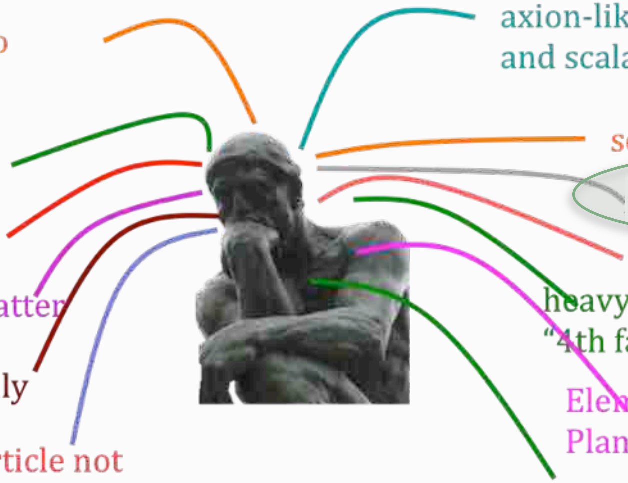
Dark Matter direct detection

P. Belli
INFN – Roma Tor Vergata

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



SUSY
(as neutralino or sneutrino
in various scenarios)

the sneutrino in the Smith
and Weiner scenario

sterile ν

electron interacting dark matter

a heavy ν of the 4-th family

even a suitable particle not
yet foreseen by theories

etc...

axion-like (light pseudoscalar
and scalar candidate)

self-interacting dark matter

Mirror dark matter

Kaluza-Klein particles (LKK)

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

Elementary Black holes,
Planckian objects, Daemons

invisible axions, ν's

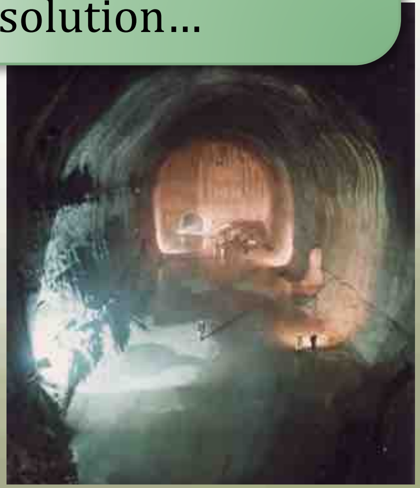
see previous talks

What accelerators can do:
to demostrate 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

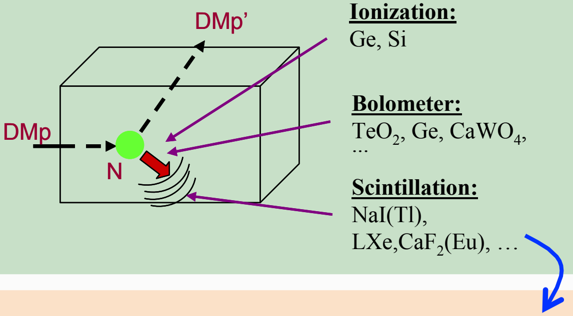
DM direct detection method using a model independent approach and a low-background widely-sensitive target material



Some direct detection processes:

- Scatterings on nuclei

  → detection of nuclear recoil energy



Ionization:
Ge, Si

Bolometer:
TeO_2, Ge, $CaWO_4$, …

Scintillation:
NaI(Tl),
LXe, CaF_2(Eu), …

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

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

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

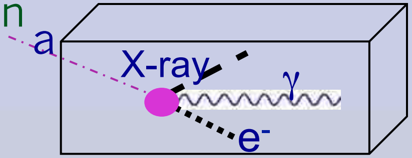
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

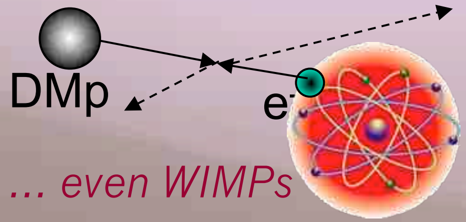
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

  → detection of e.m. radiation

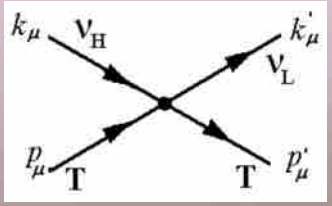


... even WIMPs

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

  → detection of electron/nucleus recoil energy

e.g. sterile ν



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

... also other ideas ...

- **... and more**

Direct detection experiments

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

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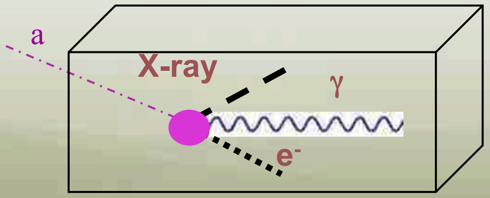
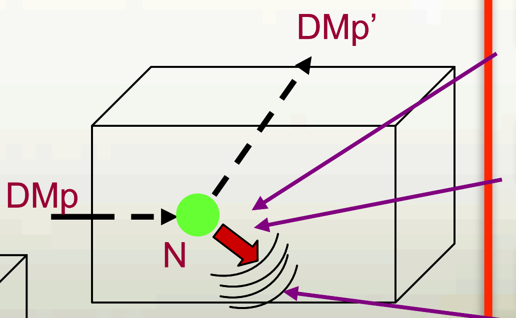
1. on the recognition of the signals due to Dark Matter particles with respect to the background by using a ***model-independent* signature**

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)





Ionization:
Ge, Si

Bolometer:
TeO_2, Ge, $CaWO_4$, …

Scintillation:
NaI(Tl), LXe, CaF_2(Eu), …

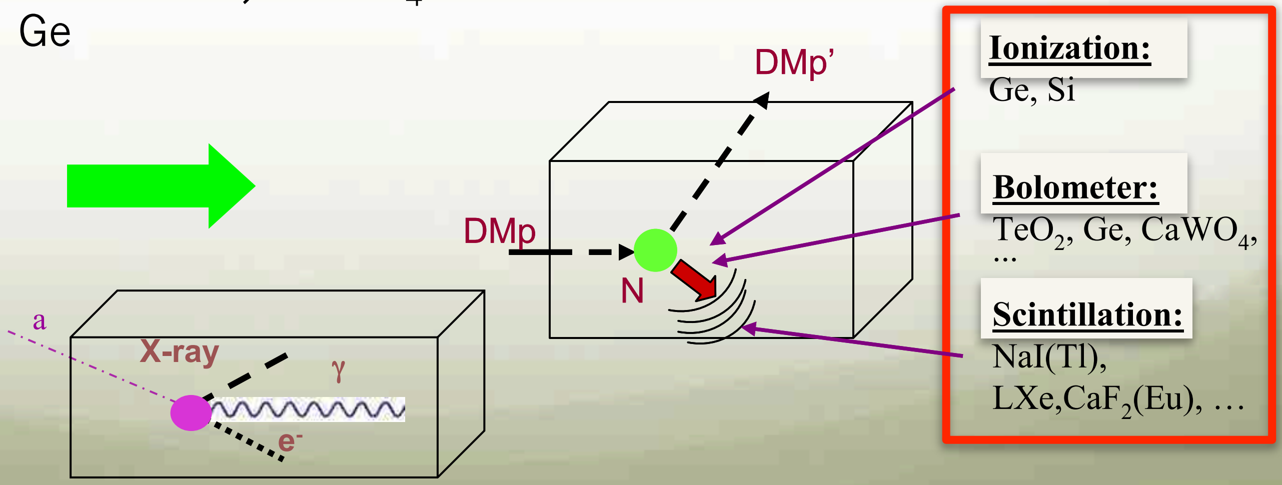
Direct detection experiments

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...



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Scintillation:
NaI(Tl),
LXe, $CaF_2(Eu)$, ...

Experiments using liquid noble gases

in single phase detector:

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

DAMA/LXe

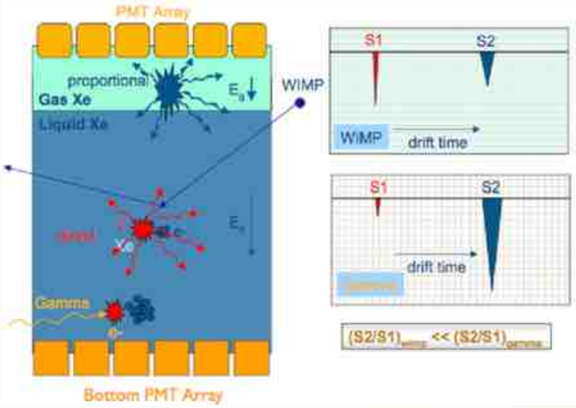
XMASS

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

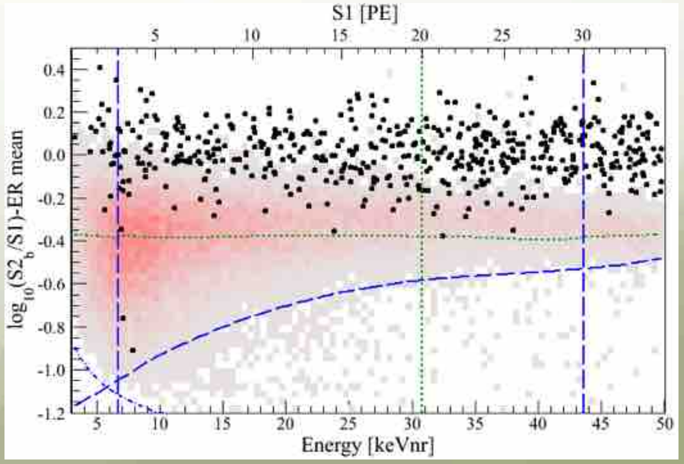
WARP, XENON10, 100, 1T, LUX, PANDAX, DarkSide, DEAP, CLEAN, ArDM



- **Non-uniform** response of detector: intrinsic limit
- **UV light**, **unlinearity** (more in larger volumes)
- **Correction** procedures applied
- **Systematics**
- **Small light responses** (2.2 ph.e./keVee) ⇒ 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.

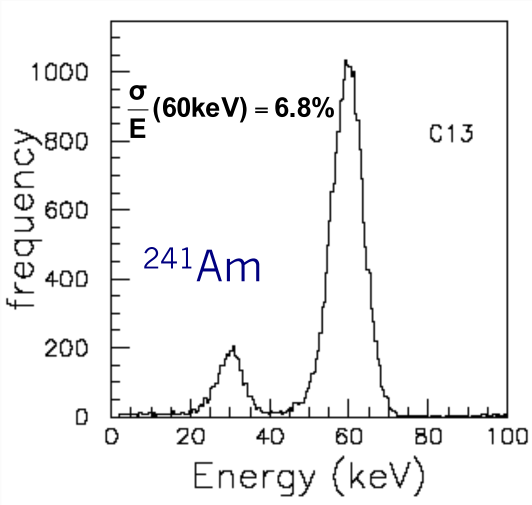
Many cuts applied, each of them can introduce systematics. The systematics can be variable along the data taking period; can they and the related efficiencies be suitably evaluated in short period calibration?

After many cuts few events survive: intrinsic limit reached?



Examples of energy resolutions

DAMA/LIBRA ULB NaI(TI)



$\frac{\sigma}{E}$(60keV) = 6.8%

^{241}Am

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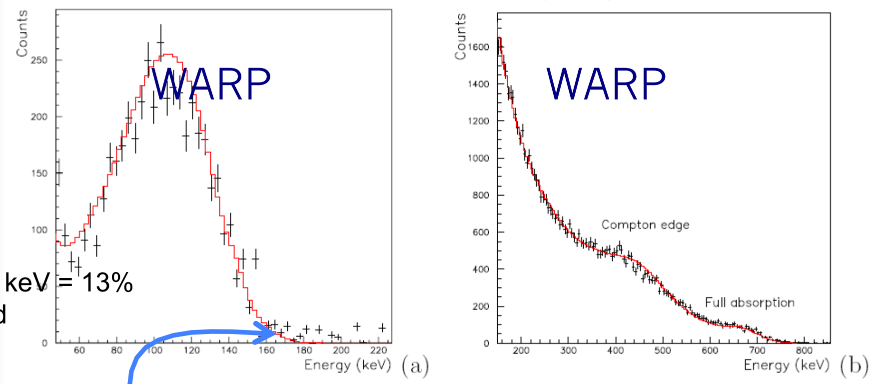

WARP

WARP

σ/E @ 122 keV = 13%
at zero field

Fig. 2. Energy spectra taken with external γ-ray sources, superimposed with the corresponding Monte Carlo simulations. (a) ^{57}Co source (E = 122 keV, B.R. 85.6%, and 136 keV, B.R. 10.7%), (b) ^{137}Cs source (E = 662 keV).

subtraction of the spectrum ?

ZEPLIN-II

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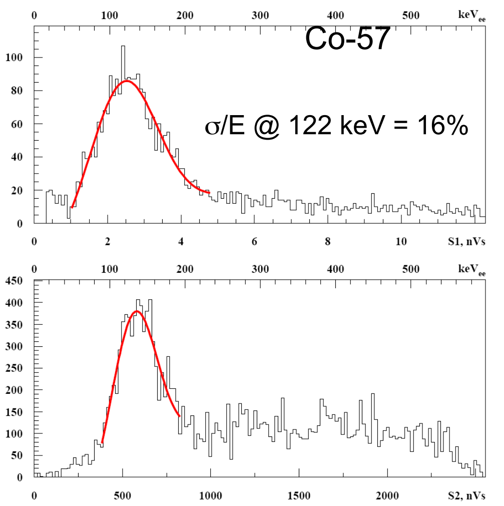
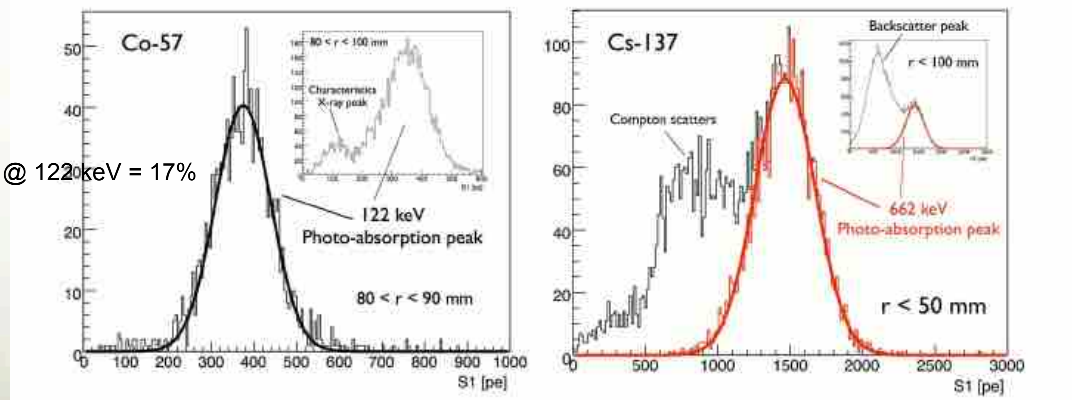


Co-57

σ/E @ 122 keV = 16%

Fig. 5. Typical energy spectra for ^{57}Co γ-ray calibrations, showing S1 spectrum (upper) and S2 spectrum (lower). The fits are double Gaussian fits which incorporate both the 122 keV and 136 keV lines in the ^{57}Co γ-ray spectrum. The energy resolution of the detector is derived from the width of the S1 peak, coupled with calibration measurements at other line energies.

XENON10 XENON10



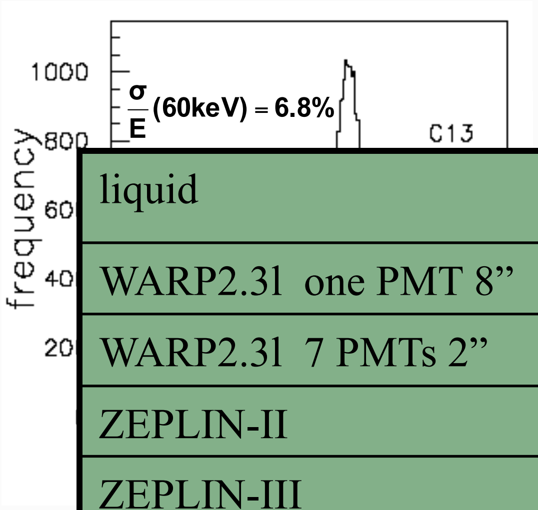
σ/E @ 122 keV = 17%

Figure 3. (left) S1 scintillation spectrum from a ^{57}Co calibration. The light yield for the 122 keV photo-absorption peak is 3.1 p.e./keV. (right) S1 scintillation spectrum from a ^{137}Cs calibration. The light yield for the 662 keV photo-absorption peak is 2.2 p.e./keV.

JoP: Conf. Ser. 65 (2007) 012015

Examples of energy resolutions

DAMA/LIBRA ULB NaI(Tl)



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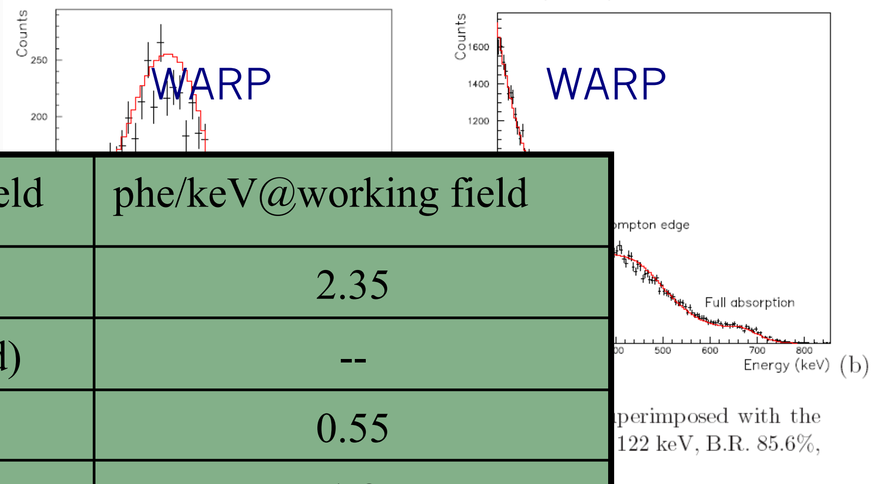

perimposed with the 122 keV, B.R. 85.6%,

liquid	phe/keV@zero field	phe/keV@working field
WARP2.31 one PMT 8”	--	2.35
WARP2.31 7 PMTs 2”	0.5-1 (deduced)	--
ZEPLIN-II	1.1	0.55
ZEPLIN-III		1.8
XENON10	--	2.2 (^{137}Cs), 3.1 (^{57}Co)
XENON100	2.7	1.57 (^{137}Cs), 2.2 (^{57}Co)
Neon	0.93	field not foreseen

Z

rum ?

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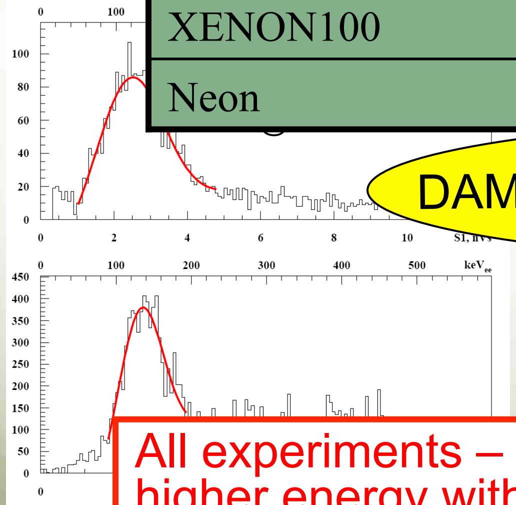
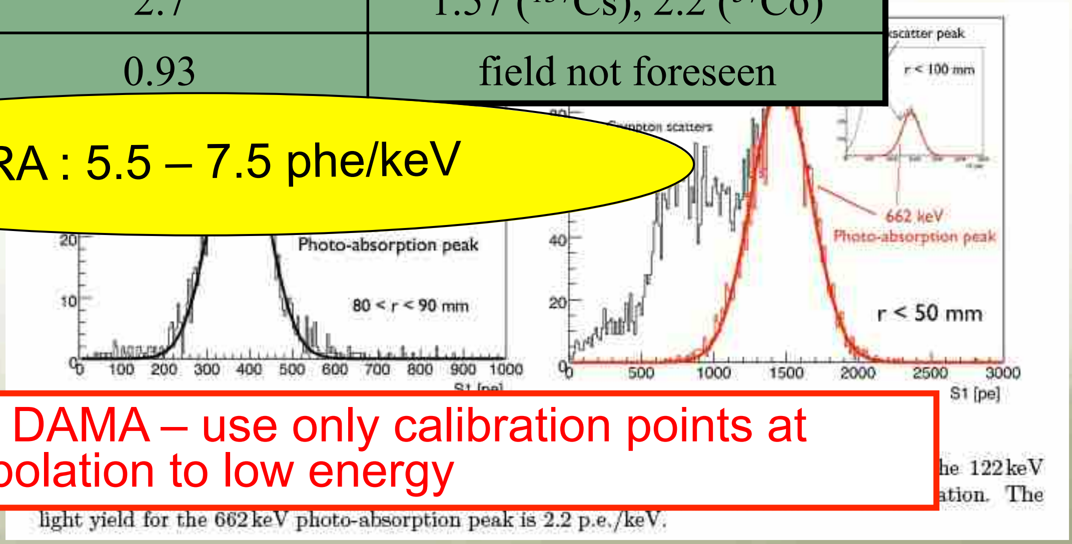


Fig. 5. Typical energy (upper) and S2 spectrum (lower). The fits are double Gaussian fits which incorporate both the 122 keV and 136 keV lines in the ^{57}Co γ-ray spectrum. The energy resolution of the detector is derived from the width of the S1 peak, coupled with calibration measurements at other line energies.



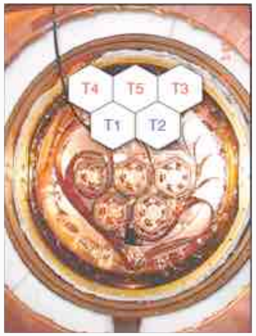
he 122 keV ation. The light yield for the 662 keV photo-absorption peak is 2.2 p.e./keV.

JoP: Conf. Ser. 65 (2007) 012015

DAMA/LIBRA : 5.5 – 7.5 phe/keV

All experiments – except DAMA – use only calibration points at higher energy with extrapolation to low energy

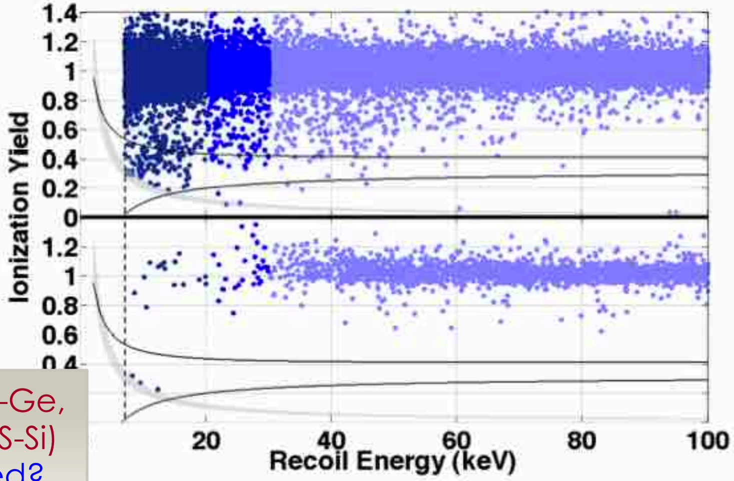
Double read-out bolometric technique (ionization vs heat)

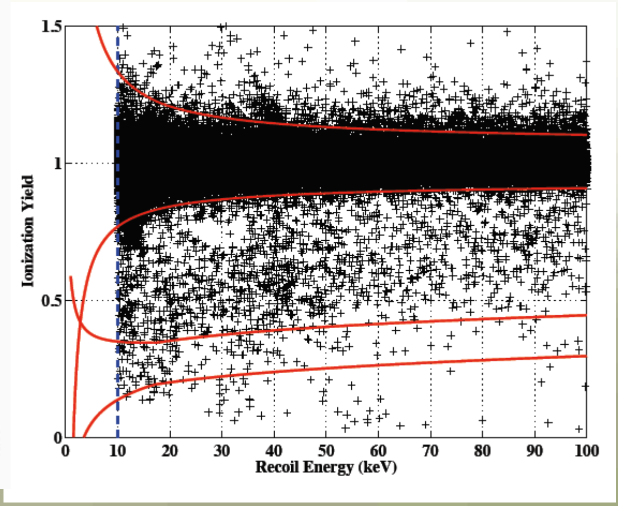


- CDMS-Ge: Soudan, 3.22 kg Ge, 194.1 kg x day; E_{th}=10 keV + other attemps at lower E_{th}
- Edelweiss: LSM, 3.85 kg Ge, 384 kg x day; E_{th}=20 keV
- CDMS-Si: 1.2 kg Si, 140.2 kg x day; E_{th}=7 keV

- **Many cuts on the data:** how about systematics?
- **Low duty cycle:** (selected exposure) / (data taking time x mass) about 10%
- The **systematics** can be variable along the data taking period; can they and the related efficiencies be suitably evaluated in short period calibration?
- **Phonon timing cut:** time and energy response vary across the detector ⇒look-up table used (stability, robustness of the reconstruction procedure, efficiency and uncertainties)
- **Poor detector performances:** many detectors excluded in the analysis
- **Critical stability of the performances**
- **Non-uniform** response of detector: intrinsic limit
- **Surface electrons:** PSD needed with related uncertainty

- Due to **small number** of events to deal after selection, even small fluctuations of parameters (energy, Y scales, noises, …) and of tails of the distributions can play a relevant role
- **Efficiencies** of both signals





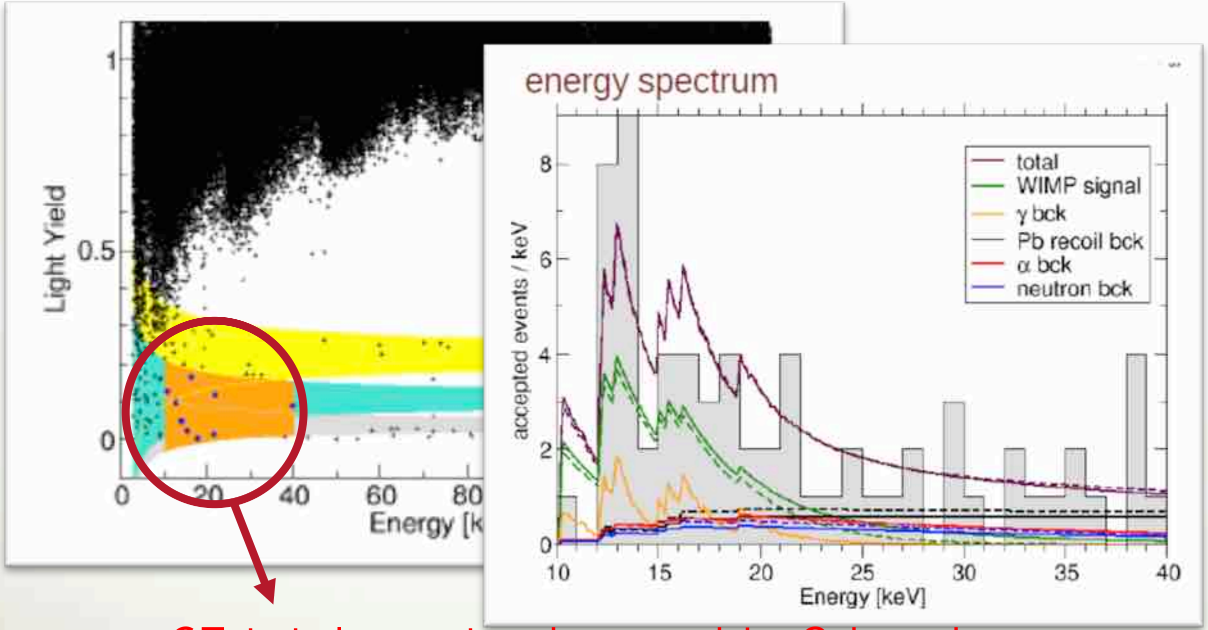
After many cuts few (two in CDMS-Ge, five in Edelweiss and three in CDMS-Si) events survive: intrinsic limit reached?

Double read-out bolometric technique (scintillation vs heat)

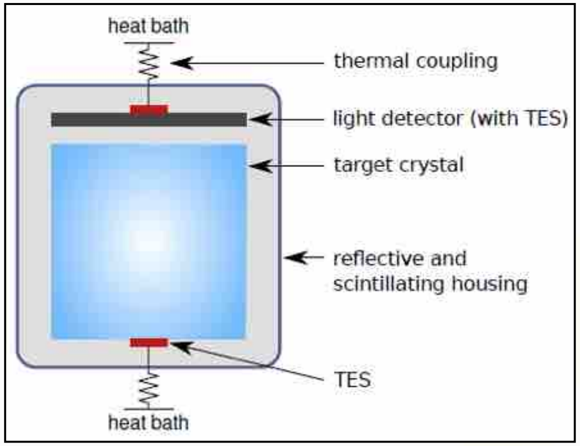
(see also above)

CRESST at LNGS: 33 $CaWO_4$ crystals (10 kg mass) data from 8 detectors. Exposure: ≈ 730 kg x day

Data from one detector

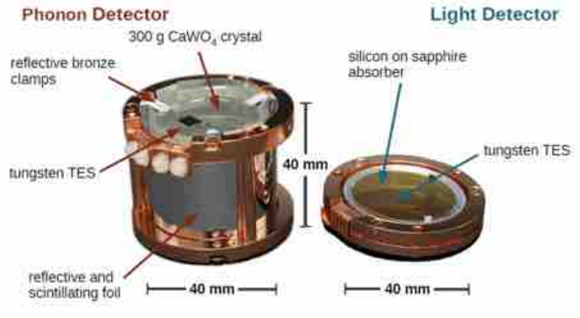


67 total events observed in O-band;



background-only hypothesis rejected with high statistical significance → additional source of events needed (Dark Matter?)

Efficiencies + stability + calibration, crucial role



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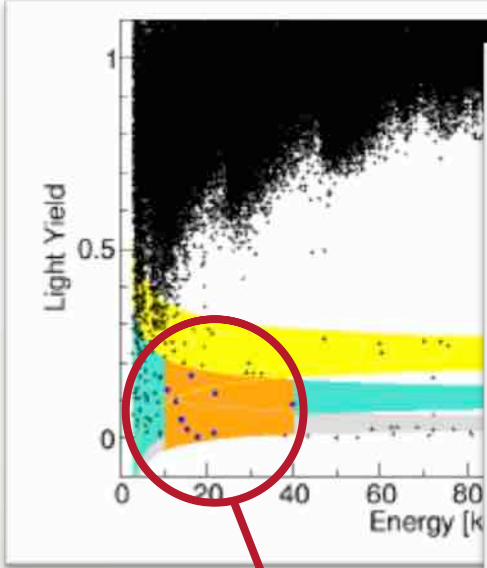

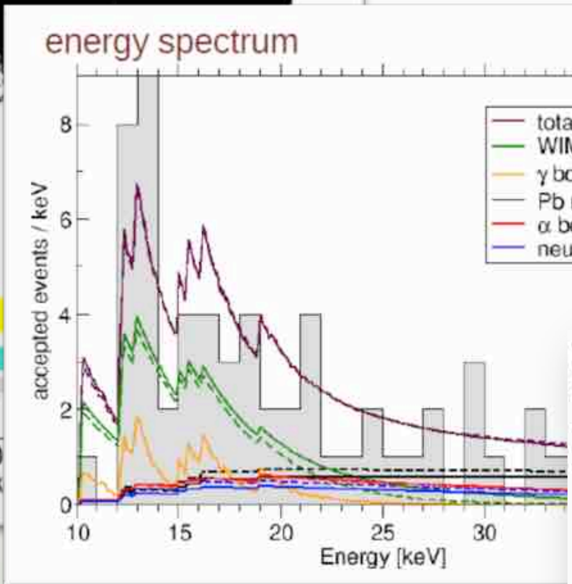

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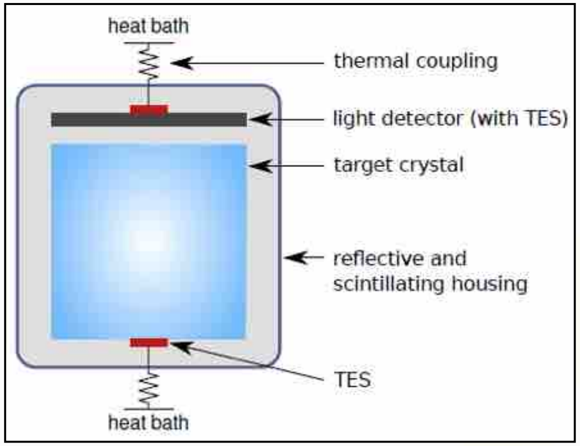

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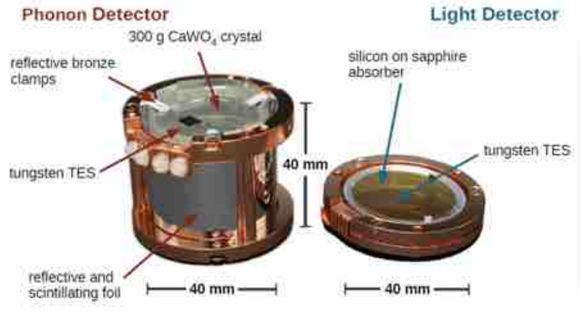
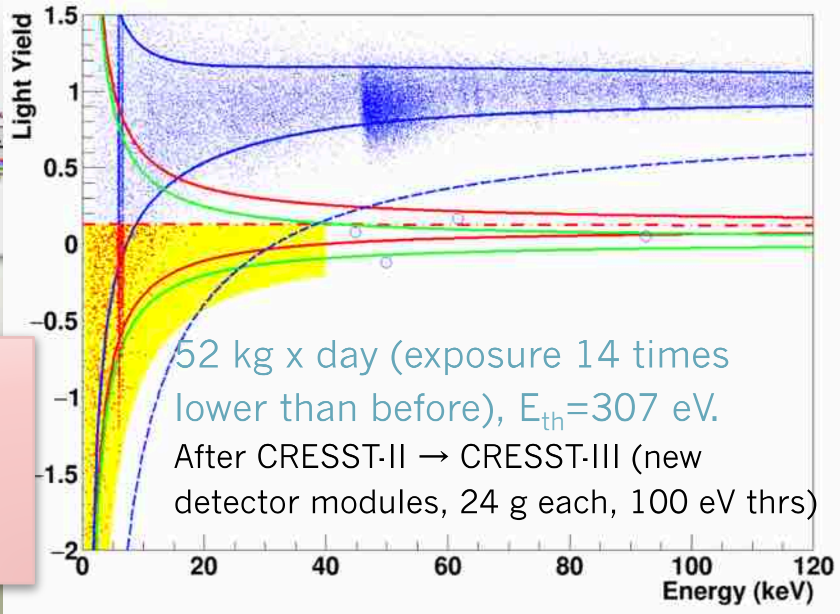


Systematics in previous runs (?):
Latest run with lower energy threshold does not confirm the excess!!!



52 kg x day (exposure 14 times lower than before), E_{th}=307 eV.

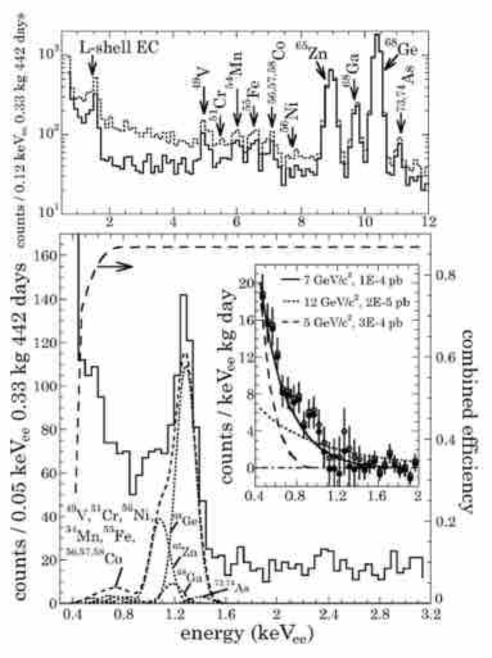
After CRESST-II → CRESST-III (new detector modules, 24 g each, 100 eV thrs)

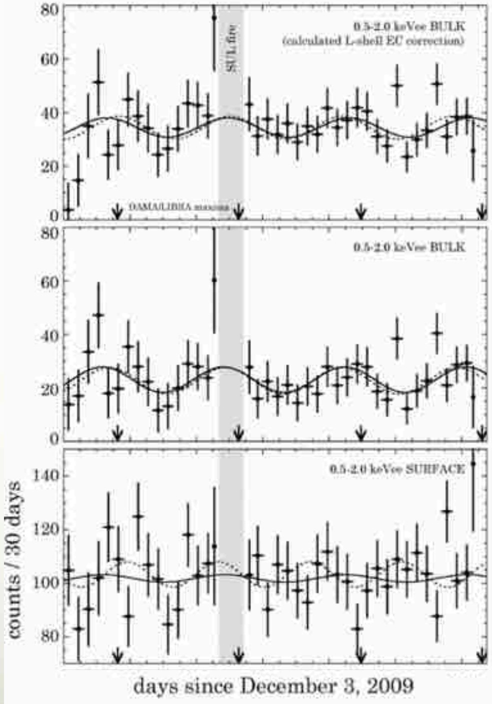
Positive hints from CoGeNT (ionization detector)

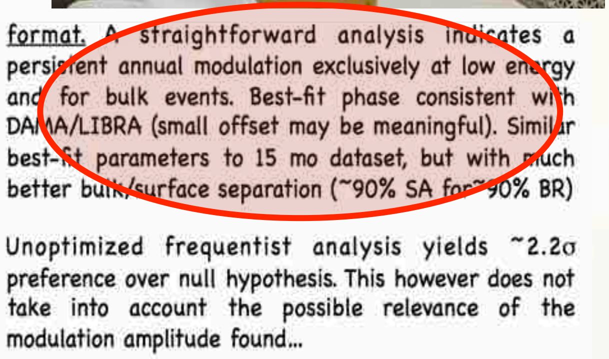
Experimental site:	Soudan Underground Lab (2100 mwe)
Detector:	440 g, p-type point contact (PPC) Ge diode 0.5 keVee energy threshold
Exposure:	146 kg x day (dec '09 - mar '11)

✓ **Irreducible excess** of bulk-like events below 3 keVee observed;

✓ **annual modulation** of the rate in 0.5-4.5 keVee at ~2.2σ C.L.







format. A straightforward analysis indicates a persistent annual modulation exclusively at low energy and for bulk events. Best-fit phase consistent with DAMA/LIBRA (small offset may be meaningful). Similar best-fit parameters to 15 mo dataset, but with much better bulk/surface separation (~90% SA for ~90% BR)

Unoptimized frequentist analysis yields ~2.2σ preference over null hypothesis. This however does not take into account the possible relevance of the modulation amplitude found...

Other Ge activity: Texono, CDEX @ CJPL

- **Other data at hand.**
- CoGeNT upgrade: C-4
- C-4 aims at x4 total mass increase, bckg decrease, and substantial threshold reduction. Soudan is still the lab

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

Diurnal modulation due to the Earth rotation around its axis

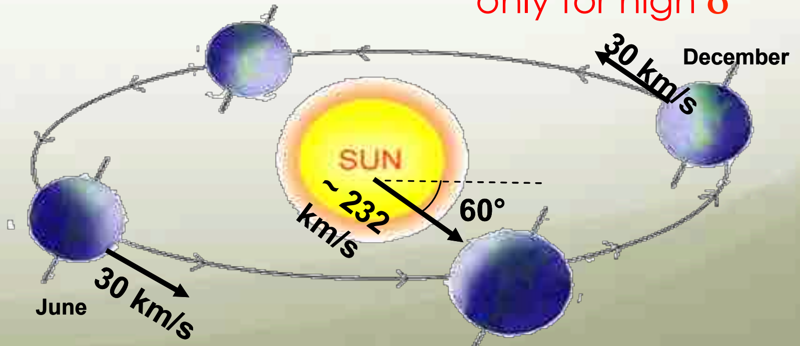
2nd order effect

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

only for high σ

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



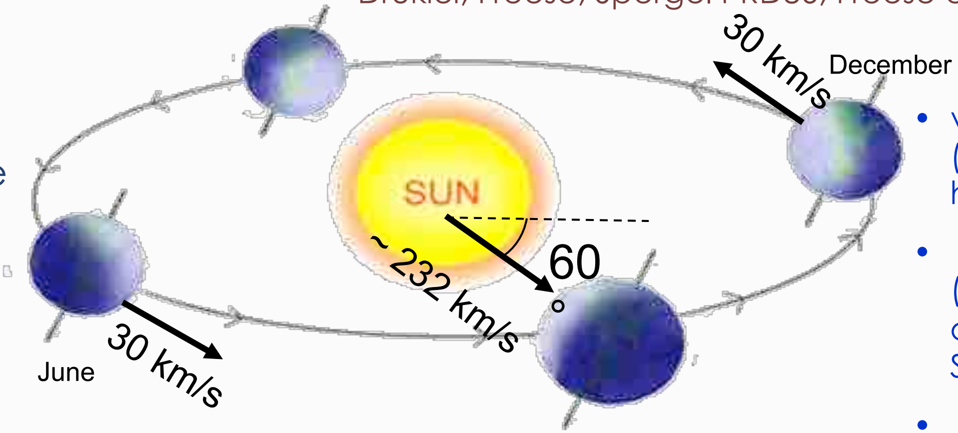
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

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.

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

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



- $v_{sun} \sim 232$ 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
- $t_0 = 2^{nd}$ June (when $v_\oplus$ is maximum)

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

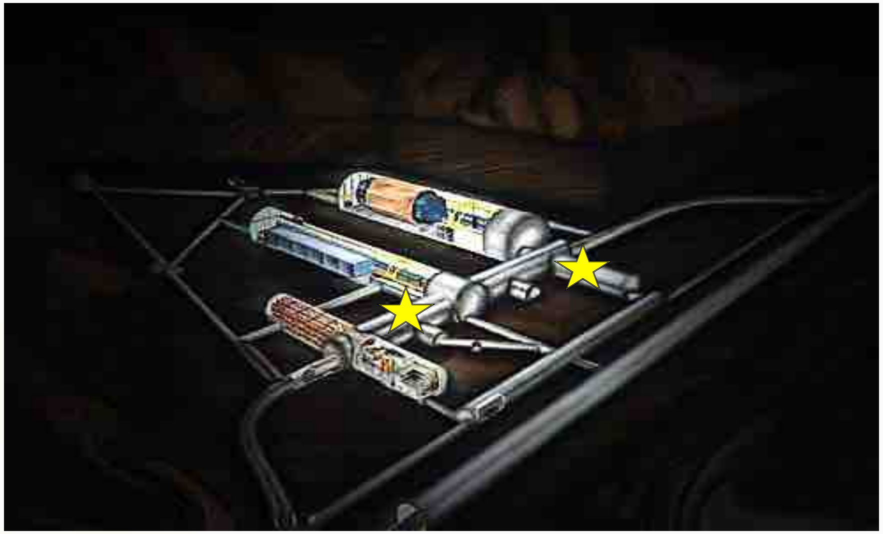
$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \cong S_{0,k} + S_{m,k}\cos[\omega(t-t_0)]$$

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

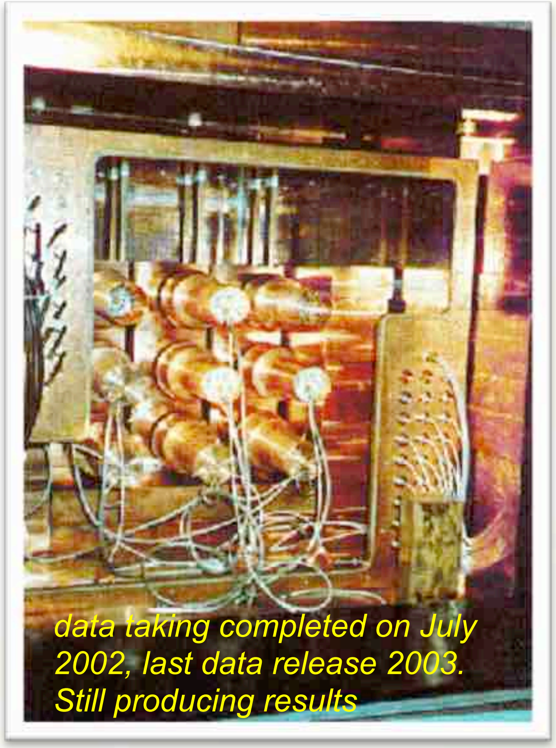
+ by-products and small scale expts.: INR-Kiev + other institutions

+ 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)


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

Performances:

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

Results on rare processes:

• Possible Pauli exclusion principle violation	PLB408(1997)439
• CNC processes	PRC60(1999)065501
• Electron stability and non-paulian transitions in Iodine atoms (by L-shell)	PLB460(1999)235
• Search for solar axions	PLB515(2001)6
• Exotic Matter search	EPJdirect C14(2002)1
• Search for superdense nuclear matter	EPJA23(2005)7
• Search for heavy clusters decays	EPJA24(2005)51

Results on DM particles:

• PSD	PLB389(1996)757
• Investigation on diurnal effect	N.Cim.A112(1999)1541
• Exotic Dark Matter search	PRL83(1999)4918
• **Annual Modulation Signature**	PLB424(1998)195, PLB450(1999)448, PRD61(1999)023512, PLB480(2000)23, EPJC18(2000)283, PLB509(2001)197, EPJC23(2002)61, PRD66(2002)043503, Riv.N.Cim.26 n.1 (2003)1, IJMPD13(2004)2127, IJMPA21(2006)1445, EPJC47(2006)263, IJMPA22(2007)3155, EPJC53(2008)205, PRD77(2008)023506, MPLA23(2008)2125

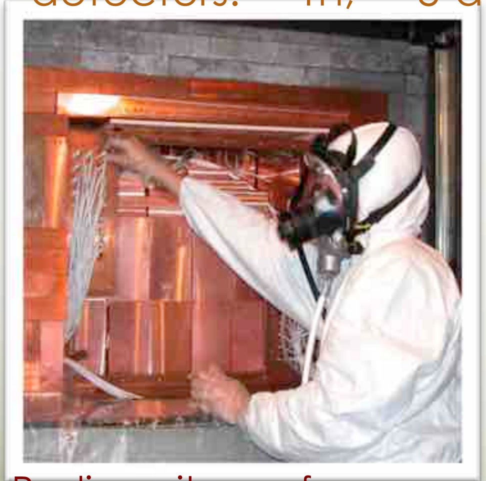
Model independent evidence of a particle DM component in the galactic halo at 6.3σ C.L.

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)

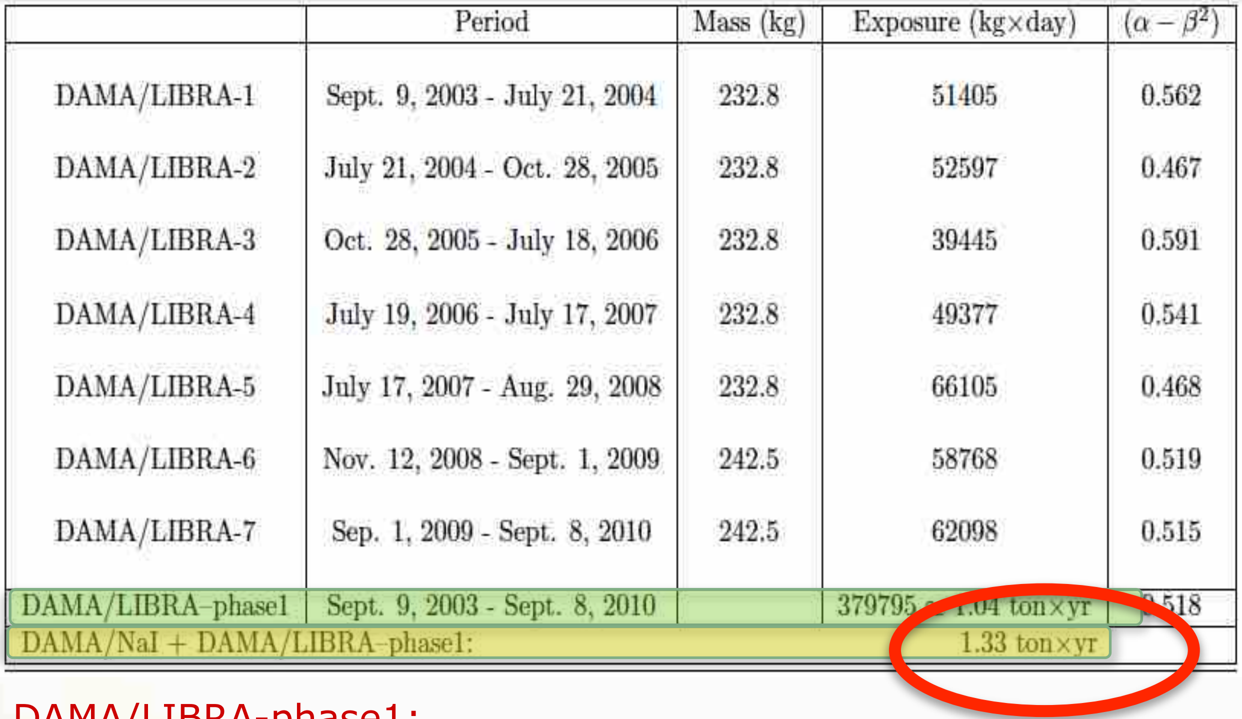
As a result of a 2nd generation R&D for more radiopure NaI(Tl) by exploiting new chemical/physical radiopurification techniques
(all operations involving - including photos - in HP Nitrogen atmosphere)

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	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 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 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

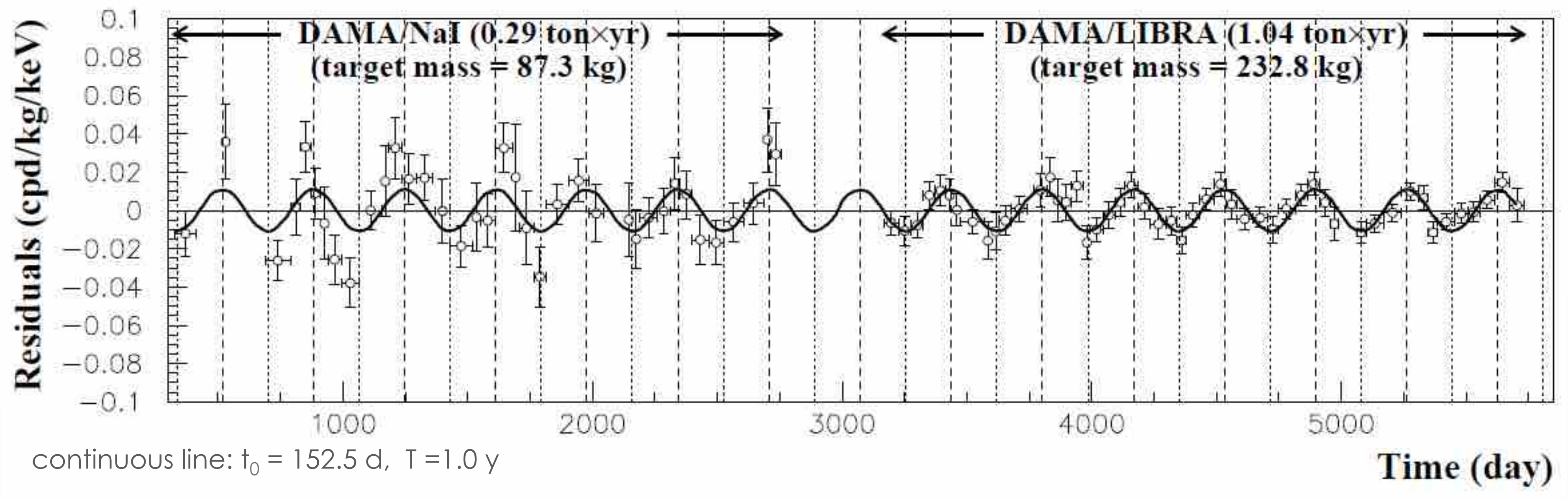
- Fall 2012: new preamplifiers installed + special trigger modules. Other new components in the electronic chain in development

Model Independent Annual Modulation Result

DAMA/NaI + **DAMA/LIBRA-phase1** Total exposure: 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



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

Absence of modulation? No

χ^2/dof=154/87

P(A=0) = 1.3×10^{-5}

Fit: 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.

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

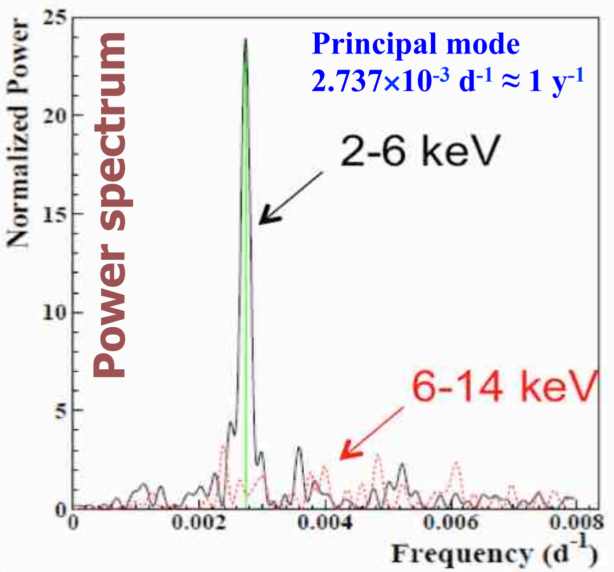
DAMA/NaI + **DAMA/LIBRA-phase1** Total exposure: 487526 kg×day = **1.33 ton×yr**

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

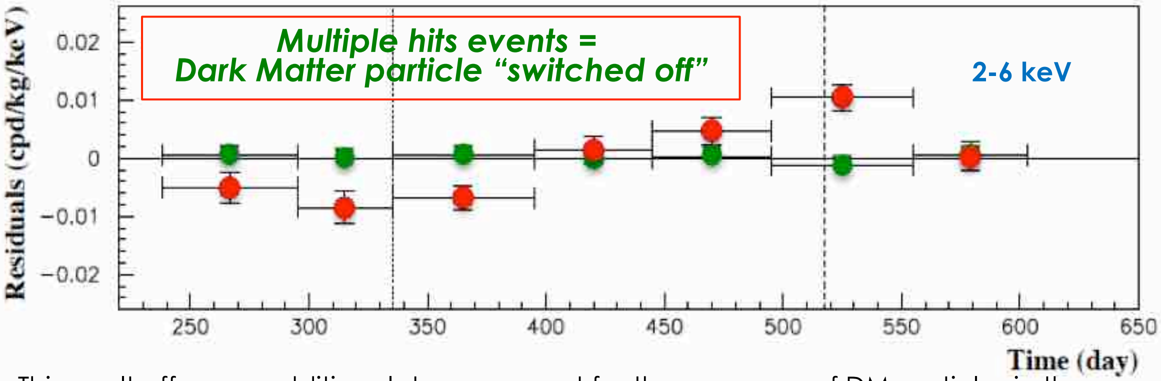
	A(cpd/kg/keV)	$T=2\pi/\omega$ (yr)	t_0 (day)	C.L.
DAMA/NaI+DAMA/LIBRA-phase1				
(2-4) keV	0.0190 ±0.0020	0.996 ±0.002	134 ± 6	9.5σ
(2-5) keV	0.0140 ±0.0015	0.996 ±0.002	140 ± 6	9.3σ
(2-6) keV	0.0112 ±0.0012	0.998 ±0.002	144 ± 7	9.3σ

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



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.

Model Independent Annual Modulation Result

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

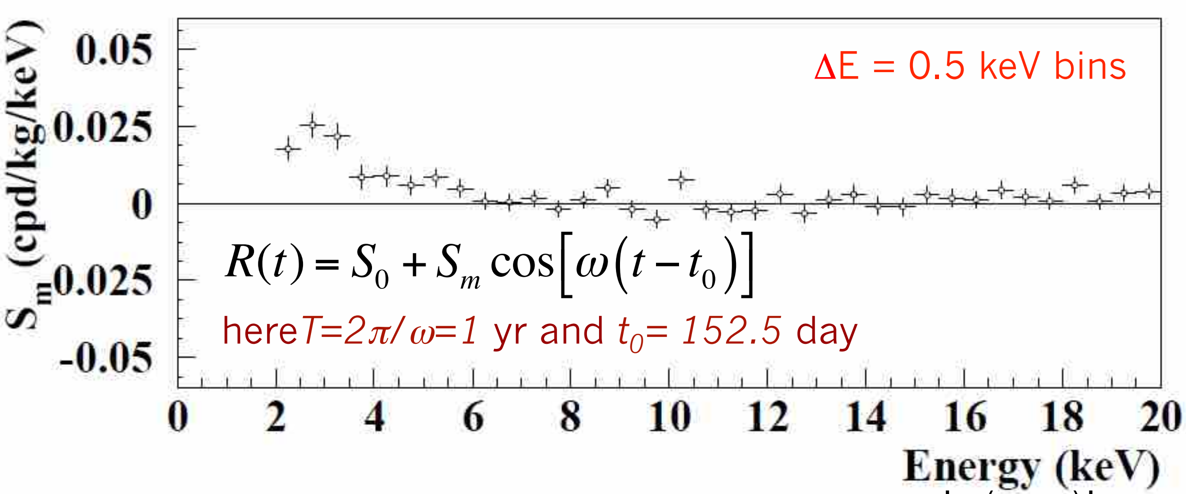
Max-lik analysis of single hit events

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%)



ΔE = 0.5 keV bins

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

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

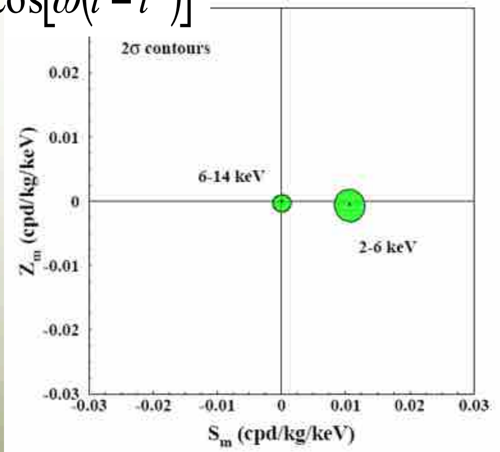
Is there a sinusoidal contribution in the signal? Phase ≠ 152.5 day?

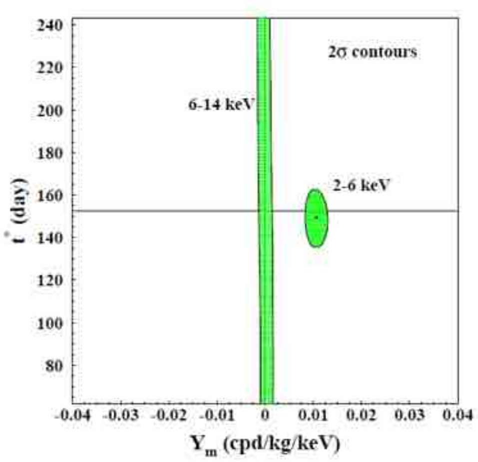
$$R(t) = S_0 + S_m \cos\left[\omega\left(t - t_0\right)\right] + Z_m \sin\left[\omega\left(t - t_0\right)\right] = S_0 + Y_m \cos\left[\omega\left(t - t^*\right)\right]$$

For Dark Matter signals:

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

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 ≈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.

✓ **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**:

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

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

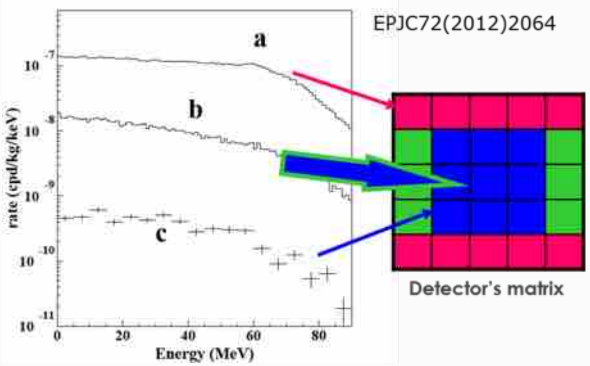
✓ **Inconsistency of the phase between DAMA signal and μ modulation**

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

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

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

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

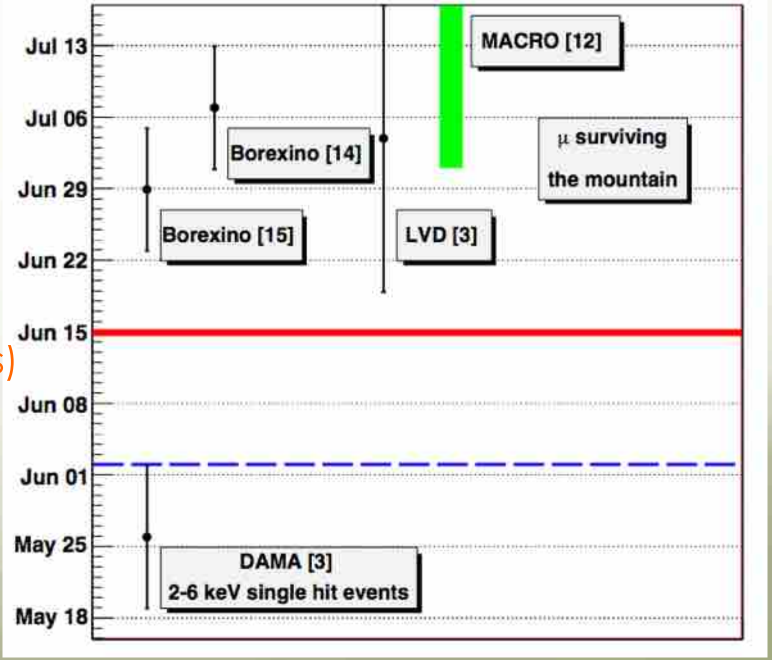


EPJC72(2012)2064

MonteCarlo simulation

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

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

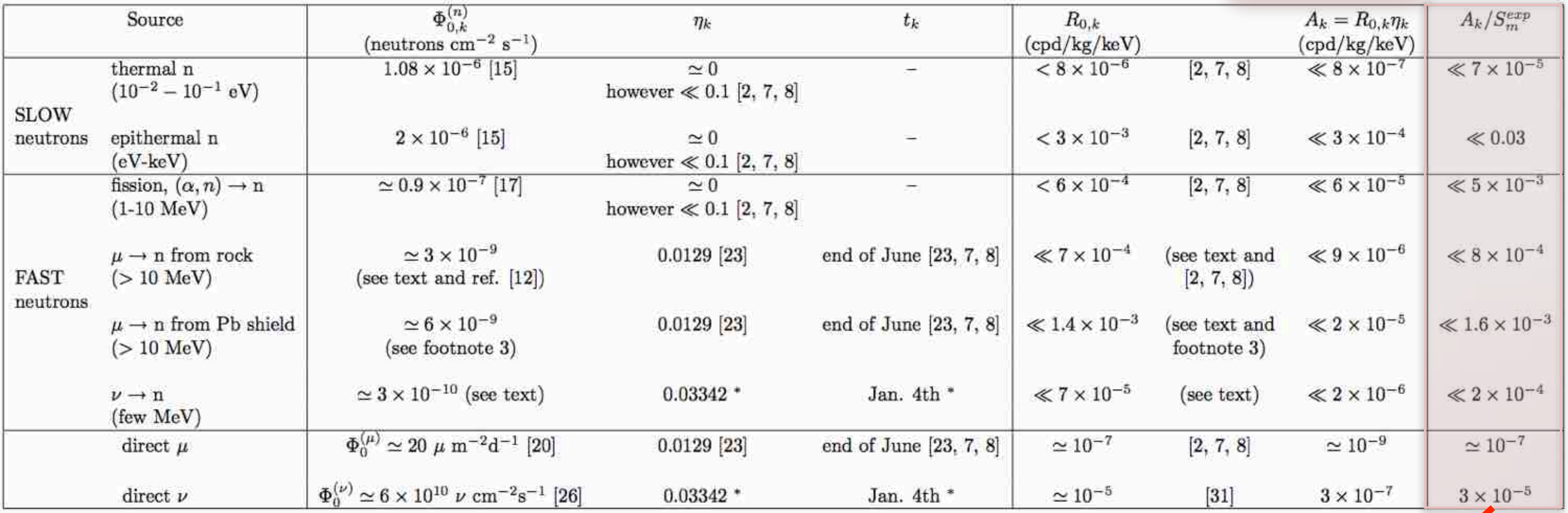


- Contributions to the total neutron flux at LNGS; →
- Counting rate in DAMA/LIBRA for *single-hit* events, in the (2 – 6) keV energy region induced by: →
  - neutrons,
  - muons,
  - solar neutrinos.

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

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

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, $(\alpha, n) \rightarrow$ 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	$\Phi_0^{(\mu)} \simeq 20$ 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), 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.	**$<2.5\times10^{-6}$ 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**

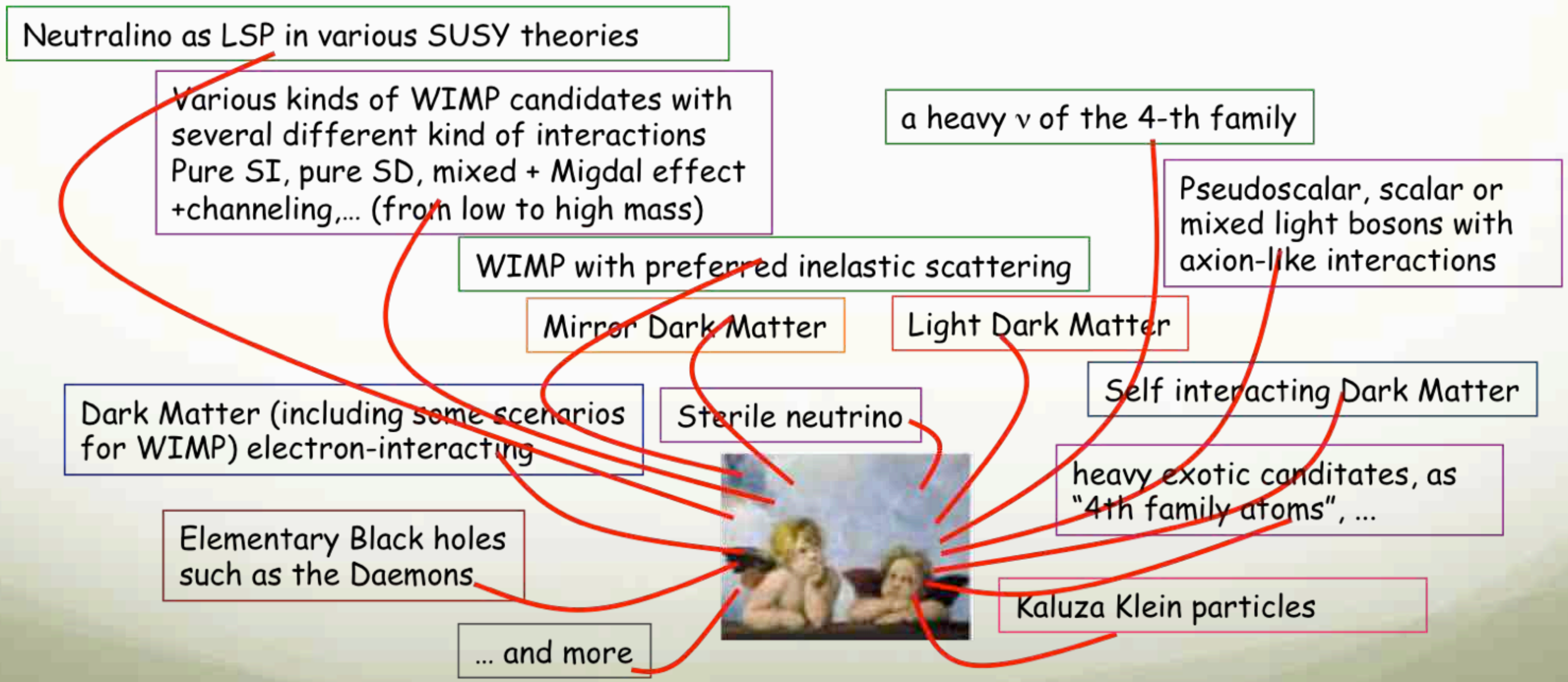
+ they cannot satisfy all the requirements of annual modulation signature

→

Thus, they cannot mimic the observed annual modulation effect

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

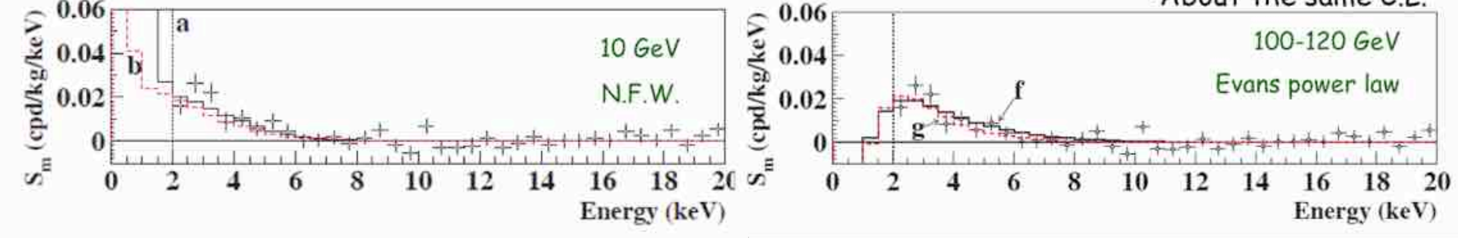
Model-independent evidence by DAMA/NaI and DAMA/LIBRA

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

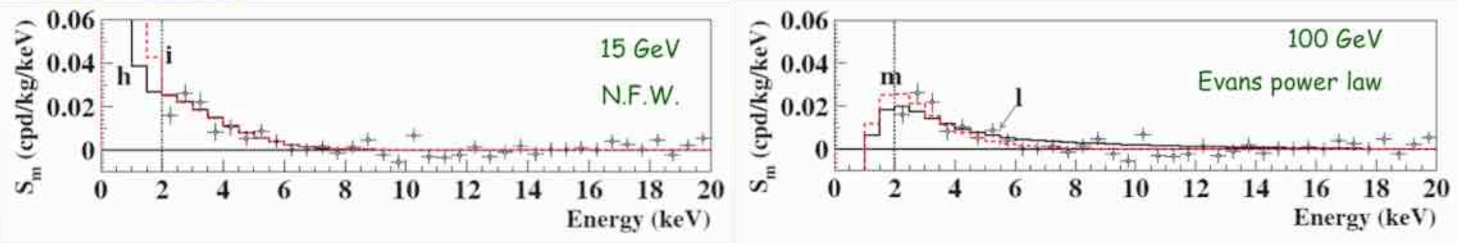
Just few examples of interpretation of the annual modulation in terms of candidate particles in some scenarios

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

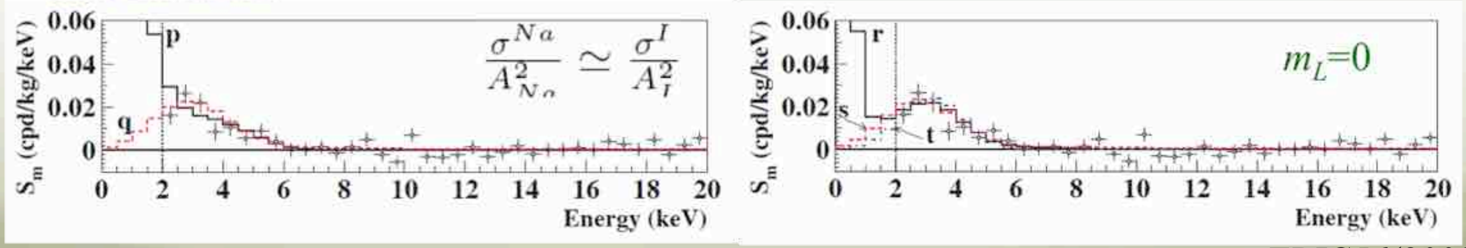
WIMP: SI



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

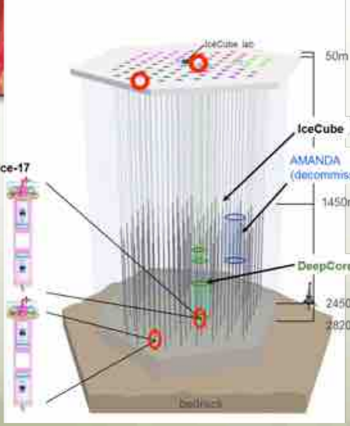
ANAIS. Project for 3×3 matrix of NaI(Tl) scintillators 12.5 kg each to study DM annual modulation at Canfranc (LSC). Several prototypes from different companies tested

- 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



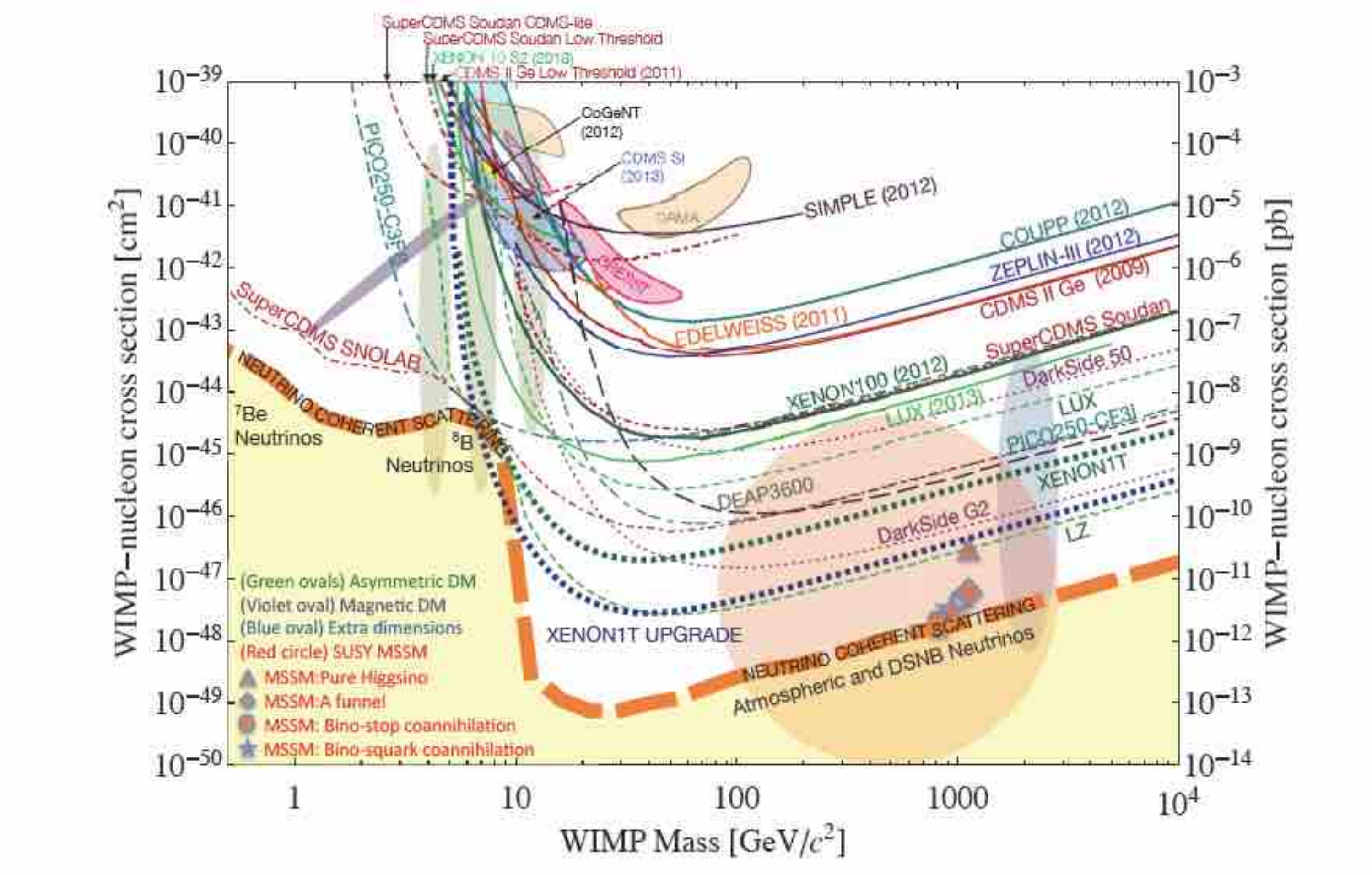
Key points: not only residual contaminants but also long-term/ high-level stability

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

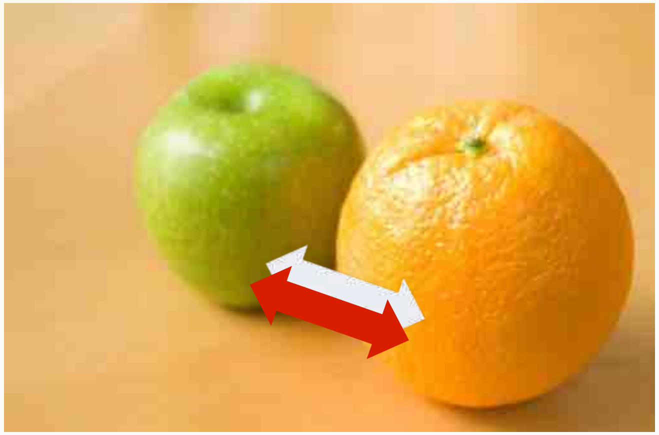
Is it an “universal” and “correct” way to approach the problem of DM and comparisons?



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, IJMPD13(2004)2127, EPJC47(2006)263, IJMPA21(2006)1445, EPJC56(2008)333, PRD84(2011)055014, IJMPA28(2013)1330022



…models…

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

…and experimental aspects…

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

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

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

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:

$\sigma_A \propto \mu^2 A^2 (1+\epsilon_A)$

$\epsilon_A = 0$ *generally assumed*

$\epsilon_A \approx \pm 1$ *in some nuclei? even* for neutralino candidate in MSSM (see Prezeau, Kamionkowski, Vogel et al., PRL91(2003)231301)

Halo models & Astrophysical scenario

- Isothermal sphere ⇒ 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

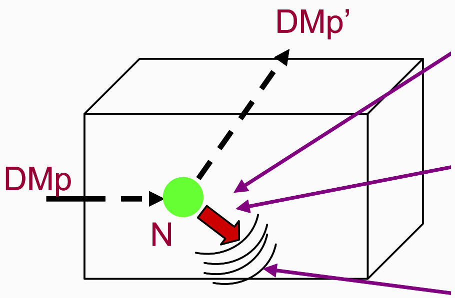
- differences are present in different experimental determinations of *q* for the same nuclei in the same kind of detector depending on its specific features (e.g. *q* depends on dopant and on the impurities; in liquid noble gas e.g.on trace impurities, on presence of degassing/releasing materials, on 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)

→ energy dependence

… and more …

... an example in literature...

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



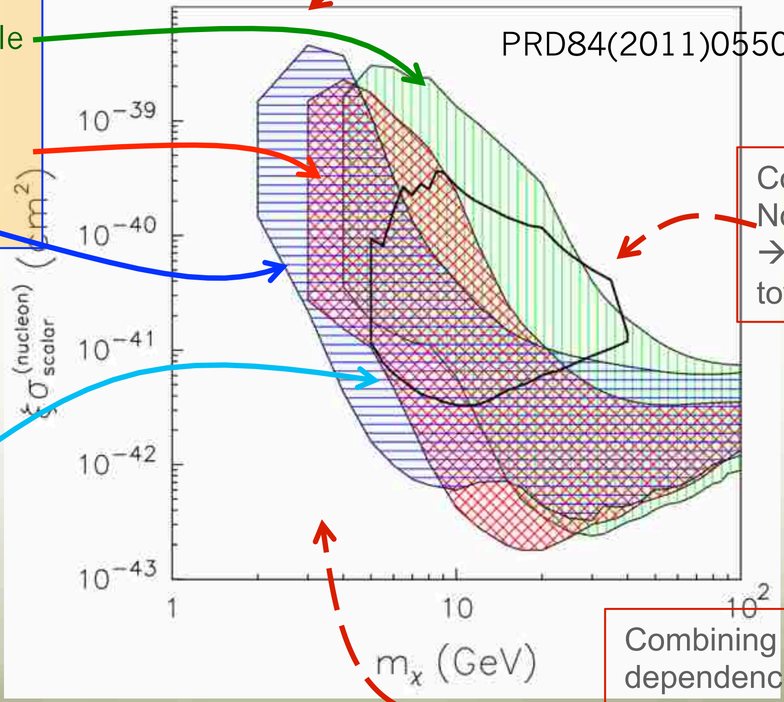
Regions in the nucleon cross section vs DM particle mass plane

- 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.

Including the Migdal effect
→Towards lower mass/higher σ

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);

7.5 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.

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

Other examples

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

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

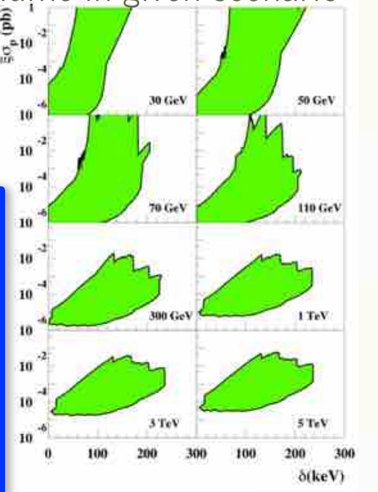
… and much more considering experimental and theoretical uncertainties

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/NaI+DAMA/LIBRA
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.

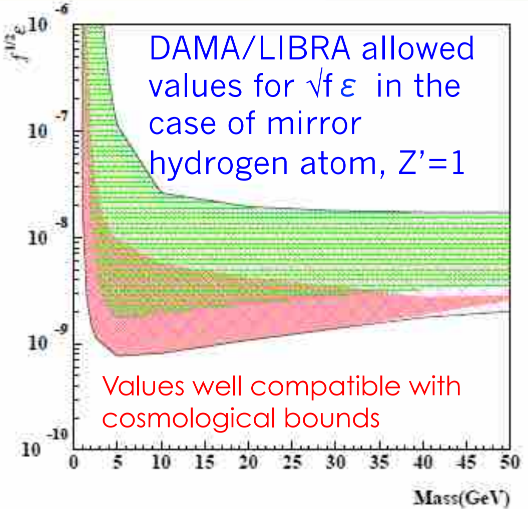
Mirror Dark Matter

EPJC75(2015)400

Asymmetric mirror matter: mirror parity spontaneously broken ⇒ 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/LIBRA allowed values for √f ε in the case of mirror hydrogen atom, Z'=1

Values well compatible with cosmological bounds

DAMA annual modulation effect and Asymmetric mirror matter

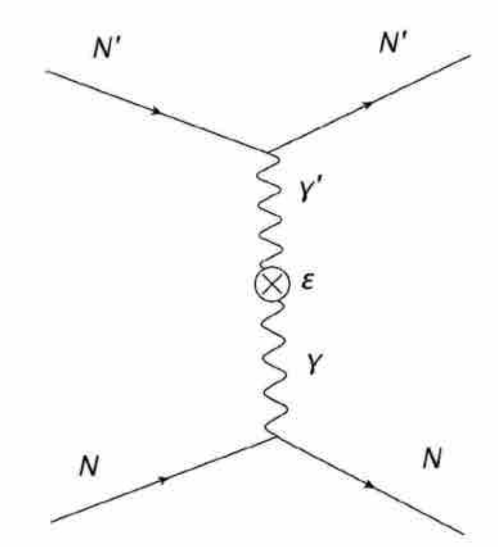
EPJC75(2015)400

Asymmetric mirror matter: mirror parity spontaneously broken at the electroweak scale ⇒ 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 $\frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu}$

$$N' + N \to N' + N$$

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

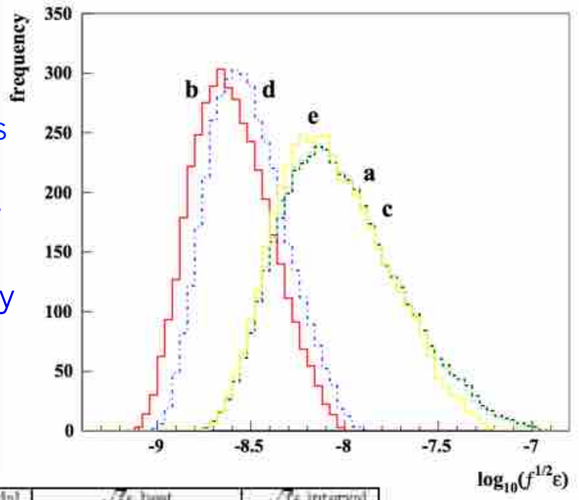
DAMA annual modulation effect and Asymmetric mirror matter

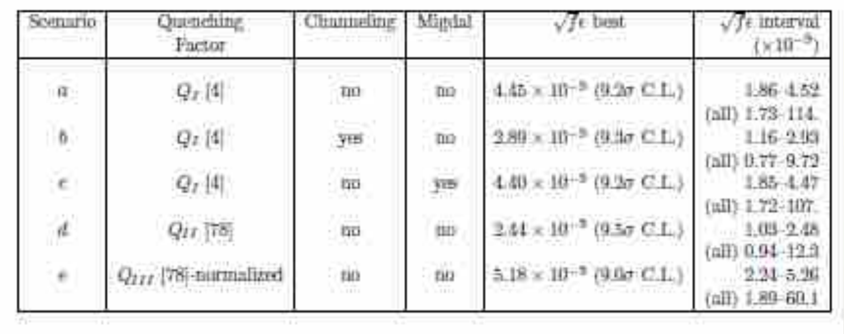
EPJC75(2015)400

- ☐ 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

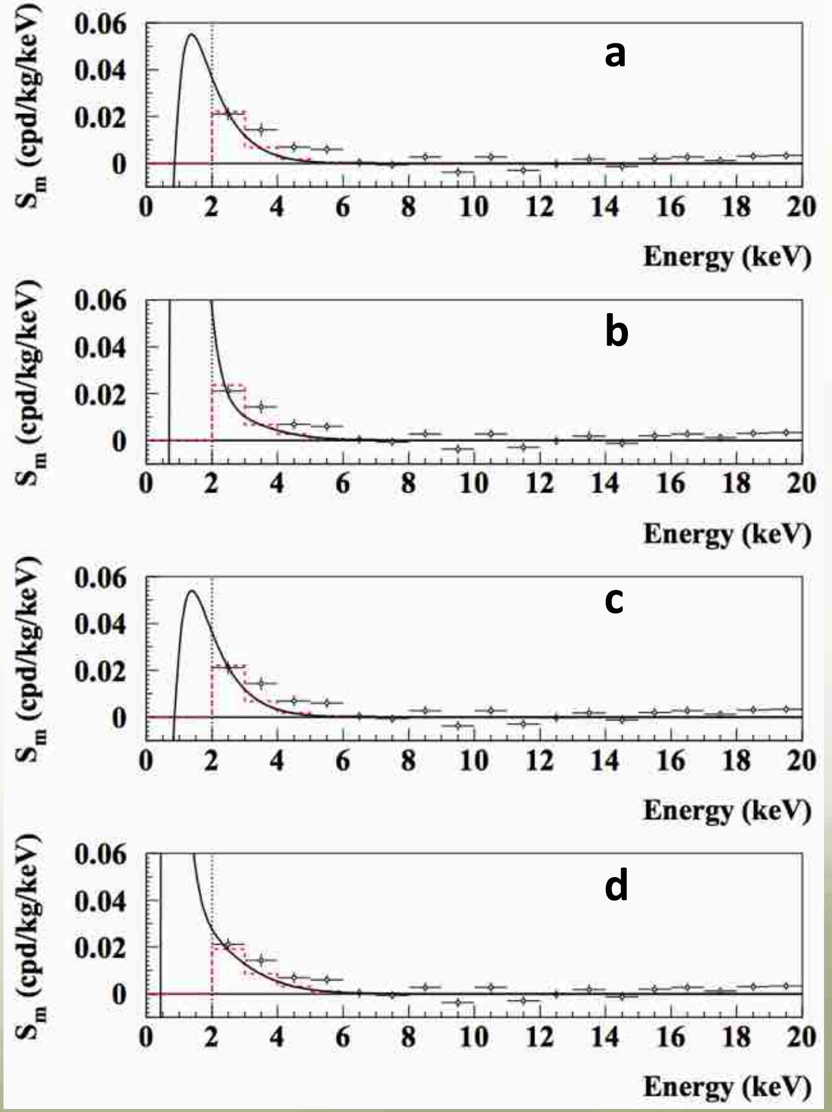
Results on the $\sqrt{f}\,\varepsilon$ parameter in the considered scenarios





Scenario	Quenching Factor	Channeling	Migdal	$\sqrt{f}\epsilon$ best	$\sqrt{f}\epsilon$ interval $(\times 10^{-9})$
a	Q_I [4]	no	no	4.45×10^{-9} (9.2σ C.L.)	1.86–4.52 (all) 1.73–114.
b	Q_I [4]	yes	no	2.89×10^{-9} (9.3σ C.L.)	1.16–2.93 (all) 0.77–9.72
c	Q_I [4]	no	yes	4.40×10^{-9} (9.2σ C.L.)	1.85–4.47 (all) 1.72–107.
d	Q_{II} [78]	no	no	2.44×10^{-9} (9.5σ C.L.)	1.03–2.48 (all) 0.94–12.3
e	Q_{III} [78]-normalized	no	no	5.18×10^{-9} (9.0σ C.L.)	2.24–5.26 (all) 1.89–60.1

Examples of expected S_m for the Mirror DM candidate considered



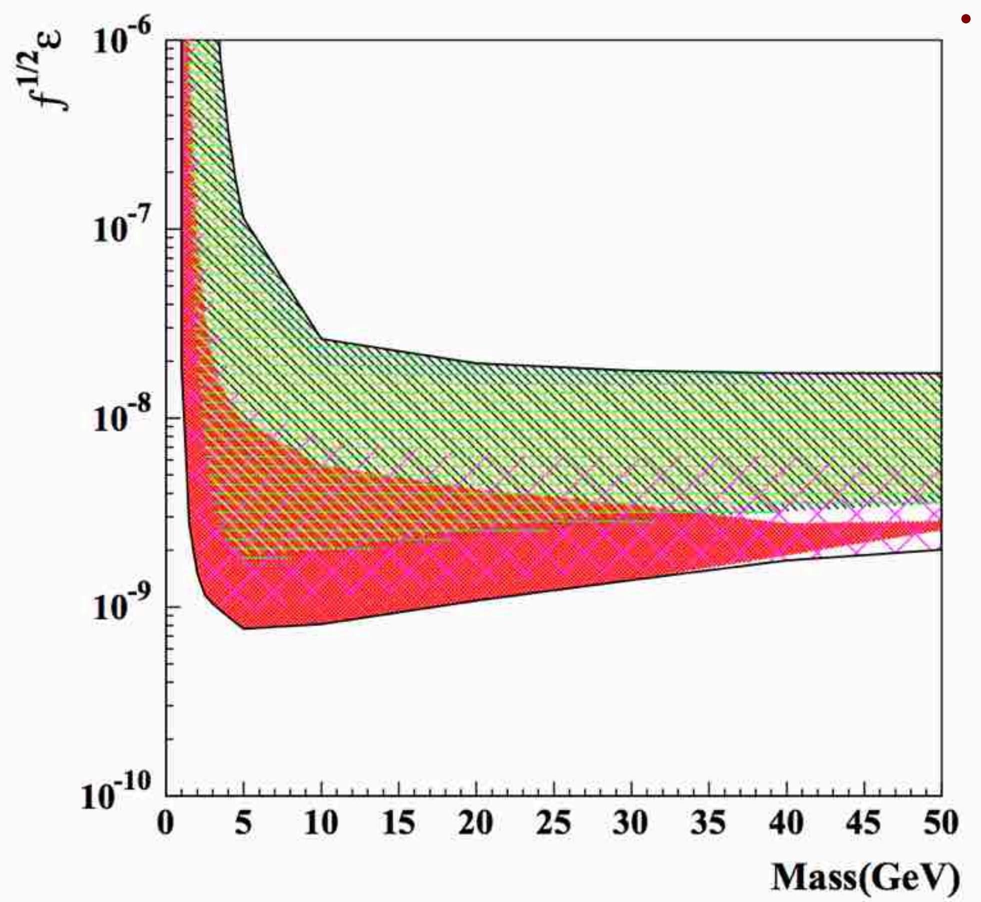
The allowed values for $\sqrt{f}\,\varepsilon$ in the case of mirror hydrogen atom, $Z' = 1$, ranges between **7.7×10^{-10} to 1.1×10^{-7}**. The values within this overall range are **well compatible with cosmological bounds**. In particular, the best fit values among all the considered scenarios gives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

DAMA annual modulation effect and Asymmetric mirror matter

EPJC75(2015)400

- When the assumption $m_{N'} \simeq 5m_p$ is released, allowed regions for the $\sqrt{f}\varepsilon$ 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 $\sqrt{f}\varepsilon$ values corresponding to C.L. larger than 5σ from the null hypothesis, that is $\sqrt{f}\varepsilon = 0$. 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 $\sqrt{f}\varepsilon$ in the case of mirror hydrogen atom, $Z' = 1$, are well compatible with cosmological bounds

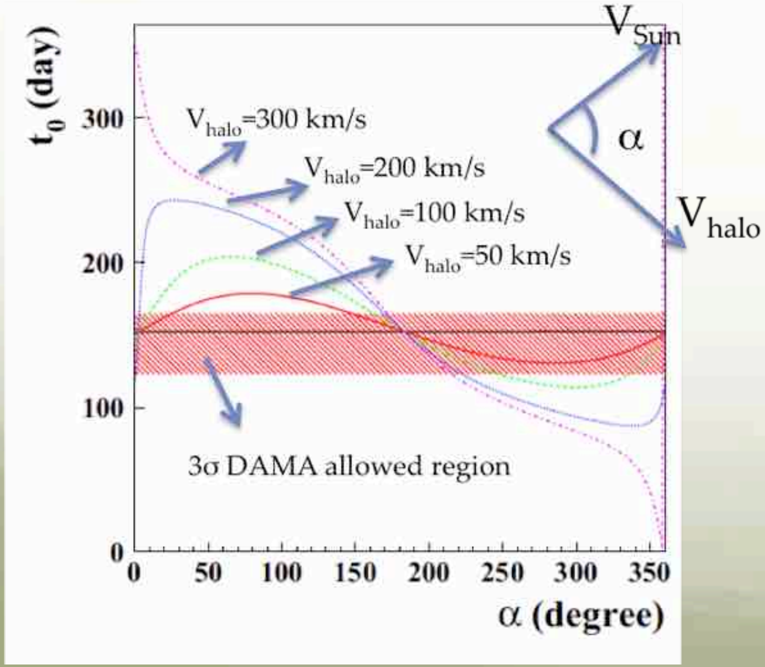
DAMA annual modulation effect and Symmetric mirror matter

EPJC77(2017)83

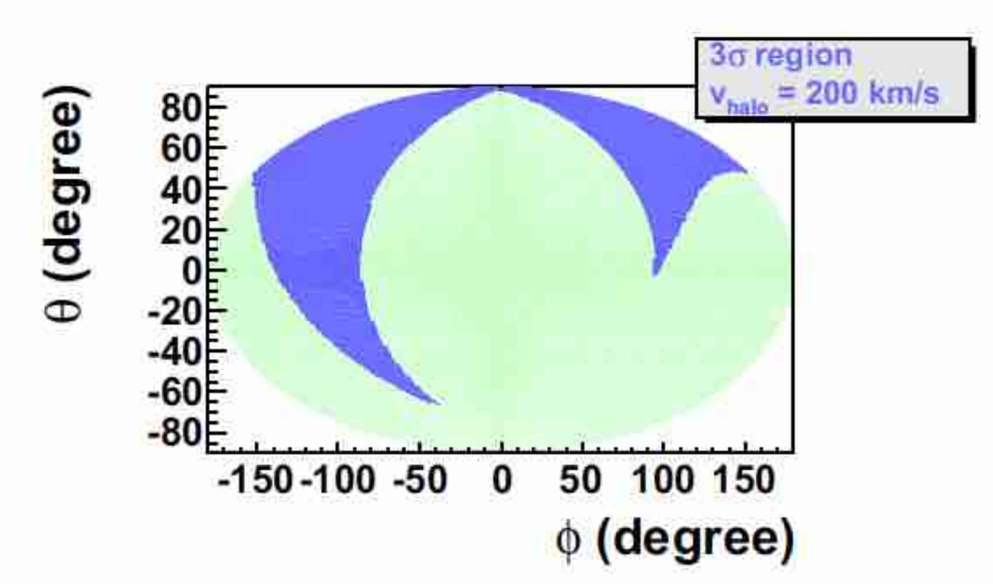
Symmetric mirror matter:

- 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



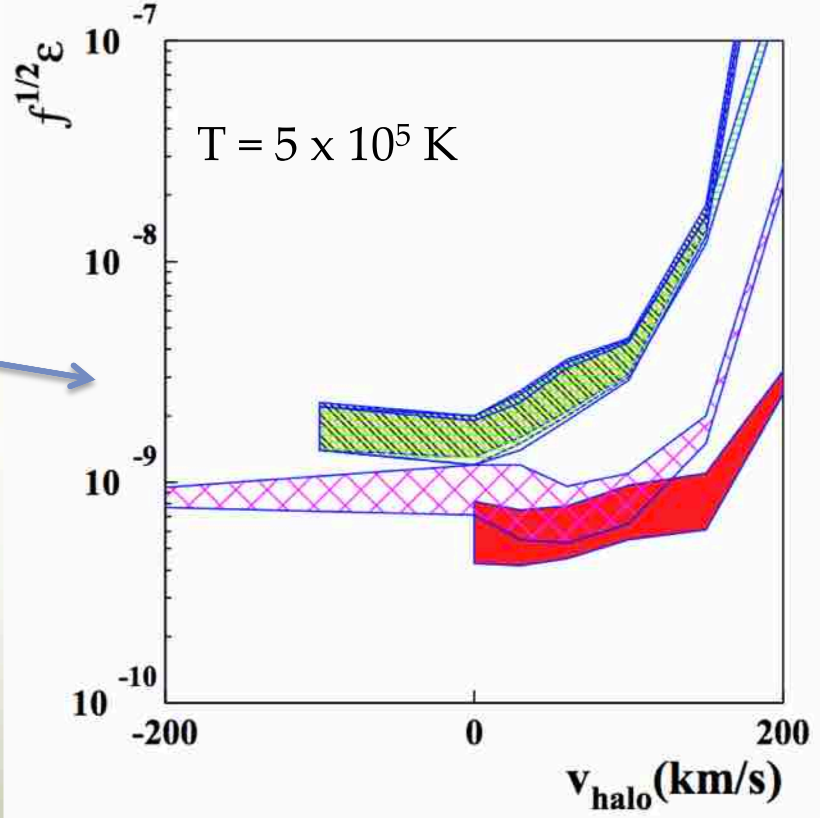
DAMA annual modulation effect and Symmetric mirror matter

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

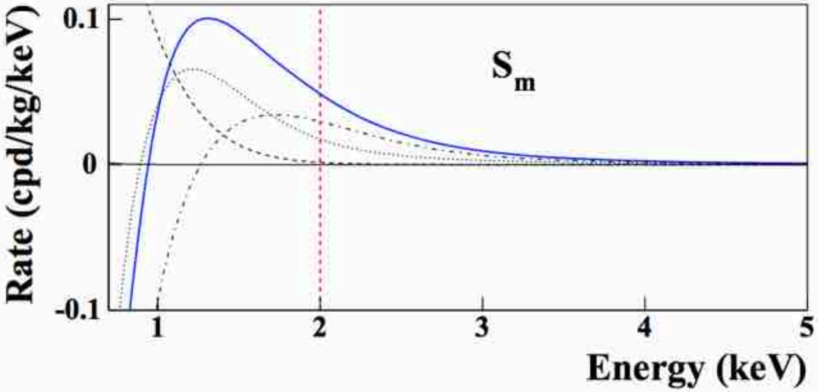
- For all the scenarios, various existing uncertainties in nuclear and particle physics quantities are considered.
- The allowed intervals identify the values corresponding to C.L. larger than 5σ from the null hypothesis

$\sqrt{f}\cdot\epsilon$ 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.

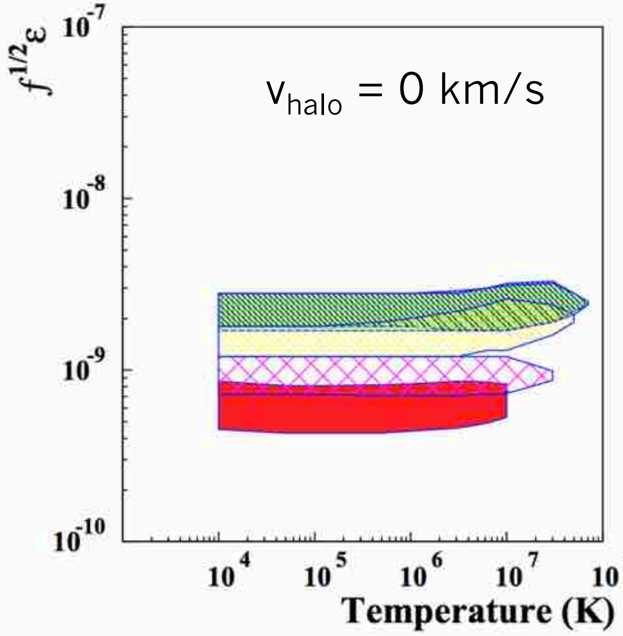
DAMA annual modulation effect and Symmetric mirror matter

EPJC77(2017)83

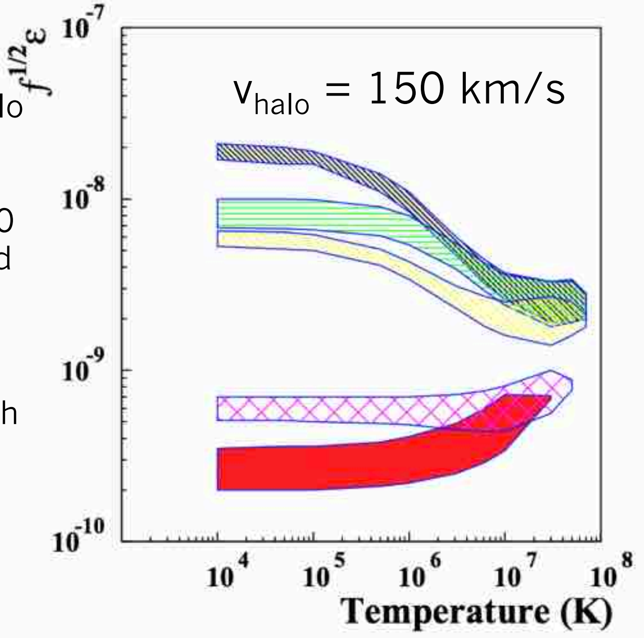


Examples of expected S_m for the Mirror DM candidate considered

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_{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_{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

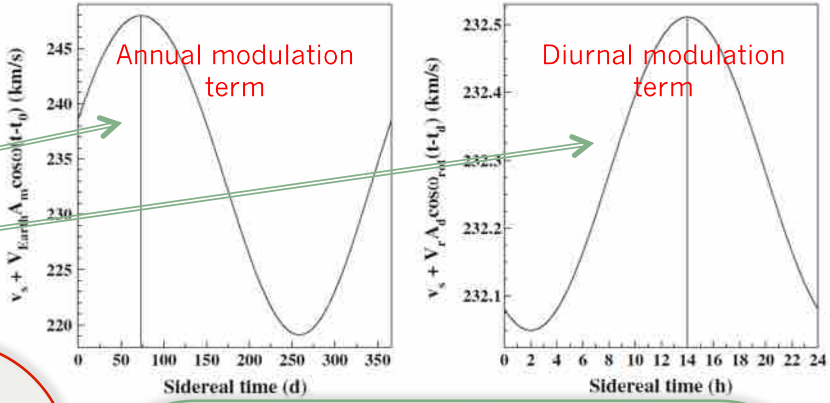
A diurnal effect with the sidereal time is expected for DM because of Earth rotation

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:

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

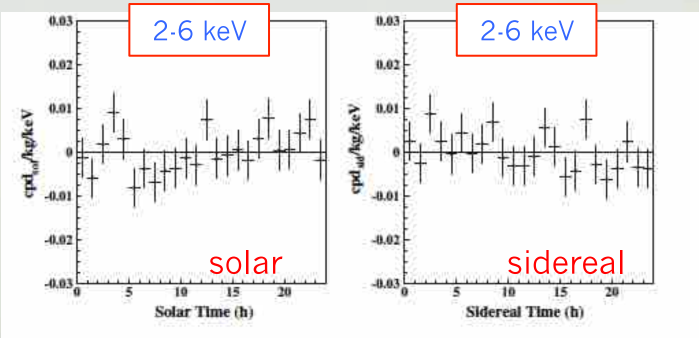
The ratio R_{dy} is a model independent constant:

$$R_{dy} = \frac{S_d}{S_m} = \frac{V_r B_d}{V_{Earth} B_m} \simeq 0.016$$ 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 $\simeq 1.5 \times 10^{-4}$ 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 keV) $< 1.2 \times 10^{-3}$ 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.

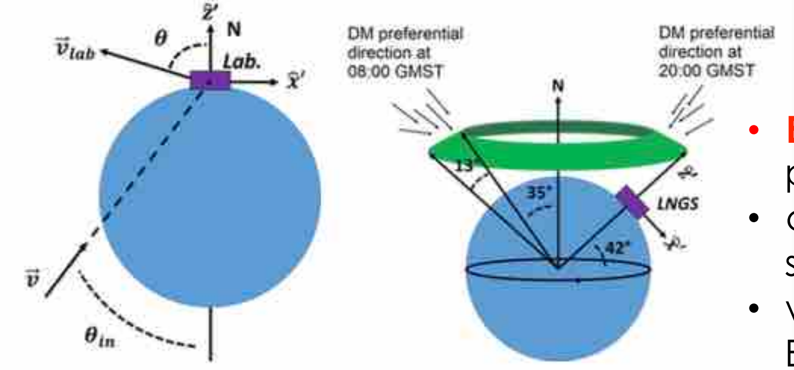
larger exposure DAMA/LIBRA–phase2 (+lower energy threshold) offers increased sensitivity to such an effect

Perspectives for the future

Other signatures?

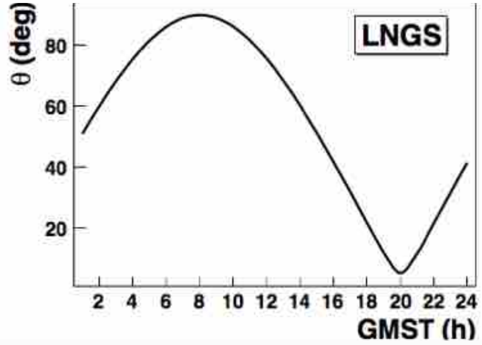
- *Diurnal effects*
- *Second order effects*
- *Shadow effects*
- *Directionality*
- *…*

Earth shadowing effect with DAMA/LIBRA–phase1

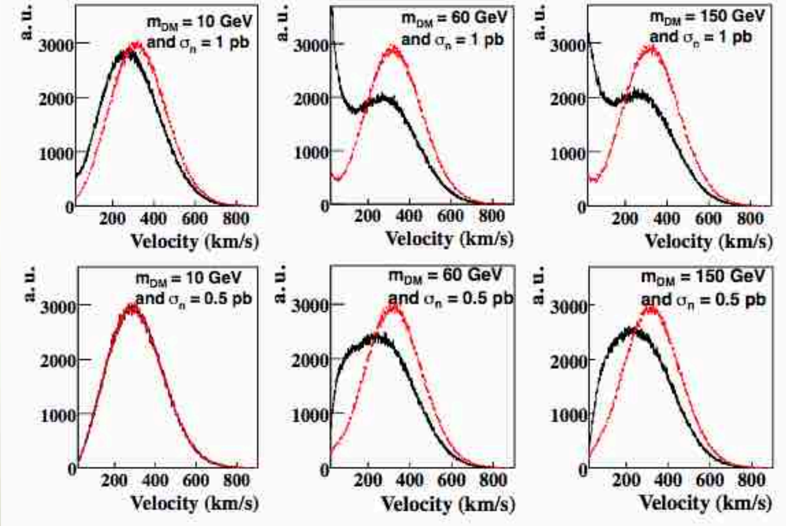


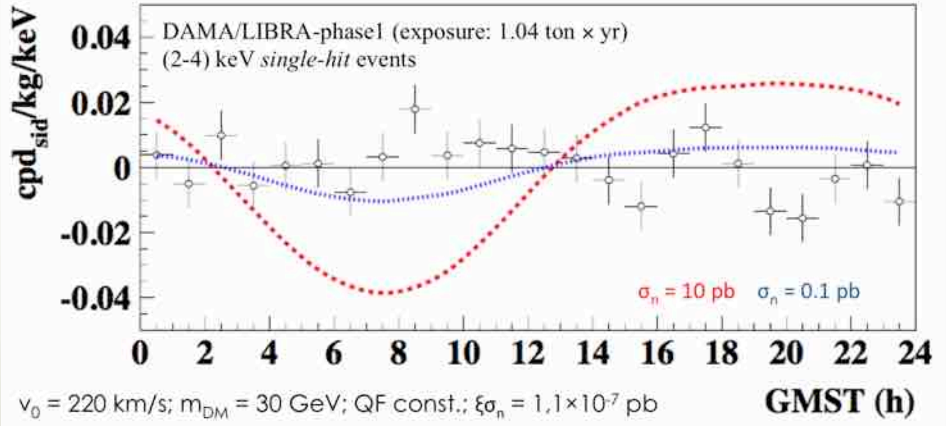
EPJC75(2015)239

- **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**)



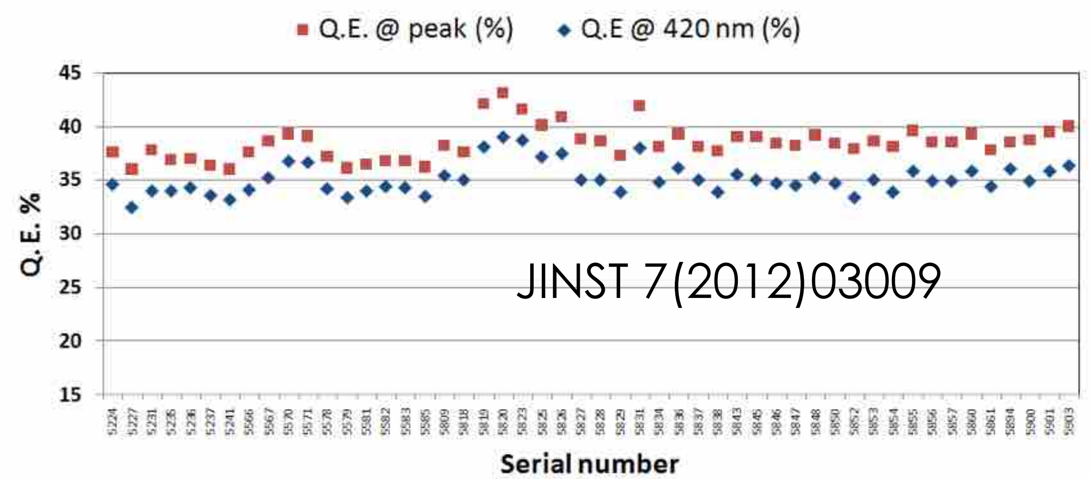


v_0 = 220 km/s; m_{DM} = 30 GeV; QF const.; $\xi\sigma_n = 1{,}1\times10^{-7}$ pb

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



JINST 7(2012)03009

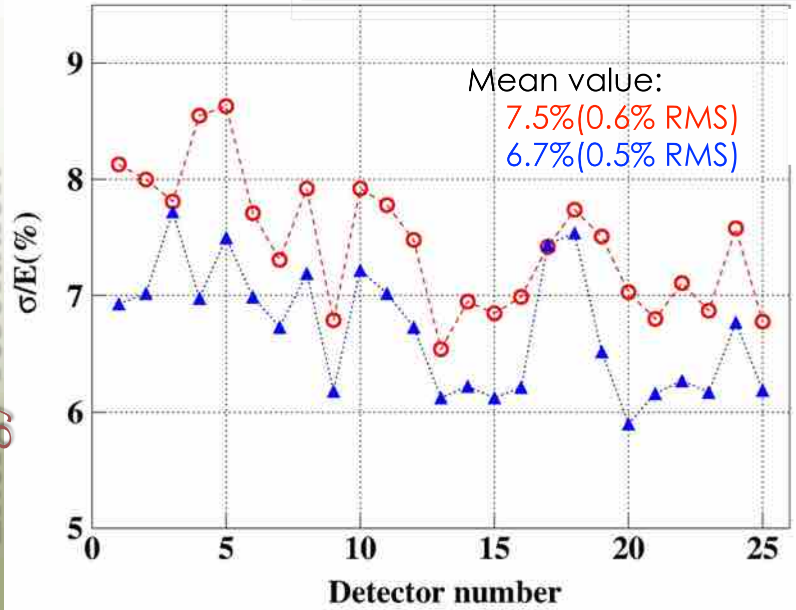
Residual Contamination

The limits are at 90% C.L.

PMT	Time (s)	Mass (kg)	^{226}Ra (Bq/kg)	^{234m}Pa (Bq/kg)	^{235}U (mBq/kg)	^{228}Ra (Bq/kg)	^{228}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 (keV)

Energy resolution



Mean value:
7.5%(0.6% RMS)
6.7%(0.5% RMS)

σ/E @ 59.5 keV for each detector with new PMTs with higher quantum efficiency (blu 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.: ≈ 1.03 x 10^8 events from sources
- ✓ Acceptance window eff. 5 a.c.: ≈ 7 x 10^7 events (≈2.8 x 10^6 events/keV)

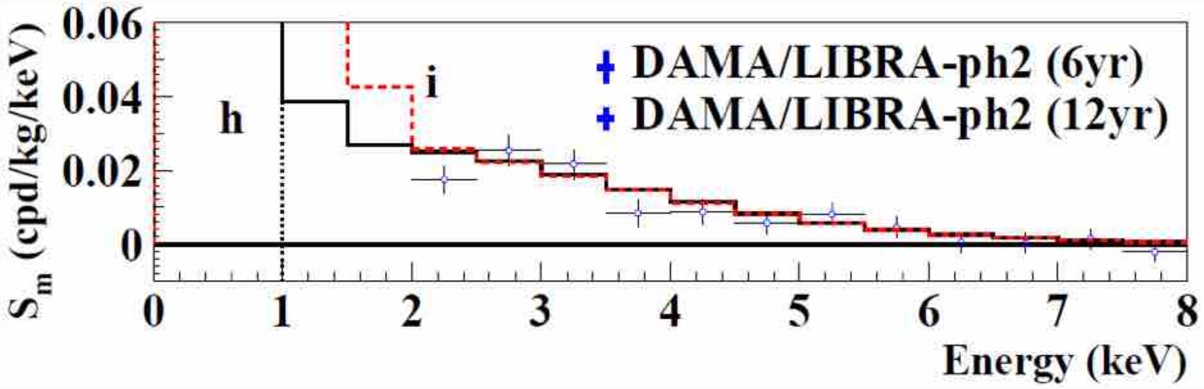
Annual Cycles	Period	Mass (kg)	Exposure (kg · day)	$(\alpha-\beta^2)$
1	Dec 2010 – Sept. 2011		Commissioning	
2	Nov. 2, 2011 – Sept. 11, 2012	242.5	62917	0.519
3	Oct. 8, 2012 – Sept. 2, 2013	242.5	60586	0.534
4	Sept. 8, 2013 – Sept. 1, 2014	242.5	73792	0.479
5	Sept. 1, 2014 – Sept. 9, 2015	242.5	71180	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. **≈ 1,1 ton x yr**

DAMA/LIBRA-phase2: constraining DM models

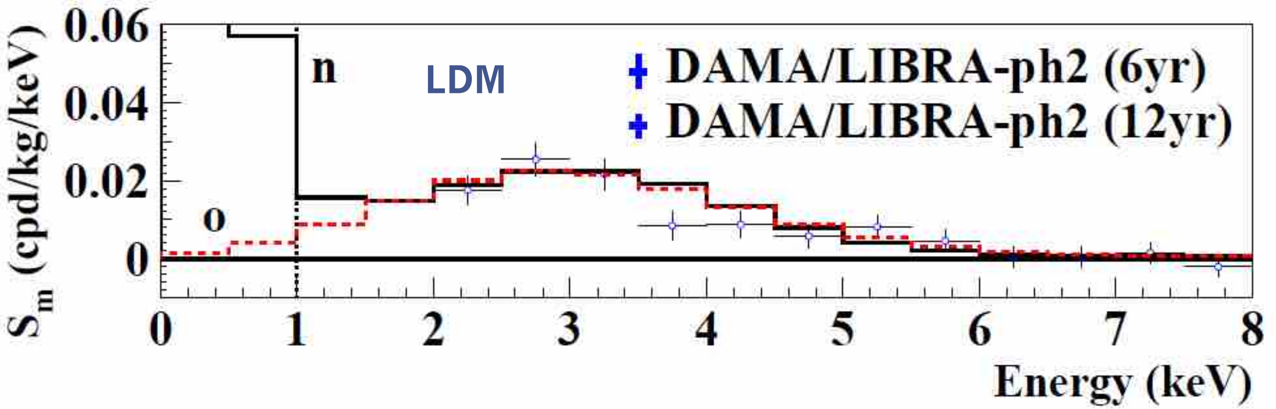


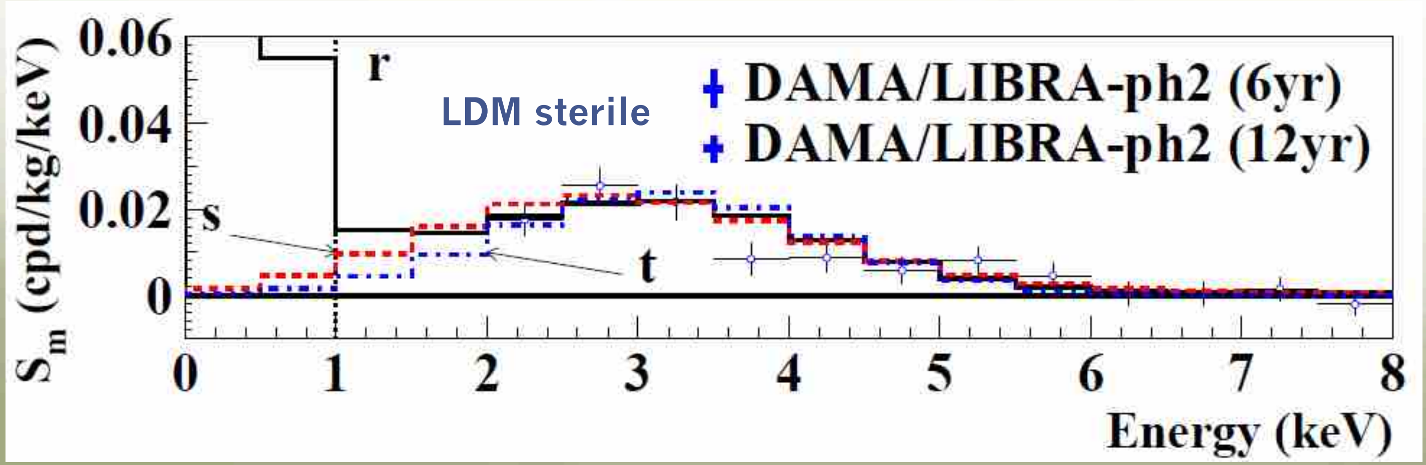
Few examples under some astrophysical, nuclear and particle physics assumptions; no best fit, same C.L.

“WIMP” SI vs SI&SD
NFW, 15 GeV

It can disentangle among:

- Different masses
- Different coupling
- Different particles





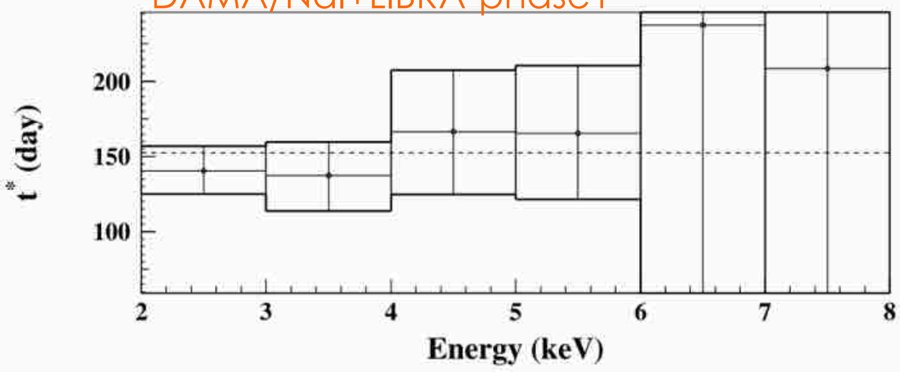
Features of the DM signal

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

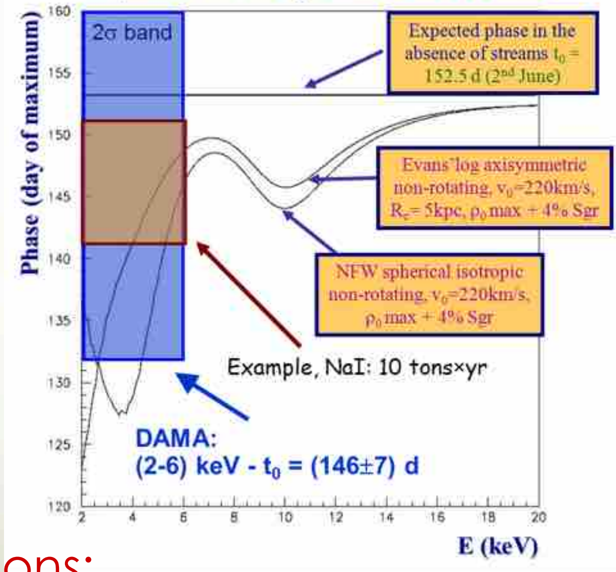
DAMA/NaI+LIBRA-phase1



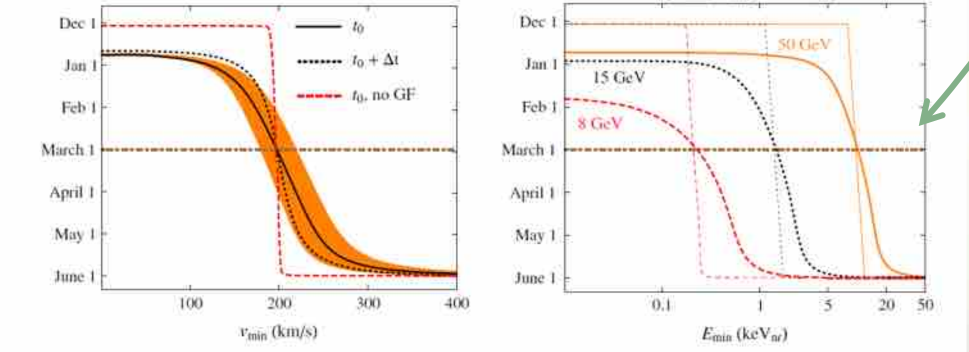
The annual modulation phase depends on :

- 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



PRL112(2014)011301



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?

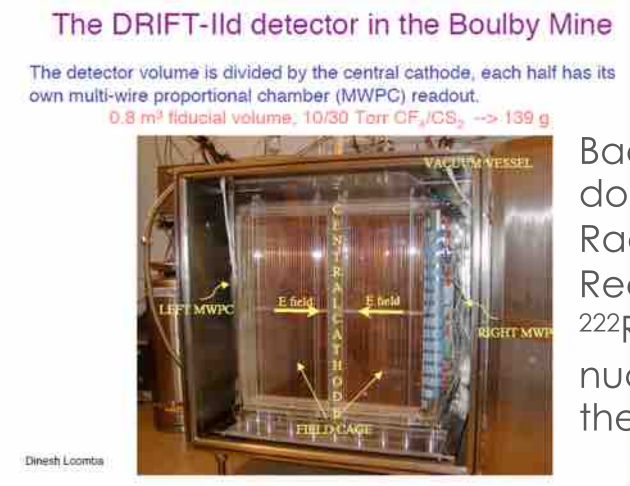
- *Diurnal effects*
- *Second order effects*
- *Shadow effects*
- *Directionality*
- *…*

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

Anisotropic scintillators: DAMA, UK, Japan

DRIFT-IId



The DRIFT-IId detector in the Boulby Mine

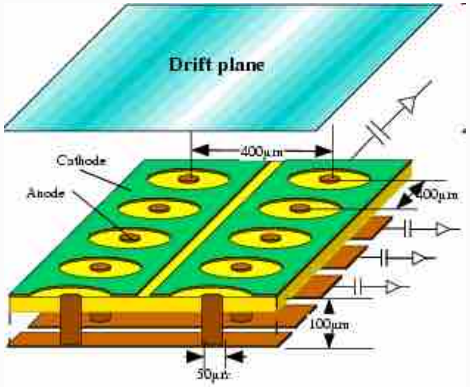
The detector volume is divided by the central cathode, each half has its own multi-wire proportional chamber (MWPC) readout.

0.8 m³ fiducial volume, 10/30 Torr CF_4/CS_2 --> 139 g

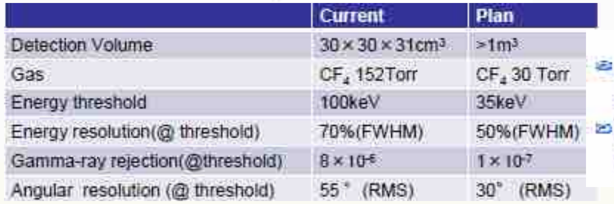
Dinesh Loomba

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

NEWAGE



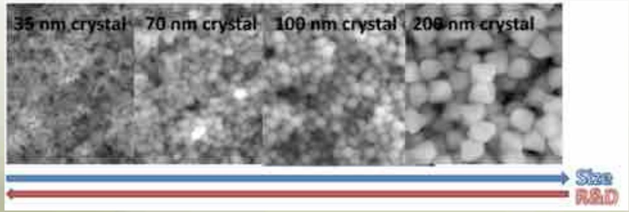
μ-PIC(Micro Pixel Chamber) is a two dimensional position sensitive gaseous detector



	Current	Plan
Detection Volume	30 × 30 × 31cm³	>1m³
Gas	CF_4 152Torr	CF_4 30 Torr
Energy threshold	100keV	35keV
Energy resolution(@ threshold)	70%(FWHM)	50%(FWHM)
Gamma-ray rejection(@threshold)	8 × 10⁻⁶	1 × 10⁻⁷
Angular resolution (@ threshold)	55° (RMS)	30° (RMS)

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

Nano Imaging Tracker (NIT) emulsions. NEWSdm @ LNGS



Track readout: track length ranges also ≤ λ. ➔ use different optical techniques and make a pre-selection on the optical microscopes (also polarization)

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

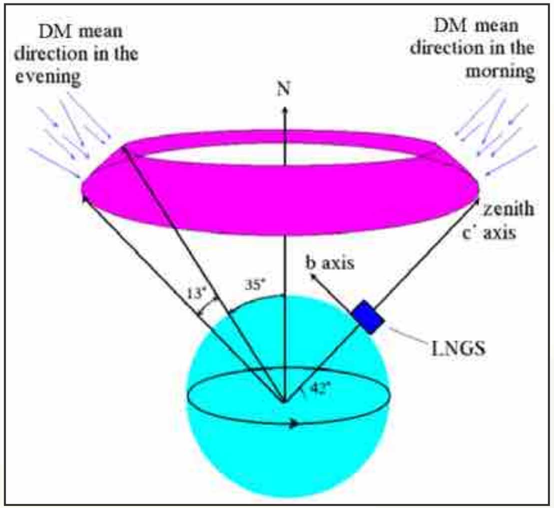
Anisotropic detectors are of great interest for many applicative fields, e.g.:

⇒ 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:

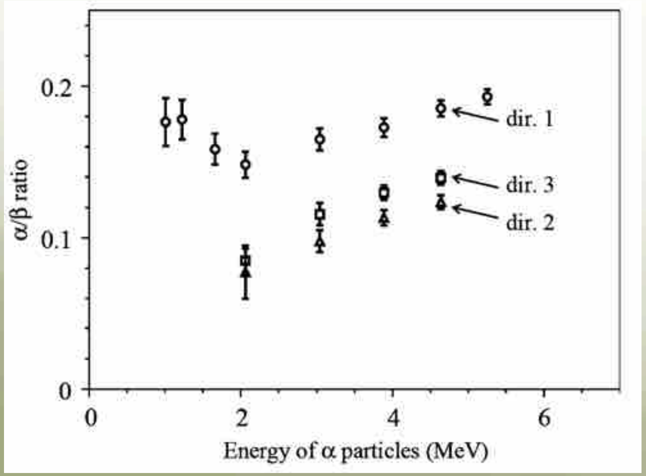
- the correlation between the direction of the nuclear recoils and the Earth motion in the galactic rest frame;
- the peculiar features of anisotropic detectors;

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



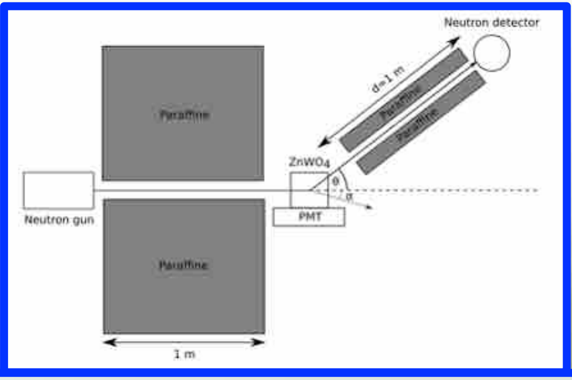
O → light masses
Zn, W → high masses

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

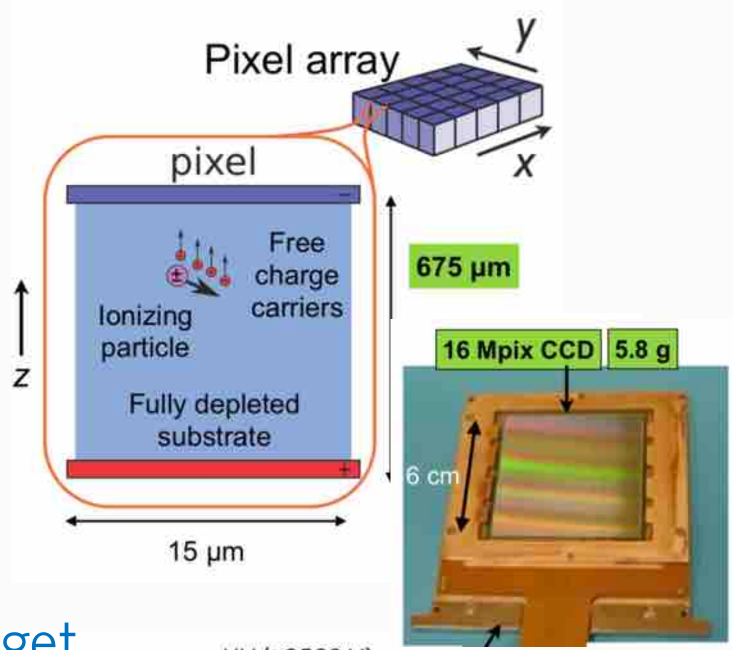


Measurements of anisotropy in keV range by neutron generator on-going at ENEA-Casaccia

Other techniques

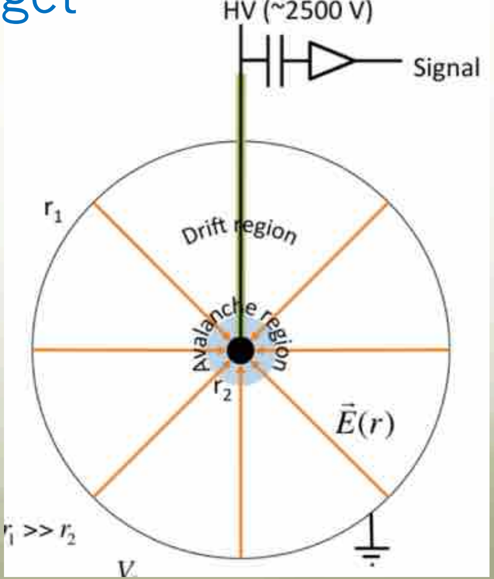
DAMIC at SNOLAB

- Charge coupled devices (CCDs) as detectors for **low-energy** particles
- Background suppression techniques
- Ongoing R&D efforts for a **DAMIC-1K**: 1 kg detector, 50 CCDs with 2e$^-$ thr.



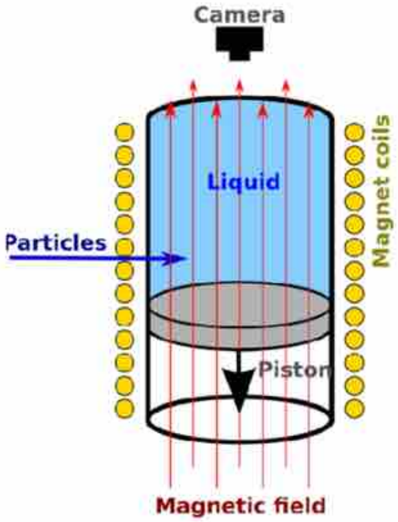
NEWS-G, a spherical TPC with low-A target

- Sensitive to low mass DM candidate



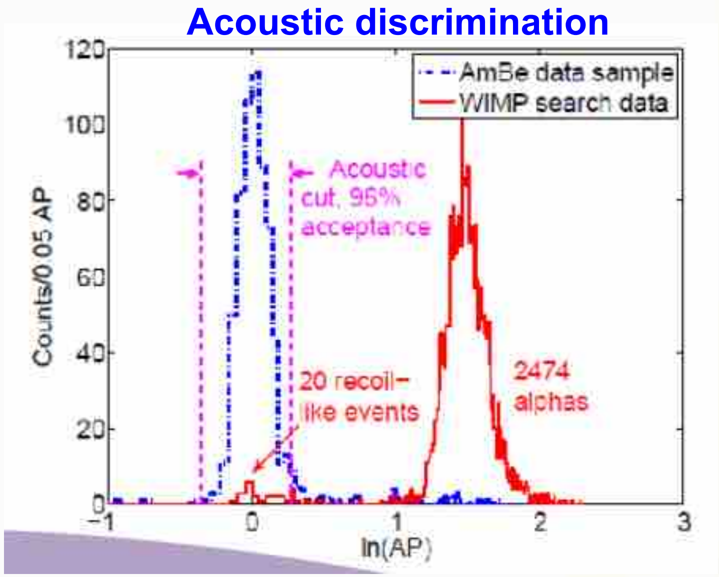
Other techniques

PICO: bubble chamber, using acoustic discrimination, C_3F_8 target



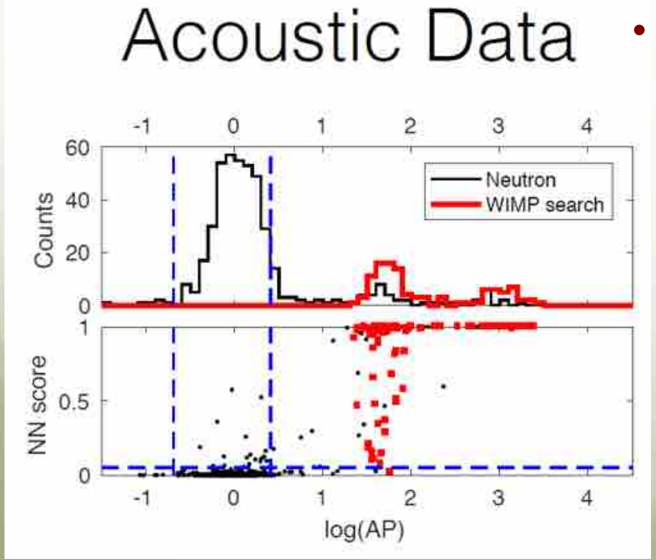
- Any bubble chamber has:
  - optical system with camera, lights
  - expansion system, piston, temperature control

C. Amole *et al.*, Phys. Rev. Lett. 118, 251301



- Alphas deposit their energy over tens of microns
- Nuclear recoils deposit theirs over tens of nanometers

- Now: PICO-60
- Next step PICO 500



Bubble Chamber – Geyser

In both cases: technical limitations on the technique (reachable sensitivities, energy thresholds, stability, ...), only DM candidates inducing recoils, tests made at very high energy recoils, what about low energy recoils?

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