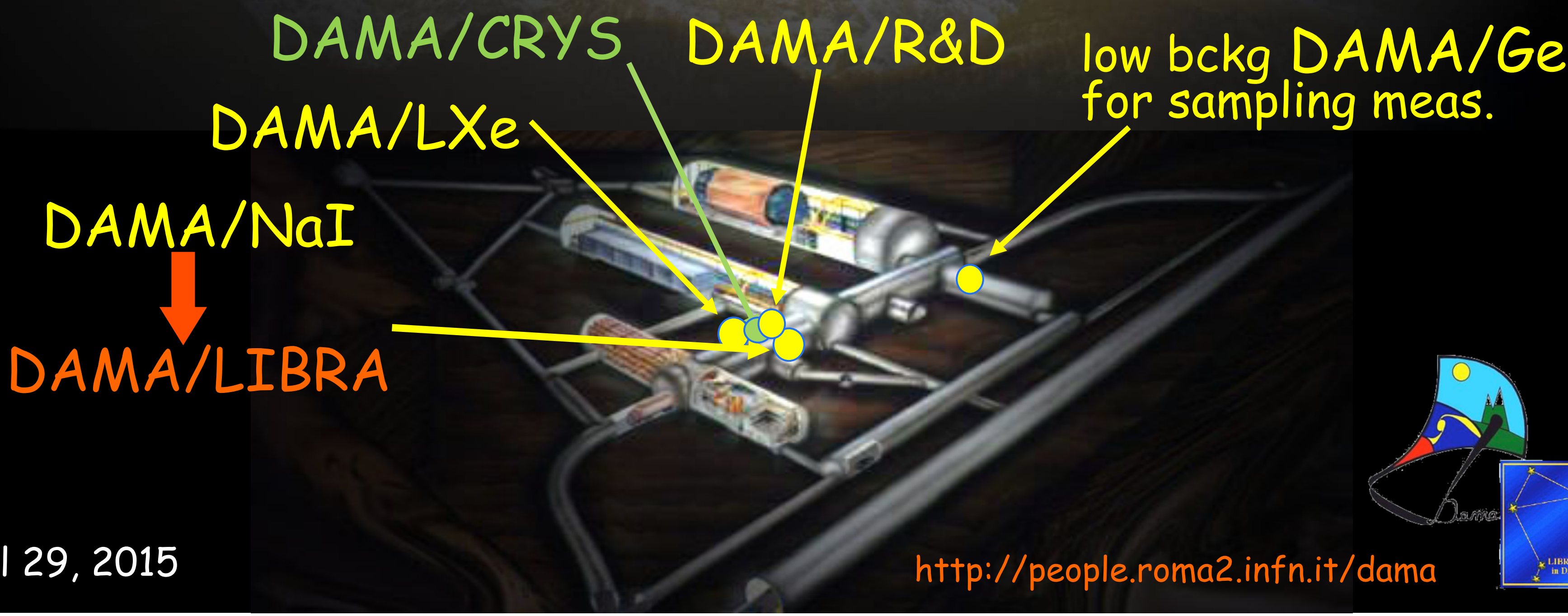
Roma2,Roma1,LNGS,IHEP/Beijing

+ by-products and small scale expts.: INR-Kiev and others (as NIIC+ITEP-Moscow+ JSC NeoChem)
+ some studies on ββ decays (DST-MAE, inter-univ. Agreem.):IIT Kharagpur/Ropar, India

- Many new ideas and detectors developed/under-development
- Many different low bckg set-ups and measurements done/in progress/foreseen
- since last DAMA presentation in open session on October 2013
  - ✓ Cumulatively ≈ 30 papers published on international reviews or on conference proceedings
  - ✓ 30 talks at conferences and seminars all over the world
  - ✓ Master degrees, PhD and Master of Science theses on the various activities
- ANVUR VQR 2004-2010 results in 2014: 24/27 full-rank products; total score 25.6/27
- All engagements with INFN always fully respected without delays



April 29, 2015

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

The DAMA/LIBRA set-up ~250 kg NaI(Tl)
(Large sodium Iodide Bulk for RAre processes)

As a result of a second generation R&D for more radiopure NaI(Tl)
by exploiting new chemical/physical radiopurification techniques
(all operations involving crystals and PMTs - including photos - 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: Ann. Mod. 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
- *Results on rare processes: PEP violation in Na, I:* EPJC62(2009)327, *CNC in I:* EPJC72(2012)1920
  IPP in ^{241}Am: EPJA49(2013)64

DAMA/LIBRA:

Main activities in the period Oct. 2013 –April 2015

1) The final model indipendent results for a total exposure of 1.04 ton×yr collected by DAMA/LIBRA-phase1 in 7 annual cycles (further 0.17 ton×yr) published;

2) Some new electronic modules developed;

3) Some review papers published;

4) The results obtained in the search of possible diurnal effects in the low energy single-hit data of DAMA/LIBRA–phase1 published;

5) A work further demonstrating that neutrons, muons and solar neutrinos do not play any significant role in the DAMA DM annual modulation effect;

6) DAMA/LIBRA-phase2 in data taking in the new configuration with lower energy threshold;

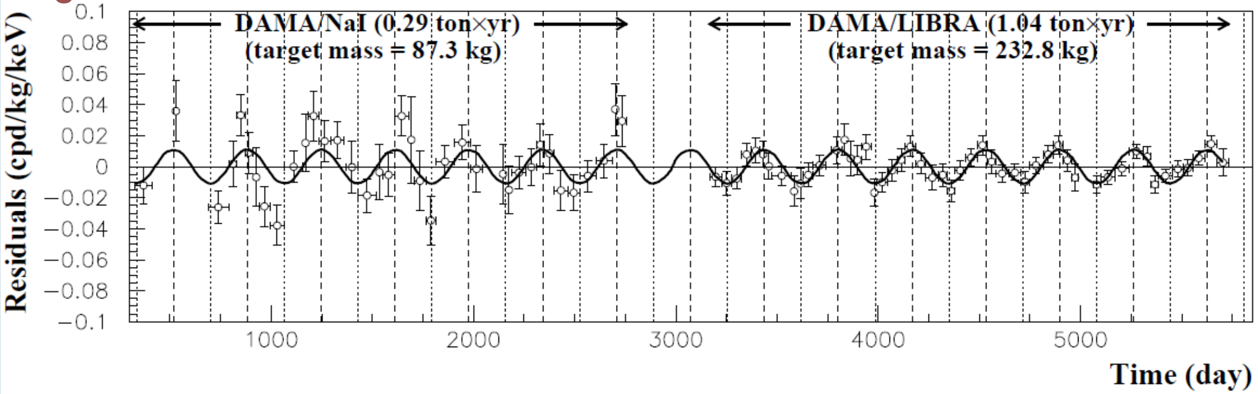
7) Investigations on corollary analyses, other DM features, second order effects, and many other rare processes with higher sensitivities progressed and some papers prepared

Model Independent Annual Modulation Result

DAMA/NaI + DAMA/LIBRA-phase1 Total exposure: 487526 kg×day = **1.33 ton×yr**

Single-hit residuals rate *vs* time in 2-6 keV

EPJC 73(2013)2648, IJMPA28(2013)1330022

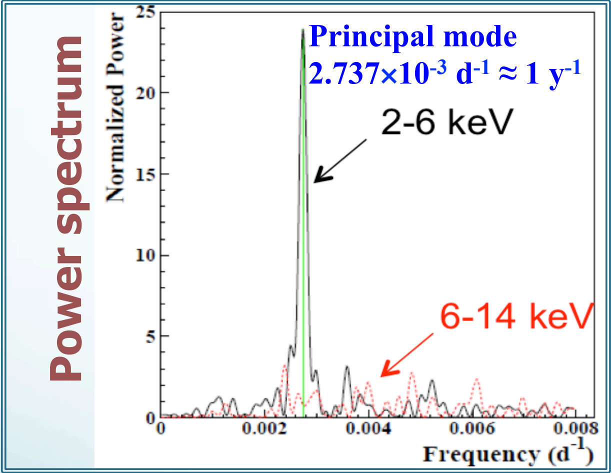


continuous line: t_0 = 152.5 d, T = 1.0 y

A=(0.0110±0.0012) cpd/kg/keV
χ^2/dof = 70.4/86 9.2 σ C.L.

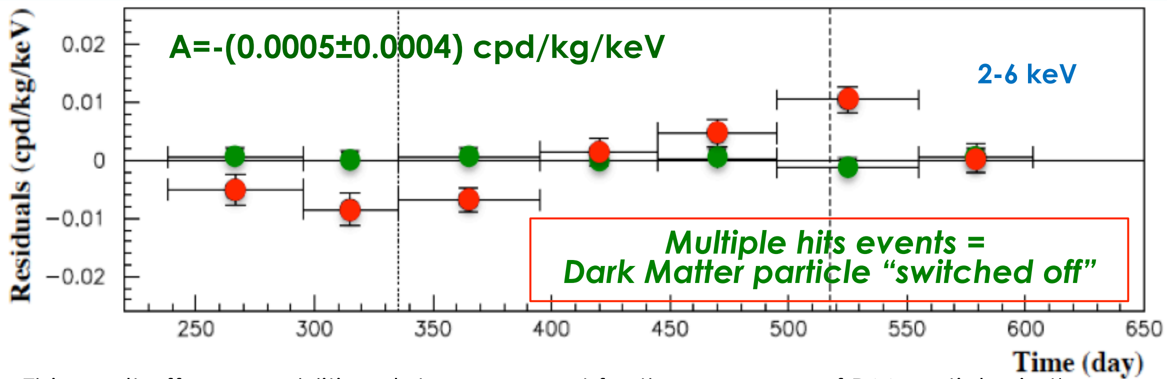
Absence of modulation? No
χ^2/dof=154/87 P(A=0) = 1.3×10^{-5}

Fit with all the parameters free:
A = (0.0112 ± 0.0012) cpd/kg/keV
t_0 = (144±7) d - T = (0.998±0.002) y



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

Comparison between **single hit residual rate (red points)** and **multiple hit residual rate (green points)**; Clear modulation in the single hit events; No modulation in the residual rate of the multiple hit events



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

The data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at about 9.2σ C.L.

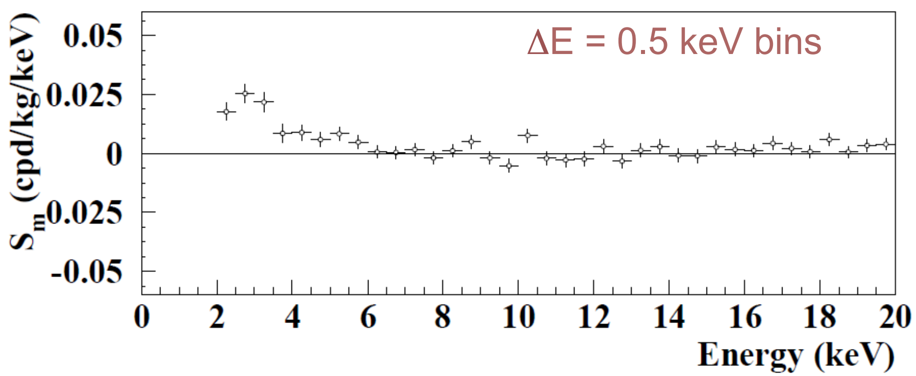
Model Independent Annual Modulation Result

DAMA/NaI + **DAMA/LIBRA-phase1** Total exposure: 487526 kg×day = **1.33 ton×yr**

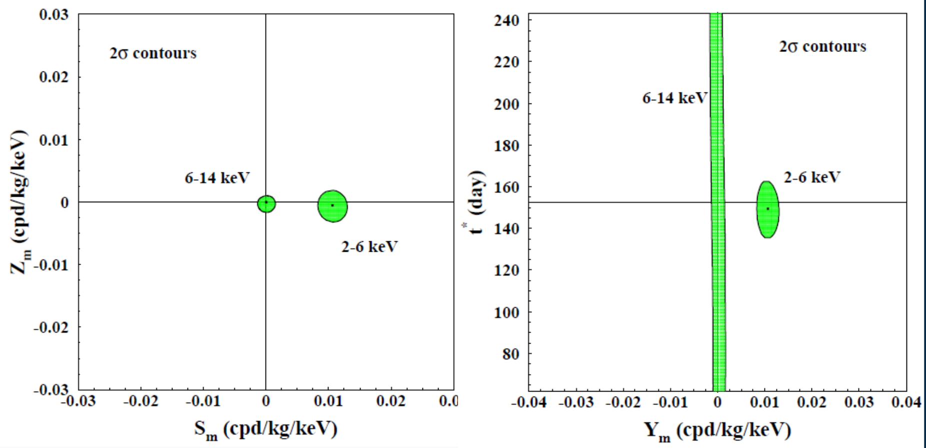
EPJC 73(2013)2648, IJMPA28(2013)1330022

$R(t) = S_0 + S_m \cos[\omega(t - t_0)]$

here *T*=2π/ω=1 yr and t_0= 152.5 day



$R(t) = S_0 + S_m \cos[\omega(t - t_0)] + Z_m \sin[\omega(t - t_0)] = S_0 + Y_m \cos[\omega(t - t^*)]$



- No modulation above 6 keV
- No modulation in the whole energy spectrum
- No modulation in the 2-6 keV multiple-hit events

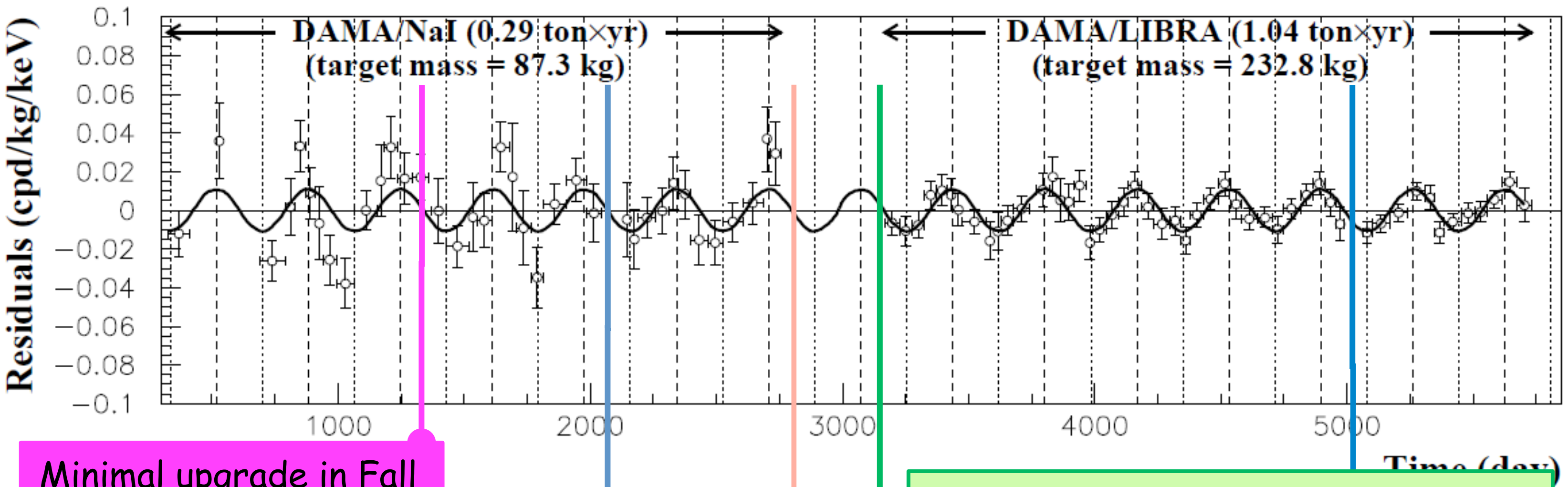
Running conditions stable at a level better than 1%

No systematics or side processes able to quantitatively account for the measured modulation amplitude and to simultaneously satisfy the many peculiarities of the signature are available.

✓ Compatibility with many low and high mass DM candidates, interaction types and astrophysical scenarios, and in particular with recent positive model dependent hints from direct or indirect searches

✓ No other experiment exists whose result can be – at least in principle – directly compared in a model-independent way with those by DAMA/NaI & DAMA/LIBRA-phase1

DAMA/NaI & DAMA/LIBRA main upgrades and improvements



PHASE2

Minimal upgrade in Fall

July 2000 new DAQ and new electronic chain installed (MULTIPLEXER removed, now one TD channel for each detector): (i) TD VXI Tektronix; (ii) Digital Unix DAQ system; (iii) GPIB-CAMAC.

July 2002 DAMA/NaI taking completed

On 2003 DAMA/LIBRA has begun first operations (one TD channel for each PMT; two for each detector)

Sept.-Oct. 2008 – DAMA/LIBRA upgrade:

- (i) one detector has been recovered by replacing a broken PMT
- (ii) new optimization of some PMTs and HVs performed
- (iii) All TD replaced with new ones
- (iv) new DAQ with optical read-out installed

The second DAMA/LIBRA upgrade in Fall 2010: replacement of all the PMTs with higher Q.E. ones
(+ new preamplifiers in fall 2012 & other developments in progress)

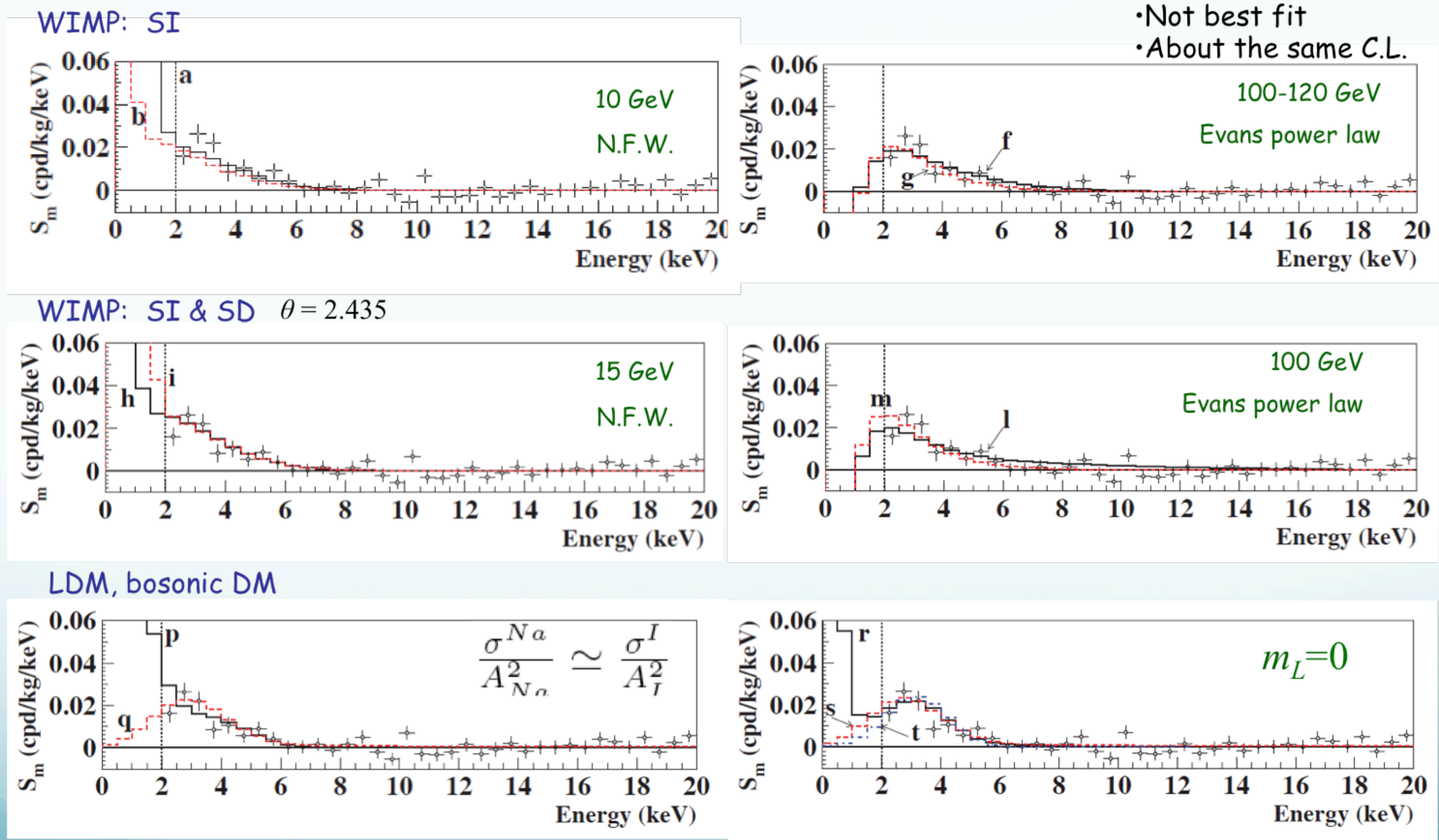
DAMA/LIBRA-phase2 ***in data taking***

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

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

Just few examples of interpretation of the annual modulation in terms of candidate particles in some scenarios

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



Compatibility with several candidates;
other ones are open

EPJC56(2008)333
IJMPA28(2013)1330022

- Contributions to the total neutron flux at LNGS; → $\Phi_k = \Phi_{0,k}\,(1 + \eta_k cos\omega\,(t - t_k))$
- Counting rate in DAMA/LIBRA for *single-hit* events, in the (2 – 6) keV energy region induced by: → $R_k = R_{0,k}\,(1 + \eta_k cos\omega\,(t - t_k))$
  - neutrons,
  - muons,
  - solar neutrinos.

(See e.g. also EPJC 56 (2008) 333, EPJC 72 (2012) 2064, IJMPA 28 (2013) 1330022)

EPJC74(2014)3196

Modulation amplitudes

	Source	$\Phi^{(n)}_{0,k}$ (neutrons cm^{-2} s^{-1})	η_k	t_k	$R_{0,k}$ (cpd/kg/keV)		$A_k = R_{0,k}\eta_k$ (cpd/kg/keV)	A_k/S_m^{exp}
SLOW neutrons	thermal n ($10^{-2} - 10^{-1}$ eV)	1.08×10^{-6} [15]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 8 \times 10^{-6}$	[2, 7, 8]	$\ll 8 \times 10^{-7}$	$\ll 7 \times 10^{-5}$
	epithermal n (eV-keV)	2×10^{-6} [15]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 3 \times 10^{-3}$	[2, 7, 8]	$\ll 3 \times 10^{-4}$	$\ll 0.03$
FAST neutrons	fission, $(\alpha, n) \to n$ (1-10 MeV)	$\simeq 0.9 \times 10^{-7}$ [17]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 6 \times 10^{-4}$	[2, 7, 8]	$\ll 6 \times 10^{-5}$	$\ll 5 \times 10^{-3}$
	$\mu \to n$ from rock (> 10 MeV)	$\simeq 3 \times 10^{-9}$ (see text and ref. [12])	0.0129 [23]	end of June [23, 7, 8]	$\ll 7 \times 10^{-4}$	(see text and [2, 7, 8])	$\ll 9 \times 10^{-6}$	$\ll 8 \times 10^{-4}$
	$\mu \to n$ from Pb shield (> 10 MeV)	$\simeq 6 \times 10^{-9}$ (see footnote 3)	0.0129 [23]	end of June [23, 7, 8]	$\ll 1.4 \times 10^{-3}$	(see text and footnote 3)	$\ll 2 \times 10^{-5}$	$\ll 1.6 \times 10^{-3}$
	$\nu \to n$ (few MeV)	$\simeq 3 \times 10^{-10}$ (see text)	0.03342 *	Jan. 4th *	$\ll 7 \times 10^{-5}$	(see text)	$\ll 2 \times 10^{-6}$	$\ll 2 \times 10^{-4}$
	direct μ	$\Phi^{(\mu)}_0 \simeq 20\ \mu$ m^{-2}d^{-1} [20]	0.0129 [23]	end of June [23, 7, 8]	$\simeq 10^{-7}$	[2, 7, 8]	$\simeq 10^{-9}$	$\simeq 10^{-7}$
	direct ν	$\Phi^{(\nu)}_0 \simeq 6 \times 10^{10}\ \nu$ cm^{-2}s^{-1} [26]	0.03342 *	Jan. 4th *	$\simeq 10^{-5}$	[31]	3×10^{-7}	3×10^{-5}

* The annual modulation of solar neutrino is due to the different Sun-Earth distance along the year; so the relative modulation amplitude is twice the eccentricity of the Earth orbit and the phase is given by the perihelion.

All the contributions are negligible w.r.t. the annual modulation amplitude observed by DAMA/LIBRA and they cannot contribute to the observed modulation amplitude.

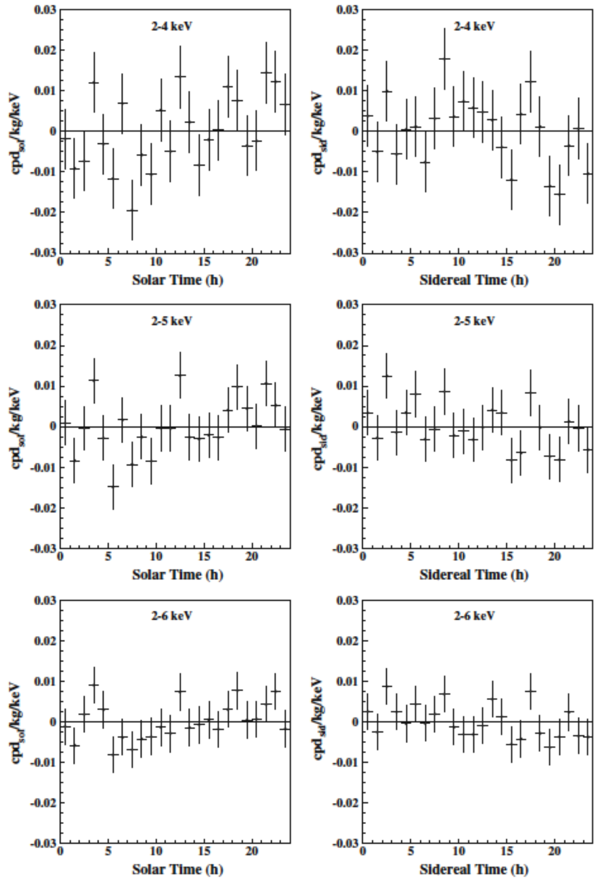
+ In no case neutrons (of whatever origin) can mimic the DM annual modulation signature since some of the **peculiar requirements of the signature** would fail, such as the neutrons would induce e.g. variations in all the energy spectrum, variation in the multiple hit events,... which were not observed.

+ In no case muon or muons induced effects can mimic the signature (see e.g. **EPJC 72 (2012) 2064**)

Model independent result on possible diurnal effect in DAMA/LIBRA-phase1

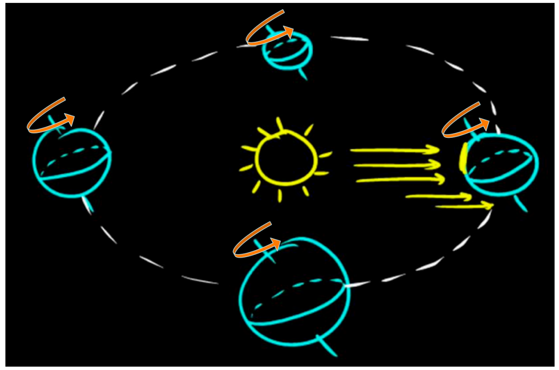
Eur. Phys. J. C 74 (2014) 2827

solar sidereal



2-4 keV

• Experimental *single-hit* residuals rate vs either sidereal and solar time and vs energy.



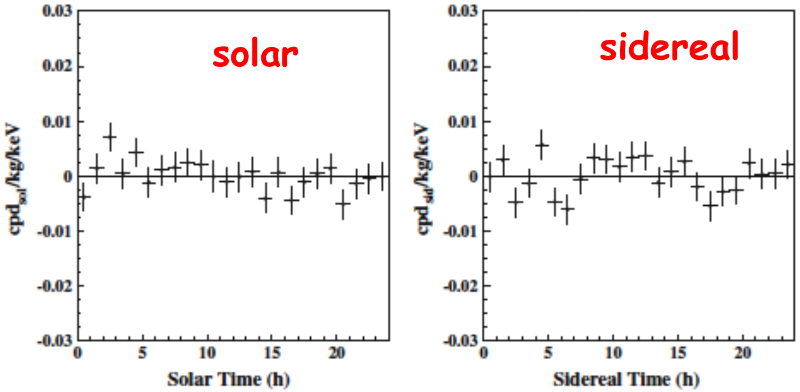
2-5 keV

Energy region where the annual modulation observed.

2-6 keV

Energy region just above.

6-14 keV



Energy	Solar Time	Sidereal Time
2–4 keV	χ^2/d.o.f. = 35.2/24 → P = 7%	χ^2/d.o.f. = 28.7/24 → P = 23%
2–5 keV	χ^2/d.o.f. = 35.5/24 → P = 6%	χ^2/d.o.f. = 24.0/24 → P = 46%
2–6 keV	χ^2/d.o.f. = 25.8/24 → P = 36%	χ^2/d.o.f. = 21.2/24 → P = 63%
6–14 keV	χ^2/d.o.f. = 25.5/24 → P = 38%	χ^2/d.o.f. = 35.9/24 → P = 6%

→ no diurnal variation with significance of 95% C.L.

+ run test to verify the hypothesis that the positive and negative data points are randomly distributed: lower tail probabilities (in the four energy regions): 43, 18, 7, 26% for solar case and 54, 84, 78, 16% for sidereal case

→ presence of any significant diurnal variation and of time structures can be excluded at the reached level of sensitivity

A diurnal effect with the sidereal time is expected for DM because of Earth rotation

Velocity of the detector in the terrestrial laboratory:

Eur. Phys. J. C 74 (2014) 2827

$$\vec{v}_{lab}(t) = \vec{v}_{LSR} + \vec{v}_{\odot} + \vec{v}_{rev}(t) + \vec{v}_{rot}(t),$$

Since:

- $|\vec{v}_s| = |\vec{v}_{LSR} + \vec{v}_{\odot}| \approx 232 \pm 50$ km/s,
- $|\vec{v}_{rev}(t)| \approx 30$ km/s
- $|\vec{v}_{rot}(t)| \approx 0.34$ km/s

$$v_{lab}(t) \simeq v_s + \hat{v}_s \cdot \vec{v}_{rev}(t) + \hat{v}_s \cdot \vec{v}_{rot}(t).$$

$\vec{v}_{LSR}$	velocity of the Local Standard of Rest (LSR) due to the rotation of the Galaxy
$\vec{v}_{\odot}$	Sun peculiar velocity with respect to LSR
$\vec{v}_{rev}(t)$	velocity of the revolution of the Earth around the Sun
$\vec{v}_{rot}(t)$	velocity of the rotation of the Earth around its axis at the latitude and longitude of the laboratory.

Annual modulation term:

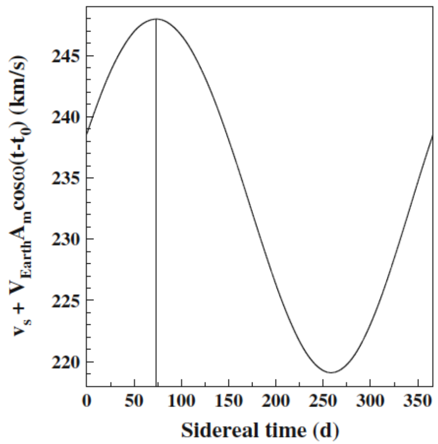
$$\hat{v}_s \cdot \vec{v}_{rev}(t) = V_{Earth} B_m \cos(\omega(t - t_0))$$

- V_{Earth} is the orbital velocity of the Earth ≈ 30 km/s
- $B_m \approx 0.489$
- $t_0 \approx t_{equinox}$ + 73.25 days ≈ June 2

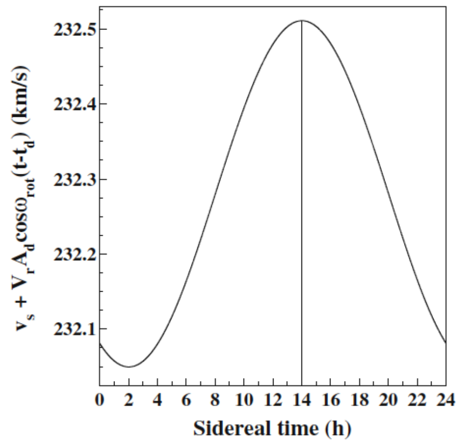
Diurnal modulation term:

$$\hat{v}_s \cdot \vec{v}_{rot}(t) = V_r B_d \cos\left[\omega_{rot}\left(t - t_d\right)\right]$$

- V_r is the rotational velocity of the Earth at the given latitude (for LNGS ≈ 0.3435 km/s)
- $B_d \approx 0.671$
- $t_d \approx 14.02$ h (at LNGS)



Velocity of the Earth in the galactic frame as a function of the sidereal time, with starting point March 21 (around spring equinox). The contribution of diurnal rotation has been dropped off. The maximum of the velocity (vertical line) is about 73 days after the spring equinox.



Sum of the Sun velocity in the galactic frame (v_s) and of the rotation velocity of a detector at LNGS ($v_s \cdot v_{rot}(t)$) as a function of the sidereal time. The maximum of the velocity is about at 14 h (vertical line).

The time dependence of the counting rate

Expected signal counting rate in a given k-th energy bin: Eur. Phys. J. C 74 (2014) 2827

$$S_k\left[v_{lab}(t)\right] \simeq S_k\left[v_s\right] + \left[\frac{\partial S_k}{\partial v_{lab}}\right]_{v_s} \left[V_{Earth} B_m \cos\omega(t-t_0) + V_r B_d \cos\omega_{rot}(t-t_d)\right]$$

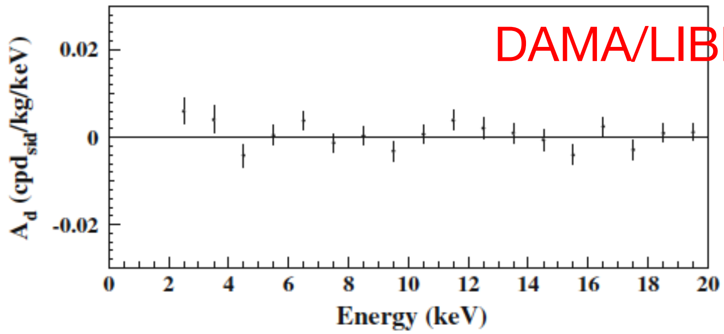
The ratio R_{dy} of the diurnal over annual modulation amplitudes is a model independent constant

- Annual modulation amplitude: $S_m = \left[\frac{\partial S_k}{\partial v_{lab}}\right]_{v_s} V_{Earth} B_m$
- Diurnal modulation amplitude $S_d = \left[\frac{\partial S_k}{\partial v_{lab}}\right]_{v_s} V_r B_d$

$$R_{dy} = \frac{S_d}{S_m} = \frac{V_r B_d}{V_{Earth} B_m} \simeq 0.016$$ at LNGS latitude

- Observed annual modulation amplitude in DAMA/LIBRA-phase1 in the (2-6) keV energy interval: (0.0097 ± 0.0013) cpd/kg/keV → thus, the expected value of the diurnal modulation amplitude is ≃1.5 × 10^{-4} cpd/kg/keV.

- When fitting the *single-hit* residuals with a cosine function with amplitude A_d as free parameter, period fixed at 24 h and phase at 14 h: all the diurnal modulation amplitudes are compatible with zero.



Energy	A_d^{exp} (cpd/kg/keV)	χ^2/d.o.f.	P
2–4 keV	$(2.0 \pm 2.1) \times 10^{-3}$	27.8/23	22%
2–5 keV	$-(1.4 \pm 1.6) \times 10^{-3}$	23.2/23	45%
2–6 keV	$-(1.0 \pm 1.3) \times 10^{-3}$	20.6/23	61%
6–14 keV	$(5.0 \pm 7.5) \times 10^{-4}$	35.4/23	5%

$A_d < 1.2 \times 10^{-3}$ cpd/kg/keV (90%CL)

A_d values compatible with zero, having random fluctuations around zero with χ^2/d.o.f. = 19.5/18

Present experimental sensitivity not yet suitable to explore the expected diurnal modulation amplitude derived from the DAMA/LIBRA-phase1 observed annual modulation effect

adequate sensitivity = larger exposure with DAMA/LIBRA-phase2 which - having a lower software energy threshold - also offers an additional alternative possibility to increase sensitivity to such an effect

Two other analyses on:

1) Investigation of *Earth Shadow Effect* with DAMA/LIBRA-phase1
2) DAMA annual modulation effect and Asymmetric mirror matter

have been concluded and papers finalized.

They will be mentioned elsewhere

DAMA/LIBRA-phase2_3-annual-cycles

PRELIMINARY

	Period	Mass (kg)	Exposure (kg×day)	(α-β^2)
DAMA/LIBRA-ph2_1*	Jan. 2011– Sept. 2011	242.5	t.b.a.	–
DAMA/LIBRA-ph2_2	Nov. 2, 2011 – Sept. 11, 2012	242.5	62917	0.519
DAMA/LIBRA-ph2_3	Oct. 8, 2012 – Sept. 2, 2013	242.5	60586	0.534
DAMA/LIBRA-ph2_4	Sept. 3, 2013 - Sept. 1, 2014	242.5	77307	0.488
DAMA/LIBRA-phase2_3-a.c.	Nov. 2, 2011 – Sept. 1, 2014	242.5	**200810** (0.55 ton×yr)	0.512
DAMA/LIBRA-phase1	Sept. 9, 2003 – Sept. 8, 2010		379795 (1.04 ton×yr)	0.518
DAMA/NaI+DAMA/LIBRA-phase1+DAMA/LIBRA-phase2_3-a.c.:			**1.88 ton×yr**	

* Commissioning, optimizations and data taking mainly focused about 1 keV software energy threshold (JINST 7 (2012) P03009). This period has: i) no data before/near Dec. 2, 2010; ii) data sets with some set-up modifications. Not used for a.m. studies.

More than a ton × yr experiment? done

- Calibrations 3 a.c.: ≈ 5.89 x 10^7 events from sources
- acceptance window eff. 3 a.c.: ≈ 4.1 x 10^7 events (≈1.6 x 10^6 events/keV)

... continuously running

✓ **Fall 2012: new preamplifiers installed + special trigger modules.**
✓ **Other new components in the electronic chain in development**

Stability parameters of DAMA/LIBRA-phase2

Modulation amplitudes obtained by fitting the time behaviours of main running parameters, acquired with the production data, when including a DM-like modulation

Running conditions stable at a level better than 1% also in the new running periods

PRELIMINARY

	DAMA/LIBRA-ph2_2	DAMA/LIBRA-ph2_3	DAMA/LIBRA-ph2_4
Temperature (°C)	(0.0012 ± 0.0051)	-(0.0002 ± 0.0049)	(0.0017± 0.0044)
Flux N_2 (l/h)	-(0.15 ± 0.18)	-(0.02 ± 0.22)	-(0.02± 0.22)
Pressure (mbar)	$(1.1 \pm 0.9)\times10^{-3}$	(0.02 ± 0.11) $)\times10^{-2}$	$-(0.9 \pm 1.0)\times10^{-3}$
Radon (Bq/m^3)	(0.015 ± 0.034)	-(0.002 ± 0.050)	-(0.009± 0.028)
Hardware rate above single ph.e. (Hz)	$-(0.12 \pm 0.16)\times10^{-2}$	$(0.00 \pm 0.12)\times10^{-2}$	$(0.09 \pm 0.12)\times10^{-2}$

All the measured amplitudes well compatible with zero
+ none can account for the observed effect
(to mimic such signature, spurious effects and side reactions must not only be able to account for the whole observed modulation amplitude, but also simultaneously satisfy all the 6 requirements)

DM annual modulation signature

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

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

- ε: increased in DAMA/LIBRA-phase2
- ΔE: increased in DAMA/LIBRA-phase2
- T: increased with DAMA/LIBRA-phase2

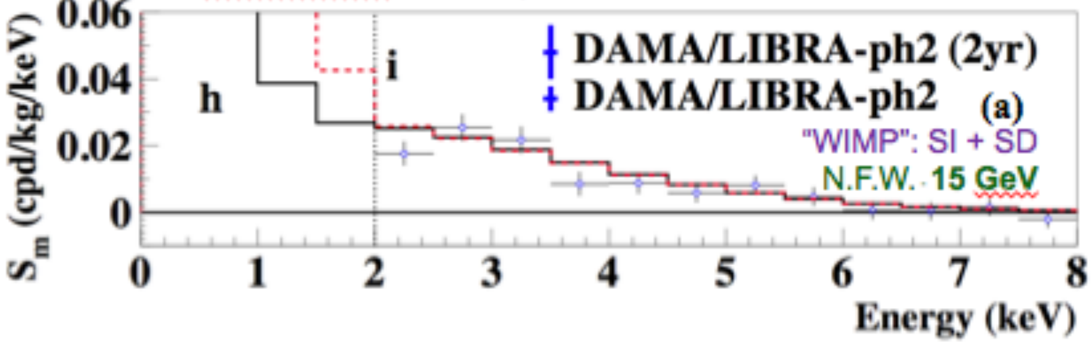
→ Upgrade at fall 2010 & running time
also equivalent to have enlarged the exposed mass

&: DM annual modulation signature acts itself as a strong bckg reduction strategy as already pointed out 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

Just few examples about the discrimination power of DAMA/LIBRA-phase2_2-annual cycles under some given set of astrophysical, nuclear and particle physics assumptions

DAMA/NaI+DAMA/LIBRA-ph1



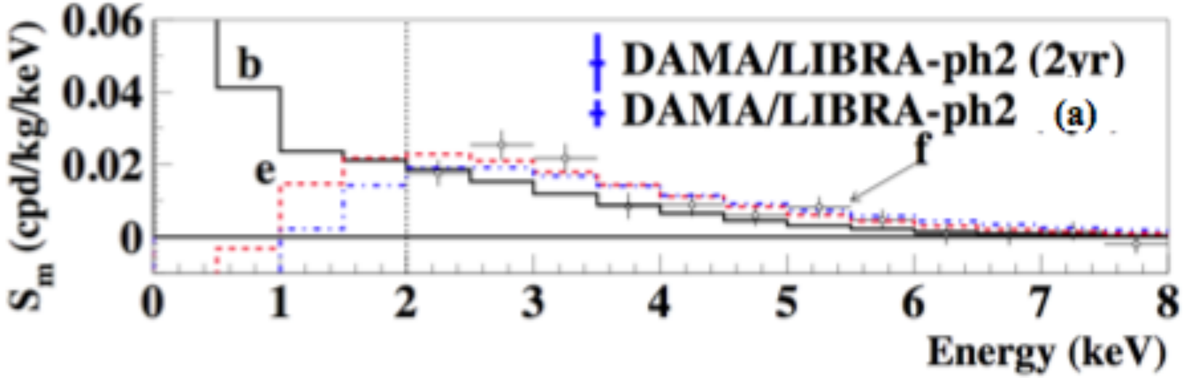
Not best fit cases, same C.L., see table above for cross sections and other assumptions in theor. expectations (i.e. labels).

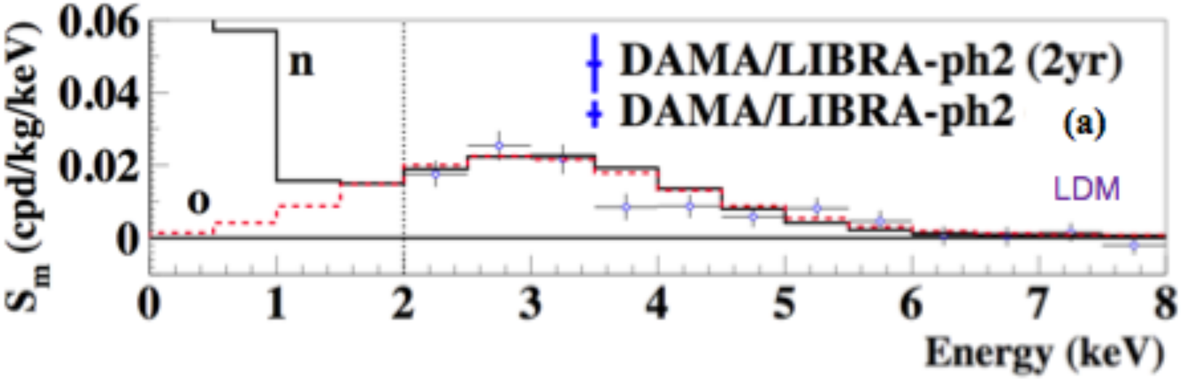
- discrimination among w/wo channeling
- discrimination among WIMP's masses
- discrimination among DM models

here q.f. vs E assumed constant

(a) Assuming MT= 464000 kg day

$$\sigma(S_m) = \sqrt{\frac{\langle R \rangle}{M \cdot T \cdot \Delta E \cdot \varepsilon \cdot (\alpha - \beta^2)}}$$





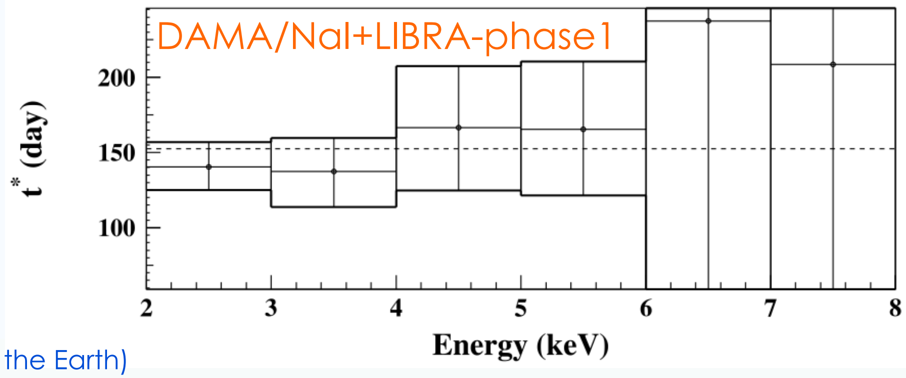
"WIMP": SI
b) 10 GeV-ch
e) 60 GeV
f) 100 GeV

The second orders effects to be investigated by DAMA/LIBRA-phase2

The importance of studying second order effects and the annual modulation phase

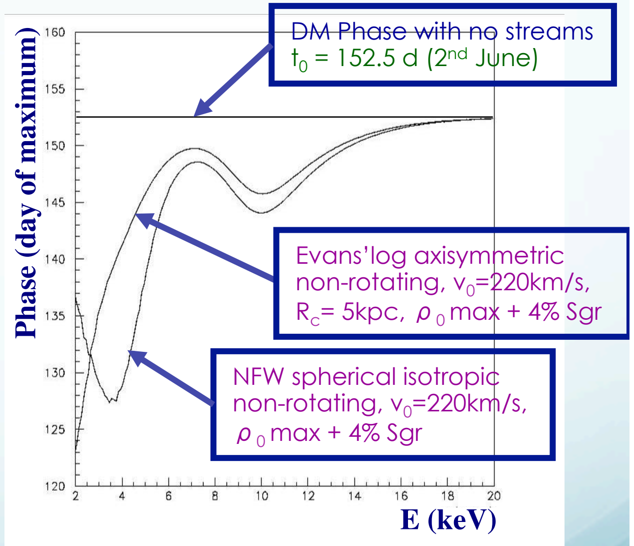
High exposure and lower energy threshold can allow further investigation on:

- the nature of the DM candidates
  - ✓ to disentangle among the different astrophysical, nuclear and particle physics models (nature of the candidate, couplings, inelastic interaction, form factors, spin-factors …)
  - ✓ scaling laws and cross sections
  - ✓ multi-component DM particles halo?
- possible diurnal effects on the sidereal time
  - ✓ expected in case of high cross section DM candidates (shadow of the Earth)
  - ✓ due to the Earth rotation velocity contribution (it holds for a wide range of DM candidates)
  - ✓ due to the channeling in case of DM candidates inducing nuclear recoils.
- astrophysical models
  - ✓ velocity and position distribution of DM particles in the galactic halo, possibly due to:
    - satellite galaxies (as Sagittarius and Canis Major Dwarves) tidal "streams";
    - caustics in the halo;
    - gravitational focusing effect of the Sun enhancing the DM flow ("spike" and "skirt");
    - possible structures as clumpiness with small scale size
    - Effects of gravitational focusing of the Sun

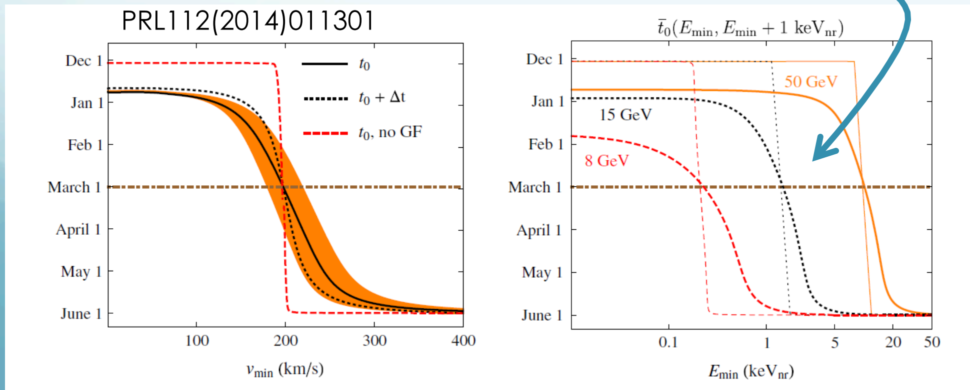


The annual modulation phase depends on :
- Presence of streams (as SagDEG and Canis Major) in the Galaxy
- Presence of caustics
- Effects of gravitational focusing of the Sun

The effect of the streams on the phase depends on the galactic halo model



PRL112(2014)011301



A step towards such investigations:

➔DAMA/LIBRA-phase2

with lower energy threshold and larger exposure

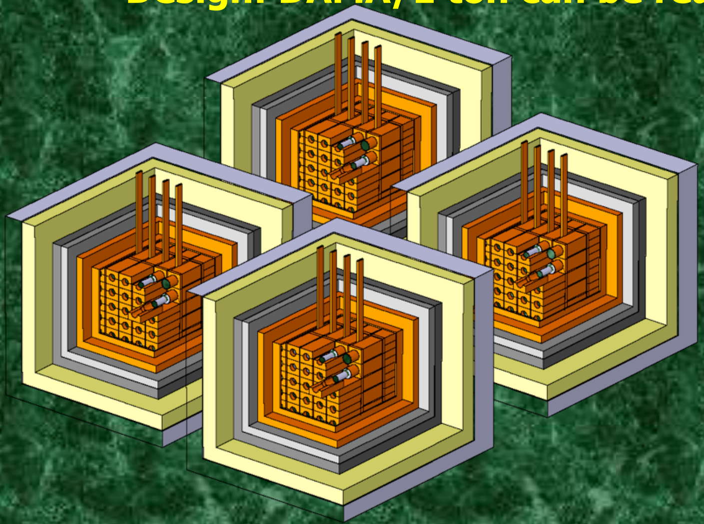
Starting studies towards an interesting phase-3 …

The strong interest in the low energy range suggest the possibility of a new development of high Q.E. PMTs with increased radiopurity to directly couple them to the DAMA/LIBRA crystals, removing the special quartz light guides which act also as otical window obtaining an ultimate number of ph.e./keV.

… and multi-purpose full sensitive mass DAMA/1ton

1) Proposed since 1996 (DAMA/NaI and DAMA/LIBRA intermediate steps)
2) Technology largely at hand and still room for further improvements in the low-background characteristics of the set-up (NaI(Tl) crystals, PMTs, shields, etc.)
3) 1 ton detector: the cheapest, the highest duty cycle, the clear signature, fast realization in few years, full sensitive mass, …

Design: DAMA/1 ton can be realized by adding 3 replicas of DAMA/LIBRA:

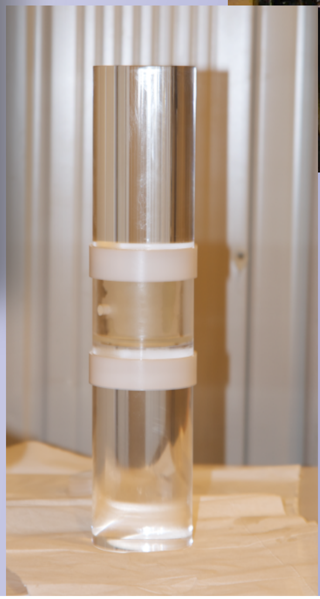


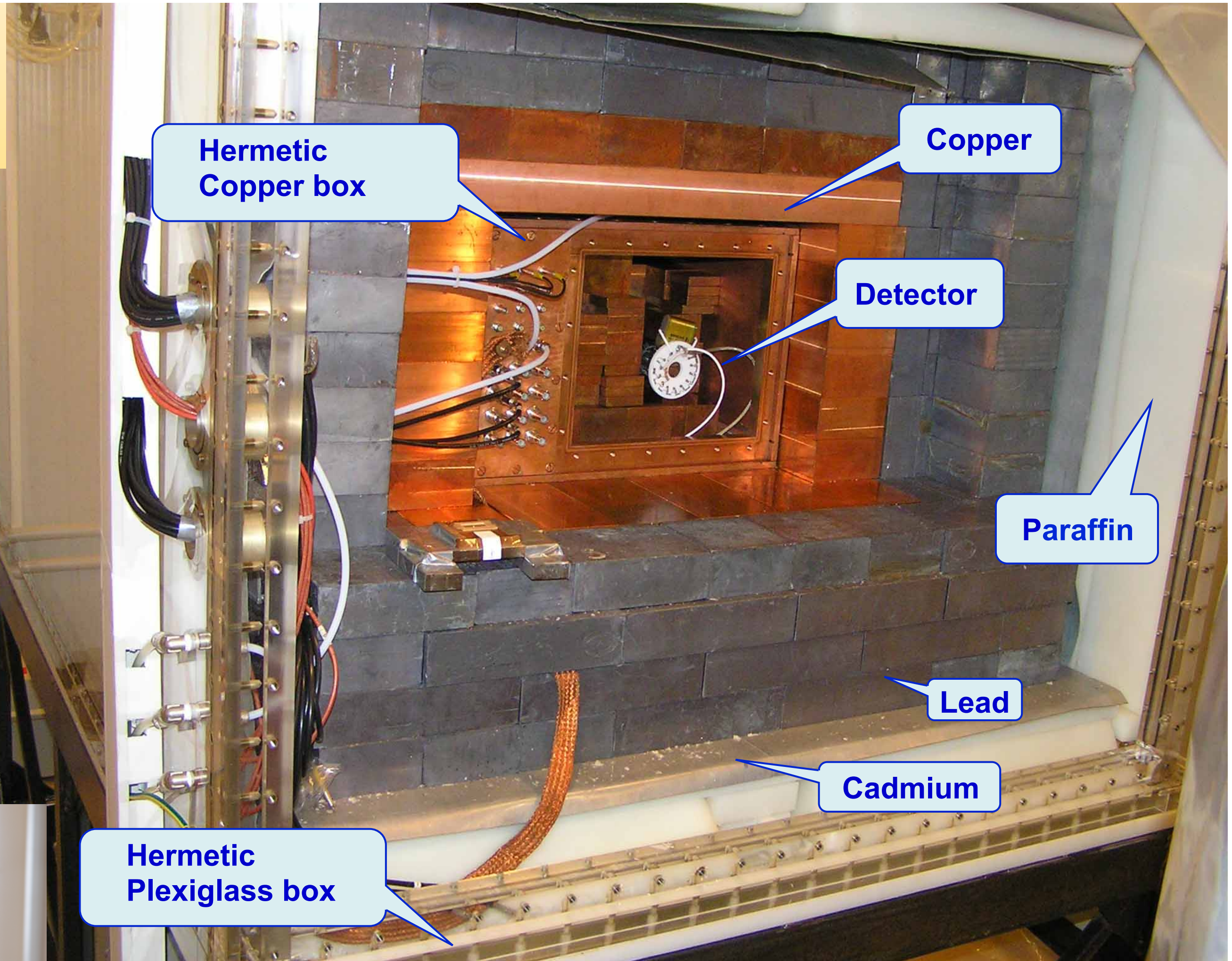
- the detectors of similar size than those already used
- the features of low-radioactivity of the set-up and of all the used materials would be assured by many years of experience in the field
- electronic chain and controls would profit by the previous experience and by the use of compact devices already developped, tested and used.
- new digitizers will offer high expandibility and high performances
- the daq can be a replica of that of DAMA/LIBRA
- Some R&Ds carried out

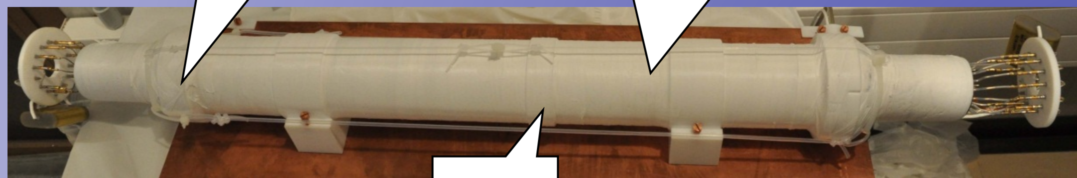
DAMA/R&D

General purpose set-up

Upgraded several times







DAMA/R&D – in this period:

1) The experiment with $CdWO_4$ crystal scintillators enriched at 82% in ^{116}Cd in progress.

2) A paper on the production strategies and on features reached by enriched $CdWO_4$ in Cd isotopes and on some future perspective has been presented at conference and published. Future strategies to develop radiopurer scintillators are in progress.

3) Further study of the highly forbidden ^{113m}Cd beta decay prepared.

4) Results obtained with a BaF_2 scintillator to search for the ββ decay of Ba isotopes and on precision measurement of the $T_{1/2}$ of some radionuclide of the U and Th families published.

5) The work towards the future installation of $^{116}CdWO_4$ detectors in the low-background GeMulti set-up started.

6) Investigation of radioactive elements segregation in crystals to develop ultra-radio-pure scintillators for rare events searches in progress.

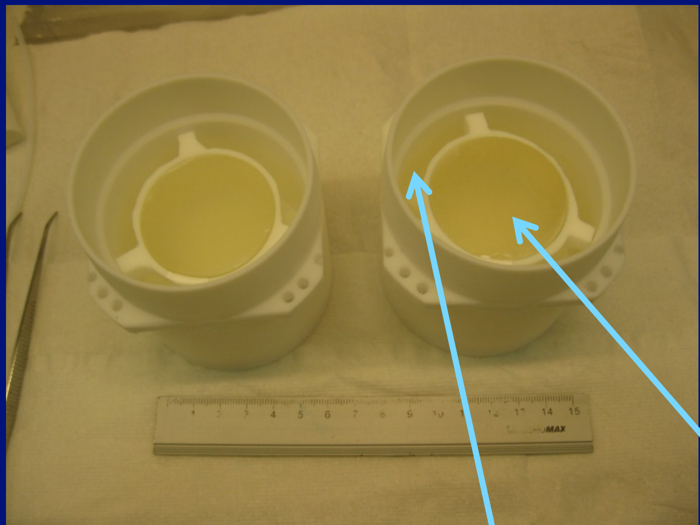
7) The paper on the search for super-heavy eka-tungsten with $ZnWO_4$ and BGO crystal scintillators in press.

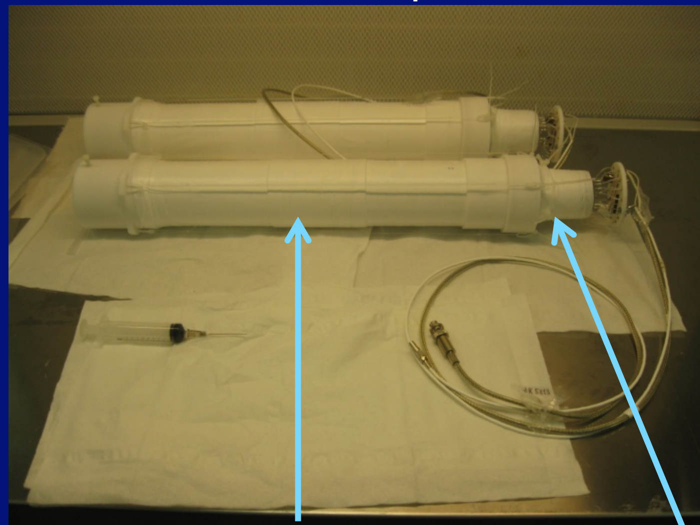
8) At the end of the $^{116}CdWO_4$ measurements, new measurements are foreseen. Among them: developments on new $SrI_2(Eu)$ crystals, on new enriched $CdWO_4$ depleted in ^{113}Cd, on highly radio-pure $ZnWO_4$…

AURORA experiment in DAMA/R&D with $^{116}CdWO_4$

Last upgrade:

The number of PMTs (the most contaminated part of the set-up) was reduced twice practically without lost of the energy resolution (~5% at the $Q_{2\beta}$ of ^{116}Cd)





$^{116}CdWO_4$

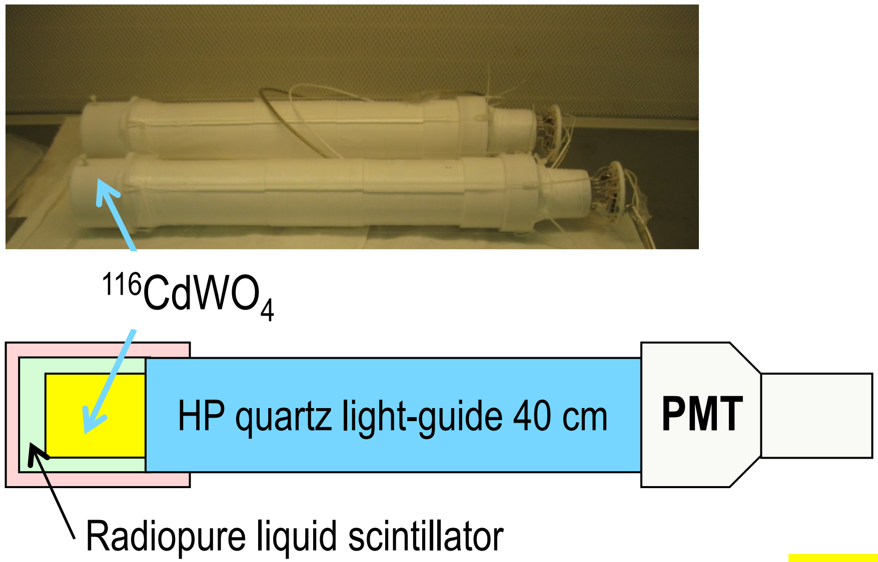
HP quartz light-guide

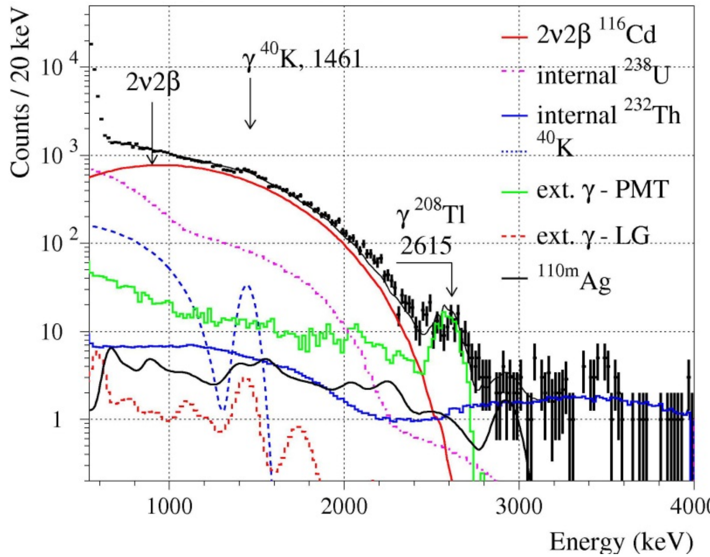
PMT

Borexino liquid scintillator in Teflon container

AURORA: Investigation of double β decay of ^{116}Cd

Experiment is going with two radiopure high quality $^{116}CdWO_4$ (1.176 kg) enriched in ^{116}Cd to 82%. After a few improvement of the set-up the FWHM (at $Q_{2\beta}$ of ^{116}Cd) = 5.2%, background in the ROI ≈ 0.1 cnt/(keV yr kg) (we have 17656 h of data with the background level).

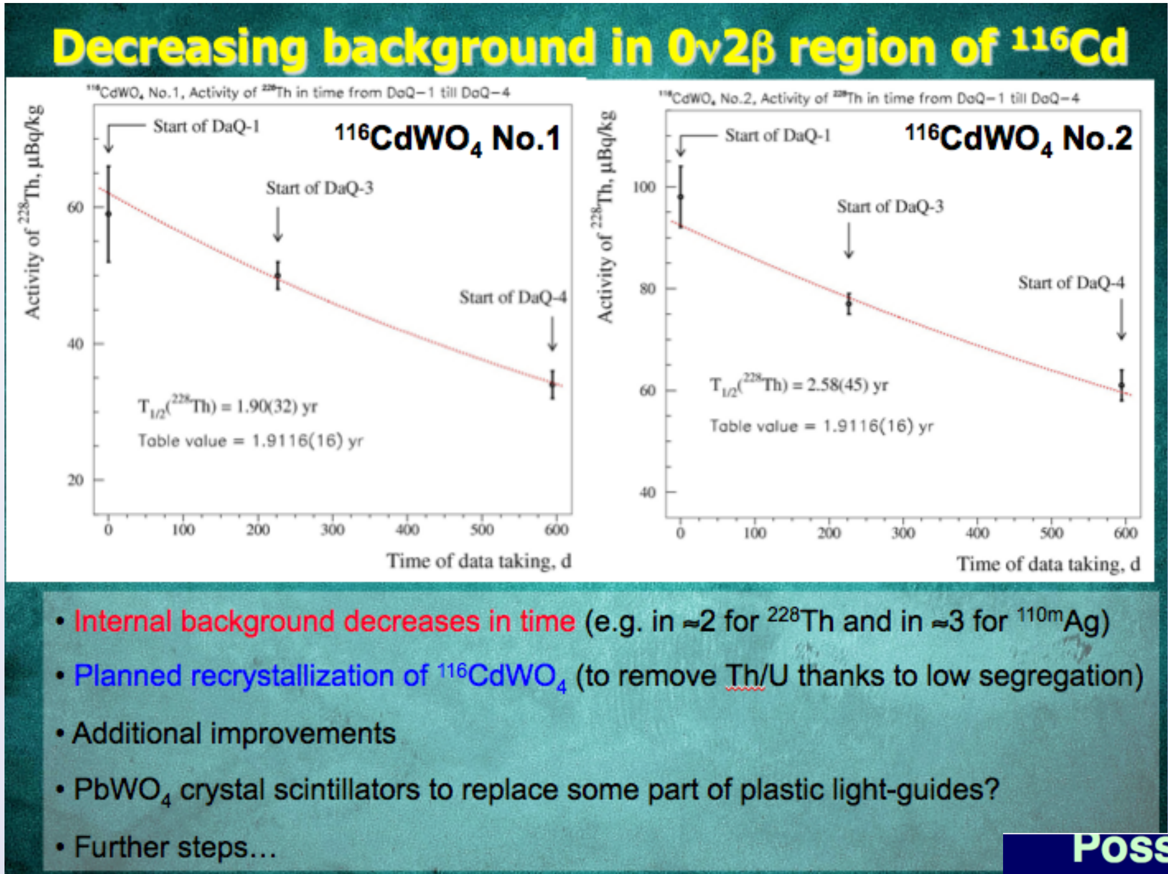




Energy spectrum accumulated over 8397 h after the last upgrade of the detector. The two neutrino decay of ^{116}Cd with the half-life ≈2.6×10^{19} y dominates in the background

Our goals are to measure the $T_{1/2}^{2\nu2\beta}$ with high (10-20%) accuracy and set new limits on different channels. Modes with majorons, transitions to the excited levels will be improved too. The experiment is in progress.

Preliminary results on EPJ Web of Conf 65 (2014) 01005

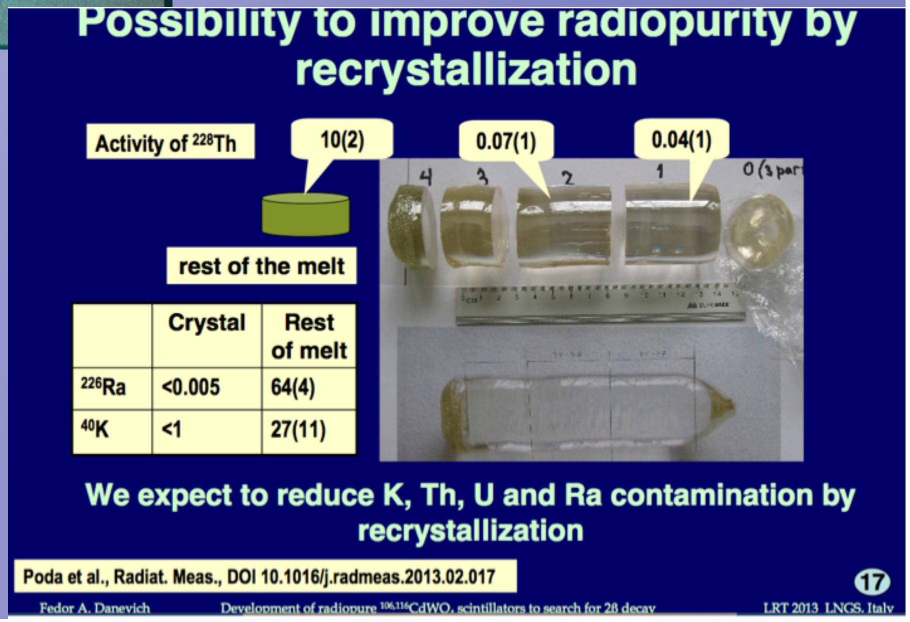


How to decrease BG in the 0ν2β region of ^{116}Cd?

- ✓ **Internal BG decreases in time** ^{228}Th in ≈2 and ^{110m}Ag in ≈3
- ✓ **Removing of one LowBg PMT** + replacing by ULB PMT

PMT	Activity, mBq/PMT	
Hamamatsu	^{228}Ra	^{226}Ra
R6233MOD	18(3)	65(9)
R11065SEL	2.3	3.3

- ✓ **Adding of quartz light guide** or made from $PbWO_4$ scintillator
- ✓ **Recrystallization of $^{116}CdWO_4$** to remove Th/U thanks to observed low segregation



Investigation of rare nuclear decays with BaF_2 crystal scintillator contaminated by radium

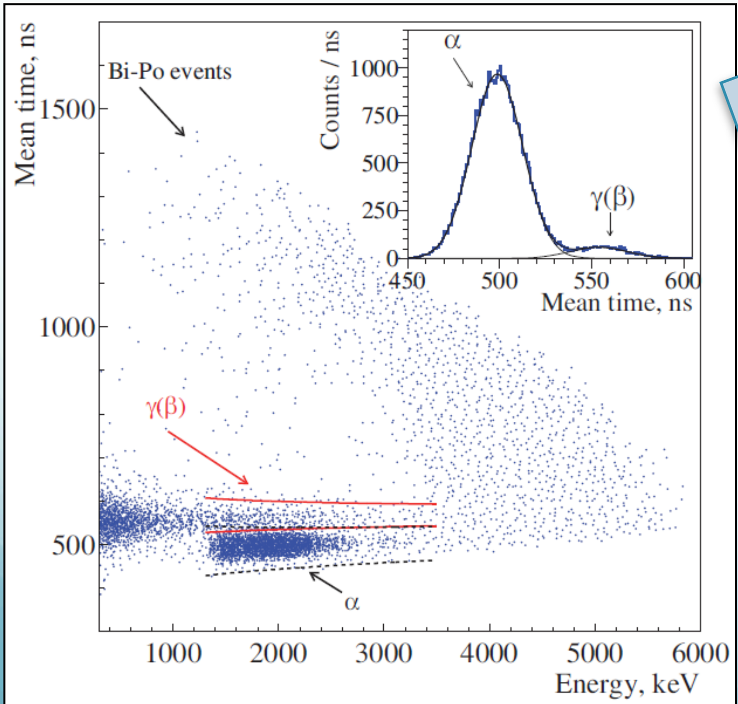
EPJ A 50 (2014) 134

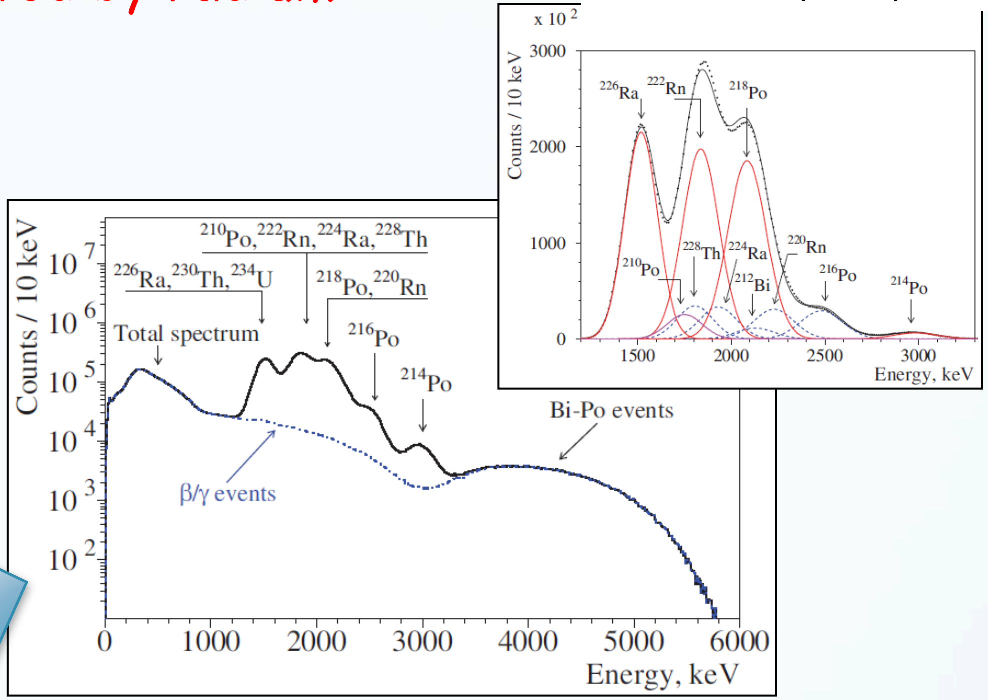
BaF_2 crystal (∅ 3″×3″, 1.714 kg)

DAMA/R&D set-up

T=101 h

1GSample/s Transient Digitizer records the signal profile over 4000 ns





Radium not removed during material preparation and crystal growth because of the chemical similarity of barium and radium ⇒ broken secular equilibrium

Chain	Nuclide	Activity, Bq/kg
^{232}Th	^{232}Th	< 0.004
	^{228}Th	1.35(6)
^{238}U	^{238}U	< 0.0002
	^{226}Ra	7.8(1)
	^{210}Pb	0.99(1)
^{235}U	^{235}U	< 0.0006
	^{231}Pa	< 0.0007
	^{227}Ac	< 0.07

Investigation of rare nuclear decays with BaF_2 crystal scintillator contaminated by radium

EPJ A 50 (2014) 134

- Analysis of Bi-Po events:
  - Half-life of ^{212}Po;
  - Search for 2β decay of ^{212}Pb
- Search for β and 2β decay of ^{222}Rn;
- Search for 2β decay of ^{226}Ra;

$$^{222}_{86}\mathrm{Rn} \xrightarrow[24\,\mathrm{keV}]{\beta?\ \simeq 4.8\times10^{5}\,\mathrm{y}} {}^{222}_{87}\mathrm{Fr} \xrightarrow[2028\,\mathrm{keV}]{\beta\ 14.2\,\mathrm{min}} {}^{222}_{88}\mathrm{Ra} \xrightarrow[6679\,\mathrm{keV}]{\alpha\ 38.0\,\mathrm{s}}$$
$$^{218}_{86}\mathrm{Rn} \xrightarrow[7263\,\mathrm{keV}]{\alpha\ 35\,\mathrm{ms}} {}^{214}_{84}\mathrm{Po} \xrightarrow[7833\,\mathrm{keV}]{\alpha\ 164.3\,\mu\mathrm{s}} {}^{210}_{82}\mathrm{Pb}(22.3\,\mathrm{y}).$$

$$^{226}_{88}\mathrm{Ra} \xrightarrow[472\,\mathrm{keV}]{2\beta?} {}^{226}_{90}\mathrm{Th} \xrightarrow[6451\,\mathrm{keV}]{\alpha\ 30.57\,\mathrm{min}} {}^{222}_{88}\mathrm{Ra} \xrightarrow[6679\,\mathrm{keV}]{\alpha\ 38.0\,\mathrm{s}}$$
$$^{218}_{86}\mathrm{Rn} \xrightarrow[7263\,\mathrm{keV}]{\alpha\ 35\,\mathrm{ms}} {}^{214}_{84}\mathrm{Po} \xrightarrow[7833\,\mathrm{keV}]{\alpha\ 164.3\,\mu\mathrm{s}} {}^{210}_{82}\mathrm{Pb}(22.3\,\mathrm{y}).$$

Nuclide	Main channel of decay and $T_{1/2}$ [24]		$T_{1/2}$ (and branching ratio, B) This work		Other works
^{212}Po	α	299 ± 2 ns	298.8 ± 0.8(stat.) ± 1.4(syst.)		294.7 ± 0.6(stat.) ± 0.8(syst.)
					299 ± 2
^{212}Pb	β	10.64 h	$2\beta2\nu > 75$ h	$(B < 14\%)$	> 146 h
			$2\beta0\nu > 20$ y	$(B < 6.0 \times 10^{-3}\%)$	> 6.7 y
^{222}Rn	α	3.8235 d	$\beta > 8.0$ y	$(B < 0.13\%)$	–
			$2\beta2\nu > 8.0$ y	$(B < 0.13\%)$	> 40 d
			$2\beta0\nu > 8.0$ y	$(B < 0.13\%)$	> 2.8 y
^{226}Ra	α	1600 y	$2\beta2\nu > 1.2 \times 10^{6}$ y	$(B < 0.13\%)$	$> 4.5 \times 10^{3}$ y
			$2\beta0\nu > 1.2 \times 10^{6}$ y	$(B < 0.13\%)$	$> 4.1 \times 10^{4}$ y

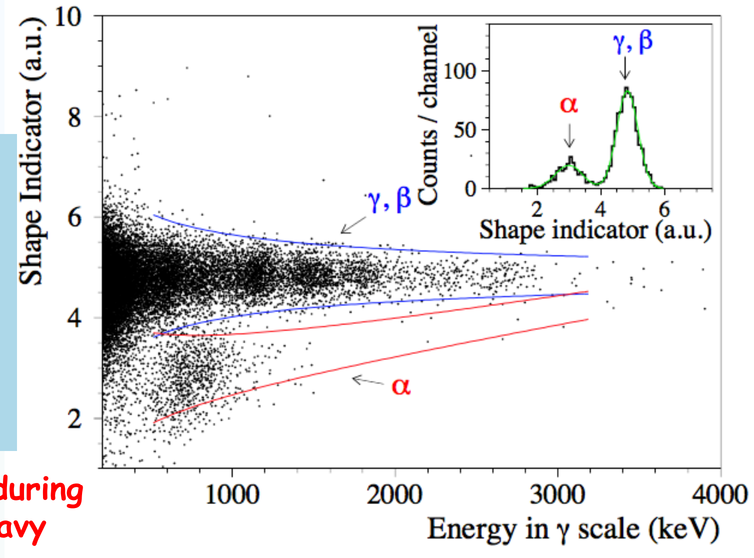
- ✓ New determination of the half-life of ^{212}Po
- ✓ First limit on the B.R. of ^{222}Rn relatively to β decay
- ✓ Improved half-life limits of ^{212}Pb, ^{222}Rn and ^{226}Ra relatively to 2β decays

- ✓ Future improvements with a detector with smaller dead time and better energy resolution
- ✓ An R&D of methods to purify Ba from Ra traces is in progress for the search for ββ decay of ^{130}Ba and ^{132} Ba which is of particular interest because of positive indications from 2 geochem. expts on ββ decay of ^{130} Ba

Search for long-lived superheavy eka-tungsten with radiopure $ZnWO_4$ crystal scintillator

Eka means "first" in Sanskrit. Used by Mendeleev as a prefix for yet-to-be-discovered elementst he predicted would "fit" into specific blank spaces in the next lowest position of the same groups in his periodic table.
E.G. : he knew that the unknown element for the blank space following Ca would be closely related to B, so he gave it the name of "eka-boron" until that unknown element, scandium, was definitely identified and named.

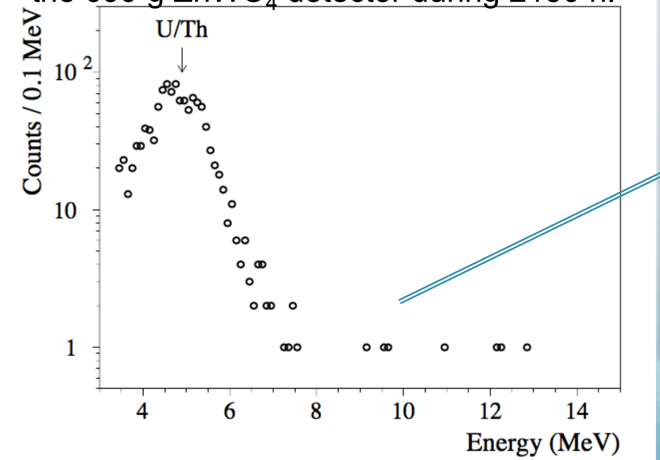
arXiv:15.04.07438
In press on Physica Scripta



- ✓ Possible existence of superheavy elements (SHE) with atomic masses $A>250$ and atomic numbers $Z>104$ was already discussed in 1950's.
- ✓ In 1960's, prediction of neutron-rich "island of stability" around the double magic $Z = 114$ or 126, $N = 184$.
- ✓ Recent calculations related to different models predict $N = 184$ as the magic number of neutrons and $Z = 114, 120$ or 126 as the proton magic number for spherical nuclei.

Data collected with a radio-pure $ZnWO_4$ crystal scintillator (699 g) during 2130 h were used to set a limit on possible concentration of superheavy eka-W (seaborgium Sg, Z = 106) in the crystal.

Energy spectrum of α particles registered by the 699 g $ZnWO_4$ detector during 2130 h.



Considering that one of the daughters in a chain of decays of the initial Sg nucleus decays with emission of high energy α particle ($Q_\alpha > 8$ MeV)

⇓

analyzing the high energy part of the measured α spectrum

⇓

N (Sg)/N (W) $< 5.5 \times 10^{-14}$ atoms/atom at 90% C.L. (for Sg half-life of 10^9 yr).

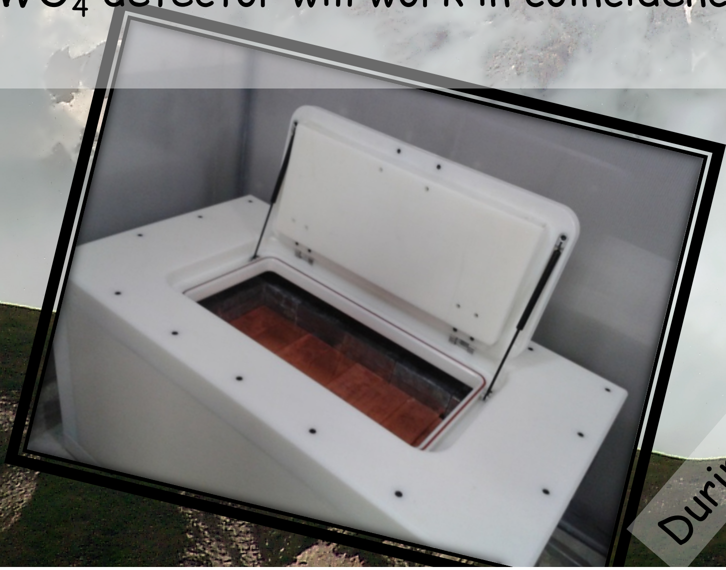
Studying eka-Bi in a large BGO scintillation bolometer in an experiment performed by another group [L. Cardani et al., JINST 7 (2012) P10022]:
N(eka-Bi)/N(Bi) $< 1.1 \times 10^{-13}$ atoms/atom with 90% C.L.

Both the limits are comparable with those obtained in recent experiments which instead look for spontaneous fission of superheavy elements or use the accelerator mass spectrometry.

DAMA/CRYS

In the period of interest:

1) At beginning of 2015 the measurement of a $ZnWO_4$ crystal produced by re-crystallization of the already tested $ZnWO_4$ crystal (aiming to estimate possible reduction in the trace contaminants) concluded.
2) The mechanical opening/closure system improved.
3) The cryogenic part (to allow measurements of the responses of variours scintillators as function of temperature) will be soon installed.
4) A new data taking with $CdWO_4$ crystal scintillator in progress, aiming the investigation of the decay schema of ^{113m}Cd.
5) Investigation of radioactive elements segregation in crystals to develop ultra-radio-pure scintillators for rare events experiments is continuing.
6) A new experiment to further increase the sensitivity to 2β processes in ^{106}Cd in progress. The enriched $^{106}CdWO_4$ detector will work in coincidence with two $CdWO_4$.



During installation

Investigation of ^{113m}Cd decay scheme

Experiments to study beta decay of ^{113m}Cd with the help of the $^{106}CdWO_4$ crystal scintillator (activity of ^{113m}Cd is ≈20 Bq) half-life and beta spectrum shape) started in DAMA/Crys

$^{106}CdWO_4$ crystal scintillator inside plastic light-guide filled by silicon oil viewed by two PMT through quartz guides in the DAMA/CRYS shield

The goals of the experiment are measurements:

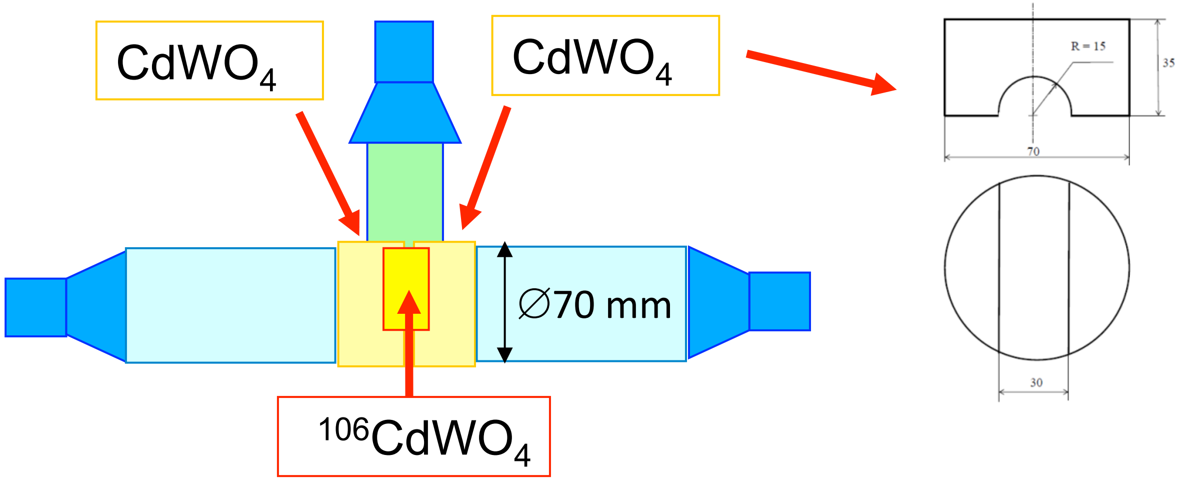
- **the ^{113m}Cd half-life**
- **the beta spectra shape of ^{113m}Cd**

By product: the background in the set-up will be estimated (for the future ^{106}Cd experiment)

Experiments to study the branching ratio for the isomeric transition and coefficient of conversion are in preparation

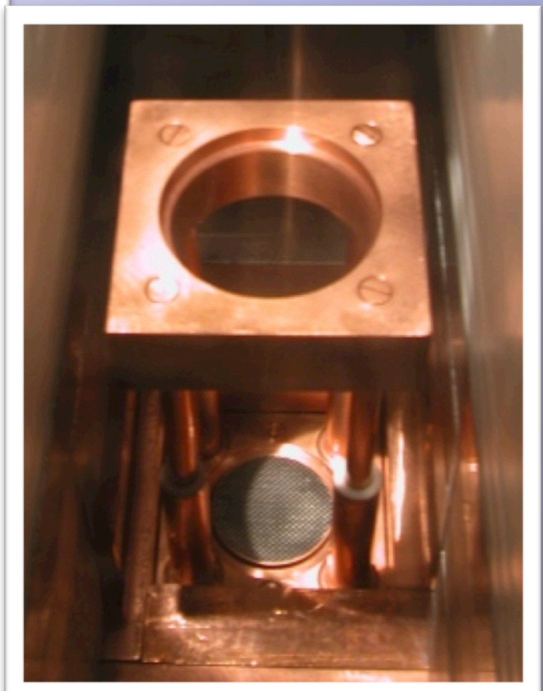
A new measurement with $^{106}CdWO_4$ is in preparation

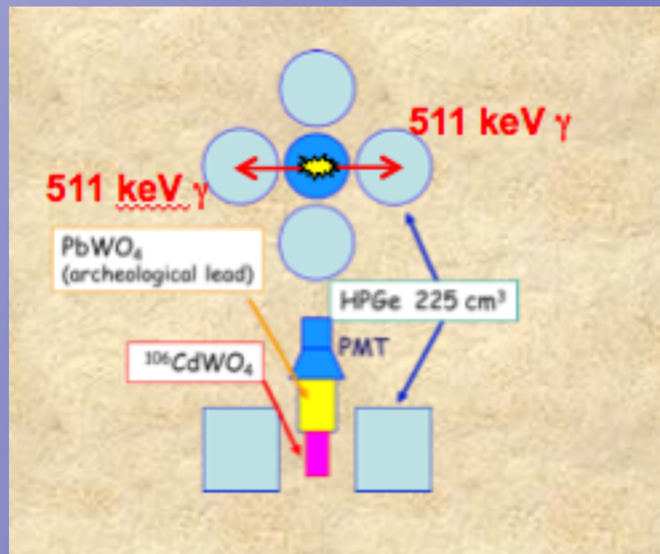
The Monte Carlo simulation has showed that the sensitivity is expected to be improved a few times due to the much higher detection efficiency of $CdWO_4$ and close geometry and a lower radioactive contamination of the detector and shield (DAMA/Crys)



In particular, the sensitivity for the two neutrino electron capture with positron emission is on the level of $T_{1/2}^{2\nu\varepsilon\beta^+} \approx 1.5\times10^{21}$ yr over 1 yr of experiment (theoretical predictions: 10^{20}-10^{22} yr)

DAMA/Ge and LNGS STELLA facility





DAMA/Ge and Ge facility at LNGS – in the period of interest

i) The data taking of the experiment to search for 2β processes in ^{106}Cd by using cadmium tungstate crystal scintillator enriched in ^{106}Cd in coincidence with the four HPGe crystals of the GeMulti detector at the STELLA facility has been concluded on February 2015. The data analysis and the paper are in progress.

ii) The deeply purified neodymium oxide samples with a total mass of about 2.381 kg have been installed in the low background GeMulti detector (four HPGe crystals in a cryostat) on February 2015 in order to search for 2β decay of ^{150}Nd to excited levels of ^{150}Sm. The data taking is started.

iii) The search for 2β decay of ^{184,192}Os (^{184}Os is of especial interest thanks to possibility of resonant neutrinoless double electron capture) and alpha decay of ^{184}Os to excited levels of daughter nuclei is waiting for the final setting of the new HPGe detector in STELLA facility, especially designed for low energy gamma-ray spectrometry.

iv) Search for ββ decay of ^{136}Ce and ^{138}Ce with a deeply purified sample of Ce oxide (732 g) measured for 1900 h with HPGe detector published.

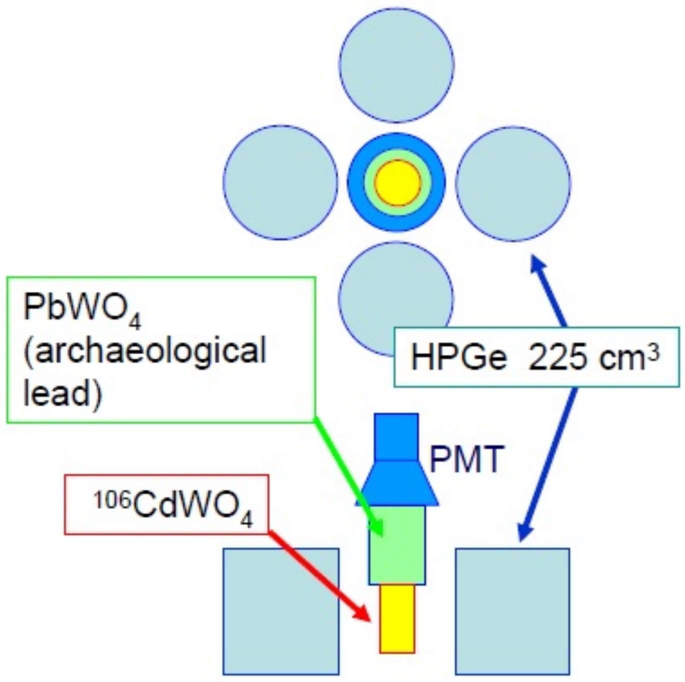
v) Further purification of the cerium sample (used in previous measurements) from thorium contamination to increase the experimental sensitivity is in preparation towards higher sensitivities.

vi) The R&D of low background GSO(Ce) crystal scintillators to investigate ββ processes in ^{152}Gd and ^{160}Gd is continuing.

vii) The R&D of methods to purify samarium, ytterbium, dysprosium and erbium is in progress. The materials are of special interest taking into account recent theoretical estimates of neutrino-less resonant double electron capture processes in ^{144}Sm, ^{162}Er, ^{164}Er and ^{168}Yb. Deep purification of the samples (by using the liquid-liquid purification method) will allow the improvement of the experimental sensitivity. Then experiments to search for "double positron" decay processes in ^{144}Sm, ^{156}Dy, ^{162}Er, ^{164}Er, ^{168}Yb and for $2\beta^-$ decay to excited levels of daughter nuclei for ^{154}Sm, ^{170}Er and ^{176}Yb will be performed.

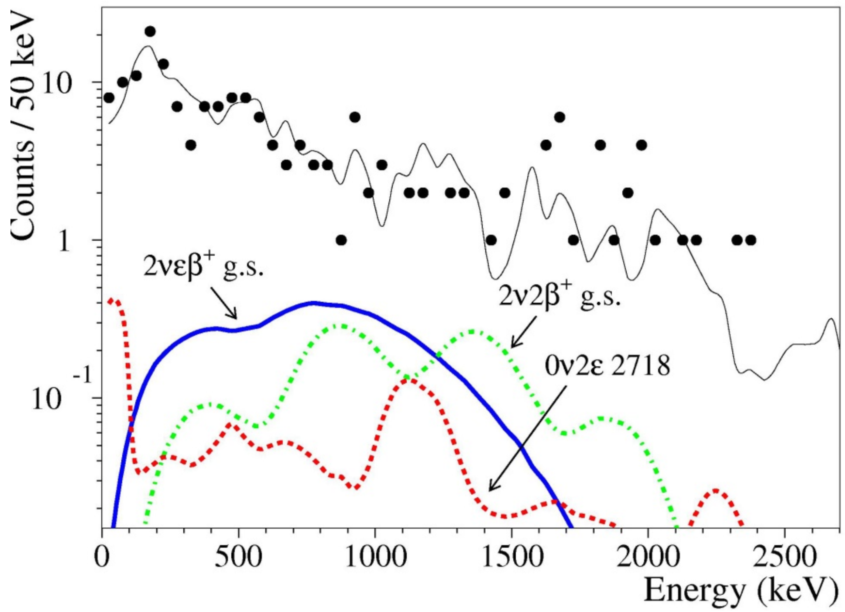
viii) Preparations of other future measurements are in progress.

Search for double β processes in ^{106}Cd



Scheme of the experimental set-up

Experiment is finished 05 Feb 2015
Total statistics is 13085 h ≈1.49 yr



The energy spectrum of the $^{106}CdWO_4$ detector accumulated over 13085 h in coincidence with 511 keV annihilation γ quanta in the HPGe detectors (circles). The model of background is shown by solid line. The Monte Carlo simulated distributions of the $2\nu\varepsilon\beta^+$ and $2\nu2\beta^+$ decays, and the $0\nu2\varepsilon$ transition of ^{106}Cd to the 2718 keV excited level of ^{106}Pd excluded at 90% C.L. are shown.

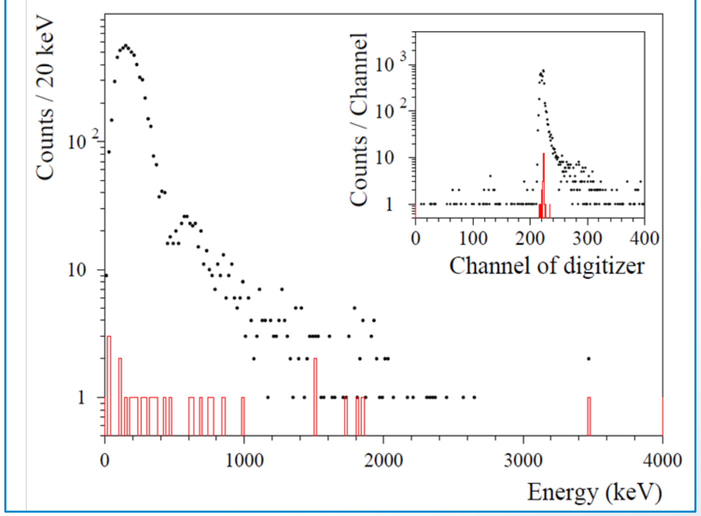
Data analysis and paper preparation are in progress

First preliminary results

EPJ Web of Conf. 65 (2014) 01004
(DOI: 10.1051/epjconf/20146501004)

Spectrum of $^{106}CdWO_4$ (3189 h) in coincidence with HPGe detectors:

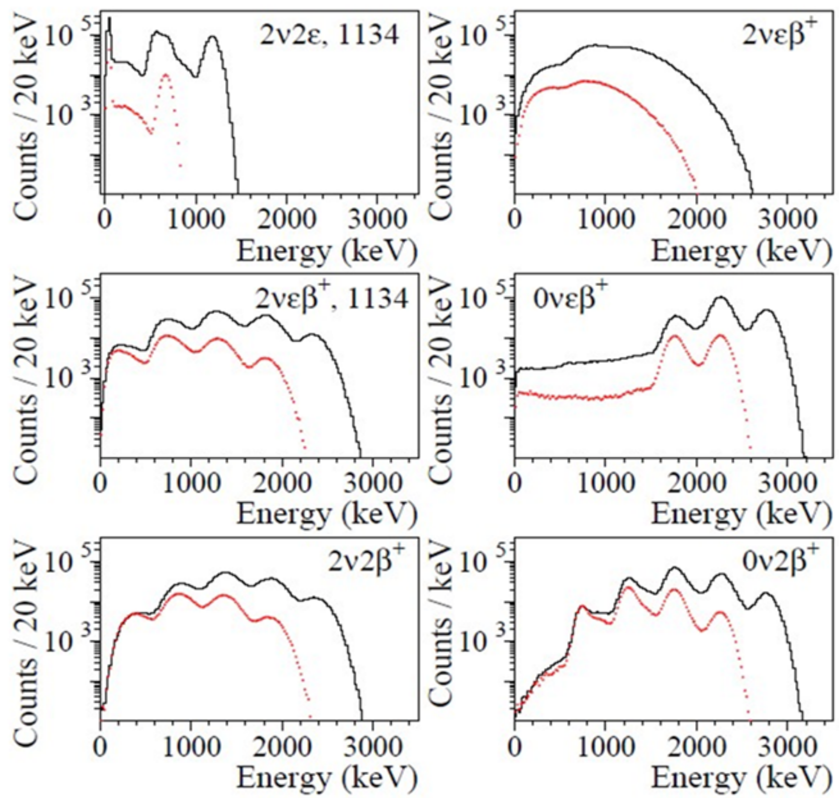
- **HPGe > 50 keV**
- **HPGe = 511 keV ± 3σ**



To compare with MC expectations

Simulation of 2β processes in ^{106}Cd:

- Anticoincidence $^{106}CdWO_4$ + HPGe
- Coincidence $^{106}CdWO_4$ + HPGe 511 keV



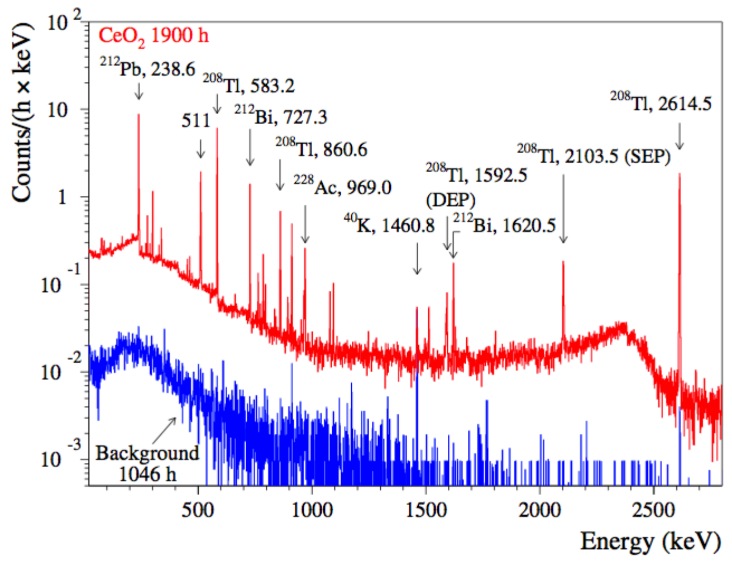
Decay channel	Decay mode	Level of ^{106}Pd (keV)	$T_{1/2}$ limit (yr) at 90% C.L.	
			Present work	Best previous limits
2ε	2ν	0_1^+ 1134	$\geq 2.2 \times 10^{20}$	$\geq 1.7 \times 10^{20}$ [7]
	0ν	g.s.	$\geq 3.6 \times 10^{19}$	$\geq 1.0 \times 10^{21}$ [7]
$\varepsilon\beta^+$	2ν	g.s.	$\geq 6.8 \times 10^{20}$	$\geq 4.1 \times 10^{20}$ [25]
	2ν	0_1^+ 1134	$\geq 8.8 \times 10^{20}$	$\geq 3.7 \times 10^{20}$ [7]
	0ν	g.s.	$\geq 8.8 \times 10^{20}$	$\geq 2.2 \times 10^{21}$ [7]
$2\beta^+$	2ν	g.s.	$\geq 1.2 \times 10^{21}$	$\geq 4.3 \times 10^{20}$ [7]
	0ν	g.s.	$\geq 1.5 \times 10^{21}$	$\geq 1.2 \times 10^{21}$ [7]

[7] P. Belli et al., PRC 85 (2012) 044610
[25] P. Belli et al., APP 10 (1999) 115

Improvements and running

Search for double beta decay of ^{136}Ce and ^{138}Ce

NPA930(2014)195

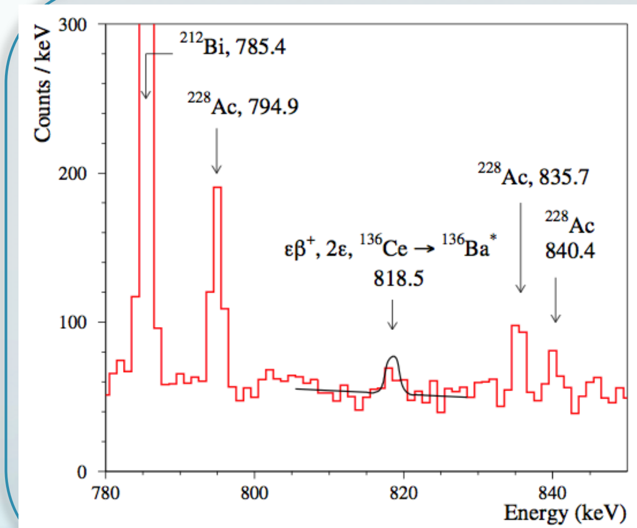


- Deeply purified CeO_2 sample (732 g)
- Measured in HPGe (STELLA facility at LNGS)
- T=1900 h

Transition	Energy release, keV	Isotopic abundance, % [20]	Allowed decay channels
$^{136}Ce \rightarrow {}^{136}Ba$	2378.53(27) [17] 2378.49(35) [18]	0.185(2)	2ε, $\varepsilon\beta^+$, $2\beta^+$
$^{138}Ce \rightarrow {}^{138}Ba$	693(10) [19]	0.251(2)	2ε
$^{142}Ce \rightarrow {}^{142}Nd$	1417.2(21) [19]	11.114(51)	$2\beta^-$

Radioactive contamination of cerium oxide before and after purification using liquid-liquid extraction method.

Chain	Nuclide	Activity (mBq/kg)				
		CeO$_2$ powder		CeCl$_3$ crystal		CeF$_3$ crystal
		before purification	after purification	by HPGe [24]	Scint. mode [25]	[23]
	^{40}K	77(28)	≤ 9	≤ 1700	–	≤ 330
	^{137}Cs	≤ 3	≤ 2	≤ 58	–	–
	^{138}La	–	≤ 0.7	680 ± 50	862 ± 31	≤ 60
	^{139}Ce	–	(6 ± 1)	–	–	–
	^{152}Eu	–	≤ 0.5	≤ 130	–	–
	^{154}Eu	–	≤ 0.9	≤ 60	–	–
	^{176}Lu	–	≤ 0.5	≤ 50	–	≤ 20
^{232}Th	^{228}Ra	850 ± 50	53 ± 3	≤ 210	–	890 ± 270
	^{228}Th	620 ± 30	573 ± 17	≤ 203	≤ 0.16	1010 ± 10
^{235}U	^{235}U	38 ± 10	≤ 1.8	–	–	≤ 40
	^{231}Pa	–	≤ 24	–	–	≤ 50
	^{227}Ac	–	≤ 3	≤ 740	284 ± 2	≤ 20
^{238}U	^{238}U	≤ 870	≤ 40	–	–	≤ 70
	^{226}Ra	11 ± 3	≤ 1.5	700 ± 70	≤ 11	≤ 60



Example of the search for ββ decay signals: the peak at 818.5 keV is expected as a result of de-excitation of excited levels of ^{136}Ba due to 2 ε or ε β^+ decay of ^{136}Ce. An excluded peak with area 53 counts is shown by solid line.

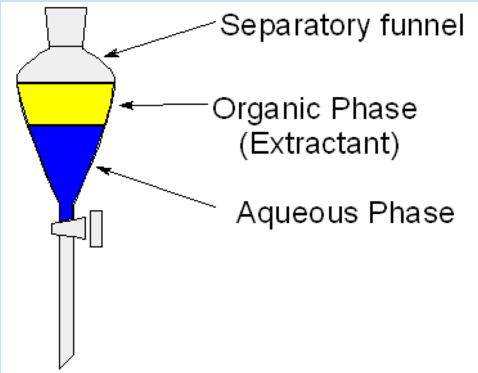
- New improved half-life limits on ββ processes in ^{136}Ce and ^{138}Ce at level of $T_{1/2}$ ~ 10^{17} – 10^{18} yr; many of them are even two orders of magnitude larger than the best previous results.
- Present sensitivity still far from theoretical predictions: $T_{1/2}$ ~ 10^{18} – 10^{21} yr even for the most probable 2ν2ε in ^{136}Ce; for 2νεβ$^+$ in ^{136}Ce $T_{1/2}$ ~ 10^{24} yr; for 0ν processes $T_{1/2}$ ~ 10^{26} –10^{29} yr (for $\langle m_\nu \rangle$ = 1 eV).

Purification of Ce, Nd and Gd for low bckg experiments

Details in RPSCINT2013

- ✓ There are 17 potentially 2β active isotopes among the lanthanide elements (^{136,138,142}Ce, ^{146,148,150}Nd, ^{144,154}Sm, ^{152,160}Gd, ^{156,158}Dy, ^{162,164,170}Er, ^{168,176}Yb)
- ✓ The most interesting are ^{150}Nd and ^{160}Gd (promising for 0ν2β), ^{136}Ce (one of the highest $Q_{2\beta}$ for $2\beta^+$), ^{156}Dy and ^{164}Er (resonant 0ν2ε)

However, even high purity grade commercial lanthanide compounds contain ^{238}U, ^{226}Ra and ^{232,228}Th typically on the level of ~ (0.1 – 1) Bq/kg



Liquid-liquid extraction technique was used to purify CeO_3, Nd_2O_3 and Gd_2O_3 from Th and U

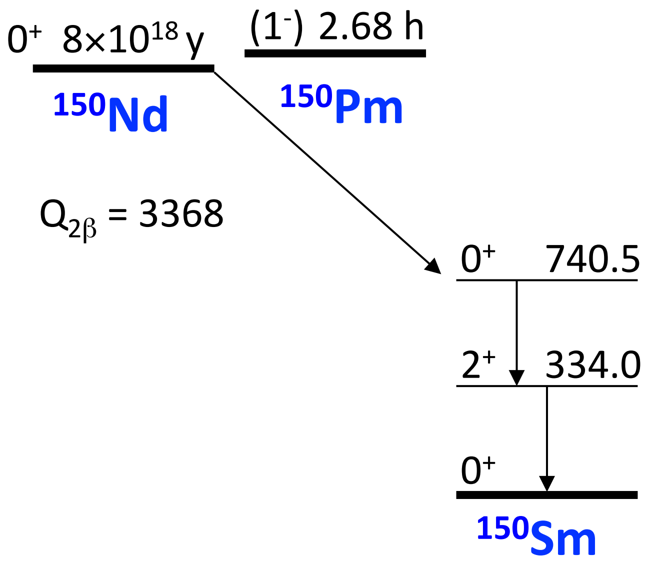
Radioactive contamination tested by using HPGe gamma spectrometry at the STELLA facility of the LNGS

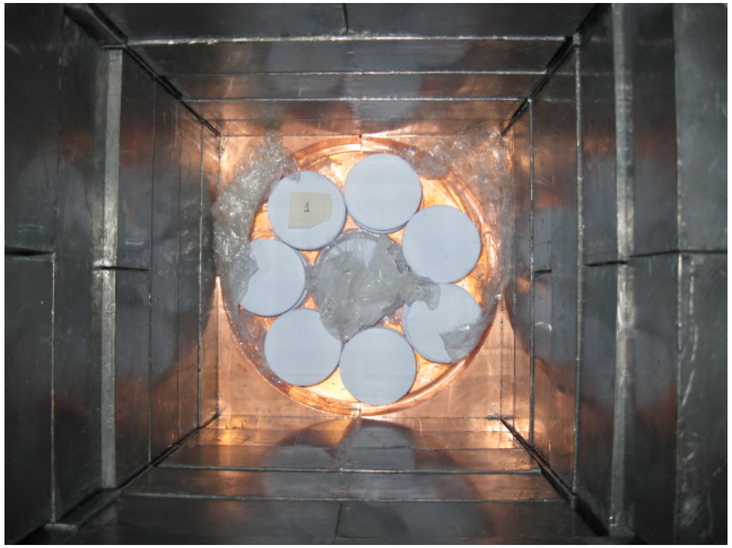
Radioactive contamination of Ce, Gd and Nd oxides before and after the purification (mBq/kg)

Chain	CeO_3	Gd_2O_3	Nd_2O_3
^{226}Ra	11 → <9	<7 → <8	<2.8 → <1.8
^{228}Ra	850 → 70	106 → <12	<2.1 → <2.6
^{228}Th	620 → 620	79 → <4	<1.3 → <1

- An experiment to search for 2β of ^{150}Nd to excited levels of ^{150}Sm is in preparation
- An R&D of radiopure GSO crystal scintillators to search for 2β decay of ^{152}Gd and ^{160}Gd is in progress
- Etc.

Study of double β decay of ^{150}Nd to the excited states of ^{150}Sm





Existing experiments:

$T_{1/2} = [1.33^{+0.36}_{-0.23}(stat)^{+0.27}_{-0.13}(syst)] \times 10^{20}$ yr [1]

$T_{1/2} = [1.07^{+0.45}_{-0.25}(stat) \pm 0.07\ (syst)] \times 10^{20}$ yr [2]

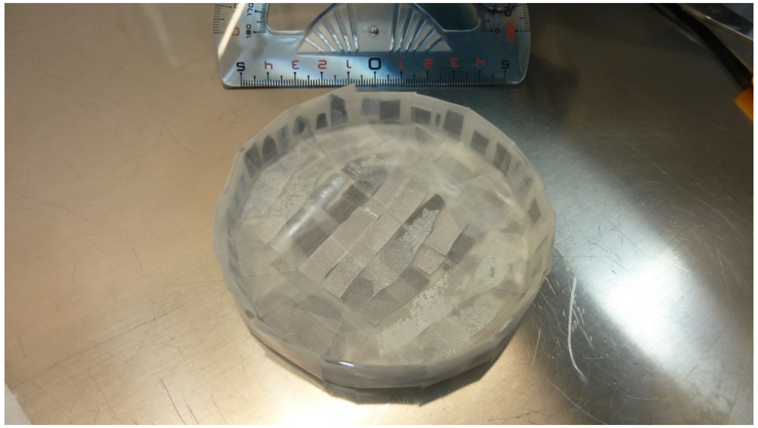
- A deeply purified Nd_2O_3 source (2.381 kg) was installed in GeMulti (4 HPGe ~220 cm^3 each) on 10 Feb 2015
- the experiment is in progress

We are going to analyze both sum and coincidence data

[1] PRC 79 (2009) 045501]

[2] [arXiv:1411.3755v1]

2β and α decay of Os to excited levels



Thin ultra-radiopure osmium sample 118.1 g

The Os sample as it should be installed on the BEGe detector

The detection efficiency should be advanced a few times due to the lover thickness of osmium (0.7-0.9 mm, instead of ∅5-7 mm roads) and application of the new broad energy HPGe detector

The experiment will be started as far as the detector is shielded and commissioned. We aim to detect α decay of ^{184}Os to the 1st excited level of ^{184}W. The theoretical estimations are in the interval 1.2 $\times 10^{15}$ - 2.6$\times 10^{15}$ yr, while the experimental sensitivity is expected to be on the level of 1-5 $\times 10^{15}$ yr.

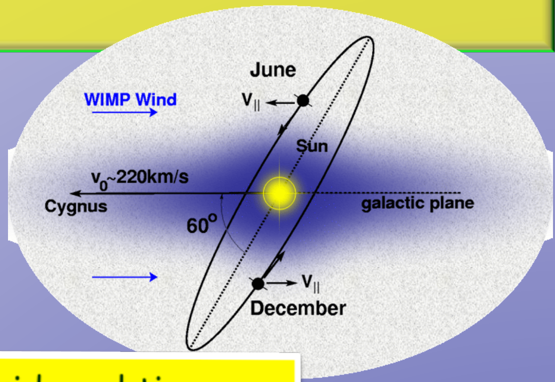
The sensitivity to the double beta processes in ^{184}Os and ^{186}Os will be improved too. It is worth to mention that ^{184}Os is one of the most interesting nuclei taking into account possible resonant neutrinoless double electron capture in ^{184}Os to the excited 1322.2 keV.

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

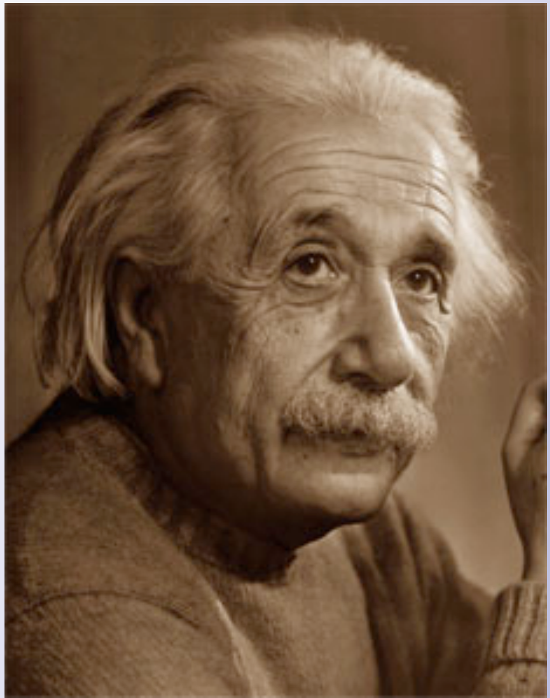
- ✓ Both light output and pulse shape have anisotropic behavior and can provide two independent ways to study directionality
- ✓ Very high reachable radio-purity;
- ✓ Threshold at keV feasible;

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..



"… The one who follows the crowd will usually get no further than the crowd. The one who walks alone, is likely to find himself in places no one has ever been."

Thanks for attention