Dark Matter direct detection:
crystals

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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

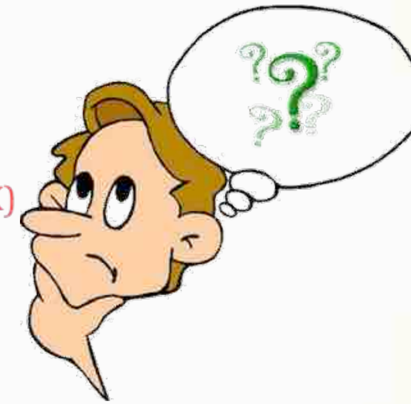
mirror dark matter

Kaluza-Klein particles (LKK)

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

Elementary Black holes,
Planckian objects, Daemons

invisible axions, ν's



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…

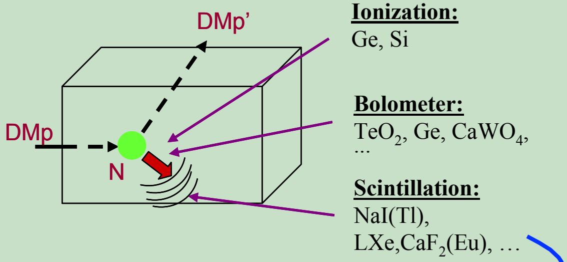
+ DM candidates and scenarios exist (even for neutralino candidate) on which accelerators cannot give any information

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



- 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

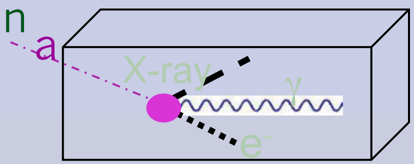
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

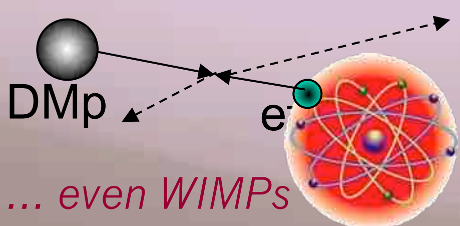
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

  → detection of e.m. radiation

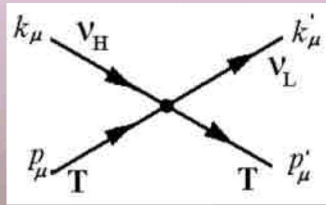


… even WIMPs

- 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 …

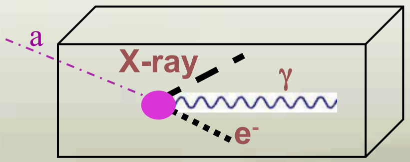
- **… and more**

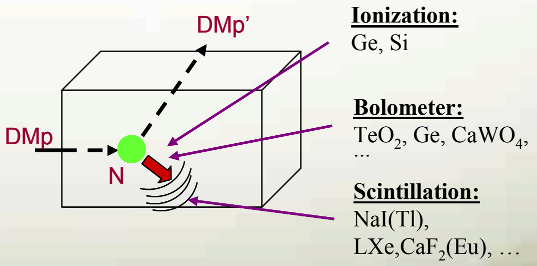
Direct detection experiments

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

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

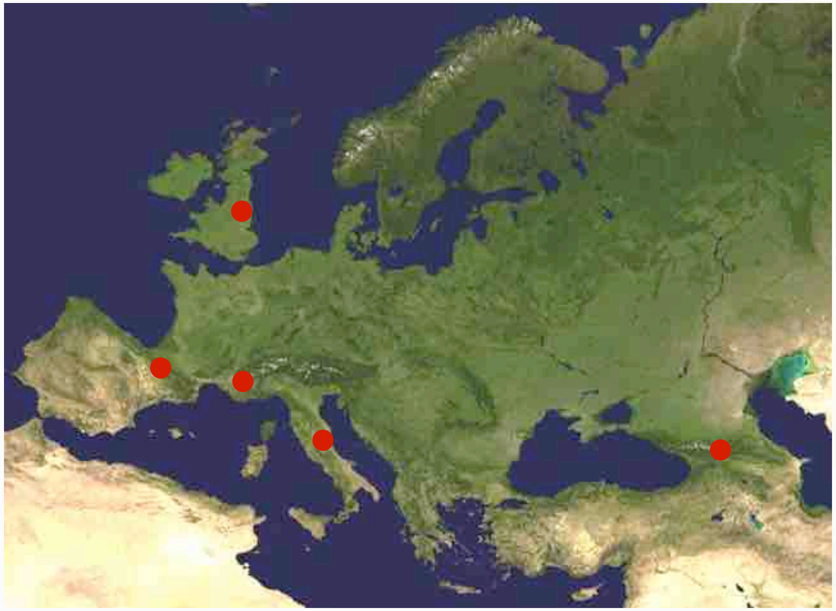
2. on the use of uncertain techniques of statistical **subtractions** of the e.m. component **of the counting rate** (adding systematical effects and lost of candidates with pure electromagnetic productions)





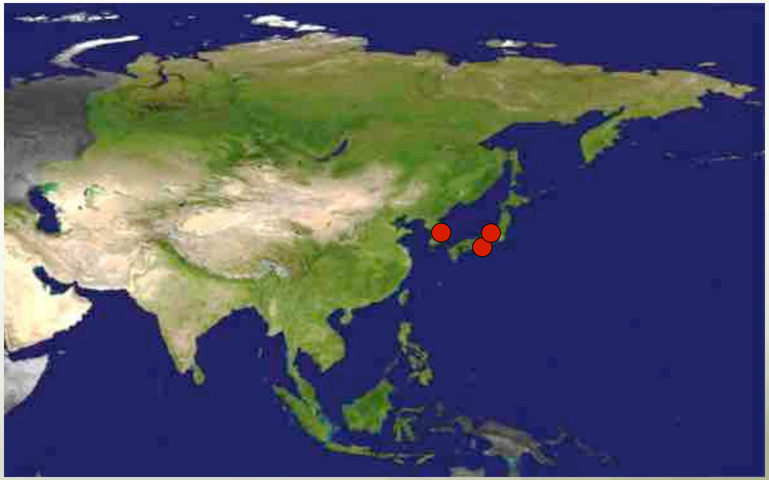
Dark Matter direct detection activities with crystals in underground labs

- Various approaches and techniques
- Various different target materials
- Various different experimental site depths
- Different radiopurity levels, etc.



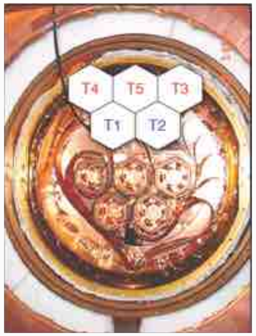
- **Gran Sasso (depth ~ 3600 m.w.e.): DAMA/NaI, DAMA/LIBRA, DAMA/LXe, HDMS, CRESST, CUORE**
- **Boulby (depth ~ 3000 m.w.e.): NAIAD**
- **Modane (depth ~ 4800 m.w.e.): Edelweiss**
- **Canfranc (depth ~ 2500 m.w.e.): ANAIS**

- **SNOlab (~ 6000 m.w.e.): SuperCDMS, DAMIC**
- **Stanford (~10 m): CDMS I**
- **Soudan (~ 2000 m.w.e.): CDMS II, SuperCDMS, CoGeNT**
- **SURF (~ 4400 m.w.e.): MALBEK**
- **South Pole: DM-ICE**



- **Y2L (depth ~ 700 m): KIMS**
- **KAMIOKA: PICO-LON**
- **CJPL (depth ~6700 m.w.e.): Texono, CDEX**

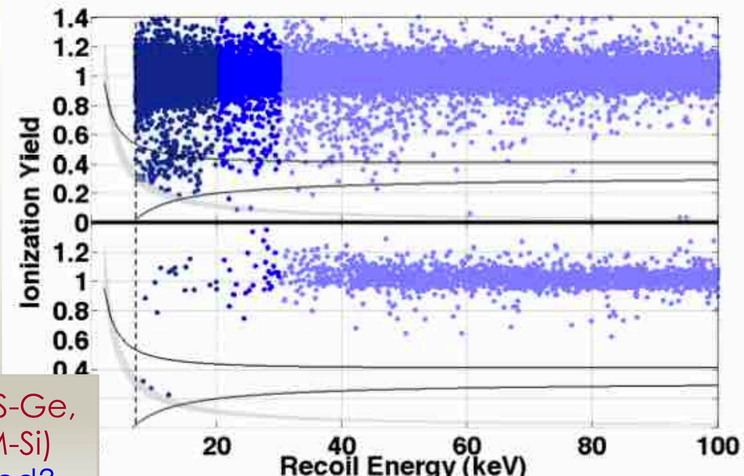
Double read-out bolometric technique (ionization vs heat)

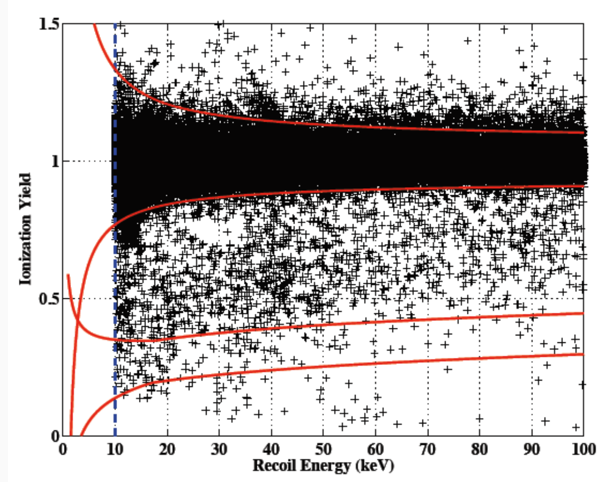


- CDMS-Ge: Soudan, 3.22 kg Ge, 194.1 kg x day; E_{th}=10 keV + other attemps at lower E_{th}
- Edelweiss: LSM, 3.85 kg Ge, 384 kg x day; E_{th}=20 keV
- CDMS-Si: 1.2 kg Si, 140.2 kg x day; E_{th}=7 keV

- **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

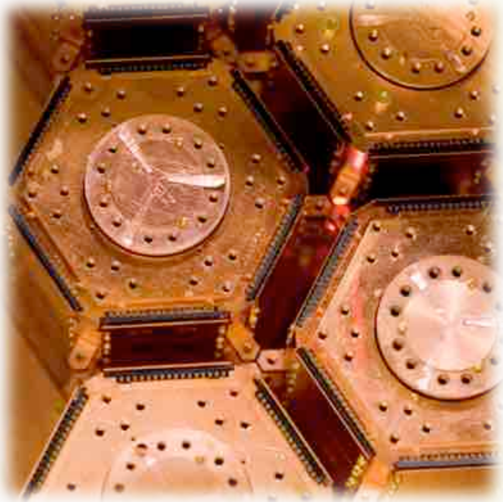
- Due to **small number** of events to deal after selection, even small fluctuations of parameters (energy, Y scales, noises, …) and of tails of the distributions can play a relevant role
- **Efficiencies** of both signals





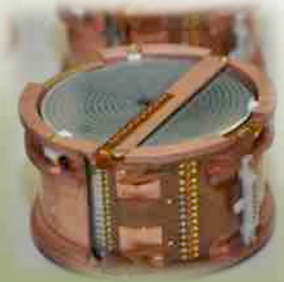
After many cuts few (two in CDMS-Ge, five in Edelweiss and three in CDM-Si) events survive: intrinsic limit reached?

Other on CDMS



- 2012 – annual modulation search [arXiv:1203.1309v2]
  - likelihood analysis and annual modulation search, but e.g. selection of detectors and runs. Data not taken evenly along the year
  - restricted to energies > 5 keVnr (not the full energy range of CoGeNT modulation)
- 2013 – CDMSlite [Phys. Rev. Lett. 112, 041302 (2014)]
  - calorimetric technique: voltage-assisted Luke-Neganov amplification of ionization energy
  - data collected with a single 0.6 kg Ge detector running for 10 live days at Soudan
  - low energy threshold of 170 eVee
- 2014 – SuperCDMS (Soudan) [Phys. Rev. Lett. 112, 241302 (2014)]
  - Increased mass: 9.0 kg Ge (15 x 600g detectors); increased acceptance; improved surface event discrimination
  - operating in DM mode since March 2012
  - exposure 577 kg×days ⇒ eleven events observed (not fully compatible with bckg expectations, even assuming the correctness of all the adopted procedures)
- SuperCDMS (SNOLAB) (R&D for 200kg Ge array, 1 kg crystals) [AIP Conf. Proc. 1534, 129 (2013)]
- 2015 – CDMSlite [arXiv:1509.02448] M. Pepin in parallel session; 56 eV thr.

Other on Edelweiss



- July 2014 – April 2015 data taking; restarted in Jun2015 , 36 detectors installed (more than 14 kg of fiducial mass in Ge)
- New results; exposure (582 kg x d) collected with eight FID detectors

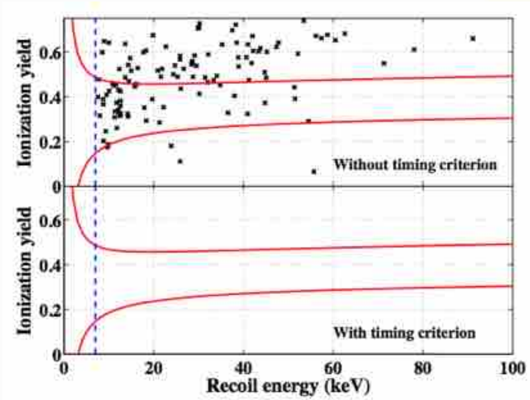
[arXiv:1504.00820]

S. Scorza in parallel session

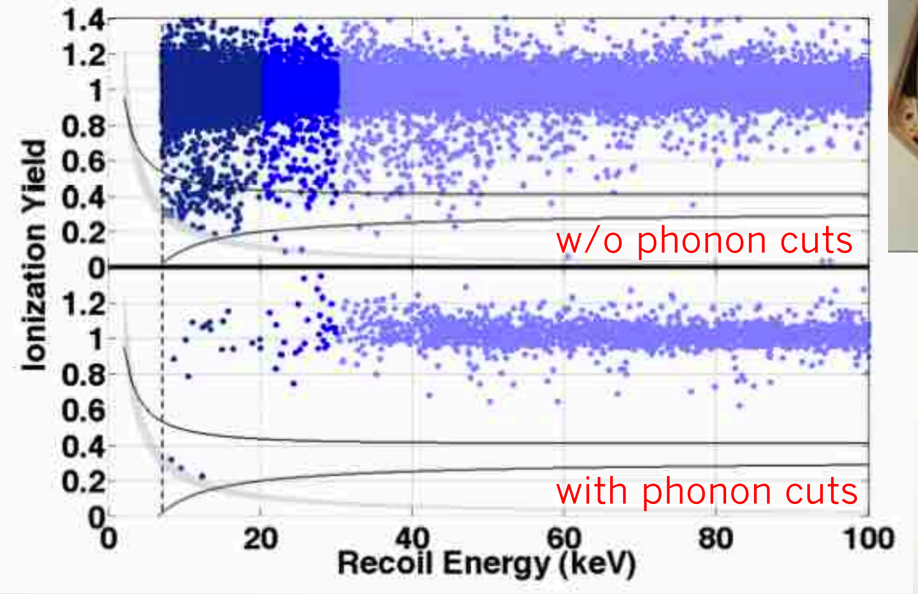
Results from double read-out bolometric technique (ionization vs heat): CDMS–Si

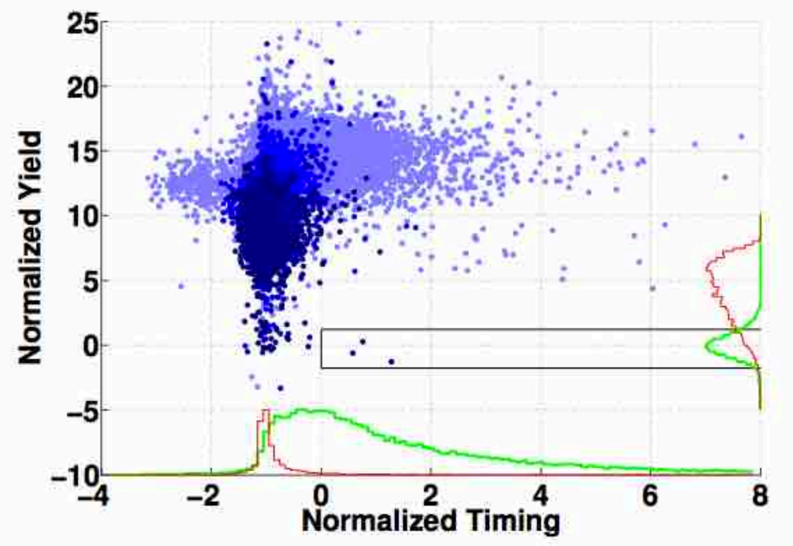
Results of CDMS-II with the Si detectors published in two close-in-time data releases:

- *no events* in six detectors (55.9 kg×day)
- *three events* in eight (over 11) detectors (140.2 kg×day)
- 1.2 kg Si (11 x 106g)
- July 2007- September 2008



PRD 88 (2013) 031104(R)
PRL 111 (2013) 251301





after many data selections and cuts, 3 Si recoil-like candidates survive in an exposure of 140.2 kg x day. Estimated residual background 0.41

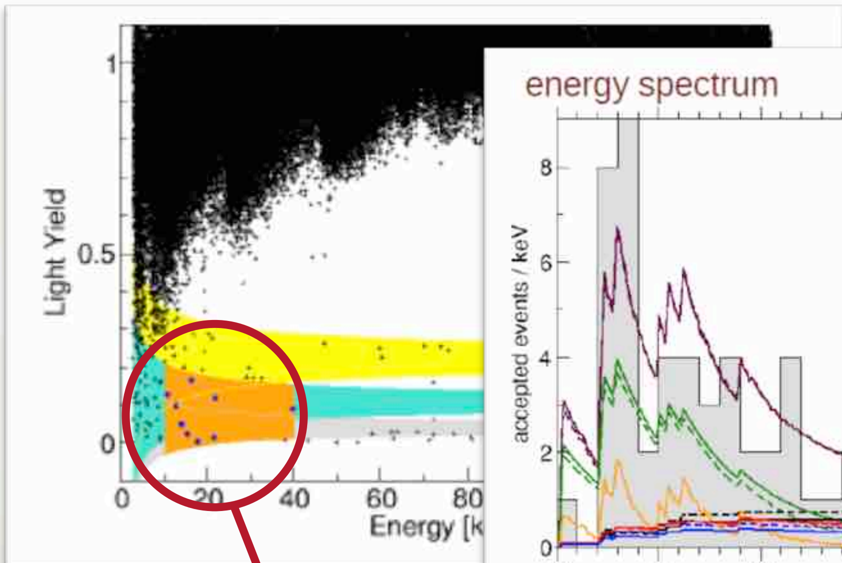
A profile likelihood analysis favors a signal hypothesis at 99.81% CL (~3 σ , p-value: 0.19%).

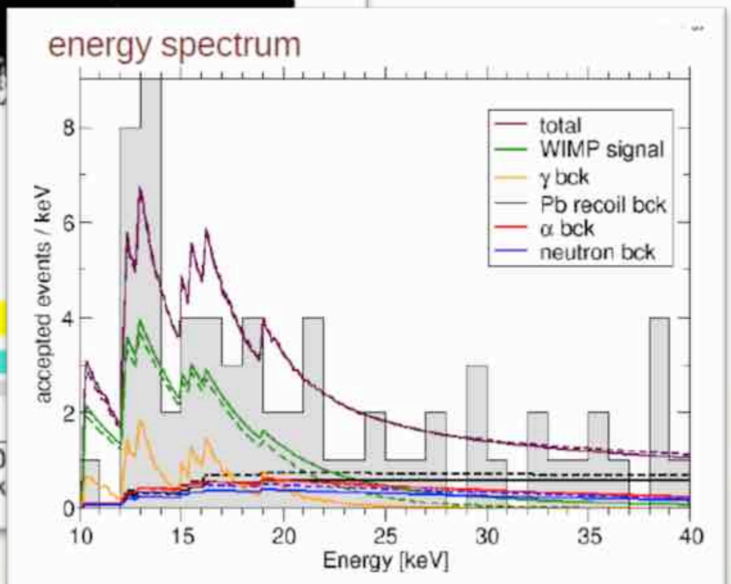
Double read-out bolometric technique (scintillation vs heat)

(see also above)

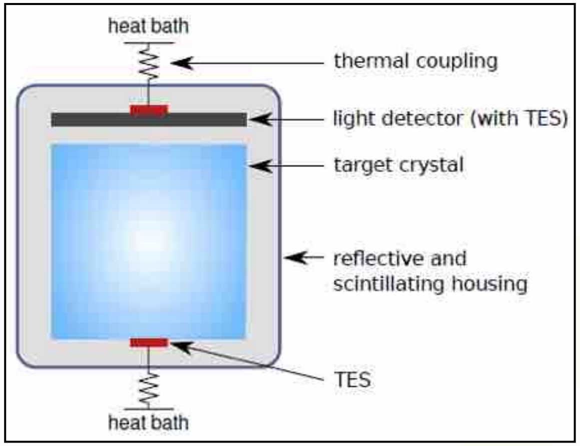
CRESST at LNGS: 33 $CaWO_4$ crystals (10 kg mass)
data from 8 detectors. Exposure: ≈ 730 kg x day

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?)**

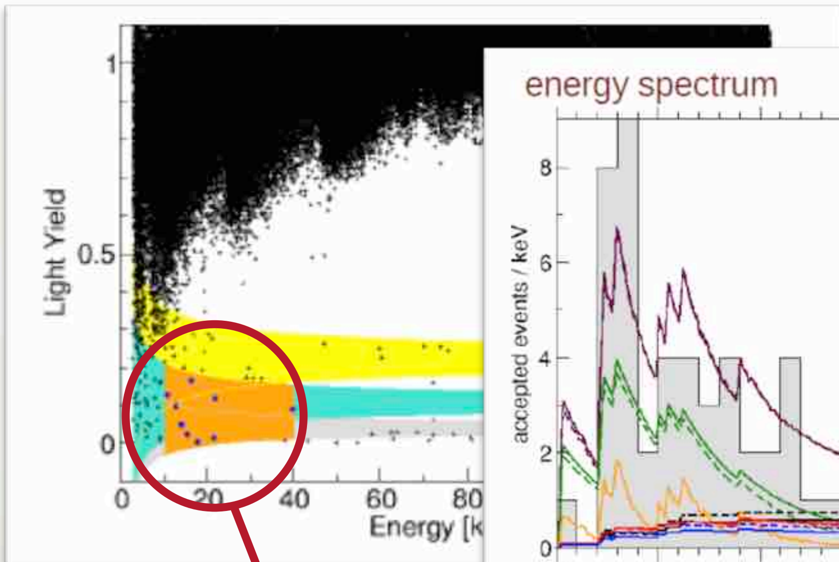
Efficiencies + stability + calibration, crucial role

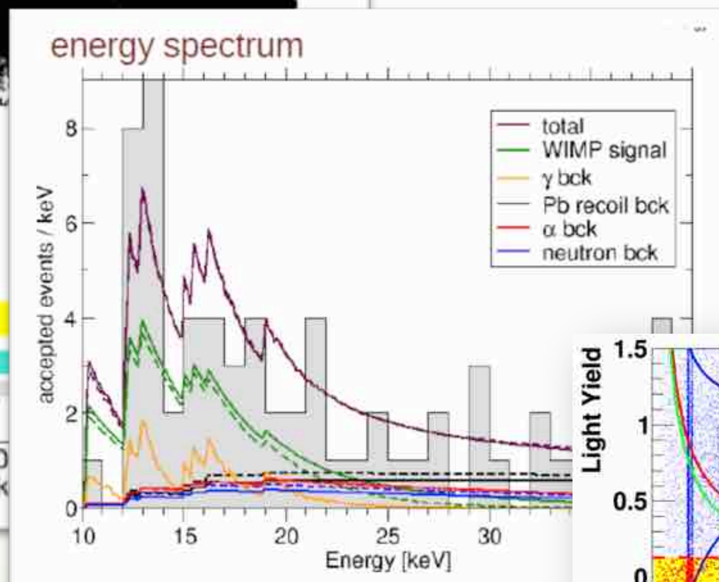
Double read-out bolometric technique (scintillation vs heat)

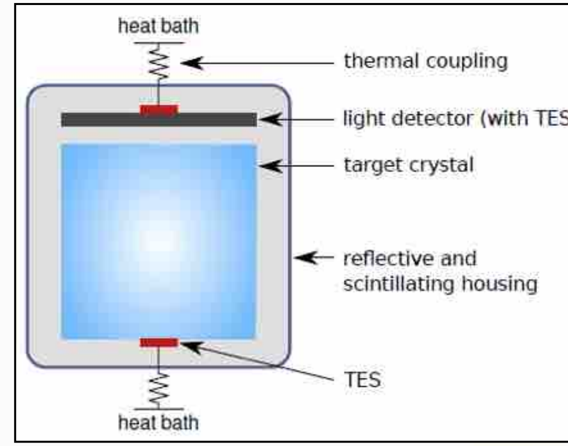
(see also above)

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

Data from one detector



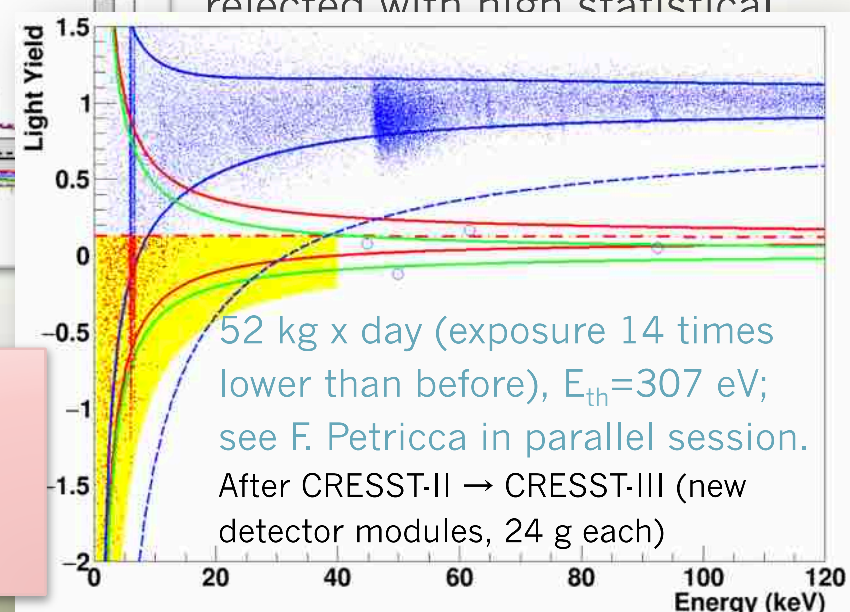




background-only hypothesis rejected with high statistical

67 total events observed in O-band;

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



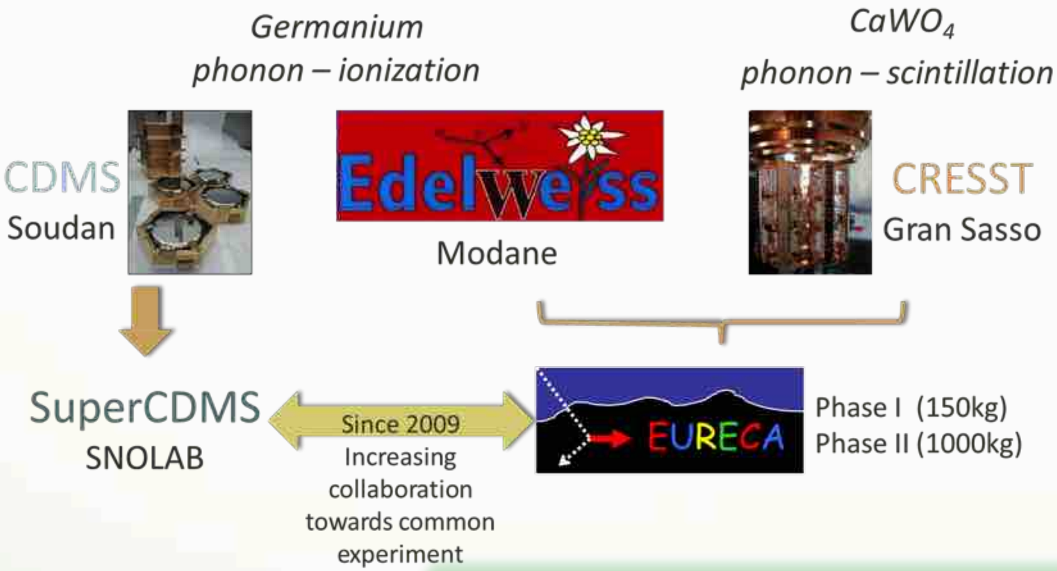
52 kg x day (exposure 14 times lower than before), E_{th}=307 eV; see F. Petricca in parallel session.

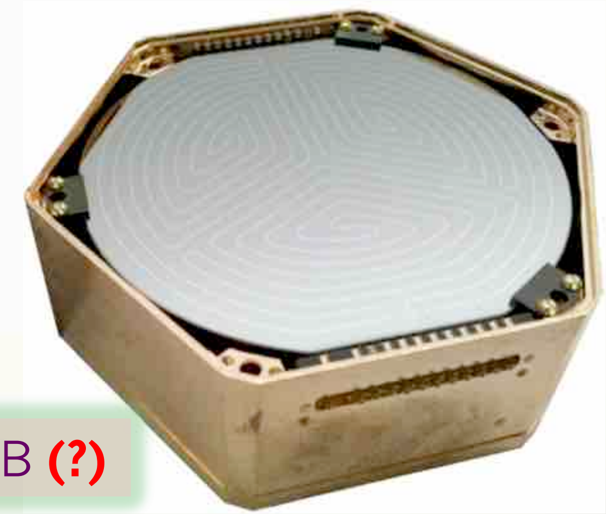
After CRESST-II → CRESST-III (new detector modules, 24 g each)

Bolometer perspectives

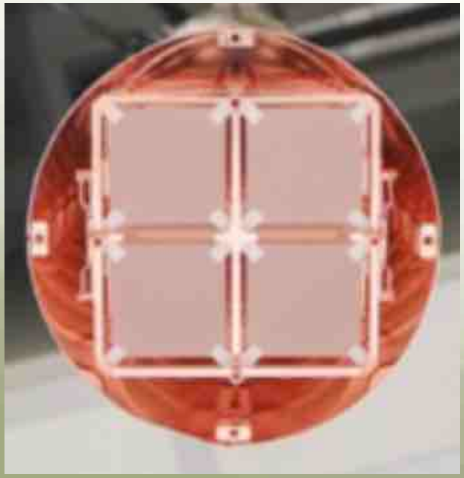
Present and future:

- SuperCDMS @ SNOLAB
- EURECA in Europe **(?)**





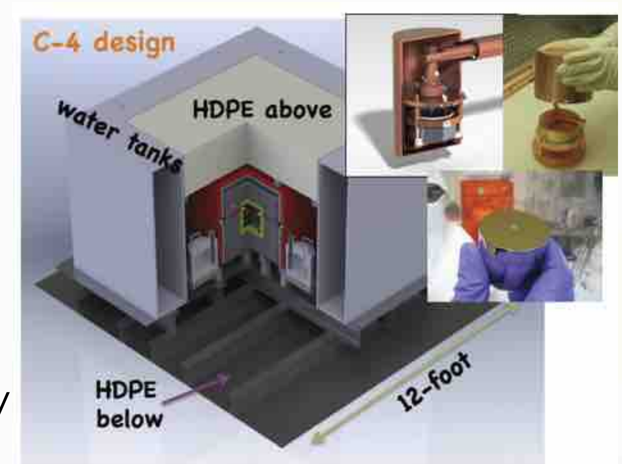
SuperCDMS/EURECA @ SNOLAB **(?)**



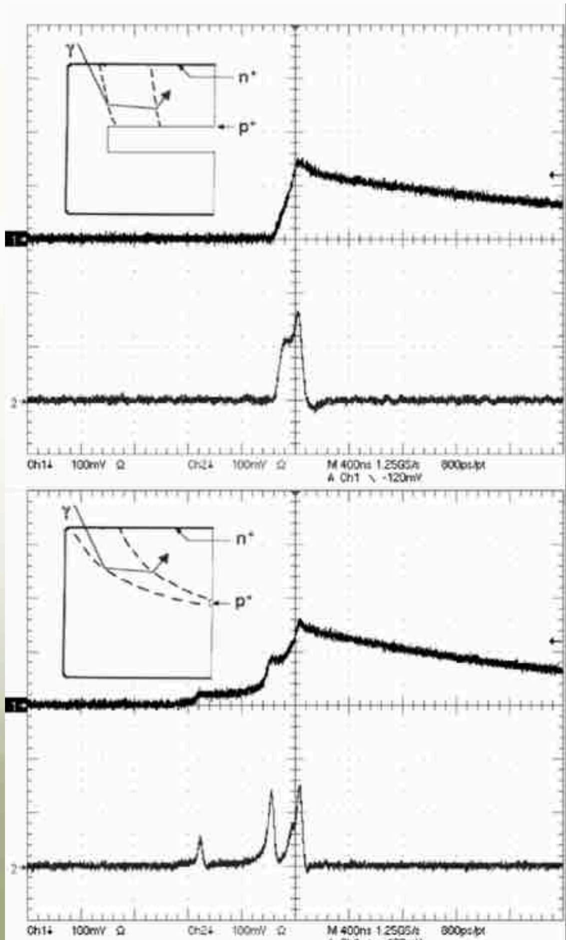
- CUORE-0 (+CUORE) @ LNGS
- CUPID developments can also be useful for DM (?)

Positive hints from CoGeNT (ionization detector)

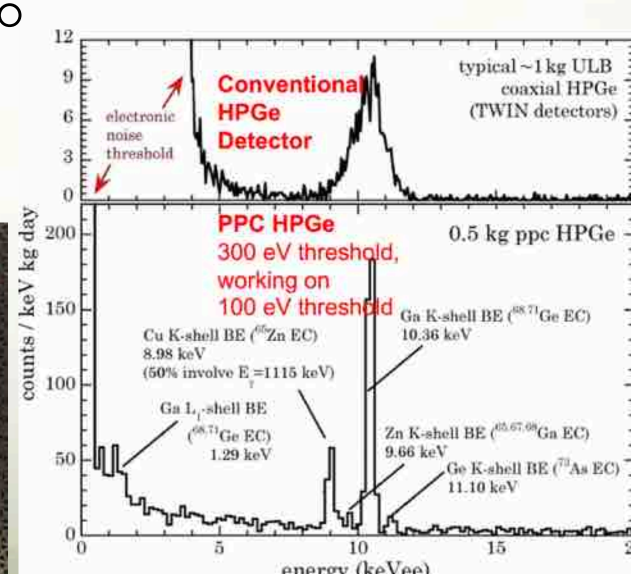
Experimental site: Soudan Underground Laboratory (2100 mwe)
Detector: 440 g, p-type point contact (PPC) Ge diode 0.5 keVee energy threshold
Exposure: 146 kg x day (dec '09 - mar '11)



PPC (P-type Point Contact Detectors)



- P-type = simpler to fabricate/ handle/instrument
- Compact electrode geometry increases drift times-clearly indicates multiple-site events
- Similar background rejection to highly-segmented detectors without added complexity/ backgrounds



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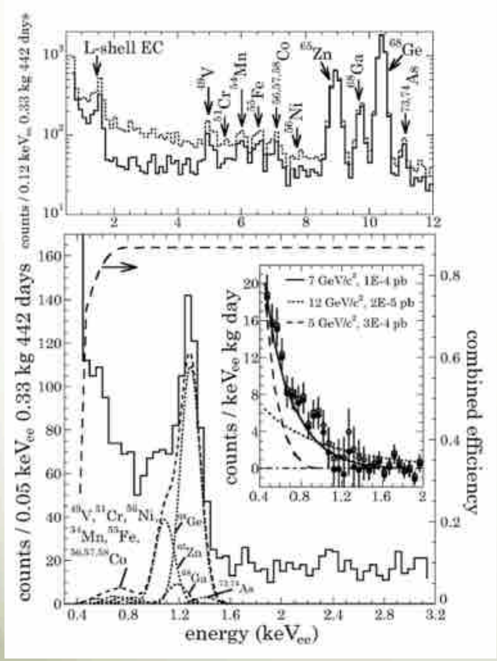
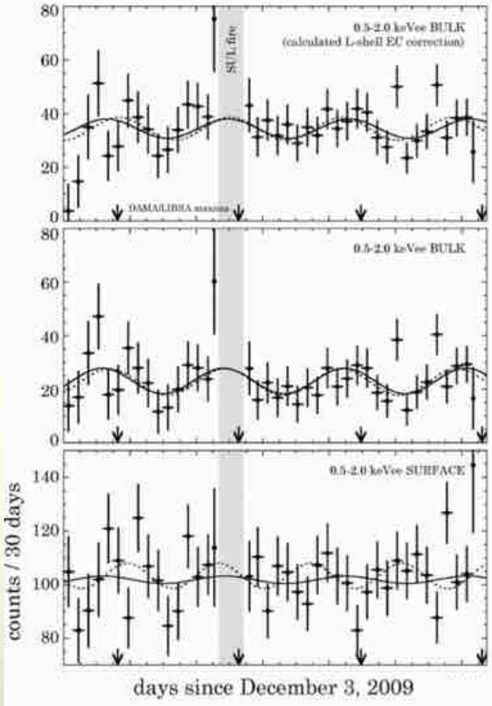
Experimental site:	Soudan Underground Lab (2100 mwe)
Detector:	440 g, p-type point contact (PPC) Ge diode 0.5 keVee energy threshold
Exposure:	146 kg x day (dec '09 - mar '11)

✓ **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

- **6 years of data at hand.**
- CoGeNT upgrade: C-4 is coming up very soon
- C-4 aims at x4 total mass increase, bckg decrease, and substantial threshold reduction. Soudan is still the lab

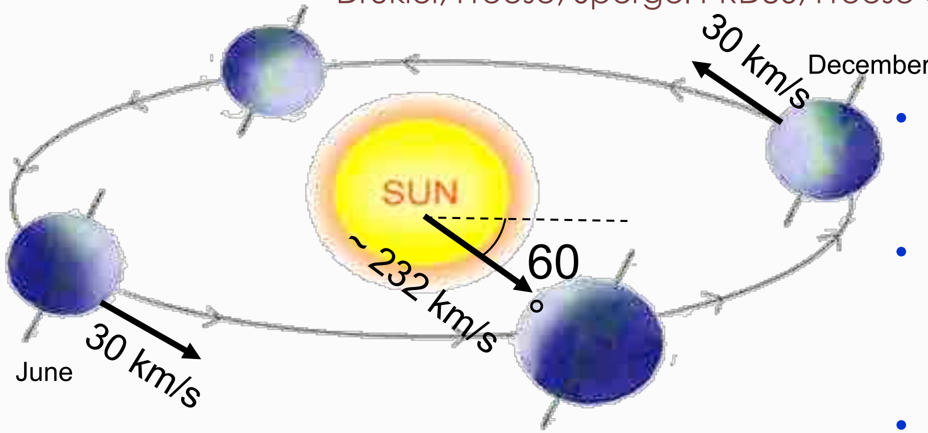
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

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

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

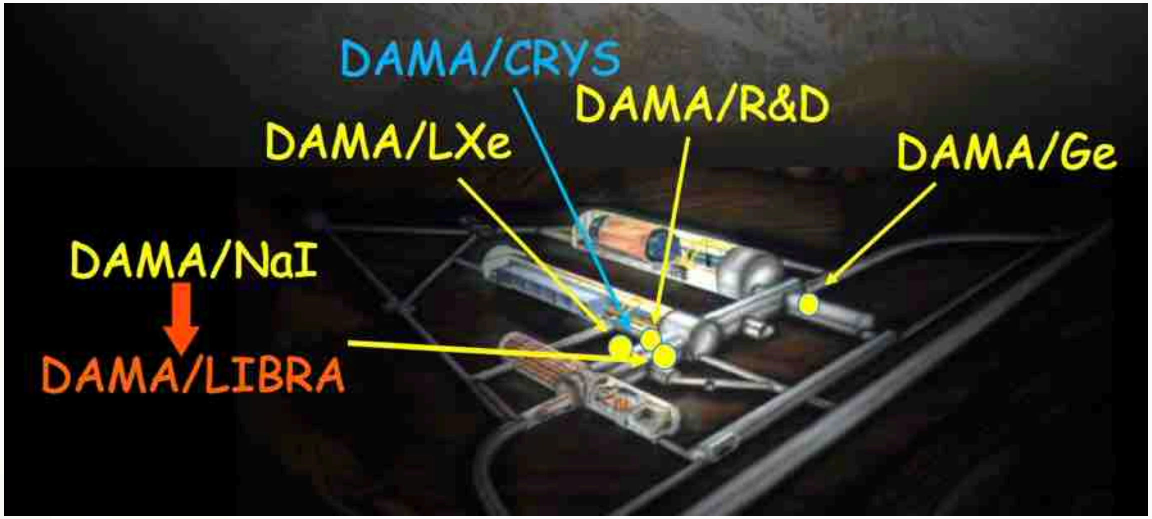
$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \cong S_{0,k} + S_{m,k} \cos[\omega(t-t_0)]$$

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

To mimic this signature, spurious effects and side reactions must not only - obviously - be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

DAMA set-ups

an observatory for rare processes @ LNGS



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

See R. Cerulli talk in parallel session

Collaboration:

Roma Tor Vergata, Roma La Sapienza, LNGS, IHEP/Beijing

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

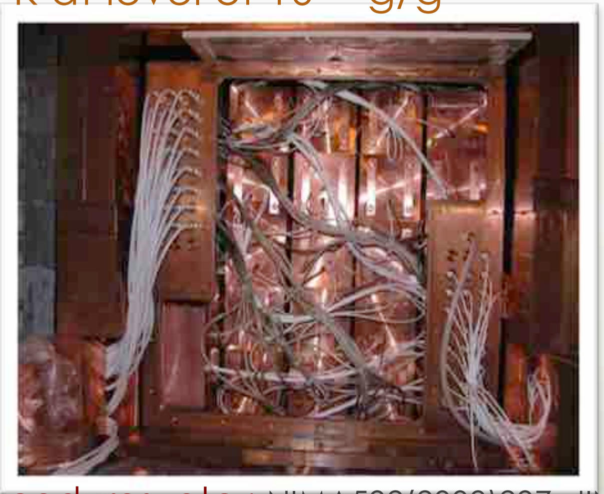
+ in some studies on ββ decays (DST-MAE and Inter-Universities project): IIT Kharagpur and Ropar, India

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

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



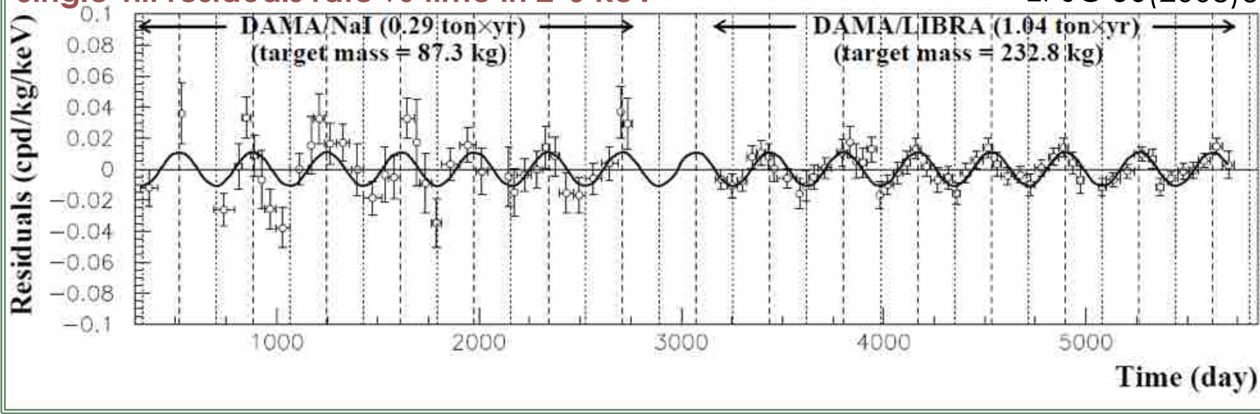
- Radiopurity, performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
- Results on DM particles, Annual Modulation Signature: EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648.
  Related results: PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022, EPJC74(2014)2827, EPJC74(2014)3196,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

Model Independent Annual Modulation Result

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

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

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



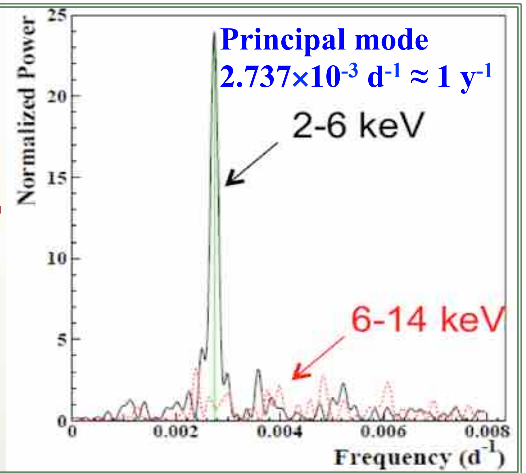
continuous line: t_0 = 152.5 d, T =1.0 y

A=(0.0110±0.0012) cpd/kg/keV
χ^2/dof = 70.4/86 9.2 σ C.L.

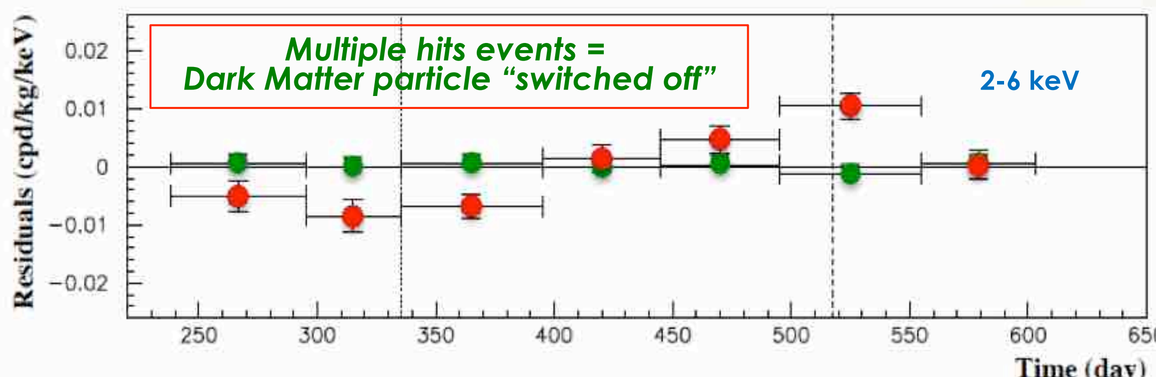
Absence of modulation? No
χ^2/dof=154/87 P(A=0) = 1.3×10^{-5}

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

Power spectrum



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

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

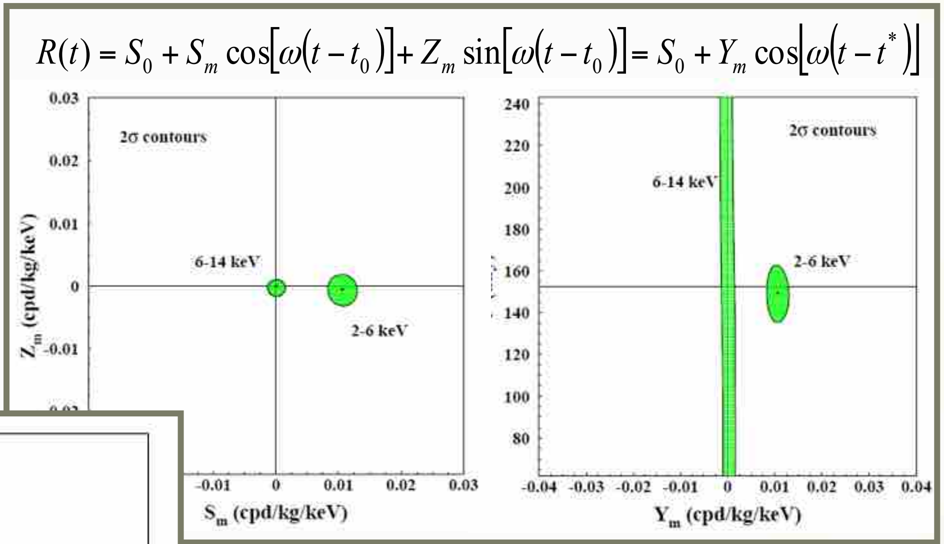
The data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at more than 9σ C.L.

Model Independent Annual Modulation Result

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

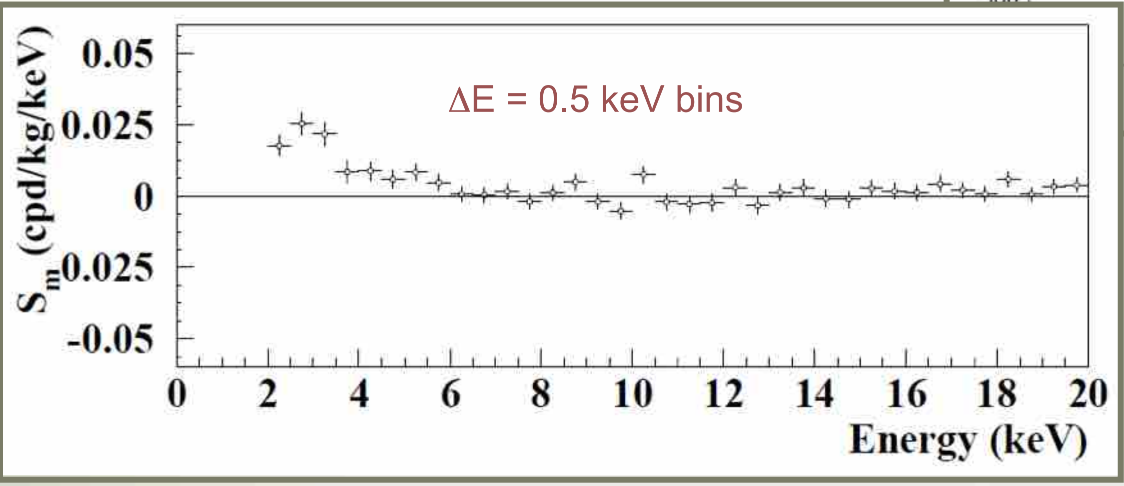
EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648

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



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

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



No systematics or side processes able to quantitatively account for the measured modulation amplitude and to simultaneously satisfy the many peculiarities of the signature are available.

•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, $(\alpha, n) \to$ n (1-10 MeV)	$\simeq 0.9 \times 10^{-7}$ [17]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 6 \times 10^{-4}$	[2, 7, 8]	$\ll 6 \times 10^{-5}$	$\ll 5 \times 10^{-3}$
	$\mu \to$ n from rock (> 10 MeV)	$\simeq 3 \times 10^{-9}$ (see text and ref. [12])	0.0129 [23]	end of June [23, 7, 8]	$\ll 7 \times 10^{-4}$	(see text and [2, 7, 8])	$\ll 9 \times 10^{-6}$	$\ll 8 \times 10^{-4}$
	$\mu \to$ n from Pb shield (> 10 MeV)	$\simeq 6 \times 10^{-9}$ (see footnote 3)	0.0129 [23]	end of June [23, 7, 8]	$\ll 1.4 \times 10^{-3}$	(see text and footnote 3)	$\ll 2 \times 10^{-5}$	$\ll 1.6 \times 10^{-3}$
	$\nu \to$ n (few MeV)	$\simeq 3 \times 10^{-10}$ (see text)	0.03342 *	Jan. 4th *	$\ll 7 \times 10^{-5}$	(see text)	$\ll 2 \times 10^{-6}$	$\ll 2 \times 10^{-4}$
	direct μ	$\Phi_0^{(\mu)} \simeq 20\ \mu$ 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	$\Phi_0^{(\nu)} \simeq 6 \times 10^{10}\ \nu$ 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

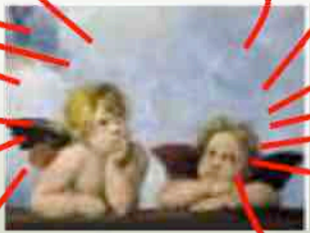
Self interacting Dark Matter

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

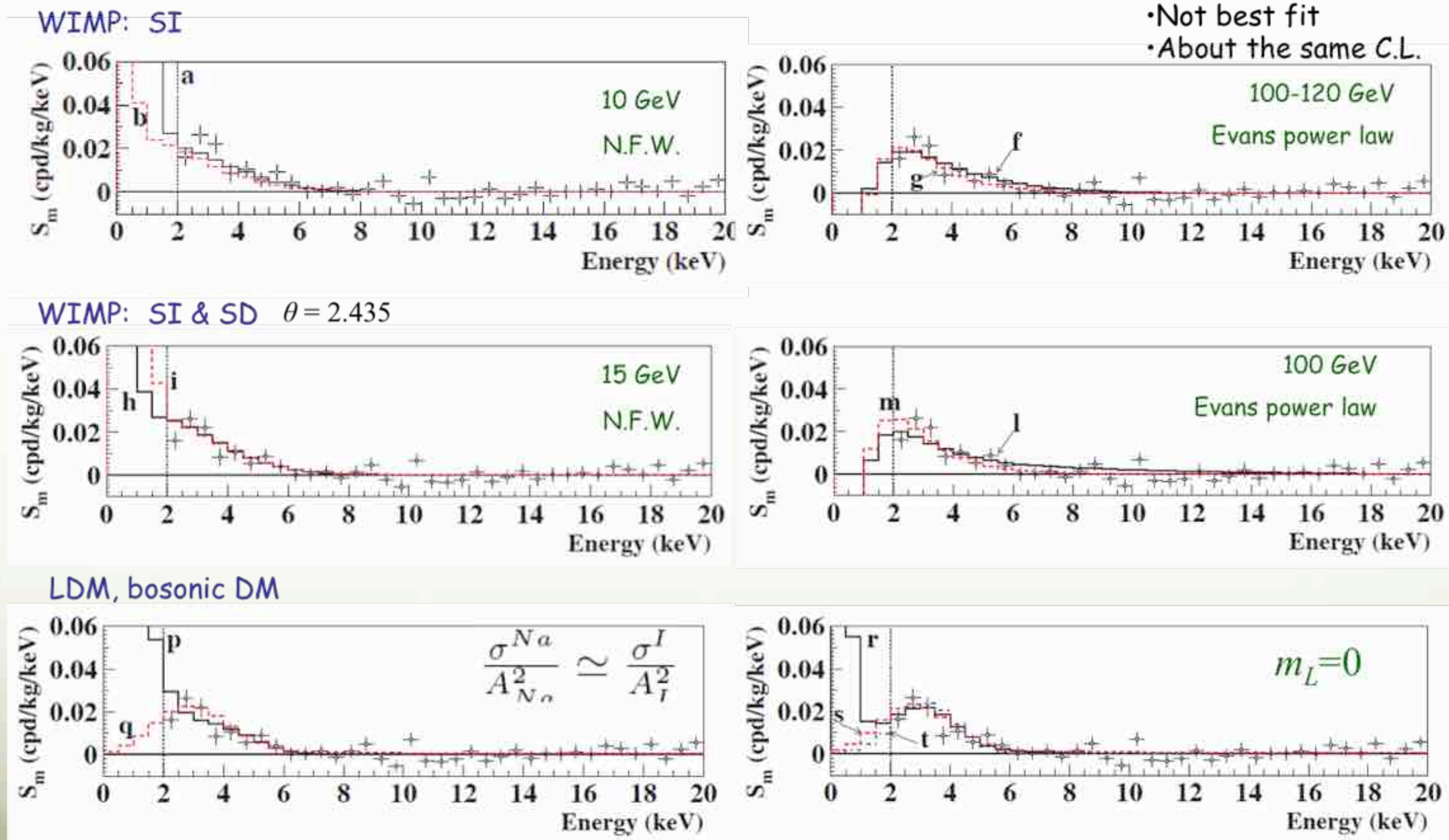
… and more

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.



Compatibility with several candidates;
other ones are open

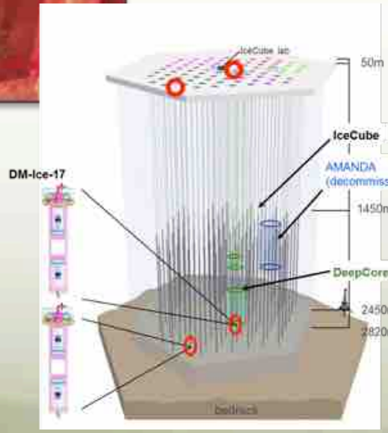
EPJC56(2008)333
IJMPA28(2013)1330022

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: new detector under test → ANAIS-37**
- Future goal: target mass of ≈112 kg

KIMS. DM with CsI(Tl) crystals since 2000 at Yangyang (Y2L, Korea). More recently KIMS-NaI
Future goal: ≈200 kg



DM-ICE. NaI(Tl) deployed at the South Pole
Future goal: ≈250 kg

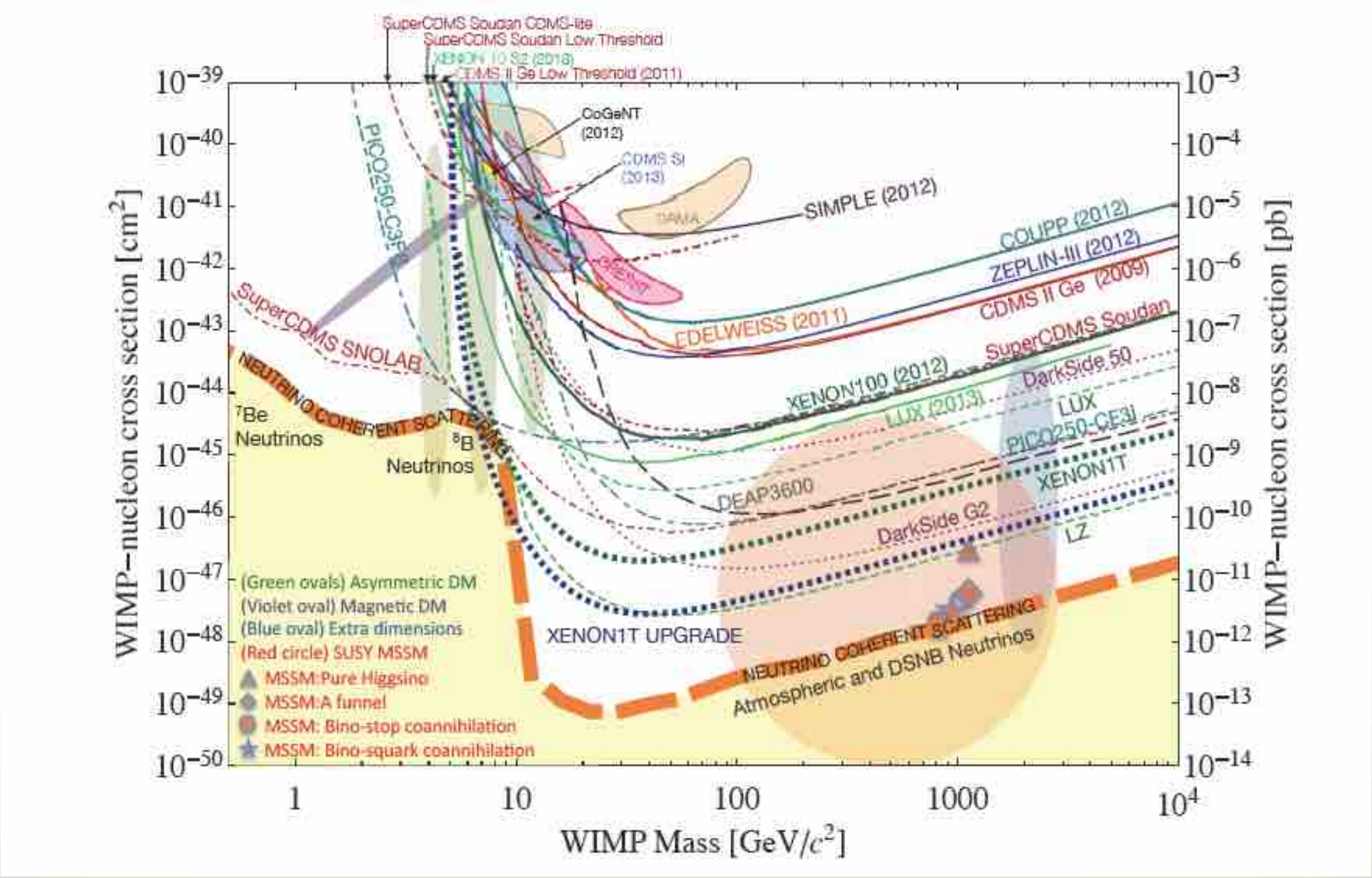
Warning: PSD with CsI(Tl), NaI(Tl), ... sometimes overestimated sensitivity; high rejection power claimed; existing systematics limit the reachable sensitivity

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

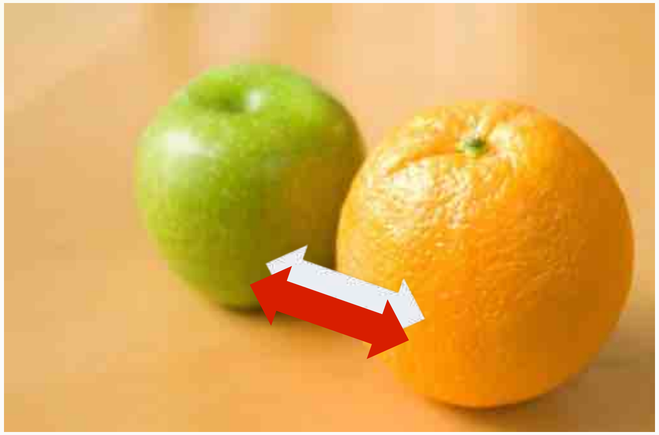
+ SABRE, picoLON, cryog. det. (see parallel sessions)

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?
- ...

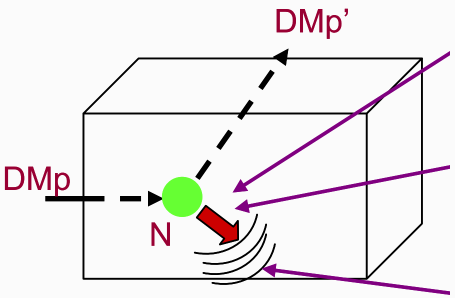
…and experimental aspects…
- Exposures
- Energy threshold
- Detector response (phe/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected 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

... 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

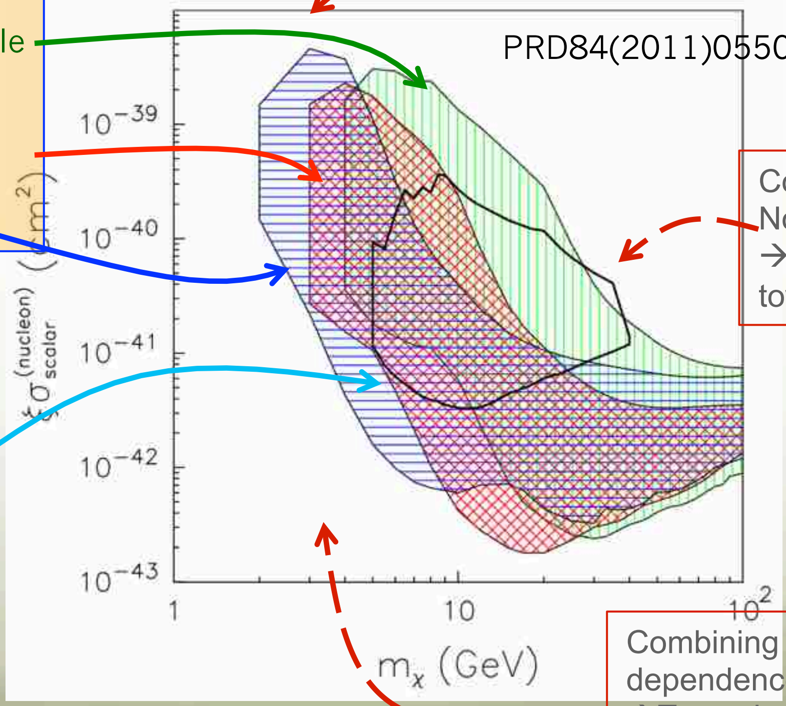
- Some velocity distributions and uncertainties considered.
- The DAMA regions represent the domain where the likelihood-function values differ more than 7.5σ from the null hypothesis (absence of modulation).
- For CoGeNT a fixed value for the Ge quenching factor and a Helm form factor with fixed parameters 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

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

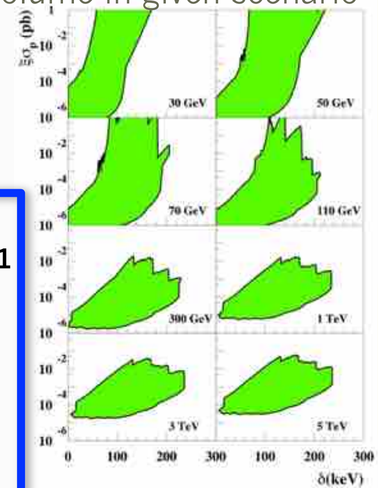
… and much more considering experimental and theoretical uncertainties

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.

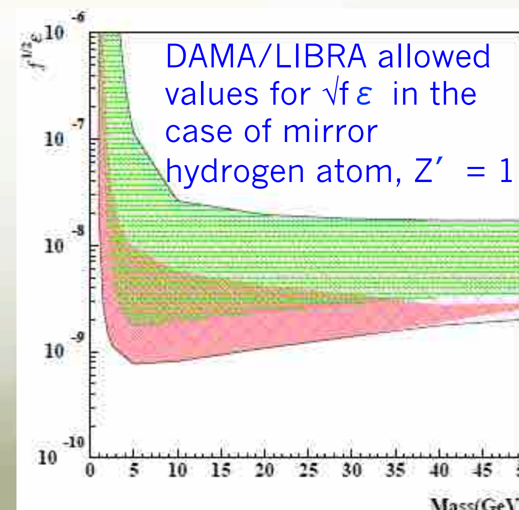
Mirror Dark Matter

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

(See EPJC75(2015)400)

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

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



Perspectives for the future

Other signatures?

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

Diurnal effects in DAMA/LIBRA-phase1

EPJC 74 (2014) 2827

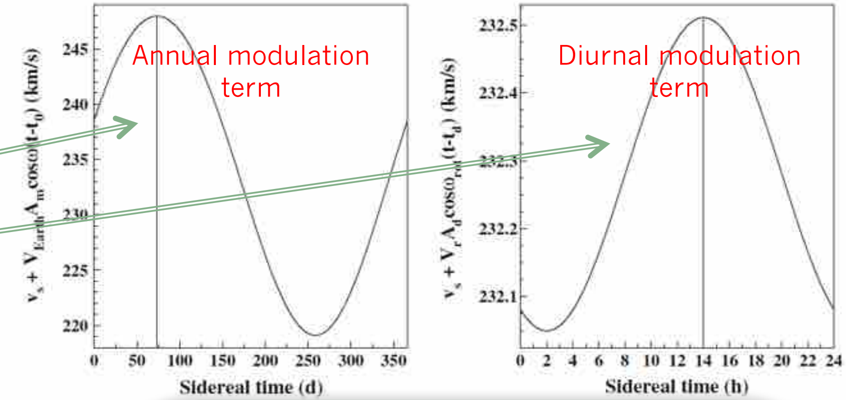
A diurnal effect with the sidereal time is expected for DM because of Earth rotation

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:

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

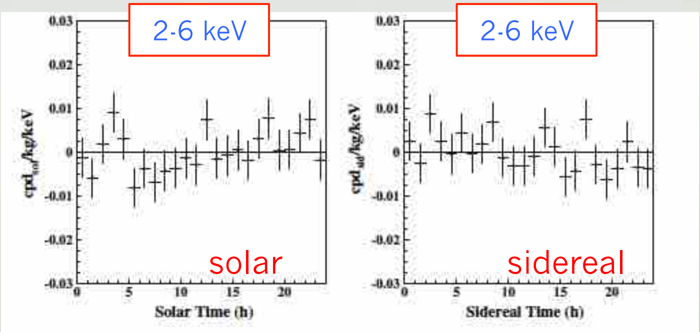
The ratio R_{dy} is a model independent constant:

$$R_{dy} = \frac{S_d}{S_m} = \frac{V_r B_d}{V_{Earth} B_m} \simeq 0.016$$ 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 ≃1.5 × 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 within the present sensitivity.

A_d (2-6 keV) < 1.2 × 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

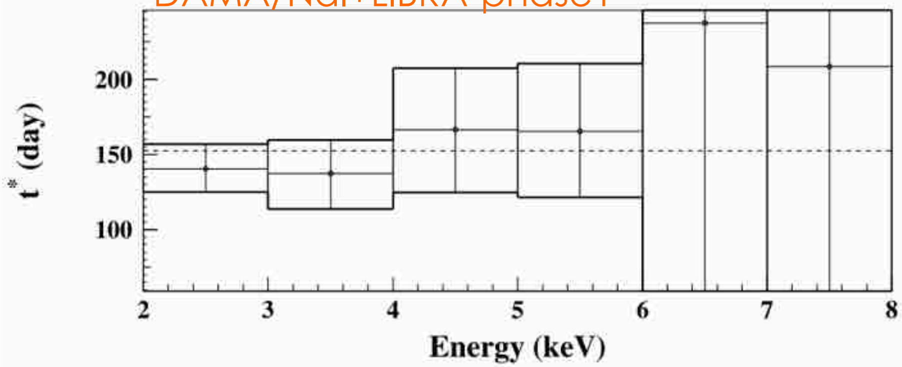
Features of the DM signal

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

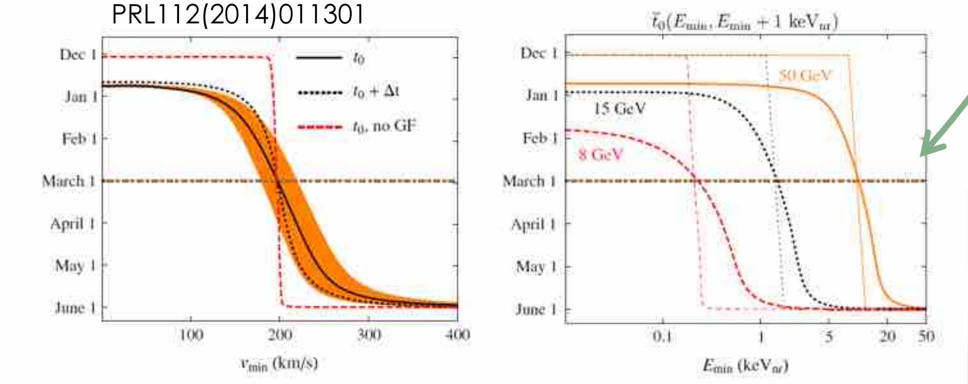
DAMA/NaI+LIBRA-phase1



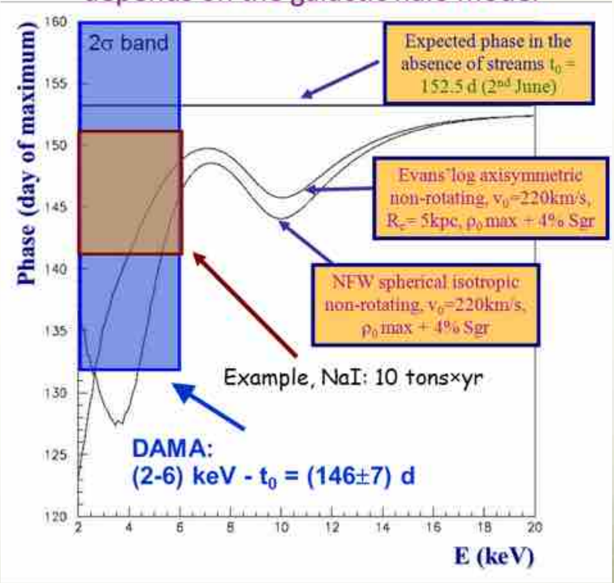
The annual modulation phase depends on :

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

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

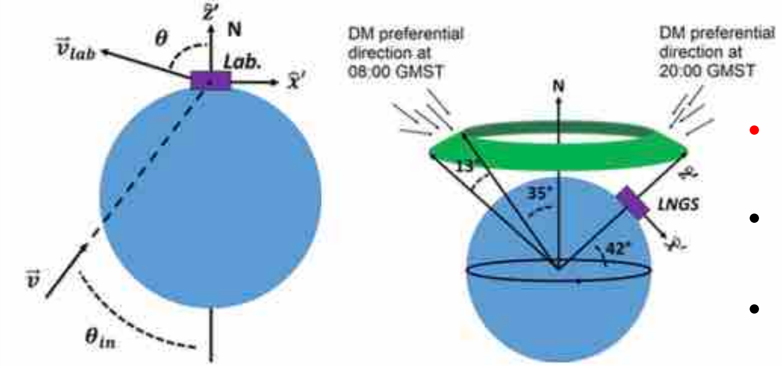
+ further possible improvements (DAMA/LIBRA-phase3) and DAMA/1ton

Other signatures?

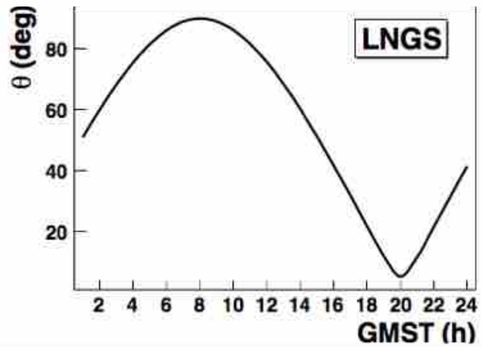
- *Diurnal effects*
- *Second order effects*
- *Shadow effects*
- *Directionality*
- *...*

Earth shadowing effect with DAMA/LIBRA–phase1

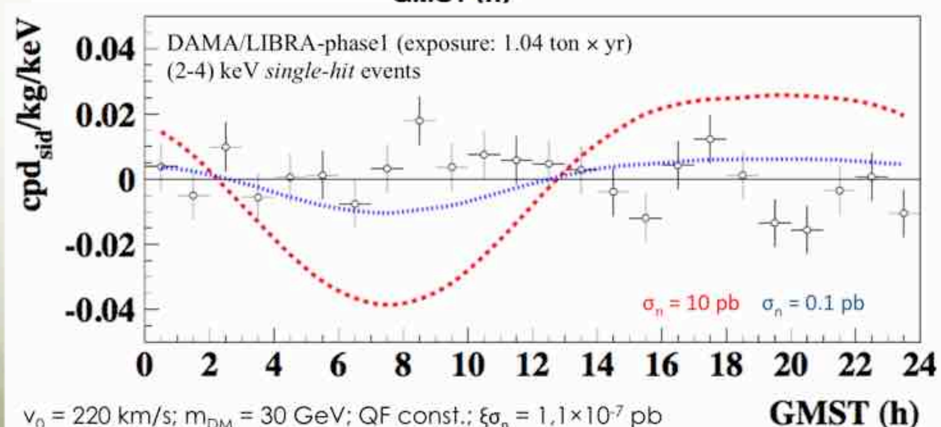
EPJC75(2015)239

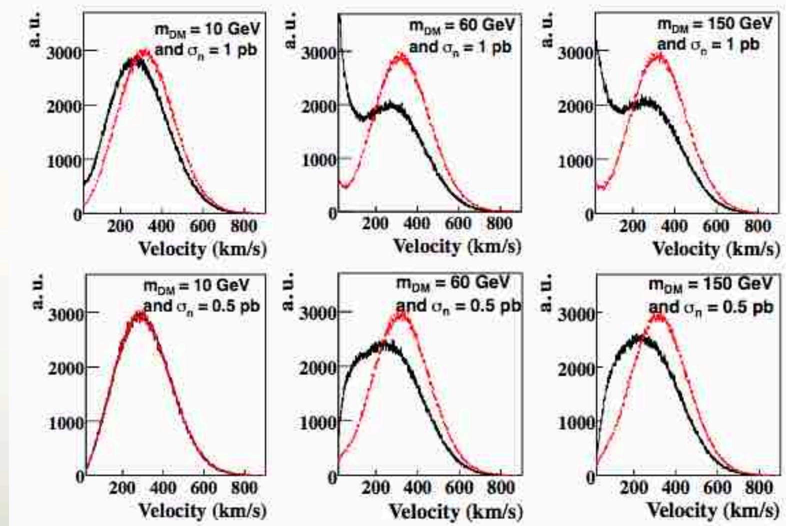


- **Earth Shadow Effect** could be expected for DM candidate particles inducing nuclear recoils
- can be pointed out only for candidates with high cross-section with ordinary matter (low DM local density)
- would be induced by the variation during the day of the Earth thickness crossed by the DM particle 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}.

Other signatures?

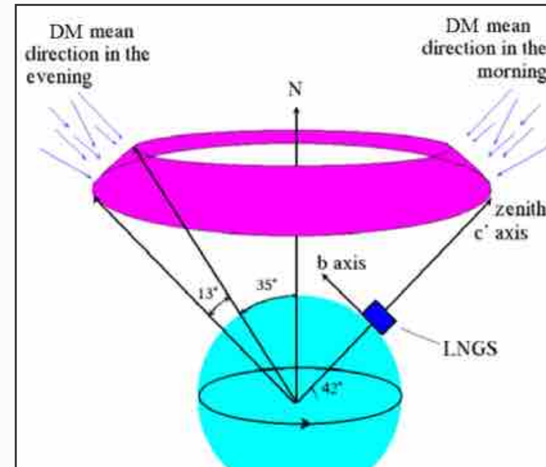
- *Diurnal effects*
- *Second order effects*
- *Shadow effects*
- *Directionality*
- *...*

Directionality technique with crystals

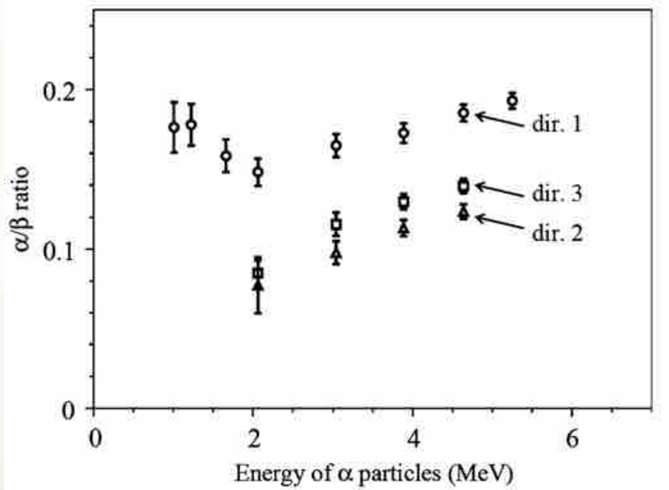
EPJ C73 (2013) 2276

- Only for candidates inducing just recoils
- Identification of the Dark Matter particles by exploiting the non-isotropic recoil distribution correlated to the Earth velocity

The use of anisotropic scintillators was proposed by DAMA (N.Cim.C15(1992)475, EPJC28(2003)203); then UK, Japan preliminary activities

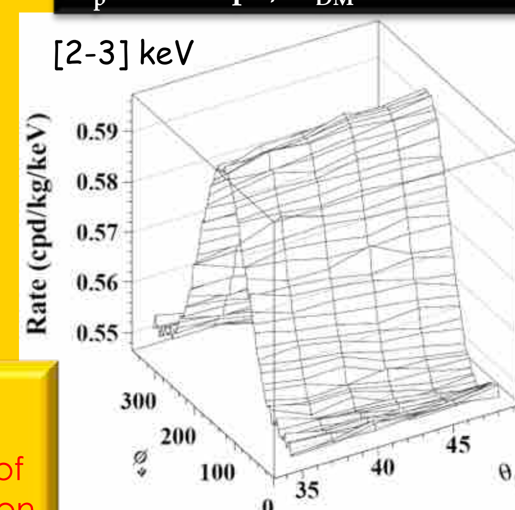


The ADAMO project: Study of the directionality approach with $ZnWO_4$ anisotropic detectors



Nuclear recoils are expected to be strongly correlated with the DM impinging direction
This effect can be pointed out through the study of the variation in the response of anisotropic scintillation detectors during sidereal day

$\sigma_p = 5\times10^{-5}$ pb, m_{DM} = 50 GeV



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

These and others competitive characteristics of $ZnWO_4$ detectors could permit to reach sensitivity comparable with that of the DAMA/LIBRA positive result

Example (for a given model framework) of the expected counting rate as a function of the detector velocity direction

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