Spokesperson:
Rita Bernabei

Anisotropic scintillators: the ADAMO project

R. Cerulli
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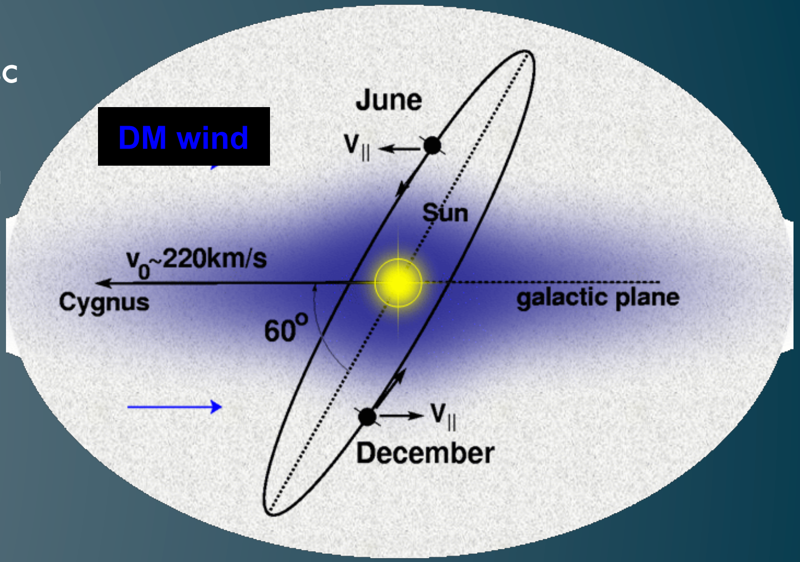
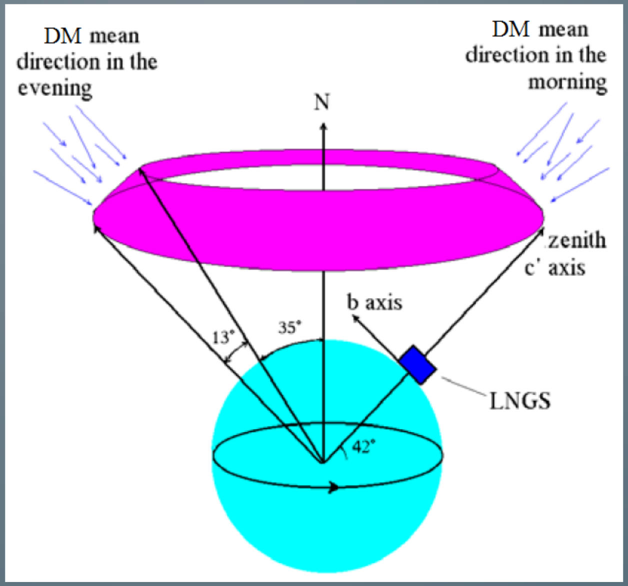
The directionality approach

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

The dynamics of the rotation of the Milky Way galactic disc through the halo of DM causes the Earth to experience a wind of DM particles apparently flowing along a direction opposite to that of solar motion relative to the DM halo





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

The **direction of the induced nuclear recoils** can offer a way for pointing out the presence of those particular candidates; in fact the direction of the recoiling nuclei are expected to be **strongly correlated** with the **impinging direction**, while the background events are not

Directionality sensitive detectors overcoming the track measurement difficulties: anisotropic scintillators

Study of the variation in the response of **anisotropic scintillation detectors** during sidereal day. In fact, **the light output and the pulse shape of these detectors depend on the direction of the impinging particles** with respect to the crystal axes

- The use of anisotropic scintillators to study the directionality signature was proposed for the first time in refs. [**P. Belli et al., Il Nuovo Cim. C 15 (1992) 475; R. Bernabei et al., Eur. Phys. J. C 28 (2003) 203**], where the case of anthracene detector was preliminarily analysed; some preliminary activities have been carried out [N.J.C. Spooner et al, IDM1997 Workshop; Y. Shimizu et al., NIMA496(2003)347]

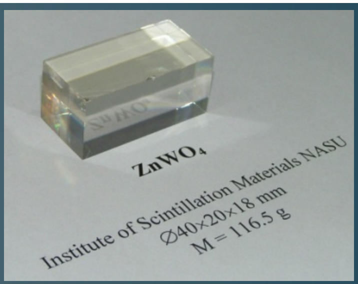
- In the comparison with the anthracene the **$ZnWO_4$ anisotropic scintillator** offers a higher atomic weight and the possibility to realize crystals with masses of some kg, with high level of radio-purity, with threshold at few keV feasible [**F. Cappella et al., Eur. Phys. J. C 73 (2013) 2276**]

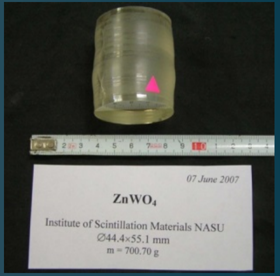
$ZnWO_4$ crystal scintillators in DAMA project

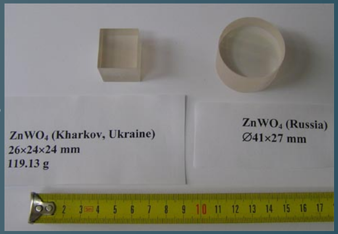
PLB658(2008)193, NPA826(2009)256
NIMA626-627(2011)31, JP38(2011)115107

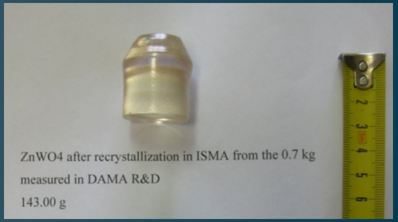
- Low background $ZnWO_4$ crystal scintillators with large volume and good scintillation properties realized (in collaboration with INR-Kiev)
- Various detectors with mass **0.1-0.7 kg** realized by exploiting different materials and techniques
- Detectors installed in a cavity (filled up with high-pure silicon oil) ϕ 47 x 59 mm in central part of a polystyrene light-guide 66 mm in diameter and 312 mm in length. The light-guides was faced by 2 low-background PMTs
- Main aim of the measurements was the study of the properties of $ZnWO_4$ and the search for 2β processes Zinc and Tungsten isotopes ($T_{1/2}$ ~10^{18} – 10^{21} yr)

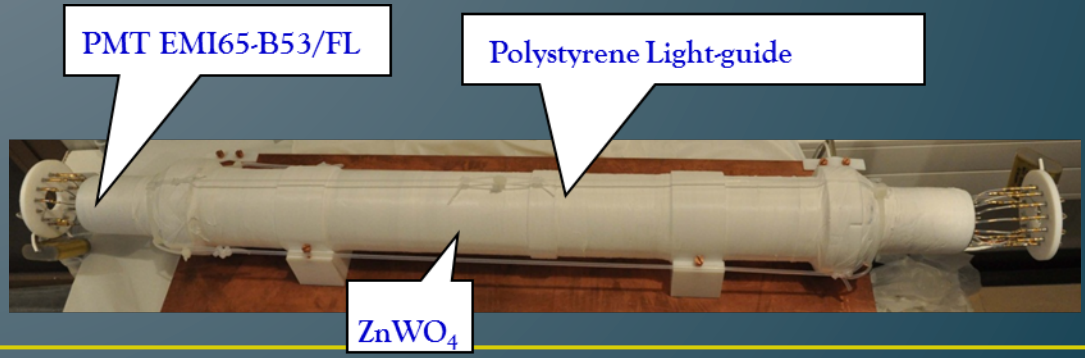
Crystal scintillator	Size (mm)	Mass (g)
ZWO-1	$20 \times 19 \times 40$	117
ZWO-2	$\oslash 44 \times 55$	699
ZWO-2a	$\oslash 44 \times 14$	168







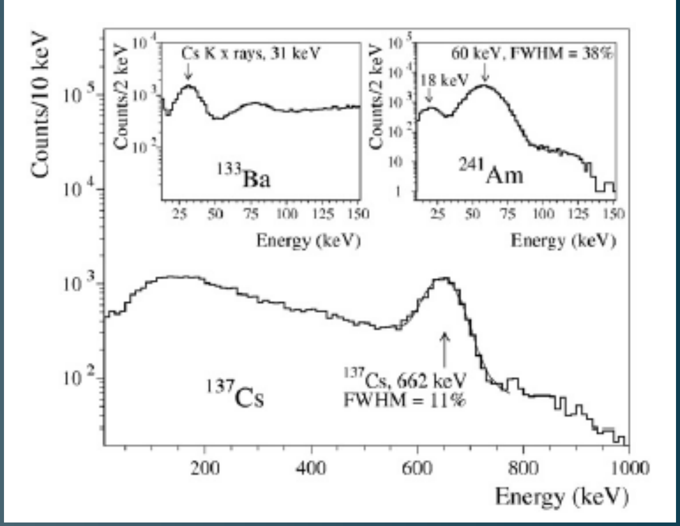




Performances of the $ZnWO_4$ crystal scintillator

➢ *Main characteristics*

Density (g/cm³)	*7.87*
Melting point (°C)	*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*

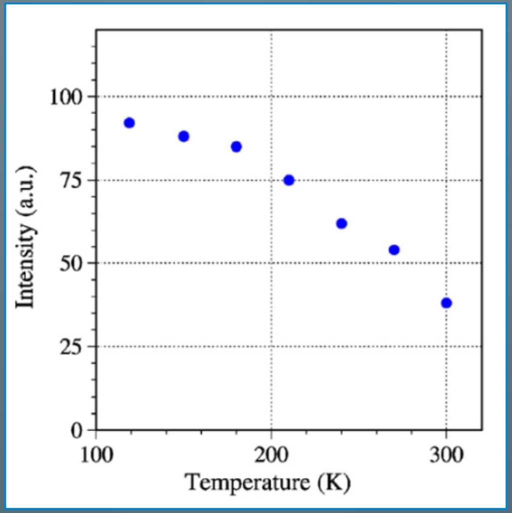


FWHM: (8.8–14.6)% @662 keV

➢ *Light yield and energy threshold*

An energy threshold of 10 keV has been used in a past experiment not optimized for the low energy region

H. Kraus et al., NIMA**600**(2009)594



- A competitive experiment for the DM investigation need a low energy threshold, that is:
  - Suitable light output (photoelectron/keV)
  - Efficient reduction of the residual noise near threshold
- Improvement of the energy threshold can be obtained e.g. by:
  - ✓ Optimization of crystal growth
  - ✓ coupling 2 PMTs in coincidence at single ph.e. level;
  - ✓ placing the crystal in silicone oil (light collection improvement ~40%);
  - ✓ using silicon photodiodes, APD, SiPM, etc.
  - ✓ decreasing the operational temperature of the $ZnWO_4$ scintillator;
  - ✓ or with a combination of the previous points
  - ✓ Low noise pre-amplifiers

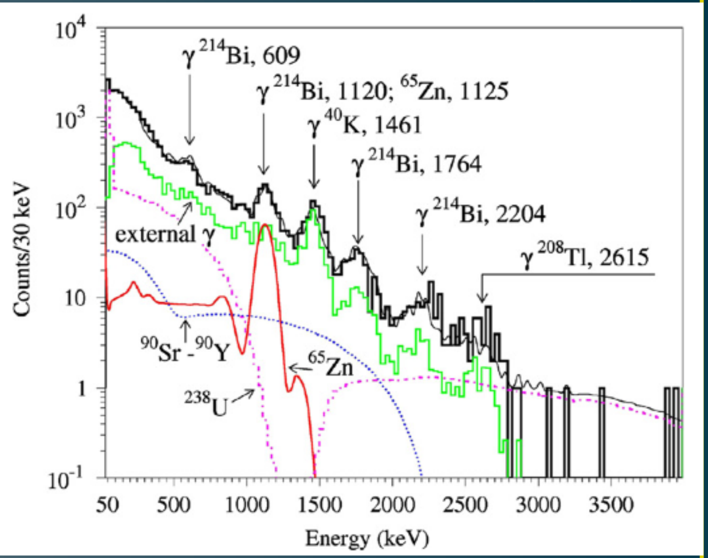
Performances of the $ZnWO_4$ crystal scintillator

NIMA 626(2011)31

- ***Radiopurity***

The measured radioactive contamination of $ZnWO_4$ approaches that of specially developed low background NaI(Tl):

- ~ 0.5 ppt for ^{232}Th;
- ~ 0.2 ppt for ^{238}U;
- < 0.02 mBq/kg for ^{40}K;
- total α activity of 0.18 mBq/kg



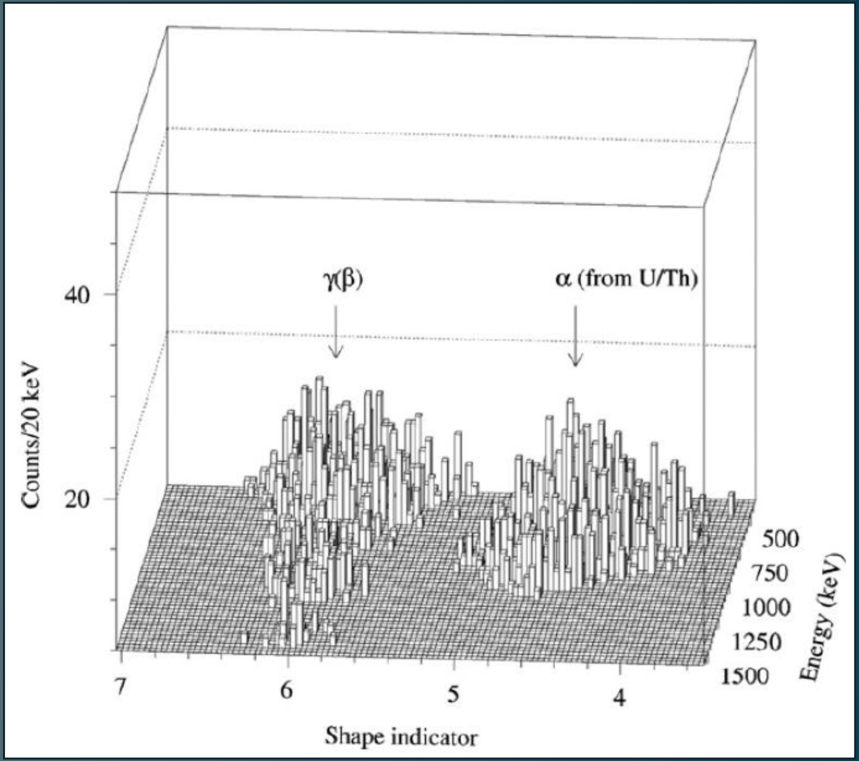
Run	Crystal	Size mass producer	t (h)	FWHM (%)	Background counting rate in counts/(day keV kg) in the energy intervals (MeV)		
					0.2–0.4	0.8–1.0	2.0–2.9
1	ZWO-1	20 × 19 × 40 mm 117 g ISMA [a]	2906	12.6	1.71(2)	0.25(1)	0.0072(7)
2	ZWO-2	⌀ 44 × 55 mm 699 g ISMA	2130	14.6	1.07(1)	0.149(3)	0.0072(4)
3	ZWO-3	⌀ 27 × 33 mm 141 g ISMA (re-crystallization of ZWO-2)	994	18.2	1.54(4)	0.208(13)	0.0049(10)
4	ZWO-4	⌀ 41 × 27 mm 239 g	834	14.2	2.38(4)	0.464(17)	0.0112(12)
5		NIIC [b]	4305	13.3	1.06(1)	0.418(7)	0.0049(4)

Developments is still ongoing: ⇒ future $ZnWO_4$ crystals with higher radiopurity expected

Performances of the $ZnWO_4$ crystal scintillator

- ***Pulse shape analysis***

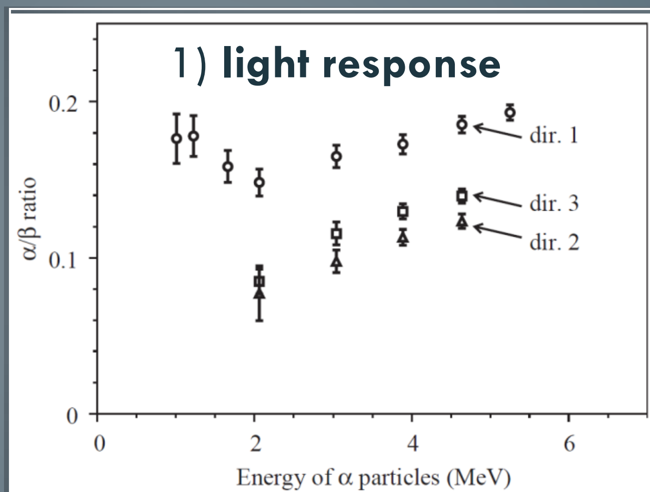
The dependence of the pulse shapes on the type of irradiation in the $ZnWO_4$ scintillator allows one to discriminate $\beta(\gamma)$ events from those induced by α particles and to identify the α background



Anisotropic features of $ZnWO_4$

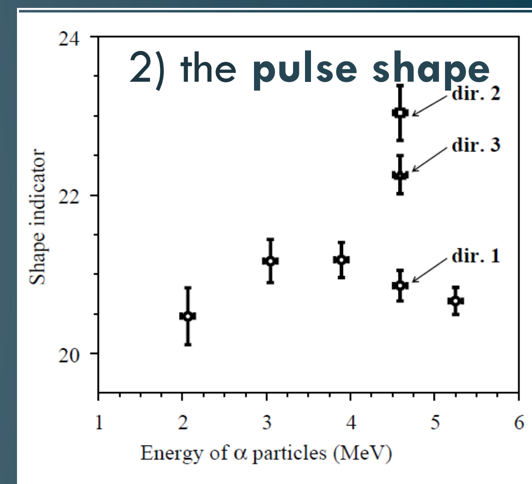
The reachable sensitivity of the directionality approach depend on the anisotropic features of the detectors in response to the low energy nuclear recoils induced by the DM candidates considered here

Measurements with α particles have shown that the 1) **light response** and 2) the **pulse shape** of a $ZnWO_4$ depend on the impinging direction of α particles with respect to the crystal axes



Such effects are absent in case of electron excitation

(010), (001) (100) crystal planes (directions 1, 2, 3)



These anisotropic effects are ascribed to preferred directions of the excitons' propagation in the crystal lattice affecting the dynamics of the scintillation mechanism

Similar effect is expected in the case of low energy nuclear recoils

$\Rightarrow$ Dedicated measurements are in preparation

Anisotropic features 1) and 2) of the ZnWO4 detectors can provide two independent ways to exploit the directionality approach

Next steps

- Measurements of anisotropy at low energy with neutrons source
- Production of higher mass crystals (fino a 8 kg, 8x20cm)
- Measurements of their radioactivity, new growth and handling protocols
- Measurement of the light output as a function of temperature
- Lowering the energy threshold (new PMT with higher QE, SiPM, APD, SDD,…)
- Development of electronics

Signal rate in a given scenario

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

As a consequence of the ***light response anisotropy***, 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

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

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 very simplified 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:

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

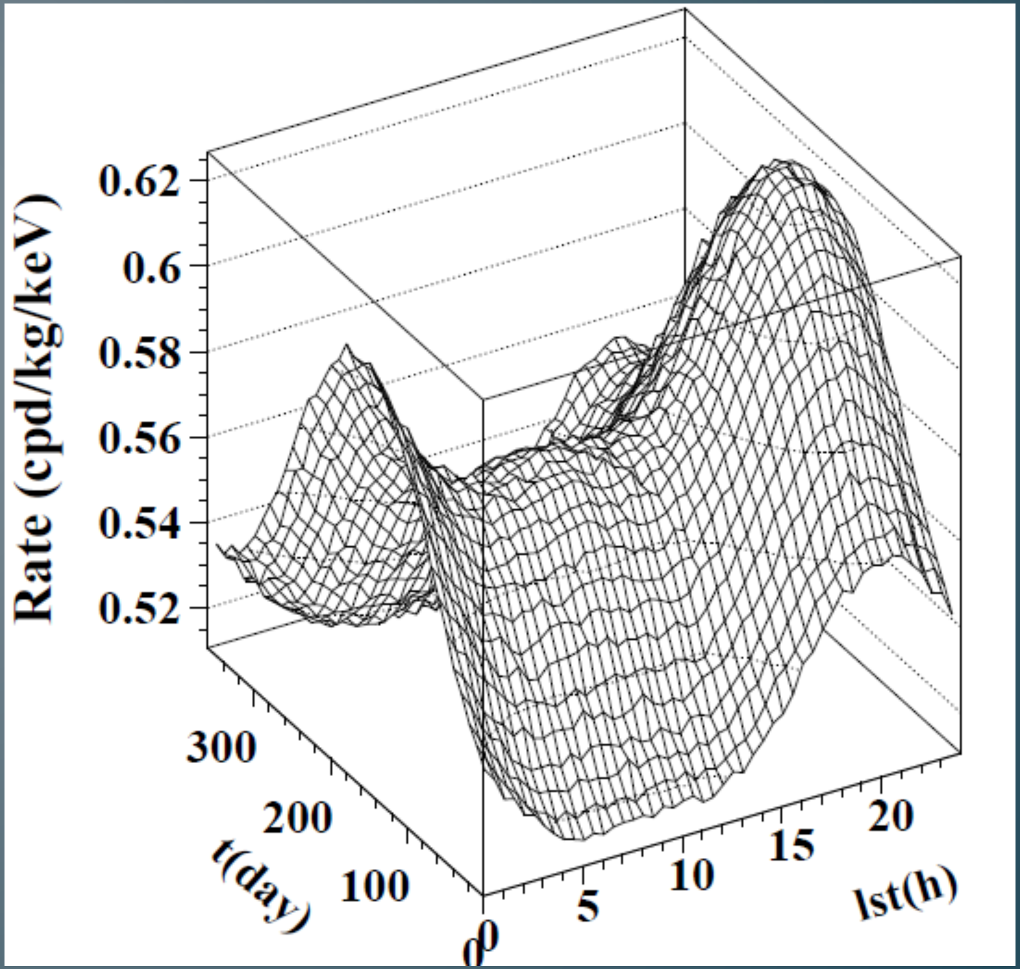
where $q_{n,i}$ is the quenching factor value for a given nucleus, *n*, with respect to the *i*-th axis of the anisotropic crystal and $\Omega_{out} = (\gamma,\phi)$ is the output direction of the nuclear recoil in the laboratory frame

$q_{n,i}$ 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: $FWHM = 2.4\sqrt{E(keV)}$

Example of the expected signal in the simplified model considered here

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



[2-3] keV

$\sigma_p = 5\times10^{-5}$ pb

m_{DM} = 50 GeV

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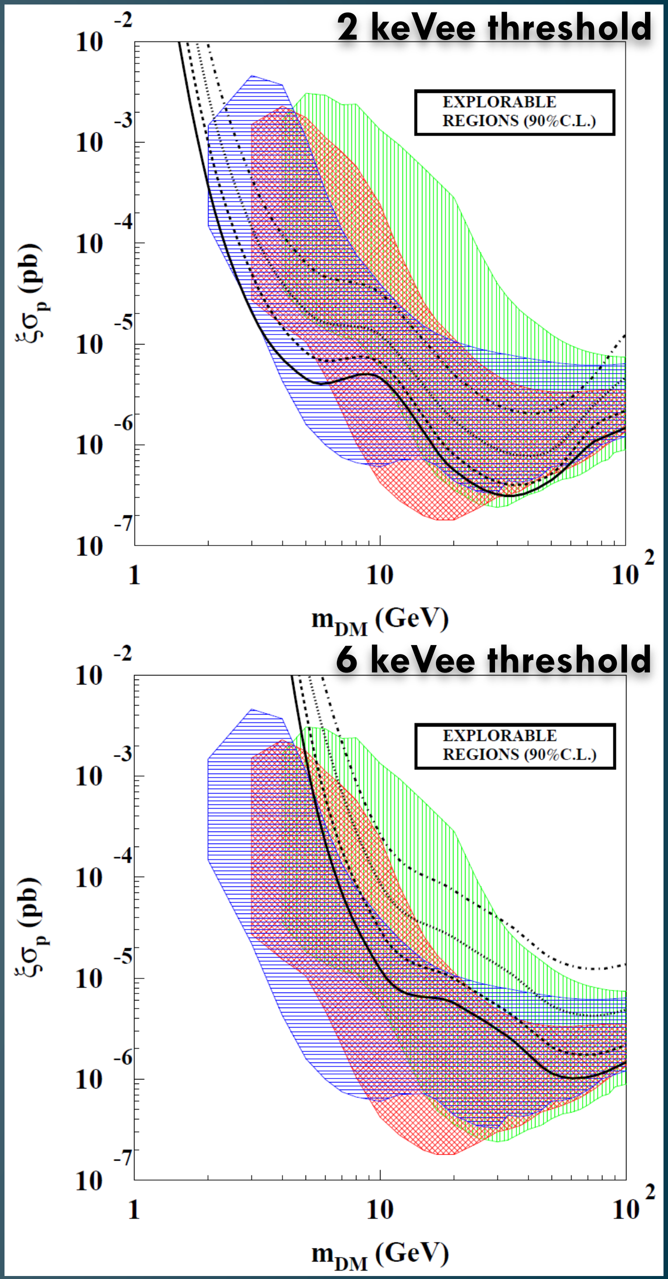
Example of the reachable sensitivity calculated considering the above mentioned simplified model framework for an experiment with:

- 200 kg of ZnWO4
- 5 years of data taking
- 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 —·—·—·



Here the allowed region of DAMA/LIBRA (obtained with the data of the DAMA/NaI and the first 6 annual cycles of DAMA/LIBRA) are reported as obtained by considering, in the case of DM candidate inducing just nuclear recoils, various model frameworks and uncertainties (see PRD84(2011)055014)

Note that DAMA/NaI & DAMA/LIBRA-phase1 have given a model independent evidence for the presence of DM particle in the Galactic halo at 9.3σ C.L.

Conclusions

- Anisotropic $ZnWO_4$ is a promising detector to investigate the directionality for those DM candidates inducing just nuclear recoils

- Several developments are needed

- The use of anisotropic scintillators could represent a first realistic attempt to investigate with the directionality approach the DM candidate inducing just nuclear recoil