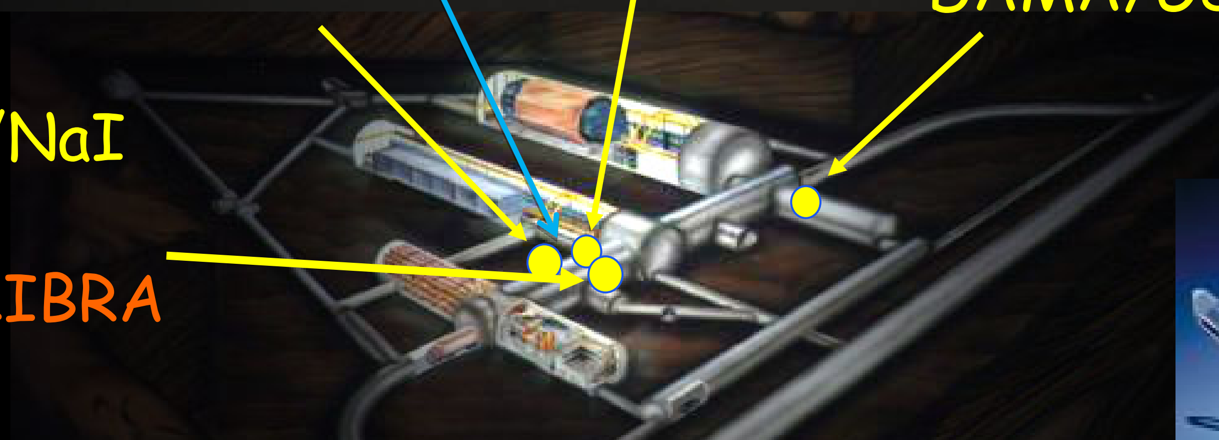
# Roma2,Roma1,LNGS,IHEP/Beijing

+ by-products and small scale expts.: INR-Kiev and others
+ neutron meas.: ENEA-Frascati
+ in some studies on ββ decays (DST-MAE project): IIT Kharagpur, India

## DARK MATTER PARTICLES IN THE GALACTIC HALO




R. Bernabei - University & INFN - Roma Tor Vergata

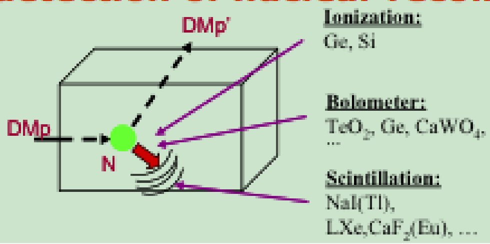
Summary for Cosmovia - July 2014

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 Two mass states $\chi$+ , $\chi$- with $\delta$ mass splitting**

  → **Kinematical constraint for the inelastic scattering of $\chi$- 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**

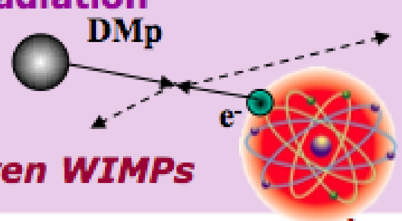
  → **detection of recoil nuclei + e.m. radiation**

- **Conversion of particle into e.m. radiation**

  → **detection of $\gamma$, X-rays, $e^-$**

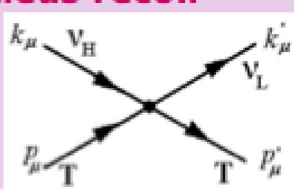

- **Interaction only on atomic electrons**

  → **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 $\nu$*

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

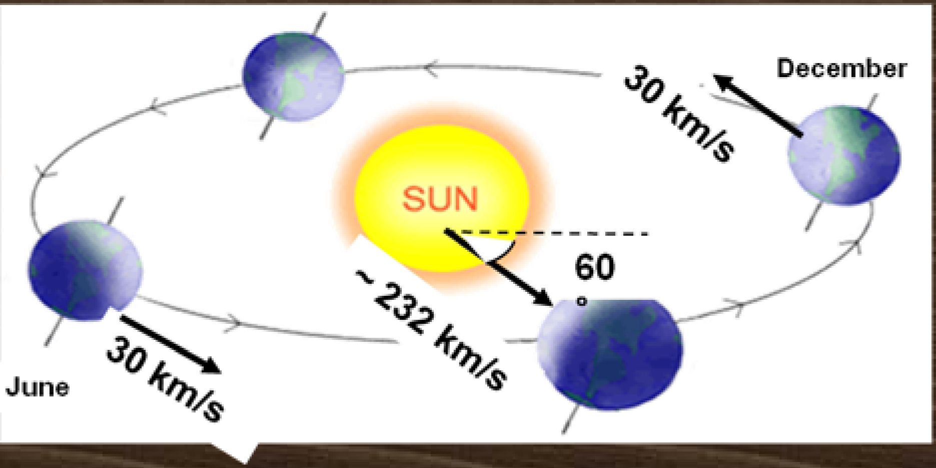
**... also other possibilities ...**

- **... and more**

# The annual modulation: a model independent signature for the investigation of Dark Matter 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




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

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

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

**Expected rate in given energy bin changes because the revolution motion of the Earth around the Sun, which is moving in the Galaxy**

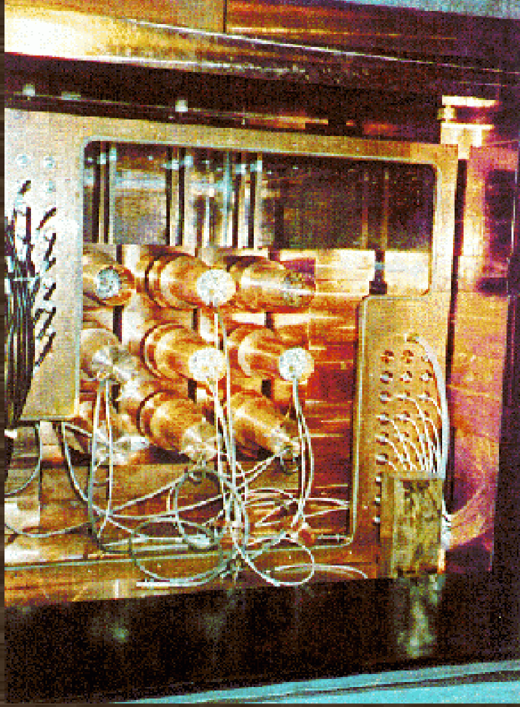
## Requirements of the annual modulation

1) Modulated rate according cosine
2) In a definite 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

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

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



*data taking completed on July 2002, last data release 2003. Still producing results*

**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 6.3 $\sigma$ 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)

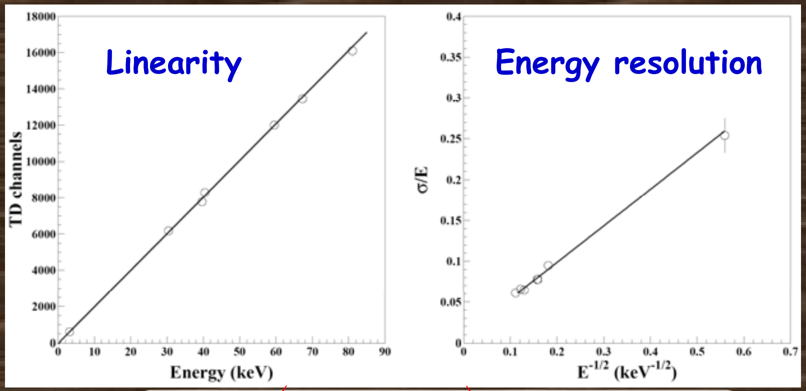
As a result of a second generation R&D for more radiopure NaI(Tl)
by exploiting new chemical/physical radiopurification techniques
(all operations involving crystals and PMTs - including photos - in HP Nitrogen atmosphere)

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

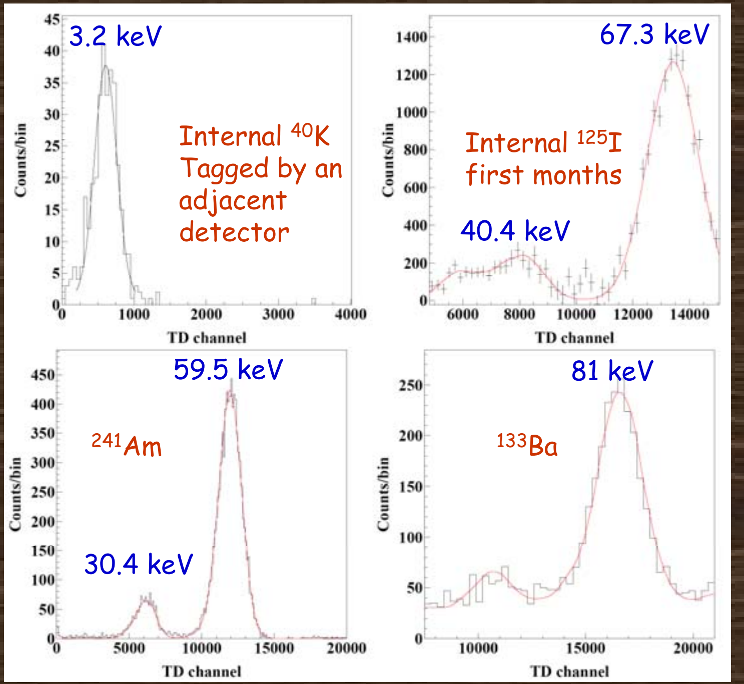
- *Radiopurity,performances, procedures, etc.:* NIMA592(2008)297, JINST 7 (2012) 03009
- *Results on DM particles: Ann. Mod. Signature:* EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648
- *related results:* PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022, EPJC74(2014)2827
- *Results on rare processes: PEP violation in Na, I:* EPJC62(2009)327, *CNC in I:* EPJC72(2012)1920
  *IPP in $^{241}$Am:* EPJA49(2013)64

# DAMA/LIBRA calibrations

Low energy: various external gamma sources ($^{241}$Am, $^{133}$Ba) and internal X-rays or gamma's ($^{40}$K, $^{125}$I, $^{129}$I), routine calibrations with $^{241}$Am

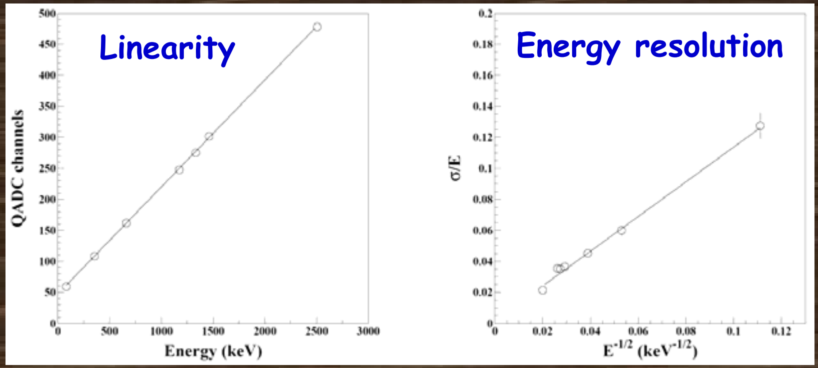



$$\frac{\sigma_{LE}}{E}=\frac{(0.448\pm0.035)}{\sqrt{E(keV)}}+(9.1\pm5.1)\cdot10^{-3}$$



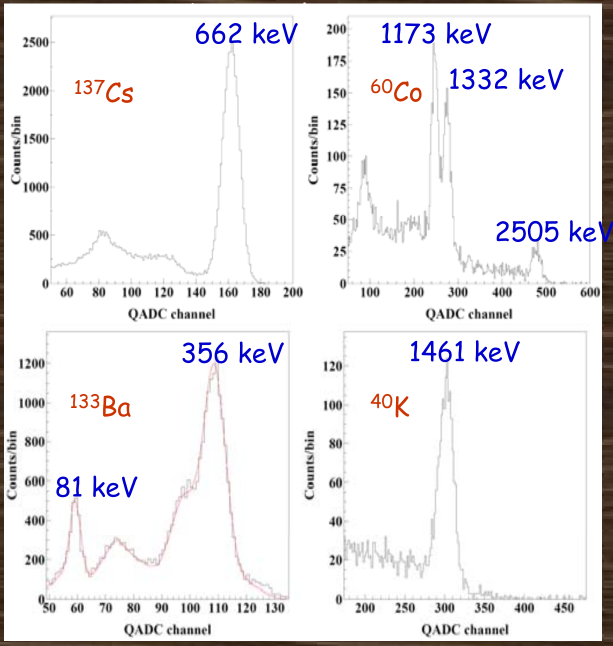

The curves superimposed to the experimental data have been obtained

High energy: external sources of gamma rays (e.g. $^{137}$Cs, $^{60}$Co and $^{133}$Ba) and gamma rays of 1461 keV due to $^{40}$K decays in an adjacent detector, tagged by the 3.2 keV X-rays




$$\frac{\sigma_{HE}}{E}=\frac{(1.12\pm0.06)}{\sqrt{E(keV)}}+(17\pm23)\cdot10^{-4}$$

The signals (unlike low energy events) for high energy events are taken only from one PMT




Thus, here and hereafter keV means keV electron

# 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 $\simeq$ 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)

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

## START of DAMA/LIBRA – phase 2

- **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

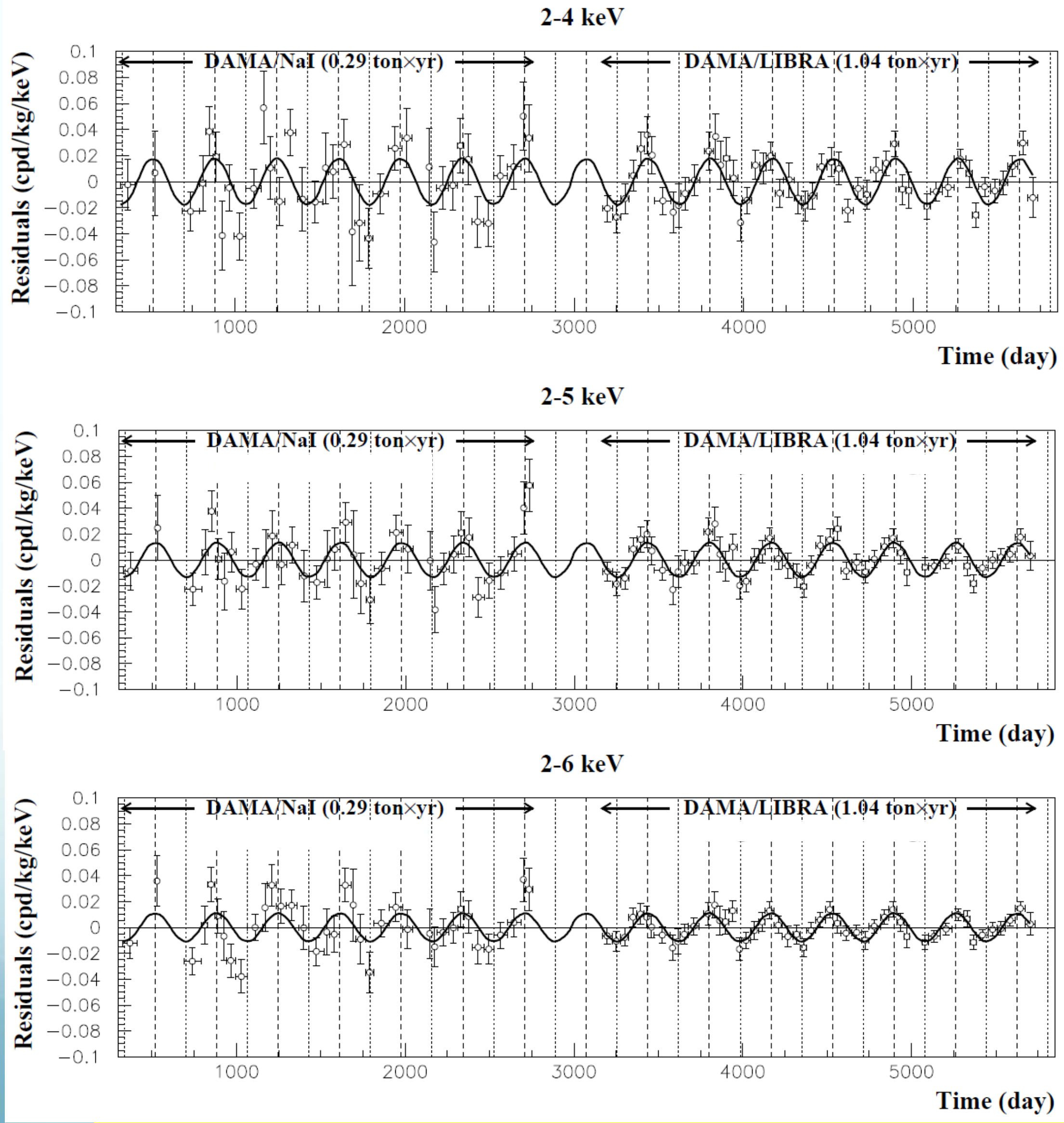
Fall 2012: new preamplifiers installed + special trigger modules. Other new components in the electronic chain in development

... continuously running

# Model Independent DM Annual Modulation Result

experimental residuals of the single-hit scintillation events rate vs time and energy

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




$A\cos[\omega(t-t_0)]$ ;

continuous lines: $t_0$ = 152.5 d, T = 1.00 y

## 2-4 keV

A=(0.0179±0.0020) cpd/kg/keV

$\chi^2$/dof = 87.1/86 **9.0 σ C.L.**

Absence of modulation? No

$\chi^2$/dof=169/87 ⇒ P(A=0) = $3.7\times10^{-7}$

## 2-5 keV

A=(0.0135±0.0015) cpd/kg/keV

$\chi^2$/dof = 68.2/86 **9.0 σ C.L.**

Absence of modulation? No

$\chi^2$/dof=152/87 ⇒ P(A=0) = $2.2\times10^{-5}$

## 2-6 keV

A=(0.0110±0.0012) cpd/kg/keV

$\chi^2$/dof = 70.4/86 **9.2 σ C.L.**

Absence of modulation? No

$\chi^2$/dof=154/87 ⇒ P(A=0) = $1.3\times10^{-5}$

The data favor the presence of a modulated behavior with proper features at 9.2σ C.L.

# Model Independent Annual Modulation Result

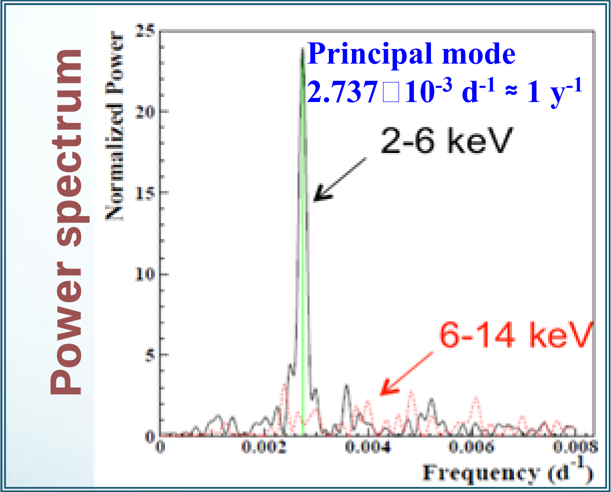
**DAMA/NaI** + **DAMA/LIBRA-phase1** Total exposure: 487526 kg×day = **1.33 ton×yr**

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

The measured modulation amplitudes (A), period (T) and phase ($t_0$) from the single-hit residual rate vs time

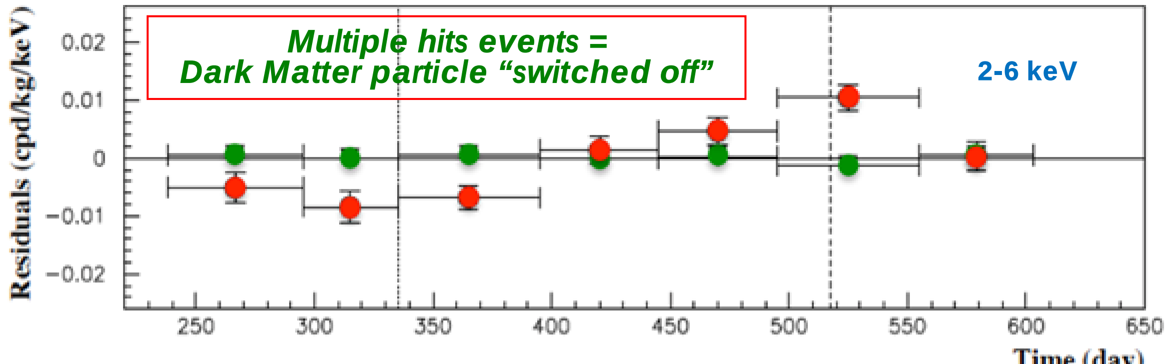
| | A(cpd/kg/keV) | T=$2\pi/\omega$ (yr) | $t_0$ (day) | C.L. |
|---|---|---|---|---|
| DAMA/NaI+DAMA/LIBRA-phase1 | | | | |
| (2-4) keV | 0.0190 ±0.0020 | 0.996 ±0.0002 | 134 ± 6 | 9.5$\sigma$ |
| (2-5) keV | 0.0140 ±0.0015 | 0.996 ±0.0002 | 140 ± 6 | 9.3$\sigma$ |
| (2-6) keV | 0.0112 ±0.0012 | 0.998 ±0.0002 | 144 ± 7 | 9.3$\sigma$ |

$A\cos[\omega(t-t_0)]$




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±0.0004) cpd/kg/keV**

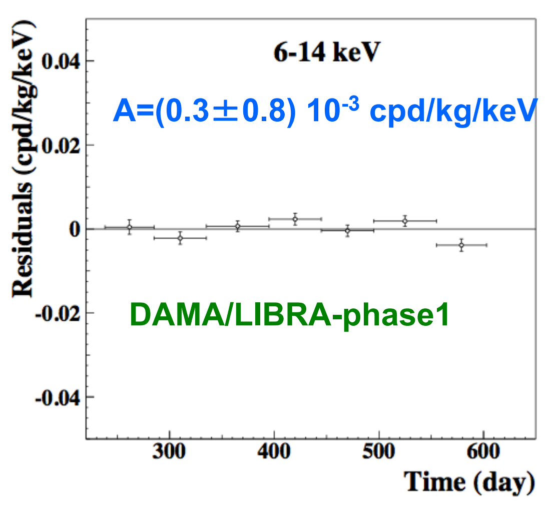



This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

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$\sigma$ C.L.

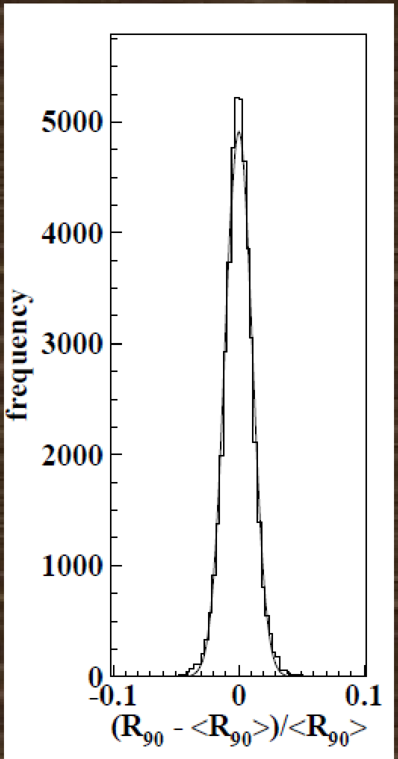
# Rate behaviour above 6 keV

- **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




- **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 |

$\sigma \approx 1\%$, fully accounted by statistical considerations

+ 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 bckg and is consistent with the studies on the various components**

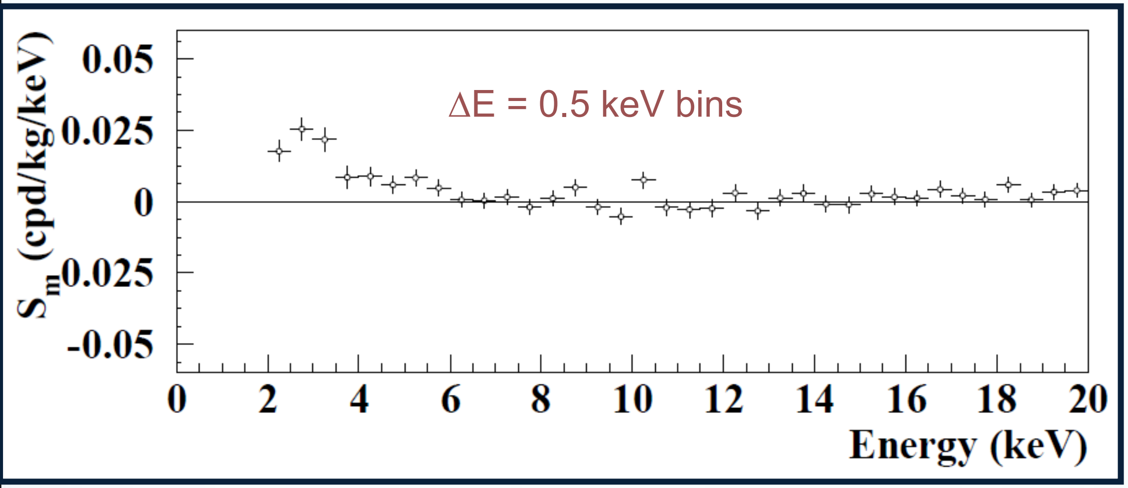
# Model Independent Annual Modulation Result

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

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

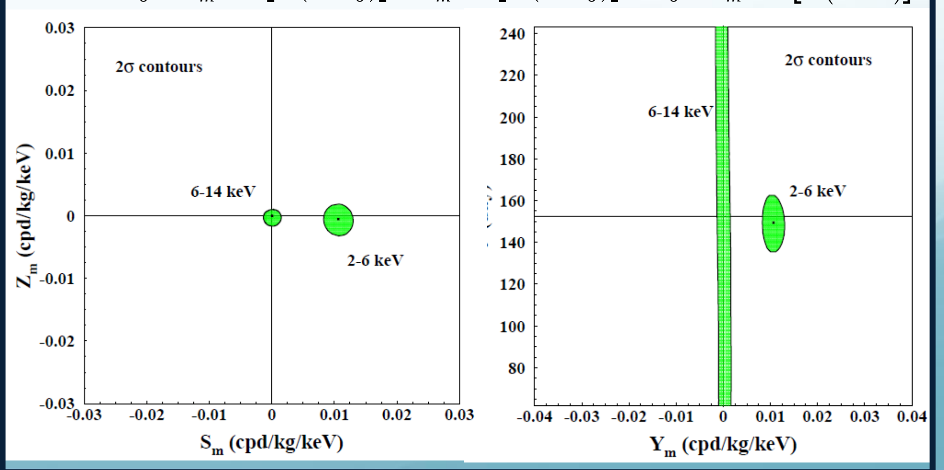
$$R(t) = S_0 + S_m \cos\left[\omega\left(t - t_0\right)\right]$$

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




**Max-likelihood analysis of the single-hit scintillation events**

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



The analysis at energies above 6 keV, the analysis of the multiple-hits events and the statistical considerations about $S_m$ already exclude any sizable presence of systematical effects

## Additional investigations on the stability parameters

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

**Running conditions stable at a level better than 1% also in the last running period**

| | DAMA/LIBRA-1 | DAMA/LIBRA-2 | DAMA/LIBRA-3 | DAMA/LIBRA-4 | DAMA/LIBRA-5 | DAMA/LIBRA-6 | DAMA/LIBRA-7 |
|---|---|---|---|---|---|---|---|
| Temperature (°C) | -(0.0001 ± 0.0061) | (0.0026 ± 0.0086) | (0.001 ± 0.015) | (0.0004 ± 0.0047) | (0.0001 ± 0.0036) | (0.0007 ± 0.0059) | (0.0000 ± 0.0054) |
| Flux $N_2$ (l/h) | (0.13 ± 0.22) | (0.10 ± 0.25) | -(0.07 ± 0.18) | -(0.05 ± 0.24) | -(0.01 ± 0.21) | -(0.01 ± 0.15) | -(0.00 ± 0.14) |
| Pressure (mbar) | (0.015 ± 0.030) | -(0.013 ± 0.025) | (0.022 ± 0.027) | (0.0018 ± 0.0074) | -(0.08 ± 0.12) $\times 10^{-2}$ | (0.07 ± 0.13) $\times 10^{-2}$ | -(0.26 ± 0.55) $\times 10^{-2}$ |
| Radon (Bq/$m^3$) | -(0.029 ± 0.029) | -(0.030 ± 0.027) | (0.015 ± 0.029) | -(0.052 ± 0.039) | (0.021 ± 0.037) | -(0.028 ± 0.036) | (0.012 ± 0.047) |
| Hardware rate above single ph.e. (Hz) | -(0.20 ± 0.18) $\times 10^{-2}$ | (0.09 ± 0.17) $\times 10^{-2}$ | -(0.03 ± 0.20) $\times 10^{-2}$ | (0.15 ± 0.15) $\times 10^{-2}$ | (0.03 ± 0.14) $\times 10^{-2}$ | (0.08 ± 0.11) $\times 10^{-2}$ | (0.06 ± 0.10) $\times 10^{-2}$ |

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

## The order of magnitude of the neutron flux @ LNGS known since more than 20 years: example of some measurements

| Energy (MeV) | Flux( $10^{-6}$ $cm^{-2}$ $s^{-1}$ ) | Reference |
|---|---|---|
| 1.0-2.5 | $0.14 \pm 0.12$ | F. Arneodo et al. (for ICARUS expt.), Il Nuov. Cim. A8 (1999) 819 (liquid scintillator PSD) |
| 2.5-5.0 | $0.13 \pm 0.04$ | |
| 5.0-10.0 | $0.15 \pm 0.04$ | |
| 10.0-15.0 | $(0.4 \pm 0.4)\cdot 10^{-3}$ | |
| > 2.5 | $0.09 \pm 0.06$ | M. Cribier et al. (for Gallex expt.), Astrop. Phys. 4 (1995) 23 (radiochemical) |
| Thermal | $1.08 \pm 0.02$ | P. Belli et al. (for Gallex expt.), Il N. Cim. A101 (1989) 959 ($BF_3$+various shields) |
| Epithermal | $1.98 \pm 0.05$ | |
| Fast (> 2.5 MeV) | $(0.23 \pm 0.07)$ | |
| 1.0-2.5 | $0.38 \pm 0.01$ | A. Rindi et al., LNGS report LNF-88/01(P) (1988) (high pressure $^3He$) |
| 2.5-5.0 | $0.27 \pm 0.14$ | |
| 5.0-10.0 | $0.05 \pm 0.01$ | |
| 10.0-15.0 | $(0.6 \pm 0.2)\cdot 10^{-3}$ | |

# Can a possible thermal neutron modulation account for the observed effect?

**NO**

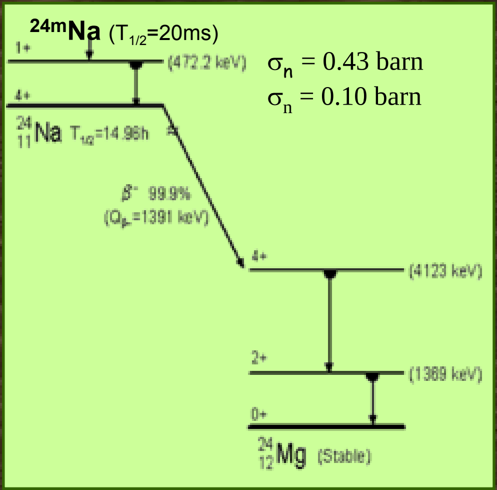
- **Thermal neutrons flux measured at LNGS :**

  **$\Phi_n = 1.08\ 10^{-6}$ n cm$^{-2}$ s$^{-1}$ (N.Cim.A101(1989)959)**

- Experimental upper limit on the thermal neutrons flux "*surviving*" the neutron shield in DAMA/LIBRA:
  - studying triple coincidences able to give evidence for the possible presence of $^{24}$Na from neutron activation:

    $\Phi_n < 1.2 \times 10^{-7}$ n cm$^{-2}$ s$^{-1}$ (90%C.L.)

- Two consistent upper limits on thermal neutron flux have been obtained with DAMA/NaI considering the same capture reactions and using different approaches.




Evaluation of the expected effect:

- **Capture rate = $\Phi_n\ \sigma_n\ N_T < 0.022$ captures/day/kg**

HYPOTHESIS: assuming very cautiously a 10% thermal neutron modulation:

→ $S_m^{(\text{thermal n})} < 0.8 \times 10^{-6}$ cpd/kg/keV ($< 0.01\%\ S_m^{\text{observed}}$)

In all the cases of neutron captures ($^{24}$Na, $^{128}$I, ...) a possible thermal n modulation induces a variation in all the energy spectrum

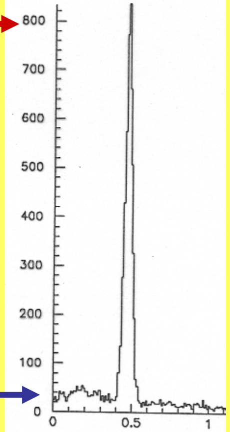
Already excluded also by $R_{90}$ analysis

**MC simulation of the process**

When $\Phi_n = 10^{-6}$ n cm$^{-2}$ s$^{-1}$:

$7\cdot10^{-5}$ cpd/kg/keV

$1.4\cdot10^{-3}$ cpd/kg/keV




**E (MeV)**

# Can a possible fast neutron modulation account for the observed effect?

**NO**

In the estimate of the possible effect of the neutron background cautiously not included the 1m concrete moderator, which almost completely surrounds (mostly outside the barrack) the passive shield

**Measured fast neutron flux @ LNGS:**
**$\Phi_n = 0.9\ 10^{-7}$ n cm$^{-2}$ s$^{-1}$ (Astropart.Phys.4 (1995)23)**

**By MC: differential counting rate above 2 keV ≈ $10^{-3}$ cpd/kg/keV**

HYPOTHESIS: assuming - very cautiously - a 10% neutron modulation:

$S_m^{(fast\ n)} < 10^{-4}$ cpd/kg/keV (< 0.5% $S_m^{observed}$)

- Experimental upper limit on the fast neutrons flux "*surviving*" the neutron shield in DAMA/LIBRA:
  - through the study of the inelastic reaction $^{23}$Na(n,n′)$^{23}$Na*(2076 keV) which produces two γ's in coincidence (1636 keV and 440 keV):

$$\Phi_n < 2.2 \times 10^{-7} \text{ n cm}^{-2} \text{ s}^{-1} \text{ (90\%C.L.)}$$

  - well compatible with the measured values at LNGS. This further excludes any presence of a fast neutron flux in DAMA/LIBRA significantly larger than the measured ones.

Moreover, a possible fast n modulation would induce:

- a variation in all the energy spectrum (steady environmental fast neutrons always accompained by thermalized component)

  already excluded also by $R_{90}$

- a modulation amplitude for multiple-hit events different from zero

  already excluded by the multiple-hit events

Thus, a possible 5% neutron modulation (ICARUS TM03-01) cannot quantitatively contribute to the DAMA/NaI observed signal, even if the neutron flux would be assumed 100 times larger than measured by various authors over more than 15 years @ LNGS

# No role for μ in DAMA annual modulation result

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

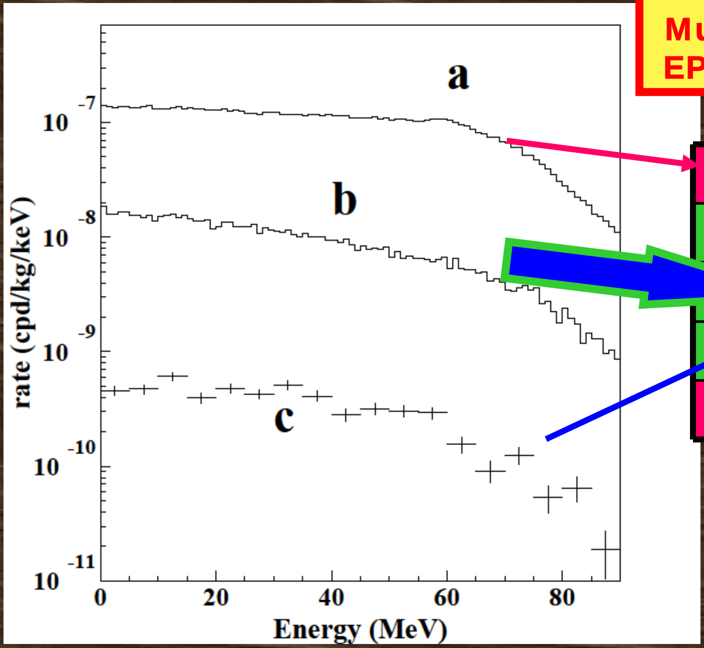
DAMA/LIBRA surface ≈0.13 $m^2$

**μ flux @ DAMA/LIBRA ≈2.5 μ/day**

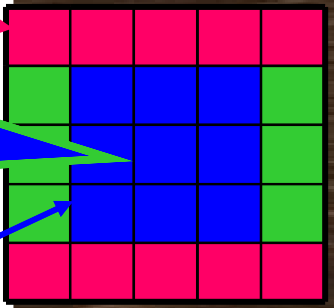
MonteCarlo simulation:

- muon intensity distribution
- Gran Sasso rock overburden map
- Single hit events

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




**Much more in EPJC72(2012)2064**



**Detector's matrix**

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

**$R_n$ = (fast n by μ)/(time unit) = $\Phi_\mu\, Y\, M_{eff}$**

•$\Phi_\mu$ @ LNGS ≈ 20 μ $m^{-2}d^{-1}$ (±1.5% modulated)

•Measured neutron Yield @ LNGS:

Y=1÷7 $10^{-4}$ n/μ/(g/cm²)

g = geometrical factor;

ε = detection eff. by elastic scattering

$f_{DE}$ = energy window (E>2keV) effic.;

$f_{single}$ = single hit effic.

**Hyp.**: $M_{eff}$ = 15 tons; $g \approx \varepsilon \approx f_{\Delta E} \approx f_{single} \approx 0.5$ (cautiously)

**Knowing that**: $M_{setup}$ ≈ 250 kg and ΔE=4keV

Annual modulation amplitude at low energy due to μ **modulation**:

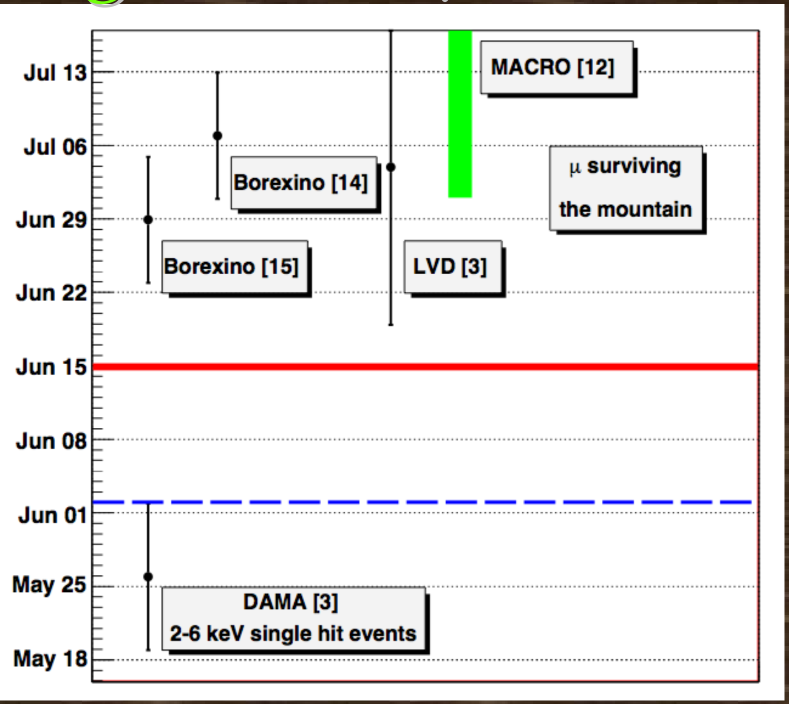
$$S_m^{(m)} = R_n\, g\, \varepsilon\, f_{DE}\, f_{single}\, 2\% / (M_{setup}\, \Delta E)$$

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

**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




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

μ flux @ LNGS (MACRO, LVD, BOREXINO) ≈$3\cdot10^{-4}$ $m^{-2}s^{-1}$; modulation amplitude 1.5%; phase: July 7 ± 6 d, June 29 ± 6 d (Borexino)

but

- the muon phase differs from year to year (error no purely statistical); LVD/BOREXINO value is a "mean" of the muon phase of each year
- The DAMA: modulation amplitude $10^{-2}$ cpd/kg/keV, in 2-6 keV energy range for single hit events; phase: May 26 ± 7 days (stable over 13 years)

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

**Similar for the whole DAMA/LIBRA-phase1**

✓ Can (whatever) hypothetical cosmogenic products be considered as side effects, assuming that they might produce:

- only events at low energy,
- only *single-hit* events,
- no sizable effect in the *multiple-hit* counting rate
- pulses with time structure as scintillation light

But, its phase should be (much) larger than μ phase, $t_\mu$ :

- if $\tau \ll T/2\pi$: $t_{side} = t_\mu + \tau$
- if $\tau \gg T/2\pi$: $t_{side} = t_\mu + T/4$

Also this cannot mimic the signature: different phase

**… and for many others arguments and details EPJC72(2012)2064**

# 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, 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. | $<2.5\times10^{-6}$ 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 + instrinsic 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 |

DAMA/LIBRA-phase1

+ they cannot satisfy all the requirements of annual modulation signature

Thus, they cannot mimic the observed annual modulation effect

# Final model independent result
# DAMA/NaI+DAMA/LIBRA-phase1

Presence of modulation over 14 annual cycles at 9.3 $\sigma$ C.L. with the proper distinctive features of the DM signature; all the features satisfied by the data over 14 independent experiments of 1 year each one

The total exposure by former DAMA/NaI and present DAMA/LIBRA is 1.33 ton $\times$ yr (14 annual cycles)

In fact, as required by the DM annual modulation signature:

**1)**
**The *single-hit* events show a clear cosine-like modulation, as expected for the DM signal**

**2)**
**Measured period is equal to (0.998 $\pm$ 0.002) yr, well compatible with the 1 yr period, as expected for the DM signal**

**3)**
**Measured phase (144 $\pm$ 7) days is well compatible with the roughly about 152.5 days as expected for the DM signal**

**4)**
**The modulation is present only in the low energy (2—6) keV energy interval and not in other higher energy regions, consistently with expectation for the DM signal**

**5)**
**The modulation is present only in the *single-hit* events, while it is absent in the *multiple-hit* ones as expected for the DM signal**

**6)**
**The measured modulation amplitude in NaI(Tl) of the *single-hit* events in the (2-6) keV energy interval is: (0.0112 $\pm$ 0.0012) cpd/kg/keV (9.3 $\sigma$ C.L.).**

No systematic or side process able to simultaneously satisfy all the many peculiarities of the signature and to account for the whole measured modulation amplitude is available

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

## well compatible with several candidates

(in many possible 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)

WIMP with preferred inelastic scattering

Mirror Dark Matter

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

Elementary Black holes such as the Daemons

… and more

Heavy fifth family neutrons

a heavy ν of the 4-th family

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

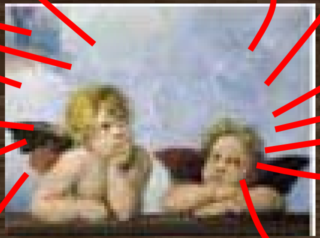
Light Dark Matter

Sterile neutrino

Self interacting Dark Matter

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

Kaluza Klein particles

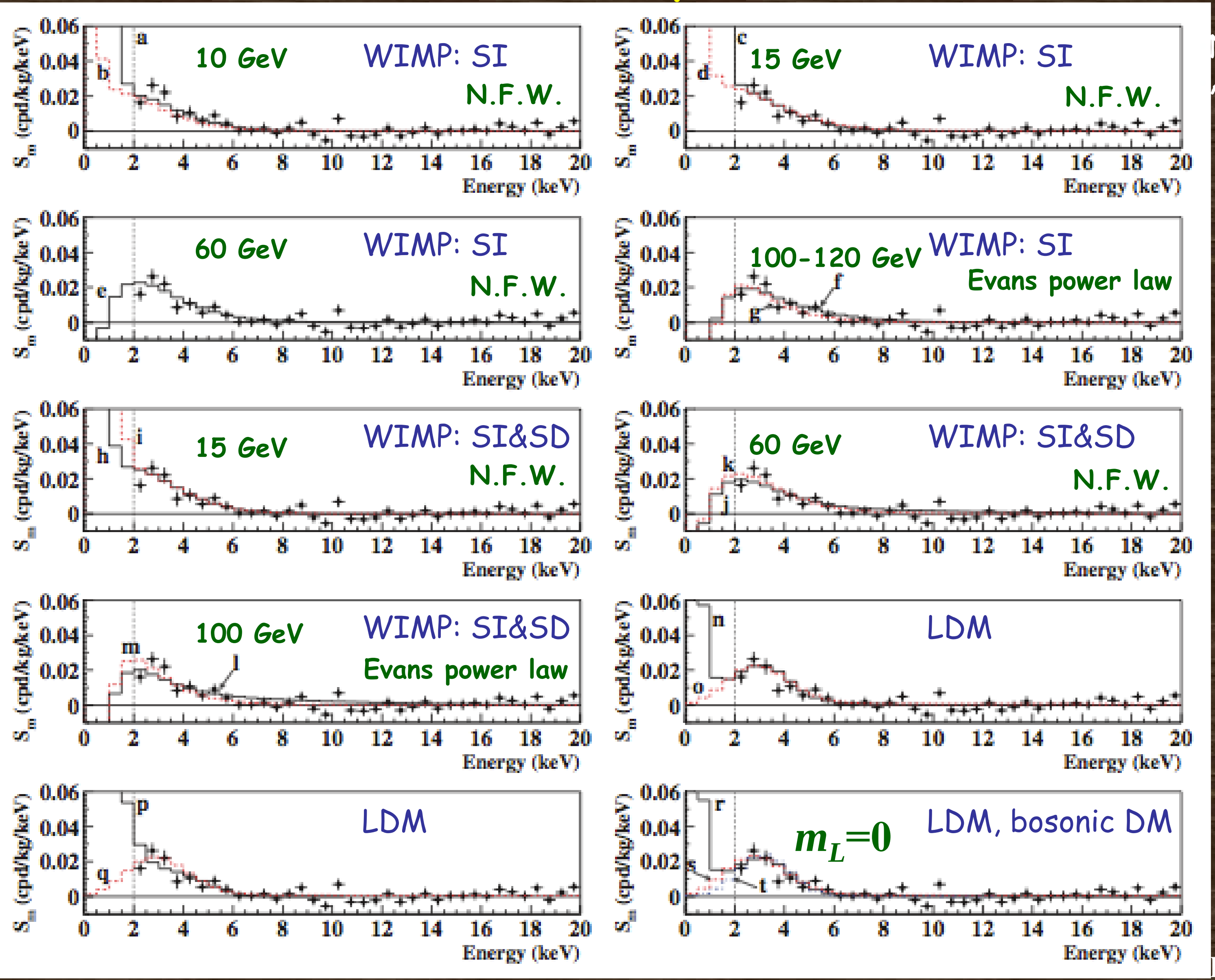


**Possible model dependent positive hints from indirect searches** (but interpretation, evidence itself, derived mass and cross sections depend e.g. on bckg modeling, on DM spatial velocity distribution in the galactic halo, etc.)

**as well null results not in conflict with DAMA results;**

**Available results from direct searches using different target materials and approaches do not give any robust conflict & compatibility with possible positive hints In various scenarios**

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




Not best fit
About the same C.L.

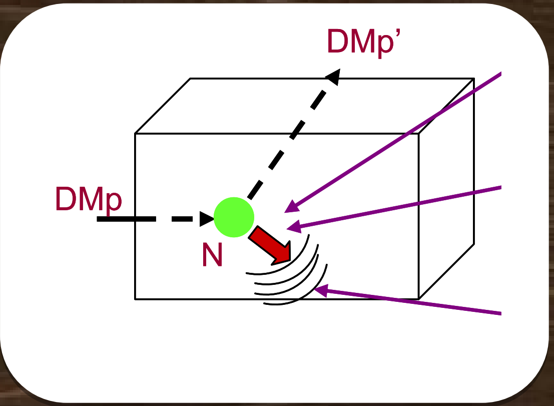
$\theta$ = 2.435

EPJC56(2008)333,
IJMPA28(2013)1330022

Compatibility with several candidates; other ones are open

# … an example …

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



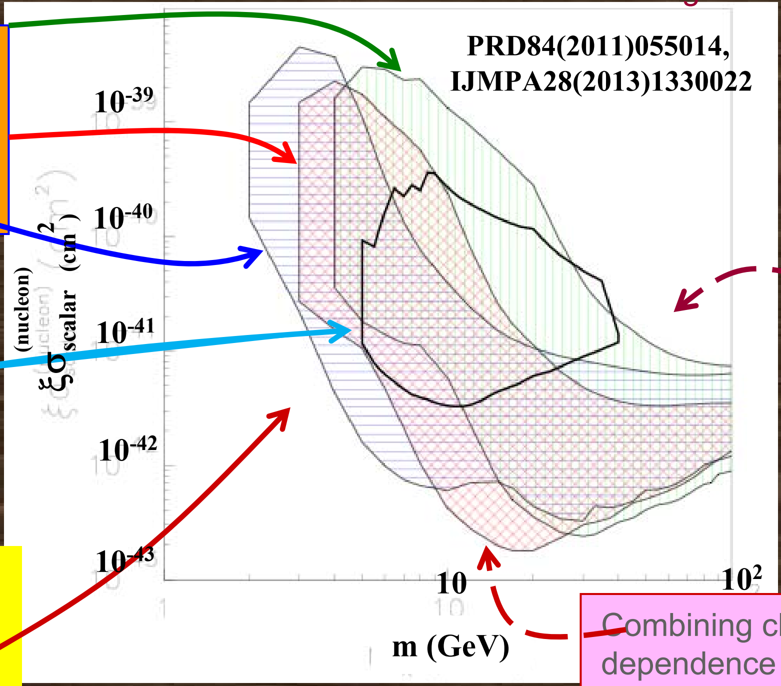

Regions in the nucleon cross section vs DM particle mass plane

- Some velocity distributions and uncertainties considered.
- The DAMA regions represent the domain where the likelihood-function values differ more than 7.5 $\sigma$ 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 1.64 $\sigma$ 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 $\sigma$

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.




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

CoGeNT

1.64σ 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

Combining channeling and energy dependence of q.f. (AstrPhys33 (2010) 40)
→Towards lower $\sigma$

# ... examples in some given frameworks

## DM particle with preferred inelastic interaction

- In the Inelastic DM (iDM) scenario, DMp scatter into an excited state, split from the ground state by an energy comparable to the available kinetic energy of a Galactic DMp.

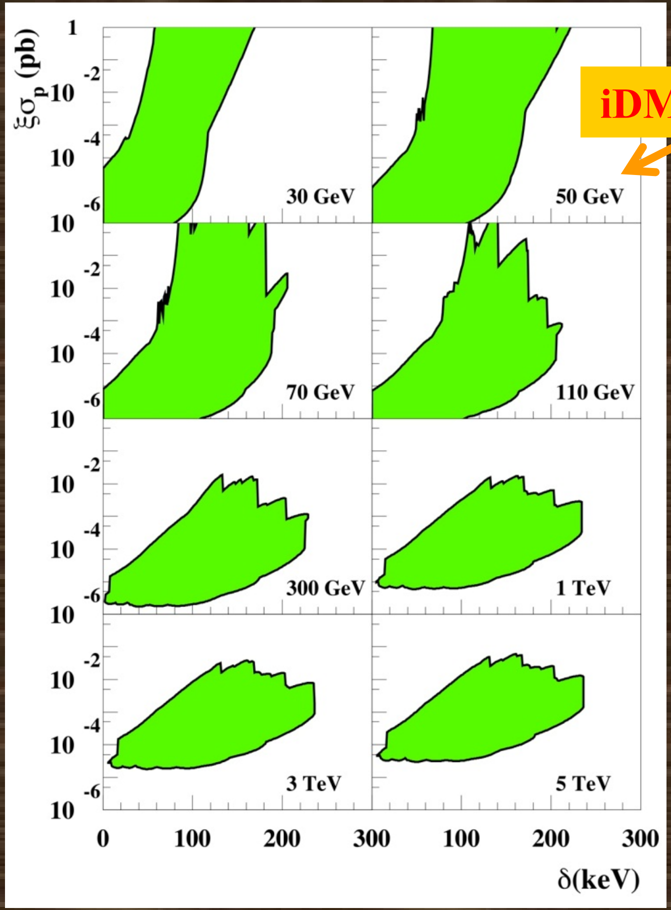
$$\chi^- + N \rightarrow \chi^+ + N$$

→ DMp has two mass states $\chi^+$, $\chi^-$ with $\delta$ mass splitting

→ Kinematical 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 3-dimensional allowed volume**




**iDM interaction on Iodine nuclei**

**Fund. Phys. 40(2010)900**

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

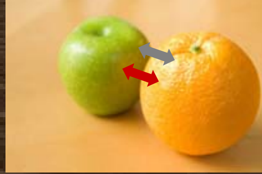
- For **large splittings**, the dominant scattering in NaI(Tl) can occur off of **Thallium nuclei**, with A~205, which are present as a dopant at the $10^{-3}$ level in NaI(Tl) crystals.

**arXiv:1007.2688**

- Inelastic scattering DMp swith **large splittings** do not give rise to sizeable contribution on Na, I, Ge, Xe, Ca, O, …nuclei.

**… and much more considering experimental and theoretical uncertainties**

# About model dependent exclusion plots



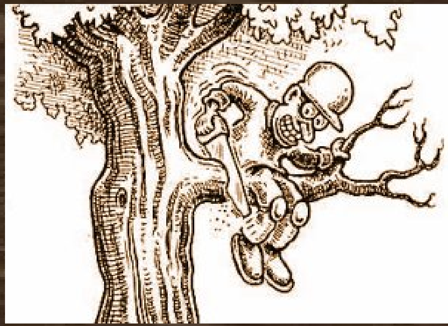
Selecting just one simplified model framework, making lots of assumptions, fixing large numbers of parameters … but…

- *which particle?*
- *which couplings? which model for the coupling?*
- *which form factors for each target material and related parameters?*
- *which nuclear model framework for each target material?*
- *Which spin factor for each case?*
- *which scaling laws?*
- *which halo profile?*
- *which halo parameters?*
- *which velocity distribution?*
- *which parameters for velocity distribution?*
- *which $v_0$?*
- *which $v_{esc}$?*
- *…etc. etc.*

road sign or labyrinth?

and experimental aspects …

- *marginal and "selected" exposures*
- *Threshold, energy scale and energy resolution when calibration in other energy region (& few phe/keV)? Stability? Too few calibration procedures and often not in the same running conditions*
- *Selections of detectors and of data*
- *handling of (many) "subtraction" procedures and stability in time of all the cuts windows and related quantities, etc.? Efficiencies?*
- *fiducial volume vs disuniformity of detector response in liquids?*
- *Used values in the calculation*
- *Used approximations etc., etc.*



**+ no uncertainties accounted for**

**No sensitivity to DM annual modulation signature,**

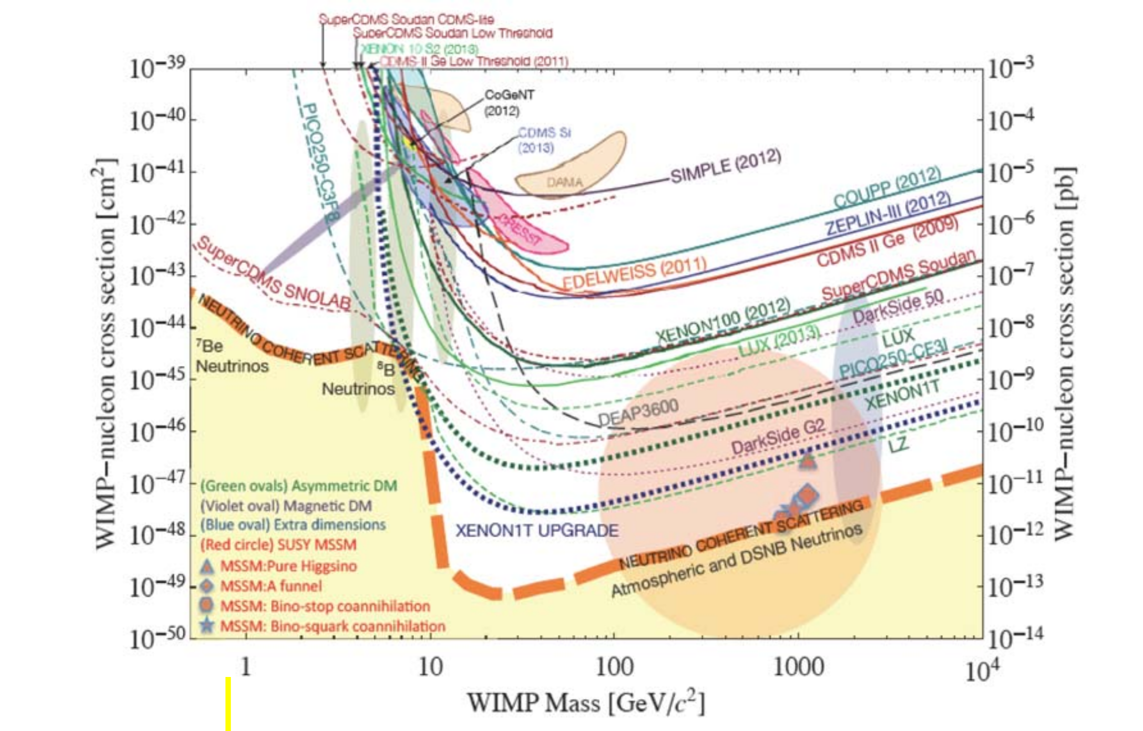
**Different target materials**

**+ generally implications of DAMA model-independent results presented in incorrect/incomplete/non-updated way**

Exclusion plots have no "universal validity" and cannot disproof a model independent result in any given general model framework (they depend not only on the general assumptions largely unknown at present stage of knowledge, but on the details of their cooking) + **generally overestimated** + methodological robustness (see R. Hudson, Found. Phys. 39 (2009) 174) + etc.

**On the other hand, possible positive hints should be interpreted. Large space for compatibility.**

Is this an “universal” and “correct” way to approach the problem of DM and the comparisons??

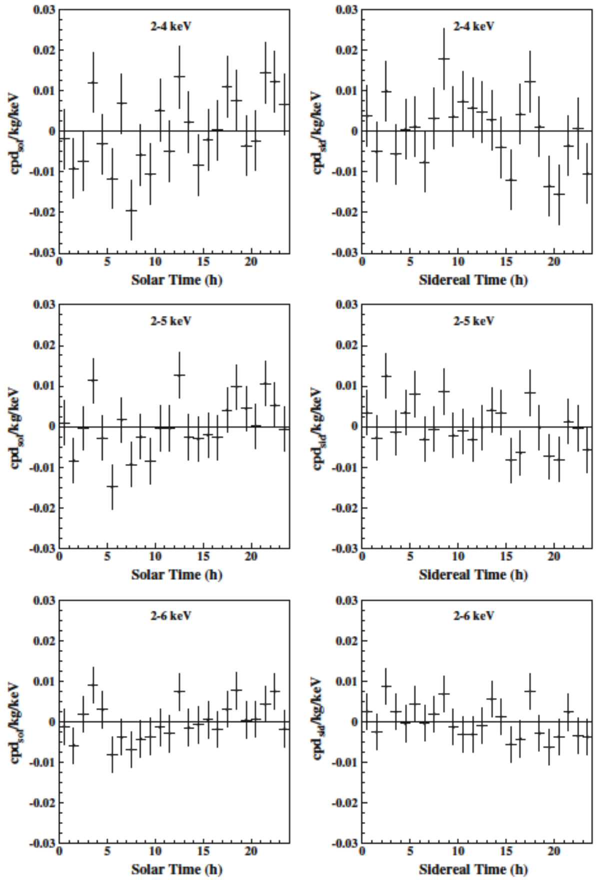



**This is just a largely arbitrary, partial, incorrect exercise**

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

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

solar sidereal

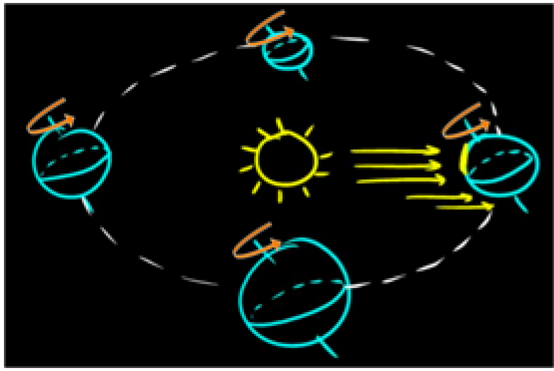



2-4 keV

2-5 keV

2-6 keV

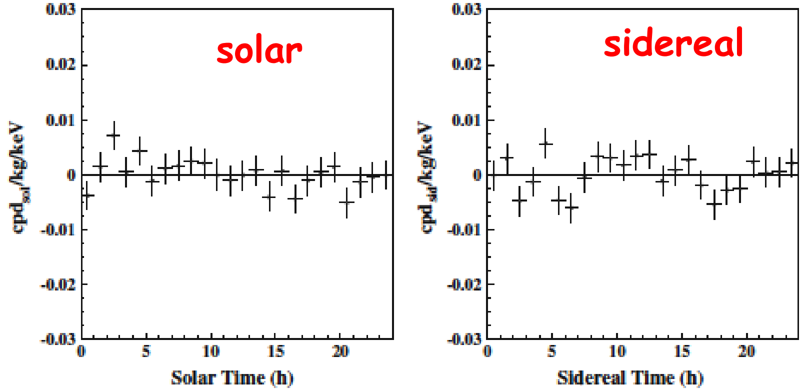
- Experimental *single-hit* residuals rate vs either sidereal and solar time and vs energy.



Energy region where the annual modulation observed.

Energy region just above.

6-14 keV




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

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

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

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

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

Velocity of the detector in the terrestrial laboratory:

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

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

Since:

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

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

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

## Annual modulation term:

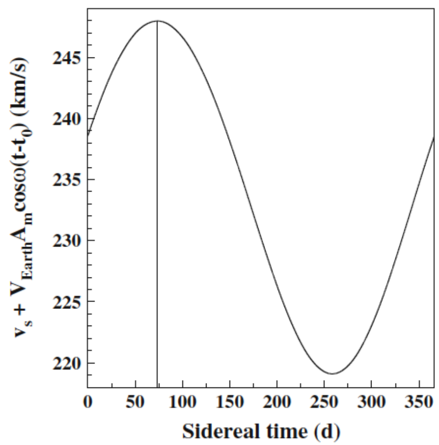
$$\hat{v}_s \cdot \vec{v}_{rev}(t) = V_{Earth} B_m \cos(\omega(t - t_0))$$

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

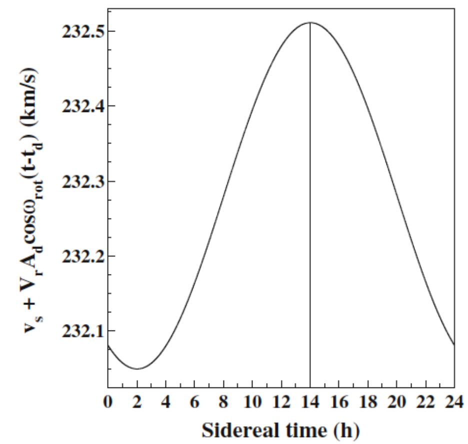
## Diurnal modulation term:

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

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




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




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

# The time dependence of the counting rate

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

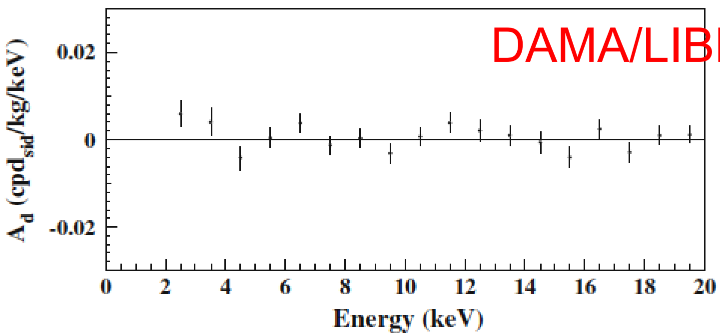
$$S_k[v_{lab}(t)] \simeq S_k[v_s] + \left[\frac{\partial S_k}{\partial v_{lab}}\right]_{v_s} [V_{Earth} B_m \cos\omega(t-t_0) + V_r B_d \cos\omega_{rot}(t-t_d)]$$

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

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

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

- Observed annual modulation amplitude in DAMA/LIBRA–phase1 in the (2–6) keV energy interval: (0.0097 ± 0.0013) cpd/kg/keV → thus, the expected value of the diurnal modulation amplitude is ≃1.5 × $10^{-4}$ cpd/kg/keV.
- When fitting the *single-hit* residuals with a cosine function with amplitude $A_d$ as free parameter, period fixed at 24 h and phase at 14 h: all the diurnal modulation amplitudes are compatible with zero.




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

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

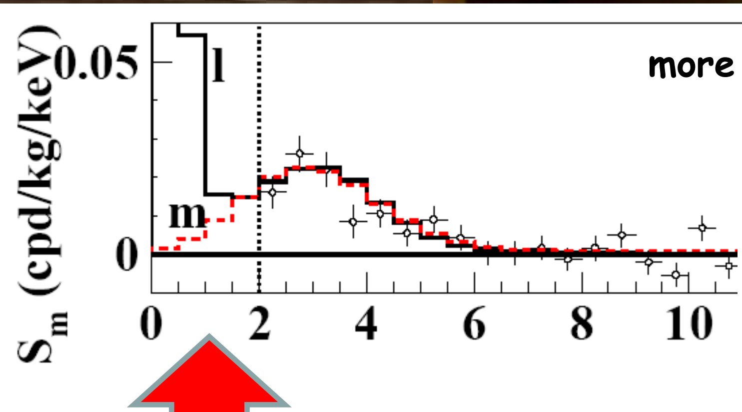
$A_d$ values compatible with zero, having random fluctuations around zero with $\chi^2$/d.o.f. = 19.5/18

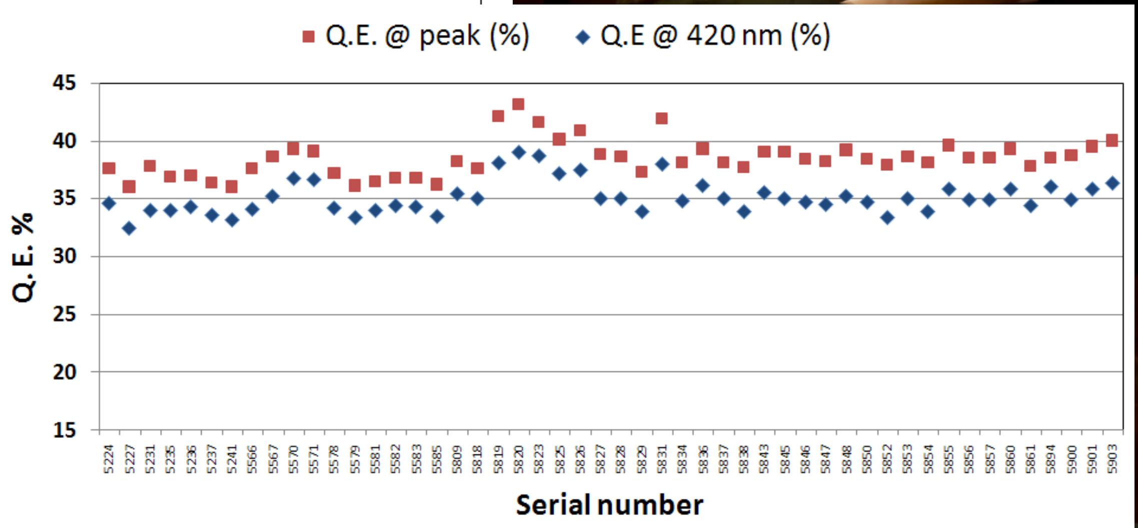
Present experimental sensitivity not yet suitable to explore the expected diurnal modulation amplitude derived from the DAMA/LIBRA–phase1 observed annual modulation effect

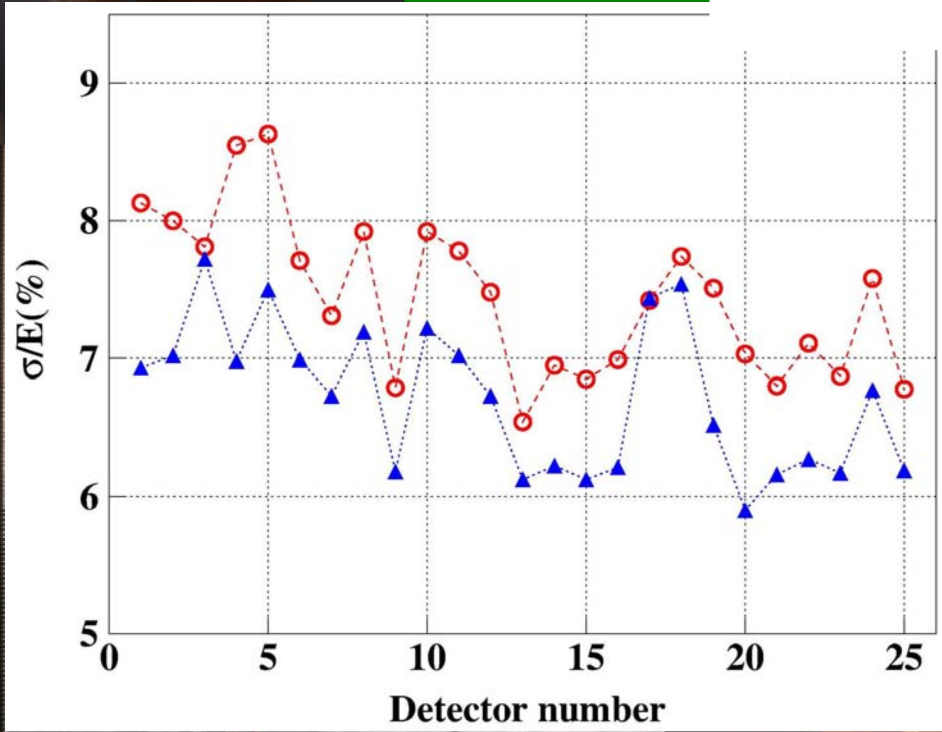
adequate sensitivity = larger exposure with DAMA/LIBRA–phase2 which - having a lower software energy threshold – also offers an additional alternative possibility to increase sensitivity to such an effect

# DAMA/LIBRA – phase2

JINST 7(2012)03009




ed with new

| ) | $^{235}U$ (mBq/kg) | $^{228}Ra$ (Bq/kg) | $^{228}Th$ (mBq/kg) | $^{40}K$ (Bq/kg) | $^{137}Cs$ (mBq/kg) | $^{60}Co$ (mBq/kg) |
|---|---|---|---|---|---|---|
| | 47 | 0.12 | 83 | 0.54 | - | - |
| | 10 | 0,02 | 17 | 0.16 | - | - |

typically
DAMA/LIBRA-phase: 5.5-7.5 ph.e./keV
→ DAMA/LIBRA-phase2: 6-10 ph.e./keV

**Since Dec 2010 data taking and optimizations in this new configuration started**

# DM annual modulation signature

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

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

increased in DAMA/LIBRA-phase2

increased in DAMA/LIBRA-phase2

increased with DAMA/LIBRA-phase2

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

&: DM annual modulation signature acts itself as a strong bckg reduction strategy as already pointed out in the original paper by Freese et al.

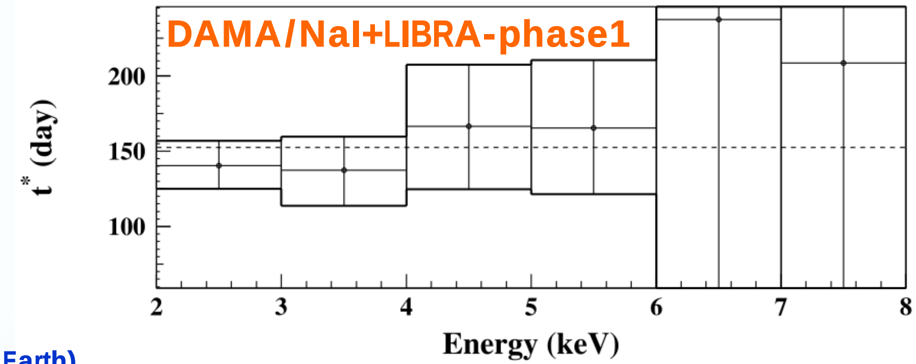
&: No systematic or side process able to simultaneously satisfy all the many peculiarities of the signature and to account for the whole measured modulation amplitude is available

# What next? Explore second orders effects with high precision

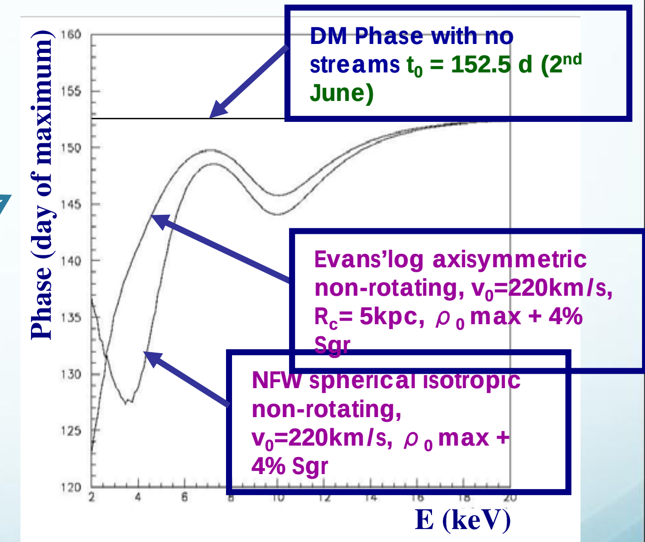
## The importance of studying second order effects and the annual modulation phase

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




**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

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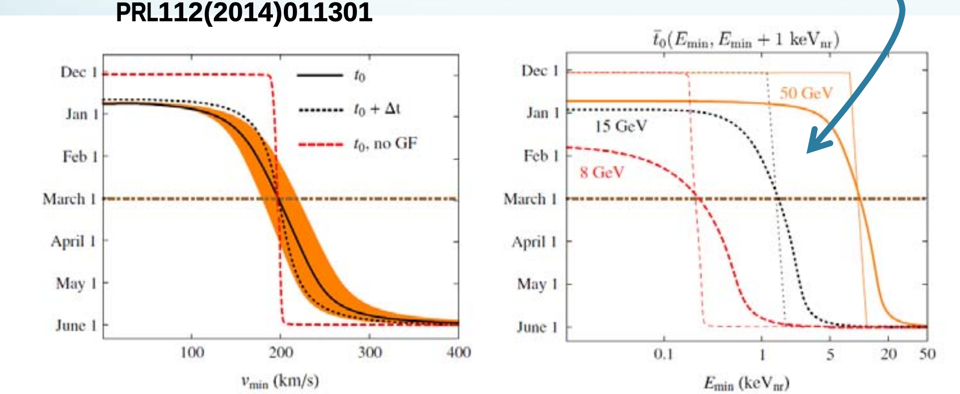

# Conclusions

New PMTs with higher Q.E.

- Positive evidence for the presence of DM particles in the galactic halo supported at 9.3$\sigma$ C.L. (14 annual cycles DAMA/NaI and DAMA/LIBRA-phase1: 1.33 ton $\times$ yr)
- The modulation parameters determined with better precision
- 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 *continuous 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

Moreover, works and efforts for:
- further improvement (phase3);
- DAMA/1ton set up;
- ADAMO project, anisotropic scintillators for directionality