The DAMA results in the light of LDM

Int. Workshop on Light Dark Matter, 24-28 May 2017,
La Biodola - Isola d'Elba

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Relic DM particles from primordial Universe

What accelerators can do:
to demostrate the existence of some of the DM candidates

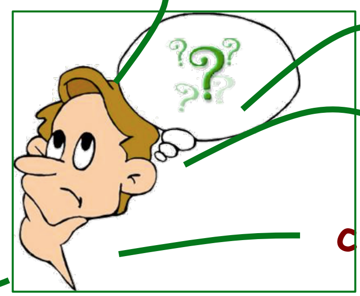
What accelerators cannot do:
to credit that a certain particle is a DM solution or the "only" DM particle solution…

\+ DM candidates and scenarios exist (even for neutralino candidate) on which accelerators cannot give any information

MULTI-MESSENGER? ONLY FOR SOME PARTICULAR CASES

- **DM multicomponent also in the particle part?**
- **Right related nuclear and particle physics?**

Right halo model and parameters?



Non thermalized components?

Caustics?

clumpiness?

etc

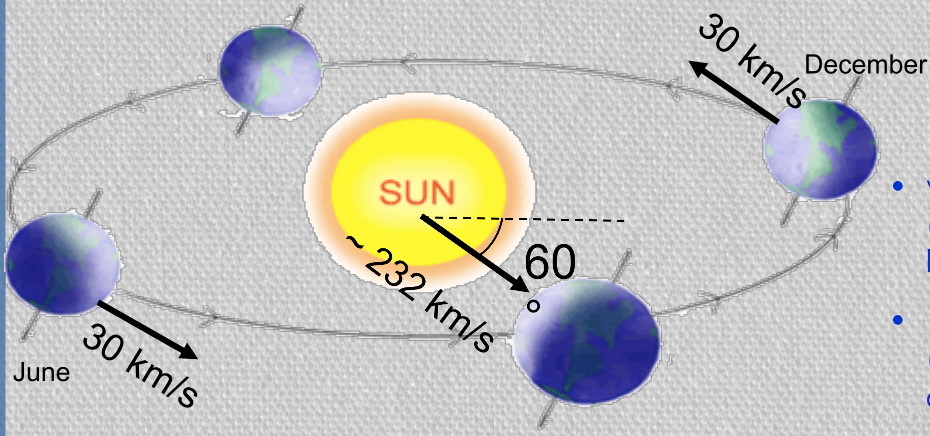
The DM annual modulation: a model independent signature to investigate the DM particles component in the galactic halo

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 of the DM 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

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



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

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

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

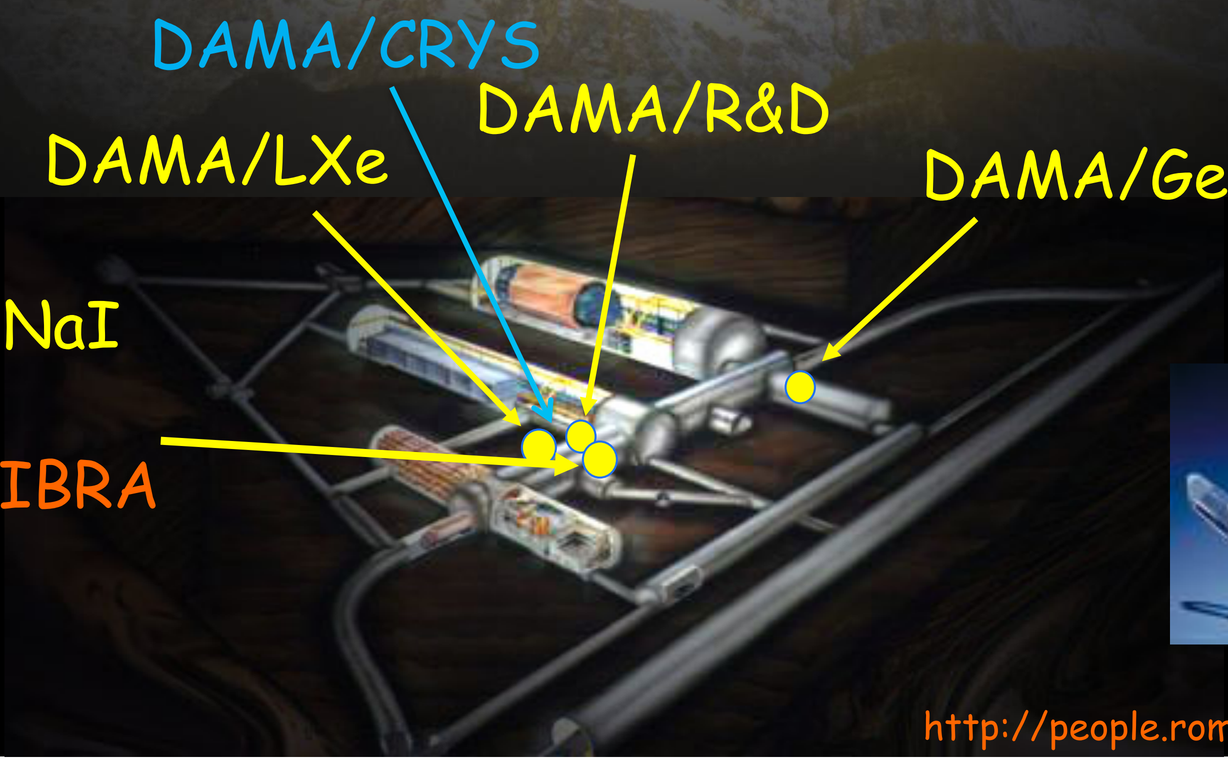
the DM annual modulation signature has a different origin and peculiarities (e.g. the phase) than those effects correlated with the seasons

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

Roma2,Roma1,LNGS,IHEP/Beijing

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

DAMA: an observatory for rare processes @LNGS



DAMA/NaI
↓
DAMA/LIBRA

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

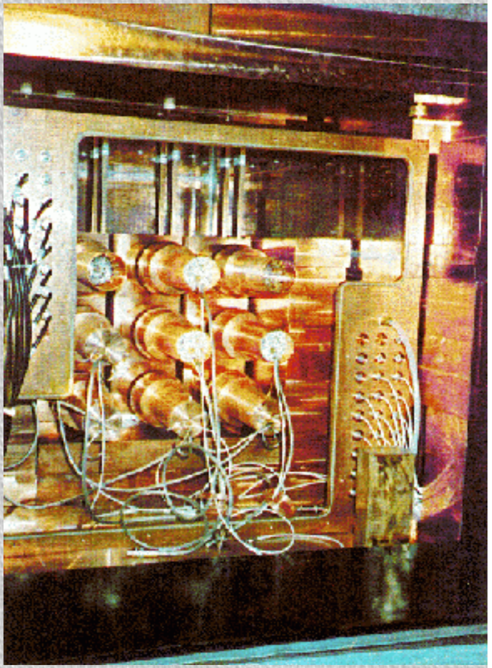
The pioneer DAMA/NaI: ≈100 kg highly radiopure NaI(Tl)

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



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

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 σ 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, EPJC75 (2015) 239, EPJC75(2015)400, IJMPA dedicated issue, EPJC77(2017)83
- *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

Complete DAMA/LIBRA-phase1

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

a ton × yr experiment? done

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

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

DAMA/LIBRA-phase1:

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

DAMA/LIBRA-phase2 (running):

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

Goal: lowering the software energy threshold

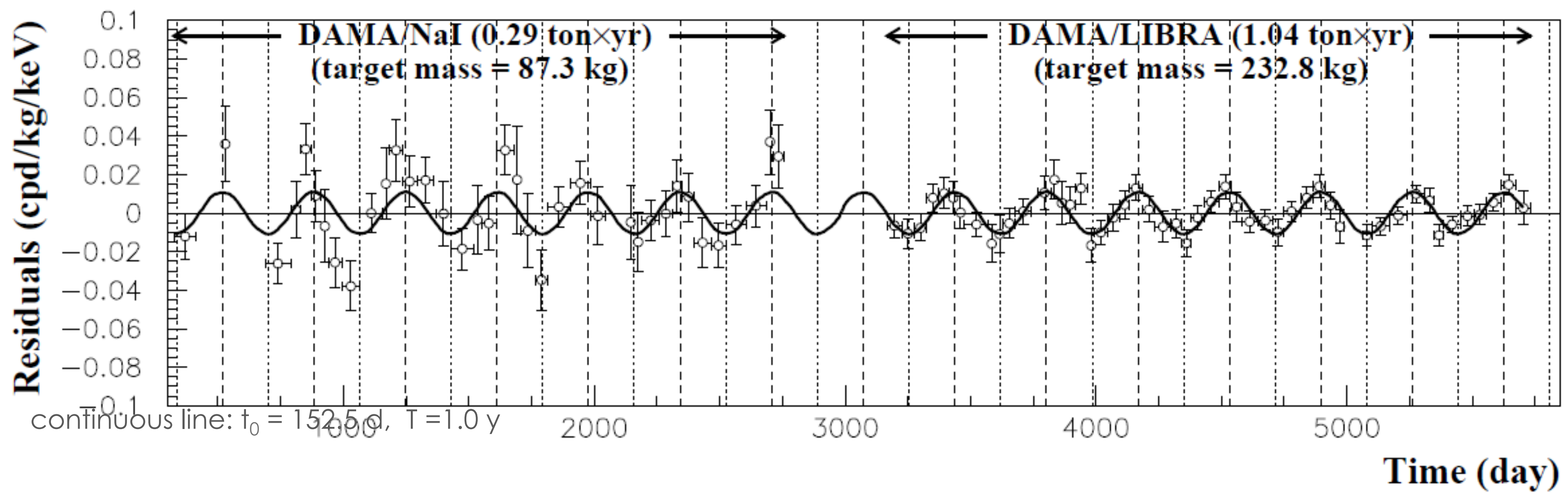
- Fall 2012: new preamplifiers installed + special trigger modules. Other new components in the electronic chain in development

Model Independent Annual Modulation Result

DAMA/NaI + DAMA/LIBRA-phase1 Total exposure: **1.33 ton×yr**

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

residual rate of the 2-6 keV single-hit scintillation events vs time



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

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

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.

Model Independent Annual Modulation Result

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

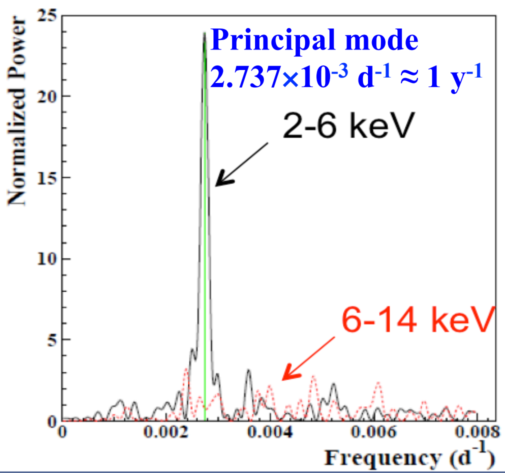
EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648

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

DAMA/NaI+DAMA/LIBRA-phase1	A(cpd/kg/keV)	$T=2\pi/\omega$ (yr)	t_0 (day)	C.L.
(2-4) keV	0.0190 ±0.0020	0.996 ±0.002	134 ± 6	9.5σ
(2-5) keV	0.0140 ±0.0015	0.996 ±0.002	140 ± 6	9.3σ
(2-6) keV	0.0112 ±0.0012	0.998 ±0.002	144 ± 7	9.3σ

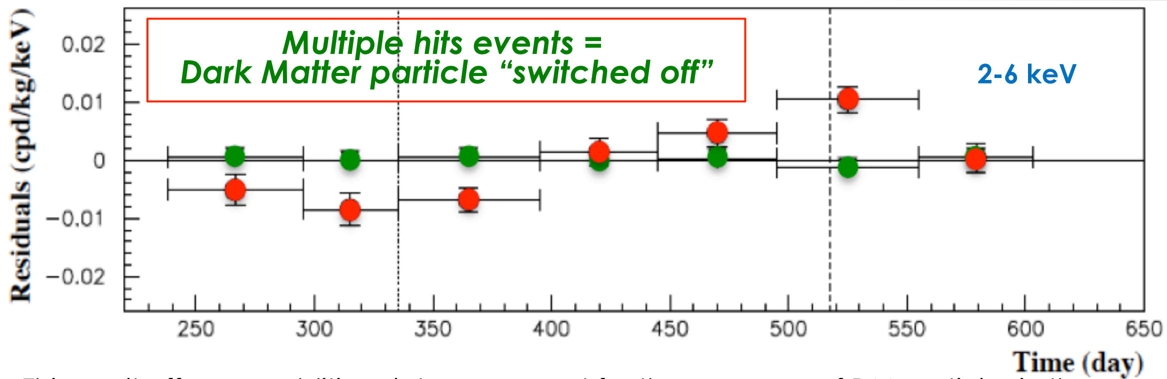
$A\cos[\omega(t-t_0)]$

Power spectrum



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

Comparison between **single hit residual rate (red points)** and **multiple hit residual rate (green points)**; Clear modulation in the single hit events; No modulation in the 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 9.2σ C.L.

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

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

Source	Main comment	Cautious upper limit (90%C.L.)
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	**$<2.5\times10^{-6}$ cpd/kg/keV**
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	**$<10^{-4}$ cpd/kg/keV**
NOISE	Effective full noise rejection near threshold	**$<10^{-4}$ cpd/kg/keV**
ENERGY SCALE	Routine + intrinsic calibrations	**$<1\text{-}2\times10^{-4}$ cpd/kg/keV**
EFFICIENCIES	Regularly measured by dedicated calibrations	**$<10^{-4}$ cpd/kg/keV**
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV *multiple-hits* events; this limit includes all possible sources of background	**$<10^{-4}$ cpd/kg/keV**
SIDE REACTIONS	Muon flux variation measured at LNGS	**$<3\times10^{-5}$ cpd/kg/keV**

+ 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; → $\Phi_k = \Phi_{0,k}\left(1 + \eta_k cos\omega\left(t - t_k\right)\right)$
- Counting rate in DAMA/LIBRA for *single-hit* events, in the (2 – 6) keV energy region induced by: → $R_k = R_{0,k}\left(1 + \eta_k cos\omega\left(t - t_k\right)\right)$
  - neutrons,
  - muons,
  - solar neutrinos.

(See e.g. also EPJC 56 (2008) 333, EPJC 72(2012) 2064, IJMPA 28 (2013) 1330022)

EPJC74(2014)3196

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]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 8 \times 10^{-6}$	[2, 7, 8]	$\ll 8 \times 10^{-7}$	$\ll 7 \times 10^{-5}$
	epithermal n (eV-keV)	2×10^{-6} [15]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 3 \times 10^{-3}$	[2, 7, 8]	$\ll 3 \times 10^{-4}$	$\ll 0.03$
FAST neutrons	fission, $(\alpha, n) \to$ n (1-10 MeV)	$\simeq 0.9 \times 10^{-7}$ [17]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 6 \times 10^{-4}$	[2, 7, 8]	$\ll 6 \times 10^{-5}$	$\ll 5 \times 10^{-3}$
	$\mu \to$ n from rock (> 10 MeV)	$\simeq 3 \times 10^{-9}$ (see text and ref. [12])	0.0129 [23]	end of June [23, 7, 8]	$\ll 7 \times 10^{-4}$	(see text and [2, 7, 8])	$\ll 9 \times 10^{-6}$	$\ll 8 \times 10^{-4}$
	$\mu \to$ n from Pb shield (> 10 MeV)	$\simeq 6 \times 10^{-9}$ (see footnote 3)	0.0129 [23]	end of June [23, 7, 8]	$\ll 1.4 \times 10^{-3}$	(see text and footnote 3)	$\ll 2 \times 10^{-5}$	$\ll 1.6 \times 10^{-3}$
	$\nu \to$ n (few MeV)	$\simeq 3 \times 10^{-10}$ (see text)	0.03342 *	Jan. 4th *	$\ll 7 \times 10^{-5}$	(see text)	$\ll 2 \times 10^{-6}$	$\ll 2 \times 10^{-4}$
	direct μ	$\Phi_0^{(\mu)} \simeq 20$ μ $m^{-2}d^{-1}$ [20]	0.0129 [23]	end of June [23, 7, 8]	$\simeq 10^{-7}$	[2, 7, 8]	$\simeq 10^{-9}$	$\simeq 10^{-7}$
	direct ν	$\Phi_0^{(\nu)} \simeq 6 \times 10^{10}$ ν $cm^{-2}s^{-1}$ [26]	0.03342 *	Jan. 4th *	$\simeq 10^{-5}$	[31]	3×10^{-7}	3×10^{-5}

* The annual modulation of solar neutrino is due to the different Sun-Earth distance along the year; so the relative modulation amplitude is twice the eccentricity of the Earth orbit and the phase is given by the perihelion.

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

\+ In no case neutrons (of whatever origin), muon or muon induced events, solar ν can mimic the DM annual modulation signature since some of the **peculiar requirements of the signature** would fail (and – in addition – quantitatively negligible amplitude with respect to the measured effect).

Investigating diurnal modulation in DAMA/LIBRA-phase1

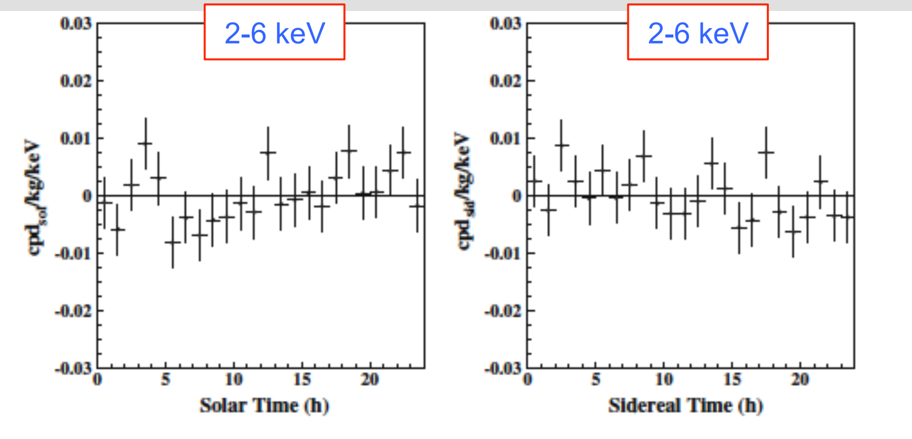
EPJC74(2014)2827

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

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

Model Independent result on Diurnal Modulation

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



Energy	Solar χ^2/d.o.f (P)	Sideral 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%)

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

The ratio R_{dy} of the diurnal over annual modulation amplitudes (sideral time) is a model independent constant at give latitude

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

@ 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

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

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

DAMA/LIBRA-phase2 will offer increased sensitivity

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

Presence of modulation over 14 annual cycles at 9.3σ 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 × 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±0.002) yr, well compatible with the 1 yr period, as expected for the DM signal

3) Measured phase (144±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 ± 0.0012) cpd/kg/keV (9.3σ 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

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

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No systematic or side process able to simultaneou
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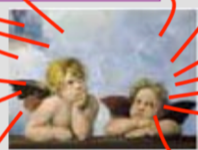
Model-independent evidence by DAMA/NaI and DAMA/LIBRA

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
- Self interacting Dark Matter
- Dark Matter (including some scenarios for WIMP) electron-interacting
- Sterile neutrino
- heavy exotic canditates, as "4th family atoms", ...
- Elementary Black holes such as the Daemons
- Kaluza Klein particles
- … and more



Some direct detection processes:

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

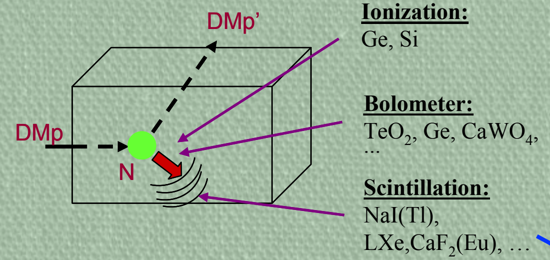
→ W has 2 mass states $\chi+$, $\chi-$ with δ mass splitting

→ Kinematic constraint for the inelastic scattering of $\chi-$ on a nucleus

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

- Elastic scatterings on nuclei

→ detection of nuclear recoil energy



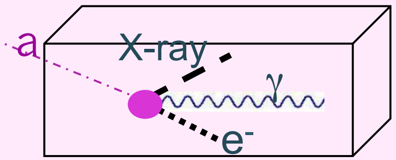
- Excitation of bound electrons in scatterings on nuclei

→ detection of recoil nuclei + e.m. radiation

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

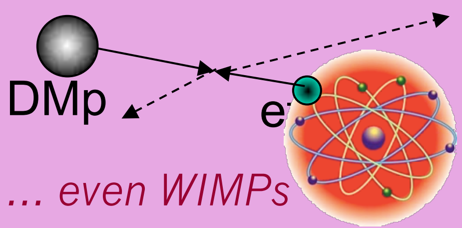
- Conversion of particle into e.m. radiation

→ detection of γ, X-rays, e^-



- Interaction only on atomic electrons

→ detection of e.m. radiation

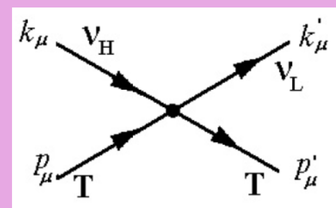


... even WIMPs

- 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

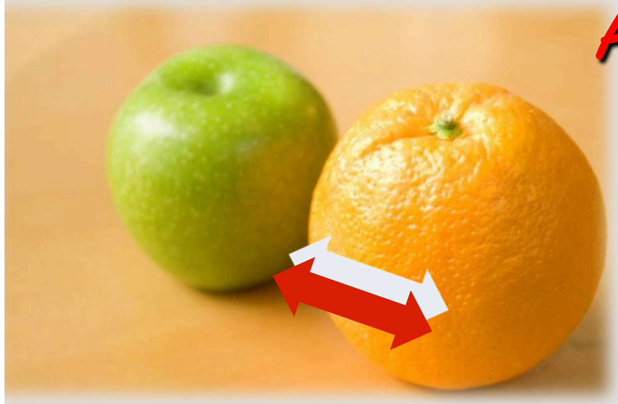


... also other ideas ...

- ... and more

About interpretation and comparisons

See e.g.: Riv.N.Cim.26 ono.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 EFT operators contribute?
- 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?
- ...

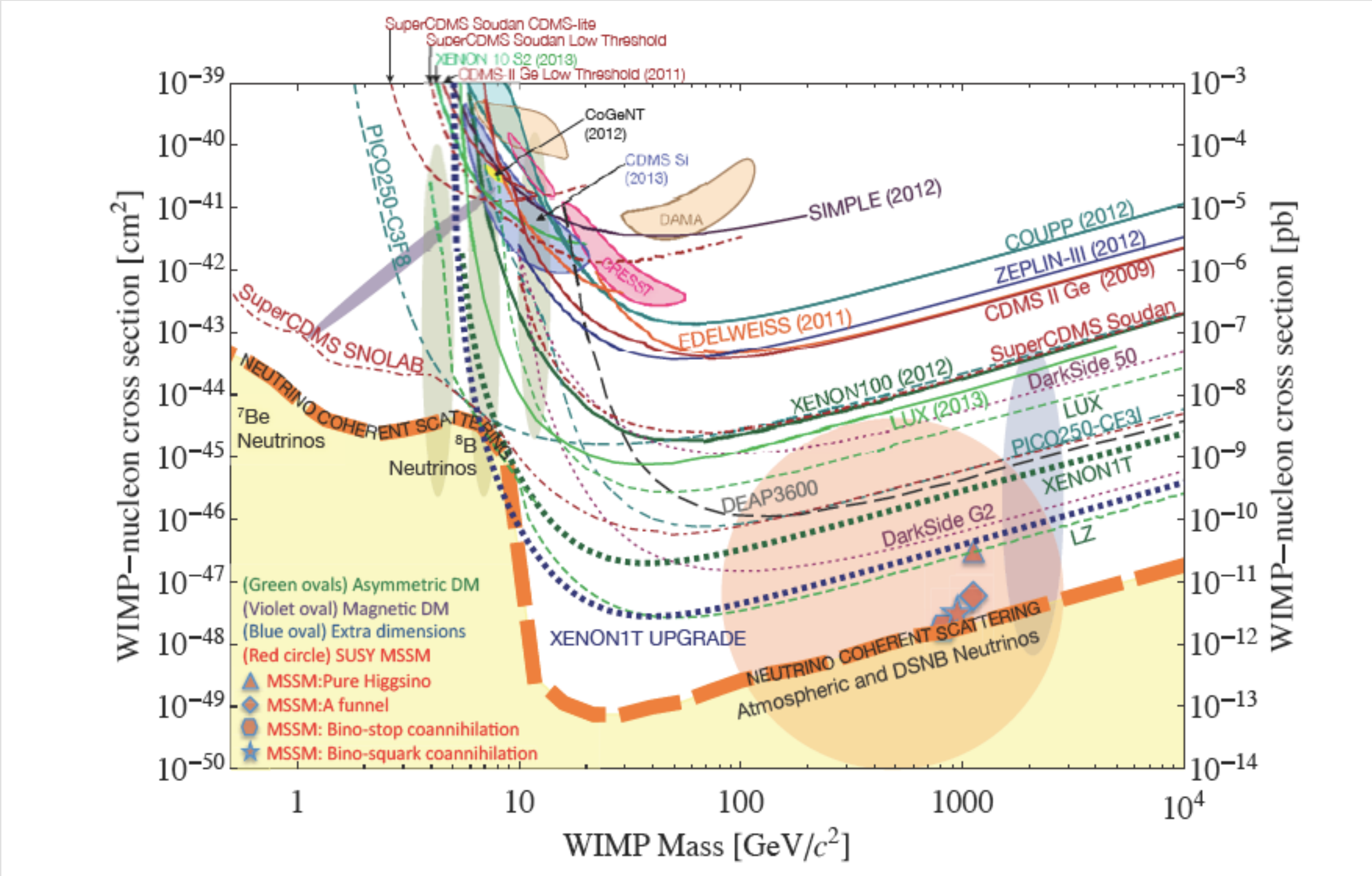
...and experimental aspects...

- 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 – at least in principle - be directly compared in a model independent way with DAMA

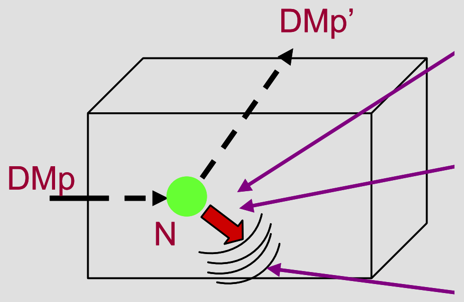
Is it an "universal" and "correct" way to approach the problem of DM and comparisons?



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

... an example in literature...

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



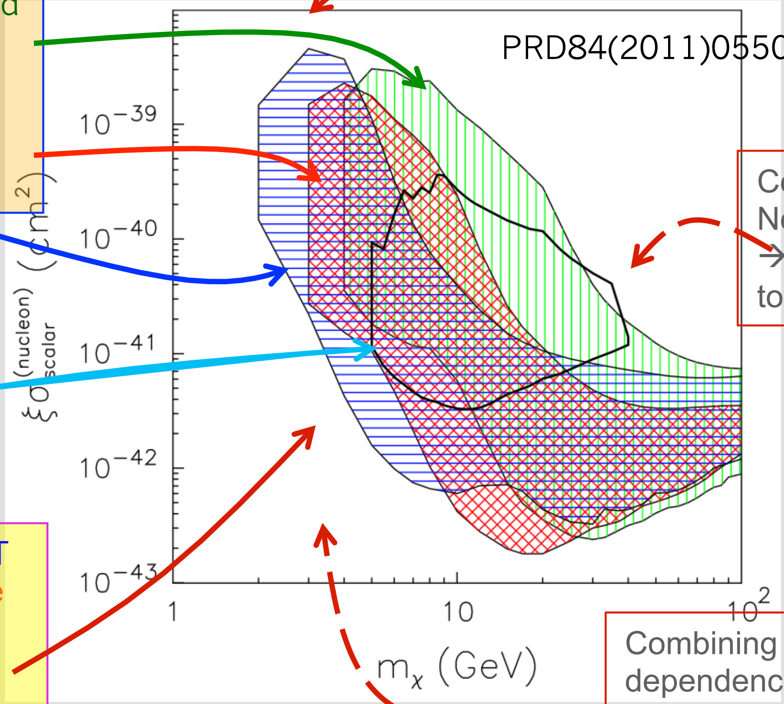
Regions in the nucleon cross section vs DM particle mass plane

- 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.

Including the Migdal effect
→Towards lower mass/higher σ

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

7.5 σ C.L.



PRD84(2011)055014, IJMPA28(2013)1330022

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

CoGeNT; qf at fixed assumed value

1.64 σ C.L.

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

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

Scratching Below the Surface of the Most General Parameter Space
(S. Scopel talk in DM2 session at MG14)

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

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

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

… and much more considering experimental and theoretical uncertainties

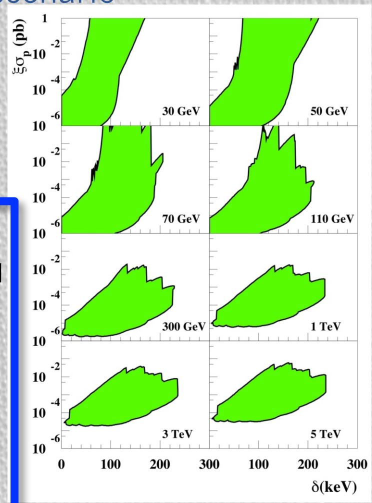
Other examples

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

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

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

DAMA slices from the 3D allowed volume in given scenario



Fund. Phys. 40(2010)900

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

PRL106(2011)011301

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

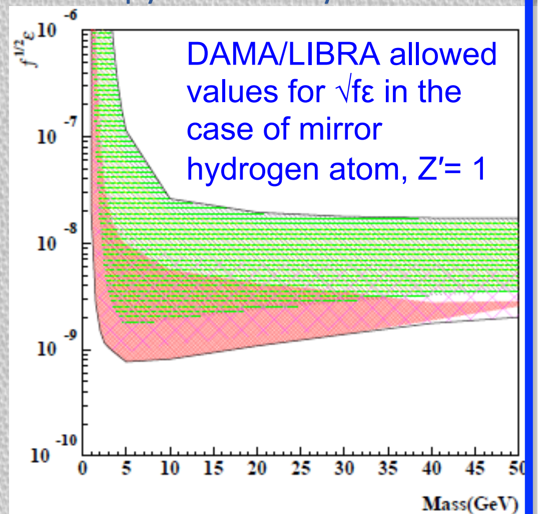
Mirror Dark Matter

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

(See **EPJC75(2015)400**)

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

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



See also Eur. Phys. J. C (2017) 77

Other DAMA investigations which involve also low mass candidates

✓ **Migdal effect** [IJMPA22(2007)3155]:

Ionization and excitation of bound atomic e^- induced by the recoiling atomic nucleus, in the case of DM particle-nucleus elastic scattering

- recoiling nucleus can "shake off" some of the atomic e
- recoil signal + e.m. contribution (escaping electron, X-rays, Auger e^- arising from rearrangement of atomic shells)
- e.m. radiation fully contained in the detector

can give an appreciable impact at low masses

✓ **electron interacting DM** [PRD77(2008)023506]

The electron in the atom is not at rest → there is a very-small but not-zero probability to have electrons with momenta of ≈ MeV/c.

Candidates expected, e.g.:

- in theories that foreseen leptonic colour interactions: $SU(3)_l \times SU(3)_c \times SU(2)_L \times U(1)$ broken at low energy.
- in models where they interact through a neutral current light (MeV scale) U boson.
- domains in general SUSY parameter space where LSP-electron interaction can dominate on LSP-quark one.

✓ **direct detection of LDM** [MPLA23(2008)2125]

in the interaction with electron or nucleus a lighter particle is produced and the target (either nucleus or electrons) recoils with an energy which can be detectable.

LDM can be either a boson or a fermion.

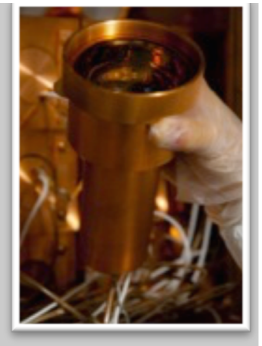
- DM candidates with sub-GeV mass can contribute to the Warm Dark Matter (such as e.g. keV-scale sterile ν, axino or gravitino)
- MeV-scale DM particles (e.g. axino, gravitino, heavy neutrinos, moduli fields from string theories,…) proposed as source of 511 keV γ's from the GC
- SUSY models exist where the LSP naturally has a MeV-scale mass and other properties required to generate the 511 keV γ's in the galactic bulge

✓ **light bosonic particles (Axion-like)** [IJMPA21(2006)1445]

detection is based on the total conversion of the absorbed bosonic mass into electromagnetic radiation

- Hypothesis: ~ keV axion-like (K.K. axion) trapped in the Sun neighborhood and γγ decay
- Astrophysical hints: solar corona problem; X-ray from dark side of the Moon; soft X-ray background radiation; "diffuse" soft X-ray excess

DAMA/LIBRA phase 2 – data taking



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

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

Energy resolution mean value: prev. PMTs 7.5% (0.6% RMS)
new HQE PMTs 6.7% (0.5% RMS)

- ✓ Fall 2012: new preamplifiers installed + special trigger modules.
- ✓ Calibrations 5 a.c.: ≈ 1.03×10^8 events from sources
- ✓ Acceptance window eff. 5 a.c.: ≈ 7×10^7 events (≈2.8×10^6 events/keV)

Annual Cycles	Period	Mass (kg)	Exposure	$(\alpha-\beta^2)$
I	Dec 2010 – Sept. 2011	commissioning		
II	Nov. 2, 2011 – Sept. 11, 2012	242.5	62917	0.519
III	Oct. 8, 2012 – Sept. 2, 2013	242.5	60586	0.534
IV	Sept. 8, 2013 – Sept. 1, 2014	242.5	73792	0.479
V	Sept. 1, 2014 – Sept. 9, 2015	242.5	71180	0.486
VI	Sept. 10, 2015 – Sept. 6, 2016	242.5	≈70000 (under analysis)	
VII	Sept 2016 –	242.5	running	

PRELIMINARY

Exposure expected for the first data release of DAMA/LIBRA-phase2: ≈ **1 ton × yr**

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

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

increased in DAMA/LIBRA-phase2 (ε)

increased in DAMA/LIBRA-phase2 (ΔE)

increased with DAMA/LIBRA-phase2 (T)

→ DAMA/LIBRA-phase2 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

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

Higher exposure and lower threshold can allow further investigation on:

- the nature of the DMp
  - ✓ to disentangle among different astrophysical, nuclear and particle physics models (nature of the candidate, couplings, form factors, spin-factors …)
  - ✓ scaling laws and cross sections
  - ✓ multi-component DMp halo?
- possible diurnal effects in 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 DMp 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

A step towards such investigations:

→**DAMA/LIBRA-phase2 with lower energy threshold**

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:

- 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).

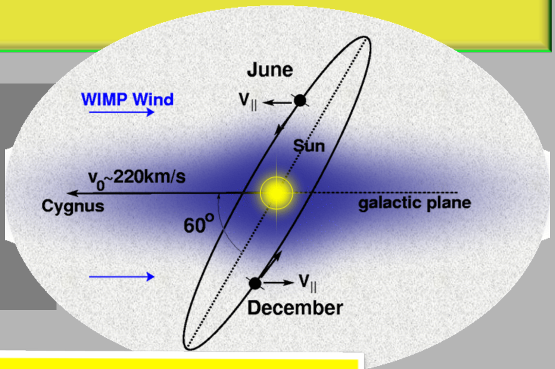
R&D efforts to obtain PMTs matching the best performances… feasible

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

Development of detectors with anisotropic response

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

Anisotropic detectors are of great interest for many applicative fields, e.g.:
⇒ they can offer a unique way to study directionality for Dark Matter candidates that induce just nuclear recoils



Taking into account:
- the correlation between the direction of the nuclear recoils and the Earth motion in the galactic rest frame;
- the peculiar features of anisotropic detectors;

The detector response is expected to vary as a function of the sidereal time

Development of $ZnWO_4$ scintillators

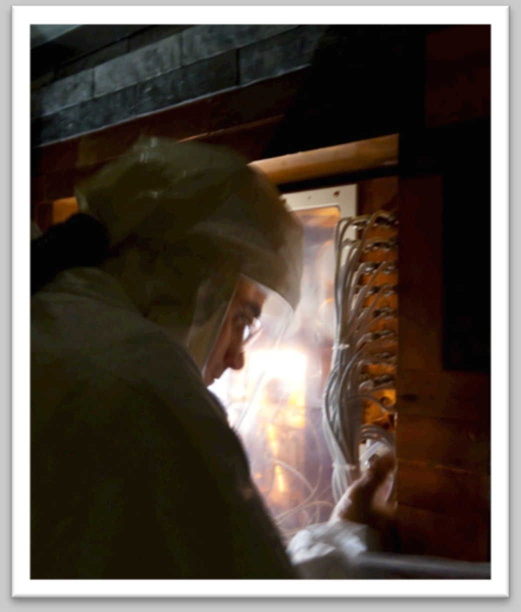
- ✓ Both light output and pulse shape have anisotropic behavior and can provide two independent ways to study directionality
- ✓ Very high reachable radio-purity;
- ✓ Threshold at keV feasible;

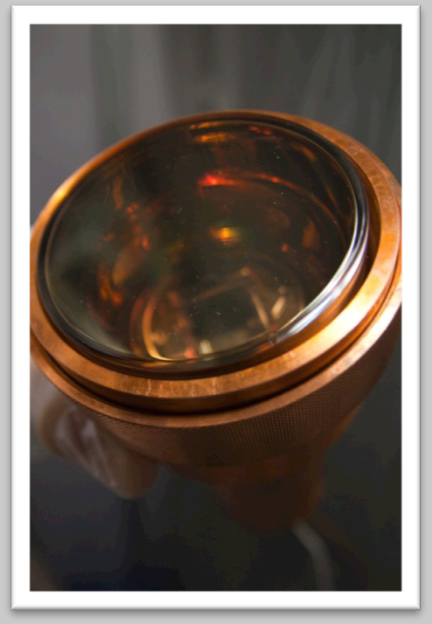
O → light masses
Zn, W → high masses

Presently running at ENEA-Casaccia with neutron generator to measure anisotropy in keV range

Conclusions

- Positive evidence for the presence of DM particles in the galactic halo at **9.3σ** C.L. (14 annual cycles DAMA/NaI and DAMA/LIBRA-phase1: 1.33 ton × yr)
- Modulation parameters determined with higher precision
- New investigations on different peculiarities of the DM signal exploited (**Diurnal Modulation** and **Earth Shadow Effect**)
- New corollary analysis on **Mirror Dark Matter**
- 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)
- Continuing investigations of rare processes other than DM
- **DAMA/LIBRA – phase3 R&D in progress**
- R&D for a possible DAMA/1ton set-up, proposed by DAMA since 1996, **continuing** as well as **some other R&Ds**