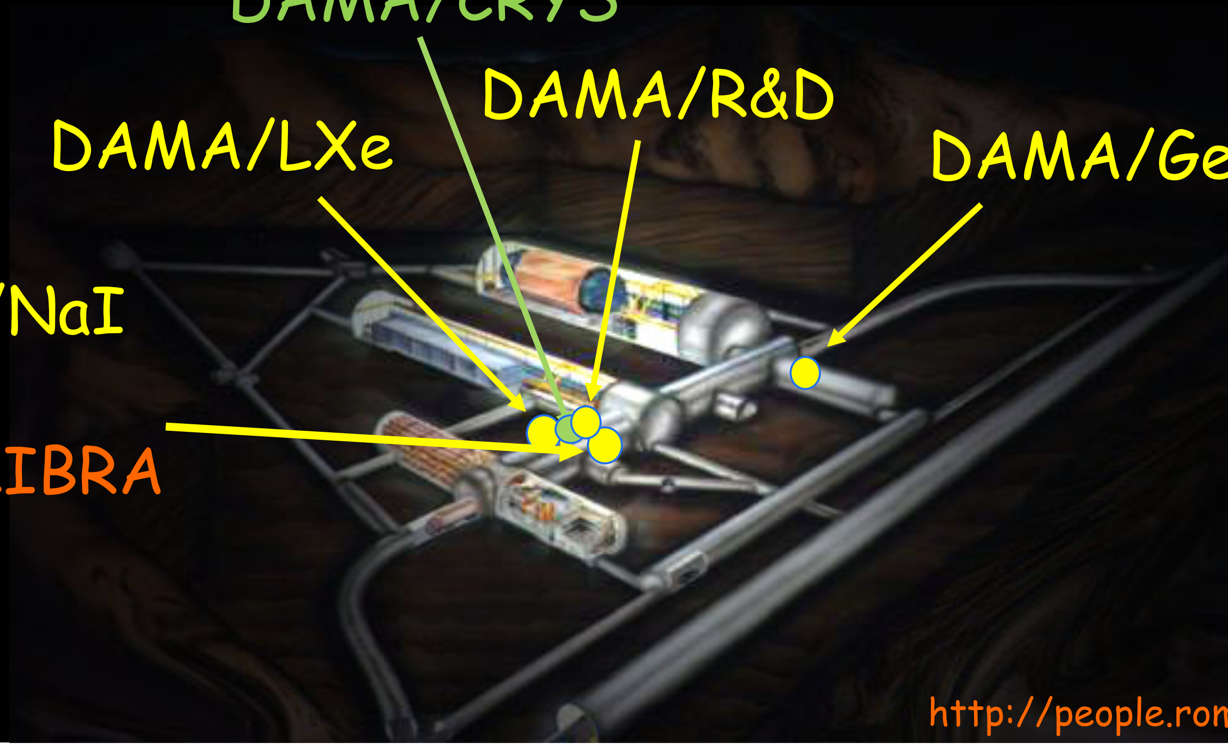
Roma2,Roma1,LNGS,IHEP/Beijing

+ by-products and small scale expts.: INR-Kiev
+ neutron meas.: ENEA-Frascati
+ in some studies on ββ decays (DST-MAE project): IIT Kharagpur/Ropar, India

DAMA: an observatory for rare processes @LNGS



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

The DAMA project

the second generation
DAMA/LIBRA
(~ 250 kg NaI(Tl) full sensitive mass)
running phase2

DAMA/R&D
(multipurpose low bckg set-up)

DAMA/Ge
(multipurpose low bckg set-up)
Low Z window

DAMA/LXe
Filled with Kr-free Xe enriched
either in ^{129}Xe or in ^{136}Xe

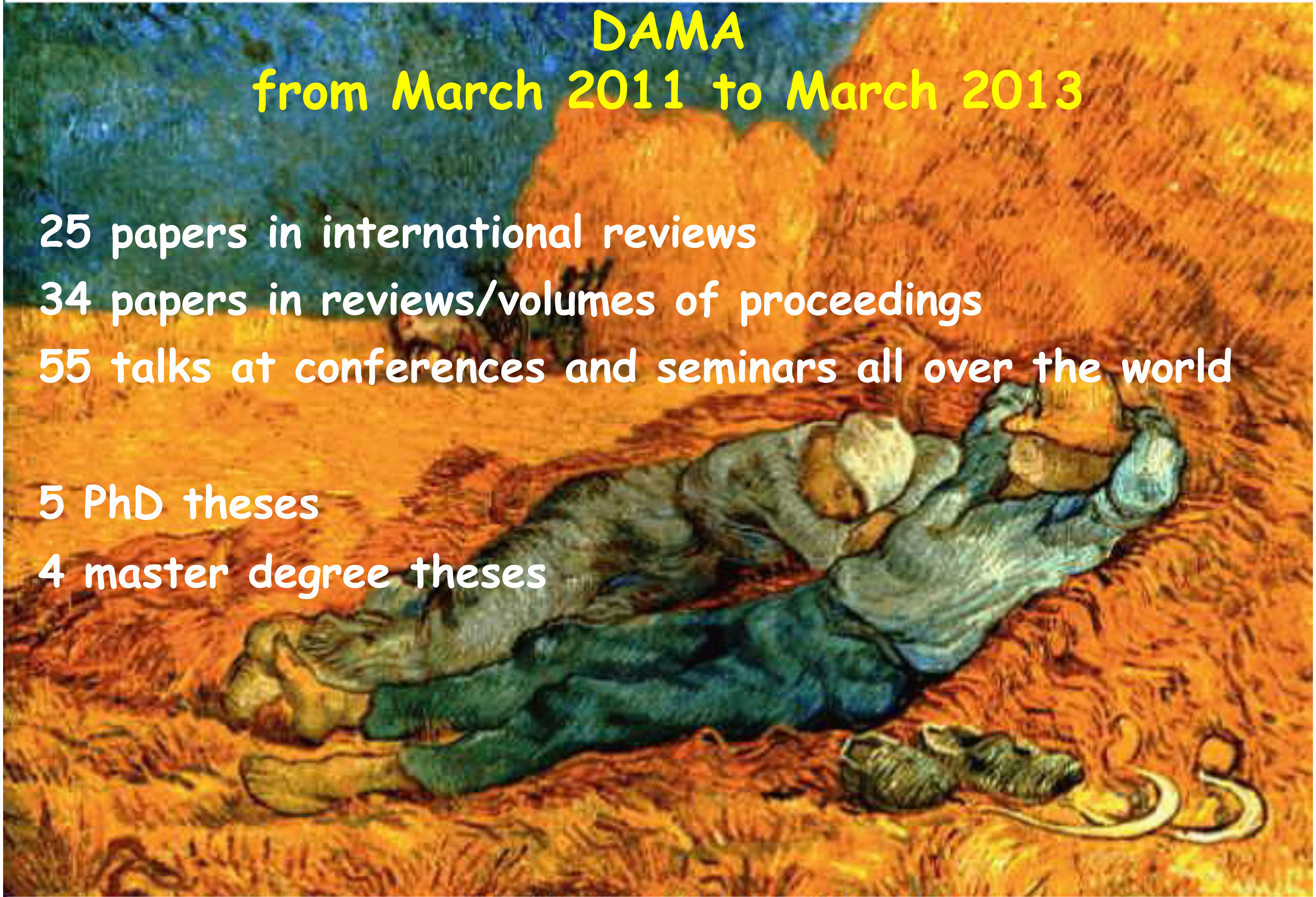
DAMA/CRYS
(multi-purpose low bckg set-up)
just installed

… and toward:

- Multipurpose DAMA/1ton proposed on 1996
- New anisotropic scintillator/nanotube detector for directionality
- Large mass set-ups for specific rare processes

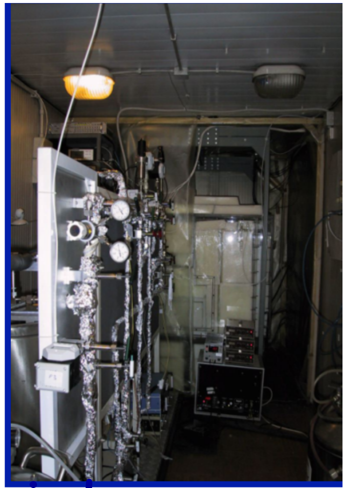
Present/future
Developing and use many low background/new/enriched scintillators/samples
to investigate rare processs

All set-ups upgraded several times


DAMA
from March 2011 to March 2013
25 papers in international reviews
34 papers in reviews/volumes of proceedings
55 talks at conferences and seminars all over the world
5 PhD theses
4 master degree theses

DAMA/LXe:

Pure liquid xenon scintillator filled either with Kr-free Xenon enriched either in ^{129}Xe or in ^{134}Xe, ^{136}Xe.



From March 2011 to March 2013:

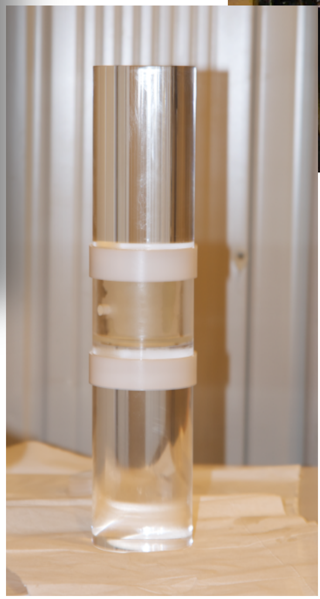
1. At beginning of 2011 an unforeseen maintenance on the old compressor (from the former Xelidon experiment) has been carried out. Then, the set-up has taken data during some months.
2. Compressor definitively dead. The search for a suitable compressor able to contemporaneously drive 2 cold heads, and at acceptable price, took some months.

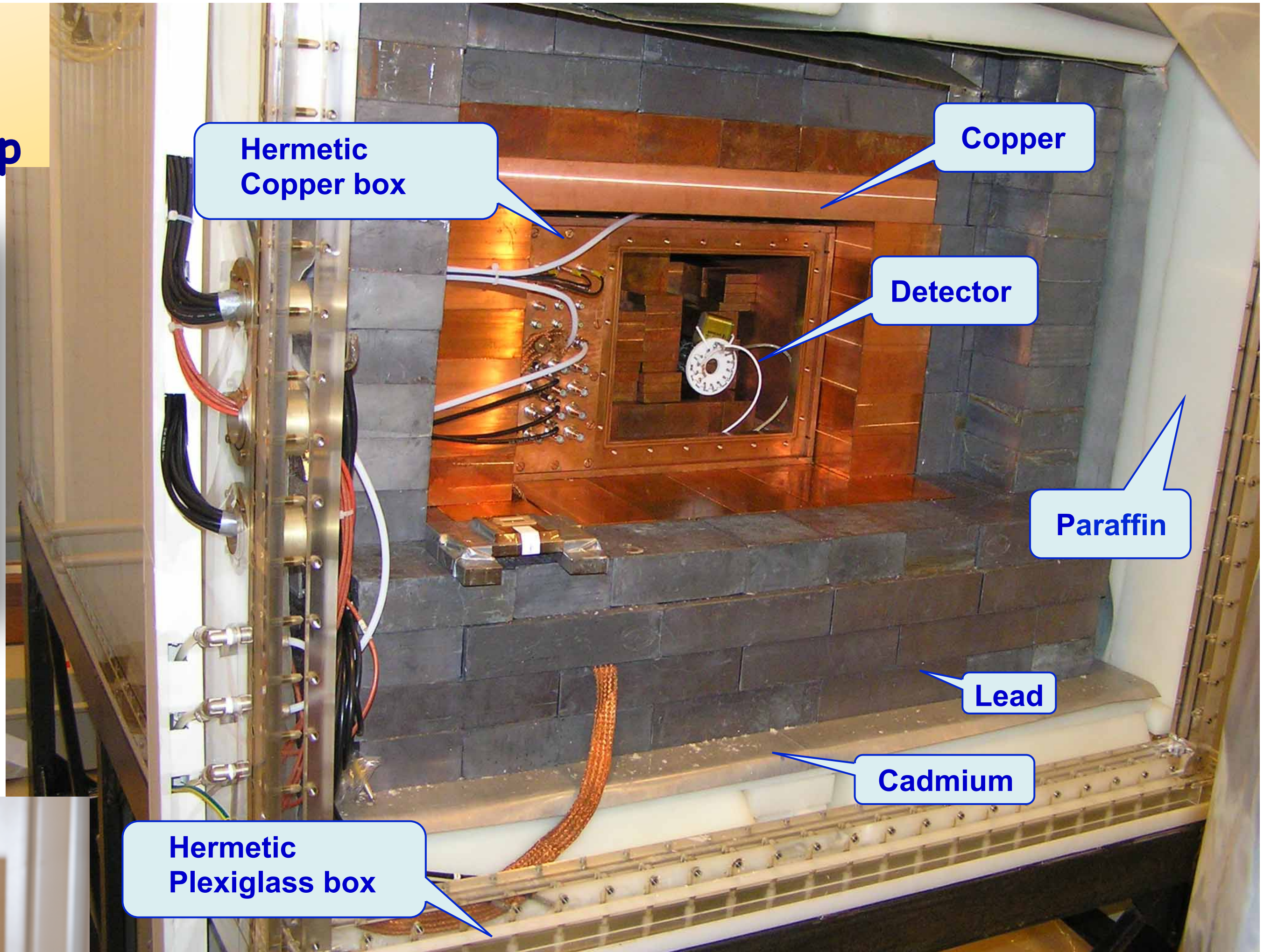
3. The new compressor installed and tested
4. Data taking restarted with Kr-free Xenon enriched in ^{136}Xe focusing the high energy region up to July 2012, then routine maintenance
5. Data taking restarted in Jan 2013
6. Several analyses in progress

DAMA/R&D

General purpose set-up

Upgraded several times





DAMA/R&D:

From March 2011 to March 2013:

BaF_2
Pres. at workshop
+further analysis in progress
+new data taking, detector at hand

$ZnWO_4$
NIMA626(2011)3, JPG38(2011)115107, EPJC73(2013)2276
+ new data analyses
+ work in progress

$CeCl_3$
JPG38(2011)015103
+developments

$^{106}CdWO_4$
Nucl.Phys.Atom.En.12(2011)124, PRC85(2012)044610
+ new data taking in GeMulti
+ new work in progress

$^{116}CdWO_4$
JINST06(2011)P08011, Rad.Meas.in press
+ several upgrades to lower bck
+ in data taking for several years
+ preparation for future GeMulti
+ new developments in progress

Developments/preparations for future meas.
In progress & DAMA/CRYS used for tests and preliminary meas.

$ZnWO_4$ Development of low background $ZnWO_4$ crystal scintillators with large volume and high scintillation properties is important to investigate double beta decay modes in Zn and W isotopes with source=detector approach

Potentially 2β active nuclides present in $ZnWO_4$ crystals.

Transition	Energy release (keV) [6]	Isotopic abundance (%) [7]	Decay channels	Number of nuclei in 100 g of $ZnWO_4$ crystal
^{64}Zn→^{64}Ni	1095.7(0.7)	48.268(0.321)	2ε, $\varepsilon\beta^+$	9.28×10^{22}
^{70}Zn→^{70}Ge	998.5(2.2)	0.631(0.009)	$2\beta^-$	1.21×10^{21}
^{180}W→^{180}Hf	144(4)	0.12(0.01)	2ε	2.31×10^{20}
^{186}W→^{186}Os	489.9(1.4)	28.43(0.19)	$2\beta^-$	5.47×10^{22}

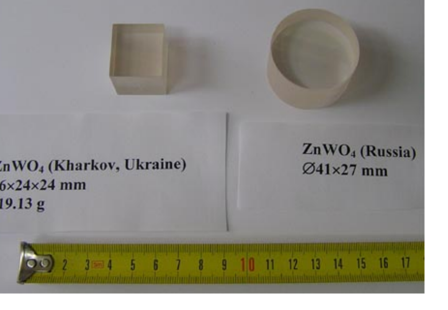
PLB658(2008)193
NPA826(2009)256
NIMA626-627(2011)31
JP38(2011)115107

Various detectors with mass 0.1-0.7 kg realized in Ucraine by exploiting different materials and techniques

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).



Final results on the present stage of investigation of ββ decay modes in Zn and W isotopes with low background $ZnWO_4$

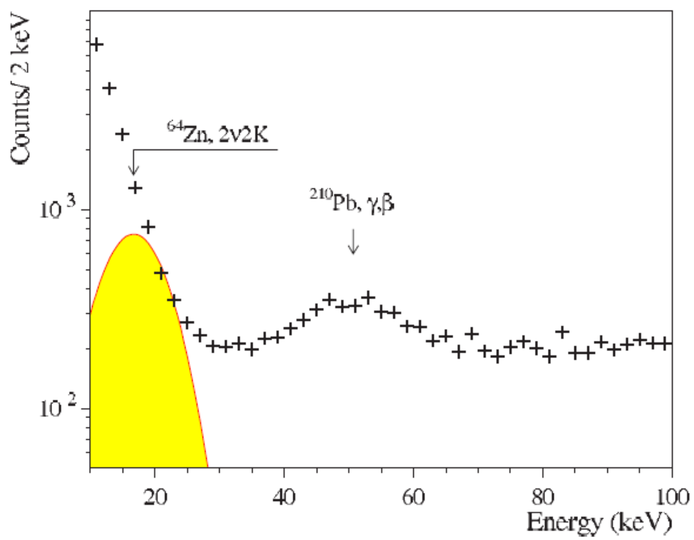
J. Phys. G: Nucl. Part. Phys. 38 (2011) 115107

Improved (up to 2 orders of magnitude) $T_{1/2}$ limits on ββ decay modes of ^{64}Zn, ^{70}Zn, ^{180}W and ^{186}W:

now at level of 10^{18} – 10^{21} yr

→ up to now only 5 nuclides (^{40}Ca, ^{78}Kr, ^{112}Sn, ^{120}Te and ^{106}Cd) over 34 candidates to 2ε, εβ⁺, 2β⁺ processes have been studied at similar level of sensitivity in direct search experiments

Total exposure = 0.529 kg x y



1. A possible positive hint of the (2ν+0ν)εβ⁺ decay in ^{64}Zn with $T_{1/2} = (1.1 \pm 0.9) \times 10^{19}$ yr [Bikit et al., Appl. Radiat. Isot. 46(1995)455] excluded
2. the 0ν2ε capture in ^{180}W is of particular interest because of possible 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 a transition of the ^{183}W to the metastable level $1/2^-$ at 375 keV of ^{179}Hf has been set: $T_{1/2} = 6.7 \times 10^{20}$ yr.

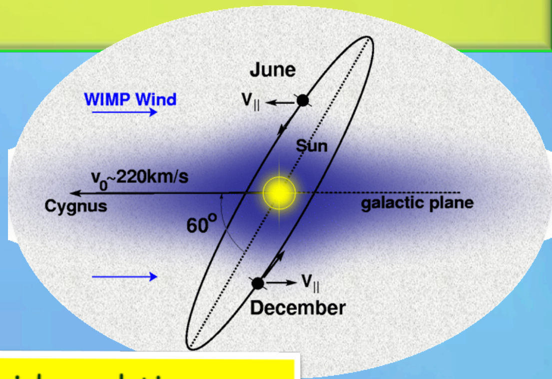
Further developments, new detector at hand
... towards suitable mass fragmented set-up

Development of detectors with anisotropic response

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

Anisotropic detectors are of great interest for many applicative fields, e.g.:
⇒ they can offer a unique way to study directionality for Dark Matter candidates that induce nuclear recoils

Taking into account:
- the correlation between the direction of the nuclear recoils and the Earth motion in the galactic rest frame;
- the peculiar features of anisotropic detectors;



The detector response is expected to vary as a function of the sidereal time

Two strategies

Development of $ZnWO_4$ scintillators

✓ Both light output and pulse shape have anisotropic behavior and can provide two independent ways to study directionality

✓ Very high reachable radio-purity;

✓ Threshold at keV feasible;

Development of Carbon Nano Tubes (CNT) detectors

The detection principle is based on variation of the transport properties due to the particle irradiation

The intrinsic 1-D nature of CNTs makes them very promising for the study of directionality

- **Spin-off and patents**
- **3D detectors multi-wire chamber-like with nanotechnology**
- **Possible other applications:**
  - ▪Particle Physics;
  - ▪Health Physics;
  - ▪etc..

PRC85(2012)044610

2β decay of ^{106}Cd

$^{106}CdWO_4$ in DAMA/R&D (6590 h live time)

^{106}Cd one of the most promising isotope for the $2\beta^+$ decay:

1) natural isotopic abundance (1.25 ± 0.06)% and possibility of enrichment up to 100%;
2) large value of $Q_{2\beta}$= (2770±7) keV and possibility to investigate all the $2\beta^+$, $\varepsilon\beta^+$ and 2ε decay modes;
3) theoretical estimates of the mean lives

	$^{106}CdWO_4$ [1]	$^{116}CdWO_4$ [2]
Attenuation length @ 480 nm	(60 ± 7) cm *	(31 ± 5) cm
FWHM (CWO on PMT) @ 662 keV of ^{137}Cs @ 2615 keV of ^{208}Tl	 10.0% 8.4% **	 10.1% 6.7% (5.6% **)
Enrichment (Isotopic abundance in ^{nat}Cd)	66.4% of ^{106}Cd (1.25%)	82.2% of ^{116}Cd (7.49%)

* – Never reported for $CdWO_4$

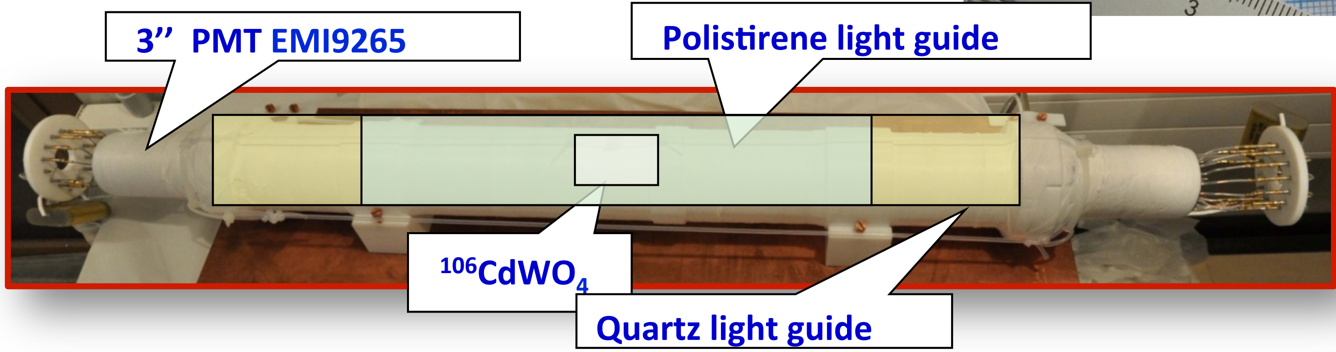
** – FWHM reached in 2β experiment

[1] NIMA615(2010)301 [2] JInst6(2011)P08011

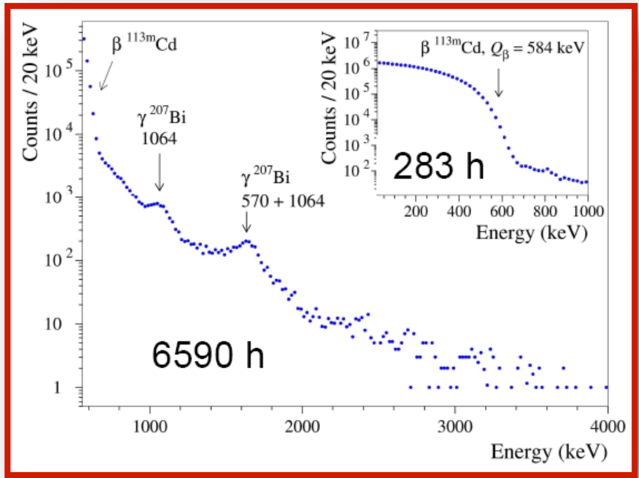
66% of ^{106}Cd, 2.66×10^{23} nuclei of ^{106}Cd

$^{106}CdWO_4$ *boule* 231 g (87.2%)
total loss of ^{106}Cd = 2.3%

$^{106}CdWO_4$ scintillator 215 g

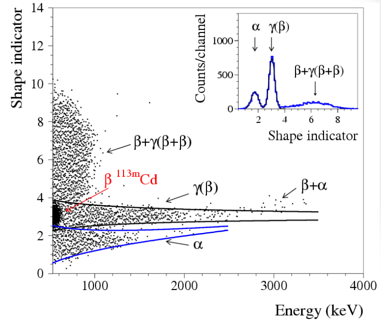


Experimental data

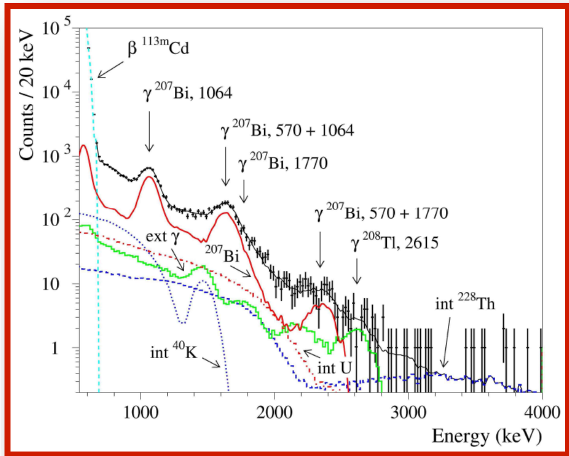


Contamination level in $^{106}CdWO_4$ (mBq/Kg)

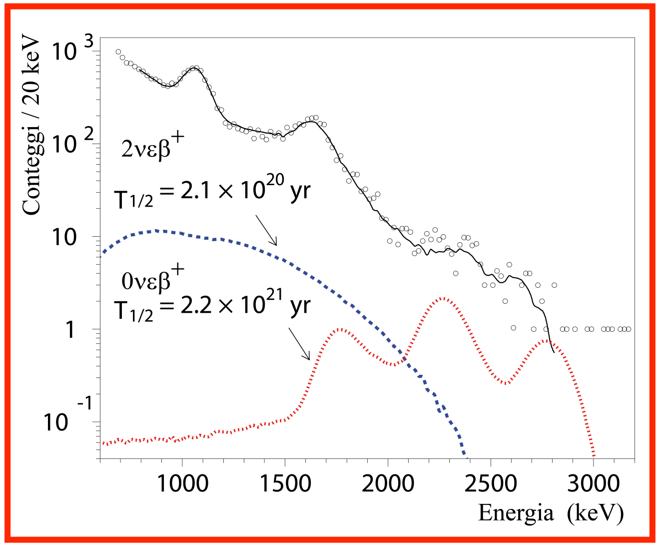
^{207}Bi	<0.7
^{113m}Cd	$116 \cdot 10^3$
^{232}Th	< 0.07
^{228}Th	0.042(4)
^{238}U	<0.6
^{226}Ra	0.012(3)
^{40}K	<1.4



γ/β events selected by PSD



Example of fit to determine the $T_{1/2}$ limit



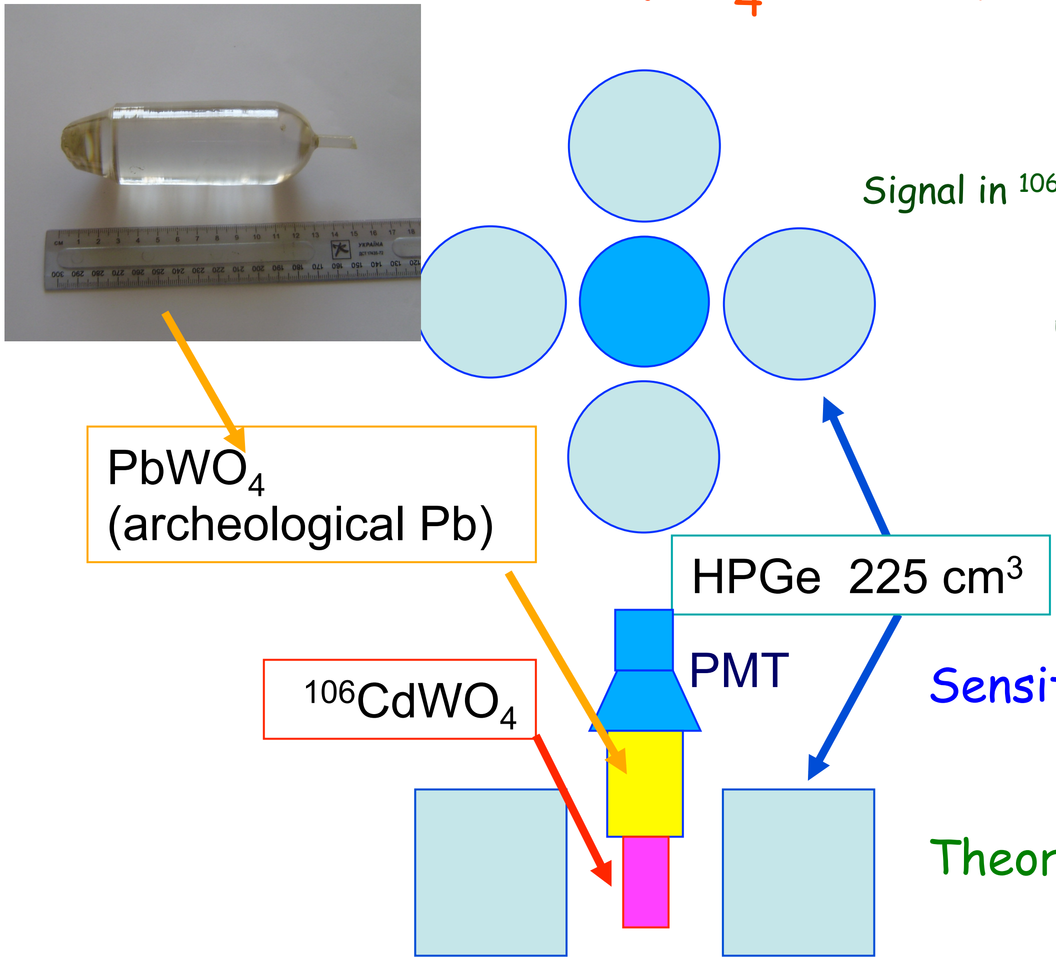
Decay channel	Decay mode	Energy level of ^{106}Pd [keV]	$T_{1/2}$ [yr] (90% CL)
2ε	2ν	1128 (2^+)	$>4.1 \cdot 10^{20}$
	0ν	g.s.	$>1.0 \cdot 10^{21}$
		512 (2^+)	$>5.1 \cdot 10^{20}$
		1128 (2^+)	$>3.1 \cdot 10^{20}$
$\varepsilon\beta^+$	2ν	g.s.	$>2.1 \cdot 10^{20}$
		512 (2^+)	$>1.1 \cdot 10^{20}$
	0ν	g.s.	$>2.2 \cdot 10^{21}$
		512 (2^+)	$>1.3 \cdot 10^{21}$
$2\beta^+$	2ν	g.s.	$>4.3 \cdot 10^{20}$
	0ν	g.s	$>1.2 \cdot 10^{21}$

PRC85(2012)044610

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

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

Now running in new set-up:
$^{106}CdWO_4$ in 4π HPGe (GeMulti)



Signal in $^{106}CdWO_4$ in coincidence with 511 keV γ in HPGe

Detection efficiency: ~ 5-7%

Expected bckg: few events per year

Sensitivity to $2\nu\varepsilon\beta^+$ and $2\beta^+$ decay in ^{106}Cd:

$T_{1/2} \sim 10^{20} - 10^{21}$ yr

Theory:

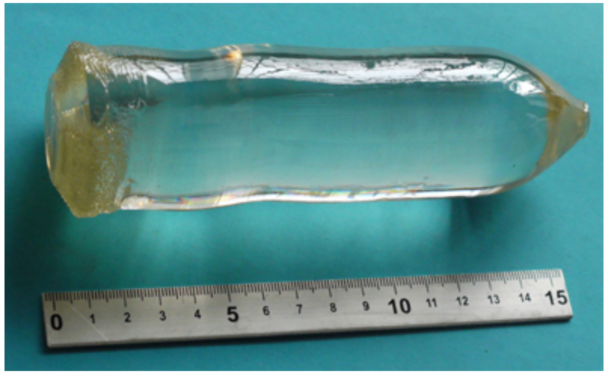
$2\nu 2K$: $T_{1/2} \sim 10^{20}$ - 5×10^{21} yr

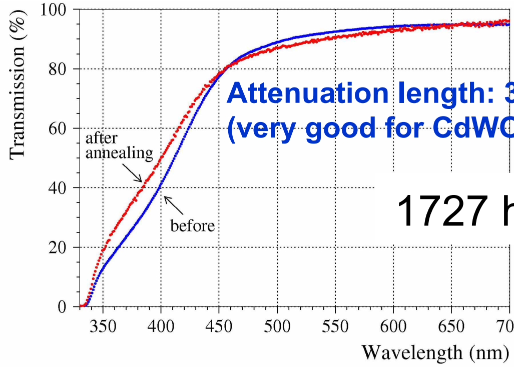
$2\nu\varepsilon\beta^+$: $T_{1/2} \sim 8\times10^{20}$ - 4×10^{22} yr

Future steps:

creation of $^{106}CdWO_4$ from ^{106}Cd depleted in ^{113}Cd to exclude ^{113m}Cd

Development of $^{116}CdWO_4$ scintillators



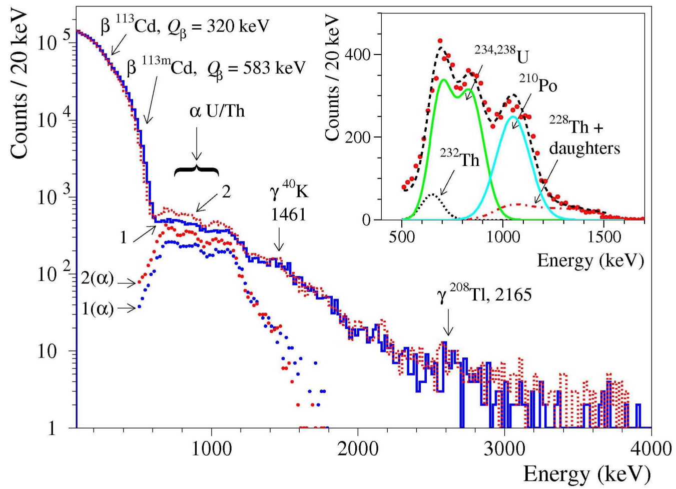


Attenuation length: 31 cm
(very good for $CdWO_4$)

1727 h

1868 g (87% of initial charge)
$^{116}Cd \approx 82\%$

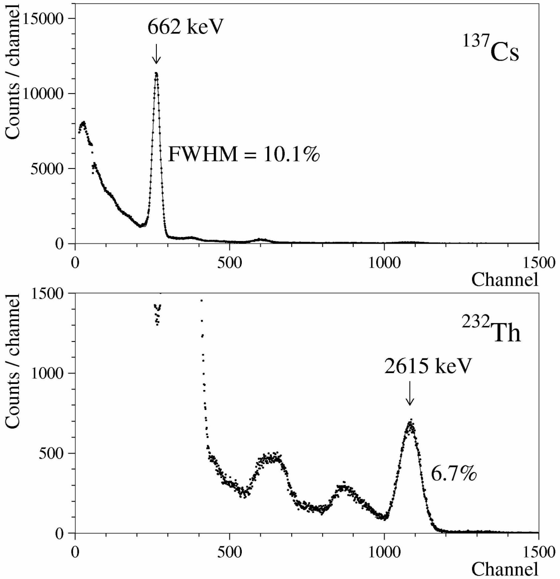
J. of INSTr. 6 (2011) P08011



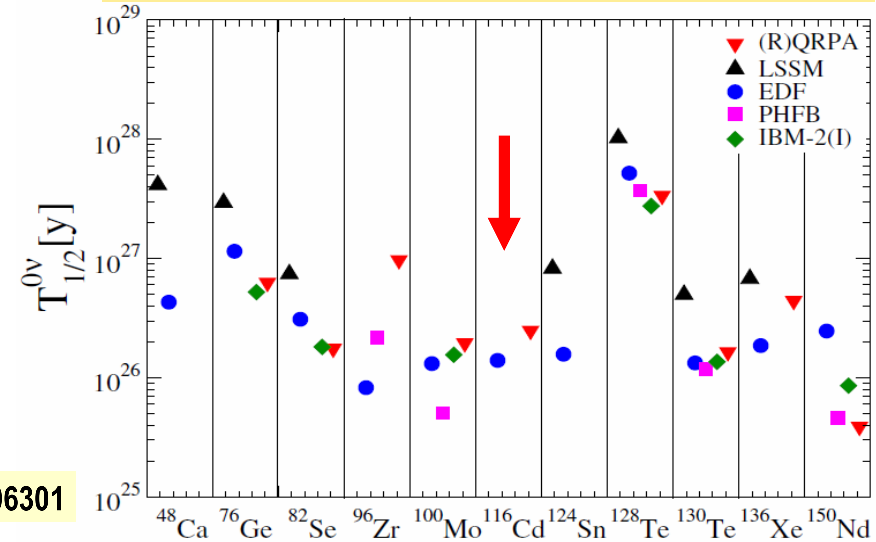
3rd crystal (326 g) tested with
HPGe (468 cm^3) γ spectrometry

Radioactive contaminations
(mBq/kg)

^{40}K	<26
^{137}Cs	2
^{207}Bi	0.6
^{228}Th	0.06
^{226}Ra	<0.005
total α	1.9-2.7



Theoretical calculations of $T_{1/2}$ for $\langle m_\nu \rangle$ = 0.05 eV [1]



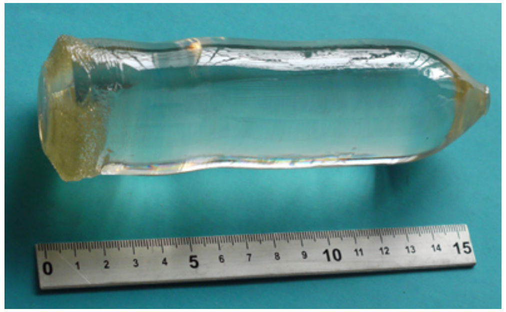
[1] J.D.Vergados, H.Ejiri, F.Simkovic, Rep. Prog. Phys. 75 (2012) 106301

AURORA

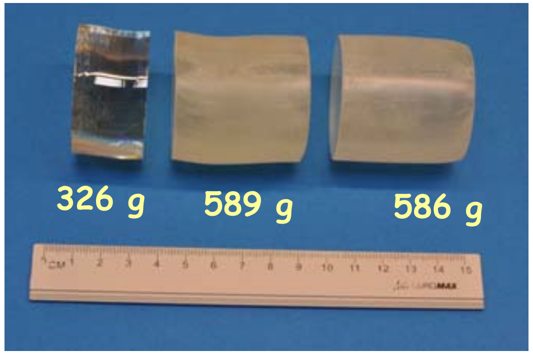
Search for 2β decay modes of ^{116}Cd with ^{116}CdWO$_4$

JINST 06 (2011) P08011
Proc. NPAE2012, 353

Coll. DAMA+INR-Kiev+NIIC+ITEP-Moscow+ JSC NeoChem

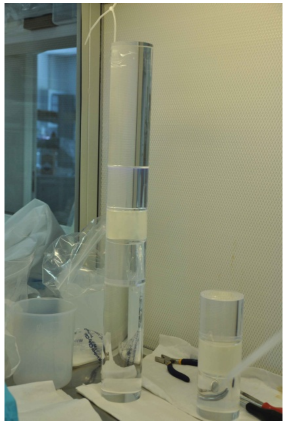


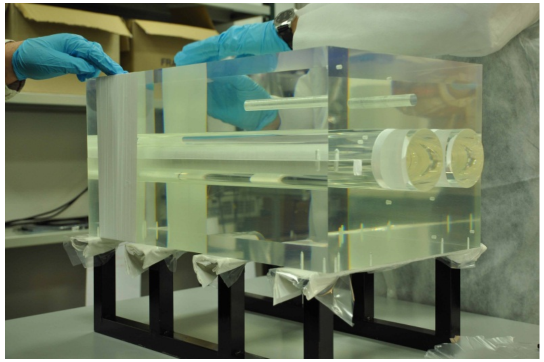
1868 g (87% of compounds)
enrichment ^{116}Cd ≈ 82%

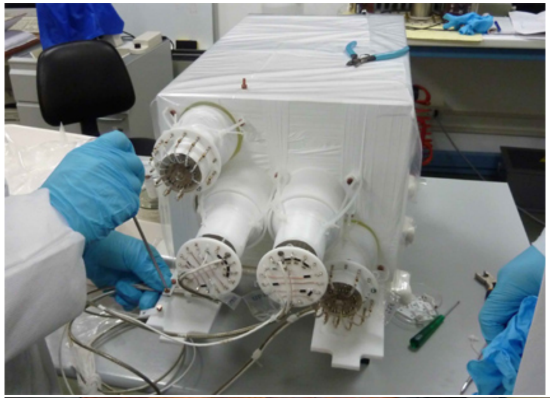


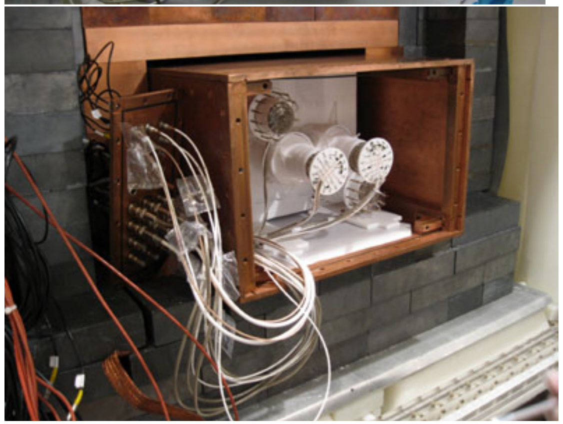
Advantage of CdWO$_4$ scintillators:

- ✓ low level of intrinsic radioactivity
- ✓ good energy resolution
- ✓ stable long time operation
- ✓ pulse-shape discrimination ability





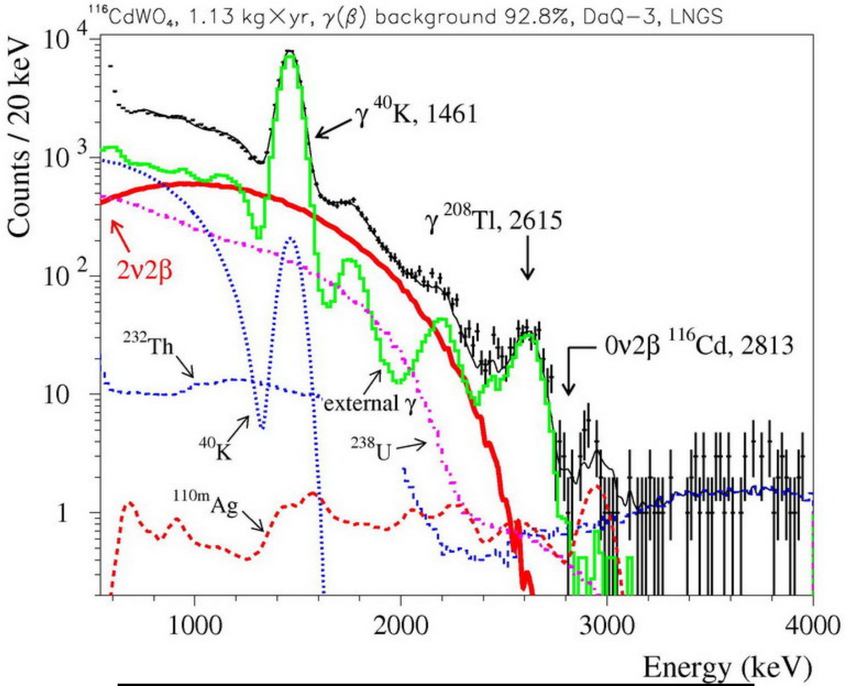




Run	Mass (g)	Livetime (h)	Some features
1	586.2 589.3	1727 [1]	Detector: Veto covered by PTFE; Light-guides covered by PTFE; LS – "LS-221" (ISMA, Kharkiv). DAQ: Sampling rate 20 MS/s; Low level threshold ≈ 20 keV.
2	579.8 582.4	2512	Detector: Veto covered by Tyvek; Light-guides covered by Mylar & PTFE; LS – Ultima Gold Liquid Scintillator. DAQ: Sampling rate 50 MS/s; Low level threshold ≈ 300 keV
3		8552 [2]	
4		3929 (running)	Detector: Plastic veto was removed; additional Cu shield was added

Background of $^{116}CdWO_4$ and 2β decay ^{116}Cd

$^{116}CdWO_4$ 1.16 kg, 8552 h, stage 3



Stage 3, Rate @ 2.7–2.9 MeV:
0.28(4) counts/(keV×kg×yr)

Observed:

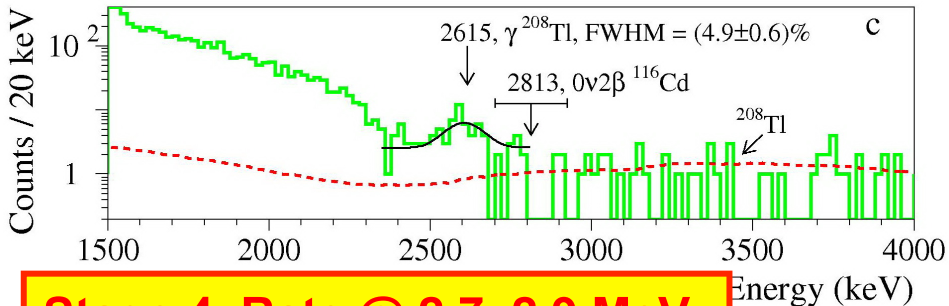
$T_{1/2}$ (2ν2β, ^{116}Cd) = 2.5(5)×10^{19} yr

in agreement with previous results

lim $T_{1/2}$ (2β, $^{116}Cd \rightarrow {}^{116}Sn^*$) ≈
≈10^{21}–10^{22} yr at 90% CL

Modification of $^{116}CdWO_4$ set-up

PSD γ(β), 1.16 kg, 3929 h



Stage 4, Rate @ 2.7–2.9 MeV:
0.11(3) counts/(keV×kg×yr)

preliminary

Estimated sensitivity over 5 yr of meas.:

$T_{1/2}$ ~ (0.5–1.5)×10^{24} yr
$\langle m_\nu \rangle$ ~ (0.4–1.4) eV

DAMA/CRYS

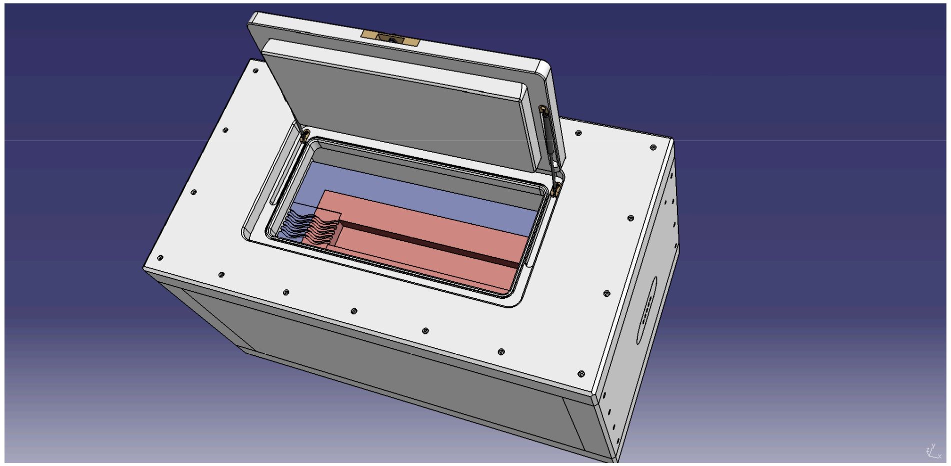
From March 2011 to March 2013:

The installation of this new small set-up, dedicated mainly to test prototypes and to qualify detectors, has been carried out during 2012.

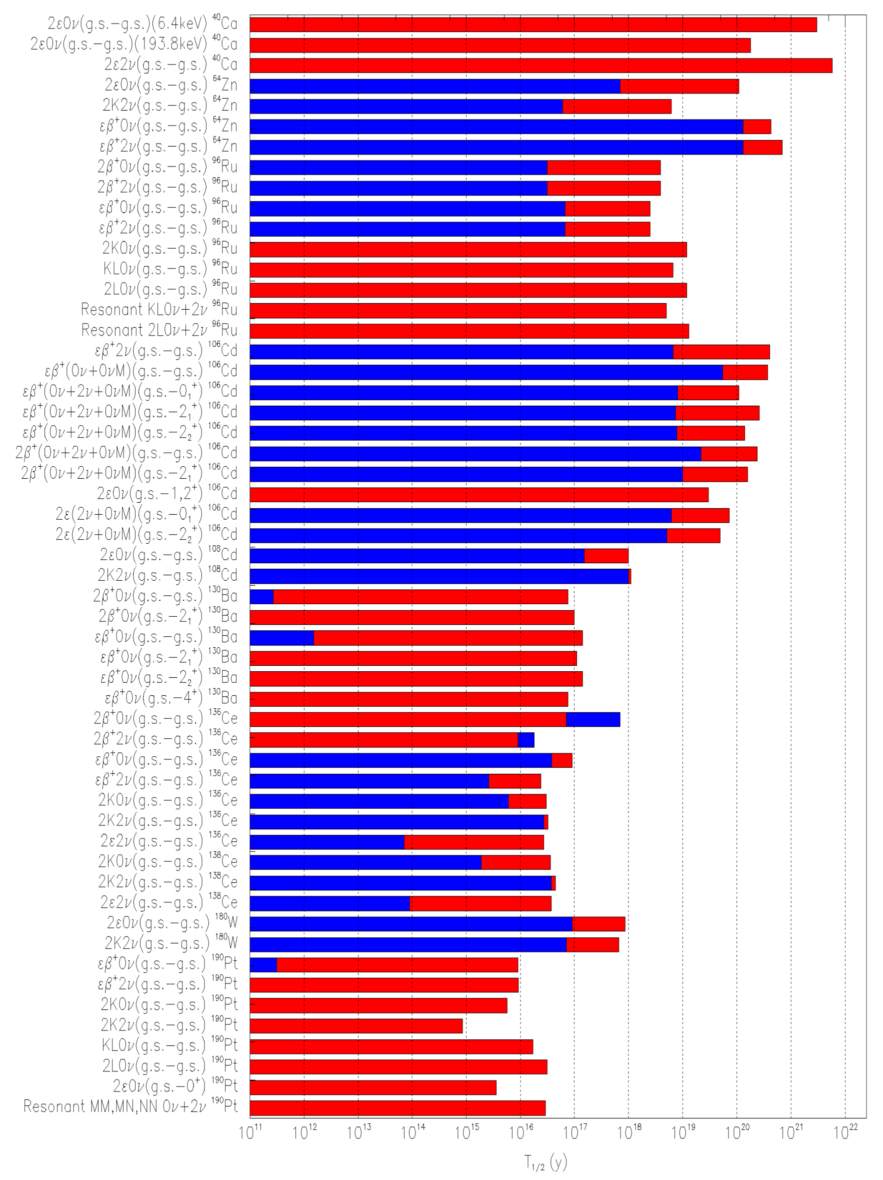
The shield, the environment, the HP nitrogen system, the electronics and the DAQ have been installed, and presently a LaCl3(Ce) crystal is used to optimize the DAQ system.

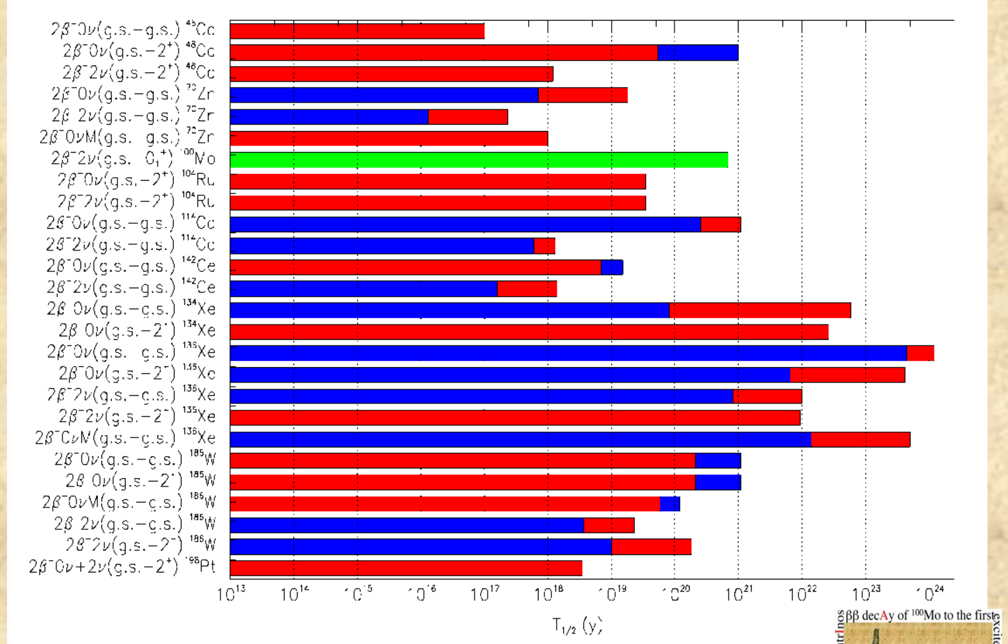
During 2013 improvements in the shield handling, and the installation of Peltier cells (to allow the investigation of some scintillator responses as a function of the temperature) are already in preparation.

This apparatus will regularly work in the future on several kinds of measurements (see also above).



Summary of searches for ββ decay modes (partial list)



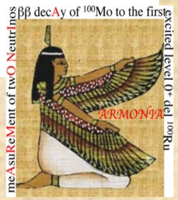


ARMONIA: New observation (green) of $2\nu2\beta^-$ $^{100}Mo \rightarrow ^{100}Ru$ (g.s.$\rightarrow 0_1^+$) decay

NPA846 (2010)143

AURORA: New observation of $2\nu2\beta^-$ ^{116}Cd decay

NPAE2012

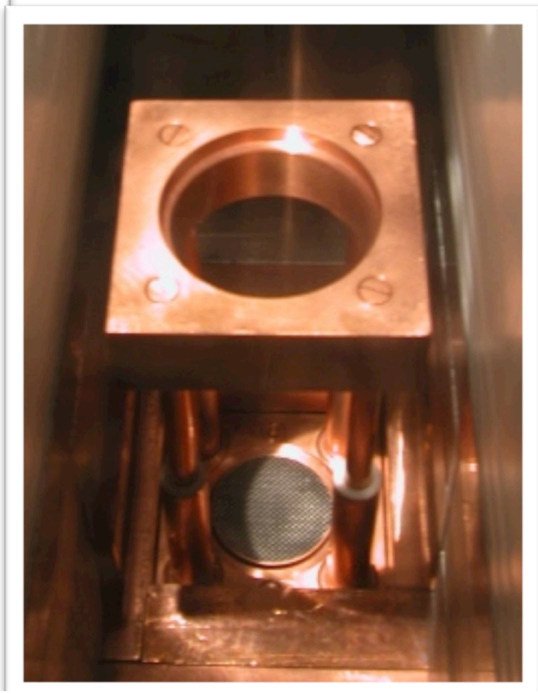


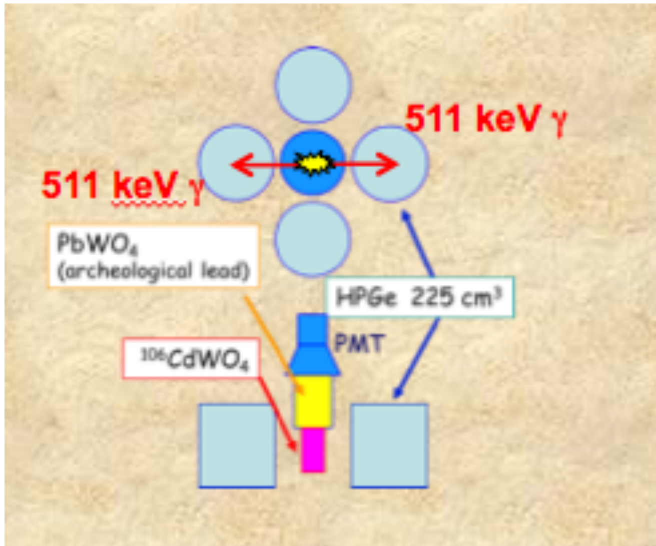
- Many competitive limits obtained on lifetime of $2\beta^+$, $\varepsilon\beta^+$ and 2ε processes (^{40}Ca, ^{64}Zn, ^{96}Ru, ^{106}Cd, ^{108}Cd, ^{130}Ba, ^{136}Ce, ^{138}Ce, ^{180}W, ^{190}Pt, …).
- First searches for resonant ββ decays in some isotopes

$T_{1/2}$ experimental limits by DAMA (in red) and previous ones (in blue). All the limits are at 90% C.L. except for $0\nu2\beta^+$ in ^{136}Ce and $2\beta^-0\nu$ in ^{142}Ce at 68% C.L.. In green observed!

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

DAMA/Ge and LNGS STELLA facility





DAMA/Ge and LNGS STELLA facility

From March 2011 to March 2013:

LiF(W)
PLB711(2012)41
+ work in progress

^{7}LiI(Eu)
NIMA704(2013)40
+ work in progress

SrI_2(Eu)
+ NIMA670(2012)10
+ work in progress

Purified ≈1 kg of Ru
PRC87(2013)034607
+ developments

322 g Dy
NPA859(2011)126
+ developments

Pt
PRC83(2011)034603, EPJA47(2011)91
+ developments in progress

Os
EPJA49(2013)24
+ in data taking
+ developments in progress

$^{106}CdWO_4$ in GeMulti
In data taking

Continuing preparation for new meas. including Sm, Er, Yr after purification of the samples at hand & other ideas

- 3.16 kg Nd_2O_3 has been purified and ~ 1.5 kg of metallic Nd are at hand
- R&D of radiopure GSO scintillators in progress
  technique to purify rare earths in dev.

First observation of α decay of ^{190}Pt to the first excited level of ^{186}Os

E_{exc} = 137.2 keV ⇒ Q_α = 3114(6) keV (Theor. half-life ~10^{13}–10^{14} yr

PRC83(2011)034603

Pt isotopes potentially unstable to α decay

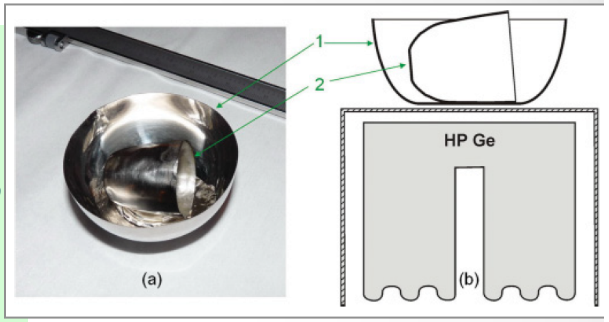
Parent isotope	δ (%) [11]	Q_α (keV) [16]	N_i/1 g
^{190}Pt	0.014(1)	3251(6)	4.32×10^{17}
^{192}Pt	0.782(7)	2418.6(2.2)	2.41×10^{19}
^{194}Pt	32.767(99)	1518.3(1.6)	1.01×10^{21}
^{195}Pt	33.832(10)	1172.0(1.6)	1.04×10^{21}
^{196}Pt	25.242(41)	808.1(2.6)	7.79×10^{20}
^{198}Pt	7.163(55)	100(4)	2.21×10^{20}

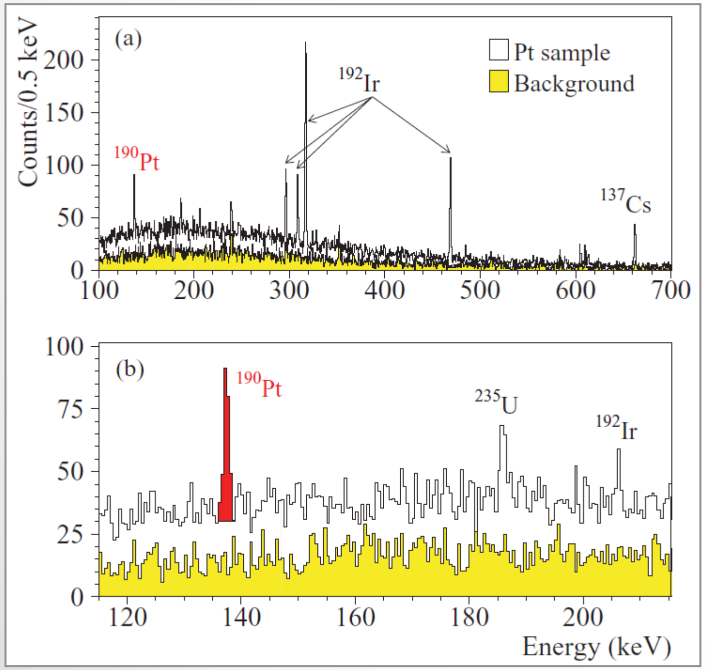
- α decay ^{190}Pt → of ^{186}Os (g.s.) previously observed: $T_{1/2} = (6.5 \pm 0.3) \times 10^{11}$ yr

Pt crucibles (42.53 g) measured in **GeCris** (468 cm^3, FWHM=2.0 keV@1332 keV)

t(sample) = 1815.4 h

t(bckg) = 1045.6 h





- No significant contamination by “usual” radioactive contaminants: U/Th series, ^{40}K, ^{60}Co
- ^{192}Ir present: 49 ±3 mBq/kg (cosmogenic activation of Pt by cosmic rays at the Earth’s surface)

Peak at (137.1 ± 0.1) keV absent in bckg spectrum

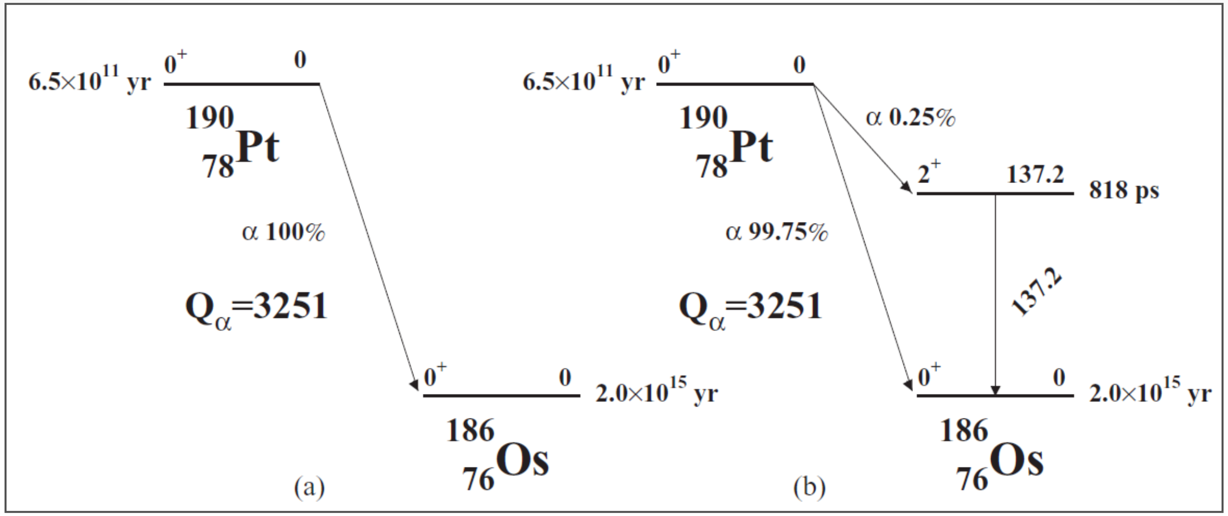
The presence of an excess around 137 keV credited at ≈ 8 σ

Other processes mimicking the decay excluded

$$T_{1/2} = 2.6^{+0.4}_{-0.3}(\text{stat.}) \pm 0.6(\text{syst.}) \times 10^{14} \text{ yr}$$

$T_{1/2}$ in relevant agreement with theoretical calculations based on the liquid drop model and the description of the α decay as a very asymmetric fission process

Implication and perspectives



Old scheme of the ^{190}Pt α decay and the updated scheme after our observation of the $^{190}\text{Pt}\rightarrow{}^{186}\text{Os}(2^+)$ transition

... and more:

- Improved $T_{1/2}$ limits for α decays of other Pt isotopes at level of 10^{16}–10^{20} **yr**

- First limits on:
  resonant 0ν2ε in ^{190}Pt: $T_{1/2} \sim 10^{14}$-10^{16}yr

  2β of ^{198}Pt to the 411.8 keV excited level of ^{198}Hg: $T_{1/2} > 3.5 \times 10^{18}$ yr

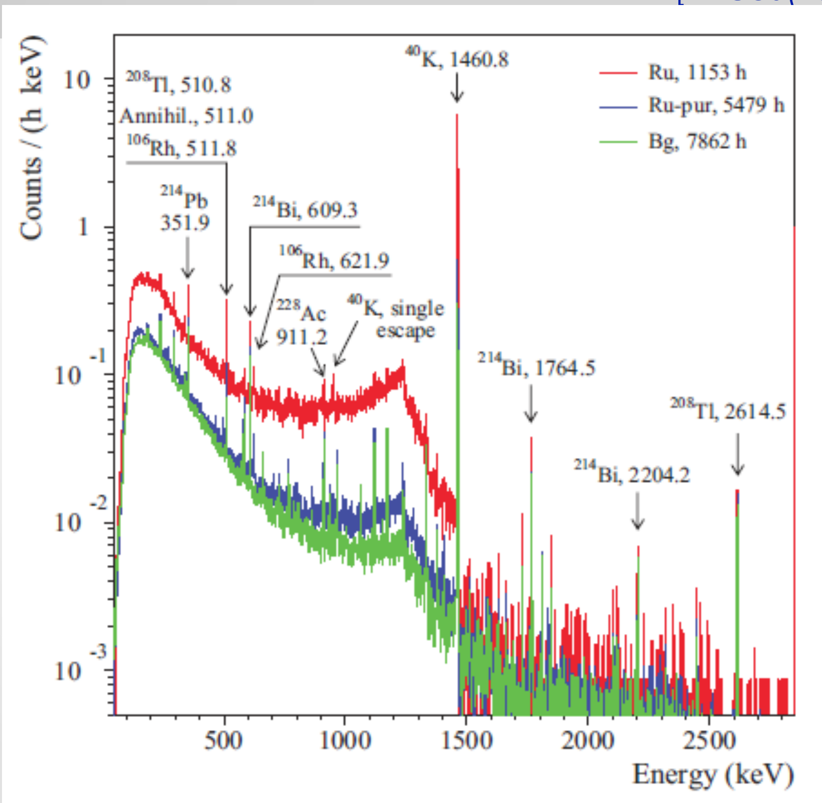
New measurements with ~200 g Pt sample are foreseen

Search for double-β decays of ^{96}Ru and ^{104}Ru by ultra-low background HP Ge γ spectrometry

EPJA42(2009)171
PRC87(2013) 034607

- ^{96}Ru potentially $2\beta^+$ active nuclei, $\delta \sim 5{,}54\%$
- Resonant $0\nu2\varepsilon$ (energy-release ≈ energy of excited level daughter's nuclei), that can arise decay rate (up to a factor of 10^6)
- Favourable theorethical $T_{1/2}$:
  $2\nu2\varepsilon$ - $(4.7\text{-}39)\times10^{20}$ yr, $2\nu\varepsilon\beta^+$ – $(2.0–23)\times10^{21}$ yr (g.s.→g.s.)
  [PRC86(2012)024301]

Possible processes:
$2\beta^+$ – g.s.
$\varepsilon\beta^+$ – g.s., 778 keV
2ε – up to 2713 keV



Stage 1

- Preliminary results EPJA, $2\beta^+/\varepsilon\beta^+/2\varepsilon$ ($0\nu+2\nu$) in ^{96}Ru
- Further measurements over 2162 h with a 473 g sample
- Preliminary limits on 2β in ^{96}Ru: $T_{1/2} \approx 10^{18–19}$ y

Stage 2

- Purification from ^{40}K with electron beam melting method (10 times decrease)
- Increased mass of Ru sample (720 g)
- T=5479 h in **Ge-Multi** (4 x 225 cm^3)
- Reached sensitivity:
  $T_{1/2} \approx 10^{20–21}$ y for ^{96}Ru
  $T_{1/2} \approx 10^{20}$ y for ^{104}Ru ($2\beta^-$)

Previous limits improved

$T^{2K0\nu}_{1/2} > 1.0 \times 10^{21}$ yr (90%C.L.) in ^{96}Ru

$T^{resKL0\nu}_{1/2} > 2.0 \times 10^{20}$ yr (90%C.L.) in ^{96}Ru

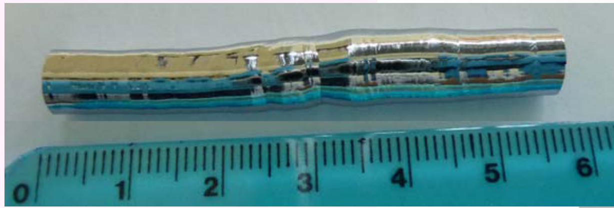
New measurement with purified sample with higher mass

First search for rare decays of Osmium by low background HPGe detector

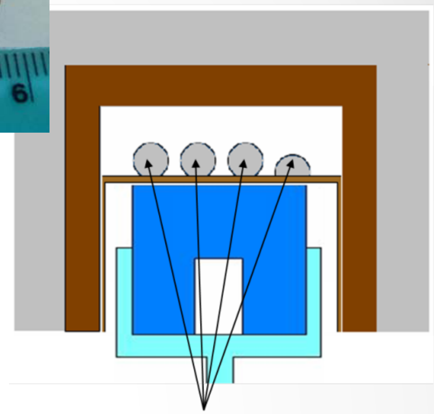
Eur. Phys. J A 49(2013)24

Osmium rare decays

- $\varepsilon\beta^{+}$, 2ε decay in ^{184}Os (Q=1454 keV, δ=0.02%)
- $2\beta^{-}$ decay in ^{192}Os (Q=412 keV, δ=40.78%)
- Possibility of ***resonant*** **$0\nu2\varepsilon$** in ^{184}Os
- ^{184}Os and ^{186}Os are potentially unstable relatively to α decay to excited levels of daughter nuclei

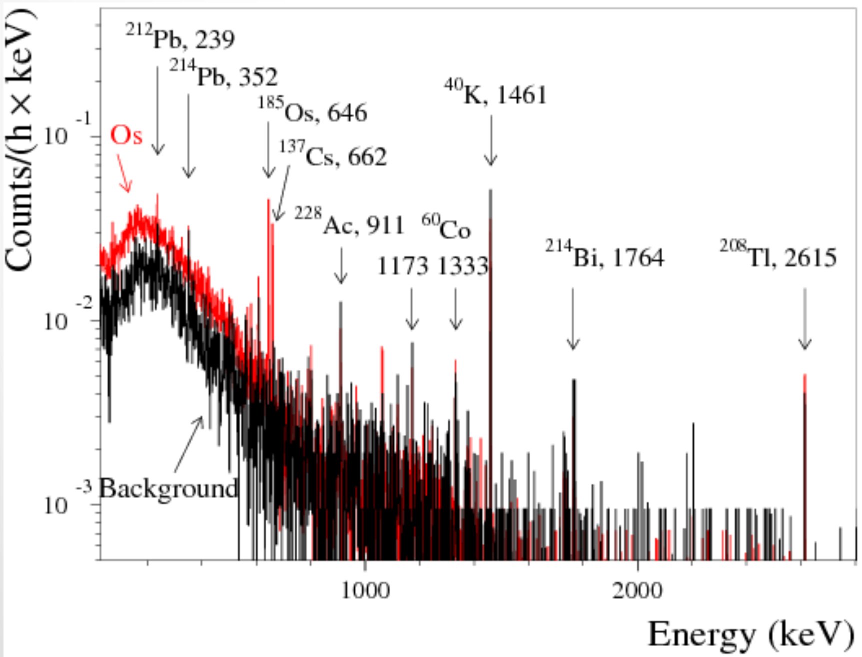


HPGe detector end cap



Osmium samples
172.5 g

bckg (1046 h) and osmium sample (2741 h)



HPGe detector (465 c m^3)
FWHM = 2 keV @1332 keV

Radioactive Contaminations

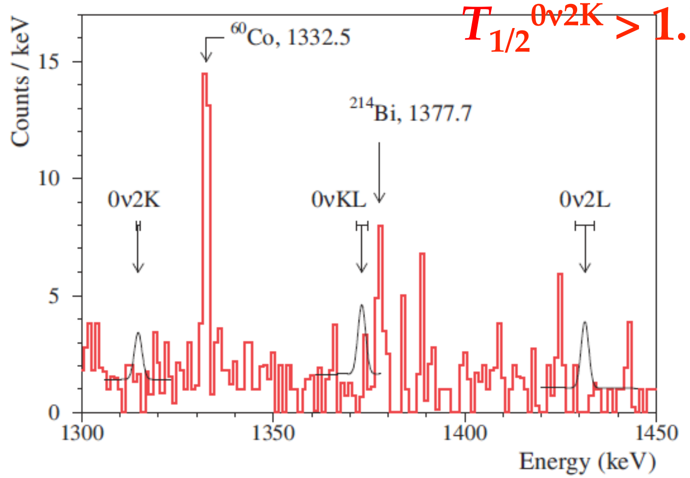
Chain	Nuclide	Activity (mBq/kg)
^{232}Th	^{228}Ra	≤ 2.0
	^{228}Th	≤ 2.3
^{238}U	^{226}Ra	≤ 0.6
	^{40}K	≤ 1.9
	^{60}Co	≤ 0.1
	^{137}Cs	1.9 ± 0.3
	^{185}Os	3.0 ± 0.3
	^{207}Bi	0.4 ± 0.1

✓ First search for 2β decay of Os isotopes

0ν2K decay in ^{184}Os

Eur. Phys. J A 49(2013)24

$T_{1/2}^{0\nu2K} > 1.7 \times 10^{17}$ yr

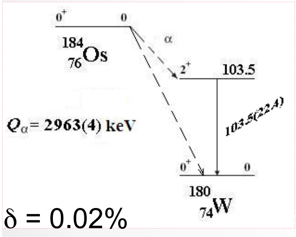


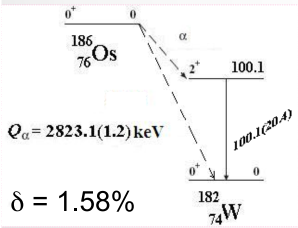
- Double β processes in ^{184}Os have been bounded on the level of $T_{1/2} > 10^{16-17}$ yr (90% C.L)
- 2β decay of ^{192}Os to the 2^+_1 level of ^{192}Pt is restricted as $T_{1/2} > 5.3 \times 10^{19}$ yr (90% C.L)

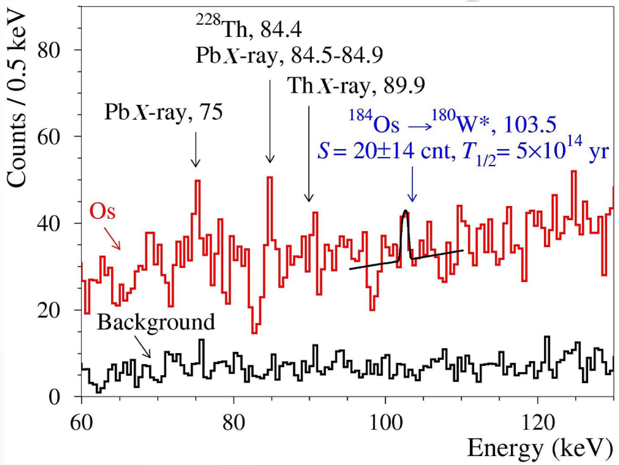
✓ First possible hint of α decay of ^{184}Os

Very Preliminary

Proc. NPAE2012, (2013) 357







Theoretical estimates:

$T_{1/2} \approx 1.2 \times 10^{15}$ yr [1] , $T_{1/2} \approx 2.6 \times 10^{15}$ yr [2]

[1] *Buck B., Merchant A.C., Perez S.M.* // J. Phys. G 17(1991)1223

[2] *Poenaru D.N., Ivascu M.* // J. Phys. 44(1983)791

- Hint for α decay of ^{184}Os to the first excited level of ^{180}W: $T_{1/2} = 5^{+8}_{-2} \times 10^{14}$ yr
- Limit on α decay of ^{186}Os to the first excited level of ^{182}W: $T_{1/2} > 4 \times 10^{16}$ yr

Measurement in progress;
new measurement with Os powder foreseen,
future enrichment in ^{184}Os considered

DAMA/LIBRA-phase2

~250 kg ULB NaI(Tl) full sensitive fragmented target-detector

(all operations involving crystals and PMTs - including photos - in HP Nitrogen atmosphere)

^{232}Th, ^{238}U and ^{40}K residual contaminations in DAMA/LIBRA NaI(Tl) detectors:
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,
  Corollary arguments: PRD84(2011)055014, EPJC72(2012)2064
- ***Results on rare processes:*** *PEP violation in Na, I:* EPJC62(2009)327, *CNC in I:* EPJC72(2012)1920

DAMA/LIBRA:

From March 2011 to March 2013:

high Q.E. PMTs

JINST7(2012)P03009

+ in operation

Phase1

NIMA630(2011)279,CanJPhys89(2011)11,
PPNP66(2011)169,PRD84(2011)055014,
PhysProc37(2012)1095,NIMA692(2012)120.
IJMP(c.s.)12(2012)37 EPJC72(2012) 2064,
EPJC72(2012)2064

+ Several data analyses in progress

Rare processes

Eur. Phys. J. C 72 (2012) 1920

+ data taking and data analyses in progress

Phase2

Data taking + analyses in progress

Upgrades/developments

+new preamp. (installed) and trigger modules(at hand)
+ design of some simplification of elect. chain in progress
+ Several kinds of data analyses in progress
....

Search for charge non-conserving processes in ^{127}I by coincidence technique

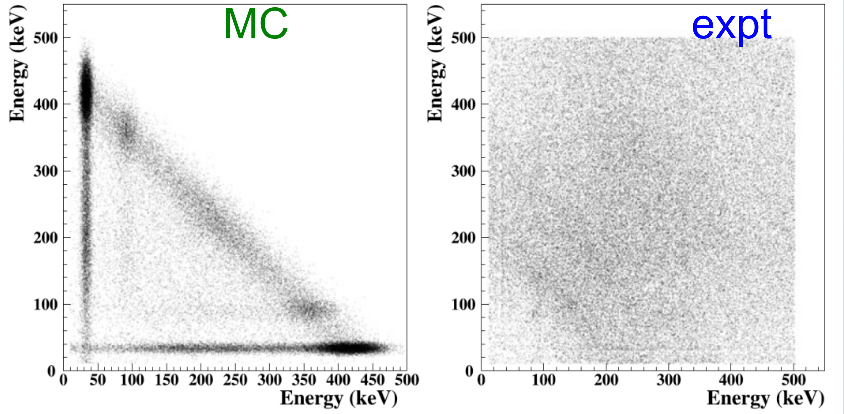
$(A,Z) + e^- \rightarrow (A,Z)^* + \nu_e$ $E=m_ec^2-E_B$

Eur. Phys. J. C 72 (2012) 1920

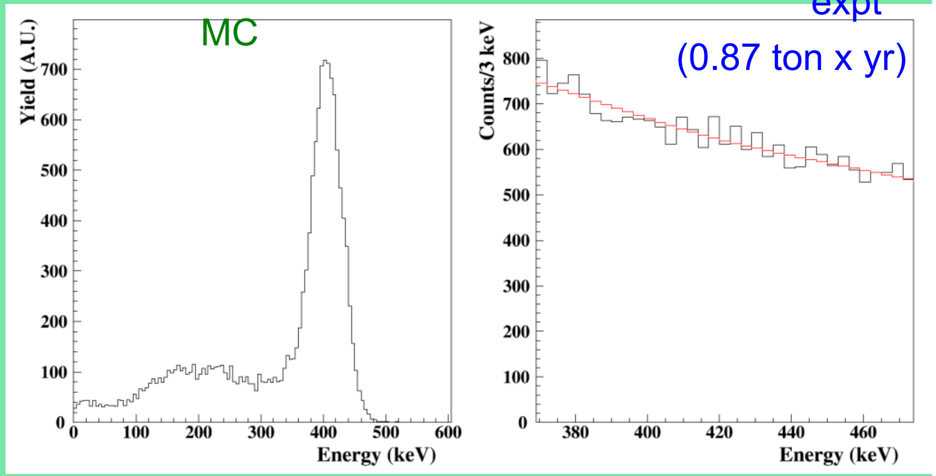
Idea:
detect double coincidence events given by the relaxation energy of the atomic shells (33.2 keV) in one detector and by de-excitation γ escaping into a nearby detector → Peculiar signature and significant bckg reduction

Most probable process involves 57.6 keV excited level of ^{127}I, but present analysis focused on the 417.9 keV one, offering the largest detection efficiency for the double-coincidence from the CNC-EC searched for as well as the lowest bckg

Events with multiplicity 2: E1 versus E2
same number of events fills the 2 scatterplots



E.g.: considering e⁻ disappearance, expected τ for 3 extra-dimensions is 9×10^{25} yr, i.e. not very far from present experimental sensitivities



Events in the other detector in the 27–40 keV window.
Signal of de-excitation γ following the CNC-EC process expected in this window.
Superimposed red line shows the best-fit curve (χ^2/d.o.f. =1.04)

New limit: $\tau > 1.2 \times 10^{24}$ yr (90 % C.L.) → about one order of magnitude larger than those previously available for CNC-EC involving nuclear level excitations of ^{127}I and of the same order of magnitude than those achieved for analogous processes in ^{129}Xe

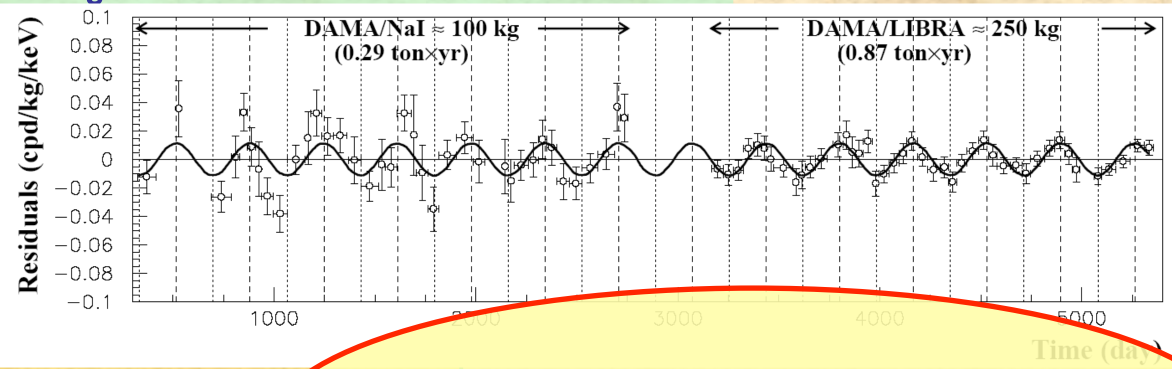
(The lifetime determination has an absolute value for each possible - past, present or future - theory and it is not model dependent)

Some on Dark Matter investigation by model-independent annual modulation signature

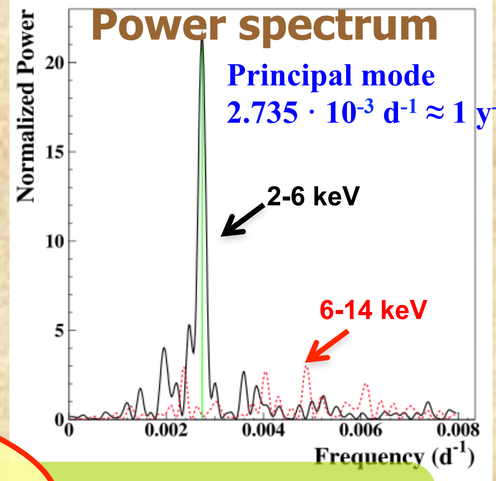
DAMA/NaI (7 years) + DAMA/LIBRA (6 years). Total exposure: **1.17 ton×yr** (the **largest** exposure ever collected in this field)

EPJC 56(2008)333, EPJC 67(2010)39

Experimental single-hit residuals rate *vs* time in 2-6 keV



Power spectrum



$A\cos[\omega(t-t_0)]$

continuous lines: t_0 = 152.5 d, T = 1.00 y

A=(0.0114±0.0013) cpd/kg/keV

χ^2/dof = 64.7/79   8.8 σ C.L.

Absence of modulation? No

χ^2/dof=140/80 P(A=0) = 4.3×10^{-5}

fit with all the parameters free:

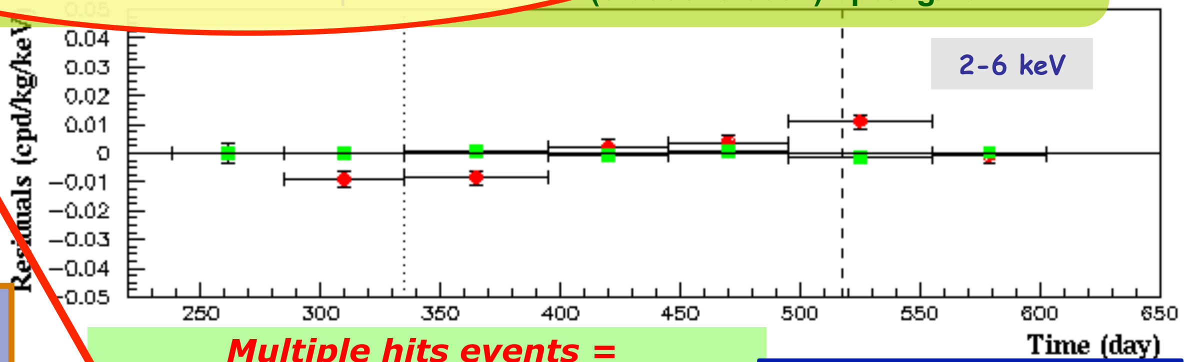
A = (0.0116 ± 0.0013) cpd/kg/keV

t_0 = (146±7) d

T = (0.999±0.002) y 8.9σ C.L.

Other kinds of independent analyses give always same conclusions

Comparison between **single hit residual rate (red points)** and **multiple hit residual rate (green points)** for (DAMA/LIBRA 1-6); Clear modulation in the single hit events A=(...) cpd/kg/keV; No modulation in the residual rate of the multiple hit events A=-(0.0006±0.0004) cpd/kg/keV



Multiple hits events = Dark Matter particle "switched off"

No modulation above 6 keV

No systematics or side reaction able to account for the measured modulation amplitude and to satisfy all the peculiarities of the signature

The data favour the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at about 9σ C.L.

This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

Summary of the results obtained in the additional investigations of possible systematics or side reactions

(NIMA592(2008)297, EPJC56(2008)333, arXiv:0912.0660, Can. J. Phys. 89 (2011) 11, S.I.F.Atti Conf.103(211) (arXiv:1007.0595), Phys.Proc.37(2012)1095, EPJC 72 (2012) 2064 and refs therein)

DAMA/LIBRA 1-6

Source	*Main comment*	*Cautious upper limit (90%C.L.)*
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	**$<2.5\times10^{-6}$ cpd/kg/keV**
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	**$<10^{-4}$ cpd/kg/keV**
NOISE	Effective full noise rejection near threshold	**$<10^{-4}$ cpd/kg/keV**
ENERGY SCALE	Routine + intrinsic calibrations	**<1-2×10^{-4} cpd/kg/keV**
EFFICIENCIES	Regularly measured by dedicated calibrations	**$<10^{-4}$ cpd/kg/keV**
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV *multiple-hits* events; this limit includes all possible sources of background	**$<10^{-4}$ cpd/kg/keV**
SIDE REACTIONS	Muon flux variation measured at LNGS	**$<3\times10^{-5}$ cpd/kg/keV**

+ they cannot satisfy all the requirements of annual modulation signature

Thus, they cannot mimic the observed annual modulation effect

No role for μ in DAMA annual modulation result

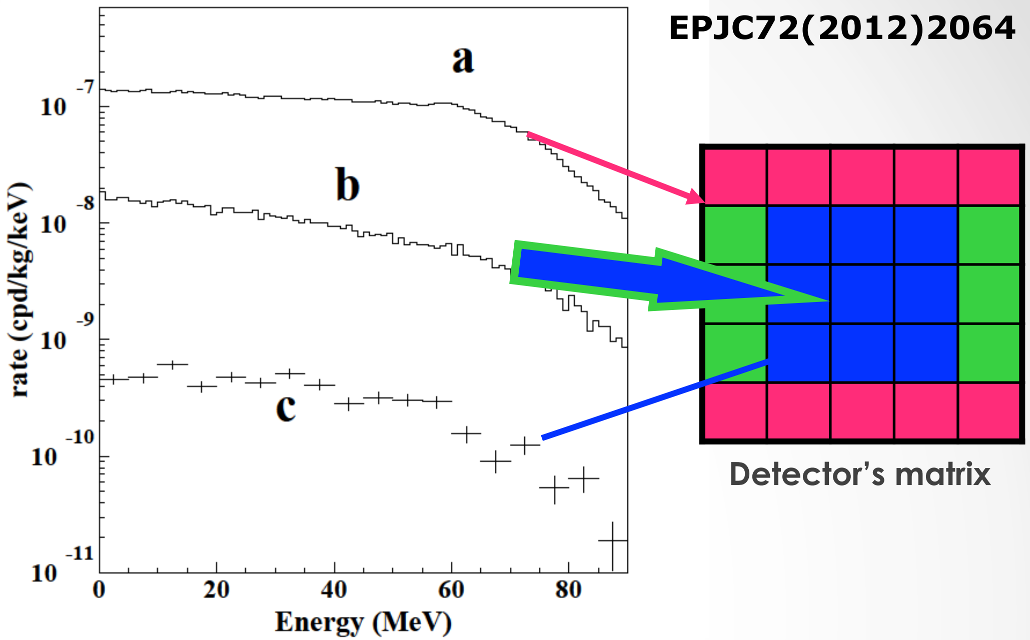
✓ **Direct μ interaction in DAMA/LIBRA set-up:**

DAMA/LIBRA surface ≈0.13 m^2
μ flux @ DAMA/LIBRA ≈2.5 μ/day

MonteCarlo simulation:
- muon intensity distribution
- Gran Sasso rock overburden map
- Single hit events

It cannot mimic the signature: already excluded by R_{90}, by *multi-hits* analysis + different phase, etc.

EPJC72(2012)2064



✓ **Rate, R_n, of fast neutrons produced by μ:**

$$R_n = (\text{fast n by } \mu)/(\text{time unit}) = \Phi_\mu \, Y \, M_{eff}$$

- Φ_μ @ LNGS ≈ 20 μ $m^{-2}d^{-1}$ (±1.5% modulated)
- Measured neutron Yield @ LNGS:

$$Y = 1 \div 7 \; 10^{-4} \; n/\mu/(g/cm^2)$$

Annual modulation amplitude at low energy due to **μ modulation**:

$$S_m^{(m)} = R_n \, g \, \varepsilon \, f_{DE} \, f_{single} \, 2\% \, /(M_{setup} \, \Delta E)$$

g = geometrical factor;
ε = detection eff. by elastic scattering
f_{DE} = energy window (E>2keV) effic.;
f_{single} = single hit effic.

Hyp.: M_{eff} = 15 tons; $g \approx \varepsilon \approx f_{\Delta E} \approx f_{single} \approx 0.5$ (cautiously)
Knowing that: $M_{setup} \approx$ 250 kg and ΔE=4keV

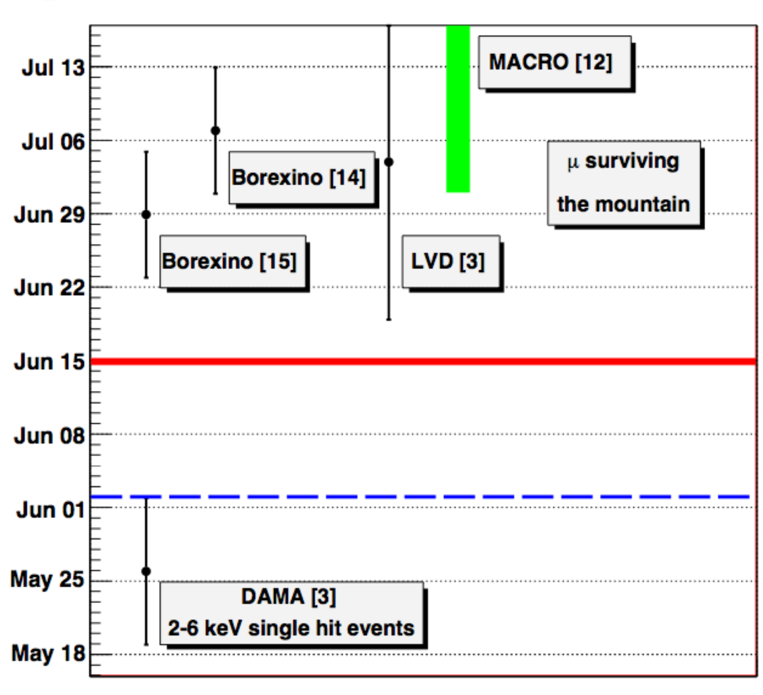
$$\boxed{S_m^{(m)} < (0.3\text{-}2.4) \times 10^{-5} \text{ cpd/kg/keV}}$$

- Moreover, this modulation also induces a variation in other parts of the energy spectrum and in the *multi-hits* events

It cannot mimic the signature: already excluded by R_{90}, by *multi-hits* analysis + different phase, etc.

Inconsistency of the phase between DAMA signal and μ modulation

For many others arguments EPJC72(2012)2064



μ flux @ LNGS (MACRO, LVD, BOREXINO) $\approx 3 \cdot 10^{-4}$ $m^{-2}s^{-1}$; modulation amplitude 1.5%; phase: July 7 ± 6 d, June 29 ± 6 d (Borexino)

but

- the muon phase differs from year to year (error no purely statistical); LVD/BOREXINO value is a "mean" of the muon phase of each year
- The DAMA: modulation amplitude 10^{-2} cpd/kg/keV, in 2-6 keV energy range for single hit events; phase:
  May 26 ± 7 days (stable over 13 years)

The DAMA phase is 5.7σ far from the LVD/BOREXINO phases of muons (7.1 σ far from MACRO measured phase)

considering the seasonal weather al LNGS, quite impossible that the max. temperature of the outer atmosphere (on which μ flux variation is dependent) is observed e.g. in June 15 which is 3 σ from DAMA

Can (whatever) hypothetical cosmogenic products be considered as side effects, assuming that they might produce:

- only events at low energy,
- only *single-hit* events,
- no sizable effect in the *multiple-hit* counting rate
- pulses with time structure as scintillation light

But, its phase should be (much) larger than μ phase, t_μ :

- if $\tau \ll T/2\pi$: $t_{side} = t_\mu + \tau$
- if $\tau \gg T/2\pi$: $t_{side} = t_\mu + T/4$

It cannot mimic the signature: different phase

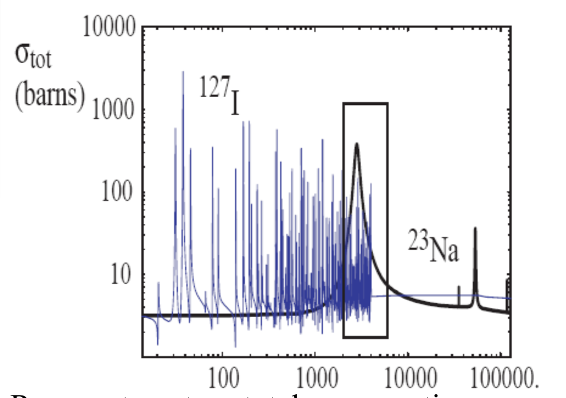
The ^{128}I case

Can.J.Phys.89(2011)141, SIF Atti Conf. 103 (2011) 157, arXiv:1007.0595, EPJC72(2012)2064

Environmental neutrons (mainly thermal and epithermal) can be captured by Iodine (arXiv:1006.5255); can the produced ^{128}I be responsible of the observed modulation? → **The answer is no.**

^{128}I decay schema	Mode	Branching r. (%)	Q-value (keV)
	β^-	93.1	2119
	EC+β^+	6.9	1252

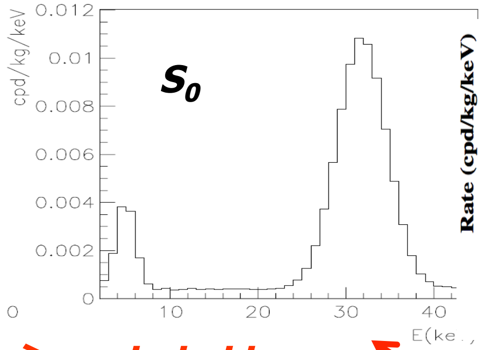
X-rays and Auger electrons produced in EC can release all the energy in the detectors (*single-hit*), corresponding to the atomic binding energy either of the K-shell (32 keV) or of the L-shells (4.3 to 5 keV) of the ^{128}Te

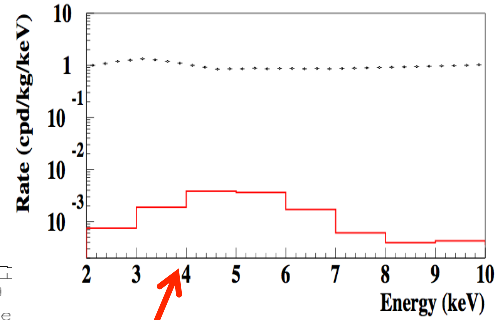


Resonant neutron total cross sections of neutrons on Sodium and Iodine

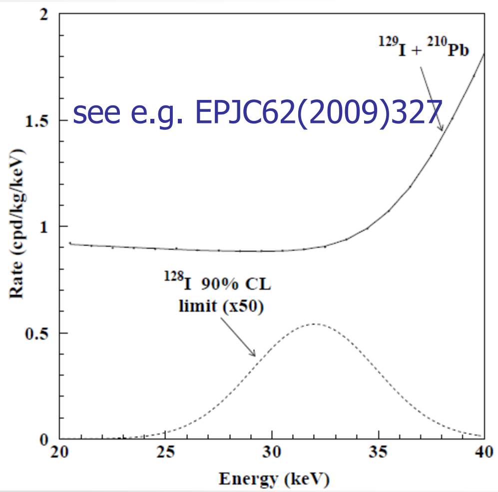
1) L-shells contribution ⇒ gaussian around 4.5 keV
2) Contribution (2-4) keV ≈ contribution (6-8) keV
3) K-shell contribution around 30 keV must be 8 times larger than that of L-shell
4) ^{128}I also decays by β^- with much larger branching ratio than EC and with β^- end-point energy at 2 MeV

→ ***no modulation observed at high energy*** → ***excluded by the data***





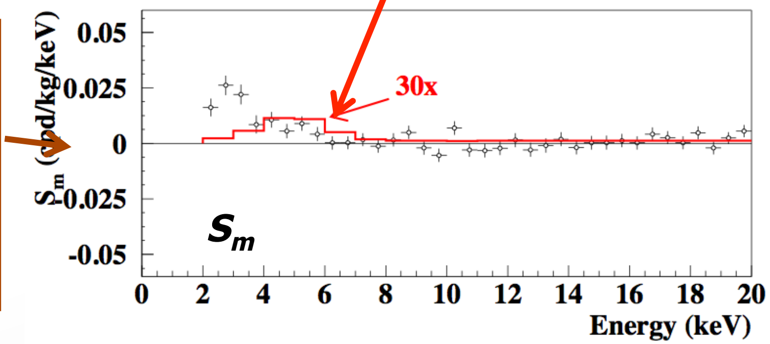
Maximum expected counting rate from ^{128}I (90%CL)



see e.g. EPJC62(2009)327

^{128}I activity <15 μBq/kg (90%CL)

Even assuming a 10% modulation in the neutron flux (!?), the contribution to S_m is $<3\times10^{-4}$ cpd/kg/keV at low energy (that is <2% of the observed modulation amplitudes)



No role is played by ^{128}I

No role for ^{40}K

e.g. in the published:
arXiv:0912.0660,
arXiv0912.4200

not evidence for any 3 keV peak in the S_m distribution. Behaviour compatible with a monotonic behaviour and with a "structure" as expected for many Dark Matter candidates (also for WIMP)

^{40}K decay cannot give any modulation, unless evoking new exotic physics.

No modulation has been observed in other energy regions where ^{40}K decay contributes

No modulation in multiple-hit events in 2-6 keV (^{40}K can give double events in two adjacent detectors and multi-site events due to Compton scatterings)

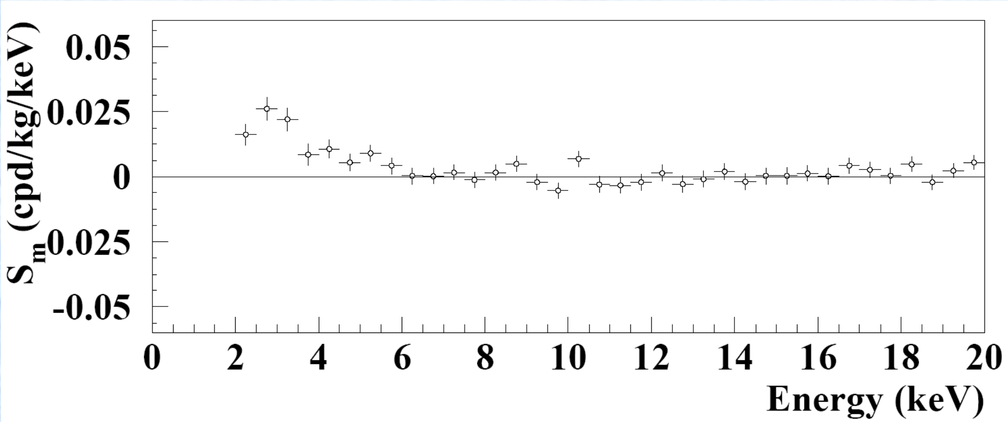
No modulation of the double coincidence events, 1461 keV-3 keV

The annual modulation signal is present in the outer and in the inner detectors.

(no dependence on the veto capability, that is different – for geometrical reasons – among the detectors)

Stability of efficiency

The annual modulation signal is equally distributed over all the detectors



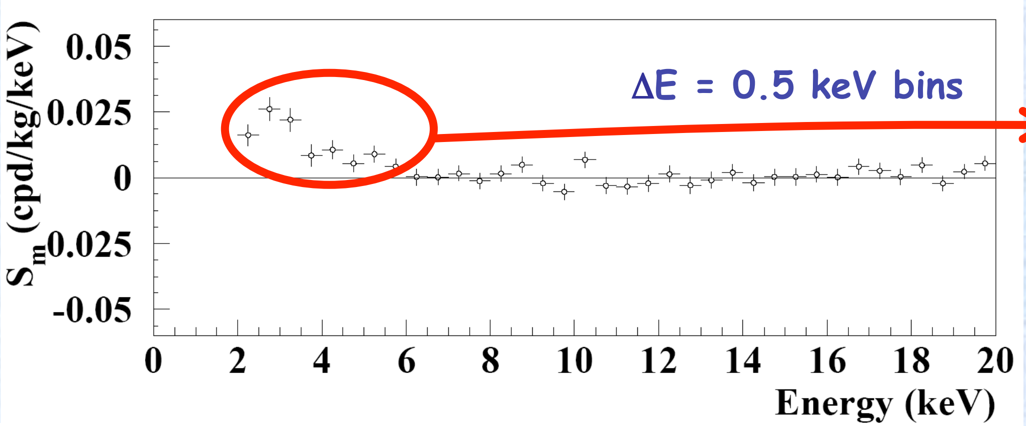
The analysis of the double coincidences rules out at more than 10 σ any modulation around 3 keV in the *single-hit* events from the hypothetical cases of : i) ^{40}K "exotic" modulation decay; ii) spill-out from double to single events and viceversa.

Even assuming the arXiv:0808.3283 scenario:

- the expected single hit modulation amplitude would be much below the measured modulation amplitude
- the phase (3 jan) would be well different from the measured phase (26 may±7 day).

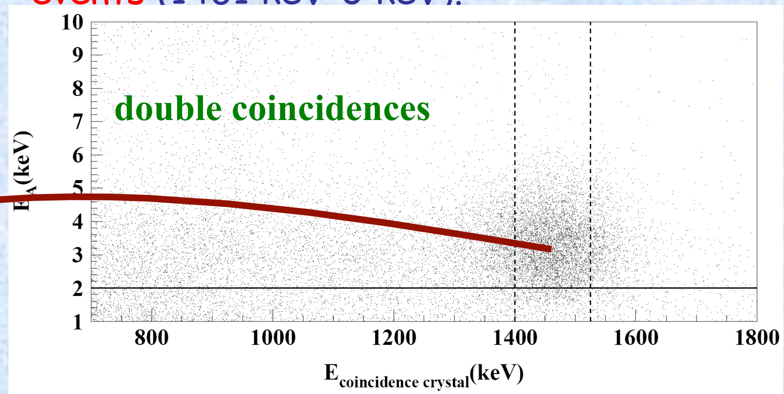
No role for ^{40}K in the experimental S_m

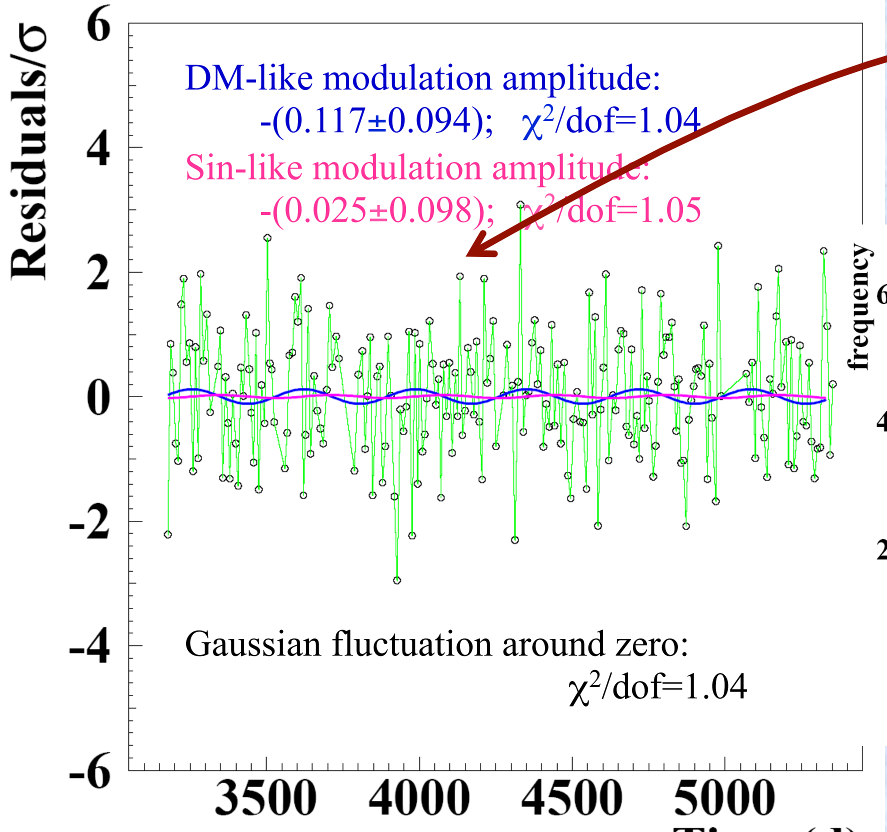
also see arXiv:0912.0660

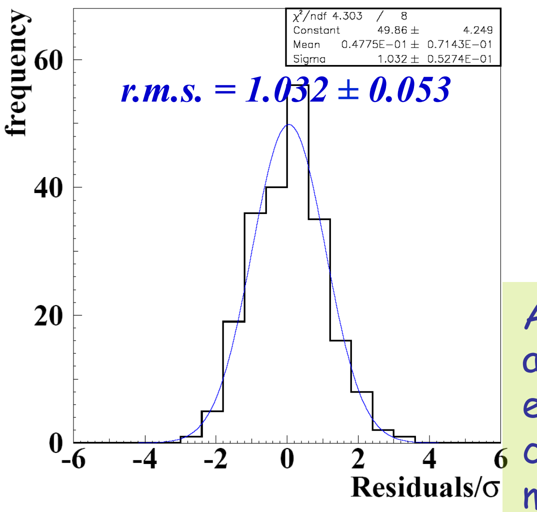


The experimental S_m cannot be due to ^{40}K for many reasons.

No modulation of the double coincidence events (1461 keV-3 keV).







DAMA/LIBRA 0.87 ton×yr

The ^{40}K double coincidence events are not modulated

Any modulation contribution around 3 keV in the single-hit events from the hypothetical cases of: i) ^{40}K "exotic" modulated decay; ii) spill-out effects from double to single events and viceversa, is ruled out at more than 10 σ

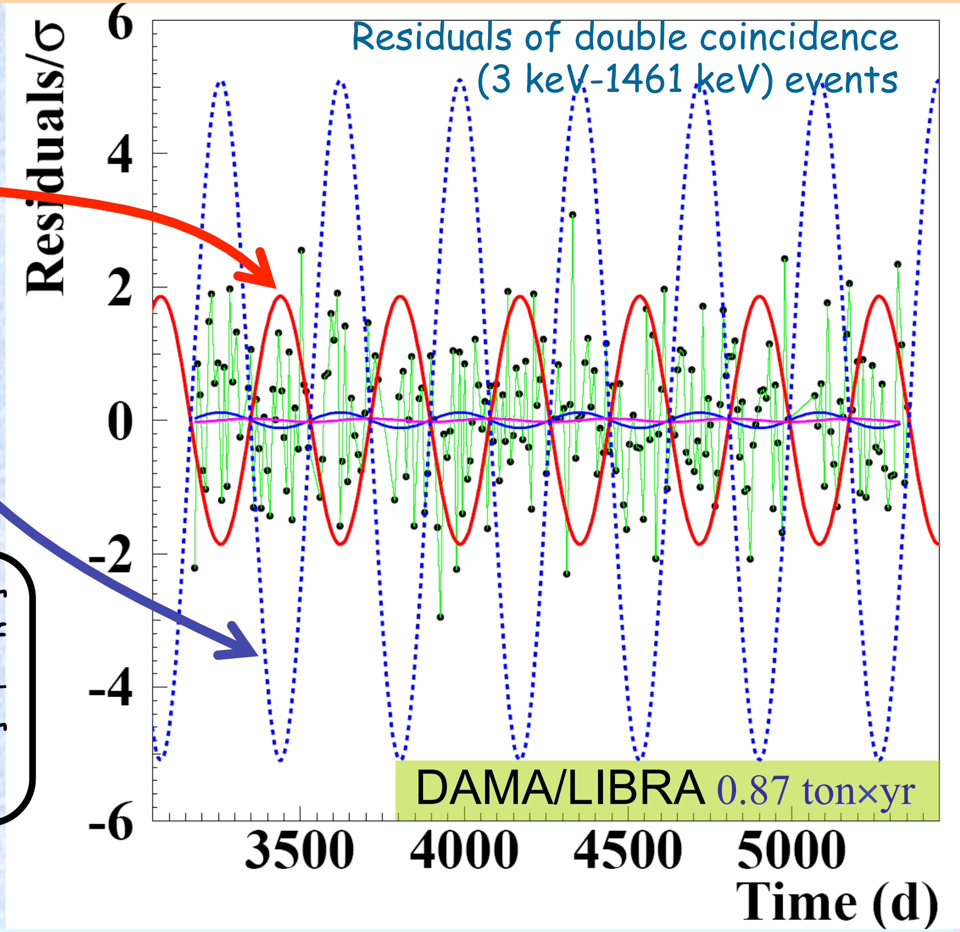
No role can be played by ^{40}K in the experimental S_m

also see arXiv:0912.0660

Expected modulation amplitude for double coincidence events when assuming that the modulation amplitude observed at low-energy for single-hit is due to:

- modulation induced by ^{40}K "exotic" modulated decay;
  hyp. 1: χ^2/dof=674/219
- spill-out of double to single events and viceversa;
  hyp. 2: χ^2/dof=3063/219

These hypotheses already ruled out by other discussed arguments, as e.g. the stability of efficiency, the absence of modulation for multi-hit events, the absence of modulation in other energy regions, their "exotic" nature, ...



The analysis of ^{40}K double coincidences rules out at level more than 10 σ any modulation contribution around 3 keV in the single-hit events from the hypothetical cases of : i) ^{40}K "exotic" modulation decay; ii) spill-out from double to single events and viceversa.

Summarizing

Presence of modulation for 13 annual cycles at 8.9σ C.L. with the proper distinctive features of the DM signature; all the features satisfied by the data over 13 independent experiments of 1 year each one

The total exposure by former DAMA/NaI and present DAMA/LIBRA is 1.17 ton × yr (13 annual cycles)

In fact, as required by the DM annual modulation signature:

1)
The *single-hit* events show a clear cosine-like modulation, <u>as expected for the DM signal</u>

2)
Measured period is equal to (0.999±0.002) yr, well compatible with the 1 yr period, <u>as expected for the DM signal</u>

3) Measured phase (146±7) days is well compatible with the roughly about 152.5 days <u>as expected for the DM signal</u>

4)
The modulation is present only in the low energy (2—6) keV energy interval and not in other higher energy regions, <u>consistently with expectation for the DM signal</u>

5)
The modulation is present only in the *single-hit* events, while it is absent in the *multiple-hit* ones <u>as expected for the DM signal</u>

6)
The measured modulation amplitude in NaI(Tl) of the *single-hit* events in the (2-6) keV energy interval is: (0.0116±0.0013) cpd/kg/keV (8.9σ C.L.).

No systematic or side process able to simultaneously satisfy all the many peculiarities of the signature and to account for the whole measured modulation amplitude is available

Model-independent evidence by DAMA/NaI and DAMA/LIBRA

well compatible with several candidates (in many possible astrophysical, nuclear and particle physics scenarios)

Neutralino as LSP in various SUSY theories

Various kinds of WIMP candidates with several different kind of interactions Pure SI, pure SD, mixed + Migdal effect +channeling,... (from low to high mass)

a heavy ν of the 4-th family

Pseudoscalar, scalar or mixed light bosons with axion-like interactions

WIMP with preferred inelastic scattering

Mirror Dark Matter

Light Dark Matter

Self interacting Dark Matter

Dark Matter (including some scenarios for WIMP) electron-interacting

Sterile neutrino

heavy exotic canditates, as “4th family atoms”, ...

Elementary Black holes such as the Daemons

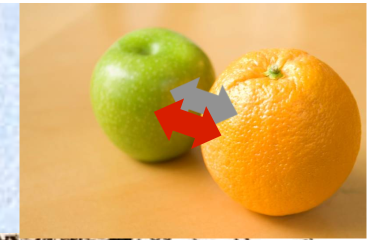
Kaluza Klein particles

... and more

Possible model dependent positive hints from Indirect searches (but interpretation, evidence itself, derived mass and cross sections depend e.g. on bckg modeling, on DM spatial velocity distribution in the galactic halo, etc.) not in conflict with DAMA results; null results not in conflict as well

Available results from direct searches using different target materials and approaches do not give any robust conflict & compatibility with positive excesses

About model dependent exclusion plots



Selecting just one simplified model framework, making lots of assumptions, fixing large numbers of parameters … but…

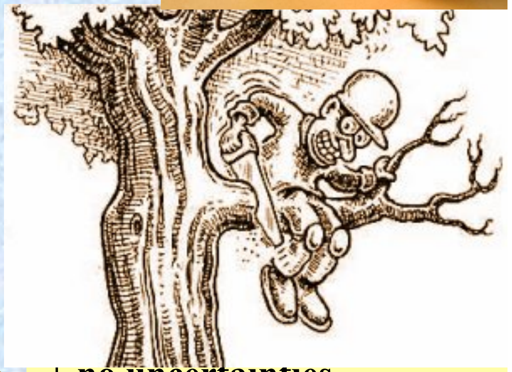
- *which particle?*
- *which couplings? which model for the coupling?*
- *which form factors for each target material and related parameters?*
- *which nuclear model framework for each target material?*
- *Which spin factor for each case?*
- *which scaling laws?*
- *which halo profile?*
- *which halo parameters?*
- *which velocity distribution?*
- *which parameters for velocity distribution?*
- *which v_0?*
- *which v_{esc}?*
- *…etc. etc.*

road sign or labyrinth?

and experimental aspects …

- *marginal and "selected" exposures*
- *Threshold, energy scale and energy resolution when calibration in other energy region (& few phe/keV)? Stability? Too few calibration procedures and often not in the same running conditions*
- *Selections of detectors and of data*
- *handling of (many) "subtraction" procedures and stability in time of all the cuts windows and related quantities, etc.? Efficiencies?*
- *fiducial volume vs disuniformity of detector response in liquids?*
- *Used values in the calculation (q.f., etc)*
- *Used approximations*

etc., etc.? (see e.g. **arXiv:1005.3723v1, 1005.0838v3,0806.0011v2, PLB637(2006)156 …)**



+ no uncertainties accounted for

No sensitivity to DM annual modulation signature

Different target materials

+ generally implications of DAMA model-independent results presented in incorrect/incomplete/non-updated way

Etc.

Exclusion plots have no "universal validity" and cannot disproof a model independent result in any given general model framework (they depend not only on the general assumptions largely unknown at present stage of knowledge, but on the details of their cooking) + **generally overestimated** + methodological robustness (see R. Hudson, Found. Phys. 39 (2009) 174)

On the other hand, possible positive hints (above an estimated background) should be interpreted. Large space for compatibility.

Interpretation of the model independent DAMA results in the case of a DM candidate with SI coupling

Comparison of allowed regions and supersymmetric expectations (points and light blue region) in MSSM where:

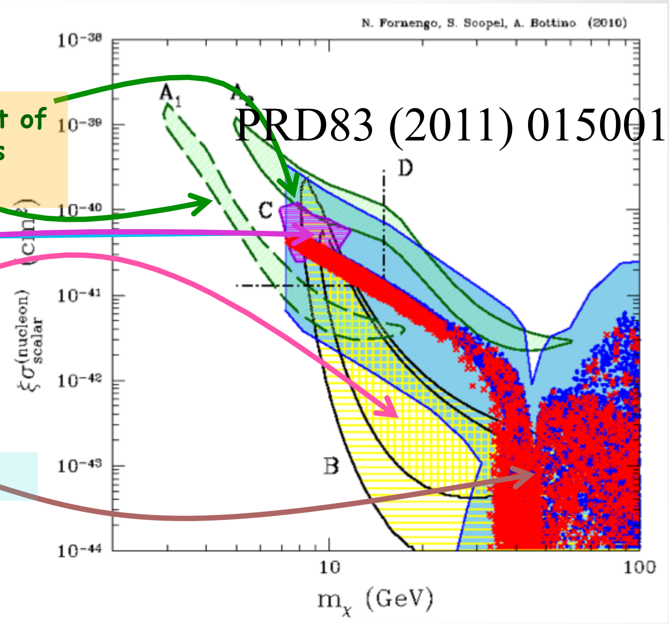
- for the neutralino a dominant purely SI coupling is assumed
- the gaugino mass unification at GUT scale is released: $M_1/M_2 \neq 0.5$ (<) (where M_1 and M_2 U(1) and SU(2) gaugino masses)

DAMA allowed regions for a particular set of astrophysical, nuclear and particle Physics assumptions with and without channeling

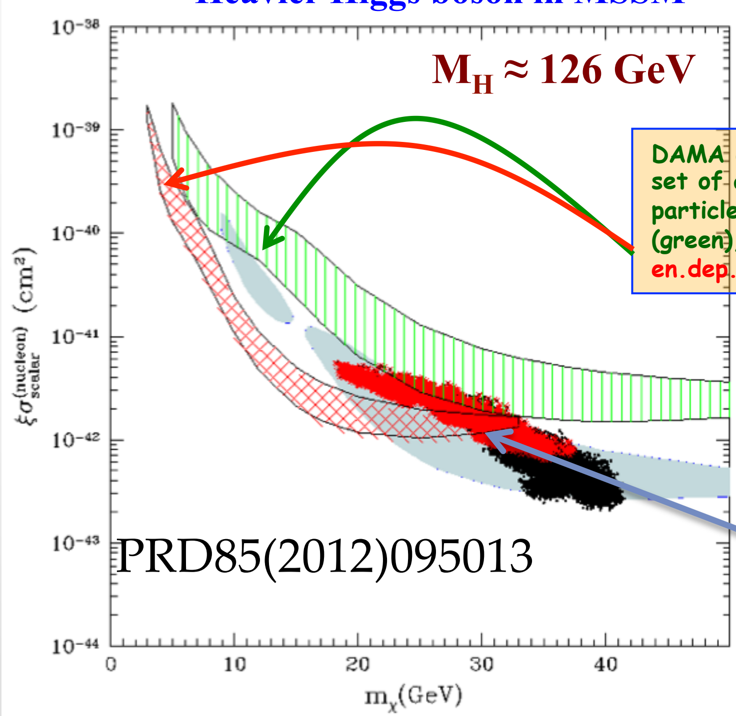
CoGeNT and CRESST

If the two CDMS events are interpreted as relic neutralino interactions

Relic neutralino in effMSSM



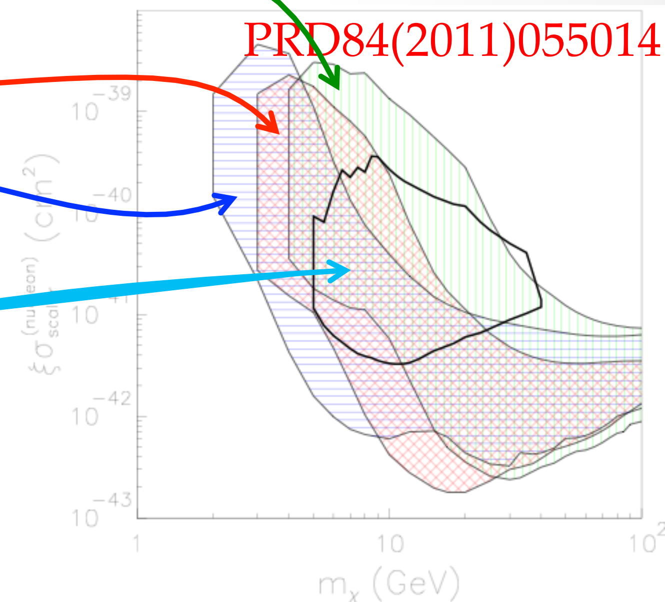
Heavier Higgs boson in MSSM



DAMA allowed regions for a particular set of astrophysical, nuclear and particle Physics assumptions without (green), with (blue) channeling, with en.dep. Q.F.(red)

CoGeNT

CRESST



Model-independent evidence by DAMA/NaI and DAMA/LIBRA

well compatible with several candidates

(in many possible astrophysical, nuclear and particle physics scenarios)

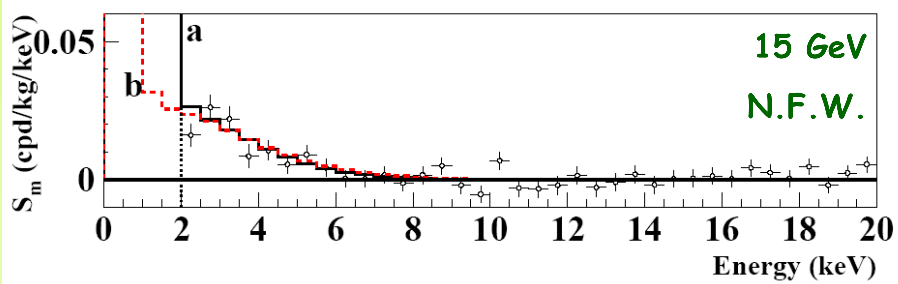
- Low mass neutralino (PRD81(2010)107302, PRD83(2011)015001, arXiv:1003.0014,arXiv:1007.1005, arXiv:1009.0549, PRD84(2011)055014, arXiv:1112.5666, PRD85(2012)095013)
- Next-to-minimal models (JCAP0908(2009)032, PRD79(2009)023510, JCAP0706(2007)008, arXiv:1009.2555,1009.0549)
- Mirror DM in various scenarios (arXiv:1001.0096, 1106.2688, PRD82(2010)095001, JCAP1107(2011)009, JCAP1009(2010)022, arXiv:1203.2387)
- Light scalar WIMP through Higgs portal (PRD82(2010)043522, JCAP0810(2010)034)
- Isospin-Violating Dark Matter (JCAP1008(2010)018, arXiv:1102.4331,1105.3734)
- Sneutrino DM (JHEP0711(2007)029, arXiv:1105.4878)
- Inelastic DM (PRD79(2009)043513, arXiv:1007.2688)
- Resonant DM (arXiv:0909.2900)
- DM from exotic 4th generation quarks (arXiv:1002.3366)
- Cogent results (arXiv:1002.4703, 1106.0650)
- DM from exotic 4th generation quarks (arXiv:1002.3366)
- Composite DM (IJMPD19(2010)1385)
- iDM on Tl (arXiv:1007:2688)
- Specific two higgs doublet models (arXiv:1106.3368)
- exothermic DM (arXiv:1004.0937)
- Secluded WIMPs (PRD79(2009)115019)
- Asymmetric DM (arXiv:1105.5431)
- Leptophobic Z0 models (arXiv:1106.0885)
- SD Inelastic DM (arXiv:0912.4264)
- Complex Scalar Dark Matter (arXiv:1005.3328)
- Singlet DM (JHEP0905(2009)036, arXiv:1011.6377)
- Specific GU (arXiv:1106.3583)
- **Long range forces** (arXiv:1108.4661)

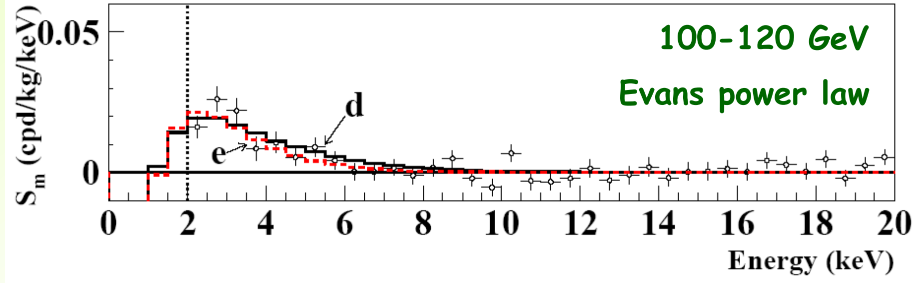
… and more (JCAP1008(2010)018, arXiv:1105.5121,1011.1499, arXiv:1108.1391, arXiv:1109.2722, arXiv:1110.5338, arXiv:1112.5457, …)

Just few <u>examples</u> of interpretation of the annual modulation in terms of candidate particles in <u>some scenarios</u>

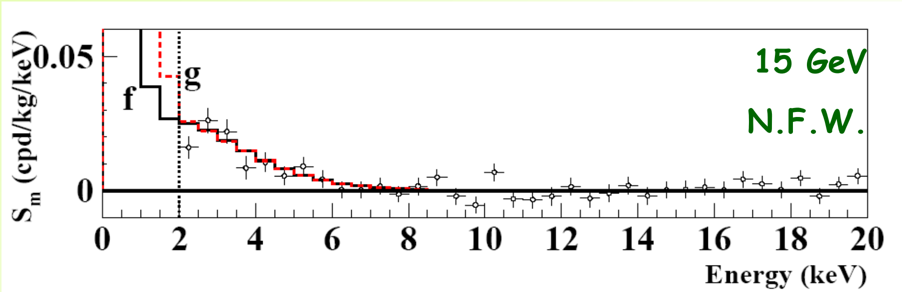
- Not best fit
- About the same C.L.

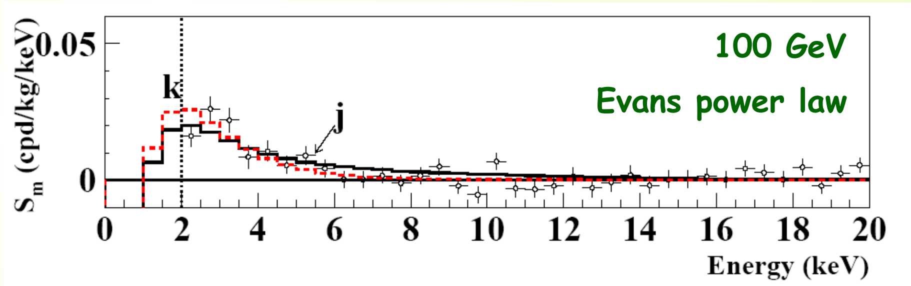
WIMP: SI



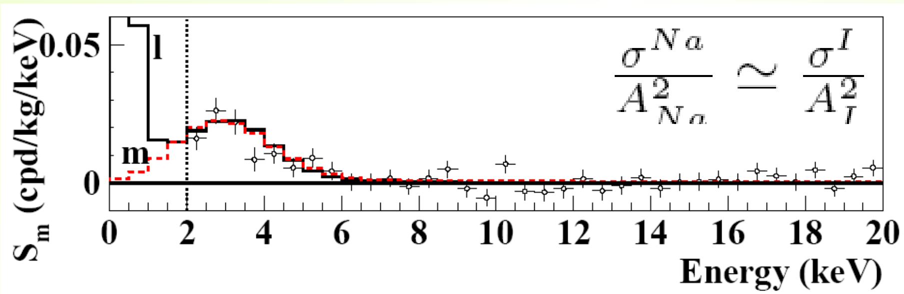


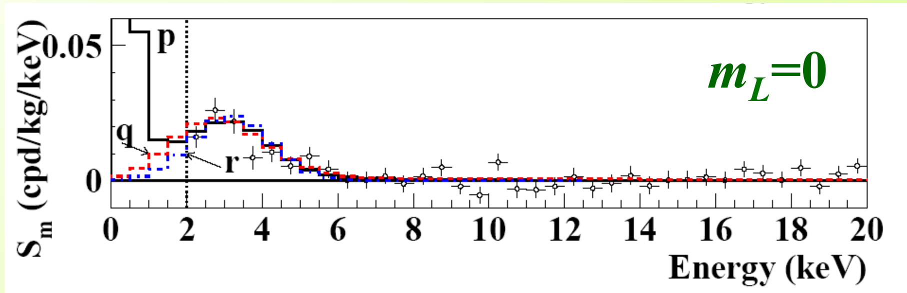
WIMP: SI & SD $\theta = 2.435$





LDM, bosonic DM

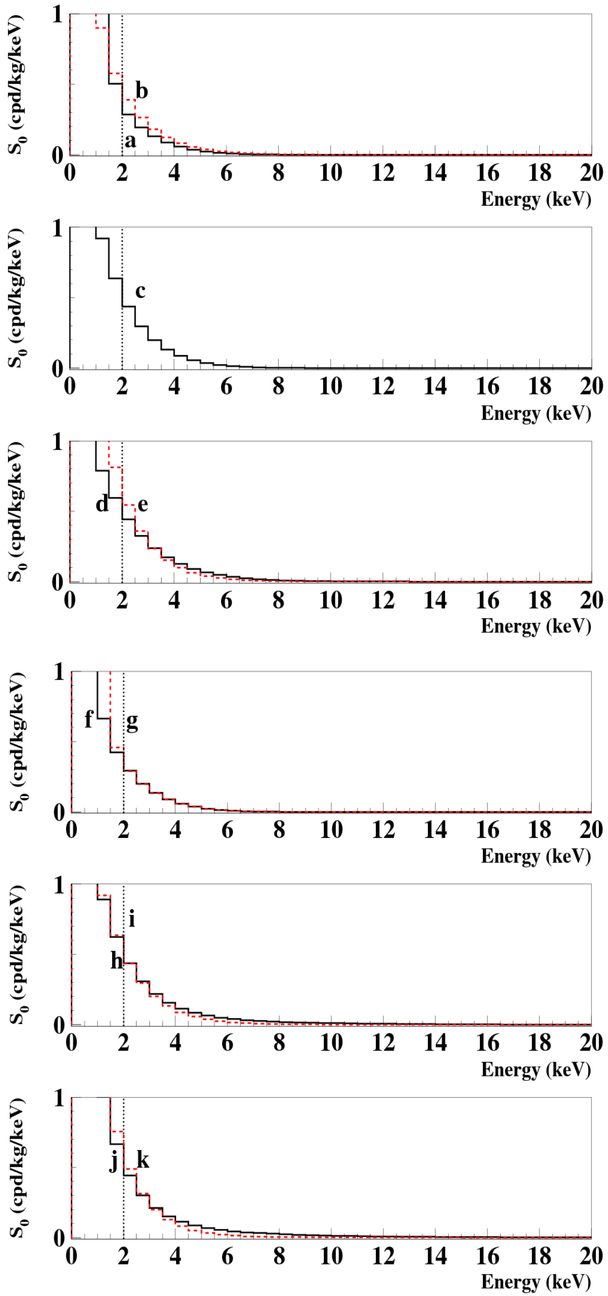


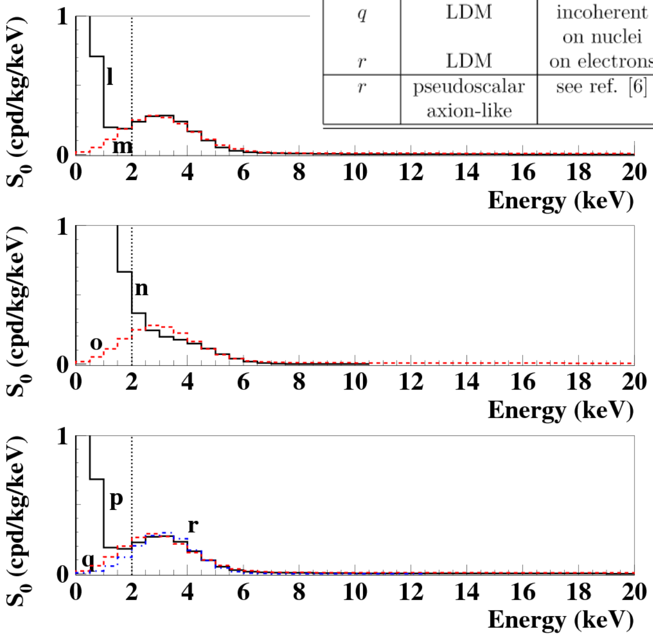


EPJC56(2008)333

Compatibility with several candidates; other ones are open

S_0 behaviours for the given examples





DM particle elastic scattering on nuclei, spin-independent (SI) and spin-dependent (SD) couplings, local velocity = 170 km/s and nuclear cross section scaling laws as in [4]

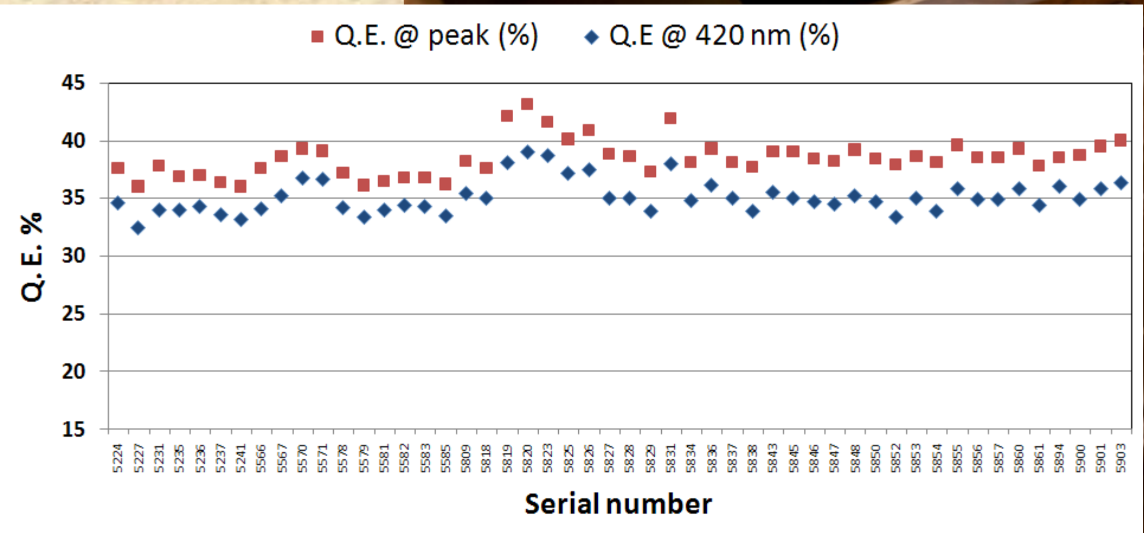
Curve label	Halo model (see ref. [4, 34])	Local density (GeV/cm^3)	Set as in [4]	DM particle mass	$\xi\sigma_{SI}$ (pb)	$\xi\sigma_{SD}$ (pb)	θ (rad)	Channeling [9]
a	A5 (NFW)	0.2	A	15 GeV	3.1×10^{-4}	0	–	no
b	A5 (NFW)	0.2	A	15 GeV	1.3×10^{-5}	0	–	yes
c	A5 (NFW)	0.2	B	60 GeV	5.5×10^{-6}	0	–	no
d	B3 (Evans power law)	0.17	B	100 GeV	6.5×10^{-6}	0	–	no
e	B3 (Evans power law)	0.17	A	120 GeV	1.3×10^{-5}	0	–	no
f	A5 (NFW)	0.2	A	15 GeV	10^{-7}	2.6	2.435	no
g	A5 (NFW)	0.2	A	15 GeV	1.4×10^{-4}	1.4	2.435	no
h	A5 (NFW)	0.2	B	60 GeV	10^{-7}	1.4	2.435	no
i	A5 (NFW)	0.2	B	60 GeV	8.7×10^{-6}	8.7×10^{-2}	2.435	no
j	B3 (Evans power law)	0.17	A	100 GeV	10^{-7}	1.7	2.435	no
k	B3 (Evans power law)	0.17	A	100 GeV	1.1×10^{-5}	0.11	2.435	no

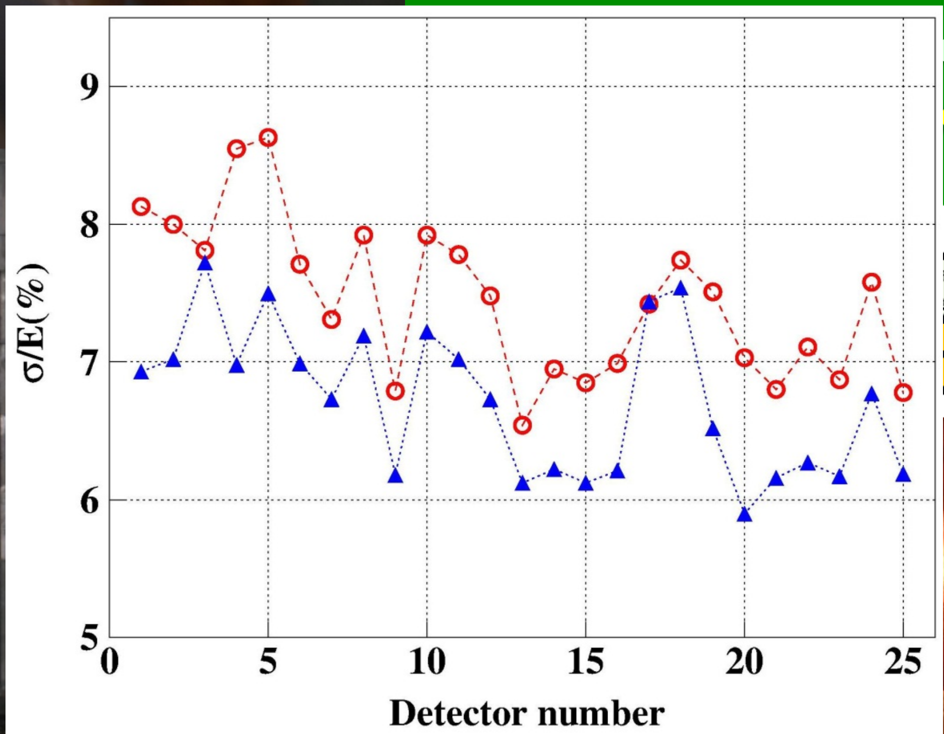
Light Dark Matter (LDM) inelastic scattering and bosonic axion-like interaction as in [6, 11], A5 (NFW) halo model as in [4, 34], local density = 0.17 GeV/cm^3, local velocity = 170 km/s

Curve label	DM particle	Interaction	Set as in [4]	m_H	Δ	Cross section (pb)	Channeling [9]
l	LDM	coherent on nuclei	A	30 MeV	18 MeV	$\xi\sigma_m^{coh} = 1.8 \times 10^{-6}$	yes
m	LDM	coherent on nuclei	A	100 MeV	55 MeV	$\xi\sigma_m^{coh} = 2.8 \times 10^{-6}$	yes
n	LDM	incoherent on nuclei	A	30 MeV	3 MeV	$\xi\sigma_m^{inc} = 2.2 \times 10^{-2}$	yes
o	LDM	incoherent on nuclei	A	100 MeV	55 MeV	$\xi\sigma_m^{inc} = 4.6 \times 10^{-2}$	yes
p	LDM	coherent on nuclei	A	28 MeV	28 MeV	$\xi\sigma_m^{coh} = 1.6 \times 10^{-6}$	yes
q	LDM	incoherent on nuclei	A	88 MeV	88 MeV	$\xi\sigma_m^{inc} = 4.1 \times 10^{-2}$	yes
r	LDM	on electrons	–	60 keV	60 keV	$\xi\sigma_m^{e} = 0.3 \times 10^{-6}$	–
r	pseudoscalar axion-like	see ref. [6]	–	Mass = 3.2 keV		$g_{aee} = 3.9 \times 10^{-11}$	–

S_0(2-4 keV)≤0.25 cpd/kg/keV

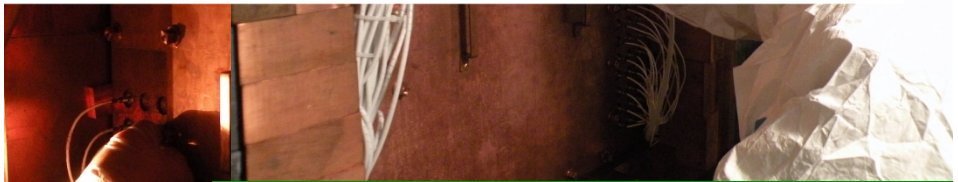
DAMA/LIBRA – stage 2 JINST 7(2012)03009



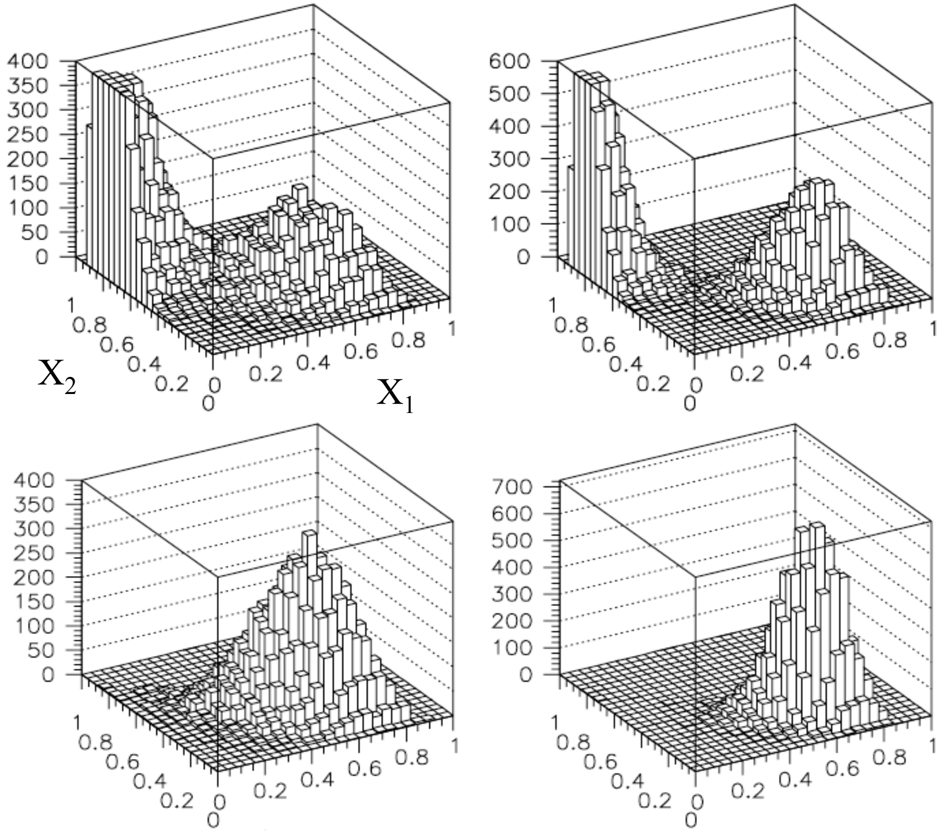


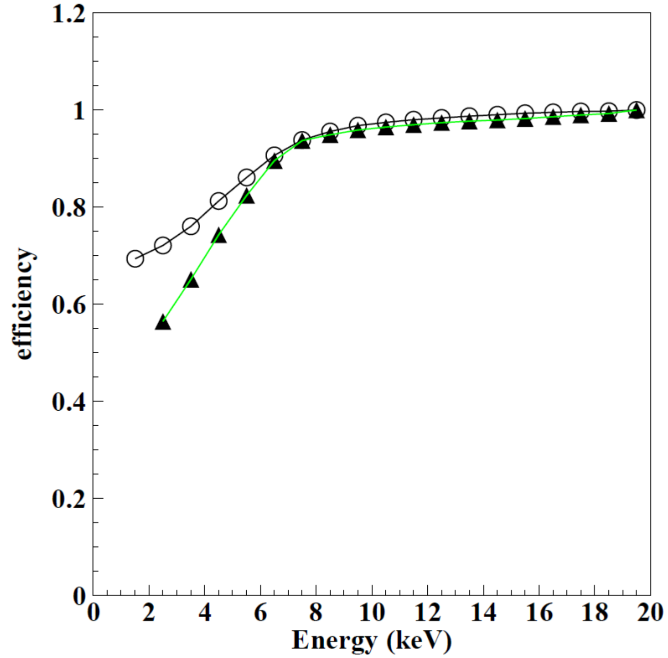
ov/Dec
ed with new

	^{235}U (mBq/kg)	^{228}Ra (Bq/kg)	^{228}Th (mBq/kg)	^{40}K (Bq/kg)	^{137}Cs (mBq/kg)	^{60}Co (mBq/kg)
	47	*0.12*	*83*	*0.54*	-	-
	10	*0,02*	*17*	*0.16*	-	-



Since Dec 2010 data taking and optimizations in this new configuration started





Total efficiency as a function of energy for single-hit events considering all DAMA/LIBRA detectors

Top: comparison of the noise and scintillation pulses for the new PMTs in 1-3 keV (left) and 3-6 keV (rigth)

top: production data
bottom: data from γ source

Noise well separated from scintillation events

i) Black triangles: data with old PMTs down to 2 keV software energy threshold

ii) Circles: data with new high Q.E PMTs down to 1 keV software energy threshold (bin = 1 keV)

Software energy threshold below 2 keV? YES

$$X_1 = \frac{\text{Area (from 100 ns to 600 ns)}}{\text{Area (from 0 ns to 600 ns)}};$$

$$X_2 = \frac{\text{Area (from 0 ns to 50 ns)}}{\text{Area (from 0 ns to 600 ns)}}$$

much more in JINST7(2012)03009

DM annual modulation signature

The sensitivity of the DM annual modulation signature depends – apart from the counting rate - on the product

$$\varepsilon \times \Delta E \times M \times T \times (\alpha-\beta^2)$$

increased
in DAMA/LIBRA-phase2

increased
in DAMA/LIBRA-phase2

increased
With DAMA/LIBRA-phase2

→ Upgrade at fall 2010 & running time
also equivalent to have enlarged the exposed mass

&: DM annual modulation signature acts itself as a strong bckg reduction strategy as discussed in the original paper by Freese et al.

&: No systematic or side process able to simultaneously satisfy all the many peculiarities of the signature and to account for the whole measured modulation amplitude is available

Some of the DAMA/LIBRA-phase 2 perspectives

Further investigation on DM model independent result

- ✓ **Increased sensitivity**
- ✓ **Reaching even higher C.L.**
- ✓ **Determining with extreme accuracy all modulation parameters**

Further investigation on Dark Matter candidates :

- ✓ **higher exposure and lower software energy threshold can allow to disentangle among different astrophysical, nuclear and particle physics models (nature of the candidate, couplings, inelastic interaction, particle conversion processes, …, form factors, spin-factors and more on new scenarios)**
- ✓ **scaling laws and cross sections**
- ✓ **multi-component DM particles halo?**

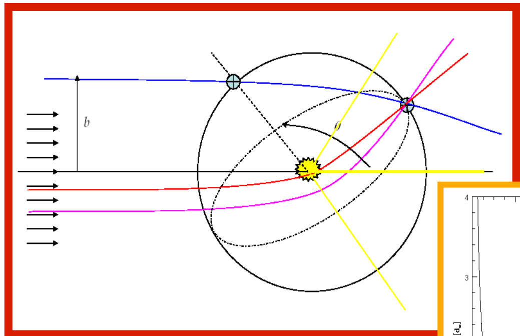
Investigation of possible diurnal effects

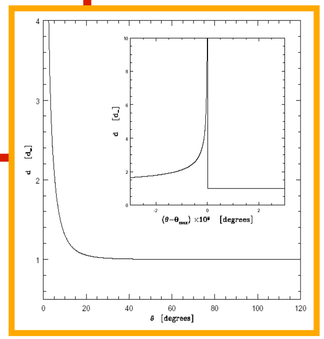
- ✓ **daily effect on the sidereal time expected in case of high cross section (small ξ) DM candidates (shadow of the Earth)**
- ✓ **daily effect on the sidereal time due to the channeling in case of DM candidates inducing nuclear recoils.**
- ✓ **daily modulation on the sidereal time due to the Earth rotation velocity contribution (it holds for a wide range of DM candidates); but it requires extremely large exposure**

e.g. IJMPD13(2004)2127

Further investigation on astrophysical models:

- ✓ **velocity and position distribution of DM particles in the galactic halo, possibly due to:**
  1. **satellite galaxies (as e.g. Sagittarius and Canis Major Dwarves) tidal "streams";**
  2. **caustics in the halo;**
  3. **gravitational focusing effect of the Sun enhancing the DM flow ("spike" and "skirt");**
  4. **possible structures as clumpiness with small scale size;**





…and more

(+ Special data taking for other rare processes

RD-III -Towards possible multi-purpose DAMA/1ton proposed since 1996:

Remind:

Also possible step towards Astrop Phys 4 (1995), 45 ?

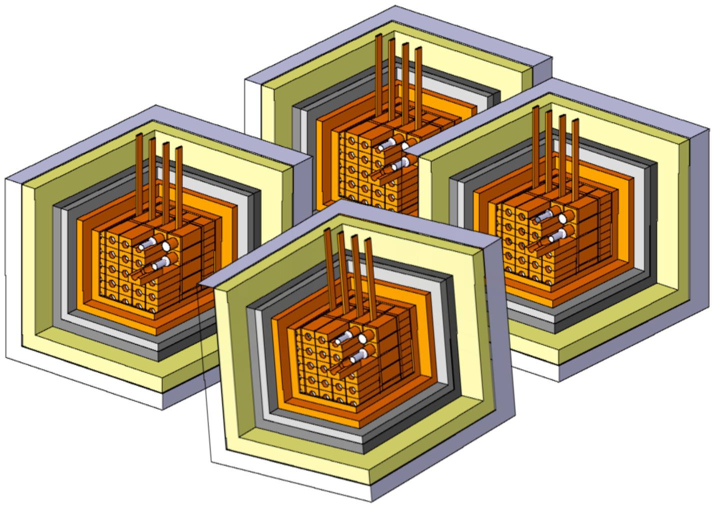
Original design consists in adding other 3 replicas of DAMA/LIBRA in 3 similar installations

New project on the basis of the ex Klapdor space promised by the previous LNGS director (also scholarship POR-Abruzzo)

Because of the different allocation proposed by previous director we have reconsidered the original project that also offer very good peculiarities. Moreover, this project is by the fact operative being DAMA/LIBRA (the base module) already running

In the period of interest:

Studies have been continued with the aim of overcome the present problems: the supply and purification of the high quality NaI powders and mainly of TlI and the creations of new protocols.



This is mandatory also because of the changes in expertise, materials suppliers and in the organization that makes now difficult developing ULB NaI(Tl) crystals at the same company + preparing new selection materials and improved design details in framework of new POR fellowship

Thanks for attention