$ZnWO_4$ anisotropic scintillator for Dark Matter investigation with the directionality technique

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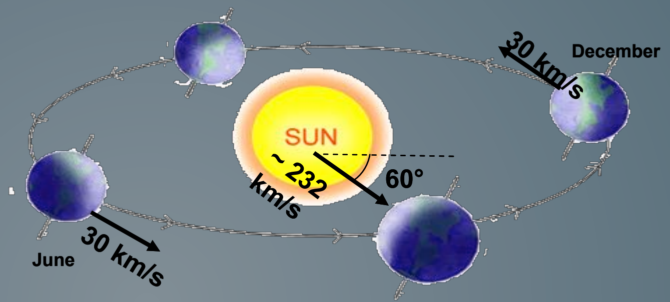
Signatures for direct detection experiments

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

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

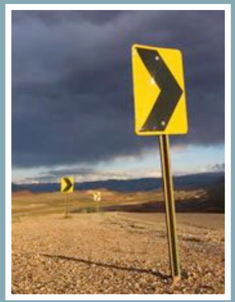
  (successfully exploited by DAMA)

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

  2nd order effect

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

  only for high σ



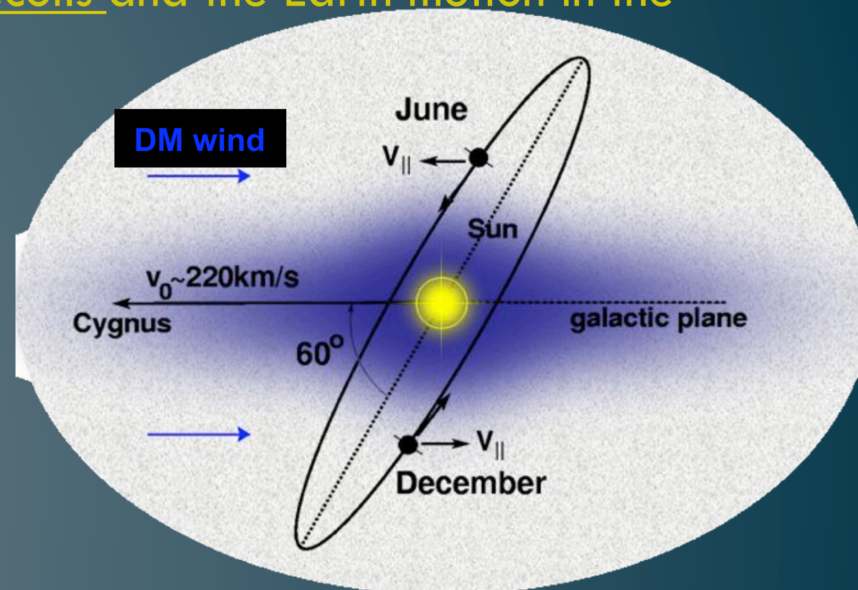
- Directionality: correlation of Dark Matter impinging direction with Earth's galactic motion

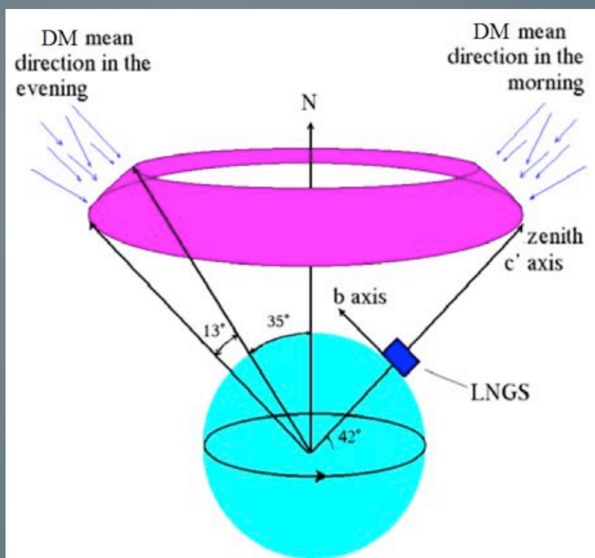
  it holds **only for DM particle inducing recoils**

The directionality approach

Based on the study of the correlation between the arrival direction of Dark Matter (DM) candidates inducing nuclear recoils 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…





… but 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 the case of DM particles interacting with nuclei, the direction of the induced nuclear recoil is strongly correlated with that of the impinging DM particle. Therefore, the observation of an anisotropy in the distribution of nuclear recoil direction could give evidence for such candidates

direction-sensitive detector

Directionality sensitive detectors: TPC

- Detection of the tracks' directions

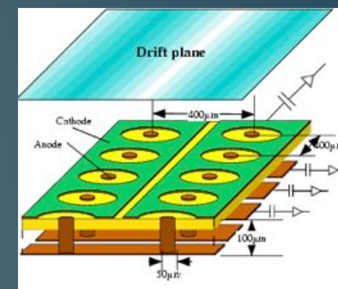
  ⇒ Low Pressure **Time Projection Chamber** might be suitable; in fact the range of recoiling nuclei is of the order of mm (while it is ~μ m in solid detectors)

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

  1. extreme operational stability
  2. high radiopurity
  3. large detector size
  4. great spatial resolution
  5. low energy threshold

Not yet competitive sensitivity

NEWAGE

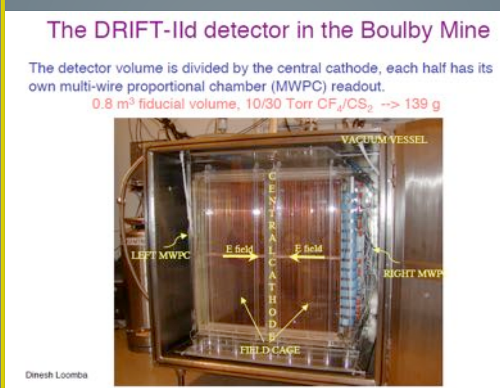


μ -PIC(Micro Pixel Chamber) is a two dimensional position sensitive gaseous detector

	Current	Plan
Detection Volume	30 × 30 × 31cm³	>1m³
Gas	CF_4 152Torr	CF_4 30 Torr
Energy threshold	100keV	35keV
Energy resolution(@ threshold)	70%(FWHM)	50%(FWHM)
Gamma-ray rejection(@threshold)	8×10^{-6}	1×10^{-7}
Angular resolution (@ threshold)	55° (RMS)	30° (RMS)

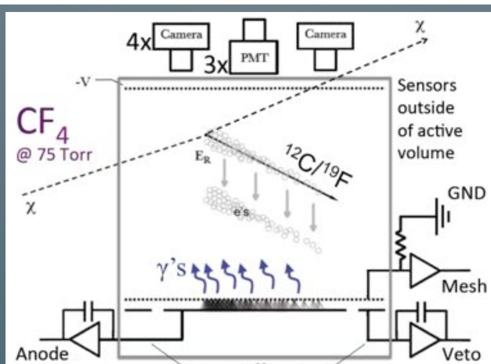
- Internal radioactive BG restricts the sensitivities
- We are working on to reduce the backgrounds!

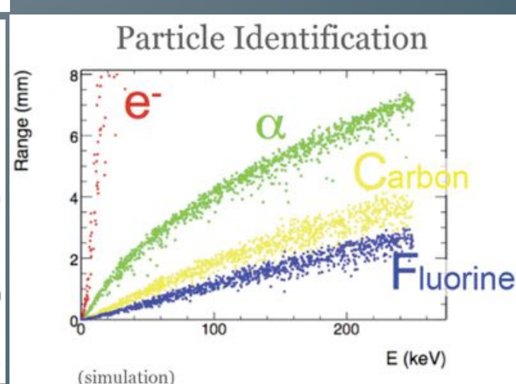
DRIFT-IId



Background dominated by Radon Progeny Recoils (decay of ^{222}Rn daughter nuclei, present in the chamber)

DM-TPC

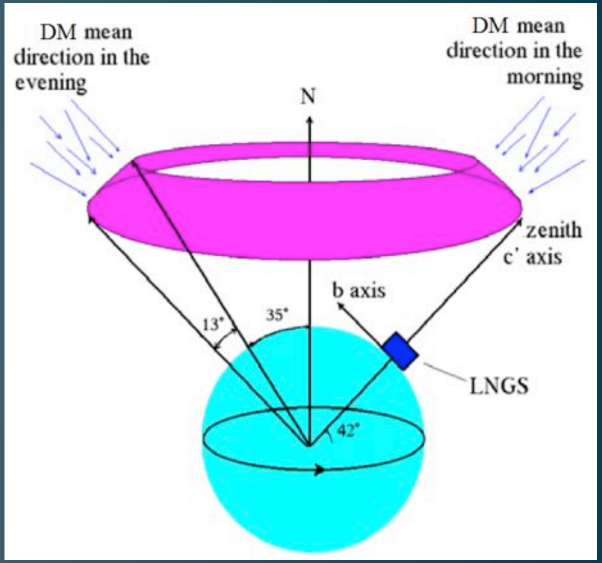




- The **"4---Shooter"** 18L (6.6 gm) TPC 4xCCD, Sea-level@MIT
- moving to WIPP
- Cubic meter funded, design underway

Directionality sensitive detectors: anisotropic scintillators

- Anisotropic Scintillator:
  - 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



The variation of the response of an **anisotropic scintillator** during sidereal day can allow to point out the presence of a DM signal due to candidate inducing nuclear recoils

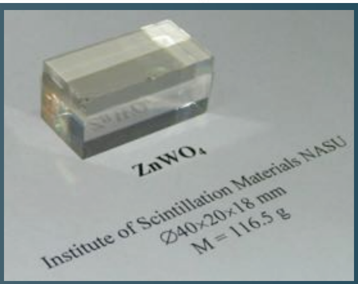
- The use of anisotropic scintillators to study the directionality signature was proposed for the first time in refs. [**P. Belli et al., Il Nuovo Cim. C 15 (1992) 475; R. Bernabei et al., EPJC28(2003)203**], where the case of anthracene was analysed; some preliminary activities have been carried out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

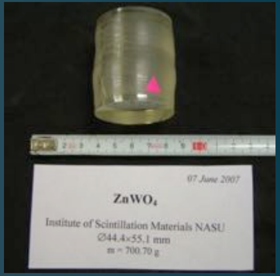
$ZnWO_4$ crystal scintillators in DAMA project

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

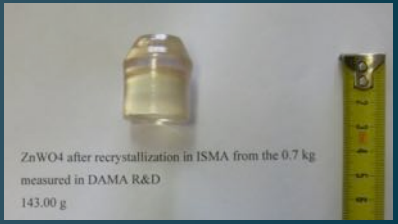
- Low background $ZnWO_4$ crystal scintillators with large volume and good scintillation properties realized (in collaboration with INR-Kiev)
- Various detectors with mass **0.1-0.7 kg** realized by exploiting different materials and techniques
- Detectors installed in a cavity (filled up with high-pure 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

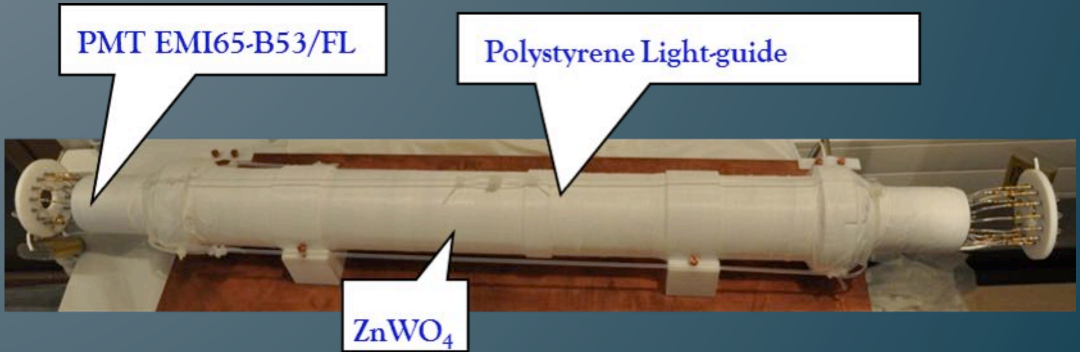
Crystal scintillator	Size (mm)	Mass (g)
ZWO-1	$20 \times 19 \times 40$	117
ZWO-2	$\oslash 44 \times 55$	699
ZWO-2a	$\oslash 44 \times 14$	168





- 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 ($T_{1/2}$ ~10^{18} – 10^{21} yr)





Advantages of the $ZnWO_4$ crystal

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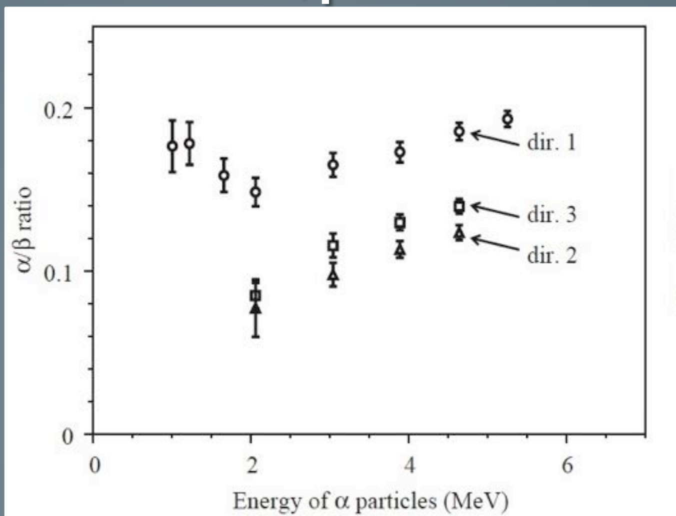
- ✓ Very good anisotropic features
- ✓ High level of radiopurity
- ✓ High light output, that is low energy threshold feasible
- ✓ High stability in the running conditions
- ✓ Sensitivity to small and large mass DM candidate particles
- ✓ Detectors with ~ kg masses

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*

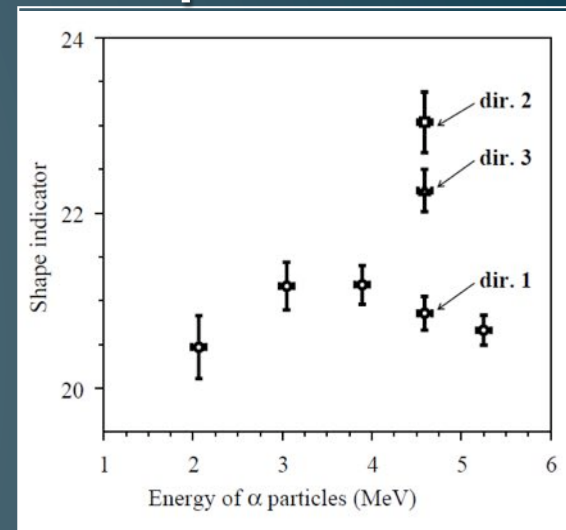
Anisotropic features in $ZnWO_4$

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

α/β ratio



PS parameter



Such effects are absent in case of electron excitation

(010), (001) and (100) crystal planes correspond to dir. 1, 2 and 3

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

Ion	Quenching factor		
	dir. 1	dir. 2	dir. 3
O	0.235	0.159	0.176
Zn	0.084	0.054	0.060
W	0.058	0.037	0.041

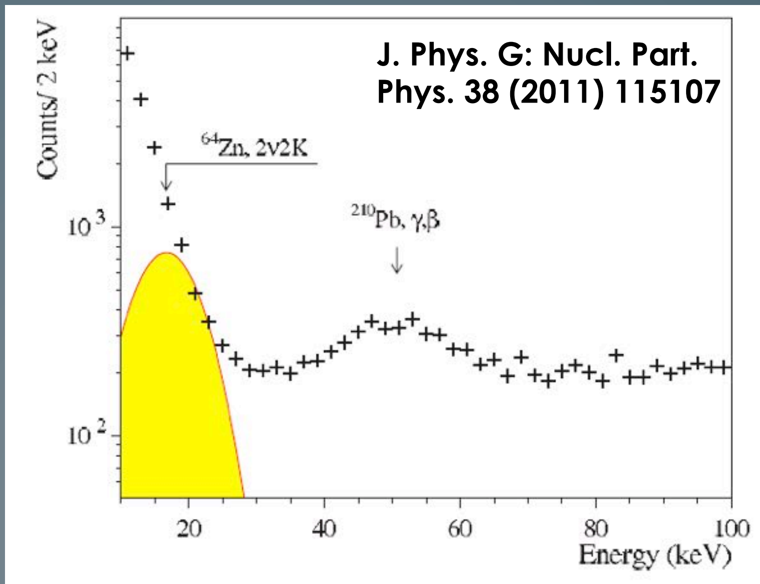
Q.F expected from V.I. Tretyak, Astropart. Phys. 33 (2010) 40

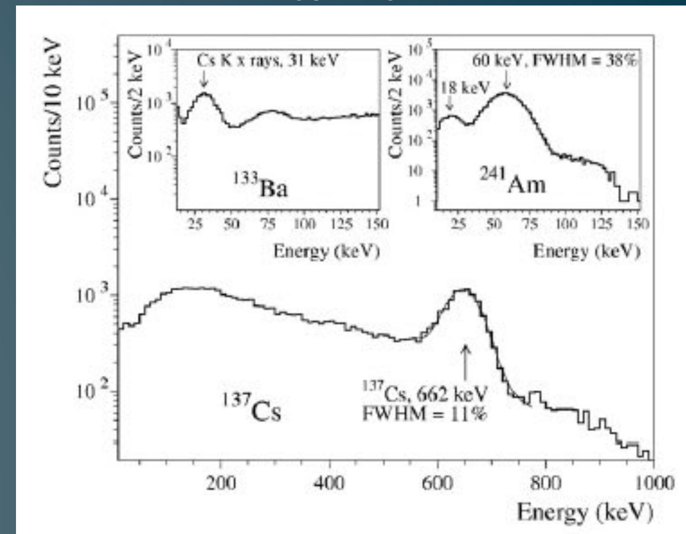
Similar effect is expected in the case of low energy nuclear recoils

⇒ **Dedicated measurements are foreseen in the next weeks**

Light output and threshold of $ZnWO_4$ crystal scintillator

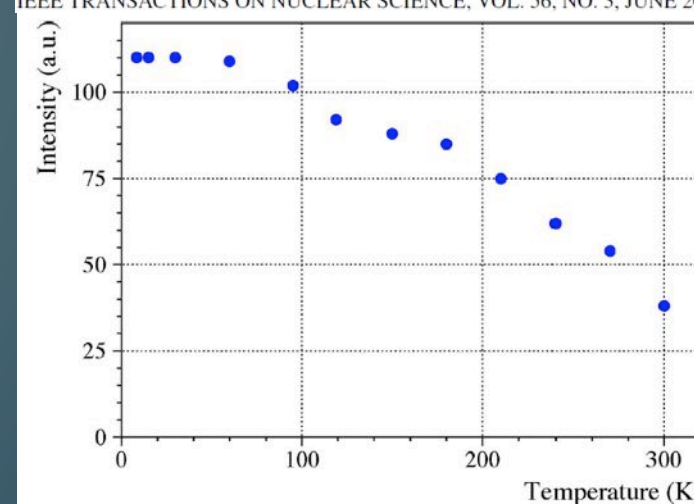
An energy threshold of 10 keV in an experiment not optimized for the low energy region





FWHM (8.8–14.6)% @662 keV

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 56, NO. 3, JUNE 2009



Improvements of the energy threshold by:

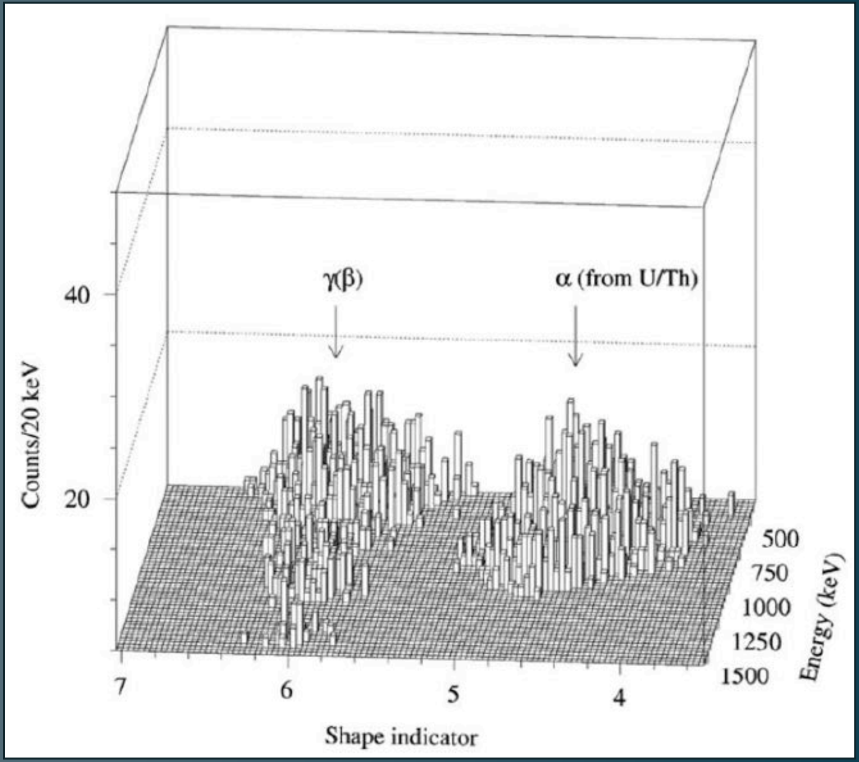
- ✓ coupling 2 PMTs in coincidence at single ph.e. level
- ✓ decreasing operational temperature
- ✓ crystal in silicone oil (light collection improvement ~40%)
- ✓ using silicon photodiodes, APD, SiPM, etc.
- ✓ or with a combination of the previous points

Low-threshold feasible

Light output measured for a ZnWO4 scintillator with ^{241}Am α particles as function of Temperature

PSD capability of the $ZnWO_4$ crystal scintillator

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



Once provided a suitable separation also at very low energy, PSD could – in principle – gives a 2nd independent but not mandatory way to exploit the directionality approach

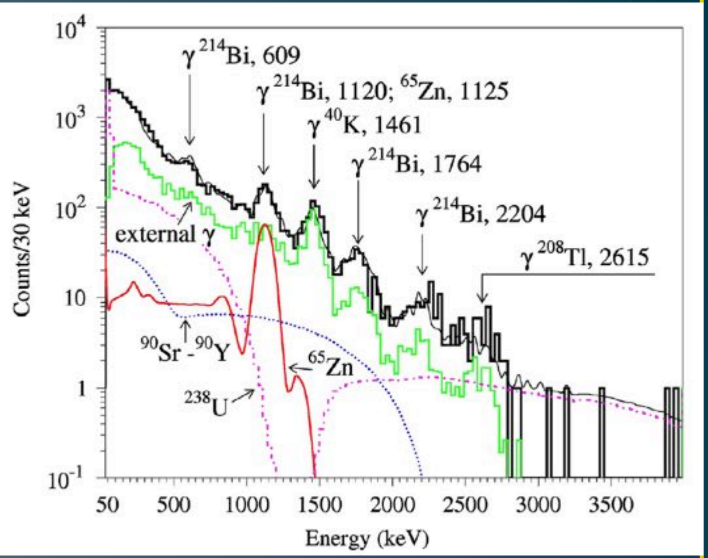
Radiopurity of the $ZnWO_4$ crystal scintillator

NIMA 626(2011)31

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

<2 μBq/kg for ^{228}Th and ^{226}Ra:

- ~ 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

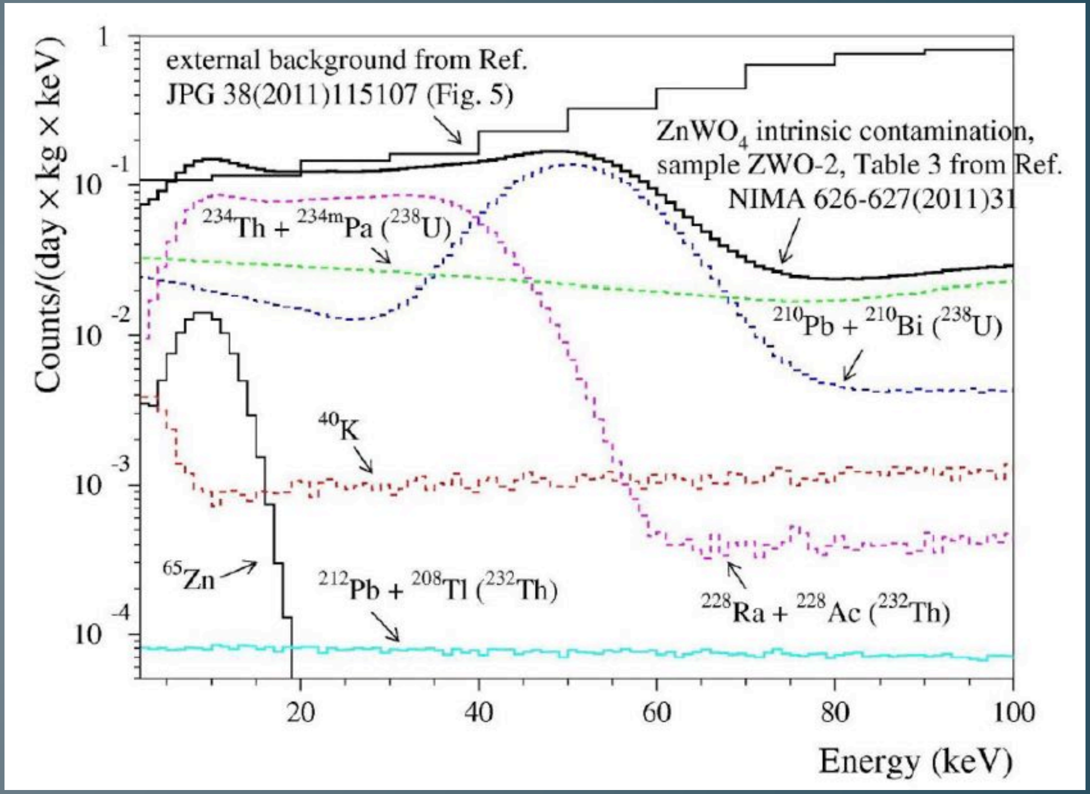


Run	Crystal	Size mass producer	t (h)	FWHM (%)	Background counting rate in counts/(day keV kg) in the energy intervals (MeV)		
					0.2–0.4	0.8–1.0	2.0–2.9
1	ZWO-1	20 × 19 × 40 mm 117 g ISMA [a]	2906	12.6	1.71(2)	0.25(1)	0.0072(7)
2	ZWO-2	∅44 × 55 mm 699 g ISMA	2130	14.6	1.07(1)	0.149(3)	0.0072(4)
3	ZWO-3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

Radiopurity of the $ZnWO_4$ crystal scintillator

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



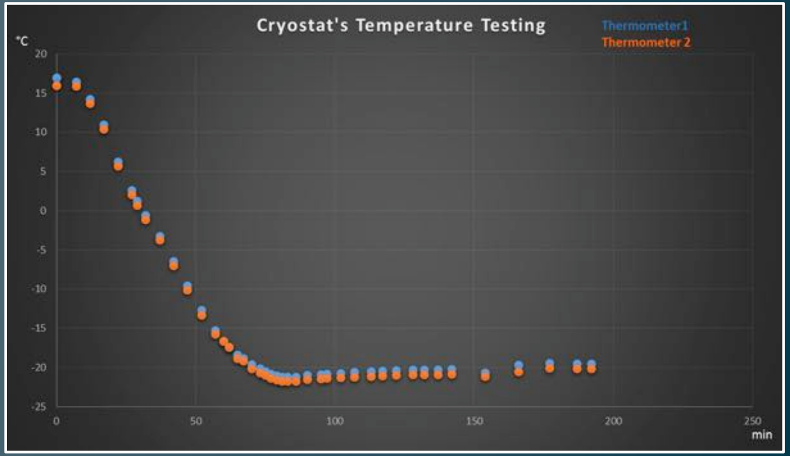
- background contribution in the low energy region is ≈ 0.1 counts/day/kg/keV
- the radiopurity of $ZnWO_4$ is very good, but still not sufficient. Our objective is to reduce by at least one order of magnitude the low energy counting rate due to the intrinsic crystal contamination

Improving radiopurity of $ZnWO_4$ crystal

- screening of zinc oxide to avoid cosmogenic ^{65}Zn
- protocol for the purification of the initial **zinc** (vacuum distillation and filtering) and **tungsten** (electron beam and zone melting)
- low-thermal gradient Czochralski technique in a platinum crucible (with very good results in producing large size crystals with high radiopurity levels)
- Segregation of radioactive elements (U, Th, Ra, K) expected (very similar compound to $CdWO_4$) and under investigation; recrystallization could further improve radiopurity level of $ZnWO_4$
- Detectors cut and assembled just after the growth of the crystalline bulk in a glove-box in controlled atmosphere.
- Selection of tools and abrasives for cutting and polishing the crystals
- Etc.

$ZnWO_4$ – work in progress…

- Cryostat for low temperature measurement with scintillation detectors realized
- Test of the Cryostat in progress
- Measurements of anisotropy at low energy with neutrons source in preparation
- Lowering the energy threshold (new PMT with higher QE, SiPM, APD, SDD,…)
- Development of electronics



Signal rate in a given scenario

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

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

- 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
- 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:

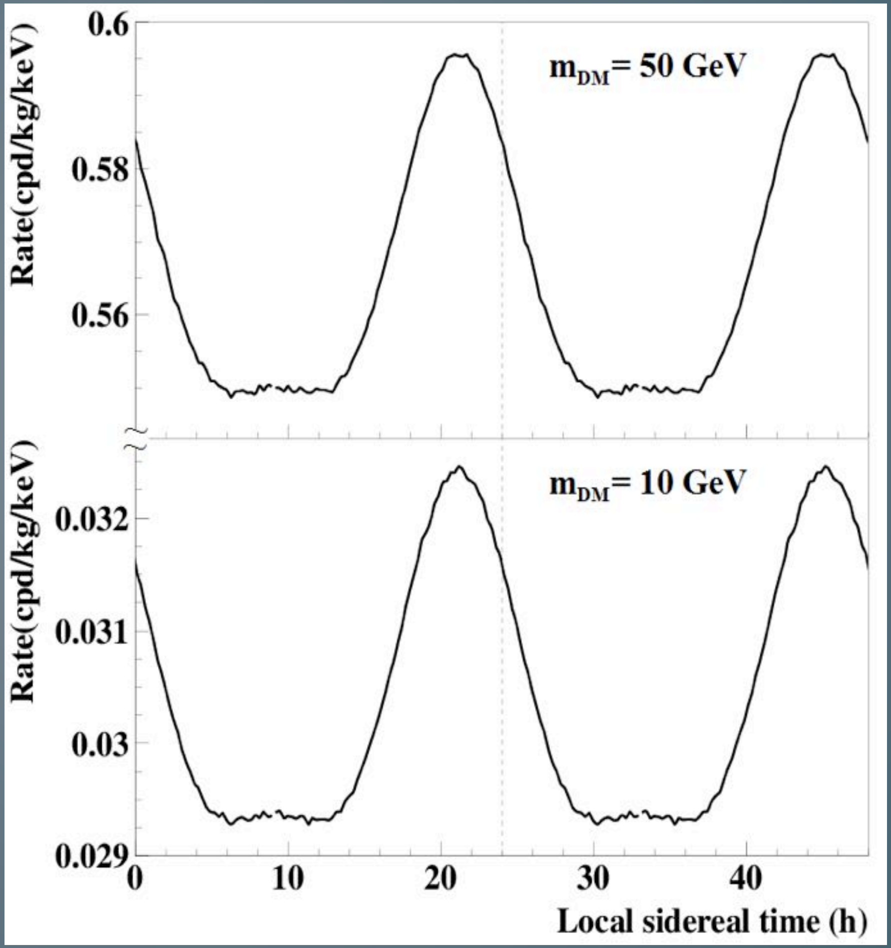
$$q_n(\Omega_{out}) = q_{n,x} \sin^2\gamma \cos^2\phi + q_{n,y} \sin^2\gamma \sin^2\phi + q_{n,z} \cos^2\gamma$$

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 expected signal rate in the given scenario

Signal rate in [2-3] keV energy range with $\xi \sigma_p = 5\times10^{-5}$ pb



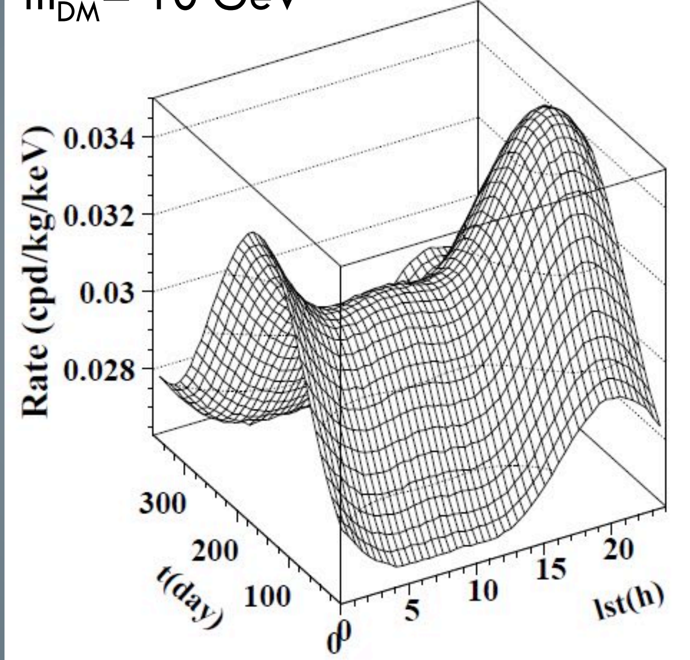
- Maximum rate at 21 h sidereal time of LNGS, when the DM preferential arrival direction is near the zenith, that is near the crystal axis with the largest light output.
- Analogous results can be obtained also analysing the anisotropic behaviour of the pulse shape of scintillation events.

The signature is very distinctive and cannot be mimicked by background

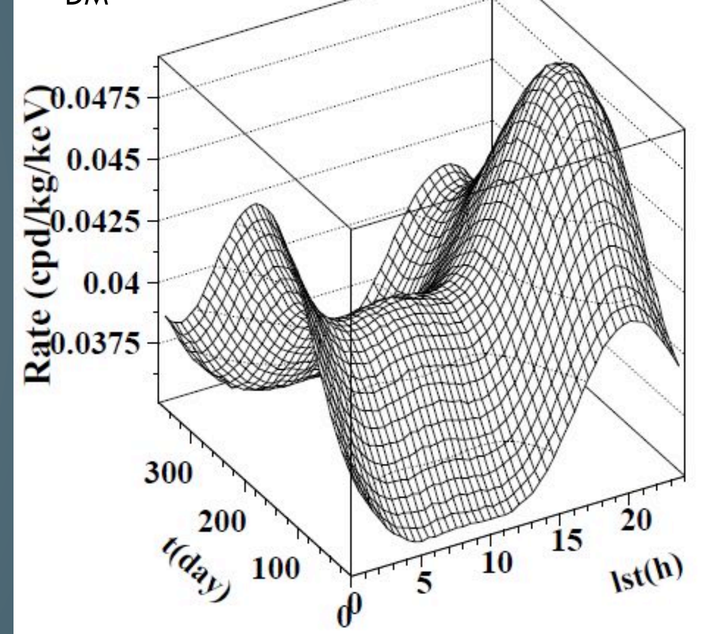
Example of expected signal

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

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



[6-7] keV $\sigma_p = 5\times10^{-5}$ pb
m_{DM}= 100 GeV



- Identical sets of crystals placed in the same set-up with different axis orientation will observe consistently different time evolution of the rate
- The diurnal effect will refer to the sidereal day and not to the solar day

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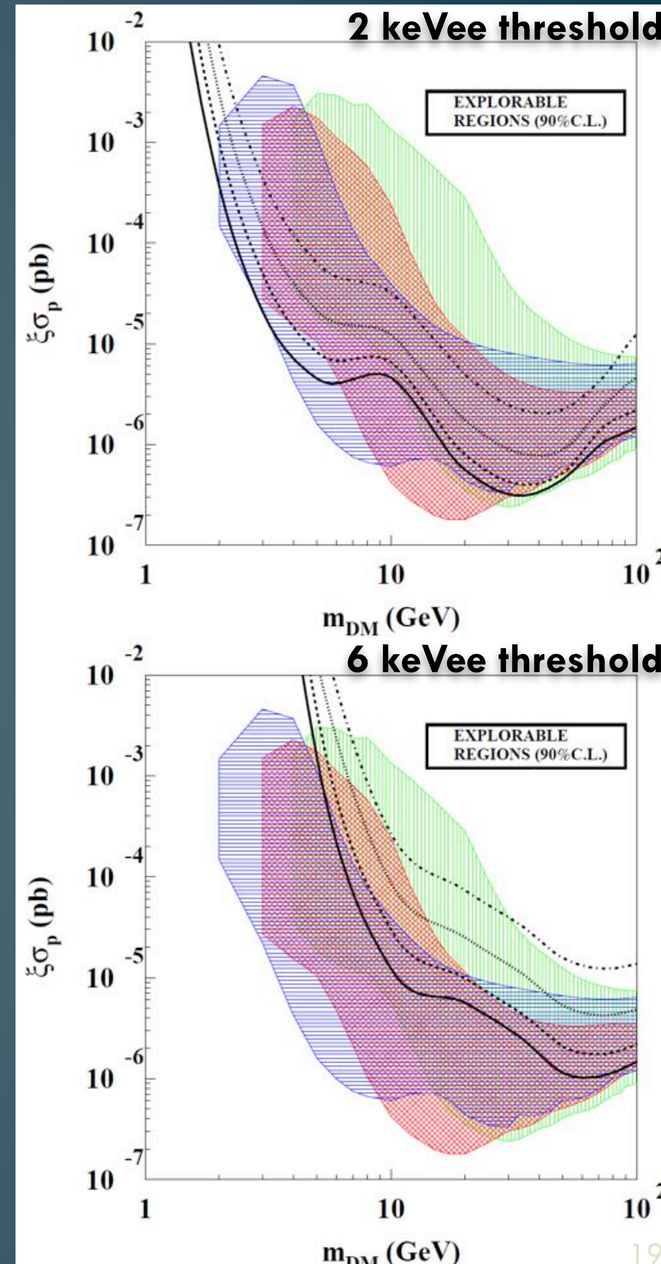
Example of the reachable sensitivity calculated considering the above mentioned simplified model framework for an experiment with:

- 200 kg of $ZnWO_4$
- 5 years of data taking
- four possible time independent background levels in the low energy region:
  - 10^{-4} cpd/kg/keV (solid line)
  - 10^{-3} cpd/kg/keV (dashed line)
  - 10^{-2} cpd/kg/keV (dotted line)
  - 0.1 cpd/kg/keV (dash-dotted line)



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 9.3σ C.L. DAMA model independent result in terms of scenarios for the DM candidates considered here

Conclusions

- Anisotropic $ZnWO_4$ detectors are promising detectors to investigate the directionality for DM candidates inducing nuclear recoils
- These detectors could permit to reach - in some given scenarios - sensitivity comparable to that of the DAMA/LIBRA positive model independent results
- Such an experiment can obtain, with a completely different new approach, further evidence for the presence of some DM candidates in the galactic halo and provide complementary information on the nature and interaction type of the DM candidate