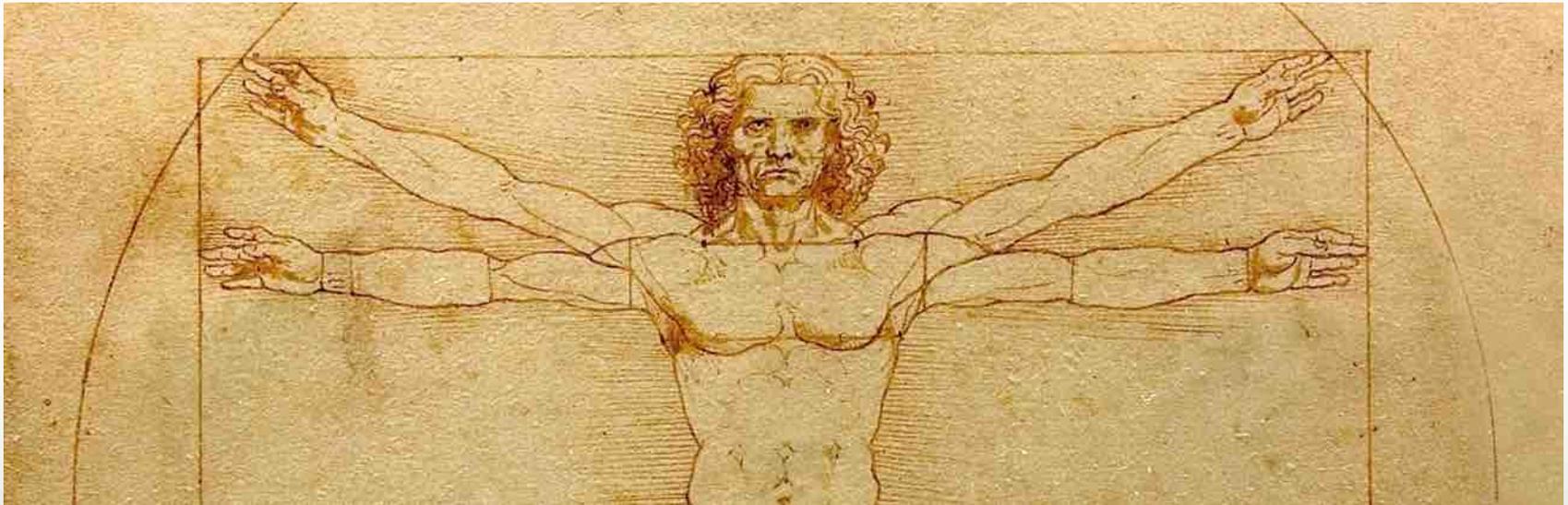


DAMA/LIBRA results and perspectives



P. Belli
INFN – Roma Tor Vergata

UCLA Dark Matter 2016
Los Angeles, USA,
February 17-19, 2016

DAMA set-ups

an observatory for rare processes @ LNGS



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

Collaboration:

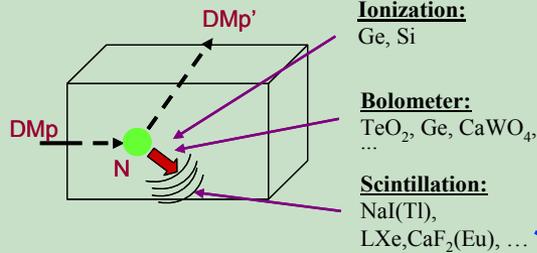
Roma Tor Vergata, Roma La Sapienza, LNGS, IHEP/Beijing
+ by-products and small scale expts.: INR-Kiev + other institutions
+ neutron meas.: ENEA-Frascati
+ in some studies on $\beta\beta$ decays (DST-MAE and Inter-Universities project):
IIT Kharagpur and Ropar, India

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

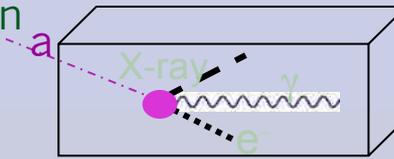
$$\frac{1}{2} \mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

→ detection of recoil nuclei + e.m. radiation

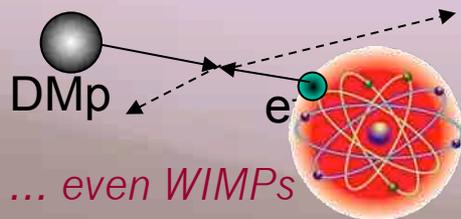
- Conversion of particle into e.m. radiation

→ detection of γ , X-rays, e^-



- Interaction only on atomic electrons

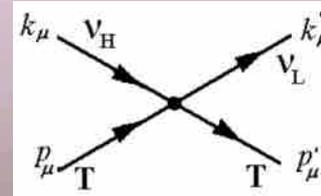
→ detection of e.m. radiation



- 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

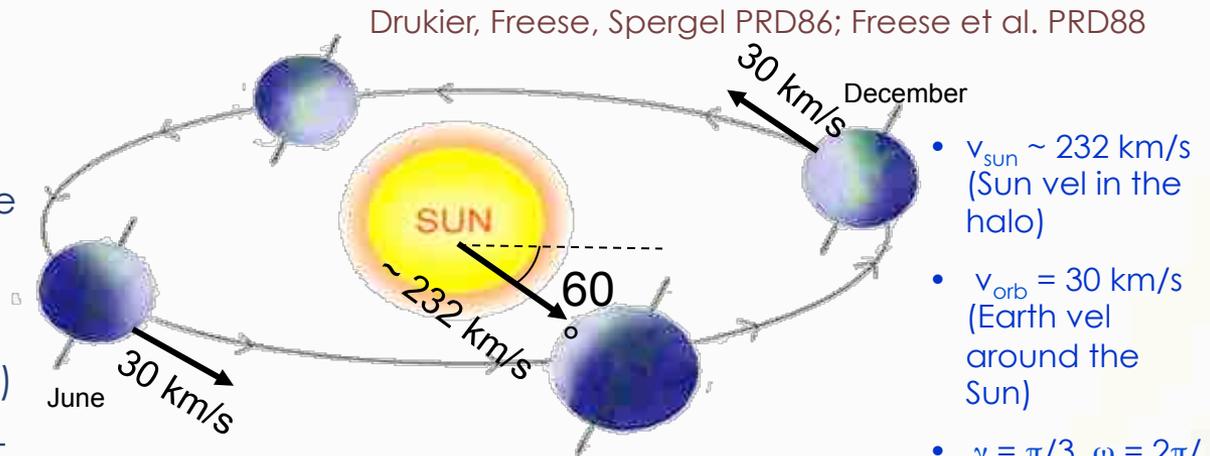
... also other ideas ...

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

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



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

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

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 not only - obviously - be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

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

Performances:

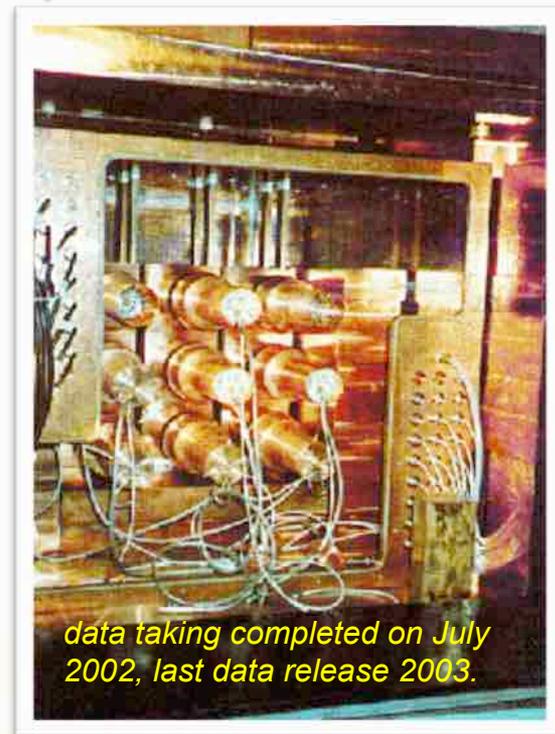
N.Cim.A112(1999)545-575, EPJC18(2000)283,
Riv.N.Cim.26 n. 1(2003)1-73, IJMPD13(2004)2127

Results on rare processes:

- Possible Pauli exclusion principle violation 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



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

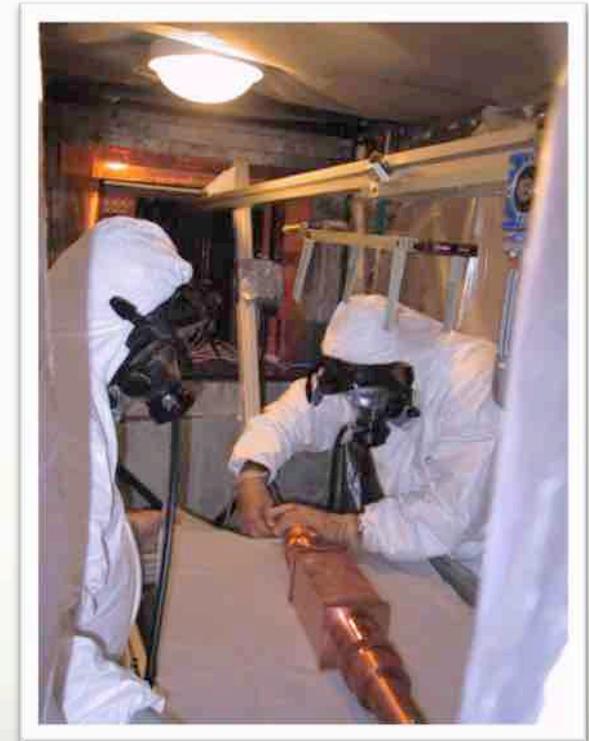
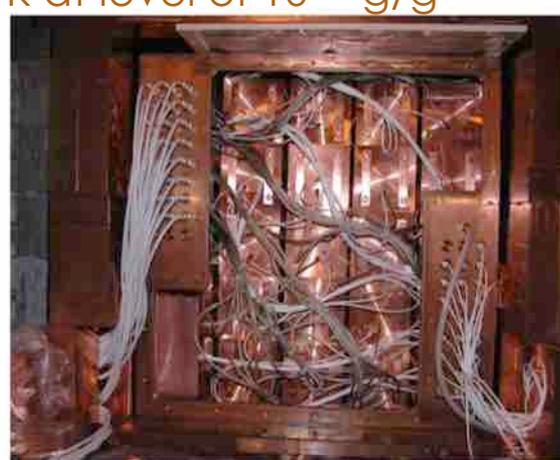
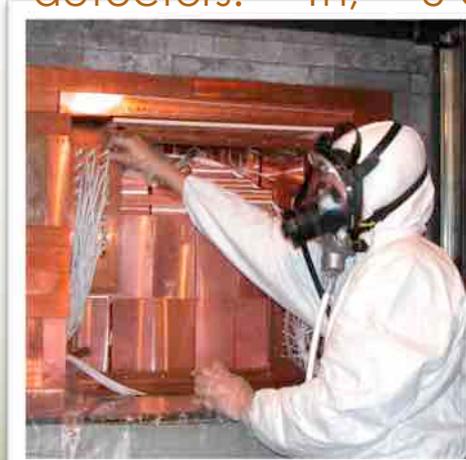
total exposure (7 annual cycles) 0.29 ton×yr

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 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

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	Sept. 1, 2009 - Sept. 8, 2010	242.5	62098	0.515
DAMA/LIBRA-phase1	Sept. 9, 2003 - Sept. 8, 2010		379795	1.04 ton×yr
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 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 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

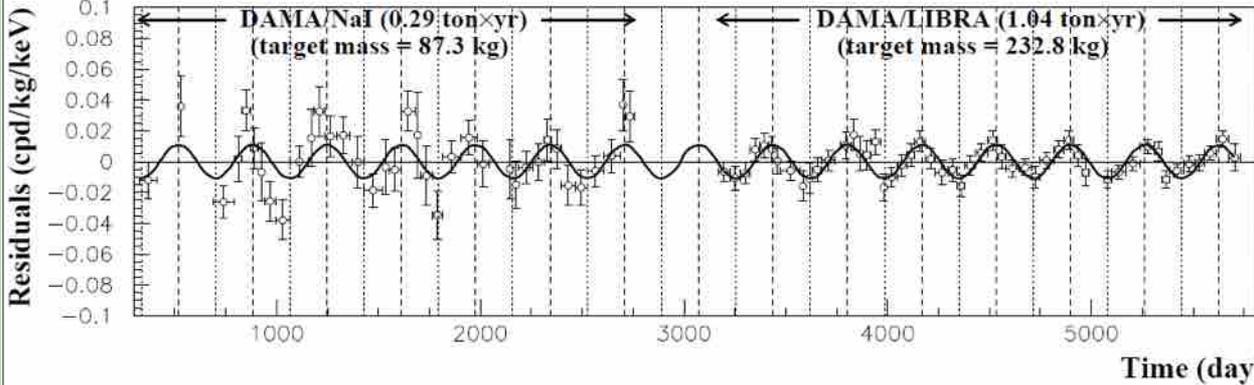


Model Independent Annual Modulation Result

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

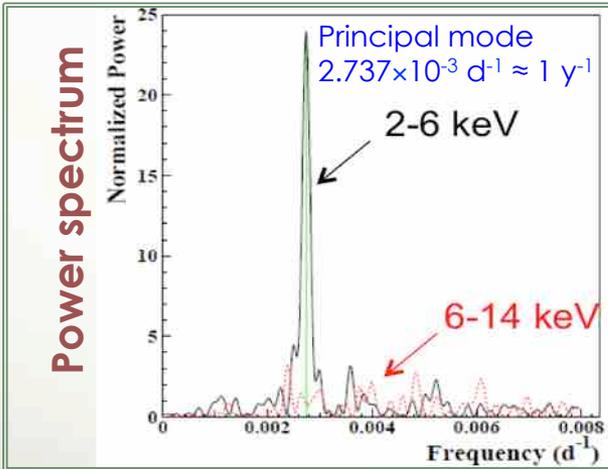


continuous line: $t_0 = 152.5$ d, $T = 1.0$ y

$A = (0.0110 \pm 0.0012)$ cpd/kg/keV
 $\chi^2/\text{dof} = 70.4/86$ 9.2 σ C.L.

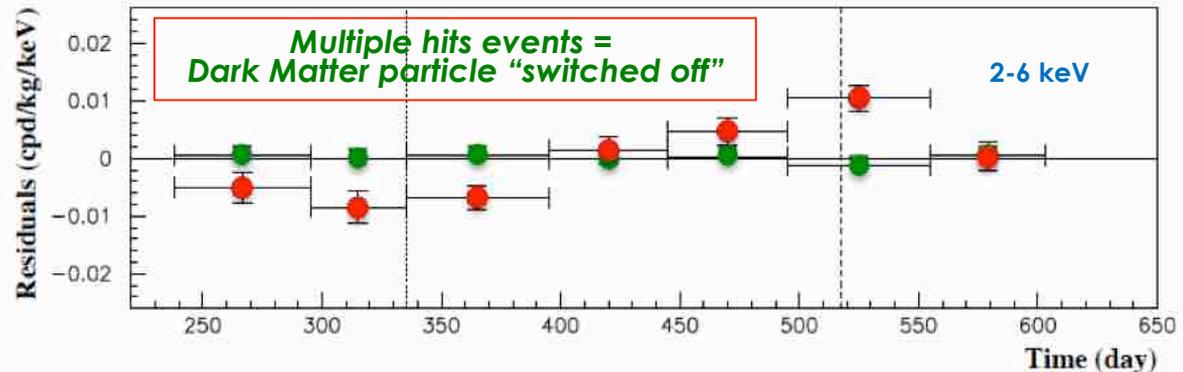
Absence of modulation? No
 $\chi^2/\text{dof} = 154/87$ $P(A=0) = 1.3 \times 10^{-5}$

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

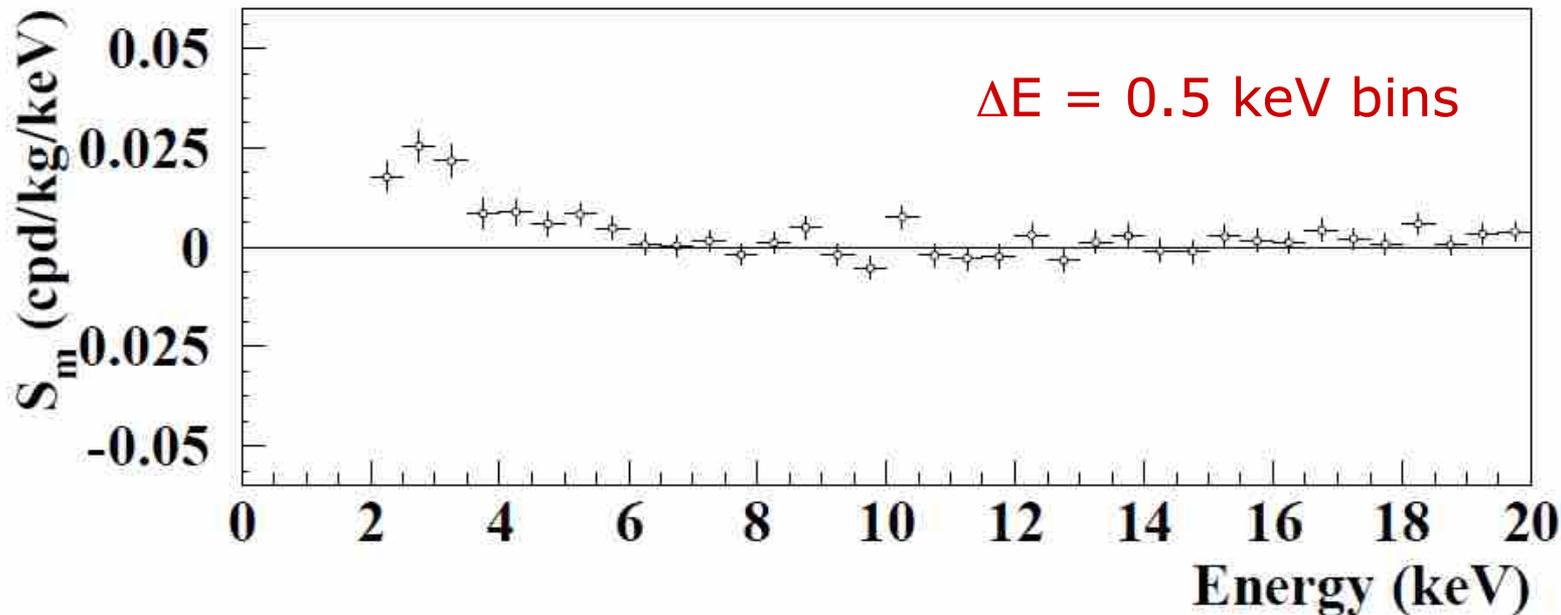
The data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at about 9.2 σ C.L.

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 \approx **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%)

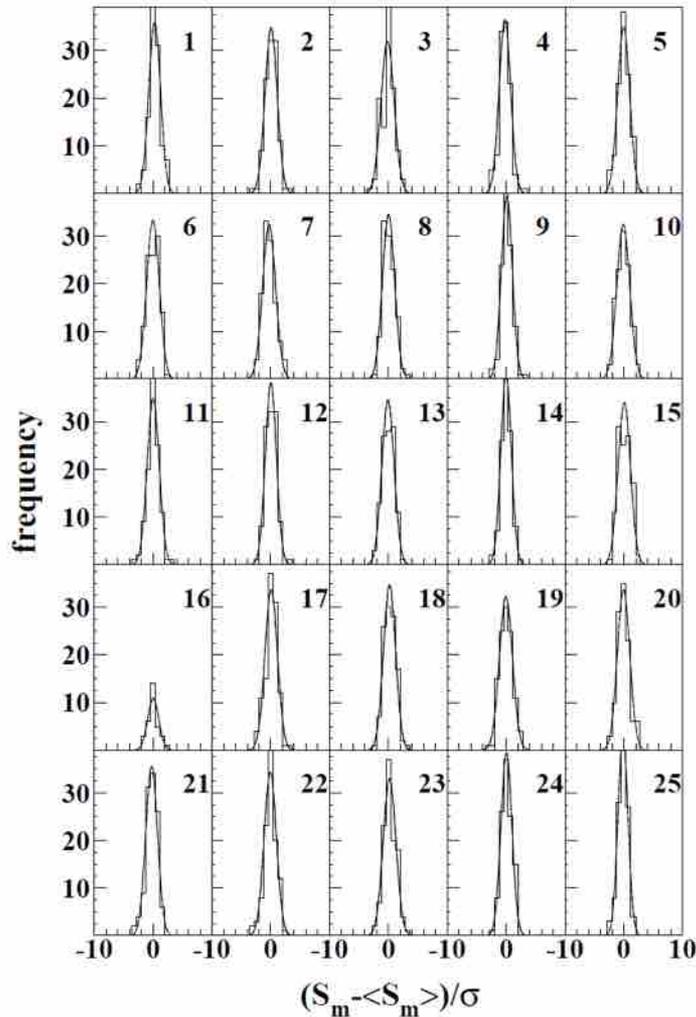
Statistical distributions of the modulation amplitudes (S_m)

- a) S_m for each detector, each annual cycle and each considered energy bin (here 0.25 keV)
- b) $\langle S_m \rangle$ = mean values over the detectors and the annual cycles for each energy bin; σ = error on S_m

DAMA/LIBRA-phase1 (7 years)

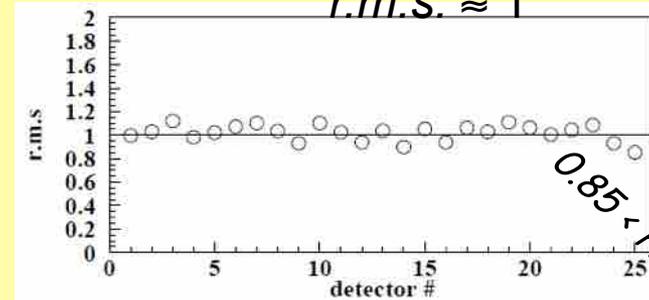
total exposure: 1.04 ton \times yr

Each panel refers to each detector separately; 112 entries = 16 energy bins in 2-6 keV energy interval \times 7 DAMA/LIBRA-phase1 annual cycles (for crys 16, 2 annual cycle, 32 entries)



2-6 keV

Standard deviations of $(S_m - \langle S_m \rangle) / \sigma$ for each detectors
r.m.s. ≈ 1



$$x = (S_m - \langle S_m \rangle) / \sigma,$$

$$\chi^2 = \sum x^2$$

Individual S_m values follow a normal distribution since $(S_m - \langle S_m \rangle) / \sigma$ is distributed as a Gaussian with a unitary standard deviation (r.m.s.)

\Rightarrow S_m statistically well distributed in all the detectors, energy bin and annual cycles

Is there a sinusoidal contribution in the signal? phase $\neq 152.5$ day?

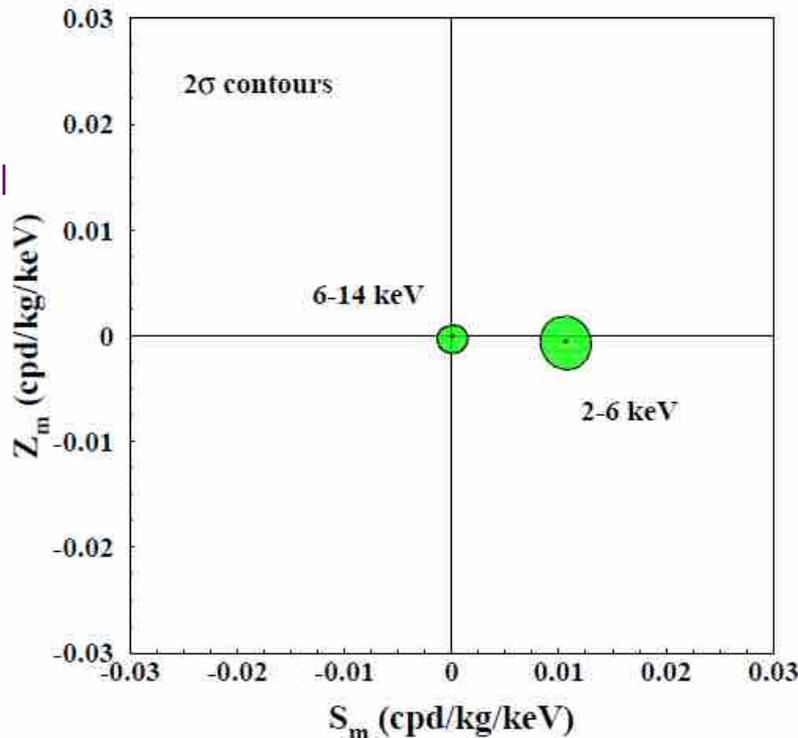
DAMA/NaI + DAMA/LIBRA-phase1

total exposure: 487526 kg×day \approx **1.33 ton×yr**

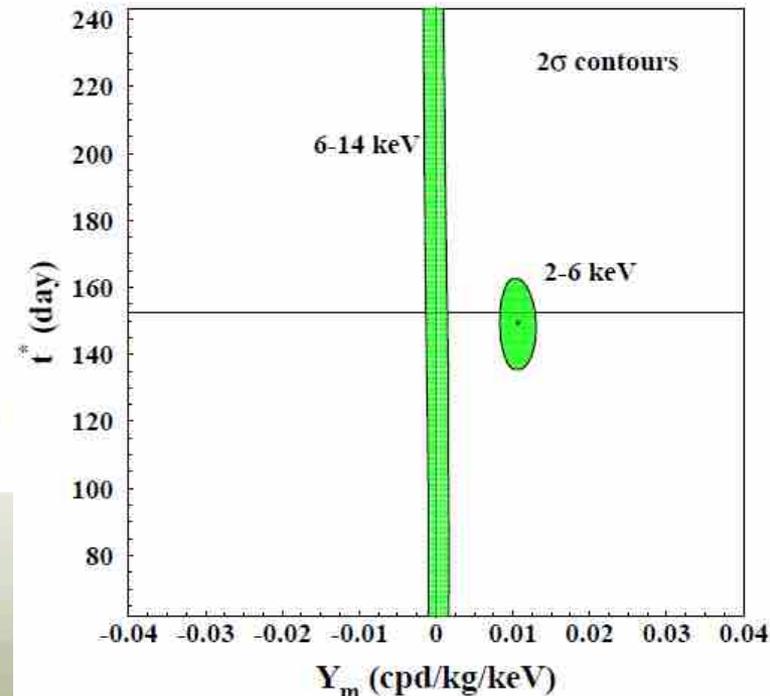
$$R(t) = S_0 + S_m \cos[\omega(t - t_0)] + Z_m \sin[\omega(t - t_0)] = S_0 + Y_m \cos[\omega(t - t^*)]$$

For Dark Matter signals:

- $|Z_m| \ll |S_m| \approx |Y_m|$
- $t^* \approx t_0 = 152.5d$
- $\omega = 2\pi/T$
- $T = 1$ year



Slight differences from 2nd June are expected in case of contributions from non thermalized DM components (as e.g. the SagDEG stream)



E (keV)	S_m (cpd/kg/keV)	Z_m (cpd/kg/keV)	Y_m (cpd/kg/keV)	t^* (day)
2-6	0.0106 ± 0.0012	-0.0006 ± 0.0012	0.0107 ± 0.0012	149.5 ± 7.0
6-14	0.0001 ± 0.0007	0.0000 ± 0.0005	0.0001 ± 0.0008	--

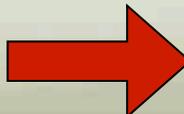
Summary of the results obtained in the additional investigations of possible systematics or side reactions – DAMA/LIBRA-phase1

(NIMA592(2008)297, EPJC56(2008)333, J. Phys. Conf. ser. 203(2010)012040, arXiv:0912.0660, S.I.F.Attn 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

- 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.

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

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

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

Modulation amplitudes

Source	$\Phi_{0,k}^{(n)}$ (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]	≈ 0 however ≪ 0.1 [2, 7, 8]	-	< 8 × 10 ⁻⁶ [2, 7, 8]	≪ 8 × 10 ⁻⁷	≪ 7 × 10 ⁻⁵
	epithermal n (eV-keV)	2 × 10 ⁻⁶ [15]	≈ 0 however ≪ 0.1 [2, 7, 8]	-	< 3 × 10 ⁻³ [2, 7, 8]	≪ 3 × 10 ⁻⁴	≪ 0.03
FAST neutrons	fission, (α, n) → n (1-10 MeV)	≈ 0.9 × 10 ⁻⁷ [17]	≈ 0 however ≪ 0.1 [2, 7, 8]	-	< 6 × 10 ⁻⁴ [2, 7, 8]	≪ 6 × 10 ⁻⁵	≪ 5 × 10 ⁻³
	μ → n from rock (> 10 MeV)	≈ 3 × 10 ⁻⁹ (see text and ref. [12])	0.0129 [23]	end of June [23, 7, 8]	≪ 7 × 10 ⁻⁴ (see text and [2, 7, 8])	≪ 9 × 10 ⁻⁶	≪ 8 × 10 ⁻⁴
	μ → n from Pb shield (> 10 MeV)	≈ 6 × 10 ⁻⁹ (see footnote 3)	0.0129 [23]	end of June [23, 7, 8]	≪ 1.4 × 10 ⁻³ (see text and footnote 3)	≪ 2 × 10 ⁻⁵	≪ 1.6 × 10 ⁻³
	ν → n (few MeV)	≈ 3 × 10 ⁻¹⁰ (see text)	0.03342 *	Jan. 4th *	≪ 7 × 10 ⁻⁵ (see text)	≪ 2 × 10 ⁻⁶	≪ 2 × 10 ⁻⁴
direct μ	$\Phi_0^{(\mu)} \approx 20 \mu \text{ m}^{-2} \text{ d}^{-1}$ [20]	0.0129 [23]	end of June [23, 7, 8]	≈ 10 ⁻⁷ [2, 7, 8]	≈ 10 ⁻⁹	≈ 10 ⁻⁷	
direct ν	$\Phi_0^{(\nu)} \approx 6 \times 10^{10} \nu \text{ cm}^{-2} \text{ s}^{-1}$ [26]	0.03342 *	Jan. 4th *	≈ 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) 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.

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

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

Neutralino as LSP in various SUSY theories

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

a heavy ν of the 4-th family

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

WIMP with preferred inelastic scattering

Mirror Dark Matter

Light Dark Matter

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

Sterile neutrino

Self interacting Dark Matter

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

Elementary Black holes such as the Daemons

Kaluza Klein particles

... and more

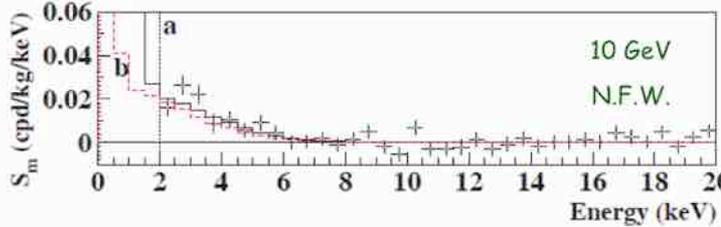


Model-independent evidence by DAMA/NaI and DAMA/LIBRA

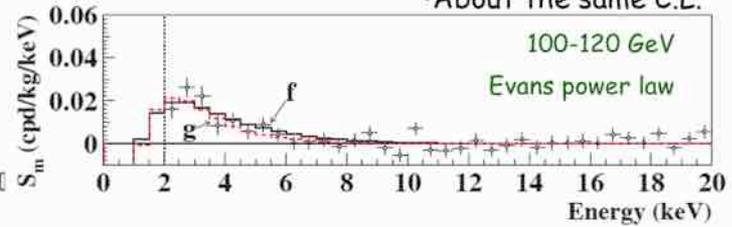
well compatible with several candidates in many astrophysical, nuclear and particle physics scenarios

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

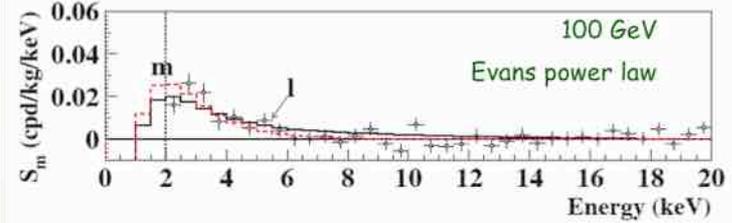
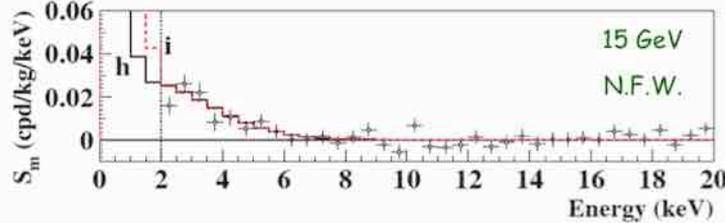
WIMP: SI



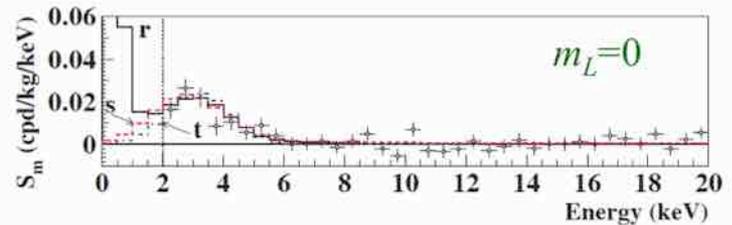
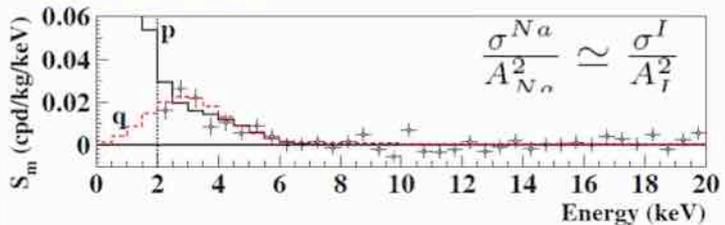
•Not best fit
•About the same C.L.



WIMP: SI & SD $\theta = 2.435$



LDM, bosonic DM



Compatibility with several candidates;
other ones are open

About interpretation

See e.g.: Riv.N.Cim.26 n.1(2003)1, JMPD13(2004)2127, EPJC47(2006)263, IJMPA21(2006)1445, EPJC56(2008)333, PRD84(2011)055014, IJMPA28(2013)1330022

...and experimental aspects...

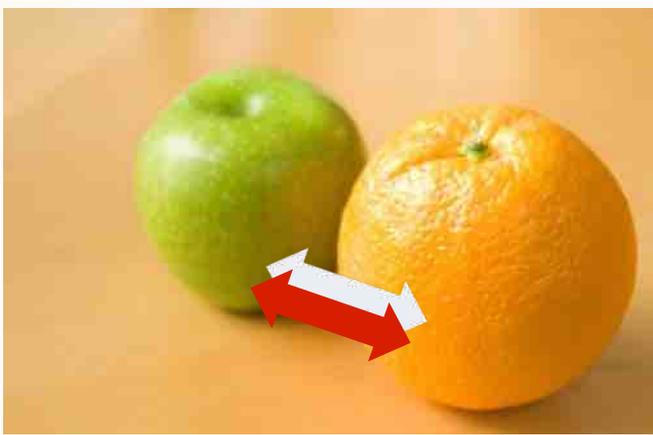
- Exposures
- Energy threshold
- Detector response (phe/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities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

...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?
- ...

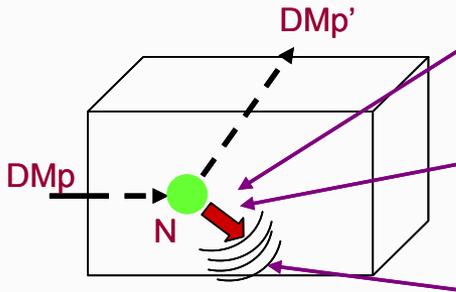
Uncertainty in experimental parameters, as well as necessary assumptions on various related astrophysical, nuclear and particle-physics aspects, affect all the results at various extent, both in terms of exclusion plots and in terms of allowed regions/volumes. Thus comparisons with a fixed set of assumptions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

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



... an example in literature...

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

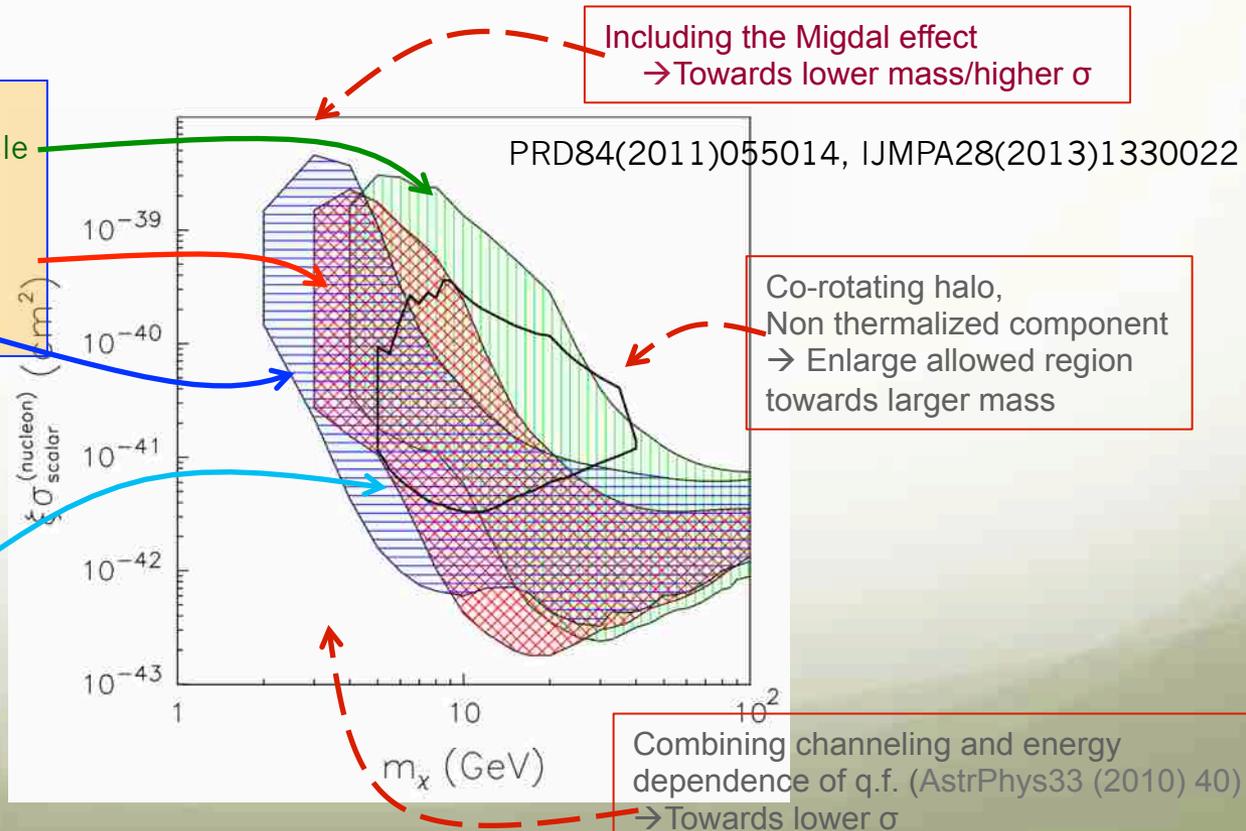


Regions in the nucleon cross section vs DM particle mass plane

- 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 a particular set of astrophysical, nuclear and particle Physics assumptions without (green), with (blue) channeling, with energy-dependent Quenching Factors (red); 7.5σ C.L.

CoGeNT; qf at fixed assumed value 1.64σ C.L.



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

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

... and much more considering experimental and theoretical uncertainties

Other examples

DMp with preferred inelastic interaction:
 $\chi^- + N \rightarrow \chi^+ + N$

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

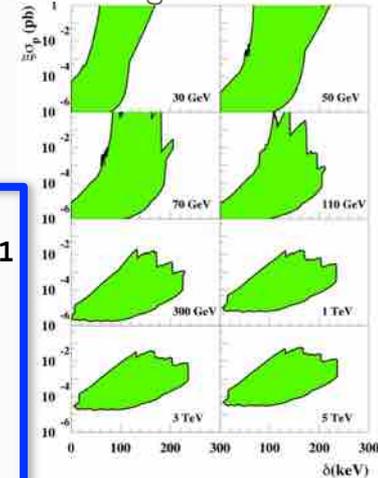
$$\frac{1}{2} \mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

iDM interaction on TI 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 $A \sim 205$, 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.

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



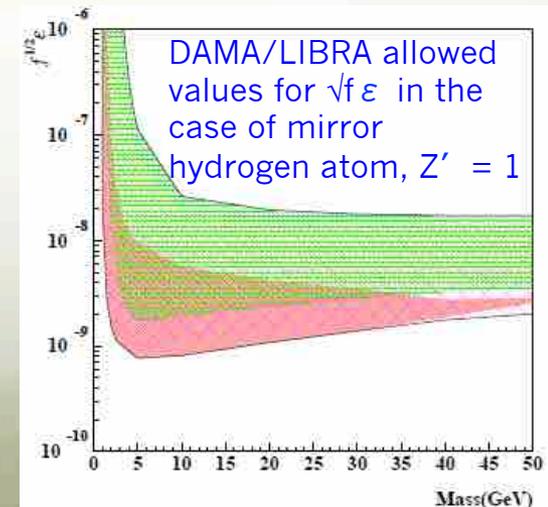
Fund. Phys. 40(2010)900

Mirror Dark Matter

Asymmetric mirror matter: mirror parity spontaneously broken \Rightarrow 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.

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



Perspectives for the future

Other signatures?

- *Diurnal effects*
- *Second order effects*
- *Shadow effects*
- *Directionality*
- *...*

Diurnal effects in DAMA/LIBRA-phase1

EPJC 74 (2014) 2827

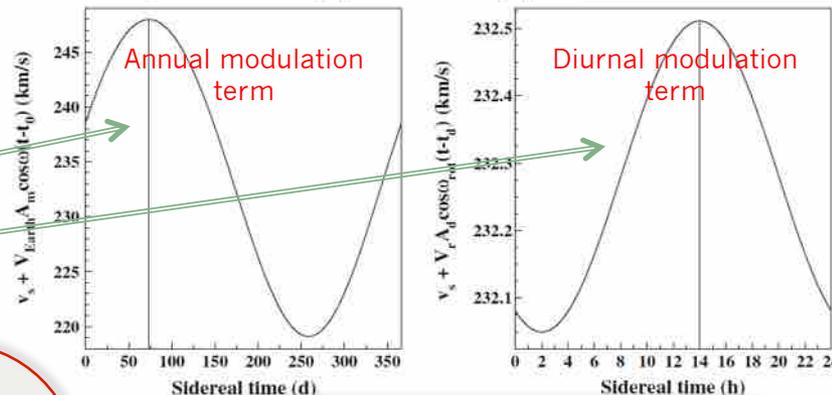
A diurnal effect with the sidereal time is expected for DM because of Earth rotation

Velocity of the detector in the terrestrial laboratory: $\vec{v}_{lab}(t) = \vec{v}_{LSR} + \vec{v}_{\odot} + \vec{v}_{rev}(t) + \vec{v}_{rot}(t)$,

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 at LNGS

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



Expected signal counting rate in a given k-th energy bin:

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

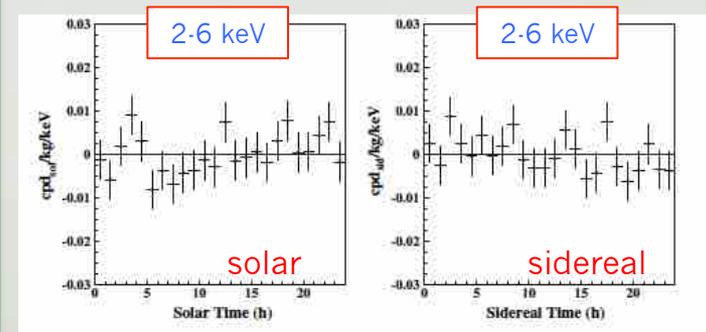
The ratio R_{dy} is a model independent constant:

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

- 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 $\approx 1.5 \times 10^{-4}$ cpd/kg/keV.
- When fitting the *single-hit* residuals with a cosine function with period fixed at 24 h and phase at 14 h: all the diurnal modulation amplitudes A_d are compatible with zero at the present level of sensitivity.

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

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



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

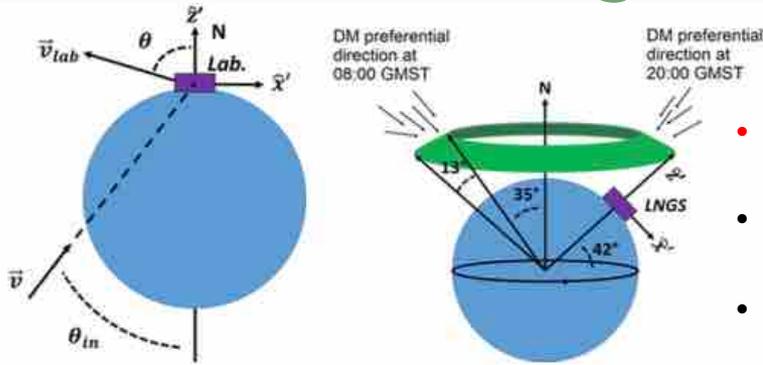
larger exposure DAMA/LIBRA-phase2 (+lower energy threshold) offers increased sensitivity to such an effect

Other signatures?

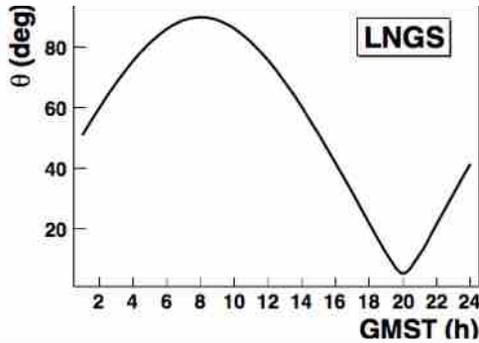
- *Diurnal effects*
- *Second order effects*
- *Shadow effects*
- *Directionality*
- *...*

Earth shadowing effect with DAMA/LIBRA-phase1

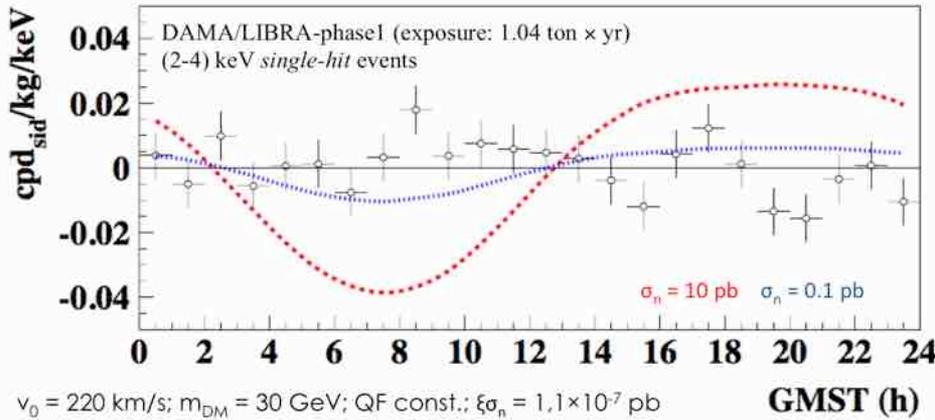
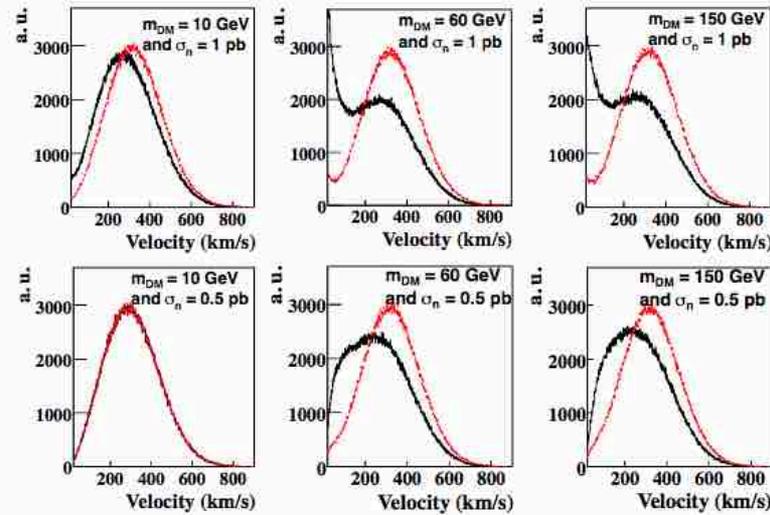
EPJC75(2015)239



- **Earth Shadow Effect** could be expected for DM candidate particles inducing nuclear recoils
- can be pointed out only for candidates with high cross-section with ordinary matter (low DM local density)
- would be induced by the variation during the day of the Earth thickness crossed by the DM particle in order to reach the experimental set-up



- DM particles crossing Earth lose their energy
- DM velocity distribution observed in the laboratory frame is modified as function of time (**GMST 8:00 black**; **GMST 20:00 red**)

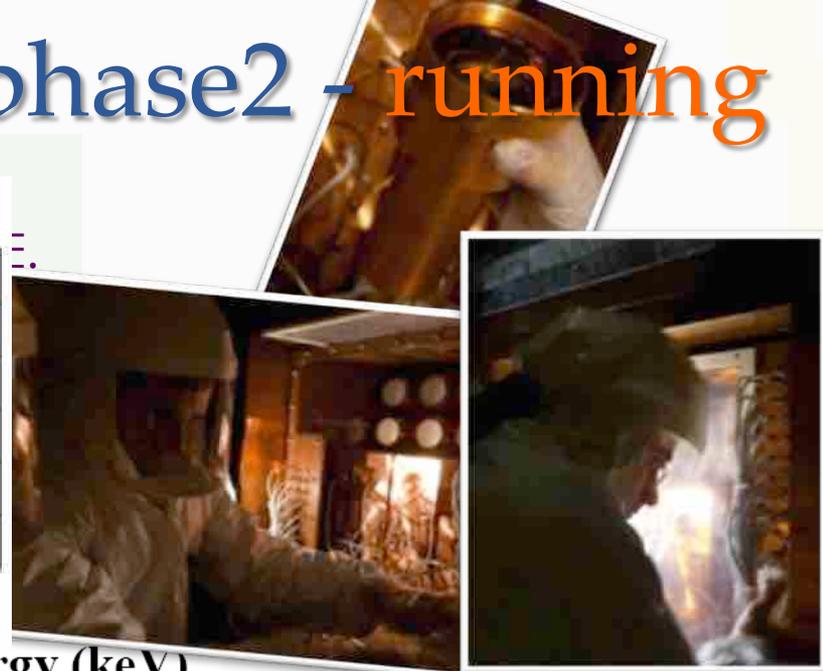
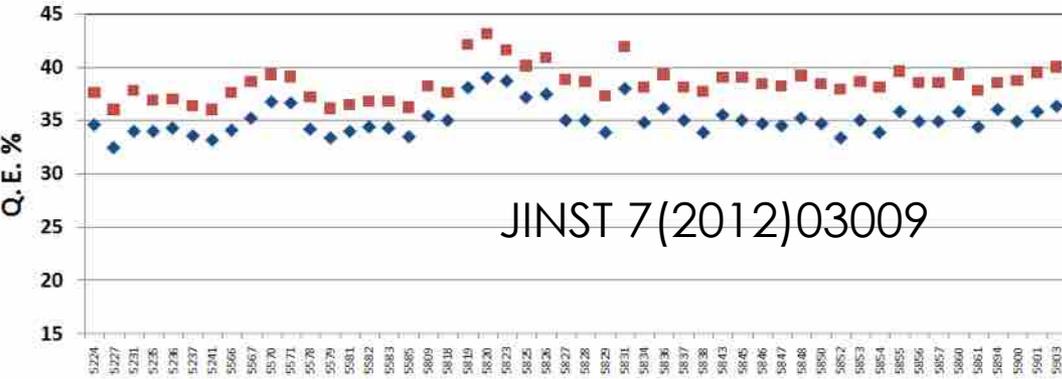


Taking into account the DAMA/LIBRA DM annual modulation result, allowed regions in the ξ vs σ_n plane for each m_{DM} .

DAMA/LIBRA phase2 - running

Quantum Efficiency features

■ Q.E. @ peak (%) ◆ Q.E. @ 420 nm (%)



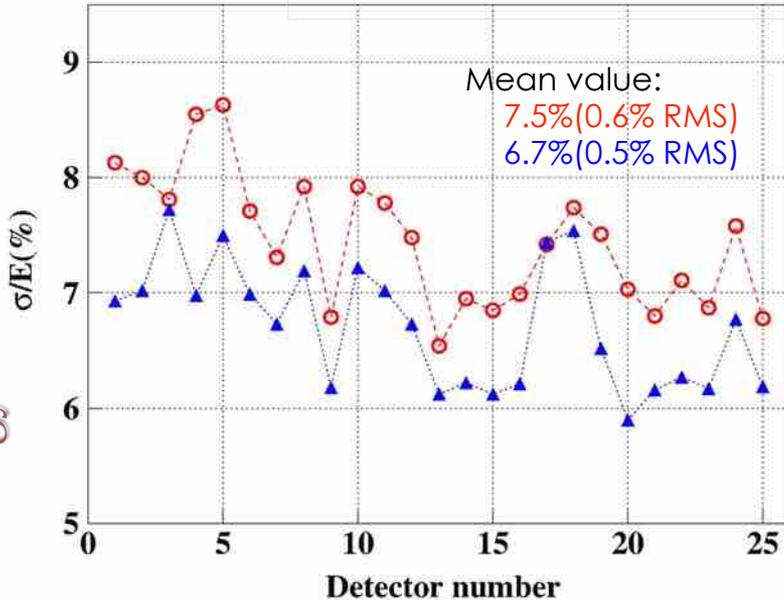
Residual
Contamination

Serial number
The limits are at 90% C.L.

Energy (keV)

PMT	Time (s)	Mass (kg)	²²⁶ Ra (Bq/kg)	²¹⁰ Pb (Bq/kg)	²³⁵ U (mBq/kg)	²²⁸ Ra (Bq/kg)	²³² Th (mBq/kg)	⁴⁰ K (Bq/kg)	¹³⁷ Cs (mBq/kg)	⁶⁰ Co (mBq/kg)
Average			0.43	-	47	0.12	83	0.54	-	-
Standard deviation			0.06	-	16	0.02	17	0.16	-	-

Energy resolution



σ/E @ 59.5 keV for each detector with new PMTs with higher quantum efficiency (blue points) and with previous PMT EMI-Electron Tube (red points).

The light responses

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

- To study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects, and to investigate second order effects
- Special data taking for *other rare processes*

Features of the DM signal

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

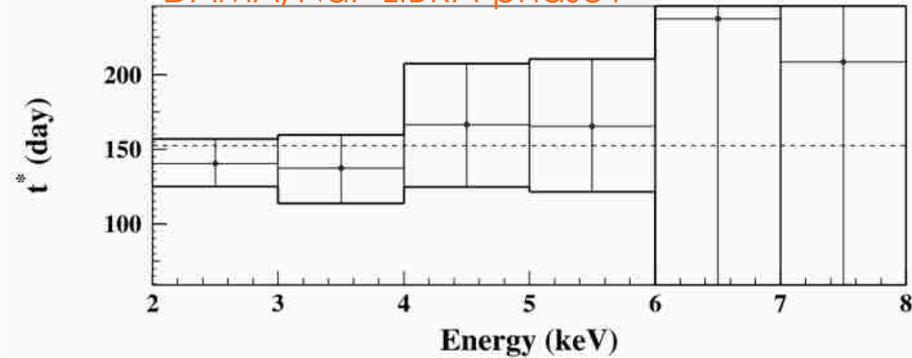
High exposure and lower energy threshold can allow further investigation on:

- the nature of the DM candidates
- possible diurnal effects on the sidereal time
- astrophysical models

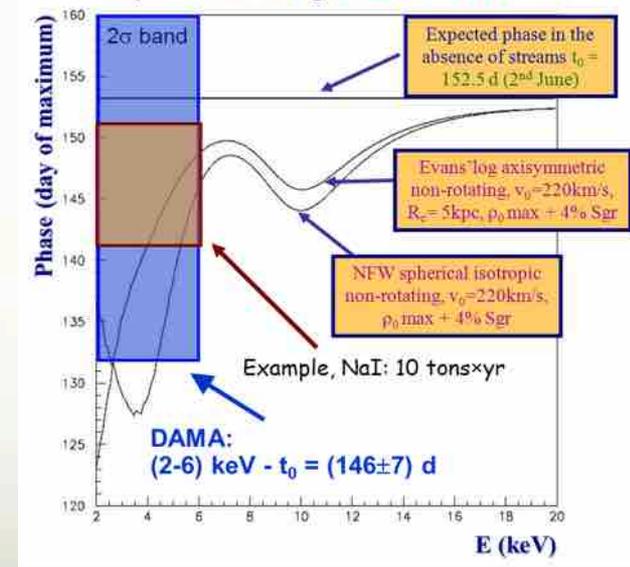
The annual modulation phase depends on :

- Presence of **streams** (as SagDEG and Canis Major) in the Galaxy
- Presence of **caustics**
- Effects of gravitational **focusing of the Sun**

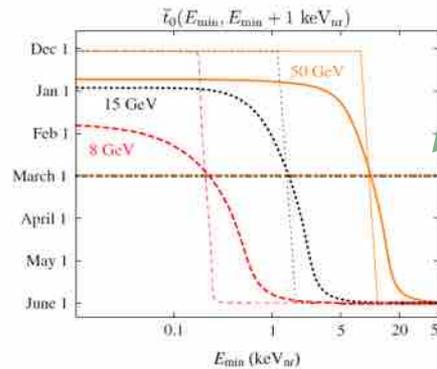
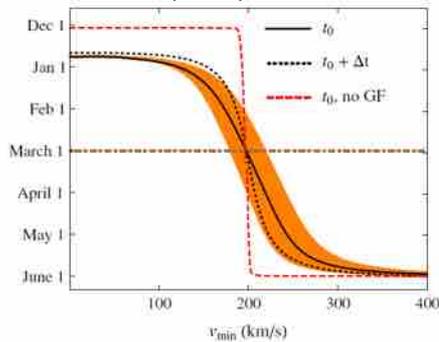
DAMA/NaI+LIBRA-phase1



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 running with lower energy threshold

+ further possible improvements (DAMA/LIBRA-phase3) and **DAMA/1ton**

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)



Other signatures?

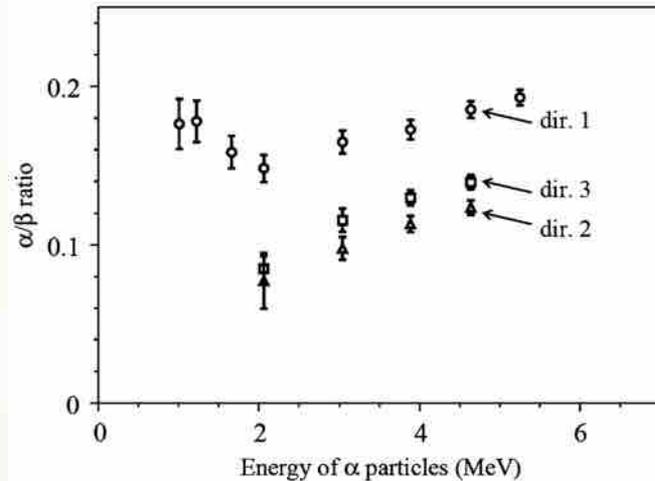
- *Diurnal effects*
- *Second order effects*
- *Shadow effects*
- *Directionality*
- *...*

Directionality technique with crystals

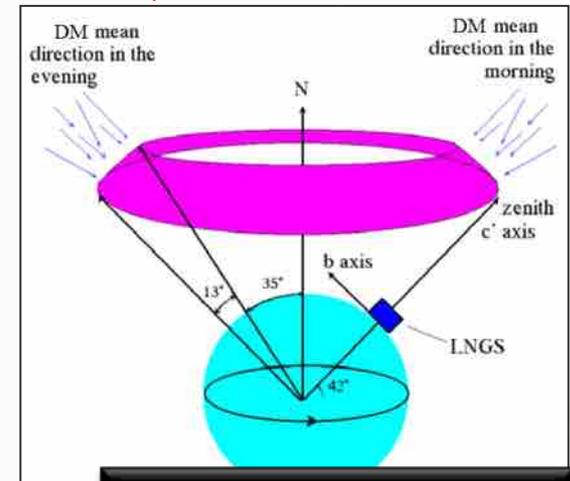
N. Cim. C15(1992)475, EPJC28(2003)203, EPJC73(2013)2276

- Only for candidates inducing just recoils
- Identification of the Dark Matter particles by exploiting the non-isotropic recoil distribution correlated to the Earth velocity

The ADAMO project: Study of the directionality approach with ZnWO_4 anisotropic detectors



Nuclear recoils are expected to be strongly correlated with the DM impinging direction. This effect can be pointed out through the study of the variation in the response of anisotropic scintillation detectors during sidereal day.



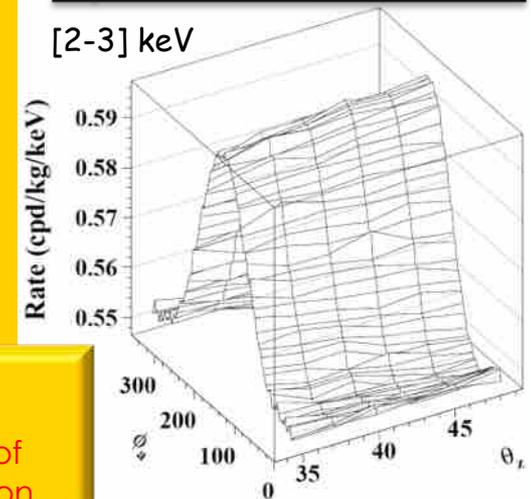
$$\sigma_p = 5 \times 10^{-5} \text{ pb}, m_{\text{DM}} = 50 \text{ GeV}$$

The light output and the pulse shape of ZnWO_4 detectors depend on the direction of the impinging particles with respect to the crystal axes.

Both these anisotropic features can provide two independent ways to exploit the directionality approach.

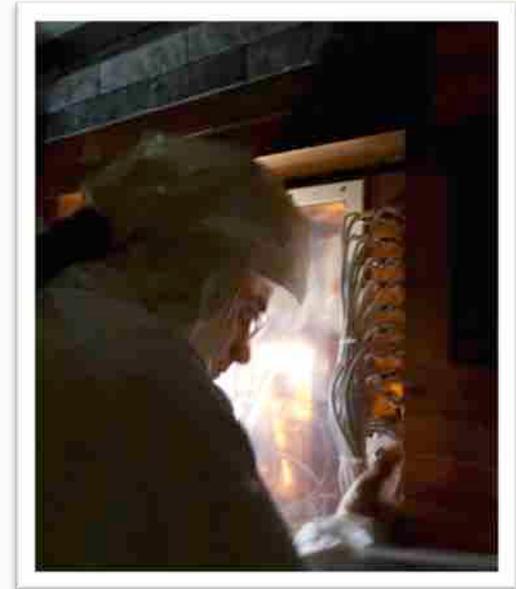
These and other competitive characteristics of ZnWO_4 detectors could permit to reach sensitivity comparable with that of the DAMA/LIBRA positive result.

Example (for a given model framework) of the expected counting rate as a function of the detector velocity direction.



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 R&D in progress**
- R&D for a possible DAMA/1ton set-up, proposed by DAMA since 1996, **continuing**
- Study of ZnWO_4 scintillator for exploiting directionality technique **in progress**