# Perspectives on the use of $ZnWO_4$ anisotropic scintillator to investigate Dark Matter particles

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*INFN What Next DM GdL*
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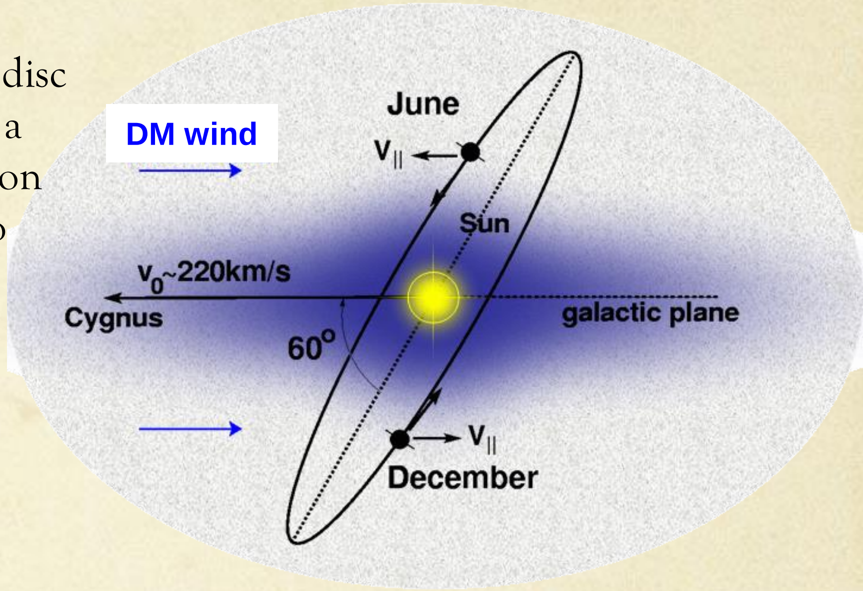
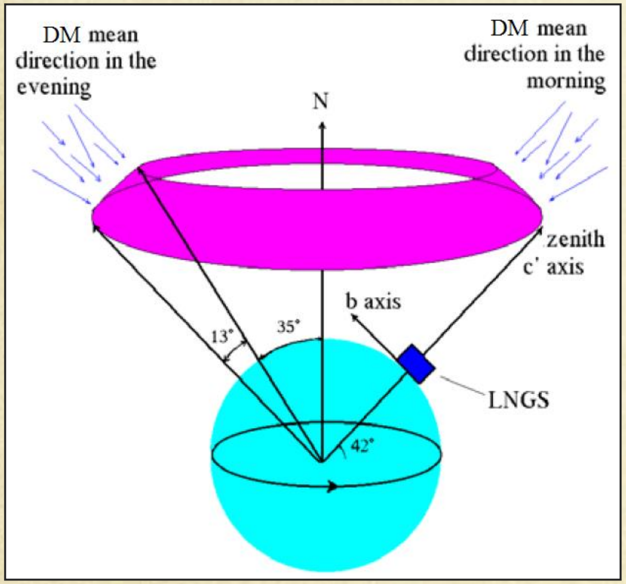
# The directionality approach

Based on the study of the correlation between the Earth motion in the galactic rest frame and the arrival direction of those Dark Matter (DM) candidate 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: TPC

- Detection of the tracks' directions

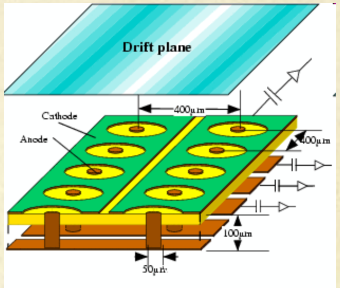
  ⇒ Low Pressure **Time Projection Chamber** might be suitable; in fact the range of recoiling nuclei is of the order of mm (while it is ~μm in solid detectors)

  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**

## NEWAGE

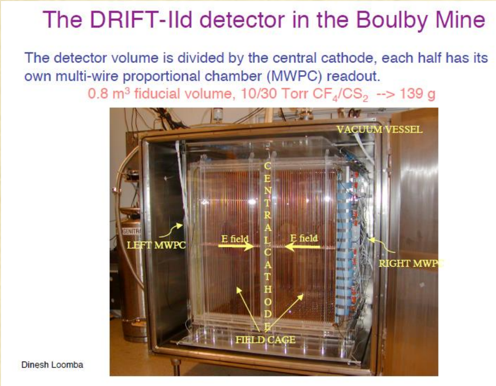



μ-PIC(Micro Pixel Chamber) is a two dimensional position sensitive gaseous detector

| | 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) | $8 \times 10^{-6}$ | $1 \times 10^{-7}$ |
| Angular resolution (@ threshold) | 55° (RMS) | 30° (RMS) |

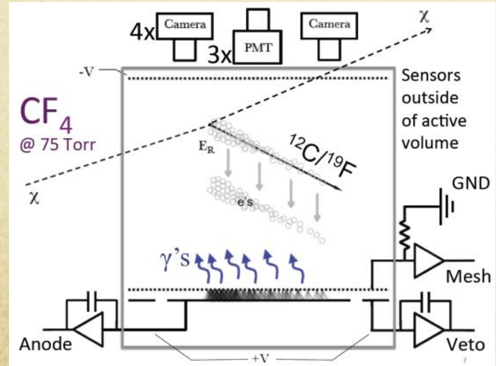
- Internal radioactive BG restricts the sensitivities
- We are working on to reduce the backgrounds!

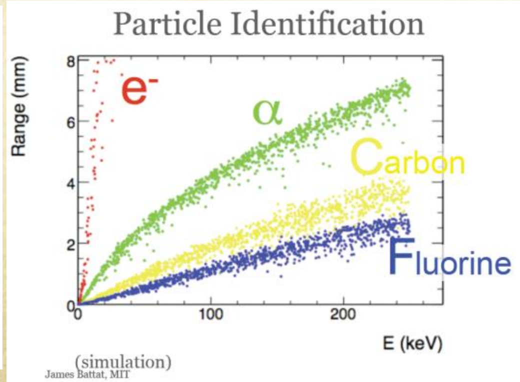
## DRIFT-IId




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

## DM-TPC

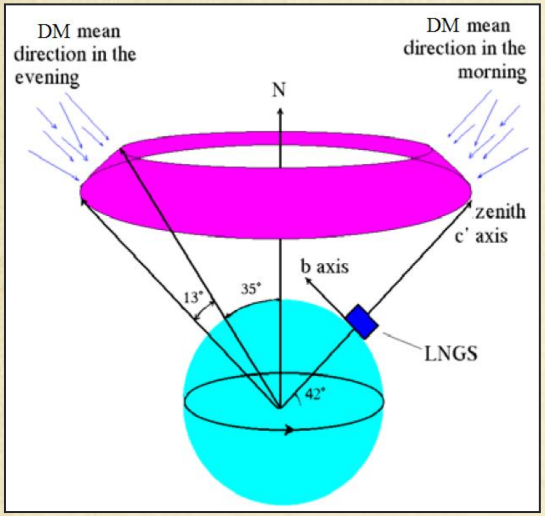



- The **"4--Shooter"** 18L (6.6 gm) TPC 4xCCD, Sea-level@MIT
- moving to WIPP
- Cubic meter funded, design underway

# Directionality sensitive detectors overcoming the track measurement difficulties: 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 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 and revisited in 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]

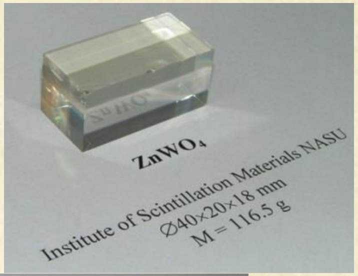
- In the comparison with the anthracene the **$ZnWO_4$ anisotropic scintillator** offers a higher atomic weight and the possibility to realize crystals with masses of some kg, with high level of radio-purity, with threshold at few keV feasible **(Eur. Phys. J. C 73 (2013) 2276)**

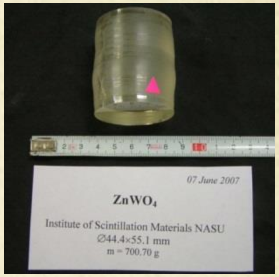
# $ZnWO_4$ crystal scintillators

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

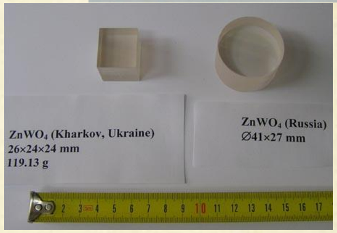
- Low background $ZnWO_4$ crystal scintillators with large volume and good scintillation properties realized
- Various detectors with mass **0.1-0.7 kg** realized by exploiting different materials and techniques
- Detectors installed in a cavity (filled up with high-pure silicon oil) $\phi$ 47 x 59 mm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

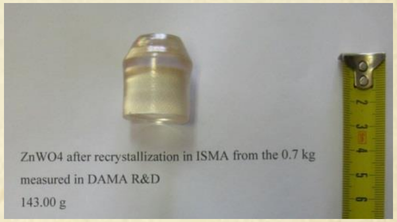
| Crystal scintillator | Size (mm) | Mass (g) |
|---|---|---|
| ZWO-1 | $20 \times 19 \times 40$ | 117 |
| ZWO-2 | $\oslash 44 \times 55$ | 699 |
| ZWO-2a | $\oslash 44 \times 14$ | 168 |

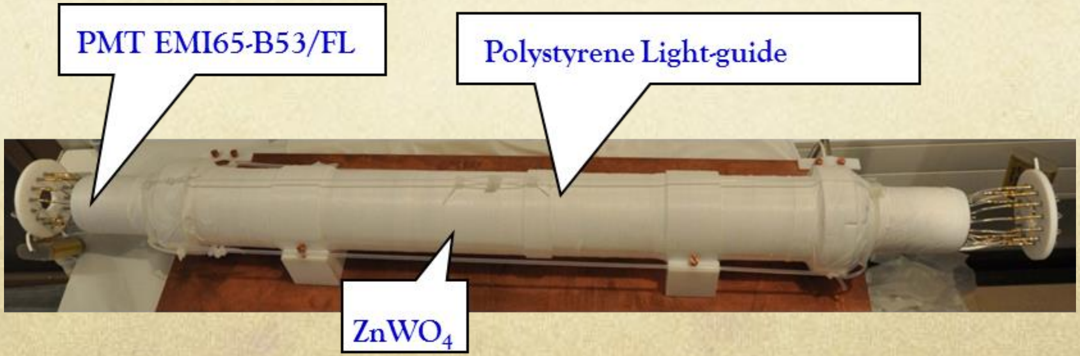



- Main aim of the measurements was the study of the properties of $ZnWO_4$ and the search for 2β processes in Zinc and Tungsten isotopes.



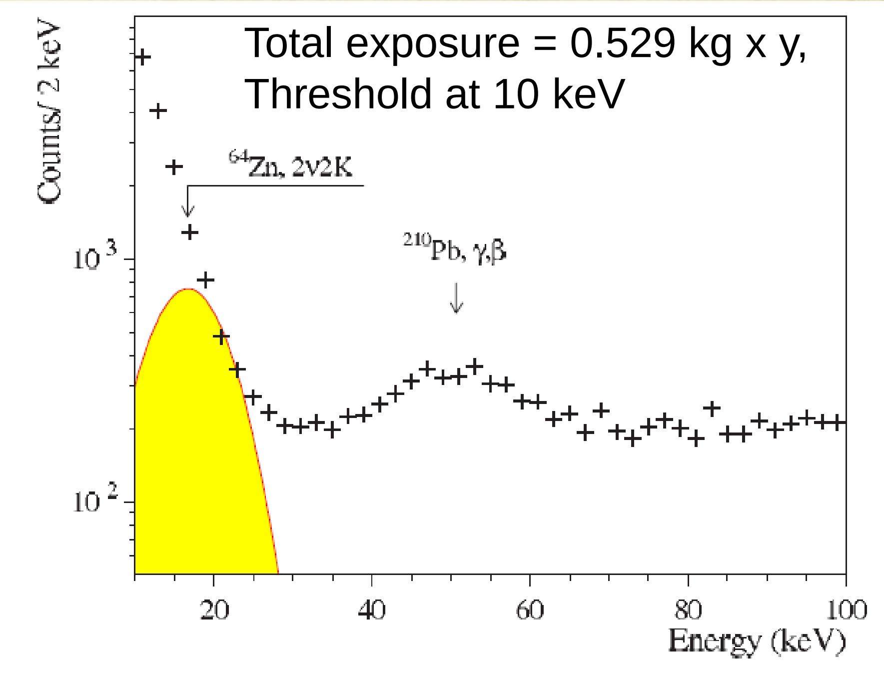
# Achieved results on ββ decay modes in Zn and W isotopes with (0.1 – 0.7 kg) low background $ZnWO_4$

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

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




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**;

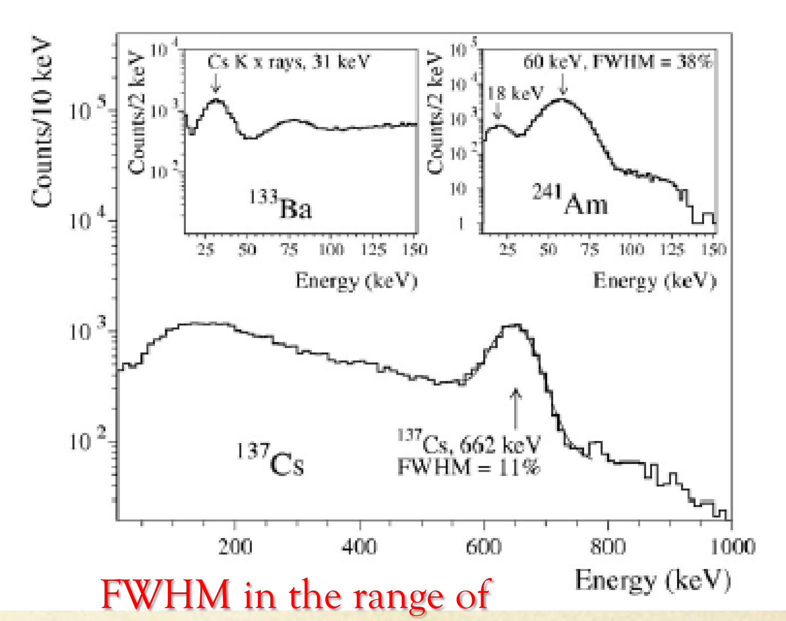
3) the **rare α decay** of the $^{180}$W with $T_{1/2}$ = $(1.3^{+0.6}_{-0.5}) \times 10^{18}$ yr **observed** and new limit on the $T_{1/2}$ of the α transition of the $^{183}$W to the metastable level 1/2$^-$ at 375 keV of $^{179}$Hf has been set:

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

# Performances of the $ZnWO_4$ crystal scintillator

## ➢ *Main characteristics*

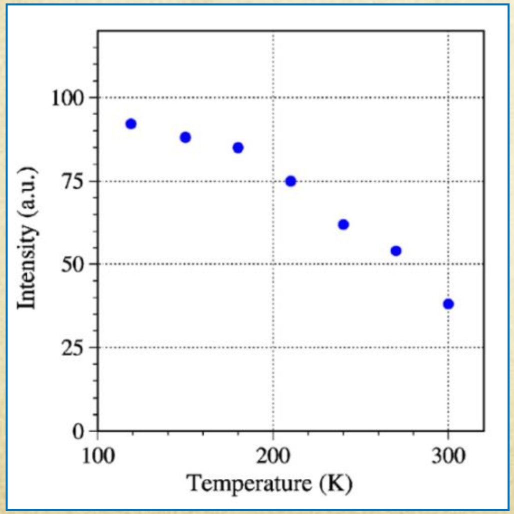
| | |
|---|---|
| *Density (g/cm$^3$)* | *7.87* |
| *Melting point (°C)* | *1200* |
| *Structural type* | *Wolframite* |
| *Cleavage plane* | *Marked (010)* |
| *Hardness (Mohs)* | *4–4.5* |
| *Wavelength of emission maximum (nm)* | *480* |
| *Refractive index* | *2.1–2.2* |
| *Effective average decay 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%);
✓ using silicon photodiodes, APD, SiPM, etc.
✓ decreasing the operational temperature of the $ZnWO_4$ scintillator;
✓ or with a combination of the previous points

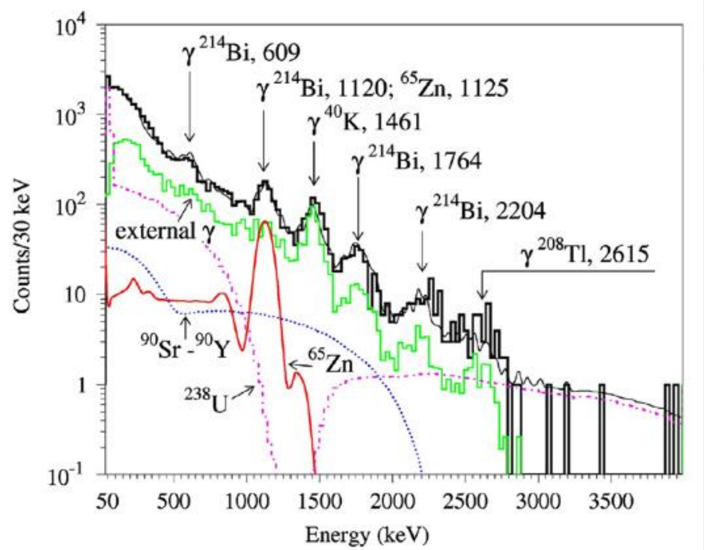
# Performances of the $ZnWO_4$ crystal scintillator

➢ ***Radiopurity***

**NIMA 626(2011)31**

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 $\alpha$ activity of 0.18 mBq/kg



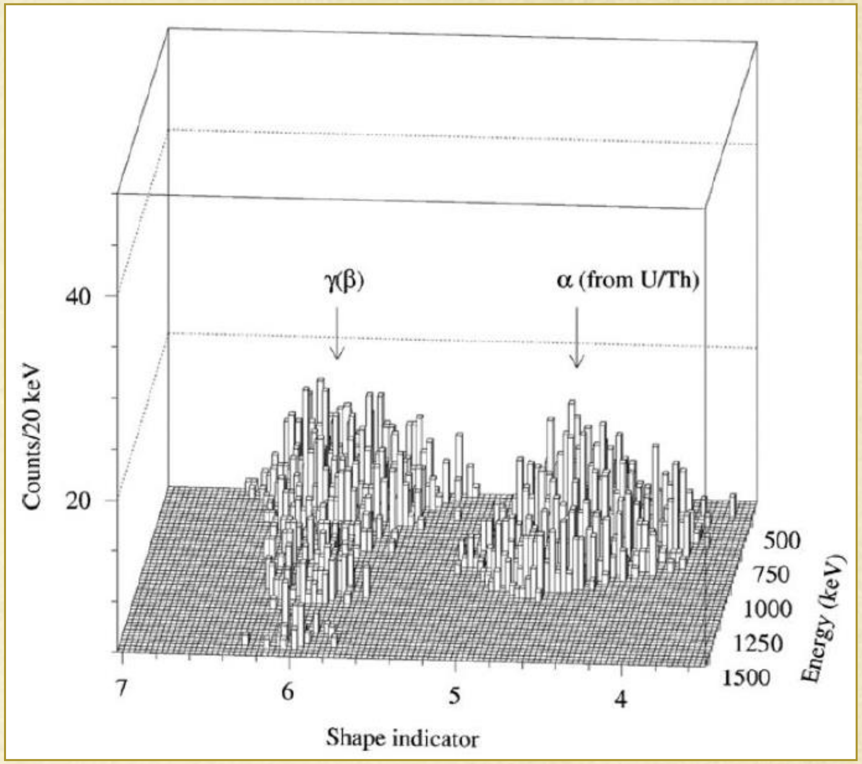

| Run | Crystal | Size mass producer | t (h) | FWHM (%) | Background counting rate in counts/(day keV kg) in the energy intervals (MeV) | | |
|---|---|---|---|---|---|---|---|
| | | | | | 0.2–0.4 | 0.8–1.0 | 2.0–2.9 |
| 1 | ZWO-1 | 20 × 19 × 40 mm 117 g ISMA [a] | 2906 | 12.6 | 1.71(2) | 0.25(1) | 0.0072(7)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

# Performances of the $ZnWO_4$ crystal scintillator

- ***Pulse shape analysis***

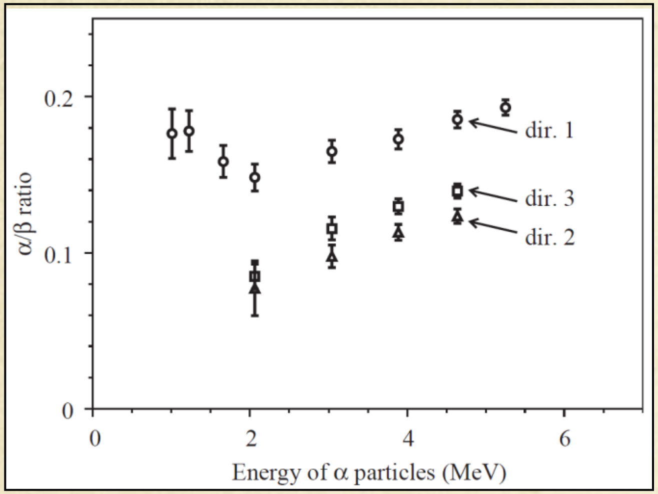
The dependence of the pulse shapes on the type of irradiation in the $ZnWO_4$ scintillator allows one to discriminate $\beta(\gamma)$ events from those induced by $\alpha$ particles and to identify the $\alpha$ background



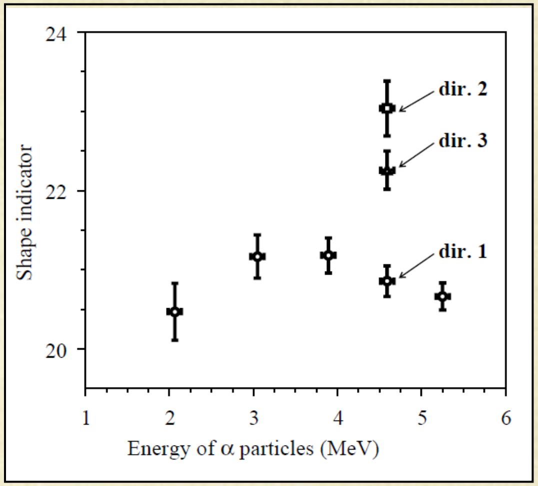
# Anisotropic features in $ZnWO_4$

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

⇒ Dedicated measurements are in preparation

Both the anisotropic features of the ZnWO4 detectors can provide two independent ways to exploit the directionality approach

# Performances of the $ZnWO_4$ crystal scintillator

- ***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

# Signal rate in a 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**)

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

- 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 $\Omega_{out}$ 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

# … 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 ($\rho_0$) and 650 km/s escape velocity;
- DM with dominant spin-independent coupling and the following scaling law (DM-nucleus elastic cross section, $\sigma_n$, in terms of the DM elastic cross section on a nucleon, $\sigma_p$):

$$\sigma_n = \sigma_p \left( \frac{M_n^{red}}{M_p^{red}} \cdot A \right)^2 = \sigma_p \left( \frac{m_p + m_{DM}}{m_n + m_{DM}} \cdot \frac{m_n}{m_p} \cdot A \right)^2$$

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

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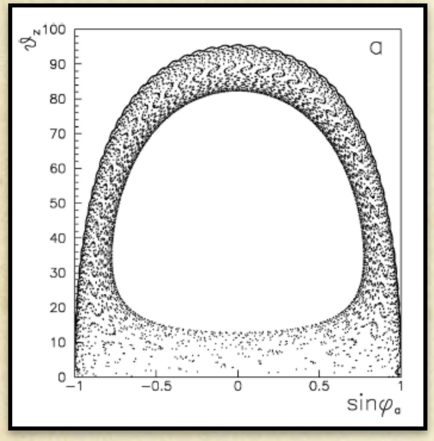
Detector velocity in the Galactic rest frame:

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

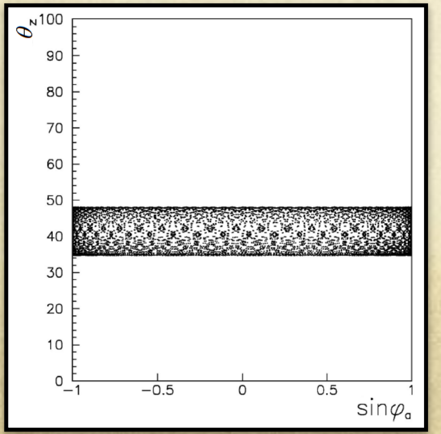
$v_{rot}$: rotational vel of Milky Way
$v_{LSR}$: solar system's vel with respect to the Local Standard of Rest
$v_E(t)$: Earth's vel around the Sun

horizontal coordinate frame described by the "polar-zenith", $\theta_z$, and by the "polar-azimuth", $\phi_a$

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)

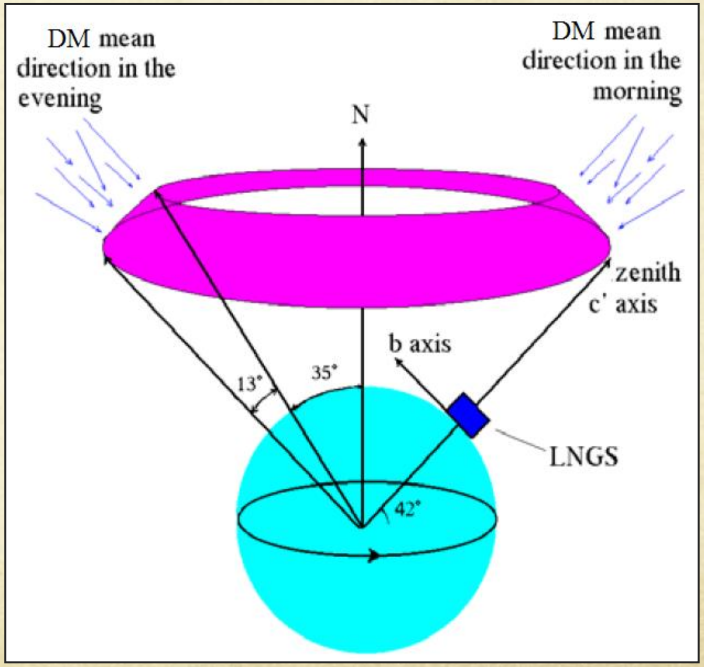



local horizontal coordinate frame




North pole coordinate frame

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




**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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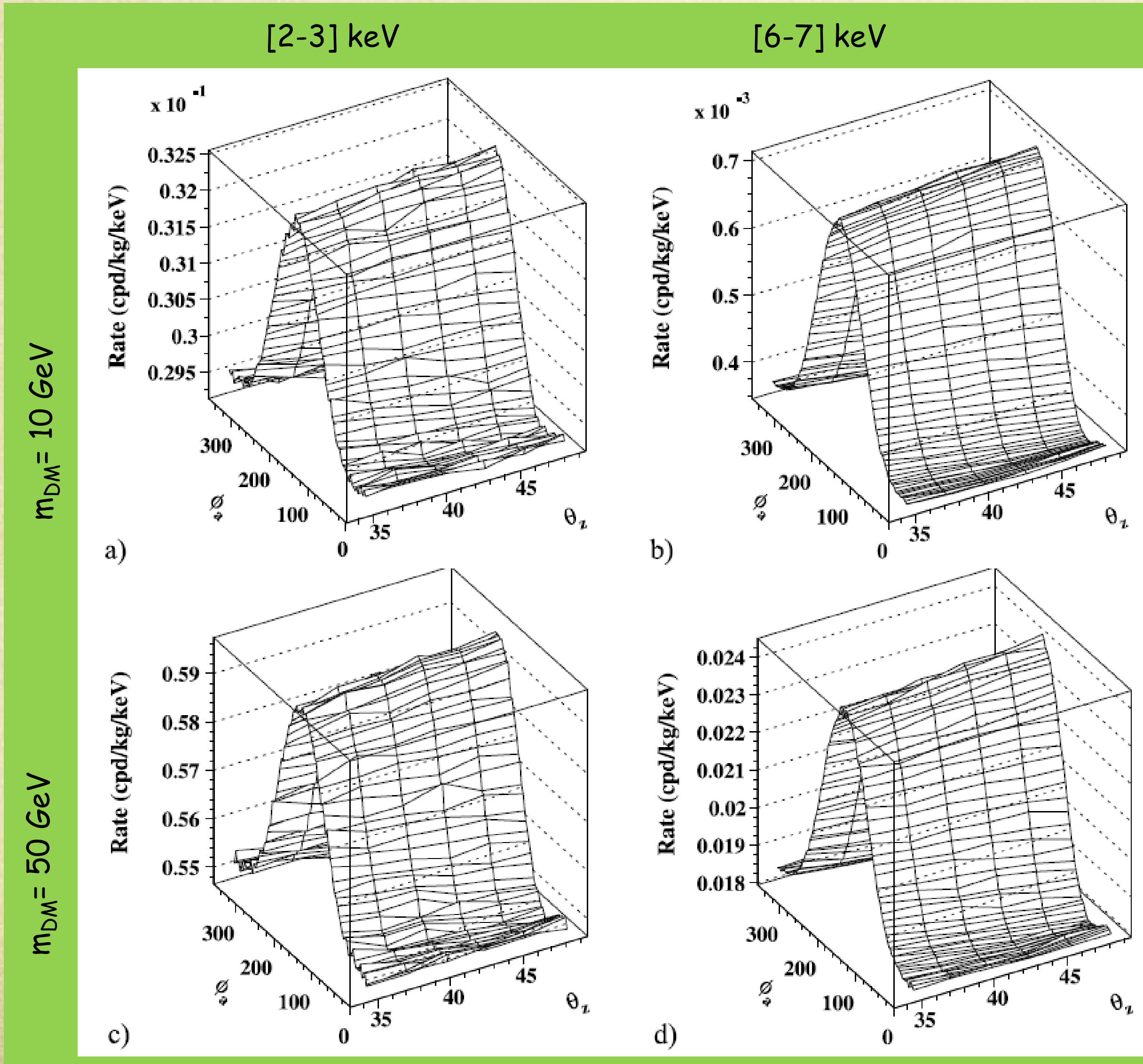
Since $\theta_z$ is always near 40°, it is convenient to consider:

- ✓ $ZnWO_4$ 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" $\phi_a$ 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

# Conclusions

- Anisotropic $ZnWO_4$ detectors is a promising detector to investigate the directionality for those DM candidate particle inducing just nuclear recoils
- These detectors could permit to reach - in some scenarios - sensitivity comparable with that of the DAMA/LIBRA positive result
- Such an experiment can obtain, with a completely different new approach, a new evidence in case of the considered candidates and provide some complementary information wrt DAMA/LIBRA on the nature and interaction type of the DM candidate
- It would represent a first realistic attempt to investigate the directionality approach through the use of anisotropic scintillators