The ADAMO Project and Developments

18th Lomonosov Conference on
Elementary Particle Physics

(MOSCOW 2017)

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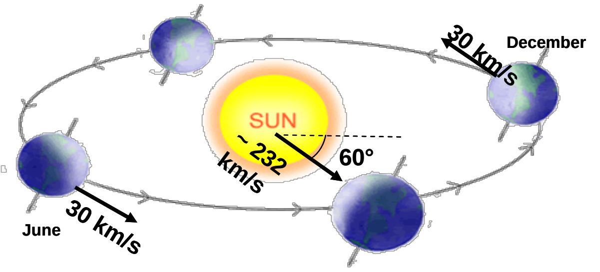
Signatures for direct detection experiments

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 rotation around its axis

2nd order effect

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

only for high σ

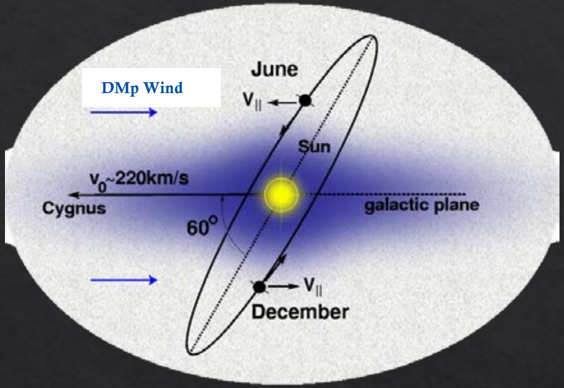
Directionality: Correlation of Dark Matter impinging direction with Earth's galactic motion

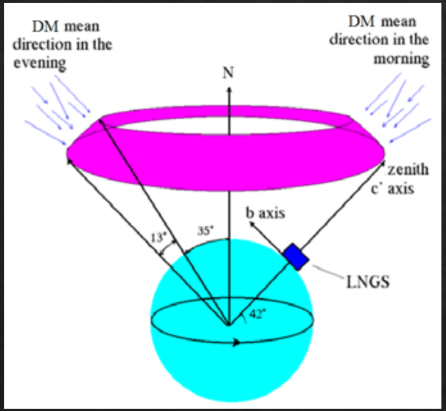
very hard to realize, it holds **only for DM particle inducing nuclear recoils**

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.

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 fixed on the Earth changes during the 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

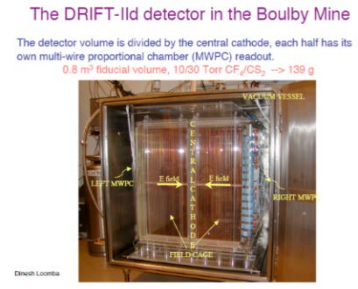
  ⇒ Low Pressure **Time Projection Chamber** might be suitable; in fact the range of recoiling nuclei is of the order of mm (while it is ~μm in solid detectors)

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

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

Not yet competitive sensitivity

DRIFT-IId



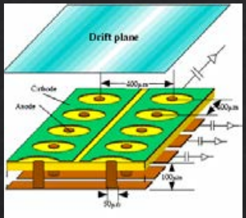
The DRIFT-IId detector in the Boulby Mine

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

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

NEWAGE

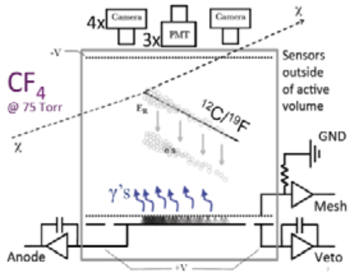


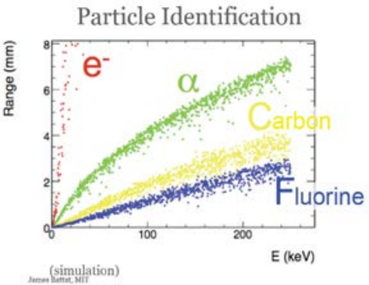
μ-PIC(Micro Pixel Chamber) is a two dimensional position sensitive gaseous detector

	Current	Plan
Detection Volume	30 × 30 × 31cm^3	>1m^3
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!

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 overcoming the track measurement difficulties: anisotropic scintillators

- 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]

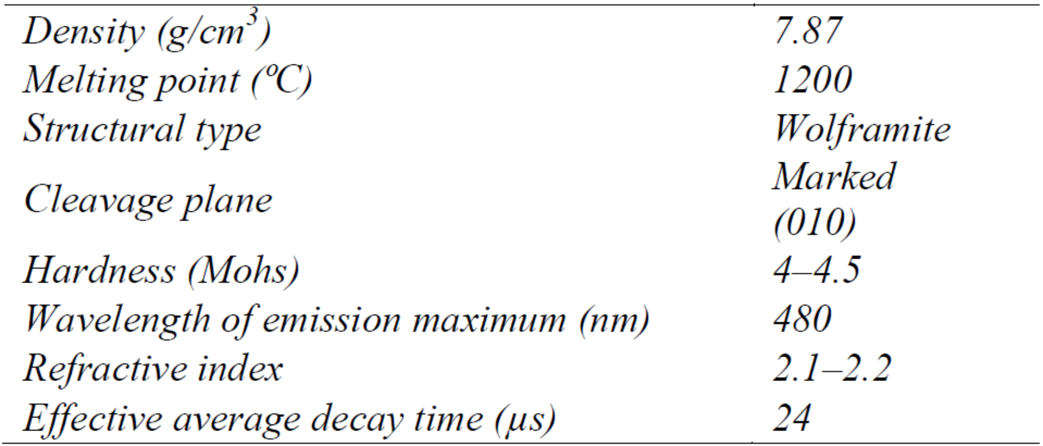
- Anisotropic Scintillator:
  - for heavy particles the light output and the pulse shape depends on the particle impinging direction with respect to the crystal axes
  - for γ/β the light output and the pulse shape are isotropic

- $ZnWO_4$ anisotropic scintillator: a very promising detector (Eur. Phys. J. C 73 (2013) 2276)

Advantages of the $ZnWO_4$ crystal

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

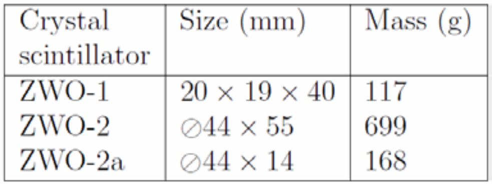
- ✓ Very good anisotropic features
- ✓ High level of radiopurity
- ✓ High light output, that is low energy threshold feasible
- ✓ High stability in the running conditions
- ✓ Sensitivity to small and large mass DM candidate particles
- ✓ Detectors with ~ kg masses



Density (g/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*

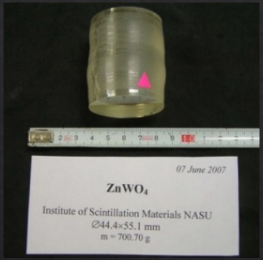
$ZnWO_4$ crystal scintillators in DAMA project

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

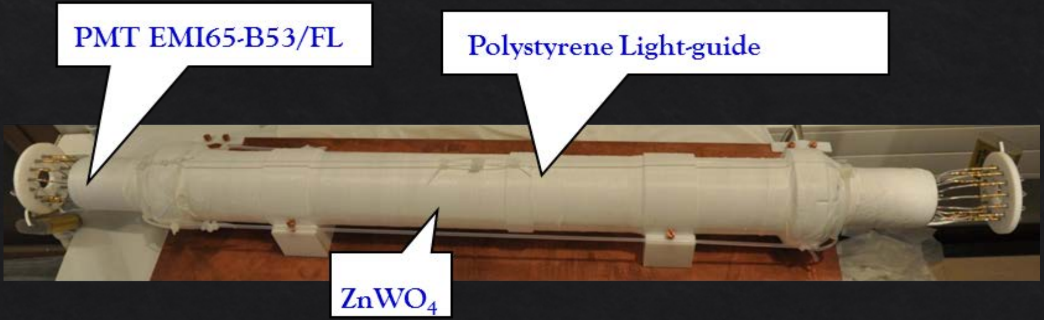


Crystal scintillator	Size (mm)	Mass (g)
ZWO-1	20 × 19 × 40	117
ZWO-2	⌀44 × 55	699
ZWO-2a	⌀44 × 14	168

- 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



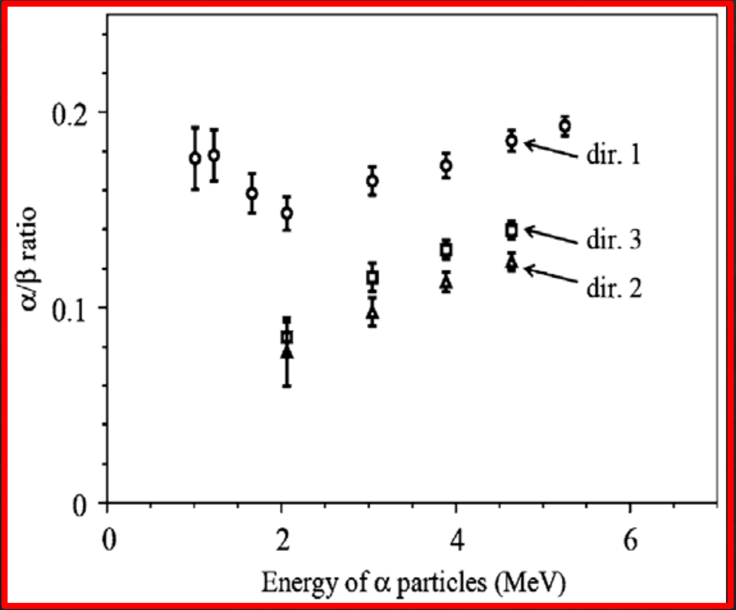
- Main aim of the measurements was the study of the properties of $ZnWO_4$ and the search for 2β processes in Zinc and Tungsten isotopes.



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

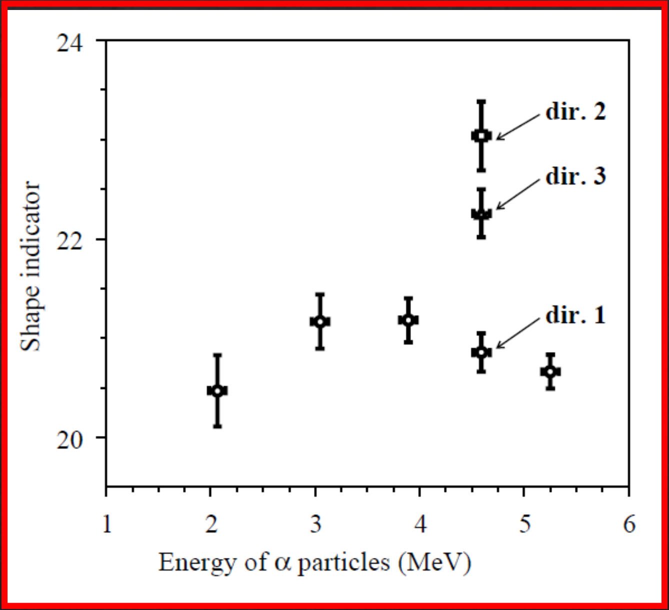
α/β **ratio**



Such effects are absent in case of electron excitation

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

Pulse Shape parameter



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

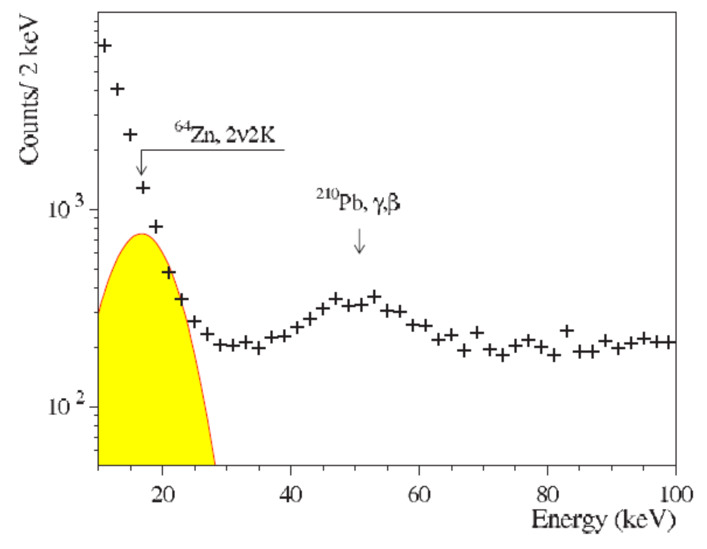
➡ Dedicated measurements are in progress

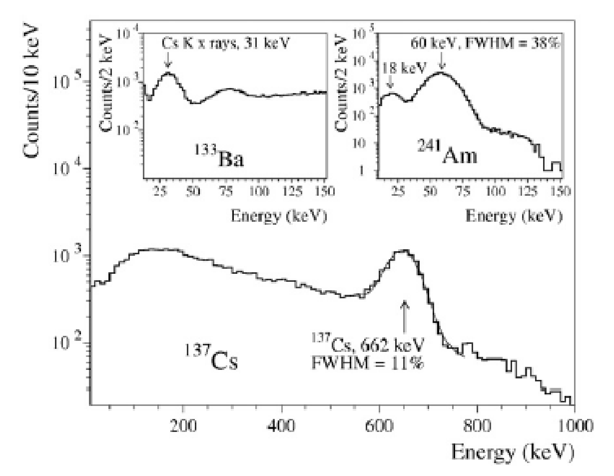
Both the anisotropic features of the $ZnWO_4$ detectors can provide two independent ways to exploit the directionality approach

Light output and threshold of $ZnWO_4$ crystal scintillator

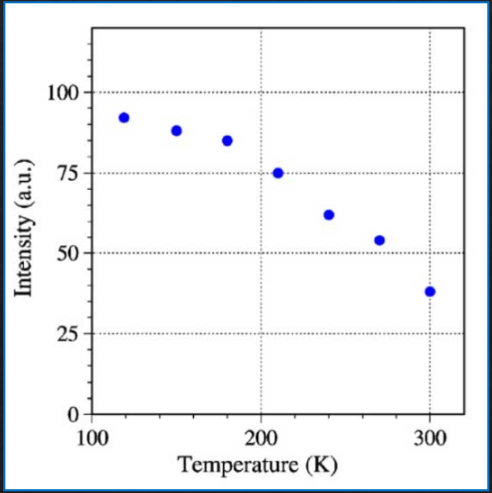
An energy threshold of 10 keV in an experiment not optimized for the low energy region

FWHM in the range of (8.8–14.6)% @662 keV





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



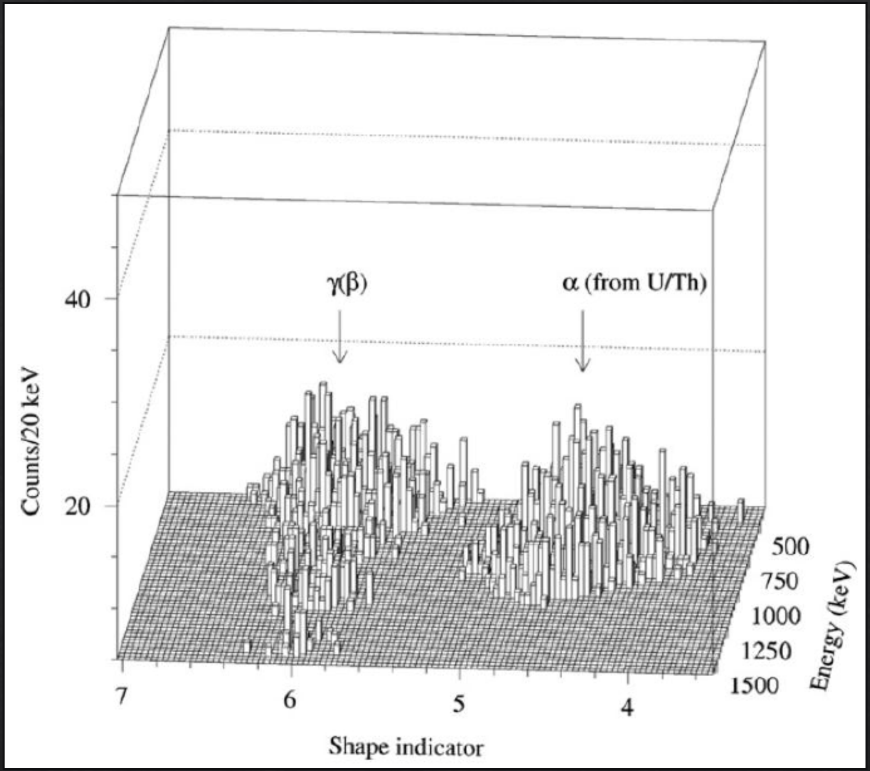
Light output measured for a $ZnWO_4$ scintillator with ^{241}Am α particles as function of Temperature

Improvement of the energy threshold can be obtained e.g. by:

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

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 β(γ) 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

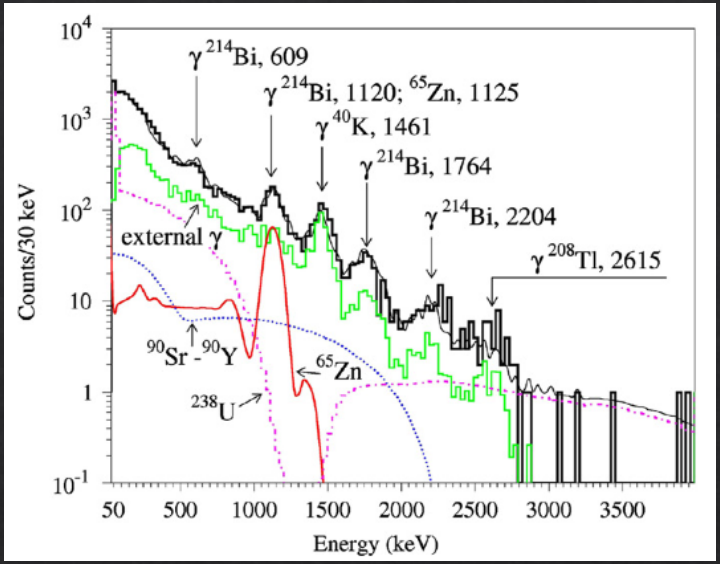
Radiopurity of the $ZnWO_4$ crystal scintillator

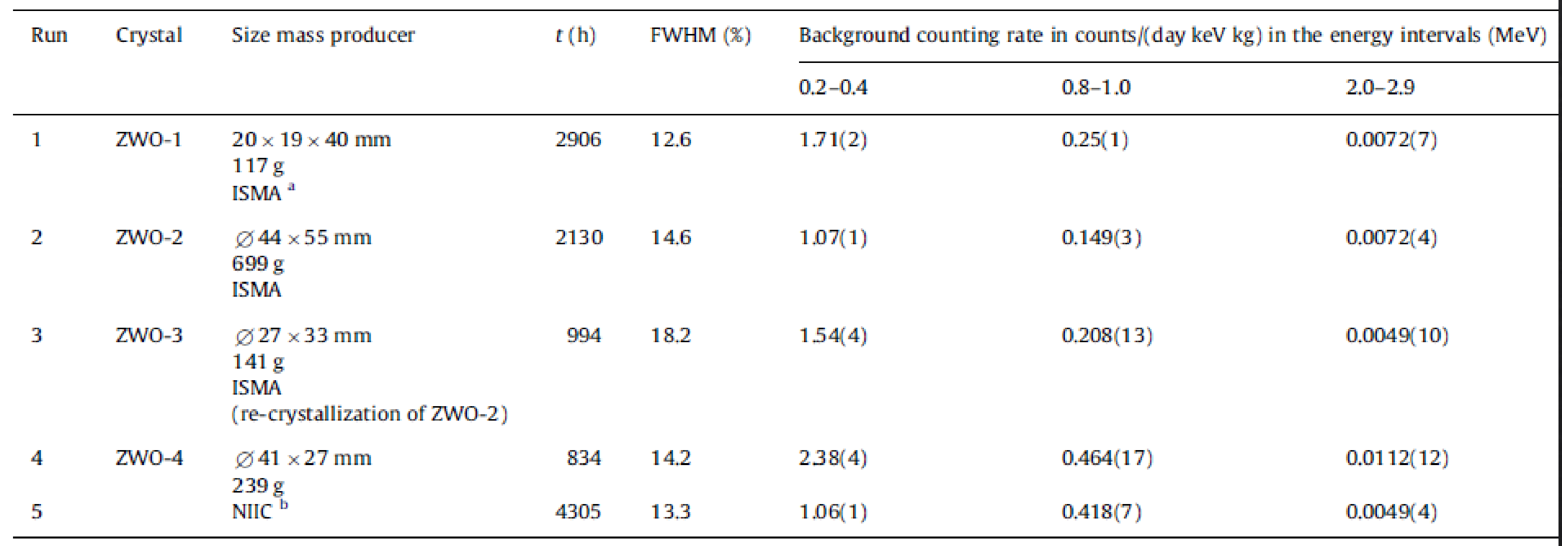
NIMA 626(2011)31

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



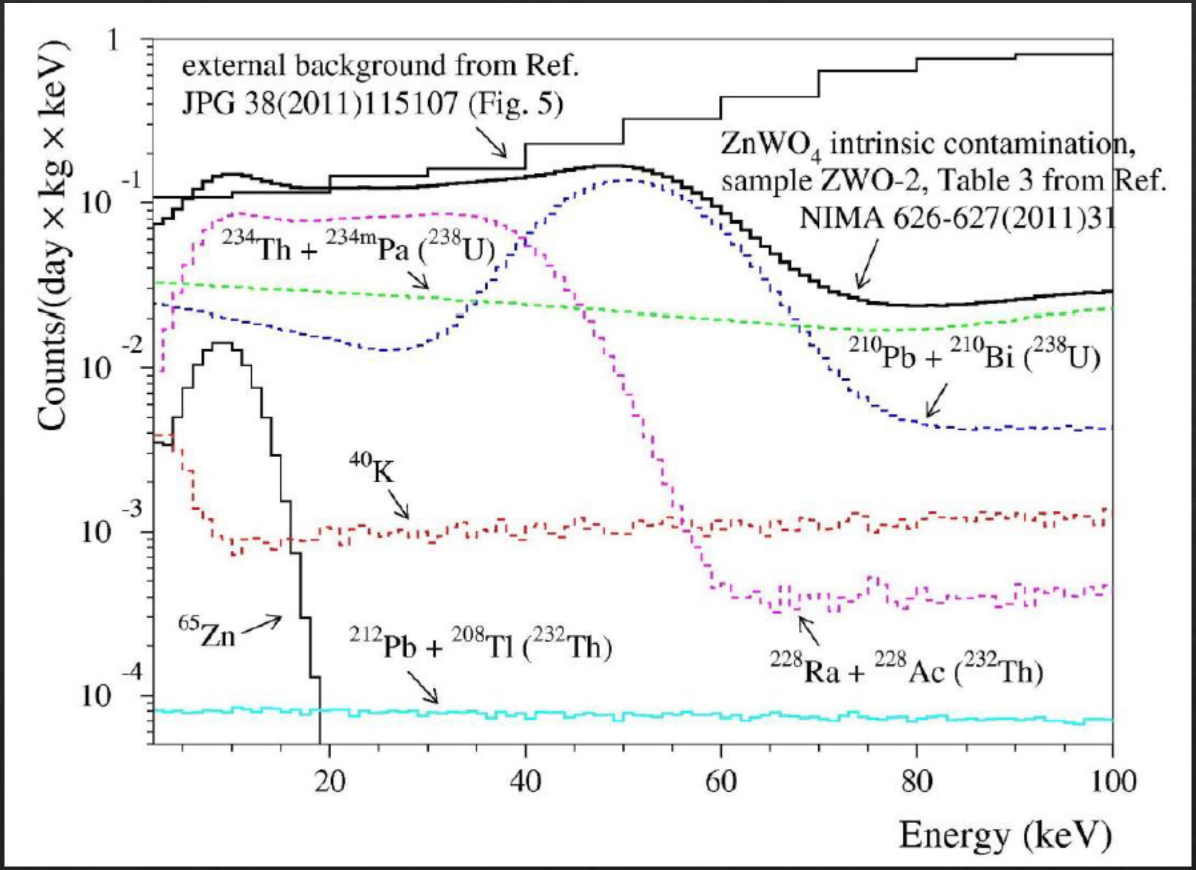


Run	Crystal	Size mass producer	*t* (h)	FWHM (%)	Background counting rate in counts/(day keV kg) in the energy intervals (MeV)		
					0.2–0.4	0.8–1.0	2.0–2.9
1	ZWO-1	20 × 19 × 40 mm 117 g ISMA [a]	2906	12.6	1.71(2)	0.25(1)	0.0072(7)
2	ZWO-2	∅44 × 55 mm 699 g ISMA	2130	14.6	1.07(1)	0.149(3)	0.0072(4)
3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

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



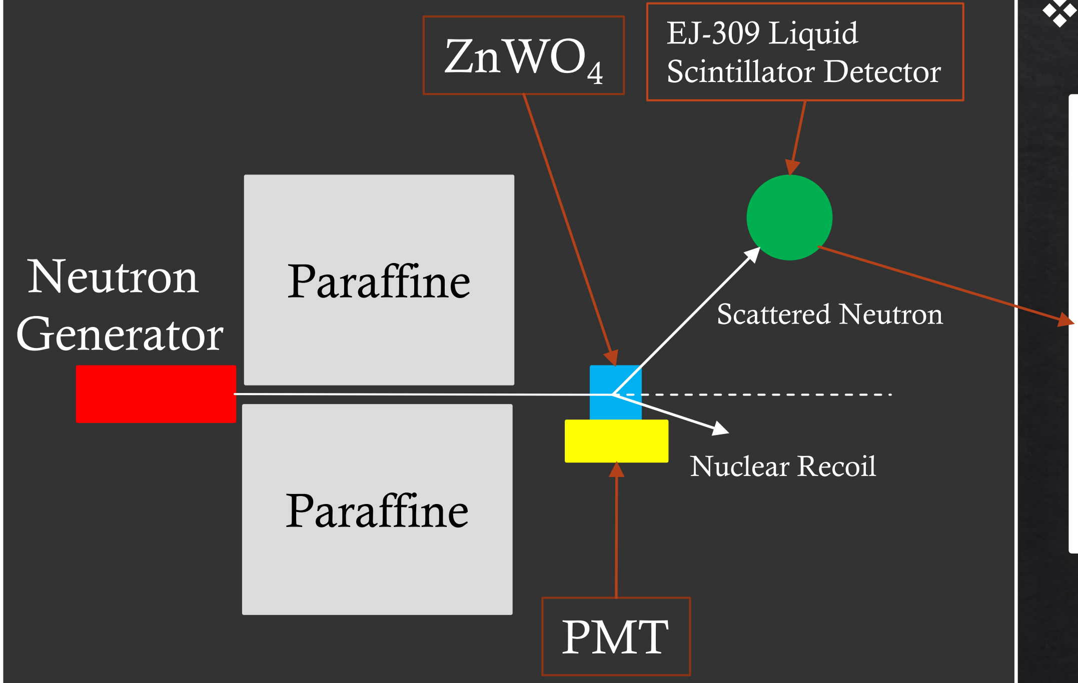
- background contribution in the low energy region is ~ 0.1 counts/day/kg/keV
- the radiopurity of $ZnWO_4$ is very good, but still not sufficient. Our objective is to reduce by at least one order of magnitude the low energy counting rate due to the intrinsic crystal contamination
- new purification techniques under study NIMA 833(2016)77-81

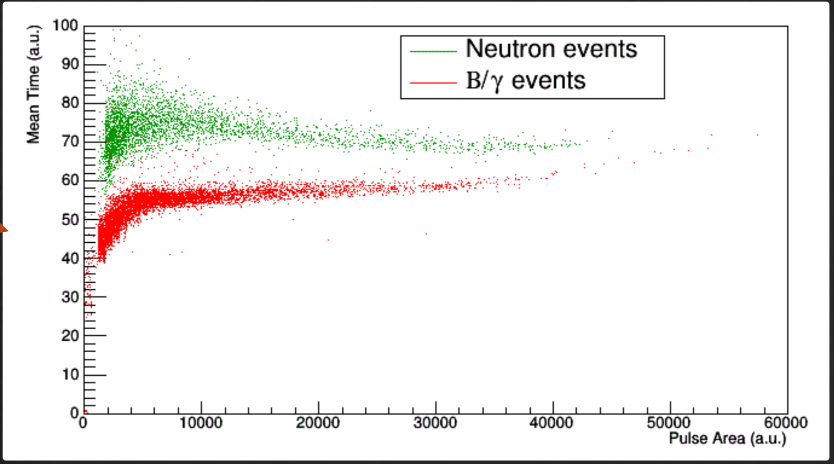
ZnWO$_4$ – work in progress…

- Cryostat for low temperature measurement with scintillation detectors realized
- Test of the Cryostat in progress
- Lowering the energy threshold (new PMT with higher QE, SiPM, APD, SDD, …)
- New purification techniques under study

- Measurements of anisotropy at low energy with MP320 Neutron Generator (E_n = 14 MeV) in progress at Casaccia ENEA lab
- Development of electronics

Exp @ ENEA-Casaccia lab





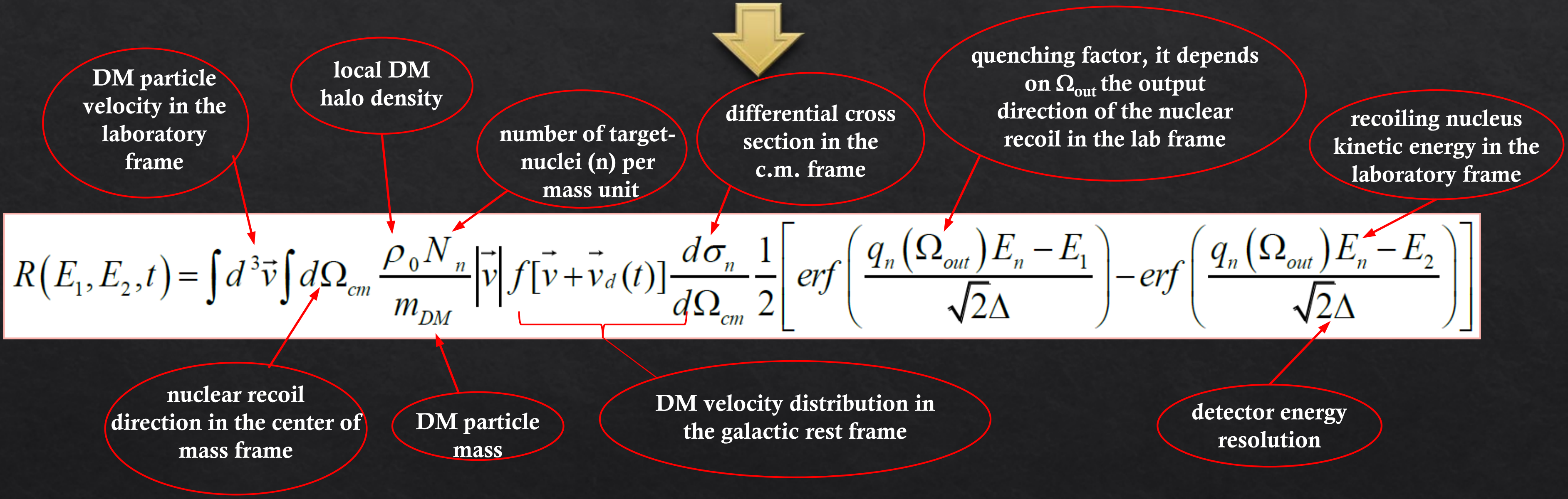
PSD capability of the EJ-309 Liquid Scintillator Detector Used

An example of the signal rate in a given simplified scenario considered here

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 simplified model framework considered here

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

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

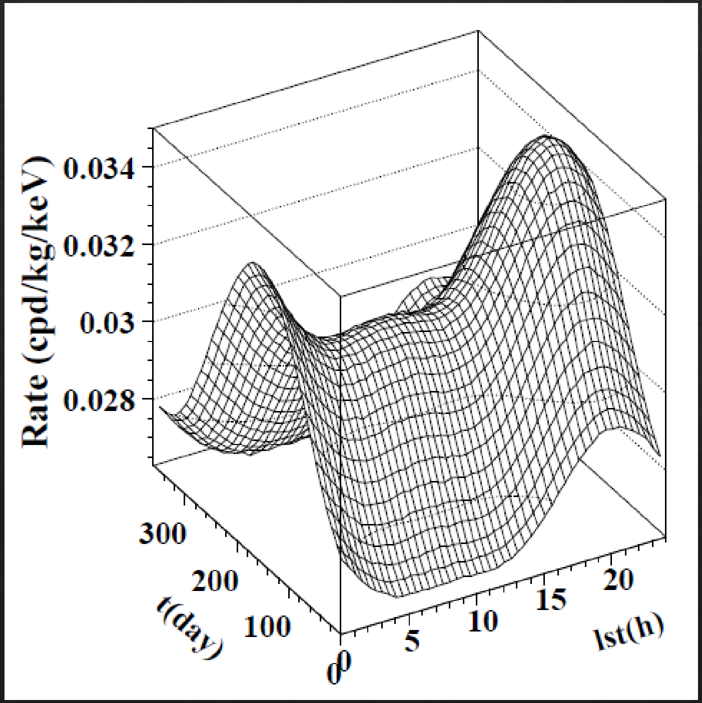
Example of the expected signal in a simplified model considered here

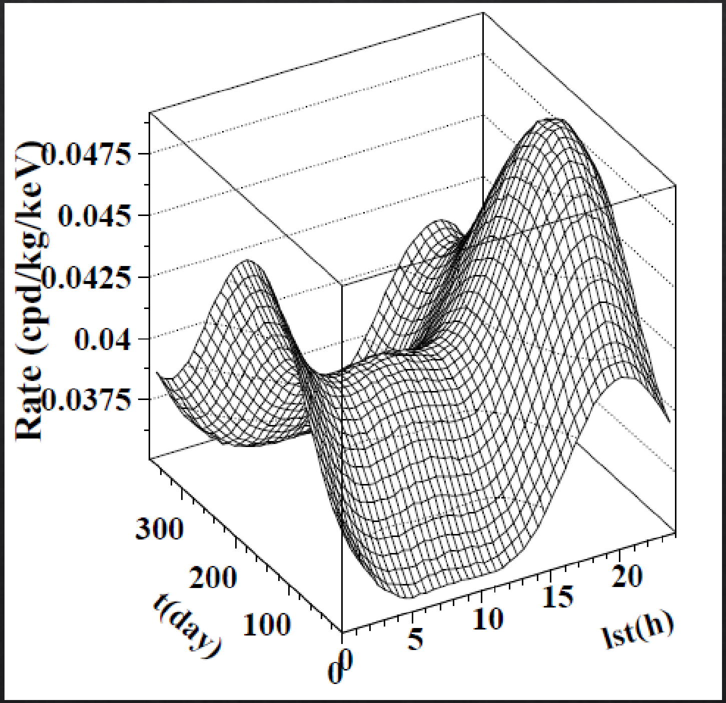
Eur. Phys. J. C 73 (2013) 2276

Expected signal 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

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





An example of model depended reachable sensitivity in simplified scenario considered here

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

Considering an experiment with:

- **200 kg of $ZnWO_4$;**
- **5 years of data taking.**
- **2 keVee threshold**
- **<u>model depended assumption</u> quoted in the previous 3 slides, and full described in EPJC73(2013)2276: <u>DM particle inducing just nuclear recoils</u>, dominant spin-ind. coupling, quenching factor, simple spherical isothermal DM halo model, etc.**

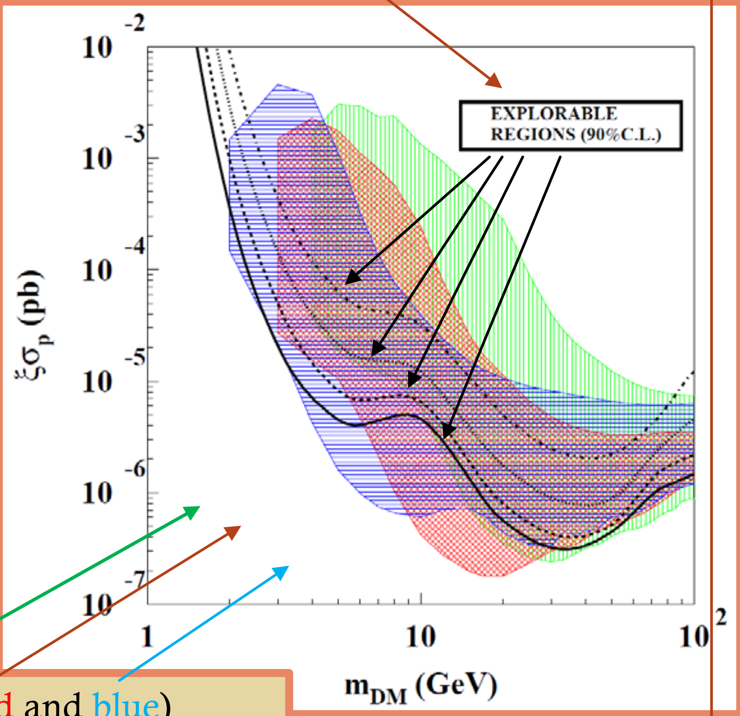
The reachable sensitivity has been calculated considering four possible time independent **background levels** in the low energy region:

- **10^{-4} cpd/kg/keV** ———————
- **10^{-3} cpd/kg/keV** – – – – – – – –
- **10^{-2} cpd/kg/keV** ························
- **0.1 cpd/kg/keV** — · — · — · —

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

Black lines are **<u>the sensitivities reachable</u>** with four possible background levels in the low energy region in a **given scenario** considered here and full described in **EPJC73(2013)2276, compared with**

compared with



For **some model** dependent comparison, there are also shown (green, red and blue) **<u>allowed regions</u>** obtained with a **<u>corollary analysis</u>** of the 9.3 σ C.L. DAMA/NaI + DAMA/LIBRA model independent result in terms of several scenarios for DM candidates inducing just nuclear recoils. <u>Obviously, the model independent DAMA annual modulation result can also be accounted as well by other DM candidates and/or scenarios which are not included here or cannot be investigated with the strategy discussed here.</u>

Phys. Rev. D 84, 055014 (2011)

Conclusions

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

- These detectors would permit to reach - in some given scenarios for DM candidates inducing just nuclear recoils - sensitivity to cross sections at level of 10^{-5}–10^{-7} pb, depending on the particle mass

- Such an experiment can provide, with a different new approach, complementary information on the nature and interaction type of some DM candidates and scenarios

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