DAMA Collaboration & INR-Kyiv

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

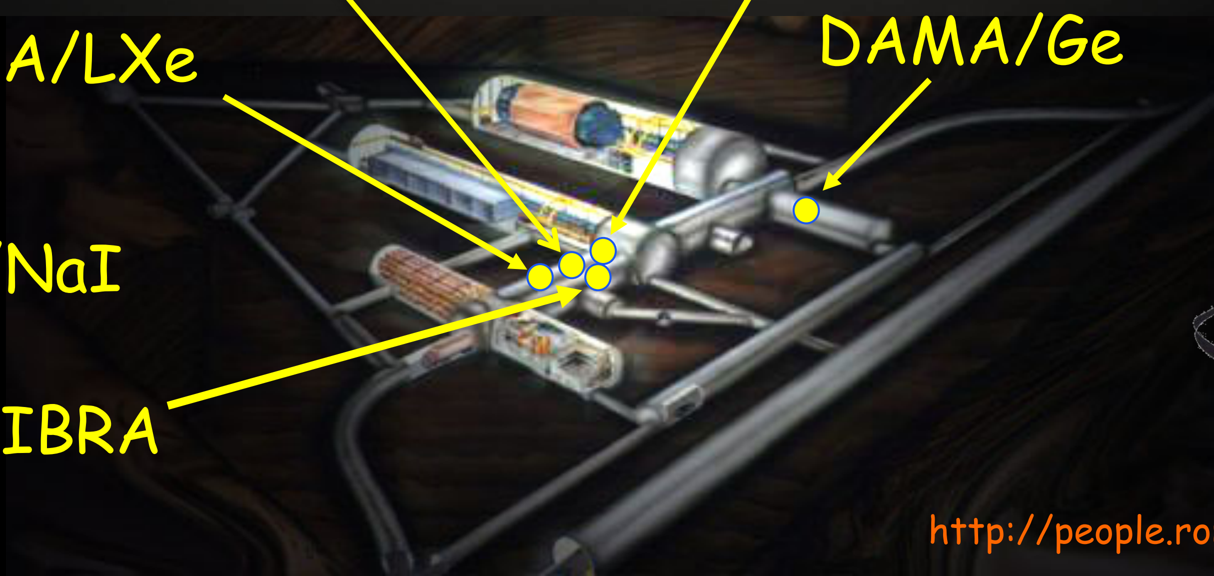
Search for rare processes with DAMA experimental set-ups

ICNFP17, August 2017

F. Cappella

INFN-ROMA

DAMA: an observatory for rare processes @LNGS



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

Collaboration

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

+ by-products and small scale experiments (MoU): INR-Kyiv

+ in some studies on ββ decays
(DST-MAE projects, inter-univ. Agreem.): IIT Ropar/Kharagpur, India

+ in some activites collaborators from

Ukraine	Kyiv National Taras Shevchenko University National Science Center Kharkiv Instit. of Physics and Technology; Institute for Scintillation Materials, Ukraine
Russia	Russian Chemistry-Technological University of D.I.Mendeleev Moscow Joint Institute for Nuclear Research, Dubna; Joint stock company NeoChem, Moscow Nikolaev Inst. of Inorganic Chemistry, Novosibirsk; Institute of Theoretical and Experimental Physics, Moscow
Australia	Department of Applied Physics, Curtin University, Perth
Finland	Dept. of Physics, University of Jyvaskyla, Jyvaskyla

Examples of rare processes studied by DAMA

- Very low cross section:
  - ✓ Dark Matter
  - ✓ Axions
  - ✓ Exotic particles (e.g. Q-balls, DAEMONS, SIMP)

- Very long lifetime:
  - ✓ Double beta decays
  - ✓ Rare α and β decays
  - ✓ Cluster decays
  - ✓ Spontaneous transition of nuclei to a superdense state;
  - ✓ Long-lived superheavy elements
  - ✓ Emission of correlated e^+e^- pairs in α decay
  - ✓ Electron stability
  - ✓ Processes violating the Pauli exclusion principle
  - ✓ Charge non-conserving (CNC) processes
  - ✓ Nucleon, di-nucleon and tri-nucleon decay into invisible channels

Examples of rare processes studied by DAMA

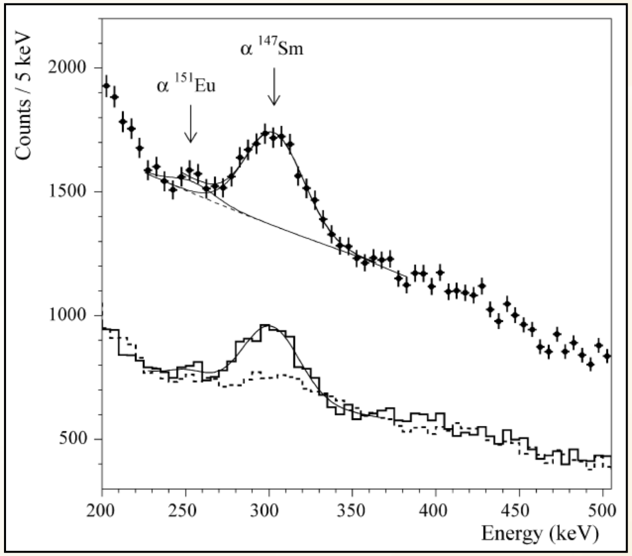
- ❑ Very low cross section:
  - ✓ Dark Matter
  - ✓ Axions
  - ✓ Exotic particles (e.g. Q-balls, DAEMONS, SIMP)

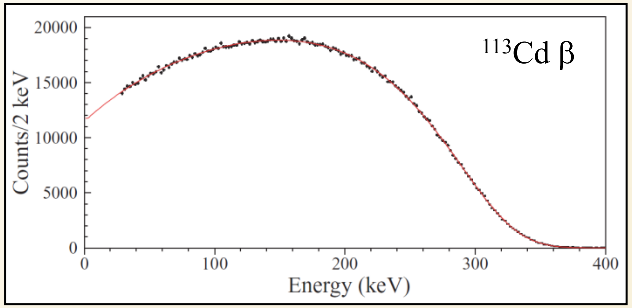
See the V. Caracciolo talk «DAMA/LIBRA Results and Perspectives» on 22/8/2017

- ❑ Very long lifetime:
  - ✓ Double beta decays
  - ✓ Rare α and β decays
  - ✓ Cluster decays
  - ✓ Spontaneous transition of nuclei to a superdense state;
  - ✓ Long-lived superheavy elements
  - ✓ Emission of correlated e^+e^- pairs in α decay
  - ✓ Electron stability
  - ✓ Processes violating the Pauli exclusion principle
  - ✓ Charge non-conserving (CNC) processes
  - ✓ Nucleon, di-nucleon and tri-nucleon decay into invisible channels

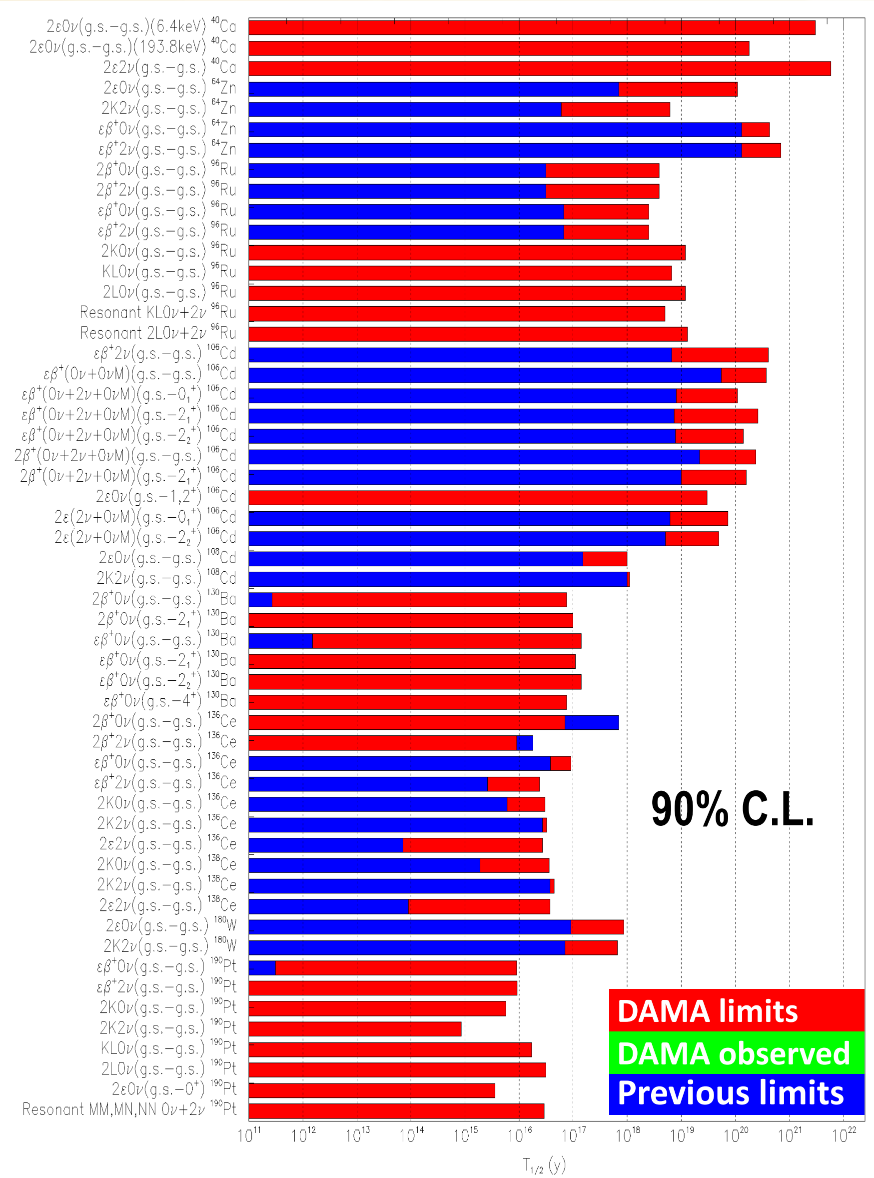
Main recent DAMA results in the search for rare processes

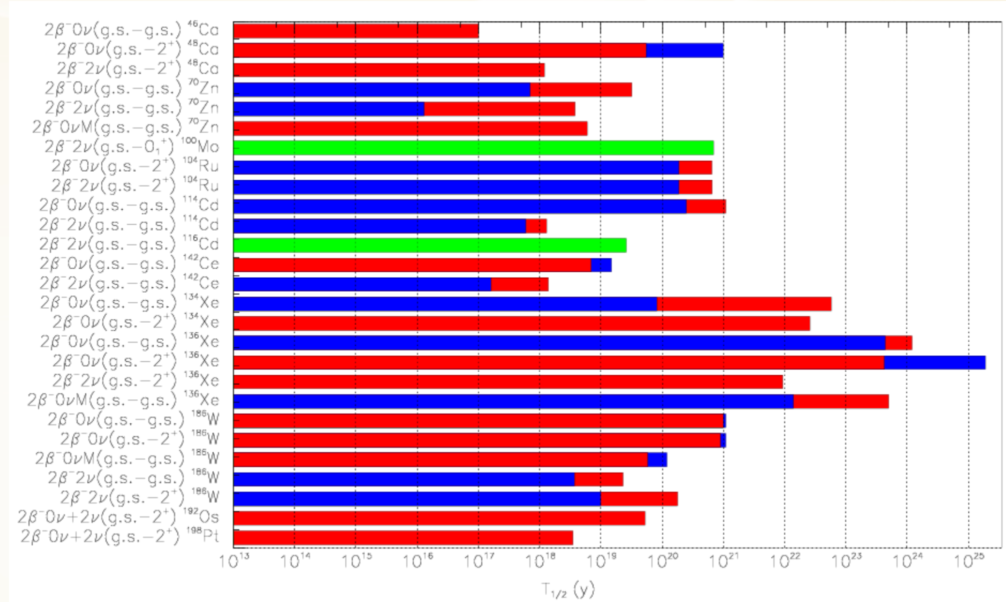
- First or improved results in the search for 2β decays of ~30 candidate isotopes: ^{40}Ca, ^{46}Ca, ^{48}Ca, ^{64}Zn, ^{70}Zn, ^{100}Mo, ^{96}Ru, ^{104}Ru, ^{106}Cd, ^{108}Cd, ^{114}Cd, ^{116}Cd, ^{112}Sn, ^{124}Sn, ^{134}Xe, ^{136}Xe, ^{130}Ba, ^{136}Ce, ^{138}Ce, ^{142}Ce, ^{156}Dy, ^{158}Dy, ^{180}W, ^{186}W, ^{184}Os, ^{192}Os, ^{190}Pt and ^{198}Pt
- The best experimental sensitivities in the field for 2β decays with positron emission
- First observation of α decays of ^{151}Eu ($T_{1/2}=5\times10^{18}$yr) with a CaF_2(Eu) scintillator and of ^{190}Pt to the first excited level (E_{exc}=137.2 keV) of ^{186}Os ($T_{1/2}=3\times10^{14}$yr)
- Investigations of rare β decays of ^{113}Cd ($T_{1/2}=8\times10^{15}$yr) with $CdWO_4$ scintillator and of ^{48}Ca with a CaF_2(Eu) detector
- Observation of correlated e^+e^- pairs emission in α decay of ^{241}Am $\left(\frac{A_{e^+e^-}}{A_\alpha} \simeq 5\times10^{-9}\right)$
- Search for long-lived super-heavy ekatungsten with radiopure $ZnWO_4$ crystal scintillator
- Search for CNC processes in ^{127}I, ^{136}Xe, ^{100}Mo and ^{139}La
- Search for ^{7}Li solar axions resonant absorption in LiF crystal
- Search for spontaneous transition of ^{23}Na and ^{127}I nuclei to superdense state;
- Search for cluster decays of ^{127}I, ^{138}La and ^{139}La
- Search for PEP violating processes in sodium and in iodine
- Search for N, NN, NNN decay into invisible channels in ^{129}Xe and ^{136}Xe





Summary of searches for ββ decay modes in various isotopes (partial list)





ARMONIA: New observation of $2\nu2\beta^-$ $^{100}Mo \rightarrow ^{100}Ru$ ($g.s. \rightarrow 0_1^+$) decay NPA846 (2010)143

AURORA: New observation of $2\nu2\beta^-$ ^{116}Cd decay J.Phys.:Conf.Ser.718(2016)062009

- Many competitive limits obtained on lifetime of $2\beta^+$, $\varepsilon\beta^+$ and 2ε processes (^{40}Ca, ^{64}Zn, ^{96}Ru, ^{106}Cd, ^{108}Cd, ^{130}Ba, ^{136}Ce, ^{138}Ce, ^{180}W, ^{190}Pt, ^{184}Os, ^{156}Dy, ^{158}Dy, …).
- First searches for resonant $0\nu2\varepsilon$ decays in some isotopes

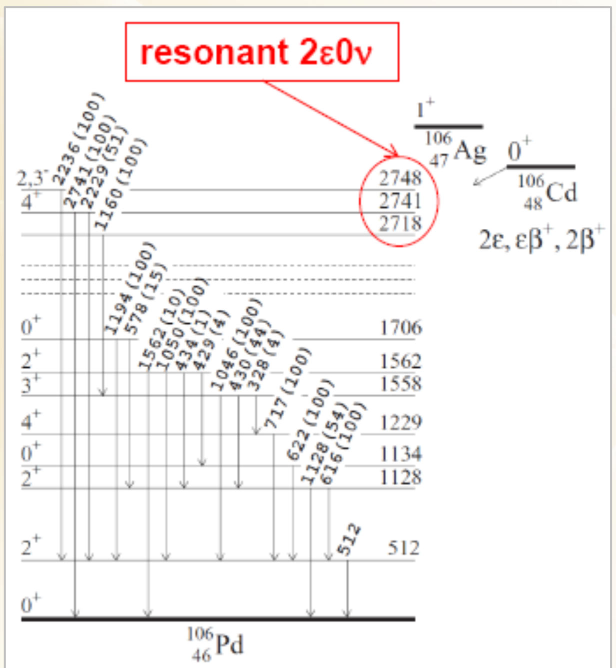
Latest results on rare processes:

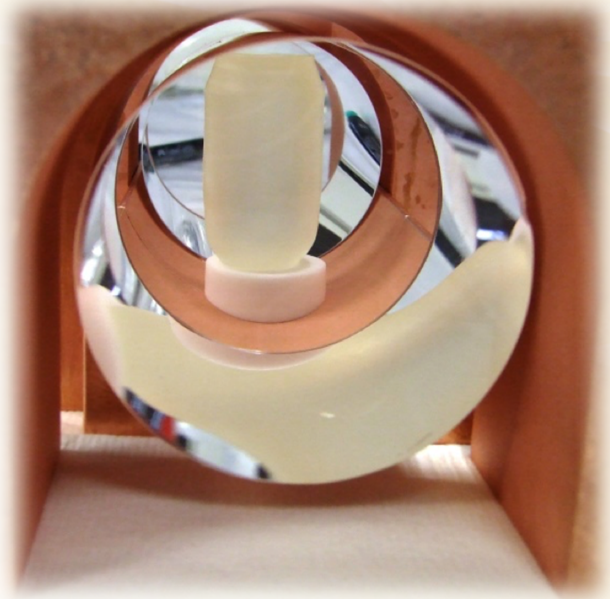
- ✓ *Search for $\beta\beta$ decay in ^{106}Cd with enriched $^{106}CdWO_4$ detector in the DAMA/CRYS setup*
- ✓ *Investigation of $\beta\beta$ decay of ^{116}Cd with enriched $^{116}CdWO_4$ detectors in DAMA/R&D setup*
- ✓ *Investigation of directionality with $ZnWO_4$ anisotropic detectors: feasibility study*

Search for ββ decay in ^{106}Cd in the DAMA/CRYS setup

^{106}Cd, a promising isotope:

1) One of the six isotopes candidate for $2\beta^+$ decay
2) Good natural abundance δ=(1.25±0.06)%; possible enrichment up to 100%;
3) $Q_{2\beta}$= (2775.39±0.10) keV $\Rightarrow$ $2\beta^+$, $\varepsilon\beta^+$, 2ε modes possible
4) Possible resonant $2\varepsilon0\nu$ captures to excited level of ^{106}Pd
5) Theoretical $T_{1/2}$ favorable for some modes (10^{20} – 10^{22} yr)





and a competitive detector $CdWO_4$

- ✓ Good scintillation properties
- ✓ Active source approach (high detection efficiency)
- ✓ Low levels of internal contamination in (U, Th K)
- ✓ α/β discrimination capability

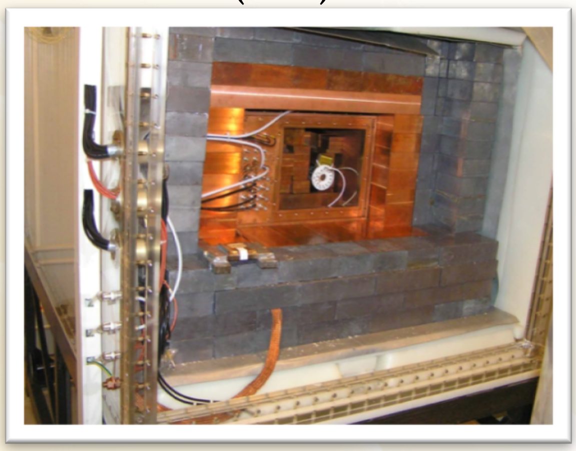
The used $^{106}CdWO_4$ crystal scintillator

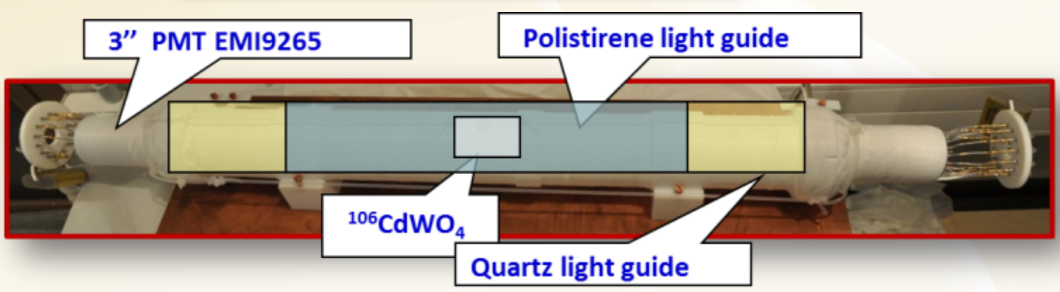
NIMA615(2010)301

- Samples of cadmium were purified by vacuum distillation (Institute of Physics and Technology, Kharkiv) and the Cadmium tungstate compounds were synthesized from solutions
- Crystal boule was grown by the low-thermal-gradient Czochralski technique (NIIC Novosibirsk) (initial powder 265 g)
- Crystal scintillator (**216 g** mass), **66.4%** enrichment in ^{106}Cd (**2.66×10^{23}** nuclei of ^{106}Cd) measured by thermal ionisation mass-spectrometry ⇒ 2^{nd} enriched $CdWO_4$ crystal ever produced

1^{st} exp: single crystal in DAMA/R&D

PRC85(2012)044610

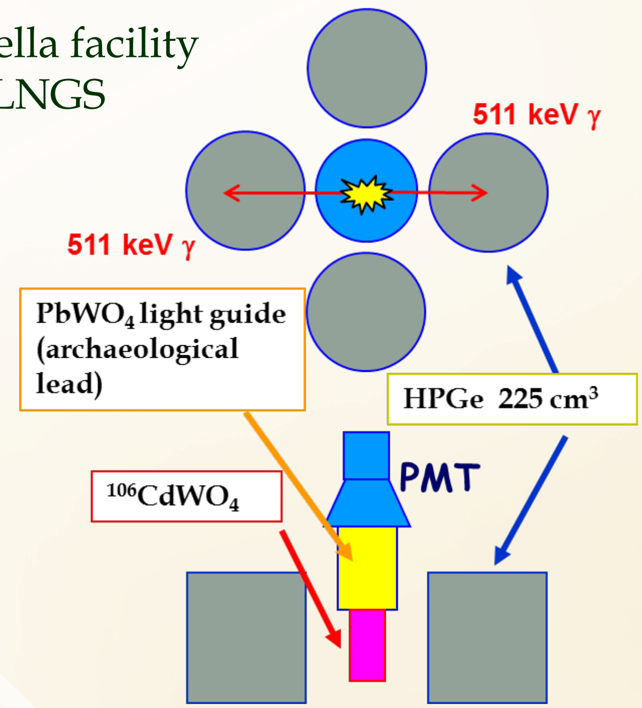




2^{nd} exp: coincidence with 4 HP-Ge

PRC93(2016)045502

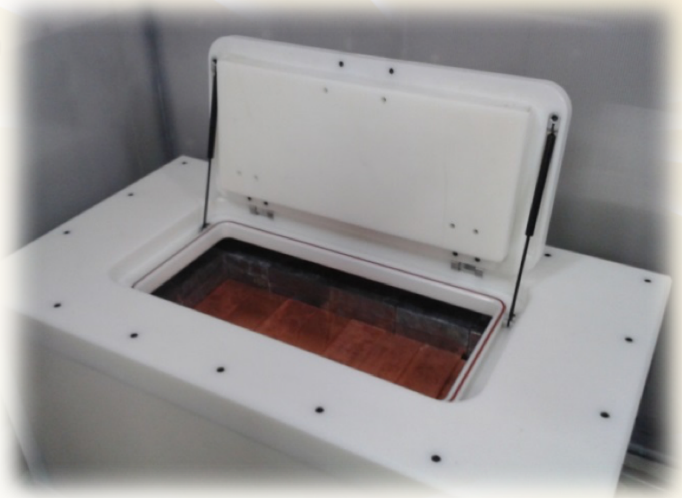
Stella facility
@LNGS

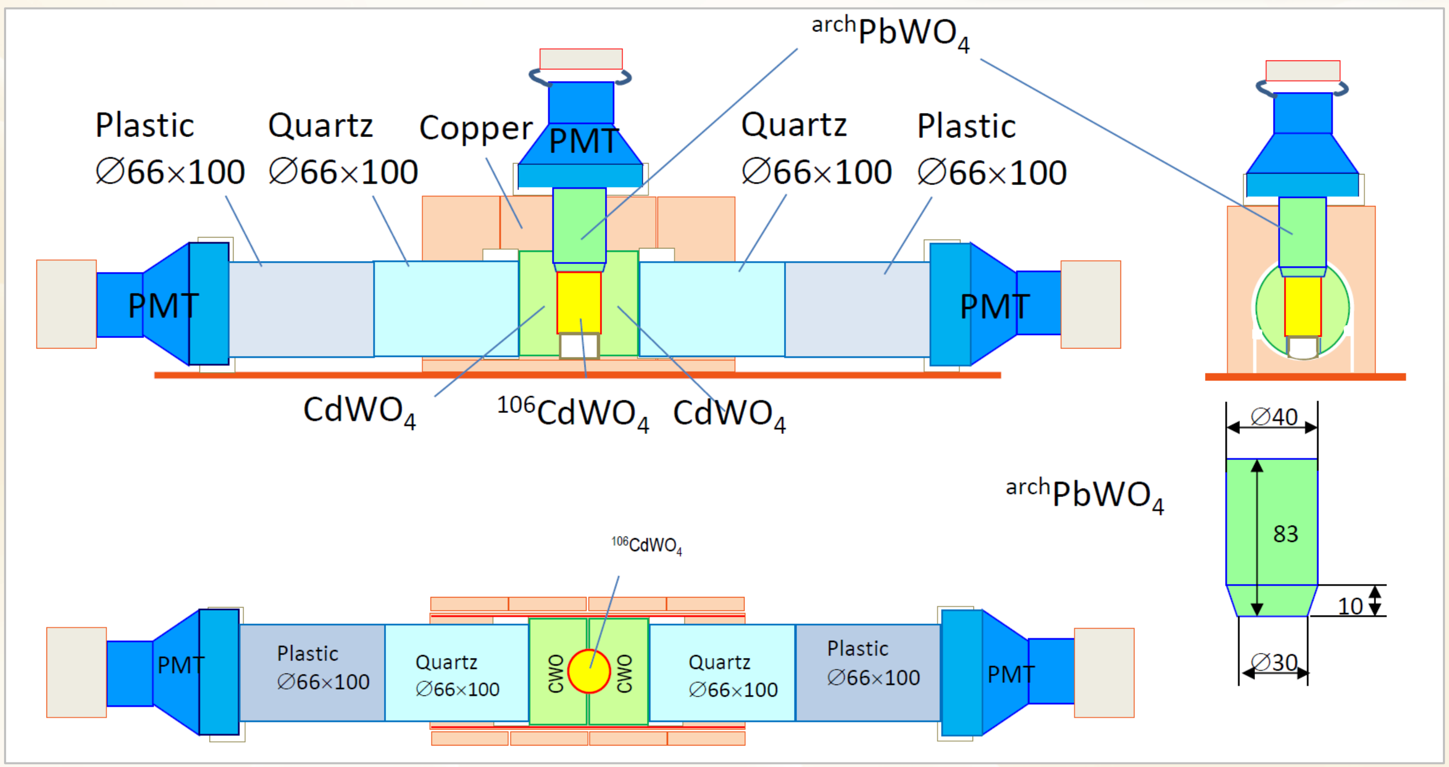


New $^{106}CdWO_4$ experiment in DAMA/CRYS set-up

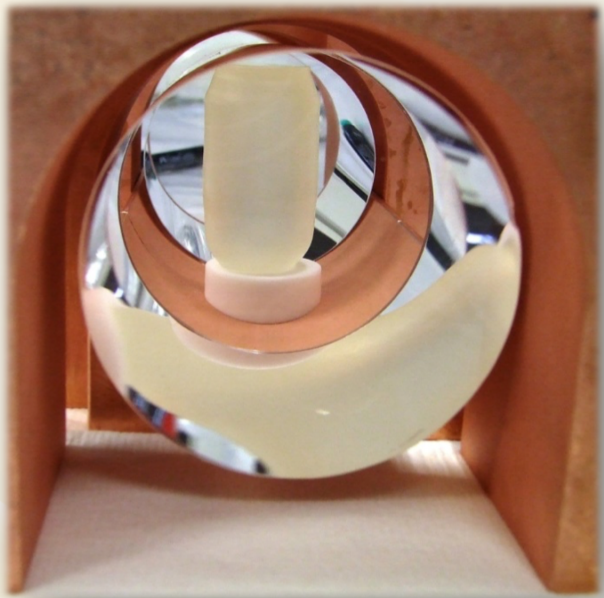
1) $^{106}CdWO_4$ in (anti)coincidence with two large $CdWO_4$ scintillators mounted in DAMA/CRYS set-up @ LNGS
2) High efficiency
3) Experiment in data taking since May 2016

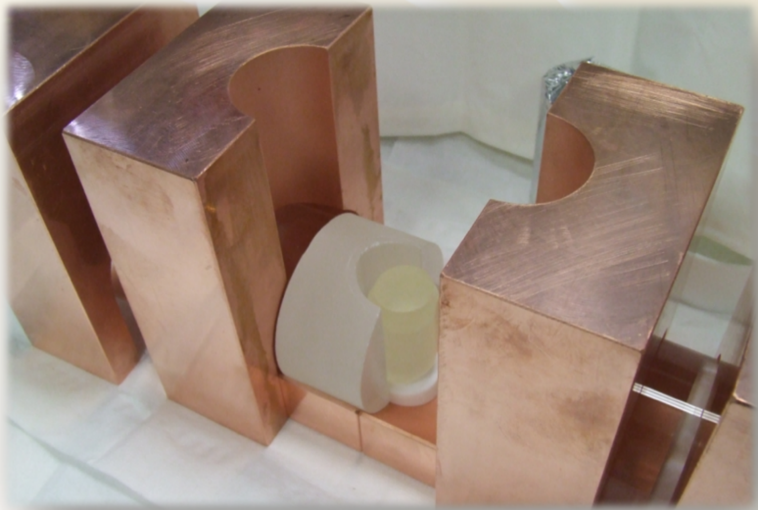
DAMA/CRYS set-up

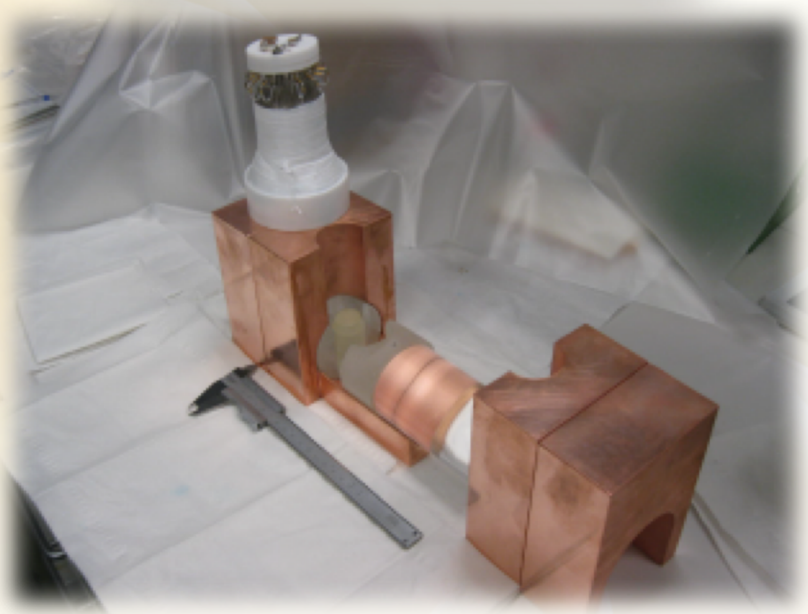




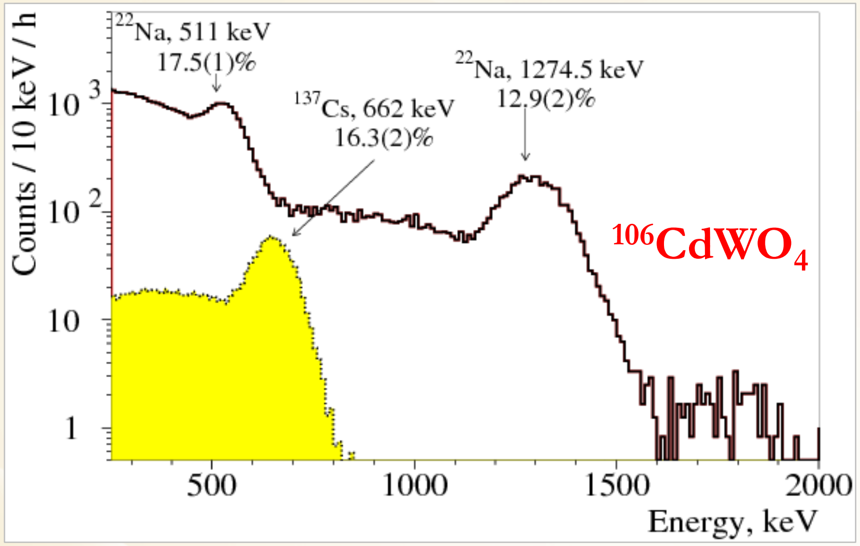
New $^{106}CdWO_4$ experiment in DAMA/CRYS set-up

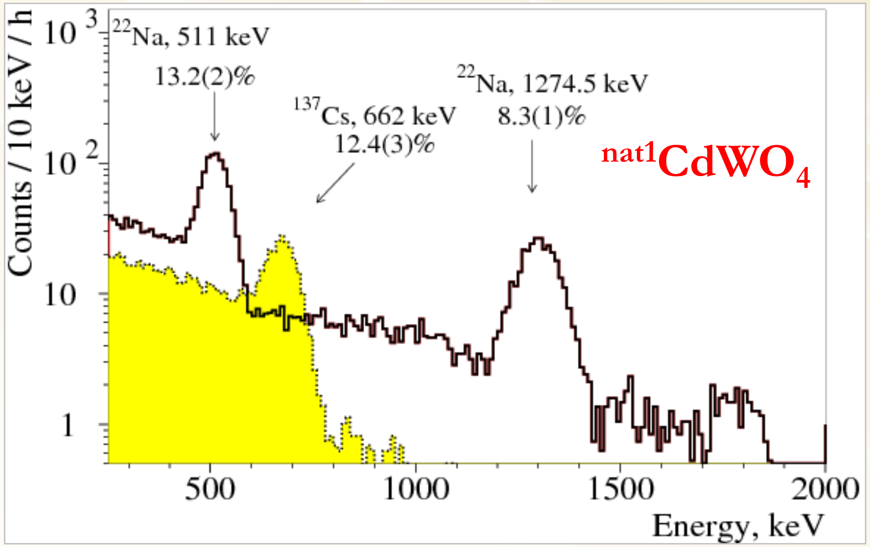


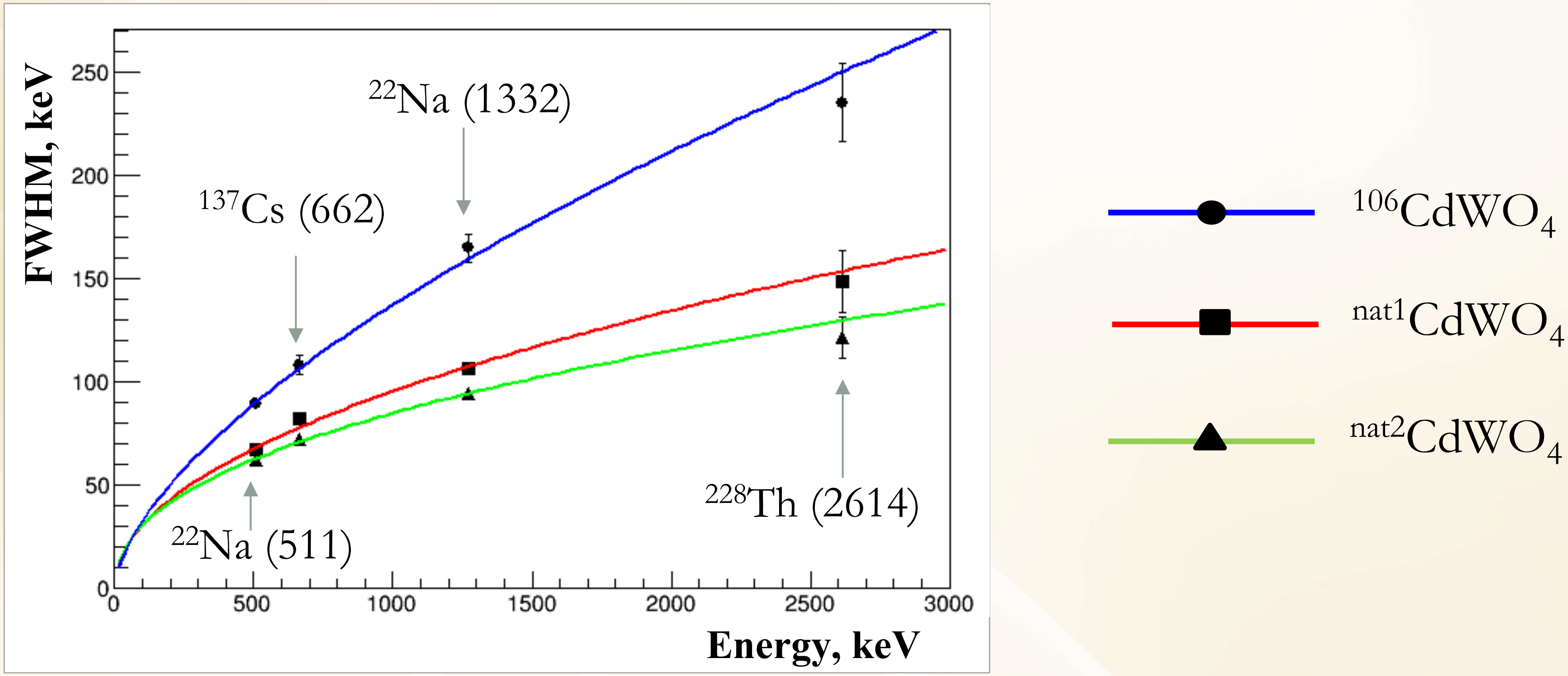




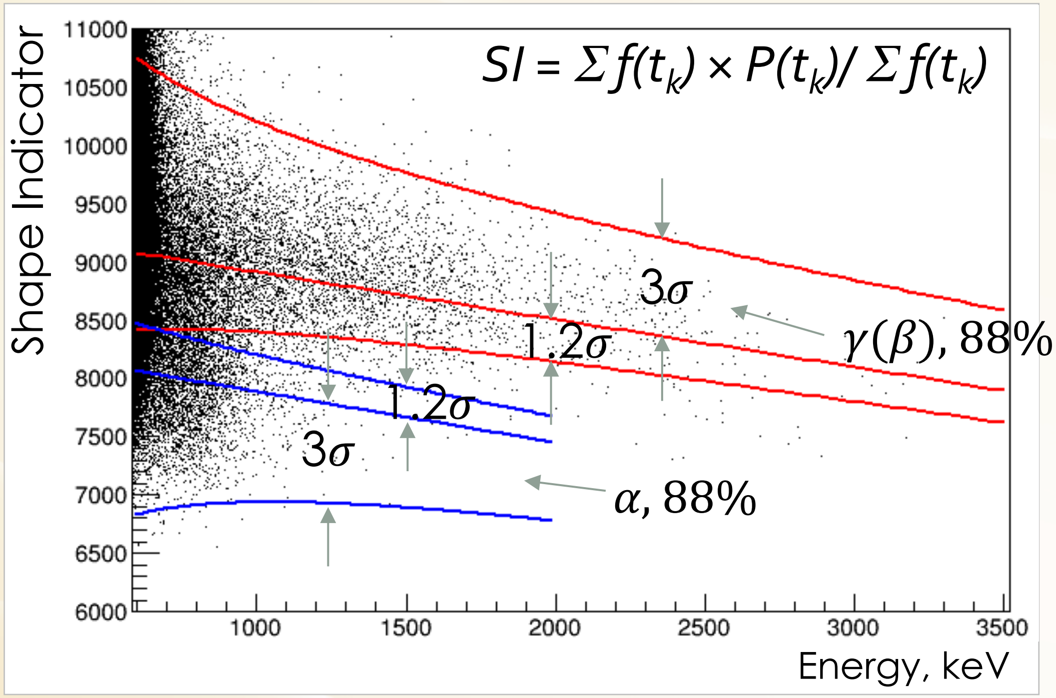
Energy resolutions for $^{106}CdWO_4$ and $CdWO_4$

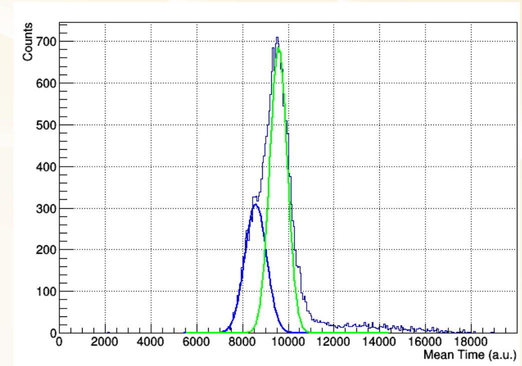






Pulse shape discrimination (PSD)

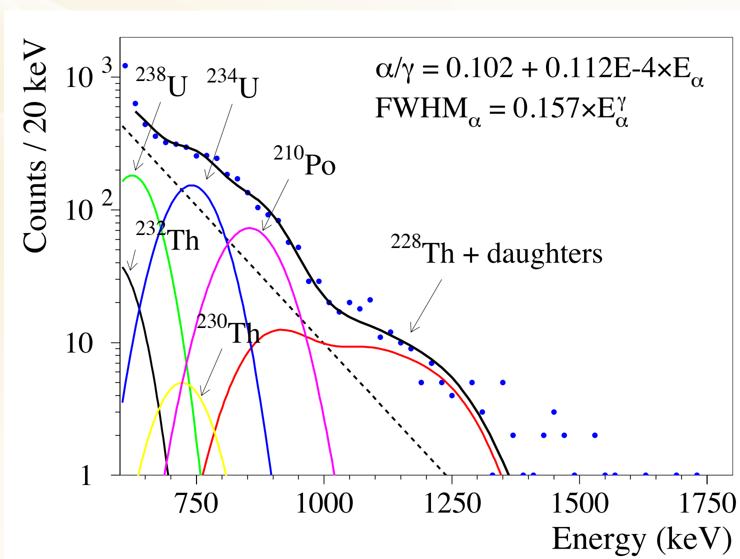




$$P(t) = [f_{\alpha}(t) - f_{\gamma}(t)]/[f_{\alpha}(t) + f_{\gamma}(t)]$$

$f(t_k)$	amplitude at t_k
$P(t_k)$	weight function
$f_{\alpha,\gamma}(t_k)$	reference pulse

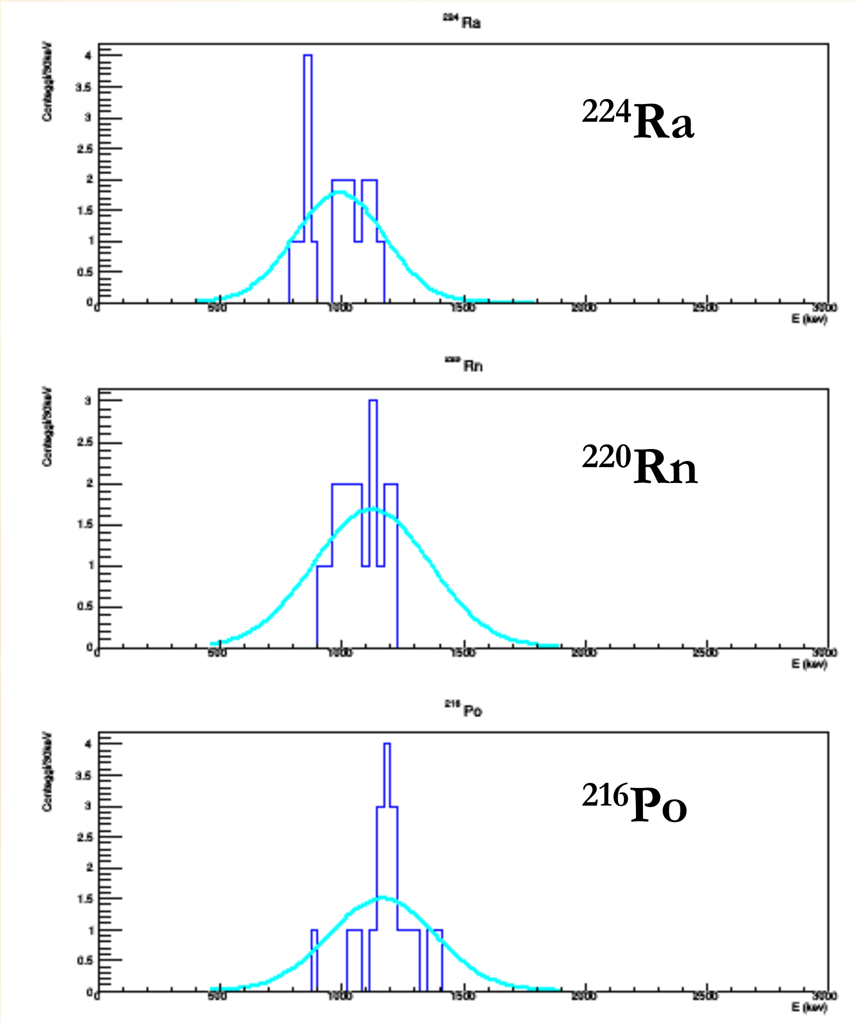
⇒ α spectrum (3300 h)



Chain	Nuclide	a (mBq/kg)
^{232}Th	^{232}Th	<0.07
	^{228}Th+subch.	<0.02
^{238}U	^{238}U	<0.6
	^{234}Th	<0.6
	^{230}Th	<0.4
	^{210}Po	<0.2

Time-Amplitude Analysis

T = 6935 h

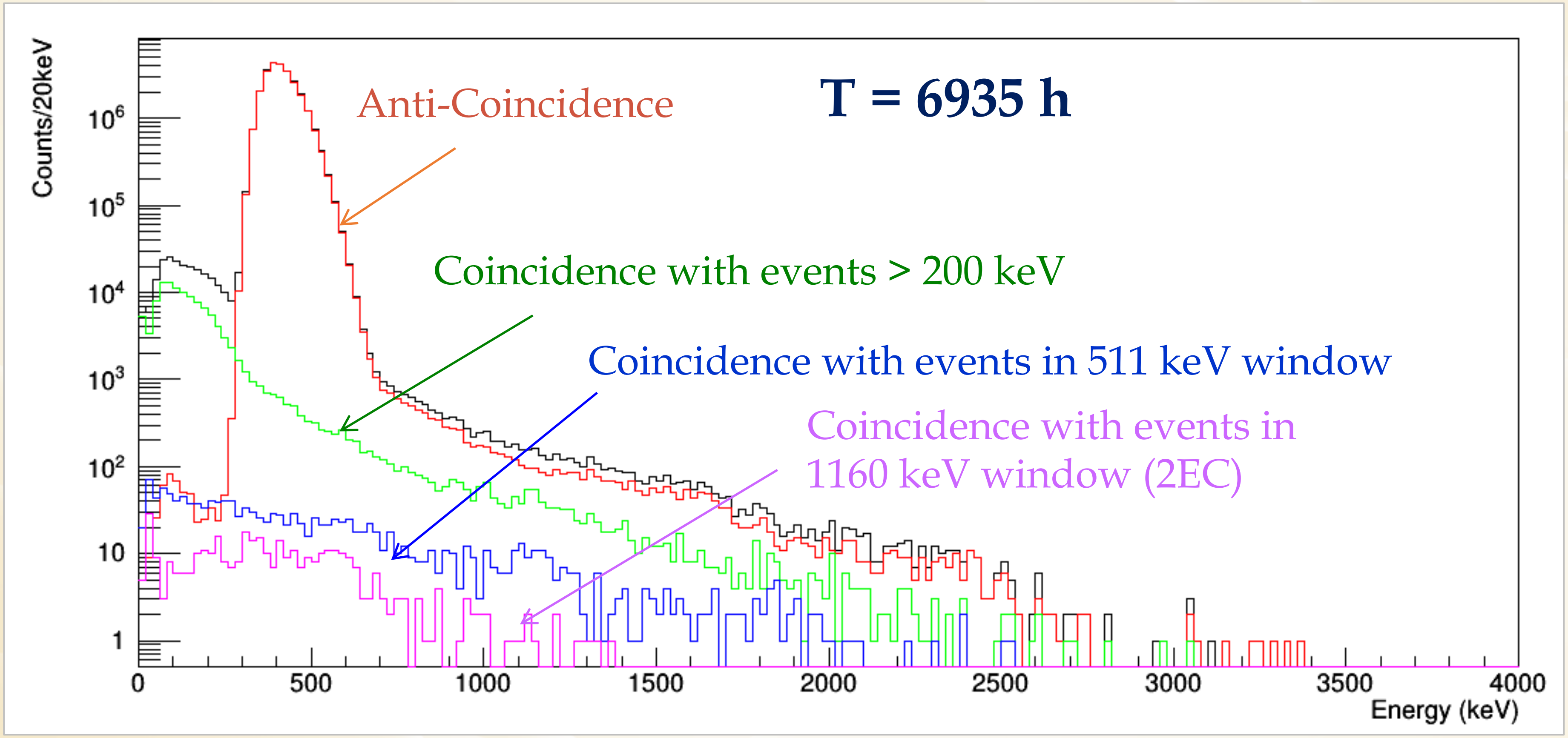


The arrival time, the energy and the pulse shape of each event were used to select the fast decay chain in the ^{228}Th sub-chain of the ^{232}Th family in $^{106}CdWO_4$ crystal:

^{224}Ra (Q = 5.789 MeV, $T_{1/2}$ = 3.66 d)
↓
^{220}Rn (Q = 6.405 MeV, $T_{1/2}$ = 55.6 s)
↓
^{216}Po (Q = 6.906 MeV, $T_{1/2}$ = 0.145 s)
↓
^{212}Pb

⇒ Activity of ^{228}Th: **5(1) μBq/kg**
⇒ Estimation of α/γ light ratio
⇒ Estimation of α energy resolution

Energy spectra of ^{106}Cd



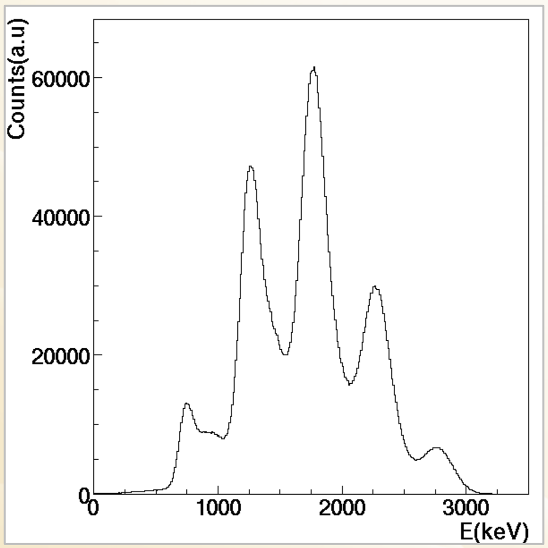
The energy spectra accumulated over **6935 h** by the ^{106}CdWO$_4$ detector:

- ➢ in anticoincidence with the ^{nat}CdWO$_4$ detectors
- ➢ in coincidence with event(s) in at least one of the ^{nat}CdWO$_4$ detectors with energy:
  - E > 200 keV
  - E in energy window around 511 keV
  - E in energy window around 1160 keV

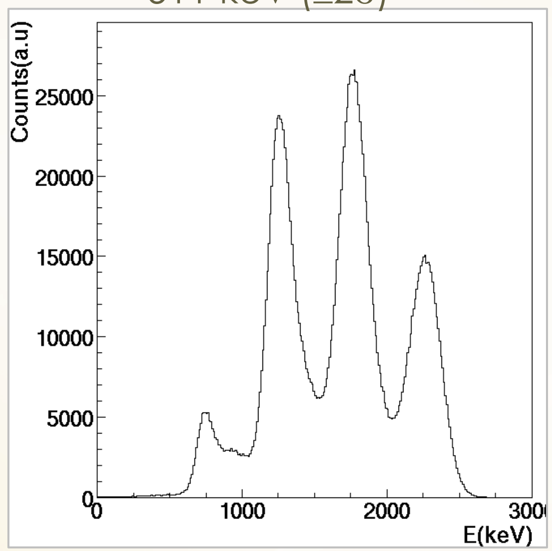
Estimation of sensitivity

Expected signal for **^{106}Cd 0ν2β($0^+ \rightarrow 0^+$)**:

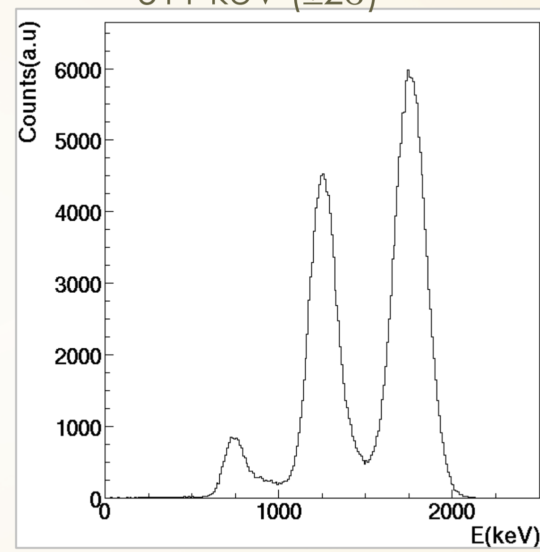
Spectrum of $^{106}CdWO_4$ detector



Spectrum of $^{106}CdWO_4$ detector when one of the two $CdWO_4$ detectors detects γ of 511 keV (±2σ)



Spectrum of $^{106}CdWO_4$ detector when both the $CdWO_4$ detectors detect γ of 511 keV (±2σ)



Sensitivity after 1yr in the hypothesis of about 30 background counts in [0.-3.] MeV:

0ν εβ$^+$ (g.s.): $T_{1/2} \approx 5 \times 10^{21}$ yr

2ν 2β$^+$ (g.s.): $T_{1/2} \approx 2 \times 10^{21}$ yr

In the region of theoretical predictions: $T_{1/2} \sim 10^{20} – 10^{22}$ yr

Note that, up to now, 2ν mode of the 2β$^+$ processes has not been detected unambiguously: there are only indications for ^{130}Ba and ^{78}Kr

Latest results on rare processes:

- ✓ *Search for $\beta\beta$ decay in ^{106}Cd with enriched $^{106}CdWO_4$ detector in the DAMA/CRYS setup*

- ✓ *Investigation of $\beta\beta$ decay of ^{116}Cd with enriched $^{116}CdWO_4$ detectors in DAMA/R&D setup*

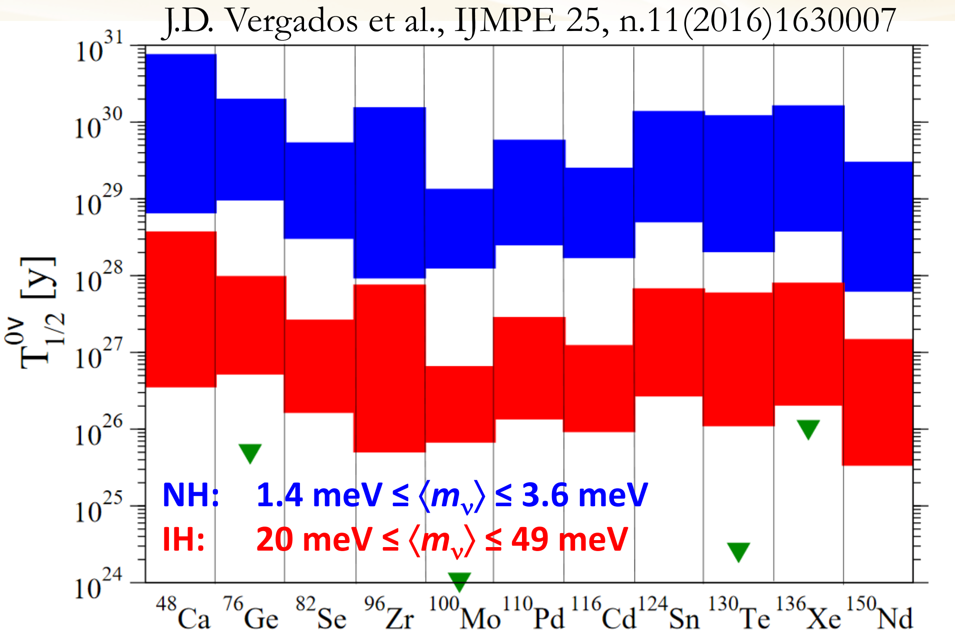
- ✓ *Investigation of directionality with $ZnWO_4$ anisotropic detectors: feasibility study*

Investigation of 2β decay of ^{116}Cd with enriched $^{116}CdWO_4$ crystal scintillators

^{116}Cd

One of the best isotope for 0ν2β decay search:

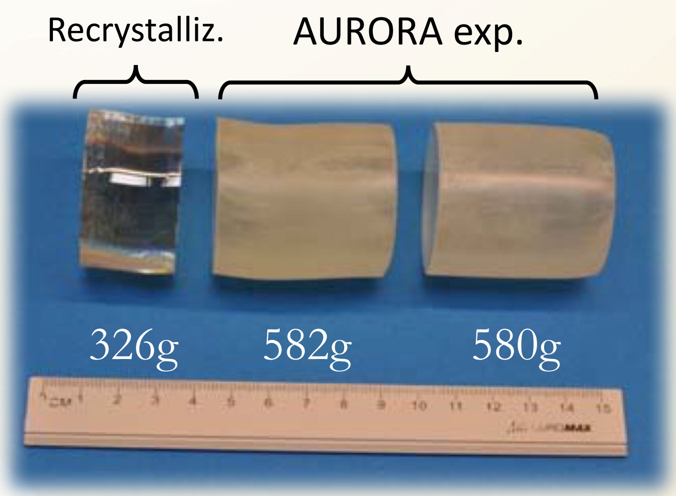
- $Q_{\beta\beta}$ = 2813.44(13) keV
- δ = 7.49(18) %
- possible high isotopic enrichment
- promising theoretical calculation



$^{116}CdWO_4$ crystal scintillators

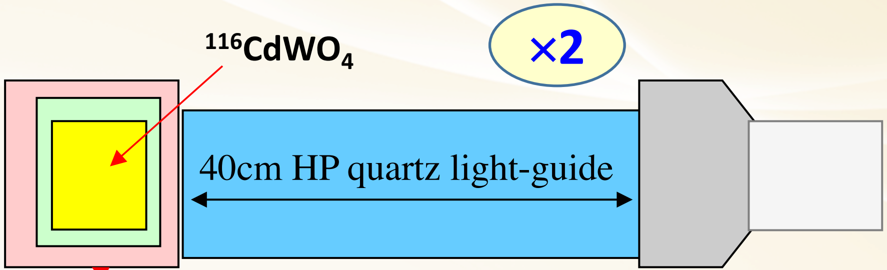
Grown by the low-thermal-gradient Czochralski technique after deep purification of ^{116}Cd and W;
+ annealing to improve the optical transmission curve

- ✓ Good optical and scintillation properties
- ✓ $^{116}CdWO_4$ crystals **enriched at 82%**
- ✓ Active source approach (high detection efficiency)
- ✓ Low levels of internal contamination in (U, Th, K)
- ✓ α/β discrimination capability

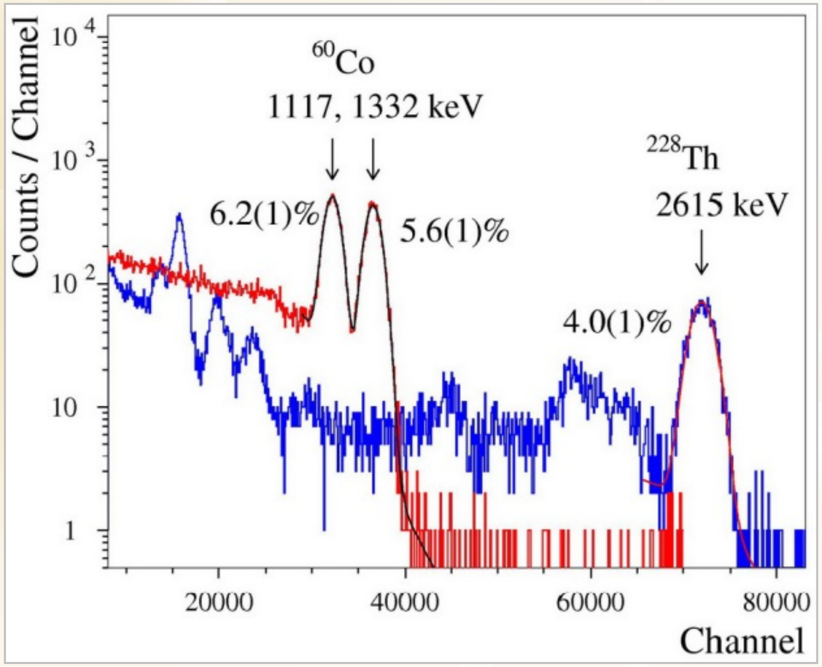


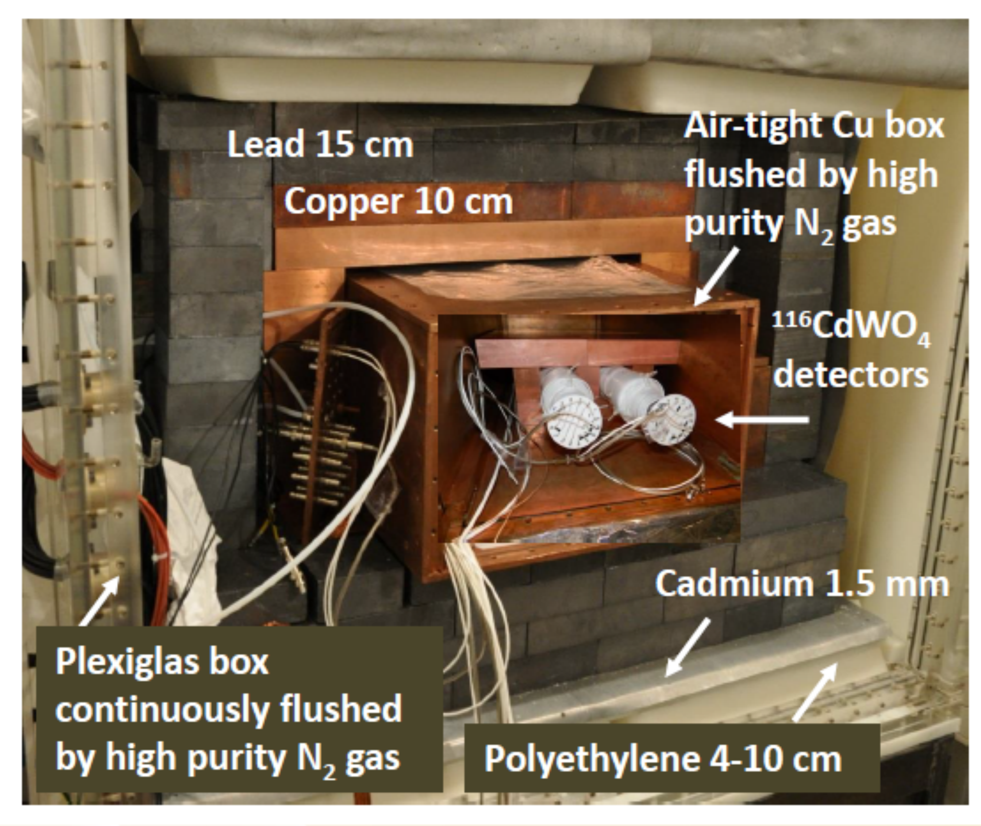
The AURORA experiment in the DAMA/R&D set-up

Two enriched ^{116}**CdWO$_4$** crystal scintillators (total mass: 1.162 kg, ^{116}Cd @ 82%)



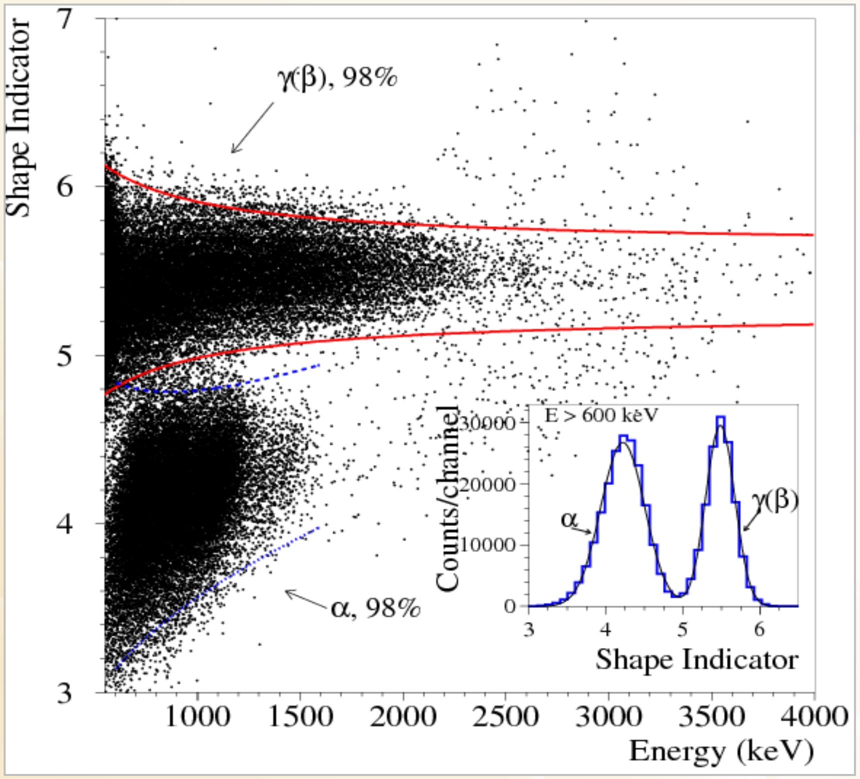
- ✓ Started in 2011
- ✓ Upgrade - March 2014
- ✓ Total live time since 2014: 25037 h
- ✓ Background level at 2.7-2.9 MeV: **0.1 counts/keV/kg/yr**





Background identification 1: Pulse Shape Discrimination

Event-by-event DAQ based on a 1 GS/s 8 bit transient digitizer (operated at 50 MS/s) records the pulse shape over a time window of 100 μs from the $^{116}CdWO_4$ detectors

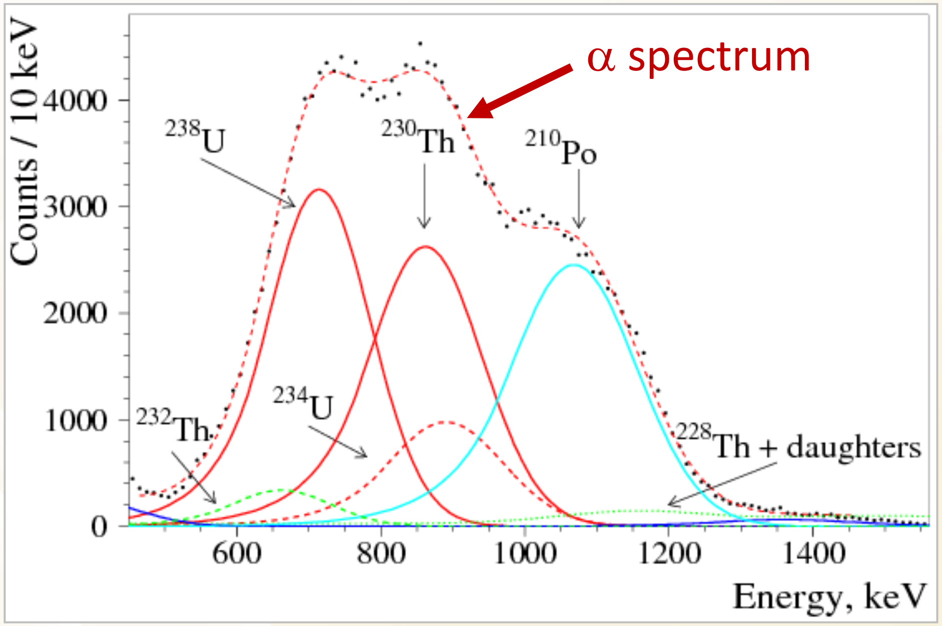


$$SI = \Sigma f(t_k) \times P(t_k) / \Sigma f(t_k)$$

$$P(t) = [f_\alpha(t) - f_\gamma(t)]/[f_\alpha(t) + f_\gamma(t)]$$

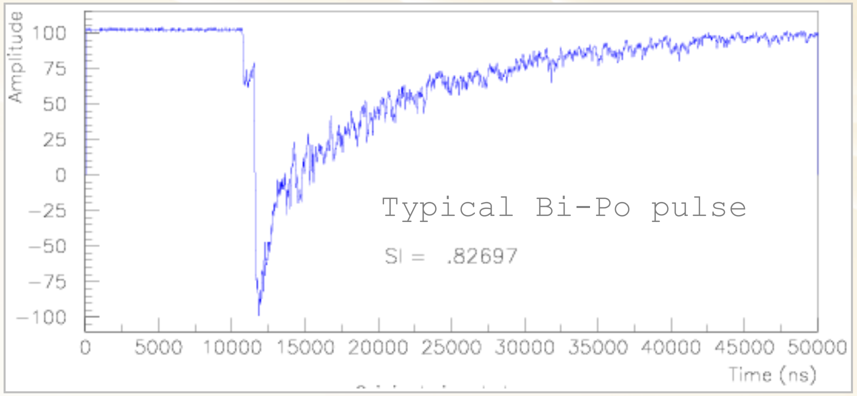
$f(t_k)$ → amplitude at t_k
$P(t_k)$ → weight function
$f_{\alpha,\gamma}(t_k)$ → reference pulse

T=25037 h
M=1.162 kg



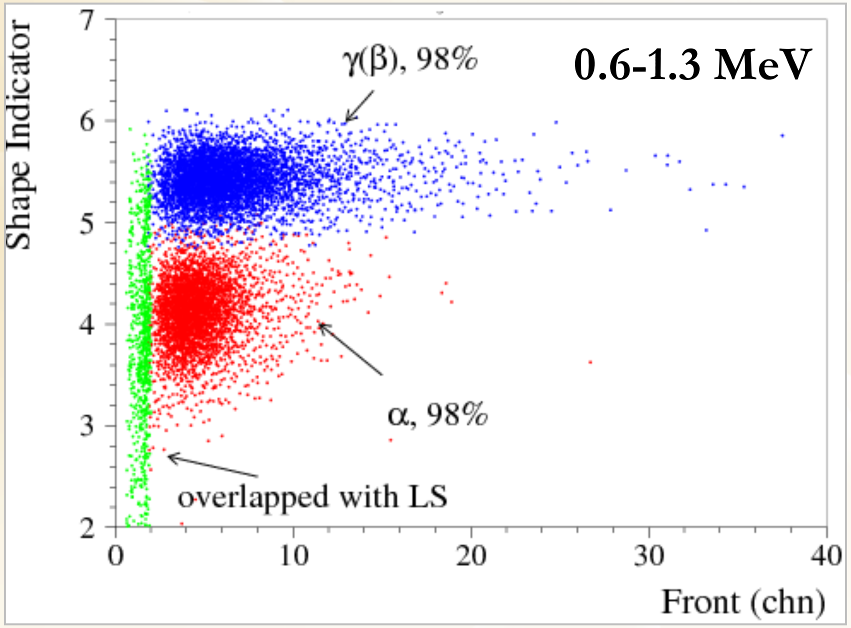
Background identification 2: Bi-Po events

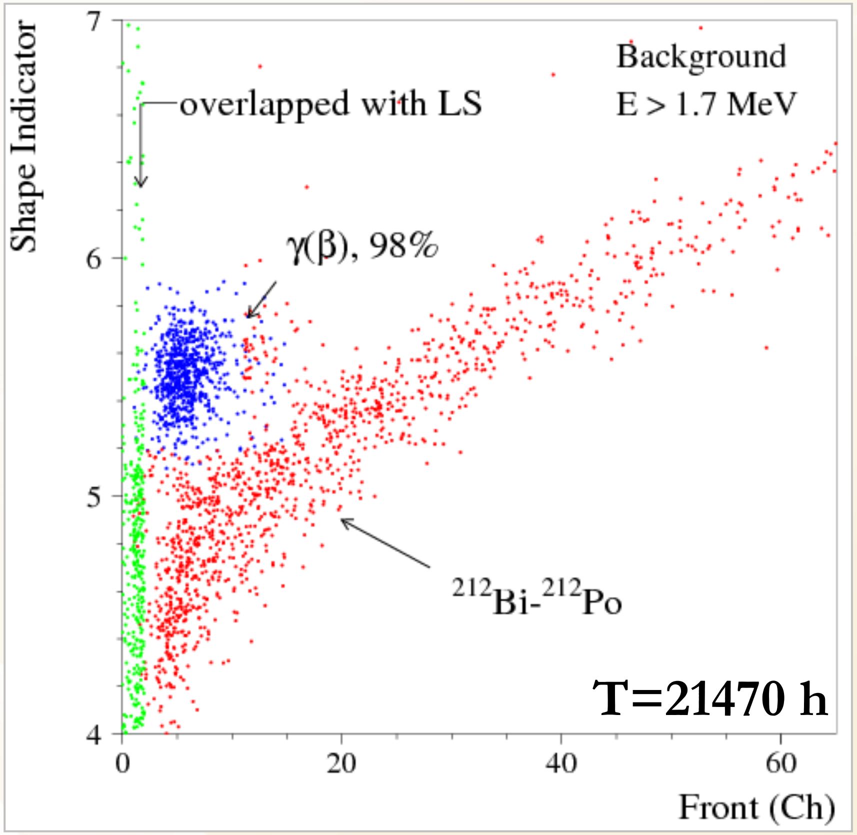
Bi-Po: fast sequence of β-α decays from ^{232}Th chain: $^{212}Bi \rightarrow ^{212}Po(T_{1/2}=299ns)$ or ^{238}U chain: $^{214}Bi \rightarrow ^{214}Po(T_{1/2}=164.3\ \mu s)$



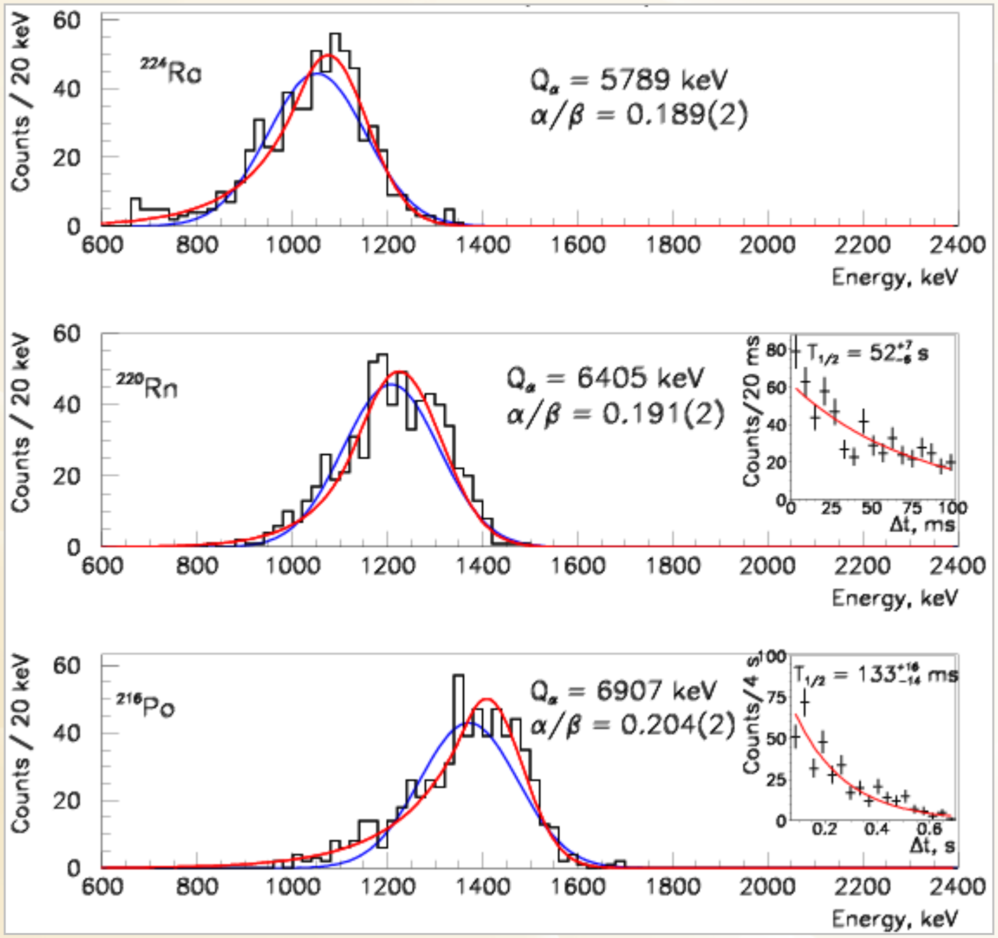
Bi-Po can be identified by pulse front edge analysis (the pulse maximum of Bi-Po pulse is delayed with the respect to single pulse)

Shape Indicator vs Front edge





Background identification 3: Time-Amplitude analysis



Data from $^{116}CdWO_4$ detector-1 (T=25037 h)

Blue: gaussian

Red: gaussian + tail ⇒

$$f(u) = \begin{cases} A \exp\left[-\frac{(u-\mu)^2}{2\sigma^2}\right], & \text{if } u \geq \mu - T \\ A \exp\left[\frac{T(2u - 2\mu + T)}{2\sigma^2}\right], & \text{if } u < \mu - T \end{cases}$$

The arrival time, the energy and the pulse shape of each event were used to select the fast decay chain:

^{224}Ra (Q = 5.789 MeV, $T_{1/2}$ = 3.66 d)

↓

^{220}Rn (Q = 6.405 MeV, $T_{1/2}$ = 55.6 s)

↓

^{216}Po (Q = 6.906 MeV, $T_{1/2}$ = 0.145 s)

↓

^{212}Pb

The obtained half-lives for **^{220}Rn (52^{+7}_{-6} s)** and **^{216}Po ($0.133^{+0.016}_{-0.014}$ s)** are in agreement with the table values (**55.6 s** and **0.145 s**)

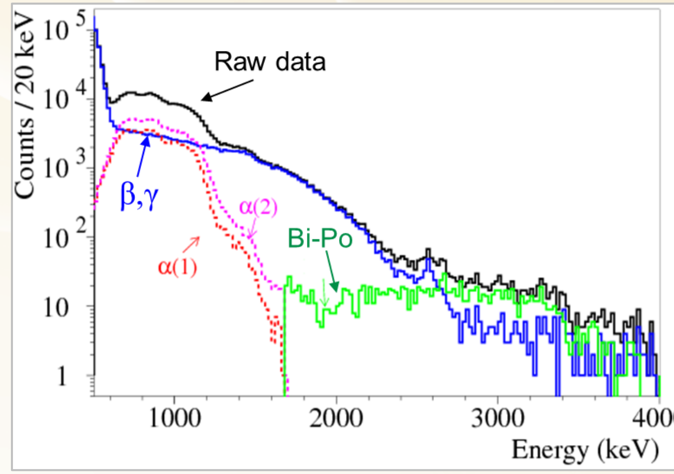
Activity ^{228}Th (μBq/kg)		
	PSD	**T-A**
Crystal 1	17(2)	17(1)
Crystal 2	26(2)	27(1)

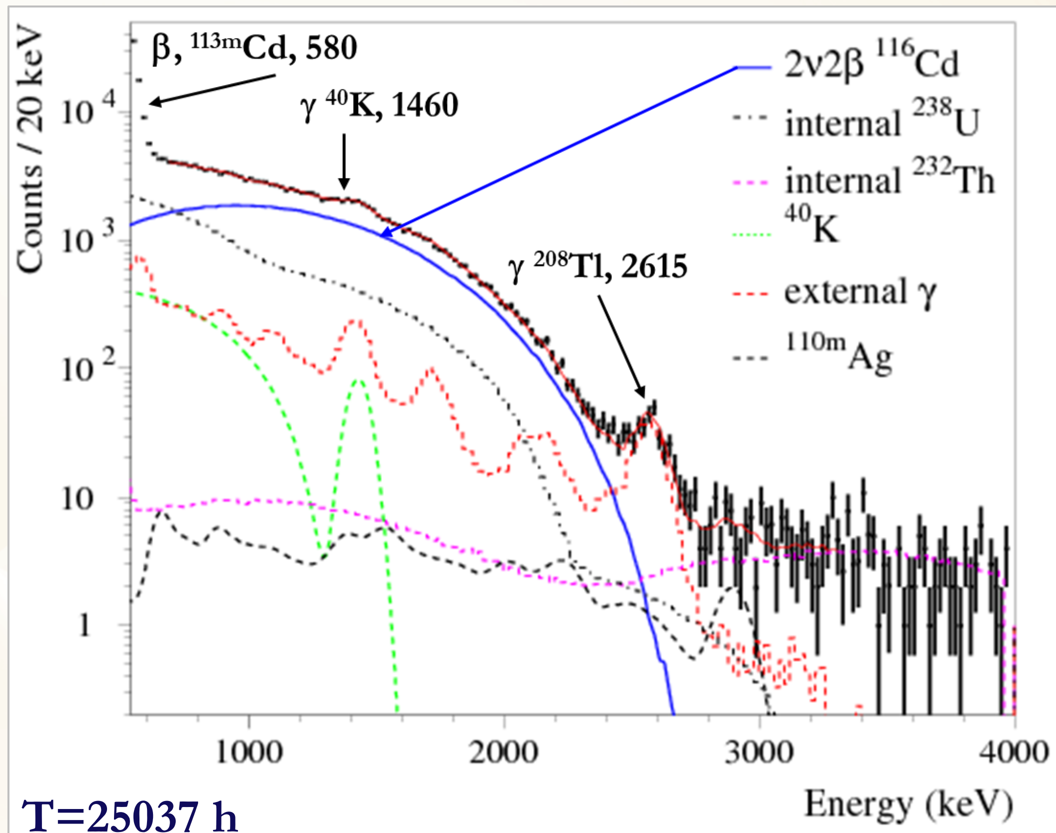
Background identification: fit and results

Radioactive contaminations of $^{116}CdWO_4$ crystal scintillators

Chain	Nuclide	Activity mBq/kg
^{232}Th	^{232}Th	0.61(2)
	^{228}Th	0.022(3)
^{238}U	^{238}U	0.59(7)
	^{234}Th	0.64(7)
	^{230}Th	0.11(2)
	^{226}Ra	$\leq$ 0.01
	^{210}Pb	0.6(1)
	^{40}K	0.20(1)
	^{110m}Ag	<0.06

Total α activity = 2.27 mBq/kg





Result for two neutrino double beta decay of ^{116}Cd

Conditions of the Fit:

- Variation of bounds for radioactive contaminations
- Model of background
- Interval of fit
- Quenching for β (non prop. light response) [1,2]

[1] PRC 76(2007)064603 [2] NIMA 696(2012)144

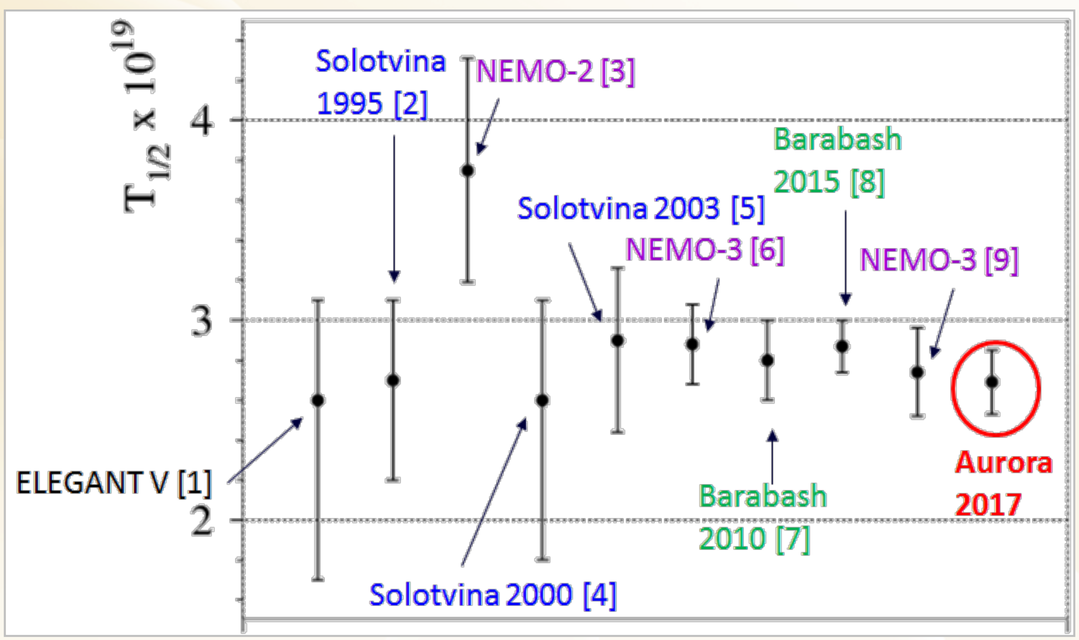
Signal to bg ratio: 2.6 in [1.1–2.8] MeV

Systematic errors

Source	SE%
Rad. contamination of $^{116}CdWO_4$ crystals	65
BG models, MC, QF	15
PSD efficiency	10
Interval of the fit	7
Number of ^{116}Cd nuclei	3

$$T_{1/2} = [2.69 \pm 0.02(\text{stat.}) \pm 0.14(\text{syst.})] \times 10^{19}\ \text{yr}$$

(the most accurate value up to date)



[1] J. Phys. Soc. Japan 64(1995)339
[2] Phys. Lett. B 344(1995)72
[3] Z. Phys. C 72(1996)239
[4] PRC 62(2000)045501
[5] PRC 68(2003)035501
[6] AIP Conf. Proc. 1572(2013)110
[7] PRC 81(2010)035501
[8] NPA 935(2015)52
[9] PRD 95(2017)012007

$T_{1/2}$ limit on 0ν2β decay of ^{116}Cd

Further background reduction (**~35%**) for 0ν2β decay by excluding events from:

^{212}**Bi** [Q_α = 6207.26(3) keV, B.R.~36%] → ^{208}**Tl** [Q_β = 4998.9(18) keV, $T_{1/2}$=3.053(4) min]

⇒ **background rate in 2.7 – 2.9 MeV: 0.07 (counts/keV/kg/yr)**

(live time reduction~15%)

Fit in 2.5–3.2 MeV: **-3.7 ± 10.6 counts**

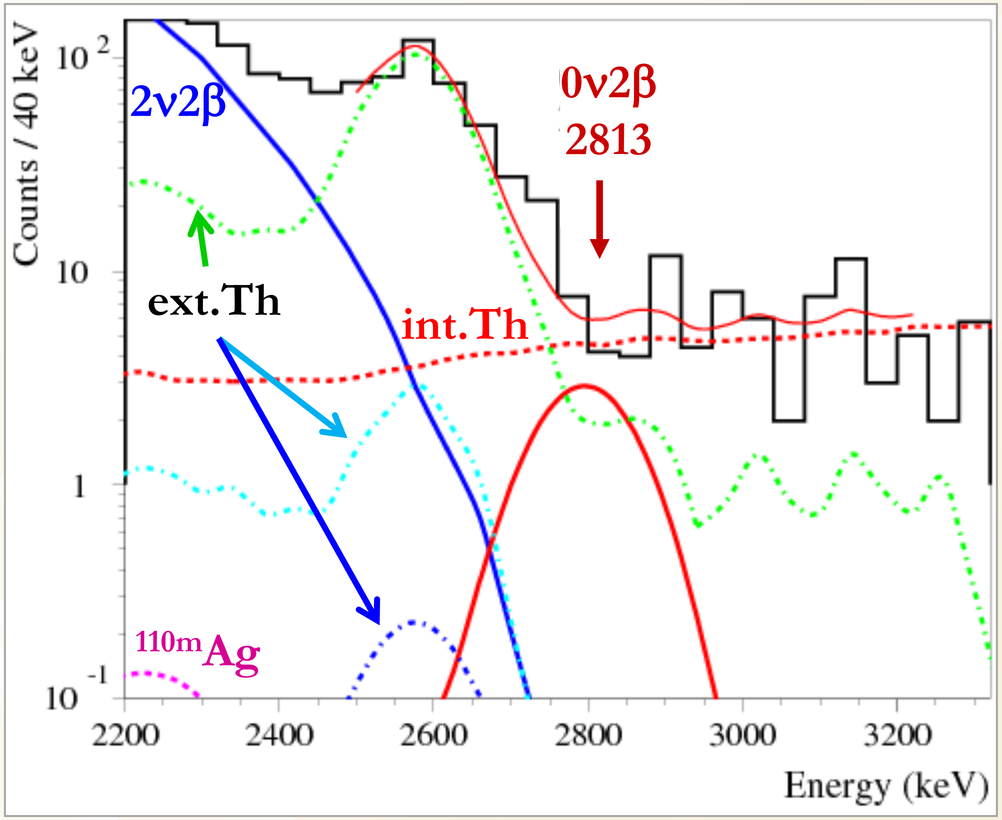
$T_{1/2} > 2.4 \times 10^{23}$ **yr** @ 90% C.L.

Effective Majorana neutrino mass:

$\langle m_\nu \rangle < 1.1 - 1.6$ eV [1-4]

+ New improved limits on $T_{1/2}$ for 0ν2β decay to excited levels of ^{116}Sn in the range:

(3.6–6.3)×10^{22} yr

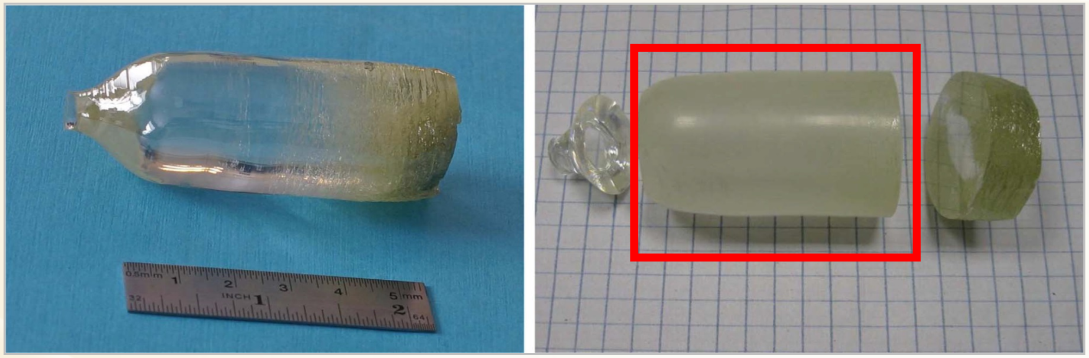


[1] T.R. Rodryguez et al., Phys.Rev.Lett. 105(2010)252503
[2] F. Simkovic et al., Phys.Rev.C 87 (2013)045501
[3] J. Hyvarinen et al., Phys.Rev.C 91 (2015)024613
[4] J. Barea et al., Phys.Rev.C 91(2015)034304

Improvement of radiopurity of $^{116}CdWO_4$ by recrystallization

A.S. Barabash et al., Nucl. Instr. Meth. A 833(2016)77

Re-crystallized by the low-thermal-gradient Czochralski technique in a platinum crucible



Crystal n.3 used (326 g mass)

60% of initial mass after re-crystallization

Side surface made opaque by grinding paper to improve light collection

Radioactive contamination of the samples (before an after recrystallization) measured in the DAMA/CRYS setup @ LNGS

Chain	Nuclide (sub-chain)	Activity (mBq/kg)	
		Before recrystallization	After recrystallization
^{232}Th	^{232}Th	0.13(7)	0.03(2)
	^{228}Th	0.10(1)	0.010(3)
^{238}U	^{238}U	1.8(2)	0.8(2)
	^{226}Ra	$\leq$0.1	$\leq$0.015
	^{234}U+^{230}Th	0.6(2)	0.4(1)
	^{210}Po	1.6(2)	0.4(1)
Total α		4.44(4)	1.62(4)

- ^{228}Th reduced by a factor ~10 $\Rightarrow$ 0.01 mBq/kg
- α activity reduced by a factor ~3 $\Rightarrow$ 1.6 mBq/kg

main background component for ^{116}Cd $0\nu2\beta$ decay

$\Rightarrow$ Strong segregation of the radioactive elements in the $CdWO_4$ crystals growing process

Latest results on rare processes:

- ✓ *Search for ββ decay in ^{106}Cd with enriched $^{106}CdWO_4$ detector in the DAMA/CRYS setup*
- ✓ *Investigation of ββ decay of ^{116}Cd with enriched $^{116}CdWO_4$ detectors in DAMA/R&D setup*
- ✓ *Investigation of directionality with $ZnWO_4$ anisotropic detectors: feasibility study*

Dark Matter and the directionality approach

Based on diurnal variation of apparent DM wind arrival direction

Sun velocity, $\vec{v}_S$, in the equatorial coordinate system (ecs)

$|\vec{v}_S| = 230 \pm 50 \, \frac{km}{s}$

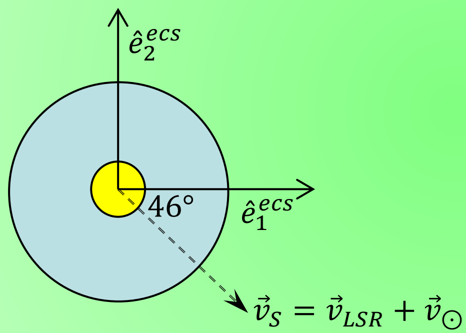
On equatorial plane:

$\hat{e}_1^{ecs} \cdot \vec{v}_S = 108.1$ km/s

$\hat{e}_2^{ecs} \cdot \vec{v}_S = -112.4$ km/s

$\Rightarrow \varphi = -46°$

$\Rightarrow$ t = 20.92 h (LST)

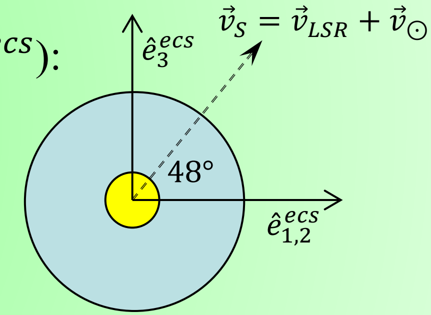


Angle w.r.t. North pole ($\hat{e}_3^{ecs}$):

$\hat{e}_3^{ecs} \cdot \vec{v}_S = 172.1$ km/s

$\Rightarrow \theta = 42°$

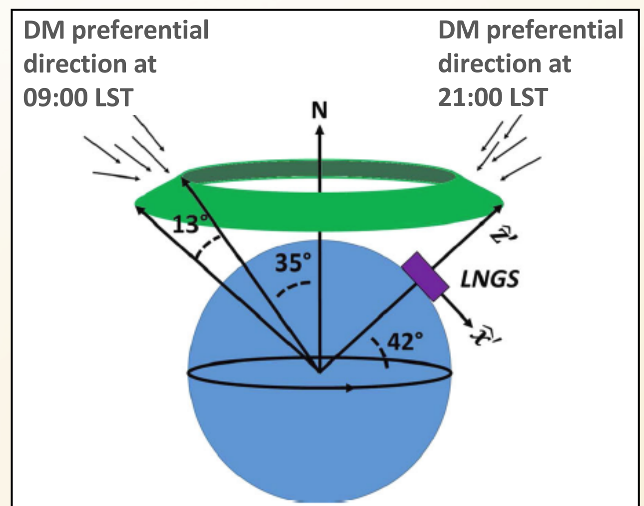
$\Rightarrow$ Lat = 48°



Study of the correlation between the arrival direction of Dark Matter candidates inducing nuclear recoils and the Earth motion in the galactic frame

The direction of the induced nuclear recoil is strongly correlated with that of the impinging DM particle

The observation of an anisotropy in the distribution of nuclear recoil direction could give evidence for such candidates



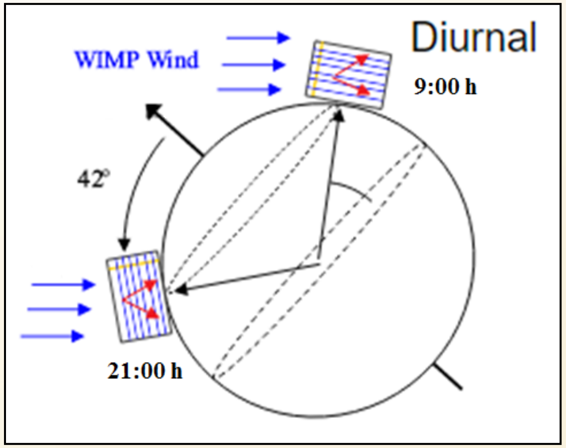
direction-sensitive detector

Directionality sensitive detectors: anisotropic scintillators

- The use of anisotropic scintillators to study the directionality approach firstly proposed in [**P. Belli et al., Il Nuovo Cim. C 15 (1992) 475; R. Bernabei et al., EPJC28(2003)203**], where the case of anthracene was analysed; some preliminary activities have been carried out [N.J.C. Spooner et al, IDM1997 Workshop; Y. Shimizu et al., NIMA496(2003)347]

- Anisotropic Scintillator:
  - for heavy particles the *light output* and the *pulse shape* depends on the particle impinging direction with respect to the crystal axes
  - for γ/e the *light output* and the *pulse shape* are isotropic

- The variation of the response of an **anisotropic scintillator** during sidereal day can allow to point out the presence of a DM signal due to candidate inducing only nuclear recoils



- $ZnWO_4$ anisotropic scintillator: a very promising detector (**Eur. Phys. J. C 73 (2013) 2276**)

Advantages of the $ZnWO_4$ crystal

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

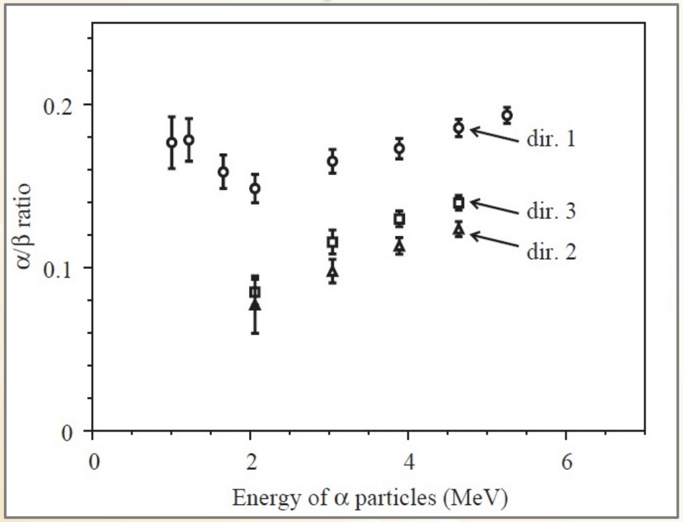
- ✓ Very good anisotropic features
- ✓ High level of radiopurity
- ✓ High light output, that is low energy threshold feasible
- ✓ High stability in the running conditions
- ✓ Sensitivity to small and large mass DM candidate particles
- ✓ Detectors with ~ kg masses

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*

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

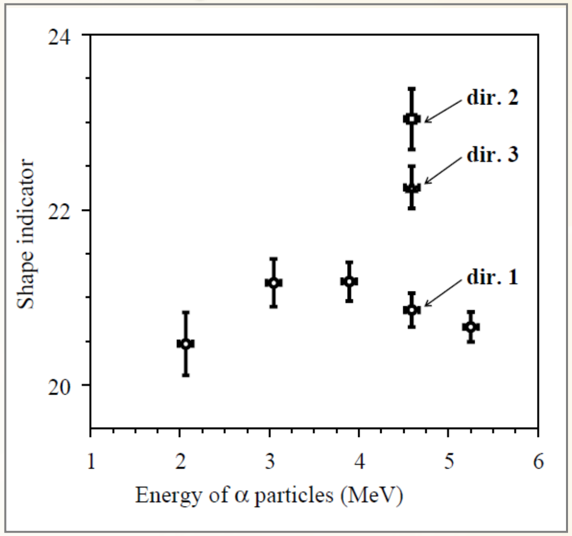
α/β ratio



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

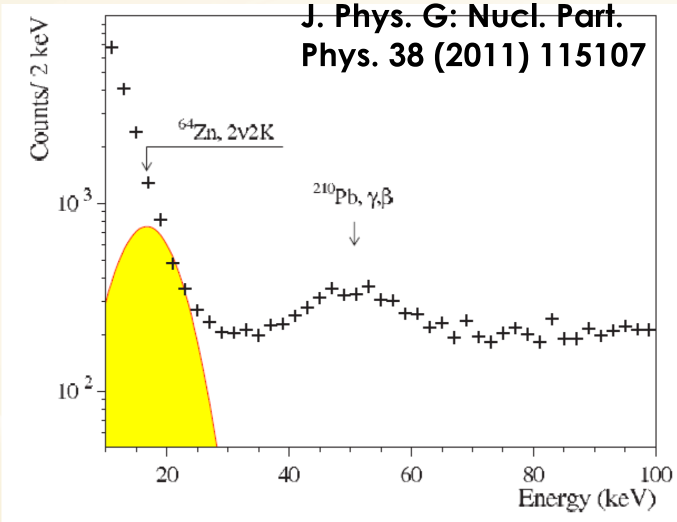
Q.F expected according to V.I. Tretyak, Astropart. Phys. 33 (2010) 40

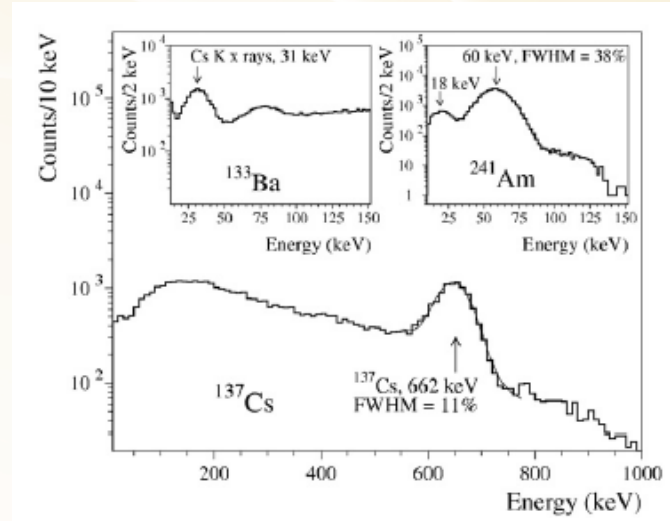
Similar effect is expected in the case of low energy nuclear recoils

⇒ **Dedicated measurements are in progress @ Casaccia lab**

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





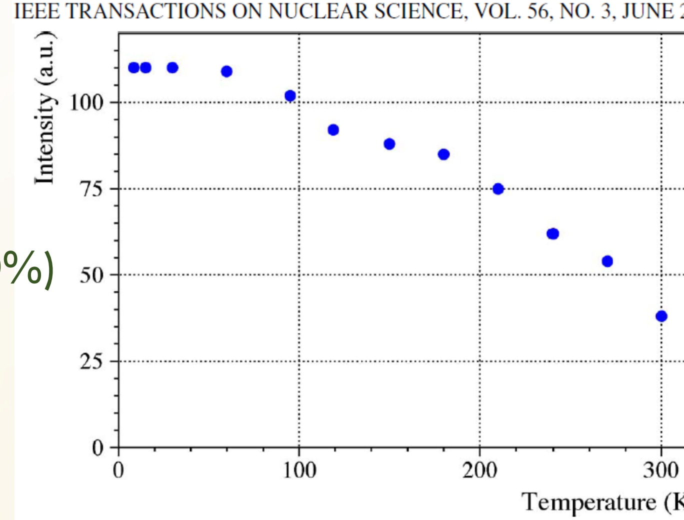
FWHM (8.8–14.6)% @662 keV

Improvements of the energy threshold by:

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

Low-threshold feasible

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 56, NO. 3, JUNE 2009

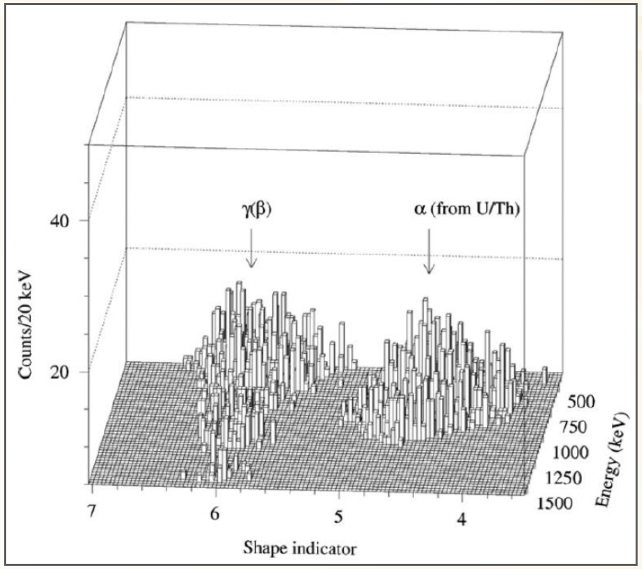


Light output measured for a $ZnWO_4$ scintillator with ^{241}Am α particles as function of Temperature

Radiopurity of the $ZnWO_4$ crystal scintillator

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 (0.6 ppb ^{nat}K);
- total α activity of 0.18 mBq/kg

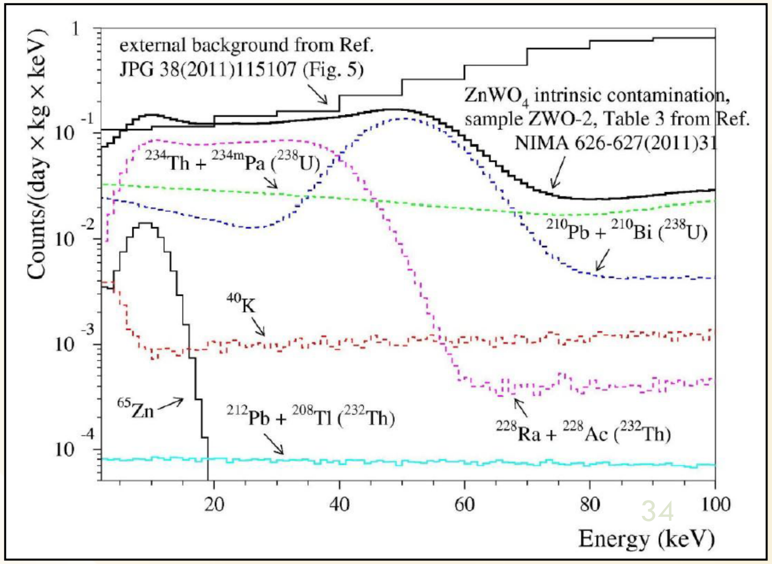


PSD capability: allow to discriminate $\beta(\gamma)$ events from those induced by α particles and to identify the α background

Montecarlo calculation for the expected background at low energy considering the measured radiopurity of the detectors

$\Rightarrow$ background in the low energy region ≈ 0.1cpd/kg/keV

The radiopurity of $ZnWO_4$ is very good and new purification techniques under study to further reduce the low energy counting rate due to the intrinsic crystal contamination



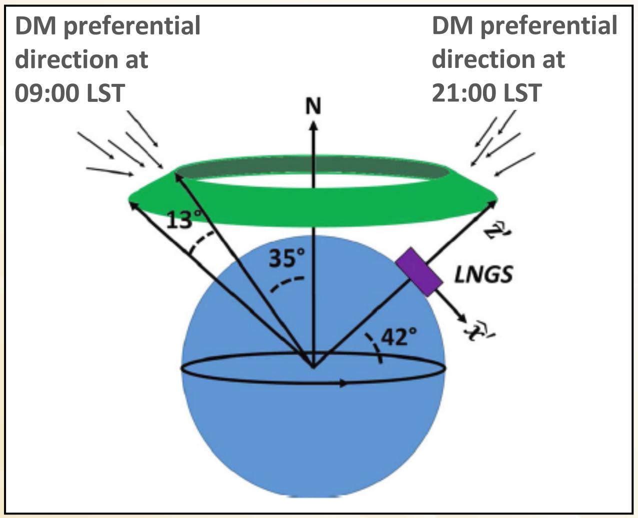
Developments still ongoing:

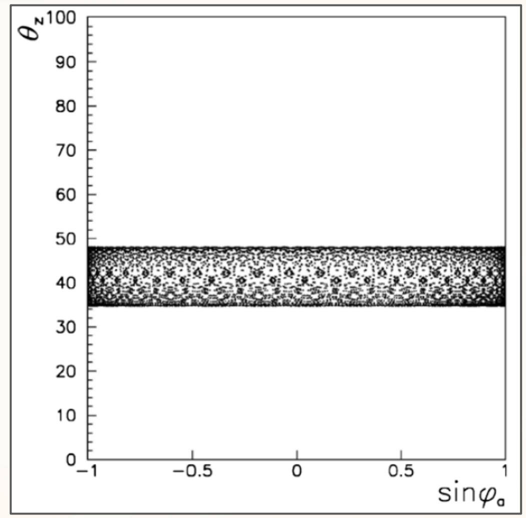
$\Rightarrow$ $ZnWO_4$ crystals with higher radiopurity expected

LNGS: a perfect place for directionality with anisotropic scintillators

It is very convenient to consider an experiment performed at the LNGS latitude (**42°27′N**)

⇒ here at 21:00 h LST the DM particles come mainly from the top, while 12 h later they come from the North and parallel to the horizon line

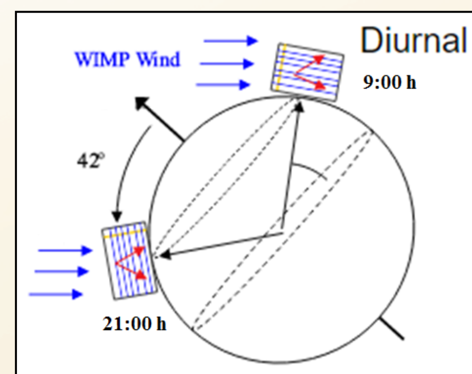




$\vec{v}_{Lab}(t)$ directions in the sky calculated for three years as viewed in the coordinate frame located to the North pole

The optimal performance for an anisotropic $ZnWO_4$ detector is obtained when arranging the crystal axis that corresponds to the largest light output in the vertical direction and the axis that gives the smallest light output towards the North

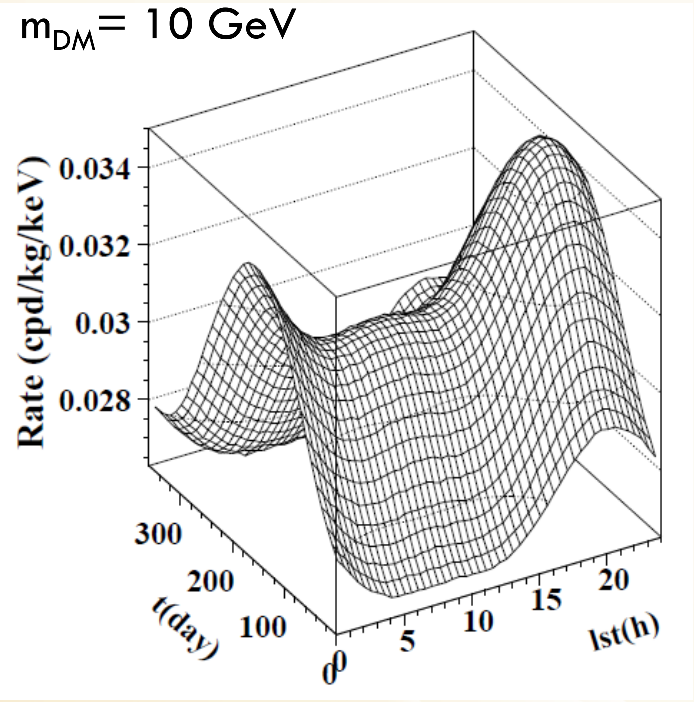
With this configuration the range of variability of the anisotropic detector response during a sidereal day is at maximum



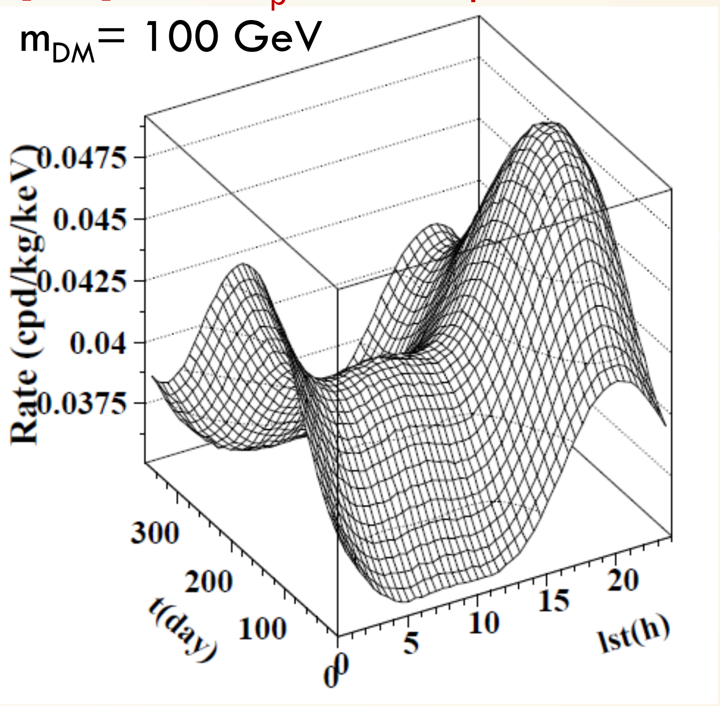
Example of expected signal

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

[2-3] keV $\sigma_p = 5\times10^{-5}$ pb



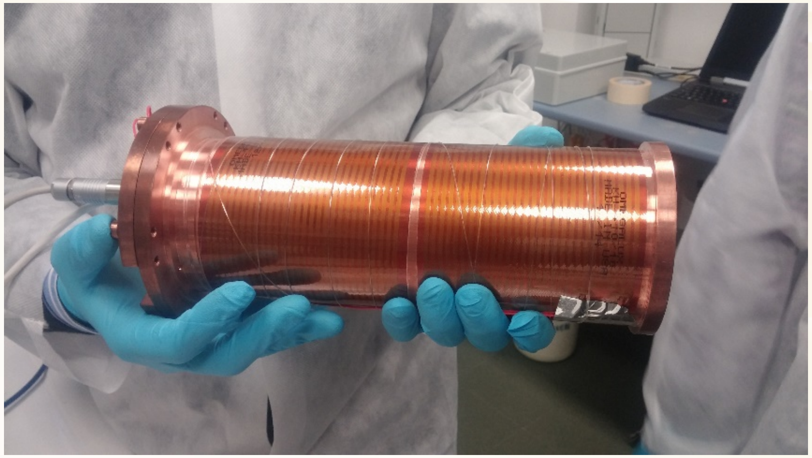
[6-7] keV $\sigma_p = 5\times10^{-5}$ pb

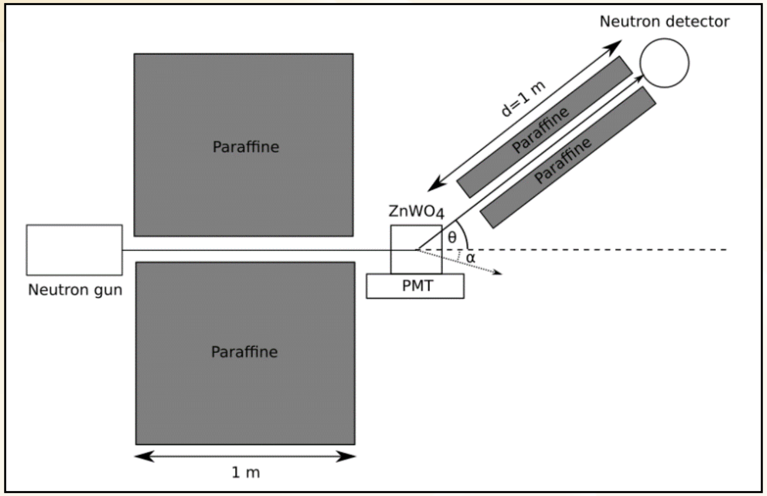


- Identical sets of crystals placed in the same set-up with different axis orientation will observe consistently different time evolution of the rate
- The diurnal effect will refer to the sidereal day and not to the solar day
- Absolute maximum rate is at day 152 and at 21h LST (when the DM flux is at maximum and the DM preferential arrival direction is near the zenith)

$ZnWO_4$ – work in progress…

- Cryostat for low temperature measurement with scintillation detectors realized
- Test of the Cryostat in progress
- Lowering the energy threshold (new PMT with higher QE, SiPM, APD, SDD, …)





- Measurements of anisotropy at low energy with MP320 Neutron Generator (E_n = 14 MeV) in progress at Casaccia lab
- Development of electronics

Conclusions

- ✓ Many and competitive results have been obtained in the search for rare processes by the DAMA experimental set-ups at LNGS

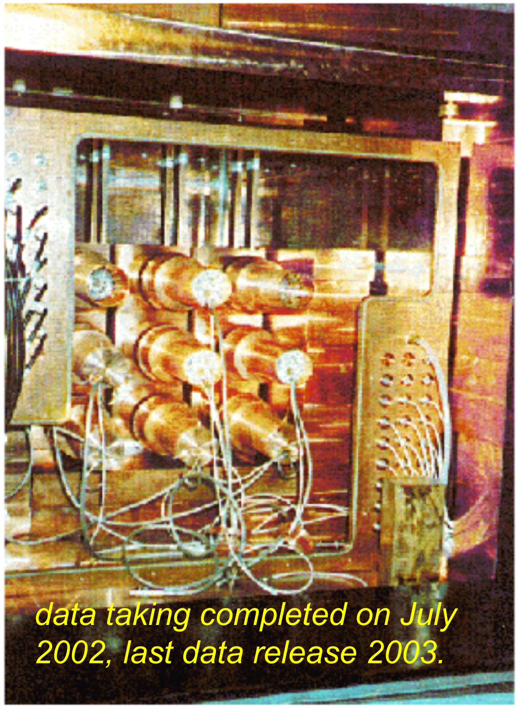
- ✓ A $^{106}CdWO_4$ detector is running in coincidence with two $^{nat}CdWO_4$ in the DAMA/Crys set-up to search for 2β processes in ^{106}Cd with expected sensitivity 10^{20}-10^{21} years (in the range of theoretical predictions)

- ✓ Search for 2β processes in ^{116}Cd with $^{116}CdWO_4$ (enriched to 82%) scintillation detectors (1.16 kg) just concluded in the DAMA/R&D set-up:
  - ➢ $T_{1/2}(2\nu2\beta) = [2.69 \pm 0.02(stat.) \pm 0.14(syst.)] \times 10^{19}$ yr (the most accurate value up to date)
  - ➢ $T_{1/2}(0\nu2\beta) \geq 2.4 \times 10^{23}$ yr $\rightarrow \langle m_\nu \rangle < (1.1 - 1.6)$ eV (the best limit)
  - ➢ Internal ^{228}Th (main bkgd) can be strongly reduced by re-crystallization

- ✓ Studies and measurements on $ZnWO_4$ crystal scintillators as detectors for the directionality technique are in progress

BACKUP slides

The pioneer DAMA/NaI
≈100 kg highly radiopure NaI(Tl)



Performances:

N.Cim.A112(1999)545-575, EPJC18(2000)283,
Riv.N.Cim.26 n. 1(2003)1-73, IJMPD13(2004)2127

Results on rare processes:

- Possible Pauli exclusion principle violation — PLB408(1997)439
- CNC processes — PRC60(1999)065501
- Electron stability and non-paulian transitions in Iodine atoms (by L-shell) — PLB460(1999)235
- Search for solar axions — PLB515(2001)6
- Exotic Matter search — EPJdirect C14(2002)1
- Search for superdense nuclear matter — EPJA23(2005)7
- Search for heavy clusters decays — EPJA24(2005)51

Results on DM particles:

- PSD — PLB389(1996)757
- Investigation on diurnal effect — N.Cim.A112(1999)1541
- Exotic Dark Matter search — PRL83(1999)4918
- **Annual Modulation Signature** — PLB424(1998)195, PLB450(1999)448, PRD61(1999)023512, PLB480(2000)23, EPJC18(2000)283, PLB509(2001)197, EPJC23(2002)61, PRD66(2002)043503, Riv.N.Cim.26 n.1 (2003)1, IJMPD13(2004)2127, IJMPA21(2006)1445, EPJC47(2006)263, IJMPA22(2007)3155, EPJC53(2008)205, PRD77(2008)023506, MPLA23(2008)2125

Evidence of modulated behaviour with all the proper features for DM particles in the galactic halo (6.3σ CL)

total exposure (7 annual cycles) 0.29 ton × yr

The DAMA/LIBRA set-up ~250 kg NaI(Tl) (**L**arge sodium **I**odide **B**ulk for **RA**re processes)

As a result of a 2nd generation R&D for more radiopure NaI(Tl) by exploiting new chemical/physical radiopurification techniques
(all operations in HP Nitrogen atmosphere)

Residual contaminations in the new DAMA/LIBRA NaI(Tl) detectors: ^{232}Th, ^{238}U and ^{40}K at level of 10^{-12} g/g

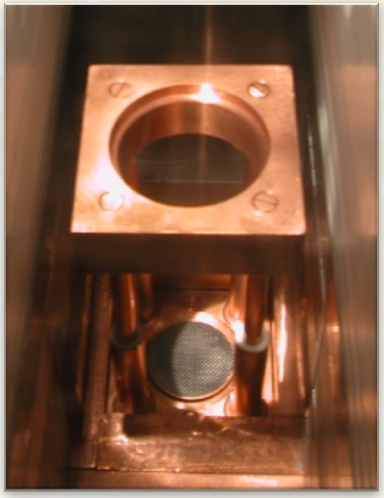
- Radiopurity, performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
- Results on DM particles, Annual Modulation Signature: EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648
  Related results: PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022, EPJC74(2014)2827, EPJC74(2014)3196, EPJC75(2015)239, EPJC75(2015)400
- Results on rare processes: PEPv: EPJC62(2009)327; CNC: EPJC72(2012)1920; IPP in ^{241}Am: EPJA49(2013)64

DAMA/R&D recent results

- Dark Matter with CaF_2(Eu)
  NPB563(1999)97, AP7(1997)73
- Double beta decay in ^{40}Ca, ^{46}Ca, ^{48}Ca, ^{64}Zn, ^{70}Zn, ^{106}Cd, ^{108}Cd, ^{114}Cd, ^{116}Cd, ^{130}Ba, ^{136}Ce, ^{138}Ce, ^{142}Ce, ^{180}W, ^{186}W with various low background scintillators
  NCimA110(1997)189, AP7(1997)73, NPB563(1999)97, AP10(1999)115, NPA705(2002)29, NIMA498(2003)352, NIMA525(2004)535, PLB658(2008)193, EPJA36(2008)167, NPA826(2009)256, NIMA615(2010)301, JPG:NPP38(2011)015103, JINST6(2011)P08011, JPG:NPP38(2011)115107, NIMA626(2011)31, PRC85(2012)044610
- Rare β decays (^{113}Cd, ^{48}Ca)
  NPA705(2002)29, PRC76(2007)064603, EPJA50(2014)134
- Rare α decays (^{nat}Eu)
  NPA789(2007)15
- Cluster decay in $LaCl_3$(Ce)
  NIMA555(2005)270
- CNC decay $^{139}La \rightarrow {}^{139}Ce$
  UJP51(2006)1037
- Search for long-lived superheavy ekatungsten with $ZnWO_4$
  Phys. Scr.90(2015)085301

DAMA/Ge and LNGS STELLA facility

- ✓ Qualification and measurement of many materials
- ✓ RDs on low background scintillators and PMTs
- ✓ Small scale experiments on double beta decays and rare processes (see next slides)



DAMA/LXe

Pure liquid xenon scintillator

Can operate with Xenon Kr-free enriched either in ^{129}Xe or in ^{134}Xe,^{136}Xe

Results on:

- ✓ Dark Matter investigations
- ✓ Double beta decays of ^{134}Xe and ^{136}Xe
- ✓ Several rare nuclear processes

Recent results from DAMA/Ge and LNGS STELLA facility

- RDs on low background scintillators and PMTs
- 2β decay in ^{100}Mo (NPA846(2010)143), ^{96}Ru and ^{104}Ru (EPJA42(2009)171), ^{136}Ce and ^{138}Ce (NPA824(2009)101, NPA930(2014)195), ^{190}Pt and ^{198}Pt (EPJA47(2011)91), ^{156}Dy and ^{158}Dy (NPA859(2011)126)
- Search for ^{7}Li solar axions (NPA806(2008)388, PLB711(2012)41)
- First observation of α decay of ^{190}Pt to the first excited level of ^{186}Os (PRC83(2011)034603)
- $^{106}CdWO4$ crystal scintillator in coincidence with four HPGe detectors (PRC93(2016)045502)
- Qualification and measurement of many materials: e.g. $CdWO_4$, $ZnWO_4$(NIMA626-7(2011)31, NIMA615(2010)301), $Li_6Eu(BO_3)_3$ (NIMA572(2007)734), Li_2MoO_4 (NIMA607(2009) 573), $SrI_2(Eu)$ (NIMA670(2012)10), $^{7}LiI(Eu)$ (NIMA704(2013)40)

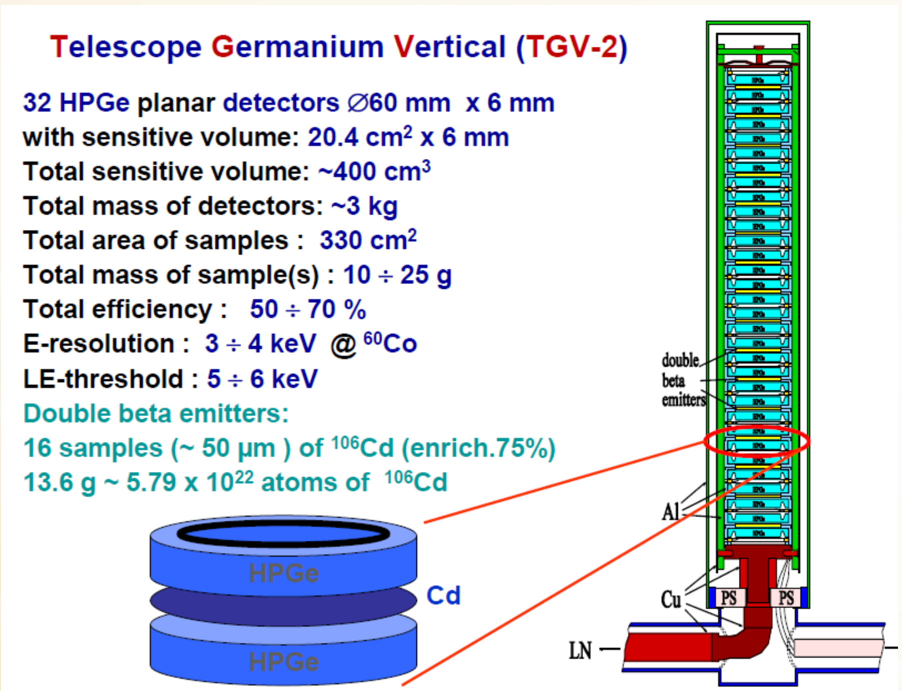
… and DAMA/LXe

- Dark Matter investigations
  - by PSD (PLB436(1998)379);
  - inelastic scattering (PLB387(1996)222, NJP2(2000)15.1);
  - neutron calibrations (PLB436(1998)379, EPJdirectC11(2001)1)
- 2β decay in ^{134}Xe, ^{136}Xe (PLB527(2002)182, PLB546(2002)23)
- CNC processes: e^- decay into invisible channels (A.P.5(1996)217);
- $e^- \rightarrow \nu_e \gamma$ (PRD61(2000)117301);
- nuclear level excitations (PLB465 (1999)315);
- CNC β decay $^{136}Xe \rightarrow ^{136}Cs$ (Beyond the Desert (2003) 365)
- N, NN, NNN decay (PLB493(2000)12, EPJA27 s01 (2006)35)

Current activity on 2β decay of ^{106}Cd

TGV-2 Experiment:

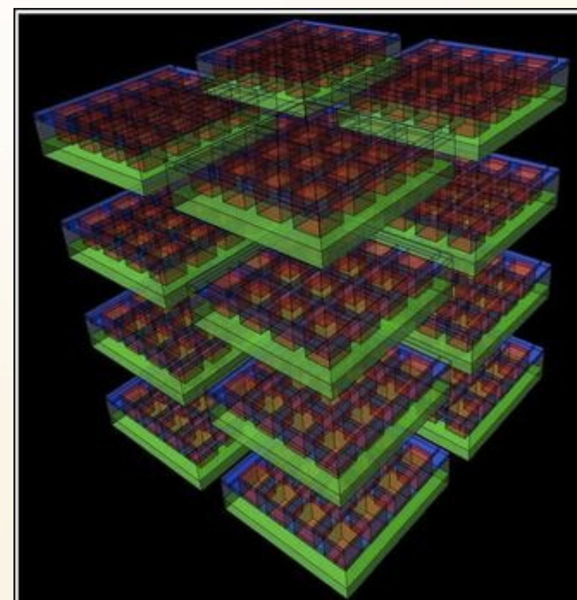
32 planar HPGe + 16 foils of ^{106}Cd (●=75%, 13,6 g), LSM (France)



Current sensitivity:

$T_{1/2} \approx 10^{20}$ yr

N.I. Rukhadze et al., NPA 852 (2011) 197, BRASP 75 (2011) 879



COBRA:

32 semiconductors CdZnTe (1 cm^3 each), LNGS (Italy)

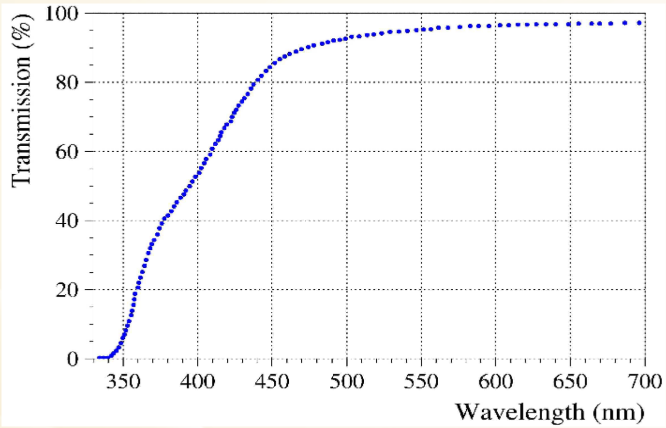
Current sensitivity: $T_{1/2} \approx 10^{18}$ yr

K. Zuber, Prog. Part. Nucl. Phys. 64 (2010) 267

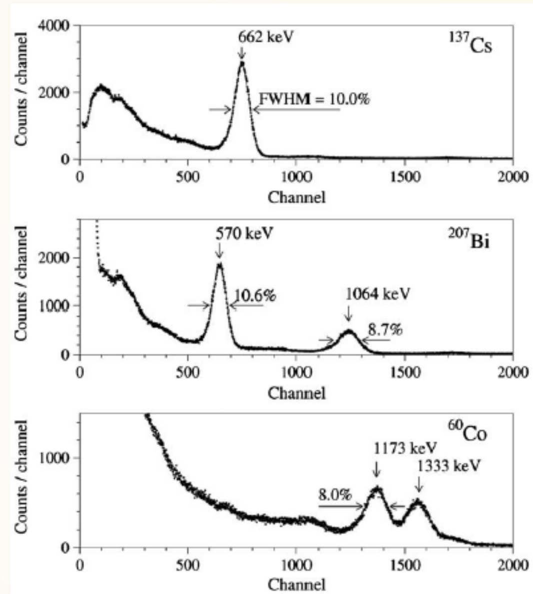
$^{106}CdWO_4$ crystal scintillator NIMA615(2010)301

Excellent optical and luminescence properties were reached thanks to a special R&D (deep purification of raw materials and low-gradient crystal growth by the Czochralski method). High light output.

Optical transmission curve

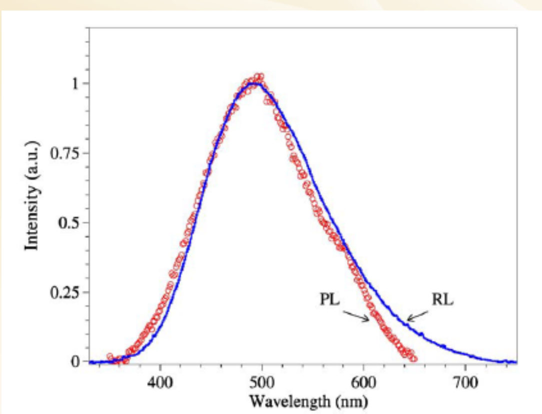


Response of the detector to γ sources



FWHM = 10% @ 662 keV

Emission spectra of ^{106}CdWO4 crystal under ultraviolet (PL) and X-ray (RL) excitation

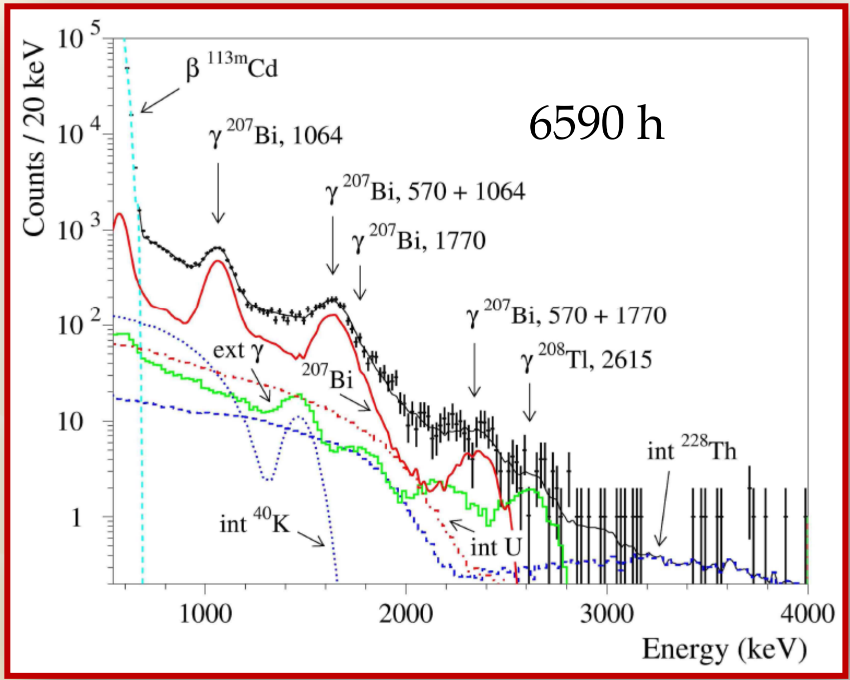


Properties	Value
Density [g/cm^3]	7.9
Melting point [K]	1598
Hygroscopic	No
Wavelength of max emission [nm]	475
Refractive index @ max em.	2.2-2.3
Primary decay time [μs]	14
Photoelectron yield [% of NaI(Tl)]	30-50

Search for 2β decay in ^{106}Cd in DAMA/R&D

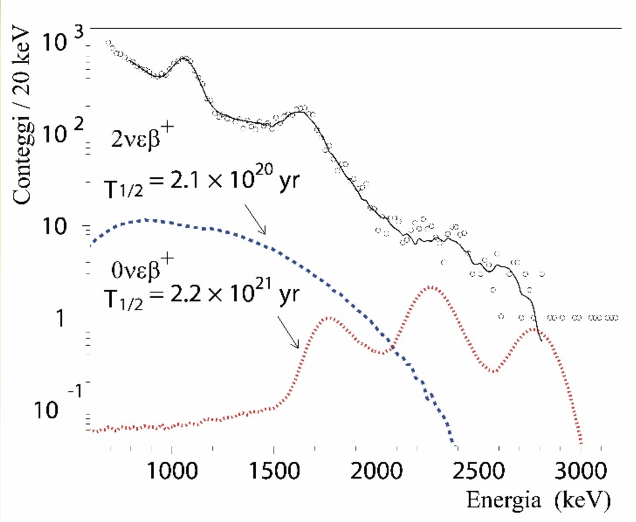
Energy distribution of the γ/β events (by PSD)

Phys. Rev. C 85 (2012) 044610



Contamination level in $^{106}CdWO_4$ (mBq/Kg)

^{207}Bi	<0.7
^{113m}Cd	116 ·10^{3}
^{232}Th	< 0.07
^{228}Th	0.042(4)
^{238}U	<0.6
^{226}Ra	0.012(3)
^{40}K	<1.4
^{207}Bi surface	0.06 mBq/cm^{3}



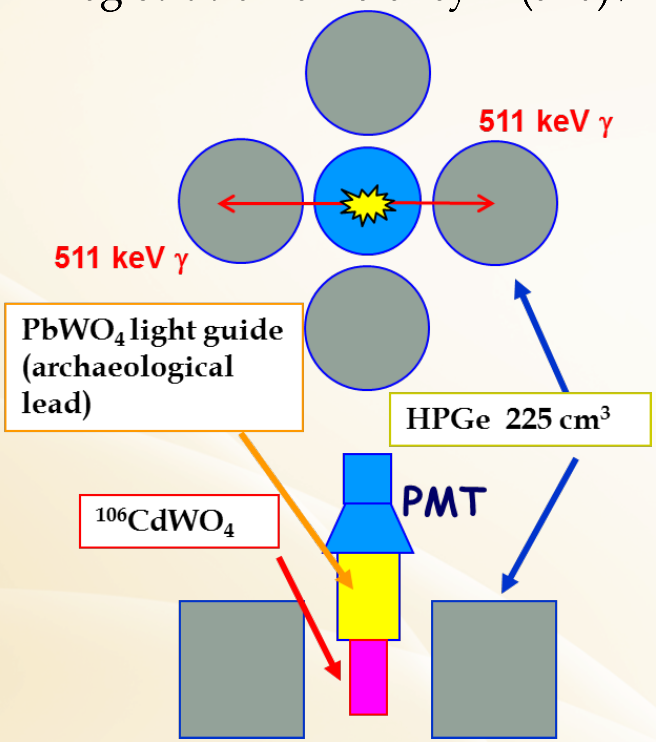
Result:

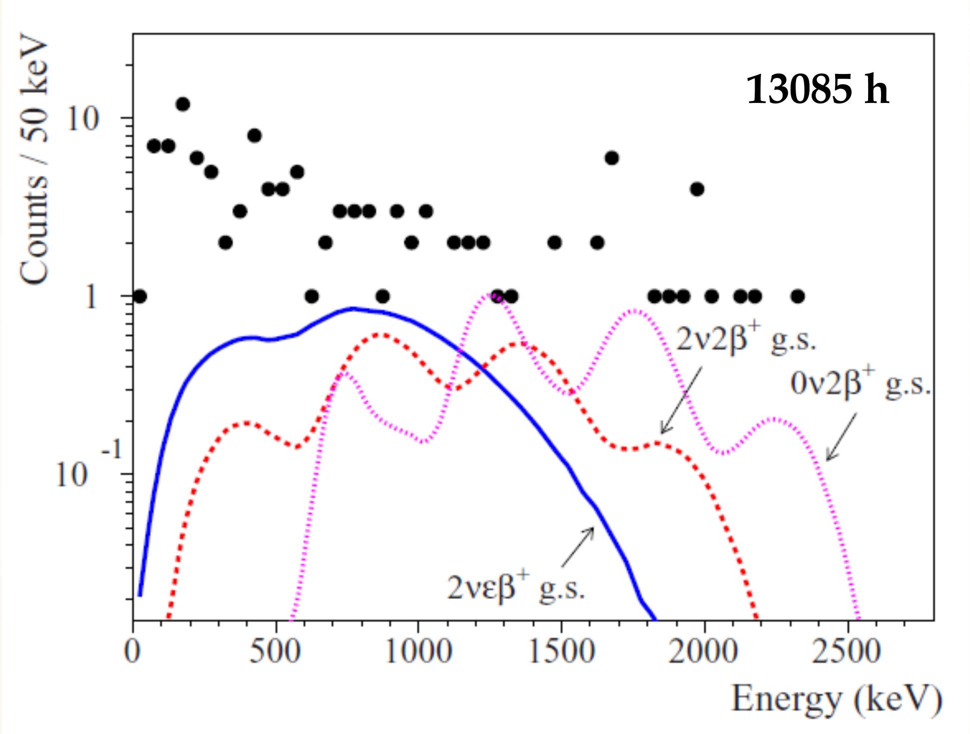
$T_{1/2}$ (2β, ^{106}Cd→ ^{106}Pd) ≥ 10^{19-21} yr

27 new results for 2β ^{106}Cd
9 of them – for the first time

$^{106}CdWO_4$ in GeMulti

- $^{106}CdWO_4$ in coincidence / anticoincidence with 4-crystals HPGe detector (GeMulti)
- Crystal Surface cleaned
- Registration efficiency ~ (3–8)%



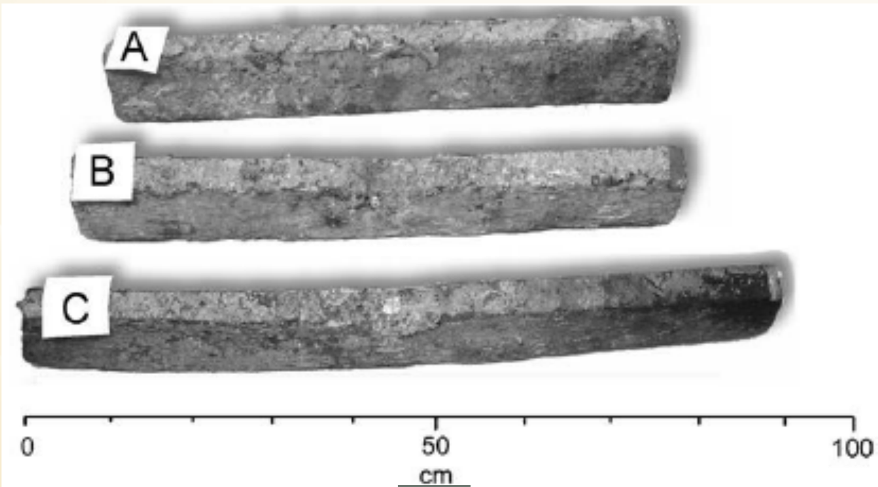


Energy spectrum of $^{106}CdWO_4$ detector in coincidence with 511 keV in HPGe (circles). Monte Carlo simulated distributions of 2β decay of ^{106}Cd excluded at 90% CL.

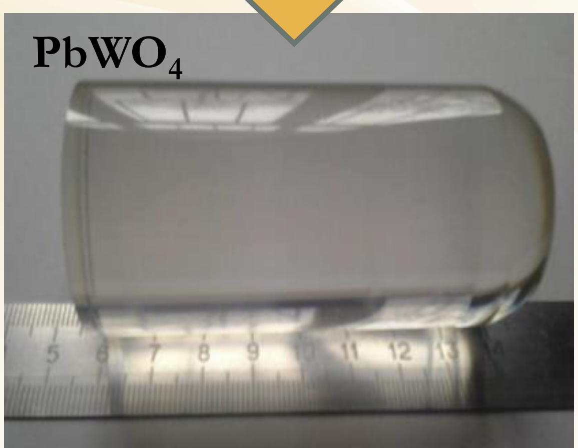
- **New limits on 2ε, εβ$^+$, 2β$^+$ processes on the level of $T_{1/2} > 10^{20}$ -10^{21} yr**
- **The half-life limit on the 2νεβ$^+$ decay, $T_{1/2} > 1.1\times10^{21}$ yr, reached the region of theoretical predictions**
- **For 0νε2 resonant captures: $T_{1/2} > (8.5 \times 10^{20} - 1.4 \times 10^{21})$ yr**

$^{arch}PbWO_4$ light guide

- $PbWO_4$ light-guide realized in order to suppress the radioactive components from the photomultiplier
- Archaeological lead: A (^{210}Pb) <0.3 mBq/kg [3]



- Purification Pb: Institute of Physics and Technology (Kharkiv)
- Crystal growth: Institute of Scintillation Materials (Kharkiv)



Firstly used in the ^{106}Cd experiment in GeMulti

[1] P. Belli et al., *PRC 85 (2012) 044610*
[2] F.A. Danevich et al., NIMA 741(2014)41
[3] NIMA 603 (2009) 328; Inorganic Mater. 47 (2011) 645.

Directionality sensitive detectors: TPC

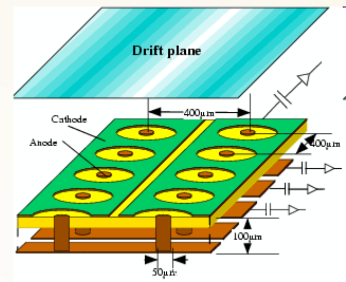
- Detection of the tracks' directions

  ⇒ 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.:

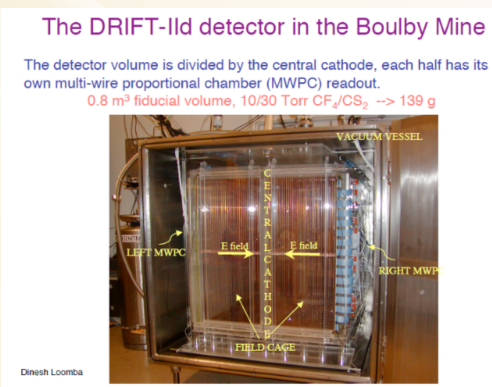
  1. extreme operational stability
  2. high radiopurity
  3. large detector size
  4. great spatial resolution
  5. low energy threshold

NEWAGE



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

DRIFT-IId



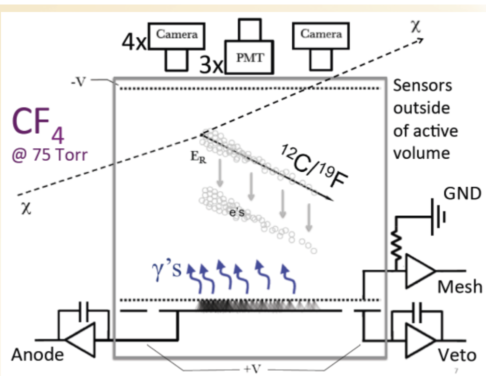
Not yet competitive sensitivity

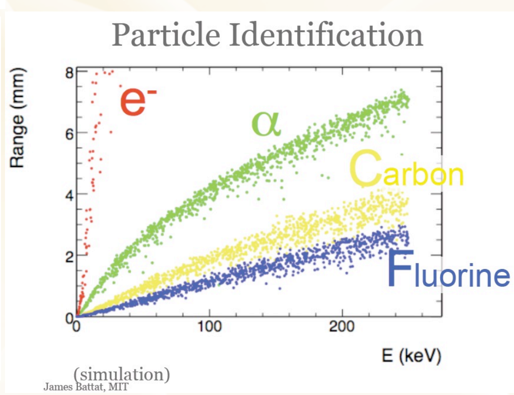
Background dominated by Radon Progeny Recoils (decay of ^{222}Rn daughter nuclei, present in the chamber)

	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!

DM-TPC





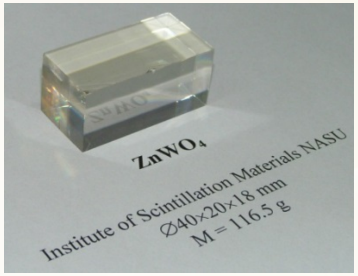
- The **"4--Shooter"** 18L (6.6 gm) TPC 4xCCD, Sea-level@MIT
- moving to WIPP
- Cubic meter funded, design underway

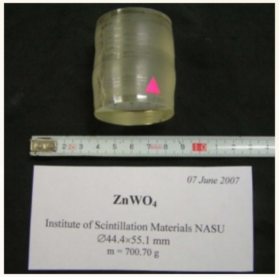
$ZnWO_4$ crystal scintillators in DAMA project

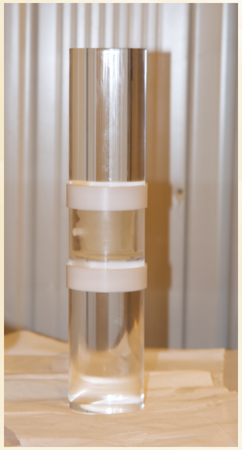
PLB658(2008)193, NPA826(2009)256
NIMA626-627(2011)31, JP38(2011)115107

- Low background $ZnWO_4$ crystal scintillators with large volume and good scintillation properties realized (in collaboration with INR-Kyiv)
- 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

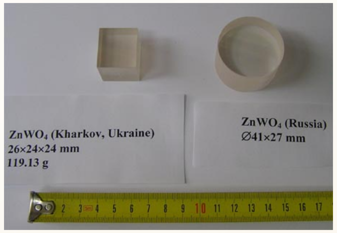
Crystal scintillator	Size (mm)	Mass (g)
ZWO-1	$20 \times 19 \times 40$	117
ZWO-2	$\oslash 44 \times 55$	699
ZWO-2a	$\oslash 44 \times 14$	168

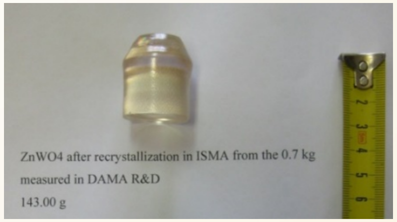


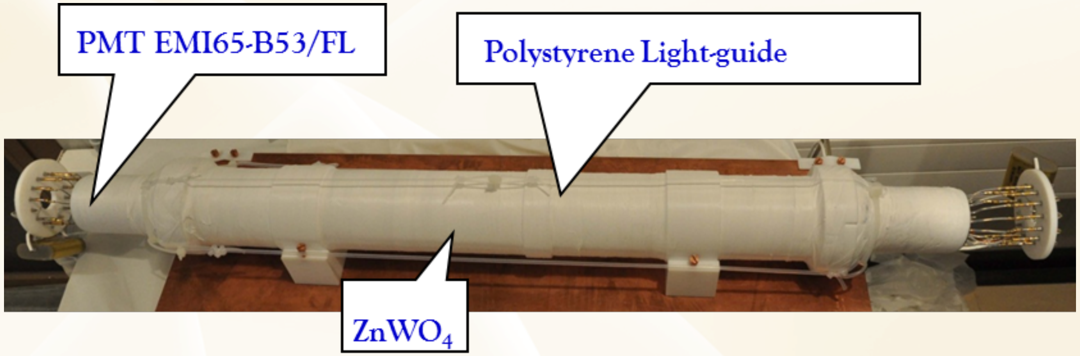




- Main aim of the measurements was the study of the properties of $ZnWO_4$ and the search for 2β processes in Zinc and Tungsten isotopes ($T_{1/2} \sim 10^{18} - 10^{21}$ yr)







Improving radiopurity of $ZnWO_4$ crystal

- 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 $CdWO_4$) and under investigation; 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.

Signal rate in a given scenario

As a consequence of the ***light response anisotropy for heavy particles***, recoil nuclei induced by the DM particles could be discriminated from the background thanks to the expected variation of their low energy distribution along the day

The expected signal counting rate in the energy window (E1,E2) is a function of the time *t*
($v_d(t)$ the **detector velocity in the galactic rest frame**)

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

- **DM particle velocity in the laboratory frame** ($\vec{v}$)
- **local DM halo density** (ρ_0)
- **number of target-nuclei (n) per mass unit** (N_n)
- **differential cross section in the c.m. frame** ($d\sigma_n/d\Omega_{cm}$)
- **quenching factor, it depends on Ω_{out} the output direction of the nuclear recoil in the lab frame** ($q_n(\Omega_{out})$)
- **recoiling nucleus kinetic energy in the laboratory frame** (E_n)
- **nuclear recoil direction in the center of mass frame** (Ω_{cm})
- **DM particle mass** (m_{DM})
- **DM velocity distribution in the galactic rest frame** ($f[\vec{v}+\vec{v}_d(t)]$)
- **detector energy resolution** (Δ)

NB: Many quantities are model dependent and a model framework has to be fixed: in this example, for simplicity, a set of assumptions and of values have been fixed, without considering the effect of the existing uncertainties on each one of them and without considering other possible alternatives

… the model framework considered here

- a simple spherical isothermal DM halo model with Maxwellian velocity distribution, 220 km/s local velocity, 0.3 GeV/cm^3 local density (ρ_0) and 650 km/s escape velocity;
- DM with dominant spin-independent coupling and the following scaling law (DM-nucleus elastic cross section, σ_n, in terms of the DM elastic cross section on a nucleon, σ_p):

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

- a simple exponential form factor:

$$F_n^2(E_n) = e^{-\frac{E_n}{E_0}} \qquad E_0 = \frac{3(\hbar c)^2}{2 m_n r_o^2} \qquad r_0 = 0.3 + 0.91 \sqrt[3]{m_n}$$

Quenching factor:

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

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

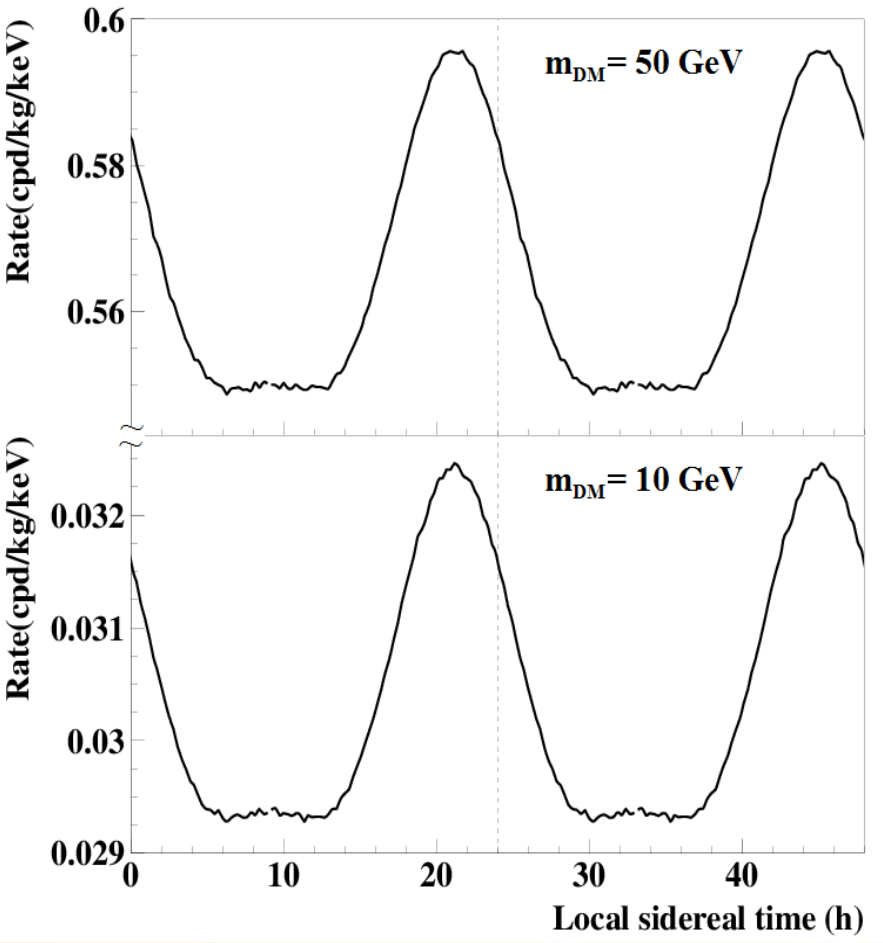
$q_{n,i}$ calculated according to [V.I. Tretyak, Astropart. Phys. 33 (2010) 40] considering the data of the anisotropy to α particles of the $ZnWO_4$ crystal

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

Example of expected signal vs sidereal time

(averaged on one year in the given scenario)

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



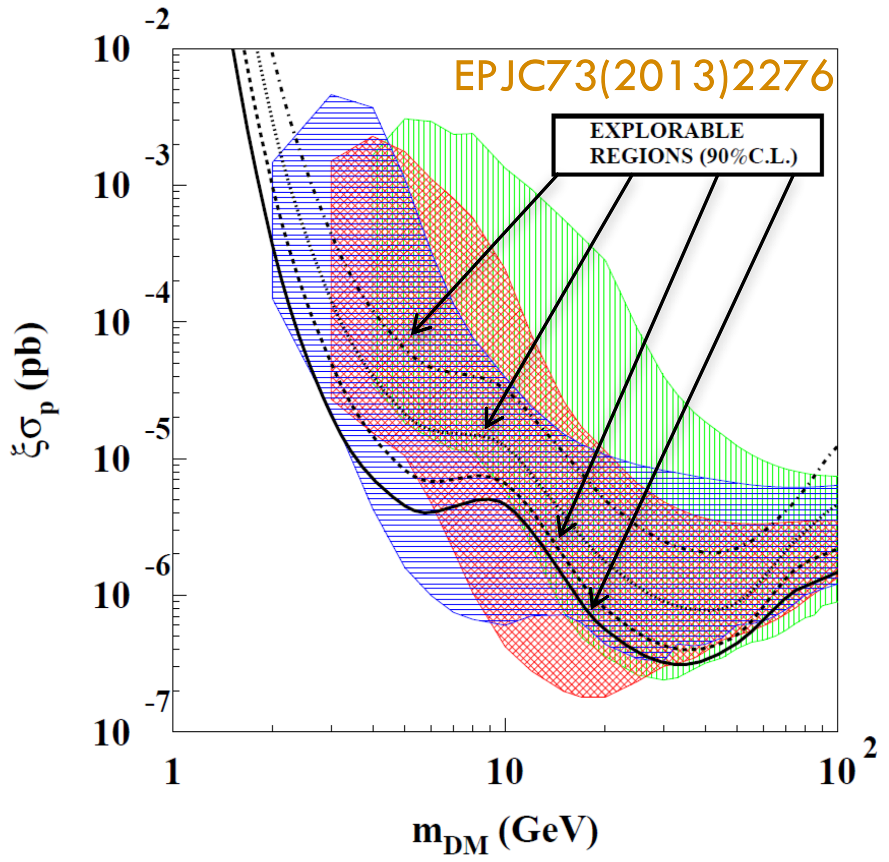
- Maximum rate at 21 h LST, when the DM preferential arrival direction is near the zenith, that is near the crystal axis with the largest light output.
- Analogous results can be obtained also analysing the anisotropic behaviour of the pulse shape of scintillation events.

The signature is very distinctive and cannot be mimicked by background

Example of reachable sensitivity

Assumptions:

- simplified model framework (see before)
- 200 kg of $ZnWO_4$
- 5 years of data taking
- 2 keVee threshold
- four possible time independent background levels in the low energy region:
  - 10^{-4} cpd/kg/keV ———
  - 10^{-3} cpd/kg/keV - - - - - - -
  - 10^{-2} cpd/kg/keV ··············
  - 0.1 cpd/kg/keV —·—·—·-



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

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