The Dark Matter Directionality Approach

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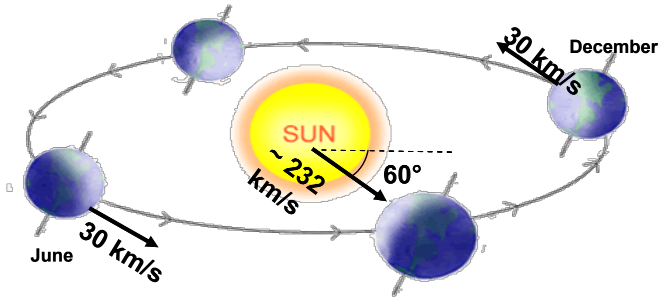
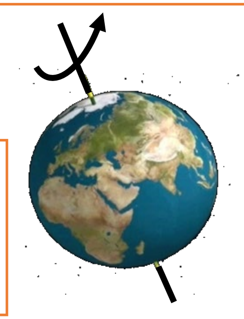
Signatures for direct detection experiments

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 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



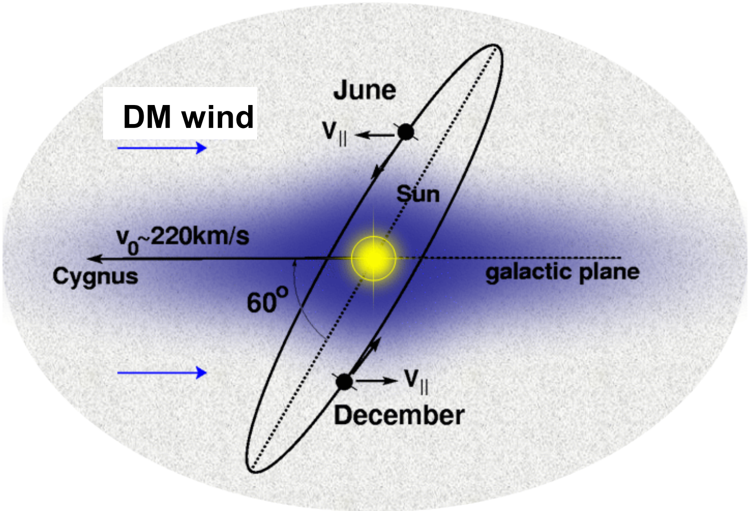
- Diurnal variation: daily variation of the interaction rate due to the different Earth depth crossed by the Dark Matter particles
  only for high cross sections

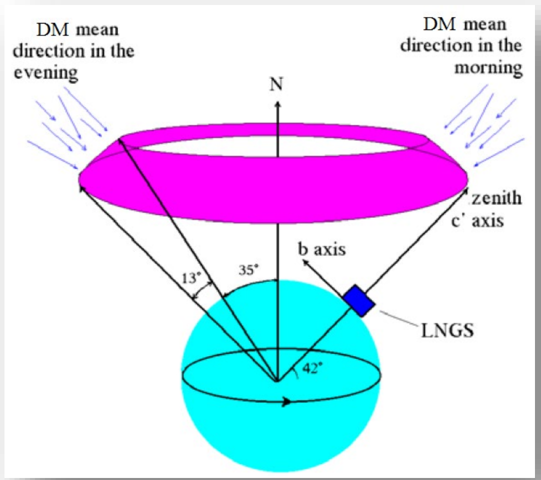
- **Directionality**: correlation of Dark Matter impinging direction with Earth's galactic motion
  only for DM candidate particle inducing recoils

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 techniques (R&D stage)

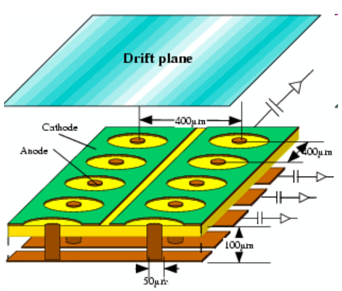
Detectors Strategies

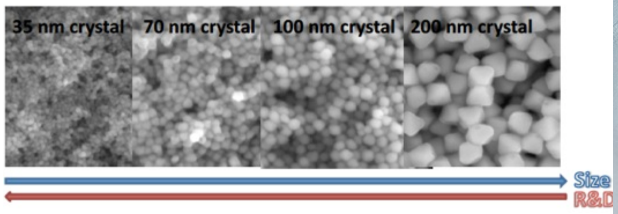
Tracking Detectors

- **TPC** (DRIFT, NIMAC, DMTTPC, NEWAGE, D3, NITEC, CYGNUS, INITIUM)
- **Nuclear Emulsions** (NEWSdm)
- **DNA**
- **Diamonds**

Detectors using Anisotropic Features

- **Anisotropic crystal scintillators** (ADAMO, Japanese group)
- **Carbon nanotubes based detector** (ATRACT, PTOLEMY)
- **Columnar Recombination in LAr/LXe-TPC** (RED)

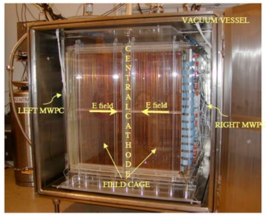




The DRIFT-IId detector in the Boulby Mine

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



Dinesh Loomba

R&D on Low Pressure Time Projection Chamber

Advantages: In Low Pressure **Time Projection Chamber** the range of recoiling nuclei is of the order of mm (while it is ~μm in solid detectors)

Experiment	Technology + Readout	Gas Mixture	Full Volume (m^3)	Pressure (mbar)	Angular Resolution
DRIFT	Negative Ion TPC, multi-wire proportional chambers	$CS_2 + CF_4 + 0_2$	1	55	
NIMAC	Matrix of micro-TPC, Micromegas	$CF_4 + CHF_3 + C_4H_{10}$	0.006	50	~10° @ 10 keV of kinetic energy of $^{19}F^+$ ion
DMTPC	TPC, Meshes + CCD +PMT	CF_4	0.02, 1	30-100	~15° @ 100 keV
NEWAGE	micro TPC, low-alpha-micro-PIC	CF_4	0.036	100	~40° @ 50 keV
D^3	TPC, Micropattern Gaseous Detectors (3D pixels)	$He + CO_2$	10^{-3}	10^3	~1° @ 1 MeV
CYGNO	GEM, CMOS, PMT/SiPM	$He + CF_4$	1	10^3	20°-- 60° @ 50 keV depending on the redout/set-up used.

Disadvantages: strong software gamma rejection used, could be present systematic effects respect to the direction of the electric field with high gain, high angular and spatial resolution is required at very low energy, low background techniques is not mature, limitations on mass and stability.

Other R&D using Tracking Detectors

NEWSdm: consists in the use of a nuclear emulsion-based detector acting both as target and as tracking device. The detector is proposed to be placed on an equatorial telescope in order to cancel out the effect of the Earth rotation. Path length of the order of <u>a few 100 nm</u> → Novel emulsion technology called: **Nano Imaging Tracker** (NIT)

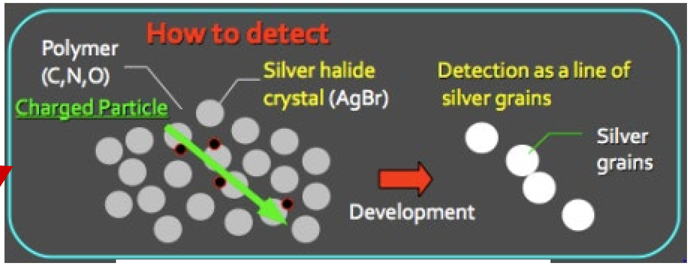
Main component of internal background:

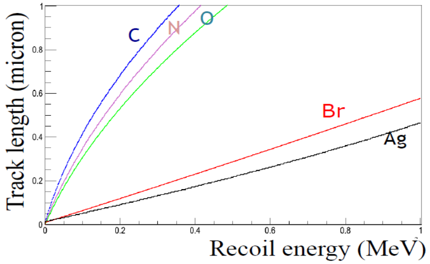
1) Radioactivity from ^{14}C or U/Th contaminations
2) Intrinsic neutrons

Readout technology:

Resonant light scattering using polarised light → measurement of track beyond the optical resolution → track length threshold (120 ± 5) nm. Exploiting further threshold lowering using **Ultra-NIT** (larger granularity).

Nuclear emulsion are basically made of silver halide crystals embedded in a gelatin matrix.

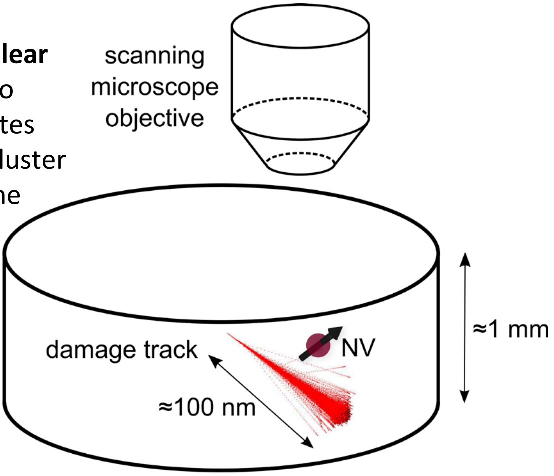




Spectroscopy of Quantum Defects in Diamonds (idea)

When a DMp scatters near a Q.D., the **induced nuclear recoil** creates a tell-tale damage cluster, localized to within 50 nm, and with an orientation that correlates well with the direction of the recoil. This **damage** cluster **induces strain** in the **crystal** and this strain **shifts** the **energy levels** of the nearby defects.

Detection technique of the shifted energy levels: exciting optical transitions, or ground state magnetic resonance spin-flip transitions.



DNA (idea):

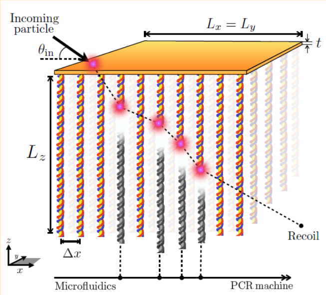
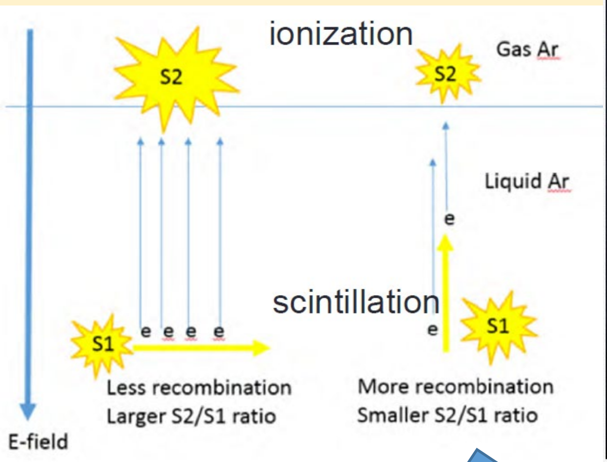
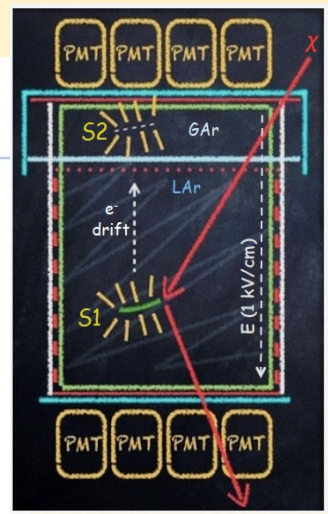


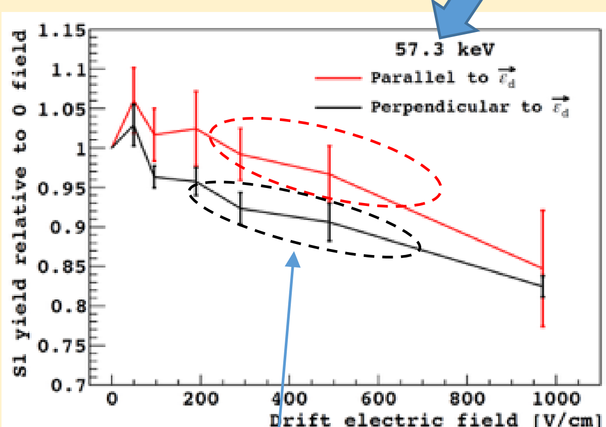
Diagram of the basic concept behind the DNA detector. The detector consists of a thin, dense inorganic holder of area A = Lx Ly and thickness t from which a regular grid of DNA strands are attached with an inter-strand spacing x. <u>The DNA strands, when broken by some incoming particle or secondary recoil</u>, fall down to a collecting area where they are transported in chronological order via microfluidics to an amplification and readout stage consisting of polymerase chain reaction (PCR) devices. A PCR device amplifies the collected strands to where the precise sequence of bases can be measured and therefore each vertex in the track can be reconstructed.

R&D Detectors using Anisotropic Features

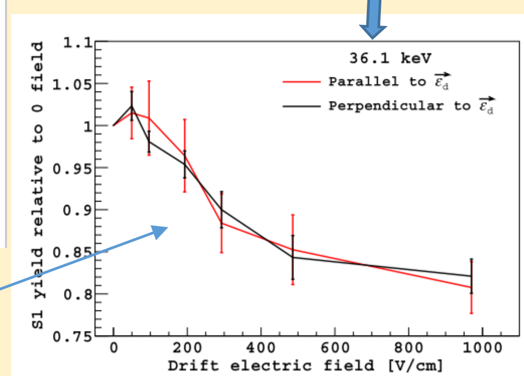
RED (R&D): Columnar Recombination in Liquid Argon TPC (LAr-TPC).







PRD 91 092007:
no more data since 2015 with a small LAr-TPC: SCENE

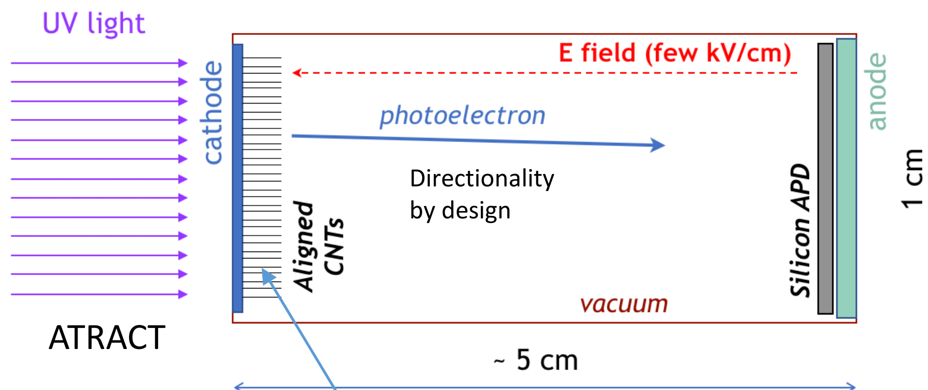


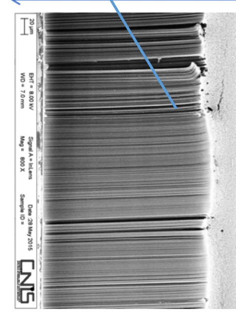
Parallel and perpendicular S1 yield are statistically compatible: more investigation needed.

Carbon Nanotubes as Anisotropic Target (idea):

"Dark-photocathode" made of aligned CNTs

- DMp could extract photoelectron of few eV
- e- escapes only if in direction of tube axis





PTOLEMY, instead, plains to use a TES to detect the electron extracted from the CNTs with a different set-up configuration

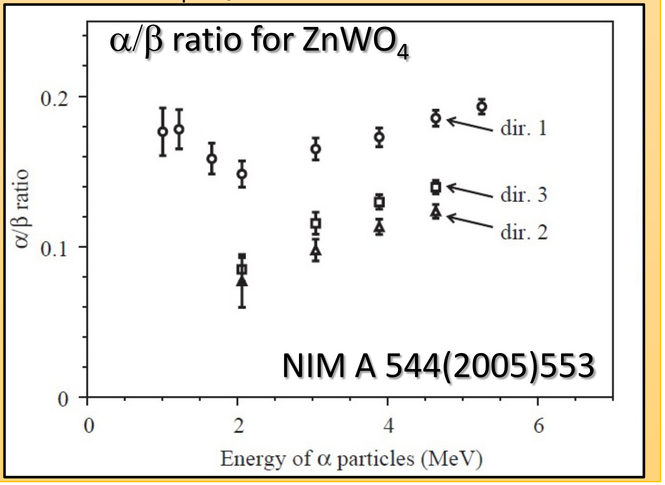
+
Anisotropic crystal scintillators

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

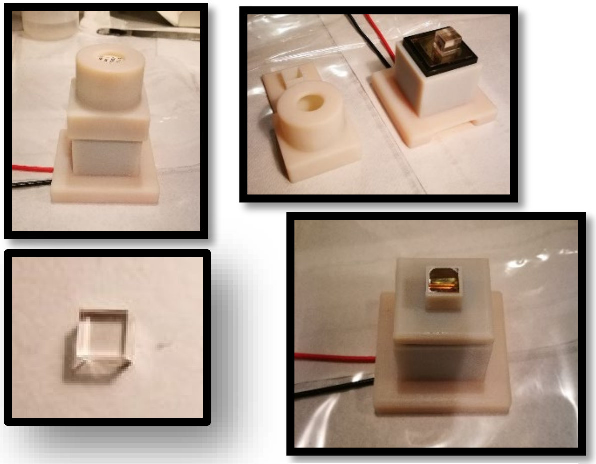
$ZnWO_4$ crystal = 10 x 10 x 10 mm^3 (detector of reduced dimensions to investigate neutron single-scattering)

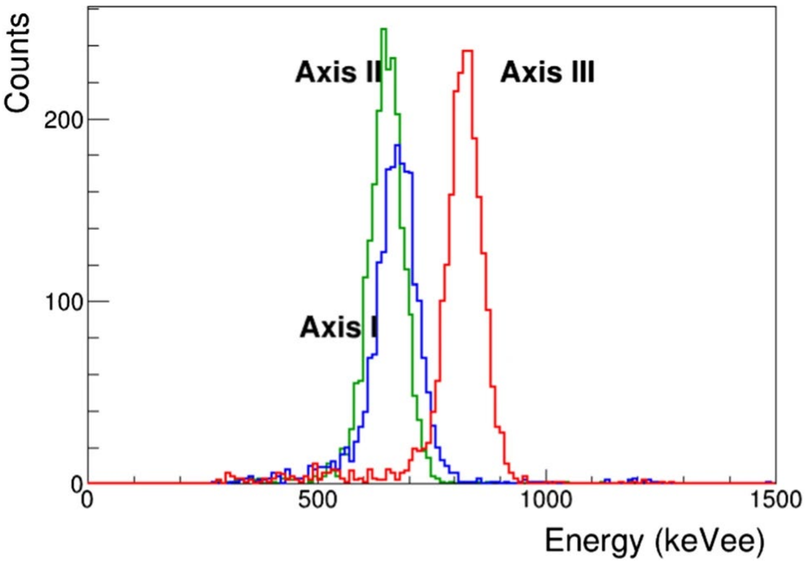
Eur.Phys.J.A 56 (2020) 83

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





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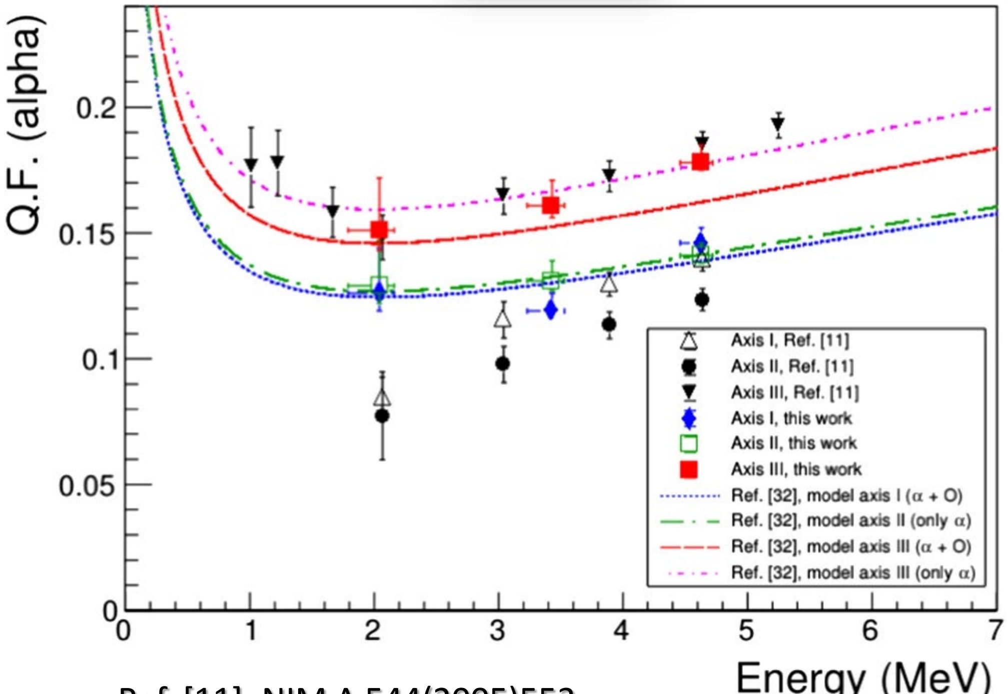
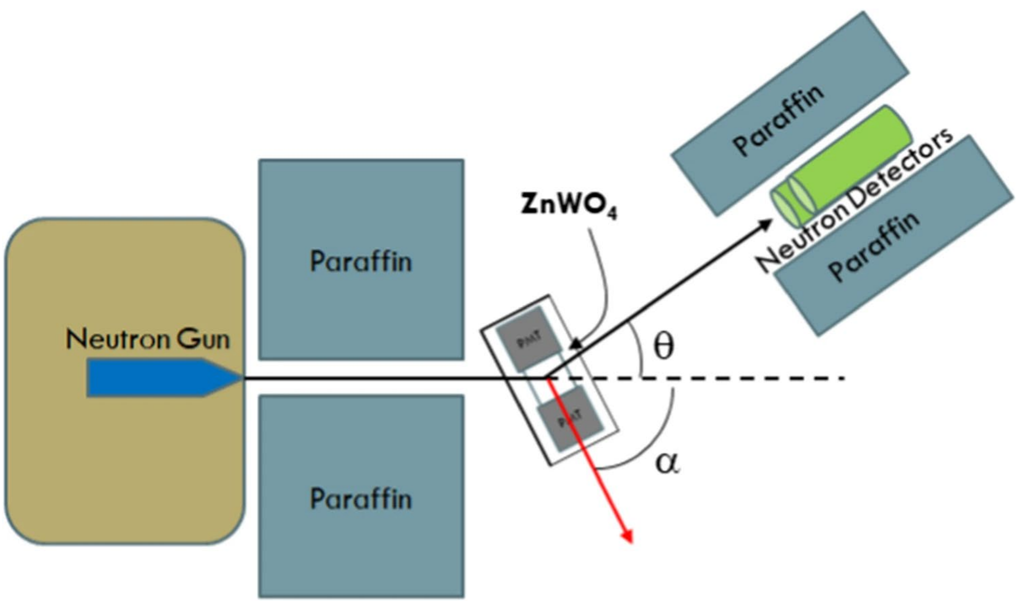


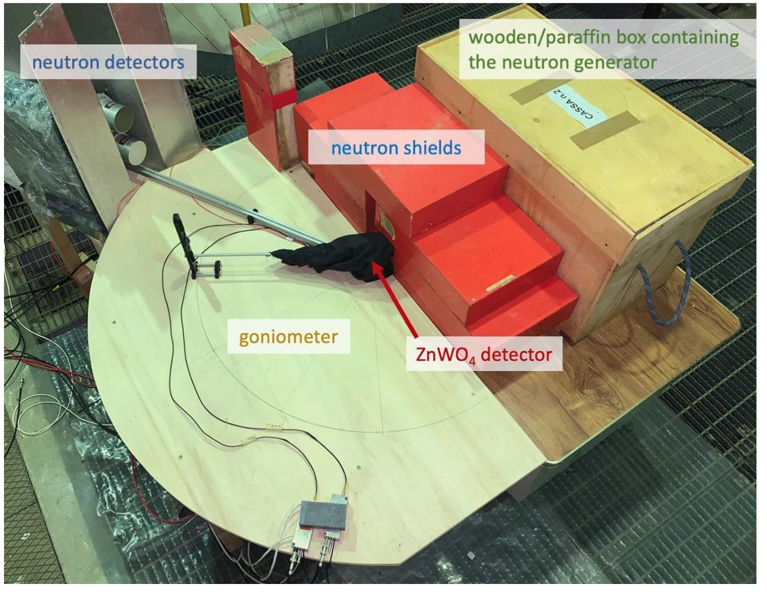
Ref. [11]: NIM A 544(2005)553

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

- 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





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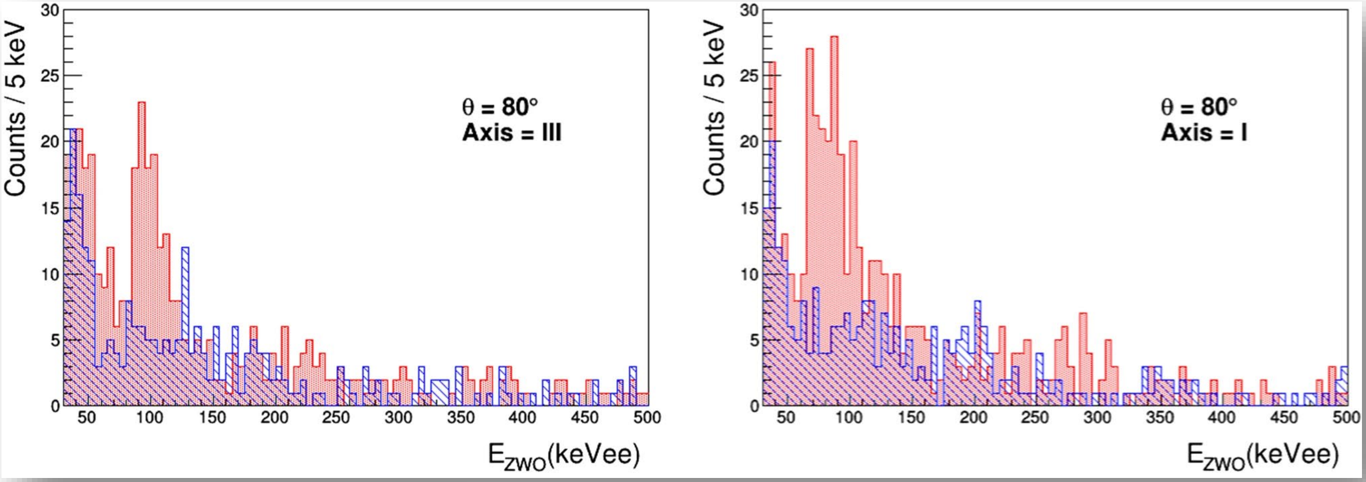
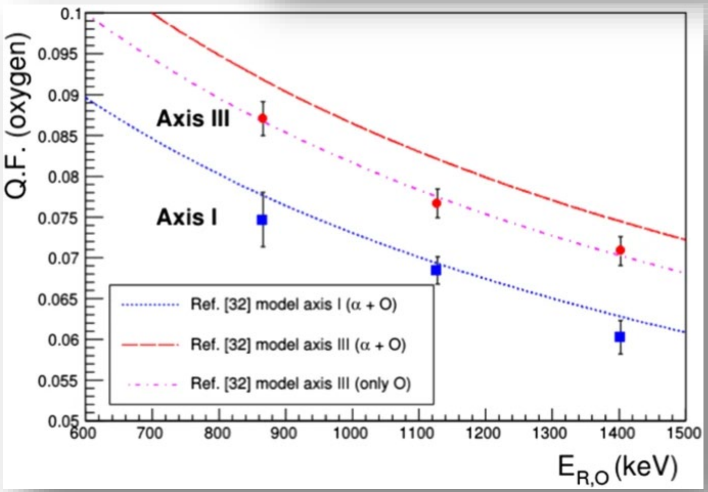
The response of $ZnWO_4$ to neutrons: results

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.

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

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**)

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

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

nuclear recoil direction in the center of mass frame

DM particle mass

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:

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

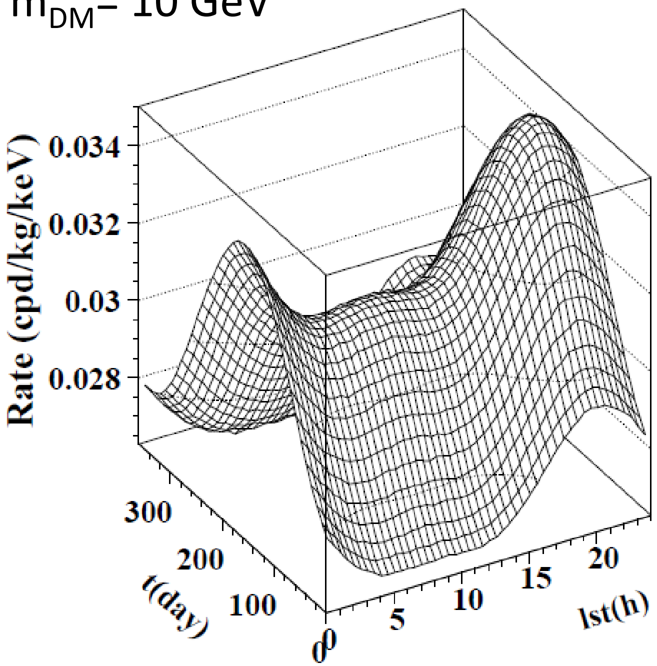
where $q_{n,i}$ is the quenching factor value for a given nucleus, n, with respect to the i-th axis of the anisotropic crystal and $\Omega_{out} = (\gamma, \phi)$ is the output direction of the nuclear recoil in the laboratory frame $q_{n,i}$ have been calculated following ref. [V.I. Tretyak, Astropart.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

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

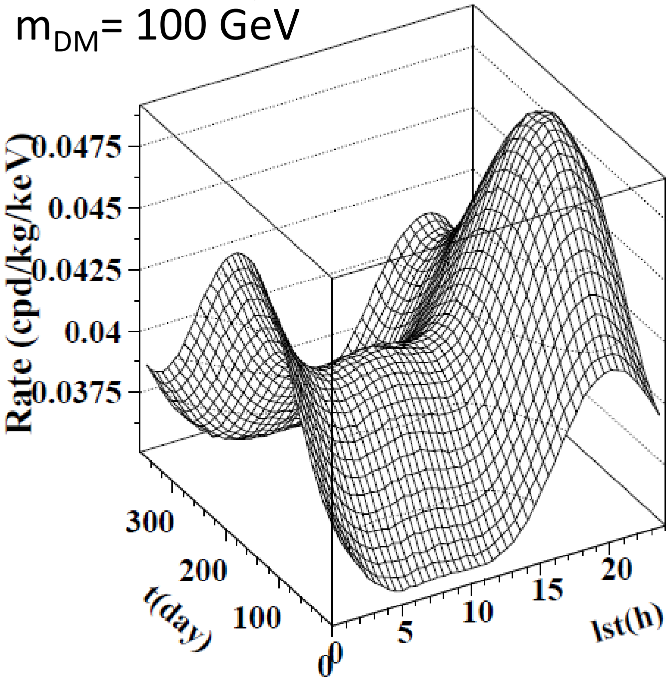
Example of expected signal

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**

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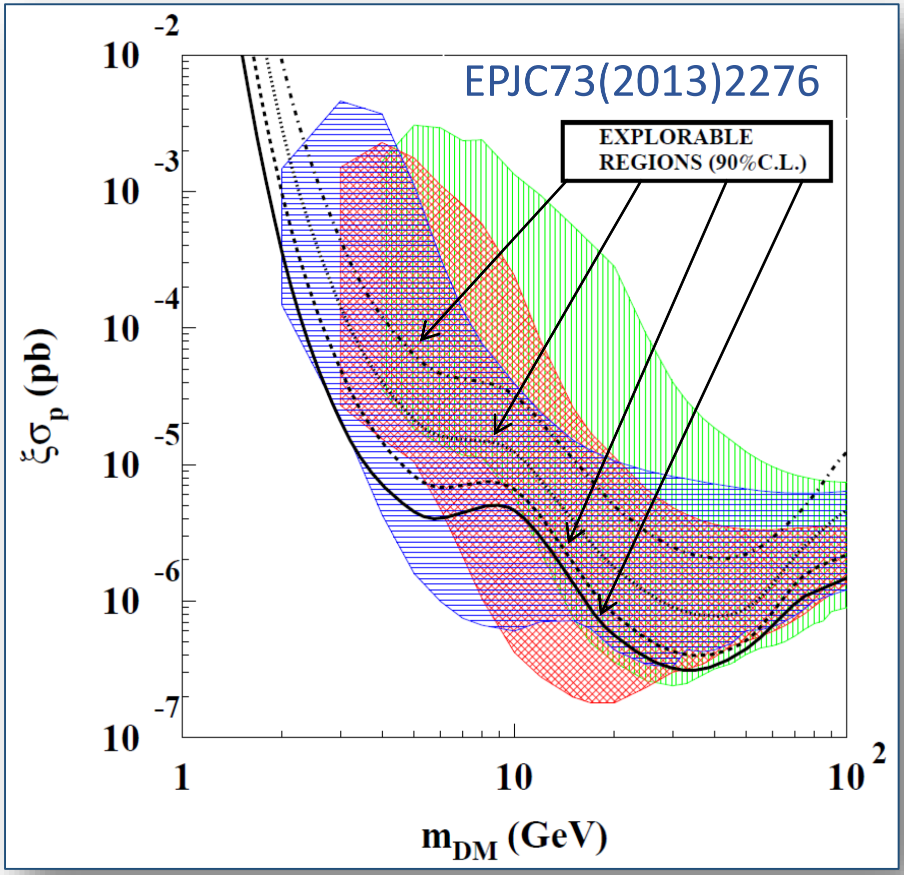
ADAMO project: example of reachable sensitivity in a given scenario

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 —·—·—··

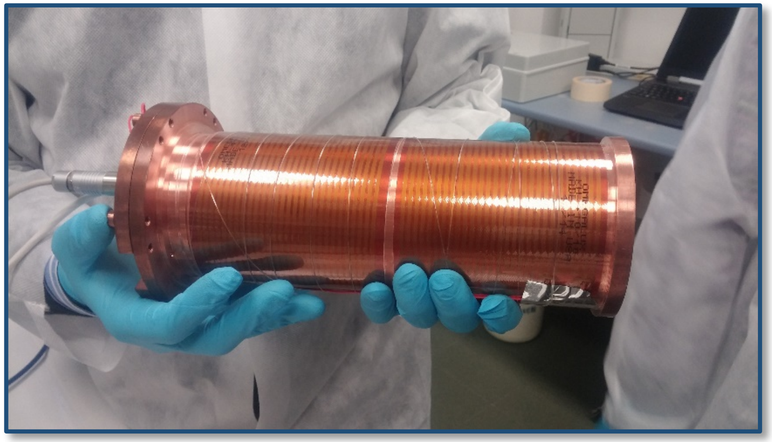


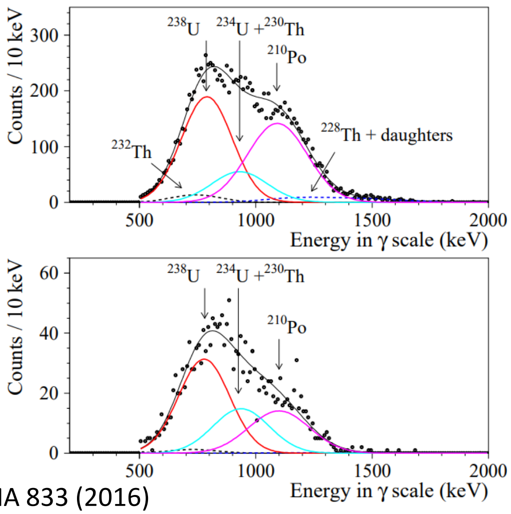
The directionality approach can reach in the given scenario a sensitivity to the cross section at level of $10^{-5} – 10^{-7}$ pb, depending on the particle mass

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)





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.
- Several TPC-based detectors are in the R&D stage. Other potentially ideas have been listed.
- 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.