Crystal scintillators for the DM directionality approach

TWENTIETH LOMONOSOV CONFERENCE ON ELEMENTARY PARTICLE PHYSICS
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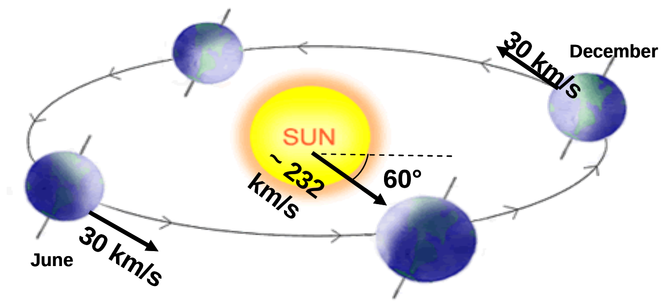
University of Roma “Tor Vergata” and INFN

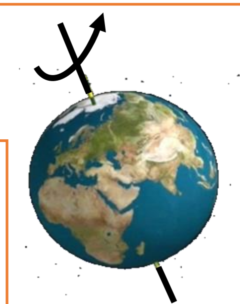
Signatures for direct detection experiments

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 which is moving in the Galaxy
  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



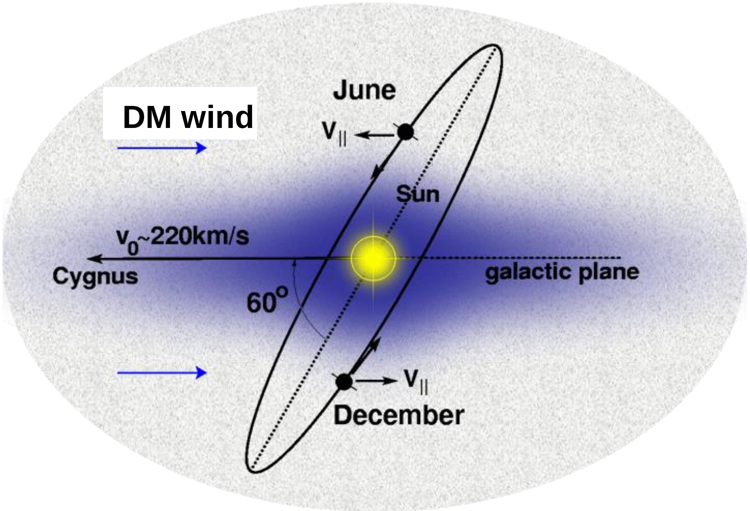
- Diurnal variation: daily variation of the interaction rate due to the different Earth depth crossed by the Dark Matter particles
  only for high cross sections

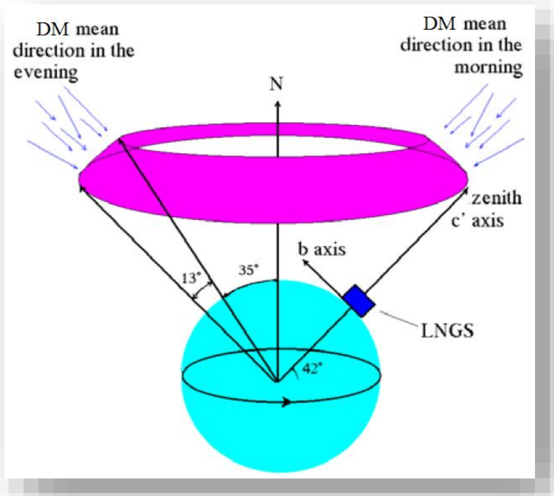
- **Directionality**: correlation of Dark Matter impinging direction with Earth's galactic motion
  only for DM candidate particle inducing recoils

What the directionality approach is?

Based on the study of the correlation between the arrival direction of those Dark Matter (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…





…and 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 case of DM candidate particles giving rise to nuclear recoils, the direction of the latter ones is expected to be strongly correlated with the direction of the impinging DM particle. Therefore, the observation of an anisotropy in the distribution of nuclear recoil direction could give further evidence and information for such candidates

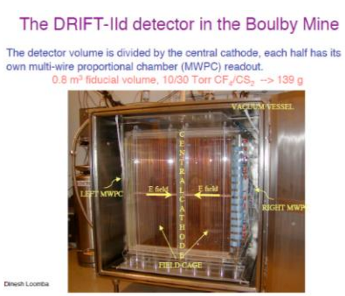
A direction-sensitive detector is needed

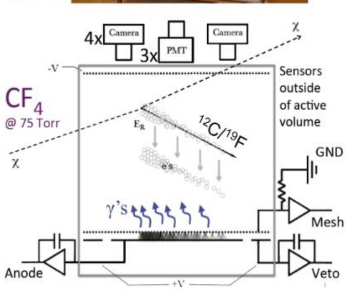
Directionality sensitive detectors: TPC

- 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

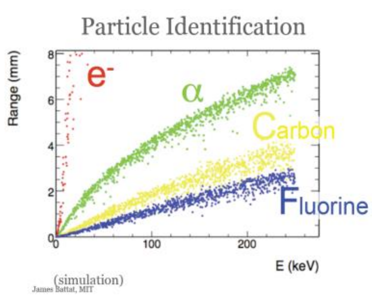
DRIFT-IId





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

DM-TPC



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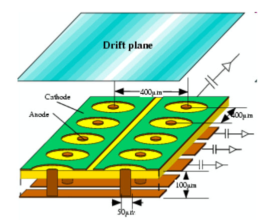


μ-PIC(Micro Pixel Chamber) is a two dimensional position sensitive gaseous detector

	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!

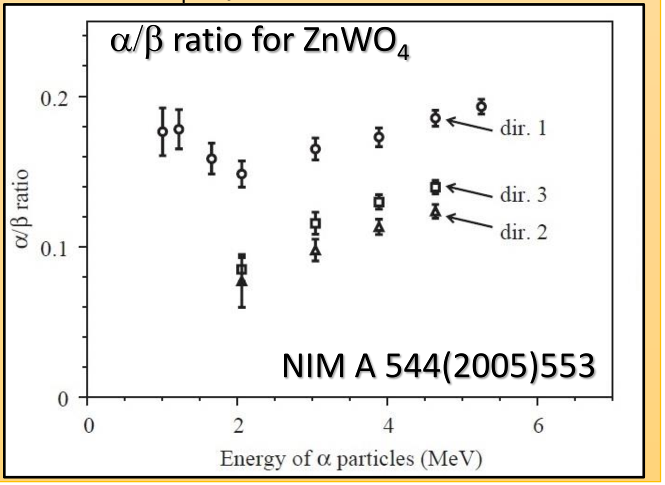
- The **"4--Shooter"** 18L (6.6 gm) TPC 4xCCD, Sea-level@MIT
- moving to WIPP
- Cubic meter funded, design underway

Directionality sensitive detectors: anisotropic scintillators

- The use of anisotropic scintillators to study the directionality signature proposed for the first time in refs. **[P. Belli et al., Il Nuovo Cim. C 15 (1992) 475**], 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]: the idea was revisited in [**R. Bernabei et al., EPJC28(2003)203**]

- 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

First indication of anisotropy properties for a $ZnWO_4$ crystal scintillator:



- **$ZnWO_4$ anisotropic scintillator:** a very promising detector (NIMA544(2005)553, Eur. Phys. J. C 73 (2013) 2276): i) very good anisotropic features; ii) high level of radiopurity; iii) high light output, that is low energy threshold feasible; iv) high stability in the running conditions; v) sensitivity to small and large mass DM candidate particles; vi) detectors with ~ kg masses feasible

Strategy and advantages to develop and study the $ZnWO_4$ anisotropic response to nuclear recoils for the ADAMO project

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

Advantages of the $ZnWO_4$ crystal

- ✓ 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

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*

The main ongoing R&Ds and studies:

- ➢ Further increase the radio-purity level
- ➢ Improve the optical properties
- ➢ Increase the light yield to further decrease the energy threshold
- ➢ **Study the anisotropies property at energy of interest for DM particle nuclear recoils**

See next slides

- Optimization of purification procedure of the starting materials for crystal growth
- Optimization of crystallization protocols
- **Study the light yield response vs the operation temperature**

JINST15(2020)07,C07037; JINST15(2020)05,C05055; NIMA935(2019)89; NIMA833(2016)77; JPCS718(2016)4,042011; EPJC73(2013)2276; NIMA626-627(2011)3; JP38(2011)115107 NPA826(2009)256; PLB658(2008)193

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

- In summer 2018 a campaign of measurements using a dedicated $ZnWO_4$ crystal to study the anisotropic features of the detector for low energy nuclear recoils started

- Preliminary measurements with a collimated α source have been performed

- After α calibrations a campaign of measurements at ENEA-Casaccia with a 14 MeV neutron beam has been carried out

Very transparent and radio-pure EPJA 56 (2020) 3

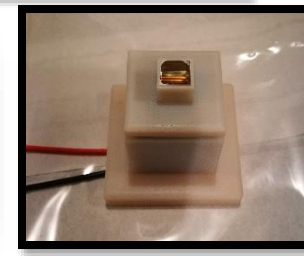
$ZnWO_4$ crystal = 10 x 10 x 10 mm^3 (detector of reduced dimensions to investigate neutron single-scattering)

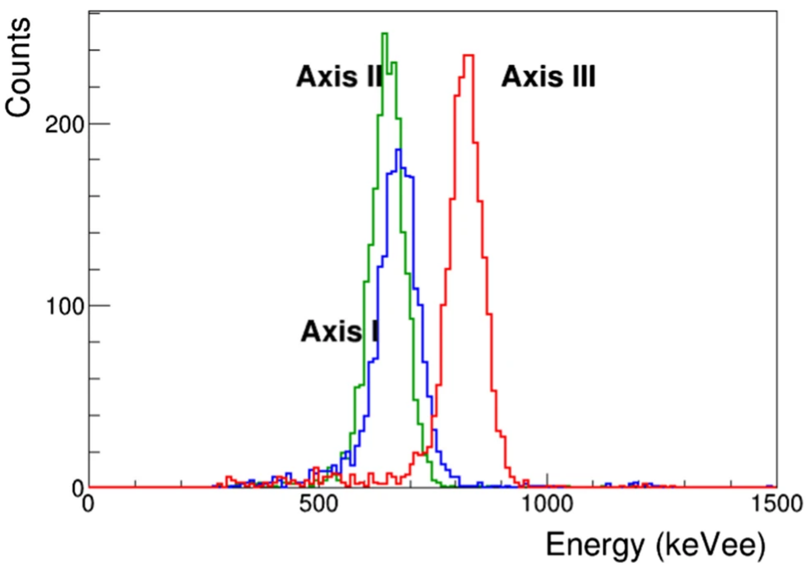
Eur.Phys.J.A 56 (2020) 83

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

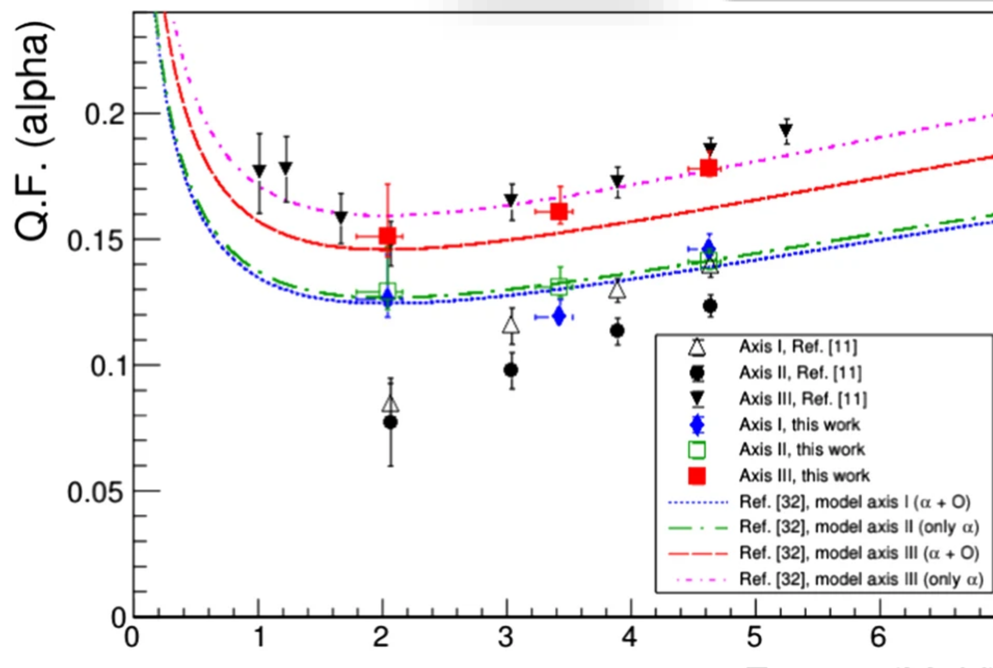
Calibration set-up:

- 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





Energy spectra of 4.63 MeV α particles impinging along the three axes of the crystal. The crystal was irradiated in the directions along the crystal axes I (blue on-line), II (green on-line), and III (red on-line), respectively



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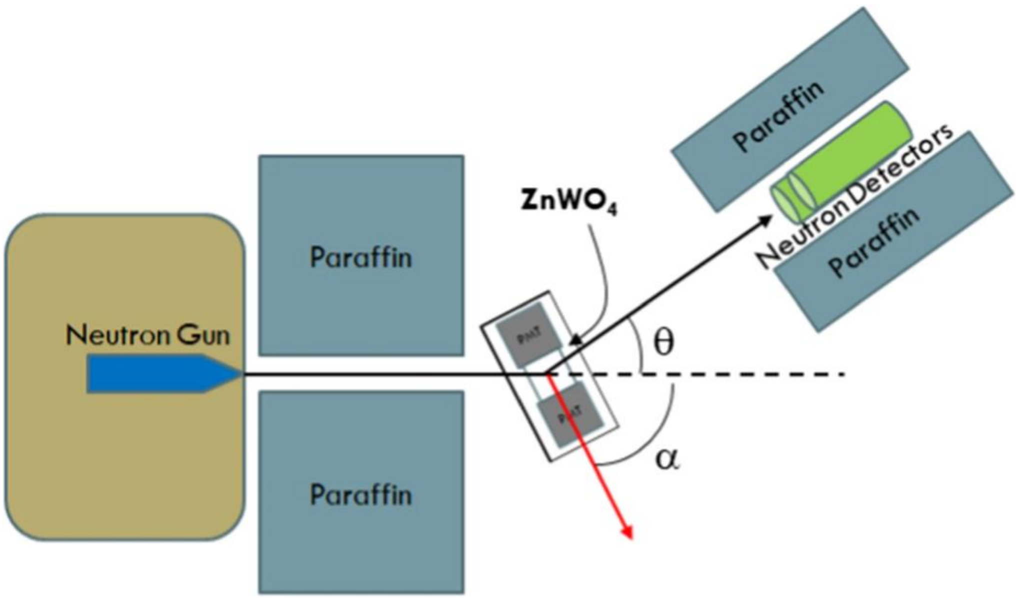
Ref. [11]: NIM A 544(2005)553

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

- Set-up:
  - ✓ $ZnWO_4$ Crystal (10 x 10 x 10 mm^3)
  - ✓ Two Hamamatsu PMTs: HAMA-H11934-200
  - ✓ 2 Neutron detectors (Scionix EJ-309)
  - ✓ Neutron Gun, Thermo Scientific MP320: 14 MeV neutrons



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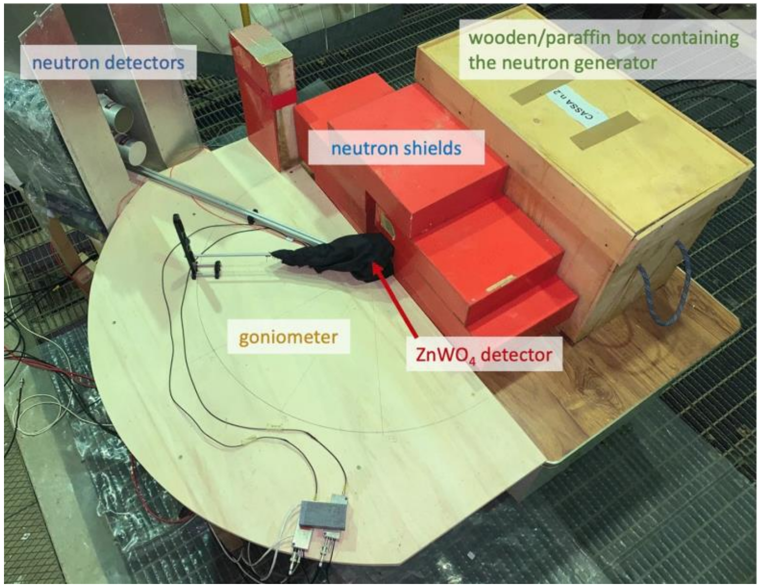
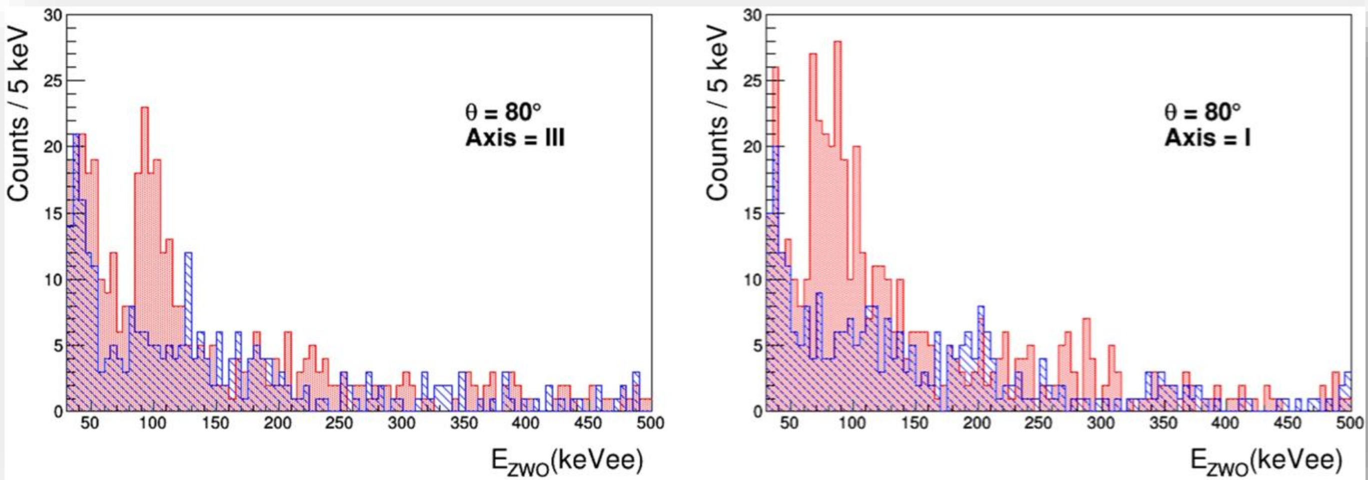
- Strategy: search for coincidence between a scattered neutron at a fixed angle and scintillation event in $ZnWO_4$ occurred in a well defined time window (ToF)
- Once fixed the θ angle, the recoil direction and energy are fixed
- Measurements performed at different θ angles

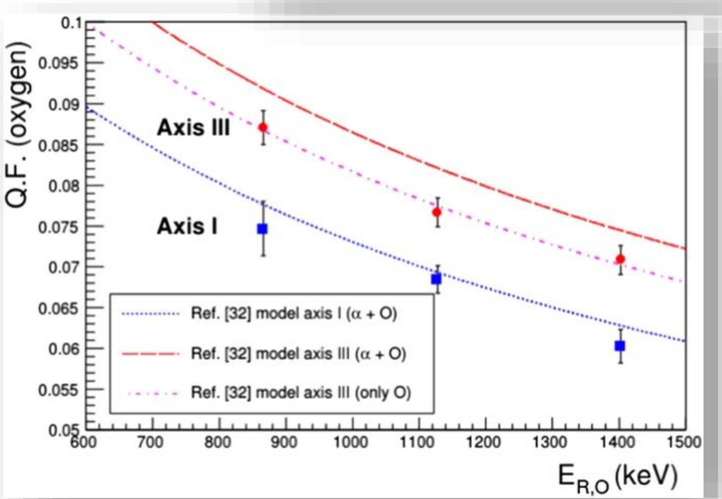


The response of $ZnWO_4$ to neutrons: results

Energy distributions in $ZnWO_4$ for coincidence events when neutrons are identified in EJ-309 and two ToF windows are considered (θ=80°) to consider the **neutron induced recoils** and to characterize the **random coincidences**

First evidence at low energy





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

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How can we profit of the anisotropic scintillators 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**)

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

- **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 adopted in the following example:

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

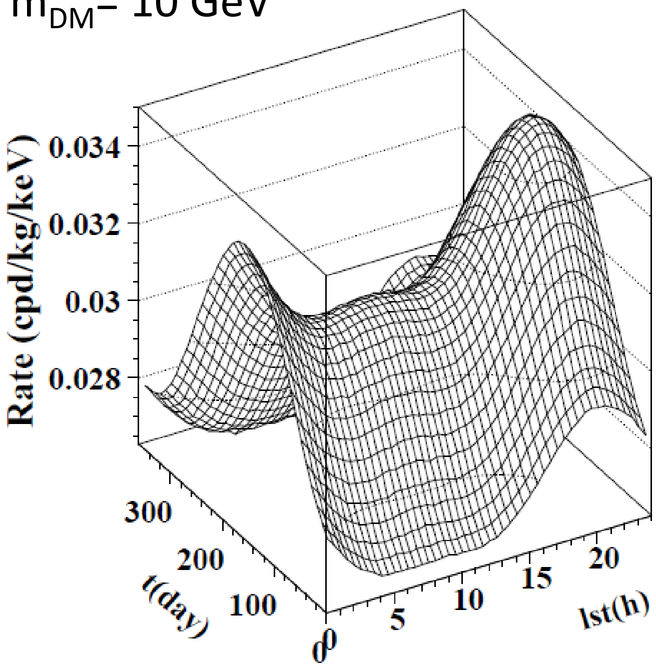
where $q_{n,i}$ is the quenching factor value for a given nucleus, n, with respect to the i-th axis of the anisotropic crystal and **$\Omega_{out} = (\gamma,\phi)$ is the output direction of the nuclear recoil in the laboratory frame**
$q_{n,i}$ have been calculated following ref. [V.I. Tretyak, Astropart. Phys. 33 (2010) 40] considering the data of the anisotropy to α particles of the $ZnWO_4$ crystal

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

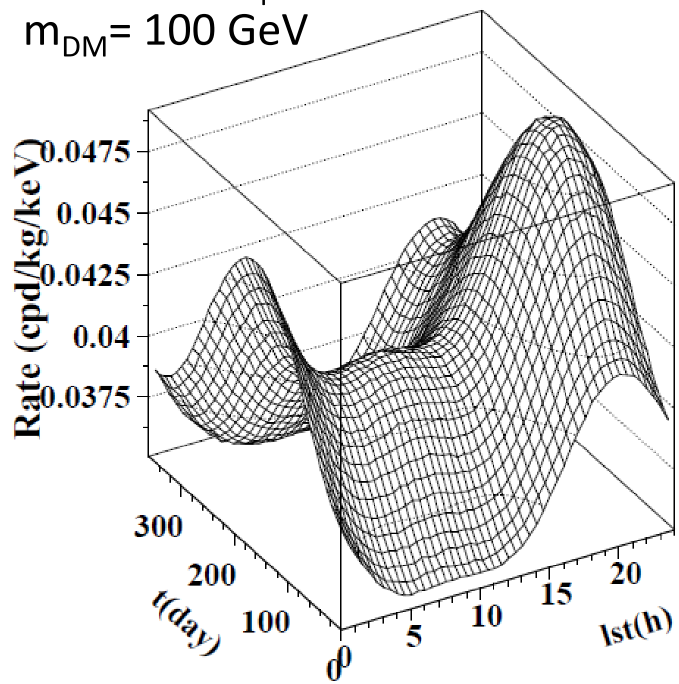
Example of expected signal

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



[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**

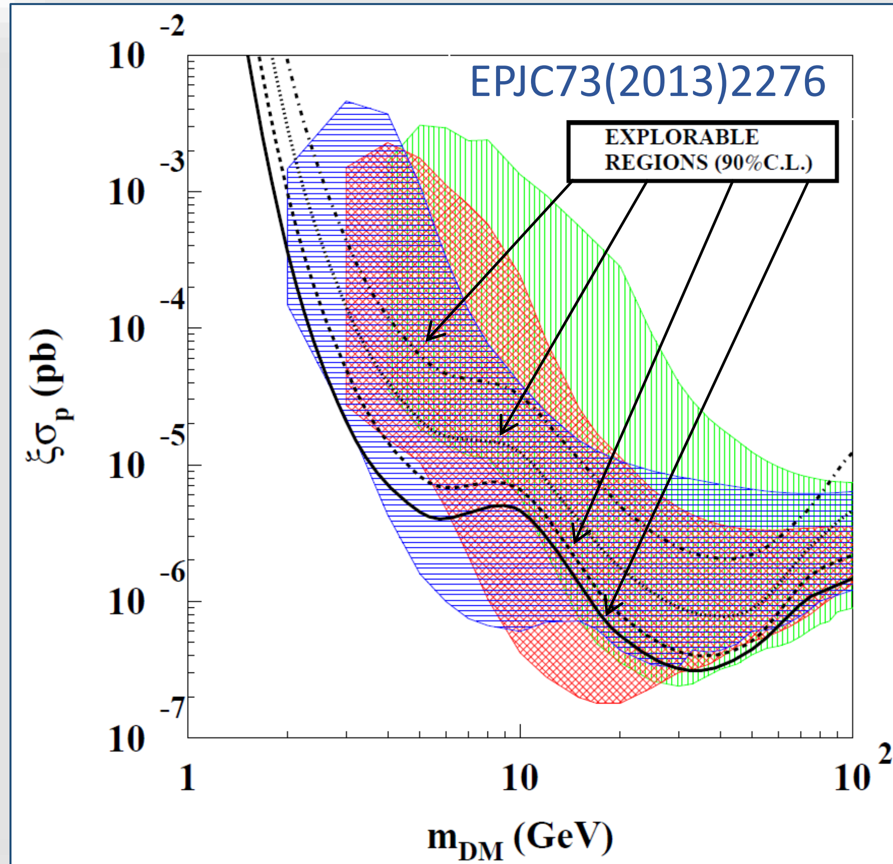
Eur. Phys. J. C 73 (2013) 2276

ADAMO project: example of reachable sensitivity in a given scenario

O → light masses
Zn, W → high masses

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 — · — · —

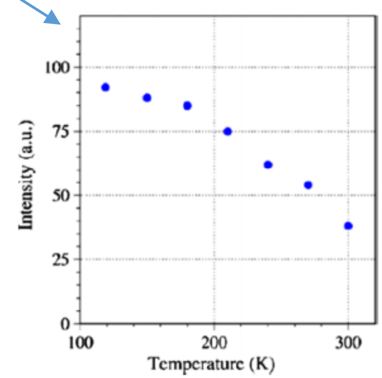


The directionality approach can reach in the given scenario a sensitivity to the cross section at level of 10^{-5} – 10^{-7} pb, depending on the particle mass

Allowed regions 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 (green, red and blue)

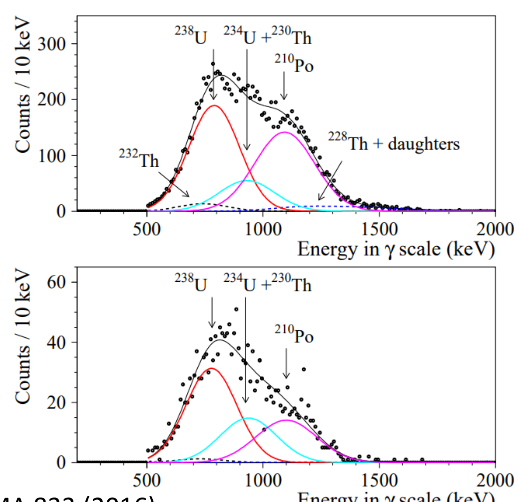
$ZnWO_4$ – work in progress…

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



Temperature dependence of the light output of the $ZnWO_4$ crystal scintillator for excitation with ^{241}Am α particles

NIM A **600** (2009) 594



An example of the radio-purity improvements after the recrystallization

NIMA 833 (2016)
JINST 15 (2020) 05,C05055

- New measurements of anisotropy at low energy with MP320 Neutron Generator (E_n = 14 MeV) at ENEA-Casaccia is ongoing
- Further improvement of the radio-purity

Conclusions

- Directionality Dark Matter experiments could obtain, with a completely different new approach, 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**.
- 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.