Collaborazione DAMA
& INR-Kiev
http://people.roma2.infn.it/dama

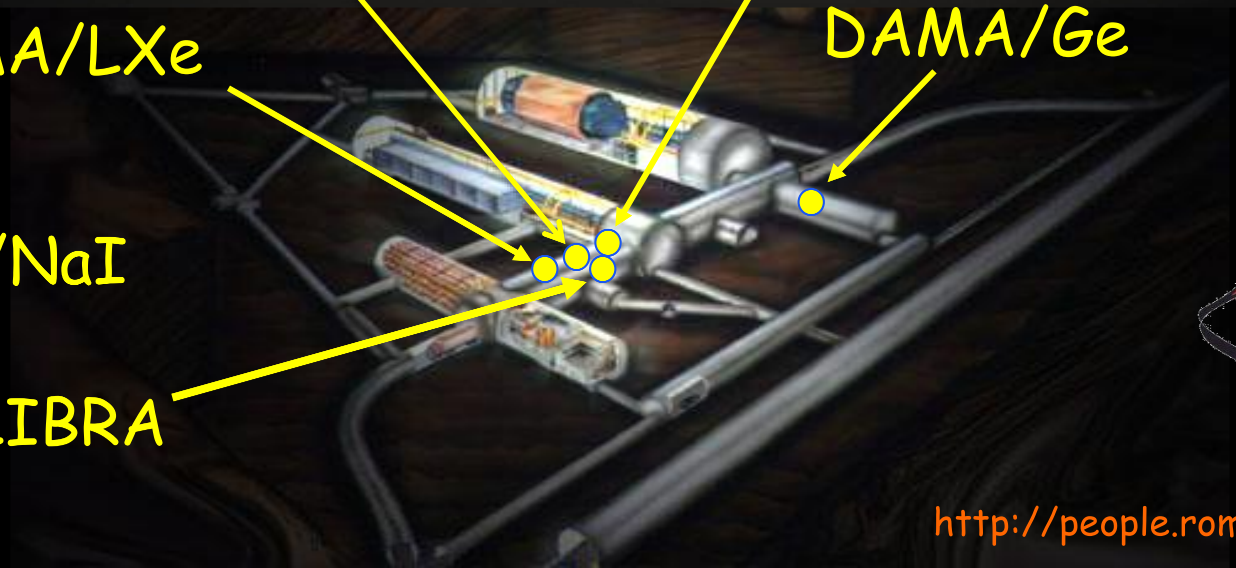
Search for rare processes with the DAMA experiment at LNGS

F. Cappella
INFN-ROMA

Roma, 27 Settembre 2017

DAMA: an observatory for rare processes @LNGS

Collaboration:
Roma Tor Vergata, Roma La Sapienza, LNGS, IHEP/Beijing
+ by-products and small scale experiments.: INR-Kiev, …
+ neutron measurement: ENEA-Frascati
+ in some studies on ββ decays (DST-MAE project): IIT Ropar, India



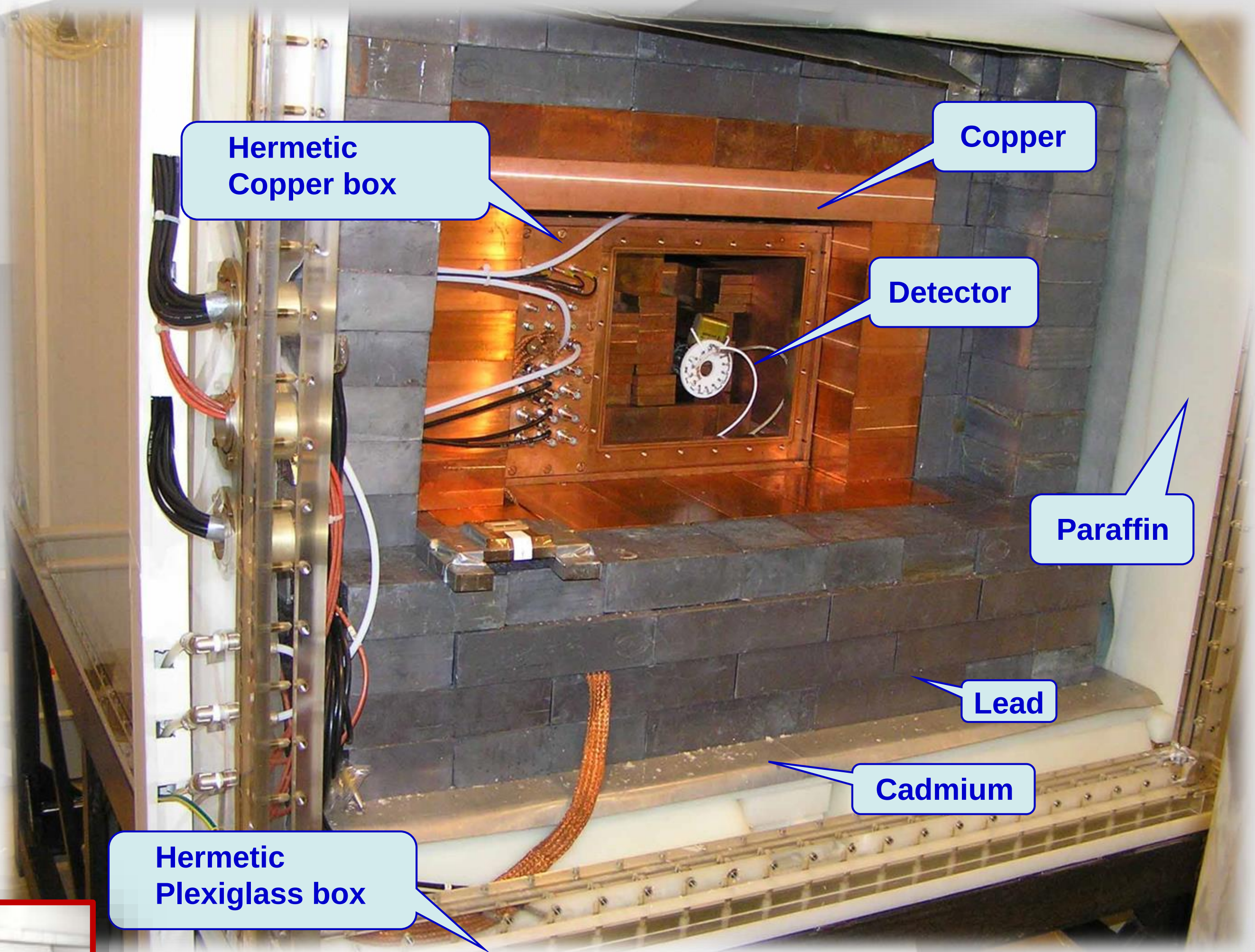
http://people.roma2.infn.it/dama

Examples of rare processes studied by DAMA

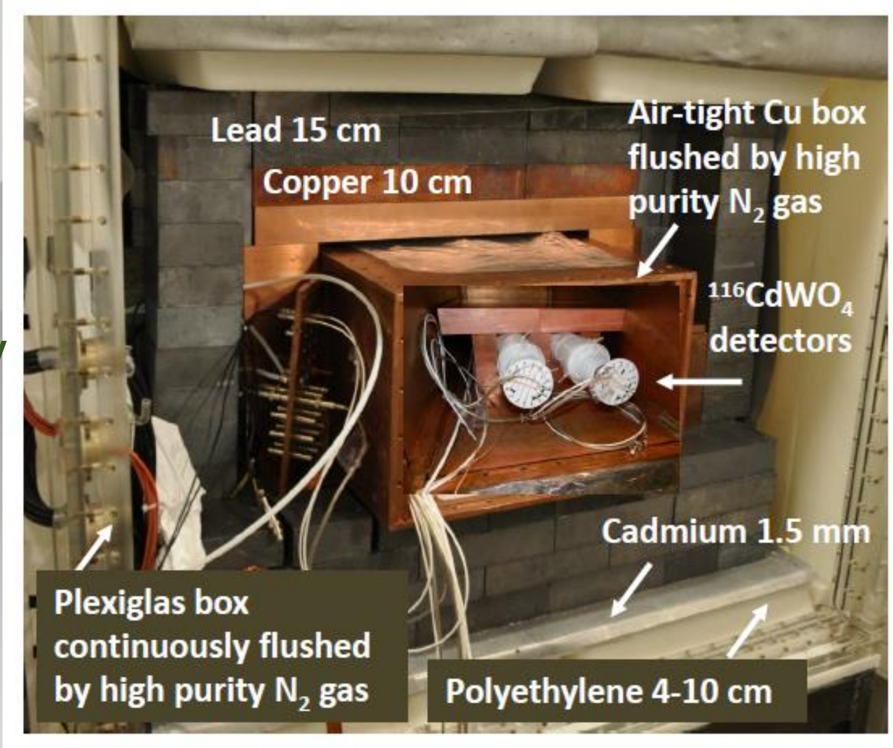
- Very low cross section:
  - Dark Matter
  - Axions
  - Exotic particles (e.g. Q-balls, DAEMONS, SIMP)
- Very long lifetime:
  - Double beta decays
  - Rare α and β decays
  - Cluster decays
  - Spontaneous transition of nuclei to a superdense state;
  - Long-lived superheavy elements
  - Emission of correlated e^+e^- pairs in α decay
  - Electron stability
  - Processes violating the Pauli exclusion principle
  - Charge non-conserving (CNC) processes
  - Nucleon, di-nucleon and tri-nucleon decay into invisible channels

DAMA/R&D

Devoted to measurements of prototypes and small scale experiments with low background crystal scintillators



Now running in DAMA/R&D



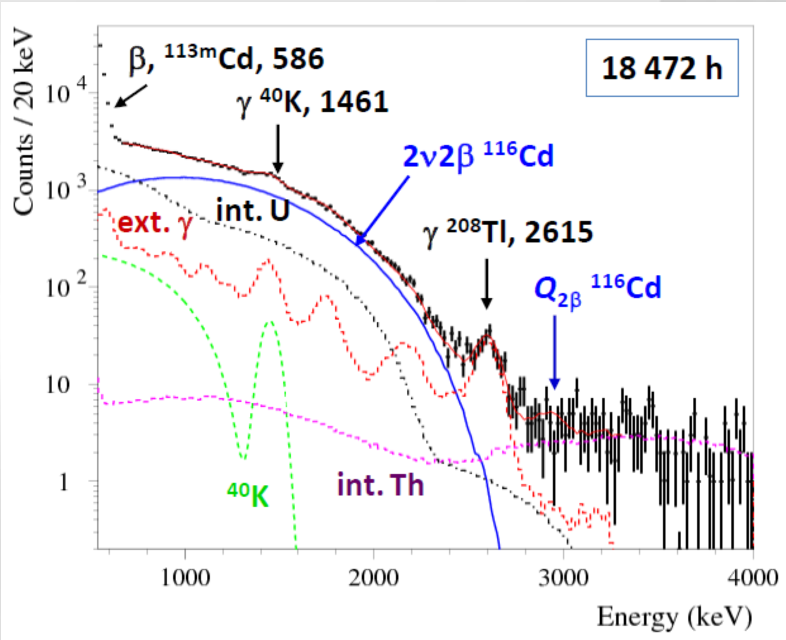
$^{116}CdWO_4$

- ✓ Data taking with two enriched **$^{116}CdWO_4$** (1.162 kg) detectors enriched in ^{116}Cd at 82%
- ✓ Background: **0.1 counts/year/kg/keV at 2.7-2.9 MeV**

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

(the best up-to-date accuracy)

$$T_{1/2}^{0\nu} > 2.0 \times 10^{23}\ \text{yr} \quad \rightarrow \quad \langle m_\nu \rangle < (1.2 - 1.8)\ eV$$



Future:

Better evaluation of background for 2β2ν by replacing $^{116}CdWO_4$ scintillators with $CdWO_4$

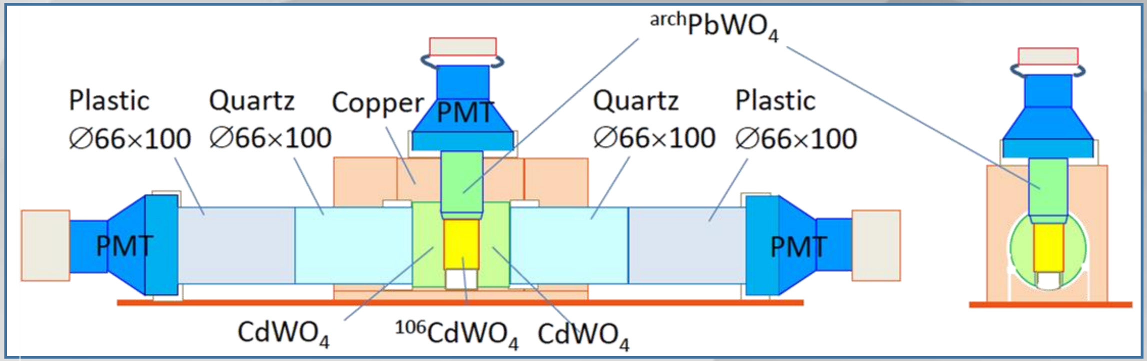
Then, installation of $^{116}CdWO_4$ detectors in GeMulti set-up for studying the 2ν2β transitions of ^{116}Cd to the excited states of ^{116}Sn

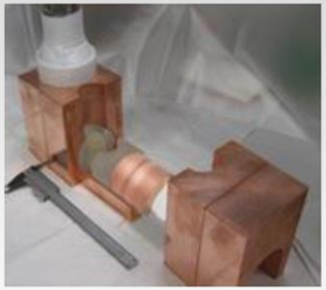
Preparations for **future measurements in progress** (new SrI_2(Eu) crystal; new enriched $CdWO_4$; highly radio-pure $ZnWO_4$; etc.)

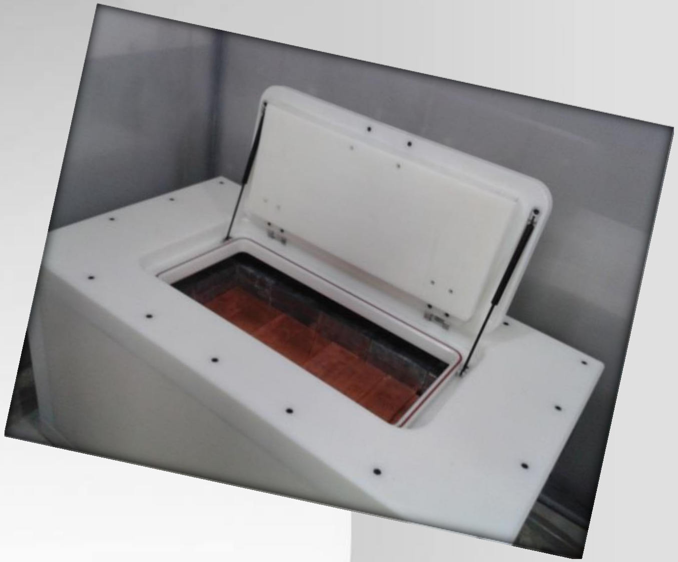
DAMA/CRYS

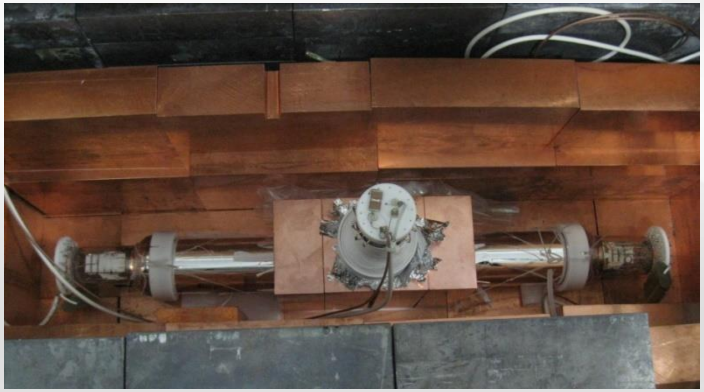
Now in data taking

$^{106}CdWO_4$ in (anti-)coincidence with two large $CdWO_4$ scintillators (search for 2β decay modes in ^{106}Cd)









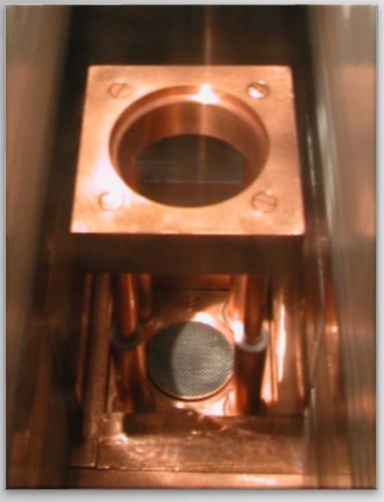
Future:

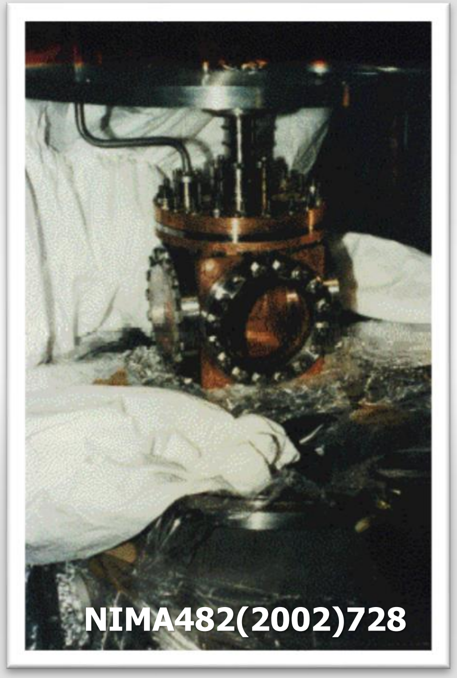
A Cryogenic system (already tested at LNGS) will be installed in DAMA/CRYS for the study of the response of scintillators at low temperature

A second one, which can be coupled to the previous one to enlarge the cryogenic volume to allocate the detectors, has been realized

DAMA/Ge and LNGS STELLA facility

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





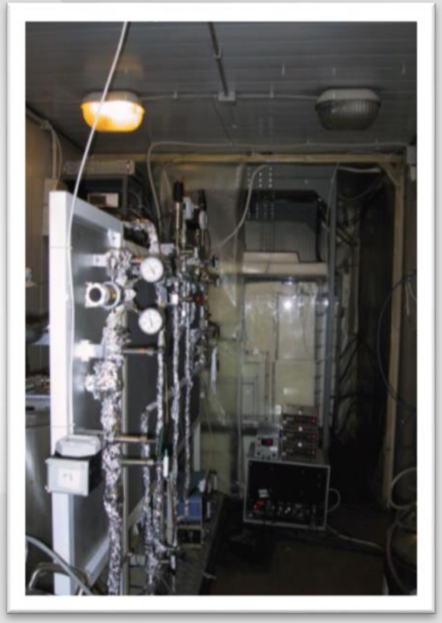
DAMA/LXe

Pure liquid xenon scintillator

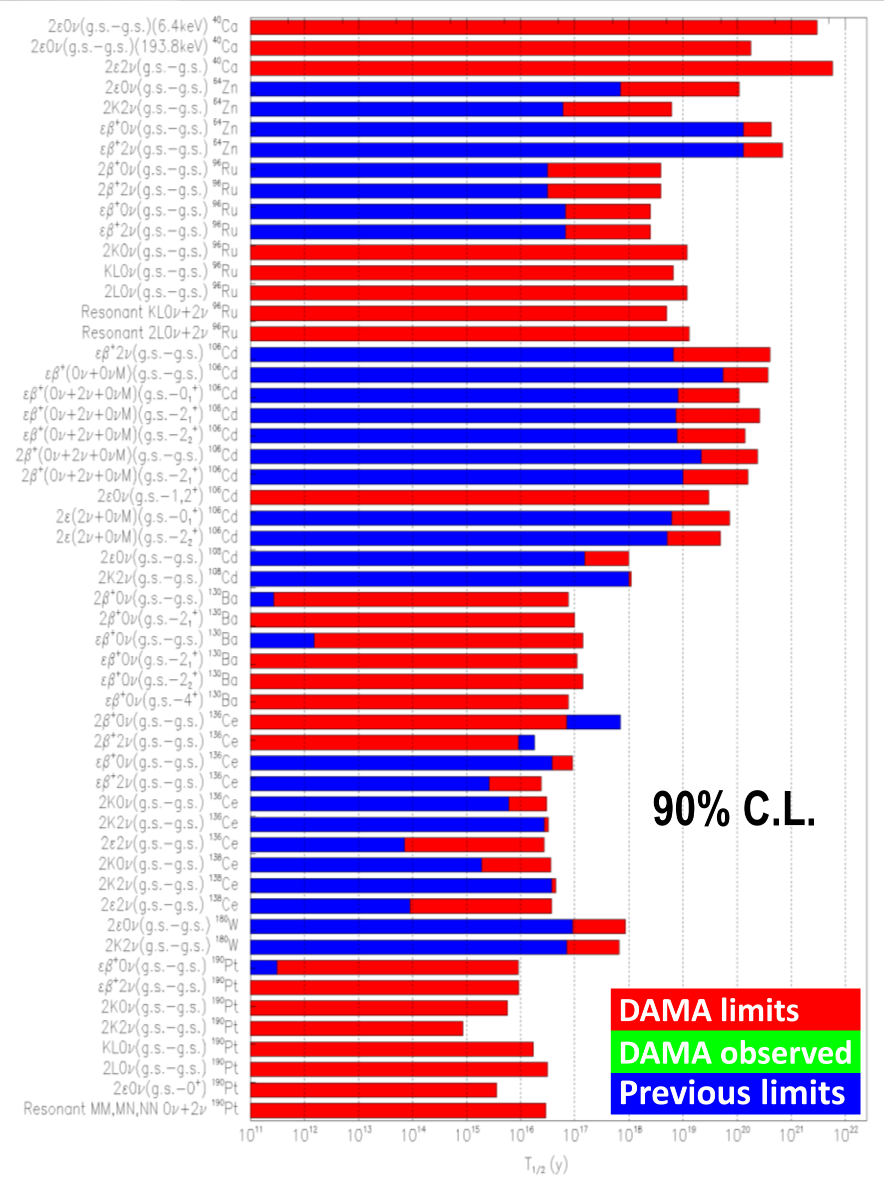
Can operate with Xenon Kr-free enriched either in ^{129}Xe or in ^{134}Xe, ^{136}Xe

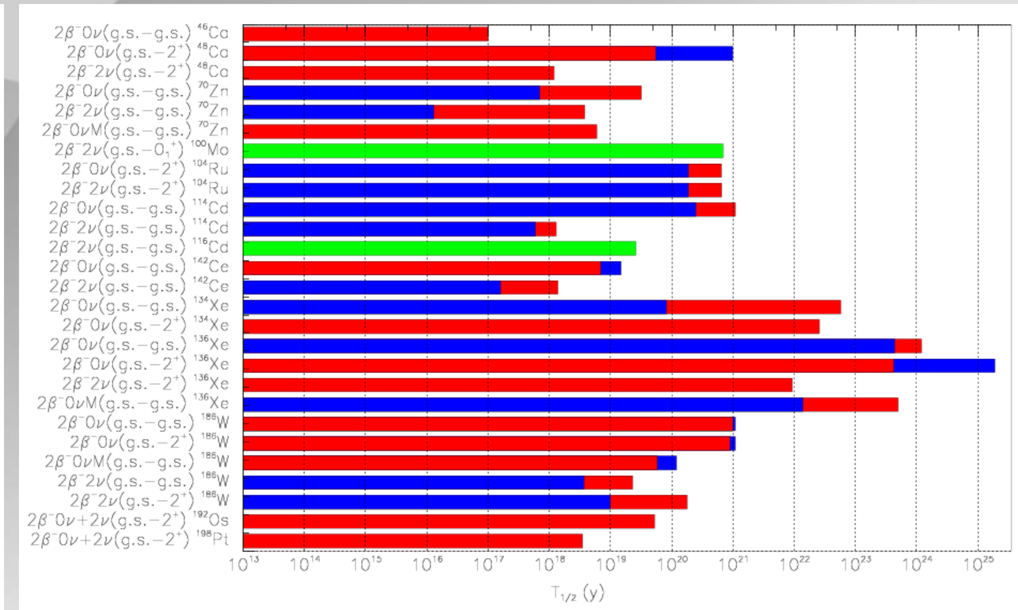
Results on:

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



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





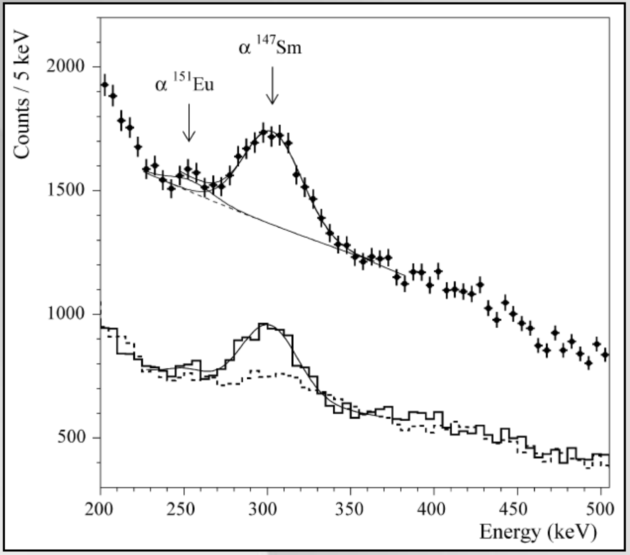
ARMONIA: New observation of $2\nu2\beta^-$ $^{100}Mo \rightarrow {}^{100}Ru$ (g.s.$\rightarrow 0_1^+$) decay NPA846 (2010)143

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

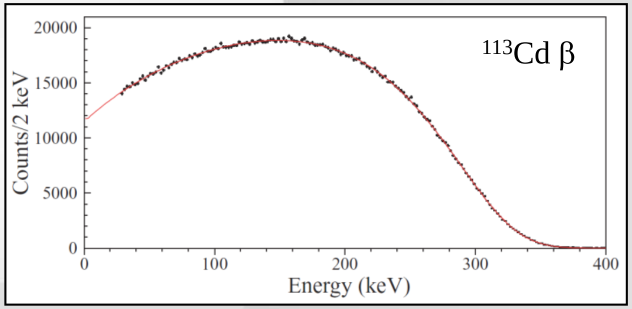
- Many competitive limits obtained on lifetime of $2\beta^+$, $\varepsilon\beta^+$ and 2ε processes
  (^{40}Ca, ^{64}Zn, ^{96}Ru, ^{106}Cd, ^{108}Cd, ^{130}Ba, ^{136}Ce, ^{138}Ce, ^{180}W, ^{190}Pt, ^{184}Os, ^{156}Dy, ^{158}Dy, …).
- First searches for resonant $0\nu2\varepsilon$ decays in some isotopes

Main recent DAMA results in the search for rare processes

- First or improved results in the search for 2β decays of ~30 candidate isotopes: ^{40}Ca, ^{46}Ca, ^{48}Ca, ^{64}Zn, ^{70}Zn, ^{100}Mo, ^{96}Ru, ^{104}Ru, ^{106}Cd, ^{108}Cd, ^{114}Cd, ^{116}Cd, ^{112}Sn, ^{124}Sn, ^{134}Xe, ^{136}Xe, ^{130}Ba, ^{136}Ce, ^{138}Ce, ^{142}Ce, ^{156}Dy, ^{158}Dy, ^{180}W, ^{186}W, ^{184}Os, ^{192}Os, ^{190}Pt and ^{198}Pt
- The best experimental sensitivities in the field for 2β decays with positron emission
- First observation of α decays of ^{151}Eu ($T_{1/2}=5\times10^{18}$yr) with a CaF_2(Eu) scintillator and of ^{190}Pt to the first excited level (E_{exc}=137.2 keV) of ^{186}Os ($T_{1/2}=3\times10^{14}$yr)

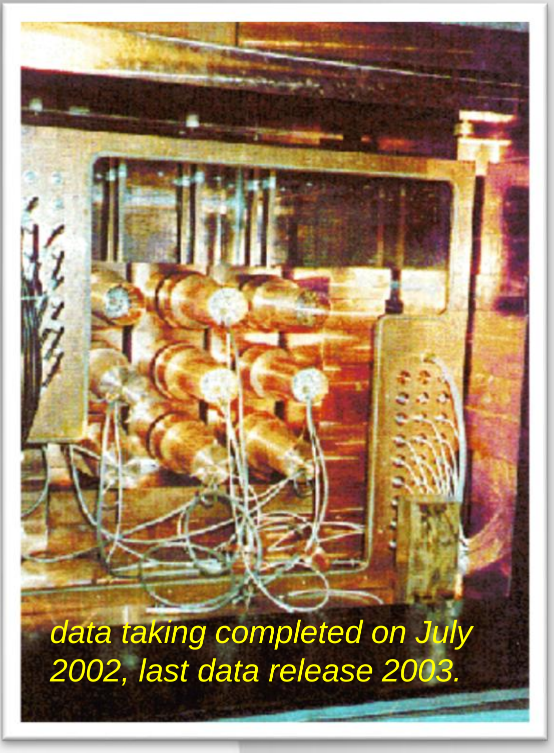


- Investigations of rare β decays of ^{113}Cd ($T_{1/2}=8\times10^{15}$yr) with $CdWO_4$ scintillator and of ^{48}Ca with a CaF_2(Eu) detector



- Observation of correlated e^+e^- pairs emission in α decay of ^{241}Am $\left(\frac{A_{e^+e^-}}{A_\alpha} \simeq 5\times10^{-9}\right)$
- CNC processes in ^{127}I, ^{136}Xe, ^{100}Mo and ^{139}La;
- Search for ^{7}Li solar axions using resonant absorption in LiF crystal
- Search for spontaneous transition of ^{23}Na and ^{127}I nuclei to superdense state;
- Search for cluster decays of ^{127}I, ^{138}La and ^{139}La;
- Search for PEP violating processes in sodium and in iodine;
- Search for N, NN, NNN decay into invisible channels in ^{129}Xe and ^{136}Xe

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



Performances:

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

Results on rare processes:

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

Results on DM particles:

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

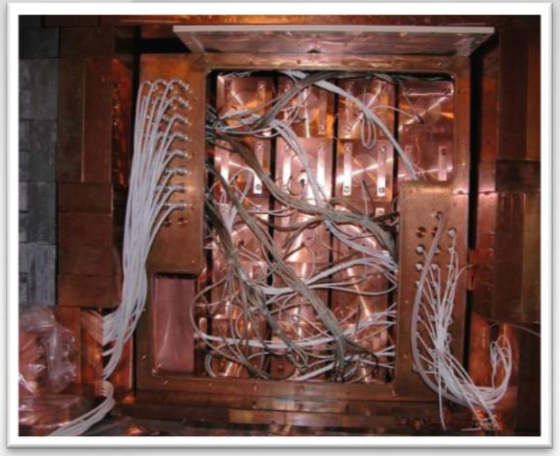
Evidence of modulated behaviour with all the proper features for DM particles in the galactic halo (6.3σ CL)

total exposure (7 annual cycles) 0.29 ton × yr

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

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

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

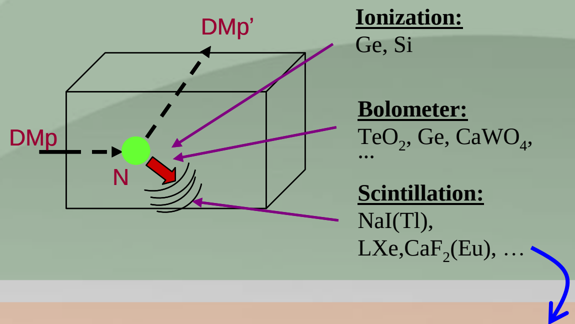


- Radiopurity, performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
- Results on DM particles, Annual Modulation Signature: EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648
  Related results: PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022, EPJC74(2014)2827, EPJC74(2014)3196,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

Some direct detection processes:

- Scatterings on nuclei

  → detection of nuclear recoil energy



- Inelastic Dark Matter: **W + N → W* + N**

  → W has 2 mass states χ+ , χ- with δ mass splitting

  → Kinematical constraint for the inelastic scattering of χ- on a nucleus

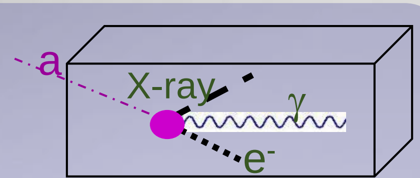
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

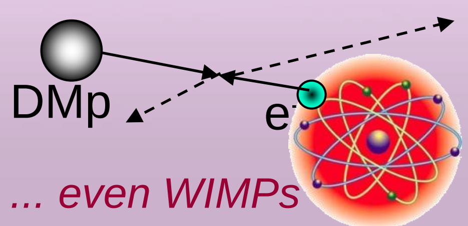
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

  → detection of e.m. radiation

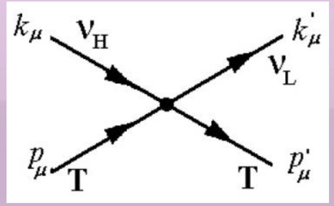


... even WIMPs

- Interaction of light DMp (LDM) on e^- or nucleus with production of a lighter particle

  → detection of electron/nucleus recoil energy

e.g. sterile ν



e.g. signals from these candidates are **completely lost** in experiments based on "rejection procedures" of the e.m. component of their rate

… also other ideas …

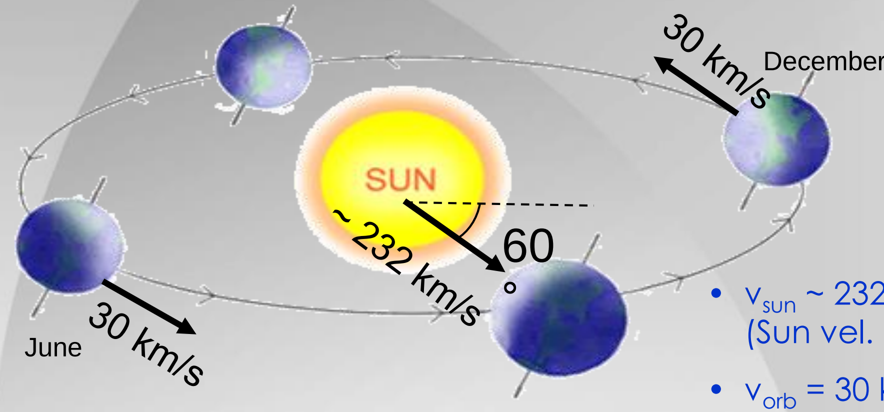
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

With the present technology, the annual modulation is the main model independent signature for the DM signal. Although the modulation effect is expected to be relatively small a suitable large-mass, low-radioactive set-up with an efficient control of the running conditions can point out its presence.

Drukier, Freese, Spergel PRD86; Freese et al. PRD88

Requirements:

1) Modulated rate according cosine
2) In low energy range
3) With a proper period (1 year)
4) With proper phase (about 2 June)
5) Just for single hit events in a multi-detector set-up
6) With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions, but it can be larger in case of some possible scenarios



- v_{sun} ~ 232 km/s (Sun vel. in the halo)
- v_{orb} = 30 km/s (Earth vel. around the Sun)
- $\gamma = \pi/3$, $\omega = 2\pi/T$, T = 1 year
- t_0 = 2^{nd} June (when $v_\oplus$ is maximum)

$$v_\oplus(t) = v_{sun} + v_{orb} \cos\gamma \cos[\omega(t-t_0)]$$

$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \cong S_{0,k} + S_{m,k} \cos[\omega(t-t_0)]$$

the DM annual modulation signature has a different origin and peculiarities (e.g. the phase) than effects correlated with the seasons

To mimic this signature, spurious effects and side reactions must not only be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

Complete DAMA/LIBRA-phase1

	Period	Mass (kg)	Exposure (kg×day)	$(\alpha - \beta^2)$
DAMA/LIBRA-1	Sept. 9, 2003 - July 21, 2004	232.8	51405	0.562
DAMA/LIBRA-2	July 21, 2004 - Oct. 28, 2005	232.8	52597	0.467
DAMA/LIBRA-3	Oct. 28, 2005 - July 18, 2006	232.8	39445	0.591
DAMA/LIBRA-4	July 19, 2006 - July 17, 2007	232.8	49377	0.541
DAMA/LIBRA-5	July 17, 2007 - Aug. 29, 2008	232.8	66105	0.468
DAMA/LIBRA-6	Nov. 12, 2008 - Sept. 1, 2009	242.5	58768	0.519
DAMA/LIBRA-7	Sep. 1, 2009 - Sept. 8, 2010	242.5	62098	0.515
DAMA/LIBRA–phase1	Sept. 9, 2003 - Sept. 8, 2010		379795 ≃ 1.04 ton×yr	0.518
DAMA/NaI + DAMA/LIBRA–phase1:			1.33 ton×yr	

a ton × yr experiment? done

- EPJC56(2008)333
- EPJC67(2010)39
- EPJC73(2013)2648

- calibrations: ≈96 Mevents from sources
- acceptance window eff: 95 Mevents (≈3.5 Mevents/keV)

DAMA/LIBRA-phase1:

- First upgrade on Sept 2008: replacement of some PMTs in HP N_2 atmosphere, new Digitizers (U1063A Acqiris 1GS/s 8-bit High-speed cPCI), new DAQ system with optical read-out installed

DAMA/LIBRA-phase2 (running):

- Second upgrade at end 2010: replacement of all the PMTs with higher Q.E. ones from dedicated developments
- commissioning on 2011

Goal: lowering the software energy threshold

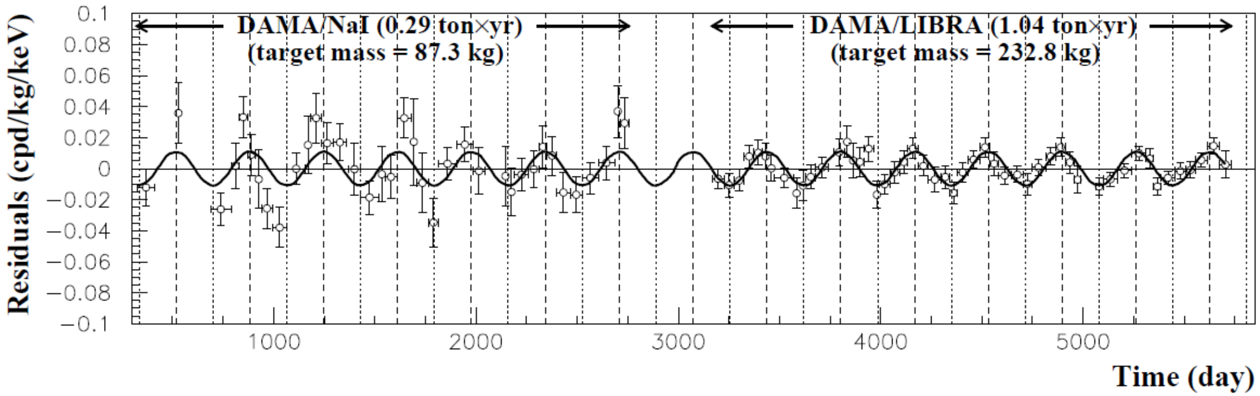
- Fall 2012: new preamplifiers installed + special trigger modules
Other new components in the electronic chain in development

Model Independent Annual Modulation Result

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

Single-hit residuals rate of scintillation events vs time in 2-6 keV

EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648



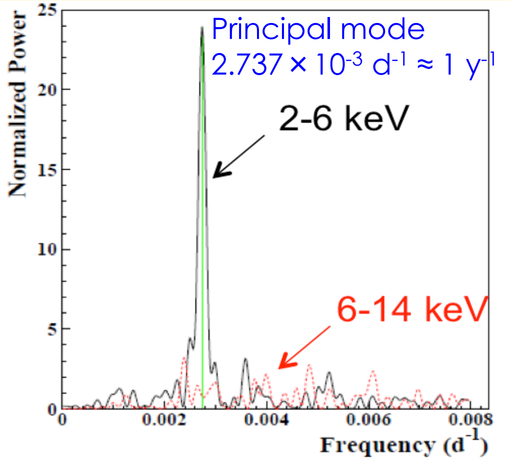
continuous line: t_0=152.5 d, T=1.0 y

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

Power spectrum

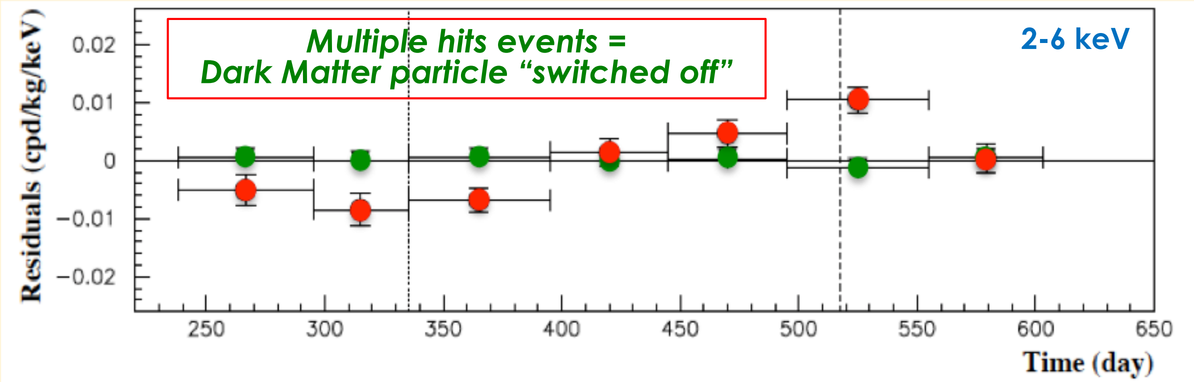


No systematics or side reaction able to account for the measured modulation amplitude and to satisfy all the peculiarities of the signature

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 multiple hit events: **A=-(0.0005±0.0004)cpd/kg/keV**

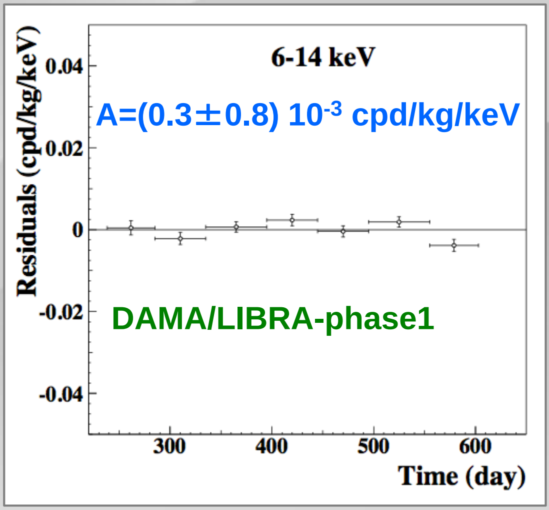


Exclude any side effect either from hardware or software procedures or from background

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

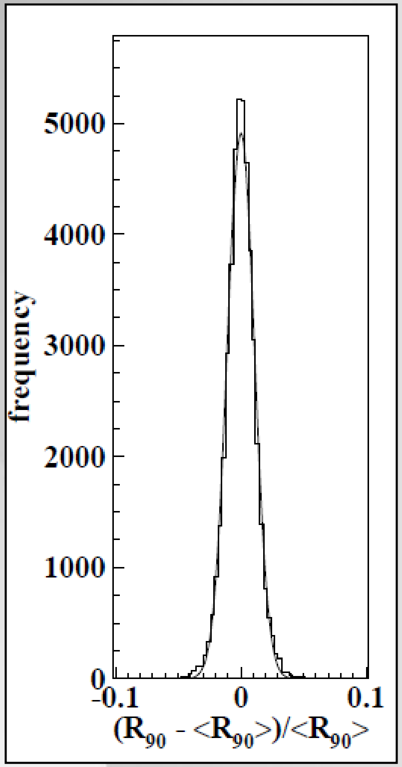
Rate behaviour above 6 keV

- No Modulation above 6 keV



Mod. Ampl. (6-10 keV): cpd/kg/keV
(0.0016 ± 0.0031) DAMA/LIBRA-1
-(0.0010 ± 0.0034) DAMA/LIBRA-2
-(0.0001 ± 0.0031) DAMA/LIBRA-3
-(0.0006 ± 0.0029) DAMA/LIBRA-4
-(0.0021 ± 0.0026) DAMA/LIBRA-5
(0.0029 ± 0.0025) DAMA/LIBRA-6
-(0.0023 ± 0.0024) DAMA/LIBRA-7
→ statistically consistent with zero

DAMA/LIBRA-phase1



σ ≈ 1%, fully accounted by statistical considerations

- No modulation in the whole energy spectrum: studying integral rate at higher energy, R_{90}
  - R_{90} percentage variations with respect to their mean values for single crystal in the DAMA/LIBRA running periods
  - Fitting the behaviour with time, adding a term modulated with period and phase as expected for DM particles:

consistent with zero

Period	Mod. Ampl.
DAMA/LIBRA-1	-(0.05±0.19) cpd/kg
DAMA/LIBRA-2	-(0.12±0.19) cpd/kg
DAMA/LIBRA-3	-(0.13±0.18) cpd/kg
DAMA/LIBRA-4	(0.15±0.17) cpd/kg
DAMA/LIBRA-5	(0.20±0.18) cpd/kg
DAMA/LIBRA-6	-(0.20±0.16) cpd/kg
DAMA/LIBRA-7	-(0.28±0.18) cpd/kg

+ if a modulation present in the whole energy spectrum at the level found in the lowest energy region → R_{90} ~ tens cpd/kg → ~ 100 σ far away

No modulation above 6 keV
This accounts for all sources of background

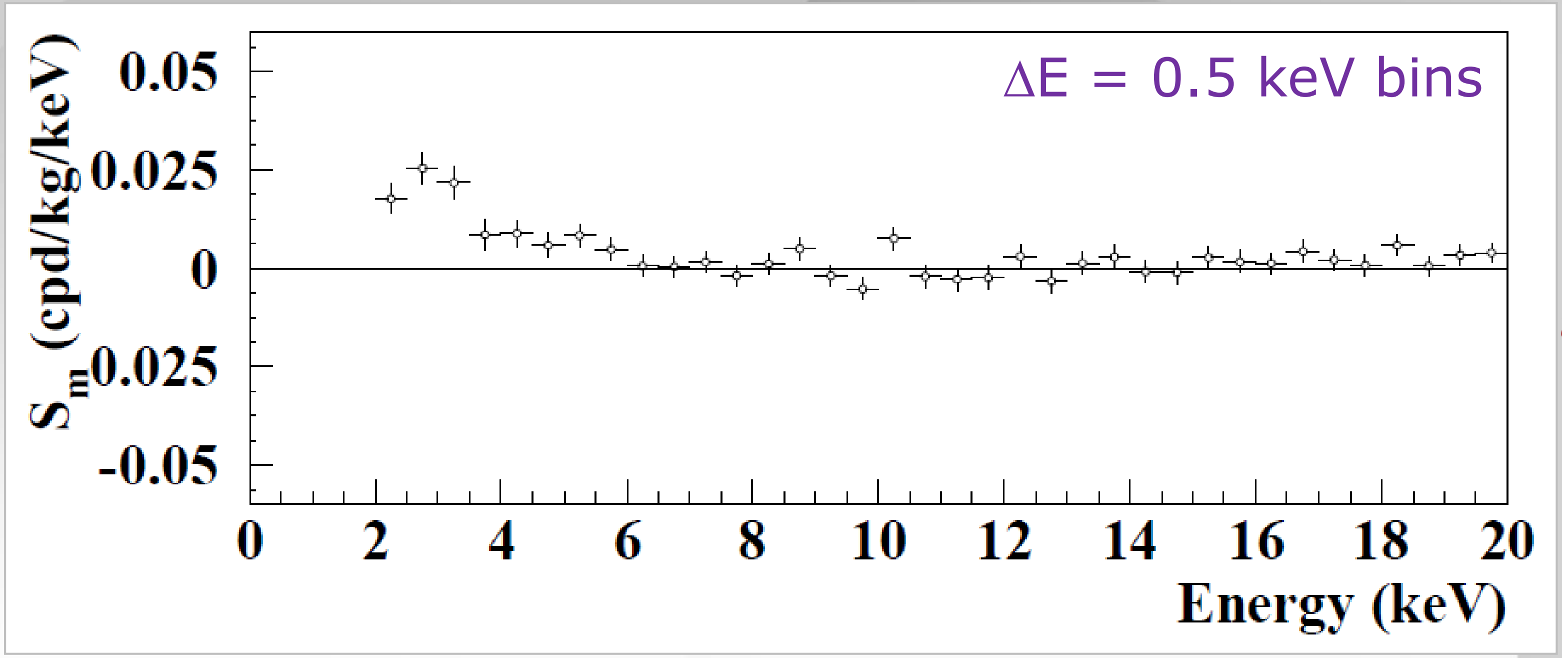
Energy distribution of the modulation amplitudes

The modulation amplitude, S_m, obtained by maximum likelihood method

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

DAMA/NaI + DAMA/LIBRA-phase1

total exposure: 487526 kg×day ≈**1.33 ton×yr**



$T = 2\pi/\omega = 1$ yr

$t_0 = 152.5$ day

A clear modulation is present in the (2-6) keV energy interval, while S_m values compatible with zero are present just above

The S_m values in the (6–20) keV energy interval have random fluctuations around zero with χ^2 equal to 35.8 for 28 degrees of freedom (upper tail probability 15%)

No role for n, μ and solar ν in the DAMA annual modulation results

$$\Phi_k = \Phi_{0,k}\left(1 + \eta_k cos\omega\left(t - t_k\right)\right)$$
$$R_k = R_{0,k}\left(1 + \eta_k cos\omega\left(t - t_k\right)\right)$$

⇒ Contributions to the total neutron flux at LNGS;

⇒ Counting rate in DAMA/LIBRA for *single-hit* events in the (2–6) keV energy region induced by:

- neutrons
- muons
- solar neutrinos

EPJC 74 (2014) 3196
(EPJC 56 (2008) 333, EPJC 72 (2012) 2064, IJMPA 28 (2013) 1330022)

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^{exp}_m
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.

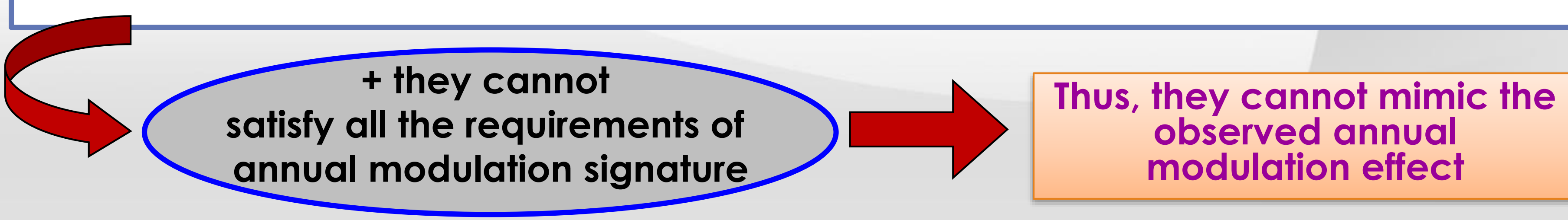
All are negligible w.r.t. the annual modulation amplitude observed by DAMA/LIBRA and they cannot contribute to the observed modulation amplitude

+ In no case neutrons (of whatever origin), muons and muon-induced events, solar ν can mimic the DM annual modulation signature since some of the **peculiar requirements of the signature** would fail

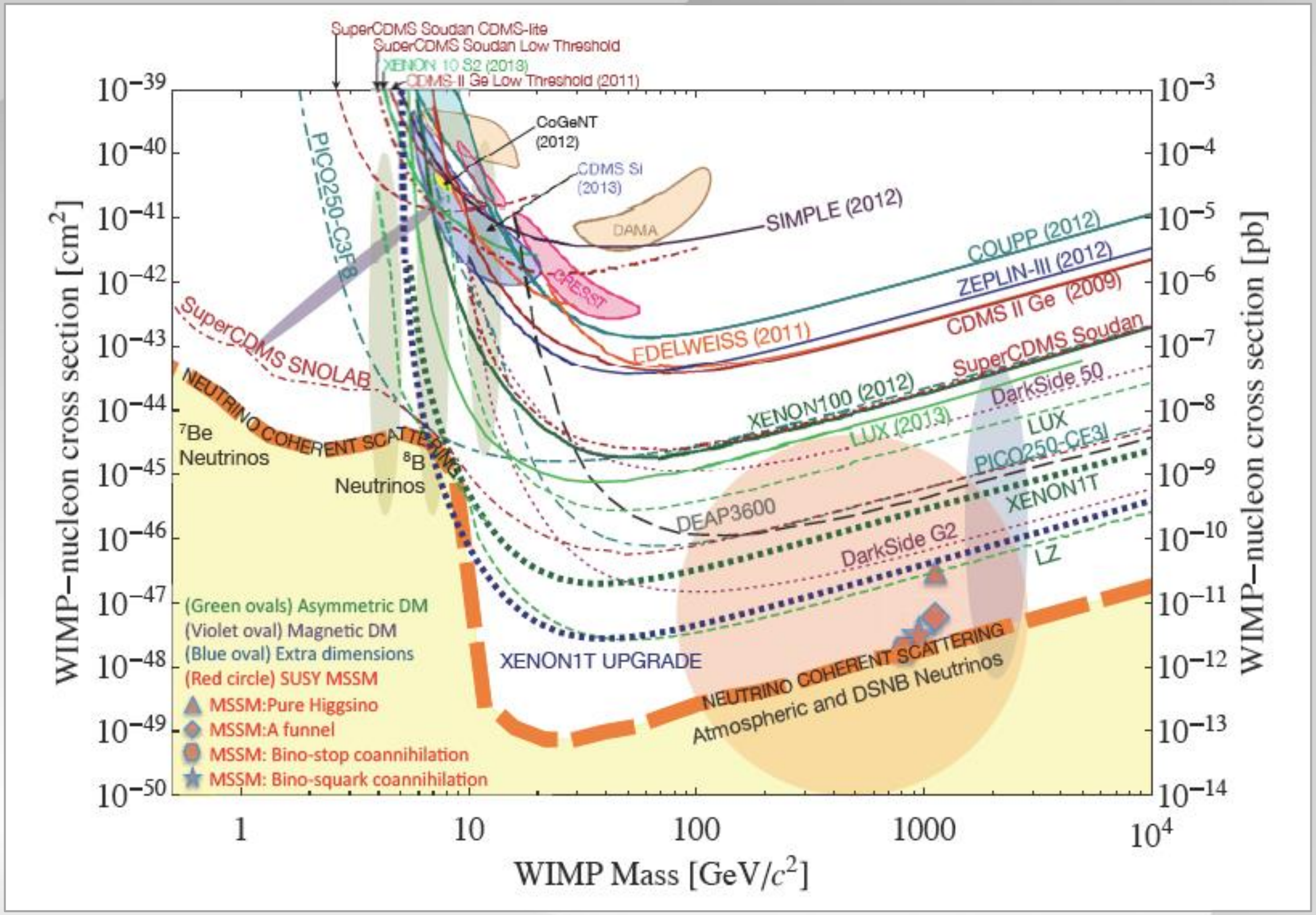
Summary of the results obtained in the additional investigations of possible systematics or side reactions – DAMA/LIBRA-phase1

(NIMA592(2008)297, EPJC56(2008)333, J. Phys. Conf. ser. 203(2010)012040, arXiv:0912.0660, S.I.F.Atti Conf.103(211), Can. J. Phys. 89 (2011) 11, Phys.Proc.37(2012)1095, EPJC72(2012)2064, arxiv:1210.6199 & 1211.6346, IJMPA28(2013)1330022, EPJC74(2014)3196)

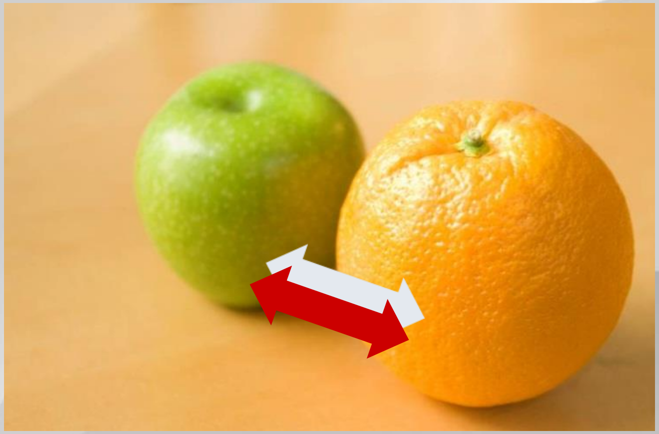
Source	Main comment	Cautious upper limit (90%C.L.)
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	$<2.5\times10^{-6}$ cpd/kg/keV
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	$<10^{-4}$ cpd/kg/keV
NOISE	Effective full noise rejection near threshold	$<10^{-4}$ cpd/kg/keV
ENERGY SCALE	Routine + intrinsic calibrations	$<1\text{-}2\times10^{-4}$ 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



Is it an "universal" and "correct" way to approach the problem of DM and comparisons?



No, it isn't. This is just a largely arbitrary/partial/incorrect exercise



About interpretation

See e.g.: Riv.N.Cim.26 n.1(2003)1, IJMPD13(2004)2127, EPJC47(2006)263, IJMPA21(2006)1445, EPJC56(2008)333, PRD84(2011)055014, IJMPA28(2013)1330022

…models…

- Which particle?
- Which interaction coupling?
- Which Form Factors for each target-material?
- Which Spin Factor?
- Which nuclear model framework?
- Which scaling law?
- Which halo model, profile and related parameters?
- Streams?
- ...

…and experimental aspects…

- Exposures
- Energy threshold
- Detector response (phe/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities
- Efficiencies
- Definition of fiducial volume and non-uniformity
- Quenching factors, channeling, …
- …

Uncertainty in experimental parameters, as well as necessary assumptions on various related astrophysical, nuclear and particle-physics aspects, affect all the results at various extent, both in terms of exclusion plots and in terms of allowed regions/volumes. Thus comparisons with a fixed set of assumptions and parameters' values are intrinsically strongly uncertain.

No experiment can be directly compared in model independent way with DAMA

Other examples

Scratching Below the Surface of the Most General Parameter Space

(S. Scopel arXiv:1505.01926)

Most general approach: consider ALL possible NR couplings, including those depending on velocity and momentum

- A much wider parameter space opens up
- First explorations show that indeed large rooms for compatibility can be achieved

$$\mathcal{O}_1 = 1_\chi 1_N,$$
$$\mathcal{O}_2 = (v^\perp)^2,$$
$$\mathcal{O}_3 = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right),$$
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N,$$
$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right),$$
$$\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$
$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp,$$
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp,$$
$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right),$$
$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N},$$
$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}.$$

… and much more considering experimental and theoretical uncertainties

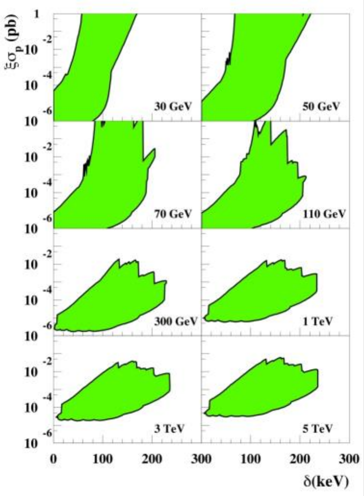
DMp with preferred inelastic interaction:

$\chi^- + N \rightarrow \chi^+ + N$

- iDM mass states χ^+, χ^- with δ mass splitting
- Kinematic constraint for iDM:

$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

DAMA/NaI+DAMA/LIBRA
Slices from the 3d allowed volume in given scenario



Fund. Phys. 40(2010)900

iDM interaction on Tl nuclei of the NaI(Tl) dopant?

PRL106(2011)011301

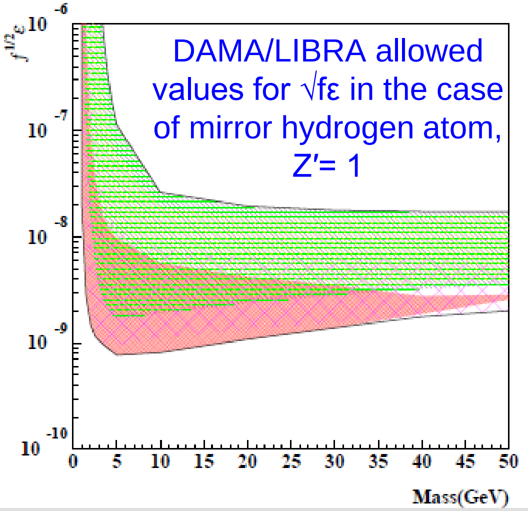
- For large splittings, the dominant scattering in NaI(Tl) can occur off of Thallium nuclei, with A~205, which are present as a dopant at the 10^{-3} level in NaI(Tl) crystals.
- large splittings do not give rise to sizeable contribution on Na, I, Ge, Xe, Ca, O, … nuclei.

Mirror Dark Matter

Asymmetric mirror matter: mirror parity spontaneously broken
⇒ mirror sector becomes a heavier and deformed copy of ordinary sector
(See EPJC75(2015)400)

- Interaction portal: photon - mirror photon kinetic mixing $\frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu}$
- mirror atom scattering of the ordinary target nuclei in the NaI(Tl) detectors of DAMA/LIBRA set-up with the Rutherford-like cross sections.

$\sqrt{f}\cdot\epsilon$ coupling const. and fraction of mirror atom

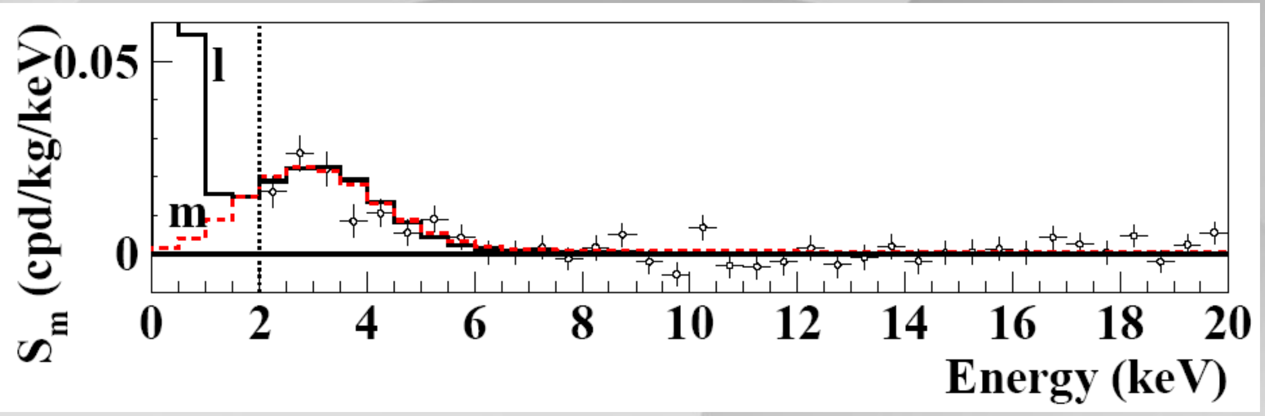


DAMA/LIBRA phase 2 - running

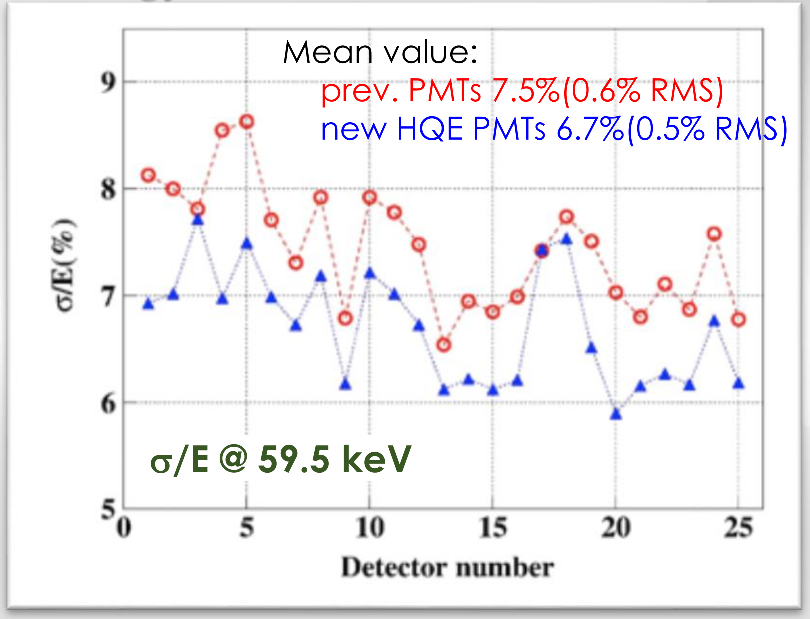
JINST 7(2012)03009

Second upgrade on end of 2010:

all PMTs replaced with new ones of higher Q.E.



Energy resolution



Residual Contamination

	^{226}Ra (Bq/kg)	^{235}U (Bq/kg)	^{228}Ra (Bq/kg)	^{228}Th (Bq/kg)	^{40}K (Bq/kg)
mean	0.43	0.047	0.12	0.083	0.54
σ	0.06	0.010	0.02	0.017	0.16

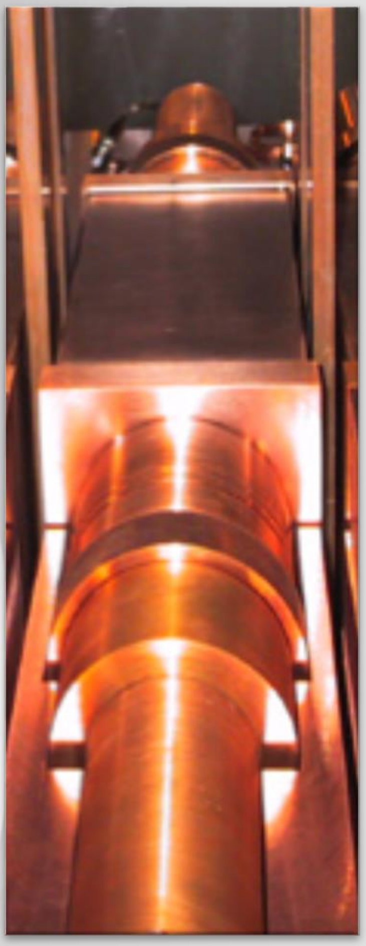
The light responses

Previous PMTs:	5.5-7.5 ph.e./keV
New PMTs:	up to 10 ph.e./keV

Possible DAMA/LIBRA-phase3

- The light collection of the detectors can further be improved
- Light yields and the energy thresholds will improve accordingly

The strong interest in the low energy range suggests 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 radio-pure quartz (Suprasil B) light guides (10 cm long), which act also as optical window



The presently-reached PMTs features, but not for the same PMT mod.:

- Q.E. around 35-40% @ 420 nm (NaI(Tl) light)
- radiopurity at level of 5 mBq/PMT (^{40}K), 3-4 mBq/PMT (^{232}Th), 3-4 mBq/PMT (^{238}U), 1 mBq/PMT (^{226}Ra), 2 mBq/PMT (^{60}Co)

R&D efforts to obtain PMTs matching the best performances… feasible

No longer need for light guides (a 30-40% improvement in the light collection is expected)

Perspectives for the future

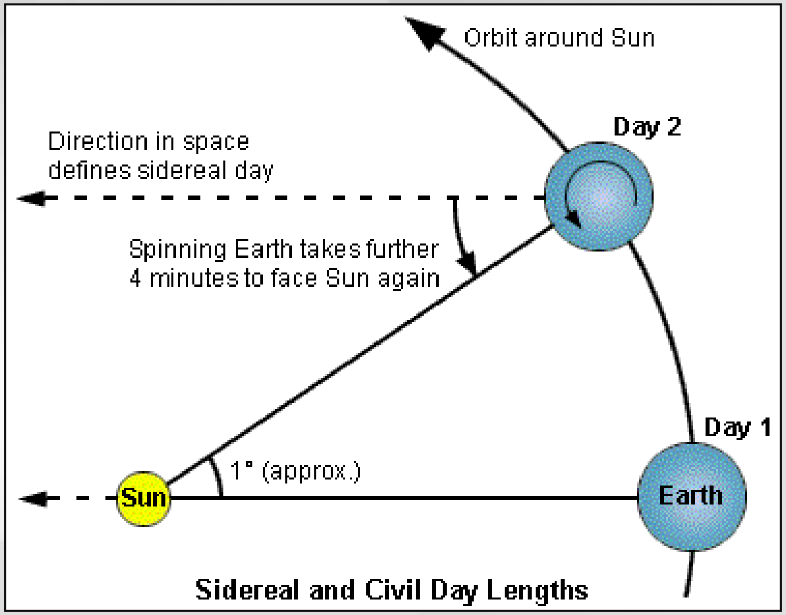
Other signatures correlated with the Earth motion in the Dark Matter halo:

- *Diurnal modulation effect due to Earth rotation*
- *Shadow effects*
- *Directionality*

All effects with different phases but the same period:
T = 1 sidereal day

1 solar day ≅ 1.00274 sidereal days
(365.25 solar days ≅ 366.25 sidereal days)

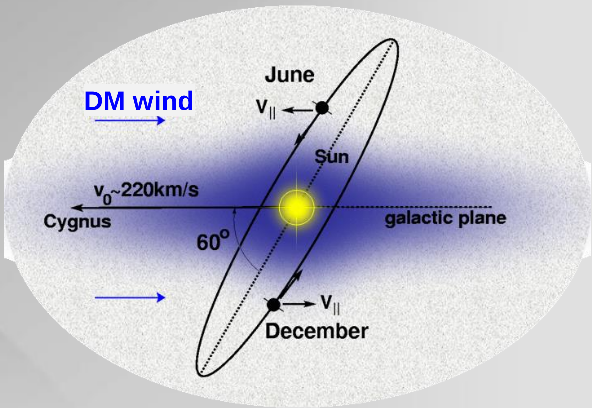
Local sidereal time is 00:00 when the vernal equinox crosses the local meridian



Velocity of a detector in a terrestrial laboratory

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

$\vec{v}_{LSR}$	Velocity of the Local Standard of Rest (LSR) due to Galaxy rotation
$\vec{v}_{\odot}$	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 @ lab (lat, lng)



The ***Sun velocity***, $\vec{v}_S$, in the *Galactic Coordinate system* is:

$$\vec{v}_{LSR} = (0, v_0, 0) \qquad (v_0 = 220 \pm 50 \text{ km/s})$$
$$\vec{v}_{\odot} = (9, 12, 7) \text{ km/s}$$
$$\Rightarrow \quad \vec{v}_S = \vec{v}_{LSR} + \vec{v}_{\odot} = (9, 232, 7) \text{ km/s}$$

The ***Earth revolution velocity*** in the *Ecliptic plane* $(\hat{e}_1^{ecl}, \hat{e}_2^{ecl})$ is:

$$\vec{v}_{rev}(t) = V_{Earth}\left(\hat{e}_1^{ecl} \sin\lambda(t) - \hat{e}_2^{ecl}\cos\lambda(t)\right)$$
$$\lambda(t) = \omega(t - t_{equinox}); \quad \omega = \frac{2\pi}{T}; \quad T\text{=}1y$$

$(V_{Earth} \approx 29.8$ km/s; $t_{equinox} \approx$ March 21)

The ***Earth rotation velocity*** in the *Equatorial plane* $(\hat{e}_1^{ecs}, \hat{e}_2^{ecs})$ is:

$$\vec{v}_{rot}(t) = -V_r(\hat{e}_1^{ecs}\sin\delta(t) - \hat{e}_2^{ecs}\cos\delta(t))$$
$$\delta(t) = \omega_{rot} t; \quad \omega_{rot} = \frac{2\pi}{T_d}; \quad T_d = 1 \text{ sidereal day}$$

(Here t is the local sidereal time)

In *Galactic Coordinate System*:

$$\begin{cases} \hat{e}_1^{ecl} = (-0.05487, 0.49411, -0.86767) \\ \hat{e}_2^{ecl} = (-0.99382, -0.11100, -0.00035) \\ \hat{e}_3^{ecl} = (-0.09648, 0.86228, 0.49715) \end{cases}$$

$\hat{e}_3^{ecl} \cdot (0, 0, 1) = 0.49715.$

$\Rightarrow$ **60°** inclination w.r.t. galactic plane

$$\begin{cases} \hat{e}_1^{ecs} = (-0.05487, 0.49411, -0.86767) \\ \hat{e}_2^{ecs} = (-0.87344, -0.44483, -0.19808) \\ \hat{e}_3^{ecs} = (-0.48384, 0.74698, 0.45599) \end{cases}$$

@ LNGS (ϕ_0 = 42°27′N; λ_0 = 13°34′E)

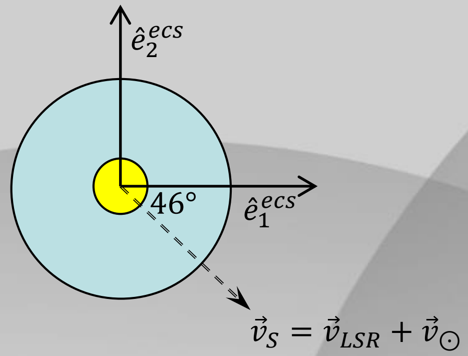
$V_r = V_{eq}\cos\phi_0 = 0.3435$ km/s

$(V_{eq} = 0.4655$ km/s$)$

Sun velocity in the Equatorial coordinate system …

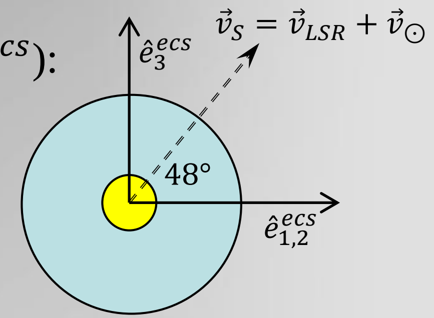
On equatorial plane:

$\hat{e}_1^{ecs} \cdot \vec{v}_S = 108.1$ km/s
$\hat{e}_2^{ecs} \cdot \vec{v}_S = -112.4$ km/s
$\Rightarrow$ $\varphi = -46°$
$\Rightarrow$ t = 20.92 h (LST)



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

$\hat{e}_3^{ecs} \cdot \vec{v}_S = 172.1$ km/s
$\Rightarrow$ $\theta = 42°$
$\Rightarrow$ Lat = 48°



$$v_{lab}(t) \simeq v_S + \hat{v}_S \cdot \vec{v}_{rev}(t) + \hat{v}_S \cdot \vec{v}_{rot}(t)$$

… and annual modulation term

Based on DM flux annual variation due to Earth Revolution

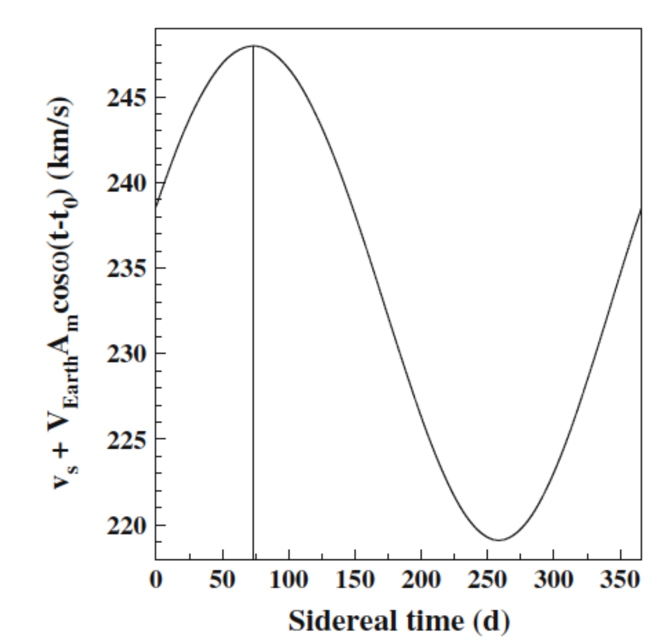
$$\hat{v}_S \cdot \vec{v}_{rev}(t) = V_{Earth}\left(\hat{v}_S \cdot \hat{e}_1^{ecl} \sin\lambda(t) - \hat{v}_S \cdot \hat{e}_2^{ecl} \cos\lambda(t)\right) =$$
$$= V_{Earth} A_m \cos[\omega(t - t_0)]$$

$A_m \approx 0.489$;
$t_0 = t_{equinox} + 73.25$ solar days
([71.8, 74.2] d when varying v_0 in [170,270] km/s)

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 is about 73 days after the spring equinox.



Sun velocity in the Equatorial coordinate system …

On equatorial plane:

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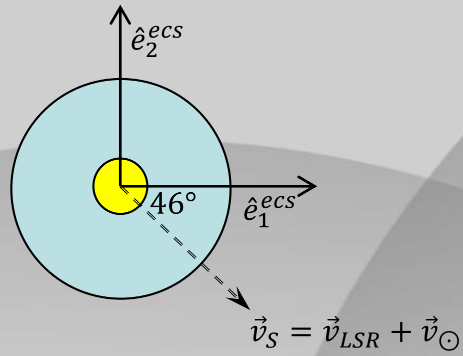
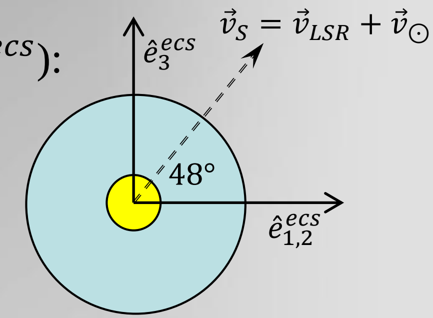
$\hat{e}_2^{ecs} \cdot \vec{v}_S = -112.4$ km/s
$\Rightarrow \varphi = -46°$
$\Rightarrow$ t = 20.92 h (LST)



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

$\hat{e}_3^{ecs} \cdot \vec{v}_S = 172.1$ km/s
$\Rightarrow \theta = 42°$
$\Rightarrow$ Lat = 48°



$$v_{lab}(t) \simeq v_S + \hat{v}_S \cdot \vec{v}_{rev}(t) + \hat{v}_S \cdot \vec{v}_{rot}(t)$$

… and diurnal modulation term

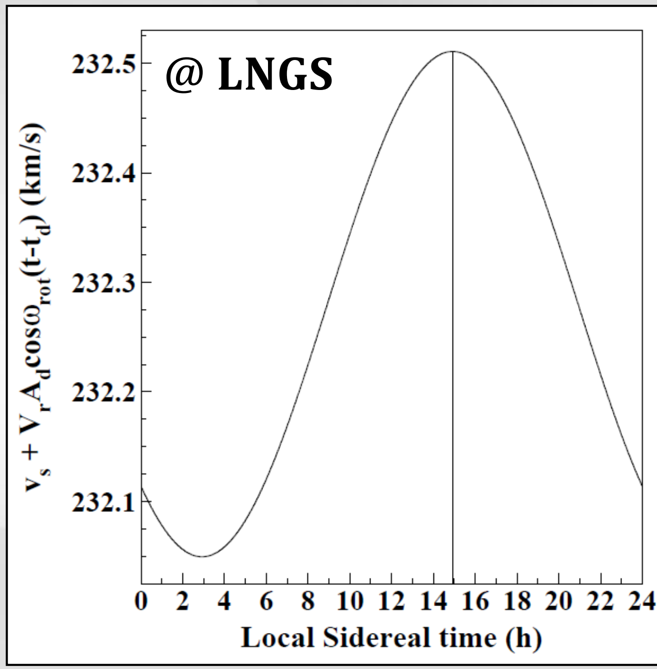
Based on DM flux annual variation due to Earth Rotation

$$\hat{v}_S \cdot \vec{v}_{rot}(t) = -V_r(\hat{v}_S \cdot \hat{e}_1^{ecs} \sin\delta(t) - \hat{v}_S \cdot \hat{e}_2^{ecs} \cos\delta(t)) =$$
$$= V_r A_d \cos[\omega_{rot}(t - t_d)]$$

$A_d \approx 0.671;$
$t_d = 14.92$ h LST
([14.84, 14.97] h when varying v_0 in [170,270] km/s)

$v_S + \hat{v}_S \cdot \vec{v}_{rot}(t)$ vs LST at LNGS

Maximum is about at 15 h LST



N.B.: The expected signal counting rate in a given k−th energy bin:

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

$\Rightarrow$ The ratio R_{dy} is a model independent constant:

$$R_{dy} = \frac{S_d}{S_m} = \frac{V_r A_d}{V_{Earth} A_m} \simeq 0.016 \text{ at LNGS latitude}$$

Diurnal effects in DAMA/LIBRA-phase1

EPJC 74 (2014) 2827

- Observed annual modulation amplitude in DAMA/LIBRA–phase1 in (2–6) keV region: (0.0097 ± 0.0013) cpd/kg/keV
- Thus, the expected value of the diurnal modulation amplitude is $\simeq 1.5 \times 10^{-4}$ cpd/kg/keV.

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

Test of null hypothesis ⇒
no diurnal variation with a significance of 95% CL

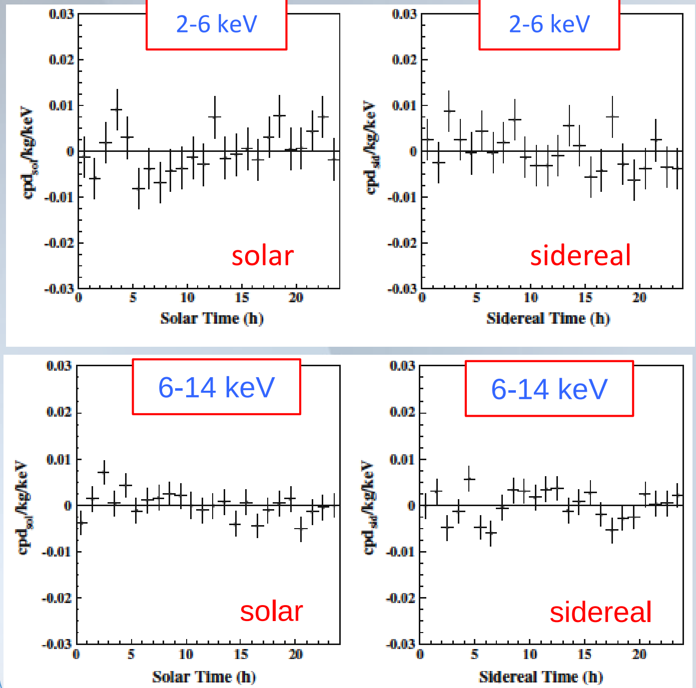
Energy	Solar Time	Sidereal Time
2–4 keV	χ^2/d.o.f. = 35.2/24 → P = 7%	χ^2/d.o.f. = 28.7/24 → P = 23%
2–5 keV	χ^2/d.o.f. = 35.5/24 → P = 6%	χ^2/d.o.f. = 24.0/24 → P = 46%
2–6 keV	χ^2/d.o.f. = 25.8/24 → P = 36%	χ^2/d.o.f. = 21.2/24 → P = 63%
6–14 keV	χ^2/d.o.f. = 25.5/24 → P = 38%	χ^2/d.o.f. = 35.9/24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

When fitting with a cosine function with T=24 h and t_d=15 h LST:
⇒ all the diurnal modulation amplitudes A_d 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 (2-6 keV) < 1.2×10^{-3} cpd/kg/keV (90%CL)

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



(here Sidereal Time = GMST)

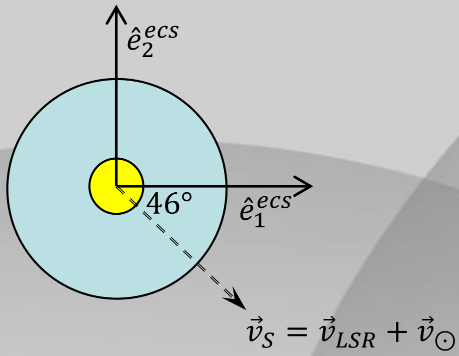
Present experimental sensitivity is not enough for the expected diurnal modulation amplitude derived from the DAMA/LIBRA–phase1 observed effect

Larger exposure DAMA/LIBRA–ph2 (+lower energy threshold) offers increased sensitivity to such an effect

Sun velocity in the Equatorial coordinate system …

On equatorial plane:

$\hat{e}_1^{ecs} \cdot \vec{v}_S = 108.1$ km/s
$\hat{e}_2^{ecs} \cdot \vec{v}_S = -112.4$ km/s
$\Rightarrow \varphi = -46°$
$\Rightarrow$ t = 20.92 h (LST)



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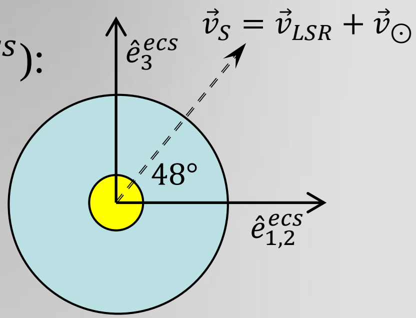
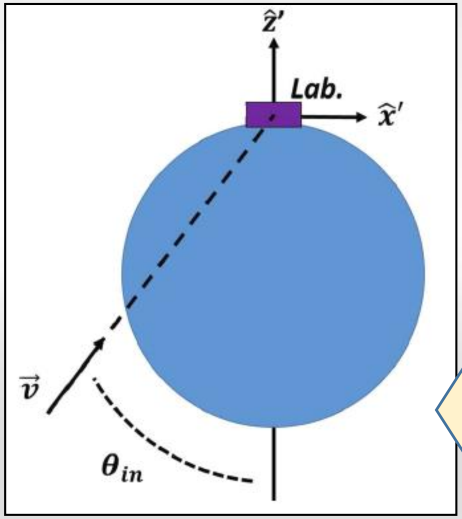


… and shadow effect

LNGS: ϕ_0 = **42°27′N**; λ_0 = **13°34′E**;
LST ~ GST + 0.904 h

Based on diurnal variation of apparent DM wind arrival direction

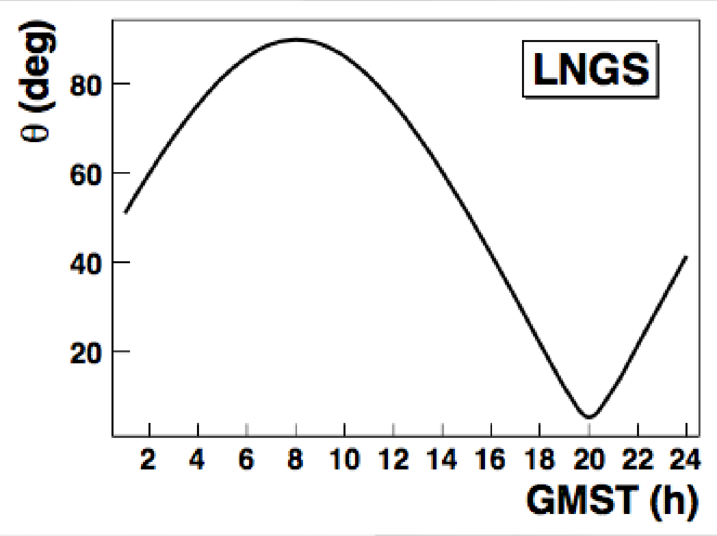
During a sidereal day the Earth shields a terrestrial detector with a varying thickness and this induces a variation of the flux of the DM candidates impinging the detector



It depends on the **θ** angle:
the "zenith distance" of $\vec{v}_{lab}(t)$

$$\cos\theta = \hat{r}_{lab}(t) \cdot \hat{v}_{lab}(t)$$

The thickness crossed before reaching a laboratory depends on the particle impinging angle θ_{in}
$\langle\theta_{in}\rangle = \pi - \langle\theta\rangle$

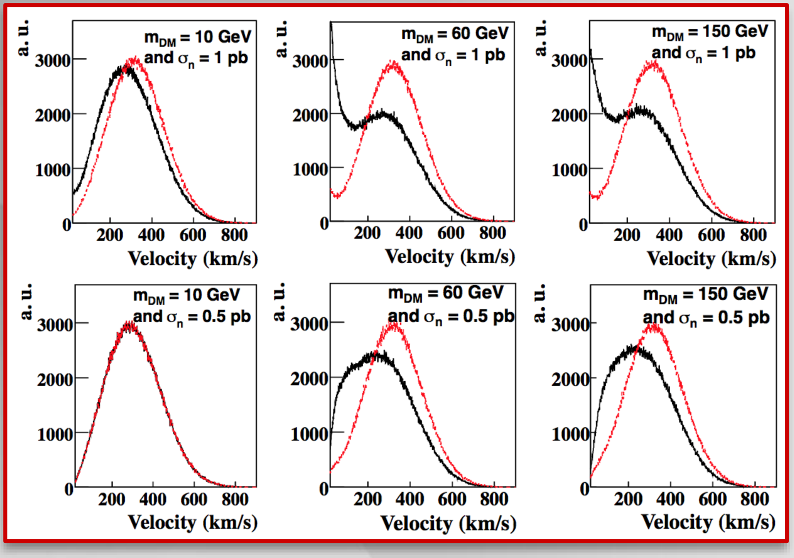


The Earth shielding is Max at ~ 9:00 h LST and Min at ~ 21:00 h LST

Earth Shadow Effect with DAMA/LIBRA–phase1

EPJC 75 (2015) 239

- **Earth Shadow Effect** expected for DM candidate particles inducing nuclear recoils
- Only for candidates with **high cross-section** with ordinary matter (low DM local density)
- DM particles crossing Earth lose their energy and the distribution observed in the laboratory frame depends on time (**LST 9:00 black**; **LST 21:00 red**)

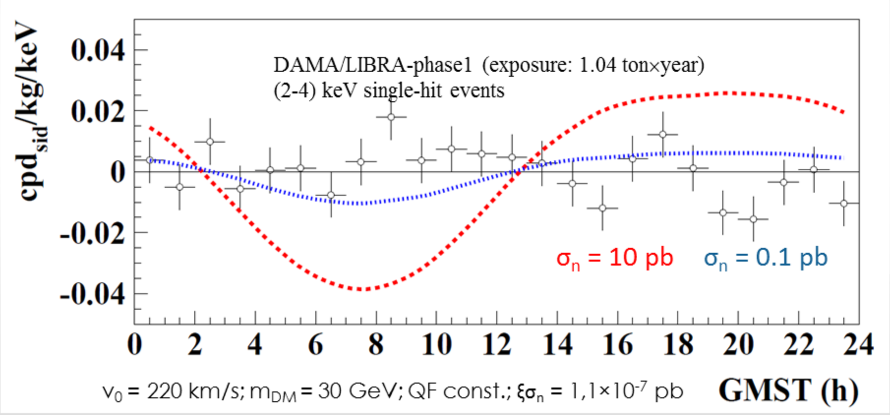


Expected counting rate for a given mass, cross section and scenario by MC:

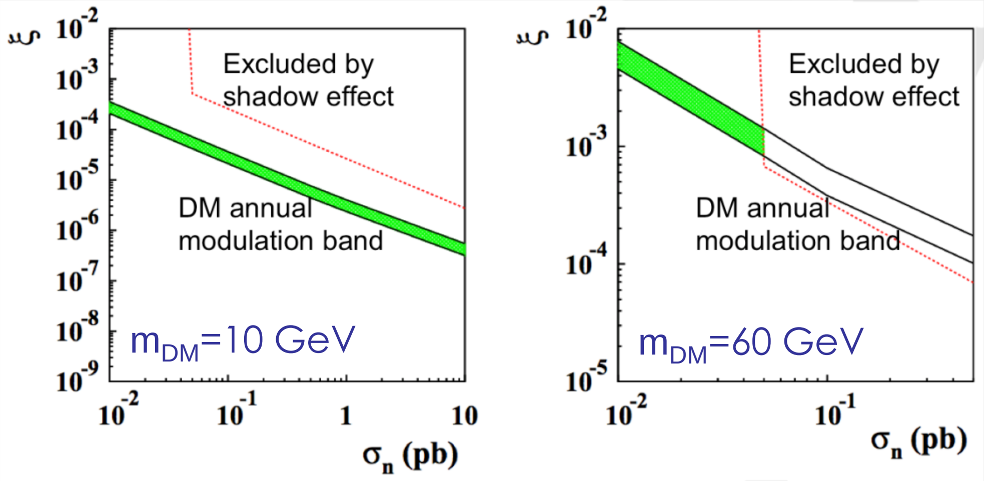
$$S_{d,sh}(t) = \xi\sigma_n \, S'_{d,sh}(t)$$

Expectations compared with diurnal residual rate of *single-hit* events of DAMA/LIBRA-phase1 in (2-4) keV

Minimizing χ^2, upper limits on ξ (relative abundance) can be evaluated



Constrain (red line) on DAMA/LIBRA DM annual modulation result from Earth Shadow Effect in the ξ vs σ_n plane for the considered model framework



Sun velocity in the Equatorial coordinate system …

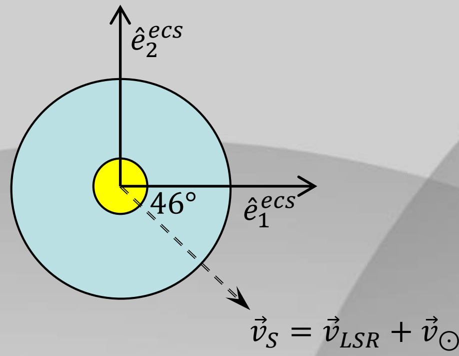
On equatorial plane:

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

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

$\Rightarrow\ \varphi = -46°$

$\Rightarrow$ t = 20.92 h (LST)

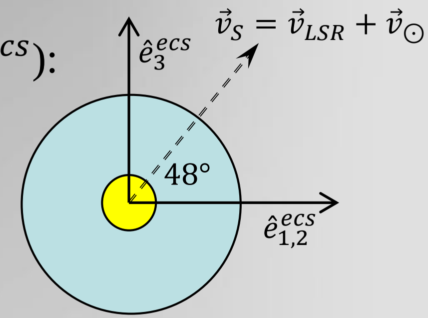


Angle w.r.t. North pole ($\hat{e}_3^{ecs}$):

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

$\Rightarrow\ \theta = 42°$

$\Rightarrow$ Lat = 48°



… and directionality

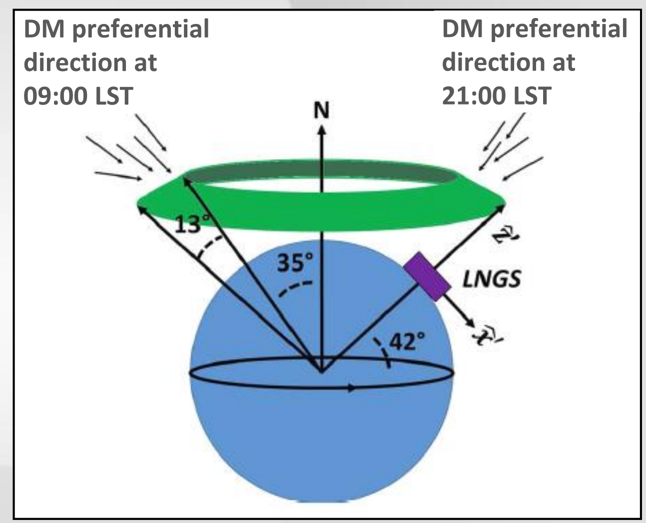
Based on diurnal variation of apparent DM wind arrival direction

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

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

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

➡ **direction-sensitive detector**



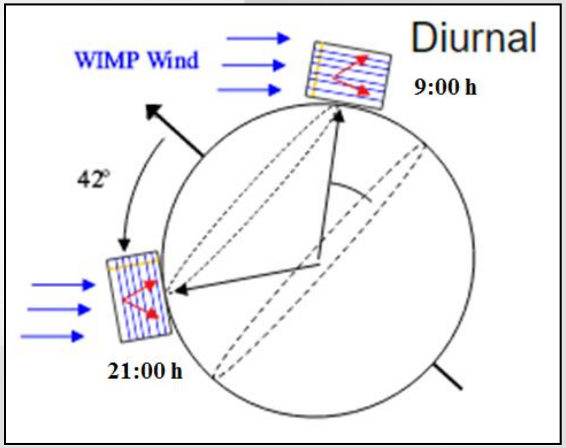
Directionality sensitive detectors: anisotropic scintillators

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

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

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

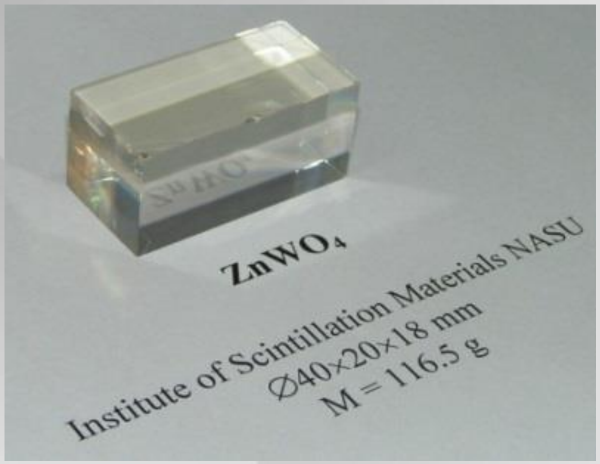
- $ZnWO_4$ anisotropic scintillator: a very promising detector (**Eur. Phys. J. C 73 (2013) 2276)**



Advantages of the $ZnWO_4$ crystal

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

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

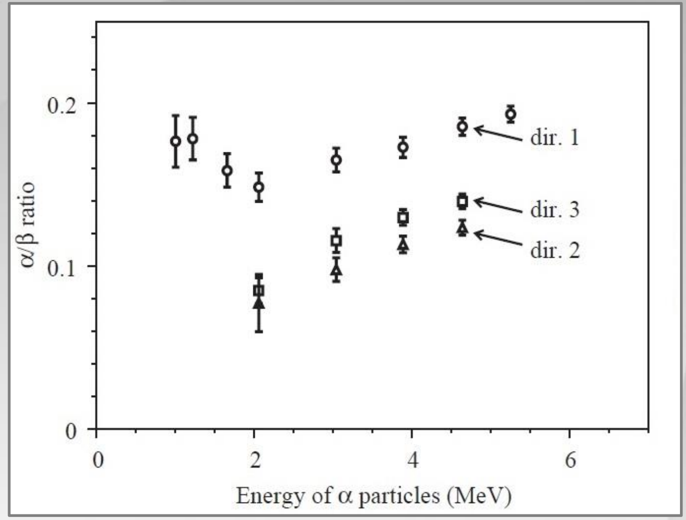


Density (g/cm³)	*7.87*
Melting point (°C)	*1200*
Structural type	*Wolframite*
Cleavage plane	*Marked (010)*
Hardness (Mohs)	*4–4.5*
Wavelength of emission maximum (nm)	*480*
Refractive index	*2.1–2.2*
Effective average decay time (μs)	*24*

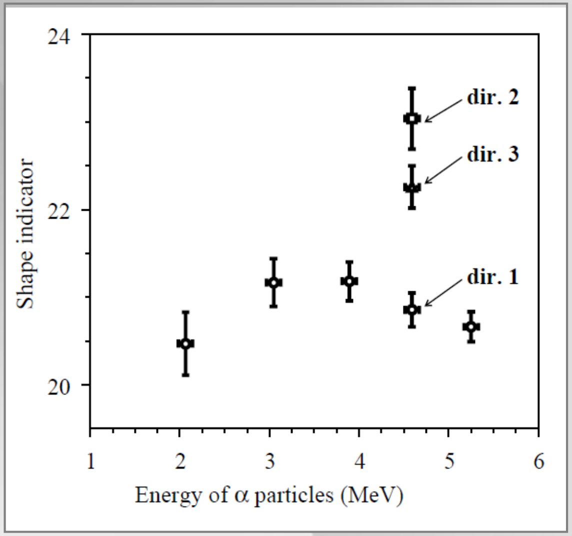
Anisotropic features in $ZnWO_4$

Measurements with α particles have shown that the **light response** and the **pulse shape** of a $ZnWO_4$ depend on the impinging direction of α particles with respect to the crystal axes

α/β ratio



PS parameter



Such effects are absent in case of electron excitation

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

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

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

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

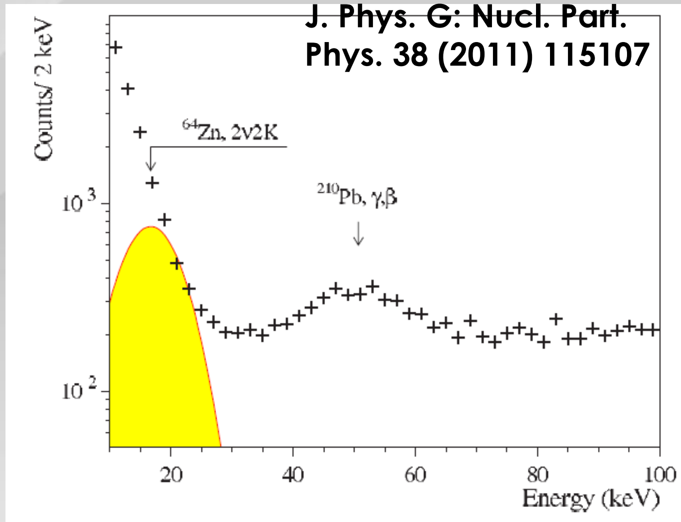
Similar effect is expected in the case of low energy nuclear recoils

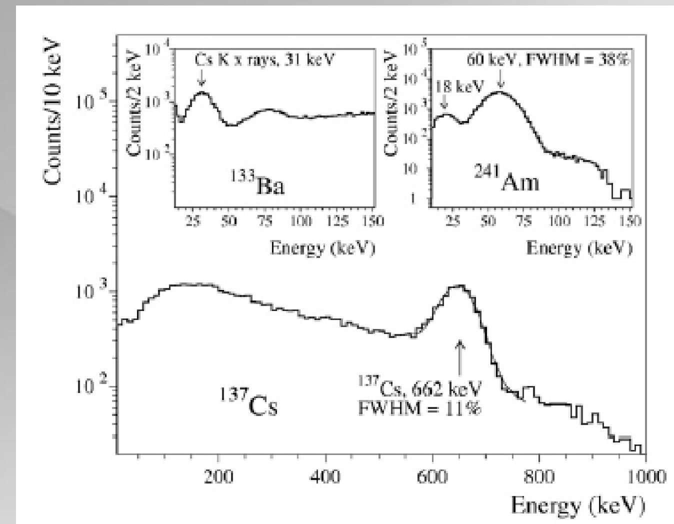
$\Rightarrow$ **Dedicated measurements are foreseen in the next weeks**

Light output and threshold of $ZnWO_4$ crystal scintillator

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

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





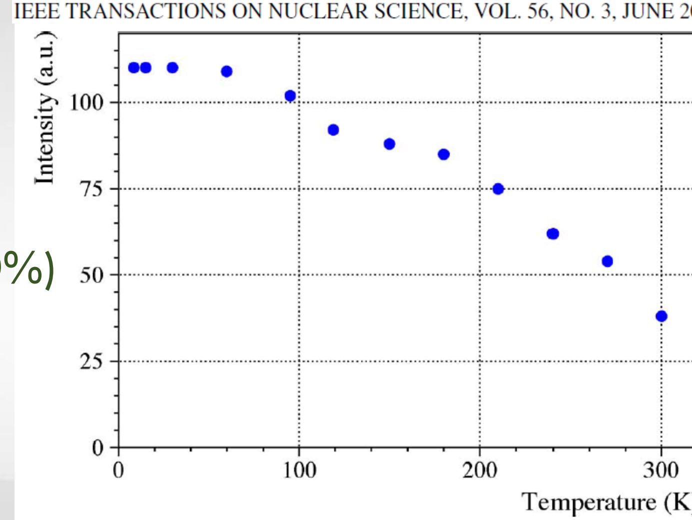
FWHM (8.8–14.6)% @662 keV

Improvements of the energy threshold by:

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

Low-threshold feasible

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

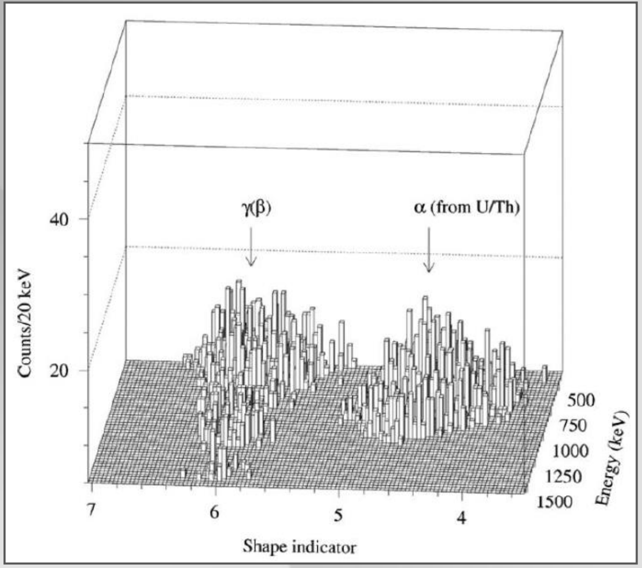


Light output measured for a ZnWO4 scintillator with ^{241}Am α particles as function of Temperature

Radiopurity of the $ZnWO_4$ crystal scintillator

The measured radioactive contamination of $ZnWO_4$ approaches that of specially developed low background NaI(Tl):

- ~ 0.5 ppt for ^{232}Th;
- ~ 0.2 ppt for ^{238}U;
- < 0.02 mBq/kg for ^{40}K (0.6 ppb ^{nat}K);
- total α activity of 0.18 mBq/kg



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

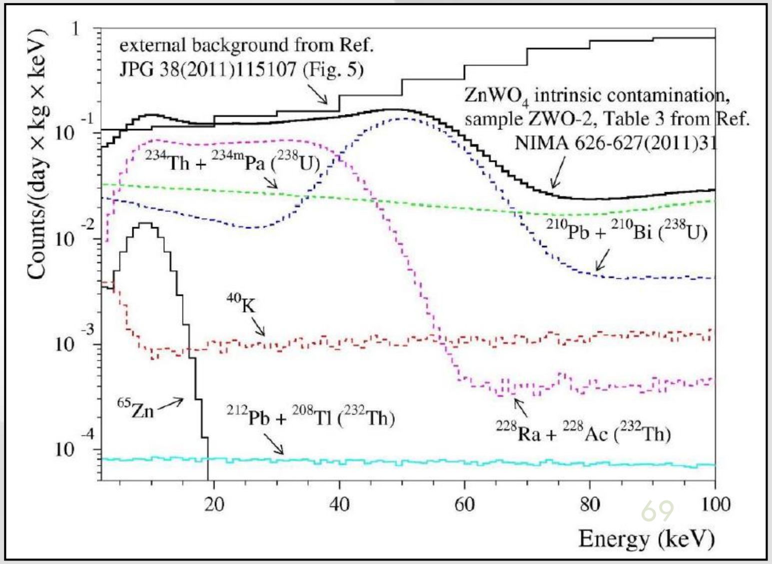
Montecarlo calculation for the expected background at low energy considering the measured radiopurity of the detectors

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

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

Developments still ongoing:

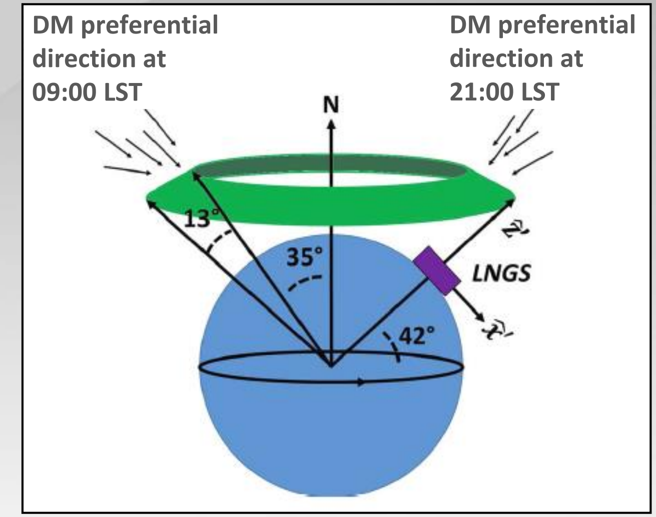
$\Rightarrow$ $ZnWO_4$ crystals with higher radiopurity expected

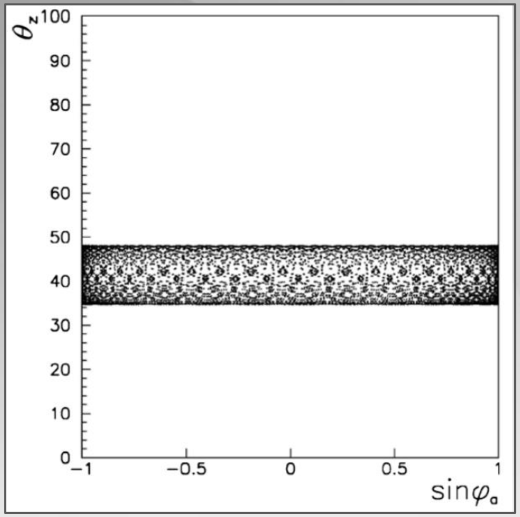


LNGS: a perfect place for directionality

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

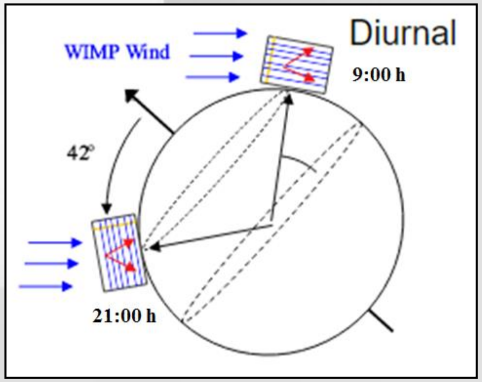
⇒ here at 21:00 h LST the DM particles come mainly from the top, while 12 h later they come from the North and parallel to the horizon line





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

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

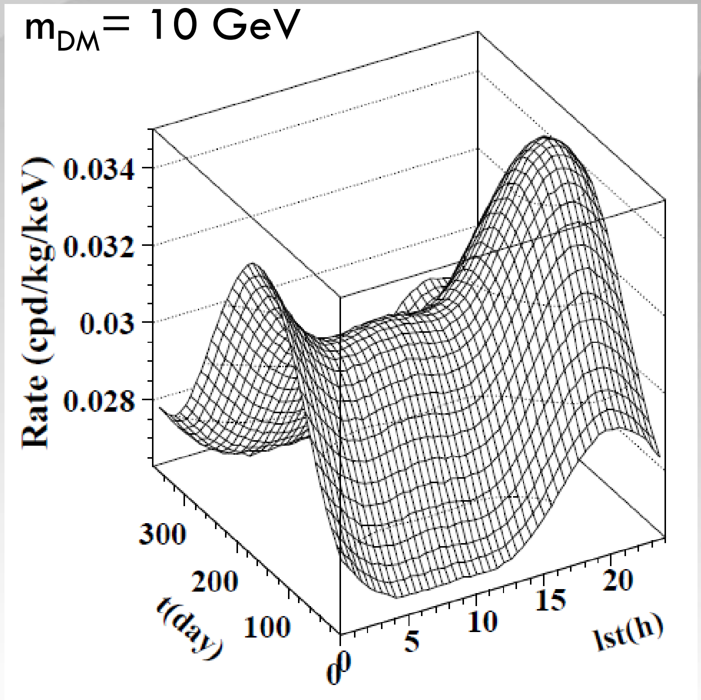


With this configuration the range of variability of the anisotropic detector response during a sidereal day is at maximum

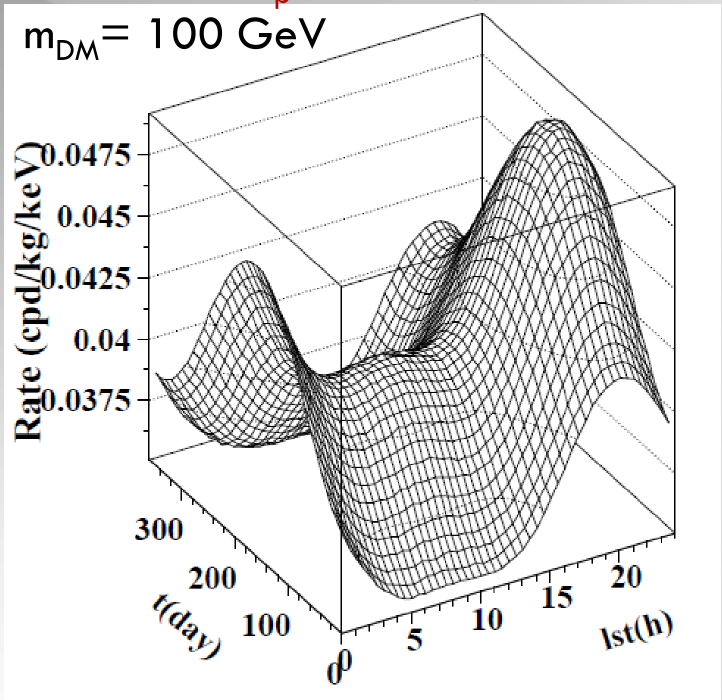
Example of expected signal

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

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



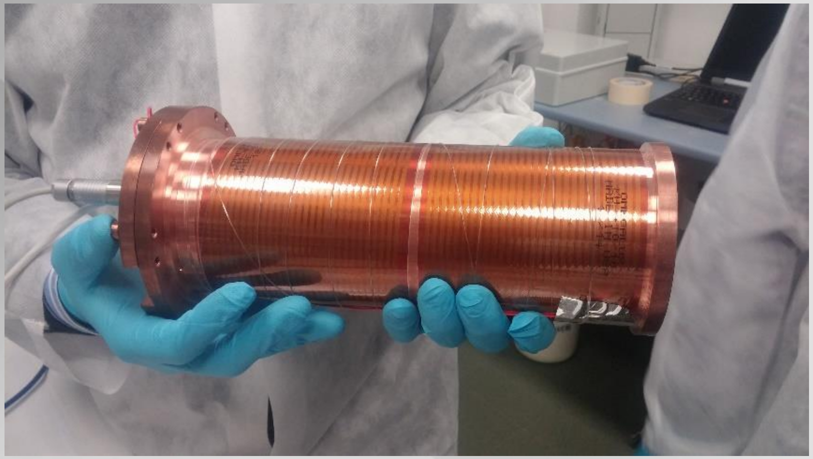
[6-7] keV $\sigma_p = 5\times10^{-5}$ pb

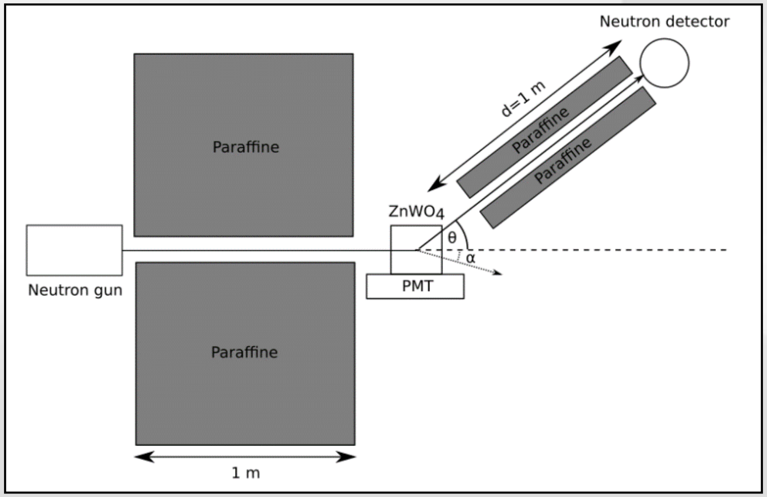


- Identical sets of crystals placed in the same set-up with different axis orientation will observe consistently different time evolution of the rate
- The diurnal effect will refer to the sidereal day and not to the solar day
- Absolute maximum rate is at day 152 and at 21h LST (when the DM flux is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

$ZnWO_4$ – work in progress…

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





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

Conclusions

- ✓ Many and competitive results have been obtained in the search for rare processes by the DAMA experiment at LNGS
- ✓ The DAMA/NaI and DAMA/LIBRA-phase1 data favour the presence of a signal with all the proper features for DM particles in the galactic halo at 9.3σ C.L. (14 annual cycles: 1.33 ton$\times$yr)
- ✓ DAMA/LIBRA-phase2 is in data taking at lower software energy threshold and DAMA/LIBRA-phase3 R&D is in progress
- ✓ Null searches are not in robust conflict with DAMA and a model independent signature is the definite strategy to investigate the presence of Dark Matter particle component(s) in the Galactic halo
- ✓ New investigation on different peculiarities of the DM signal exploited (Diurnal Modulation and Earth Shadow Effect)
- ✓ Study of $ZnWO_4$ scintillator for exploiting directionality technique in progress