Ricerche Dirette di Materia Oscura

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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

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", ...

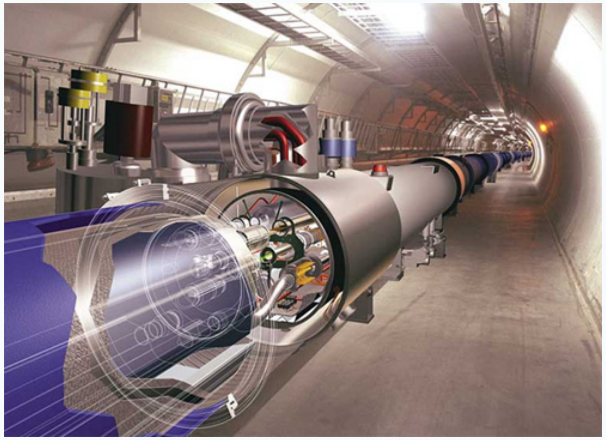
Elementary Black holes,
Planckian objects, Daemons

invisible axions, ν's

etc...

Moreover, several questions arise about:

- interaction type with ordinary matter and its description
- related nuclear and particle physics
- halo model and parameters
- halo composition. DM multicomponent also in the particle sector?
- non thermalized components?
- caustics?
- clumpiness?
- etc.



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…

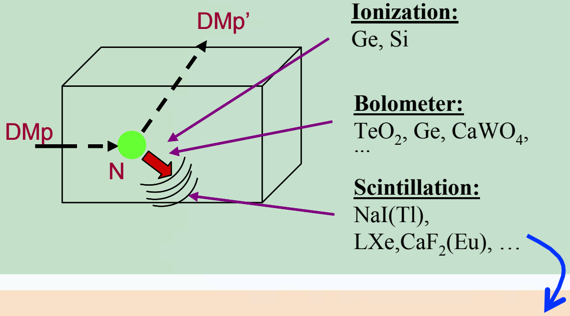
+ DM candidates and scenarios exist (even for neutralino candidate) on which accelerators cannot give any information

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

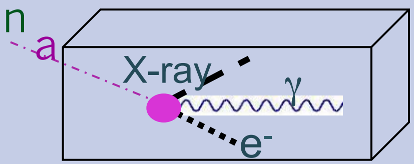
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

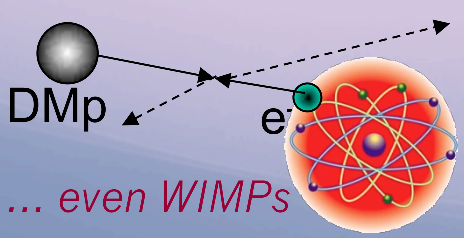
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

  → detection of e.m. radiation

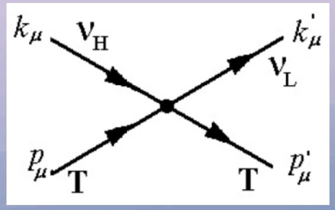


... even WIMPs

- 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

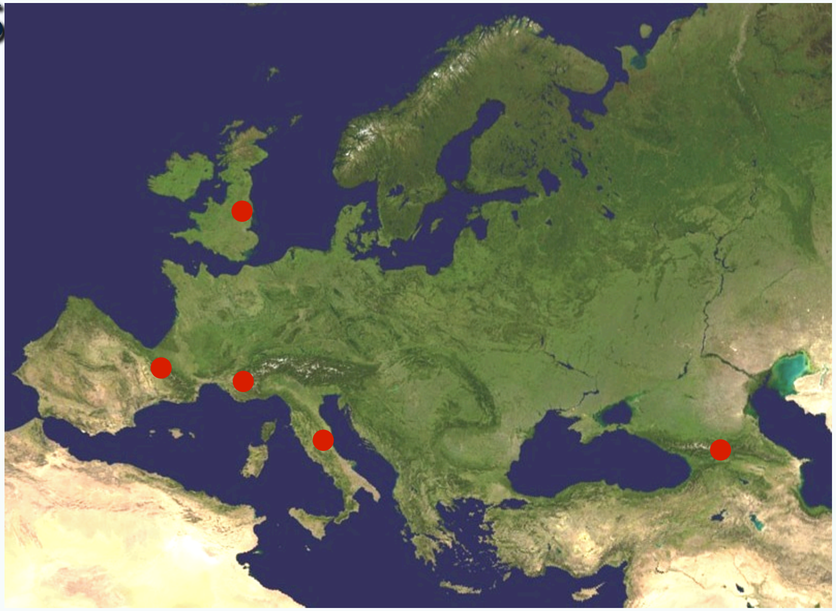


e.g. signals from these candidates are **completely lost** in experiments based on "rejection procedures" of the e.m. component of their rate

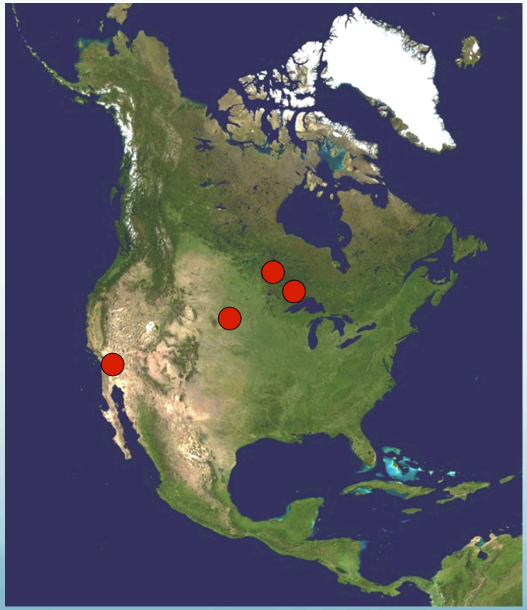
... also other ideas ...

Dark Matter direct detection activities in underground labs

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

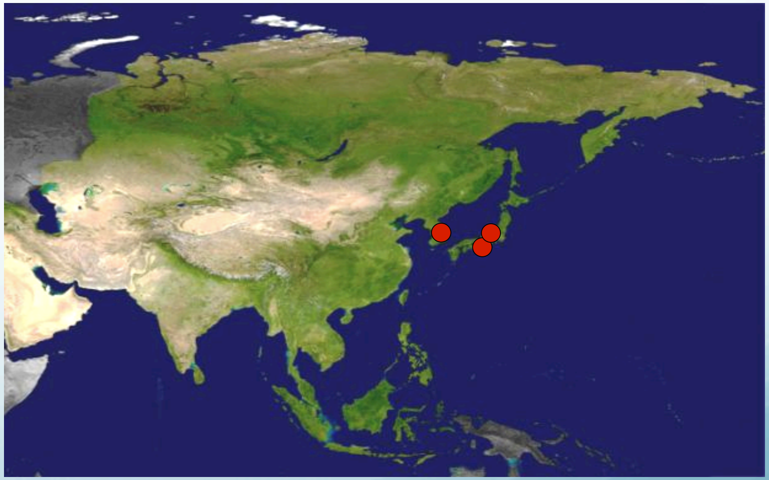


- Gran Sasso (depth ~ 3600 m.w.e.): DAMA/NaI, DAMA/LIBRA, DAMA/LXe, HDMS, WARP, CRESST, Xenon, Dark Side
- Boulby (depth ~ 3000 m.w.e.): Drift, Zeplin, NAIAD
- Modane (depth ~ 4800 m.w.e.): Edelweiss
- Canfranc (depth ~ 2500 m.w.e.): ANAIS, Rosebud, ArDM



- Snolab (~ 6000 m.w.e.): Picasso, DEAP, CLEAN
- Stanford (~10 m): CDMS I
- Soudan (~ 2000 m.w.e.): CDMS II, CoGeNT, COUPP (also FNAL)
- DUSEL (~4400 m.w.e.): LUX
- WIPP (~1600 m.w.e.): DMTPC

- South Pole: DM-ICE



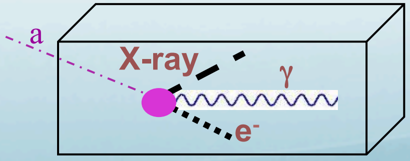
- Y2L (depth ~ 700 m): KIMS
- Oto (depth ~ 1400 m.w.e.): PICO-LON
- Kamioka (depth ~2700 m.w.e.): XMASS, NEWAGE

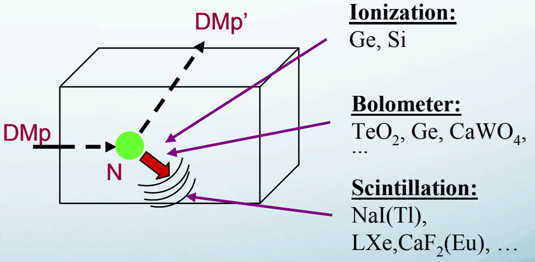
Direct detection experiments

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)





Experiments using liquid noble gases

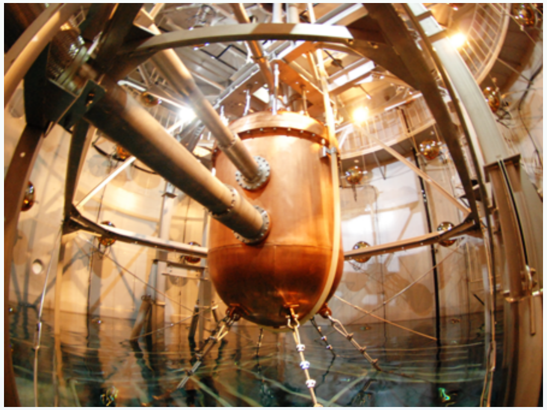
- Single phase: LXe, LAr, LNe → scintillation, ionization
- Dual phase liquid /gas → prompt scintillation + secondary scintillation

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

in single phase detector:

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

DAMA/LXe

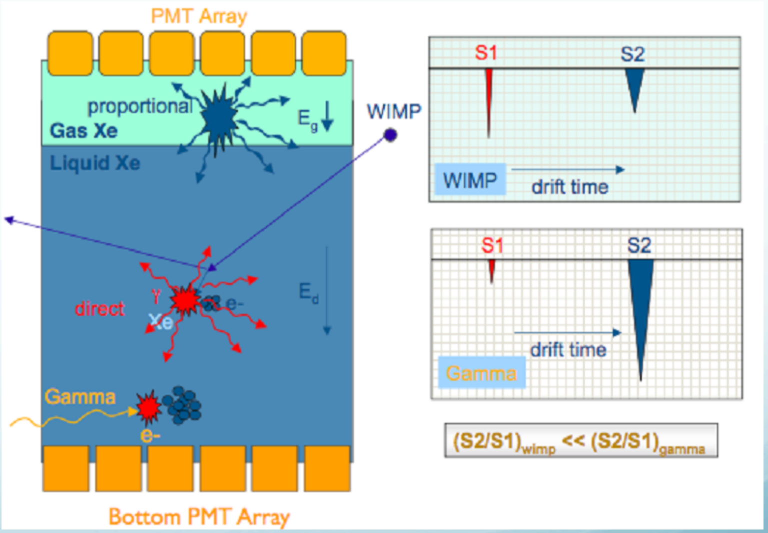


XMASS

DAMA/LXe: low background developments and applications to dark matter investigation (since N.Cim. A 103 (1990) 767)

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

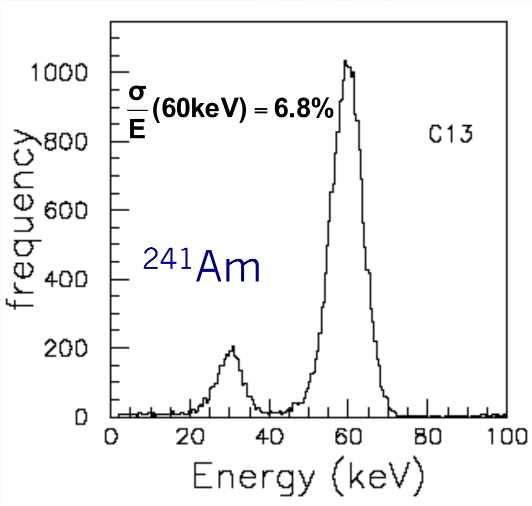


XENON10, 100, WARP, Dark Side, LUX

but e.g. UV light, disuniformity, self-absorption, unlinearity in large volumes

Examples of energy resolutions

DAMA/LIBRA ULB NaI(TI)



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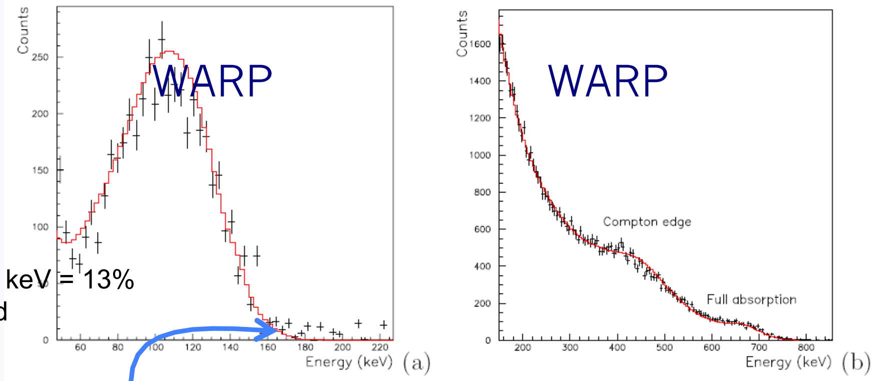


σ/E @ 122 keV = 13%
at zero field

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

AP 28 (2007) 287

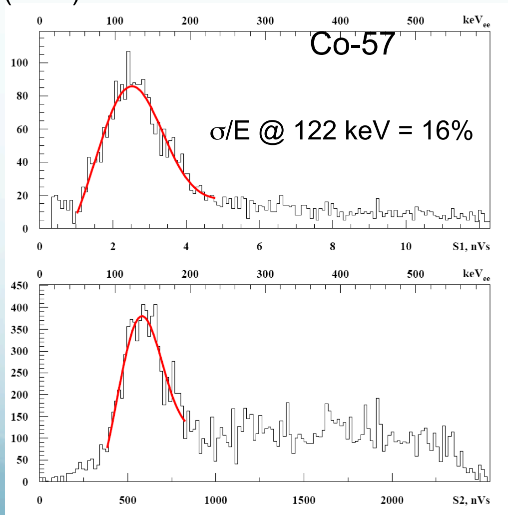


Fig. 5. Typical energy spectra for ^{57}Co γ-ray calibrations, showing S1 spectrum (upper) and S2 spectrum (lower). The fits are double Gaussian fits which incorporate both the 122 keV and 136 keV lines in the ^{57}Co γ-ray spectrum. The energy resolution of the detector is derived from the width of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

XENON10 XENON10

σ/E @ 122 keV = 17%

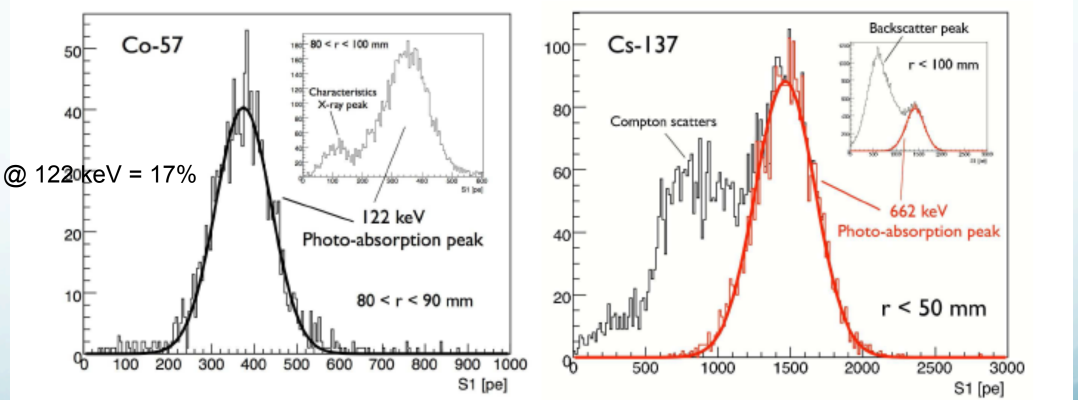
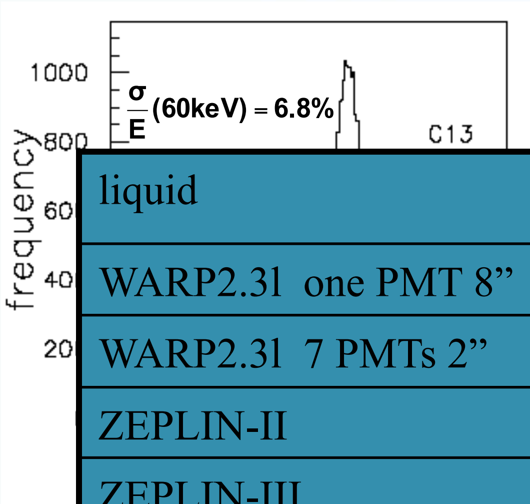


Figure 3. (left) S1 scintillation spectrum from a ^{57}Co calibration. The light yield for the 122 keV photo-absorption peak is 3.1 p.e./keV. (right) S1 scintillation spectrum from a ^{137}Cs calibration. The light yield for the 662 keV photo-absorption peak is 2.2 p.e./keV.

JoP: Conf. Ser. 65 (2007) 012015

Examples of energy resolutions

DAMA/LIBRA ULB NaI(Tl)



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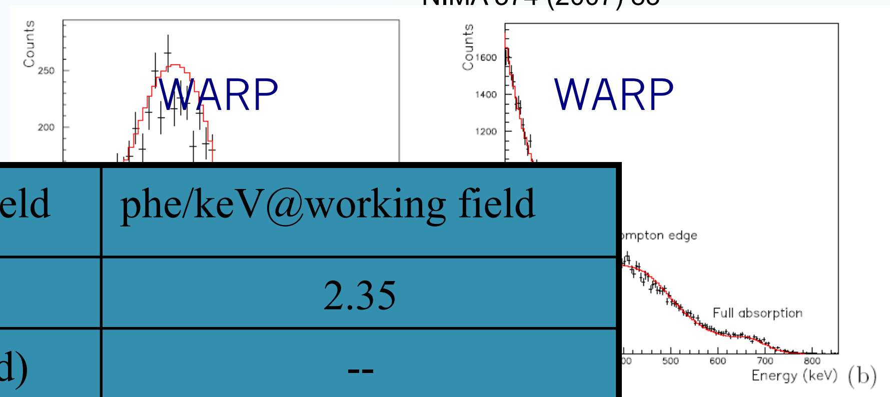

...perimposed with the
...122 keV, B.R. 85.6%,

...rum ?

Z...

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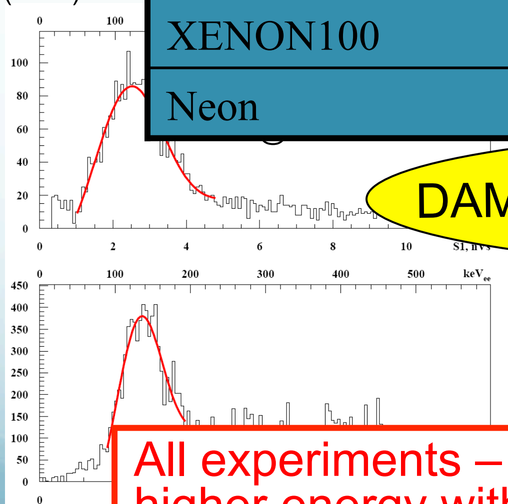
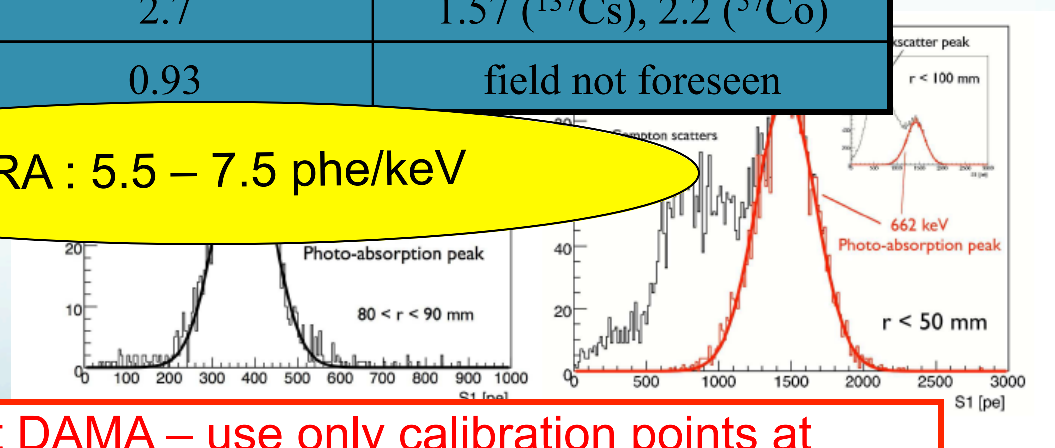


liquid	phe/keV@zero field	phe/keV@working field
WARP2.31 one PMT 8”	--	2.35
WARP2.31 7 PMTs 2”	0.5-1 (deduced)	--
ZEPLIN-II	1.1	0.55
ZEPLIN-III		1.8
XENON10	--	2.2 (^{137}Cs), 3.1 (^{57}Co)
XENON100	2.7	1.57 (^{137}Cs), 2.2 (^{57}Co)
Neon	0.93	field not foreseen

DAMA/LIBRA : 5.5 – 7.5 phe/keV



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

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.

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

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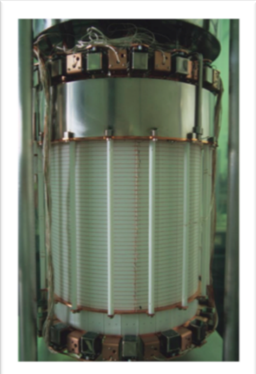
XENON100 results

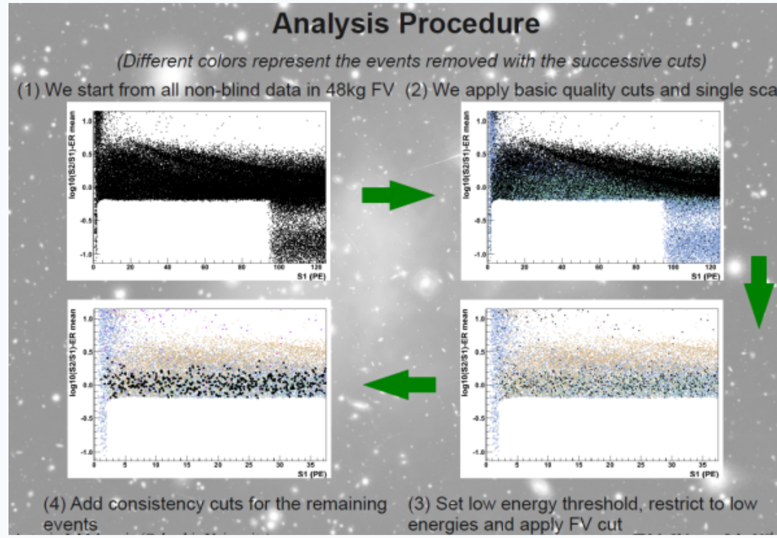


Experimental site: Gran Sasso (1400 m depth)

Target material: ^{nat}Xe

Target mass: ≈161 kg (fiducial: 34 kg)

Used exposure: 224.6 days



Statistical discrimination between e$^-$/γ and nuclear recoils. The two populations are quite overlapped.

- **Non-uniform** response of detector: intrinsic limit
- **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.

Cuts Explanation

(see Xenon-10)

QC0: Basic quality cuts

Designed to remove noisy events, events with unphysical parameters or events which are not interesting for a WIMP search

- S1 coincidence cut
- S1 single peak cut
- S2 saturation cut
- S2 single peak cut
- S2 width cut
- S2 χ^2 cut

QC1: Fiducial volume cuts

Because of the high stopping power of LXe, fiducialization is a very effective way of reducing background.

- $r < 80\,\mathrm{mm}$
- $15\,\mu s < dt < 65\,\mu s$

QC2: High level cuts

Cuts based on the distribution of the S1 signal on the top and bottom PMTs. They are designed to remove events with anomalous or unusual S1 patterns

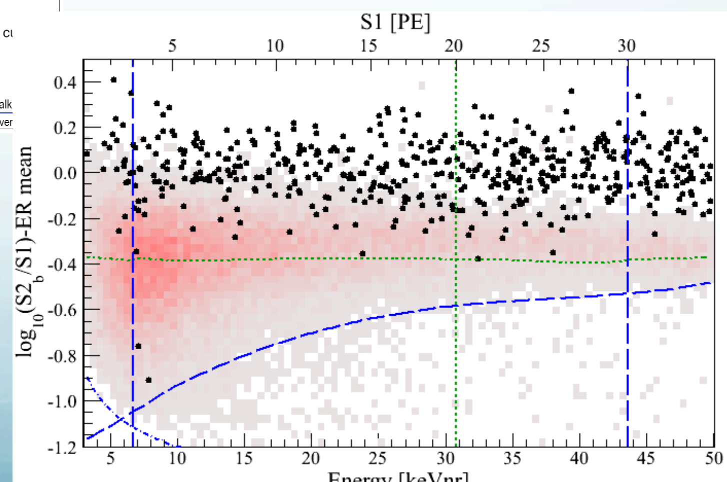
- S1 top-bottom asymmetry cut
- S1 top RMS cut
- S1 bottom RMS cu

see Guillaume Plante, Columbia, APS Talk

Noble Liquids / Dark Matter — Rick Gaitskell, Brown Univer

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 2 events survive (estimated surviving background (1.0 ±0.2)

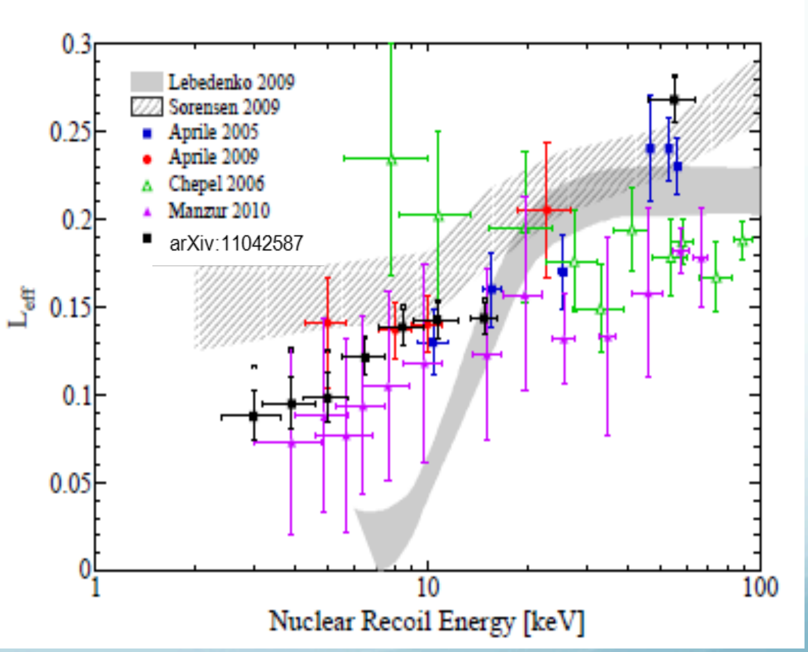


For example: what about the response of LXe set-ups at low-energy recoils?

see also: arXiv:1005.0838, 1006.2031, 1005.3723, 1010.5187, 1106.0653, 1104.2587

Remind: **open question about the real energy threshold**

- A low mass WIMP (7 GeV) can induce a maximum recoil energy of 4 keVr to a Xe nucleus: 90% of the events are below 1.5 keVr.
- Tail distribution is more sensitive to the experimental (small number of ph.el./keV, small energy resolution, stability of the energy scale, stability of all the selection windows, ...) and theoretical (models, parameters, such as escape velocity, form factors, ...) uncertainties
- L_{eff} is assumed by XENON-100 either constant at 0.12 below 10 keVr or extrapolated. But this is not the case.
  - L_{eff} drastically drops at lower energy?
  - Kinematic cutoff?
  - More precise measurements and/or more reliable theoretical evaluations required.



The measurements must be performed in the same set-up used for the DM search

1106.0653: "A lingering critical question is to what extent a determination of L_{eff} performed using highly-optimized compact calibration detectors like those in … can be applied with confidence to a much larger device like the XENON100 detector, featuring a small S1 light-detection efficiency (just ~6%), different hardware trigger configuration, data processing, etc."

All this yields to overstimate the sensitivity and to achieve too optimistic exclusion plots

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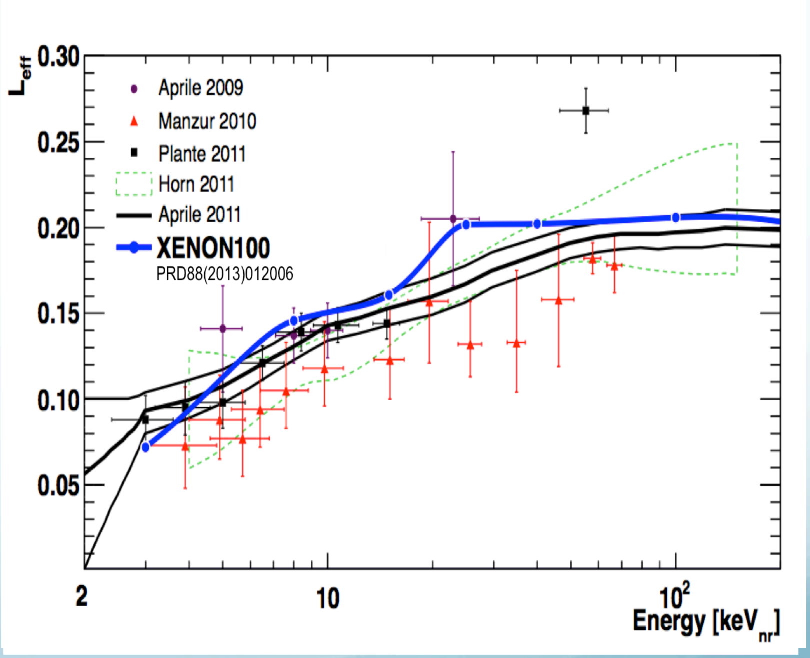
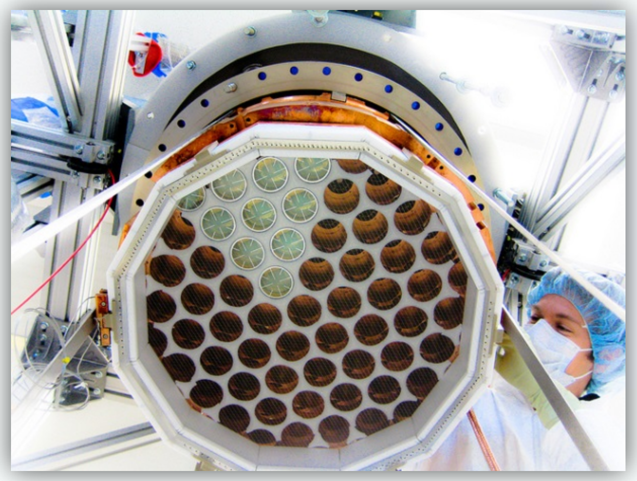


All this yields to overstimate the sensitivity and to achieve too optimistic exclusion plots

Recent results from LUX

arXiv:1310.8214



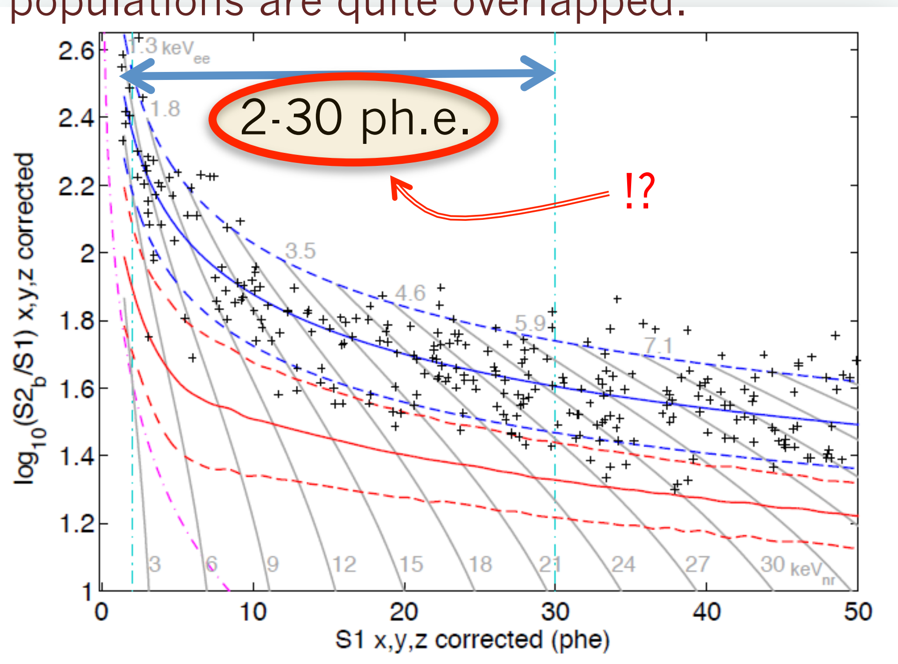
Experimental site: Sanford Underground Research Facility (SURF, 4300 m.w.e.)

Target: 370 kg LXe (≈250 kg dual phase actively monitored) fiducial volume (118.3±6.5) kg

Live time: 85.3 days

Experimental approach: statistical discrimination between electrons (e^-/γ) and nuclear recoils. The two populations are quite overlapped.

- Response: 8.8 phe/keV_{ee} at 122 keV (and at low energy ?)
- Analysis applied after data cuts (''high'' acceptance ?)
- Data events subtractions (efficiency ?)
- WIMP S1 and S2 expected reference distributions obtained by simulations
- Threshold: 2 phe ≈ 3 keV_r (!?)
- 160 events after the cuts



ER band (±1.28σ)
NR band (±1.28σ)
Approx. location of the minimum S2 cut

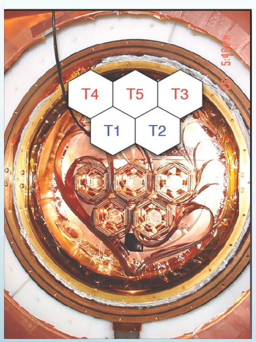
All NR band events assumed to be due to ER bkg events

(0.64 ± 0.16) ER events expected below NR mean
It confirms that the two populations are quite overlapped

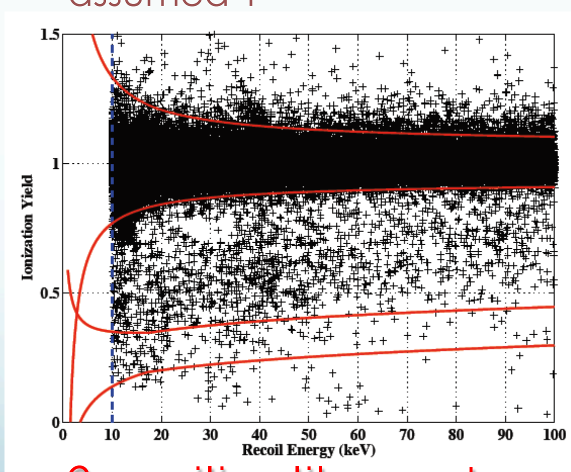
Results from double read-out bolometric technique (ionization vs heat)

	CDMS-II	Edelweiss II
Experimental site:	Soudan	Lab. Souterrain de Modane (LSM) (4800 m.w.e., 4 μ/m^2/day)
Set-up:	19 Ge detectors (≈ 230 g) + 11 Si detectors (100 g) , only 10 Ge detectors used in the data analysis	3.85 kg Ge (10 Ge ID detectors, 5 x 360 g, 5 x 410 g),
Target:	3.22 kg Ge	^{nat}Ge fiducial volume = 2.0 kg
Exposure:	194.1 kg x day	384 kg x day (2 periods:July-Nov 08, April 09-May 10)
Approaches:	nuclear recoils + subtraction	nuclear recoils + subtraction
Neutron shield:	50 cm polyethylene	30 cm paraffin
Quenching factor:	assumed 1	assumed 1

- 85% live time ("regular maintenance and unscheduled stops")
- 16 days devoted to γ and n calibration
- 17% reduction of exposure for run selection



PRL102,011301(2009), arXiv:0912.3592



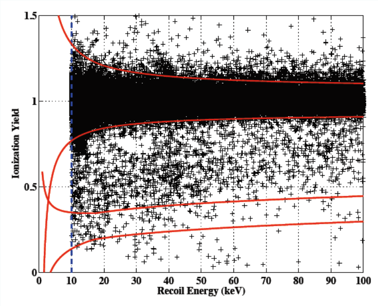
2 recoiling-like events "survived " (exp. bckg = 0.8)

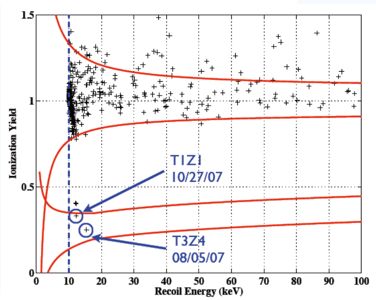
5 events observed (4 with E<22.5keV$_{recoil}$; 1 with E=172keV$_{recoil}$)

PLB702,5 (2011) 329

Data selection, handling and e.m. rejection procedures

CDMS-II





Event Selection:

- ☑ ***Veto-anticoincidence cut***
- ☑ ***Single-scatter cut***
- ☑ ***Q_{inner} (fiducial volume) cut***
- ☑ ***Ionization yield cut***
- ☑ ***Phonon timing cut***

from arXiv: 0912.3592

Data reduction and selection:

- poor detector performances, many detectors excluded in the analysis some other detectors excluded in subsets, etc.
- critical stability of the performances

scatters. Five Ge detectors were not used for WIMP detection because of poor performance or insufficient calibration data; four more detectors were similarly excluded during subsets of the four periods. We excluded Si detectors in this analysis due to their lower sensitivity to coherent nuclear elastic scattering.

A subset of events were analyzed to monitor detector stability and identify periods of poor detector performance. Data quality criteria were developed on

tests performed on parameter distributions. Our detectors require regular neutralization [15] to maintain full ionization collection. We monitor the yield distribution and remove periods with poor ionization collection. After these data quality selections, the total exposure to WIMPs considered for this work was 612 kg-days.

Phonon timing cut: time and energy response vary across the detector ⇒look-up table used (stability, robustness of the reconstruction procedure, efficiency and uncertainties)

… comments

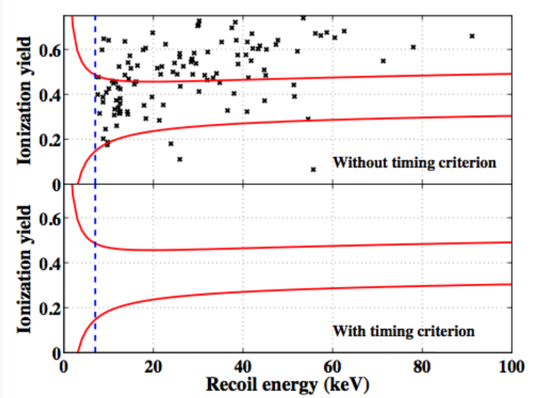
- Strong data selection (some detectors excluded in the analysis, some other detectors excluded in subsets, ..., poor detectors performance)
- Many cuts on the data: how about systematics? The systematics can be variable along the data taking period; can they and the related efficiencies be suitably 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 ?
- Efficiencies of cuts and of coincidence of the ionized and heat signals
- 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
- Not uniform detector responses vs surface electrons

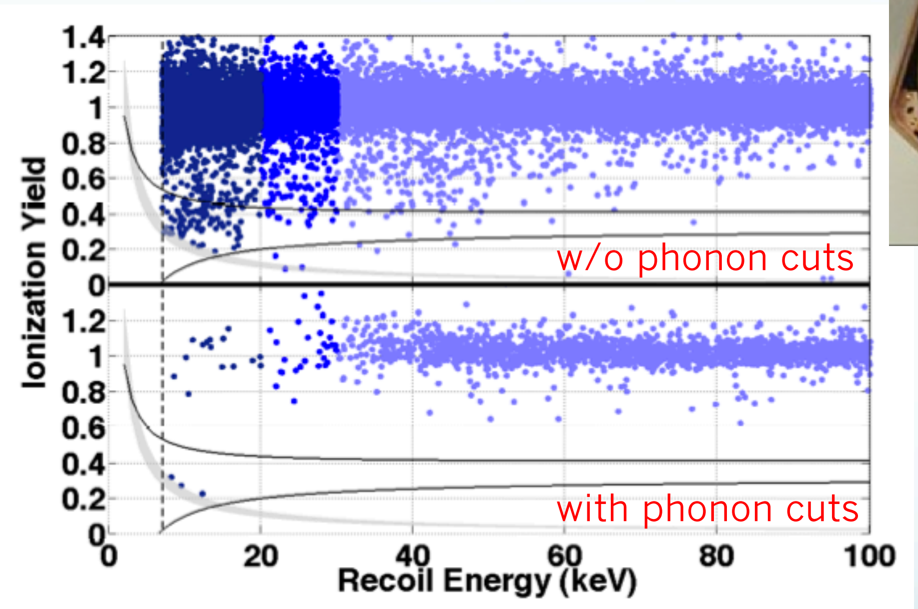
Final results from CDMS – Si

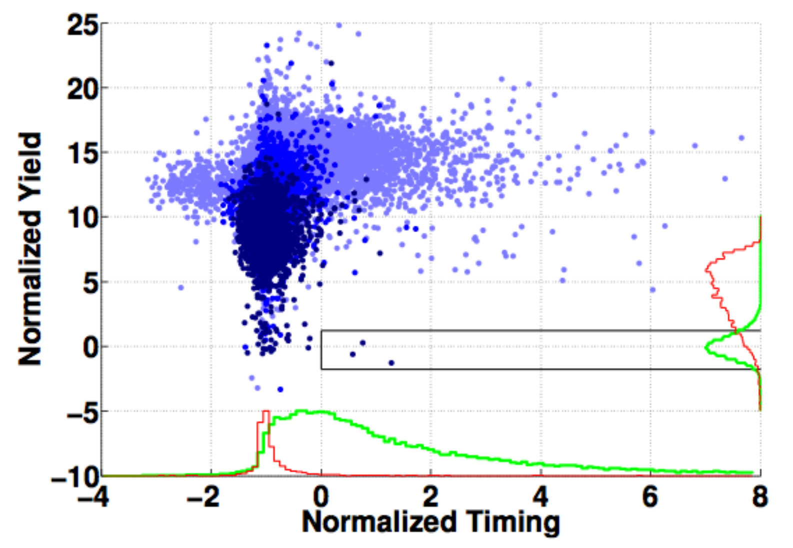
arXiv:1304.3706
arXiv:1304.4279

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 detectors (140.2 kg×day, estimated background of ≈ 0.4)
- 1.2 kg Si (11 x 106g)
- July 2007- September 2008





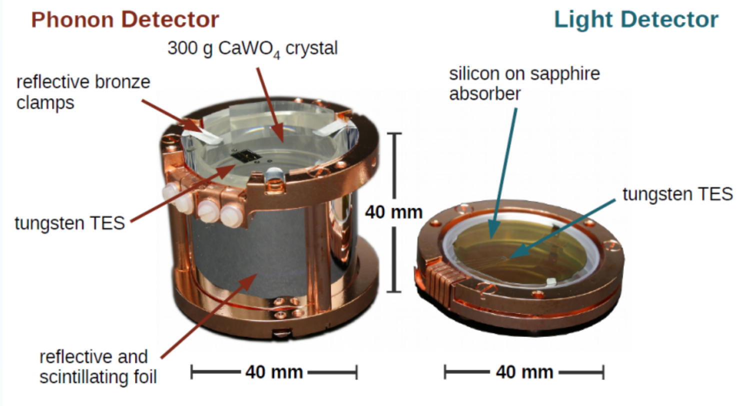


after many data selections and cuts, 3 Si recoil-like candidates survive in an exposure of 140.2 kg x day. Estimated residual background 0.41

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

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

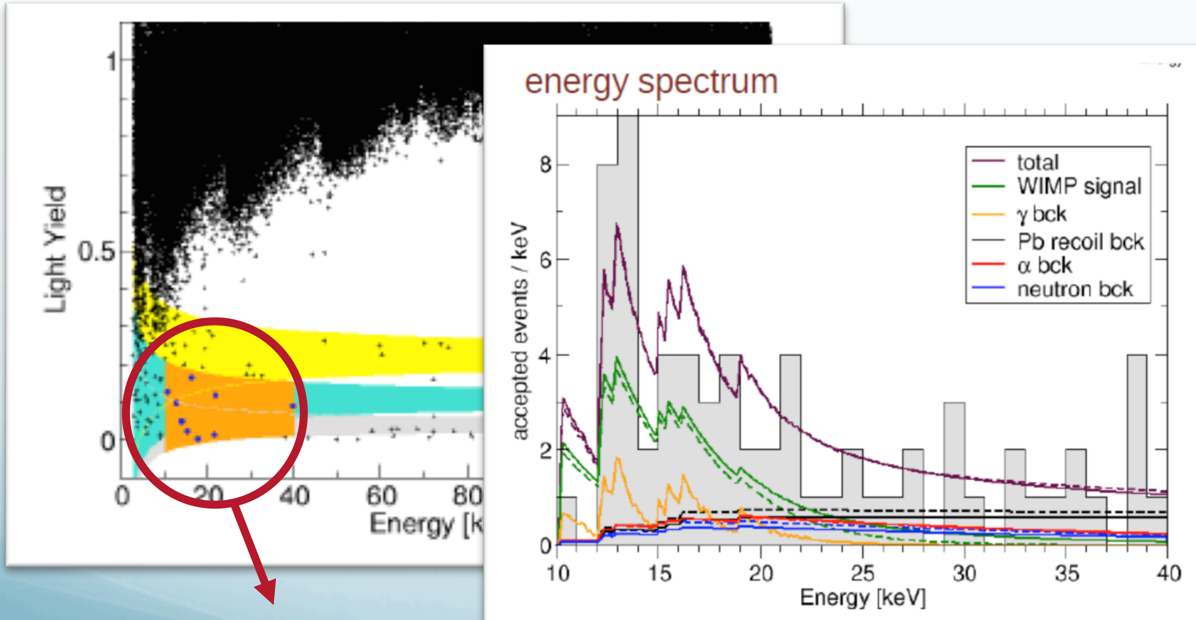


Discrimination of nuclear recoils from radioactive backgrounds by simultaneous measurement of phonons and scintillation light

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



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

67 total events observed in O-band;

Efficiencies + stability + calibration, crucial role

Future Run with improvement in preparation

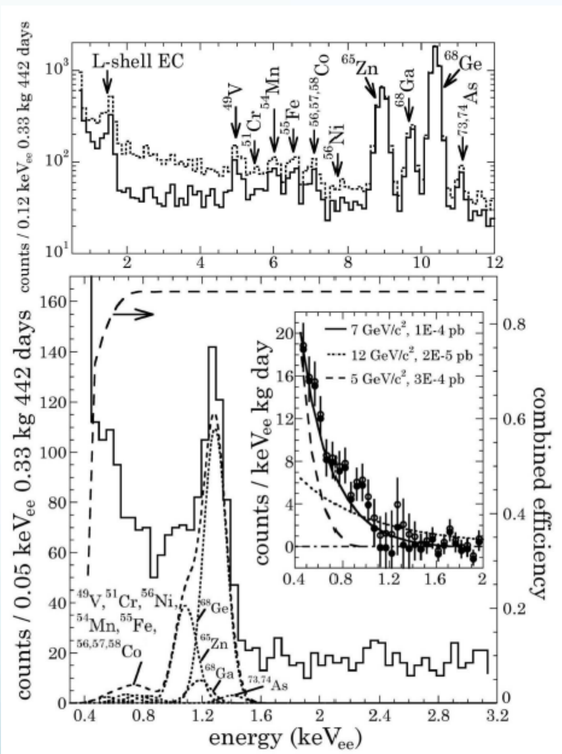
Positive hints from CoGeNT (ionization detector)

PRL107(2011)141301

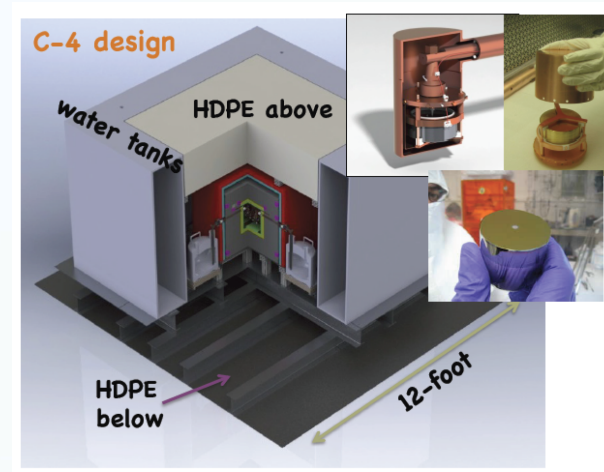
Experimental site: Soudan Underground Laboratory (2100 mwe)

Detector: 440 g, p-type point contact (PPC) Ge diode 0.4 keVee energy threshold

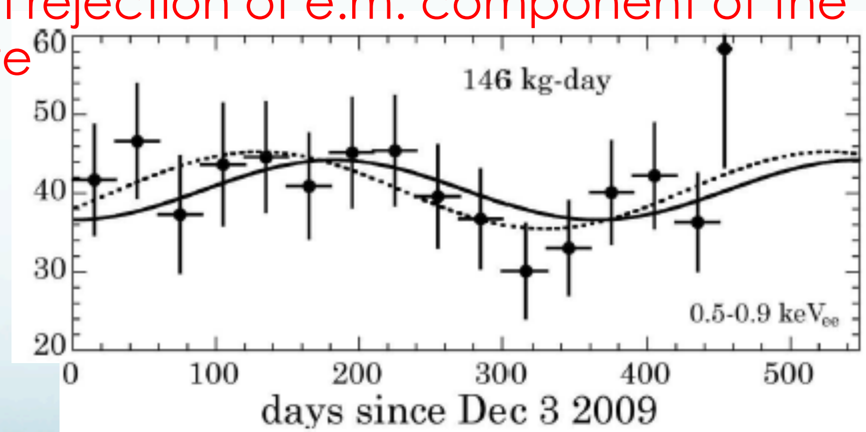
Exposure: 146 kg x day (dec '09 - mar '11)



- Energy region for DM search (0.4-3.2 keVee)
- Statistical discrimination of surface/bulk events
- Efficiencies for cumulative data cut applied



No Statistical rejection of e.m. component of the counting rate



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

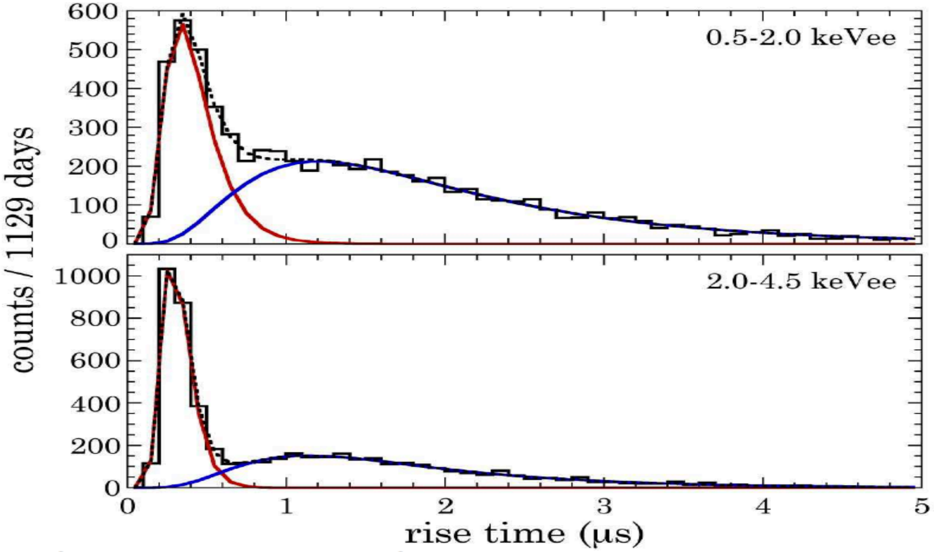
✓ **annual modulation** of the rate in 0.5-3 keVee at ~2.8σ C.L.

In data taking since July 2011 after the fire in Soudan

New data from COGENT

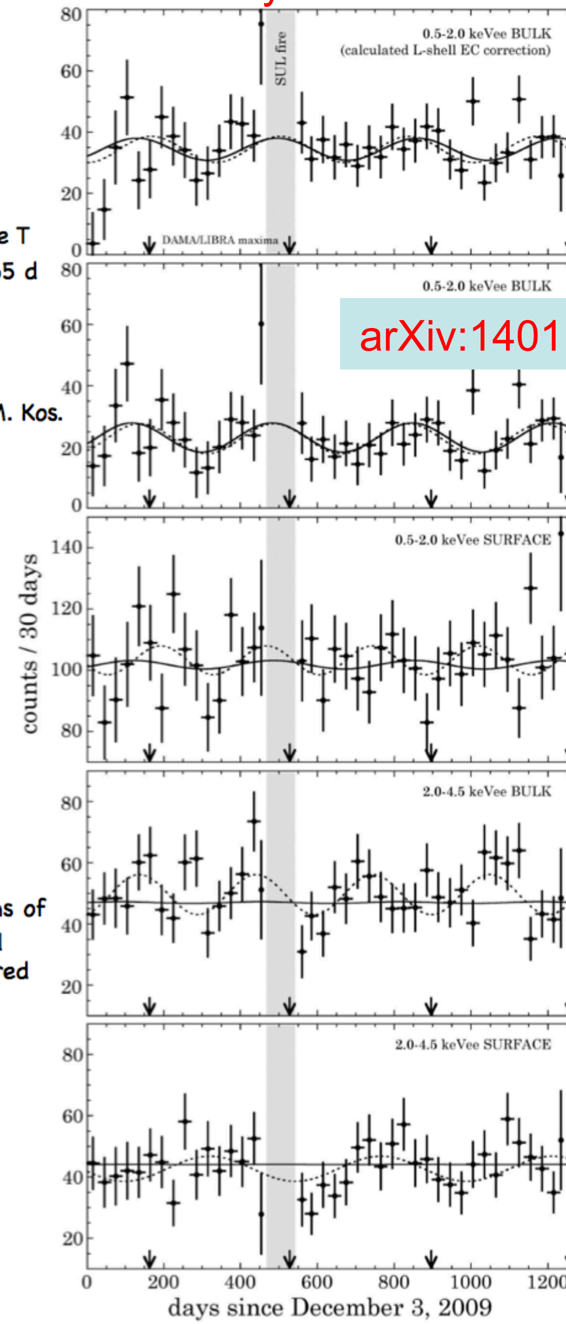
from talk by Collar at TAUP2013

What is new?



Dotted: free T
Solid: T= 365 d

See also poster by M. Kos.



BULK

arXiv:1401.3295

BULK

Surface

BULK

Surface

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...

Additional four months of unanalyzed data acquired (run is still ongoing)

& also excess of recoil-like events with respect to estimated backgrounds surviving the cuts applied by those expts: CRESST 4 σ C.L. effect, CDMS marginal (exposures orders of magnitude lower than DAMA)

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 Dark Matter impinging direction with Earth's galactic motion due to the distribution of Dark Matter particles velocities

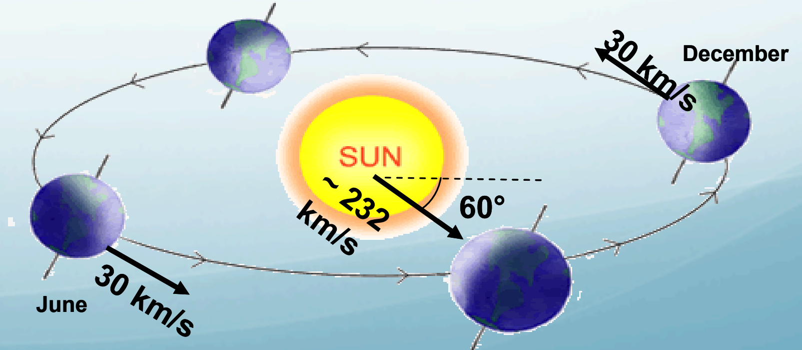
very hard to realize, it holds for some DM candidates

Diurnal modulation Daily variation of the interaction rate due to different Earth depth crossed by the Dark Matter 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



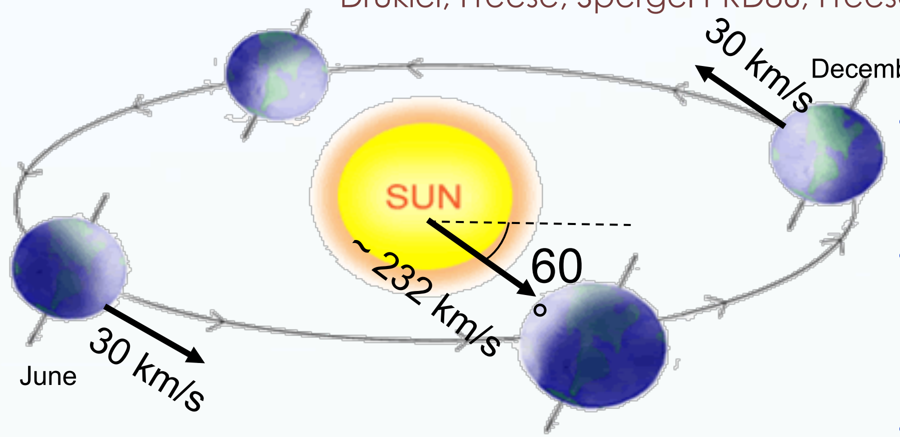
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

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.

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)

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

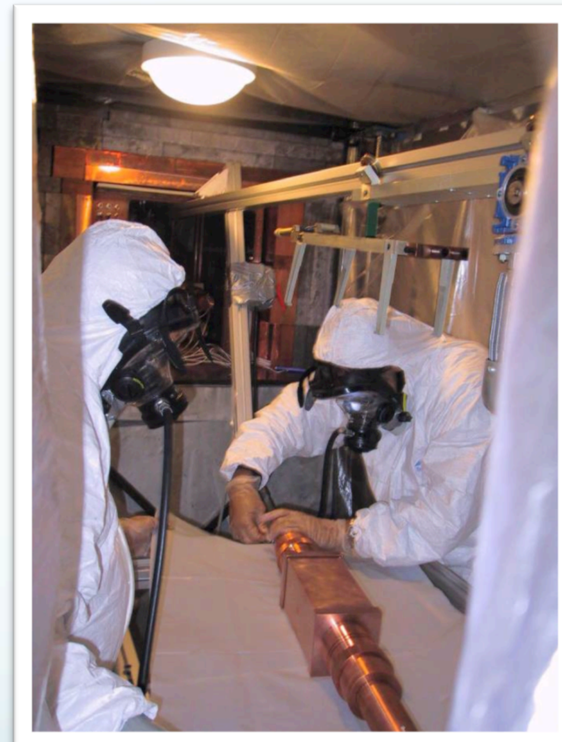
$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \cong S_{0,k} + S_{m,k}\cos[\omega(t-t_0)]$$

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

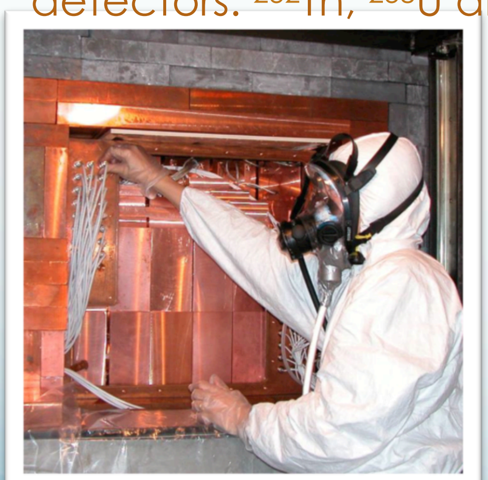
To mimic this signature, spurious effects and side reactions must not only - obviously - be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

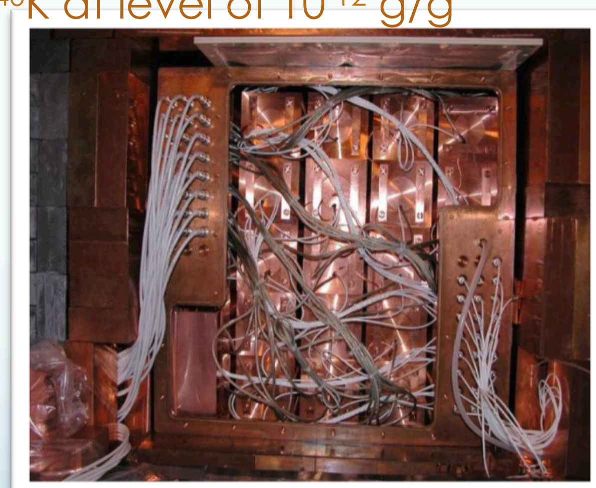
The DAMA/LIBRA set-up ~250 kg NaI(Tl) (Large sodium Iodide Bulk for RAre processes)

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





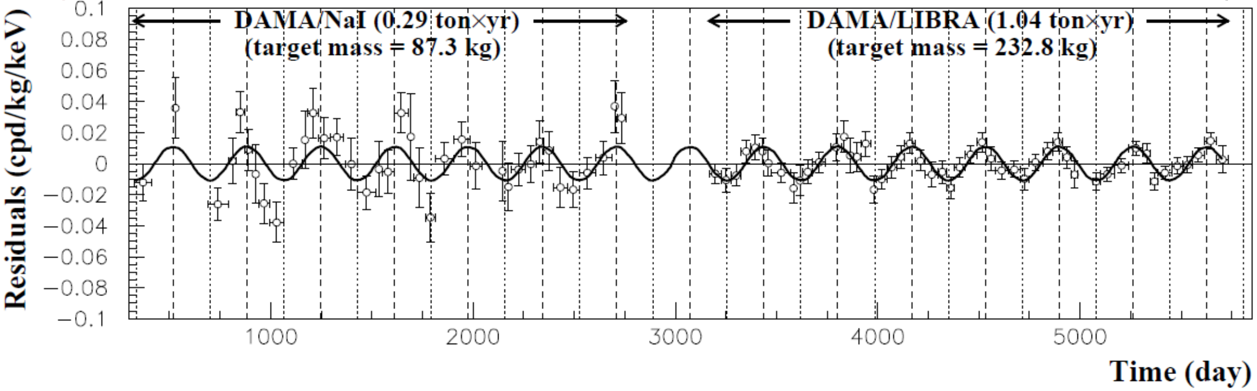
- Radiopurity, performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
- Results on DM particles, Annual Modulation Signature: EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648.
  Related results: PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022
- Results on rare processes: PEP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



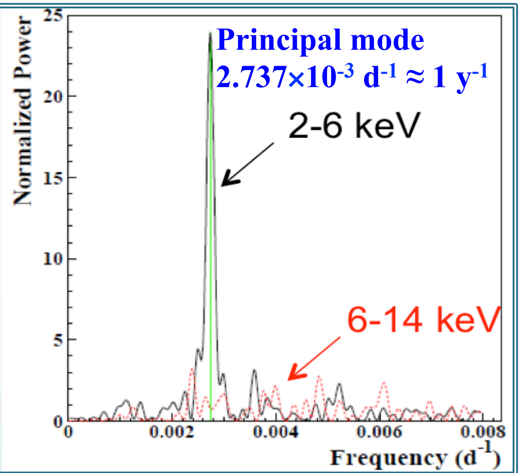
continuous line: t_0 = 152.5 d, T =1.0 y

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}

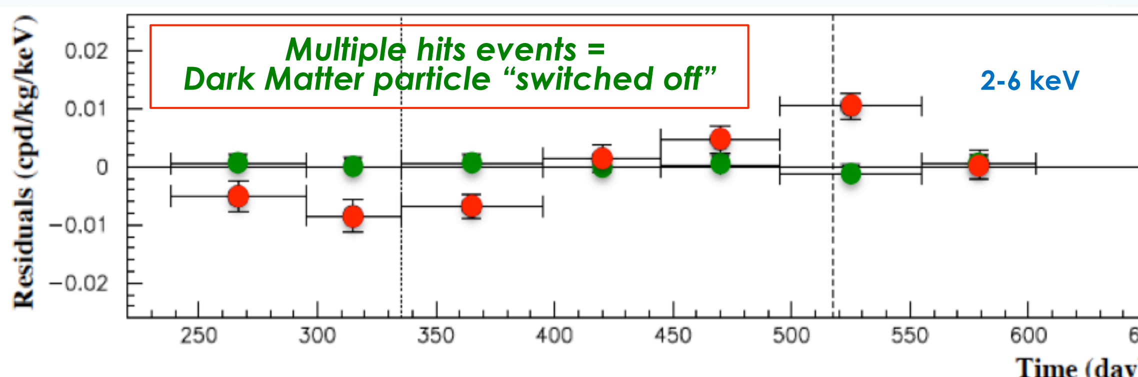
Fit with all the parameters free:
A = (0.0112 ± 0.0012) cpd/kg/keV
t_0 = (144±7) d - T = (0.998±0.002) y

Power spectrum



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

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



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

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

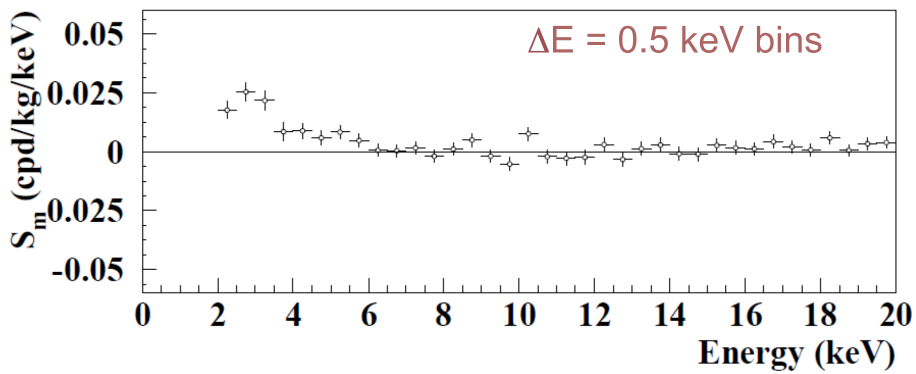
Model Independent Annual Modulation Result

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

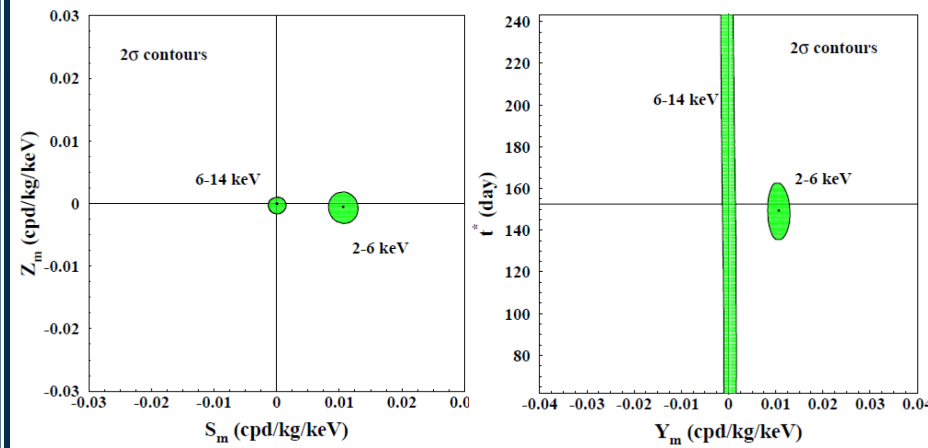
EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648

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

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



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



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

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.

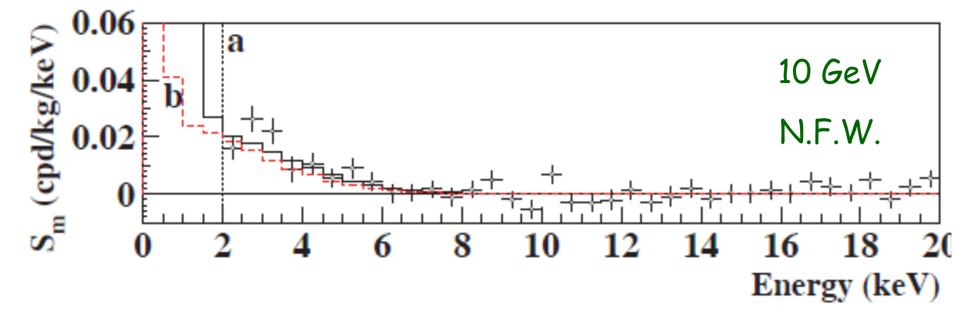
✓ Compatibility with many low and high mass DM candidates, interaction types and astrophysical scenarios, and in particular with recent positive model dependent hints from direct or indirect searches

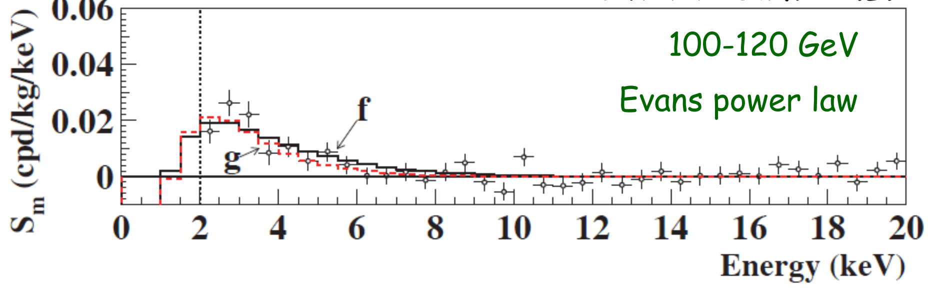
✓ No other experiment exists whose result can be – at least in principle – directly compared in a model-independent way with those by DAMA/NaI & DAMA/LIBRA-phase1

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

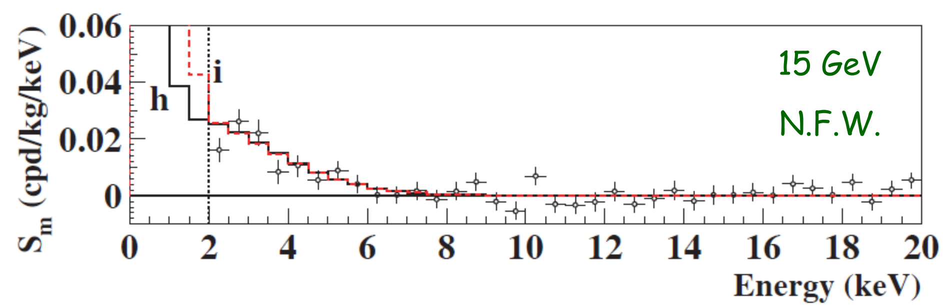
- Not best fit
- About the same C.L.

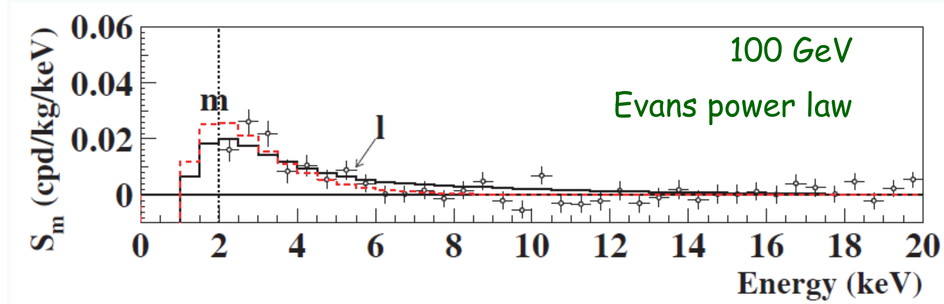
WIMP: SI



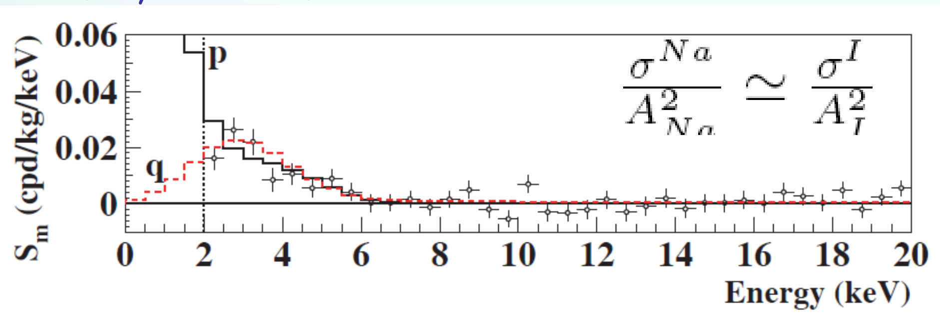


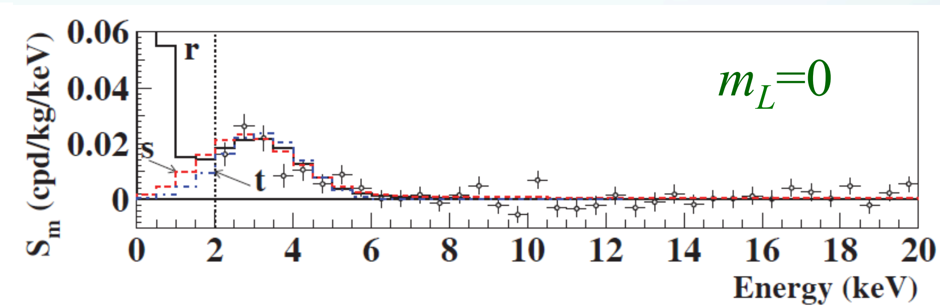
WIMP: SI & SD $\theta = 2.435$





LDM, bosonic DM



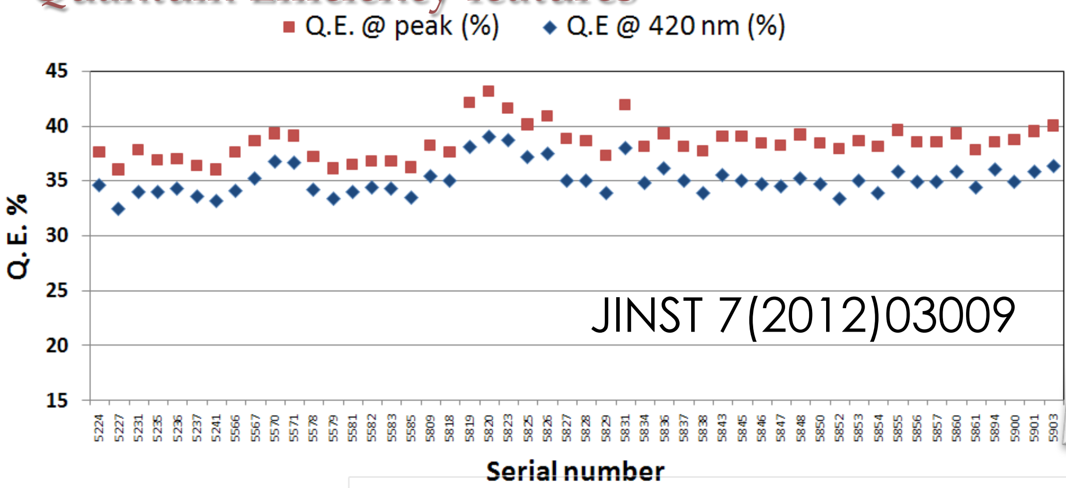


EPJC56(2008)333
IJMPA28(2013)1330022

Compatibility with several candidates; other ones are open

DAMA/LIBRA-phase2 - running

Quantum Efficiency features

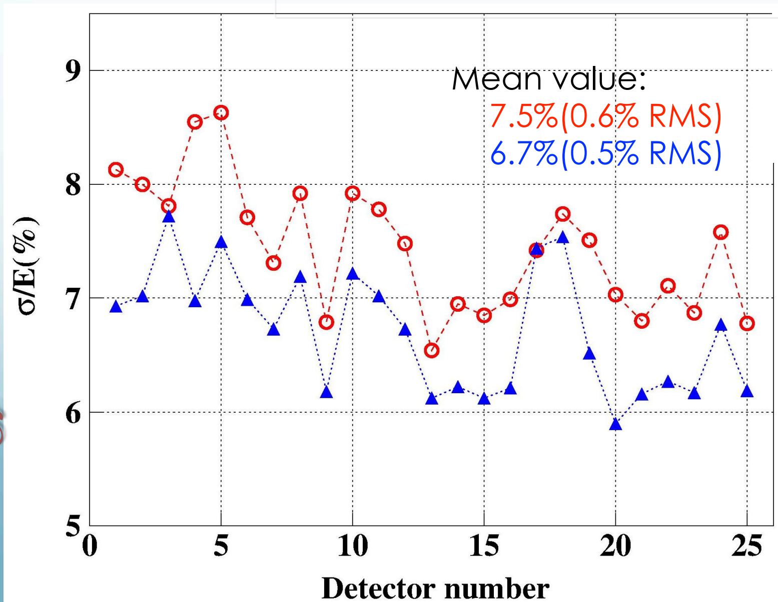


Residual Contamination

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 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

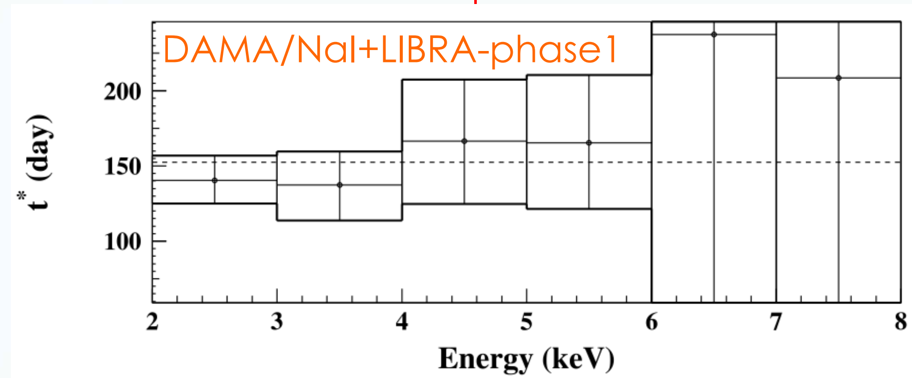
- To study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects, and to investigate second order effects
- Special data taking for *other rare processes*

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:

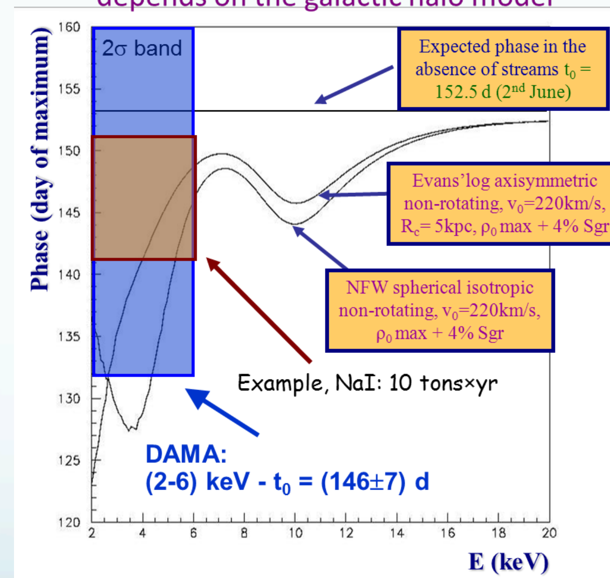
- the nature of the DM candidates
- possible diurnal effects on the sidereal time
- astrophysical models

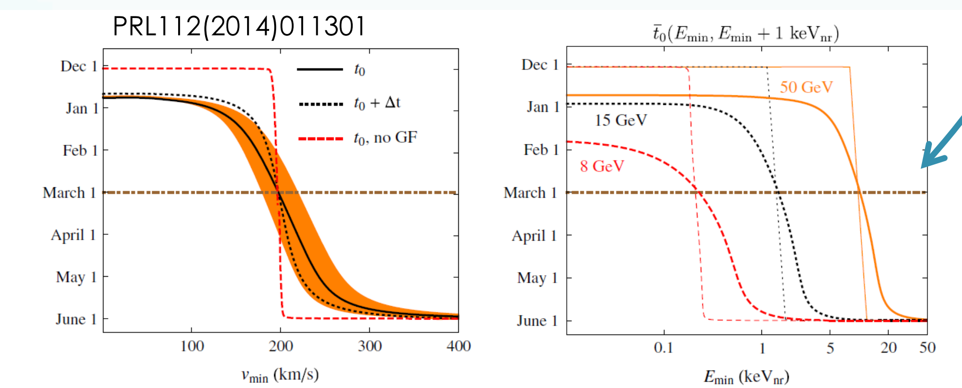


The annual modulation phase depends on :

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

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





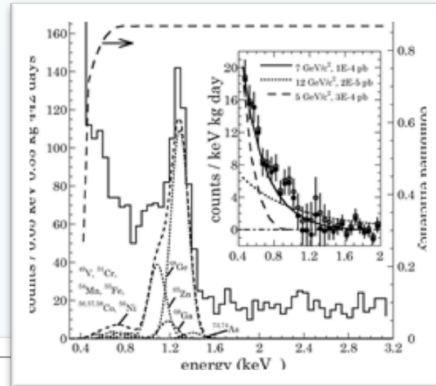
A step towards such investigations:

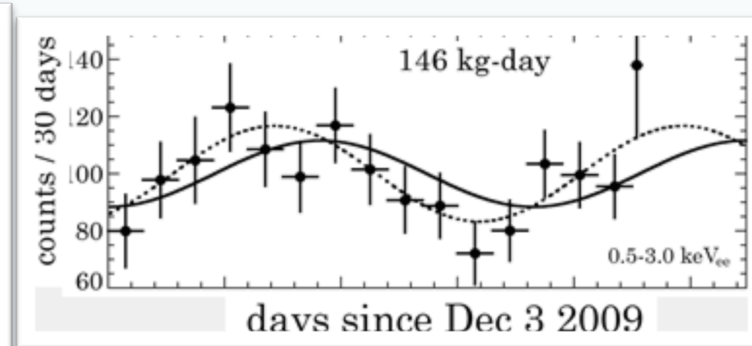
➔**DAMA/LIBRA-phase2**

with lower energy threshold and larger exposure

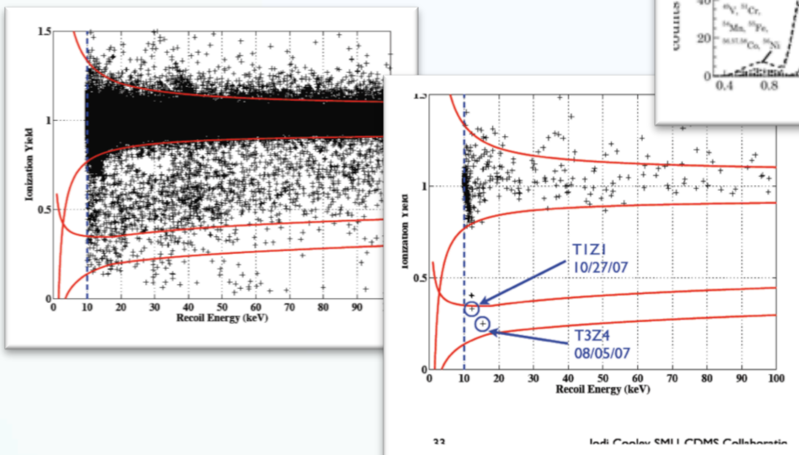
+ further possible improvements (DAMA/LIBRA-phase3) and DAMA/1ton

DAMA vs possible positive hints 2010 - 2013

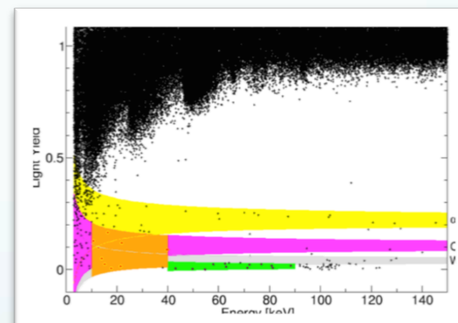




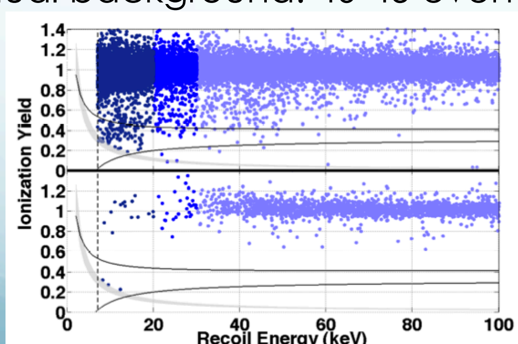
CoGeNT:
low-energy rise in the spectrum ("irreducible" by the applied background reduction procedures) + annual modulation



CDMS-Ge:
after many data selections and cuts, 2 Ge recoil-like candidates survive in an exposure of 194.1 kg x day (0.8 estimated as expected from residual background)

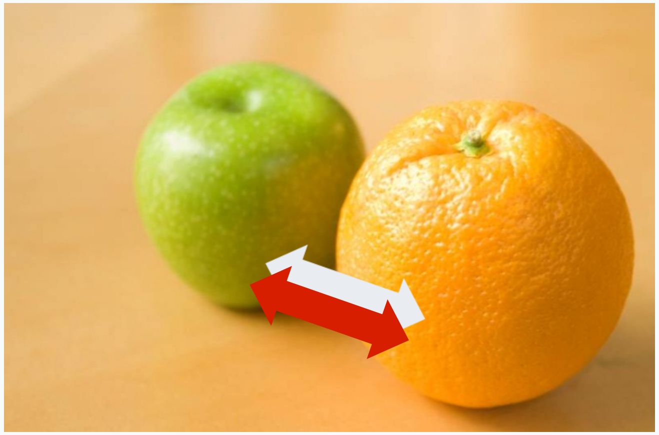


CRESST: after many data selections and cuts, 67 recoil-like candidates in the O/Ca bands survive in an exposure of 730 kg x day (expected residual background: 40-45 events, depending on minimization)



CDMS-Si:
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

All those recoil-like excesses with respect to an estimated bckg surviving cuts as well as the CoGeNT result are compatible with the DAMA 9.3 σ C.L. annual modulation result in various scenarios



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

see for some details e.g.:
Riv.N.Cim.26 n.1 (2003) 1, IJMPD13(2004)2127, EPJC47 (2006)263, IJMPA21 (2006)1445

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).

Instrumental quantities

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

Quenching Factor

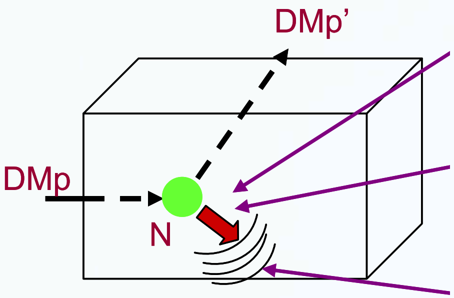
- differences are present in different experimental determinations of *q* for the same nuclei in the same kind of detector depending on its specific features (e.g. *q* depends on dopant and on the impurities; in liquid noble gas e.g.on trace impurities, on presence of degassing/ releasing materials,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

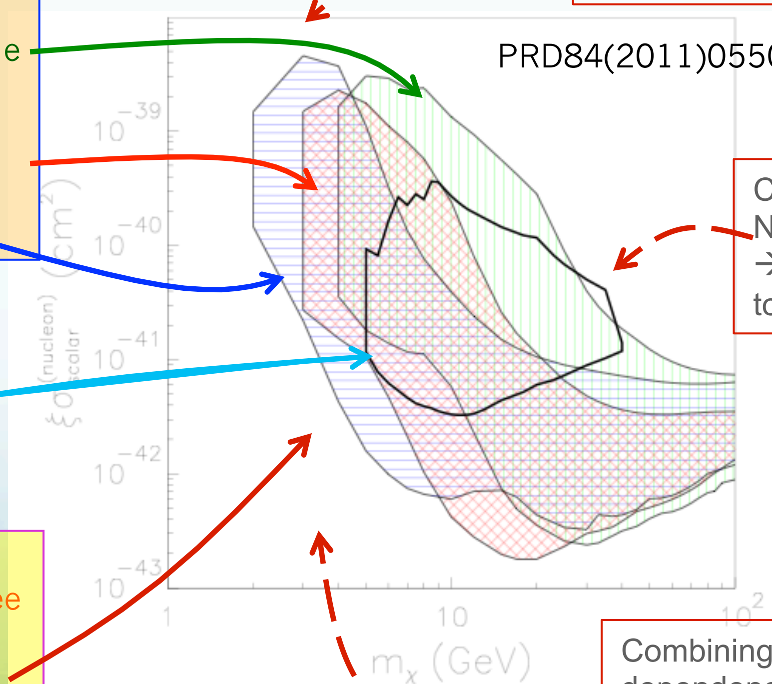
- Some velocity distributions and uncertainties considered.
- The DAMA regions represent the domain where the likelihood-function values differ more than 7.5σ from the null hypothesis (absence of modulation).
- For CoGeNT a fixed value for the Ge quenching factor and a Helm form factor with fixed parameters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

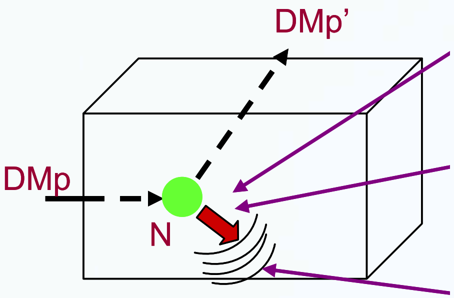
1.64 σ C.L.

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



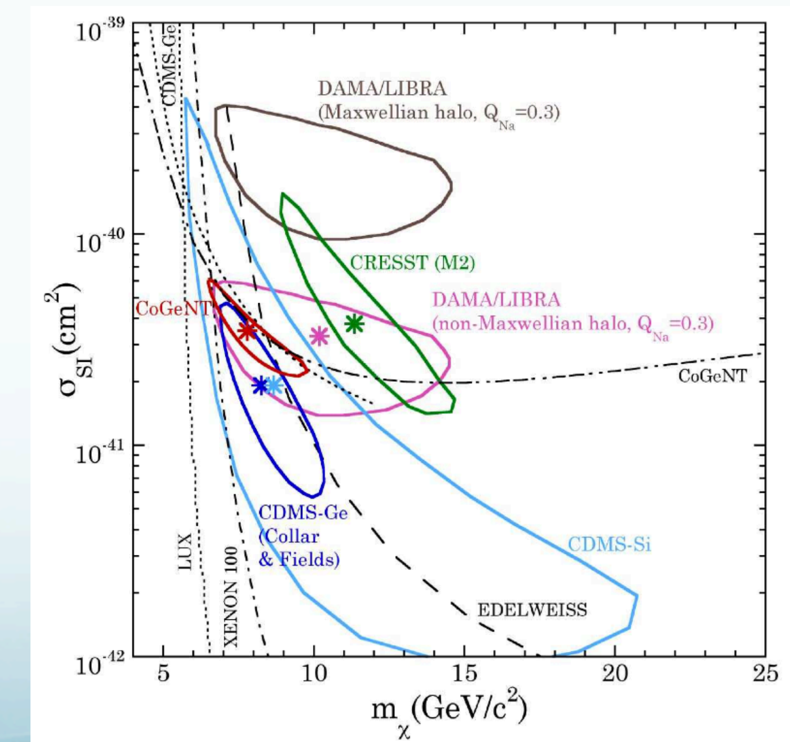
Regions in the nucleon cross section vs DM particle mass plane

... 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.

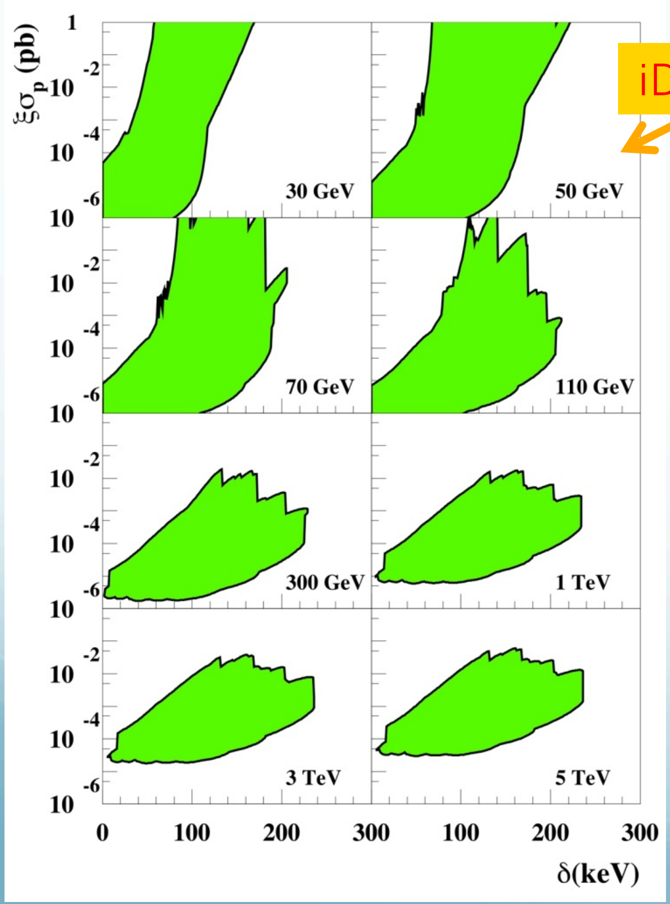
$$\chi^- + N \rightarrow \chi^+ + N$$

- 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

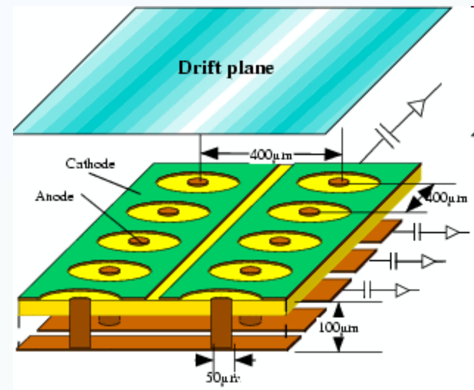
- For large splittings, the dominant scattering in NaI(Tl) can occur off of Thallium nuclei, with A~205, which are present as a dopant at the 10^{-3} level in NaI(Tl) crystals.
- Inelastic scattering WIMPs with large splittings do not give rise to sizeable contribution on Na, I, Ge, Xe, Ca, O, … nuclei.

… and more considering experimental and theoretical uncertainties

Directionality technique (at R&D stage)

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

NEWAGE



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!

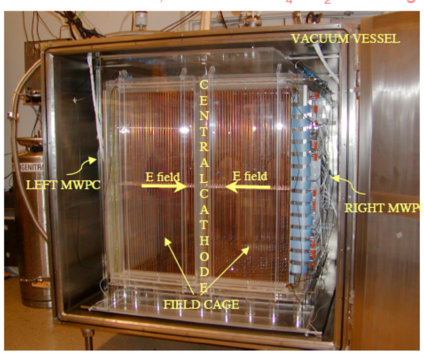
Anisotropic scintillators: DAMA, UK, Japan

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.

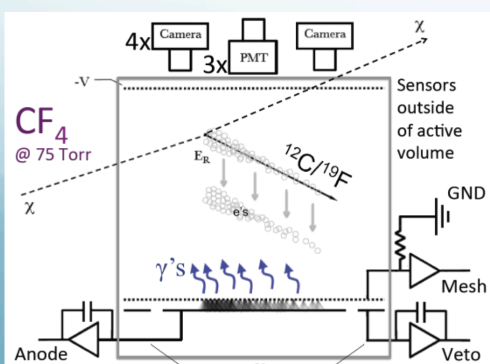
0.8 m³ fiducial volume, 10/30 Torr CF_4/CS_2 --> 139 g

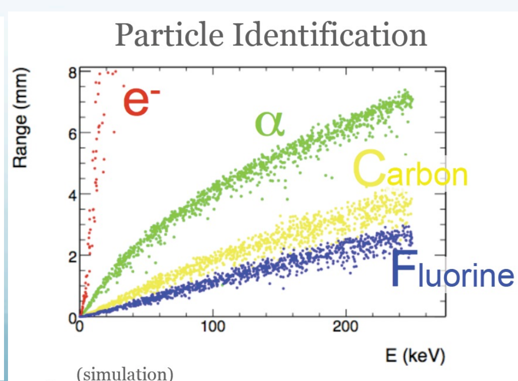


Dinesh Loomba

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

DM-TPC





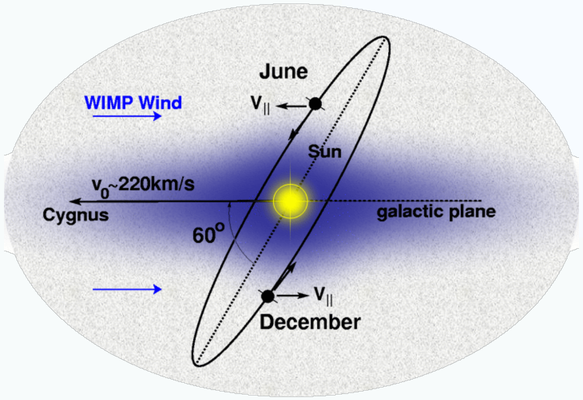
- The "**4---Shooter**" 18L (6.6 gm) TPC 4xCCD, Sea-level@MIT
- moving to WIPP
- Cubic meter funded, design underway

Not yet competitive sensitivity

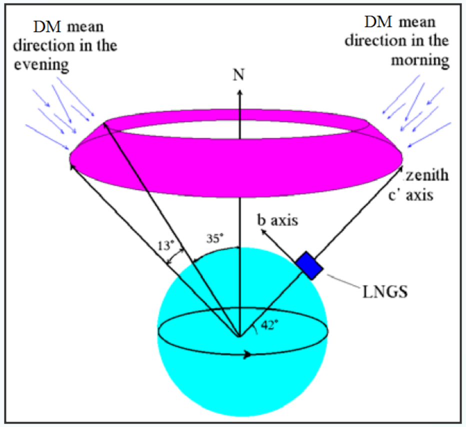
The ADAMO project: Study of the directionality approach with $ZnWO_4$ anisotropic detectors

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

Directionality approach: based on the study of the correlation between the Earth motion in the galactic rest frame and the arrival direction of the Dark Matter (DM) particles able to induce nuclear recoils



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



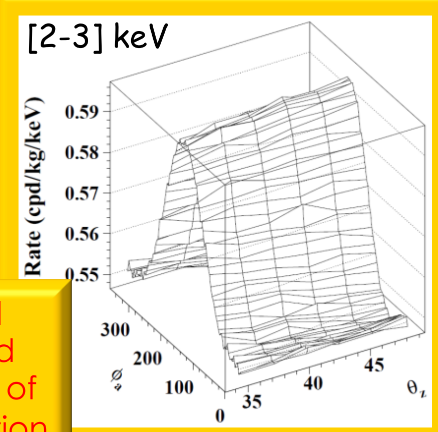
Nuclear recoils are expected to be strongly correlated with the DM impinging direction
This effect can be pointed out through the study of the variation in the response of anisotropic scintillation detectors during sidereal day

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

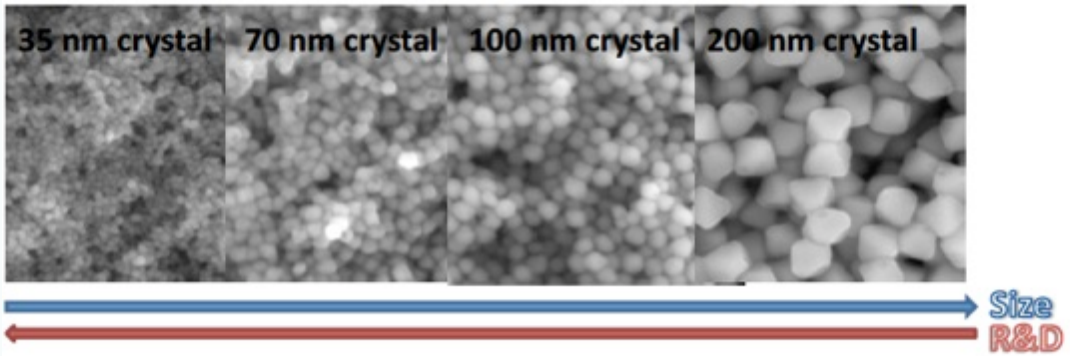
These and others competitive characteristics of $ZnWO_4$ detectors could permit to reach - in given scenarios - sensitivity comparable with that of the DAMA/LIBRA positive result and of the CoGeNT and CRESST positive hints

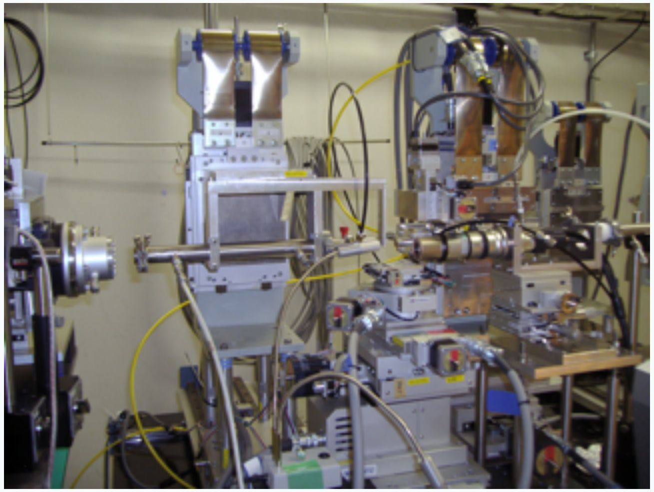
$\sigma_p = 5\times10^{-5}$ pb, m_{DM}= 50 GeV



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

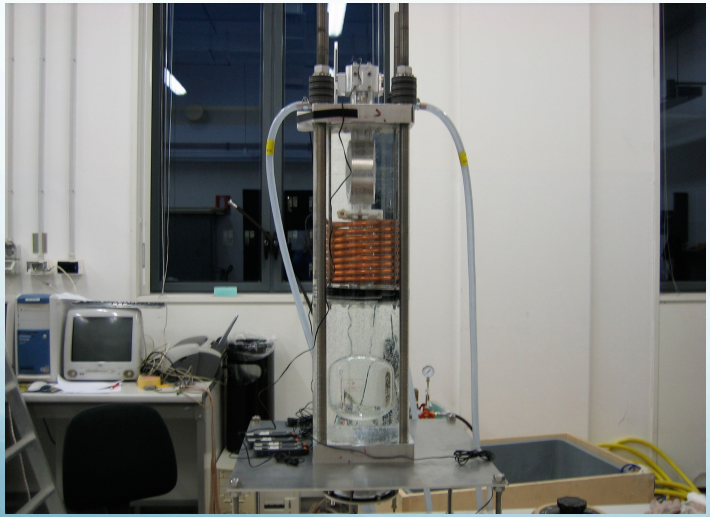
Nano Imaging Tracker (NIT) emulsions





Track readout: track length ranges also ≤ λ . ➔ use an expansion technique on the films and make a pre-selection on the optical microscopes ➔use X-ray microscopy

Camera a bolle – Geyser (MOSCAB in CSN5)



20 L in construction

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

Altre idee fuori Italia: SIMPLE, PICASSO, COUPP; DRIFT, NEWAGE, DM-TPC, ...

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