Evidences and hints of Dark Matter

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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", ...

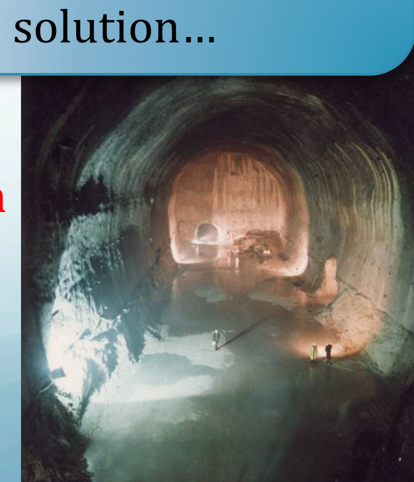
Elementary Black holes,
Planckian objects, Daemons

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

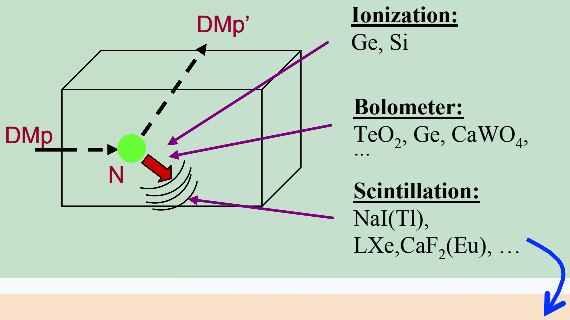


DM direct detection method using a model independent approach and a low-background widely-sensitive target material

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

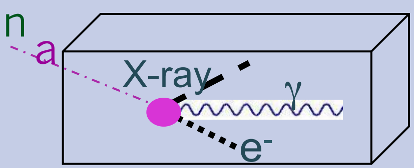
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

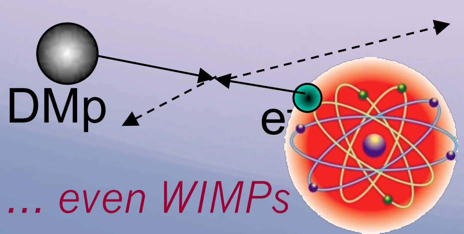
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

  → detection of e.m. radiation

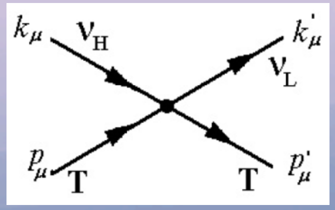


… even WIMPs

- 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**

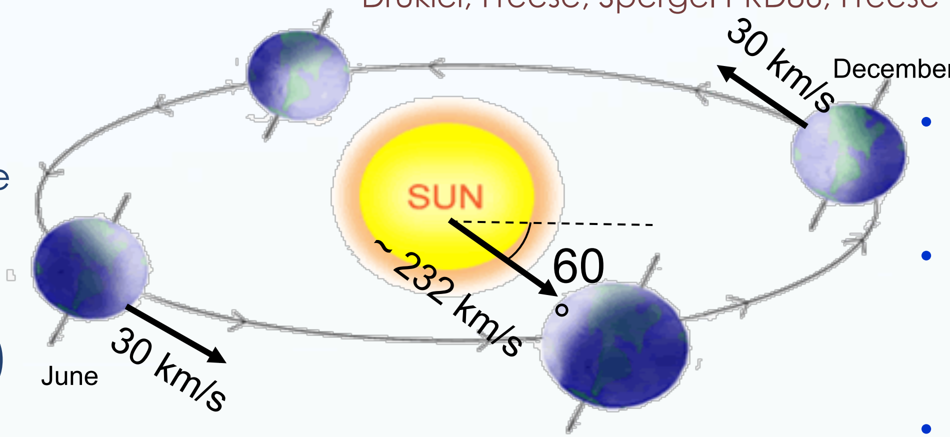
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

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} ~ 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)

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

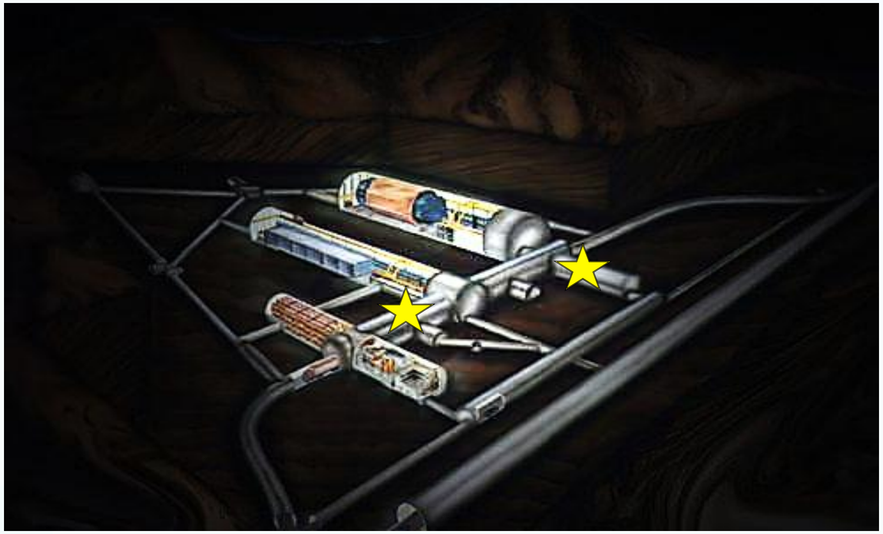
$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \cong S_{0,k} + S_{m,k}\cos[\omega(t-t_0)]$$

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

Collaboration:

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

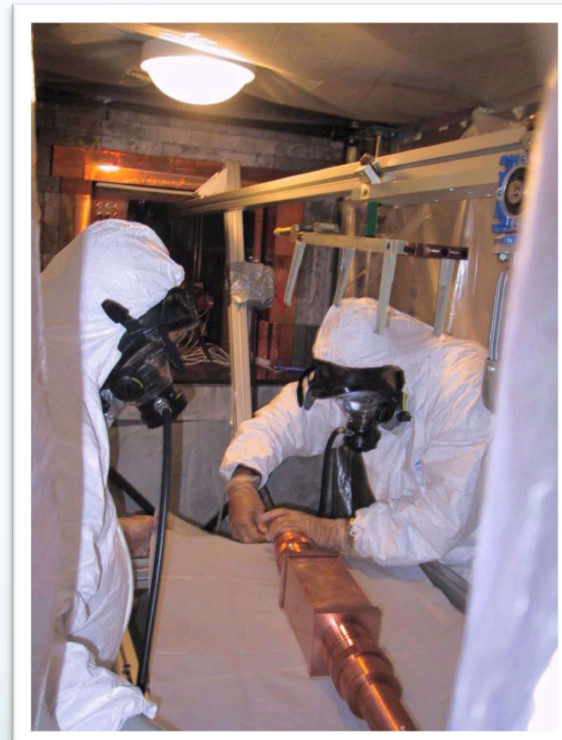
+ by-products and small scale expts.: INR-Kiev

+ neutron meas.: ENEA-Frascati

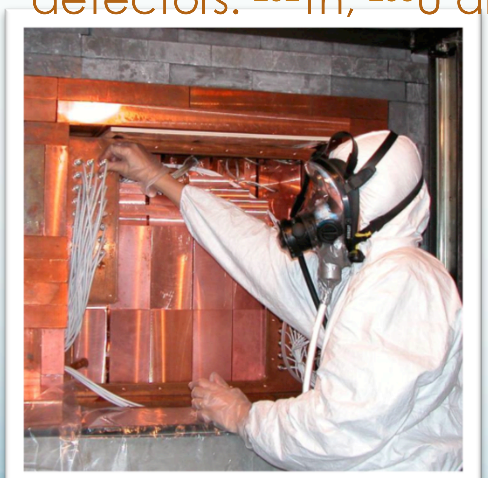
+ in some studies on ββ decays (DST-MAE and Inter-Unversities project): IIT Kharagpur and Ropar, India

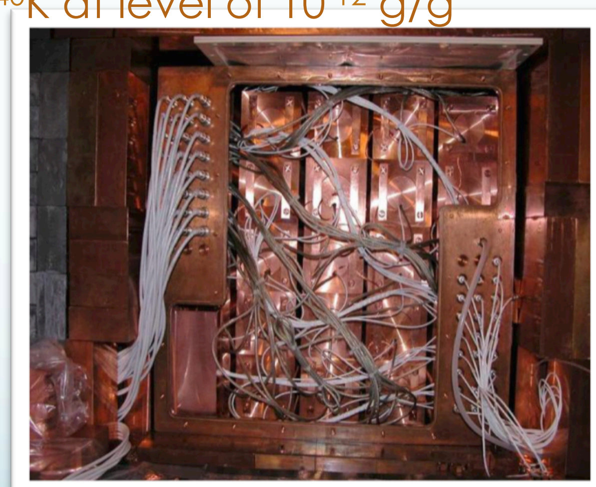
The DAMA/LIBRA set-up ~250 kg NaI(Tl)
(Large sodium Iodide Bulk for RAre processes)

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

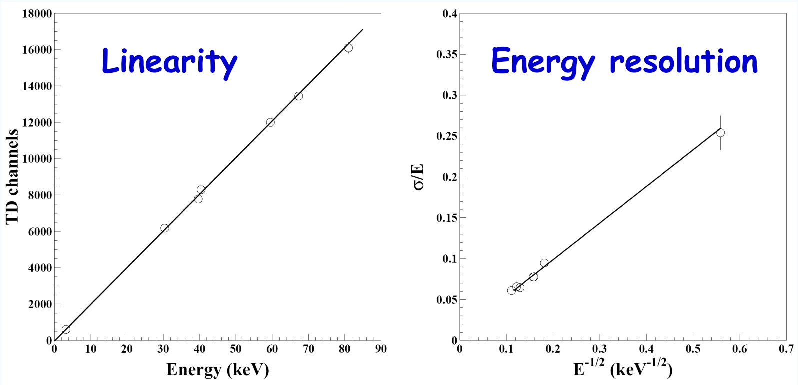




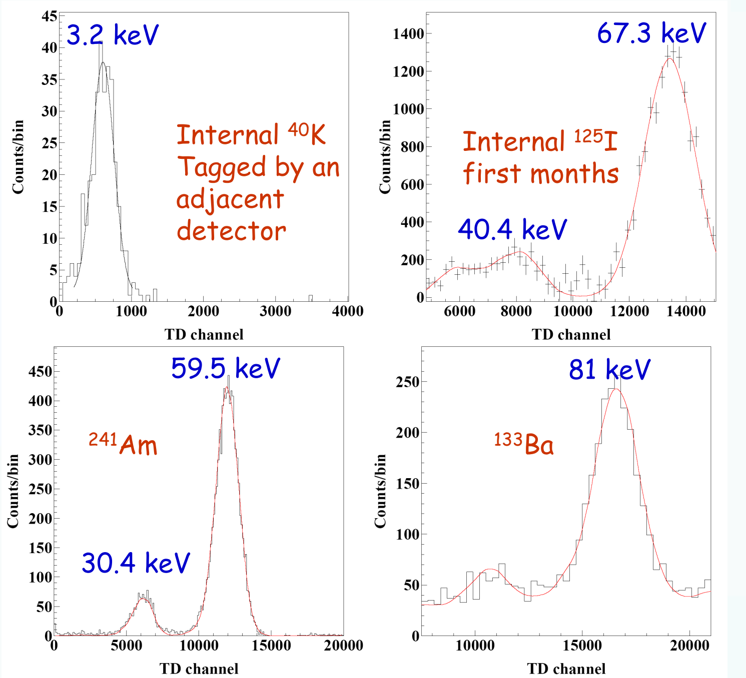
- Radiopurity, performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
- Results on DM particles, Annual Modulation Signature: EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648.
  Related results: PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022. Diurnal: EPJC74(2014)2827
- Results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

DAMA/LIBRA calibrations

Low energy: various external gamma sources (^{241}Am, ^{133}Ba) and internal X-rays or gamma's (^{40}K, ^{125}I, ^{129}I), routine calibrations with ^{241}Am

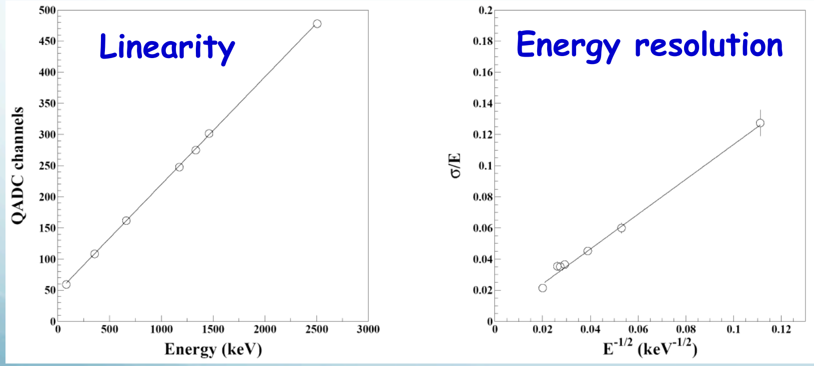


$$\frac{\sigma_{LE}}{E} = \frac{(0.448 \pm 0.035)}{\sqrt{E(keV)}} + (9.1 \pm 5.1)\cdot 10^{-3}$$

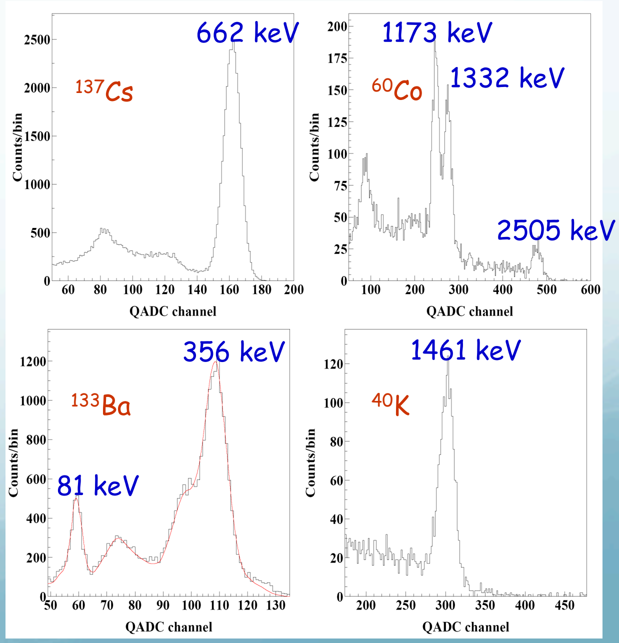


The curves superimposed to the experimental data have been obtained by simulations

High energy: external sources of gamma rays (e.g. ^{137}Cs, ^{60}Co and ^{133}Ba) and gamma rays of 1461 keV due to ^{40}K decays in an adjacent detector, tagged by the 3.2 keV X-rays



The signals (unlike low energy events) for high energy events are taken only from one PMT



$$\frac{\sigma_{HE}}{E} = \frac{(1.12 \pm 0.06)}{\sqrt{E(keV)}} + (17 \pm 23)\cdot 10^{-4}$$

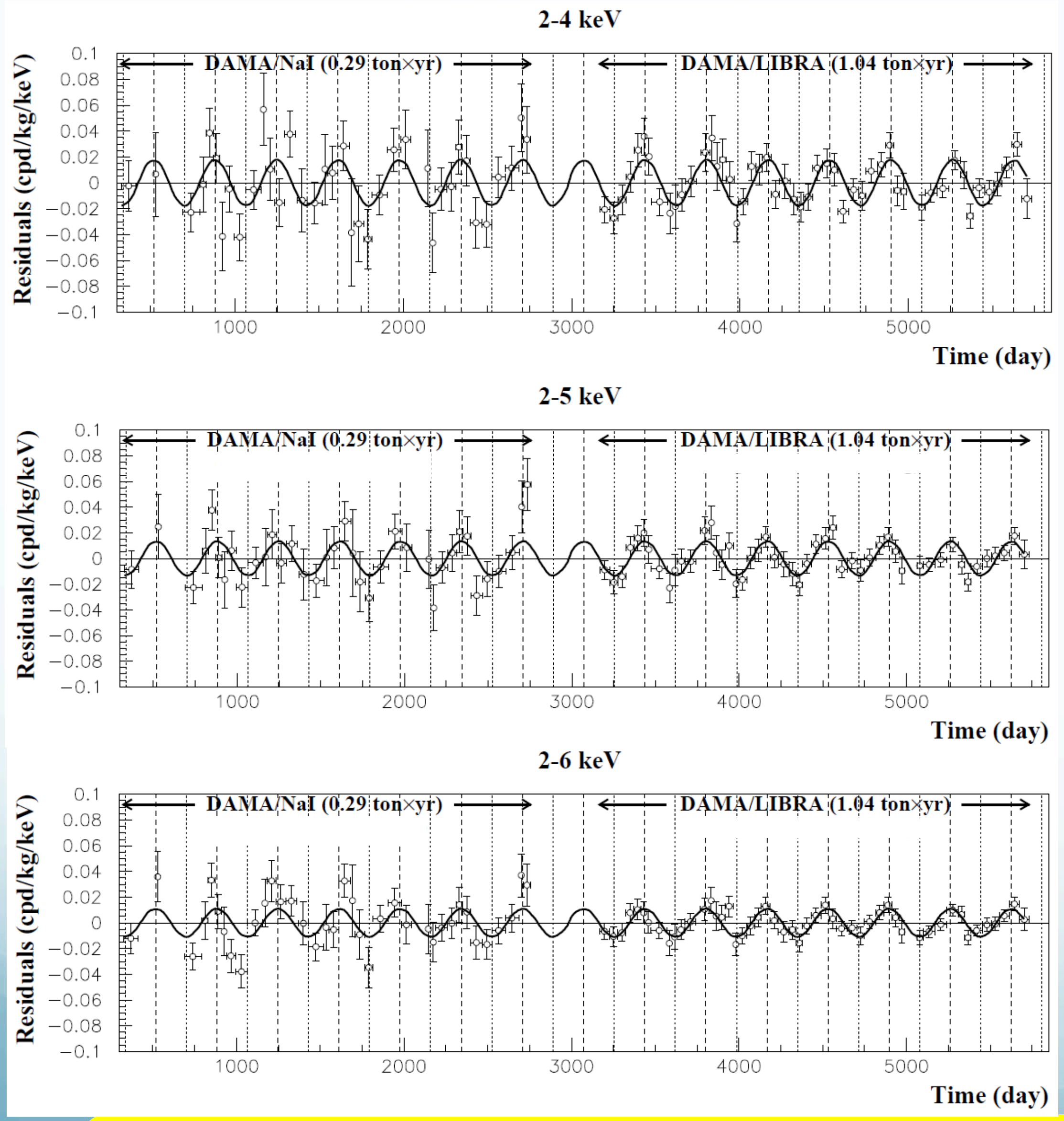
Thus, here and hereafter keV means keV electron equivalent

Model Independent DM Annual Modulation Result

experimental residuals of the single-hit scintillation events rate vs time and energy

DAMA/NaI + DAMA/LIBRA-phase1

Total exposure: 487526 kg×day = 1.33 ton×yr



$A\cos[\omega(t-t_0)]$;
continuous lines: t_0 = 152.5 d, T = 1.00 y

2-4 keV

A=(0.0179±0.0020) cpd/kg/keV

χ^2/dof = 87.1/86 **9.0 σ C.L.**

Absence of modulation? No

χ^2/dof=169/87 ⇒ P(A=0) = 3.7×10^{-7}

2-5 keV

A=(0.0135±0.0015) cpd/kg/keV

χ^2/dof = 68.2/86 **9.0 σ C.L.**

Absence of modulation? No

χ^2/dof=152/87 ⇒ P(A=0) = 2.2×10^{-5}

2-6 keV

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}

The data favor the presence of a modulated behavior with proper features at 9.2σ C.L.

Model Independent Annual Modulation Result

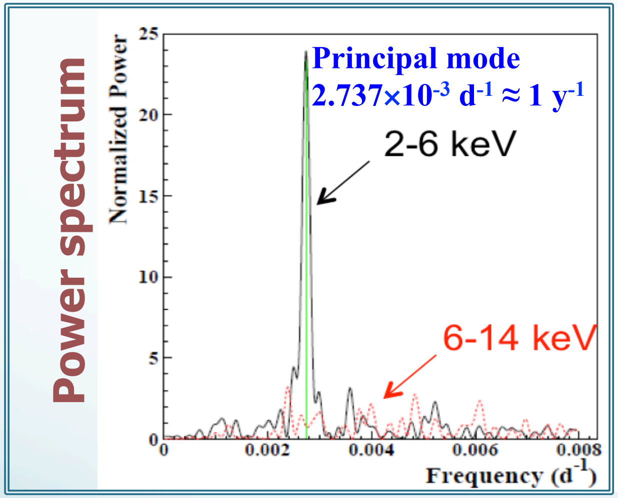
DAMA/NaI + **DAMA/LIBRA-phase1** Total exposure: 487526 kg×day = **1.33 ton×yr**

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

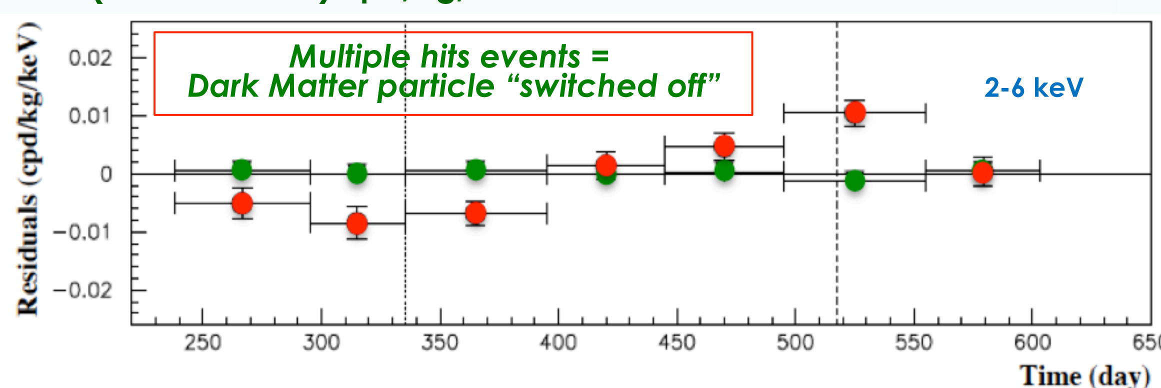
	A(cpd/kg/keV)	$T=2\pi/\omega$ (yr)	t_0 (day)	C.L.
DAMA/NaI+DAMA/LIBRA-phase1				
(2-4) keV	0.0190 ±0.0020	0.996 ±0.0002	134 ± 6	9.5σ
(2-5) keV	0.0140 ±0.0015	0.996 ±0.0002	140 ± 6	9.3σ
(2-6) keV	0.0112 ±0.0012	0.998 ±0.0002	144 ± 7	9.3σ

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



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

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



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

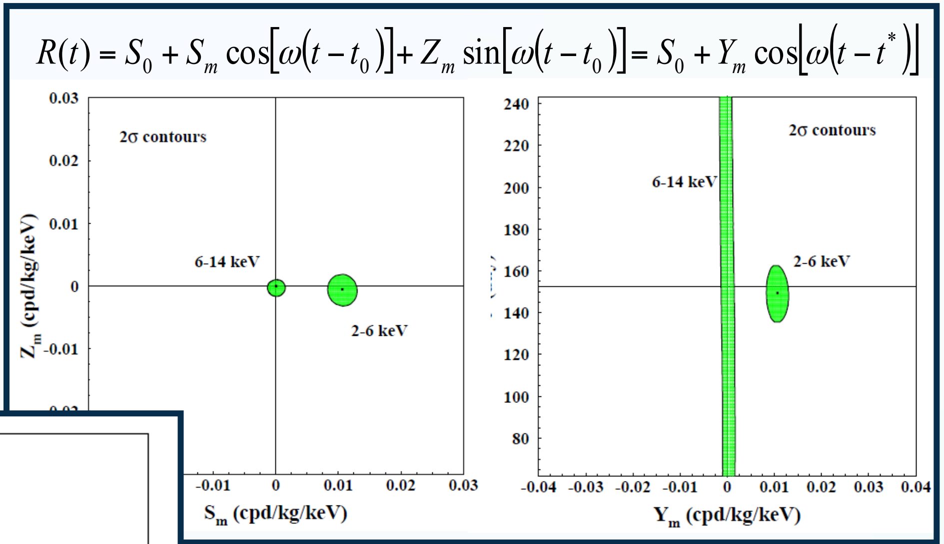
The data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at about 9.2σ C.L.

Model Independent Annual Modulation Result

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

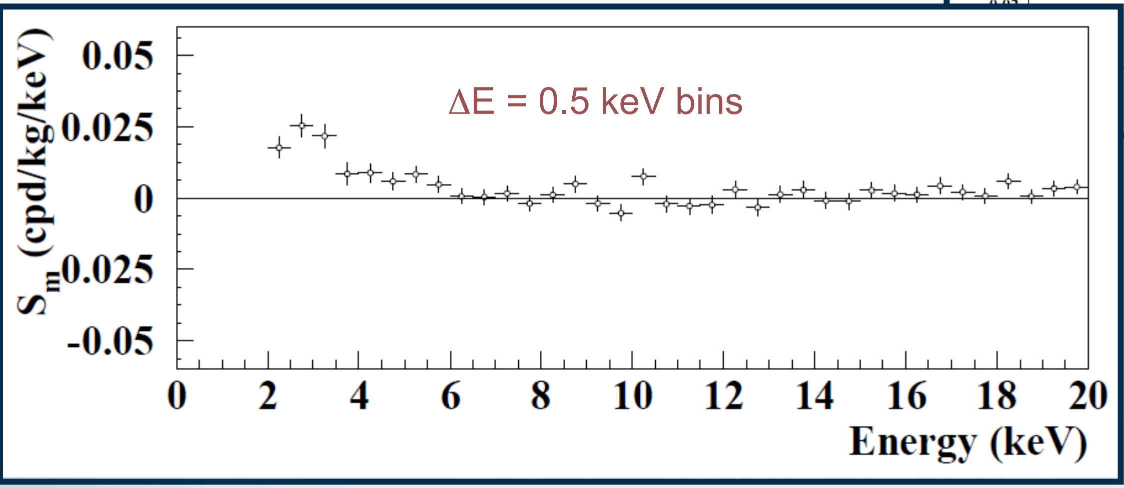
EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648

- 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.

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)

Source	Main comment	Cautious upper limit (90%C.L.)
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	**<2.5×10^{-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	**<1-2 ×10^{-4} cpd/kg/keV**
EFFICIENCIES	Regularly measured by dedicated calibrations	**<10^{-4} cpd/kg/keV**
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV *multiple-hits* events; this limit includes all possible sources of background	**<10^{-4} cpd/kg/keV**
SIDE REACTIONS	Muon flux variation measured at LNGS	**<3×10^{-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

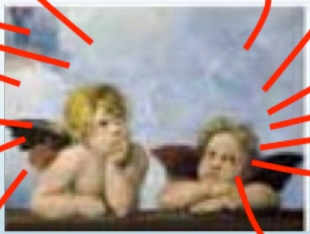
Self interacting Dark Matter

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



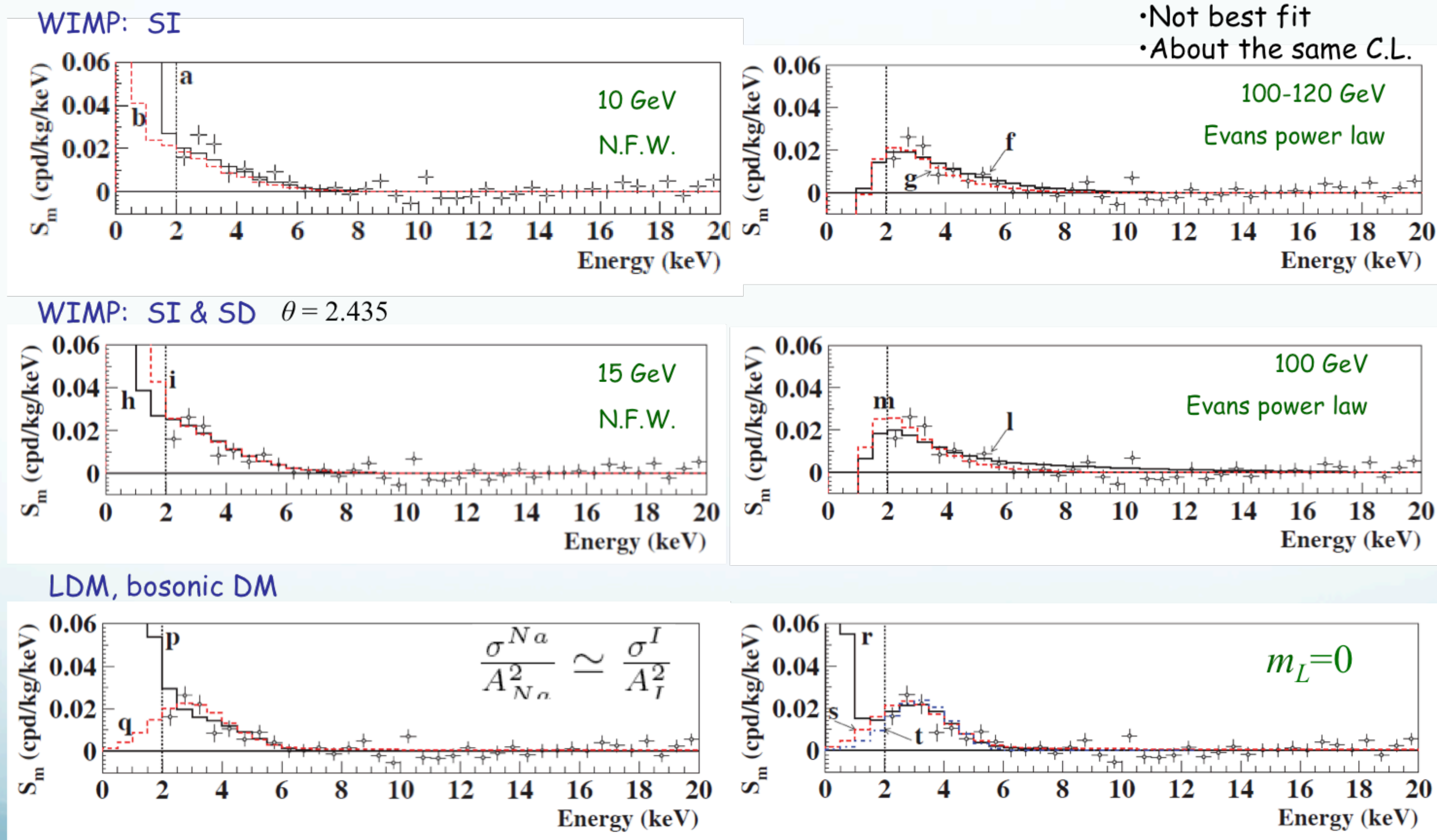
Kaluza Klein particles

... 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 <u>examples</u> of interpretation of the annual modulation in terms of candidate particles in <u>some scenarios</u>



Compatibility with several candidates;
other ones are open

EPJC56(2008)333
IJMPA28(2013)1330022

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

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

No other experiment whose result can be directly compared in model independent way with those of DAMA/NaI and DAMA/LIBRA available

Available results from direct searches using different target materials and approaches do not give any robust conflict

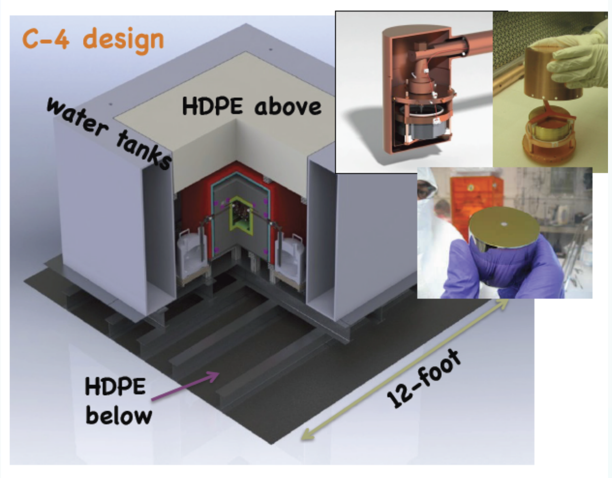
Possible model dependent positive hints from indirect searches not in conflict with DAMA; but interpretation and the evidence itself in indirect searches depend e.g. on bckg modeling (also including pulsars, supernovae remnants, ...), on DM spatial velocity distribution, either on forced boost factor or on unnatural clumpiness, etc.

Moreover, whatever **hints** from other direct searches must be interpreted; in any case large room of compatibility with DAMA is present

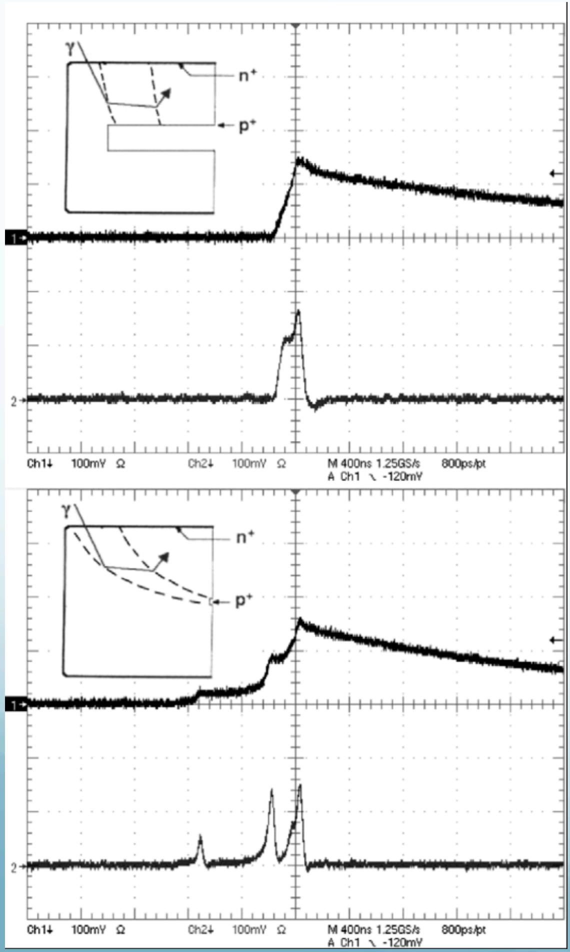
Positive hints from CoGeNT (ionization detector)

PRL107(2011)141301

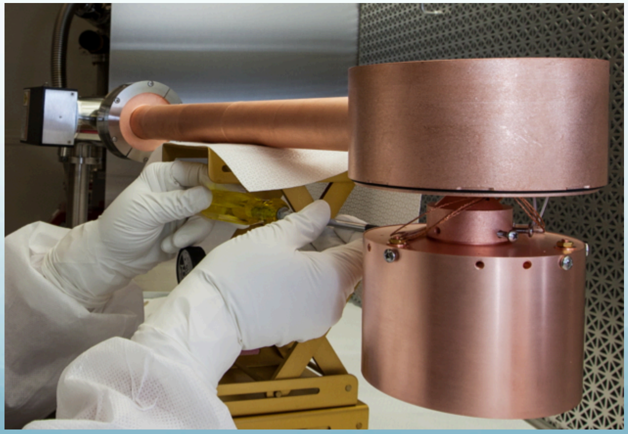
Experimental site:	Soudan Underground Laboratory (2100 mwe)
Detector:	440 g, p-type point contact (PPC) Ge diode 0.5 keVee energy threshold
Exposure:	146 kg x day (dec '09 - mar '11)

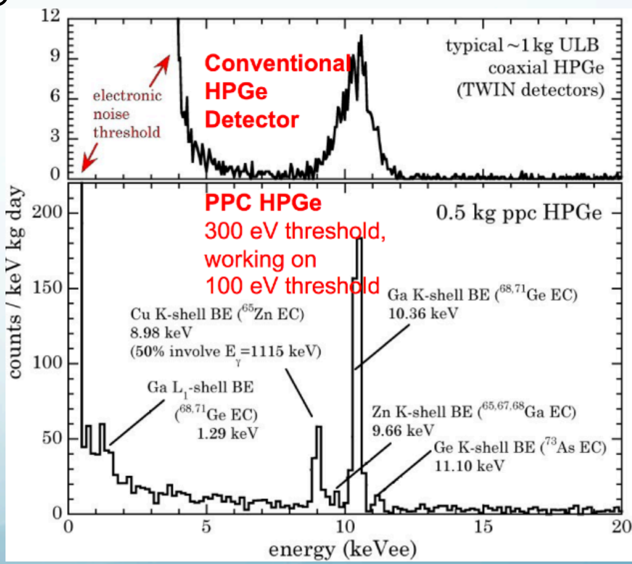


PPC (P-type Point Contact Detectors)



- 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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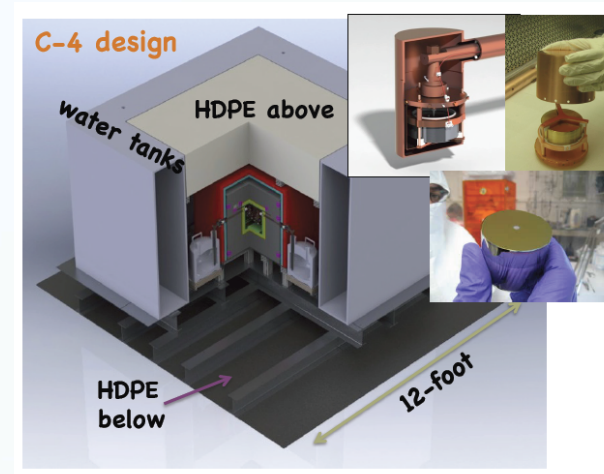
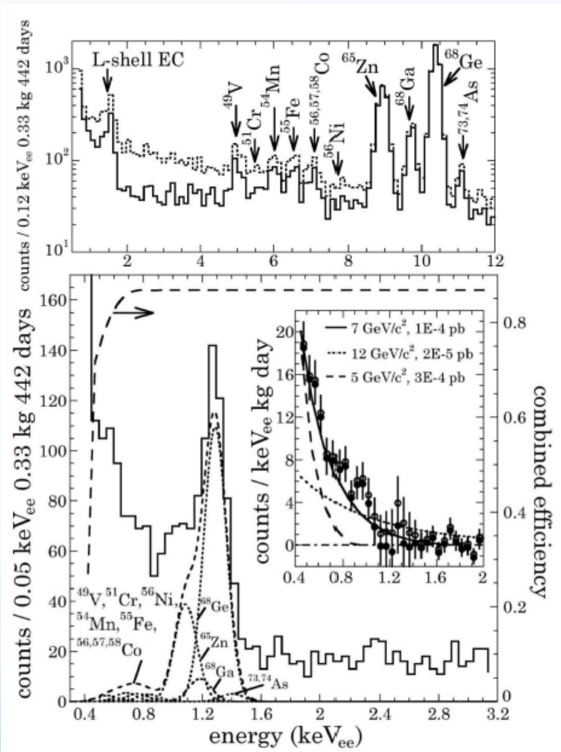
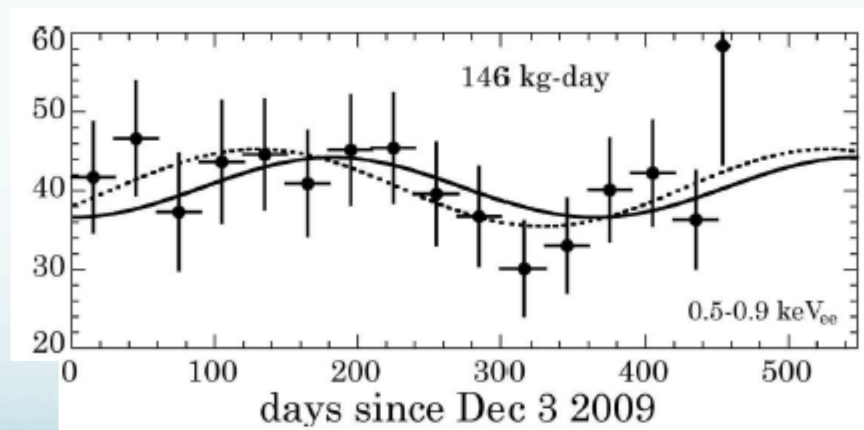




- Energy region for DM search (0.5-3.2 keVee)
- Statistical discrimination of surface/bulk events
- Efficiencies for cumulative data cut applied



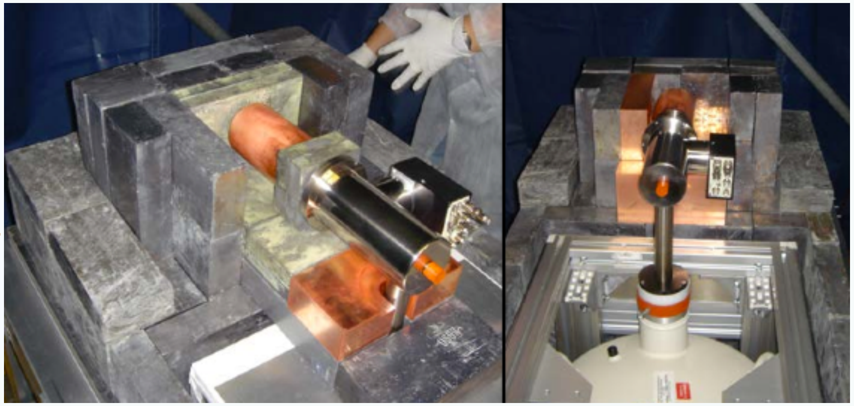
✓ **Irreducible excess** of bulk-like events below 3 keVee observed;

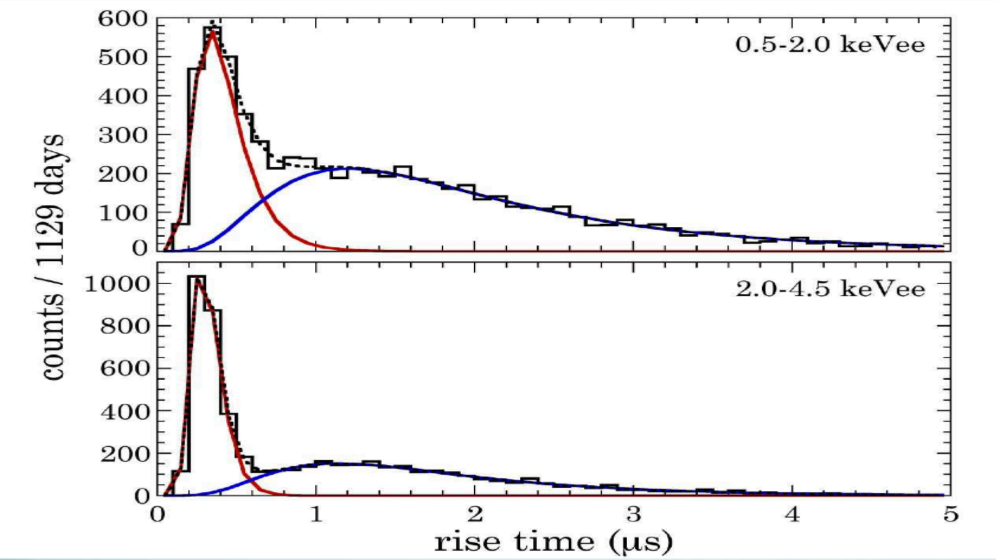
✓ **annual modulation** of the rate in 0.5-3 keVee at ~2.8σ C.L.

In data taking since July 2011 after the fire in Soudan

Positive hints from CoGeNT (ionization detector)

New data: arXiv:1401.3295
Experimental site: Soudan Underground Laboratory (2100 mwe)
Detector: 440 g, p-type point contact (PPC) Ge diode 0.5 keVee energy threshold
Exposure: 3.4 yr operation (restart in July '11)





Discrimination between bulk (fast pulses) and surface (slow pulses) events

- Surface events (background dominated) have slower pulses than bulk events
- Discrimination gets worse at lower energies due to electronic noise

Positive hints from CoGeNT

New data: arXiv:1401.3295

Experimental site: Soudan Underground Laboratory (2100 mwe)

Detector: 440 g, p-type point contact (PPC) Ge diode 0.5 keVee energy threshold

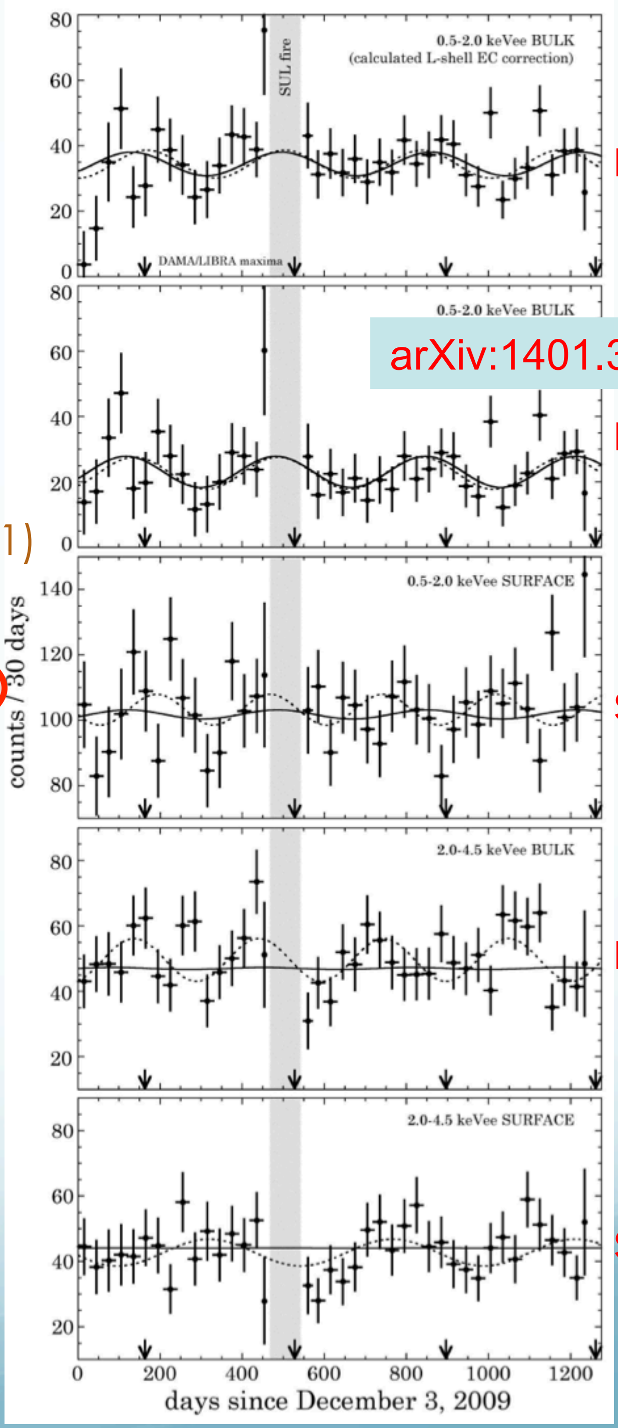
Exposure: 3.4 yr operation (restart in July ‘11)

- 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…

CoGeNT upgrade: C-4 is coming up very soon

C-4 aims at a x10 total mass increase, ~x20 background decrease, and substantial threshold reduction. Soudan is still the laboratory, assuming its continuity.



BULK

arXiv:1401.3295

BULK

Surface

BULK

Surface

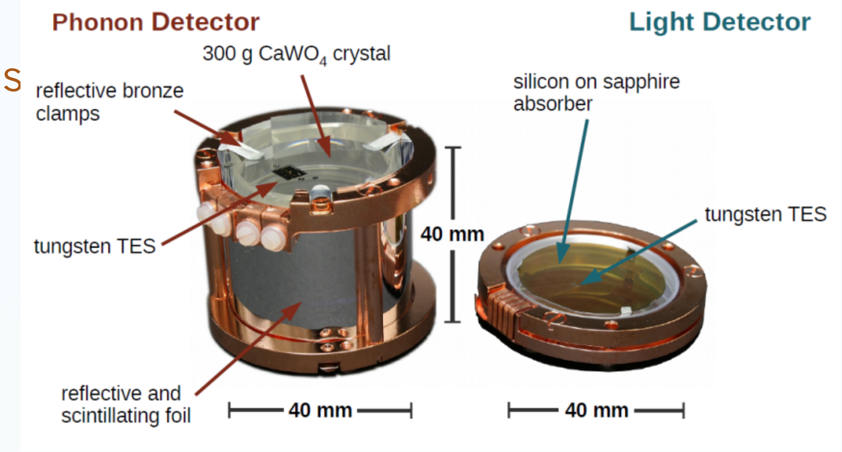
Positive hint from CRESST (scintillation vs heat)

Experimental site: Gran Sasso (LNGS)

Detector: 33 $CaWO_4$ crystals (10 kg mass

data from 8 detectors

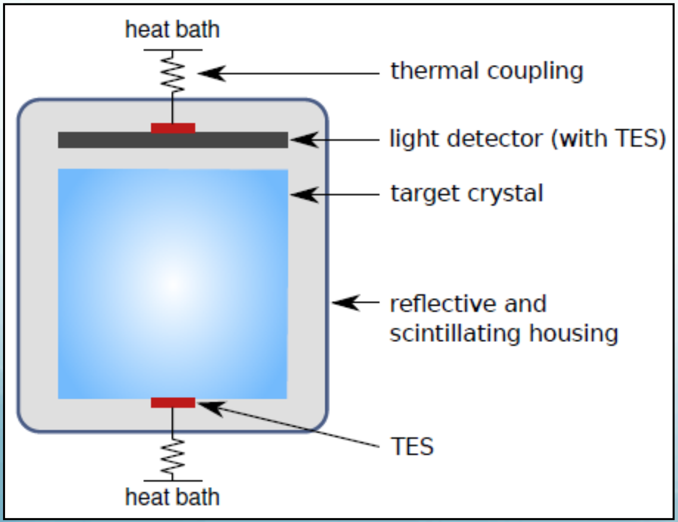
Exposure: ≈ 730 kg x day

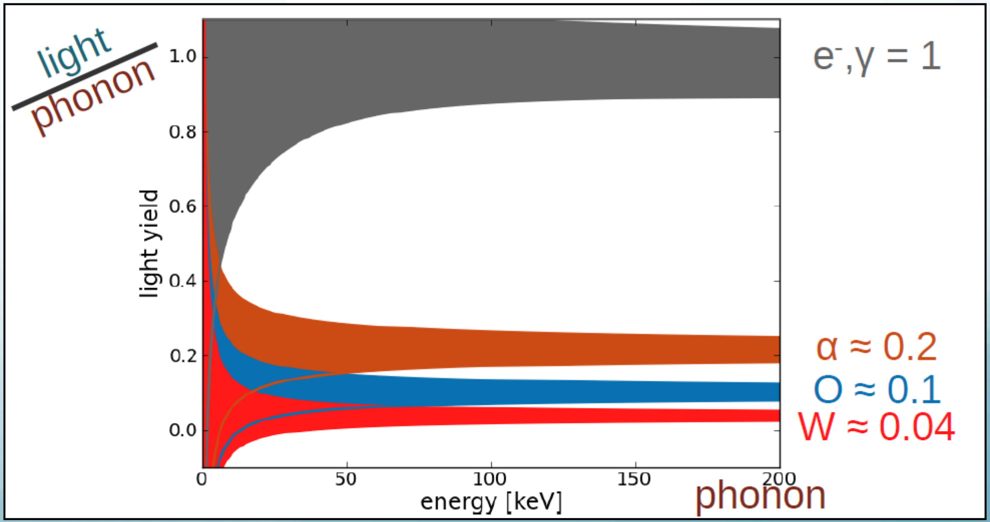


Discrimination of nuclear recoils from radioactive backgrounds by simultaneous measurement of phonons and scintillation light:

- Phonon: $CaWO_4$ crystals read out with TES
- Light: recorded by separate light detector also read out with TES

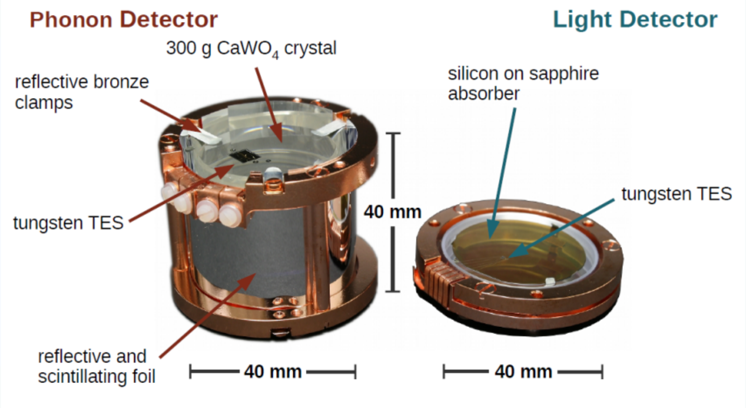
$$\text{Light Yield} = \frac{E_{\text{Light}}}{E_{\text{Phonon}}}$$





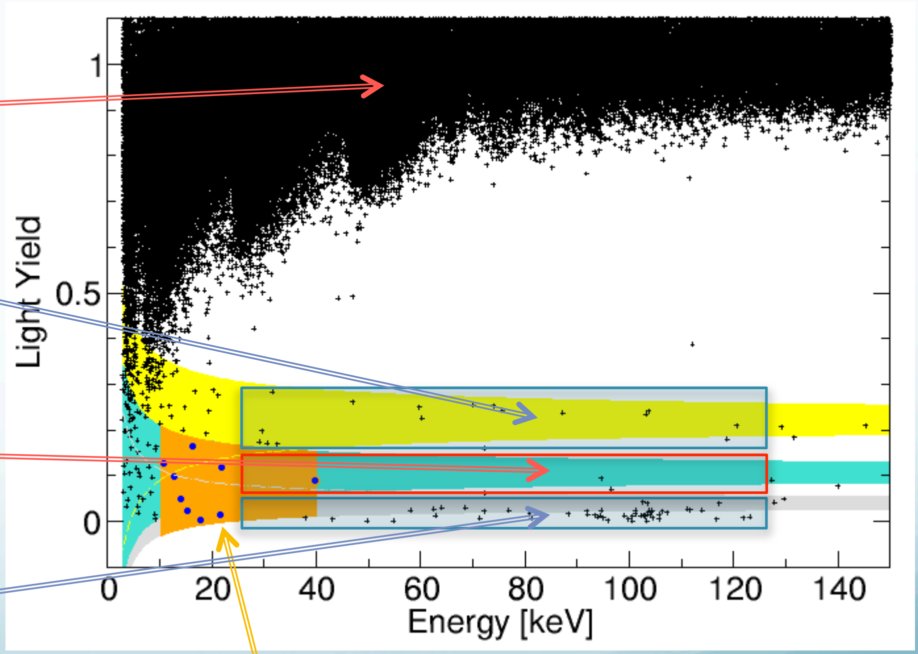
Positive hint from CRESST (scintillation vs heat)

Experimental site: Gran Sasso (LNGS)
Detector: 33 $CaWO_4$ crystals (10 kg mass)
data from 8 detectors
Exposure: ≈ 730 kg x day



Typical Detector Module - Backgrounds

- γ/e⁻ background (dominant) ~ 10^4 events/kg/yr defines lower threshold of acceptance region
- α background: e.g. **^{210}Po** in clamps holding the crystals (degraded alphas down to keV)
- Neutron background (mainly scatter off oxygen)
- Pb recoil background: **^{210}Po** decay on surface



Acceptance region: O,Ca,W bands; ~10-40 keV

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data from 8 detectors
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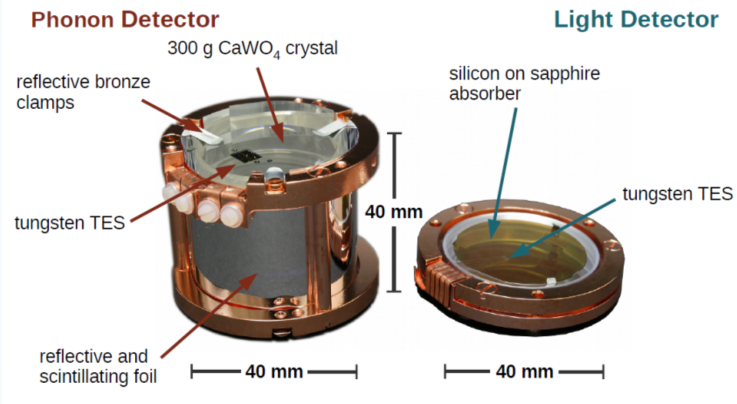
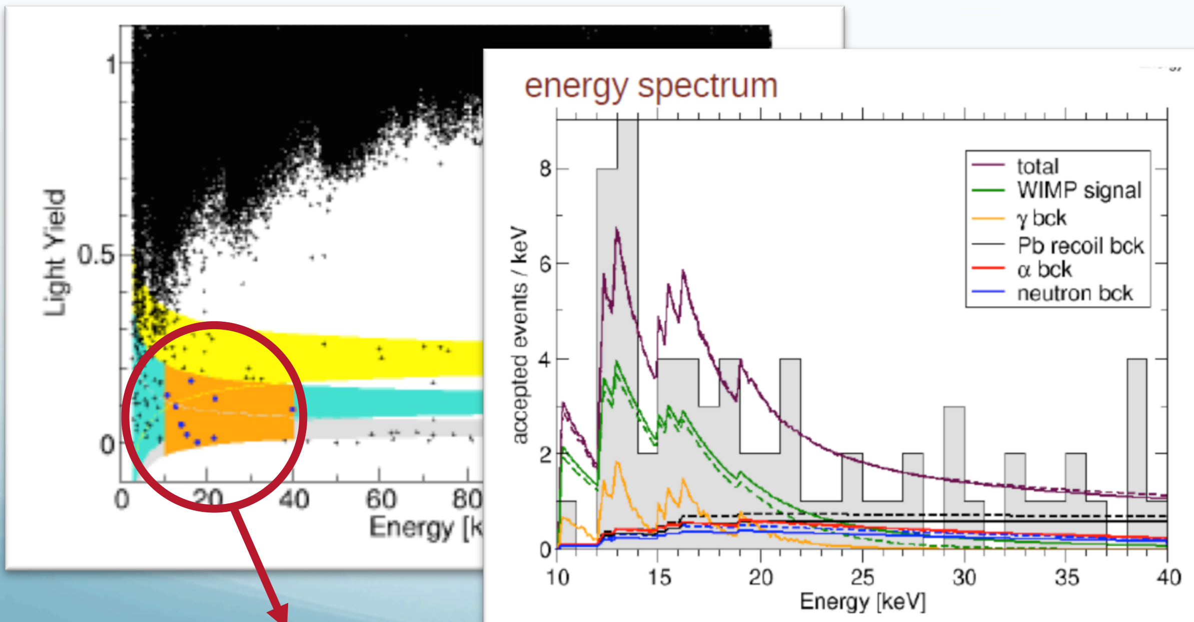


- 67 events observed in WIMP search region
- Data analyzed with 2d likelihood fit of signal and background model

Likelihood Analysis

	M1	M2
e^-/γ-events	8.00 ± 0.05	8.00 ± 0.05
α-events	$11.5^{+2.6}_{-2.3}$	$11.2^{+2.5}_{-2.3}$
neutron events	$7.5^{+6.3}_{-5.5}$	$9.7^{+6.1}_{-5.1}$
Pb recoils	$15.0^{+5.2}_{-5.1}$	$18.7^{+4.9}_{-4.7}$
signal events	$29.4^{+8.6}_{-7.7}$	$24.2^{+8.1}_{-7.2}$
m_χ [GeV]	25.3	11.6
σ_{WN} [pb]	$1.6 \cdot 10^{-6}$	$3.7 \cdot 10^{-5}$
stat. significance	4.7 σ	4.2 σ

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

Positive hint from CRESST (scintillation vs heat)

Present and future:

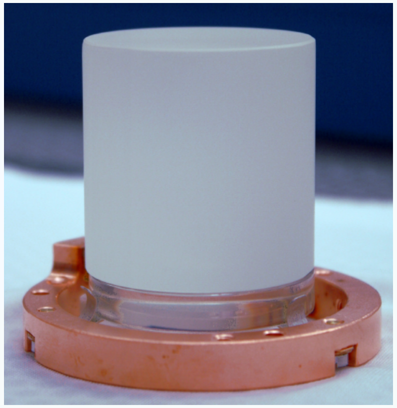
Next run highest priority: reduction of the overall background level

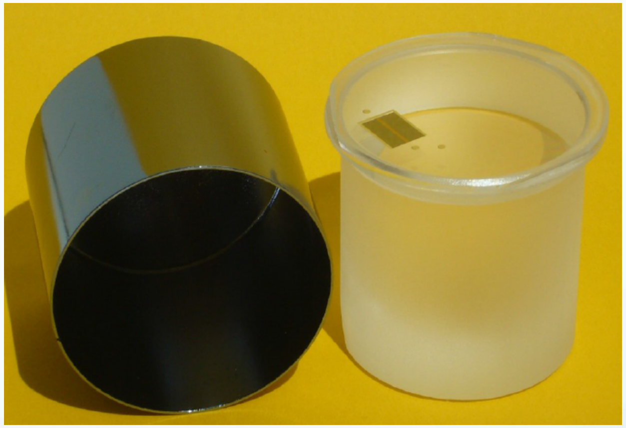
- *Reduction of neutrons originating in the Pb/Cu shield:*
  additional 5cm PE layer inside the Pb/Cu shield)
- *Reduction of low energy α from clamps:*
  new clamps from ultra pure Sn + low background Cu and careful monitoring of all production steps
- *Reduction of background of ^{206}Pb recoils due to radon exposure of clamps after production:*
  1. Avoid any radon exposure of clamps
  2. Detect the emitted α to veto the events

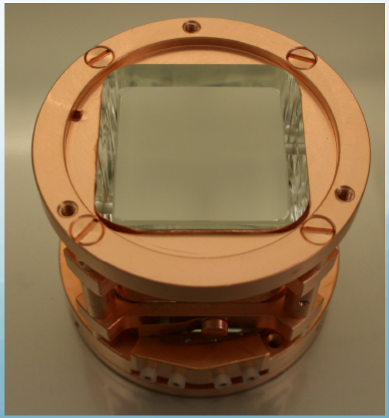
18 modules installed (~5.4 kg): 12 conventional detector modules + 6 active Pb recoil discriminating modules (3 different designs tested)

Dark Matter data taking since August 2013

Expect ~2000 kg-days of data within 2 years



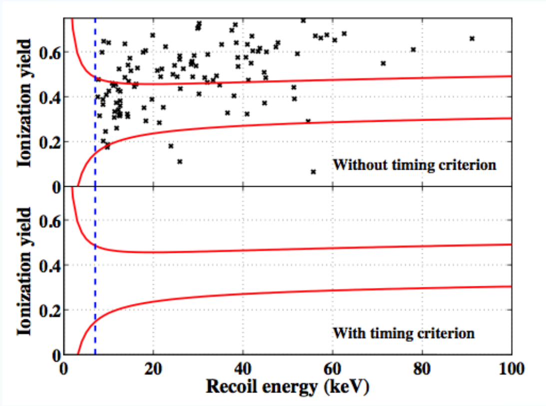




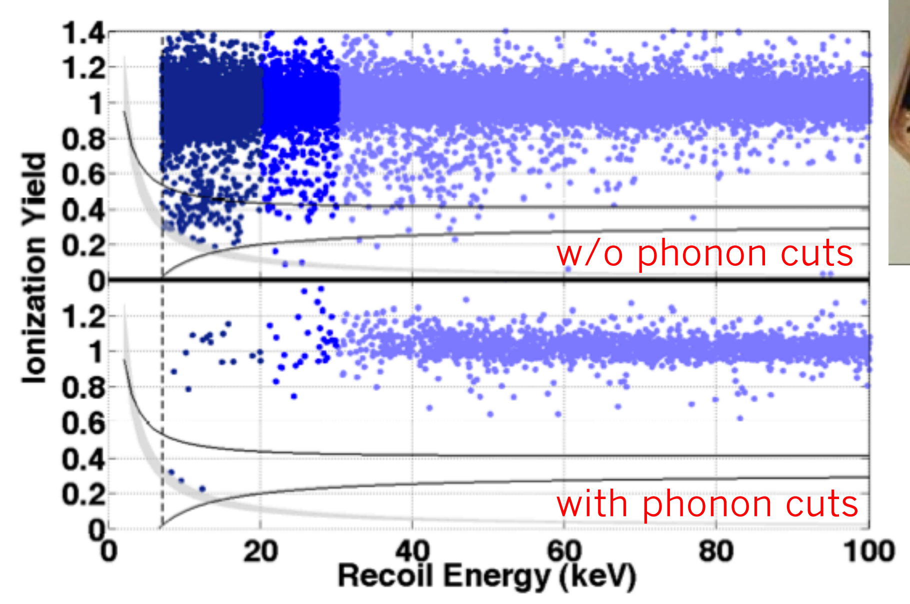
Results from double read-out bolometric technique (ionization vs heat)

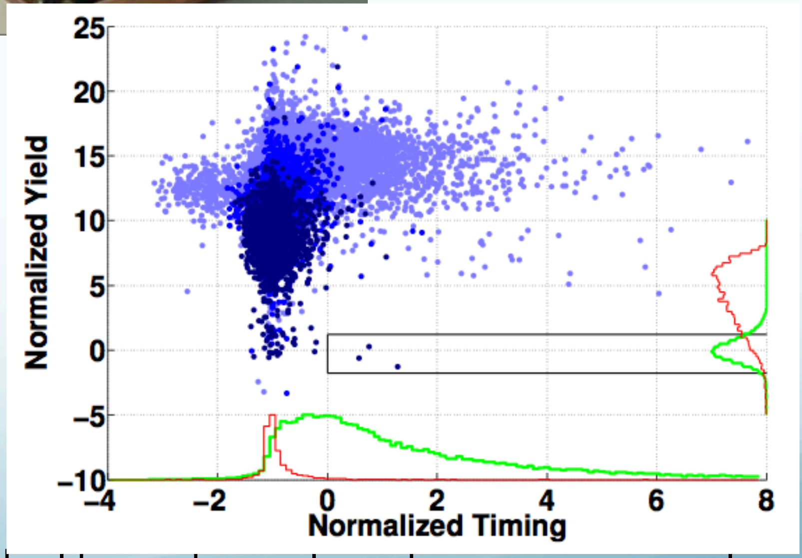
Results of CDMS-II with the Si detectors published in two close-in-time data releases:

- *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



arXiv:1304.3706
arXiv:1304.4279

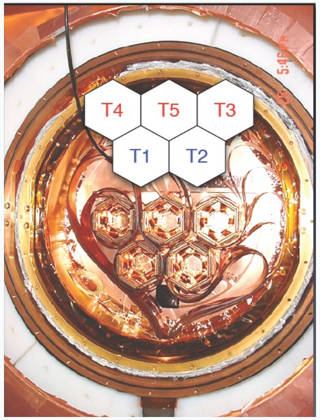


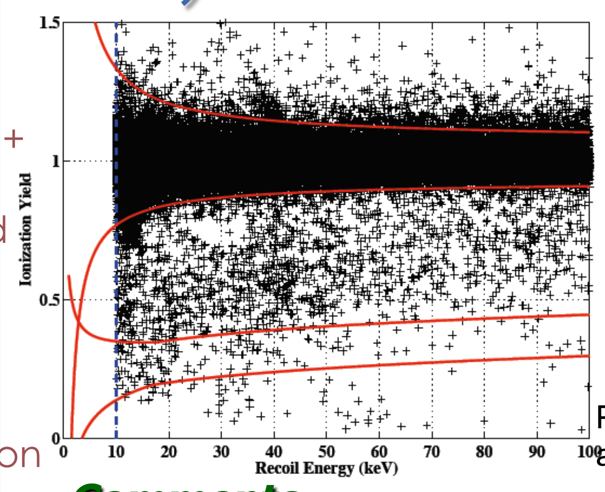


after many data selections and cuts, 3 Si recoil-like candidates survive in an exposure of 140.2 kg x day. Estimated residual background 0.41

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

Results from double read-out bolometric technique (ionization vs heat)

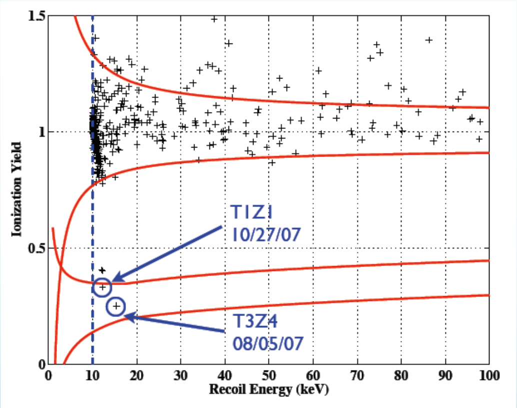




PRL102,011301(2009), arXiv:0912.3592

CDMS-II

Experimental site:	Soudan
Set-up:	19 Ge detectors (≈ 230 g) + 11 Si detectors (100 g) , only 10 Ge detectors used in the data analysis
Target:	3.22 kg Ge
Exposure:	194.1 kg x day for Ge and 140.2 kg x day for Si
Approaches:	nuclear recoils + subtraction
Neutron shield:	50 cm polyethylene
Quenching factor:	assumed 1



Surface Background
$0.6 \pm 0.1(\text{stat.})$

Neutron Background
Cosmogenic $0.04^{+0.04}_{-0.03}(\text{stat.})$
Radiogenic 0.03 - 0.06

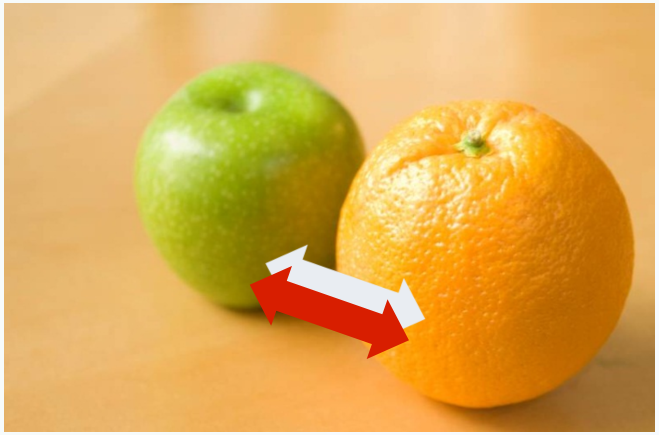
2 recoiling-like events "survived " (exp. bckg = 0.8)

Comments

- Strong data selection (some detectors excluded in the analysis, some other detectors excluded in subsets, …, poor detectors performances)
- Many cuts on the data: how about systematics? The systematics can be variable along the data taking period; can they and the related efficiencies be suitably evaluated in short period calibration?
- Knowledge and control of "physical" energy threshold, energy scale, Y scale, quenching factor, sensitive volumes, efficiencies, …? + stability with time of all these quantities ?
- 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
- Disuniformity of the detectors' responses vs surface electrons

The results cannot be interpreted as significant evidence for WIMP interactions.
However, one cannot reject either event as signal.

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...

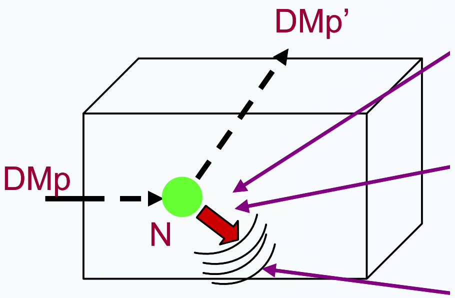
- Exposures
- Energy threshold
- Detector response (phe/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities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



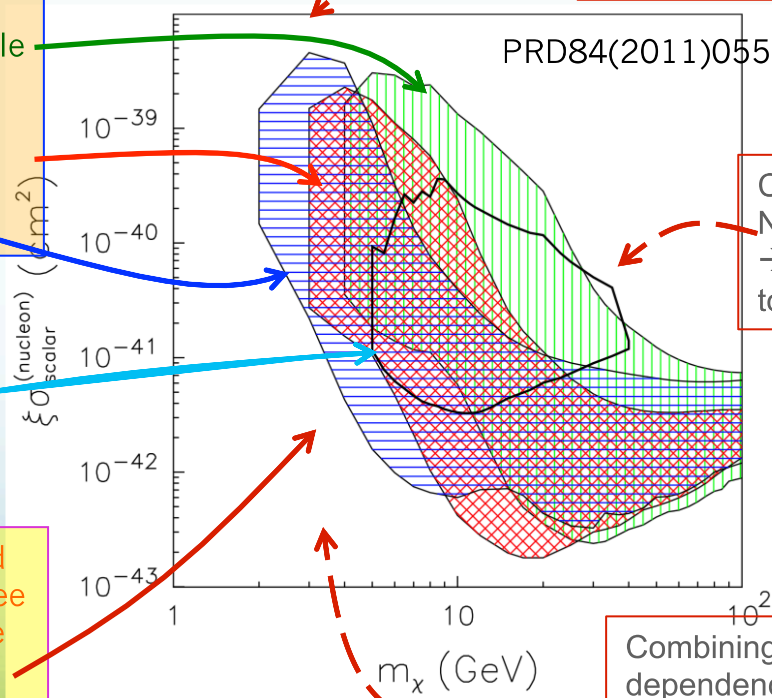
Regions in the nucleon cross section vs DM particle mass plane

- 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.



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

CoGeNT; qf at fixed assumed value

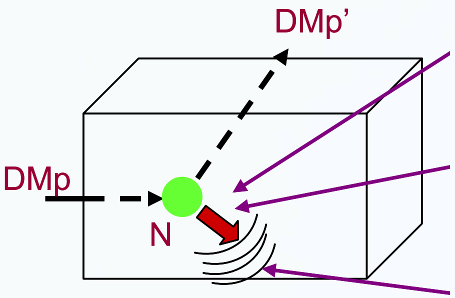
1.64 σ C.L.

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

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

... an example in literature...

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



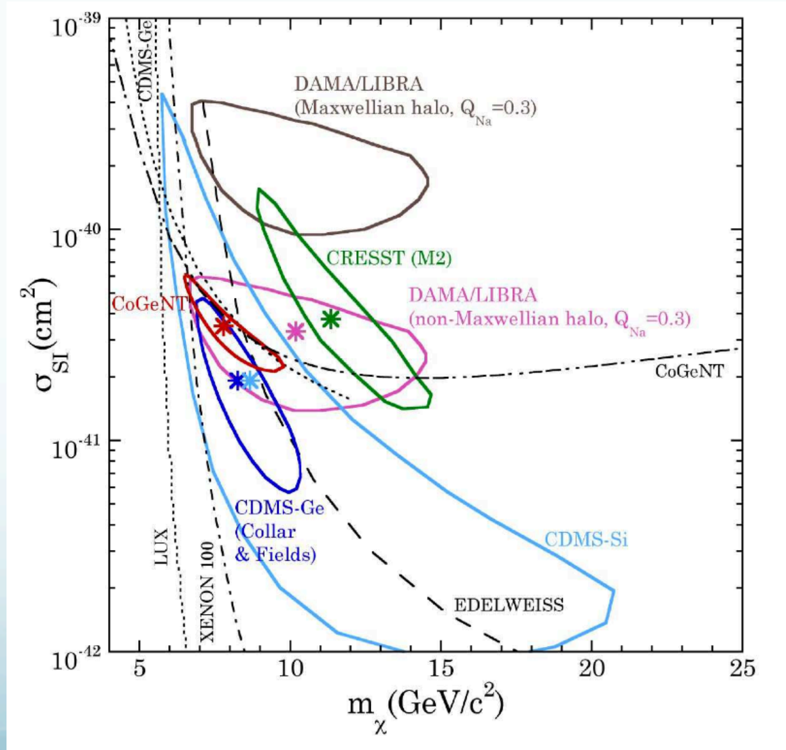
Regions in the nucleon cross section vs DM particle mass plane

... a recent conjecture ...

arXiv:1401.3295

- Non-Maxwellian halo model is considered.
- The DAMA regions are for both Maxwellian and non-Maxwellian halo models.
- Na quenching factor taken at the fixed value 0.3
- A fractional modulation amplitude corresponding to that found for CoGeNT data is assumed for DAMA.
- 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.

nium data [69] would be insensitive to up to a 100% modulation amplitude in a possible CDMS-Ge signal [63]. Liquid xenon (LUX, XENON-100) sensitivity to $m_\chi < 12$ GeV/c^2 is presently under test, using an ^{88}Y/Be neutron source [61].



Another example of compatibility

DM particle with preferred inelastic interaction

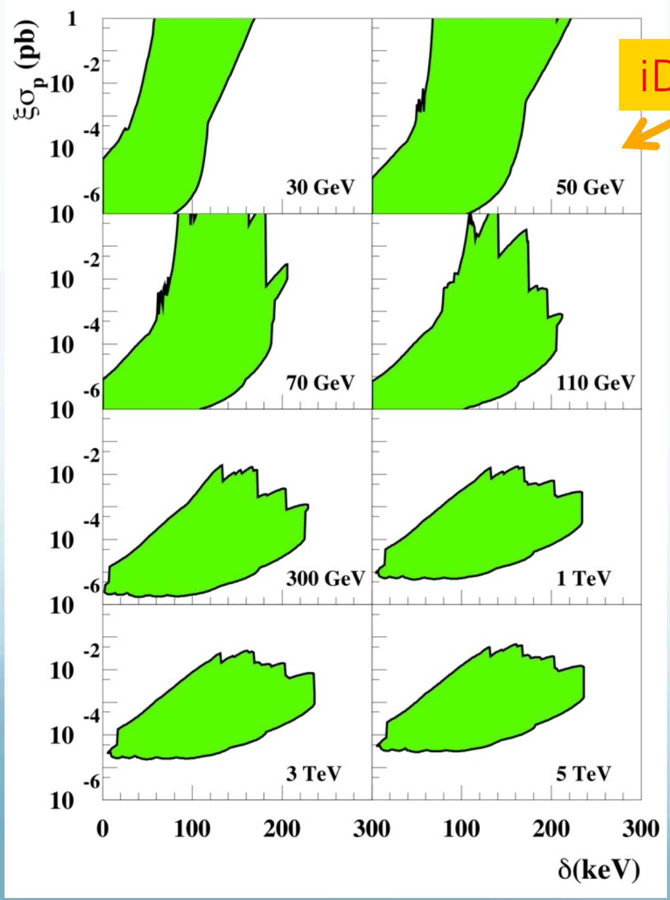
In the Inelastic DM (iDM) scenario, WIMPs scatter into an excited state, split from the ground state by an energy comparable to the available kinetic energy of a Galactic WIMP.

$$\chi^- + N \rightarrow \chi^+ + N$$

- iDM has two mass states χ^+, χ^- with δ mass splitting
- Kinematical 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 Fund. Phys. 40(2010)900
Slices from the 3-dimensional allowed volume



iDM interaction on Iodine nuclei

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

arXiv:1007.2688

- 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.
- Inelastic scattering WIMPs with large splittings do not give rise to sizeable contribution on Na, I, Ge, Xe, Ca, O, … nuclei.

… and more considering experimental and theoretical uncertainties

- *Other signatures?*
- *Second order effects*
- *…*

DAMA →

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

Eur. Phys. J. C 74 (2014) 2827

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:

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

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

$\vec{v}_{LSR}$	velocity of the Local Standard of Rest (LSR) due to the rotation of the Galaxy
$\vec{v}_{\odot}$	Sun peculiar velocity with respect to LSR
$\vec{v}_{rev}(t)$	velocity of the revolution of the Earth around the Sun
$\vec{v}_{rot}(t)$	velocity of the rotation of the Earth around its axis at the latitude and longitude of the laboratory.

Annual modulation term:

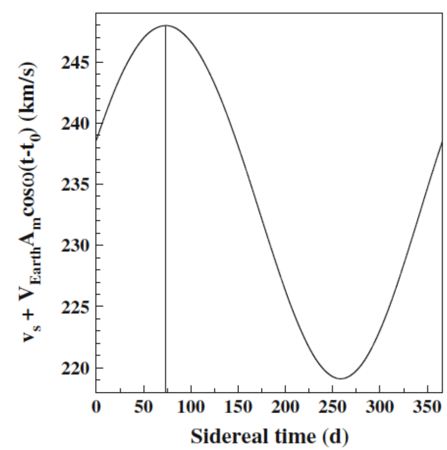
$$\hat{v}_s \cdot \vec{v}_{rev}(t) = V_{Earth} B_m \cos(\omega(t - t_0))$$

- V_{Earth} is the orbital velocity of the Earth ≈ 30 km/s
- $B_m \approx 0.489$
- $t_0 \approx t_{equinox}$ + 73.25 days ≈ June 2

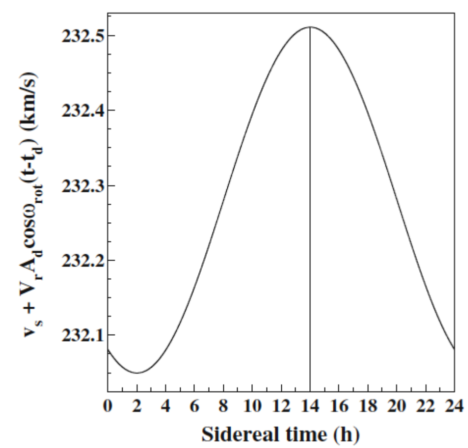
Diurnal modulation term:

$$\hat{v}_s \cdot \vec{v}_{rot}(t) = V_r B_d \cos\left[\omega_{rot}(t - t_d)\right]$$

- V_r is the rotational velocity of the Earth at the given latitude (for LNGS ≈ 0.3435 km/s)
- $B_d \approx 0.671$
- $t_d \approx 14.02$ h (at LNGS)

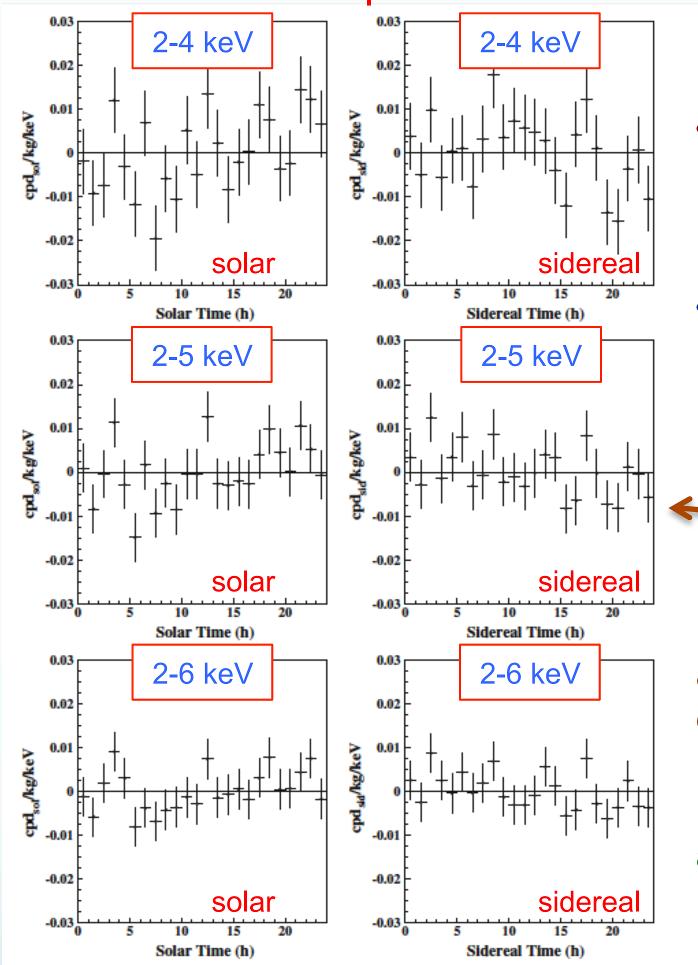


Velocity of the Earth in the galactic frame as a function of the sidereal time, with starting point March 21 (around spring equinox). The contribution of diurnal rotation has been dropped off. The maximum of the velocity (vertical line) is about 73 days after the spring equinox.



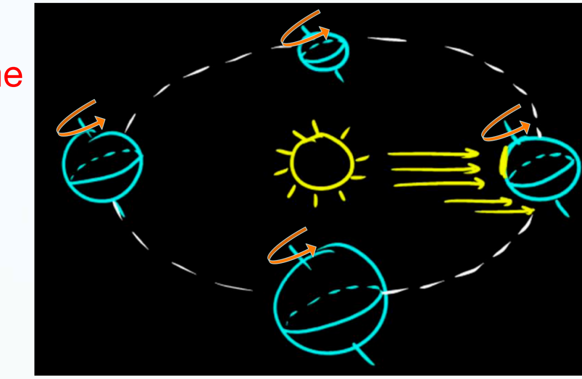
Sum of the Sun velocity in the galactic frame (v_s) and of the rotation velocity of a detector at LNGS ($v_s \cdot v_{rot}(t)$) as a function of the sidereal time. The maximum of the velocity is about at 14 h (vertical line).

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



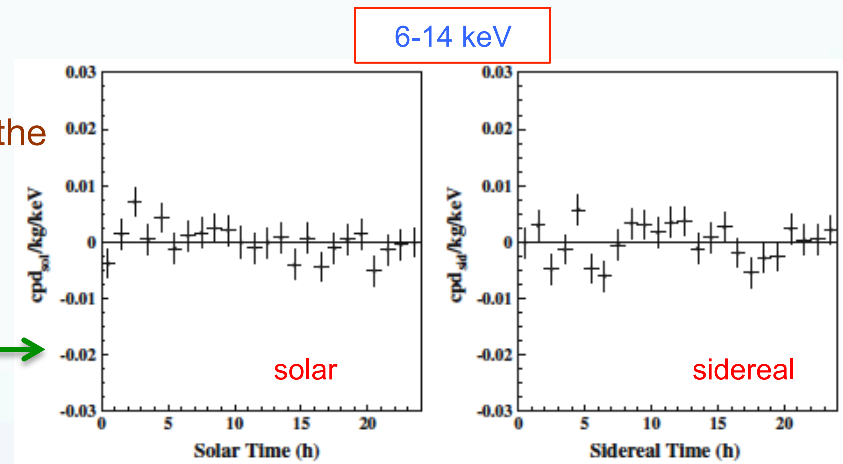
Eur. Phys. J. C 74 (2014) 2827

- Experimental *single-hit* residuals rate vs either sidereal and solar time and vs energy.
- These residual rates are calculated from the measured rate of the *single-hit* events after subtracting the constant part



Energy region where the annual modulation is observed.

Energy region just above.



Energy	Solar Time	Sidereal Time
2–4 keV	χ^2/d.o.f. = 35.2/24 → P = 7%	χ^2/d.o.f. = 28.7/24 → P = 23%
2–5 keV	χ^2/d.o.f. = 35.5/24 → P = 6%	χ^2/d.o.f. = 24.0/24 → P = 46%
2–6 keV	χ^2/d.o.f. = 25.8/24 → P = 36%	χ^2/d.o.f. = 21.2/24 → P = 63%
6–14 keV	χ^2/d.o.f. = 25.5/24 → P = 38%	χ^2/d.o.f. = 35.9/24 → P = 6%

no diurnal variation with a significance of 95% C.L.

+ run test to verify the hypothesis that the positive and negative data points are randomly distributed. The lower tail probabilities (in the four energy regions) are: 43, 18, 7, 26% for the solar case and 54, 84, 78, 16% for the sidereal case.

Thus, the presence of any significant diurnal variation and of time structures can be excluded at the reached level of sensitivity.

The time dependence of the counting rate

Eur. Phys. J. C 74 (2014) 2827

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

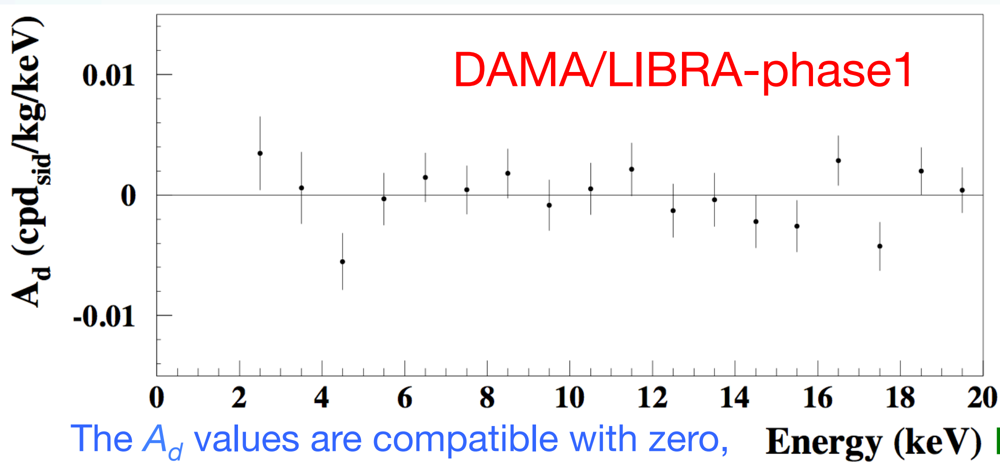
$$S_k\left[v_{lab}(t)\right] \simeq S_k\left[v_s\right] + \left[\frac{\partial S_k}{\partial v_{lab}}\right]_{v_s}\left[V_{Earth}A_m\cos\omega(t-t_0) + V_r A_d \cos\omega_{rot}(t-t_d)\right]$$

- Annual modulation amplitude: $S_m = \left[\frac{\partial S_k}{\partial v_{lab}}\right]_{v_s} V_{Earth}B_m$
- Diurnal modulation amplitude: $S_d = \left[\frac{\partial S_k}{\partial v_{lab}}\right]_{v_s} V_r B_d$

The ratio R_{dy} of the diurnal over annual modulation amplitudes 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 amplitude A_d as free parameter, period fixed at 24 h and phase at 14 h: all the diurnal modulation amplitudes are compatible with zero.



Energy	A_d^{exp} (cpd/kg/keV)	χ^2/d.o.f.	P
2–4 keV	$(2.0 \pm 2.1) \times 10^{-3}$	27.8/23	22%
2–5 keV	$-(1.4 \pm 1.6) \times 10^{-3}$	23.2/23	45%
2–6 keV	$-(1.0 \pm 1.3) \times 10^{-3}$	20.6/23	61%
6–14 keV	$(5.0 \pm 7.5) \times 10^{-4}$	35.4/23	5%

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

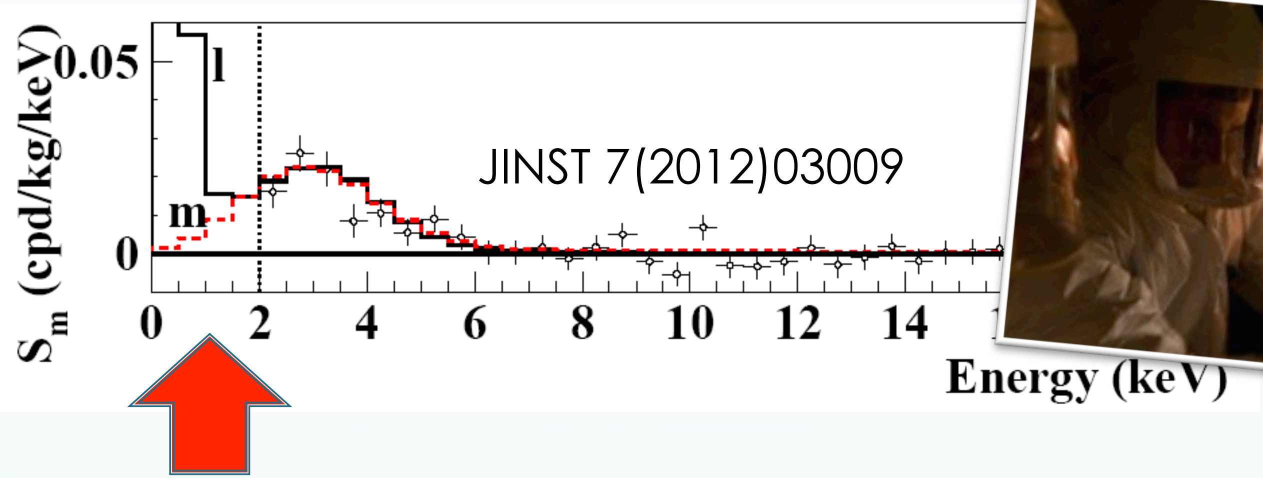
The A_d values are compatible with zero, having random fluctuations around zero with χ^2 equal to 19.5 for 18 dof

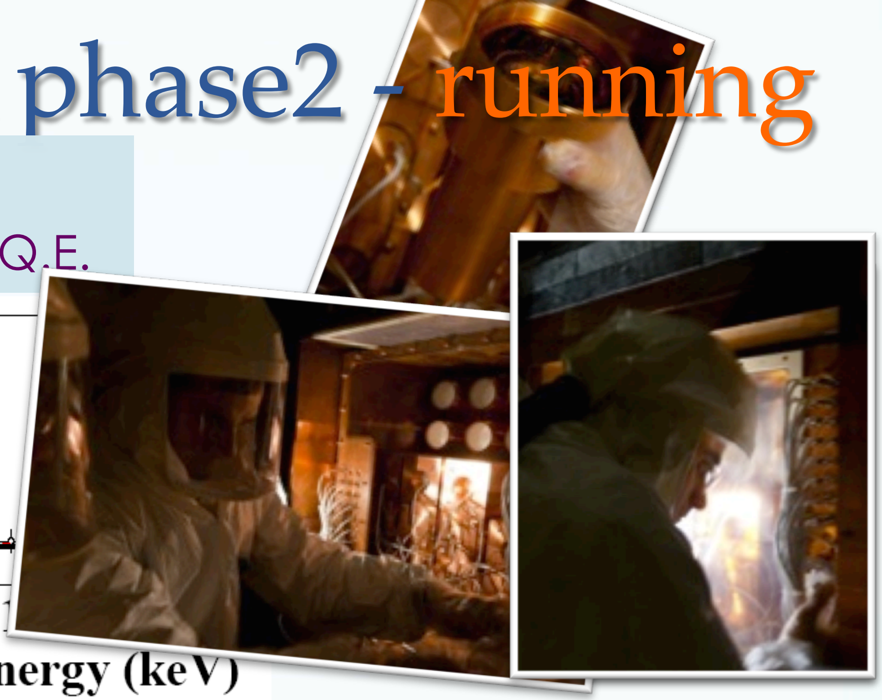
Present experimental sensitivity more modest than the expected diurnal modulation amplitude derived from the DAMA/LIBRA–phase1 observed effect.

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

DAMA/LIBRA phase2 - running

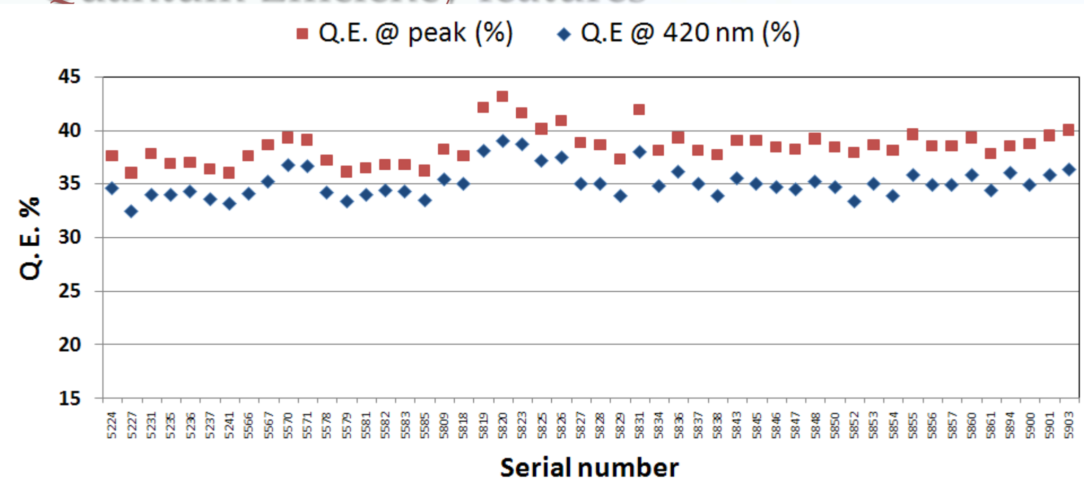
Second upgrade on end of 2010:
all PMTs replaced with new ones of higher Q.E.

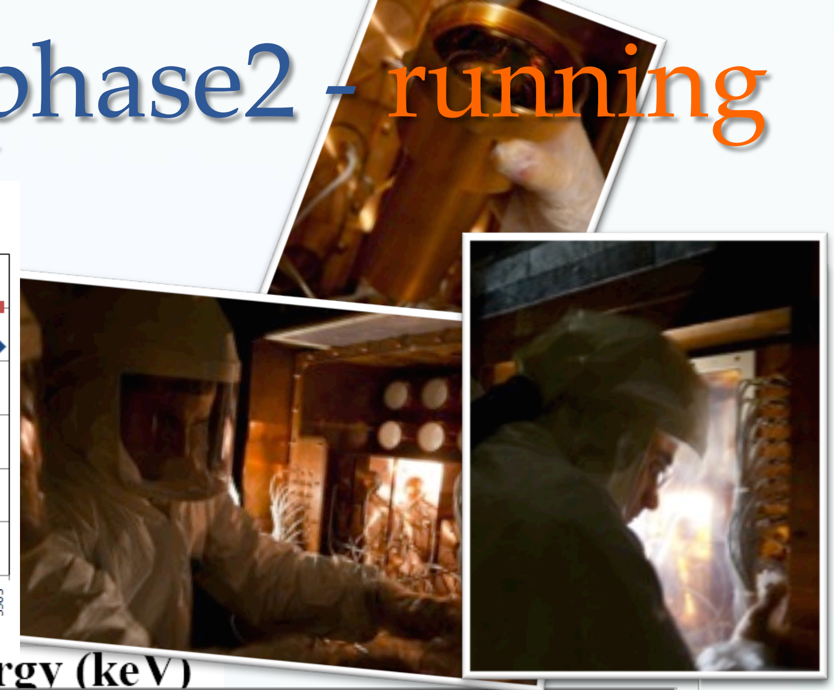




DAMA/LIBRA phase2 - running

Quantum Efficiency features





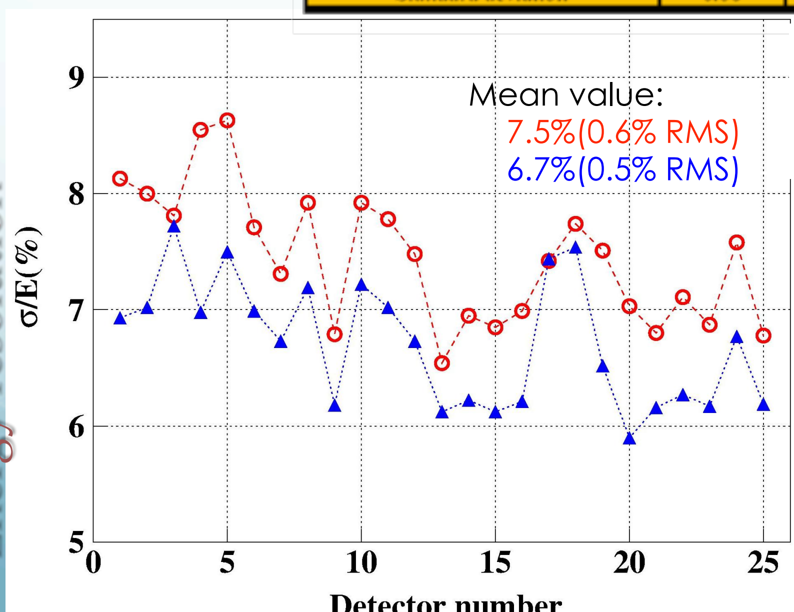
Residual Contamination

The limits are at 90% C.L.

Energy (keV)

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 resolution



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

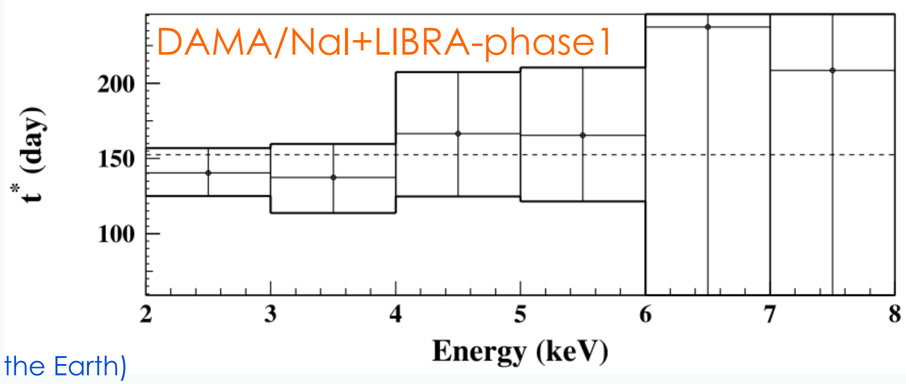
- To study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects, and to investigate second order effects
- Special data taking for *other rare processes*

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:

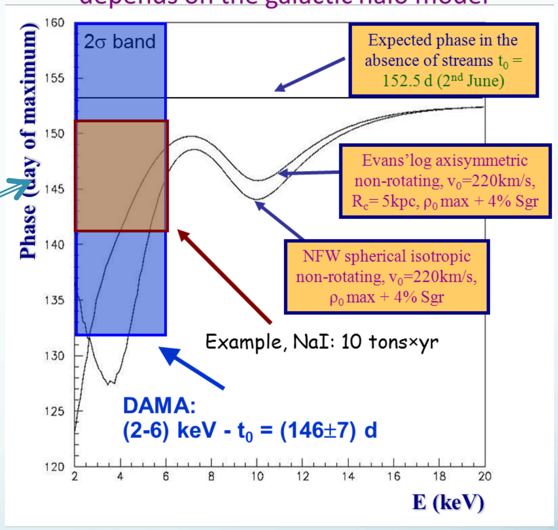
- the nature of the DM candidates
  - ✓ to disentangle among the different astrophysical, nuclear and particle physics models (nature of the candidate, couplings, inelastic interaction, form factors, spin-factors …)
  - ✓ scaling laws and cross sections
  - ✓ multi-component DM particles halo?
- possible diurnal effects on the sidereal time
  - ✓ expected in case of high cross section DM candidates (shadow of the Earth)
  - ✓ due to the Earth rotation velocity contribution (it holds for a wide range of DM candidates)
  - ✓ due to the channeling in case of DM candidates inducing nuclear recoils.
- astrophysical models
  - ✓ velocity and position distribution of DM particles in the galactic halo, possibly due to:
    - satellite galaxies (as Sagittarius and Canis Major Dwarves) tidal "streams";
    - caustics in the halo;
    - gravitational focusing effect of the Sun enhancing the DM flow ("spike" and "skirt");
    - possible structures as clumpiness with small scale size
    - Effects of gravitational focusing of the Sun

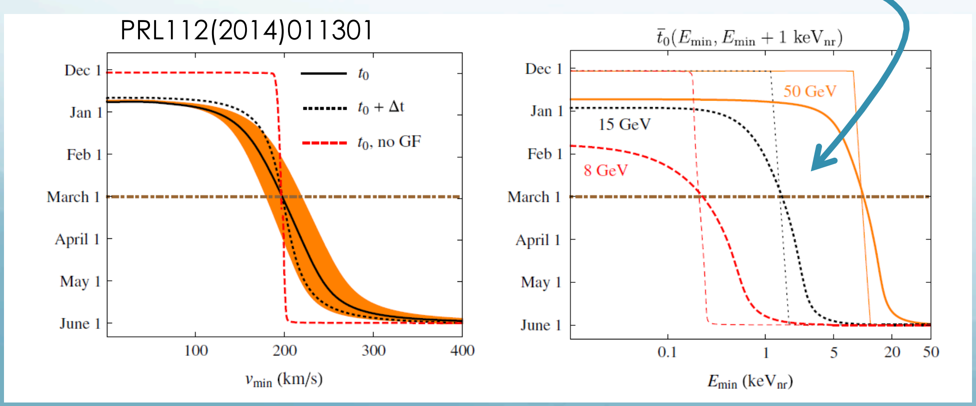


The annual modulation phase depends on :

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

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





A step towards such investigations:

➔**DAMA/LIBRA-phase2**

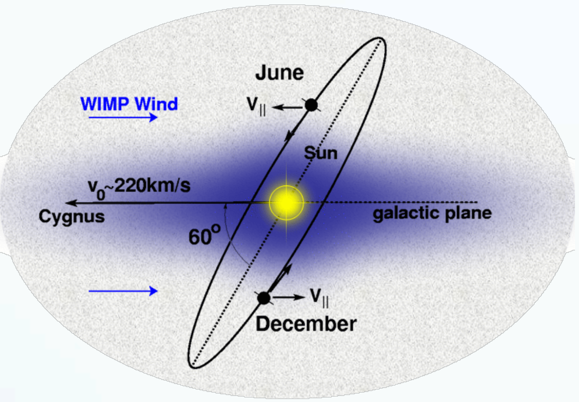
with lower energy threshold and larger exposure

Directionality technique

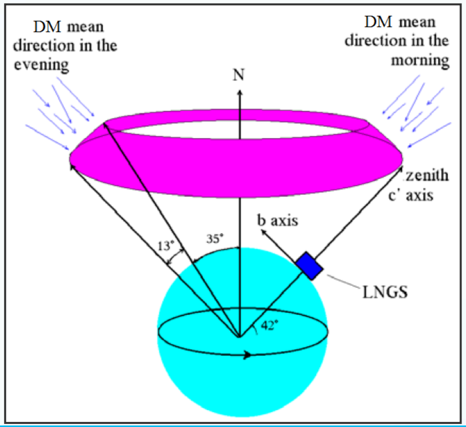
- Only for candidates inducing just recoils
- Identification of the Dark Matter particles by exploiting the non-isotropic recoil distribution correlated to the Earth velocity

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

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



The dynamics of the rotation of the Milky Way galactic disc through the halo of DM causes the Earth to experience a wind of DM particles apparently flowing along a direction opposite to that of solar motion relative to the DM halo …but, because of the Earth's rotation around its axis, the DM particles average direction with respect to an observer fixed on the Earth changes during the sidereal day



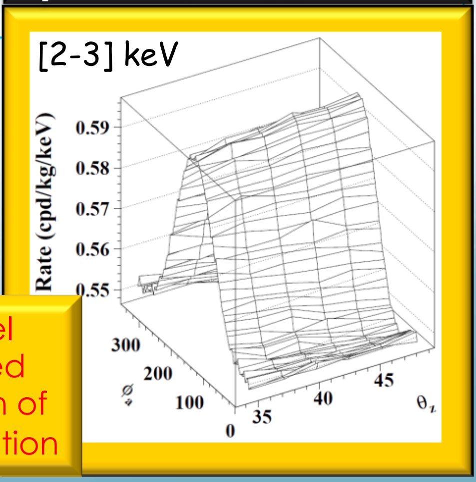
Nuclear recoils are expected to be strongly correlated with the DM impinging direction
This effect can be pointed out through the study of the variation in the response of anisotropic scintillation detectors during sidereal day

The light output and the pulse shape of $ZnWO_4$ detectors 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 - in given scenarios - sensitivity comparable with that of the DAMA/LIBRA positive result and of the CoGeNT and CRESST positive hints

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



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

Conclusions

Evidences and hints of DARK MATTER

- DAMA: positive evidence for the presence of DM particles in the galactic halo supported at 9.2σ 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 in direct searches are compatible with DAMA in many scenarios; null searches not in robust conflict. Consider also the experimental and theoretical uncertainties.
        - Different **solid** techniques can give complementary results: some further efforts to demonstrate the **solidity** of some of them are needed

- The **model-independent signature** is the definite strategy to investigate the presence of Dark Matter particle component(s) in the Galactic halo