra under X-ray irradiation at 85 K and 295 K

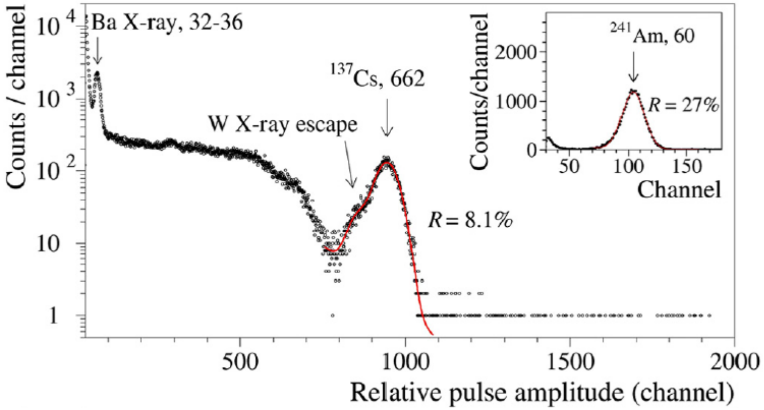


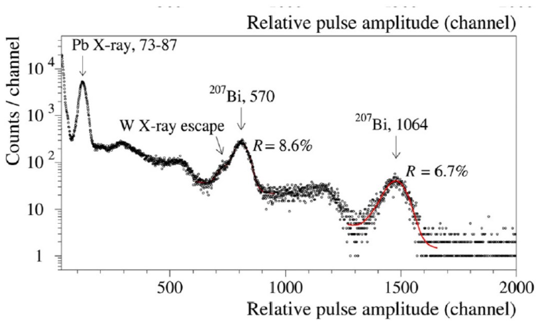


Bigger spread at 295 K
The difference can be explained by presence of non-radiative recombination centers (caused by defects of different nature) that compete with the radiative recombination centers.



The luminescence intensity increased with temperature decrease, in agreement with the data of other studies





The energy spectra of γ-ray quanta of ^{137}Cs and ^{207}Bi measured by scintillation detector with the $ZnWO_4$ crystal sample No. 84. Energy spectrum of γ-ray quanta of ^{241}Am is shown in Inset. Energy of X-ray and γ-ray quanta is in keV.

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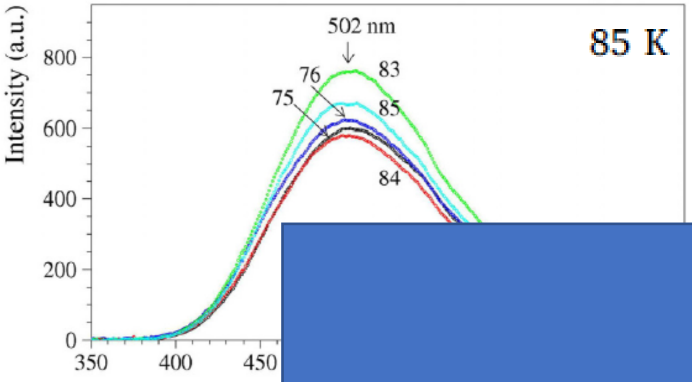
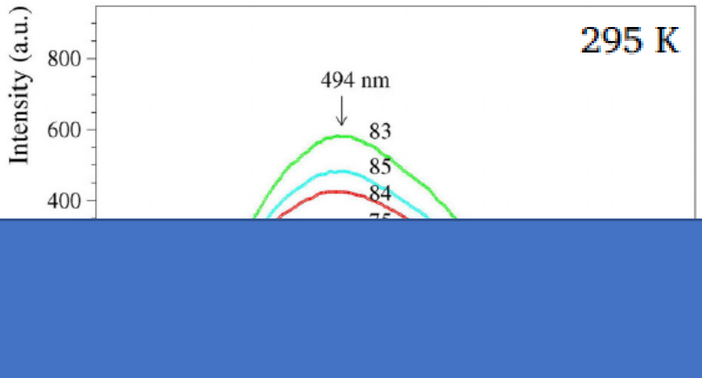
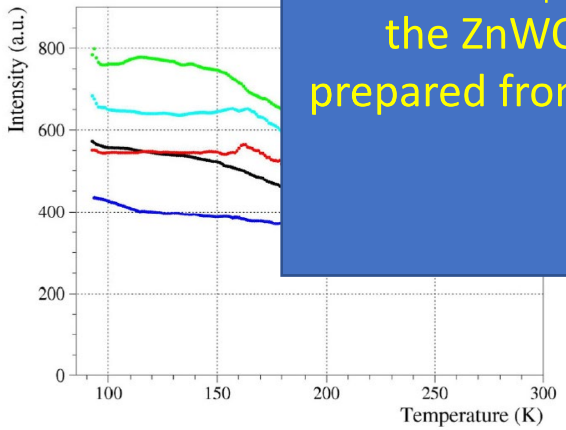




Bigger spread at 295 K
The difference can be explained by presence of non-radiative recombination centers (caused by defects of different nature)
e with the radiative
on centers.

The best optical and scintillation characteristics were obtained with $ZnWO_4$ crystal samples grown by **single crystallization** from the $ZnWO_4$ compound of the **stoichiometric composition** prepared from deeply purified WO_3, **annealed** in air atmosphere.



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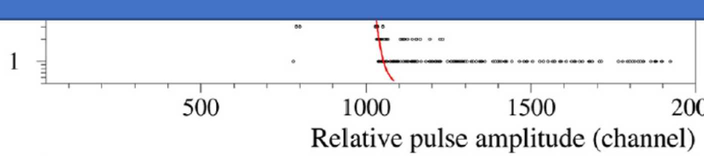

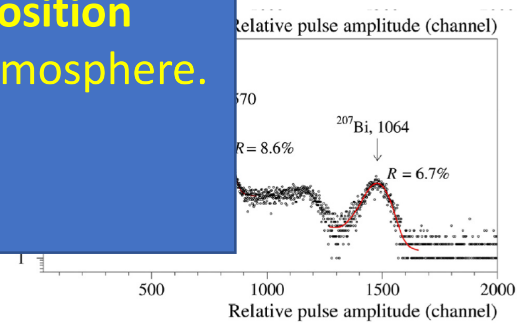

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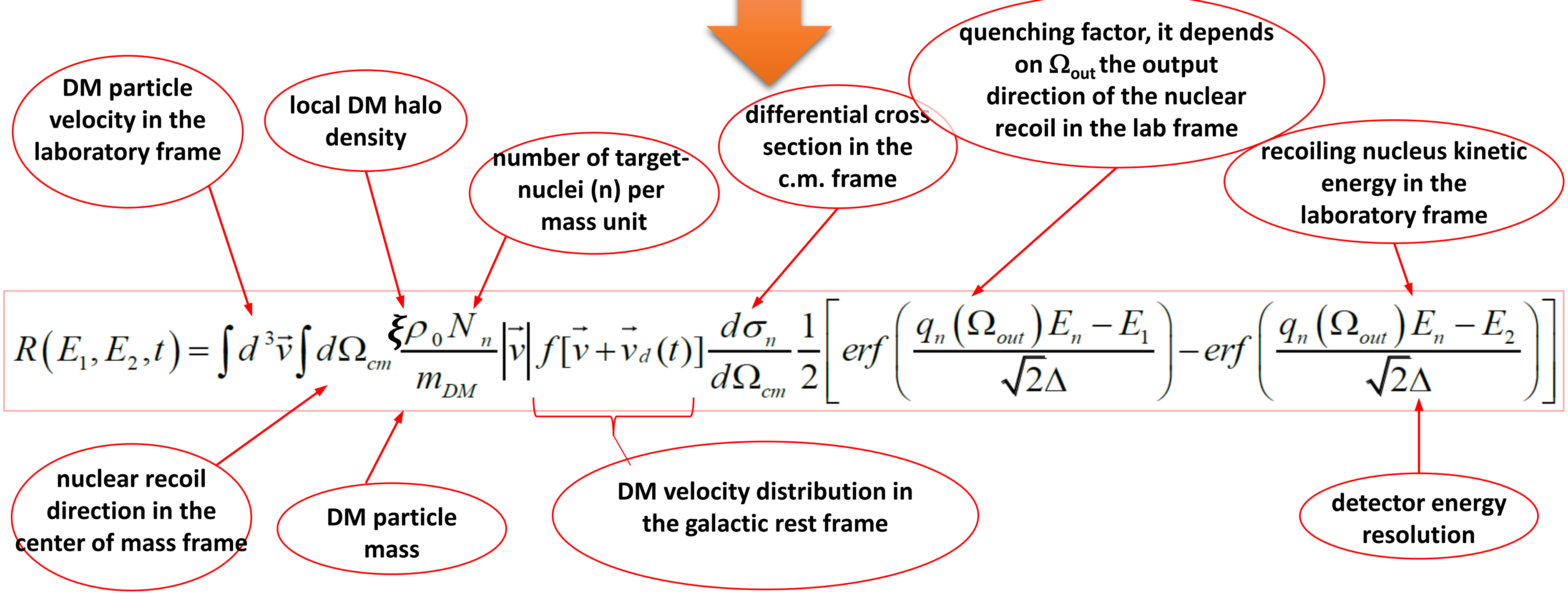
How can we profit of the anisotropic scintillator features?

As a consequence of the ***anisotropy light response for heavy particles***, recoil nuclei induced by the considered DM candidates could be discriminated from the background thanks to the expected variation of their low energy distribution along the day

The expected signal counting rate in the energy window (E1,E2) is a function of the time *t* ($v_d(t)$ the **detector velocity in the galactic rest frame**)



DM particle velocity in the laboratory frame

local DM halo density

number of target-nuclei (n) per mass unit

differential cross section in the c.m. frame

quenching factor, it depends on Ω_{out} the output direction of the nuclear recoil in the lab frame

recoiling nucleus kinetic energy in the laboratory frame

$$R(E_1,E_2,t)=\int d^3\vec{v}\int d\Omega_{cm}\frac{\xi\rho_0 N_n}{m_{DM}}\underbrace{|\vec{v}|\,f[\vec{v}+\vec{v}_d(t)]}\frac{d\sigma_n}{d\Omega_{cm}}\frac{1}{2}\left[erf\left(\frac{q_n(\Omega_{out})E_n-E_1}{\sqrt{2}\Delta}\right)-erf\left(\frac{q_n(\Omega_{out})E_n-E_2}{\sqrt{2}\Delta}\right)\right]$$

nuclear recoil direction in the center of mass frame

DM particle mass

DM velocity distribution in the galactic rest frame

detector energy resolution

NB: **Many quantities are model dependent,** and a model framework has to be fixed: in this example, for simplicity, a set of assumptions and of values have been fixed, **without considering** the effect of the existing **uncertainties** on each one of them and without considering other possible alternatives

… the model framework considered here

- a **simple spherical isothermal** DM halo model with **Maxwellian** velocity distribution, 220 km/s local velocity, 0.3 GeV/cm^3 **local density** (ρ_0) and 650 km/s escape velocity;
- DM with dominant **spin-independent coupling** and the following **scaling law** (DM-nucleus elastic cross section, σ_n, in terms of the DM elastic cross section on a nucleon, σ_p):

$$\sigma_n = \sigma_p \left(\frac{M_n^{red}}{M_p^{red}} \cdot A \right)^2 = \sigma_p \left(\frac{m_p + m_{DM}}{m_n + m_{DM}} \cdot \frac{m_n}{m_p} \cdot A \right)^2$$

- a simple exponential **form factor**:

$$F_n^2(E_n) = e^{-\frac{E_n}{E_0}} \qquad E_0 = \frac{3(\hbar c)^2}{2 m_n r_o^2} \qquad r_0 = 0.3 + 0.91\sqrt[3]{m_n}$$

Quenching factor adopted in the following example:

$$q_n(\Omega_{out}) = q_{n,x}\sin^2\gamma\cos^2\phi + q_{n,y}\sin^2\gamma\sin^2\phi + q_{n,z}\cos^2\gamma$$

where **$q_{n,i}$ is the quenching factor value for a given nucleus**, *n*, with respect to the ***i*-th axis** of the anisotropic crystal and Ω_{out} = *(γ,ϕ)* is the output direction of the nuclear recoil in the laboratory frame

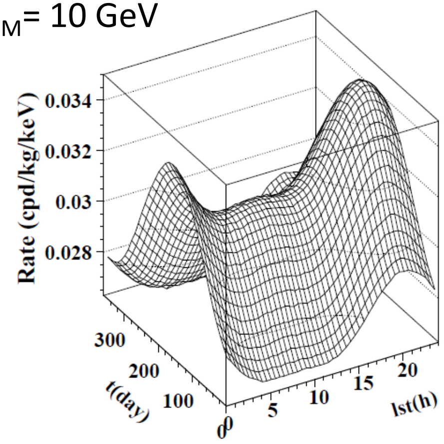
$q_{n,i}$ have been calculated following ref. [V.I. Tretyak, Astropart. Phys. 33 (2010) 40] considering the data of the anisotropy to α particles of the ZnWO$_4$ crystal

Energy resolution: $FWHM = 2.4\sqrt{E(keV)}$

Example of expected signal

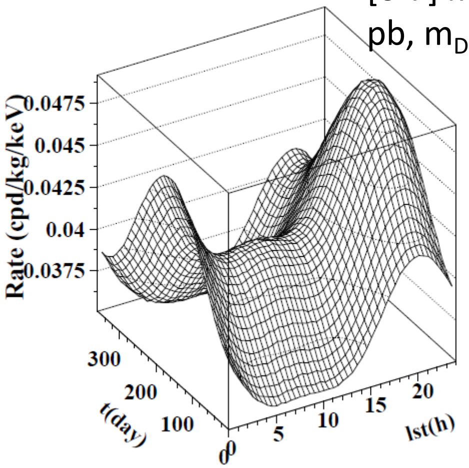
Expected rate as a function of sidereal time and days of the year

[2-3] keV σ_p=5×10^{-5} pb
m_{DM}= 10 GeV



Identical sets of crystals placed in the same set-up with different axis orientation will observe consistently different time evolution of the rate

[6-7] keV σ_p=5×10^{-5} pb, m_{DM}= 100 GeV



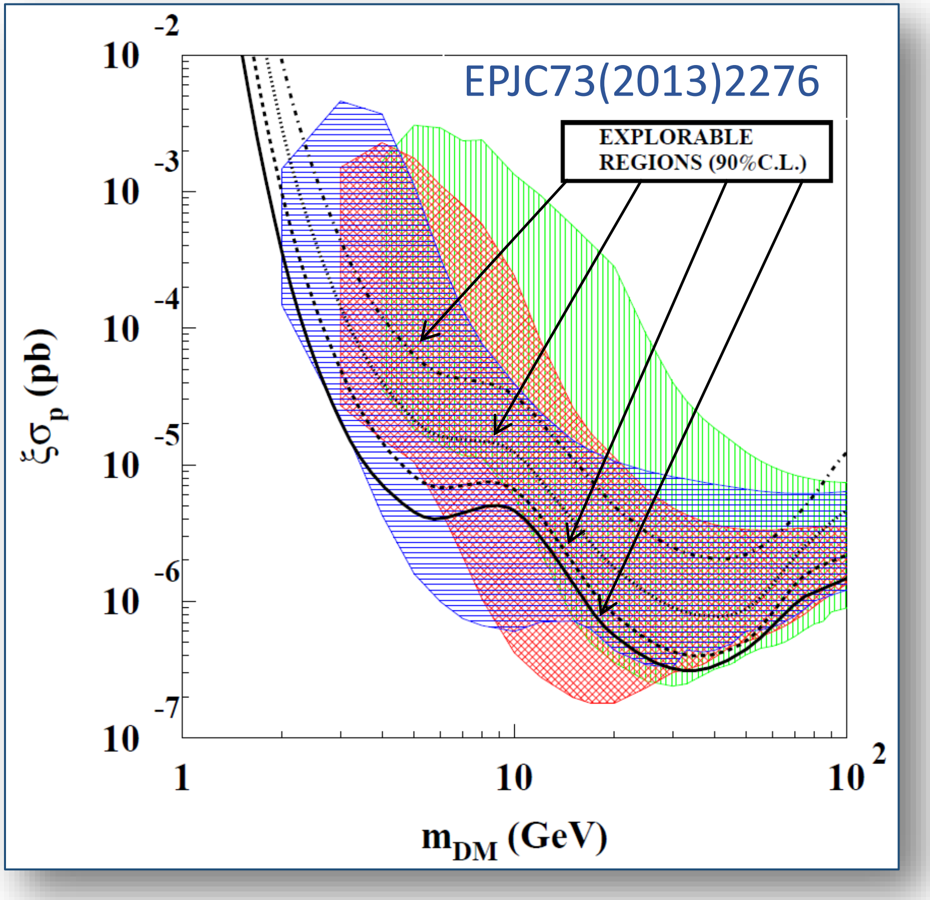
Eur. Phys. J. C 73 (2013) 2276

ADAMO project: example of reachable sensitivity in a given scenario

O → light masses
Zn, W → high masses

Assumptions:

- simplified model framework
- 200 kg of $ZnWO_4$
- 5 years of data taking
- 2 keVee threshold
- four possible time independent background levels in the low energy region:
  - 10^{-4} cpd/kg/keV ————
  - 10^{-3} cpd/kg/keV - - - - - - - -
  - 10^{-2} cpd/kg/keV ……………………
  - 0.1 cpd/kg/keV —·—·—·—

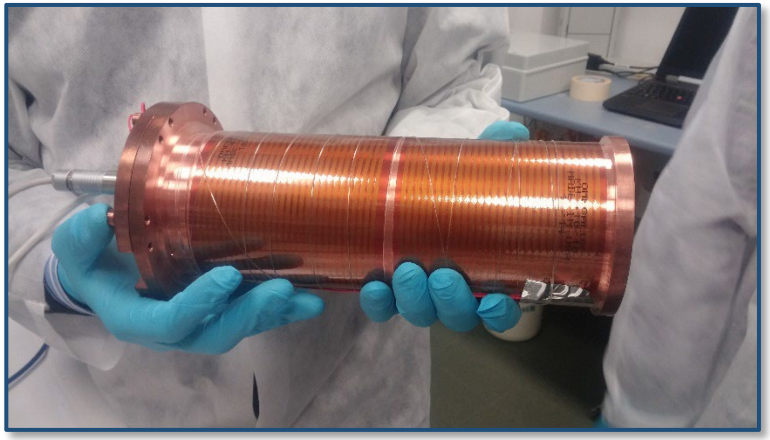


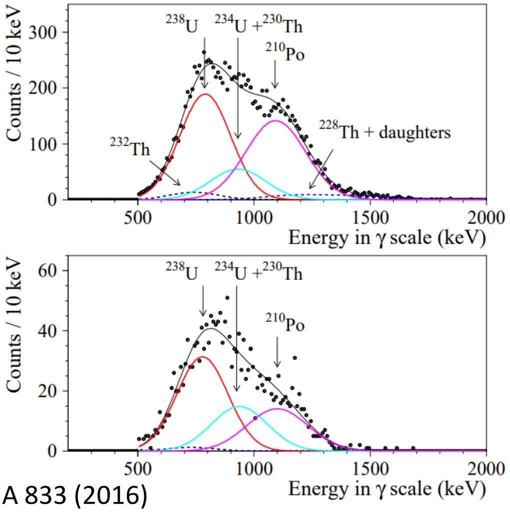
The directionality approach can reach in the given scenario a sensitivity to the cross section at level of 10^{-5} – 10^{-7} pb, depending on the particle mass

Allowed regions obtained with a corollary analysis of the 9.3σ C.L. DAMA model independent result in terms of scenarios for the DM candidates considered here (green (channeling), red(no-ch.) and blue (no ch. but QF energy depended))

$ZnWO_4$ – work in progress…

- ❖ A cryostat for low temperature measurement with scintillation detectors has been realized
- ❖ Test of the cryostat is in progress
- ❖ Lowering the energy threshold (new PMT with higher QE optimized to the fluorescence light emission and temperature operation)





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An example of the radio-purity improvements after the recrystallization

- ❖ New measurements of anisotropy at low energy with MP320 Neutron Generator (E_n = 14 MeV) at ENEA-Casaccia is ongoing
- ❖ Further improvement of the radio-purity

Conclusions

- Directionality Dark Matter experiments could obtain, with a completely different new approach, further evidence for the presence of DM candidates inducing nuclear recoils in the galactic halo and/or provide complementary information on the nature and interaction type of DM particle candidates.
- Several TPC-based detectors are in the R&D stage. Other potential ideas have shortly been listed.
- The anisotropic $ZnWO_4$ detectors are promising to investigate the directionality for DM candidates inducing nuclear recoils
- First evidence of anisotropy in the response of $ZnWO_4$ crystal scintillator to low energy nuclear recoils reported
- The data presented here confirm the anisotropic response of the $ZnWO_4$ crystal scintillator to α particles in the MeV energy region. The anisotropy is significantly evident also for oxygen nuclear recoils in the energy region down to some hundreds keV at 5.4 σ confidence level.