# Search for rare processes with $ZnWO_4$ crystal scintillators

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**INFN-LNGS**

**RPSCINT 2013**
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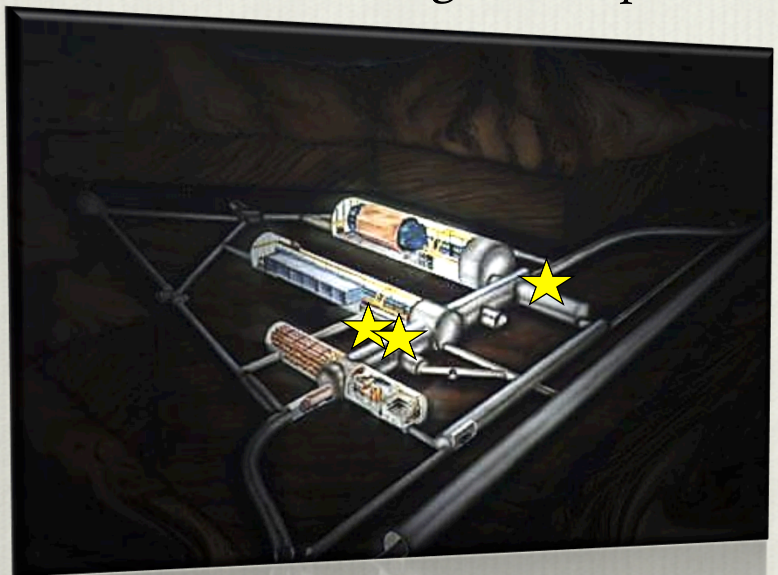
# DAMA project

The DAMA project develops and exploits low background scintillator in order to investigate rare processes



- DAMA/LIBRA ( DAMA/NaI)
- DAMA/LXe
- DAMA/R&D
- DAMA/Crys
- DAMA/Ge and Ge facility (STELLA)

## Collaboration:

Roma Tor Vergata, Roma La Sapienza, LNGS, IHEP/Beijing

+ by-products and small scale expts.: INR-Kiev

+ in LNGS: Chemistry Lab and Ge facility (STELLA)

+ some activities: JINR-Dubna Russia, ITEP-Moscow Russia, Nikolaev Institute of Inorganic Chemistry - Novosibirsk Russia, Institute of Physics and Technology- Kharkiv Russia, University of Jyvaskyla Finland, IIT-Ropar India

+ neutron meas.: ENEA-Frascati

## Web Site: http://people.roma2.infn.it/dama

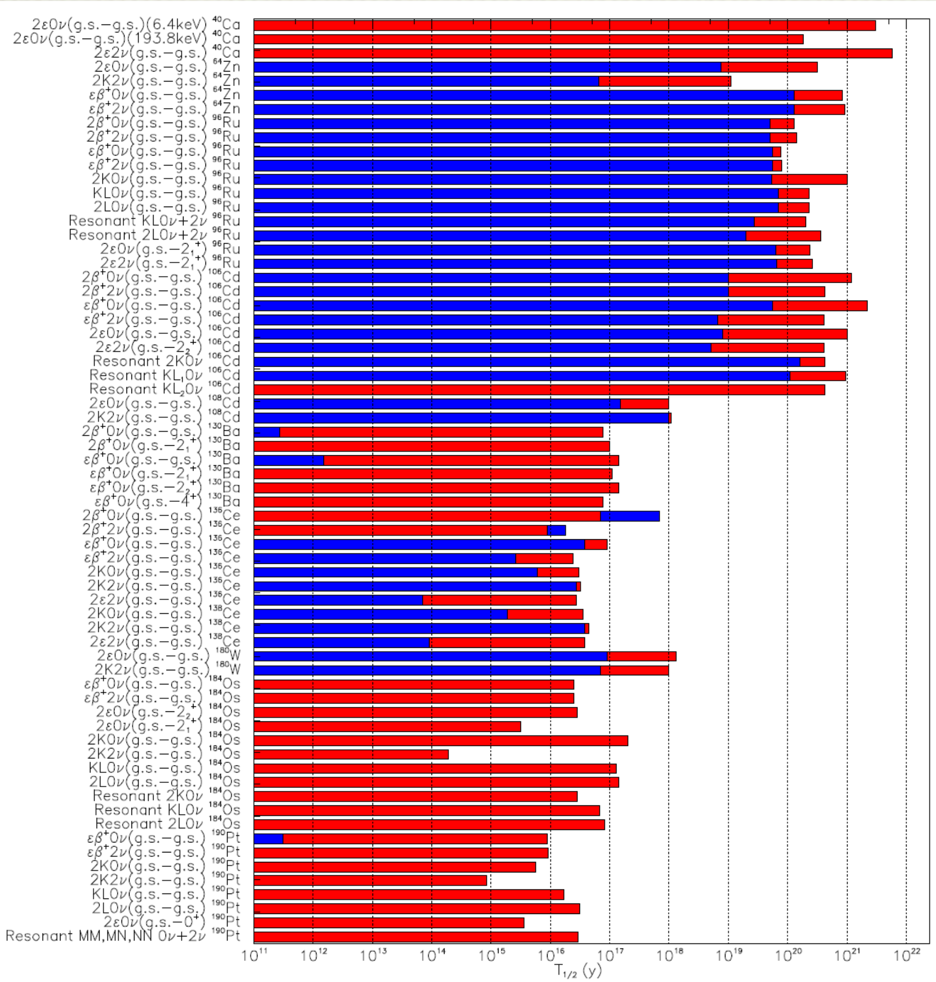
# Physics in DAMA/R&D

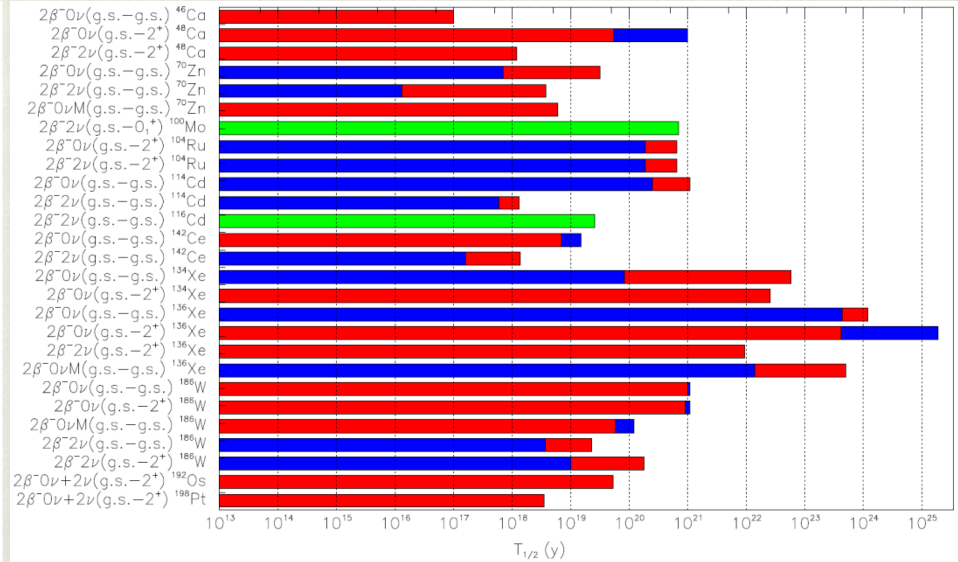
- Dark Matter with CaF2(Eu)
- Solar Axions
- 2$\beta$ decay in various isotopes
- First observations of rare $\alpha$ decays
- Highly forbidden $\beta$ decay
- Cluster decay
- CNC decay
- Etc.

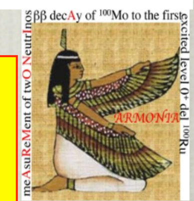
AP7(1997)73, N.Cim.A110(1997)189, NPB563(1999)97, AP10(1999)115, NPA705(2002)29, NIMA498(2003)352, NIMA525(2004)535, NIMA555(2005)270, UJP51(2006)1037, NPA789(2007)15, PRC76(2007)064603, PLB658(2008)193, EPJA36(2008)167, NPA824(2009)101, NPA826(2009)256, JPG:NPP38 (2011)115107, JPG: NPP38(2011)015103, PRC85(2012)044610, JINST6(2011)P08011, PRC85(2012)044610

NIMA572(2007)734, NPA806(2008)388, EPJA42(2009)171, NPA824(2009)101, NIMA607(2009) 573, NIMA846(2010)143, NIMA615(2010)301, NPA846 (2010)143, EPJA47(2011)91, NPA859(2011)126, PRC83(2011)034603, NIMA626-7(2011)31, PLB711(2012)41, NIMA670(2012)10, NIMA704(2013)40, EPJC73(2013)2276, EPJA49(2013)24, PRC87(2013) 034607

# Summary of searches for ββ decay modes (partial list)




$T_{1/2}$ experimental limits by DAMA (in red) and previous ones (in blue). All the limits are at 90% C.L. except for $0\nu 2\beta^+$ in $^{136}$Ce and $2\beta^- 0\nu$ in $^{142}$Ce at 68% C.L.. In green observed

ARMONIA: New observation (green) of $2\nu 2\beta^-$ $^{100}Mo \rightarrow ^{100}Ru$ (g.s.$\rightarrow 0_1^+$) decay
NPA846 (2010)143

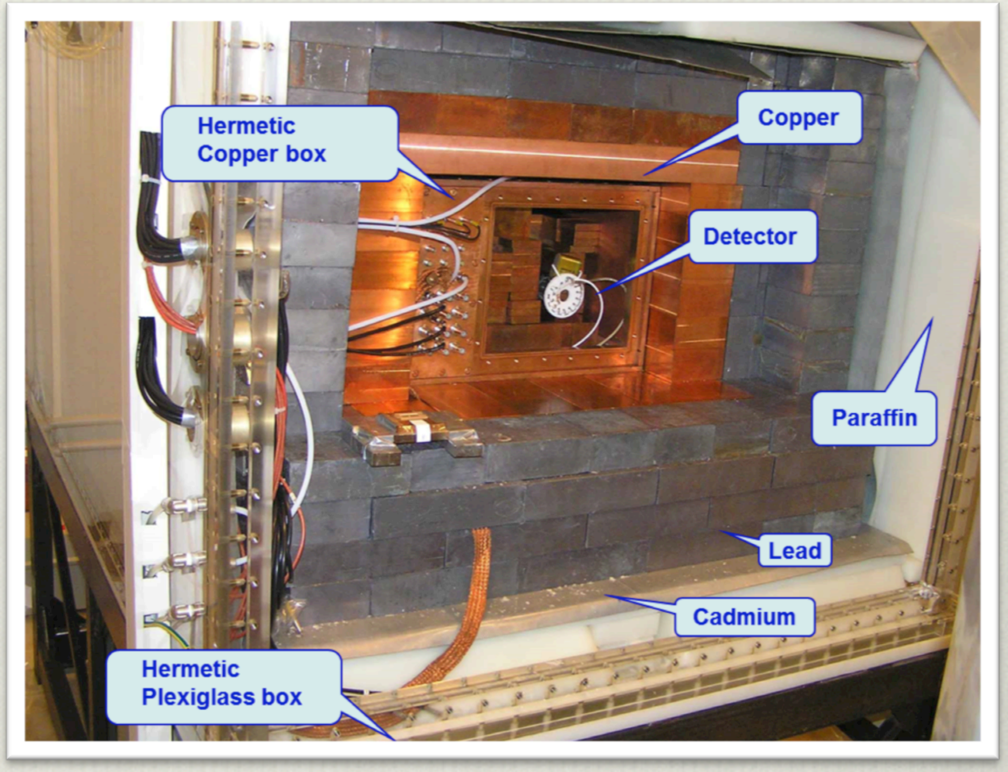
AURORA: New observation of $2\nu 2\beta^-$ $^{116}$Cd decay
NPAE2012

- Many competitive limits obtained on lifetime of $2\beta^+$, $\varepsilon\beta^+$ and $2\varepsilon$ processes ($^{40}$Ca, $^{64}$Zn, $^{96}$Ru, $^{106}$Cd, $^{108}$Cd, $^{130}$Ba, $^{136}$Ce, $^{138}$Ce, $^{180}$W, $^{190}$Pt, …)
- First searches for resonant $2\beta$ decays in some isotopes

Many publications on detectors developments and results
Many future measurements in preparation

# Low background $ZnWO_4$ crystal scintillators

- DAMA in collaboration with INR-Kiev group has 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

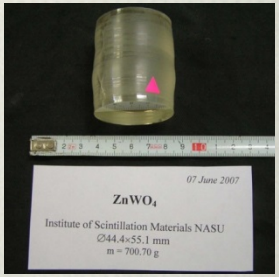
- Air-tight Cu box continuously flushed with HP $N_2$
- 10 cm of high purity Cu
- 15 cm of low radioactive lead
- 1.5 mm of cadmium
- 4/10 cm polyethylene/paraffin
- The whole shield closed inside a Plexiglas box also continuously flushed with HP $N_2$

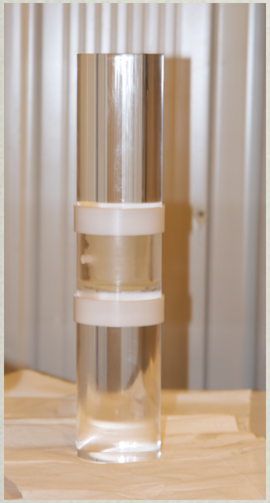
# $ZnWO_4$ crystal scintillators

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

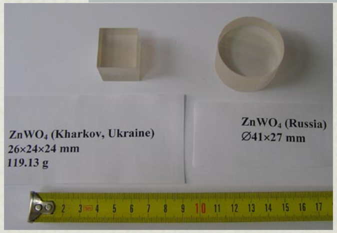
- Low background $ZnWO_4$ crystal scintillators with large volume and good scintillation properties realized
- Various detectors with mass **0.1-0.7 kg** realized by exploiting different materials and techniques
- Detectors installed in a cavity (filled up with high-pure silicon oil) $\phi$ 47 x 59 mm in central part of a polystyrene light-guide 66 mm in diameter and 312 mm in length. The light-guides were coupled to 2 low-background PMTs

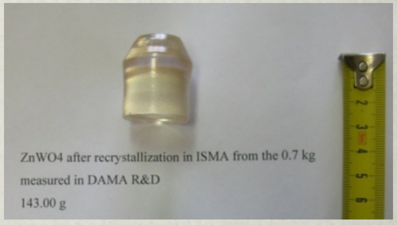
| Crystal scintillator | Size (mm) | Mass (g) |
|---|---|---|
| ZWO-1 | $20 \times 19 \times 40$ | 117 |
| ZWO-2 | $\oslash 44 \times 55$ | 699 |
| ZWO-2a | $\oslash 44 \times 14$ | 168 |

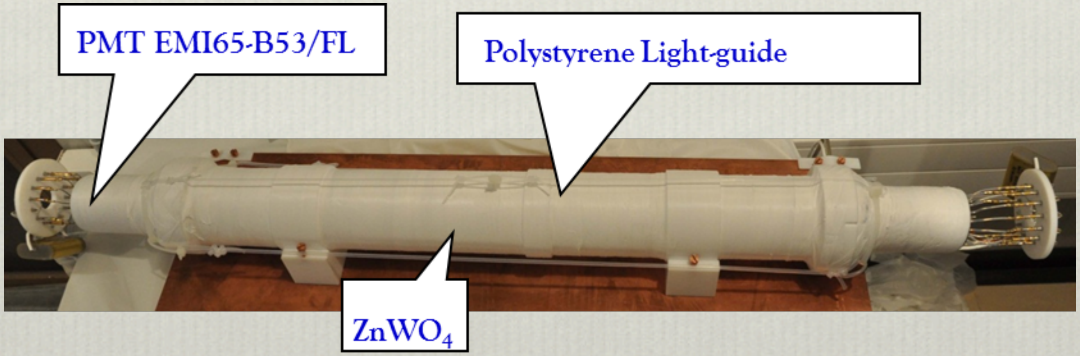



- Main aim of the measurements was the study of the properties of $ZnWO_4$ and the search for 2β processes in Zn and W isotopes.



# Potentially 2β active nuclides in $ZnWO_4$ crystals

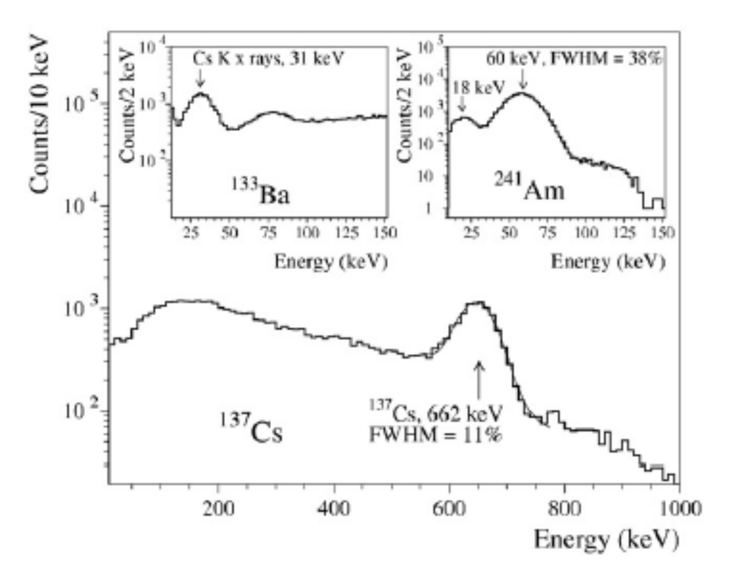
| Transition | Energy release ($Q_{\beta\beta}$) (keV) [26] | Isotopic abundance (%) [27] | Decay channels | Number of mother nuclei in 100 g of $ZnWO_4$ crystal |
|---|---|---|---|---|
| $^{64}Zn \rightarrow {}^{64}Ni$ | 1095.7(0.7) | 49.17(75) | $2\varepsilon$, $\varepsilon\beta^+$ | $9.45 \times 10^{22}$ |
| $^{70}Zn \rightarrow {}^{70}Ge$ | 998.5(2.2) | 0.61(10) | $2\beta^-$ | $1.17 \times 10^{21}$ |
| $^{180}W \rightarrow {}^{180}Hf$ | 144(4) | 0.12(1) | $2\varepsilon$ | $2.31 \times 10^{20}$ |
| $^{186}W \rightarrow {}^{186}Os$ | 489.9(1.4) | 28.43(19) | $2\beta^-$ | $5.47 \times 10^{22}$ |

- ✓ The nucleus $^{64}Zn$ is one of the few exceptions among $2\beta^+$ nuclei having big natural isotopic abundance
- ✓ $ZnWO_4$ scintillators offer good potentiality in searching for double beta processes in Zinc and Tungsten isotopes.

# Performances of the $ZnWO_4$ crystal scintillator

## ➢ *Main features*

| | |
|---|---|
| *Density (g/cm³)* | *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

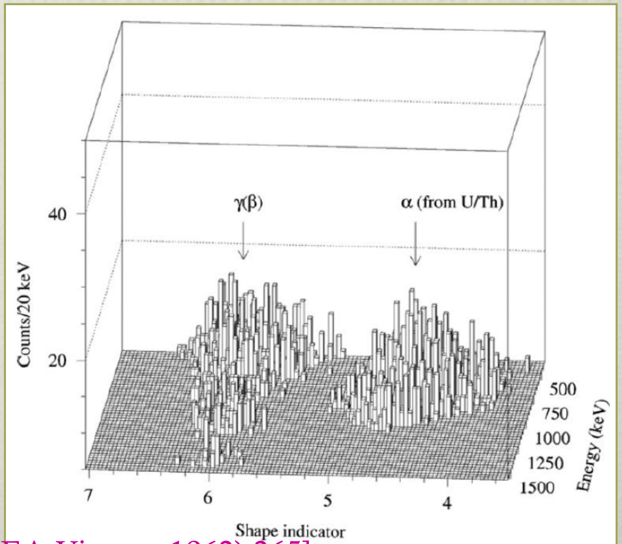
## ➢ *Light yield and energy threshold*

An energy threshold of 10 keV has been used in a past experiment not optimized for the low energy region

## ➢ *Pulse shape analysis*

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

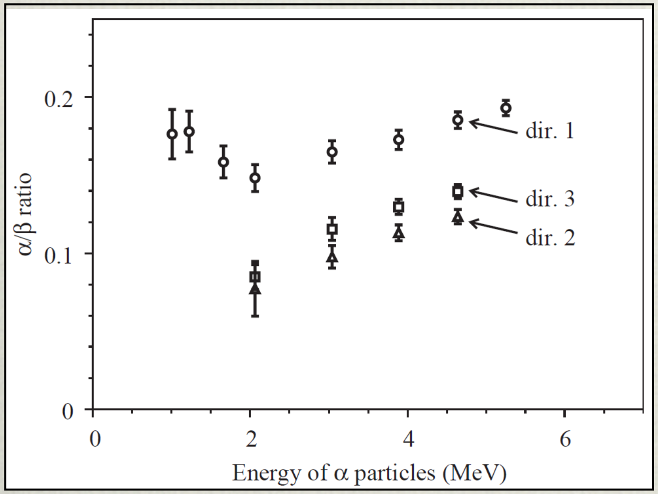
$$SI = \frac{\sum_k f(t_k)P(t_k)}{\sum_k f(t_k)} \qquad P(t) = \frac{f_\alpha(t) - f_\beta(t)}{f_\alpha(t) + f_\beta(t)}$$



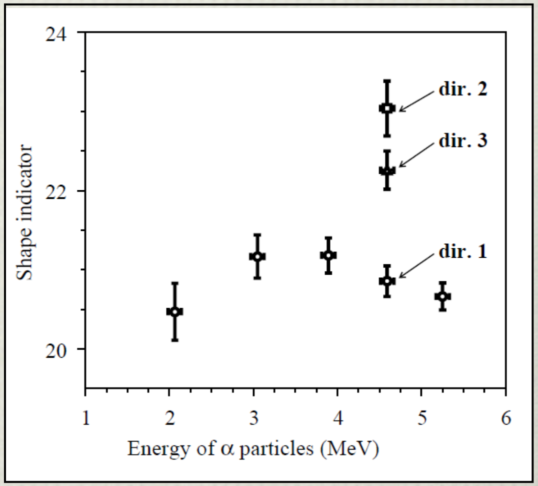

*Optimal filter technique* [E. Gatti e F. DeMartini, *Nucl. Electronics 2* (IAEA,Vienna, 1962) 265]

# Anisotropic features of $ZnWO_4$

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




**Such effects are absent in case of electron excitation**



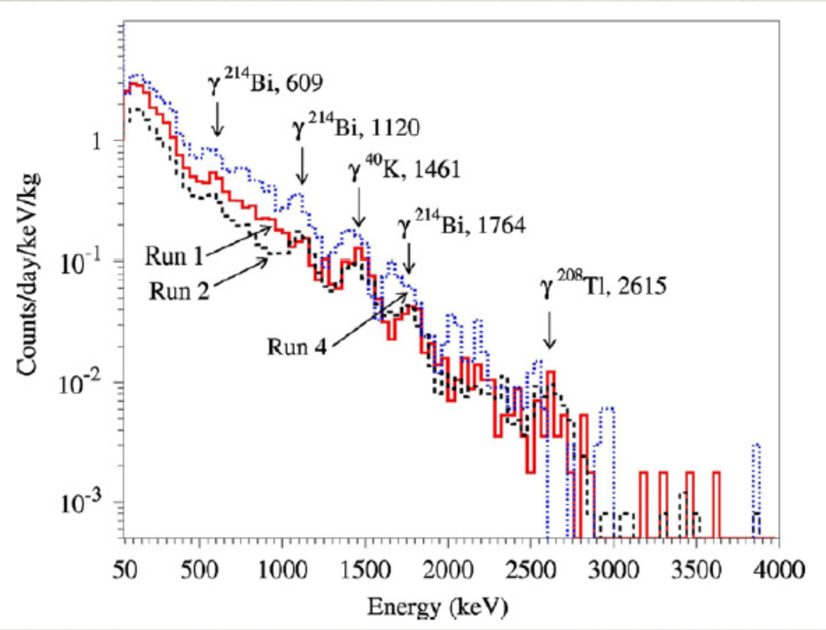

These anisotropic effects are ascribed to preferred directions of the excitons' propagation in the crystal lattice affecting the dynamics of the scintillation mechanism

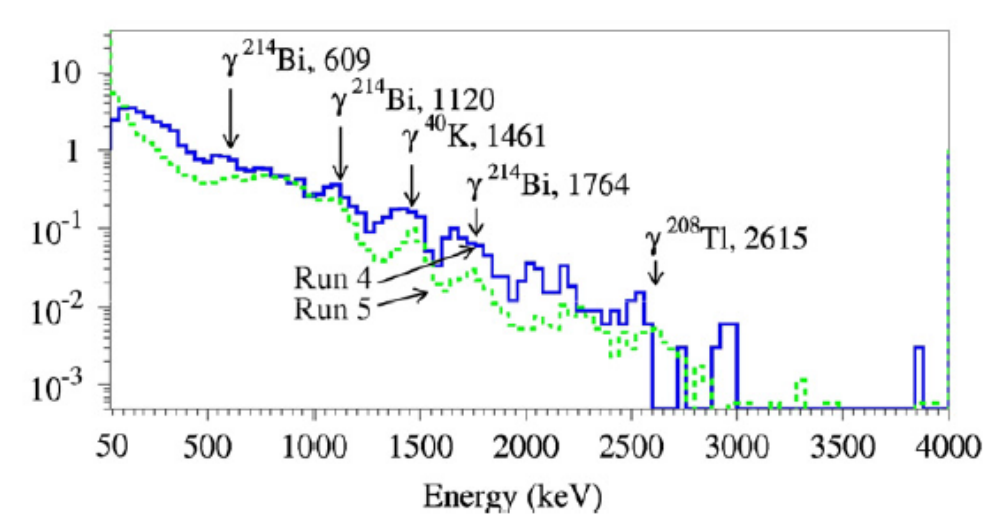
Similar effect is expected in the case of low energy nuclear recoils
⇒ Dedicated measurements are in preparation

# Radiopurity of the $ZnWO_4$ crystal scintillators

**NIMA 626(2011)31**

| Run | Crystal | T (h) | Background (cpd/kg/keV) 0.2-0.4 MeV | 0.8-1.0 MeV | 2.0-2.9 MeV |
|---|---|---|---|---|---|
| 1 | ZWO-1 (ISMA) 20 x 19 x 40 mm 117 g | 2906 | 1.71(2) | 0.25(1) | 0.0072(7) |
| 2 | ZWO-2 (ISMA) ∅ 44 x 55 mm 669 g | 2130 | 1.07(1) | 0.149(3) | 0.0072(4) |
| 3 | ZWO-3 (ISMA) ∅ 27 x 33 mm 141 g | 994 | 1.54(4) | 0.208(13) | 0.0049(10) |
| 4 | ZWO-4 (NIIC) 41 x 27 mm 239 g | 834 | 2.38(4) | 0.464(17) | 0.0112(12) |
| 5 | | 4305 | 1.06(1) | 0.418(7) | 0.0049(4) |

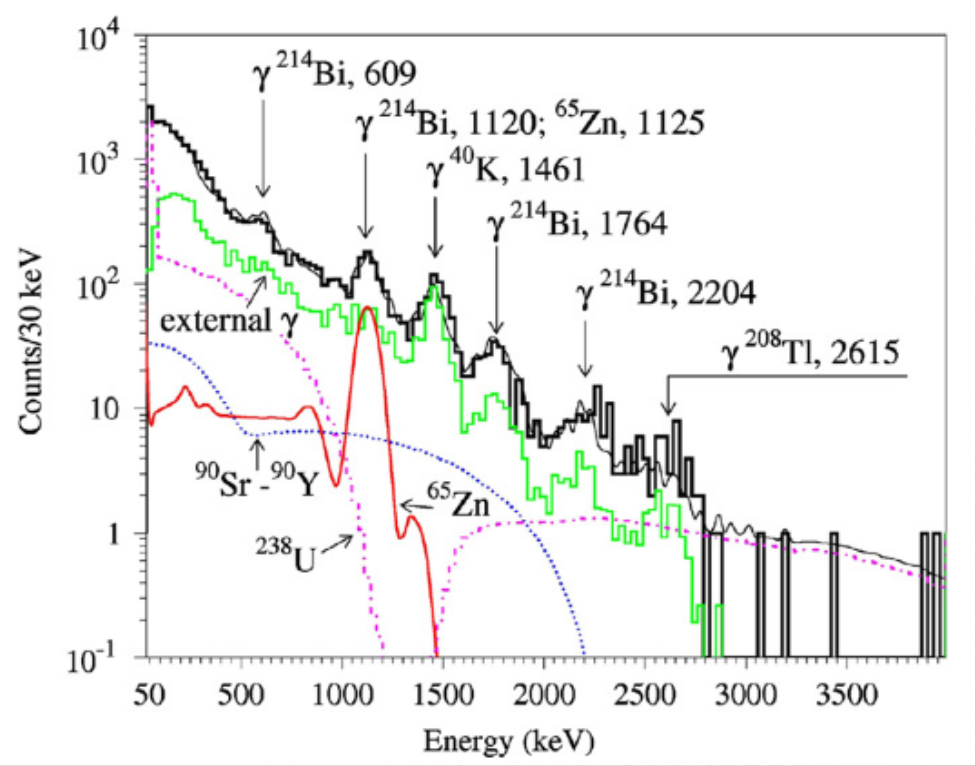


# Radiopurity of the $ZnWO_4$ crystal scintillators

NIMA 626(2011)31

Fit of the background spectrum (run 5)




Reconstruction of the background spectra and estimation of the radioactive contamination of the $ZnWO_4$ detectors with Time Amplitude Analysis, PSD, Monte Carlo

- ~ 0.5 ppt for $^{232}$Th;
- ~ 0.2 ppt for $^{238}$U;
- < 0.02 mBq/kg for $^{40}$K;
- $\alpha$ contamination 0.2 - 2 mBq/kg

# Radioactive contamination of $ZnWO_4$ crystal scintillators

NIMA 626(2011)31

Radioactive contamination of $ZnWO_4$ scintillators determined by different methods.

| Chain | Nuclide | Activity (mBq/kg) | | | | |
|---|---|---|---|---|---|---|
| | | ZWO-1 | ZWO-2 | part of ZWO-2 | ZWO-3 | ZWO-4 |
| $^{232}$Th | $^{232}$Th | ≤ 0.11 [a] | ≤ 0.1 [a] | – | ≤ 0.03 [a] | ≤ 0.25 [a] |
| | $^{228}$Ra | ≤ 0.2 [b] | ≤ 0.05 [b] | ≤ 3.4 [d] | ≤ 0.02 [b] | ≤ 0.1 [b] |
| | $^{228}$Th | 0.005(3) [c] | 0.002(1) [c] | ≤ 8.3 [d] | 0.002(2) [c] | 0.018(2) [c] |
| $^{235}$U | $^{227}$Ac | ≤ 0.007 [c] | ≤ 0.003 [c] | – | ≤ 0.01 [c] | 0.011(3) [c] |
| $^{238}$U | $^{238}$U+$^{234}$U | ≤ 0.1 [a] | ≤ 0.08 [a] | – | ≤ 0.2 [a] | ≤ 0.12 [a] |
| | $^{230}$Th | ≤ 0.13 [a] | ≤ 0.07 [a] | – | ≤ 0.15 [a] | ≤ 0.16 [a] |
| | $^{226}$Ra | ≤ 0.006 [a] | 0.002(1) [a] | ≤ 5.7 [d] | 0.021(15) [a] | 0.025(6) [a] |
| | $^{210}$Po | ≤ 0.2 [a] | ≤ 0.06 [a] | – | ≤ 0.01 [a] | ≤ 0.64 [a] |
| Total α activity | | 0.38(5) [a] | 0.18(3) [a] | – | 0.47(7) [a] | 2.3(2) [a] |
| | $^{40}$K | ≤ 1 [b] | ≤ 0.4 [b] | ≤ 24 [d] | ≤ 0.1 [b] | ≤ 0.02 [b] |
| | $^{60}$Co | ≤ 0.05 [b] | ≤ 0.1 [b] | ≤ 2.5 [d] | ≤ 0.03 [b] | ≤ 0.03 [b] |
| | $^{65}$Zn | ≤ 0.8 [b] | 0.5(1) [b] | ≤ 1.5 [d] | 0.8(2) [b] | 0.7(2) [b] |
| | $^{87}$Rb | ≤ 2.6 [b] | ≤ 2.3 [b] | – | ≤ 4.0 [b] | ≤ 4.2 [b] |
| | $^{90}$Sr–$^{90}$Y | ≤ 0.6 [b] | ≤ 0.4 [b] | – | ≤ 0.1 [b] | ≤ 0.1 [b] |
| | $^{137}$Cs | ≤ 0.3 [b] | ≤ 0.05 [b] | ≤ 1.7 [d] | ≤ 0.5 [b] | ≤ 1.3 [b] |
| | $^{147}$Sm | ≤ 0.01 [a] | ≤ 0.01 [a] | – | ≤ 0.01 [a] | ≤ 0.05 [a] |
| | $^{207}$Bi | ≤ 0.2 [b] | ≤ 0.2 [b] | ≤ 1.4 [d] | ≤ 0.4 [b] | ≤ 0.2 [b] |

[a] Pulse–shape discrimination (see Section 3.2.2).
[b] Fit of background spectra (see Section 3.2.3).
[c] Time–amplitude analysis (see Section 3.2.1).
[d] HP Ge γ spectrometry (see Section 3.3).

**Also ICP-MS analysis**

$\alpha$ contamination at level of 0.2 -2 mBq/kg , further improvement under investigation

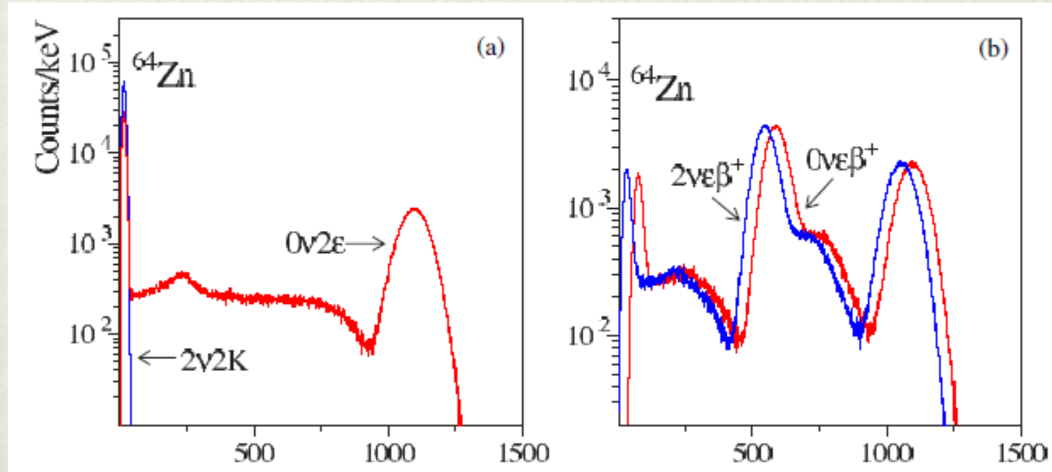
# Search for 2ε and εβ$^+$ decay of $^{64}$Zn

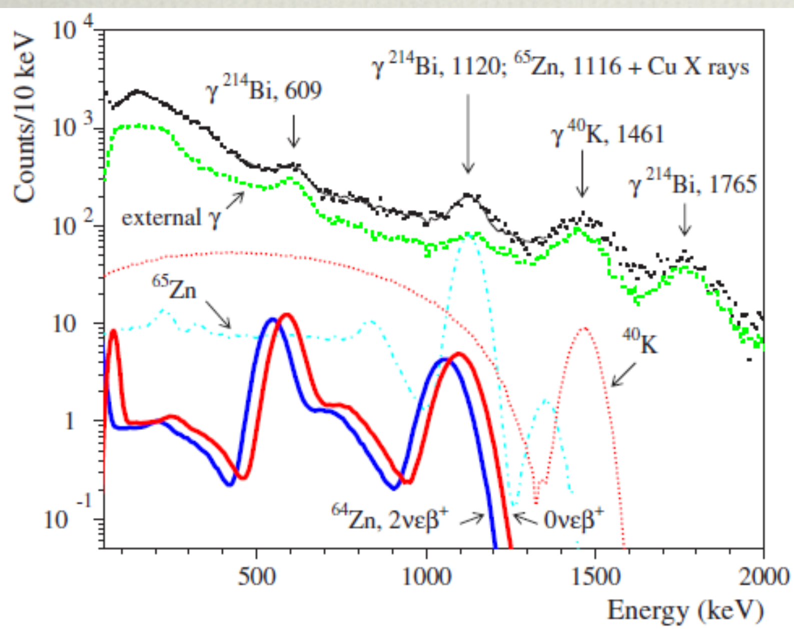
J. Phys. G: Nucl. Part. Phys. 38 (2011) 115107

No clear peculiarities in the measured energy spectra can be interpreted as a signal for 2β decays of Zn or W

$$\lim T_{1/2} = N \cdot \eta \cdot t \cdot \ln 2 / \lim S$$

Energy spectrum fitted by model functions sum of the backg. model + expected energy distribution.




| Transition | Decay channel | Level of the daughter nucleus | Experimental limits on $T_{1/2}$, yr at 90% CL: Present work | The best previous results |
|---|---|---|---|---|
| $^{64}$Zn → $^{64}$Ni | $2\nu 2K$ | g.s. | $\geqslant 1.1 \times 10^{19}$ | $\geqslant 6.0 \times 10^{16}$ [54] |
| | $0\nu 2\varepsilon$ | g.s. | $\geqslant 3.2 \times 10^{20}$ | $\geqslant 7.4 \times 10^{18}$ [55] |
| | $2\nu\varepsilon\beta^+$ | g.s. | $\geqslant 9.4 \times 10^{20}$ | $= (1.1 \pm 0.9) \times 10^{19}$ [58] |
| | | | | $\geqslant 1.3 \times 10^{20}$ [59] |
| | $0\nu\varepsilon\beta^+$ | g.s. | $\geqslant 8.5 \times 10^{20}$ | $\geqslant 1.3 \times 10^{20}$ [59] |

$T_{1/2}$ ~$10^{19}$ – $10^{21}$ yr

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

# Search for $2\nu 2k$ decay of $^{64}Zn$

Requiring the theoretical energy distribution should not exceed the experimental one in any energy interval

$$T_{1/2}^{2k2\varepsilon}\,(^{64}Zn) > 1.1 \times 10^{19}\ \text{yr}$$

The half-life limits is more than 2 order of magnitude higher than the one set in previous experiments.

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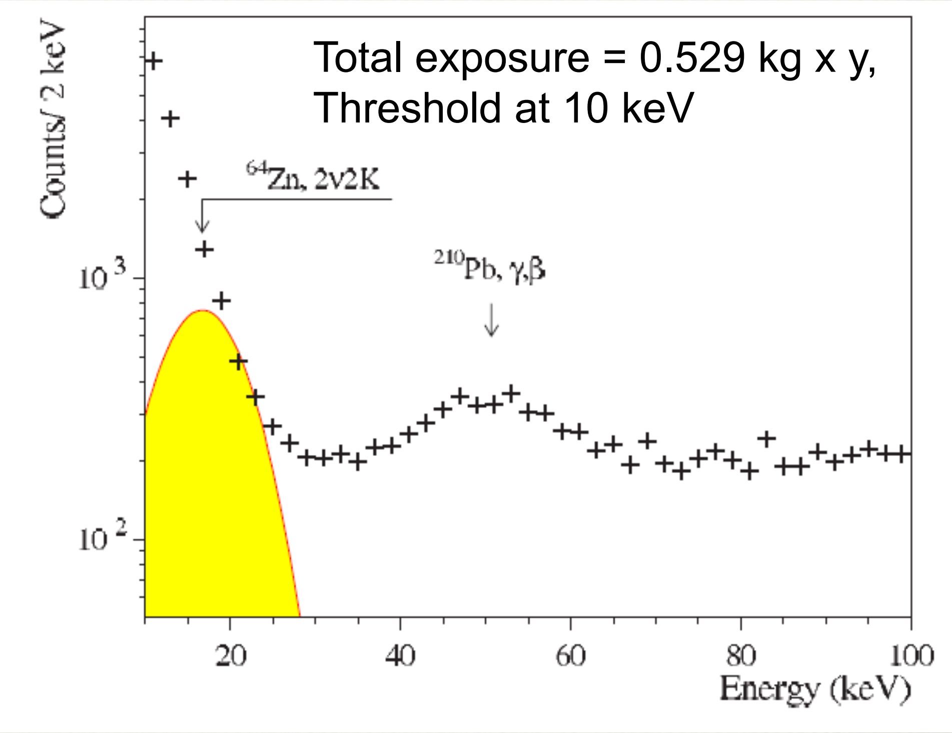


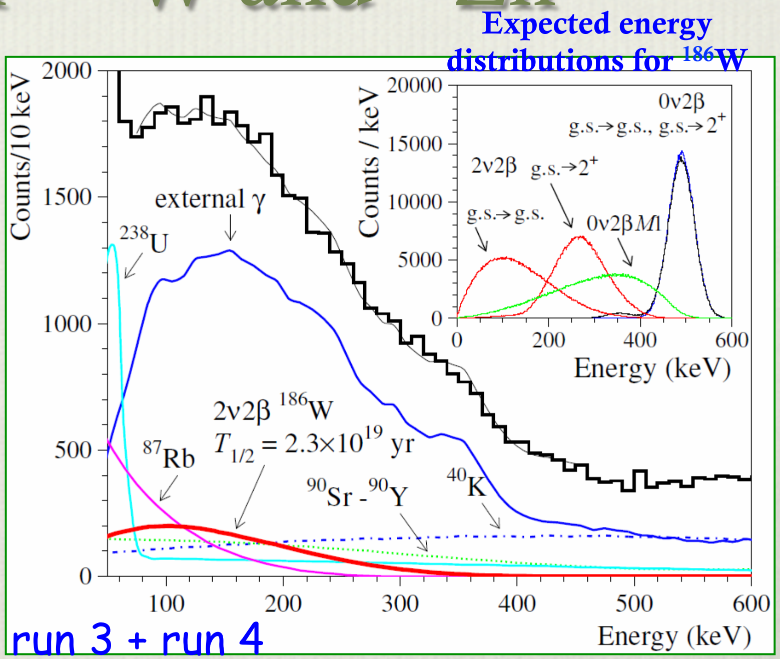
# Search for 2β decay of $^{186}W$ and $^{70}Zn$

Energy spectra collected in Runs 1-4 have been fitted (using background model and the expected signal) to determine the best limit for the searched decay modes

Sensitivity: $T_{1/2}$ ($^{70}Zn$) ~$\mathbf{10^{18}}$ **yr**

$T_{1/2}$ ($^{186}W$) ~$\mathbf{10^{18} – 10^{21}}$ **yr**

The half-life limits on the 2β processes in $^{70}Zn$ and the two neutrino mode of 2β decay in $^{186}W$ are one order of magnitude higher than those set in previous experiments.



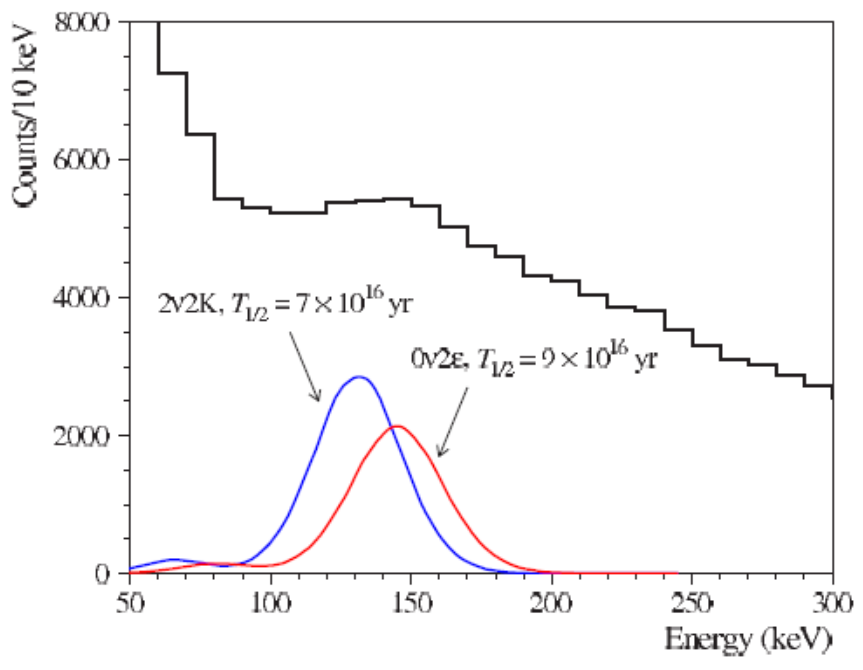

| Transition | Decay channel | Level of the daughter nucleus | Experimental limits on $T_{1/2}$, yr at 90% CL: Present work | The best previous results |
|---|---|---|---|---|
| $^{70}Zn \rightarrow {}^{70}Ge$ | $2\nu2\beta^-$ | g.s. | $\geqslant 3.8 \times 10^{18}$ | $\geqslant 1.3 \times 10^{16}$ [46] |
| $^{186}W \rightarrow {}^{186}Os$ | $2\nu2\beta^-$ | g.s. | $\geqslant 2.3 \times 10^{19}$ | $\geqslant 3.7 \times 10^{18}$ [30] |
| | $2\nu2\beta^-$ | $2_1^+$(137 keV) | $\geqslant 1.8 \times 10^{20}$ | $\geqslant 1.0 \times 10^{19}$ [30] |
| | $0\nu2\beta^-$ | g.s. | $\geqslant 1.0 \times 10^{21}$ | $\geqslant 1.1 \times 10^{21}$ [30] |
| | $0\nu2\beta^-$ | $2_1^+$(137 keV) | $\geqslant 9.0 \times 10^{20}$ | $\geqslant 1.1 \times 10^{21}$ [30] |
| | $0\nu2\beta^- M1$ | g.s. | $\geqslant 5.8 \times 10^{19}$ | $\geqslant 1.2 \times 10^{20}$ [30] |
| | $0\nu2\beta^- M2$ | g.s. | $\geqslant 1.1 \times 10^{19}$ | – |
| | $0\nu2\beta^- bM$ | g.s. | $\geqslant 1.1 \times 10^{19}$ | – |

# Search for 2ε decay of $^{180}W$

- The sum of the background spectra of the $ZnWO_4$ detectors accumulated in all four Runs was used to set limits on the 0ν2ε process in $^{180}W$.

- Possibility to have resonant process

Limits obtained by the least squares fit of the spectrum in the 70-270 keV energy interval




| Transition | Decay channel | Level of the daughter nucleus | Experimental limits on $T_{1/2}$, yr at 90% CL: Present work | The best previous results |
|---|---|---|---|---|
| $^{180}W \rightarrow {}^{180}Hf$ | $2\nu 2K$ | g.s. | $\geqslant 1.0 \times 10^{18}$ | $\geqslant 7.0 \times 10^{16}$ [30] |
| | $0\nu 2\varepsilon$ | g.s. | $\geqslant 1.3 \times 10^{18}$ | $\geqslant 9.0 \times 10^{16}$ [30] |

# 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

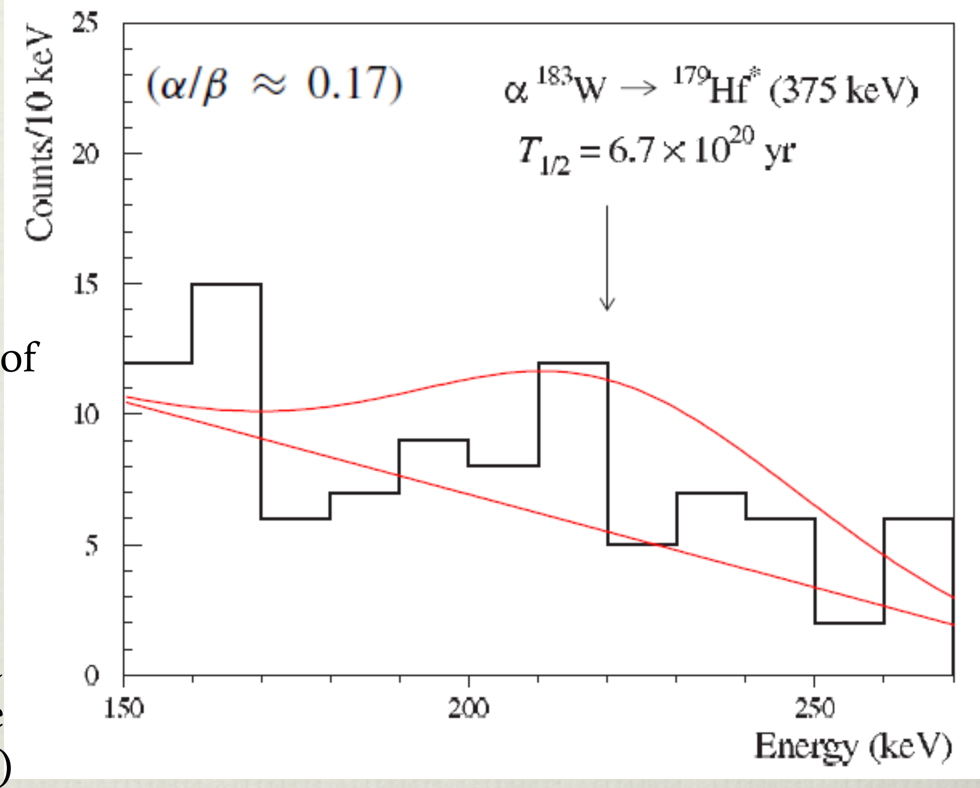
| Transition | Decay channel | Level of the daughter nucleus | Experimental limits on $T_{1/2}$, yr at 90% CL: Present work | Experimental limits on $T_{1/2}$, yr at 90% CL: The best previous results | Theoretical estimations of the half-lives $T_{1/2}$, yr ($\langle m_\nu \rangle = 1$ eV for $0\nu2\beta$ decay) |
|---|---|---|---|---|---|
| $^{64}Zn \to {}^{64}Ni$ | $2\nu2K$ | g.s. | $\geqslant 1.1 \times 10^{19}$ | $\geqslant 6.0 \times 10^{16}$ [54] | $(1.9–7.1) \times 10^{26}$ [56]<br>$(1.2 \pm 0.2) \times 10^{25}$ [57] |
| | $0\nu2\varepsilon$ | g.s. | $\geqslant 3.2 \times 10^{20}$ | $\geqslant 7.4 \times 10^{18}$ [55] | – |
| | $2\nu\varepsilon\beta^+$ | g.s. | $\geqslant 9.4 \times 10^{20}$ | $= (1.1 \pm 0.9) \times 10^{19}$ [58]<br>$\geqslant 1.3 \times 10^{20}$ [59] | $(0.9–2.2) \times 10^{35}$ [56]<br>$(4.7 \pm 0.9) \times 10^{31}$ [57] |
| | $0\nu\varepsilon\beta^+$ | g.s. | $\geqslant 8.5 \times 10^{20}$ | $\geqslant 1.3 \times 10^{20}$ [59] | – |
| $^{70}Zn \to {}^{70}Ge$ | $2\nu2\beta^-$ | g.s. | $\geqslant 3.8 \times 10^{18}$ | $\geqslant 1.3 \times 10^{16}$ [46] | $4.5 \times 10^{21} - 3.6 \times 10^{24}$ [60]<br>$2.5 \times 10^{21} - 6.4 \times 10^{23}$ [61]<br>$7.0 \times 10^{23}$ [56]<br>$\geqslant 3.1 \times 10^{22}$ [62] |
| | $0\nu2\beta^-$ | g.s. | $\geqslant 3.2 \times 10^{19}$ | $\geqslant 7.0 \times 10^{17}$ [46] | $9.8 \times 10^{25}$ [60] |
| | $0\nu2\beta^- M1$ | g.s. | $\geqslant 6.0 \times 10^{18}$ | – | – |
| | $0\nu2\beta^- M2$ | g.s. | $\geqslant 4.7 \times 10^{18}$ | – | – |
| | $0\nu2\beta^- bM$ | g.s. | $\geqslant 5.4 \times 10^{18}$ | – | – |
| $^{180}W \to {}^{180}Hf$ | $2\nu2K$ | g.s. | $\geqslant 1.0 \times 10^{18}$ | $\geqslant 7.0 \times 10^{16}$ [30] | – |
| | $0\nu2\varepsilon$ | g.s. | $\geqslant 1.3 \times 10^{18}$ | $\geqslant 9.0 \times 10^{16}$ [30] | $2.5 \times 10^{24} - 2.5 \times 10^{26}$ [23]<br>$3.3 \times 10^{27} - 5.0 \times 10^{30}$ [24]<br>$3.0 \times 10^{22} - 4.0 \times 10^{27}$ [25] |
| $^{186}W \to {}^{186}Os$ | $2\nu2\beta^-$ | g.s. | $\geqslant 2.3 \times 10^{19}$ | $\geqslant 3.7 \times 10^{18}$ [30] | $7.1 \times 10^{23} - 1.2 \times 10^{25}$ [60]<br>$\geqslant 6.1 \times 10^{24}$ [19] |
| | $2\nu2\beta^-$ | $2^+_1$(137 keV) | $\geqslant 1.8 \times 10^{20}$ | $\geqslant 1.0 \times 10^{19}$ [30] | – |
| | $0\nu2\beta^-$ | g.s. | $\geqslant 1.0 \times 10^{21}$ | $\geqslant 1.1 \times 10^{21}$ [30] | $6.4 \times 10^{24}$ [60] |
| | $0\nu2\beta^-$ | $2^+_1$(137 keV) | $\geqslant 9.0 \times 10^{20}$ | $\geqslant 1.1 \times 10^{21}$ [30] | – |
| | $0\nu2\beta^- M1$ | g.s. | $\geqslant 5.8 \times 10^{19}$ | $\geqslant 1.2 \times 10^{20}$ [30] | – |
| | $0\nu2\beta^- M2$ | g.s. | $\geqslant 1.1 \times 10^{19}$ | – | – |
| | $0\nu2\beta^- bM$ | g.s. | $\geqslant 1.1 \times 10^{19}$ | – | – |

# Search for rare α decay in W isotopes

**New measurement of the α decay of $^{180}W$ in $^{176}Hf$ (g.s. → g.s.):**

Total exposure = 0.529 kg x y,

$$T_{1/2} = 1.3^{+0.6}_{-0.5} \times 10^{18}\ \text{yr}$$



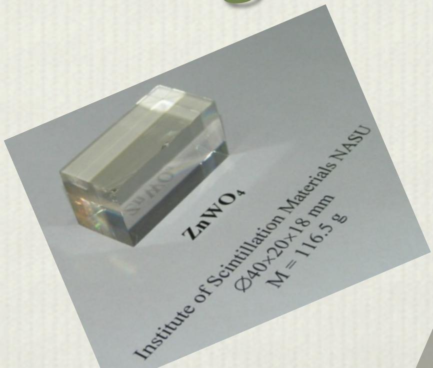

**New limit on α decay of $^{183}W$ in $^{179}Hf^*$ (375 keV)**

- the signature is delayed γ after the emission of the α in $T_{1/2}$ = 18.67 s
- Time Amplitude Analysis performed, 95 events found
- Fitting the events distribution by a simple model built by a first degree polynomial function (to describe the background) plus a Gaussian (the α peak searched for) gives the area of the effect searched for as (10.5±17.6) counts, lim $S$ = 39.4 events

$$T^{\alpha}_{1/2}(^{183}\text{W} \rightarrow\ ^{179}\text{Hf}^*, 375\ \text{keV}) \geqslant 6.7 \times 10^{20}\text{yr}.$$

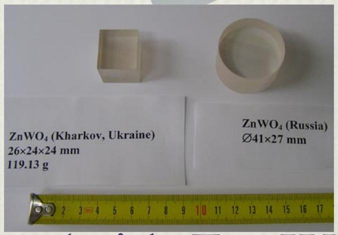
The obtained limit is far away from the theoretical predictions (~$10^{50}$ yr) but it is almost two orders higher than the previous one

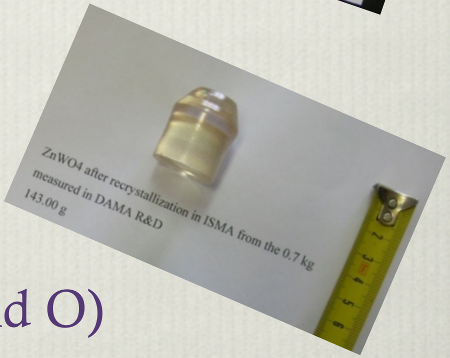
# $ZnWO_4$ to exploit directionality approach to investigate DM candidate inducing nuclear recoils





- ✓ 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



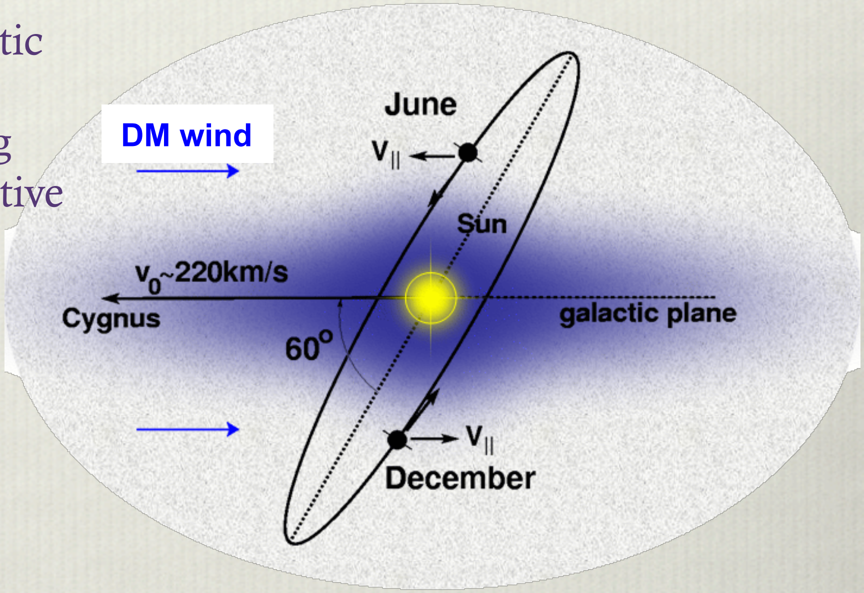



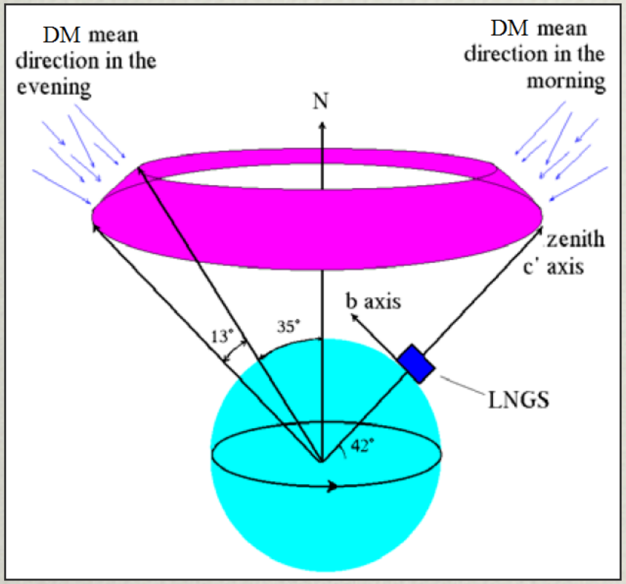

These **anisotropic features** make this detector suitable to exploit directionality approach to investigate those DM candidate particles inducing just nuclear recoils

# 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

# Expected signal in anisotropic scintillators

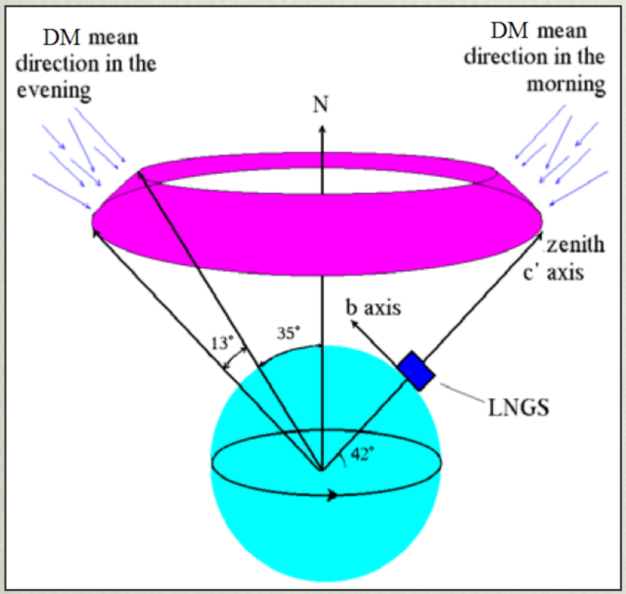
Eur. Phys. J. C 73 (2013) 2276

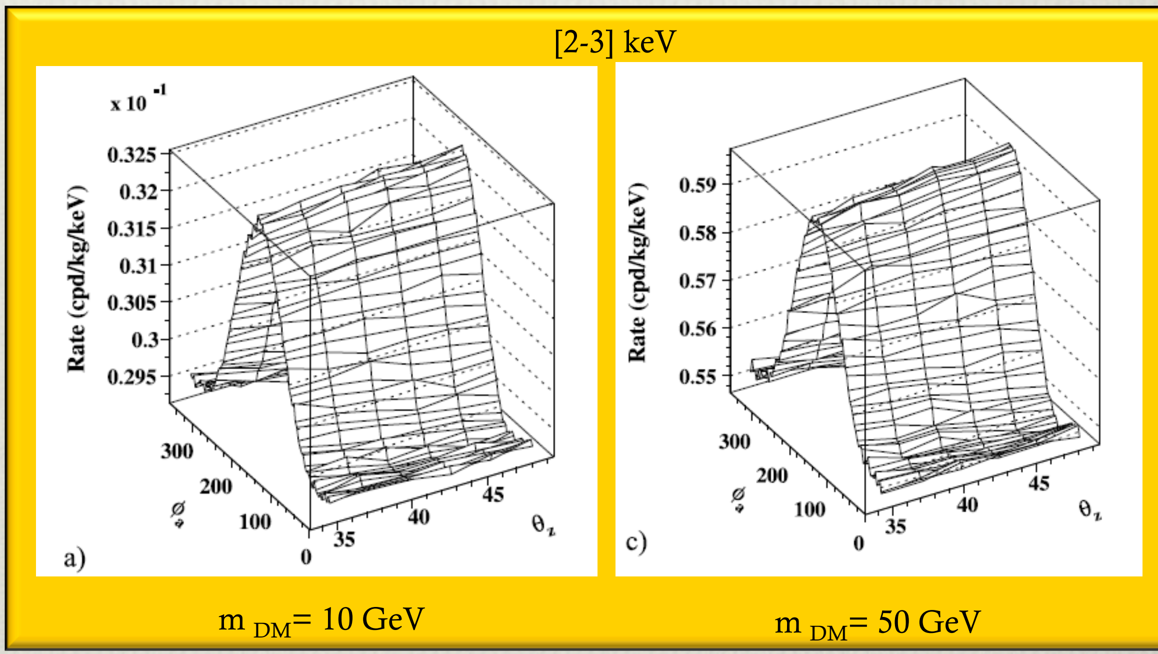
Detector velocity in the Galactic rest frame:
$v_d(t) = v_{rot} + v_{LSR} + v_E(t)$

$v_{rot}$: 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", $\phi_a$

$\sigma_p = 5\times10^{-5}$ pb




**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**

**Example (for a given model framework) of the expected counting rate as a function of the detector velocity direction**

# Example of reachable sensitivity in a given scenario

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

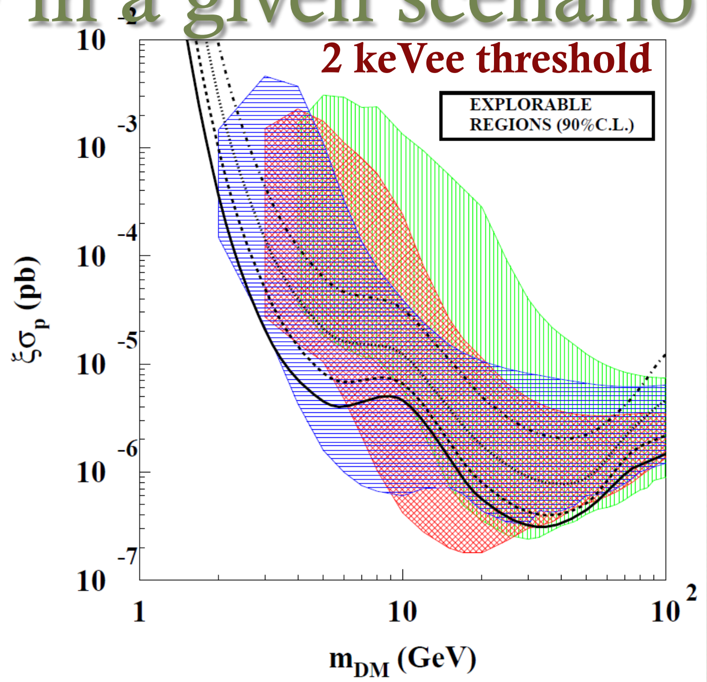
**Experiment with:**

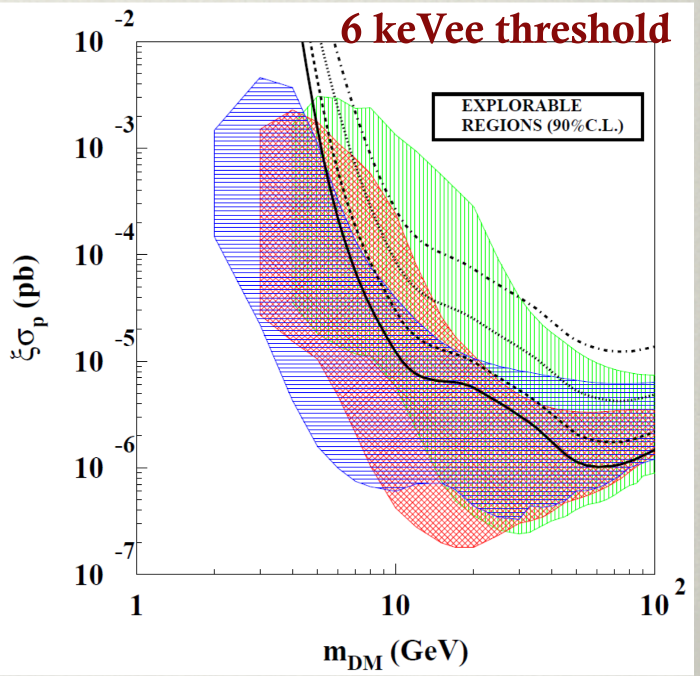
- **200 kg of $ZnWO_4$;**
- **5 years of data taking.**

4 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 — · — · — ·

- Specific simplified model framework considered to derive quantitative evaluations
- Plots are model dependent and, thus, always affected by several uncertainties




***In the given scenario the cross section sensitivity to is $10^{-5}$ – $10^{-7}$ pb, depending on the particle mass***

green, red and blue regions are the allowed regions obtained with a corollary analysis in PRD84(2011)055014 of the 8.9 σ C.L. DAMA model independent result in terms of scenarios for the DM candidates considered here

- Positive results ⇒ evidence for the presence of such DM candidate particles with a new approach & complementary information on the nature and interaction type of the DM with respect to the positive model independent evidence already pointed out by the DAMA experiments with high C.L.
- Negative results ⇒ experiment would favour other kinds of scenarios for the DM, which can account as well for the high C.L. DM model independent evidence already observed by the DAMA experiments

# Conclusions

- Low background experiments to search for rare processes were carried out over more than 10000 h @ LNGS by using low background 0.1–0.7 kg $ZnWO_4$ crystal scintillators:

✓ **improved** (up to 2 orders of magnitude) limits on the $\beta\beta$ decay of $^{64}Zn$, $^{70}Zn$, $^{180}W$ and $^{186}W$:

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

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

✓ A possible positive hint of the $(2\nu+0\nu)EC\beta^+$ decay in $^{64}Zn$ with $T_{1/2} = (1.1 \pm 0.9) \times 10^{19}$ yr [I. Bikit et al., Appl. Radiat. Isot. 46 (1995)455] **excluded**

✓ **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 α transition of the $^{183}W$ to the metastable level $1/2^-$ at 375 keV of $^{179}Hf$ set: $T_{1/2} = 6.7 \times 10^{20}$ yr

- Anisotropic ZnWO4 are very promising detectors to investigate the directionality for DM particle inducing just nuclear recoils:
  - ✓ It can give evidence for the presence of such DM candidate particles with a new approach & complementary information on the nature and interaction type of the DM with respect to the positive model independent evidence already pointed out by the DAMA experiments with high C.L.
  - ✓ In case of negative results it would favour other kinds of scenarios for the DM, which can account as well for the high C.L. DM model independent evidence already observed by the DAMA experiments
  - ✓ In any case it would represent a first realistic attempt to investigate the directionality approach through the use of anisotropic scintillators

Further developments, new detectors … towards suitable mass fragmented set-up