DAMA collaboration
& INR-Kiev
http://people.roma2.infn.it/dama

A Solid Technique to Investigate Directionality

CYGNUS-TPC kick-off meeting:
a mini-workshop on directional Dark Matter searches and coherent neutrino scattering

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INTRODUCTION

- The development of low-background anisotropic detectors is of great interest in many applicative fields. In particular, they can offer a unique way to further investigate those Dark Matter (DM) candidate particles able to Induce just nuclear recoils, through the so-called directionality approach.

- In this talk the possibility of a low background pioneer experiment (named ADAMO: Anisotropic detectors for DArk Matter Observation) to exploit deep underground the directionality approach by using anisotropic $ZnWO_4$ scintillators is discussed.

DIRECT DETECTION EXPERIMENTS

- **The direct detection experiments can be classified in two classes, depending on what they are based**:

1. on the identification of the signals due to Dark Matter particles by using a **model-independent signature**

2. on the use of **uncertain techniques of subtractions of the e.m. component of the counting rate**; in this case you have to face some facts:

    - systematics in the data selections, in statistical discrimination and in rejection procedures difficult to estimate at the needed sensitivity

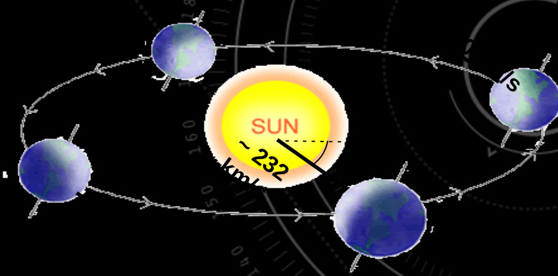
    - e.m. component of the rate can contain the signal or part of it

    - even assuming pure recoil case and ideal discrimination the result will NOT be the identification of the presence of WIMP elastic scatterings as DM signal, because of the well known existing recoil-like undistinguishable background

Therefore, even in the ideal case an "excellent suppression of the e.m. component of the counting rate" can not provide a "signal identification"

A model independent signature is needed

EXPERIMENTAL SIGNATURES



Model independent annual modulation Annual variation of the interaction rate due to Earth motion around the Sun

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

2^{nd} order effect

... WHEN ASSUMING A DM CANDIDATE INDUCING JUST NUCLEAR RECOILS:

Earth Shadow Effect Daily variation of the interaction rate due to different Earth depth crossed by the Dark Matter particles

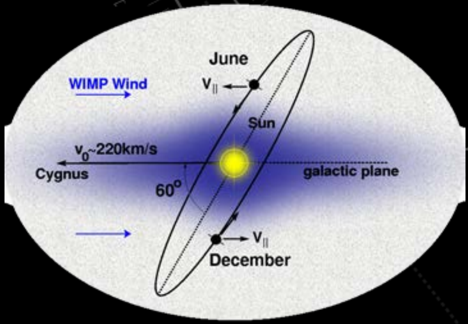
only for high σ

Directionality Correlation of Dark Matter impinging direction with Earth's galactic motion

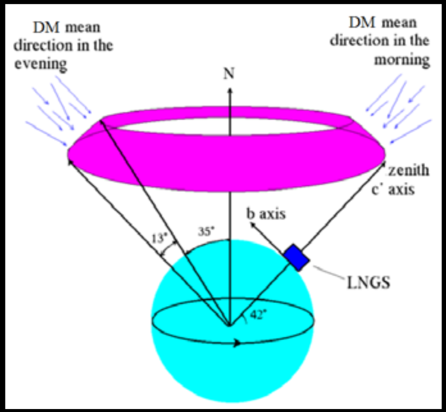
very hard to realize, it holds only for DM particle inducing nuclear recoils

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 Dark Matter (DM) particles 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 candidate particles; in fact the nuclear recoils are expected to be **strongly correlated** with their **impinging direction**, while the background events are not

DIRECTIONALITY SENSITIVE DETECTORS: 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 (complementary approaches) of these detectors depend on the direction of the impinging particles** with respect to the crystal axes

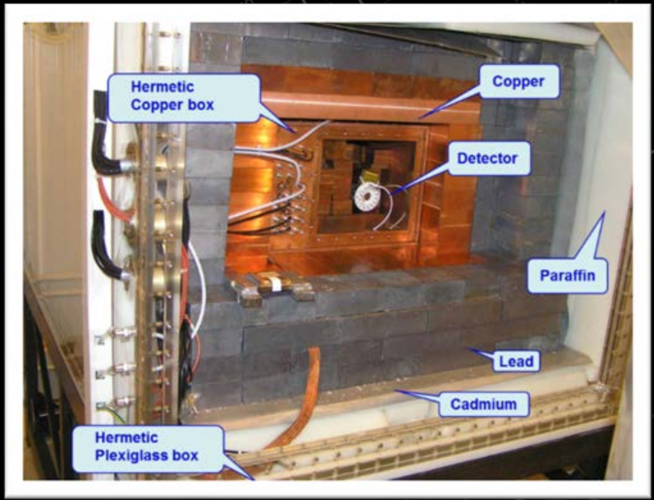
  - The use of anisotropic scintillators to study the directionality signature was proposed for the first time in refs. [P. Belli et al., Il Nuovo Cim. C 15 (1992) 475; R. Bernabei et al., Eur. Phys. J. C 28 (2003) 203], where the case of anthracene detector was preliminarily analysed; some preliminary 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 **(Eur. Phys. J. C 73 (2013) 2276)**

LOW BACKGROUND $ZnWO_4$ CRYSTAL SCINTILLATORS

- DAMA in collaboration with INR-Kiev group has developed low background $ZnWO_4$ crystal scintillators to search for 2β decay processes

- Low background measurements performed in the DAMA/RD set-up at LNGS



DAMA/RD set-up

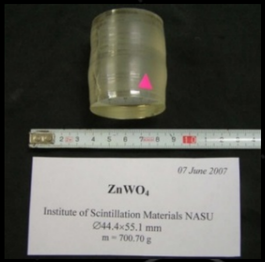
- Air-tight Cu box continuously flushed with HP N_2
- 10 cm of high purity Cu
- 15 cm of low radioactive lead
- 1.5 mm of cadmium
- 4 to 10 cm polyethylene/paraffin
- The whole shield closed inside a Plexiglas box also continuously flushed with HP N_2

$ZnWO_4$ CRYSTAL SCINTILLATORS

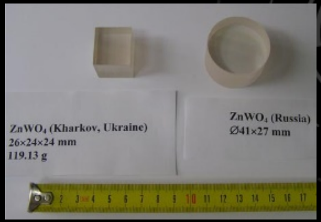
- Low background $ZnWO_4$ crystal scintillators with large volume and good scintillation properties realized
- Various detectors with mass **0.1 - 0.7 kg** realized by exploiting different materials and techniques
- Detectors installed in a cavity (filled up with high-pure silicon oil) ϕ 47 x 59 mm in 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

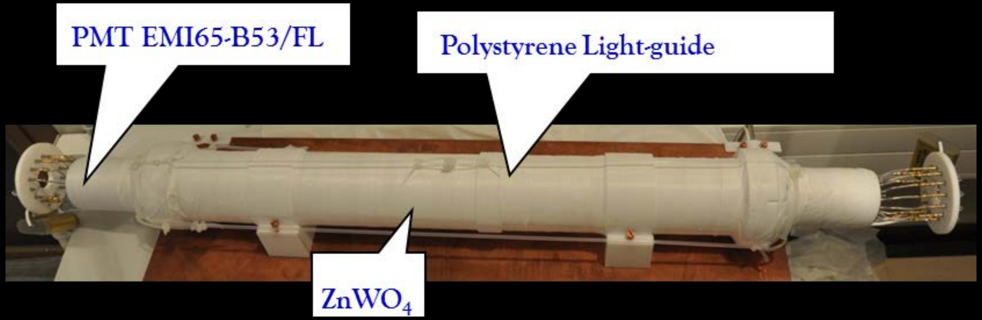
PLB658(2008)193, NPA826(2009)256
NIMA626-627(2011)31,
JP38(2011)115107

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



- Main aim of the measurements was the study of the properties of $ZnWO_4$ and the search for 2β processes in Zinc and Tungsten isotopes.





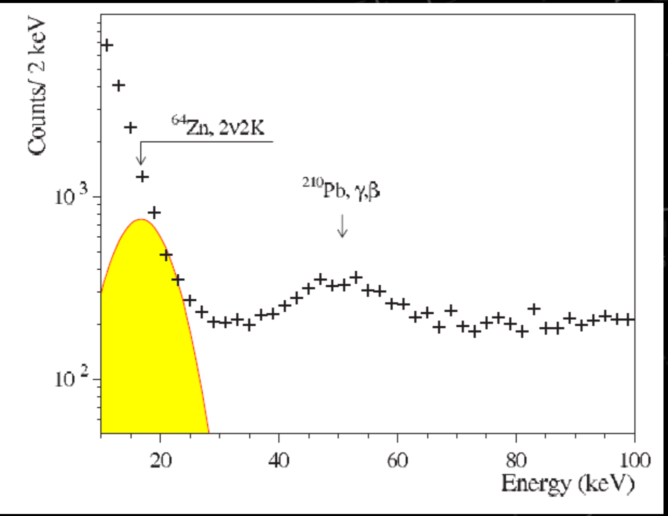
ACHIEVED RESULTS ON DECAY MODES IN Zn AND W ISOTOPES WITH (0,1-0,7 kg) LOW BACKGROUND $ZnWO_4$

Obtained limits on the ββ decay modes of ^{64}Zn, ^{70}Zn, ^{180}W and ^{186}W:

$T_{1/2}$ **~10^{18} – 10^{21} yr.**

- up to now only 5 nuclides (^{40}Ca, ^{78}Kr, ^{112}Sn, ^{120}Te and ^{106}Cd) over 34 candidates to 2ε, εβ$^+$, 2β$^+$ processes have been studied at this level of sensitivity in direct experiments

J. Phys. G: Nucl. Part. Phys. 38 (2011) 115107



1) A possible positive hint of the (2ν+0ν)ECβ$^+$ decay in ^{64}Zn with $T_{1/2}$ = (1.1 ± 0.9) × 10^{19} yr [I. Bikit et al., Appl. Radiat. Isot. 46(1995)455] excluded

2) 0ν2EC in ^{180}W is of particular interest due to the possibility of the **resonant process**;

3) the **rare α decay** of the ^{180}W with $T_{1/2} = (1.3^{+0.6}_{-0.5}) \times 10^{18}$ yr **observed** and new limit on the $T_{1/2}$ of the α transition of the ^{183}W to the metastable level 1/2$^-$ at 375 keV of ^{179}Hf has been set:

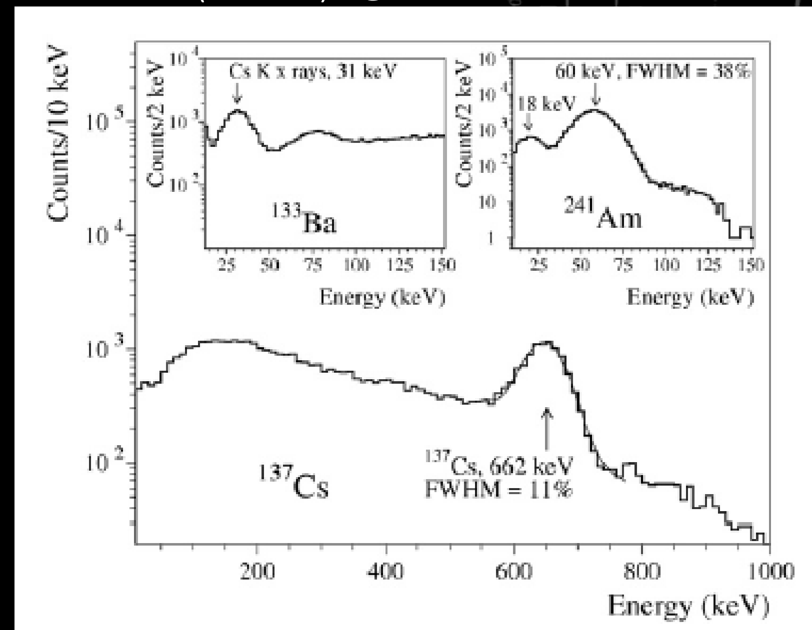
$T_{1/2} > 6.7 \times 10^{20}$ yr.

PERFORMANCES OF $ZnWO_4$ CRYSTAL SCINTILLAOR

➢ *Main characteristics*

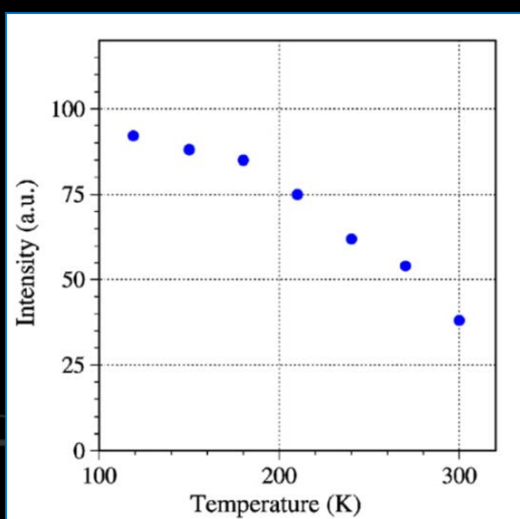
Density (g/cm^3)	*7.87*
Melting point (°C)	*1200*
Structural type	*Wolframite*
Cleavage plane	*Marked (010)*
Hardness (Mohs)	*4–4.5*
Wavelength of emission maximum (nm)	*480*
Refractive index	*2.1–2.2*
Effective average decay time (μs)	*24*

FWHM in the range of
(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



A competitive experiment for the DM investigation needs 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:

- ✓ coupling 2 PMTs in coincidence at single ph.e. level;
- ✓ placing the crystal in silicone oil (light collection improvement ~40%);
- ✓ decreasing the operational temperature of the $ZnWO_4$ scintillator;
- ✓ or with a combination of the previous points

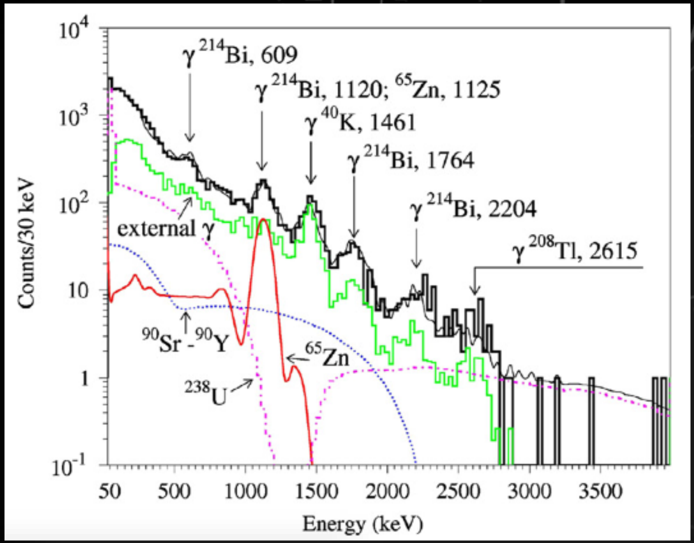
PERFORMANCES OF $ZnWO_4$ CRYSTAL SCINTILLAOR

- ***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

NIMA 626(2011)31



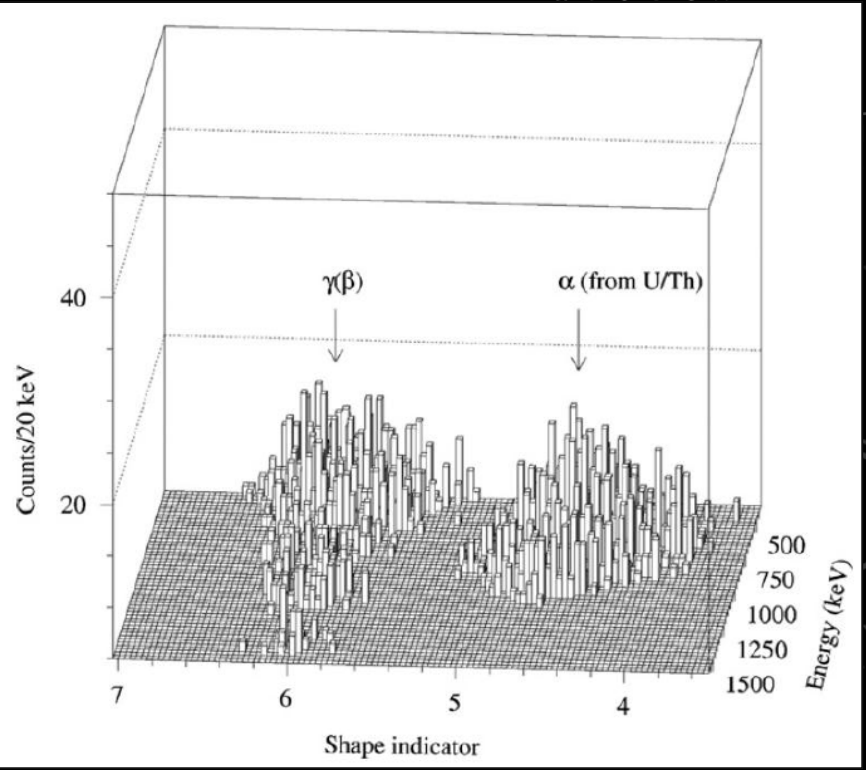
Run	Crystal	Size mass producer	t (h)	FWHM (%)	Background counting rate in counts/(day keV kg) in the energy intervals (MeV)		
					0.2–0.4	0.8–1.0	2.0–2.9
1	ZWO-1	20 × 19 × 40 mm 117 g ISMA [a]	2906	12.6	1.71(2)	0.25(1)	0.0072(7)
2	ZWO-2	∅44 × 55 mm 699 g ISMA	2130	14.6	1.07(1)	0.149(3)	0.0072(4)
3	ZWO-3	∅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 $ZnWO_4$ CRYSTAL SCINTILLAOR

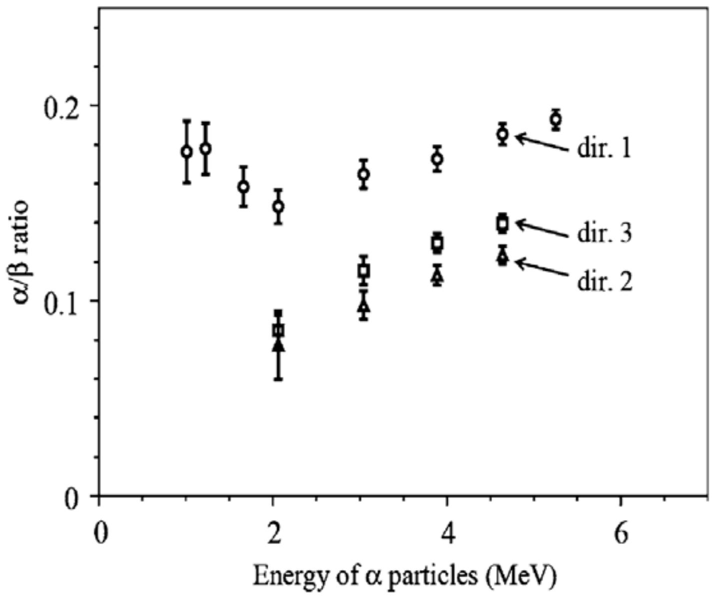
➢ ***Pulse shape analysis***

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



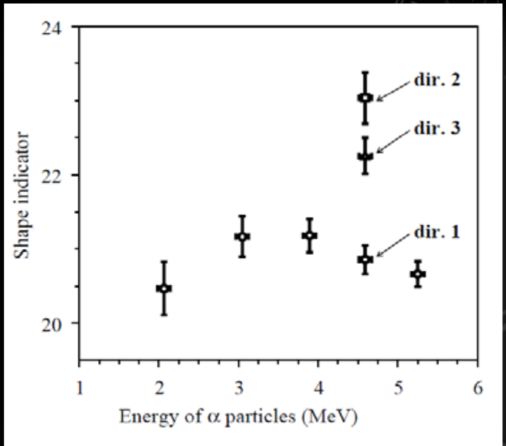
ANISOTROPIC FEATURES IN $ZnWO_4$

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 particles



Measurements with α **particles** have shown that the **light response** and 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



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

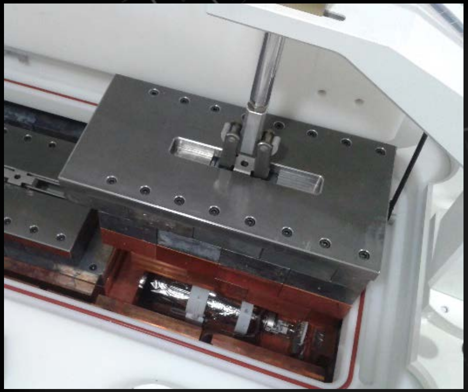
Similar effect is expected in the case of low energy nuclear recoils $\Rightarrow$ Dedicated measurements are in preparation

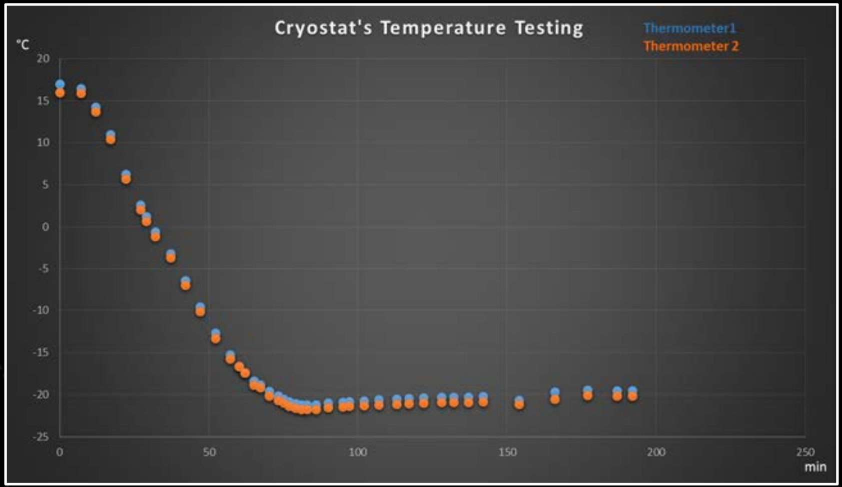
Both the anisotropic features of the $ZnWO_4$ detectors can provide two independent ways to exploit the directionality approach

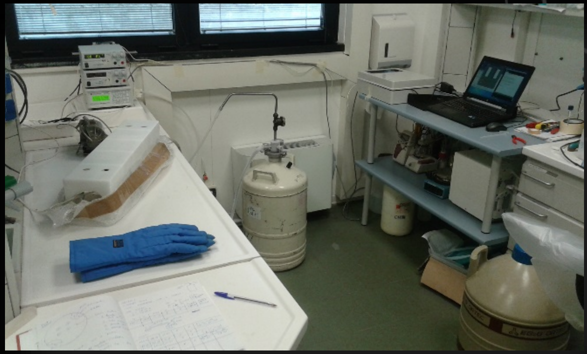
$ZnWO_4$ – work in progress…

At present:

- building a new dedicated experimental-setup for rare events at LNGS underground laboratory
- tests for light response a low temperature (~ -20 °C) of $ZnWO_4$ crystal scintillator
- tests about operational stability a low temperature (~ -20 °C) of $ZnWO_4$ crystal scintillator
- studies about light response vs neutron interactions in the $ZnWO_4$
- measurements about new technique in order to develop $ZnWO_4$ crystal scintillator with an extremely high level of radiopurity







PERFORMANCES OF $ZnWO_4$ CRYSTAL SCINTILLAOR

- ***Summarizing***
  - ✓ Large mass crystals
  - ✓ High level of radiopurity
  - ✓ Suitable light output
  - ✓ keV energy threshold
  - ✓ Pulse shape discrimination
  - ✓ Sensitivity to different DM masses (with Zn, W and O)
  - ✓ High stability of the running conditions
  - ✓ Suitable anisotropic features

AN EXAMPLE OF THE SIGNAL RATE IN 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*
(i.e. of Type equation here. $v_d(t)$ 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

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

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

…SOME ABOUT A MODEL FRAMEWORK

Model description:

- 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

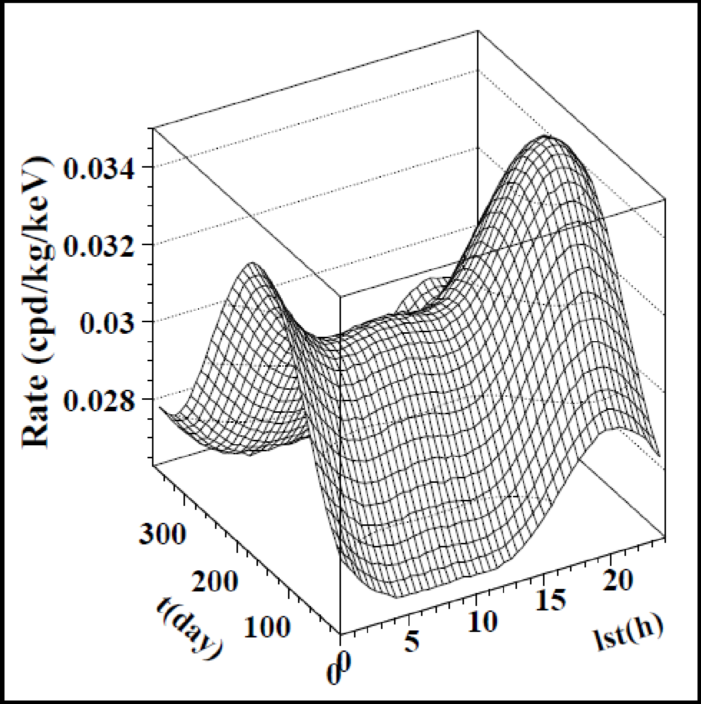
$q_{n,i}$ have been calculated following ref. [V.I. Tretyak, Astropart. Phys. 33 (2010) 40] considering the data of the anisotropy to α particles of the $ZnWO_4$ crystal

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

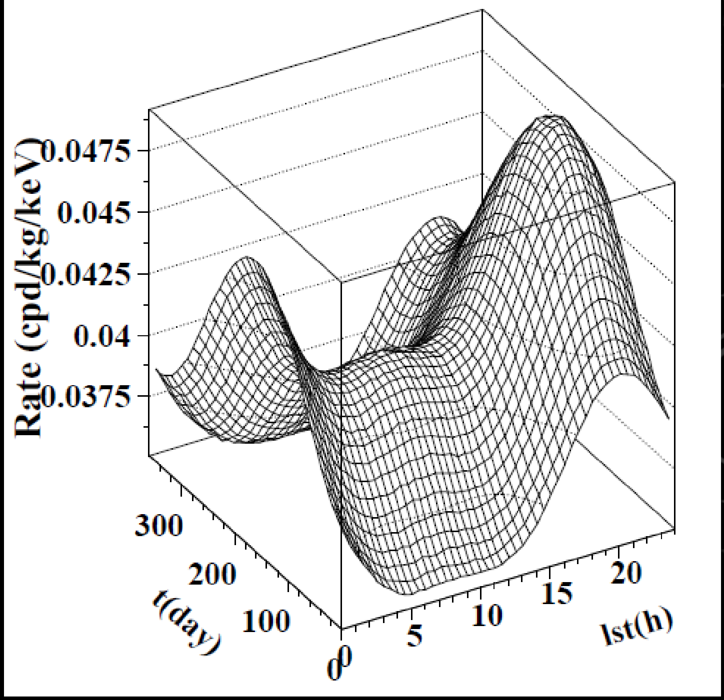
EXAMPLE OF THE EXPECTED SIGNAL IN A SIMPLIFIED MODEL

Expected signal 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



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



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MODEL DEPENDENT COMPARISONS; SAMPLE OF REACHABLE SENSITIVITY IN A SCENARIO CONSIDERED IN EPJC73(2013)2276

Considering an experiment with:

- **200 kg of $ZnWO_4$;**
- **5 years of data taking.**

The reachable sensitivity has been calculated considering 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** — · — · —

Black lines are the **sensitivities reachable** with four possible background levels in the low energy region in a given scenario

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

For comparison, there are also shown (green, red and blue) allowed regions obtained with a corollary analysis of the 9.3 σ C.L. DAMA/NaI + DAMA/LIBRA model independent result in terms of scenarios for the DM candidates considered here

Phys. Rev. D 84, 055014 (2011)

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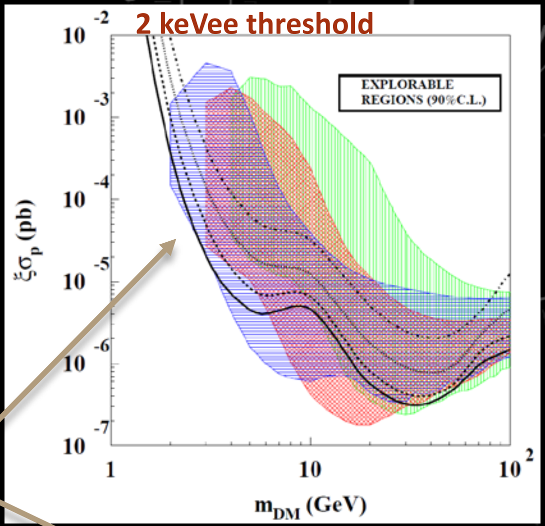
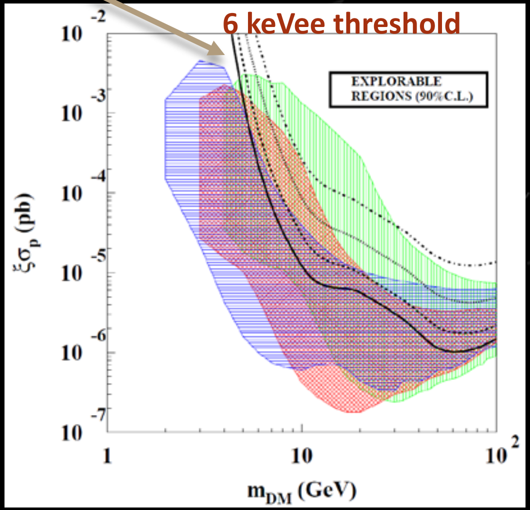




For completeness: within this project directionality sensitive detectors made of carbon nanotube fibers (CNT) was presented by DAMA as first in proposals and conferences

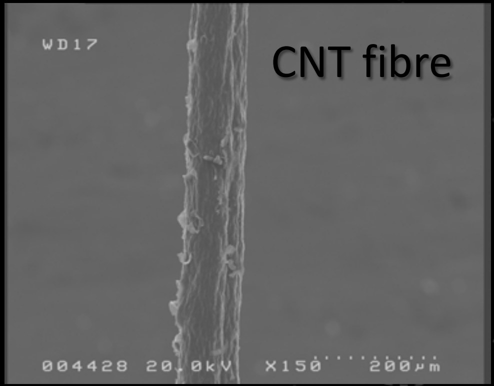
.... but

R&Ds needs and uncertainties

- New conceptual detector: 3D detectors with carbon nanotube fibers (CNT)

✓ The CNT are thin graphene foils, rolled as tubes with l-100 nm diameters and lengths well above one μm; they can be aligned by chemical process to obtain fibres

✓ The intrinsic 1-D nature of CNTs fibers makes them very promising for the study of directionality (diameter ~ 10-100μm; length ~ m); metallic material can be deposited on them



✓ The physical characteristic to be measured for the detection of the passage of dark matter: **alteration of the electrical characteristics** induced by the interaction with high-energy particles, which determines a **change of resistivity** in CNTs.

✓ Three possible nano-devices considered: bare CNT, CNT coated with standard materials, CNT coated with superconducting materials as Nb and NbN. These new detectors can realized as grid of oriented bundles of CNT or fibers, with spatial resolution comparable to the width of the components themselves (1 μm to 100 μm). Fibers of CNT will be used for a sort of multi-wire chamber detector configuration with a high spatial resolution.

CONCLUSIONS

- Anisotropic $ZnWO_4$ detectors is a very promising detector to investigate the directionality for those DM candidate particle inducing just nuclear recoils

- These detectors could permit to reach - in some given scenarios - sensitivity to the cross section down to 10^{-7} pb, depending on the particle mass

- Such an experiment can investigate with new approach the presence of DM candidate inducing just nuclear recoils, providing information complementary to the model-independent one already reached by DAMA expts

- ADAMO with Anisotropic $ZnWO_4$ detectors would represent a first realistic attempt to investigate the directionality approach

Radioactive contamination of $ZnWO_4$ crystal scintillators

Summary of the measurements

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)
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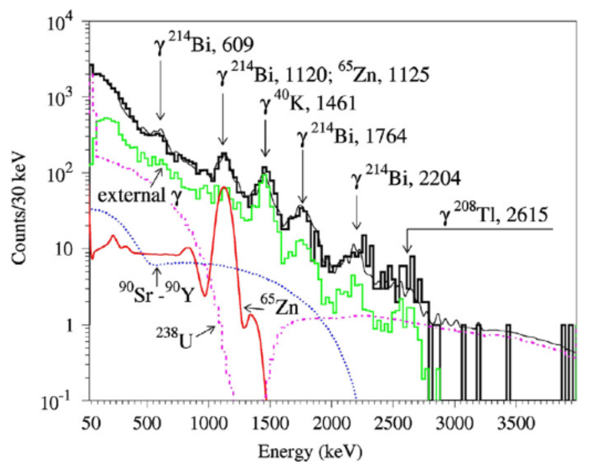


Radioactive contamination of $ZnWO_4$ scintillators determined by different methods.

Chain	Nuclide	Activity (mBq/kg)				
		ZWO-1	ZWO-2	part of ZWO-2	ZWO-3	ZWO-4
^{232}Th	^{232}Th	≤ 0.11 [a]	≤ 0.1 [a]	–	≤ 0.03 [a]	≤ 0.25 [a]
	^{228}Ra	≤ 0.2 [b]	≤ 0.05 [b]	≤ 3.4 [d]	≤ 0.02 [b]	≤ 0.1 [b]
	^{228}Th	0.005(3) [c]	0.002(1) [c]	≤ 8.3 [d]	0.002(2) [c]	0.018(2) [c]
^{235}U	^{227}Ac	≤ 0.007 [c]	≤ 0.003 [c]	–	≤ 0.01 [c]	0.011(3) [c]
^{238}U	^{238}U+^{234}U	≤ 0.1 [a]	≤ 0.08 [a]	–	≤ 0.2 [a]	≤ 0.12 [a]
	^{230}Th	≤ 0.13 [a]	≤ 0.07 [a]	–	≤ 0.15 [a]	≤ 0.16 [a]
	^{226}Ra	≤ 0.006 [a]	0.002(1) [a]	≤ 5.7 [d]	0.021(15) [a]	0.025(6) [a]
	^{210}Po	≤ 0.2 [a]	≤ 0.06 [a]	–	≤ 0.01 [a]	≤ 0.64 [a]
Total α activity		0.38(5) [a]	0.18(3) [a]	–	0.47(7) [a]	2.3(2) [a]
	^{40}K	≤ 1 [b]	≤ 0.4 [b]	≤ 24 [d]	≤ 0.1 [b]	≤ 0.02 [b]
	^{60}Co	≤ 0.05 [b]	≤ 0.1 [b]	≤ 2.5 [d]	≤ 0.03 [b]	≤ 0.03 [b]
	^{65}Zn	≤ 0.8 [b]	0.5(1) [b]	≤ 1.5 [d]	0.8(2) [b]	0.7(2) [b]
	^{87}Rb	≤ 2.6 [b]	≤ 2.3 [b]	–	≤ 4.0 [b]	≤ 4.2 [b]
	^{90}Sr–^{90}Y	≤ 0.6 [b]	≤ 0.4 [b]	–	≤ 0.1 [b]	≤ 0.1 [b]
	^{137}Cs	≤ 0.3 [b]	≤ 0.05 [b]	≤ 1.7 [d]	≤ 0.5 [b]	≤ 1.3 [b]
	^{147}Sm	≤ 0.01 [a]	≤ 0.01 [a]	–	≤ 0.01 [a]	≤ 0.05 [a]
	^{207}Bi	≤ 0.2 [b]	≤ 0.2 [b]	≤ 1.4 [d]	≤ 0.4 [b]	≤ 0.2 [b]

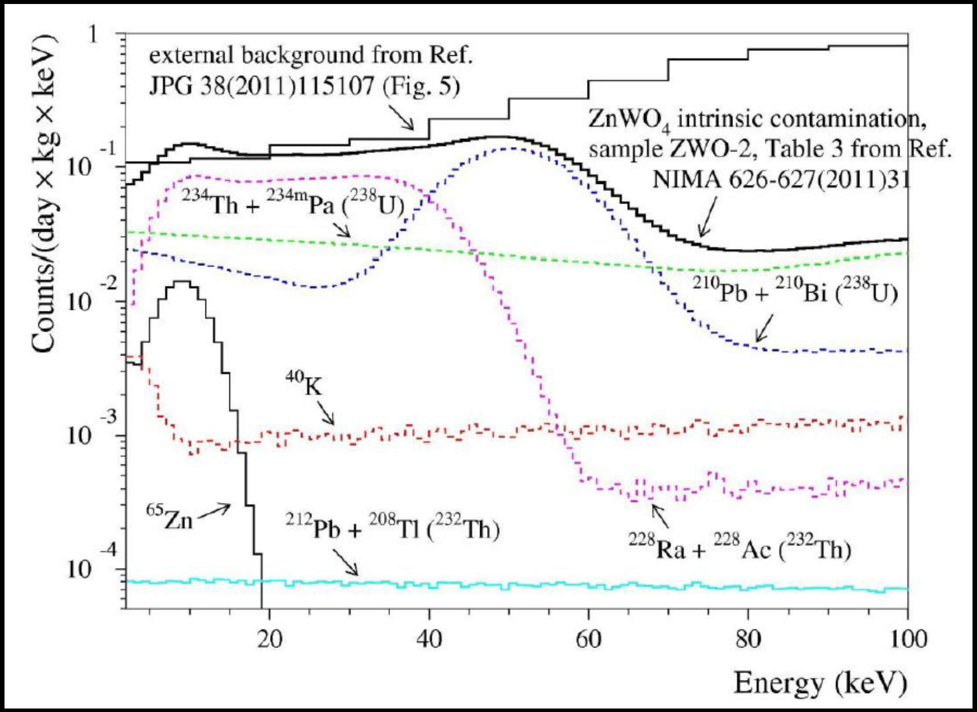
[a] Pulse-shape discrimination (see Section 3.2.2).
[b] Fit of background spectra (see Section 3.2.3).
[c] Time-amplitude analysis (see Section 3.2.1).
[d] HP Ge γ spectrometry (see Section 3.3).

Also ICP-MS analysis

α contamination at level of 0.2 -2 mBq/kg , further improvement under investigation

Performances of the $ZnWO_4$ crystal scintillator

Montecarlo calculation for the expected background at low energy considering the measured radiopurity of the developed detectors



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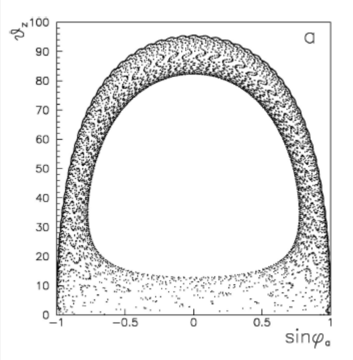
Detector velocity in the Galactic rest frame:

$$v_d(t) = v_{rot} + v_{LSR} + v_E(t)$$

v_{rot}: rotational vel of Milky Way
v_{LSR}: solar system's vel with respect to the Local Standard of Rest
$v_E(t)$: Earth's vel around the Sun

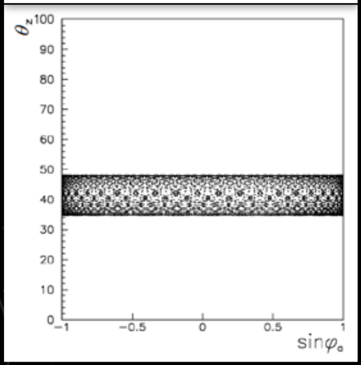
horizontal coordinate frame described by the "polar-zenith", θ_z, and by the "polar-azimuth", ϕ_a

The various directions, in the sky, of the detector Galactic velocity $\mathbf{v}_d(t)$ calculated for the next three years as viewed from LNGS (42°27N latitude and 13°10'50'' E longitude)

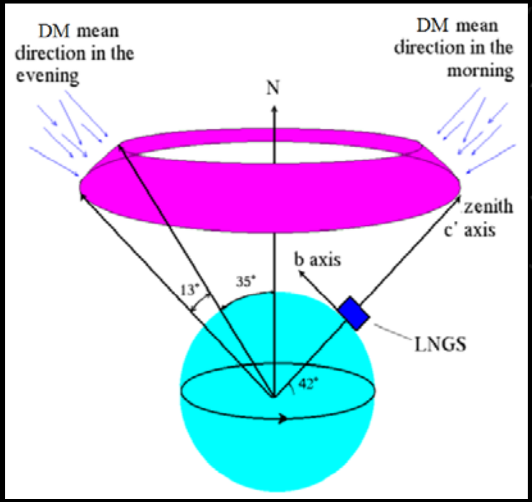


local horizontal coordinate frame

⇒ **the area described in the sky by the direction of the detector velocity, $\vec{v}_d$, is only a strip**



North pole coordinate frame



At LNGS latitude at a certain time of the day the DM particles come mainly from the top, while 12 h later they come near the horizon and from North

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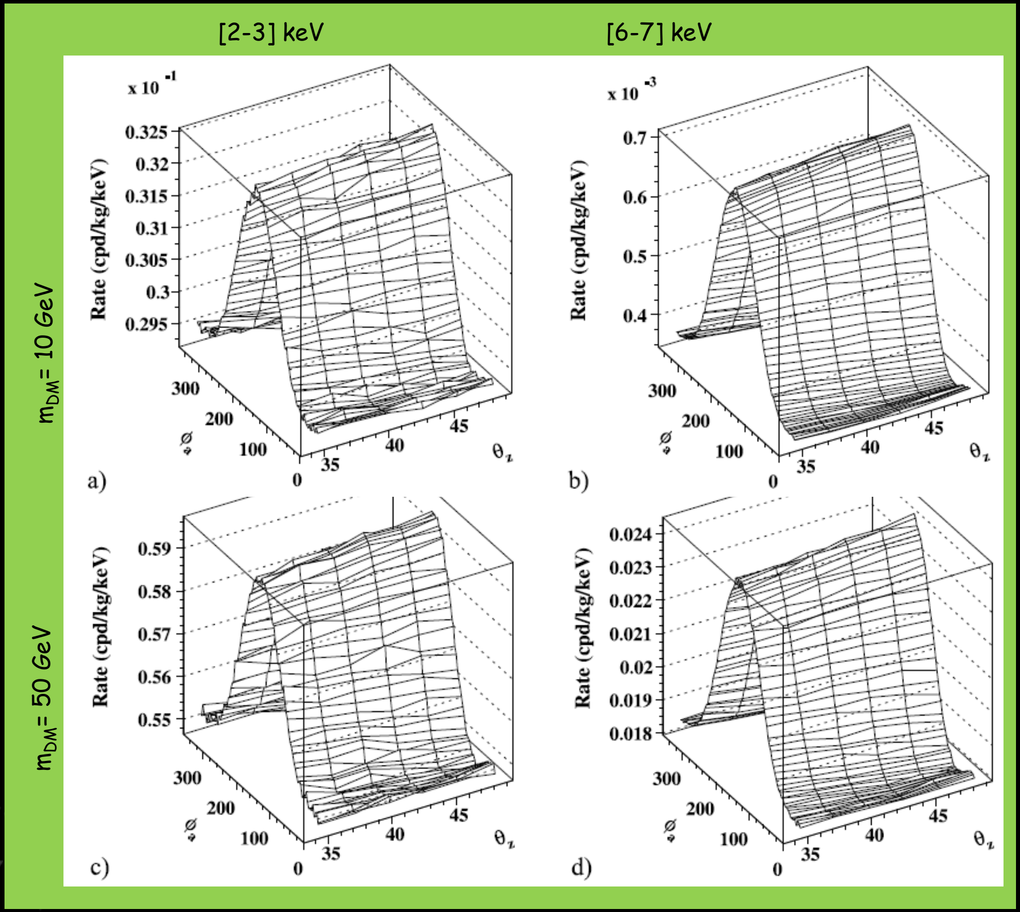
Since θ_z is always near 40º, it is convenient to consider:

- ✓ $ZnWO_4$ crystals with the axis having the largest q.f. in the vertical direction, and with the axis having the smallest q.f. towards the North

Expected counting rate as a function of $\vec{v}_d$ in the given model framework for $\sigma_p=5\times10^{-5}$ pb



- ✓ Strong dependence on the "polar-azimuth" ϕ_a that induces a diurnal variation of the rate
- ✓ Diurnal variation of the energy spectrum expected
- ✓ Diurnal variation of the nuclear recoils induced by DM interaction