



Nuovi risultati da DAMA/LIBRA-fase1

A. Di Marco, INFN & Univ. Roma Tor Vergata
101° Congresso Nazionale SIF, Roma 21 Settembre 2015

DAMA SET-UPS

an observatory for rare processes @ LNGS



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

Collaboration:

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

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

+ neutron meas.: ENEA-Frascati

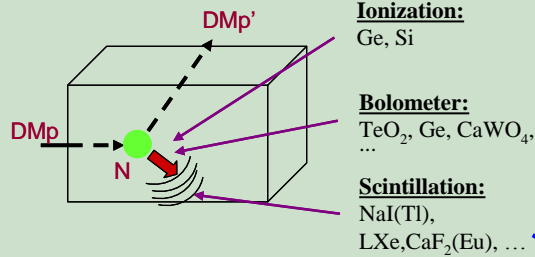
+ in some studies on $\beta\beta$ decays (DST-MAE project): IIT Ropar, India

Web Site: <http://people.roma2.infn.it/dama>

Some direct detection processes:

- Scatterings on nuclei

→ detection of nuclear recoil energy



- Inelastic Dark Matter: $W + N \rightarrow W^* + N$

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

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

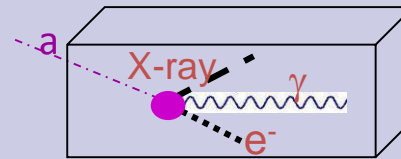
$$\frac{1}{2} \mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

→ detection of recoil nuclei + e.m. radiation

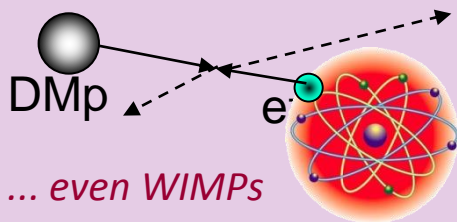
- Conversion of particle into e.m. radiation

→ detection of γ , X-rays, e^-



- Interaction only on atomic electrons

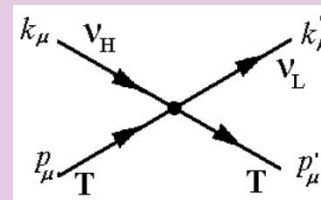
→ detection of e.m. radiation



- 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 ...

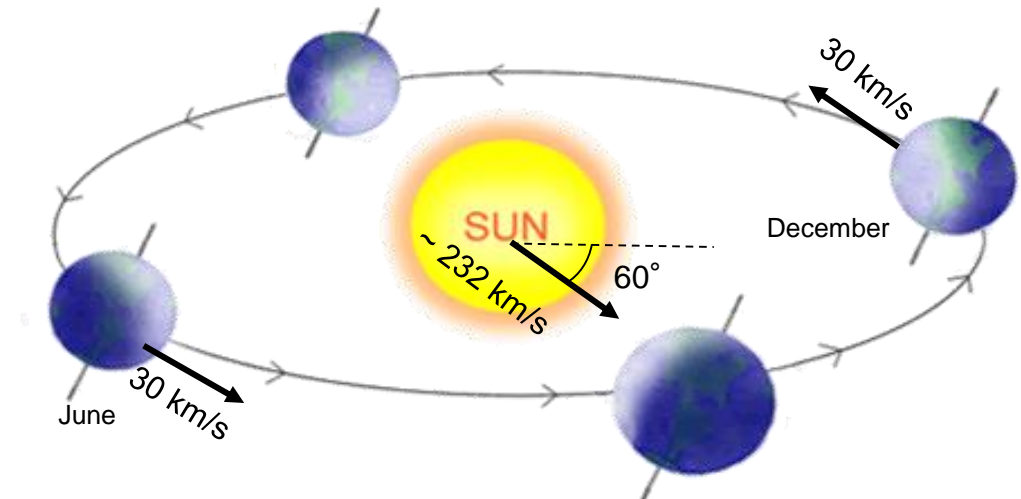
The **annual modulation**: a model independent signature for the investigation of DM particles

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.

Requirements:

- 1) Cosine-like modulation of the rate
- 2) In low energy range
- 3) Period of 1 year
- 4) Phase at about June 2nd
- 5) 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

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



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

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

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

To mimic this signature, spurious effects and side reactions must be able to account for the whole observed modulation amplitude, and also to satisfy simultaneously all the requirements

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
- CNC processes
- Electron stability and non-paulian transitions in Iodine atoms (by L-shell)
- Search for solar axions
- Exotic Matter search
- Search for superdense nuclear matter
- Search for heavy clusters decays

PLB408(1997)439
PRC60(1999)065501

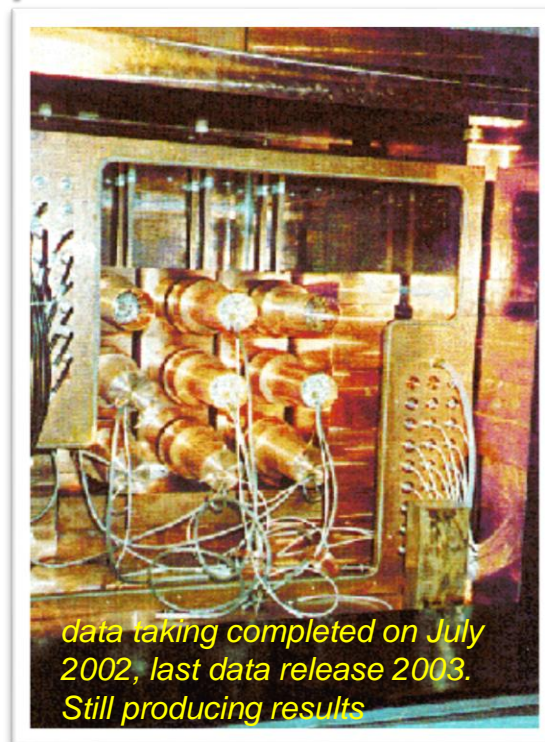
PLB460(1999)235
PLB515(2001)6
EPJdirect C14(2002)1
EPJA23(2005)7
EPJA24(2005)51

Results on DM particles:

- PSD
- Investigation on diurnal effect
- Exotic Dark Matter search
- **Annual Modulation Signature**

PLB389(1996)757
N.Cim.A112(1999)1541
PRL83(1999)4918

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



**Model independent evidence of a particle DM
component in the galactic halo at 6.3σ C.L.**

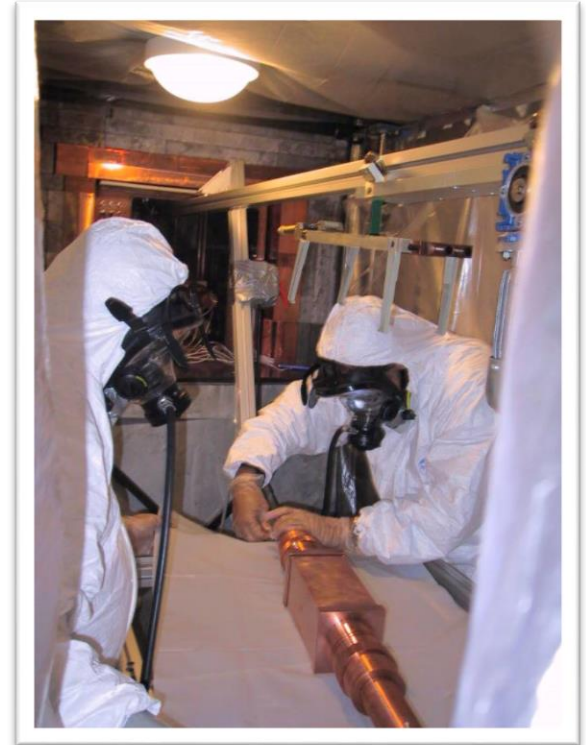
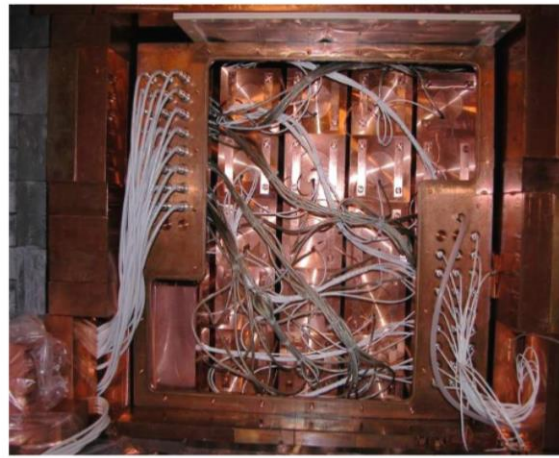
total exposure (7 annual cycles) 0.29 ton \times yr

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

As a result of a 2nd generation R&D for more radiopure NaI(Tl) by exploiting new chemical/physical radiopurification techniques (all operations involving - 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, 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**
- Rare processes: PEP viol.: **EPJC62(2009)327**, CNC in I: **EPJC72(2012)1920**, IPP in Am: **EPJA49(2013)64**

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 M events from sources
- acceptance window eff: 95 M events (≈3.5 M events/keV)

DAMA/LIBRA-phase1:

- First upgrade on Sept 2008: replacement of some PMTs in HP N₂ 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 on Oct./Nov. 2010: replacement of all the PMTs with higher Q.E. ones from dedicated developments

Goal: lowering the software energy threshold

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

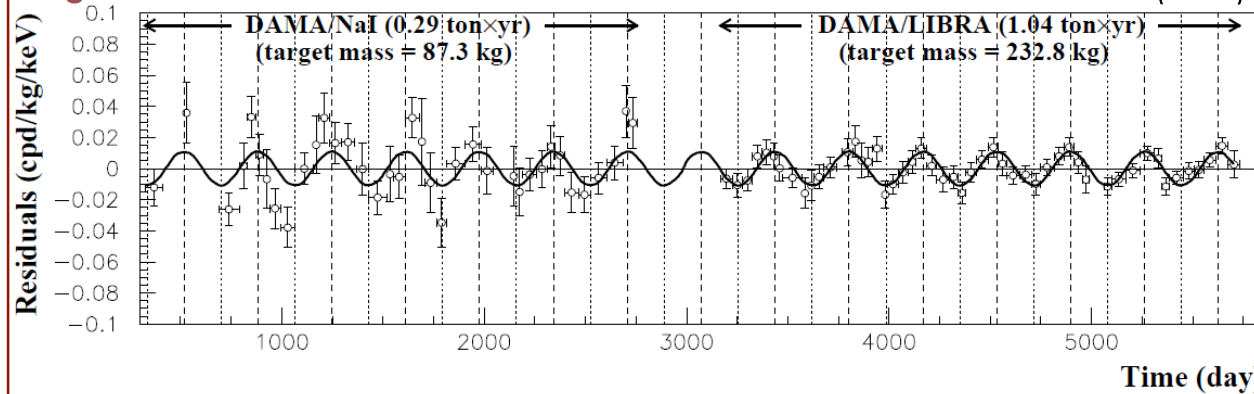


Model Independent Annual Modulation Result

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

Single-hit residuals rate 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

$A = (0.0110 \pm 0.0012)$ cpd/kg/keV

$\chi^2/\text{dof} = 70.4/86$ 9.2 σ C.L.

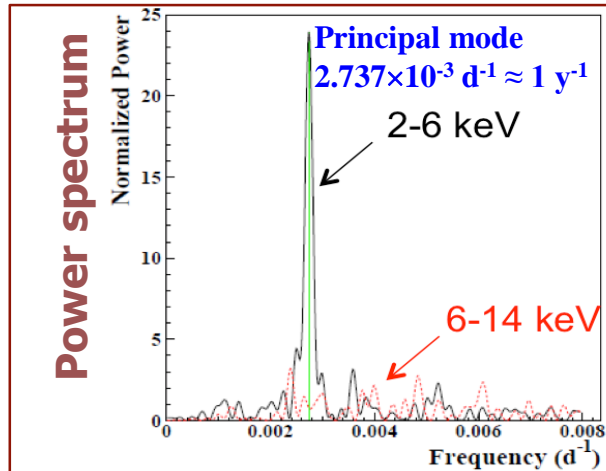
Absence of modulation? No

$\chi^2/\text{dof} = 154/87$ $P(A=0) = 1.3 \times 10^{-5}$

Fit with all the parameters free:

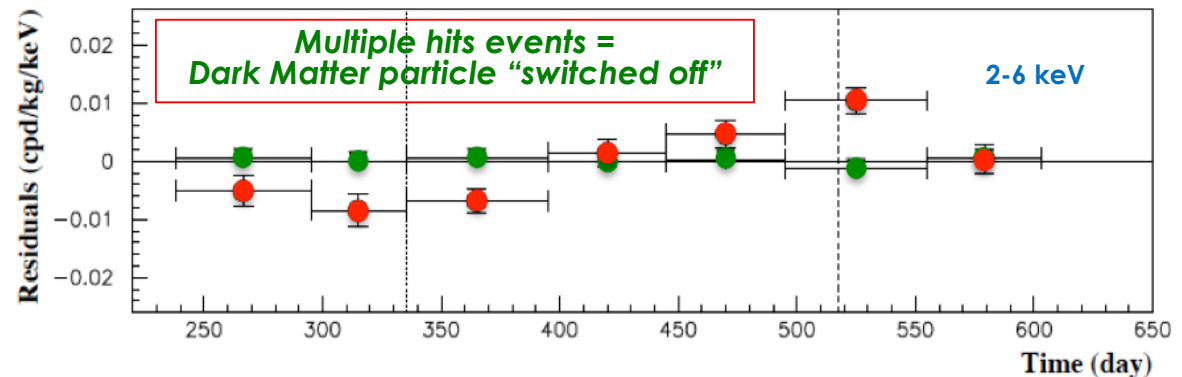
$A = (0.0112 \pm 0.0012)$ cpd/kg/keV

$t_0 = (144 \pm 7)$ d - $T = (0.998 \pm 0.002)$ 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
 $A = -(0.0005 \pm 0.0004)$ cpd/kg/keV



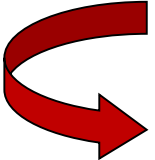
This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

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

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, AIPConf.Proc.1223(2010)50, 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.	$<2.5 \times 10^{-6}$ cpd/kg/keV
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	$<10^{-4}$ cpd/kg/keV
NOISE	Effective full noise rejection near threshold	$<10^{-4}$ cpd/kg/keV
ENERGY SCALE	Routine + intrinsic calibrations	$<1-2 \times 10^{-4}$ cpd/kg/keV
EFFICIENCIES	Regularly measured by dedicated calibrations	$<10^{-4}$ cpd/kg/keV
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV <i>multiple-hits</i> events; this limit includes all possible sources of background	$<10^{-4}$ cpd/kg/keV
SIDE REACTIONS	Muon flux variation measured at LNGS	$<3 \times 10^{-5}$ cpd/kg/keV



+ they cannot satisfy all the requirements of annual modulation signature



Thus, they cannot mimic the observed annual modulation effect

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

well compatible with several candidates (in several of the many possible astrophysical, nuclear and particle physics scenarios); other ones are open

Neutralino as LSP in various SUSY theories

a heavy n of the 4-th family

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

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

Sterile neutrino

WIMP with preferred inelastic scattering

Light Dark Matter

Mirror Dark Matter

Self interacting Dark Matter

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

heavy exotic candidates, as "4th family atoms", ...

Elementary Black holes such as the Daemons

Kaluza Klein particles

... and more

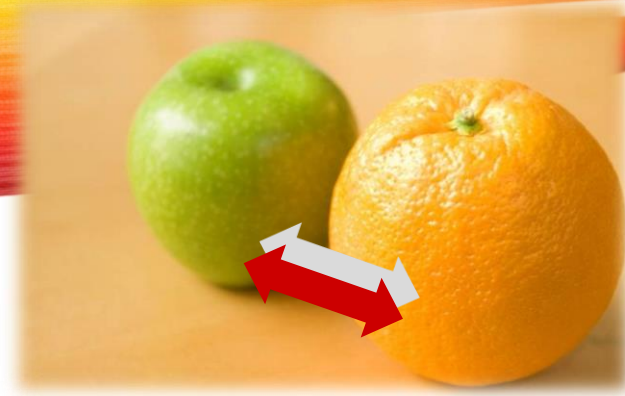


Possible model dependent positive hints from Indirect searches (but interpretation, evidence itself, derived mass and cross sections depend e.g. on bckg modeling, on DM spatial velocity distribution in the galactic halo, etc.) not in conflict with DAMA results; null results not in conflict as well

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

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, JMPA28(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
- ...

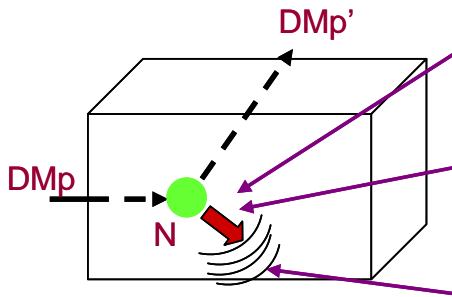
Uncertainty in experimental parameters, as well as necessary assumptions on various related astrophysical, nuclear and particle-physics aspects, affect all the results at various extent, both in terms of exclusion plots and in terms of allowed regions/volumes. Thus comparisons with a fixed set of assumptions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

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

... an example...

DM particles inducing elastic scatterings on target-nuclei, SI case

Regions in the nucleon cross section vs DM particle mass plane

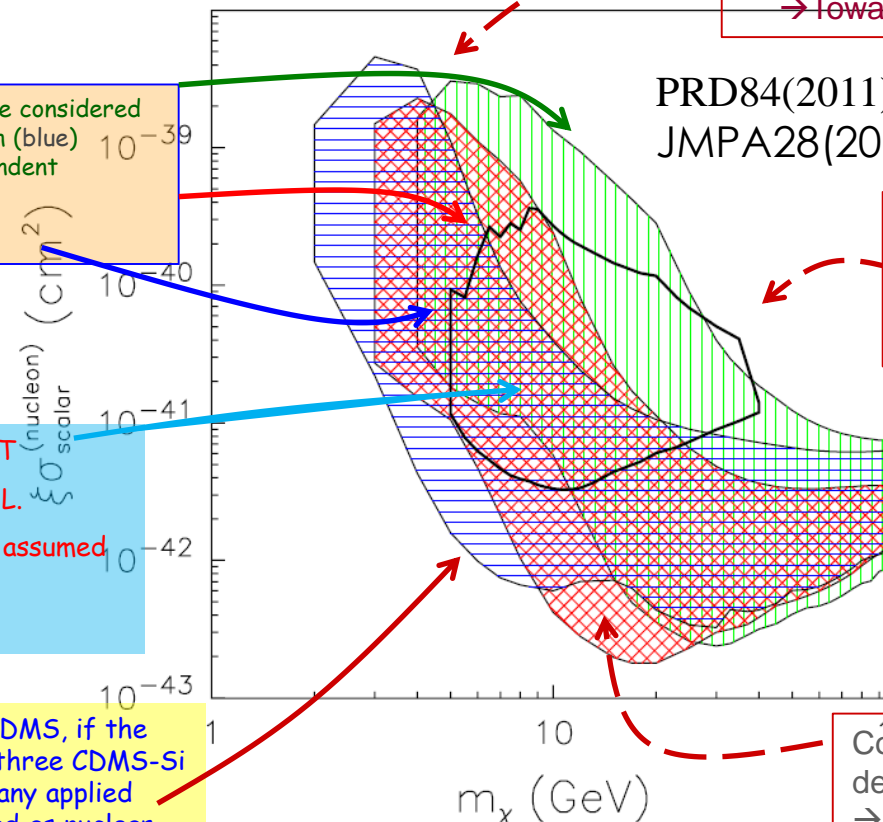


- Some velocity distributions and uncertainties considered.
- The DAMA regions represent the domain where the likelihood-function values differ more than 7.5σ from the null hypothesis (absence of modulation).
- For CoGeNT a fixed value for the Ge quenching factor and a Helm form factor with fixed parameters are assumed.
- The CoGeNT region includes configurations whose likelihood-function values differ more than 1.64σ from the null hypothesis (absence of modulation). This corresponds roughly to 90% C.L. far from zero signal.

DAMA allowed regions for the considered scenario without (green), with (blue) channeling, with energy-dependent Quenching Factors (red);
7.5 σ C.L.

CoGeNT
1.64s C.L.
q.f. at a fixed assumed value

Compatibility also with CRESST and CDMS, if the two CDMS-Ge recoil-like events, the three CDMS-Si and the CRESST ones surviving the many applied cuts in marginal exposures are assumed as nuclear recoils induced by DM interactions



PRD84(2011)055014
JMPA28(2013)1330022)

Co-rotating halo,
Non thermalized component
→ Enlarge allowed region
towards larger mass

Combining channeling and q.f. energy
dependence (AstrPhys33(2010)40)
→ Towards lower σ

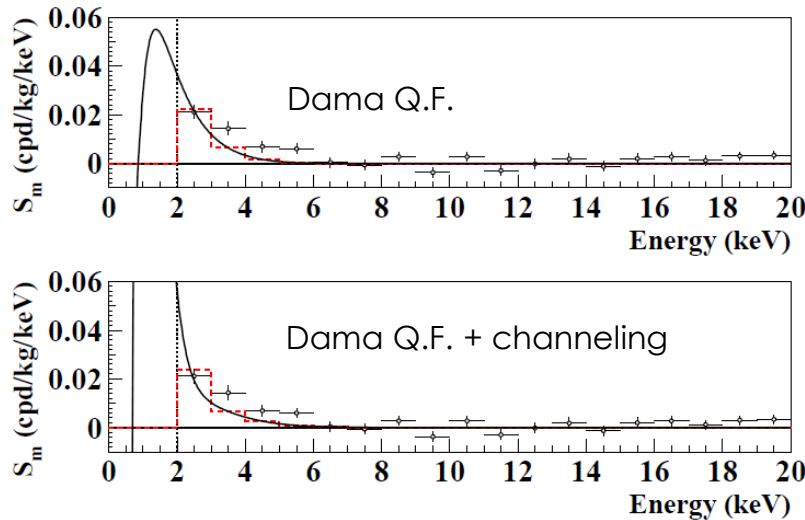
DAMA annual modulation effect and Asymmetric mirror matter

EPJC75(2015)400

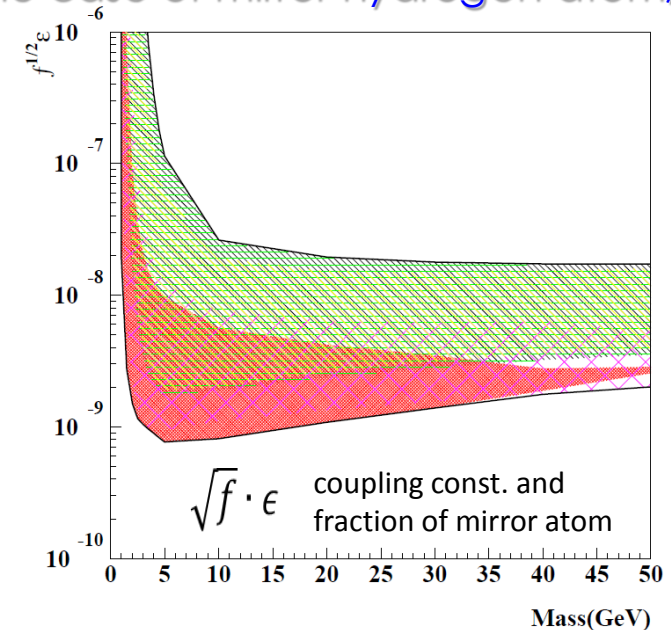
Asymmetric mirror matter: mirror parity spontaneously broken \Rightarrow mirror sector becomes a heavier and deformed copy of ordinary sector

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

Examples of expected S_m for the Mirror DM candidate for different values of quenching factor



DAMA/LIBRA allowed values for $\sqrt{f}\epsilon$ in the case of mirror hydrogen atom, $Z'=1$



The allowed values for $\sqrt{f}\epsilon$ in the case of mirror hydrogen atom, $Z'=1$, ranges between 7.7×10^{-10} to 1.1×10^{-7} . The values within this overall range are well compatible with cosmological bounds. In particular, the best fit values among all the considered scenarios gives $\sqrt{f}\epsilon_{b.f.} = 2.4 \times 10^{-9}$

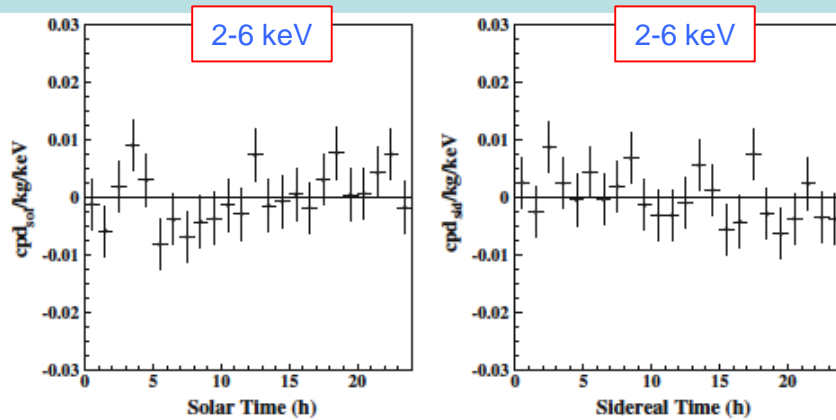
Investigating diurnal modulation in DAMA/LIBRA-phase1

EPJ C74(2014)2827

A diurnal modulation with sidereal time is expected because of Earth rotation

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

- Experimental *single-hit* residuals rate vs either sidereal and solar time and vs energy.
- These residual rates are calculated from the measured rate of the *single-hit* events after subtracting the constant part



Solar Sidereal

Energy	$\chi^2/\text{d.o.f}$ (P)	$\chi^2/\text{d.o.f}$ (P)
2-4 keV	35.2/24 (7%)	28.7/24 (23%)
2-5 keV	35.5/24 (6%)	24.0/24 (46%)
2-6 keV	25.8/24 (36%)	21.2/24 (63%)
6-14 keV	25.5/24 (38%)	35.9/24 (6%)

Diurnal variation
(sidereal and solar)
excluded at 95% C.L.
at the reached level
of sensitivity

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

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

- Annual modulation amplitude in DAMA/LIBRA-phase1 in the (2-6) keV: (0.0097 ± 0.0013) cpd/kg/keV
- Expected value of diurnal modulation amplitude:
 $\simeq 1.5 \times 10^{-4}$ cpd/kg/keV.
- Fitting the *single-hit* residuals with a cosine function with amplitude A_d as free parameter, period 24 h and phase 14 h

$$A_d^{(2-6 \text{ keV})} < 1.2 \times 10^{-3} \text{ cpd/kg/keV} \quad (90\% \text{CL})$$

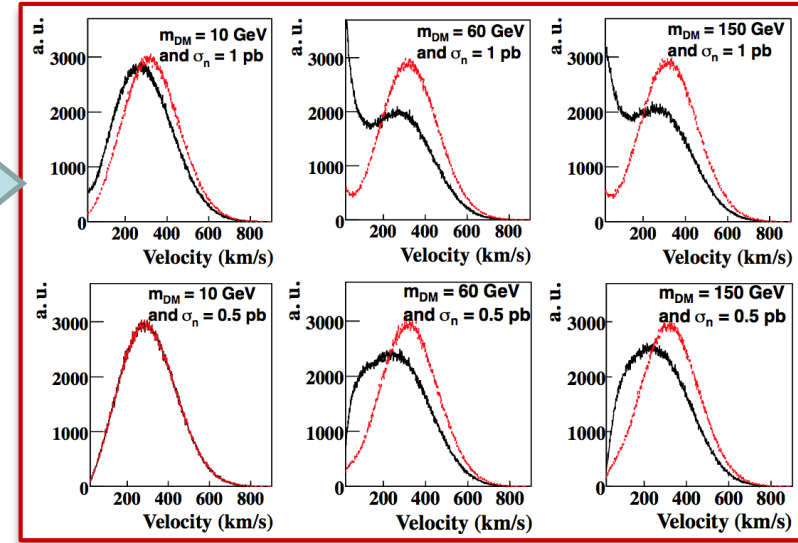
Present experimental sensitivity lower than the diurnal modulation amplitude expected from the DAMA/LIBRA-phase1 observed effect.

DAMA/LIBRA-phase2 will offer increased sensitivity

Investigation of Earth Shadow Effect

Eur. Phys. J. C 75 (2015) 239

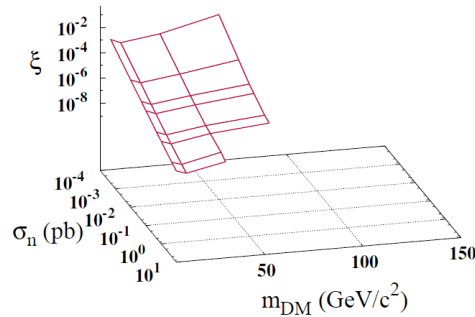
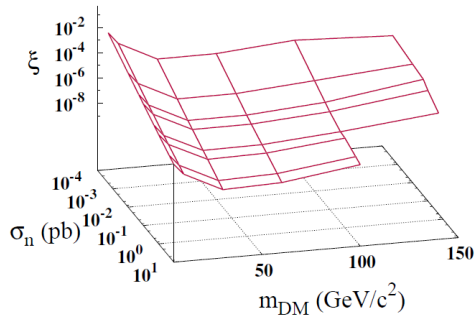
- **Earth Shadow Effect** expected for DM candidate particles inducing nuclear recoils
- Only for candidates with **high cross-section** with ordinary matter (low DM local density)
- Induced by the **variation** during the day of the Earth **thickness crossed by the DM particle** reaching the experimental set-up



Considering DAMA/LIBRA DM annual modulation result, allowed regions in the ξ vs σ_n plane for each m_{DM} .

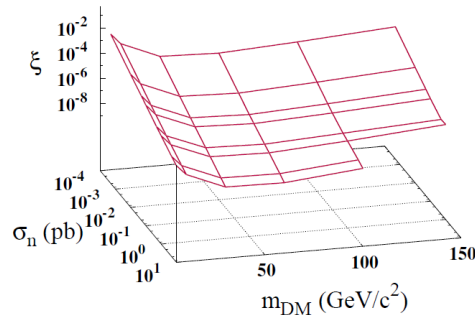
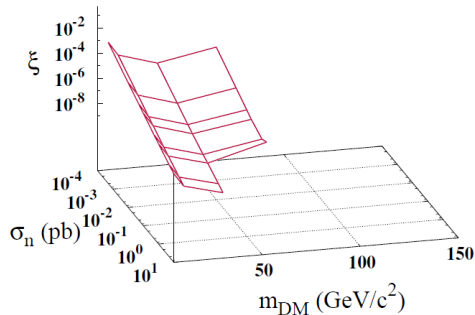
(a)

(b)



(c)

(d)



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 the *single-hit* events of DAMA/LIBRA-phase1 in (2-4) keV

Minimizing χ^2 , upper limits on ξ can be evaluated

Red surface: 95% C.L. allowed mean value (uncertainties $\pm 30\%$)

DAMA/LIBRA phase 2 - running

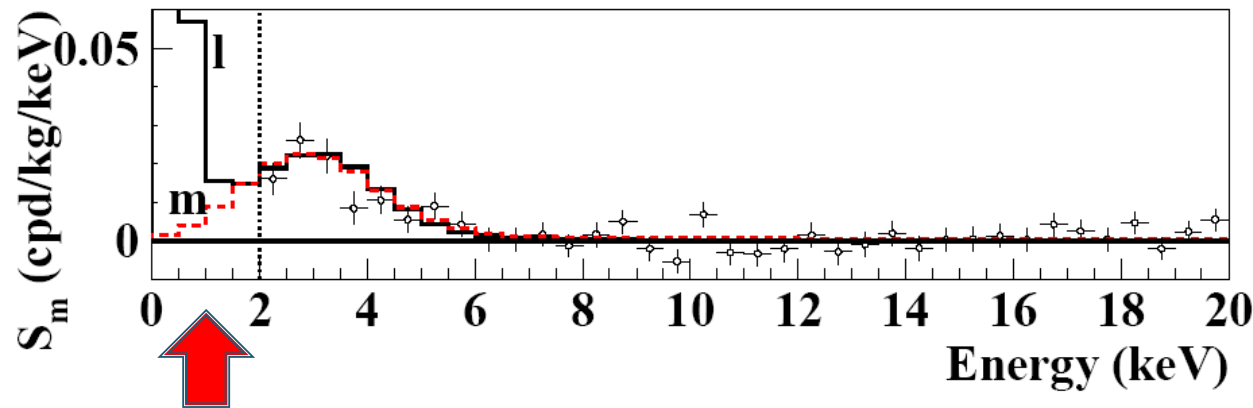
Second upgrade on end of 2010:

JINST 7(2012)03009

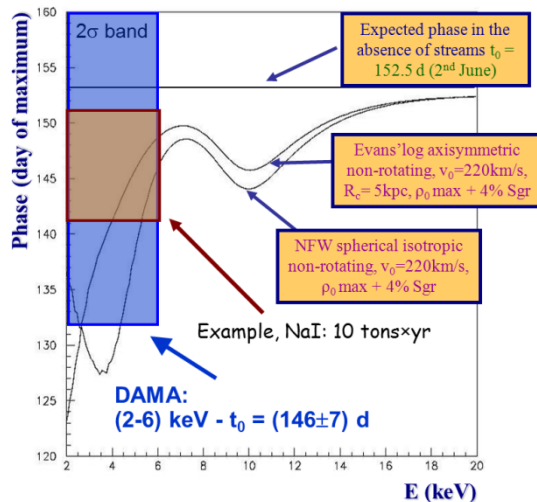
all PMTs replaced with new ones of higher Q.E.

Previous PMTs: 5.5-7.5 ph.e./keV

New PMTs: up to 10 ph.e./keV



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



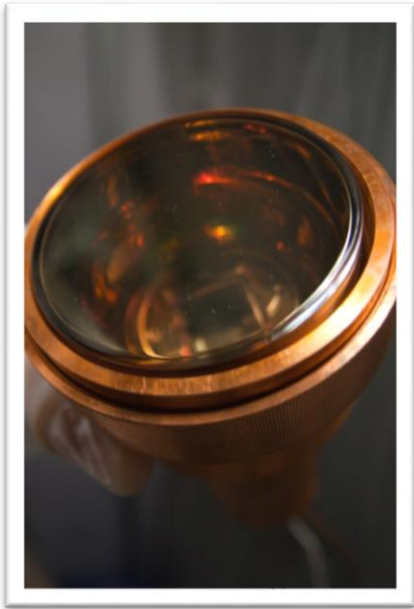
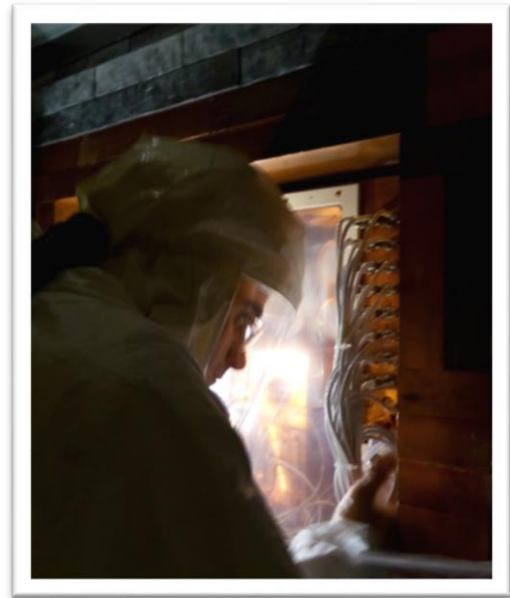
Possible DAMA/LIBRA-phase3

- 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.

Conclusions

- Positive evidence for the presence of DM particles in the galactic halo supported at **9.3σ** C.L. (14 annual cycles DAMA/NaI and DAMA/LIBRA-phase1: 1.33 ton \times yr)
- Modulation parameters determined with high precision
- New investigation on different peculiarities of the DM signal exploited (**Diurnal Modulation** and **Earth Shadow Effect**)
- Full sensitivity to many kinds of DM candidates and interactions types (both inducing recoils and/or e.m. radiation), full sensitivity to low and high mass candidates



- **DAMA/LIBRA – phase2 in data taking** at lower software energy threshold (below 2 keV) to investigate further features of DM signals and second order effects
- Continuing investigations of rare processes other than DM as well as further developments
- **DAMA/LIBRA – phase3 under study**
- R&D for a possible DAMA/1ton set-up in progress