Investigating Dark Matter with directionality

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INFN-LNGS

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Direct detection experiments

The direct detection experiments can be classified in **two classes**, depending on what they are based:

1. on the identification of the signals due to Dark Matter particles with respect to the background by using a **model-independent signature**

2. on the use of uncertain techniques of **subtractions** of the e.m. component **of the counting rate;** in this case you have face some facts:

    - systematics in the data selections, in statistical discrimination and in rejection procedures difficult to estimate at the needed sensitivity
    - e.m. component of the rate can contain the signal or part of it
    - even assuming pure recoil case and ideal discrimination the result will NOT be the identification of the presence of WIMP elastic scatterings as DM signal, because of the well known existing recoil-like indistinguishable background

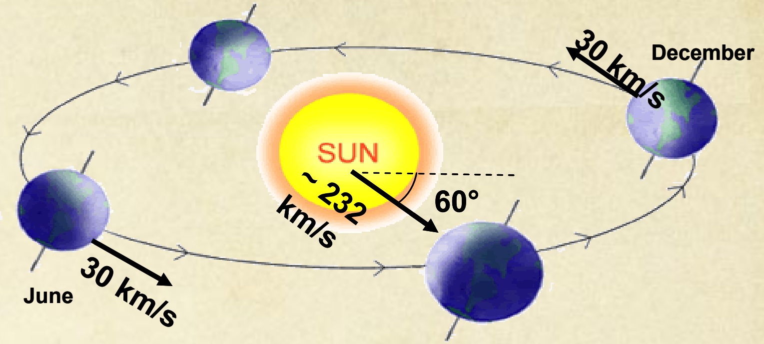
Therefore, even in the ideal case the "excellent suppression of the e.m. component of the counting rate" can not provide a "signal identification"

A model independent signature is needed

Signatures

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)

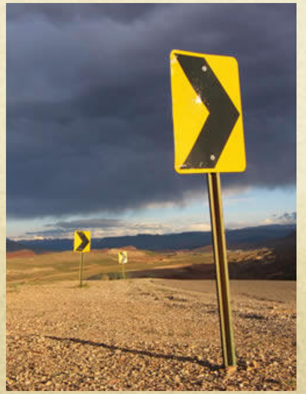


Model independent Diurnal modulation due to the Earth revolution around its axis

2nd order effect

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

only for high **σ**



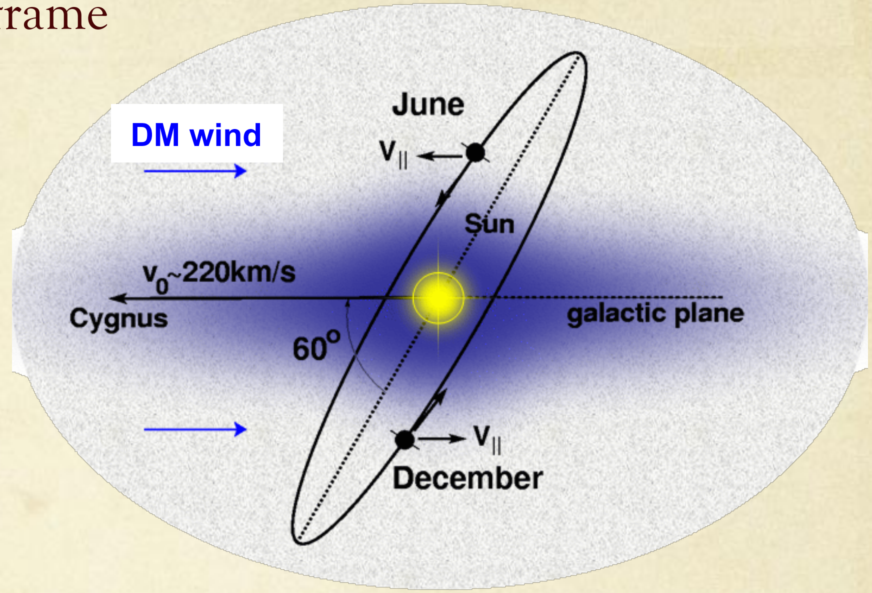
Directionality Correlation of Dark Matter impinging direction with Earth's galactic motion

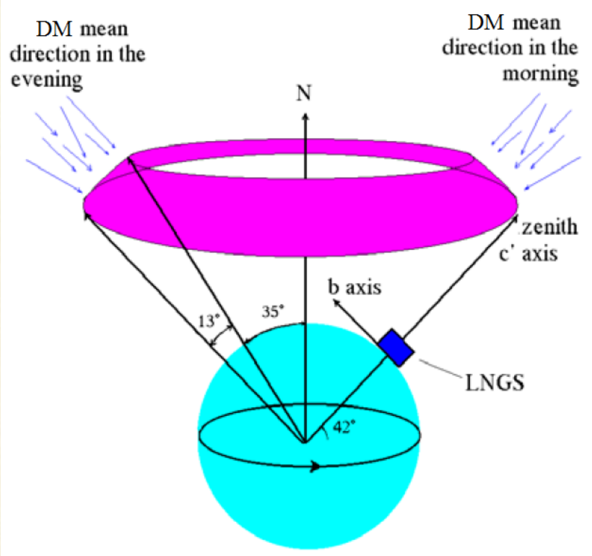
very hard to realize, it holds **only for DM particle inducing recoils**

The directionality approach

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

Impinging direction of DM particle is (preferentially) opposite to the velocity of the Earth 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 with a period of a 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 nuclear recoil directions could give evidence for such candidates

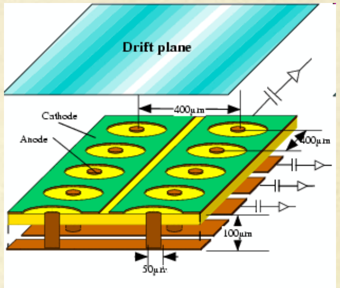
direction-sensitive detector

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 ~μ m 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

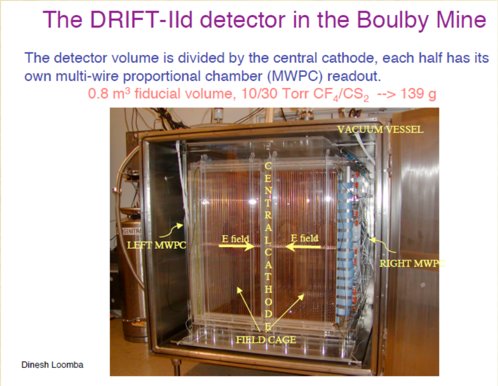


μ-PIC(Micro Pixel Chamber) is a two dimensional position sensitive gaseous detector

	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)	8×10^{-6}	1×10^{-7}
Angular resolution (@ threshold)	55° (RMS)	30° (RMS)

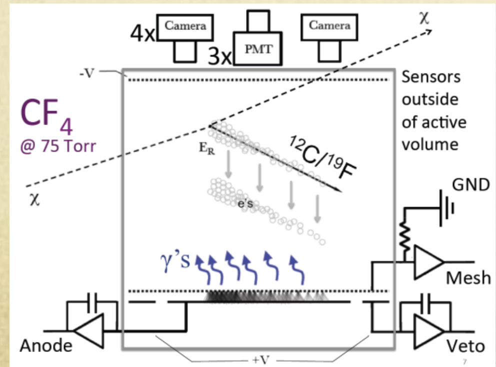
- Internal radioactive BG restricts the sensitivities
- We are working on to reduce the backgrounds!

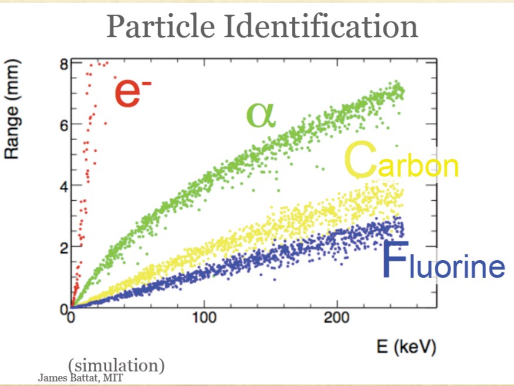
DRIFT-IId



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

Directionality sensitive detectors: 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 for heavy particles depend on their impinging direction** 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; R. Bernabei et al., Eur. Phys. J. C 28 (2003) 203], where the case of 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]

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
- ✓ Scintillator and bolometer

Density (g/cm^3)	*7.87*
Melting point (ºC)	*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*

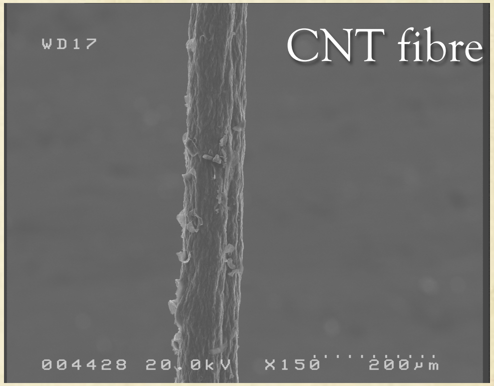
Directionality sensitive detectors: carbon nanotube fibers (CNT)

- We discussed for the first time in written project and Conferences the potentiality to build detectors with anisotropic features by using Carbon Nanotubes (CNT)*

- New conceptual detector: 3D detectors with carbon nanotube fibers (CNT)

  ✓ The CNT are thin graphene foils, rolled as tubes with l-100 nm diameters and lengths well above one μm; they can be aligned by chemical process to obtain fibres

  ✓ The intrinsic 1-D nature of CNTs fibers makes them very promising for the study of directionality (diameter ~ 10-100μm; length ~ m); metallic material can be deposited on them



  ✓ Three possible nano-devices: bare CNT, CNT coated with standard materials, CNT coated with superconducting materials as Nb and NbN. These new detectors can realized as grid of oriented bundles of CNT or fibers, with spatial resolution comparable to the width of the components themselves (1 μm to 100 μm). Fibers of CNT will be used for a sort of multi-wire chamber detector configuration with a high spatial resolution.

* FIRB 2013: \Sviluppo di rivelatori a risposta anisotropa", PI: Cappella Fabio, Reference number: RBFR13THVM; Talk by R. Cerulli at Int. Conf. Dark matter, Dark Energy and their detection, Novosibirsk, Russia, July 2013, http://people.roma2.infn.it/dama/pdf/cerulli novosibirsk2013.pdf; Talk by P. Belli at What Next workshop, Tor Vergata University, Rome, Italy, March 2014, http://people.roma2.infn.it/belli/belli TorVergata mar14.pdf

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Physics programme

- 3 techniques:
  - $ZnWO_4$ scintillator,
  - $ZnWO_4$ scintillating bolometer,
  - CNT based detector:
- Phase I:
  - Development of radiopure $ZnWO_4$ detectors
  - $ZnWO_4$ as scintillator
  - $ZnWO_4$ as scintillating bolometer
  - Development of new anisotropic detectors based on CNT
  - Neutron calibration for precise measurement of anisotropic properties of the detectors

Selection of the most promising technique for the construction of a new DM experiment

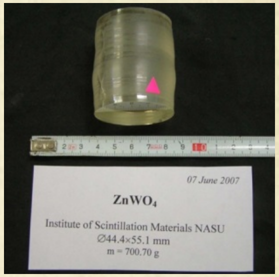
- Phase II
  - Production of the new detectors
  - Assembling and commissioning of the new experimental setup
  - Data taking and analysis

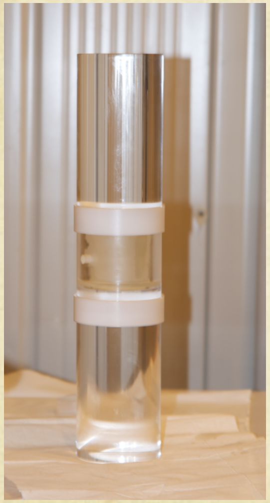
State of art of $ZnWO_4$ crystal scintillators

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

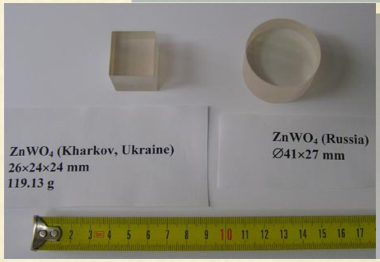
- Low background $ZnWO_4$ crystal scintillators with large volume and good scintillation properties realized
- Various detectors with mass **0.1-0.7 kg** realized by exploiting different materials and techniques
- Detectors installed in a cavity (filled up with high-pure silicon oil) ϕ 47 x 59 mm in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

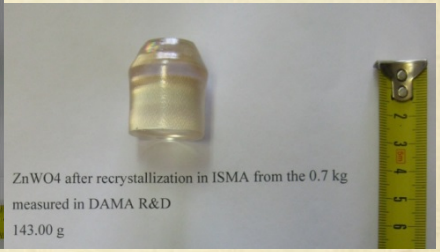
Crystal scintillator	Size (mm)	Mass (g)
ZWO-1	$20 \times 19 \times 40$	117
ZWO-2	$\oslash 44 \times 55$	699
ZWO-2a	$\oslash 44 \times 14$	168

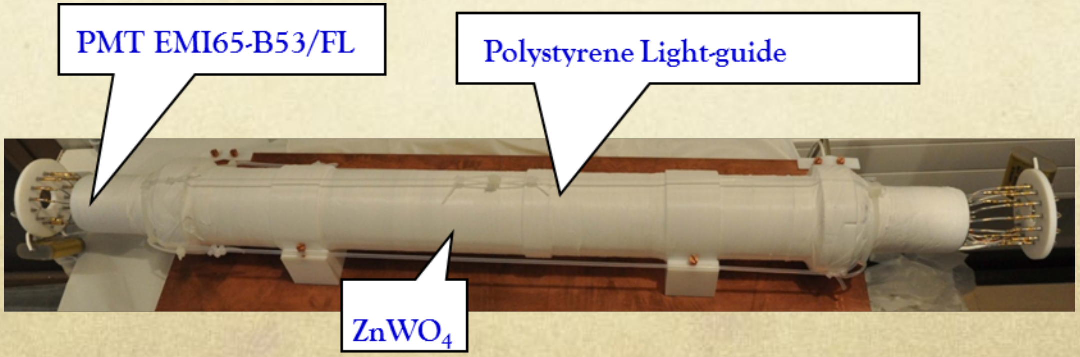




- Main aim of the measurements was the study of the properties of $ZnWO_4$ and the search for 2β processes in Zinc and Tungsten isotopes.







Achieved results with (0.1 – 0.7 kg) low background $ZnWO_4$

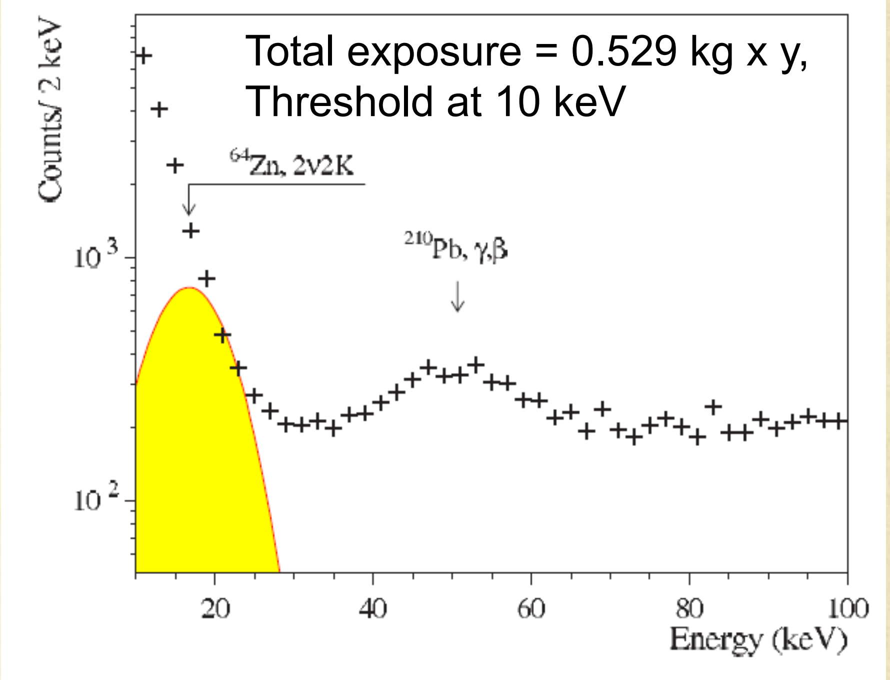
ββ decay modes in Zn and W isotopes

Obtained limits on the ββ decay modes of ^{64}Zn, ^{70}Zn, ^{180}W and ^{186}W:

$$T_{1/2} \sim 10^{18} - 10^{21} \text{ yr.}$$

- up to now only 5 nuclides (^{40}Ca, ^{78}Kr, ^{112}Sn, ^{120}Te and ^{106}Cd) over 34 candidates to 2ε, $\varepsilon\beta^+$, $2\beta^+$ processes have been studied at this level of sensitivity in direct experiments

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



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**;

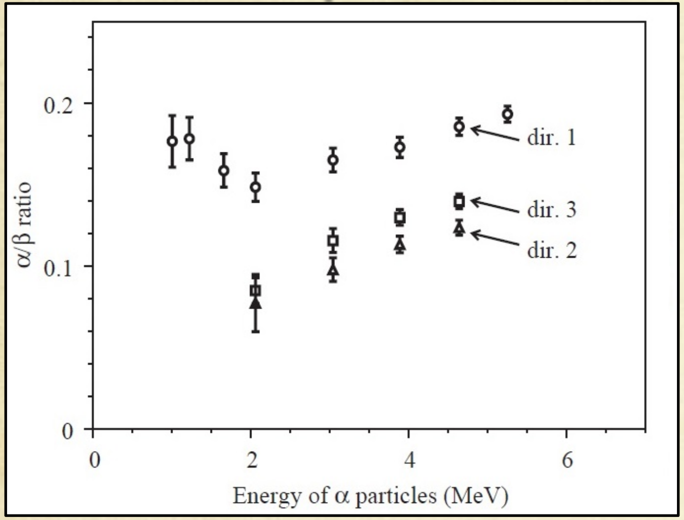
3) the **rare α decay** of the ^{180}W with $T_{1/2} = (1.3^{+0.6}_{-0.5}) \times 10^{18}$ yr **observed** and new limit on the $T_{1/2}$ of the α transition of the ^{183}W to the metastable level 1/2$^-$ at 375 keV of ^{179}Hf has been set:

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

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

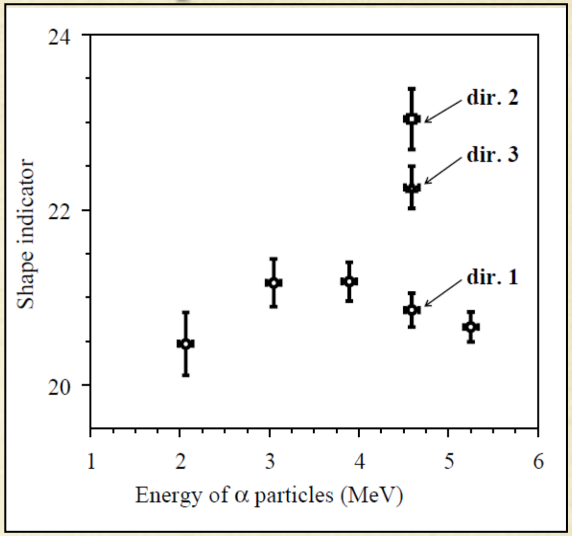
α/β ratio



Such effects are absent in case of electron excitation

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

PS parameter



These anisotropic effects are ascribed to preferred directions of the excitons' propagation in the crystal lattice affecting the dynamics of the scintillation mechanism

Ion	Quenching factor		
	dir. 1	dir. 2	dir. 3
O	0.235	0.159	0.176
Zn	0.084	0.054	0.060
W	0.058	0.037	0.041

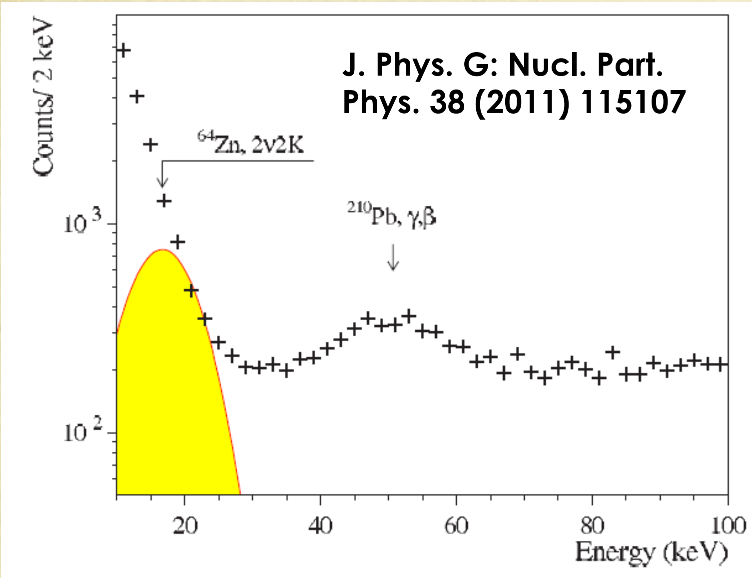
Q.F expected from V.I. Tretyak, Astropart. Phys. 33 (2010) 40

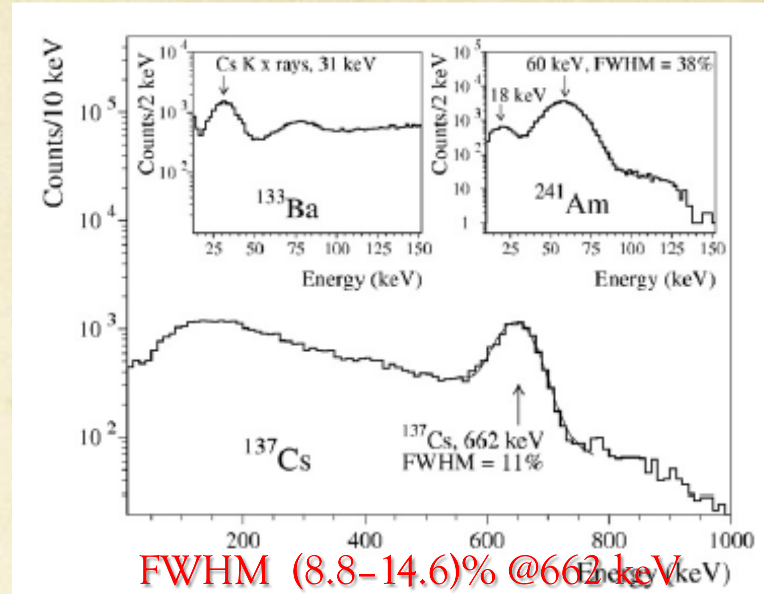
Similar effect is expected in the case of low energy nuclear recoils

⇒ Dedicated measurements are in preparation

Light output and threshold of $ZnWO_4$ crystal scintillator

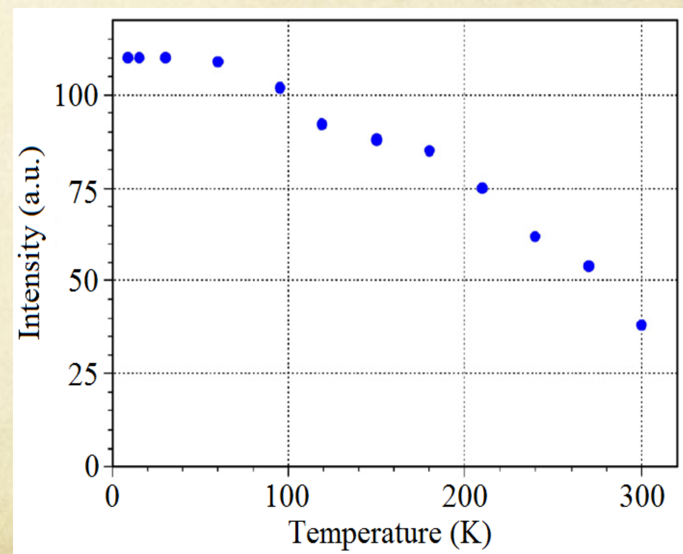
An energy threshold of 10 keV in an experiment not optimized for the low energy region





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

- ✓ coupling 2 PMTs in coincidence at single ph.e. level;
- ✓ crystal in silicone oil (light collection improvement ~40%);
- ✓ using silicon photodiodes, APD, SiPM, etc.
- ✓ decreasing operational temperature
- ✓ or with a combination of the previous points

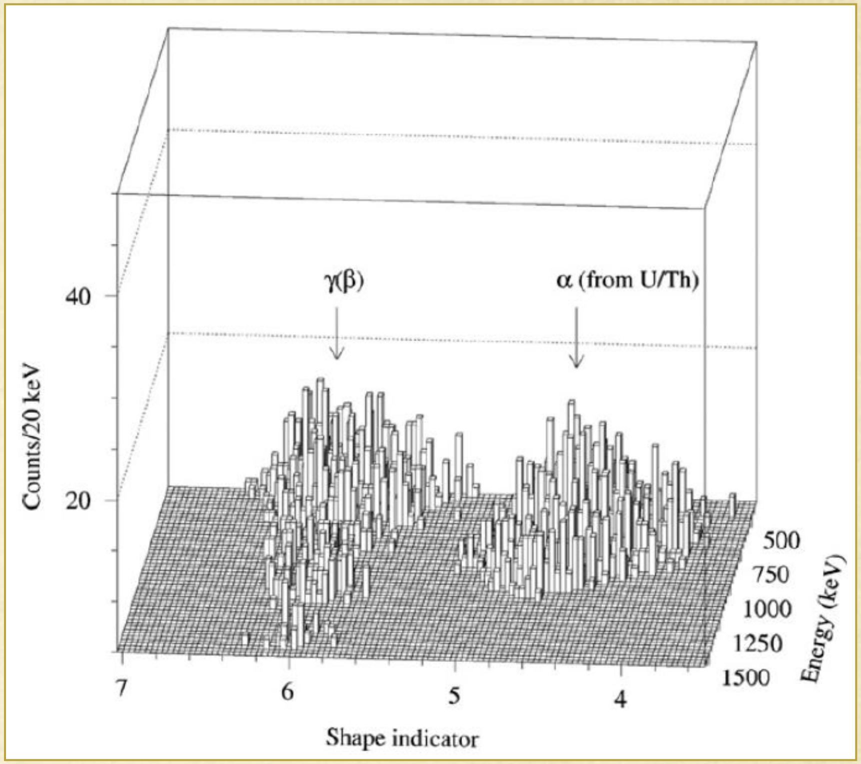


H. Kraus et al., NIMA600(2009)594

Low-threshold feasible

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 $\beta(\gamma)$ events from those induced by α particles and to identify the α background



Provided a suitable separation also at very low energy, PSD could – in principle - provide a 2nd independent but not mandatory ways to exploit the directionality approach

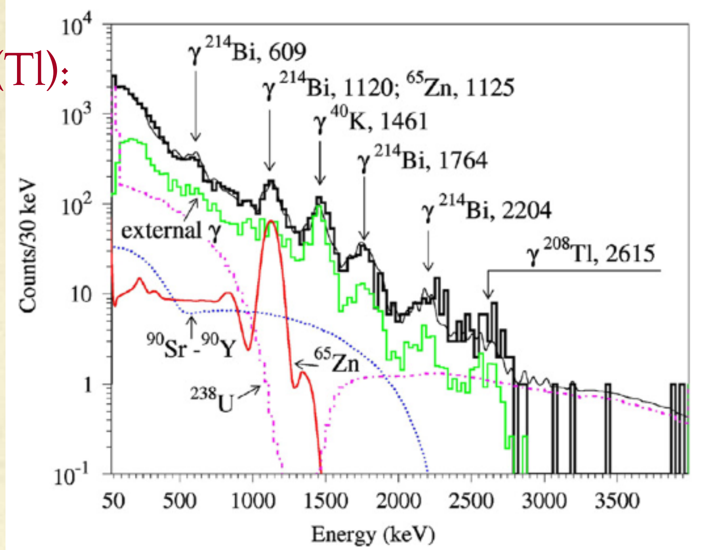
Radiopurity of the $ZnWO_4$ crystal scintillator

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

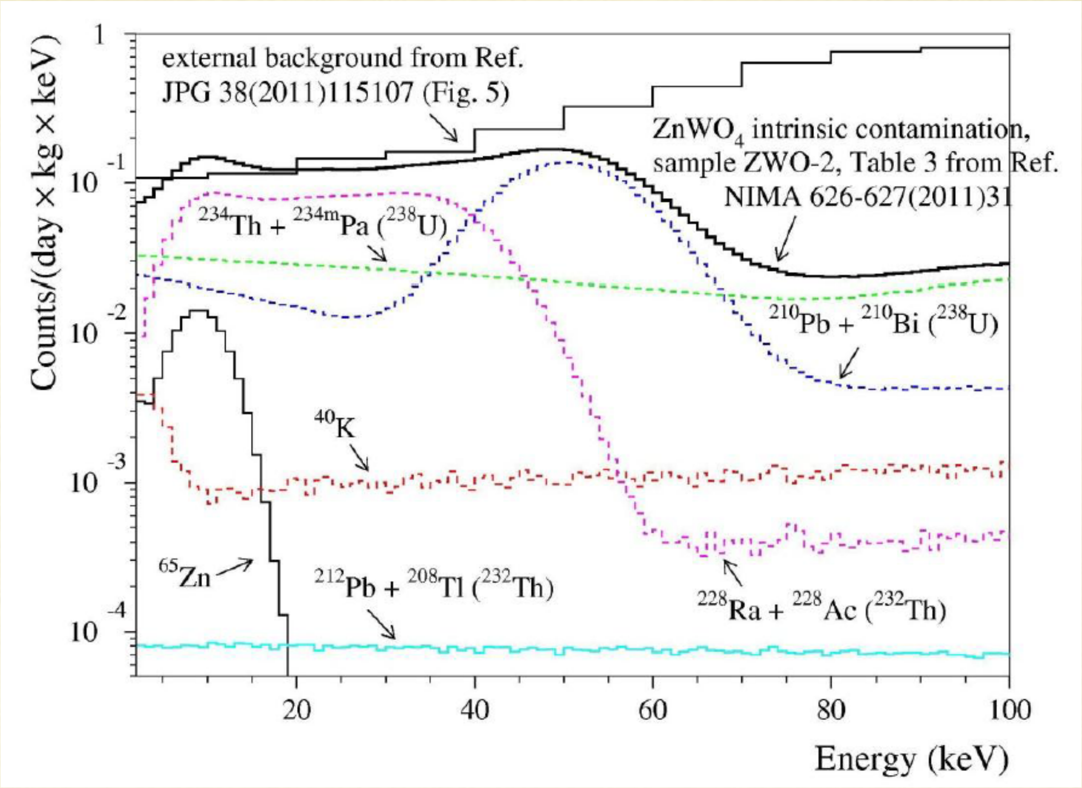


Run	Crystal	Size mass producer	t (h)	FWHM (%)	Background counting rate in counts/(day keV kg) in the energy intervals (MeV)		
					0.2–0.4	0.8–1.0	2.0–2.9
1	ZWO-1	20 × 19 × 40 mm 117 g ISMA [a]	2906	12.6	1.71(2)	0.25(1)	0.0072(7)
2	ZWO-2	∅44 × 55 mm 699 g ISMA	2130	14.6	1.07(1)	0.149(3)	0.0072(4)
3	ZWO-3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

Montecarlo 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

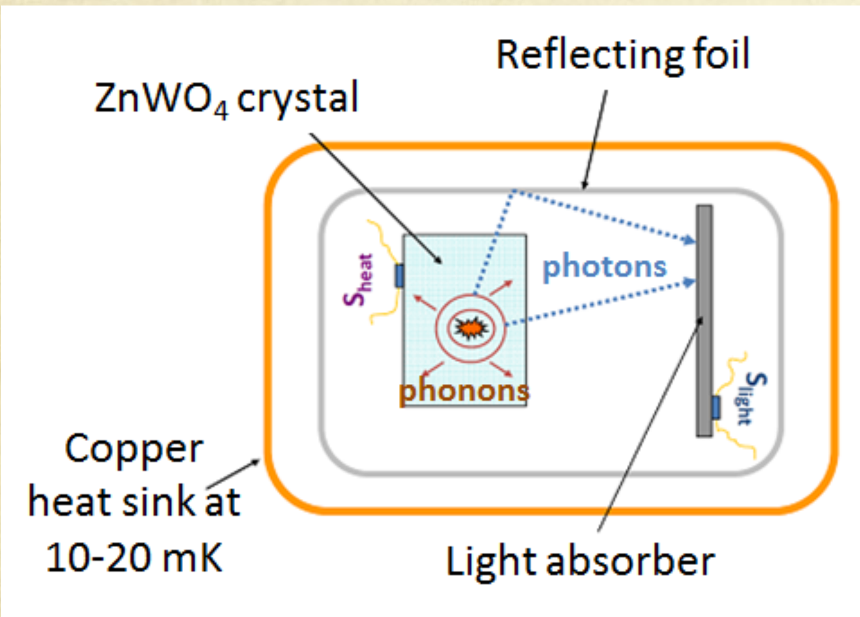
Improving radiopurity of $ZnWO_4$ crystal

New $ZnWO_4$ crystals:

- screening of zinc oxide to avoid cosmogenic ^{65}Zn.;
- protocol for the purification of the initial **zinc** (vacuum distillation and filtering) and **tungsten** (electron beam and zone melting)
- low-thermal gradient Czochralski technique in a platinum crucible (with very good results in producing large size crystals with high radiopurity levels)
- Segregation of radioactive elements (U, Th, Ra, K) expected (very similar compound to $CdWO_4$). Recrystallization could further improve radiopurity level of $ZnWO_4$
- Detectors cut and assembled just after the growth of the crystalline bulk in a glove-box in controlled atmosphere.
- Selection of tools and abrasives for cutting and polishing the crystals
- Etc.

ZnWO4 as scintillating bolometers towards possible 10^{-4} c/keV/kg/d ?

Main absorber: $ZnWO_4$



e.m./recoils discrimination capability with double read-out phonons and light

Light yield for betas: ~ 10 photons/keV
Energy/photon: ~ 2.4 eV

Few eV threshold needed for light detector

Providing adequate scintillation efficiency at mK, adquate light collection, measurement of phonon/light signal coincidence efficiency, stability of energy scale and operational condition

Neganov-Luke based light detectors

1) Event creates e-h pairs
2) e-h pairs are drifted by E_{bias}
3) Phonon emission while e-h pairs drift. The external generator provide the energy

$$W_{gen} = Q \int_0^d \vec{E} \cdot d\vec{l}$$

Signal amplification

An amplification factor of the order of 10 already achieved in preliminary tests with light signals

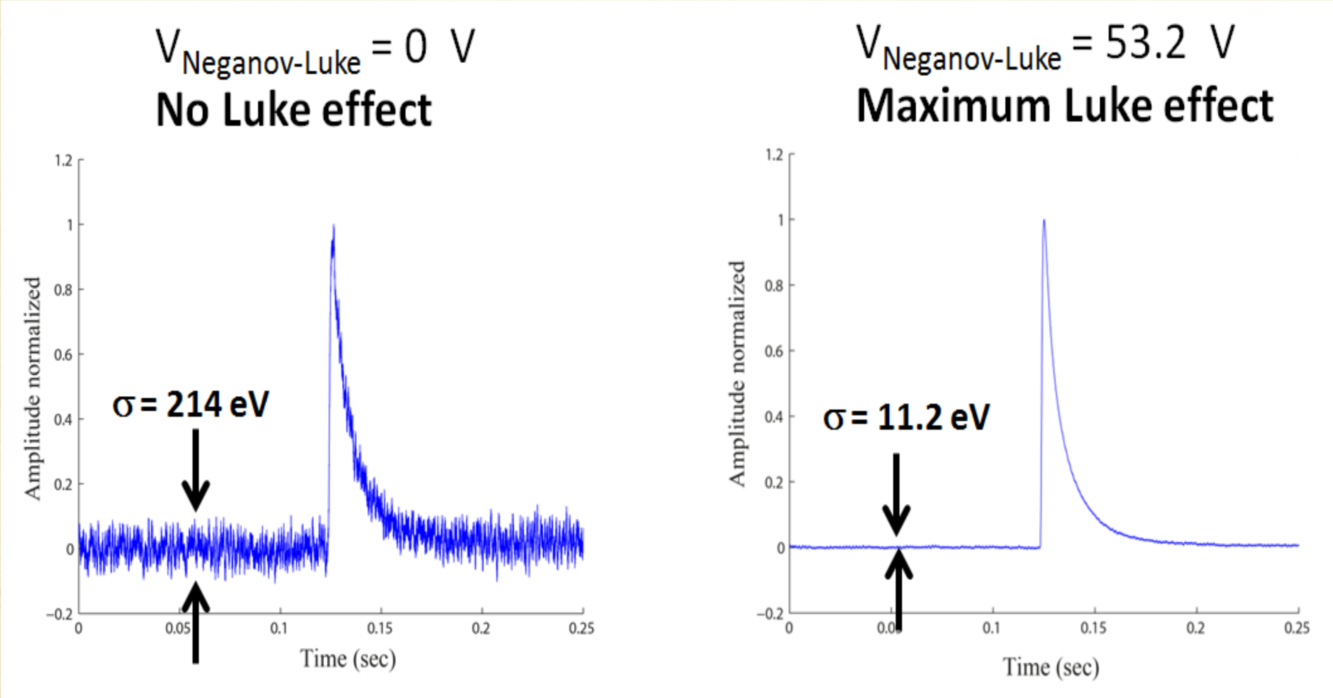


Figure 1.6 – *Temperature pulses induced by equally intense infrared light flashes (induced by a LED) in a Neganov-Luke effect Ge bolometer with NTD readout, respectively with Neganov-Luke voltage off (left panel) and on (right panel). The dramatic improvement of the signal-to-noise ratio is apparent.*

Signal rate in a given scenario

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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**)

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

- 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

… 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 (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:

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

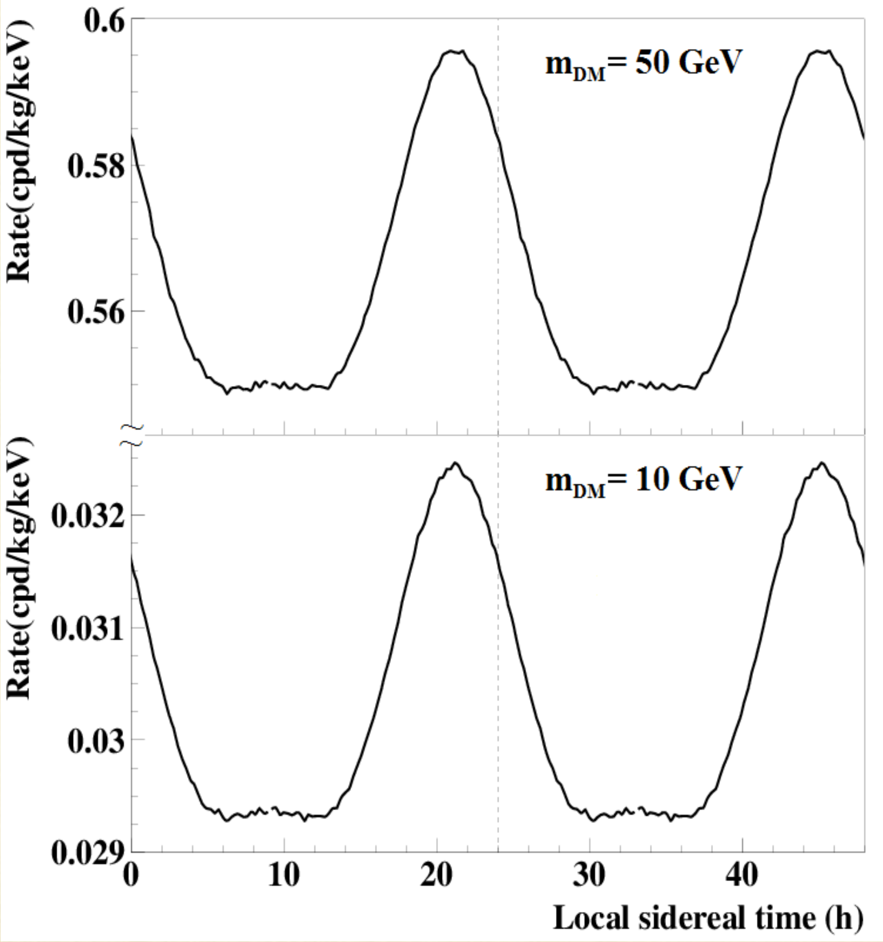
where $q_{n,i}$ is the quenching factor value for a given nucleus, n, with respect to the i-th axis of the anisotropic crystal and $\Omega_{out} = (\gamma,\phi)$ is the output direction of the nuclear recoil in the laboratory frame

$q_{n,i}$ 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: $FWHM = 2.4\sqrt{E(keV)}$

Expected signal rate in the given scenario

Signal rate in [2-3] keV energy range with
$\xi \, \sigma_p = 5\times10^{-5}$ pb



- Maximum rate at 21 h sidereal time of LNGS, when the DM preferential arrival direction is near the zenith, that is near the crystal axis with the largest light output.
- Analogous results can be obtained also analysing the anisotropic behaviour of the pulse shape of scintillation events.

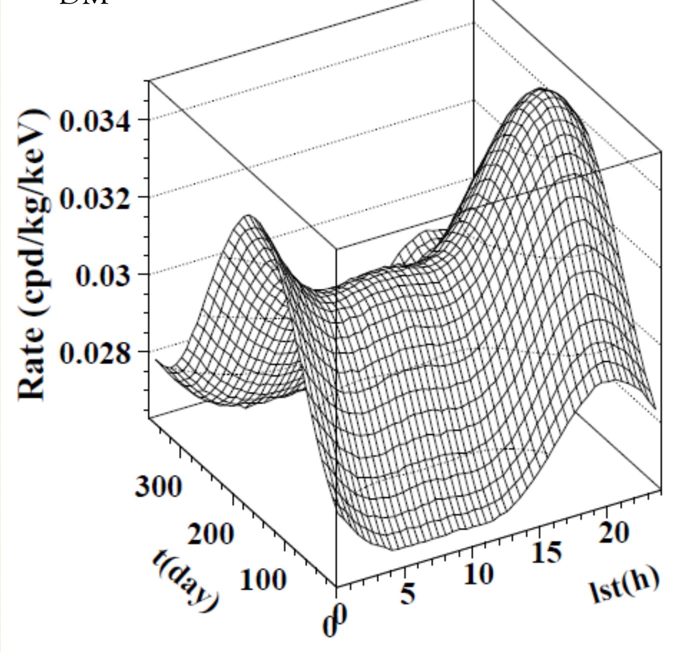
The signature is very distinctive and cannot be mimicked by any background

Example of the expected signal in a simplified model

Expected rate as a function of sideral time and days of the year

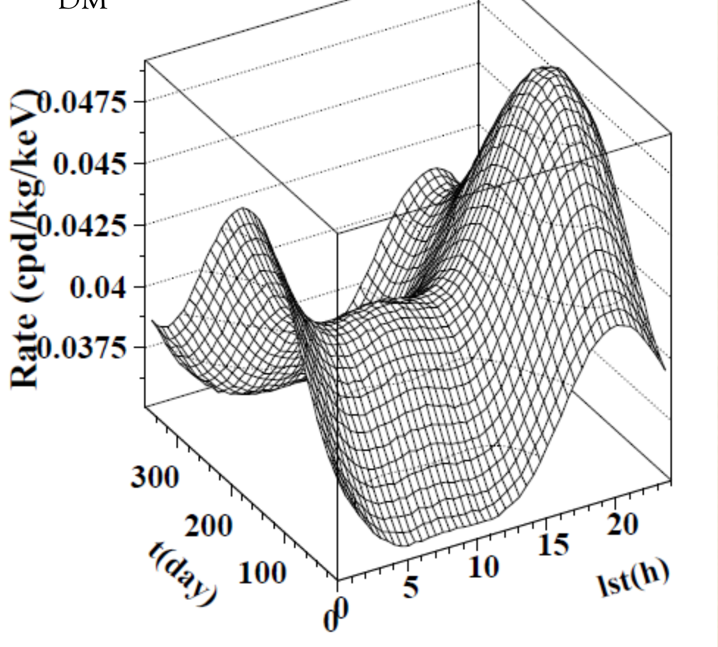
[2-3] keV σ_p=5×10^{-5} pb

m_{DM}= 10 GeV



[6-7] keV σ_p=5×10^{-5} pb

m_{DM}= 100 GeV



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Signal identification with anisotropic crystal

Tools to confirm that a diurnal effect is actually due to dark matter:

- ✓ 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

And in case of bolometer experiment

- ✓ The heat signal associated to the recoil events – acquired in coincidence with the light signal – will show no diurnal effect

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Considering an experiment with:

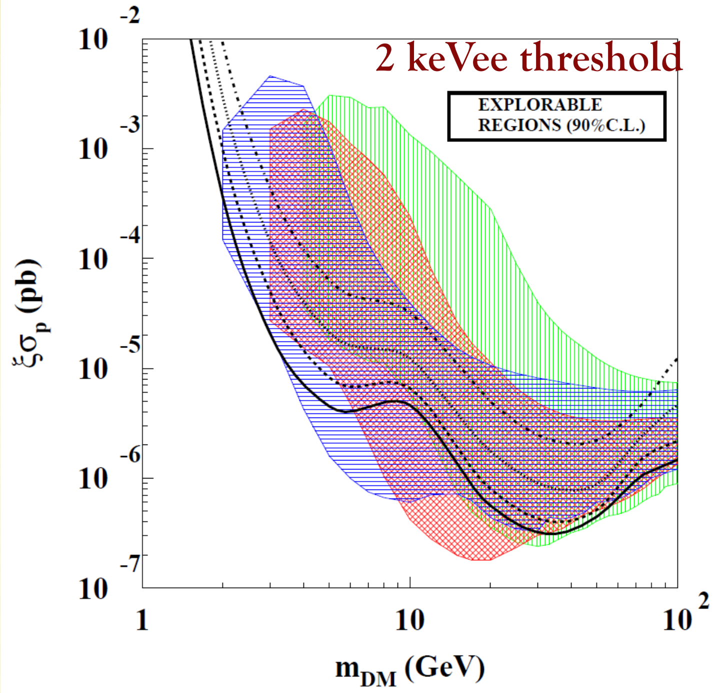
- 200 kg of $ZnWO_4$;
- 5 years of data taking.

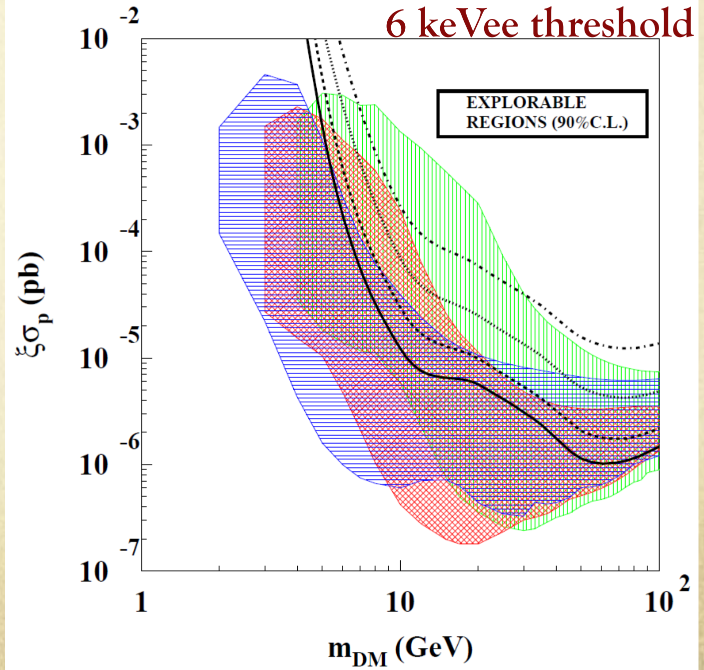
The reachable sensitivity has been calculated considering four possible time independent background levels in the low energy region:

- 10^{-4} cpd/kg/keV (solid line)
- 10^{-3} cpd/kg/keV (dashed line)
- 10^{-2} cpd/kg/keV (dotted line)
- 0.1 cpd/kg/keV (dash-dotted line)

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 model independent result in terms of scenarios for the DM candidates considered here





Time Scale of the program – Phase I

PHASE I									
Activity area	**Tasks**	**Months**							
		6	**12**	**18**	**24**	**30**	**36**	**42**	**48**
1 High radiopurity	1. Selection & purification of initial powders	■	■						
	2. Selection & purification of materials for crystal production	■	■						
	3. Selection of the best $ZnWO_4$ crystal growth technique		■	■	■				
	4. Test on recrystallization effectiveness			■	■	■			
	5. Underground measurements of test prototypes				■	■	■		
2 $ZnWO_4$ Scintillation detector	1. Test on light collection: silicone oil, crystal shape, surface treatment				■	■			
	2. Test on detector directly coupled to new ULB/VLB PMTs					■	■		
	3. Measurements at low temperature					■	■		
	4. Optimization of the single detector module						■	■	
3 $ZnWO_4$ Scintillating bolometer	1. Test of the bolometric response				■	■			
	2. Test of light detectors based on the Luke-Neganov effect				■	■	■		
	3. Test of light detectors based on superconductive films					■	■	■	
	4. Optimization of the single detector module						■	■	■
4 CNT Detectors	1. Deposition of CNT in the form of oriented fibers on substrates	■	■						
	2. Standard photolithographic processes on Si and SiO_2 substrates	■	■						
	3. Preliminary test of particle irradiation on planar devices			■	■				
	4. Study of transport properties as a function of the device orientation				■	■	■		
	5. Prototypes of 3D CNT detectors						■	■	■
5 Neutron calibrations	1. Pure scintillator: study of light yield and pulse shape anisotropy						■	■	
	2. Pure scintillator: study of PSD capability versus β/γ events						■	■	
	3. Scintillating bolometer: study of light yield anisotropy						■	■	■
	4. Scintillating bolometer: study of background cut efficiency							■	■
	5. CNT: study of the anisotropic response to nuclear recoils							■	■

Time Scale of the program – Phase II

PHASE II						
Activity area	**Tasks**	**Years**				
		0.5	**1**	**2 → 5**		**6**
DM Experiment	1. Construction and installation of the refrigerator	■				
	2. Assembly of shield and Radon removal system	■				
	3. Production and assembling of the single detector modules	■	■			
	4. Test of electronic chain and DAQ		■			
	5. Commissioning		■			
	6. Test runs		■			
	7. Data taking			■	■	■
	8. First physical results					■

Requests for Laboratory space / technical and technological infrastructures

Phase I

- already existing infrastructures of INFN at LNGS:
  - DAMA/Ge, STELLA facility and etc. and the chemical laboratory for the material selections and purifications while the
  - DAMA/R&D and DAMA/CRYS for test measurements on the new developed prototype detectors.
- Tor Vergata University: CNT detectors
- CSNSM-Orsay in France (for the development of bolometric $ZnWO_4$ detectors).
- Other Italian and foreign institutions or company involved in the development of the new detectors: e.g., the Salerno University and the Rice University of Houston (USA) for the CNT detectors, Russian and Ukrainian institutions specialized in the growth of high purity $ZnWO_4$ crystals.
- Neutron calibrations at ENEA, Frascati (Italy).

Phase II

- Construction of a matrix of the single detector modules selected in the Phase I. The new DM experiment will be installed in a inner low radioactive shield in an new installation deep underground at LNGS.

Costs (preliminary estimate)

Phase I (4 years): 875 k€

- *Travel: 100 k€ (missions for team members)*
- *Equipment: 255 k€*

  (Cryostat conception and production and related miscellanea: 200 k€

  (based on Cryoconcept quotation)

  Thermometry and related read-out: 15 €

  Electronics channels to instrument the dedicated dilution refrigerator and two DAQ cards : 40 k€
- *Consumables: 500 k€*

  Selection and purification of the initial materials for the $ZnWO_4$ *crystals: 150 k€*

  Ultrapure Ge wafers for light detectors: 15 k€ (based on UMICORE quotation)

  Consumables for evaporations (crucibles, raw materials): 40 k€

  Electronics components: 5 k€

  Nano-structuring of NbSi thin films and their fabrication: 40 k€

  Cryostat shield design and assembly, including automatic opening system: 40 k€

  Lead shield for the cryostat: 20 k€

  Polyethylene shield for the cryostat: 25 k€

  Copper and detector holders: 25 k€

  Complements to bonding machine: ball bonding head and tools, including pull/shear: 60 k€

  Radiopure photomultipliers for tests: 30 k€

  DAQ: 10 k€

  Cooling system based on liquid nitrogen to be installed in the DAMA/CRYS setup: 40 k€

Costs (preliminary estimate)

Phase II (6 years): 1.1 M€ / 2.8 M€ / 1.1 M€

The costs for the second phase will strongly depend on the characteristic of the single detector module selected at the end of the first phase.

- *Travel: 140 k€* (missions to LNGS for team members, etc.)
- *Consumables: 777 k€ / 950 k€ / 200 k€*

  Construction of single detector modules (3 cases):

  $ZnWO_4$ pure scintillator: 500 k€ for crystals growth + radiopure photomultipliers;

  $ZnWO_4$ scintillating bolometer: 500 k€ for crystals (200kg – 400 crystals of 500g)
  + 50 k€ for light detectors

  CNT detectors: 200 k€

  Copper for passive shield: 91 k€ (about 2600 kg, 35 €/kg)

  Copper for holders and production: 400 k€

  Lead for passive shield: 26 k€ (about 5400 kg, 4.85 €/kg)

  Cadmium, paraffin and Plexiglas box for passive shield: 10 k€

  HP N2 fluxing 30 k€/y
- *Equipment: 174 k€*

  Mechanical system to lower the front side of the shield: **16 k€**

  Monitoring system (for temperature, flux and pressure of HP N_2 gas): **8 k€**

  Electronic chain, the PMTs, the Waveform analysers and the DAQ system: **150 k€**

  Electronics and DAQ: 800

If the decided option will be scintillating bolometers, no existing infrastructure could host 400 bolometers. It means that a new infrastructure has to be done: Dilution refrigerator + shields (lead & Polyethylene) + thermometry: 1000 keuro

Conclusions

- Anisotropic $ZnWO_4$ detectors are promising detectors to investigate the directionality for DM candidates inducing nuclear recoils
- These detectors could permit to reach - in some given scenarios - sensitivity comparable to that of the DAMA/LIBRA positive model independent results
- Such an experiment can obtain, with a completely different new approach, further evidence for the presence of some DM candidates in the galactic halo and provide complementary information on the nature and interaction type of the DM candidate
- It would represent a first realistic attempt to investigate the directionality approach