DAMA/LIBRA-phase1 results, perspectives of phase-2 and beyond

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DAMA set-ups

an observatory for rare processes @ LNGS

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

Collaboration:

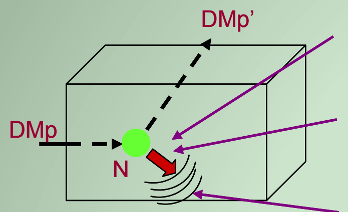
Roma Tor Vergata, Roma La Sapienza, LNGS, IHEP/Beijing
+ by-products and small scale expts.: INR-Kiev
+ neutron meas.: ENEA-Frascati
+ in some studies on ββ decays (DST-MAE project): IIT Kharagpur, India

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 → W* + N**

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

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

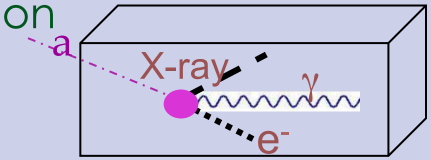
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

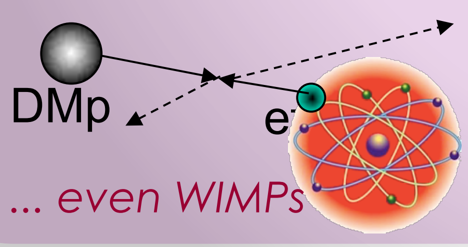
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

  → detection of e.m. radiation

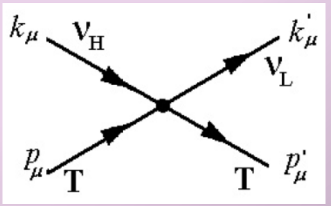


... even WIMPs

- 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 ...

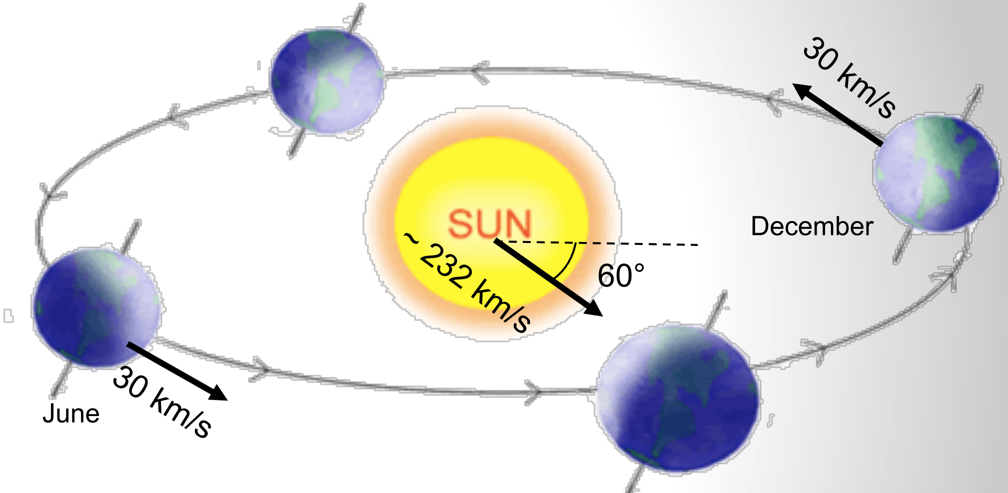
The **annual modulation**: a model independent signature for the investigation of DM particles

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) 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



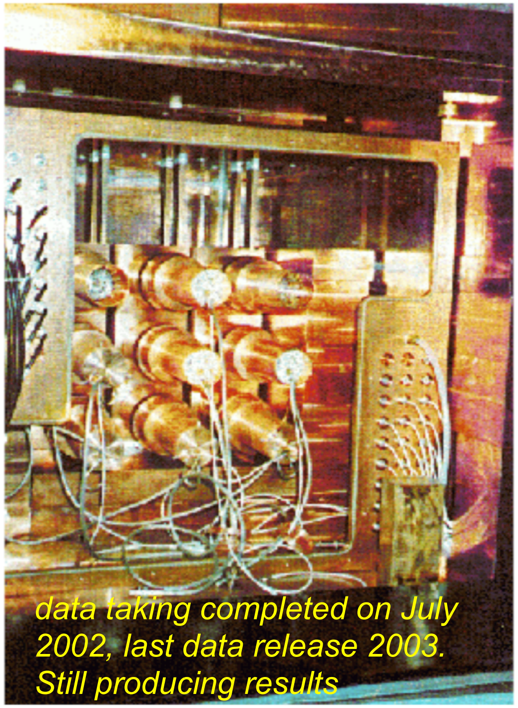
$$v_{\oplus}(t) = v_{sun} + v_{orb} \cos\gamma \cos[\omega(t-t_0)]$$

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

the DM annual modulation signature has a different origin and peculiarities (e.g. the phase) than 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 — 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

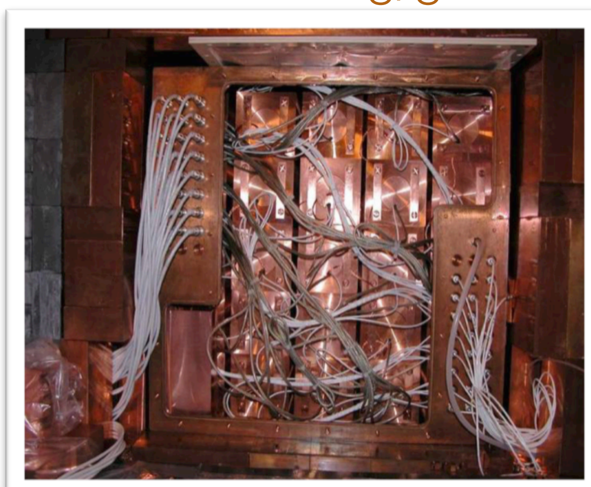
Model independent evidence of a particle DM component in the galactic halo at 6.3σ C.L.

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, 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, arXiv:1505.05336**
- 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 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 on Oct./Nov. 2010: replacement of all the PMTs with higher Q.E. ones from dedicated developments

  Goal: lowering the software energy threshold

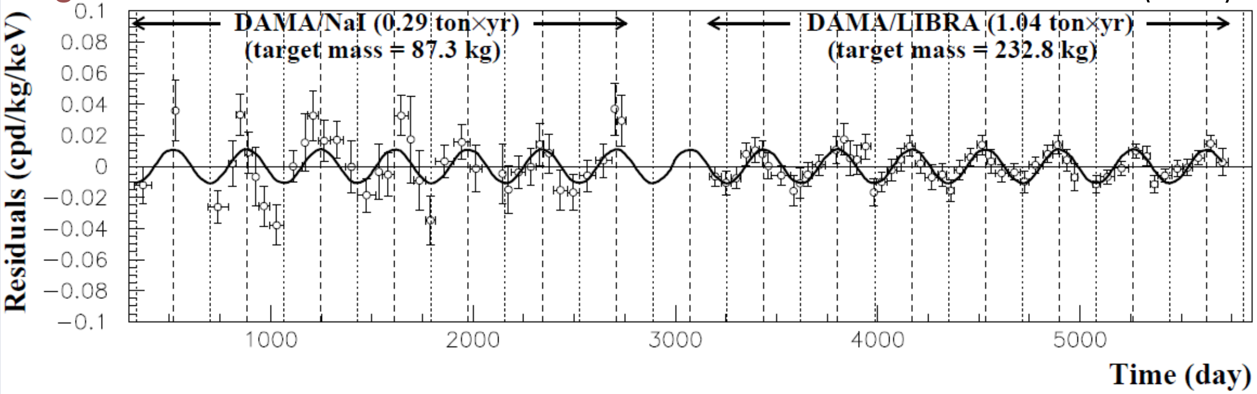
- Fall 2012: new preamplifiers installed + special trigger modules. Other new components in the electronic chain in development

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



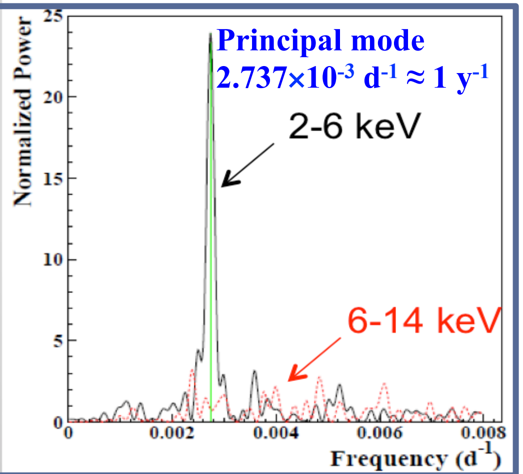
continuous line: t_0 = 152.5 d, T =1.0 y

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

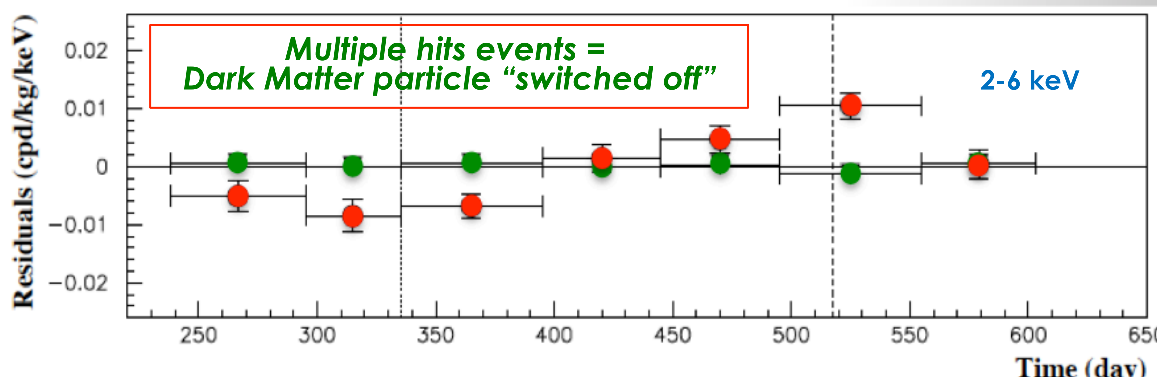
Absence of modulation? No
χ^2/dof=154/87 P(A=0) = 1.3×10^{-5}

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



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±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

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

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

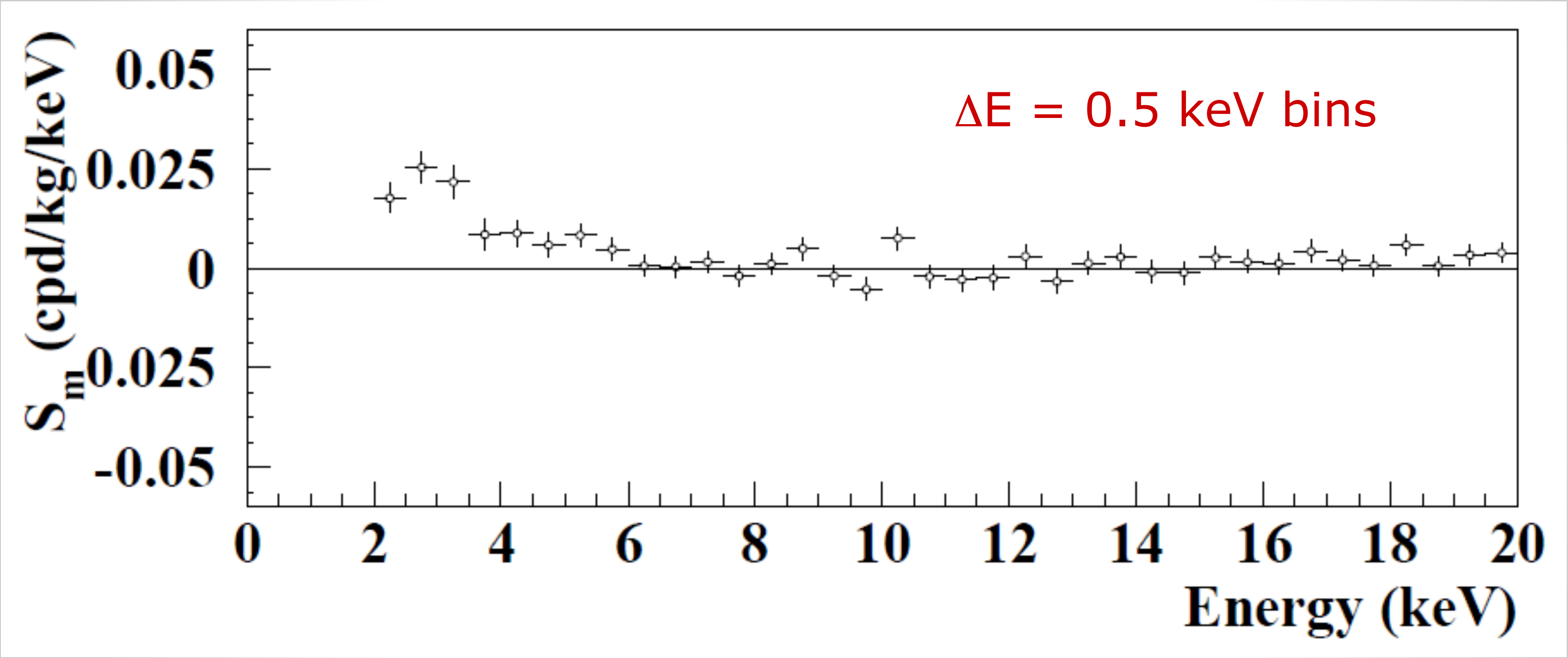
Energy distribution of the modulation amplitudes

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

$T=2\pi/\omega=1$ yr $\quad t_0= 152.5$ day

DAMA/NaI + DAMA/LIBRA-phase1

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



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%)

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)

Source	Main comment	Cautious upper limit (90%C.L.)
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	**<2.5×10^{-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 $\times10^{-4}$ 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	**<3×10^{-5} cpd/kg/keV**

+ they cannot satisfy all the requirements of annual modulation signature

Thus, they cannot mimic the observed annual modulation effect

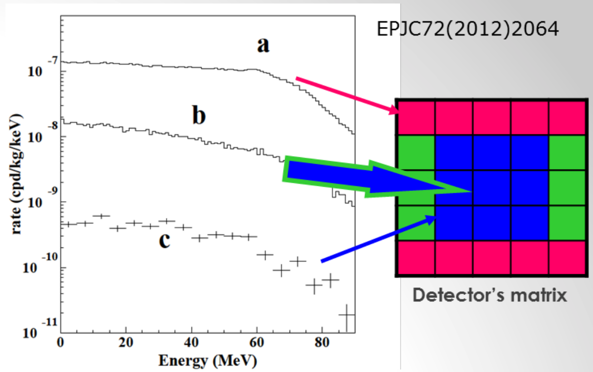
No role for μ in DAMA annual modulation result

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

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

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

EPJC72(2012)2064



MonteCarlo simulation

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

- Φ_μ @ LNGS ≈ 20 μ $m^{-2}d^{-1}$ (±1.5% modulated)
- Annual modulation amplitude at low energy due to μ **modulation**:

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

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

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

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

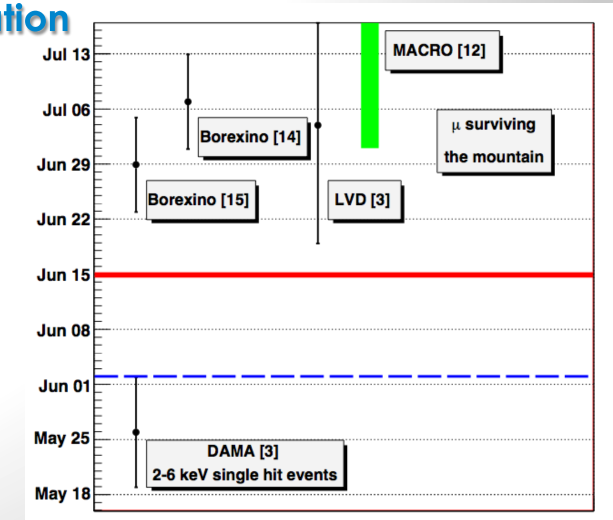
✓ **Inconsistency of the phase between DAMA signal and μ modulation**

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

The DAMA phase: May 26 ± 7 days (stable over 13 years)

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

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



For many others arguments EPJC72(2012)2064

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

Self interacting Dark Matter

Mirror Dark Matter

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

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

Elementary Black holes such as the Daemons

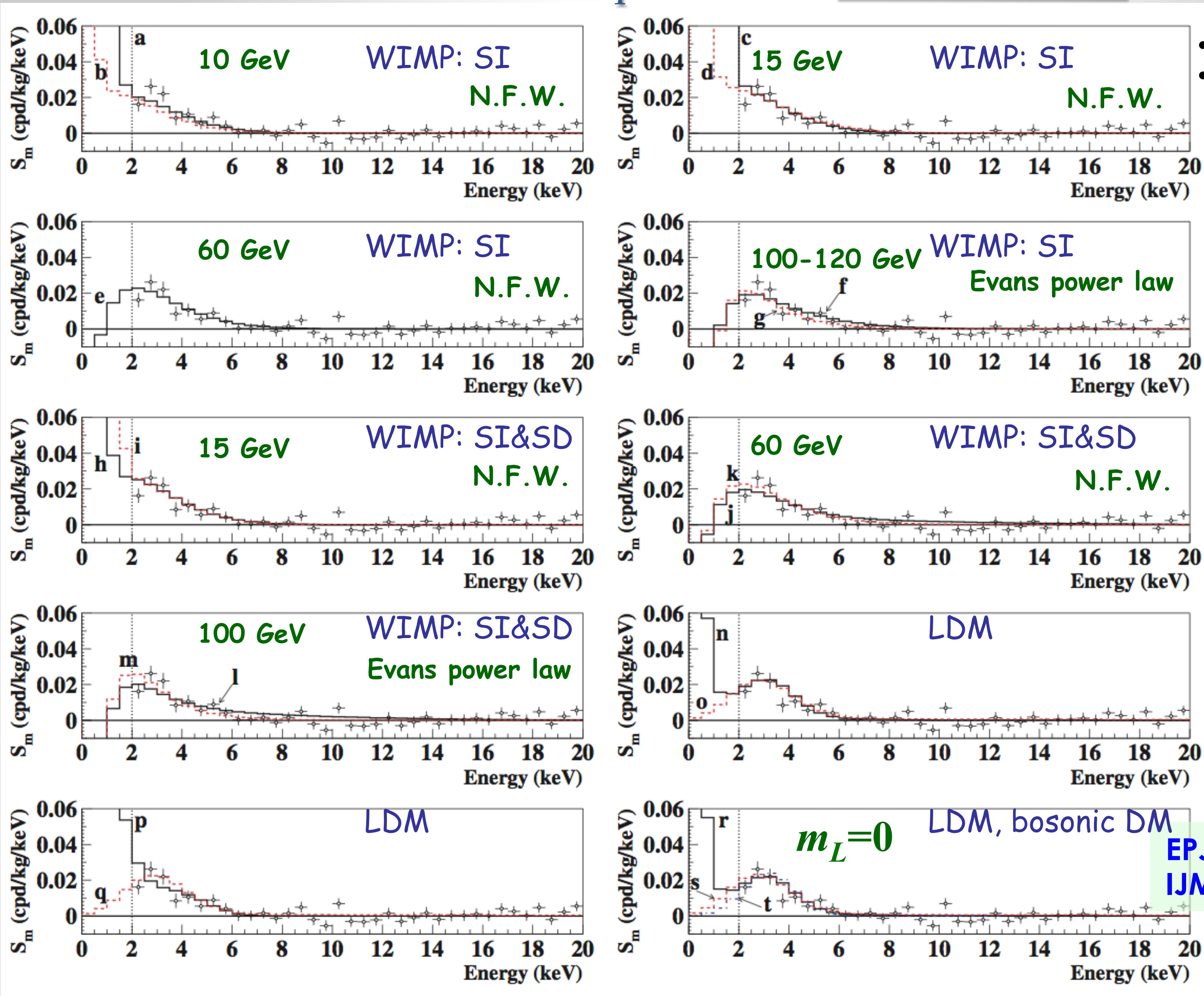
Kaluza Klein particles

… and more

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

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

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

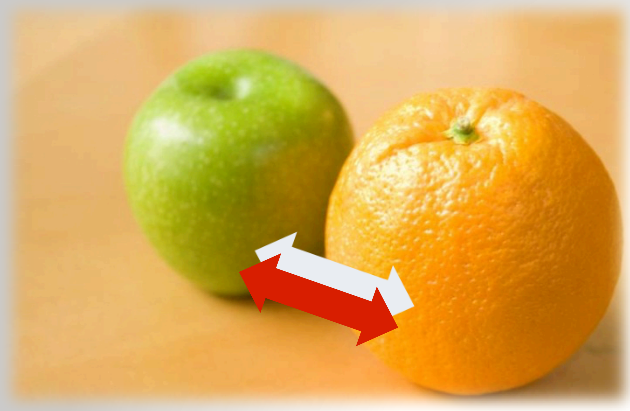


- Not best fit
- About the same C.L.

θ = 2.435

EPJC56(2008)333
IJMPA28(2013)1330022

Compatibility with several candidates; other ones are open



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
- …

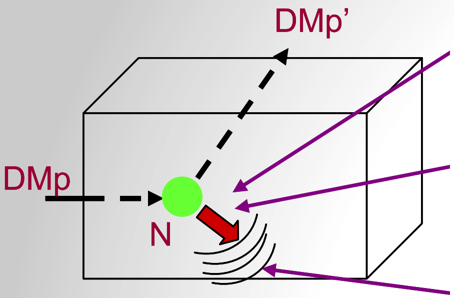
Uncertainty in experimental parameters, as well as necessary assumptions on various related astrophysical, nuclear and particle-physics aspects, affect all the results at various extent, both in terms of exclusion plots and in terms of allowed regions/volumes. Thus comparisons with a fixed set of assumptions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

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

... an example in literature...

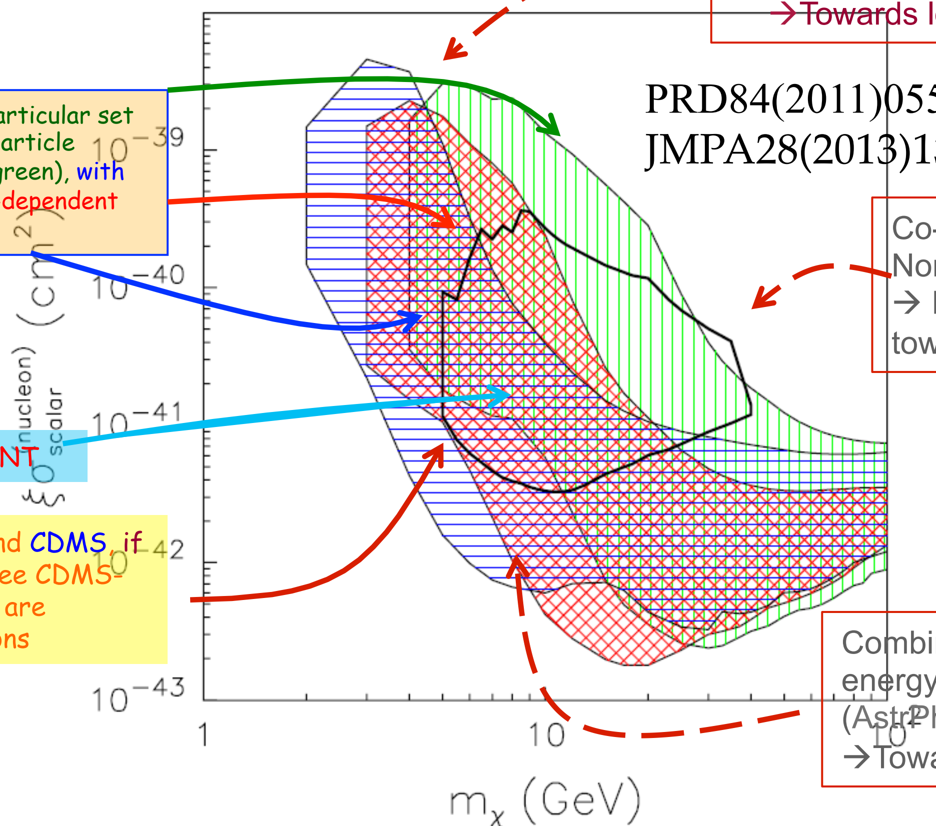
Case of DM particles inducing elastic scatterings on target-nuclei

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.

Including the Migdal effect
→Towards lower mass/higher σ



PRD84(2011)055014
JMPA28(2013)1330022)

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)

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

CoGeNT

Compatibility also with CRESST and CDMS, if the two CDMS-Ge events, the three CDMS-Si events and the CRESST events are interpreted as relic DM interactions

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

... many other interpretations available in literature

Dark Matter Diurnal Modulation

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

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

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

detector velocity

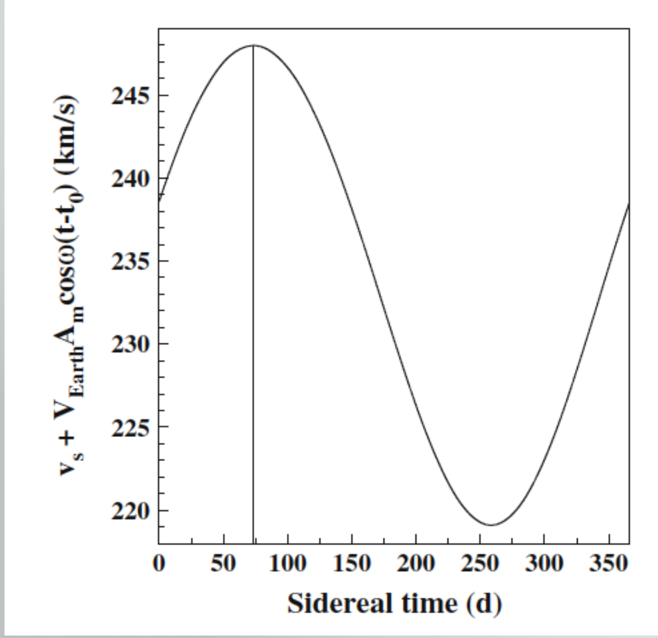
It can be written:

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

Annual modulation term:

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

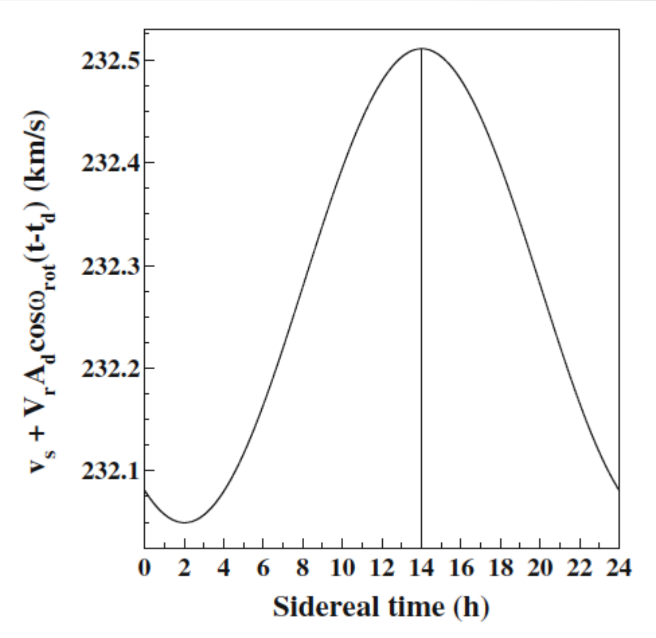
- V_{Earth} is the orbital velocity of the Earth ≈ 30 km/s
- $B_m \approx 0.489$
- $t_0 \approx t_{equinox}$ + 73.25 days ≈ June 2



Diurnal modulation term:

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

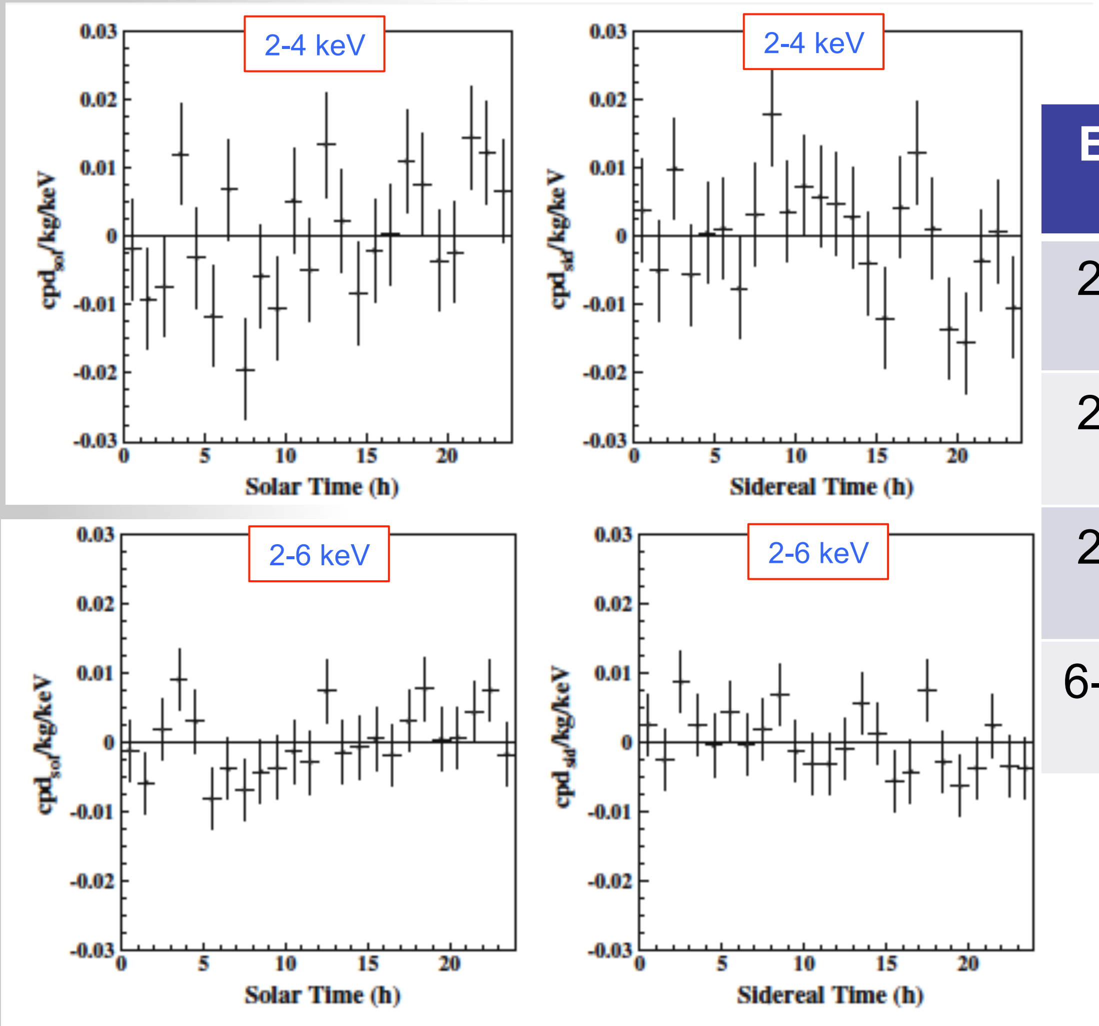
- V_r is the rotational velocity of the Earth at the given latitude (for LNGS ≈ 0.3435 km/s)
- $B_d \approx 0.671$
- $t_d \approx 14.02$ *h (at LNGS)*



Diurnal effect in DAMA/LIBRA–phase1

EPJC74(2014)2827

- 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	Sideral
Energy	**χ^2/d.o.f (P)**	**χ^2/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%)

Run-Test gives similar results

Diurnal variation (sideral and solar) excluded at 95% C.L.

Investigating diurnal modulation in DAMA/LIBRA-phase1

EPJC74(2014)2827

Expected modulation amplitude

- Annual modulation amplitude:

$$S_m = \left[\frac{\partial S_k}{\partial v_{lab}}\right]_{v_s} V_{Earth} B_m$$

- Diurnal modulation amplitude:

$$S_d = \left[\frac{\partial S_k}{\partial v_{lab}}\right]_{v_s} V_r B_d$$

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

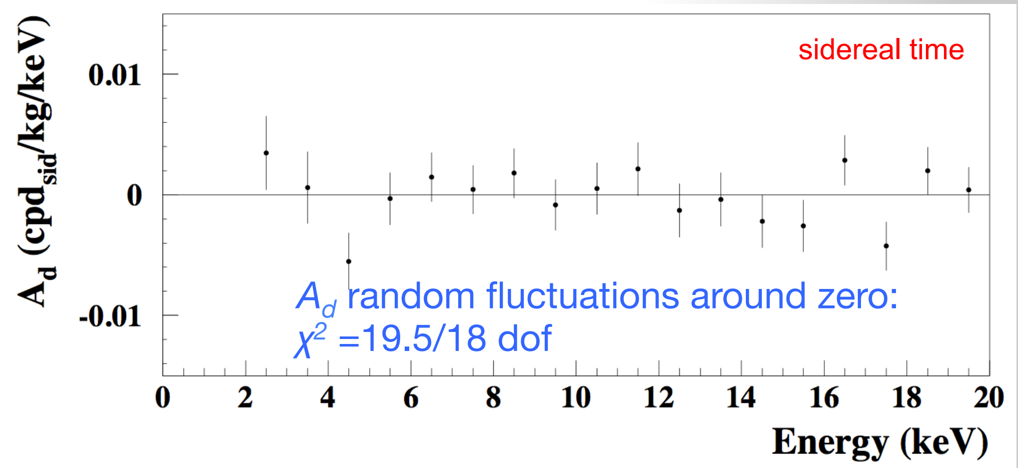
$$R_{dy} = \frac{S_d}{S_m} = \frac{V_r B_d}{V_{Earth} B_m} \simeq 0.016$$

@ 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:

≃1.5×10^{-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



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%

$\boxed{A_d^{(2\text{-}6\ kev)} < 1.2\times10^{-3}\ \text{cpd/kg/keV}\ \ (90\%\text{CL})}$

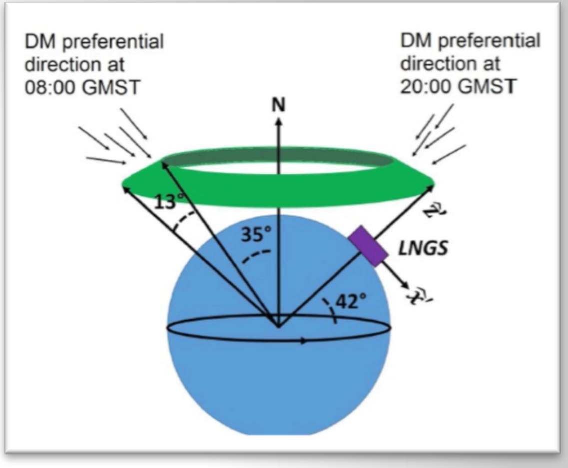
Present experimental sensitivity lower than the diurnal modulation amplitude expected from the DAMA/LIBRA–phase1 observed effect.

DAMA/LIBRA–phase2 will offer increased sensitivity

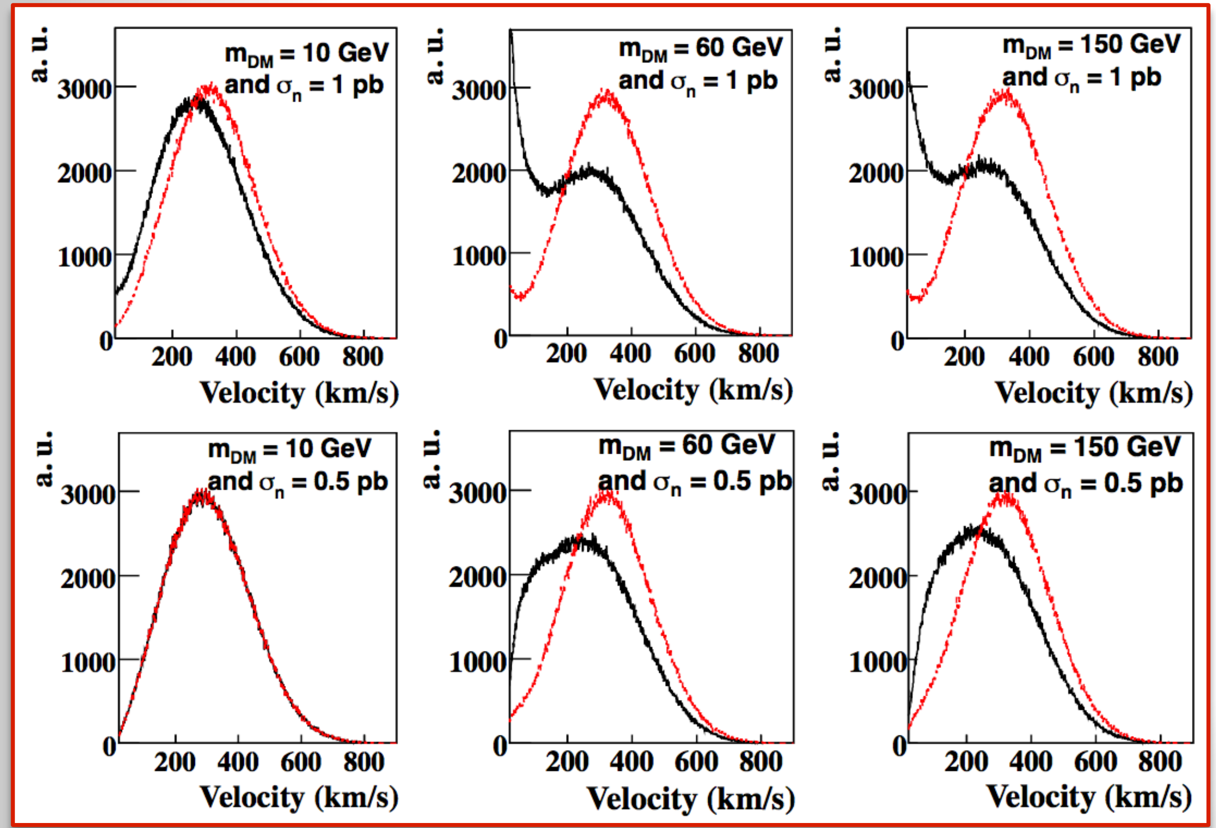
Investigation of Earth Shadow Effect

arXiv:1505.05336

- **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



DM particles crossing Earth lose their energy → **DM velocity distribution observed in the laboratory frame is distorted as function of time**



At LNGS:

20:00 GMST
→ Minimum thickness crossed
→ Maximum counting rate

08:00 GMST
→ maximum thickness crossed
→ Minimum counting rate

Investigation of Earth Shadow Effect

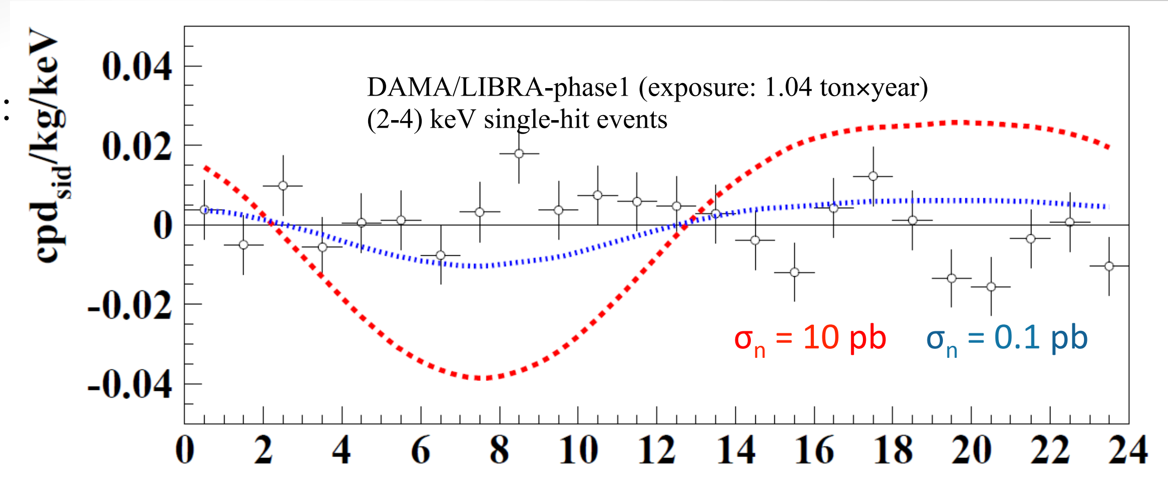
arXiv:1505.05336

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

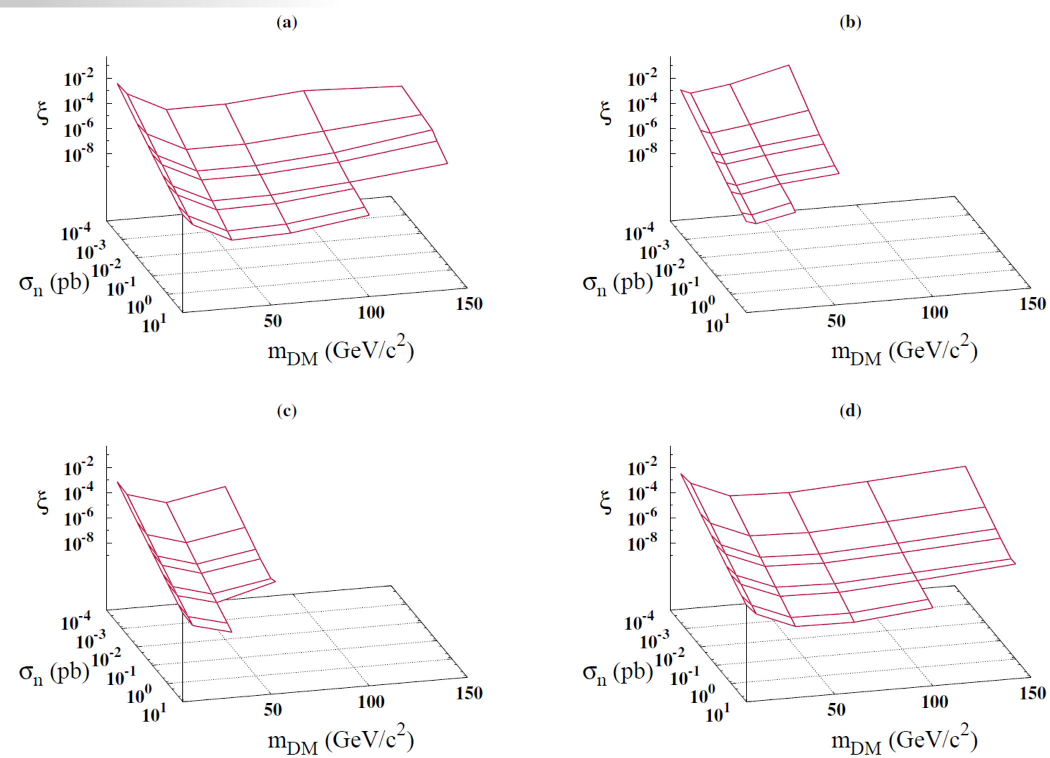
$$S_{d,sh}(t) = \xi\sigma_n \, S'_{d,sh}(t)$$

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



v_0 = 220 km/s; m_{DM} = 30 GeV; QF const.; $\xi\sigma_n$ = 1,1×10^{-7} pb



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

In these examples:
Isothermal halo model with v_0=220 km/s and v_{esc}=650 km/s

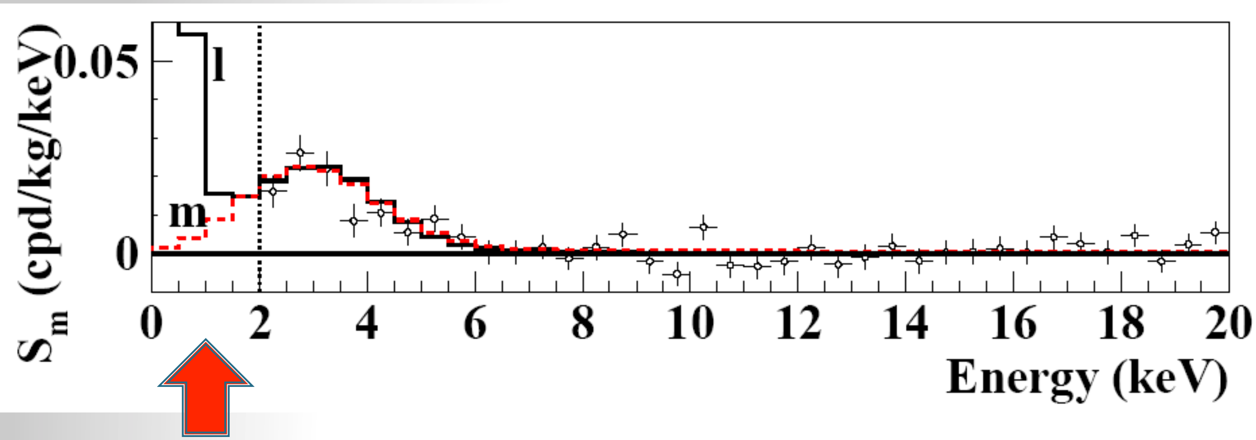
a) QF const. without channeling
b) QF const. including channeling
c) QF depending on energy
d) QF depending on energy renormalized to DAMA/LIBRA values

Red surface: 95% C.L. allowed mean value (uncertanties ± 30%)

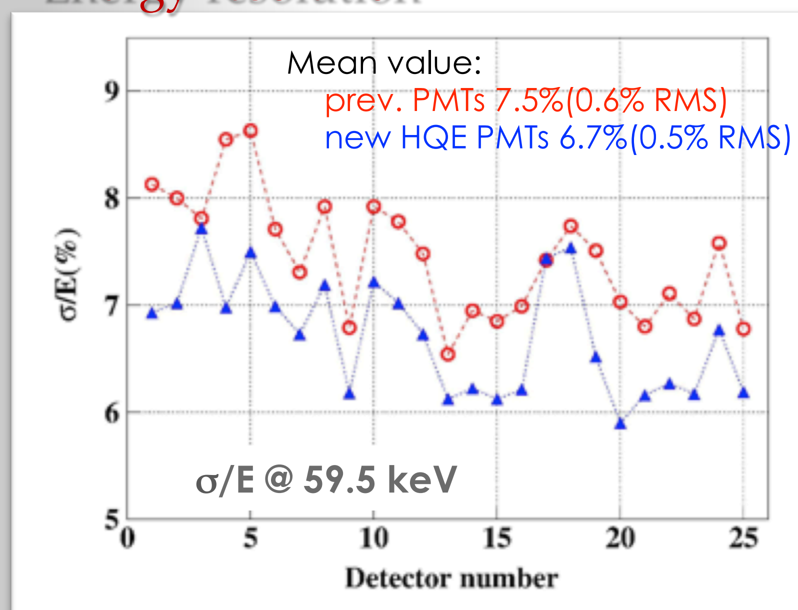
DAMA/LIBRA phase 2 - running

Second upgrade on end of 2010: JINST 7(2012)03009

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



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

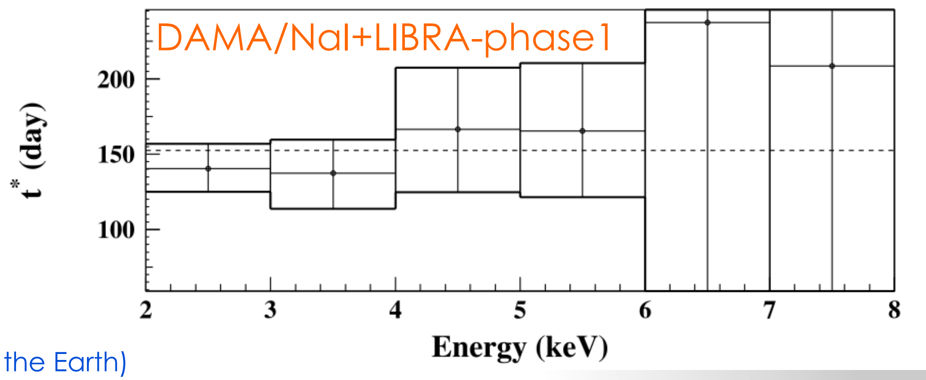
New PMTs: up to 10 ph.e./keV

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

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

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

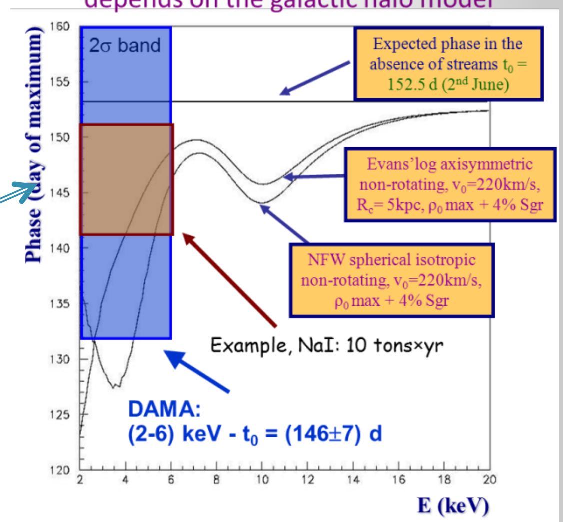
- the nature of the DM candidates
  - ✓ to disentangle among the different astrophysical, nuclear and particle physics models (nature of the candidate, couplings, inelastic interaction, form factors, spin-factors …)
  - ✓ scaling laws and cross sections
  - ✓ multi-component DM particles halo?
- possible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

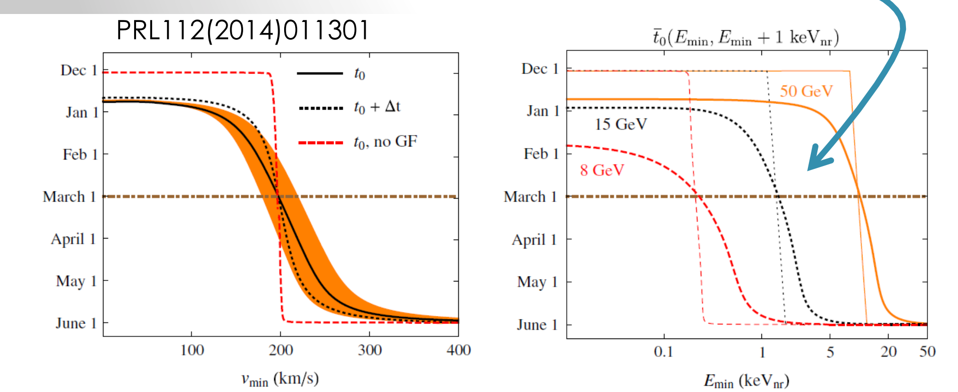


The annual modulation phase depends on :

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

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





A step towards such investigations:

➔**DAMA/LIBRA-phase2**

with lower energy threshold and larger exposure

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.

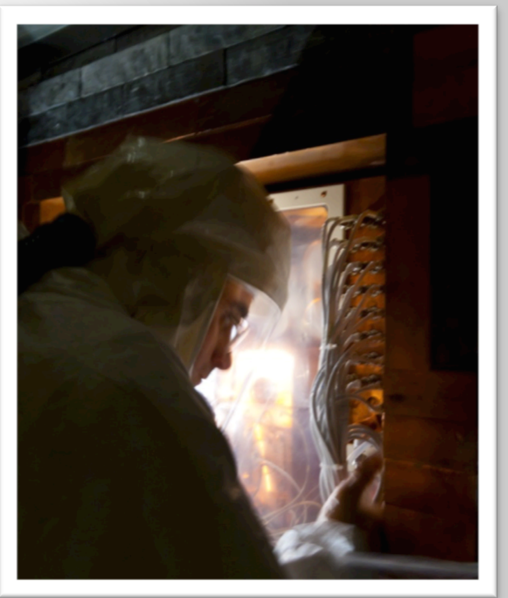
The presently-reached PMTs features, but not for the same PMT mod.:

- 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)

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 × yr)
- Modulation parameters determined with better precision
- New investigation on different peculiarities of the DM signal exploited
- 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