Study of Dark Matter with directionality approach using ZnWO$_4$ crystal scintillators

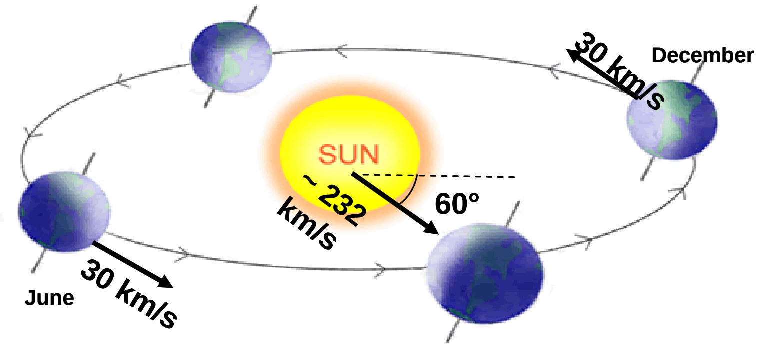
September 23rd – 27th , 2024 – Frascati, Roma, Hotel Villa Tuscolana

A. Leoncini [1,2], L.A. Afanasieva[3], P. Belli[1,2], R. Bernabei[1,2], Yu.A. Borovlev[4,5], F. Cappella[6,7], V. Caracciolo[1,2], R. Cerulli[1,2], N. Cherubini[9], F.A. Danevich[2,3], V. Ya. Degoda[8], A. Incicchitti [6,7], D. V. Kasperovych[3], Ya. P. Kogut[8], V. Merlo[1,2], G.P. Podust[8], O.G. Polischuk [3,6], A. G. Postupaeva[5], V. N. Shlegel[4] and V. I. Tretyak[3,10]

[1] Dipartimento di Fisica, Università di Roma 'Tor Vergata', I-00133 Rome, Italy
[2] INFN Sezione di Roma Tor Vergata, I-00133 Rome, Italy
[3] Institute for Nuclear Research of NASU, 03028 Kyiv, Ukraine
[4] Nikolaev Institute of Inorganic Chemistry, 630090 Novosibirsk, Russia
[5] CML Ltd, 630090 Novosibirsk, Russia
[6] INFN Sezione Roma, I-00185 Rome, Italy
[7] Dipartimento di Fisica, Università di Roma 'La Sapienza', I-00185 Rome, Italy
[8] Taras Shevchenko National University of Kyiv, 01601 Kyiv, Ukraine
[9] ENEA, Italian National Agency for New Technologies, Energy and Sustainable Economic Development, C.R. Casaccia, 00123, Rome, Italy
[10] INFN Laboratori Nazionali del Gran Sasso, 67100 Assergi (AQ), Italy

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.



- **<u>Model independent annual modulation</u>**: 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)

- **<u>Model independent diurnal modulation</u>**: due to the Earth revolution around its axis

  2nd order effect

- **<u>Diurnal variation</u>**: daily variation of the interaction rate due to the different Earth depth crossed by the Dark Matter particles

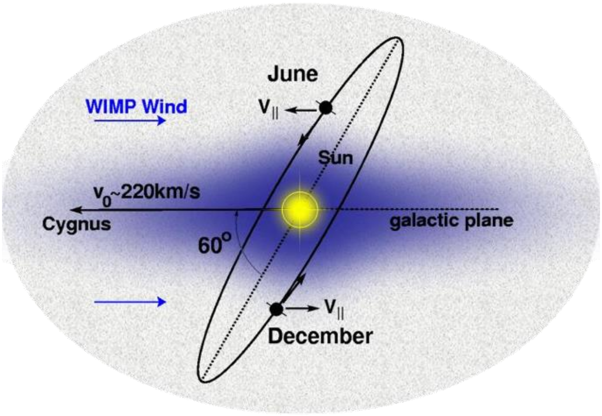
  only for high **cross sections**

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

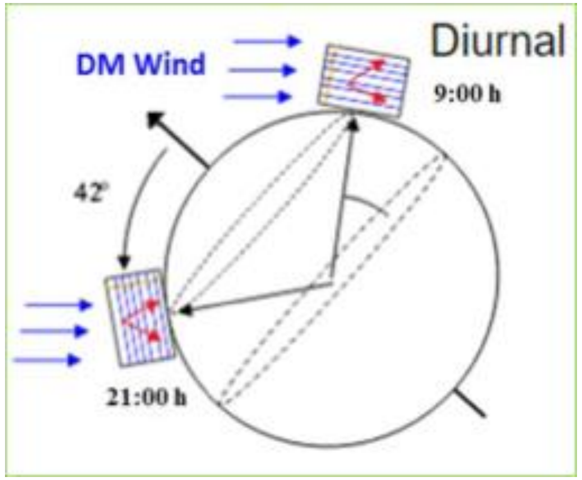
  <u>only for DM candidate particle inducing recoils</u>

The directionality approach

Based on the study of the correlation between the arrival direction of 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.
- Due to 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.
- The direction of the induced nuclear recoil is strongly correlated with that of the impinging DM particle.
- The observation of an anisotropy in the distribution of nuclear recoil direction could give evidence for such DM candidates.



A direction-sensitive detector is needed

Directionality techniques (R&D stage and ideas)

Tracking Detectors:

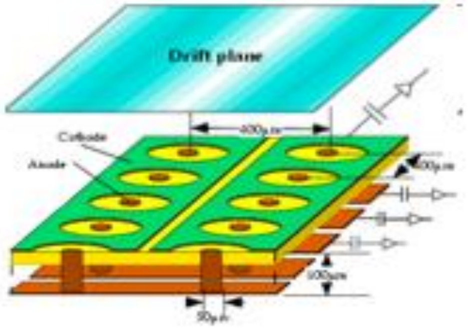
- LP-TPC (DRIFT, NIMAC, DMTTPC, NEWAGE, D3, NITEC, CYGNUS, INITIUM)
- Nuclear Emulsions (NEWSdm)
- Ideas: DNA, diamonds

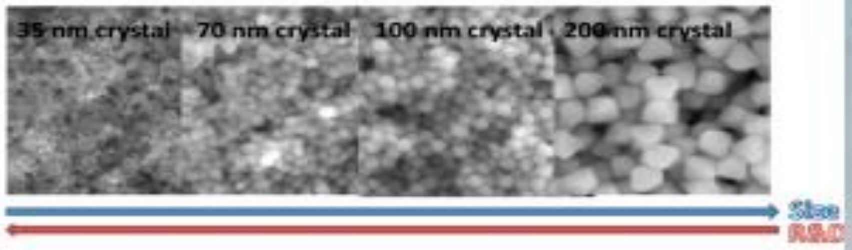
Detectors using Anisotropic Features:

- Anisotropic crystal scintillators (ADAMO)
- Carbon nanotubes based detectors (PTOLEMY)
- Columnar Recombination in LAr/LXe-TPC (RED)

In order to reach a significant sensitivity, a realistic detector experiment needs e.g.:

- **extreme operational stability**
- high radio-purity
- **high mass**
- great spatial resolution (for tracks' detection)
- low energy threshold
- …

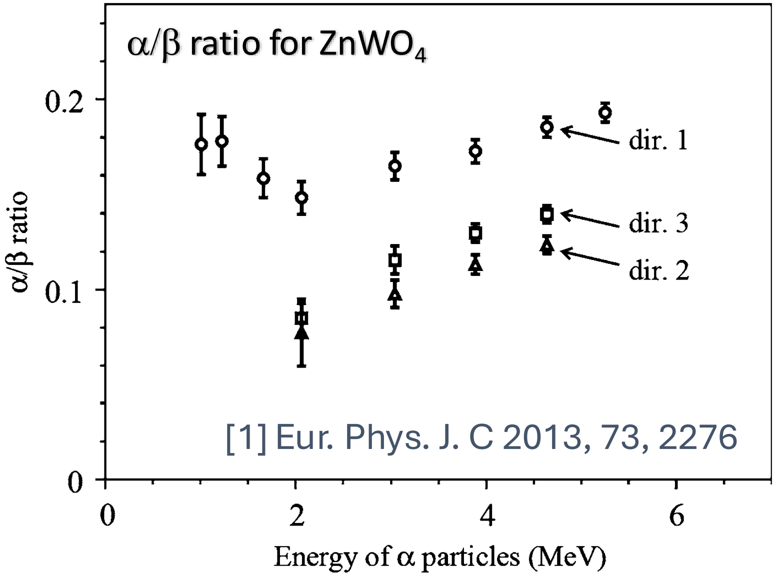




Anisotropic scintillators: $ZnWO_4$

- For **heavy particles** (p, α, nuclear recoils), 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:



[1] Eur. Phys. J. C 2013, 73, 2276

Advantages in the use of $ZnWO_4$ crystal scintillators:

- 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;

Some general properties	
Density (g/cm^3)	7.87
Melting point (°C)	1200
Light yield (ph/MeV)	7170
Wavelength of emission maximum (nm)	480
Refractive index	2.1-2.2
Effective average decay time (μs)	24

P. Belli et al. Eur. Phys. J. A 56 (2020) 83

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

In the framework of the ADAMO project, recent measurements were performed in order to verify the anisotropic response of a $ZnWO_4$ crystal scintillator to:

1. **α particles** : a small $ZnWO_4$ crystal ($10 \times 10 \times 10\, mm^3$, with mass of 7.99 g), irradiated by a collimated beam of α particles from an ^{241}Am source in the directions along the crystal axes I, II and III.
2. **Oxygen nuclear recoils**: neutron beam of 14 MeV produced by a neutron generator at ENEA-Casaccia.

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

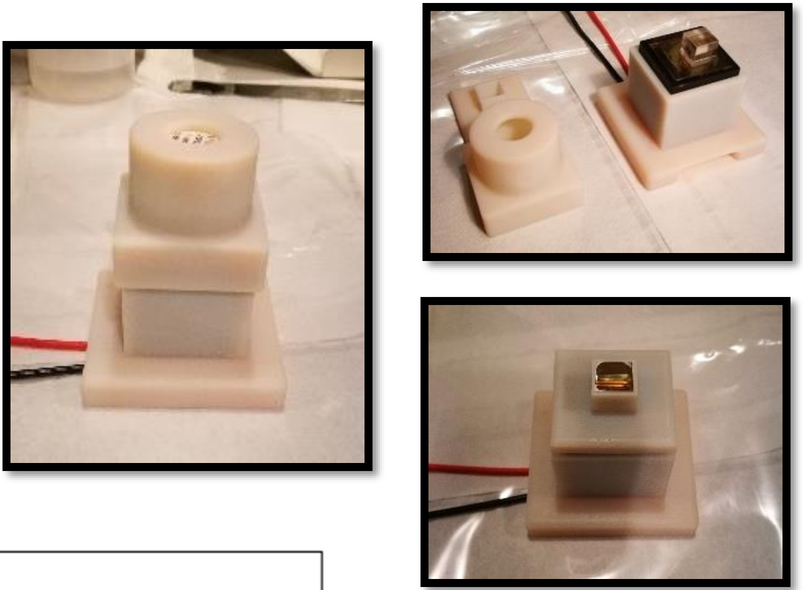
P. Belli et al. Eur. Phys. J. A 56 (2020) 83

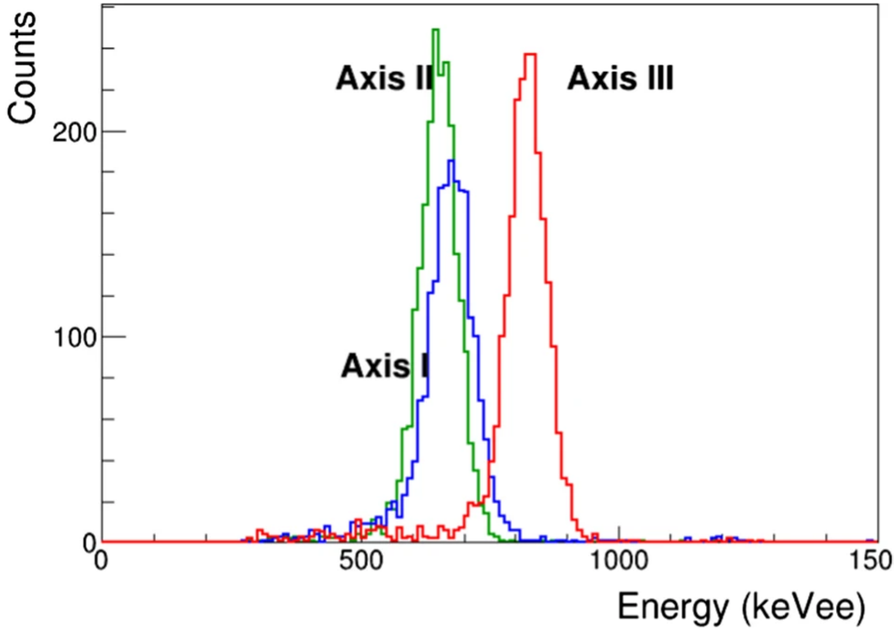
Studying the response of the $ZnWO_4$ with ^{241}Am α source

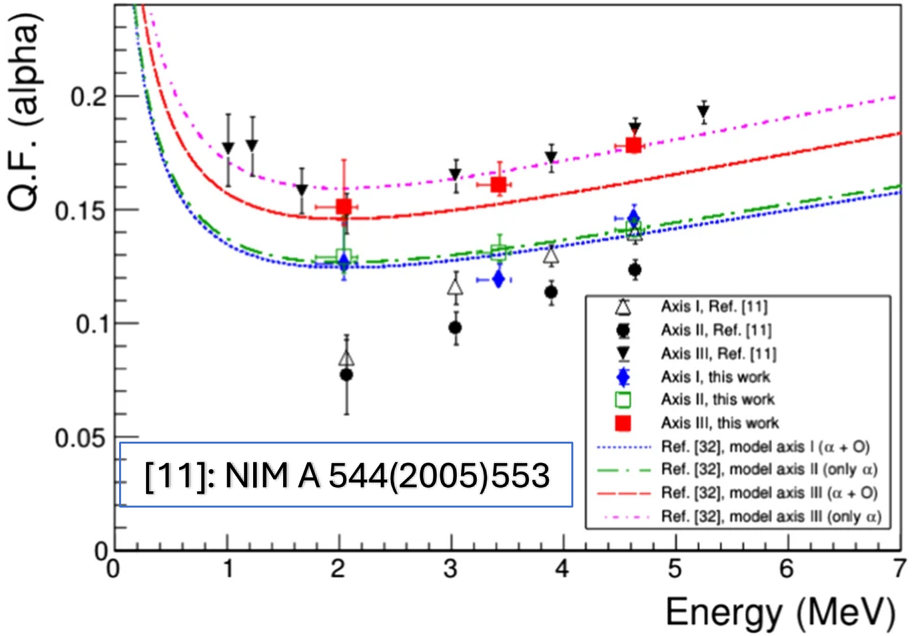
Calibration set-up:

- 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

- ➢ Crystal irradiated at the same time with γ (^{22}Na) and α (^{241}Am) sources along the three crystal axes.
- ➢ Different α energies obtained with Mylar foils and measured with Si detector.
- ➢ Very efficient PSD capability to discriminate α and γ.



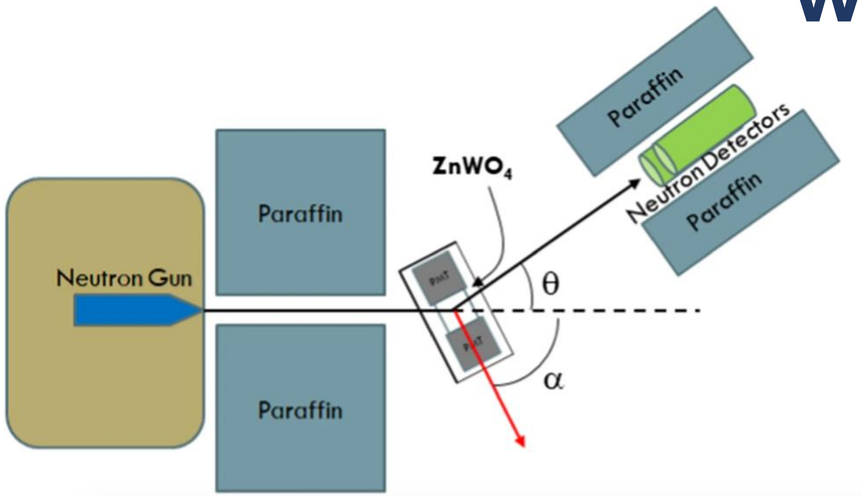




[11]: NIM A 544(2005)553

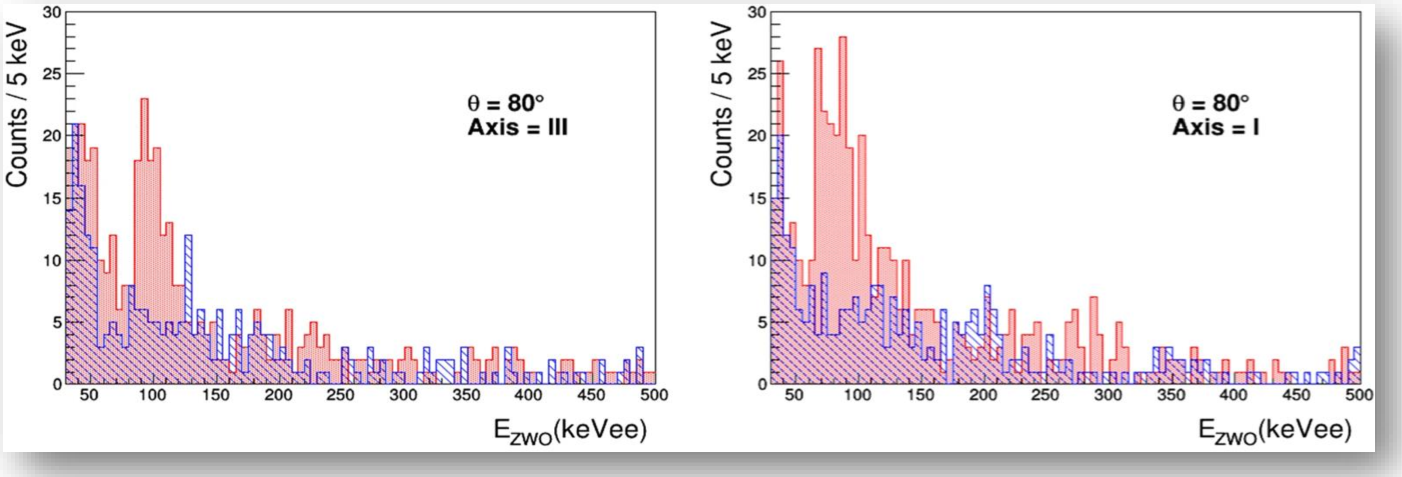
P. Belli et al. Eur. Phys. J. A 56 (2020) 83

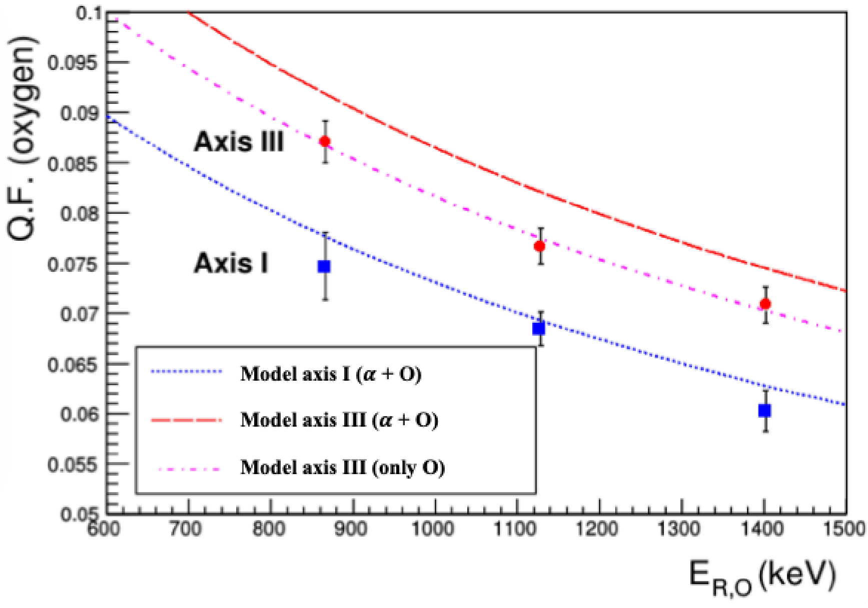
Studying the response of the $ZnWO_4$ with a neutron gun



- **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.

First evidence at low energy





The anisotropy is significantly evident also for oxygen nuclear recoils in the energy region down to 100 keV at **5.4 σ confidence level**.

P. Belli et al. NIMA1029(2022)166400

Optical and scintillation properties of advanced $ZnWO_4$ crystal scintillators

Developed by using the **low-thermal gradient Czochralski technique:**

- 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.

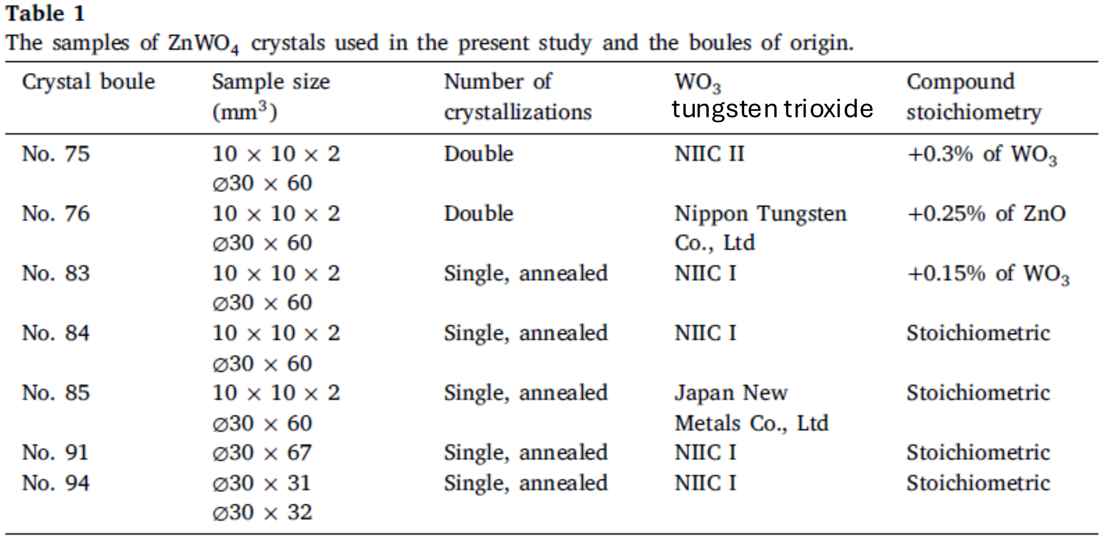
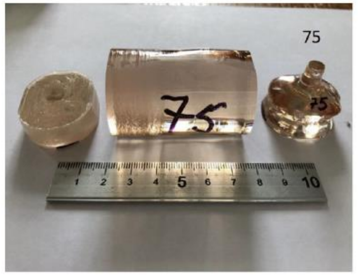
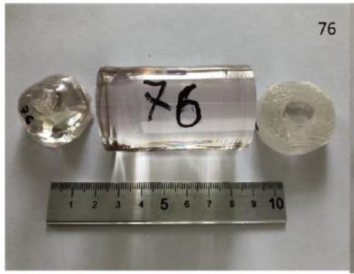
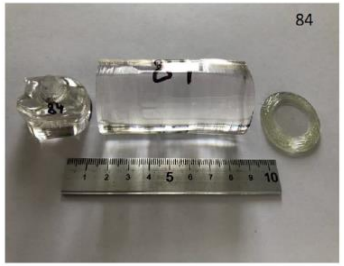


Table 1
The samples of $ZnWO_4$ crystals used in the present study and the boules of origin.

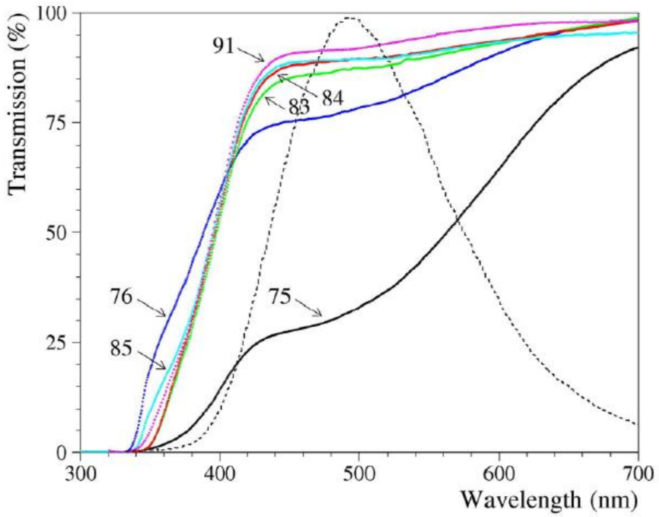
Crystal boule	Sample size (mm^3)	Number of crystallizations	WO_3 tungsten trioxide	Compound stoichiometry
No. 75	10 × 10 × 2 ⌀30 × 60	Double	NIIC II	+0.3% of WO_3
No. 76	10 × 10 × 2 ⌀30 × 60	Double	Nippon Tungsten Co., Ltd	+0.25% of ZnO
No. 83	10 × 10 × 2 ⌀30 × 60	Single, annealed	NIIC I	+0.15% of WO_3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







Optical transmission

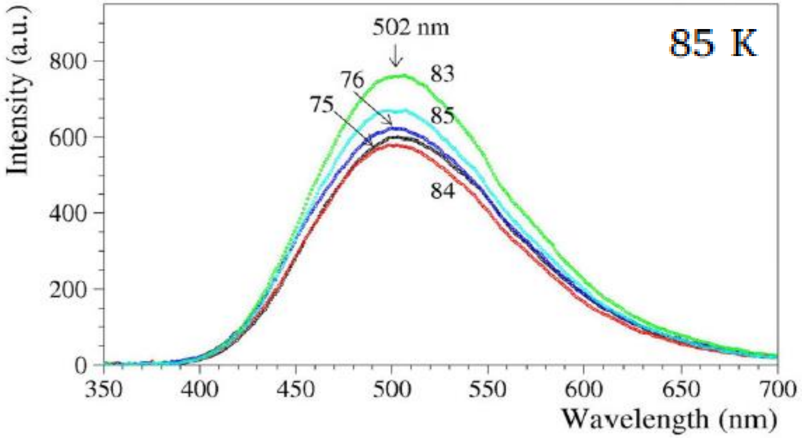


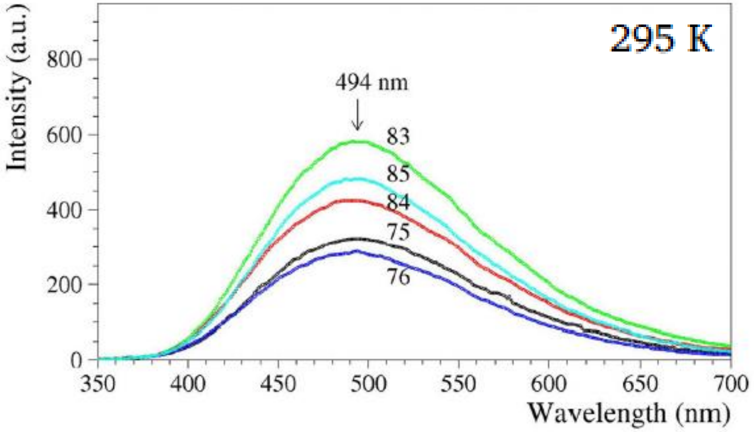
The **transmission** spectra **agree** with the **literature** data. However, the transmission varies substantially **depending** on the sample **production protocol**. In particular, the samples produced by <u>double crystallization (samples 75, 76) are definitely of worse optical quality</u>

P. Belli et al. NIMA1029(2022)166400

Optical and scintillation properties of advanced $ZnWO_4$ crystal scintillators

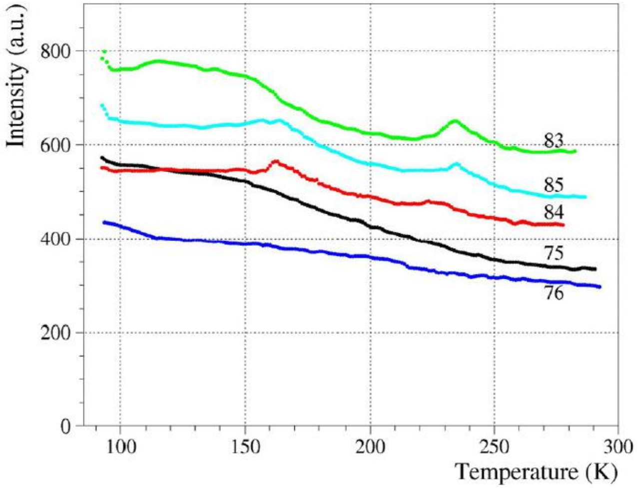
Luminescence under X-ray excitation and scintillation properties



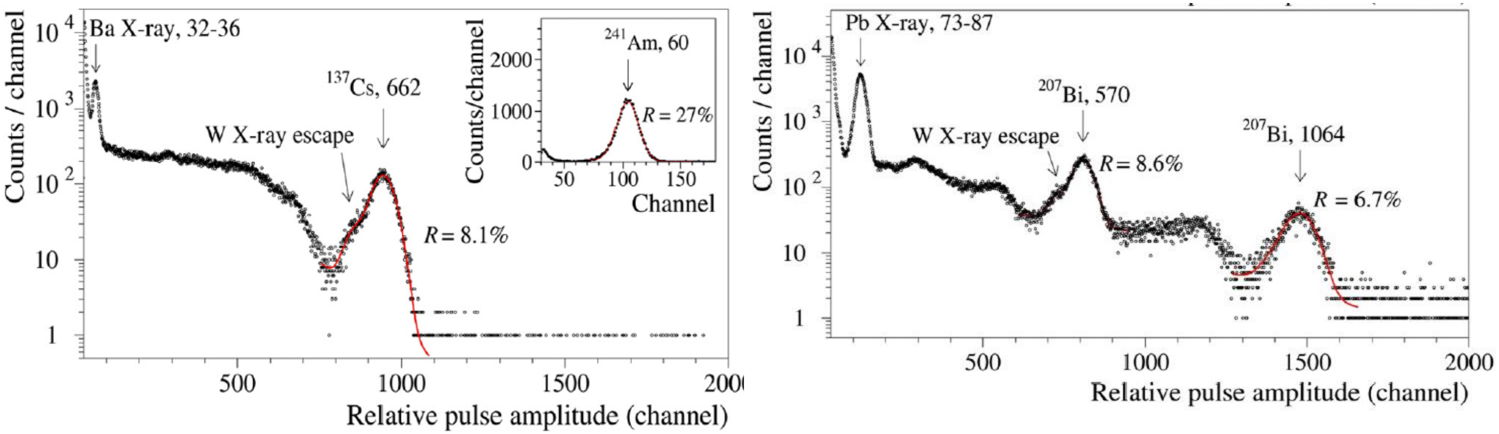


Bigger spread at 295 K

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.

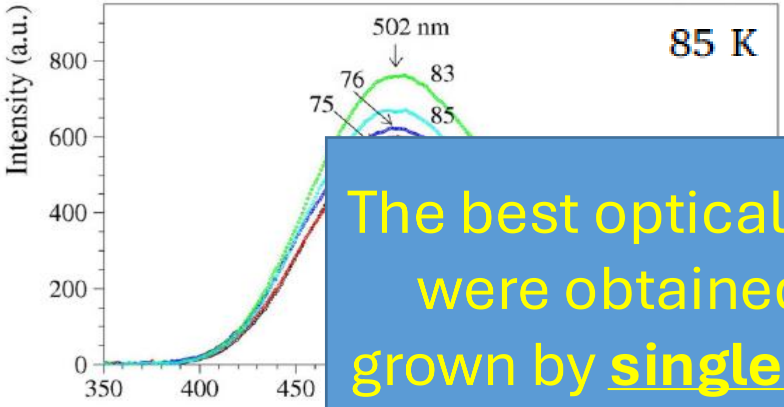


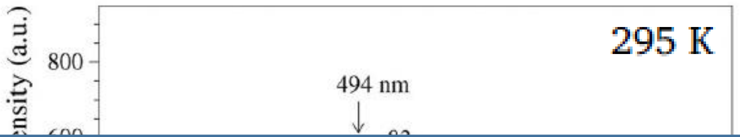
The energy spectra of γ-ray quanta of ^{137}Cs and ^{207}Bi measured by scintillation detector with the $ZnWO_4$ crystal sample No. 84.

P. Belli et al. NIMA1029(2022)166400

Optical and scintillation properties of advanced $ZnWO_4$ crystal scintillators

Luminescence under X-ray excitation and scintillation properties

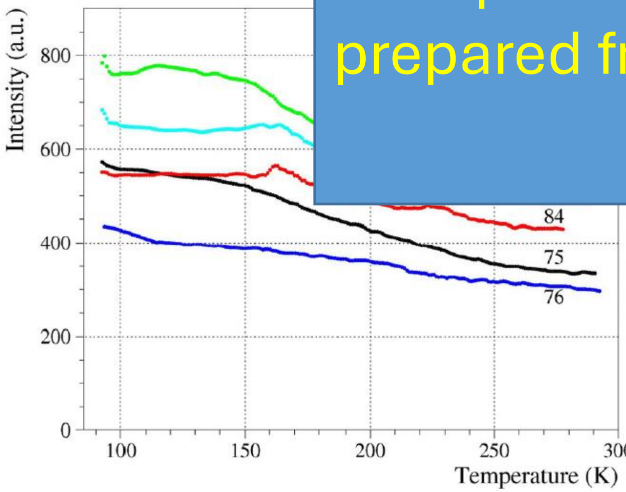




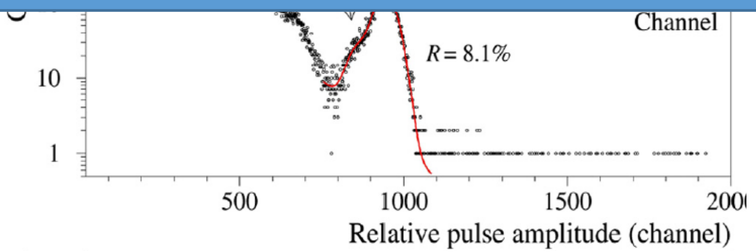
The best optical and scintillation characteristics were obtained with $ZnWO_4$ crystal samples grown by **single crystallization** from the $ZnWO_4$ compound of the **stoichiometric composition** prepared from deeply purified WO_3, **annealed** in air atmosphere.

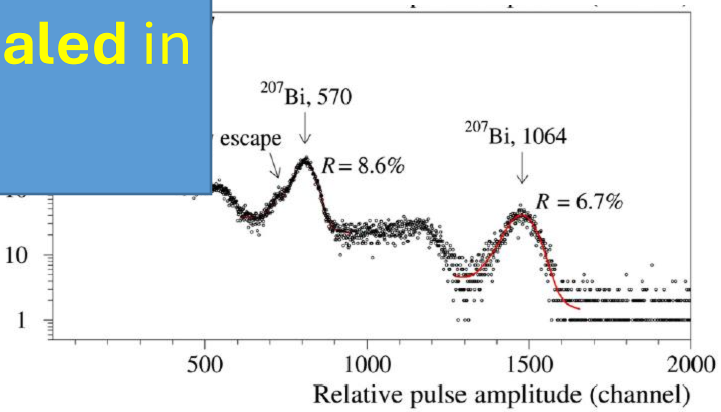
Bigger spread at 295 K

The difference can be ained by presence of radiative recombination ers (caused by defects of rent nature) that pete with the radiative mbination centers.



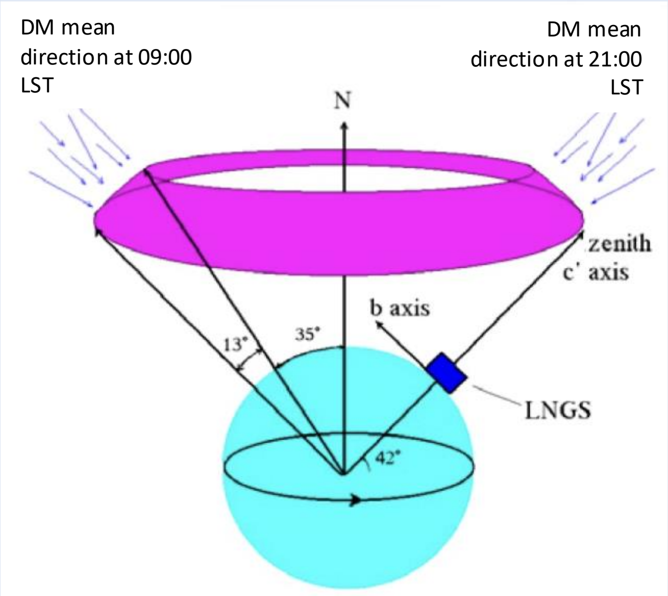
The luminescence intensity increased with temperature decrease, in agreement with the data of other studies.





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.

Example of expected signal



- It is very convenient to consider an experiment performed at the LNGS latitude (**42°27’N**):

❖ DM particles come mainly from the top at 21.00 h LST

❖ 12 h later they come from the North and parallel to the horizontal plane

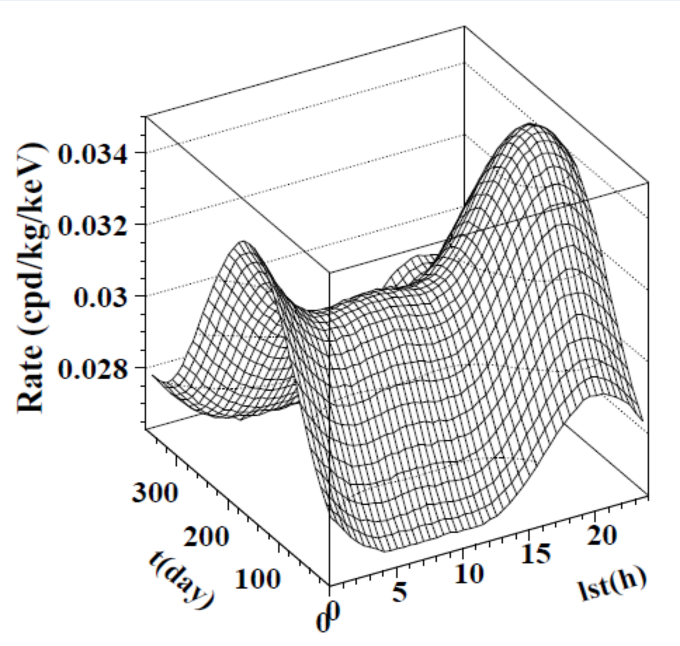
- If we arrange the $ZnWO_4$ crystal axis so that:

➢ The one with the largest light output is vertical and

➢ the one with the smallest light output points north

⇒ We obtain the maximum range of variability of the anisotropic detector response during a sidereal day

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



[2-3] keV
$\sigma_p = 5\times10^{-5}$ pb
m_{DM} = 10 GeV

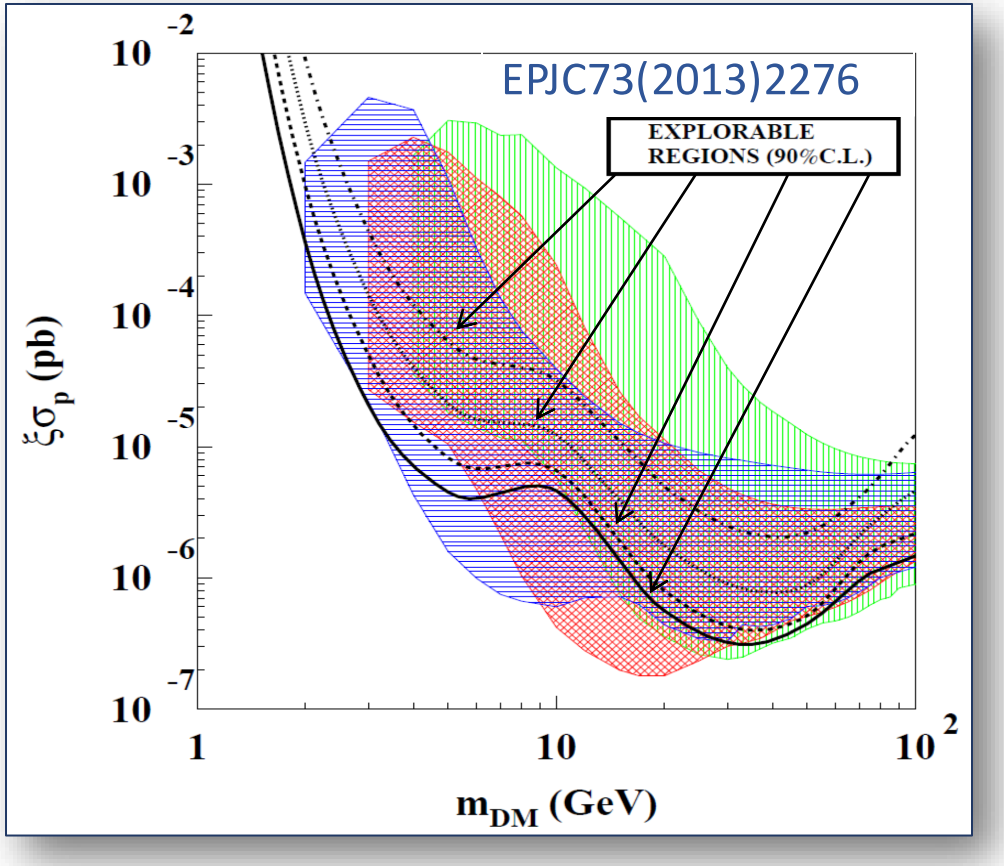
Absolute maximum rate is at day 152 and at 21h LST (when the DM flux is at maximum and the DM preferential arrival direction is near the zenith)

The ADAMO project: example of reachable sensitivity in a given scenario

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 —·—·—·—

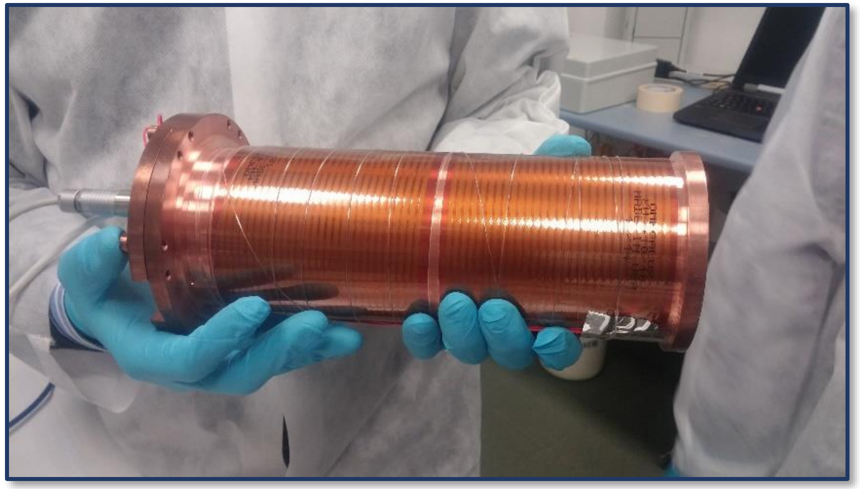

EPJC73(2013)2276

- 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 (green, red, blue) 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.

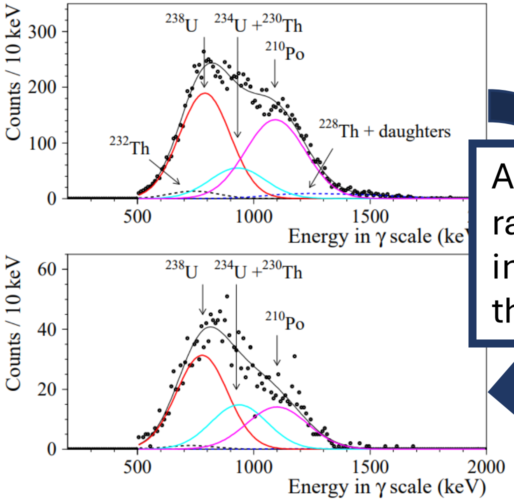
$ZnWO_4$ – work in progress...

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



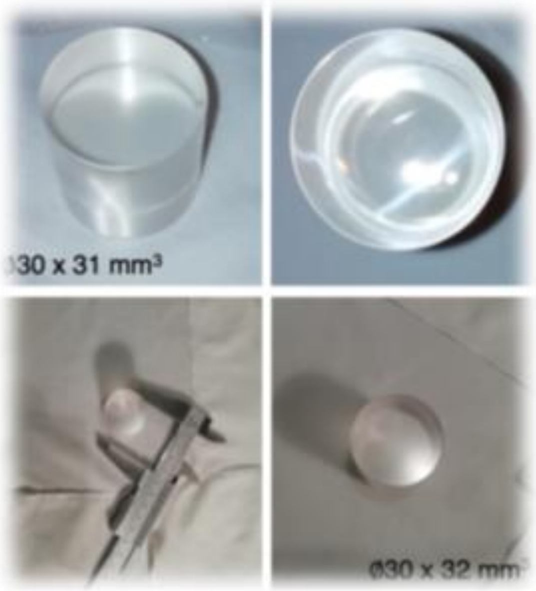
NIMA 833 (2016)

JINST 15 (2020) 05,C05055



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 are planned.
- Further improvement of the radio-purity.



Conclusions

- **Directionality Dark Matter experiments** could obtain 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.

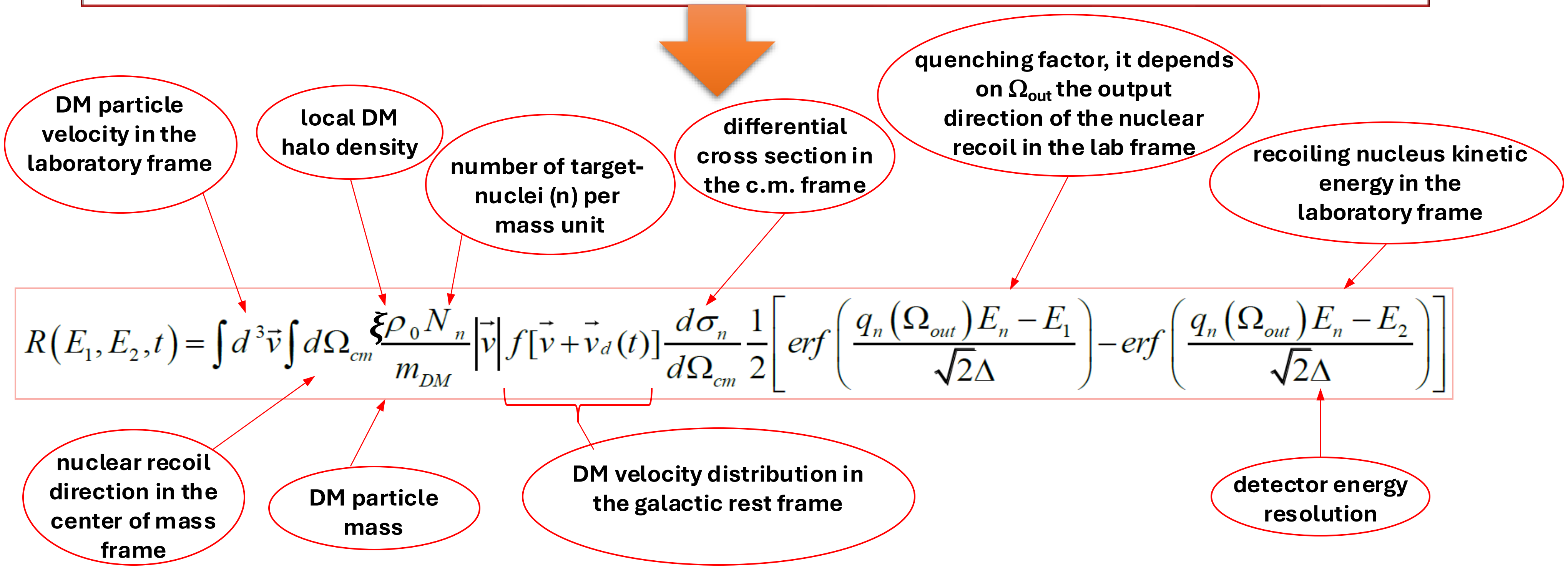
Thanks for attention!

BACKUP SLIDES

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

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

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 $\Omega_{out} = (\gamma,\phi)$ 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: $FWHM = 2.4\sqrt{E(keV)}$