

Dark Matter direct detection



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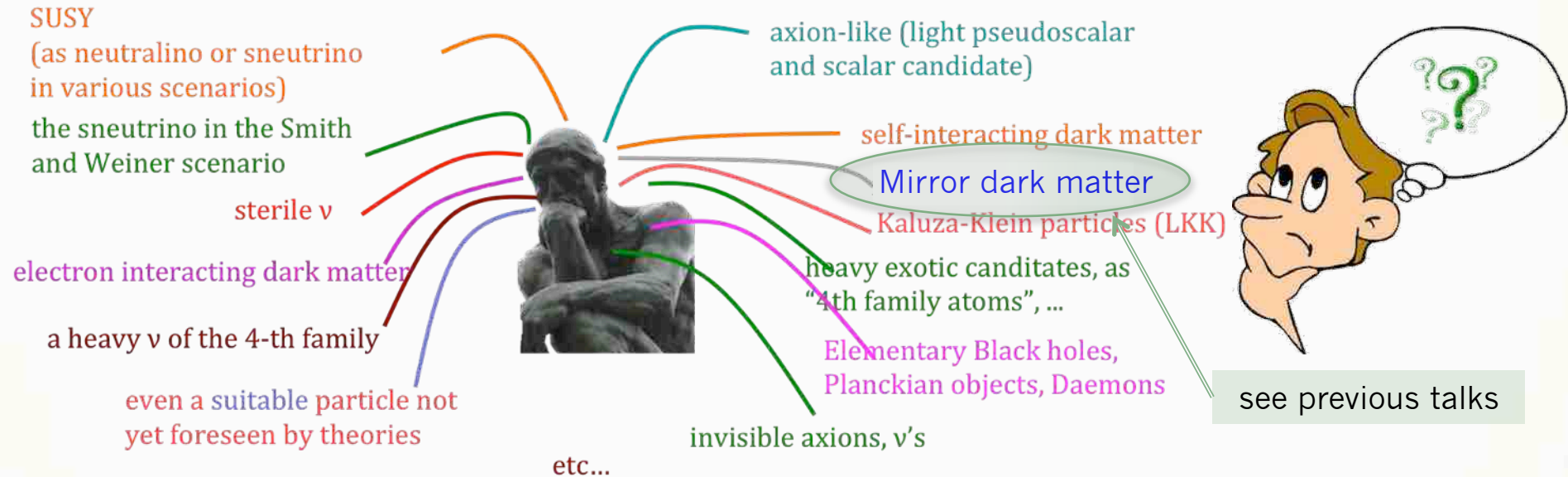
INT Workshop “Neutron-Antineutron Oscillations:
Appearance, Disappearance, and Baryogenesis”

INT-17-69W

Seattle, WA, USA

October 23 – 27, 2017

Relic DM particles from primordial Universe



What accelerators can do:

to demonstrate the existence of
some of the possible DM candidates

What accelerators cannot do:

to credit that a certain particle is the
Dark Matter solution or the "single"
Dark Matter particle solution...

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

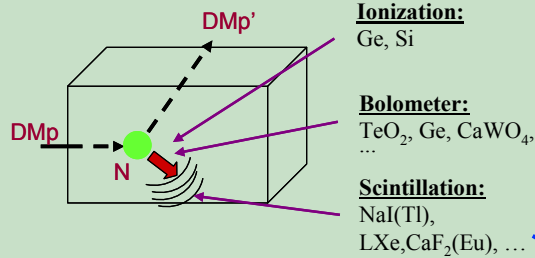
DM direct detection method using a model
independent approach and a low-background
widely-sensitive target material



Some direct detection processes:

- Scatterings on nuclei

→ detection of nuclear recoil energy



- Inelastic Dark Matter: $W + N \rightarrow W^* + N$

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

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

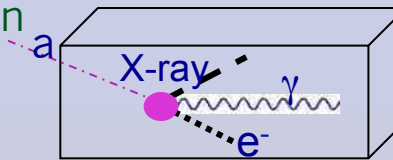
$$\frac{1}{2} \mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

→ detection of recoil nuclei + e.m. radiation

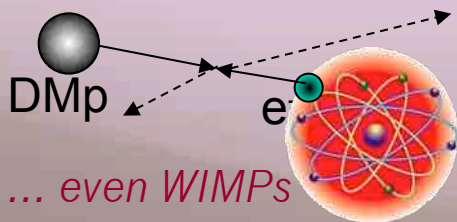
- Conversion of particle into e.m. radiation

→ detection of γ , X-rays, e^-



- Interaction only on atomic electrons

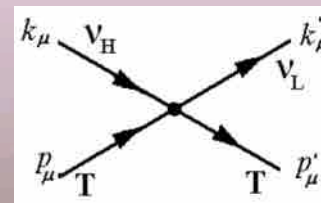
→ detection of e.m. radiation



- Interaction of light DMp (LDM) on e^- or nucleus with production of a lighter particle

→ detection of electron/nucleus recoil energy

e.g. sterile ν



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

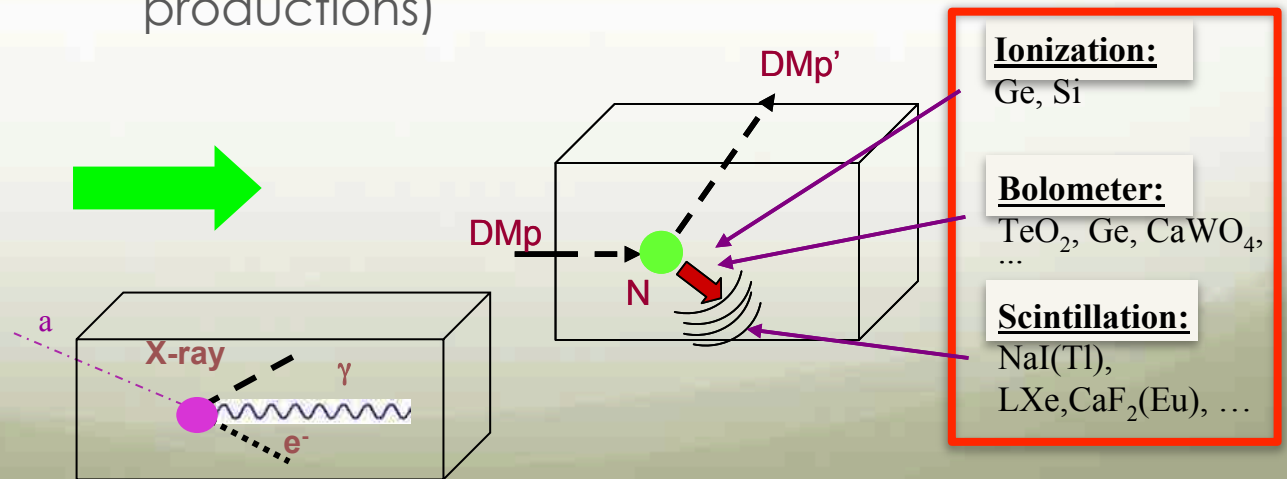
... also other ideas ...

• ... and more

Direct detection experiments

The direct detection experiments can be classified in **two classes**, depending on what they are based:

1. on the recognition of the signals due to Dark Matter particles with respect to the background by using a ***model-independent signature***
2. on the use of uncertain techniques of statistical **subtractions** of the e.m. component **of the counting rate** (adding systematical effects and lost of candidates with pure electromagnetic productions)



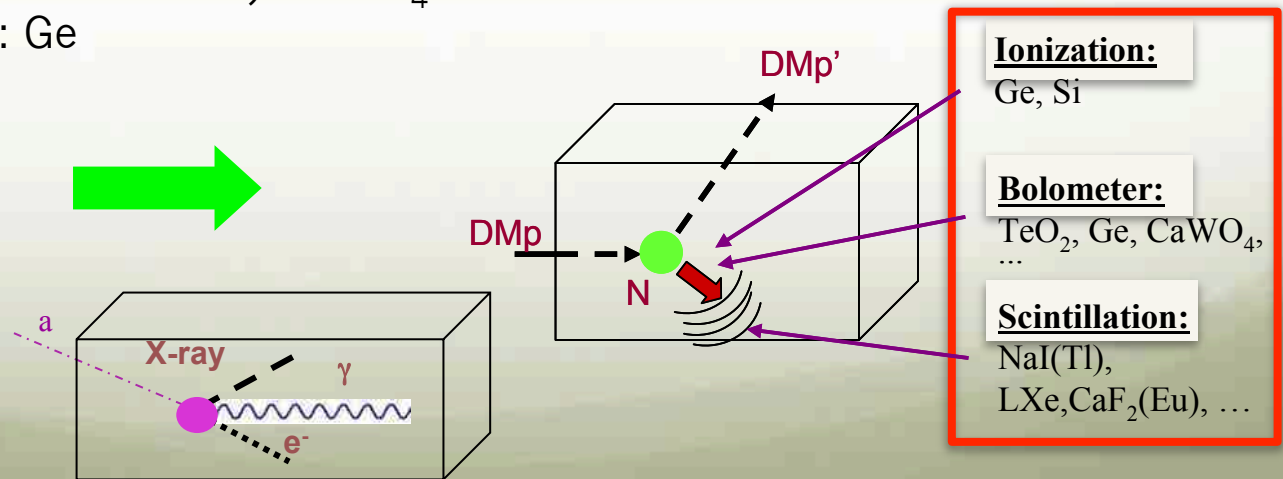
Direct detection experiments

Summarizing, the detectors for DM:

- must have very low-energy thresholds (order of keV at least)
- must have very low intrinsic bckg
- must be well shielded by external environmental radiation (muons, neutrons, gammas, ...)
- must be stable with time
- must have very good experimental features (energy resolution, check of the energy scale, uniformity of the detector, and many others)

Many techniques/experiments on the market:

- Scintillation detectors: NaI(Tl) ...
- Liquid noble gases: LXe, LAr, LNe
- Bolometers (heat vs ionization): Ge, Si
- Bolometers (heat vs scintillation): CaWO_4
- Ionization detectors: Ge
- and others...



Experiments using liquid noble gases

in single phase detector:

- pulse shape discrimination γ /recoils from the UV scintillation photons



DAMA/LXe



XMASS

- **Non-uniform** response of detector: intrinsic limit
- **UV light, nonlinearity** (more in larger volumes)
- **Correction** procedures applied
- **Systematics**
- **Small light responses** (2.2 ph.e./keVee) \Rightarrow energy threshold at few keV unsafe
- Physical **energy threshold unproved** by source calibrations
- Poor energy **resolution**; resolution at threshold **unknown**
- **Light responses** for electrons and recoils at low energy
- **Quenching factors** measured with a much-more-performing detector **cannot be used** straightforward
- Etc.

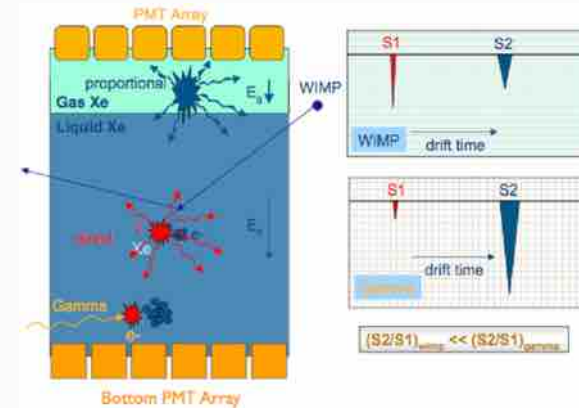
After many cuts few events survive: intrinsic limit reached?

in dual phase detector:

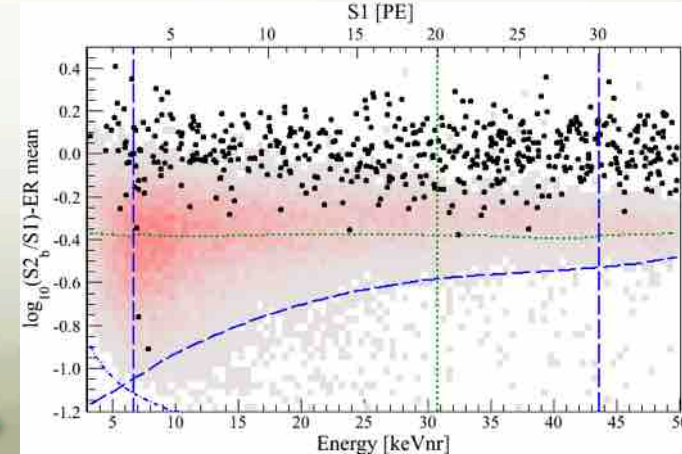
- prompt signal (S1): UV photons from excitation and ionization
- delayed signal (S2): e^- drifted into gas phase and secondary scintillation due to ionization in electric field

Statistical rejection of e.m. component of the counting rate

WARP, XENON10, 100, 1T, LUX, PANDAX, DarkSide, DEAP, CLEAN, ArDM



Many cuts applied, each of them can introduce **systematics**. The systematics can be variable along the data taking period; can they and the related efficiencies be suitably evaluated in short period calibration?



Even very small **systematics** in the data selections and statistical discrimination and rejection procedures can be difficult to estimate;

e.m. component of the rate can contain the signal or part of it

Even assuming pure recoil case and ideal discrimination on an event-by-event base, the result will NOT be the identification of the presence of WIMP elastic scatterings as DM signal, because of the well **known existing recoil-like indistinguishable background**

Therefore, even in the ideal case the “excellent suppression of the e.m. component of the counting rate” can **not** provide a “signal identification”

A model independent signature is needed

Directionality Correlation of DM impinging direction with Earth's galactic motion

only for DM inducing recoils



Annual modulation Annual variation of the interaction rate due to Earth motion around the Sun

at present the only feasible one, sensitive to many DM candidates and scenarios

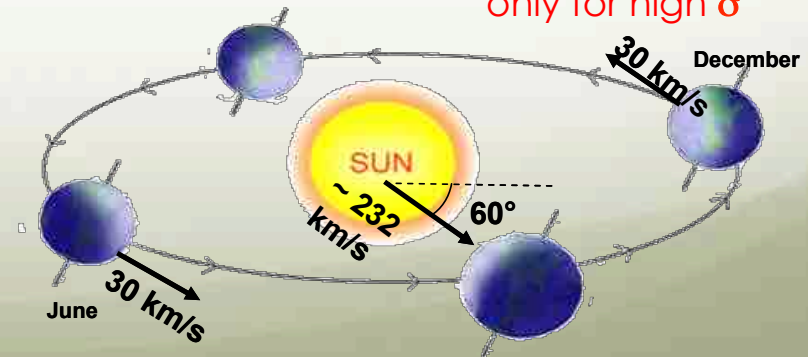
Diurnal modulation due to the Earth rotation around its axis

2nd order effect



Shadow effect Daily variation of the interaction rate due to different Earth depth crossed by the DM particles

only for high σ



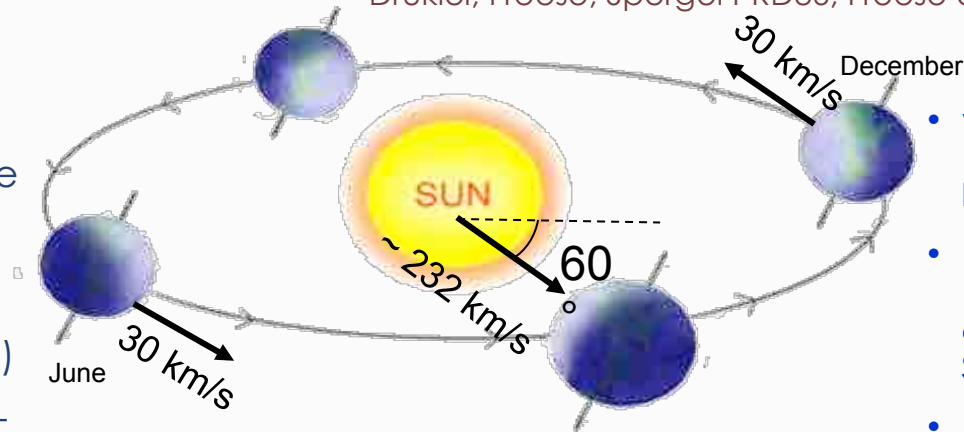
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

With the present technology, the annual modulation is the main model independent signature for the DM signal. Although the modulation effect is expected to be relatively small a suitable large-mass, low-radioactive set-up with an efficient control of the running conditions can point out its presence.

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

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



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

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

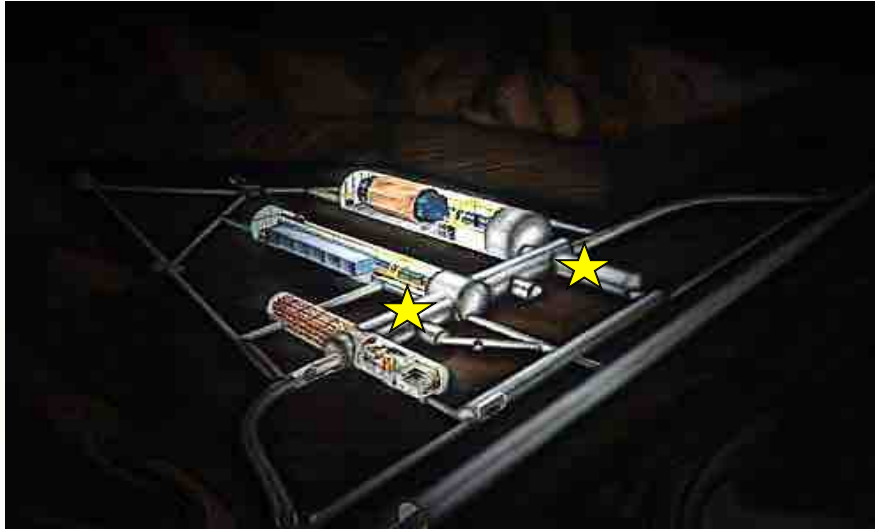
$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \approx S_{0,k} + S_{m,k} \cos[\omega(t-t_0)]$$

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

DAMA set-ups

an observatory for rare processes @ LNGS



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

Collaboration:

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

web site: <http://people.roma2.infn.it/dama>

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
- CNC processes
- Electron stability and non-paulian transitions in Iodine atoms (by L-shell)
- Search for solar axions
- Exotic Matter search
- Search for superdense nuclear matter
- Search for heavy clusters decays

PLB408(1997)439
PRC60(1999)065501

PLB460(1999)235
PLB515(2001)6
EPJdirect C14(2002)1
EPJA23(2005)7
EPJA24(2005)51

Results on DM particles:

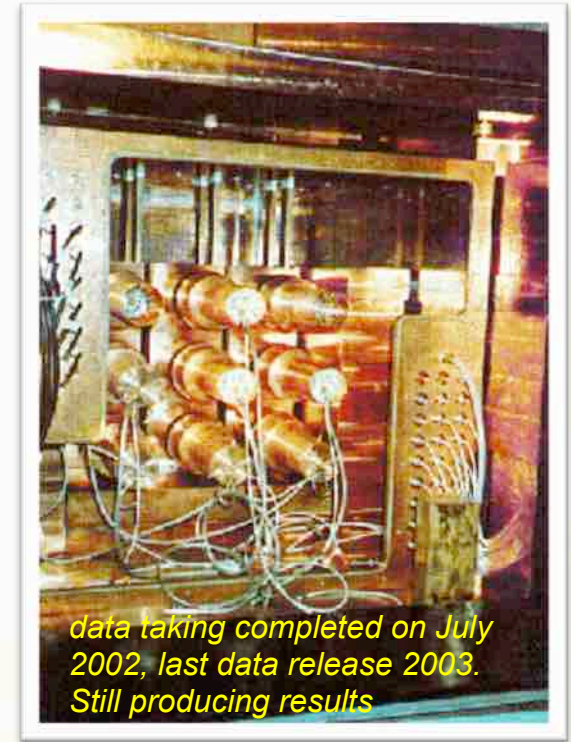
- PSD
- Investigation on diurnal effect
- Exotic Dark Matter search
- **Annual Modulation Signature**

PLB389(1996)757
N.Cim.A112(1999)1541
PRL83(1999)4918

PLB424(1998)195, PLB450(1999)448, PRD61(1999)023512,
PLB480(2000)23, EPJC18(2000)283, PLB509(2001)197, EPJC23(2002)61,
PRD66(2002)043503, Riv.N.Cim.26 n.1 (2003)1, IJMPD13(2004)2127,
IJMPA21(2006)1445, EPJC47(2006)263, IJMPA22(2007)3155,
EPJC53(2008)205, PRD77(2008)023506, MPLA23(2008)2125

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

total exposure (7 annual cycles) 0.29 ton×yr



The DAMA/LIBRA set-up ~250 kg NaI(Tl) (Large sodium Iodide Bulk for RAre processes)

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



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



- Radiopurity, performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
- Results on DM particles, **Annual Modulation Signature**: EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648.
Related results: PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022, EPJC74(2014)2827, EPJC74(2014)3196, EPJC75(2015)239, EPJC75(2015)400, IJMPA31(2016) dedicated issue, EPJC77(2017)83
- Results on rare processes: **PEPv**: EPJC62(2009)327; **CNC**: EPJC72(2012)1920; **IPP in ^{241}Am** : EPJA49(2013)64

Complete DAMA/LIBRA-phase1

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

a ton × yr scale experiment

- EPJC56(2008)333
- EPJC67(2010)39
- EPJC73(2013)2648
- calibrations: ≈96 Mevents from sources
- acceptance window eff: 95 Mevents (≈3.5 Mevents/keV)

DAMA/LIBRA-phase1:

- First upgrade on Sept 2008: replacement of some PMTs in HP N₂ atmosphere, new Digitizers (U1063A Acqiris 1GS/s 8-bit High-speed cPCI), new DAQ system with optical read-out installed

DAMA/LIBRA-phase2 (running):

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

Goal: lowering the software energy threshold

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

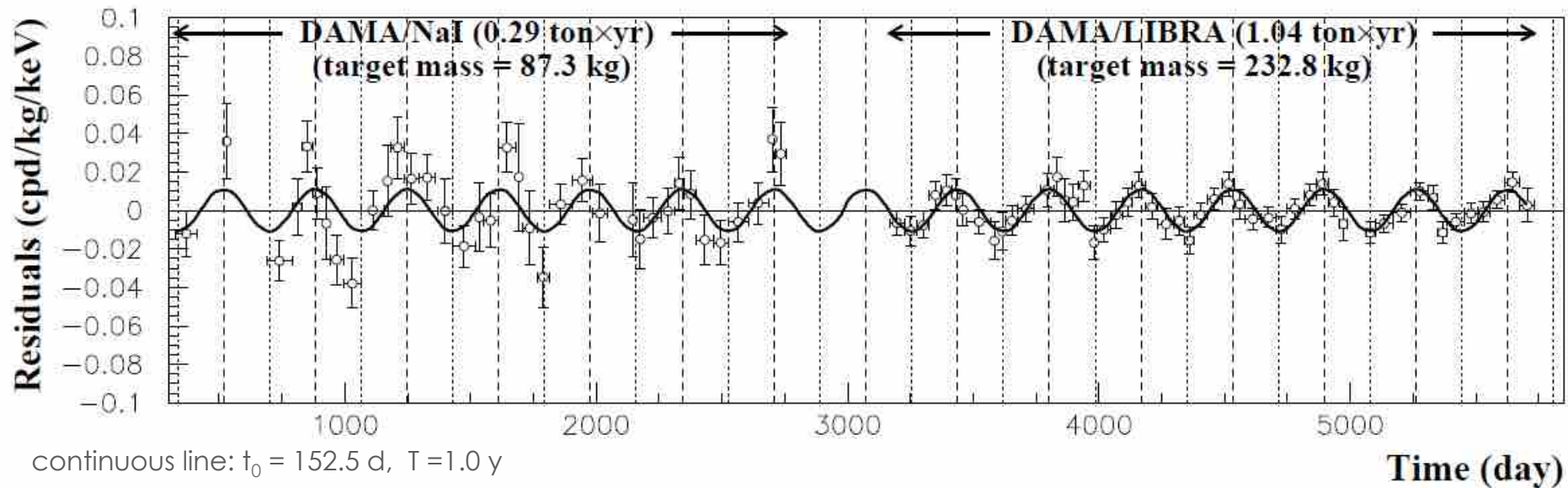


Model Independent Annual Modulation Result

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

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

Single-hit residuals rate vs time in 2-6 keV



Absence of modulation? No

$$\chi^2/\text{dof} = 154/87$$

$$P(A=0) = 1.3 \times 10^{-5}$$

$$\text{Fit: } t_0 = 152.5 \text{ d, } T = 1.0 \text{ y}$$

$$A = (0.0110 \pm 0.0012) \text{ cpd/kg/keV}$$

$$\chi^2/\text{dof} = 70.4/86 \quad 9.2 \sigma \text{ C.L.}$$

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

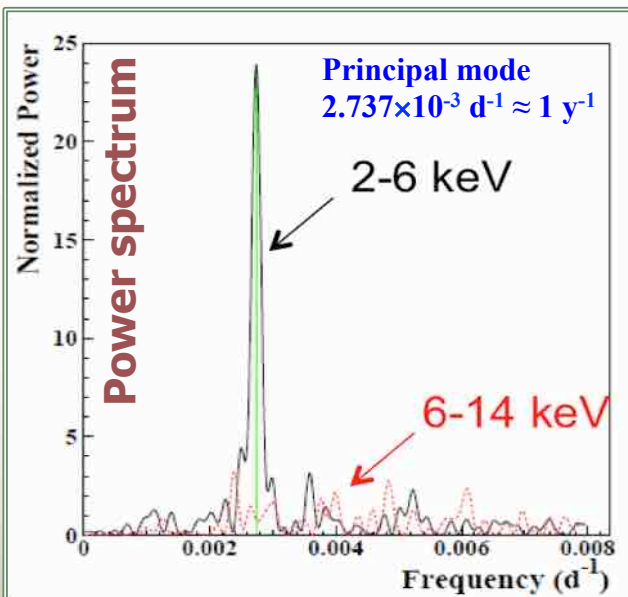
DAMA/NaI + DAMA/LIBRA-phase1 Total exposure: 487526 kg×day = **1.33 ton×yr**

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

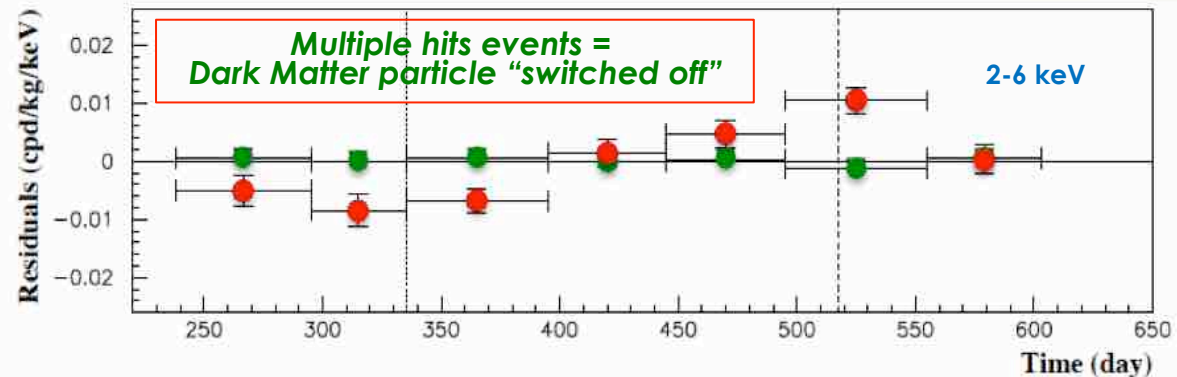
The measured modulation amplitudes (A), period (T) and phase (t_0) from the single-hit residual rate vs time

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

$$\text{Acos}[\omega(t-t_0)]$$



Comparison between **single hit residual rate (red points)** and **multiple hit residual rate (green points)**; Clear modulation in the single hit events; No modulation in the residual rate of the multiple hit events
A = -(0.0005 \pm 0.0004) cpd/kg/keV



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

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

Model Independent Annual Modulation Result

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

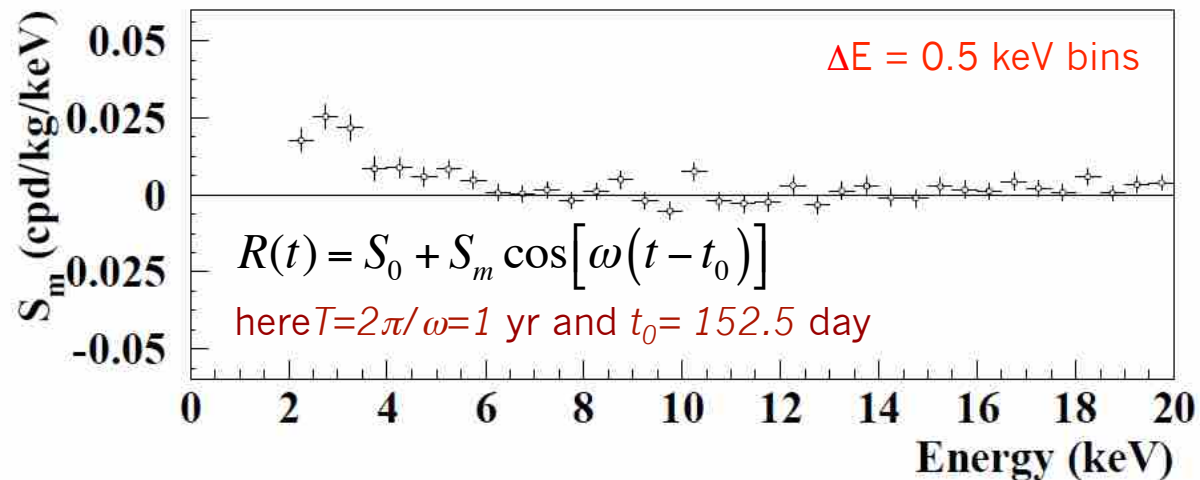
Max-lik analysis of single hit events

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

- No modulation above 6 keV
- No modulation in the whole energy spectrum
- No modulation in the 2-6 keV multiple-hit events

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%)



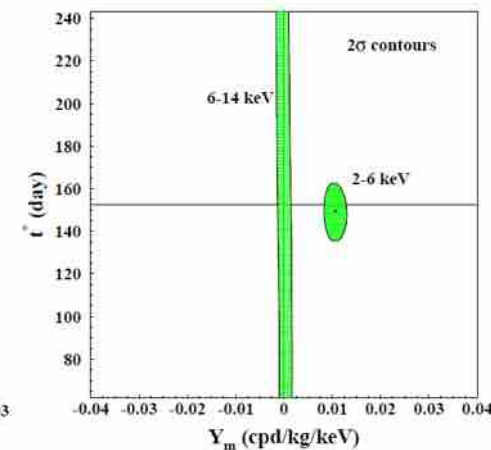
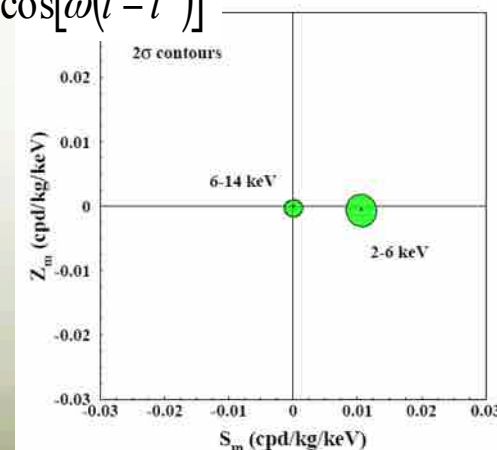
Is there a sinusoidal contribution in the signal? Phase $\neq 152.5$ day?

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

For Dark Matter signals:

- $|Z_m| \ll |S_m| \approx |Y_m|$
- $t^* \approx t_0 = 152.5$ day

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



No role for μ in DAMA annual modulation result

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

DAMA/LIBRA surface $\approx 0.13 \text{ m}^2$

μ flux @ DAMA/LIBRA $\approx 2.5 \mu/\text{day}$

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

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

- Φ_μ @ LNGS $\approx 20 \mu \text{ m}^{-2} \text{ d}^{-1}$ ($\pm 1.5\%$ modulated)
- Annual modulation amplitude at low energy due to μ modulation:

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

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

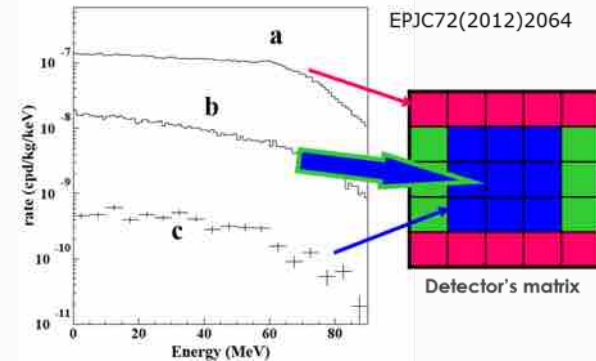
✓ Inconsistency of the phase between DAMA signal and μ modulation

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

The DAMA phase: May $26 \pm 7 \text{ days}$ (stable over 13 years)

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

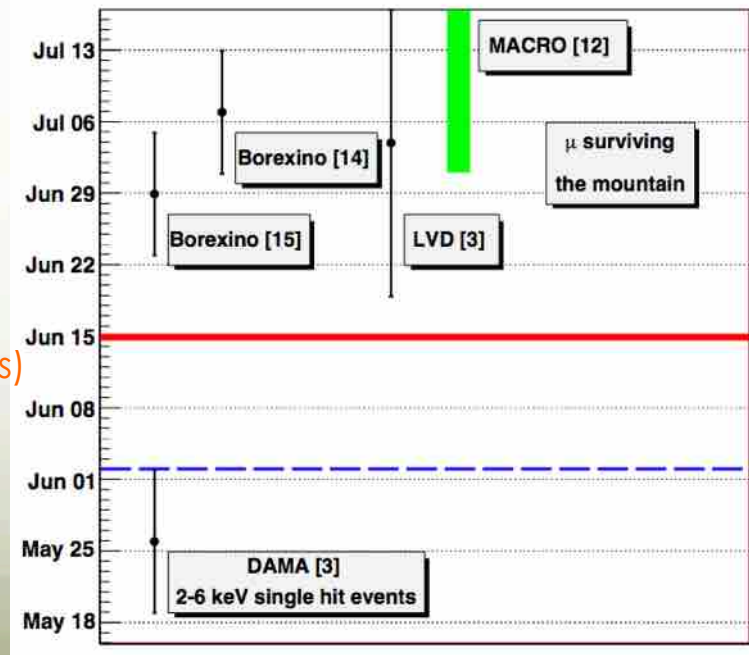
... many others arguments EPJC72(2012)2064, EPJC74(2014)3196



MonteCarlo simulation

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

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



- Contributions to the total **neutron flux** at LNGS;
- **Counting rate** in DAMA/LIBRA for *single-hit* events, in the (2 – 6) keV energy region induced by:

- neutrons,
- muons,
- solar neutrinos.

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

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

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

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, (α, n) → 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]	$\ll 6 \times 10^{-5}$	$\ll 5 \times 10^{-3}$
	$\mu \rightarrow n$ 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])	$\ll 9 \times 10^{-6}$	$\ll 8 \times 10^{-4}$
	$\mu \rightarrow n$ 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)	$\ll 2 \times 10^{-5}$	$\ll 1.6 \times 10^{-3}$
	$\nu \rightarrow n$ (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	$\Phi_0^{(\mu)} \simeq 20 \mu \text{ m}^{-2} \text{ d}^{-1}$ [20]	0.0129 [23]	end of June [23, 7, 8]	$\simeq 10^{-7}$ [2, 7, 8]	$\simeq 10^{-9}$	$\simeq 10^{-7}$
direct ν	$\Phi_0^{(\nu)} \simeq 6 \times 10^{10} \nu \text{ cm}^{-2} \text{ s}^{-1}$ [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.

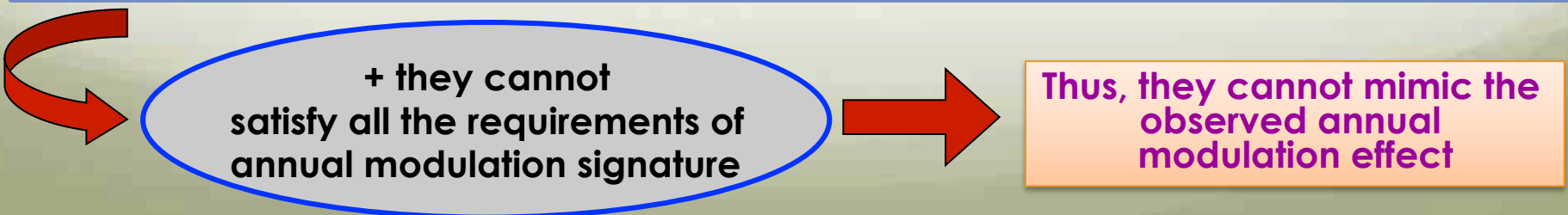
All are negligible w.r.t. the annual modulation amplitude observed by DAMA/LIBRA and they cannot contribute to the observed modulation amplitude.

+ In no case neutrons (of whatever origin), muons and muon-induced events, solar ν can mimic the DM annual modulation signature since some of the peculiar requirements of the signature would fail

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.	$<2.5 \times 10^{-6}$ cpd/kg/keV
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield \rightarrow huge heat capacity + T continuously recorded	$<10^{-4}$ cpd/kg/keV
NOISE	Effective full noise rejection near threshold	$<10^{-4}$ cpd/kg/keV
ENERGY SCALE	Routine + intrinsic calibrations	$<1-2 \times 10^{-4}$ cpd/kg/keV
EFFICIENCIES	Regularly measured by dedicated calibrations	$<10^{-4}$ cpd/kg/keV
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV <i>multiple-hits</i> events; this limit includes all possible sources of background	$<10^{-4}$ cpd/kg/keV
SIDE REACTIONS	Muon flux variation measured at LNGS	$<3 \times 10^{-5}$ cpd/kg/keV



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

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

Neutralino as LSP in various SUSY theories

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

a heavy ν of the 4-th family

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

WIMP with preferred inelastic scattering

Mirror Dark Matter

Light Dark Matter

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

Sterile neutrino

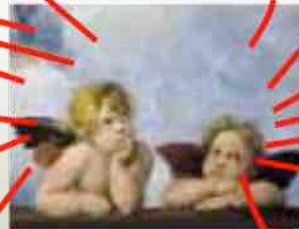
Self interacting Dark Matter

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

Elementary Black holes such as the Daemons

Kaluza Klein particles

... and more

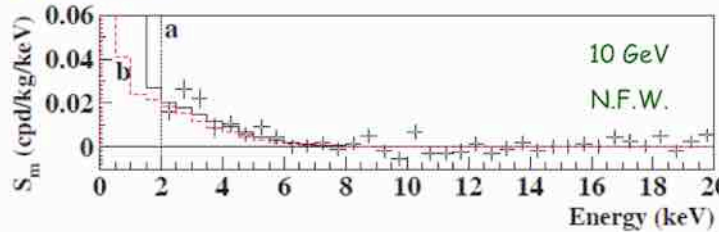


Model-independent evidence by DAMA/NaI and DAMA/LIBRA

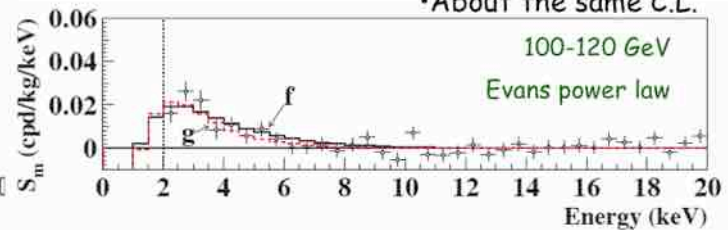
well compatible with several candidates in many astrophysical, nuclear and particle physics scenarios

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

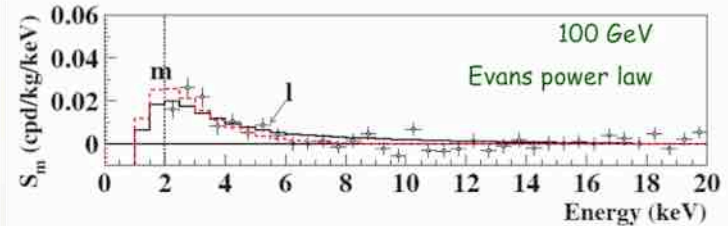
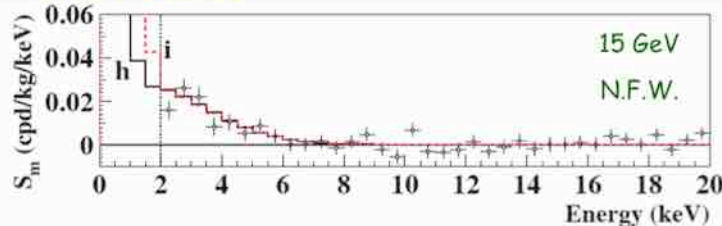
WIMP: SI



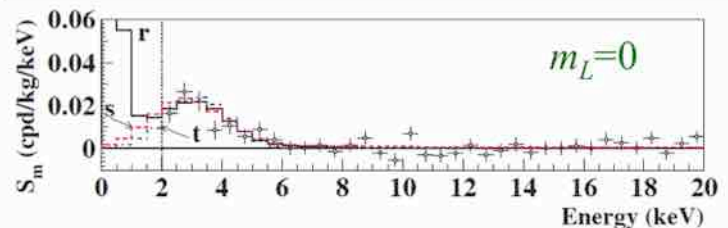
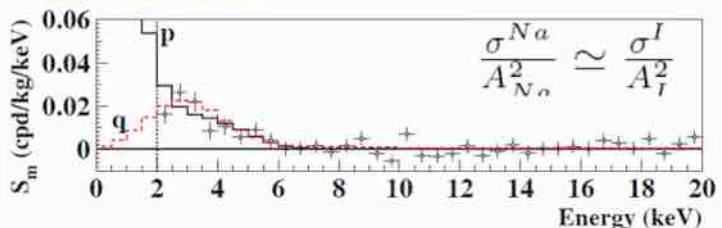
•Not best fit
•About the same C.L.



WIMP: SI & SD $\theta = 2.435$



LDM, bosonic DM



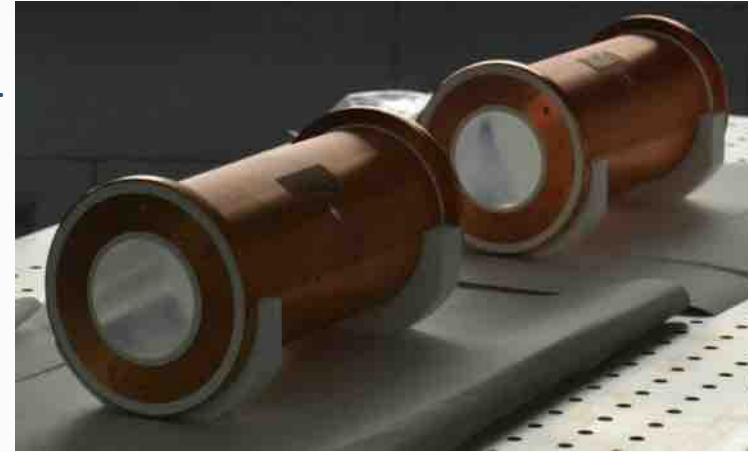
Compatibility with several candidates;
other ones are open

EPJC56(2008)333
IJMPA28(2013)1330022

Other scintillating detectors

ANAIS. Project for 3×3 matrix of NaI(Tl) scintillators 12.5 kg each to study DM annual modulation at Canfranc (LSC). Several prototypes from different companies tested

- A ^{210}Pb contamination out-of-equilibrium is present in ANAIS-25 crystals.
- Origin of the ^{210}Pb contamination identified (crystal growing) and being solved by Alpha Spectra.
- **New material prepared at Alpha Spectra using improved protocols**
- Running: target mass of ≈ 112 kg



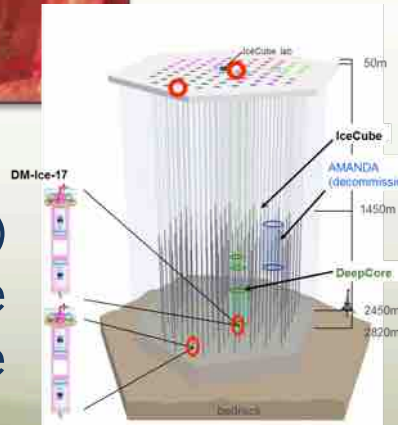
KIMS. DM with CsI(Tl) crystals since 2000 at Yangyang (Y2L, Korea). More recently KIMS-NaI

COSINE-100 = DM-ICE+KIMS
Running since sept 2016: ≈ 100 kg NaI in Y2L

Warning: PSD with CsI(Tl), NaI(Tl), ... sometimes overestimated sensitivity; high rejection power claimed; existing systematics limit the reachable sensitivity

Key points: not only residual contaminants but also long-term/high-level stability

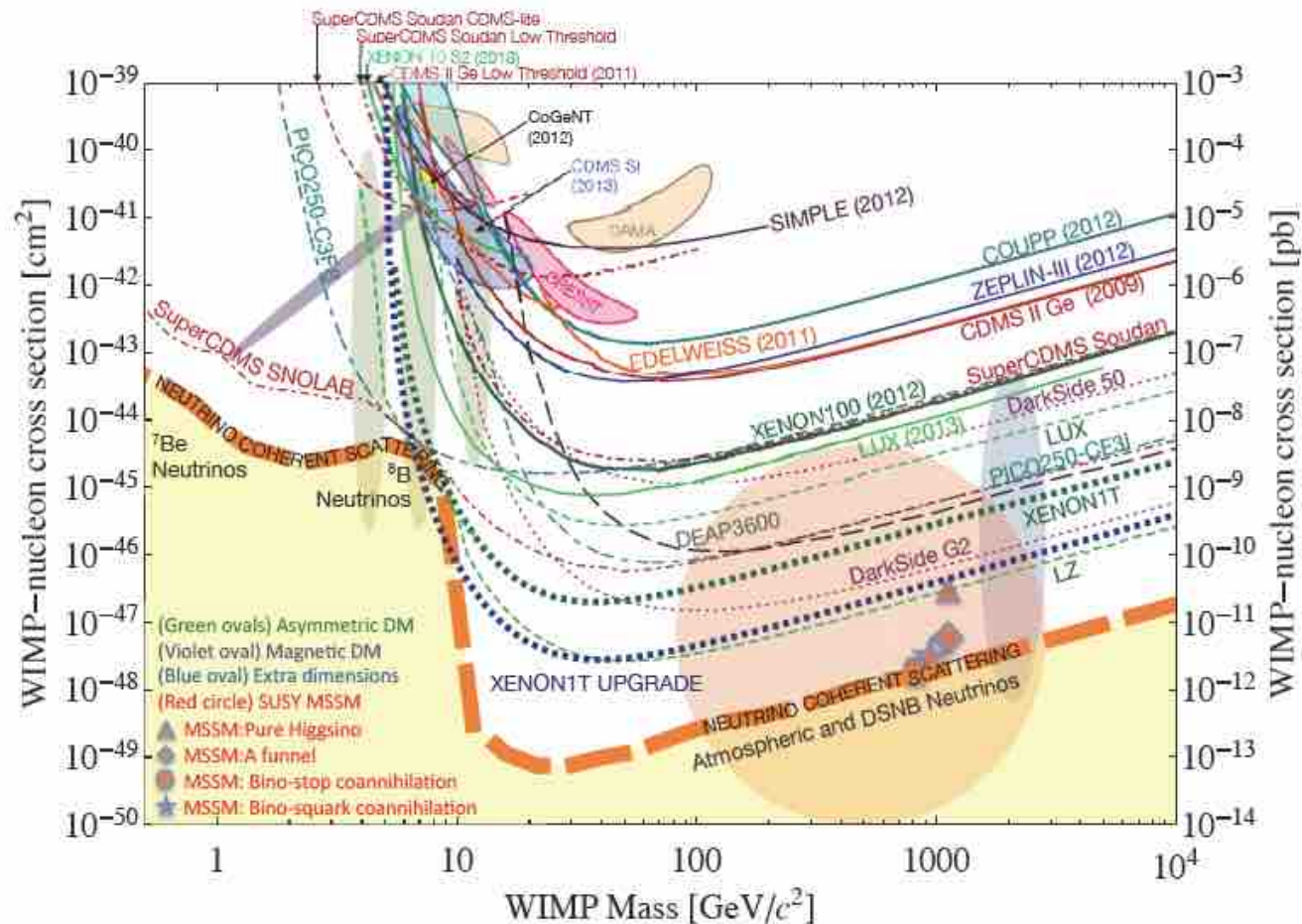
DM-ICE. NaI(Tl) deployed at the South Pole



+ **SABRE** (at the end of 2017),
picoLON, cryog. detectors

At R&D stage to obtain competitive NaI(Tl) detectors wrt 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

About interpretation

See e.g.: Riv.N.Cim.26 n.1(2003)1, JIMPD13(2004)2127, EPJC47(2006)263, IJMPA21(2006)1445, EPJC56(2008)333, PRD84(2011)055014, IJMPA28(2013)1330022

...and experimental aspects...

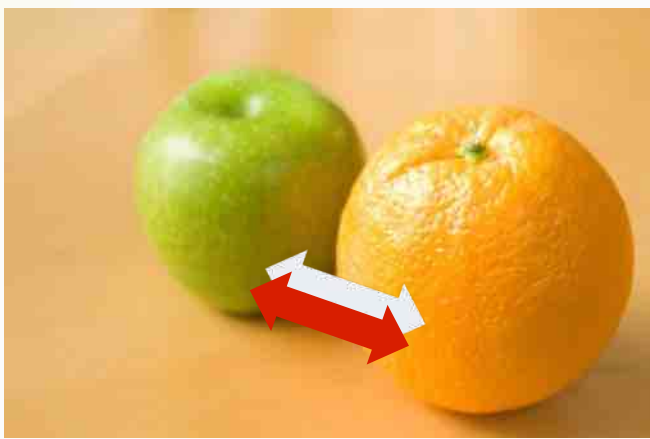
- Exposures
- Energy threshold
- Detector response (phe/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities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

...models...

- Which particle?
- Which interaction coupling?
- Which Form Factors for each target-material?
- Which Spin Factor?
- Which nuclear model framework?
- Which scaling law?
- Which halo model, profile and related parameters?
- Streams?
- ...

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

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



Examples of uncertainties in models and scenarios

Nature of the candidate and couplings

- WIMP class particles (neutrino, sneutrino, etc.): SI, SD, mixed SI&SD, preferred inelastic + e.m. contribution in the detection
- Light bosonic particles
- Kaluza-Klein particles
- Mirror dark matter
- Heavy Exotic candidate
- ...etc. etc.

Scaling laws of cross sections for the case of recoiling nuclei

- Different scaling laws for different DM particle:
 $\sigma_A \propto \mu^2 A^2 (1 + \varepsilon_A)$
 $\varepsilon_A = 0$ generally assumed
 $\varepsilon_A \approx \pm 1$ in some nuclei? even for neutralino candidate in MSSM (see Prezeau, Kamionkowski, Vogel et al., PRL91(2003)231301)

Halo models & Astrophysical scenario

- Isothermal sphere \Rightarrow very simple but unphysical halo model
- Many consistent halo models with different density and velocity distribution profiles can be considered with their own specific parameters (see e.g. PRD61(2000)023512)
- Caustic halo model
- Presence of non-thermalized DM particle components
- Streams due e.g. to satellite galaxies of the Milky Way (such as the Sagittarius Dwarf)
- Multi-component DM halo
- Clumpiness at small or large scale
- Solar Wakes
- ...etc. ...

Form Factors for the case of recoiling nuclei

- Many different profiles available in literature for each isotope
- Parameters to fix for the considered profiles
- Dependence on particle-nucleus interaction
- In SD form factors: no decoupling between nuclear and Dark Matter particles degrees of freedom + dependence on nuclear potential

Spin Factors for the case of recoiling nuclei

- Calculations in different models give very different values also for the same isotope
- Depend on the nuclear potential models
- Large differences in the measured counting rate can be expected using:
 either SD not-sensitive isotopes or SD sensitive isotopes depending on the unpaired nucleon (compare e.g. odd spin isotopes of Xe, Te, Ge, Si, W with the ^{23}Na and ^{127}I cases).

see for some details e.g.:

Riv.N.Cim.26 n.1 (2003) 1, IJMPD13(2004)2127, EPJC47 (2006)263, IJMPA21 (2006)1445

Instrumental quantities

- Energy resolution
- Efficiencies
- Quenching factors
- Channeling effects
- Their dependence on energy
- ...

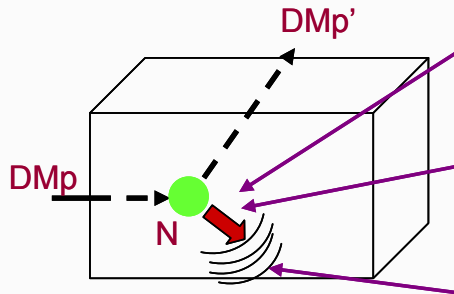
Quenching Factor

- differences are present in different experimental determinations of q for the same nuclei in the same kind of detector depending on its specific features (e.g. q depends on dopant and on the impurities; in liquid noble gas e.g. on trace impurities, on presence of degassing/releasing materials, on thermodynamical conditions, on possibly applied electric field, etc); assumed 1 in bolometers
- channeling effects possible increase at low energy in scintillators (dL/dx)
 possible larger values of q (AstropPhys33 (2010) 40)
 \rightarrow energy dependence

... and more ...

... an example in literature...

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

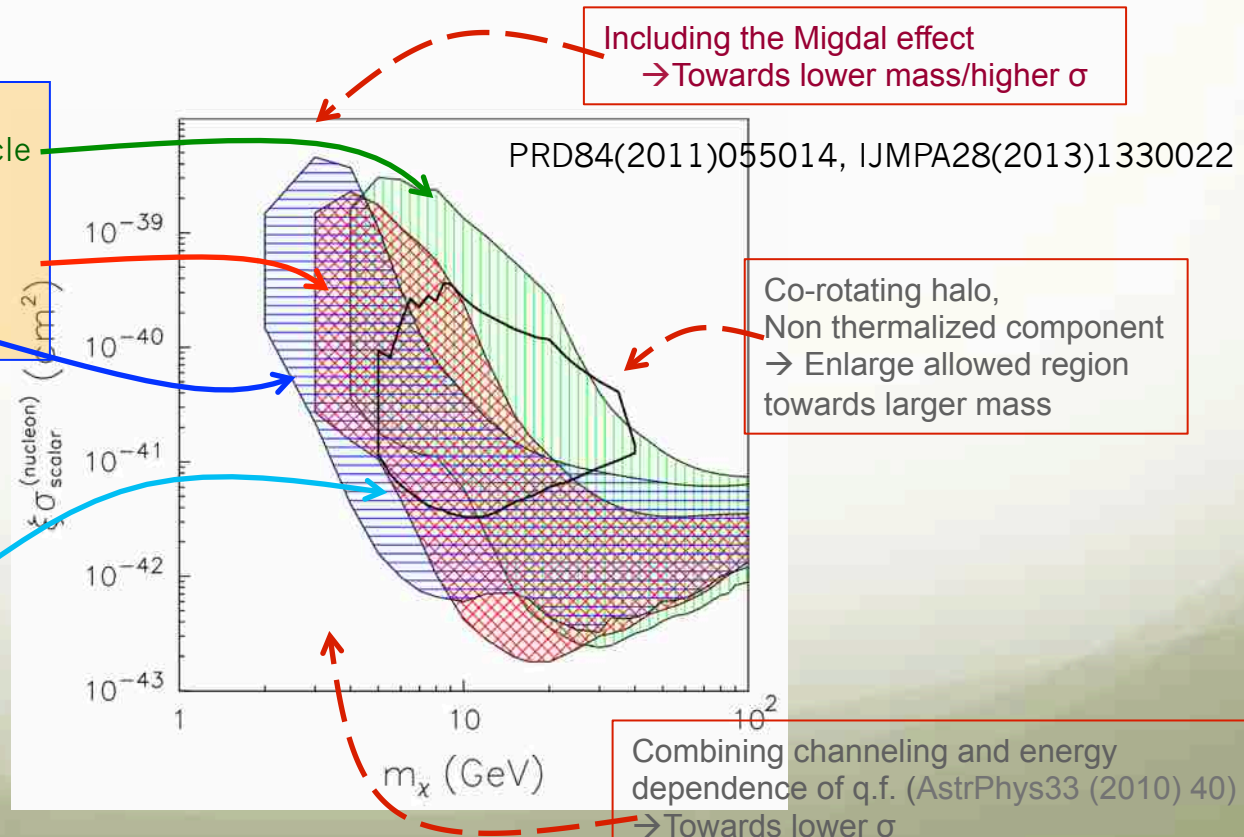


Regions in the nucleon cross section vs DM particle mass plane

- Some velocity distributions and uncertainties considered.
- The DAMA regions represent the domain where the likelihood-function values differ more than 7.5σ from the null hypothesis (absence of modulation).
- For CoGeNT a fixed value for the Ge quenching factor and a Helm form factor with fixed parameters are assumed.
- The CoGeNT region includes configurations whose likelihood-function values differ more than 1.64σ from the null hypothesis (absence of modulation). This corresponds roughly to 90% C.L. far from zero signal.

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

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



Scratching Below the Surface of the Most General Parameter Space (S. Scopel arXiv:1505.01926)

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

- A much wider parameter space opens up

- First explorations show that indeed large rooms for compatibility can be achieved

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

... and much more considering experimental and theoretical uncertainties

Other examples

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

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

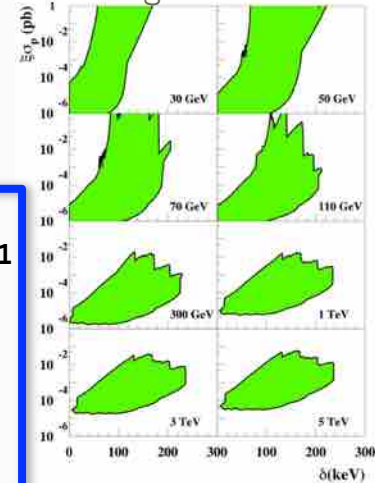
$$\frac{1}{2} \mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

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

PRL106(2011)011301

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

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



Fund. Phys. 40(2010)900

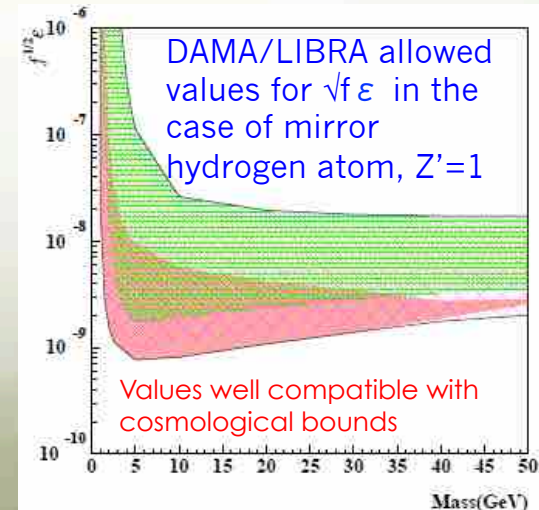
Mirror Dark Matter

EPJC75(2015)400

Asymmetric mirror matter: mirror parity spontaneously broken \Rightarrow 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 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



DAMA annual modulation effect and Asymmetric mirror matter

EPJC75(2015)400

Asymmetric mirror matter: mirror parity spontaneously broken at the electroweak scale
 \Rightarrow mirror sector becomes heavier and deformed copy of ordinary sector; mirror hydrogen can be stable and a good DM candidate

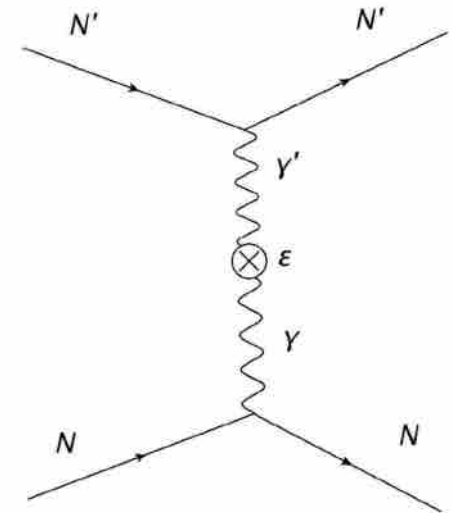
Interaction portal: photon - mirror photon kinetic mixing $\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$

$$\mathcal{N}' + \mathcal{N} \rightarrow \mathcal{N}' + \mathcal{N}$$

mirror atom scattering off the ordinary target nuclei in the NaI(Tl) detectors of DAMA/LIBRA set-up with Rutherford-like cross sections.

$$\frac{d\sigma_{A,A'}}{dE_R} = \frac{C_{A,A'}}{E_R^2 v^2}$$

and
$$C_{A,A'} = \frac{2\pi\epsilon^2\alpha^2 Z^2 Z'^2}{M_A} \mathcal{F}_A^2 \mathcal{F}_{A'}^2$$



Knowing that $\Omega_{B'}/\Omega_B \approx 5$, two cases are considered:

- **Separate baryogenesis.** $\eta = n_B/n_\gamma$ and $\eta' = n_{B'}/n'_\gamma$ are equal, and $n'_\gamma/n_\gamma \ll 1$. The $m_{N'}$ can be **tens of GeV**.
- **Co-genesis** of baryon and mirror baryon asymmetries. $n_{B'} = n_B$, we need $m_{N'}/m_N \approx 5$, which singles out the mass of dark atom of **about 5 GeV**.

DAMA annual modulation effect and Asymmetric mirror matter

EPJC75(2015)400

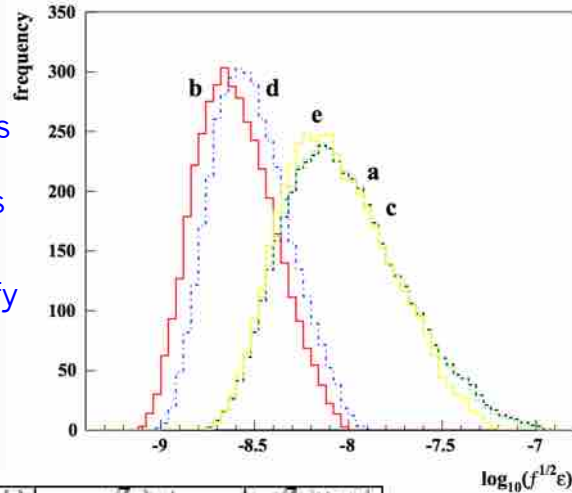
□ Case of $m_{N'} = 5$ GeV

□ Free parameter in the analysis:

- ε = coupling constant
- f = fraction of mirror atoms in the halo

- For all the scenarios, various existing uncertainties in nuclear and particle physics quantities are considered.
- The allowed intervals identify the values corresponding to C.L. larger than 5σ from the null hypothesis

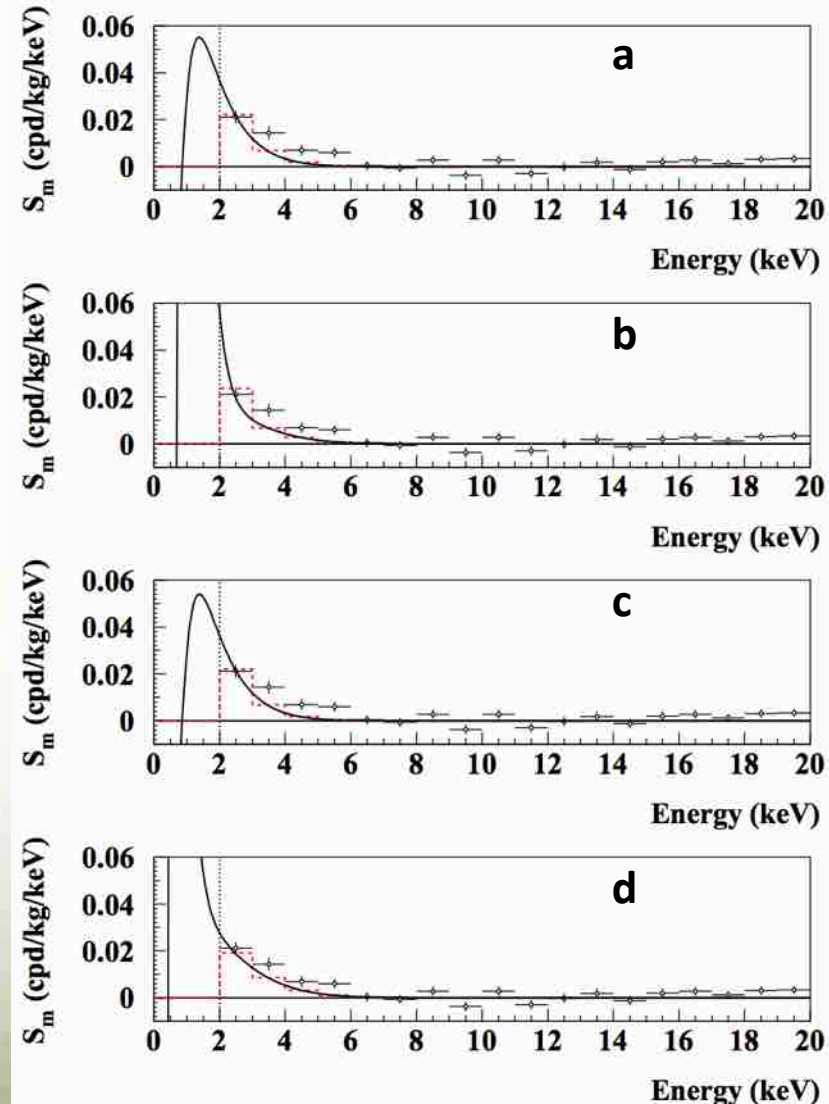
Results on the $\sqrt{f\varepsilon}$ parameter in the considered scenarios



Scenario	Quenching Factor	Channeling	Mipral	$\sqrt{f\varepsilon}$ best	$\sqrt{f\varepsilon}$ interval ($\times 10^{-9}$)
a	Q_T [4]	no	no	4.45×10^{-3} (0.2 σ C.L.)	1.86-4.52 (all) 1.73-11.4
b	Q_T [4]	yes	no	2.89×10^{-3} (0.1 σ C.L.)	1.16-2.93 (all) 0.77-9.72
c	Q_T [4]	no	yes	4.40×10^{-3} (0.2 σ C.L.)	1.85-4.47 (all) 1.72-10.7
d	Q_{irr} [78]	no	no	2.44×10^{-3} (0.3 σ C.L.)	1.03-2.48 (all) 0.94-12.3
e	Q_{irr} [78]-normalized	no	no	5.18×10^{-3} (0.0 σ C.L.)	2.24-5.26 (all) 1.89-60.1

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 $\sqrt{f\varepsilon}_{b.f.} = 2.4 \times 10^{-9}$

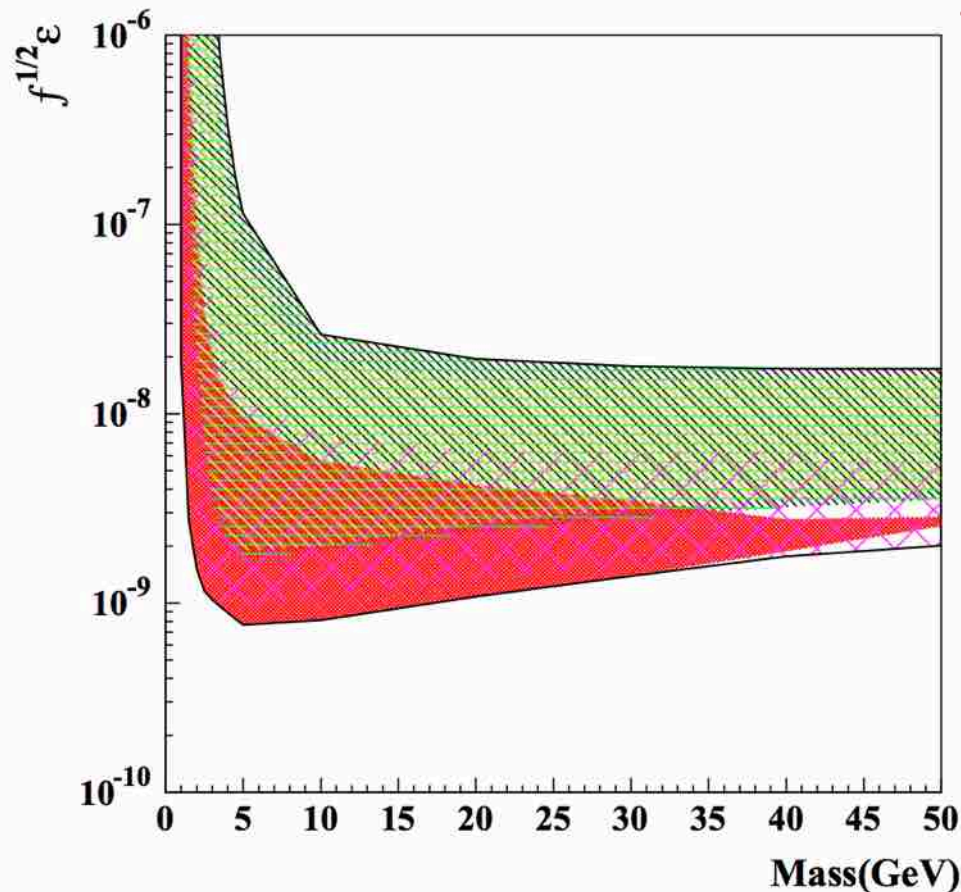
Examples of expected S_m for the Mirror DM candidate considered



DAMA annual modulation effect and Asymmetric mirror matter

EPJC75(2015)400

- When the assumption $m_{N'} \approx 5m_p$ is released, allowed regions for the $\sqrt{f\epsilon}$ parameter as function of $m_{N'}$, obtained by marginalizing all the models for each considered scenarios as given in the previous Table.
- The $m_{N'}$ interval from few GeV up to 50 GeV is explored.



- These allowed intervals identify the $\sqrt{f\epsilon}$ values corresponding to C.L. larger than 5σ from the null hypothesis, that is $\sqrt{f\epsilon} = 0$. The five scenarios defined in the previous Table can be recognized on the basis of different hatching of the allowed regions; the black line is the overall boundary.

The allowed values for $\sqrt{f\epsilon}$ in the case of mirror hydrogen atom, $Z' = 1$, are well compatible with cosmological bounds

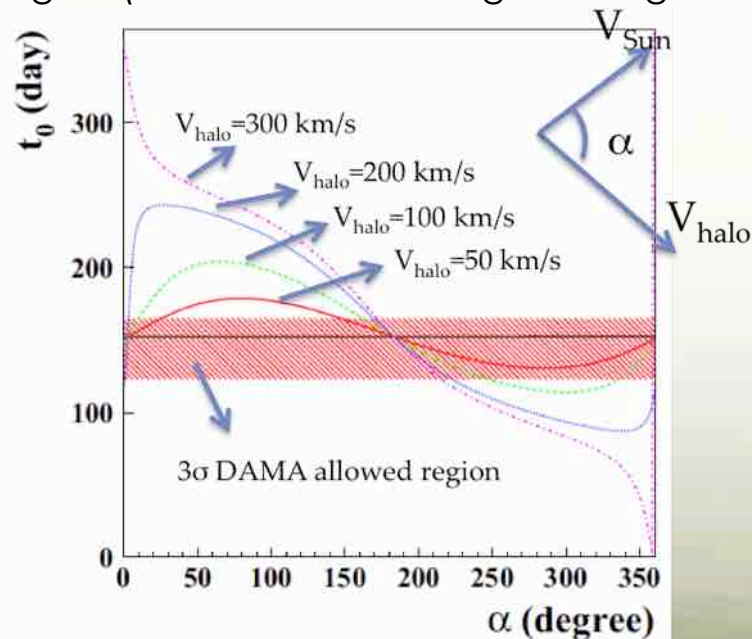
DAMA annual modulation effect and Symmetric mirror matter

EPJC77(2017)83

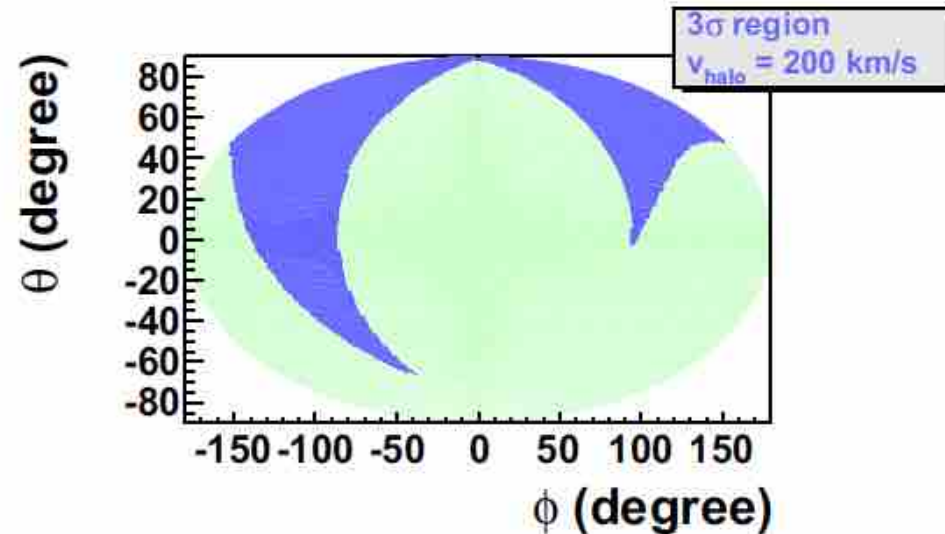
Symmetric mirror matter:

- an exact duplicate of ordinary matter from parallel hidden sector, which chemical composition is dominated by mirror Helium, while it can also contain significant fractions of heavier elements as Carbon and Oxygen.
- halo composed by a bubble of Mirror particles of different species; Sun is travelling across the bubble which is moving in the Galactic Frame (GF) with v_{halo} velocity;
- the mirror particles in the bubble have Maxwellian velocity distribution in a frame where the bubble is at rest; cold and hot bubble with temperature from 10^4 K to 10^8 K
- interaction via photon - mirror photon kinetic mixing

Examples of expected phase of the annual modulation signal (case of halo moving on the galactic plane)



The blue regions correspond to directions of the halo velocities in GC (θ, ϕ) giving a phase compatible at 3σ with DAMA phase



DAMA annual modulation effect and Symmetric mirror matter

EPJC77(2017)83

Symmetric mirror matter:

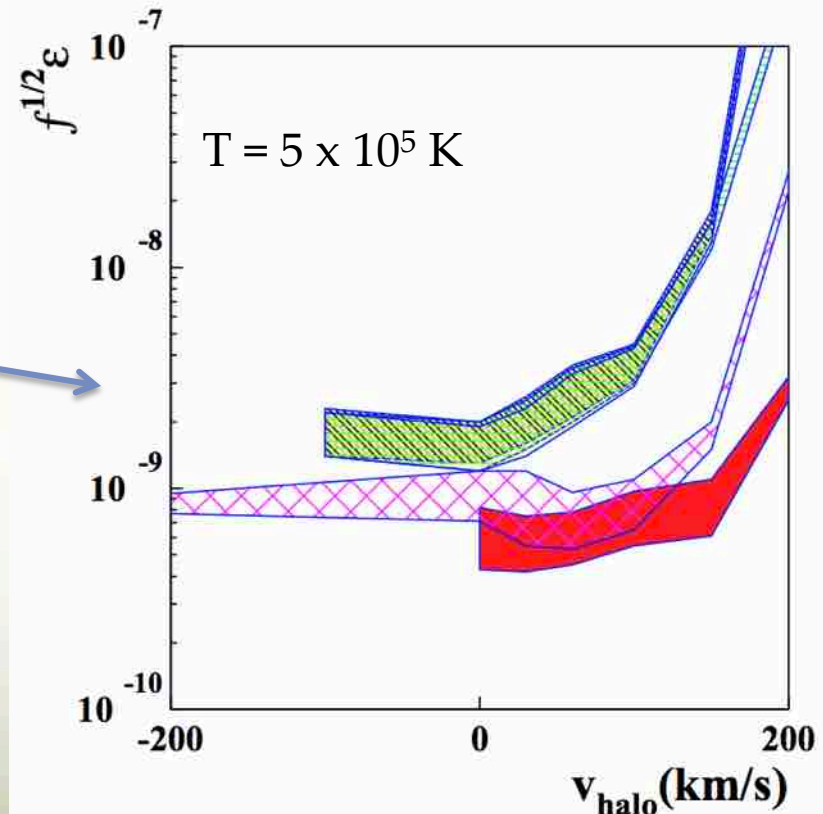
- Results refers to halo velocities parallel or anti-parallel to the Sun ($\alpha = 0, \pi$). For these configurations the expected phase is June 2
- The free parameters in the analysis are v_{halo} (positive values correspond to halo moving in the same direction of the Sun while negative values correspond to opposite direction) and the equilibrium Temperature, T , of the halo

Mirror matter composition	H (%)	He (%)	C (%)	O (%)	Fe (%)
H', He'	25	75	—	—	—
H', He', C', O'	12.5	75.	7.	5.5	—
H', He', C', O', Fe'	20	74	0.9	5.	0.1

DAMA/LIBRA allowed values for $\sqrt{f} \epsilon$ in different scenarios

- For all the scenarios, various existing uncertainties in nuclear and particle physics quantities are considered.
- The allowed intervals identify the values corresponding to C.L. larger than 5σ from the null hypothesis

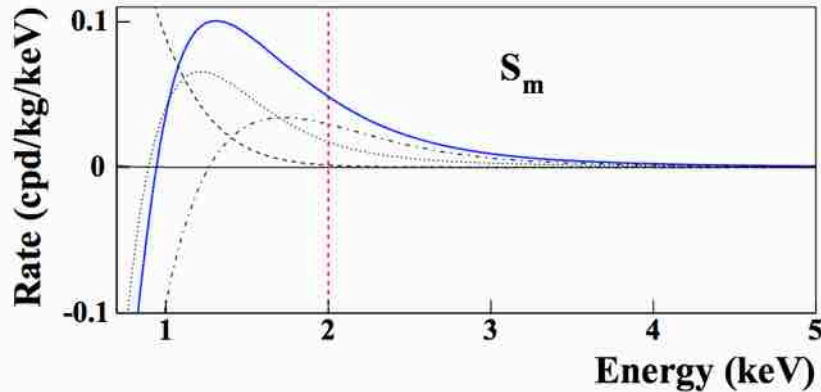
$\sqrt{f} \cdot \epsilon$ coupling const. and DM fraction as mirror atom



Many configurations and halo models favored by the DAMA annual modulation effect corresponds to couplings values **well compatible with cosmological bounds**.

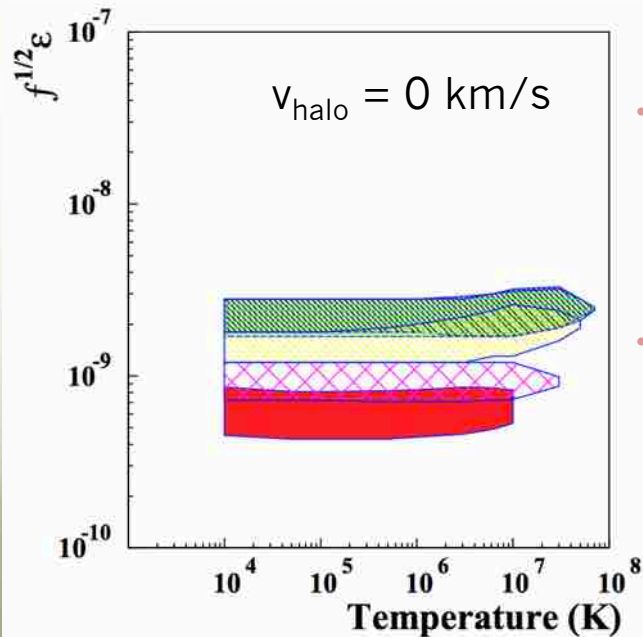
DAMA annual modulation effect and Symmetric mirror matter

EPJC77(2017)83

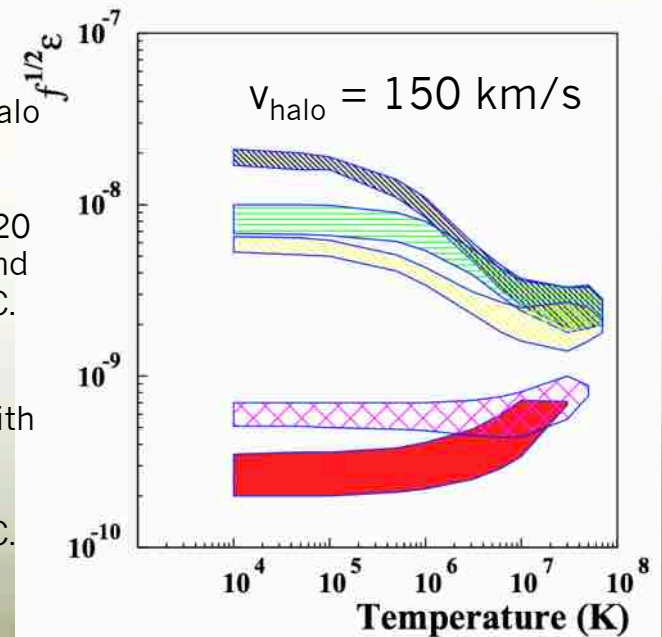


Examples of expected S_m for the Mirror DM candidate considered

Examples of DAMA/LIBRA allowed values for $\sqrt{f} \varepsilon$ in different scenarios as function of the equilibrium temperature of the halo



- *Left.* Composite dark halo H' (20%), He' (74%), C' (0.9%), O' (5%), Fe' (0.1%), with $v_0 = 220$ km/s, $v_{\text{halo}} = 0$ km/s and parameters in the set C.
- *Right.* Composite dark halo H' (24%), He' (75%), Fe' (1%), with $v_0 = 220$ km/s, $v_{\text{halo}} = 150$ km/s and parameters in the set C.



Perspectives for the future

Other signatures?

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

Diurnal effects in DAMA/LIBRA-phase1

EPJC 74 (2014) 2827

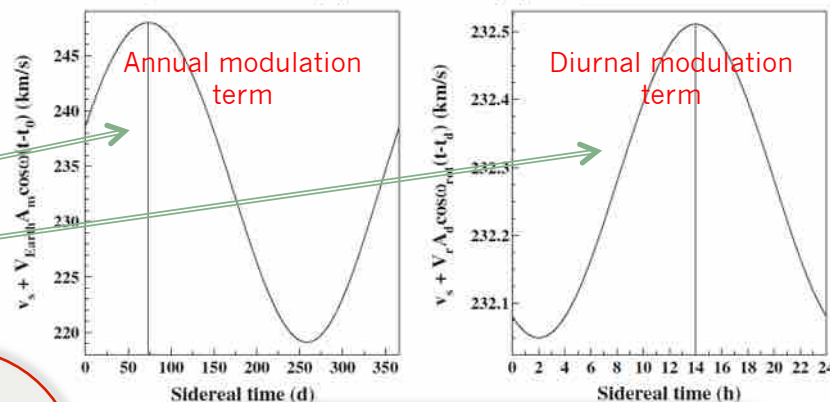
A diurnal effect with the sidereal time is expected for DM because of Earth rotation

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

Since:

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

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



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

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

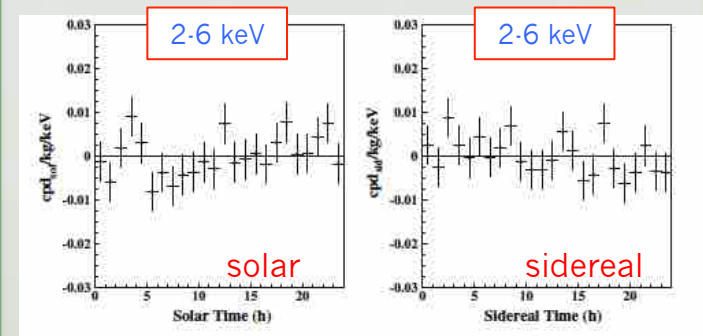
The ratio R_{dy} is a model independent constant:

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

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

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

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



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

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

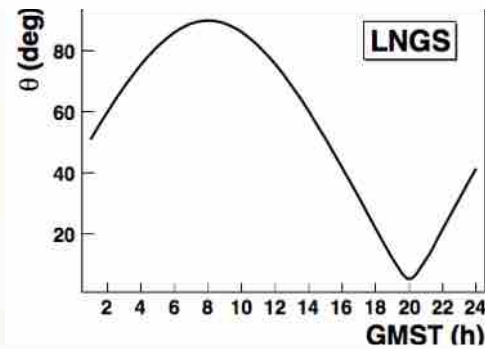
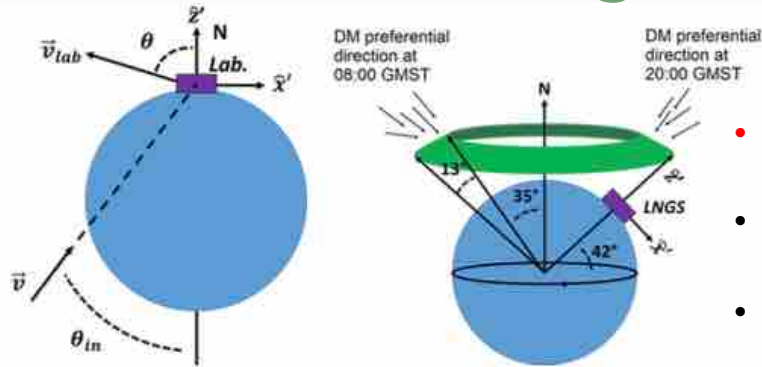
Perspectives for the future

Other signatures?

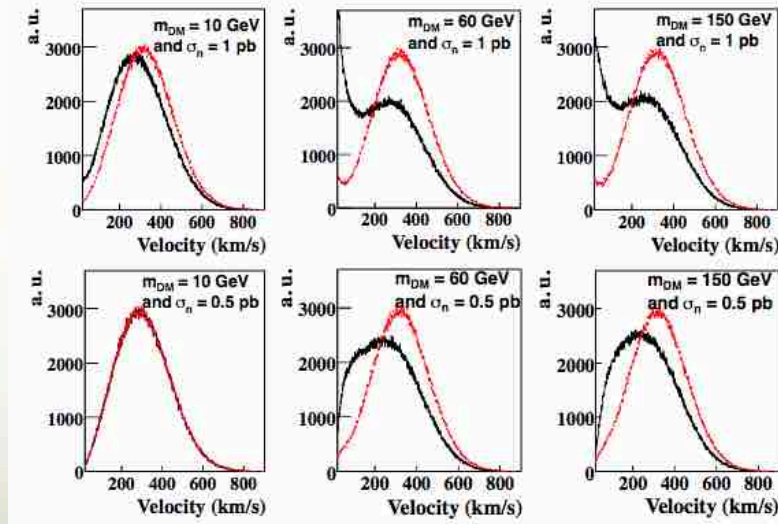
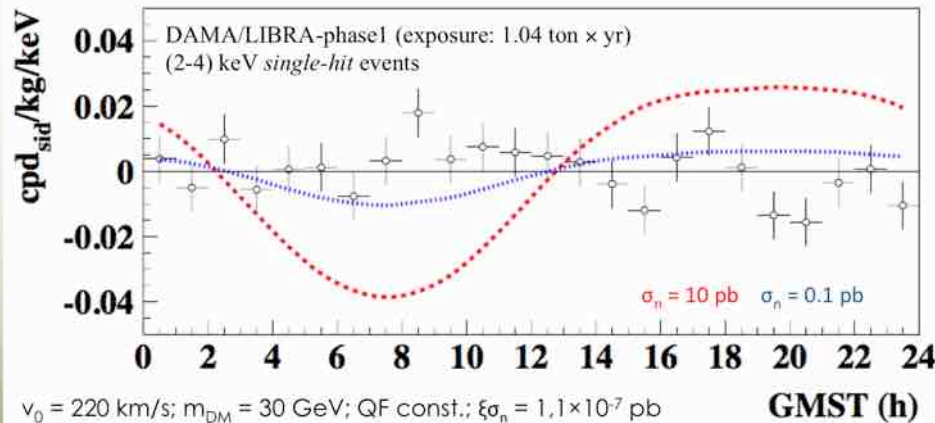
- *Diurnal effects*
- *Second order effects*
- *Shadow effects*
- *Directionality*
- *...*

Earth shadowing effect with DAMA/LIBRA-phase1

EPJC75(2015)239



- **Earth Shadow Effect** could be expected for DM candidate particles inducing nuclear recoils
- can be pointed out only for candidates with high cross-section with ordinary matter (low DM local density)
- would be induced by the variation during the day of the Earth thickness crossed by the DM particle in order to reach the experimental set-up
- DM particles crossing Earth lose their energy
- DM velocity distribution observed in the laboratory frame is modified as function of time (**GMST 8:00 black**; **GMST 20:00 red**)

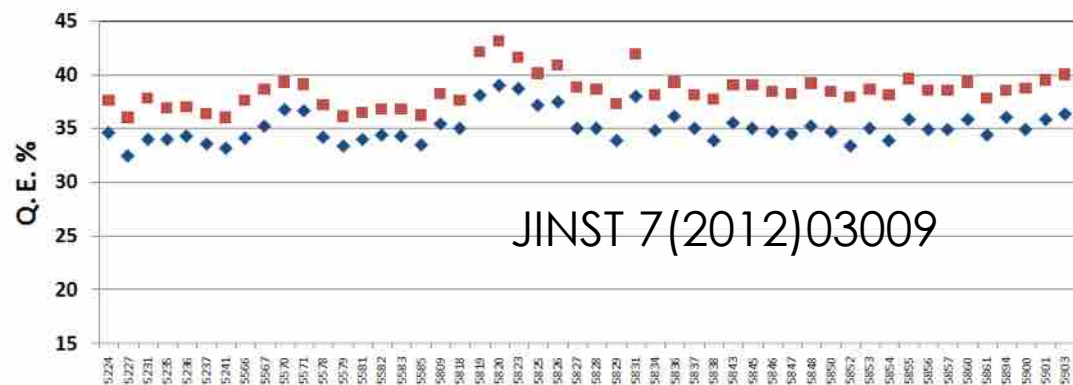


Taking into account the DAMA/LIBRA DM annual modulation result, allowed regions in the ξ vs σ_n plane for each m_{DM} .

DAMA/LIBRA phase2 - running

Quantum Efficiency features

■ Q.E. @ peak (%) ◆ Q.E. @ 420 nm (%)



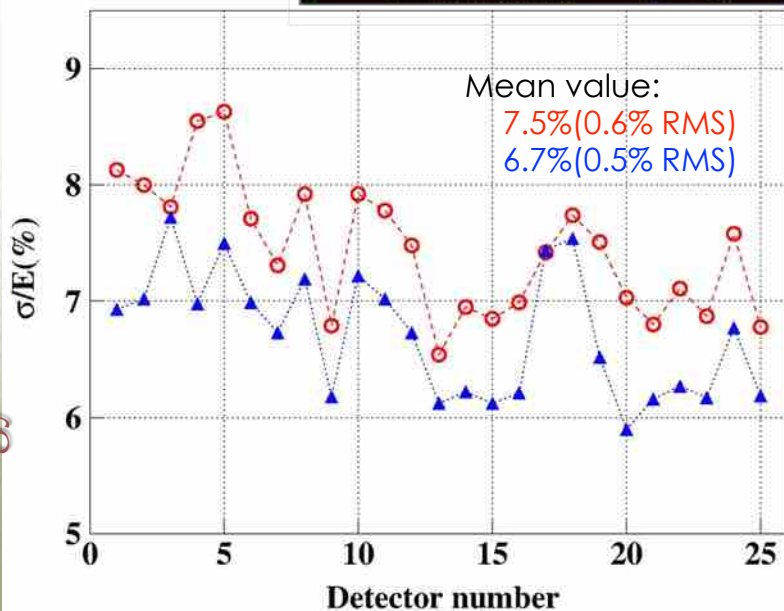
Residual
Contamination

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

Energy (keV)

PMT	Time (s)	Mass (kg)	^{226}Ra (Bq/kg)	^{232}Th (Bq/kg)	^{235}U (mBq/kg)	^{226}Ra (Bq/kg)	^{232}Th (mBq/kg)	^{40}K (Bq/kg)	^{137}Cs (mBq/kg)	^{60}Co (mBq/kg)
Average			0.43	-	47	0.12	83	0.54	-	-
Standard deviation			0.06	-	10	0.02	17	0.16	-	-

Energy resolution



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

The light responses

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

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

DAMA/LIBRA phase 2 – data taking

- ✓ Calibrations 5 a.c.: $\approx 1.03 \times 10^8$ events from sources
- ✓ Acceptance window eff. 5 a.c.: $\approx 7 \times 10^7$ events ($\approx 2.8 \times 10^6$ events/keV)

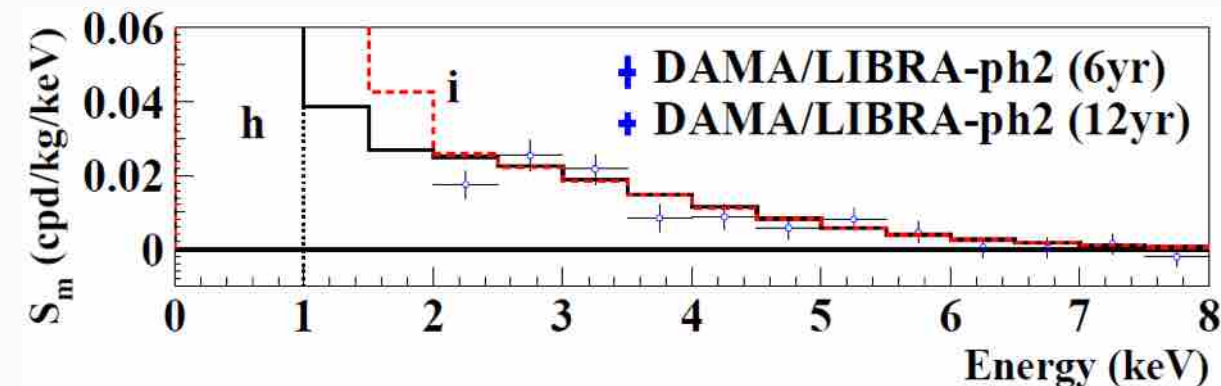
Annual Cycles	Period	Mass (kg)	Exposure (kg · day)	(α - β^2)
1	Dec 2010 – Sept. 2011		Commissioning	
2	Nov. 2, 2011 – Sept. 11, 2012	242.5	62917	0.519
3	Oct. 8, 2012 – Sept. 2, 2013	242.5	60586	0.534
4	Sept. 8, 2013 – Sept. 1, 2014	242.5	73792	0.479
5	Sept. 1, 2014 – Sept. 9, 2015	242.5	71180	0.486
6	Sept. 10, 2015 – Aug. 24, 2016	242.5	67527	0.522
7	Sept 2016 – Sept. 2017	242.5	≈ 70000	≈ 0.5

PRELIMINARY

Exposure collected in the first 5 a.c. of DAMA/LIBRA-phase2: **0,92 ton x yr**

Expected exposure in the first 6 a.c. \approx **1,1 ton x yr**

DAMA/LIBRA-phase2: constraining DM models

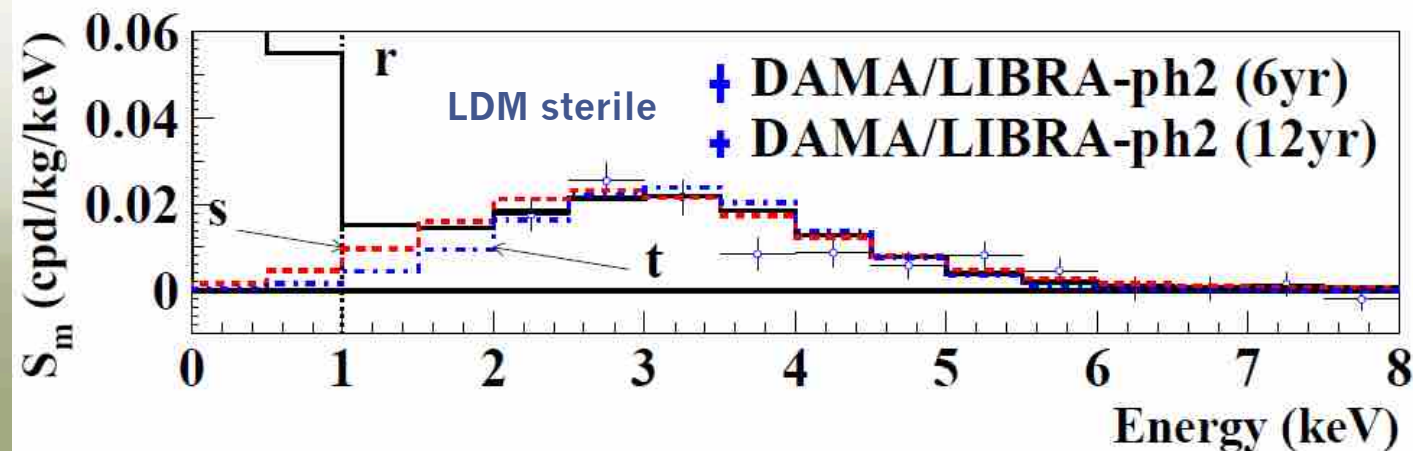
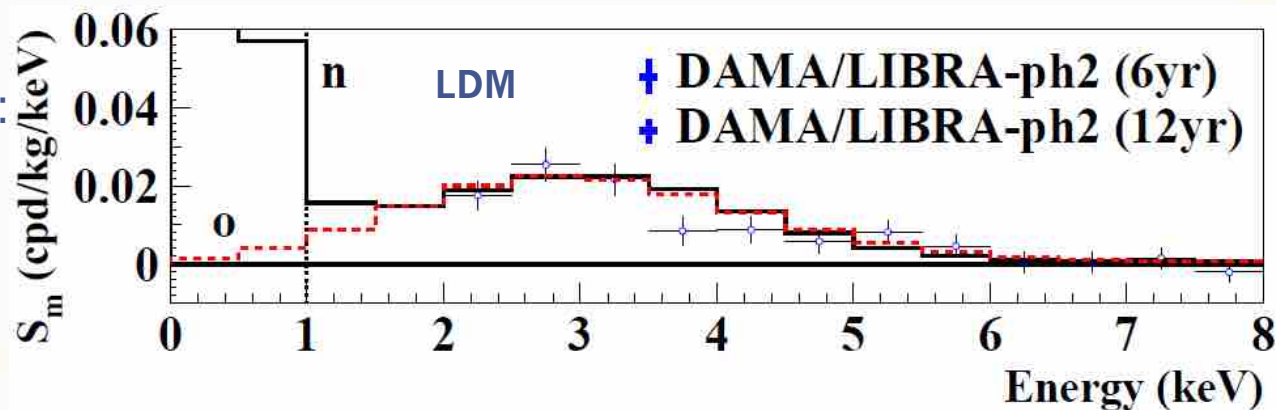


Few examples under some astrophysical, nuclear and particle physics assumptions; no best fit, same C.L.

“WIMP” SI vs SI&SD
NFW, 15 GeV

It can disentangle among:

- Different masses
- Different coupling
- Different particles



Features of the DM signal

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

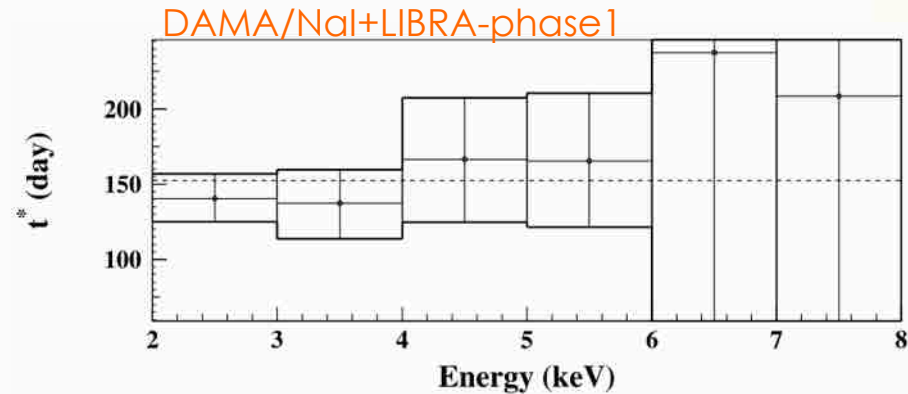
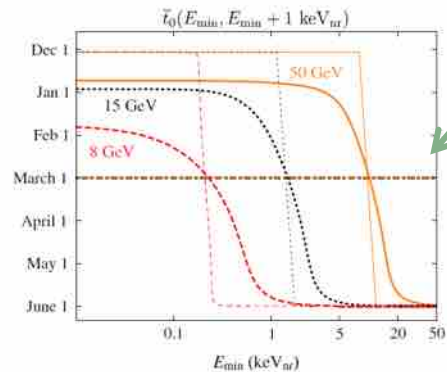
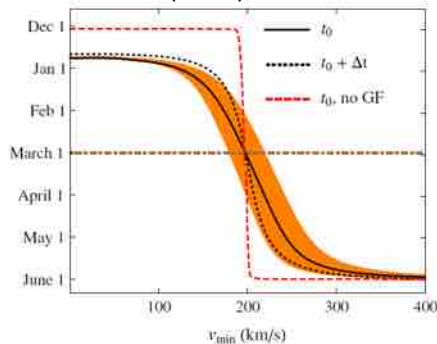
High exposure and lower energy threshold can allow further investigation on:

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

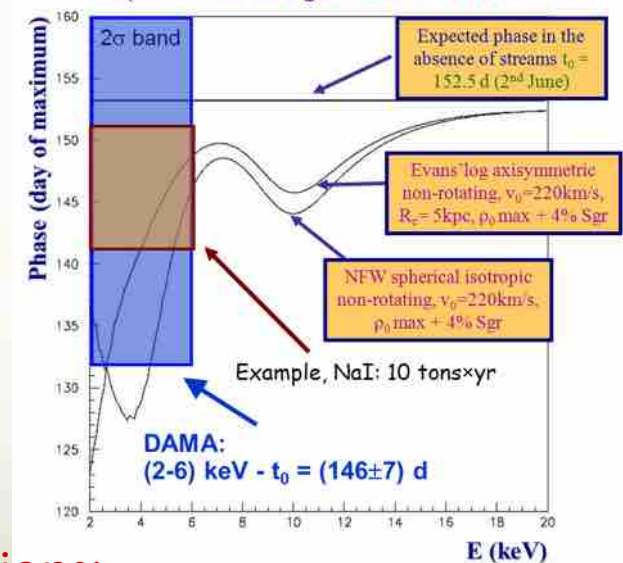
The annual modulation phase depends on :

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

PRL112(2014)011301



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



A step towards such investigations:

➔ **DAMA/LIBRA-phase2**

running with lower energy threshold and larger exposure
+ further possible improvements (DAMA/LIBRA-phase3) and DAMA/1ton

Towards future DAMA/LIBRA-phase3

DAMA/LIBRA-phase3 (enhancing sensitivities for corollary aspects, other DM features, second order effects and other rare processes):

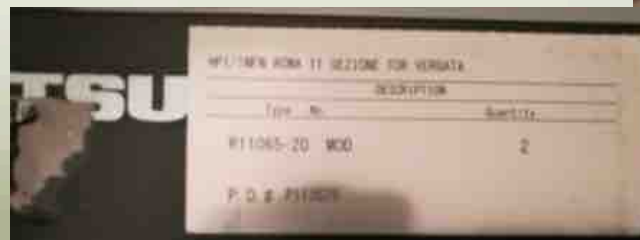
- R&D studies towards the possible DAMA/LIBRA-phase3 are continuing in particular as regards new protocols for possible modifications of the detectors; moreover, four new PMT prototypes from a dedicated R&D with HAMAMATSU are already at hand.
- Improving the light collection of the detectors (and accordingly the light yields and the energy thresholds). Improving the electronics.
- **Other possible option:** new ULB crystal scintillators (e.g. ZnWO_4) placed in between the DAMA/LIBRA detectors to add also a high sensitivity directionality meas.

The presently-reached metallic 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).



4 prototypes at hand



Perspectives for the future

Other signatures?

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

Directionality technique (at R&D stage)

- Only for candidates inducing just recoils
- Identification of the Dark Matter particle by exploiting the non-isotropic recoil distribution correlated to the Earth position with to the Sun

NEWAGE

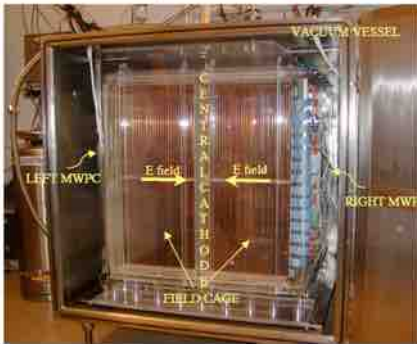
Anisotropic scintillators: DAMA, UK, Japan

DRIFT-II_d

The DRIFT-II_d detector in the Boulby Mine

The detector volume is divided by the central cathode, each half has its own multi-wire proportional chamber (MWPC) readout.

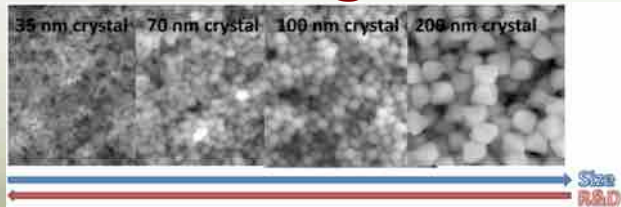
0.8 m³ fiducial volume; 10/30 Torr CF₄/CS₂ → 139 g



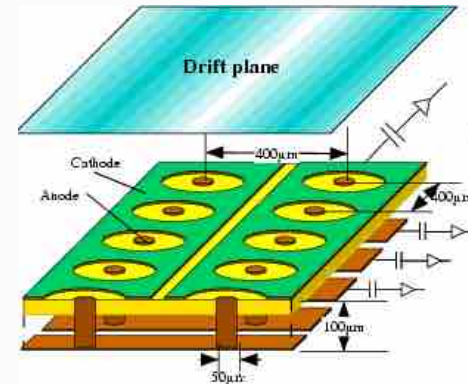
Dinesh Lomita

Background dominated by Radon Progeny Recoils (decay of ²²²Rn daughter nuclei, present in the chamber)

Nano Imaging Tracker (NIT) emulsions.
NEWSdm @ LNGS



Track readout: track length ranges also $\leq \lambda$. → use different optical techniques and make a pre-selection on the optical microscopes (also polarization)



	Current	Plan
Detection Volume	30 × 30 × 31 cm ³	> 1 m ³
Gas	CF ₄ 152 Torr	CF ₄ 30 Torr
Energy threshold	100 keV	35 keV
Energy resolution (@ threshold)	70% (FWHM)	50% (FWHM)
Gamma-ray rejection (@ threshold)	8 × 10 ⁻⁶	1 × 10 ⁻⁷
Angular resolution (@ threshold)	55° (RMS)	30° (RMS)

μ -PIC (Micro Pixel Chamber) is a two dimensional position sensitive gaseous detector

Internal radioactive BG restricts the sensitivities
We are working on to reduce the backgrounds!



DM-TPC

- The “4---Shooter” 18L (6.6 gm) TPC 4xCCD, Sea-level@MIT
- moving to WIPP
- Cubic meter funded, design underway

Not yet competitive sensitivity

Development of detectors with anisotropic response

DAMA - Seminal paper: N.Cim.C15(1992)475; revisited: EPJC28(2003)203; more recently other suitable materials: EPJC73(2013)2276; now: work in progress

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 nuclear recoils by exploiting the non-isotropic recoil distribution correlated to the Earth velocity

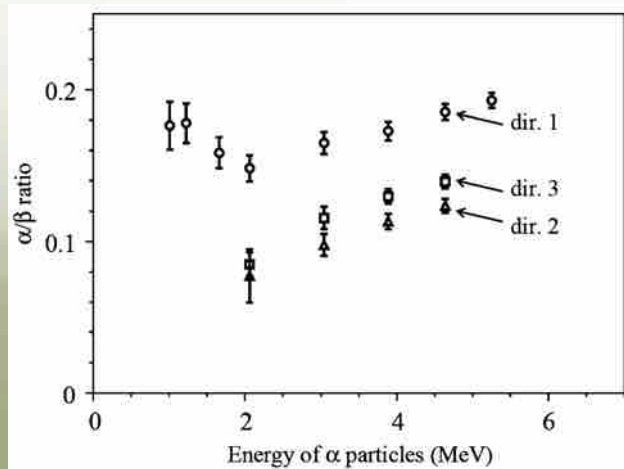
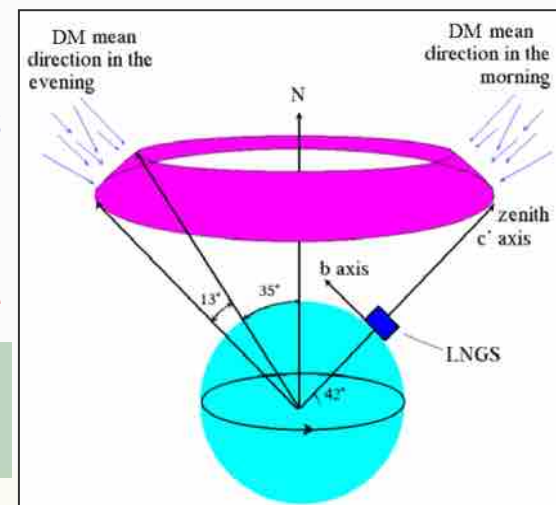
Taking into account:

- 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

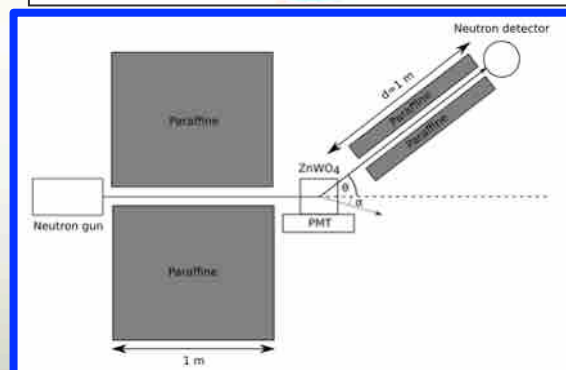
O → light masses
Zn, W → high masses

The ADAMO project: Development of ZnWO_4 anisotropic scintillators



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

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



Measurements of anisotropy in keV range by neutron generator on-going at ENEA-Casaccia

Conclusions

DARK MATTER investigation with direct detection approach

- Different **solid** techniques can give complementary results
- Some further efforts to demonstrate the **solidity** of some techniques are needed
- Higher exposed mass not a synonymous of **higher sensitivity**
- **DAMA** positive evidence (9.3σ C.L.). The modulation parameters determined with **better precision**.
+ **full sensitivity** to many kinds of DM candidates and interactions both inducing recoils and/or e.m. radiation.
- Possible positive hints are compatible with DAMA in many scenarios; null searches not in robust conflict. Consider also the experimental and theoretical uncertainties.
- The **model independent signature** is the definite strategy to investigate the presence of Dark Matter particle component(s) in the Galactic halo

