DAMA collaboration
& INR-Kiev

http://people.roma2.infn.it/dama

# Rivelatori a risposta anisotropa $ZnWO_4$ per l'investigazione su particelle di Materia Oscura con la tecnica della direzionalità

Vincenzo Caracciolo

Laboratori Nazionali del Gran Sasso (INFN)

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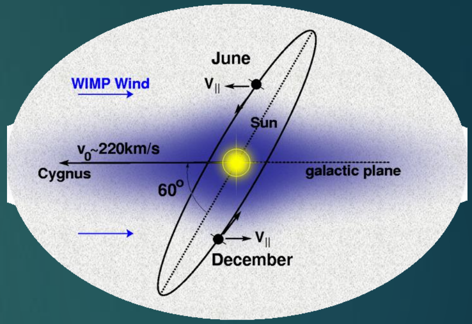
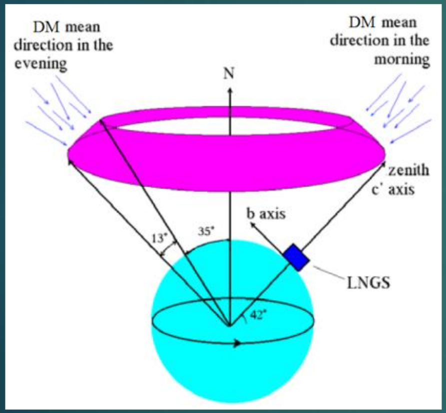
# The directionality approach for DM candidates inducing just nuclear recoils

Based on the study of the correlation between the Earth motion in the galactic rest frame and the arrival direction of Dark Matter (DM) particles inducing 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




… 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 that kind of candidate particles; in fact the nuclear recoils are expected to be **correlated** with their **impinging direction**,

# Directionality sensitive detectors: TPC

- Detection of the tracks' directions

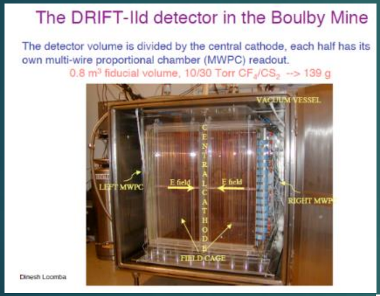
  ⇒ Low Pressure **Time Projection Chamber** might be suitable; in fact the range of recoiling nuclei is of the order of mm (while it is ~µm in solid detectors)

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

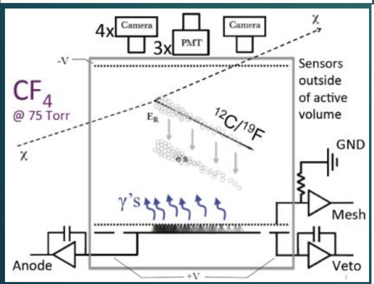
  1. extreme operational stability
  2. high radiopurity
  3. extremely large detector size
  4. great spatial resolution
  5. low energy threshold

Not yet competitive sensitivity

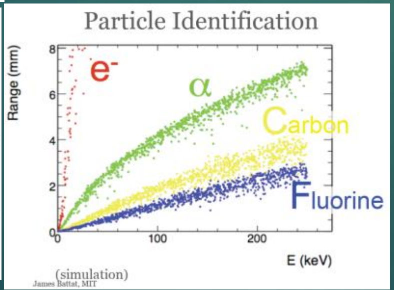
DRIFT-IId



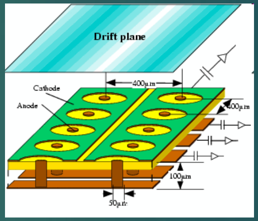

Background dominated by Radon Progeny Recoils (decay of $^{222}$Rn daughter nuclei, present in the chamber)




DM-TPC




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




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!

# 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 ( complementary approaches ) of these detectors depend on the direction of the impinging particles** with respect to the crystal axes

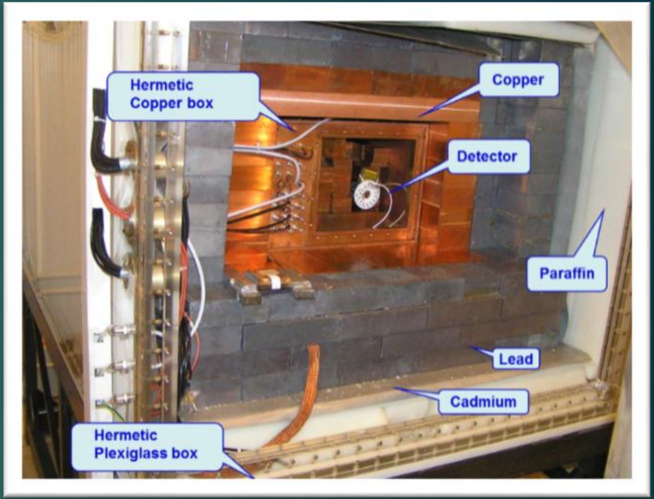
  - The use of anisotropic scintillators to study the directionality signature was proposed for the first time in ref. [P. Belli et al., Il Nuovo Cim. C 15 (1992) 475], where the case of anthracene detector was preliminarily analysed, and revisited in ref. [R. Bernabei et al., Eur. Phys. J. C 28 (2003) 203]. 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)**

# Low background $ZnWO_4$ crystal scintillators

- DAMA in collaboration with INR-Kiev group have developed low background $ZnWO_4$ crystal scintillators to search 2β decay processes

- Low background measurements performed in the DAMA/RD set-up at LNGS




DAMA/RD set-up

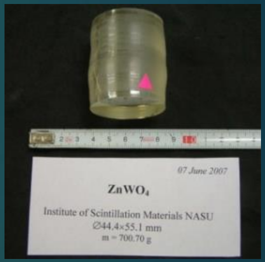
- Air-tight Cu box continuously flushed with HP $N_2$
- 10 cm of high purity Cu
- 15 cm of low radioactive lead
- 1.5 mm of cadmium
- 4/10 cm polyethylene/paraffin
- The whole shield closed inside a Plexiglas box also continuously flushed with HP $N_2$

# $ZnWO_4$ crystal scintillators

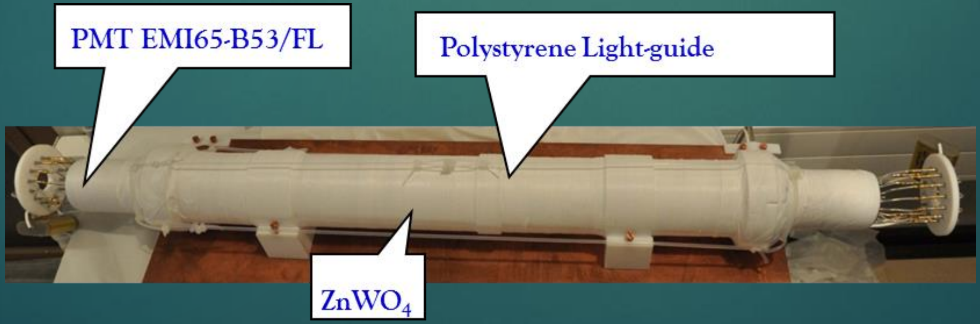
- Low background $ZnWO_4$ crystal scintillators with large volume and good scintillation properties realized
- Various detectors with mass **0.1-0.7 kg** realized by exploiting different materials and techniques
- Detectors installed in a cavity (filled up with high-pure silicon oil) $\phi$ 47 x 59 mm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

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

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

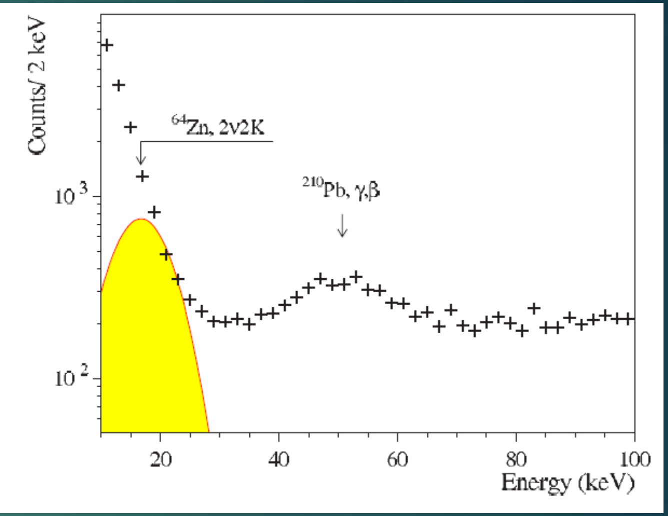




- Main aim of the measurements was the study of the properties of $ZnWO_4$ and the search for $2\beta$ processes in Zinc and Tungsten isotopes.


# 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:

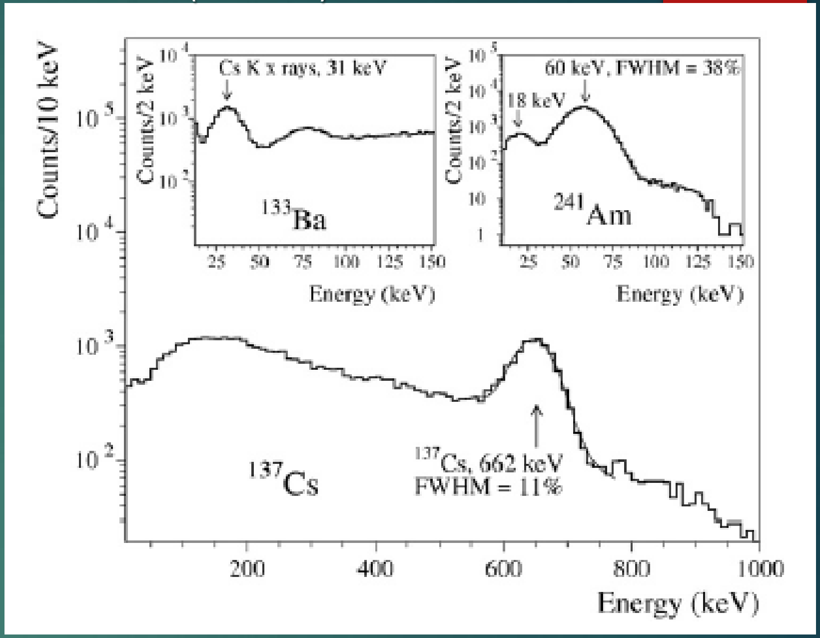
$$T_{1/2} > 6.7 \times 10^{20} \text{ yr.}$$

# Performances of the $ZnWO_4$ crystal scintillator

## ➢ *Main characteristics*

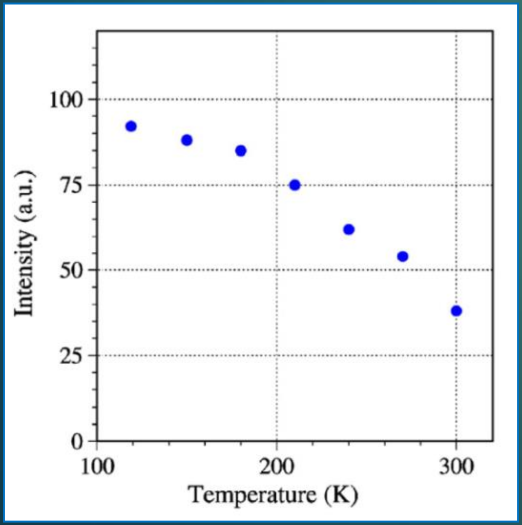
| | |
|---|---|
| *Density (g/cm$^3$)* | *7.87* |
| *Melting point (°C)* | *1200* |
| *Structural type* | *Wolframite* |
| *Cleavage plane* | *Marked (010)* |
| *Hardness (Mohs)* | *4–4.5* |
| *Wavelength of emission maximum (nm)* | *480* |
| *Refractive index* | *2.1–2.2* |
| *Effective average decay 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:

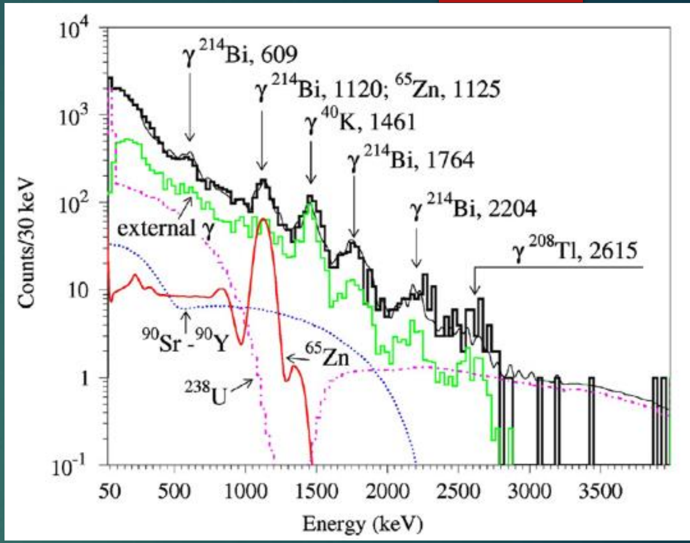
- Suitable light output (photoelectron/keV)
- Efficient reduction of the residual noise near threshold

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%);
- ✓ decreasing the operational temperature of the $ZnWO_4$ scintillator;
- ✓ or with a combination of the previous points

# Performances of the $ZnWO_4$ crystal scintillator

NIMA 626(2011)31




- ***Radiopurity***

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

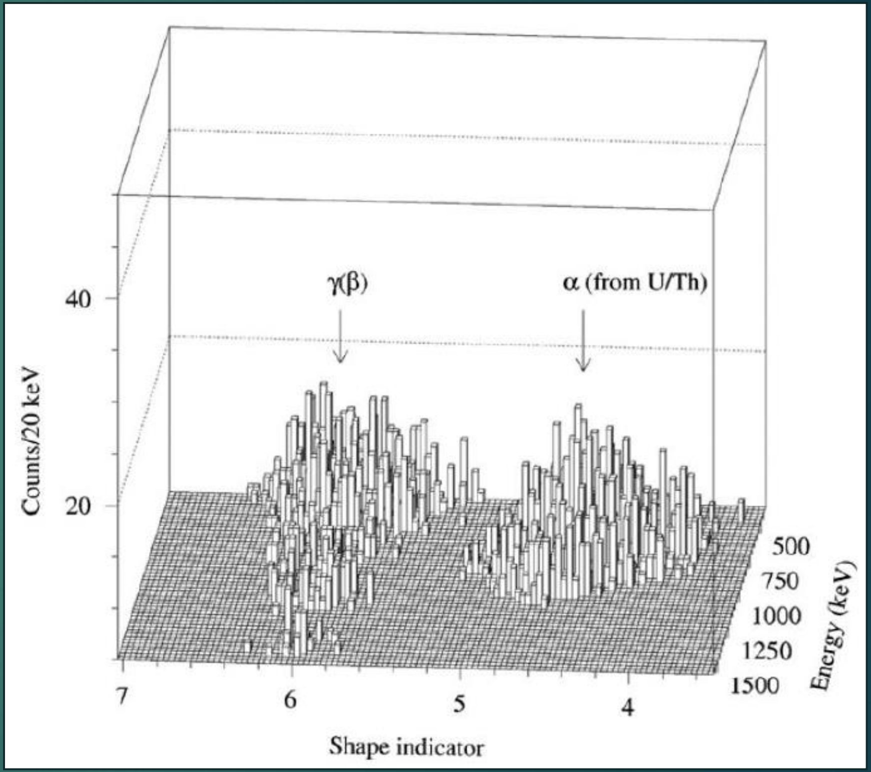
| Run | Crystal | Size mass producer | $t$ (h) | FWHM (%) | Background counting rate in counts/(day keV kg) in the energy intervals (MeV) | | |
|---|---|---|---|---|---|---|---|
| | | | | | 0.2–0.4 | 0.8–1.0 | 2.0–2.9 |
| 1 | ZWO-1 | 20 × 19 × 40 mm<br>117 g<br>ISMA [a] | 2906 | 12.6 | 1.71(2) | 0.25(1) | 0.0072(7) |
| 2 | ZWO-2 | ∅44 × 55 mm<br>699 g<br>ISMA | 2130 | 14.6 | 1.07(1) | 0.149(3) | 0.0072(4) |
| 3 | ZWO-3 | ∅27 × 33 mm<br>141 g<br>ISMA<br>(re-crystallization of ZWO-2) | 994 | 18.2 | 1.54(4) | 0.208(13) | 0.0049(10) |
| 4 | ZWO-4 | ∅41 × 27 mm<br>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

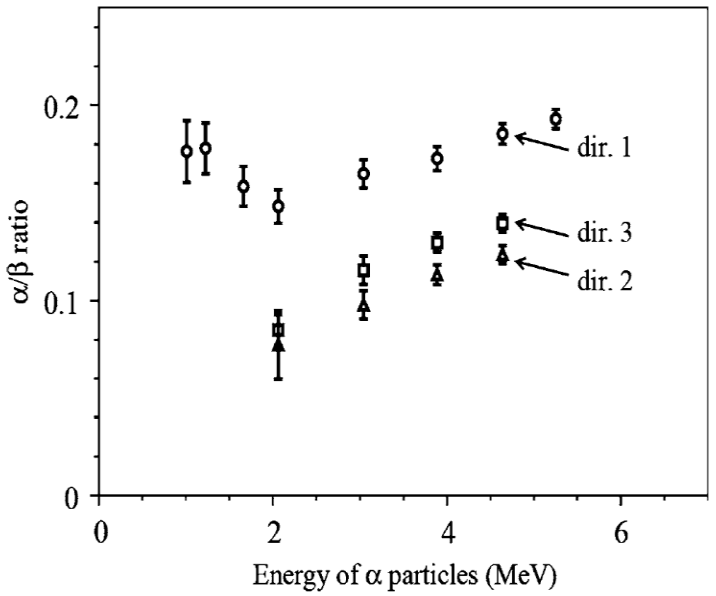
# Performances of the $ZnWO_4$ crystal scintillator

- ***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



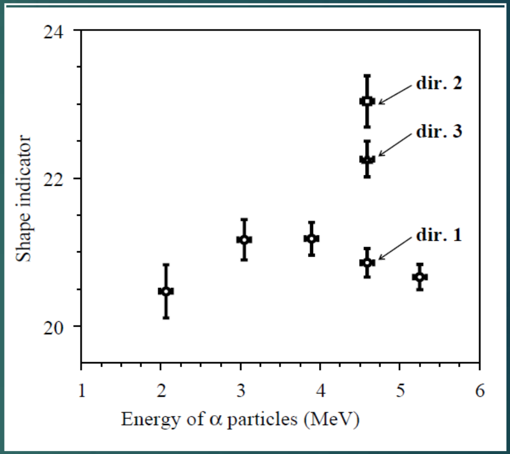
# Anisotropic features in $ZnWO_4$




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 $\alpha$ **particles** have shown that the **light response** and the **pulse shape** of a $ZnWO_4$ depend on the impinging direction of $\alpha$ 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 $\Rightarrow$ Dedicated measurements are in preparation

Both the anisotropic features of the $ZnWO_4$ 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

# An example of the signal rate in 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**)

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

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:**

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

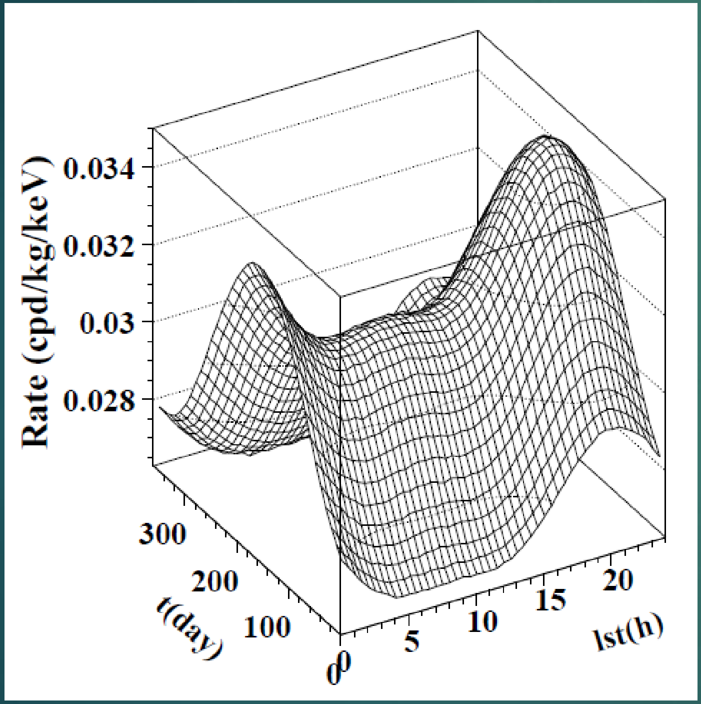
where $q_{n,i}$ is the quenching factor value for a given nucleus, *n*, with respect to the *i*-th axis of the anisotropic crystal and $\Omega_{out} = (\gamma, \phi)$ is the output direction of the nuclear recoil in the laboratory frame
$q_{n,i}$ have been calculated following ref. [V.I. Tretyak, Astropart.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

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

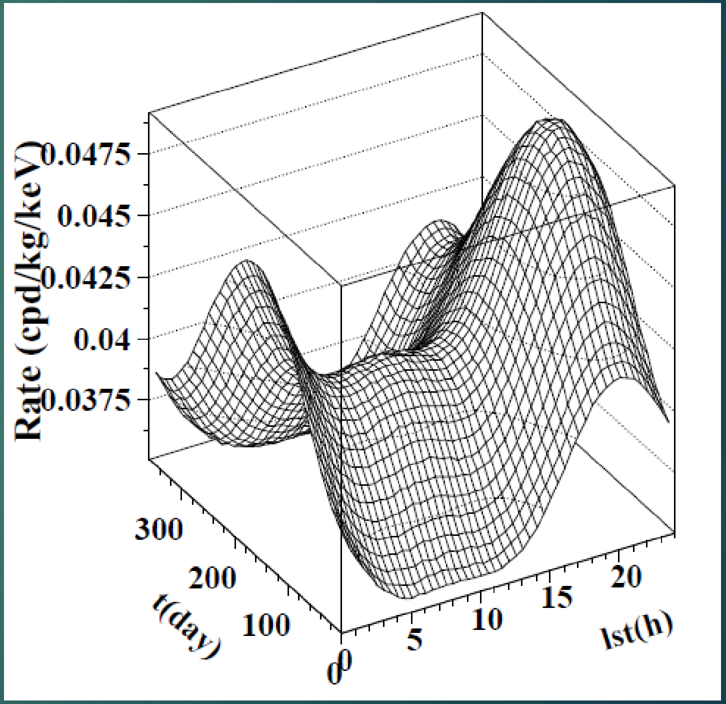
# Example of the expected signal in a simplified model

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

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# Model dependent comparisons; example of reachable sensitivity in a scenario considered in EPJC73(2013)2276

**Considering an experiment with:**

- **200 kg of $ZnWO_4$;**
- **5 years of data taking.**

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** — · — · —

**Black lines** are the **sensitivities reachable** with four possible background levels in the low energy region in a given scenario

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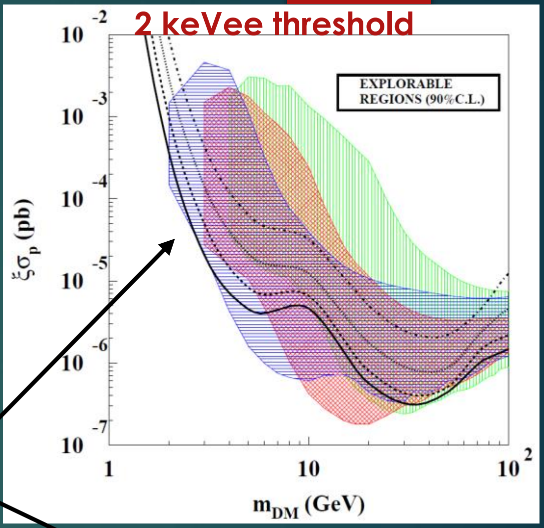


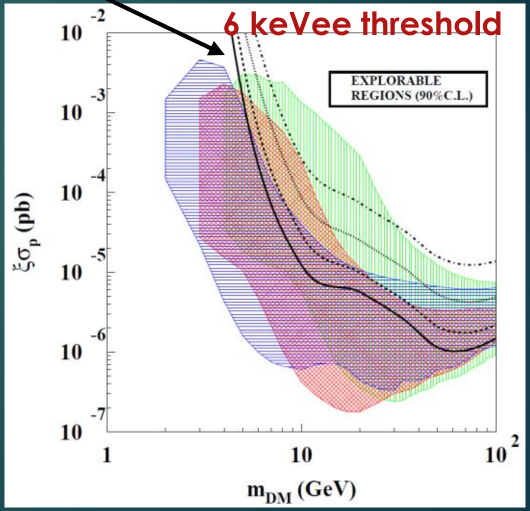


***The directionality approach can reach in the given scenario a sensitivity to the cross section at level of $10^{-5}$ – $10^{-7}$ pb, depending on the particle mass***

For comparison, there are also shown (green, red and blue) allowed regions obtained with a corollary analysis of the 9.3 σ C.L. DAMA/NaI + DAMA/LIBRA model independent result in terms of scenarios for the DM candidates considered here

Phys. Rev. D 84, 055014 (2011)

# Conclusions

- Anisotropic $ZnWO_4$ detectors is a very promising detector to investigate the directionality for DM particle inducing recoils
- These detectors could permit to reach - in given scenarios - sensitivity to the cross section at level of $10^{-5} – 10^{-7}$ pb, depending on the particle mass
- Such an experiment can investigate with the new approach the presence of DM candidates induce just nuclear recoils, providing complementary information on their nature and interaction
- It would represent a first realistic attempt to investigate the directionality approach