Recent analyses on the DAMA/LIBRA-phase1 data

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TAUP 2015
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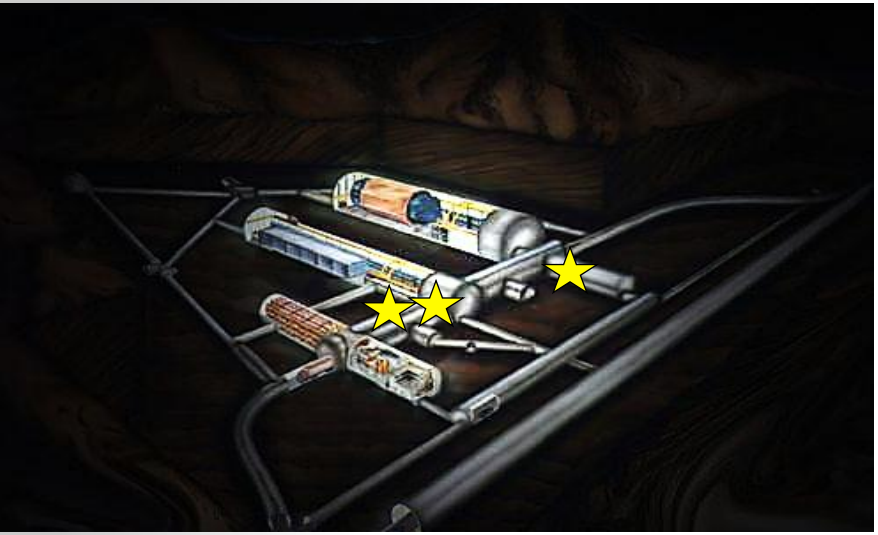
VIA session

DAMA set-ups

an observatory for rare processes @ LNGS



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

Collaboration:

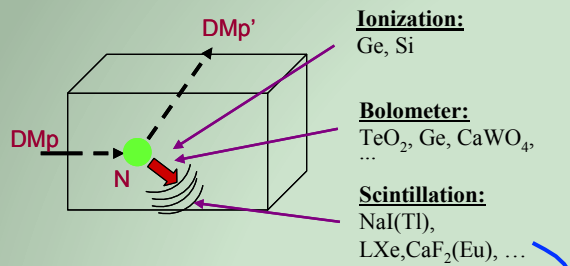
Roma Tor Vergata, Roma La Sapienza, LNGS, IHEP/Beijing
+ by-products and small scale
+ collaborators from several foreigner institution depending on the measurement
+ in some studies on ββ decays (DST-MAE project): IIT Ropar, India

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

Some direct detection processes:

- Scatterings on nuclei

  → detection of nuclear recoil energy



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

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

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

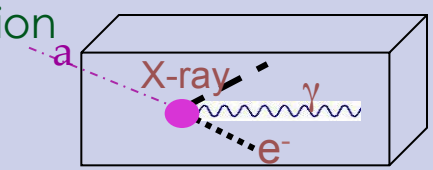
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

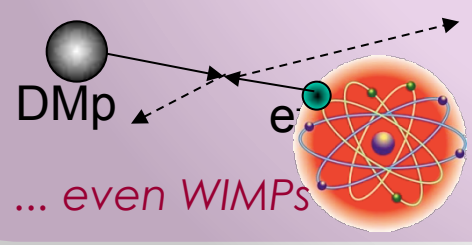
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

  → detection of e.m. radiation

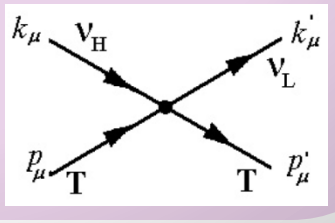


… even WIMPs

- 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 …

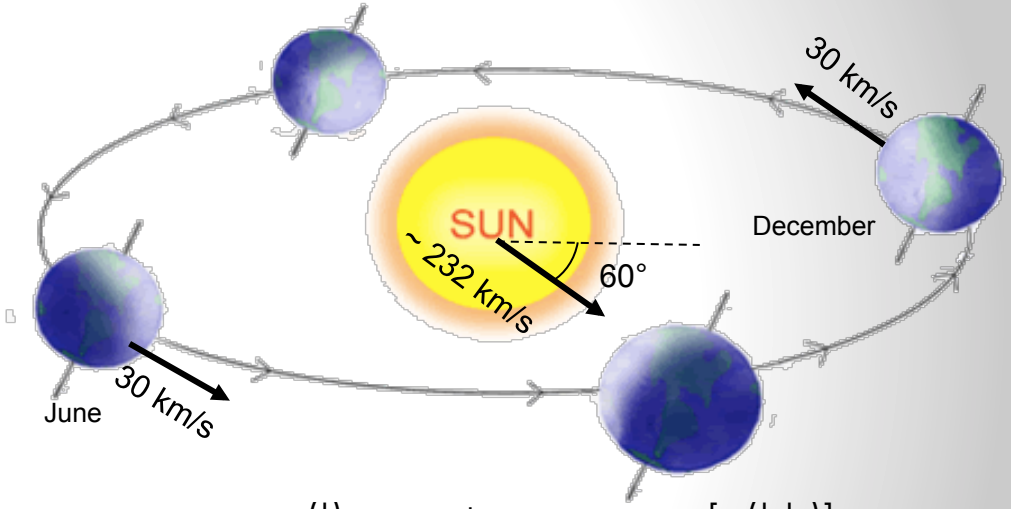
The annual modulation: a model independent signature for the investigation of DM particles

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.

Requirements:

1) Cosine-like modulation of the rate
2) In low energy range
3) Period of 1 year
4) Phase at about June 2nd
5) For single-hit events in a multi-detector set-up
6) With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions, but it can be larger in case of some possible scenarios

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



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

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

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:

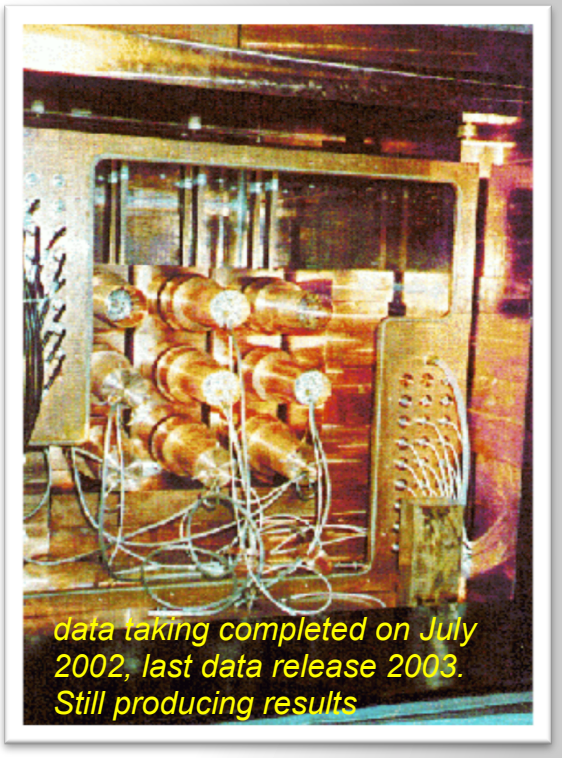
N.Cim.A112(1999)545-575, EPJC18(2000)283, Riv.N.Cim.26 n. 1(2003)1-73, IJMPD13(2004)2127

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



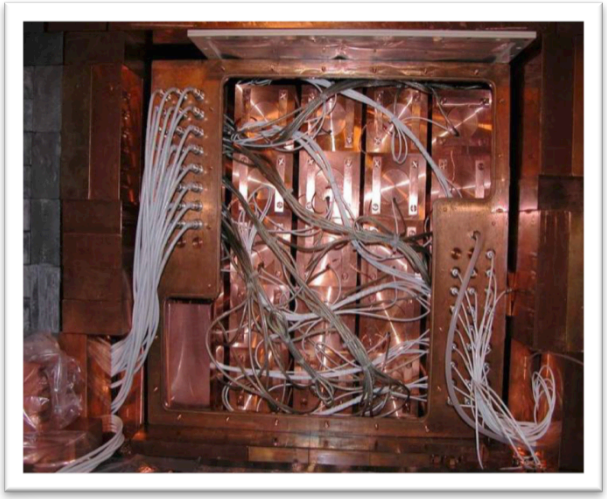
Model independent evidence of a particle DM component in the galactic halo at 6.3 σ C.L.

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 2nd generation R&D for more radiopure NaI(Tl) by exploiting new chemical/physical radiopurification techniques (all operations involving - including photos - in HP Nitrogen atmosphere)

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



- Radiopurity, performances, procedures, etc.: **NIMA592(2008)297, JINST 7 (2012) 03009**
- Results on DM, Annual Modulation Signature: **EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648**
  related results: **PRD84(2011)055014, EPJC72(2012)2064, IJMPA28 (2013)1330022, EPJC74(2014)2827, EPJC74(2014)3196, EPJC75 (2015)239, EPJC75(2015)400**

Rare processes: PEP viol.: **EPJC62(2009)327**, CNC in I: **EPJC72(2012)1920**, IPP in Am: **EPJA49(2013)64**

Complete DAMA/LIBRA-phase1

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

a ton × yr experiment? done

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

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

DAMA/LIBRA-phase1:

- First upgrade on Sept 2008: replacement of some PMTs in HP 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 and optimization tests 2011: replacement of all the PMTs with higher Q.E. ones from dedicated developments

  Goal: lowering the software energy threshold

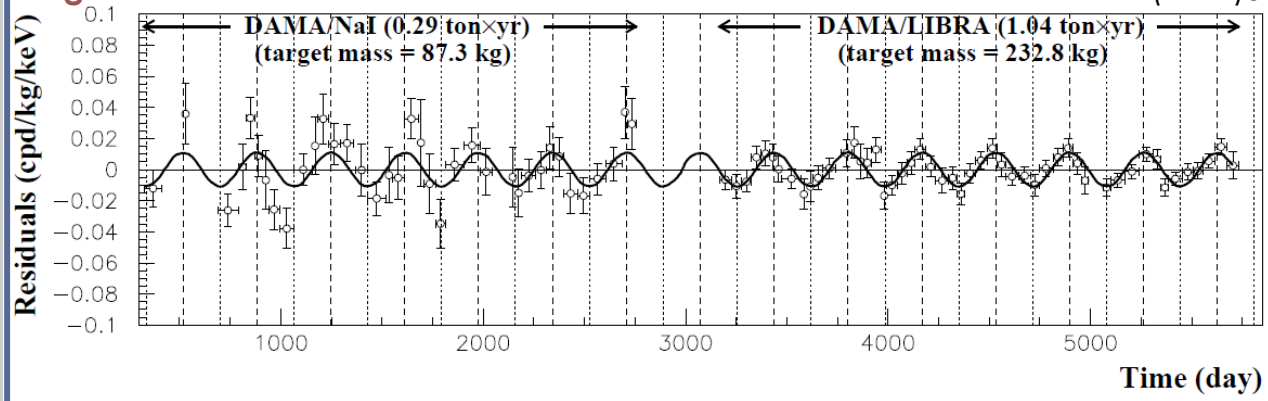
- Fall 2012: new preamplifiers installed + special trigger modules. Other new components in the electronic chain in development

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



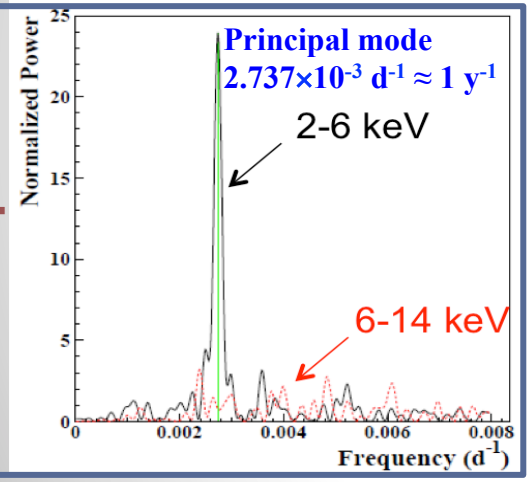
continuous line: t_0 = 152.5 d, T =1.0 y

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}

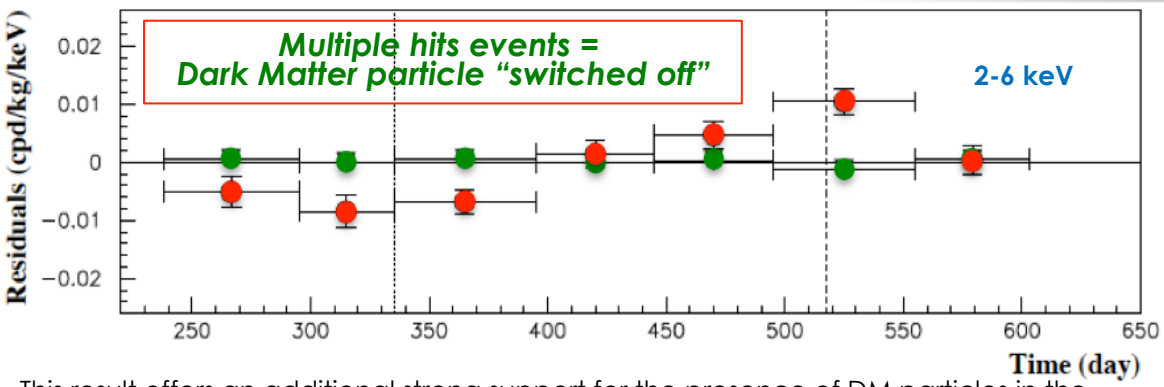
Fit with all the parameters free:
A = (0.0112 ± 0.0012) cpd/kg/keV
t_0 = (144±7) d - T = (0.998±0.002) y

Power spectrum



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.

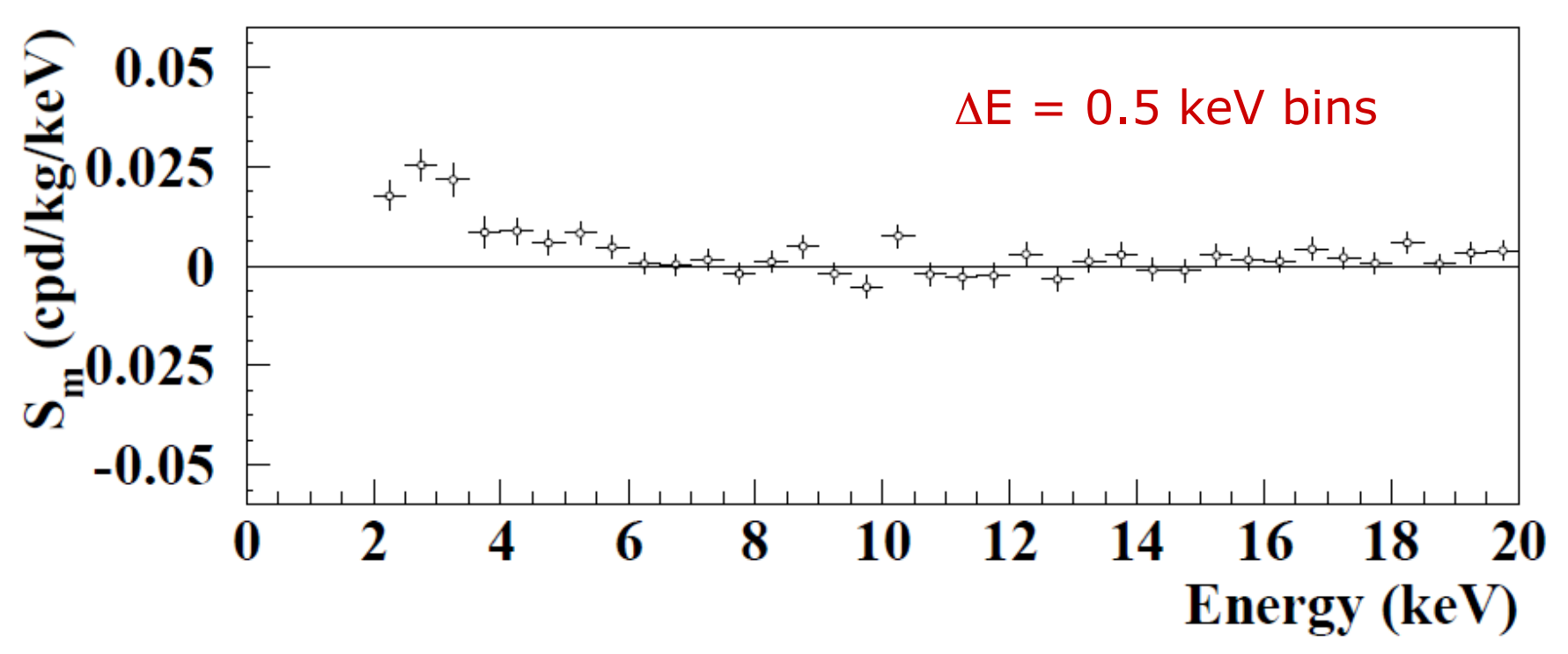
Energy distribution of the modulation amplitudes

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

$T=2\pi/\omega=1$ yr 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, 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

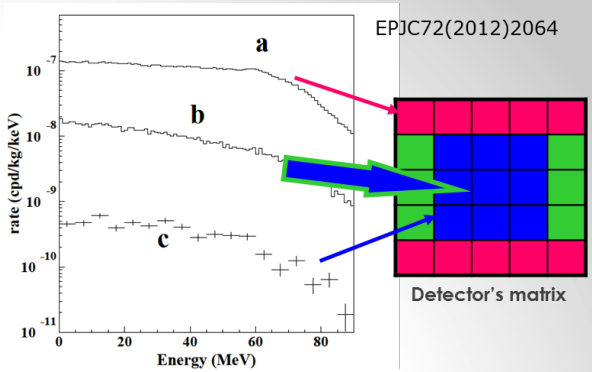
No role for μ in DAMA annual modulation result

- ✓ **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.



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

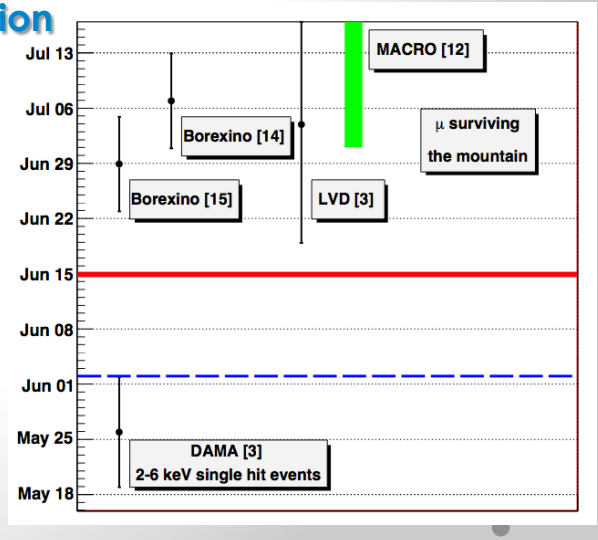
It cannot mimic the signature: already excluded by R_{90}, by *multi-hits* analysis + different phase, etc.

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

  μ flux @ LNGS (MACRO, LVD, BOREXINO) ≈$3 \cdot 10^{-4}$ $m^{-2}s^{-1}$; 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

... many other arguments EPJC72(2012)2064, EPJC74(2014)3196

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", …

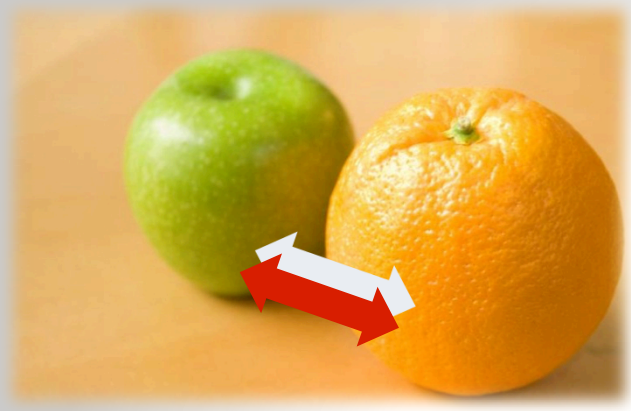
Kaluza Klein particles

Elementary Black holes such as the Daemons

… and more

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

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



About interpretation

See e.g.: Riv.N.Cim.26 n.1(2003)1, IJMPD13(2004)2127, EPJC47(2006)263, IJMPA21(2006)1445, EPJC56(2008)333, PRD84(2011)055014, JMPA28(2013)1330022

…models…

- Which particle?
- Which interaction coupling?
- Which 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
- …

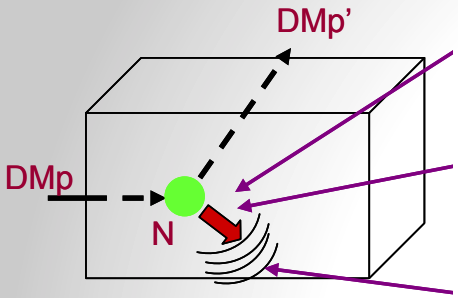
Uncertainty in experimental parameters, as well as necessary assumptions on various related astrophysical, nuclear and particle-physics aspects, affect all the results at various extent, both in terms of exclusion plots and in terms of allowed regions/volumes. Thus comparisons with a fixed set of assumptions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

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

… an example…

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

Regions in the nucleon cross section vs DM particle mass plane



- Some velocity distributions and uncertainties considered.
- The DAMA regions represent the domain where the likelihood-function values differ more than 7.5 σ 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 σ from the null hypothesis (absence of modulation). This corresponds roughly to 90% C.L. far from zero signal.

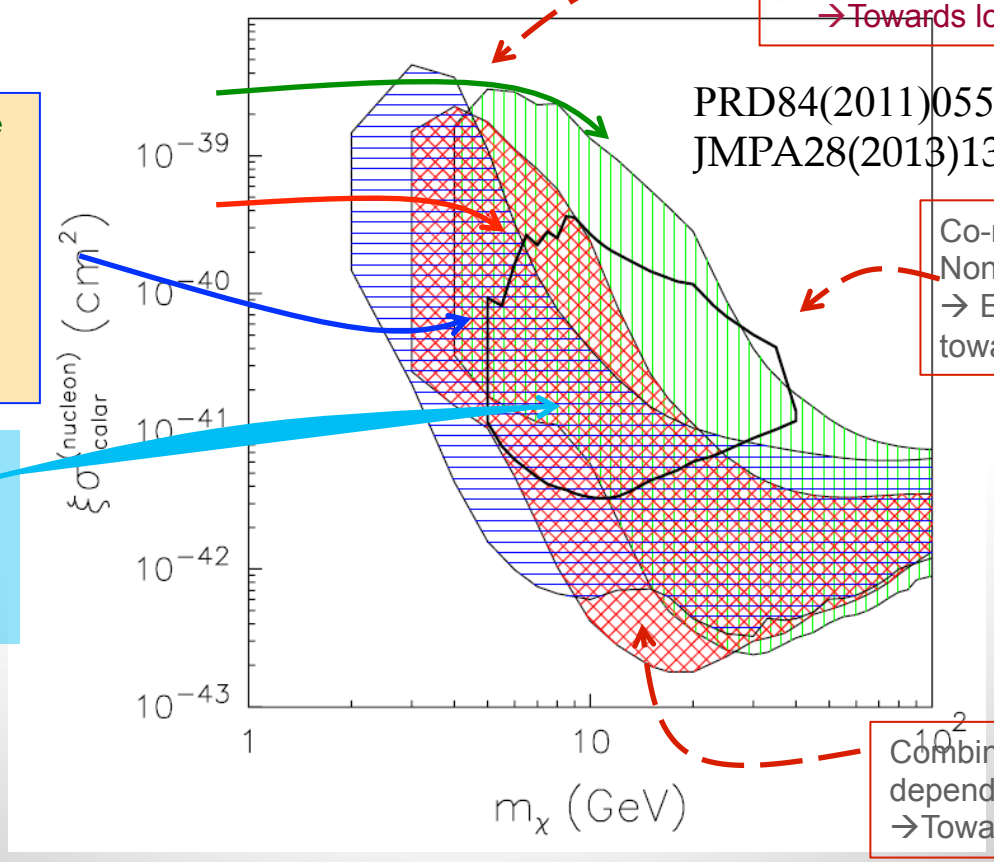
Including the Migdal effect
→Towards lower mass/higher σ

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

7.5 σ C.L.

CoGeNT: q.f. at a fixed assumed value

1.64s C.L.



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

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

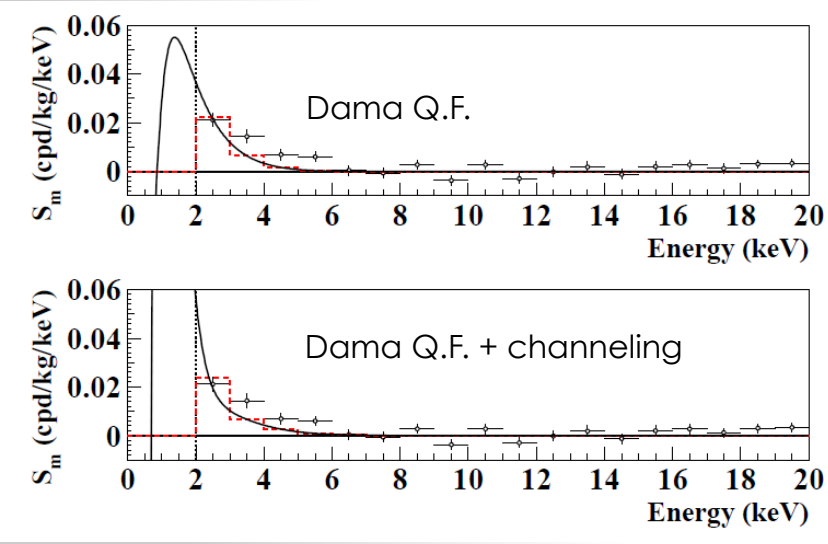
DAMA annual modulation effect and Asymmetric mirror matter

EPJC75(2015)400

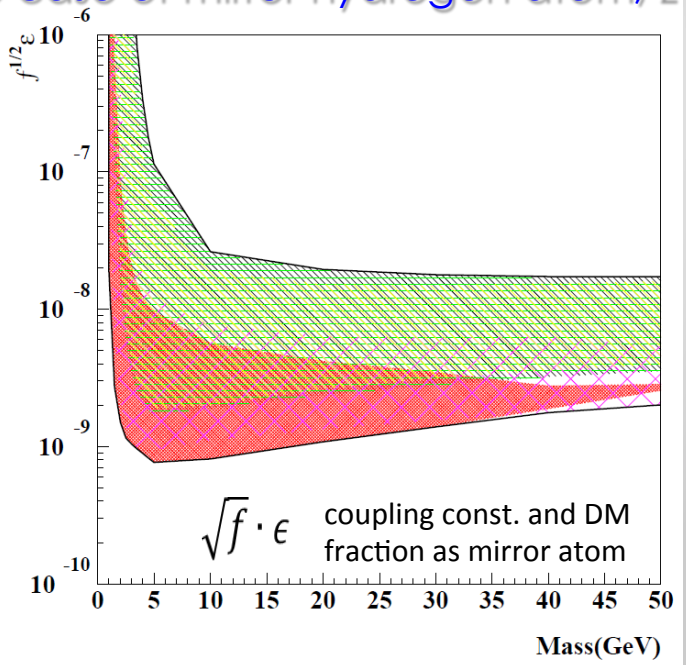
Asymmetric mirror matter: mirror parity spontaneously broken at the level of electroweak interactions ⇒ mirror sector heavier and deformed copy of ordinary sector; mirror hydrogen can be stable and a good DM candidate

- Interaction portal: photon - mirror photon kinetic mixing $\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$
- mirror atom scattering off the ordinary target nuclei with Rutherford-like cross sections.

Examples of expected S_m for the Mirror DM candidate for different values of quenching factor , $M=5m_p$ (≈ 5 GeV)



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



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

Investigating diurnal modulation in DAMA/LIBRA-phase1

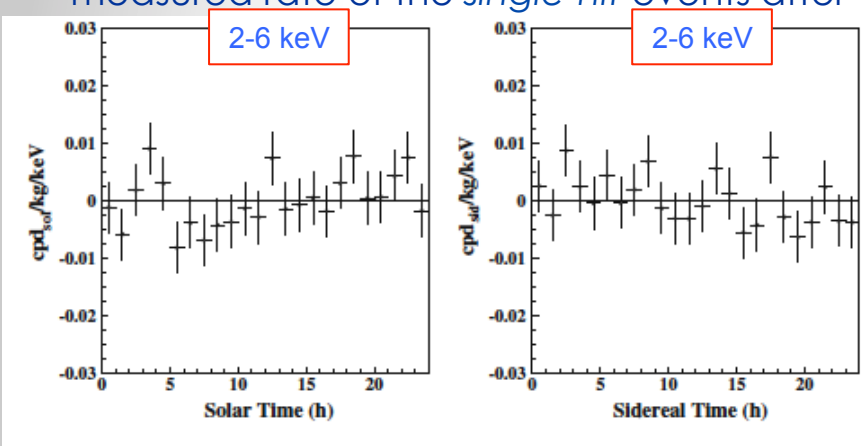
EPJC74(2014)2827

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.
- These residual rates are calculated from the measured rate of the *single-hit* events after



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) not observed at 95% C.L. at the reached level of sensitivity

The ratio R_{dy} of the diurnal over annual modulation amplitudes is a <u>model independent</u> constant at given latitude

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

at LNGS

- Annual modulation amplitude in DAMA/LIBRA–phase1 in the (2–6) keV: (0.0097 ± 0.0013) cpd/kg/keV
- Expected value of diurnal modulation amplitude:

$\simeq 1.5\times10^{-4}$ cpd/kg/keV

- Fitting the *single-hit* residuals as function of sidereal time with a cosine function with amplitude A_d as free parameter, period 24 h and phase 14 h:

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

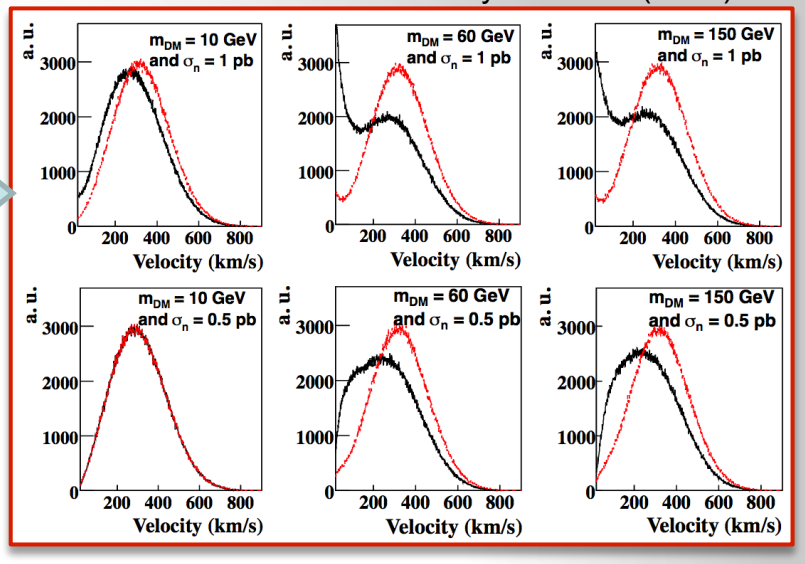
→ experimental sensitivity more modest than the expected diurnal modulation amplitude derived from the DAMA/LIBRA–phase1 annual modulation observed effect.

DAMA/LIBRA–phase2 will offer increased sensitivity

Investigation of Earth Shadow Effect

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

- **Earth Shadow Effect** expected for DM candidate particles inducing just 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



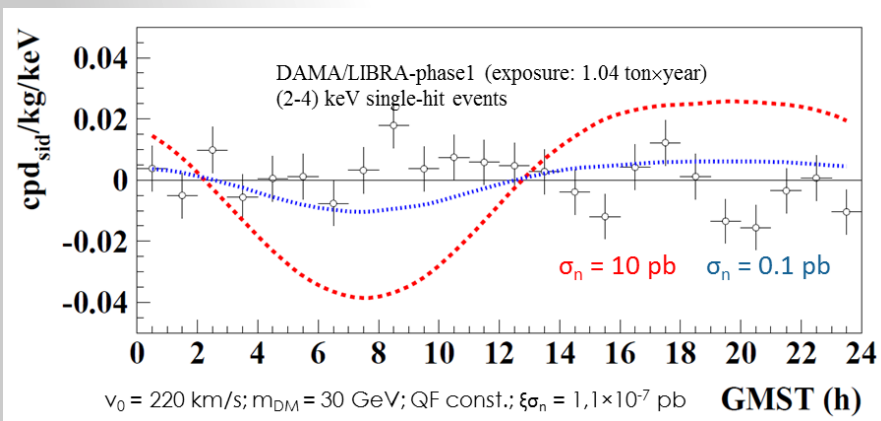
Expected counting rate for a given mass, cross section and scenario by MC:

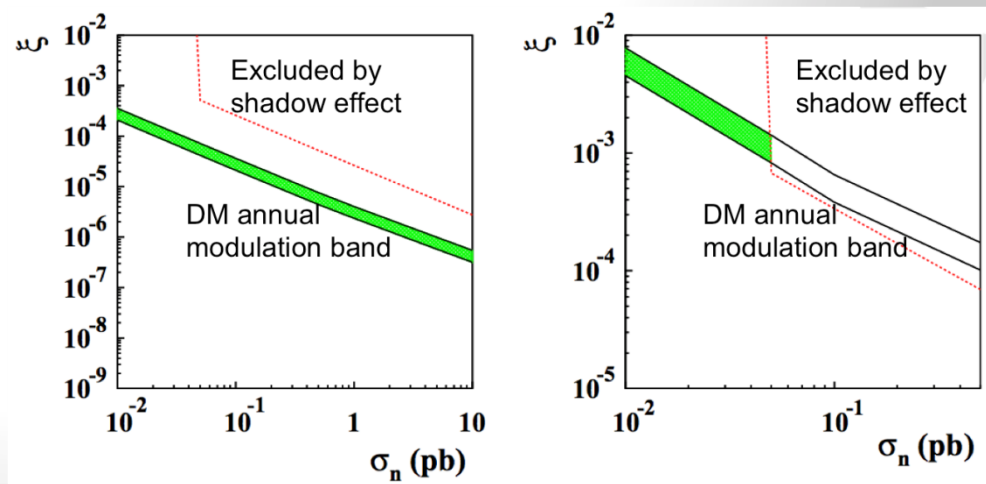
$$S_{d,sh}(t) = \xi\sigma_n S'_{d,sh}(t)$$

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

Constrain (red line) on DAMA/LIBRA DM annual modulation result from Earth Shadow Effect in the ξ vs σ_n plane for some m_{DM}(left: 10 GeV, right: 60 GeV)for the considered model framework



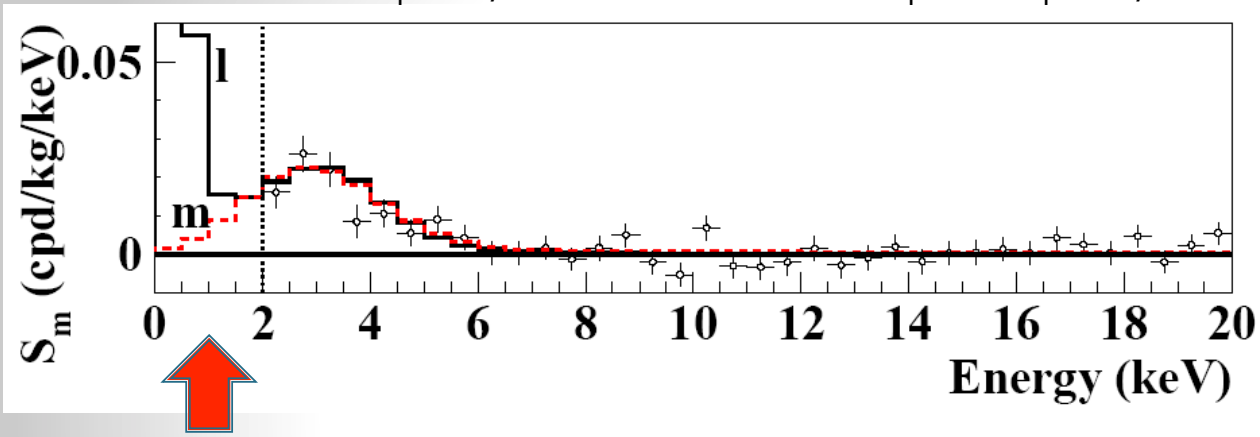


DAMA/LIBRA phase 2 - running

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

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

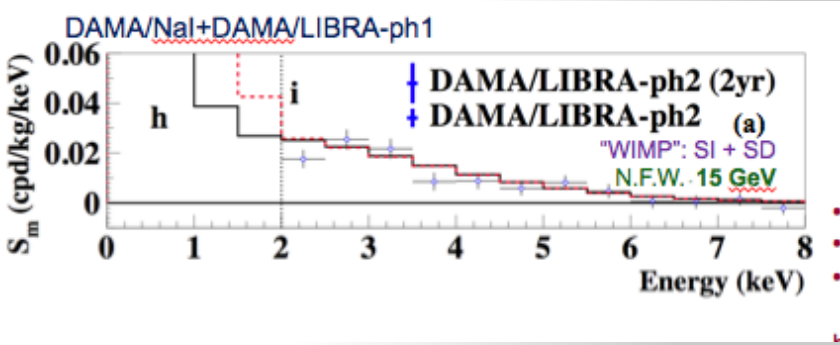
Previous PMTs: 5.5-7.5 ph.e./keV New PMTs: up to 10 ph.e./keV



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

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

Increased in DAMA/LIBRA-phase2; equivalent to have enlarged the exposed mass



(a) Assuming MT= 464000 kg day

$$\sigma(S_m) = \sqrt{\frac{\langle R \rangle}{M \cdot T \cdot \Delta E \cdot \varepsilon \cdot (\alpha - \beta^2)}}$$

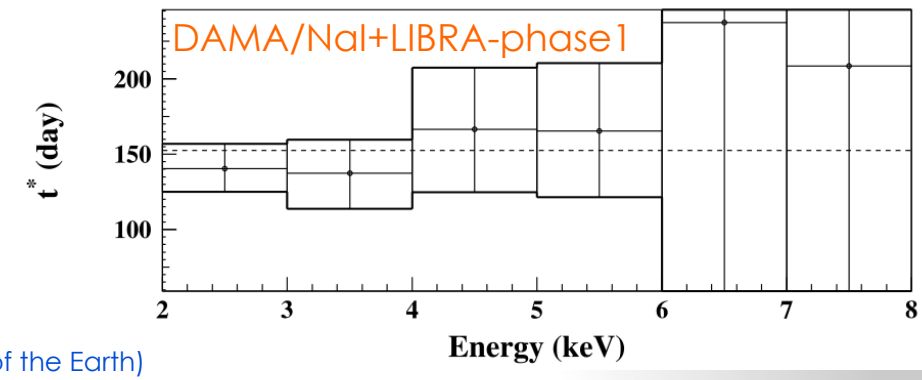
- First data release after 6 annual cycles
- Further annual cycles to collect exposure to investigate other peculiarities and second order effect

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:

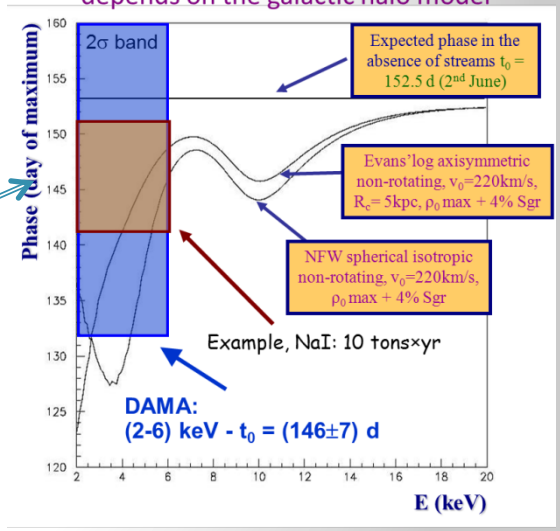
- the nature of the DM candidates
  - ✓ to disentangle among the different astrophysical, nuclear and particle physics models (nature of the candidate, couplings, inelastic interaction, form factors, spin-factors …)
  - ✓ scaling laws and cross sections
  - ✓ multi-component DM particles halo?
- possible 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



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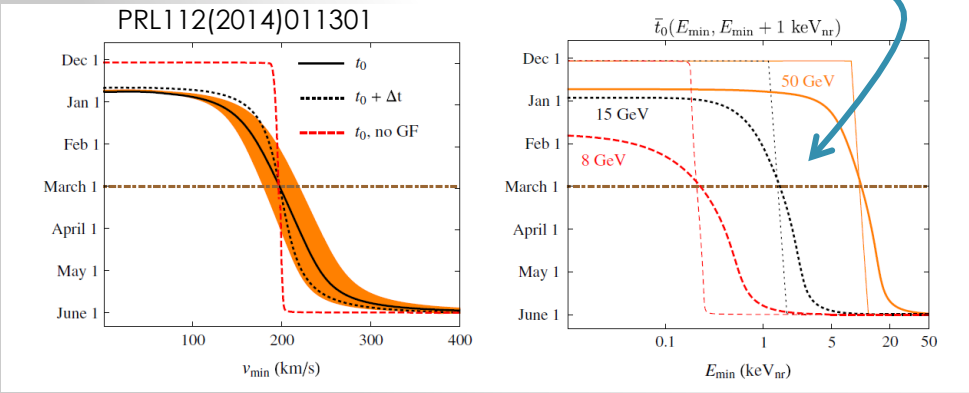
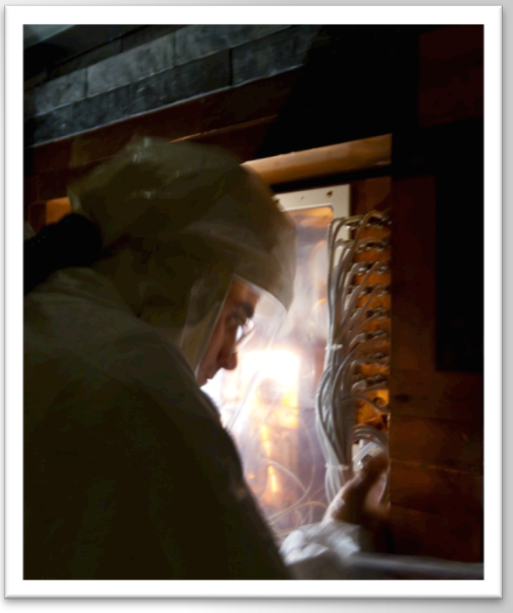


A step towards such investigations:

➔**DAMA/LIBRA-phase2**

with lower energy threshold and larger exposure

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 high precision
- New investigation 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) 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 full sensitive mass DAMA/1ton, DAMA proposed already in 1996, in progress