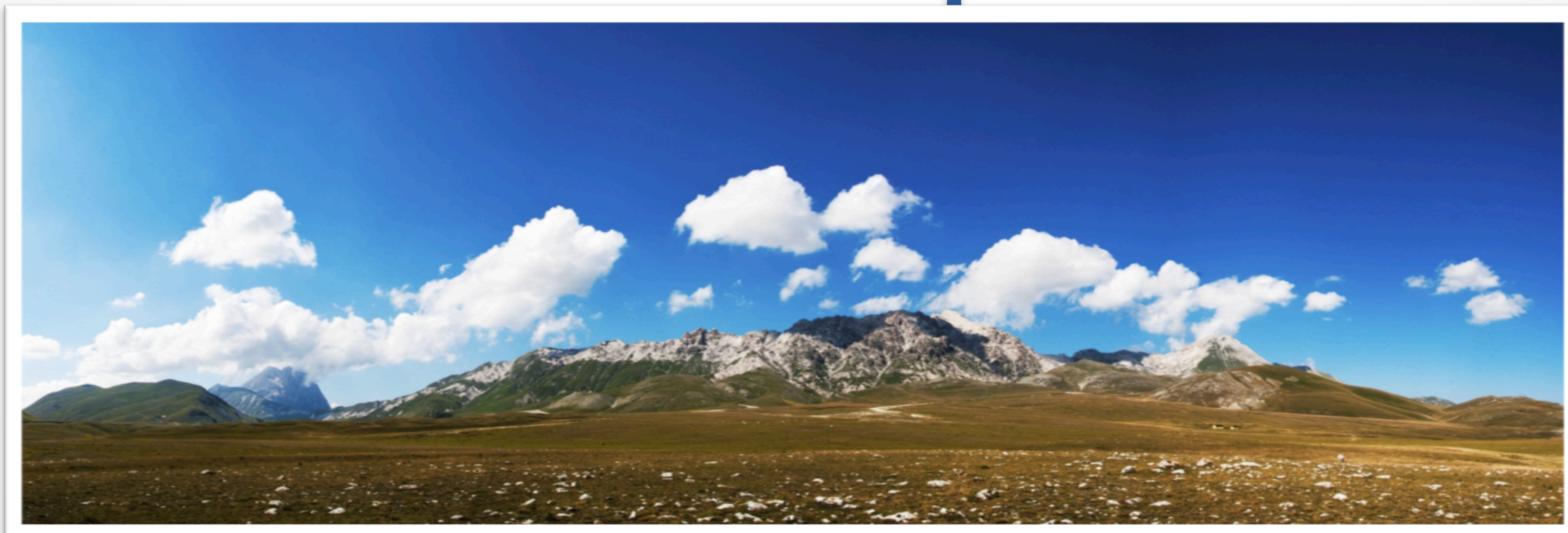
Direct detection of Dark Matter particles



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INFN-LNGS

DARK2012 - Dark Forces at Accelerators
LNF Frascati (Rome), Italy
16th - 19th, October 2012

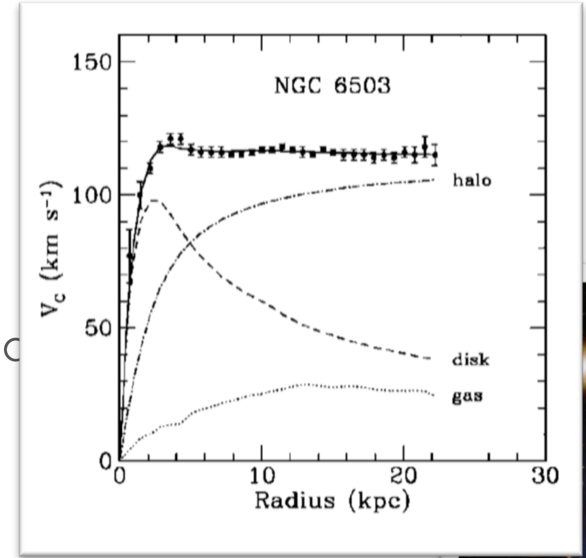
The Dark Side of the Universe: experimental evidences

First evidence and confirmations:

1933 F. Zwicky: studying dispersion velocity of Coma galaxies

1936 S. Smith: studying the Virgo cluster

1974 two groups: systematical analysis of *mass density* vs *distance from center* in many galaxies

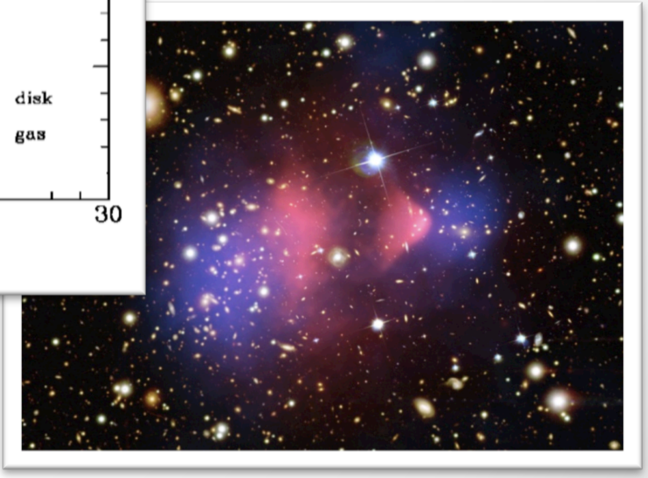


rotational curve of a spiral galaxy

Other experimental evidences

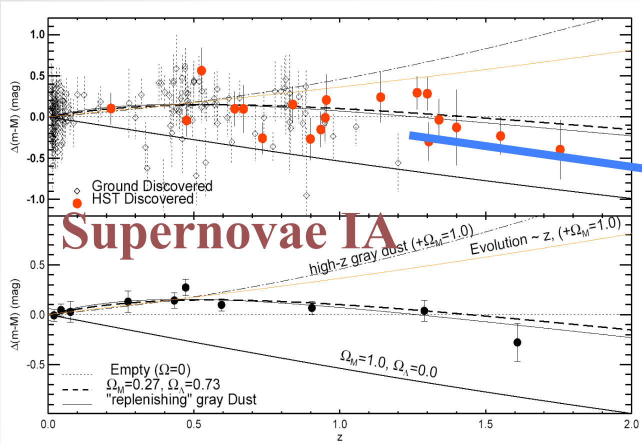
- ✓ from LMC motion around Galaxy
- ✓ from X-ray emitting gases surround elliptical galaxies
- ✓ from hot intergalactic plasma velocity distribution in clusters
- ✓ ...
- ✓ bullet cluster 1E0657-558

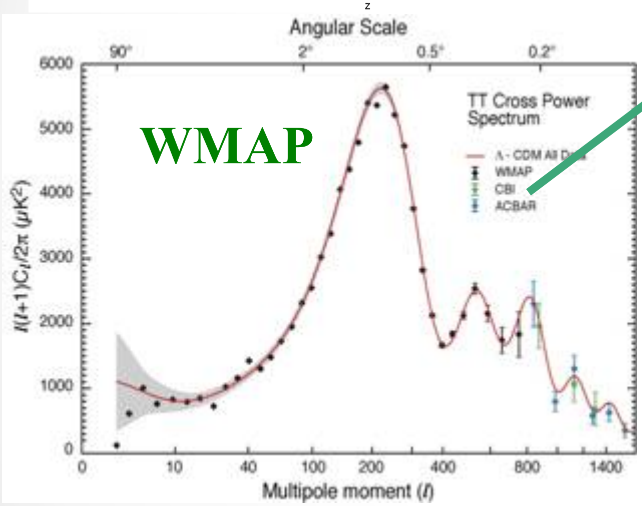
bullet cluster

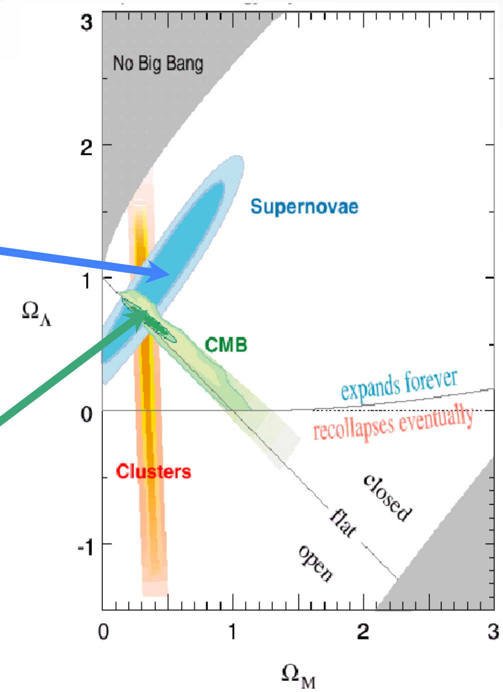


$M_{\text{visible Universe}} << M_{\text{gravitational effect}}$ ⇒ about 90% of the mass is **DARK**

"Concordance model"







$\Omega = \Omega_\Lambda + \Omega_M =$ close to 1

Ω = density/critical density

6 atoms of H/m^3

$\Omega_\Lambda \approx 0.74$
$\Omega_M \approx 0.26$

The Universe is flat

Primordial Nucleosynthesis

Observations on:
- light nuclei abundance
- microlensings
- visible light.

Structure formation in the Universe

The **baryons** give "too small" contribution

$\Omega_b \sim 4\%$

Non baryonic Cold Dark Matter is dominant

$\Omega_{CDM} \sim 22\%$,
$\Omega_{HDM,\nu} < 1\ \%$

~ **90%** of the matter in the Universe is **non baryonic**
A large part of the Universe is in form of **non baryonic Cold Dark Matter particles**

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

hidden dark sector

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

etc...

even a suitable particle not yet foreseen by theories &

(& invisible axions, ν's)

Right halo model and parameters?

- Composition? DM multicomponent also in the particle part?
- Right related nuclear and particle physics?

Non thermalized components?

Caustics?

clumpiness?

etc... etc...

Complementary information

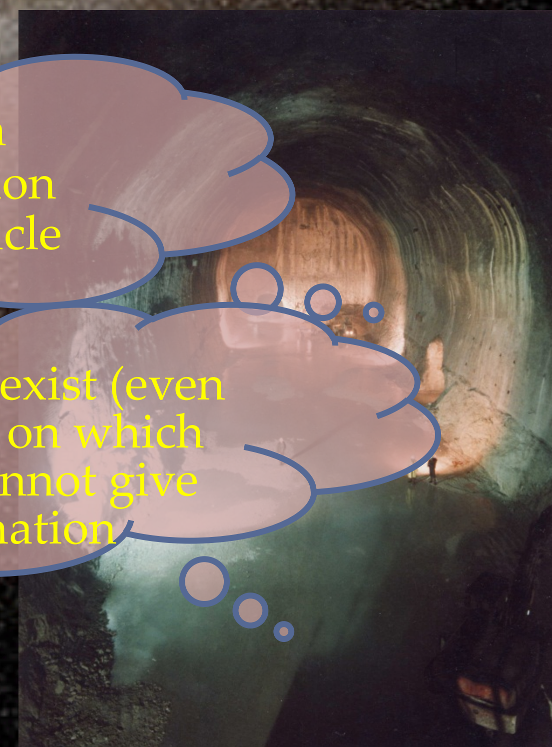
What can accelerators do?

to demostrate the existence of some of the possible DM candidates

What can accelerators **not** do?

to credit that a certain particle is the DM solution or the "single" DM particle solution

DM candidates exist (even for neutralino) on which accelerators cannot give any information

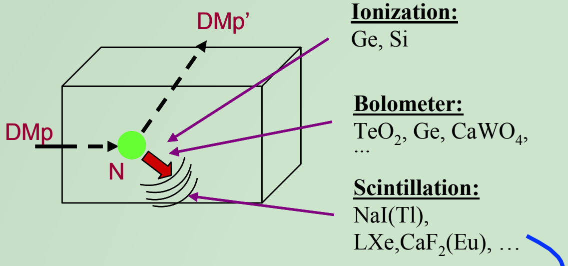


DM direct detection method using a model independent approach and a low-background widely-sensitive target material

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

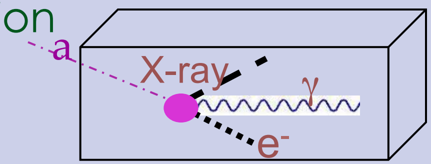
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

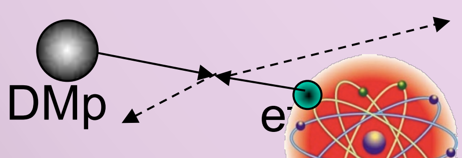
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

  → detection of e.m. radiation

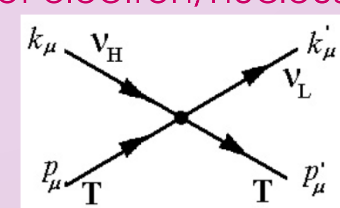


... even WIMPs

- 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

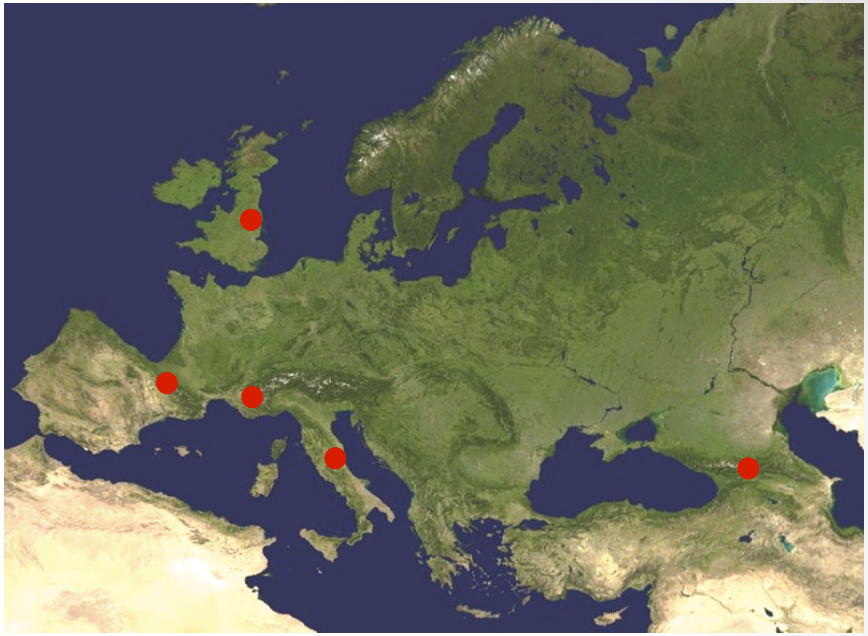


e.g. signals from these candidates are **completely lost** in experiments based on "rejection procedures" of the e.m. component of their rate

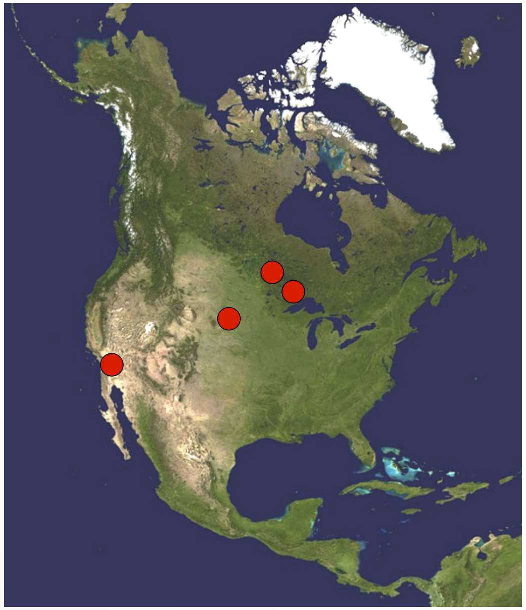
... also other ideas ...

Dark Matter direct detection activities in underground labs

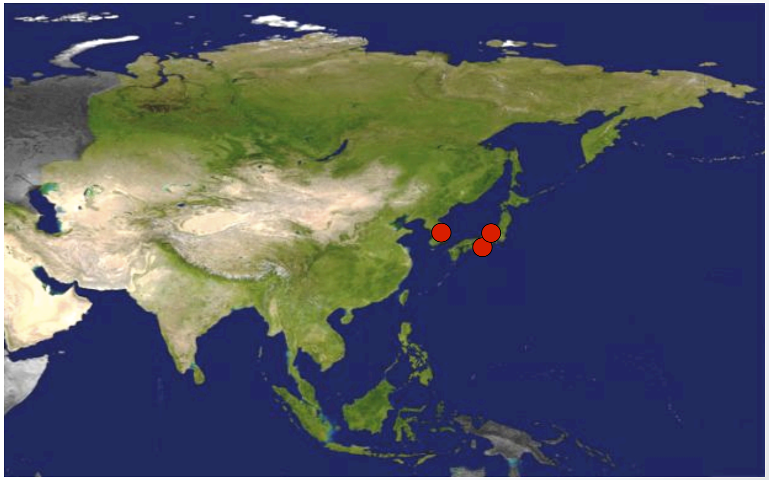
- Various approaches and techniques
- Various different target materials
- Various different experimental site depths
- Different radiopurity levels, etc.



- 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



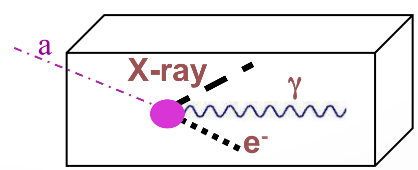
- Y2L (depth ~ 700 m): KIMS
- Oto (depth ~ 1400 m.w.e.): PICO-LON
- Kamioka (depth ~2700 m.w.e.): XMASS, NEWAGE

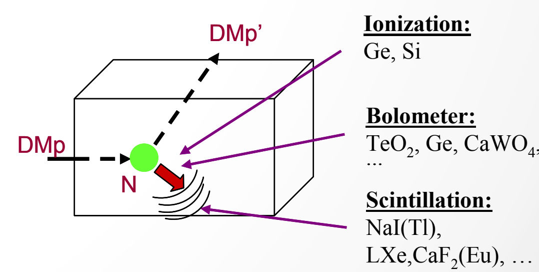
Direct detection experiments

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

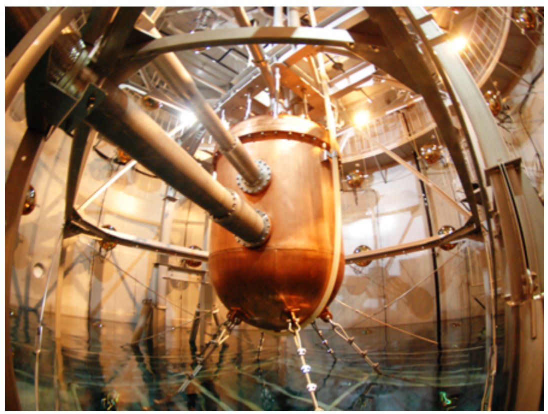
- Single phase: LXe, LAr, LNe → scintillation, ionization
- Dual phase liquid /gas → prompt scintillation + secondary scintillation

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

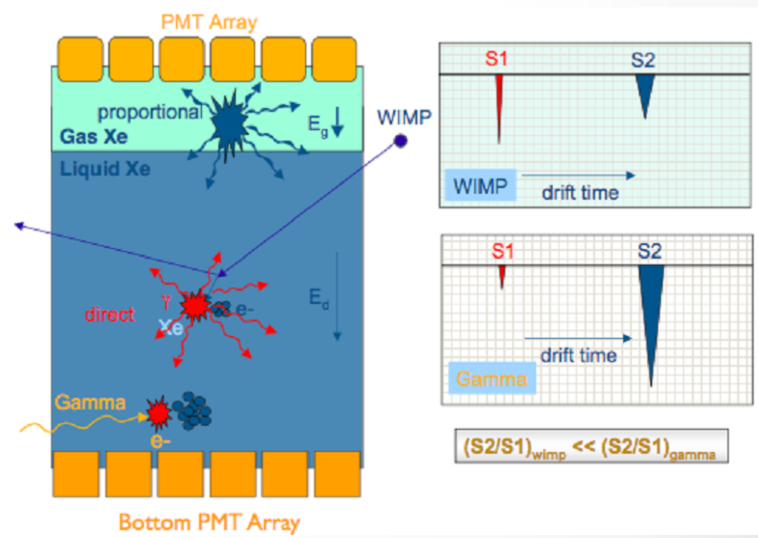


XMASS

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

Recent results of a liquid noble gas experiment: XENON100

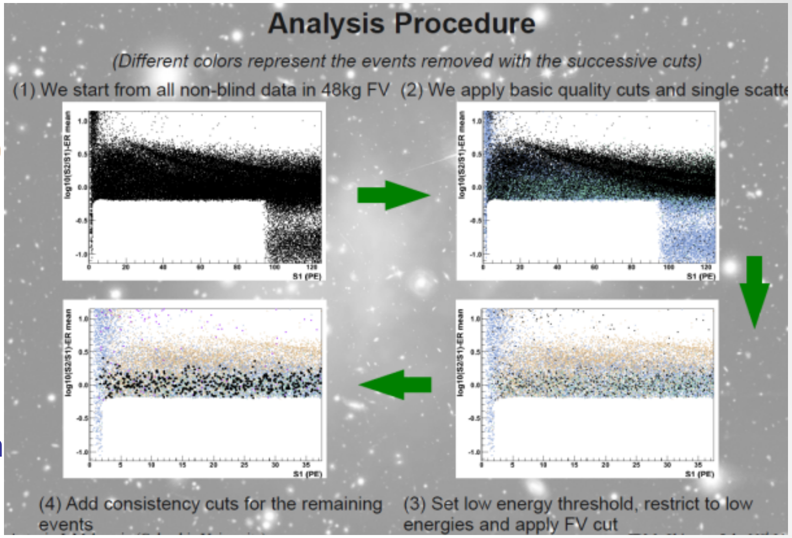
(arXiv:1207.5988)

Experimental site: Gran Sasso (1400 m depth)

Target material: ^{nat}Xe

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

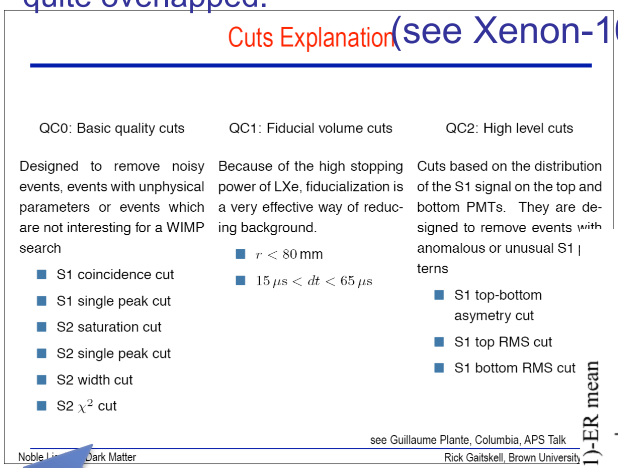
Used exposure: 224.6 days



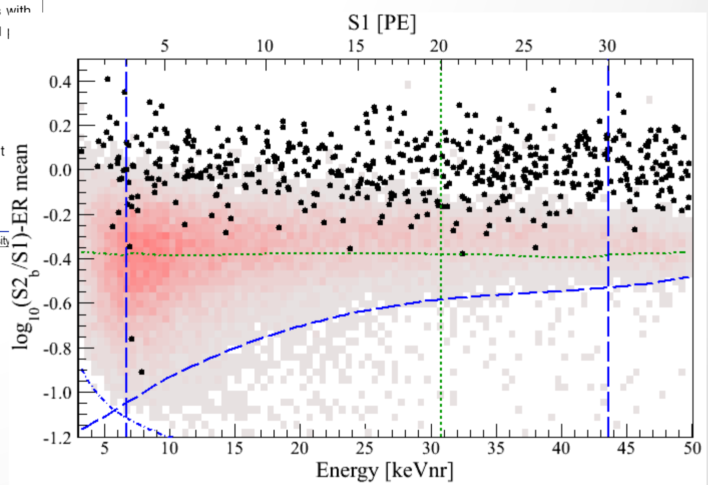
- **Non-uniform** response of detector: intrinsic limit
- **Correction** procedures applied: which systematics?
- **Small light responses** (2.2 ph.e./keVee) ⇒ energy threshold at few keV unsafe
- Physical **energy threshold unproved** by source calibrations
- Poor energy **resolution**; resolution at threshold **unknown**
- **Questionable light responses** for electrons and recoils at low energy
- Efficiencies for the coincidence of S1 and S2 and for cuts at claimed low energy, etc.
- Definition of the fiducial volume
- Etc.

Statistical discrimination between electrons (e^-/γ,) and nuclear recoils. The two populations are quite overlapped.

(see Xenon-10)



Many cuts are 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 ?



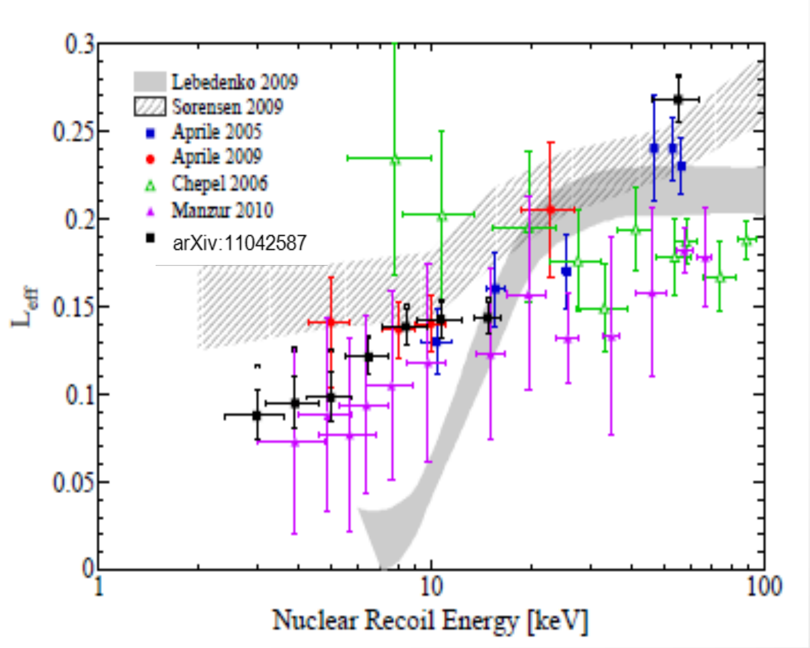
- After many cuts 2 events survive (estimated surviving background (1.0 ±0.2)

For example: what about the low-mass WIMP sensitivity claimed by XENON-100?

see also: arXiv:1005.08380, 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

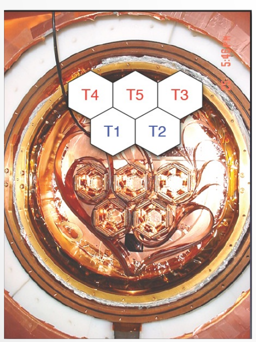
1106.0653: "A lingering critical question is to what extent a determination of L_{eff} performed using highly-optimized compact calibration detectors like those in … can be applied with confidence to a much larger device like the XENON100 detector, featuring a small S1 light-detection efficiency (just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

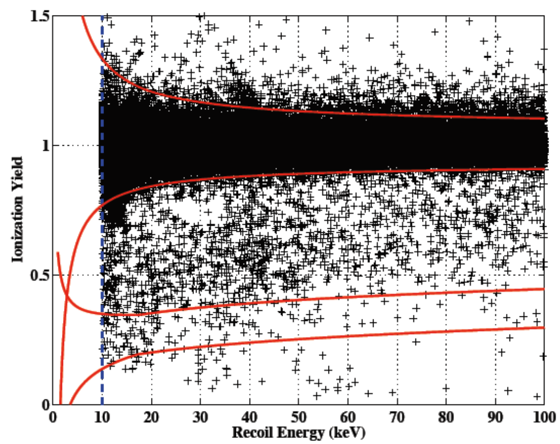
- All this yields to overestimate the sensitivity and to achieve too optimistic exclusion plots

Recent 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





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

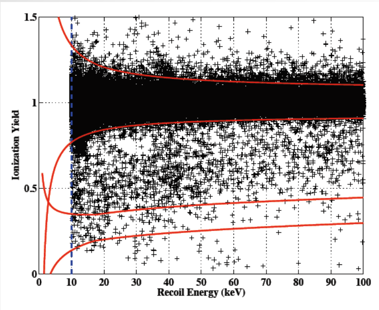
PRL102,011301(2009), arXiv:0912.3592

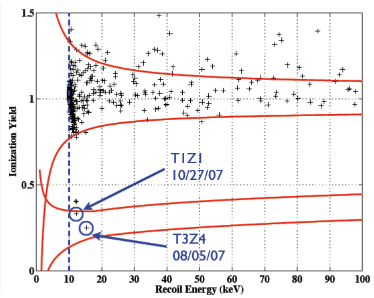
5 events observed (4 with E<22.5keV$_{recoil}$; 1 with E=172keV$_{recoil}$)

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)

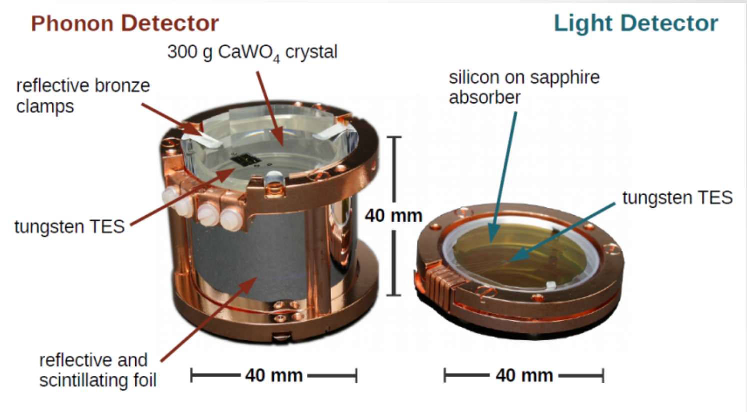
… comments

- 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

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

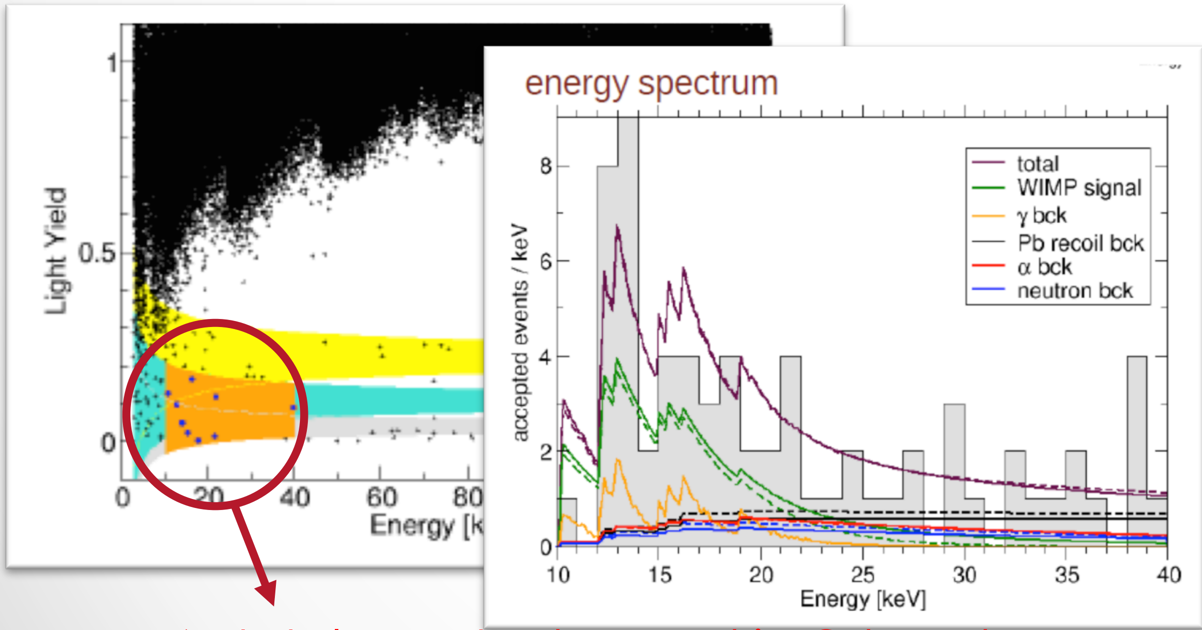
Discrimination of nuclear recoils from radioactive backgrounds by simultaneous measurement of phonons and scintillation light



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



67 total events observed in O-band;

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

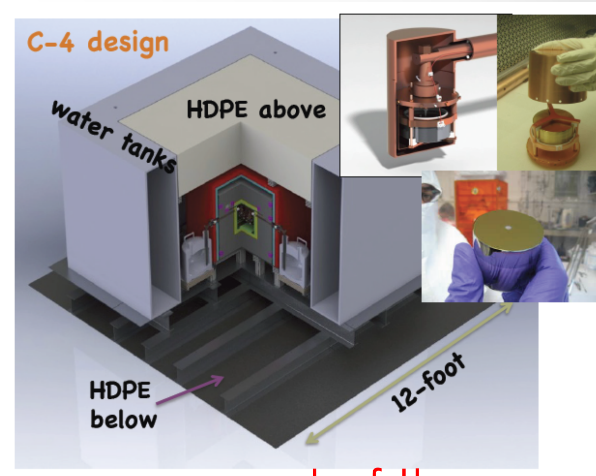
Efficiencies + stability + calibration, crucial role

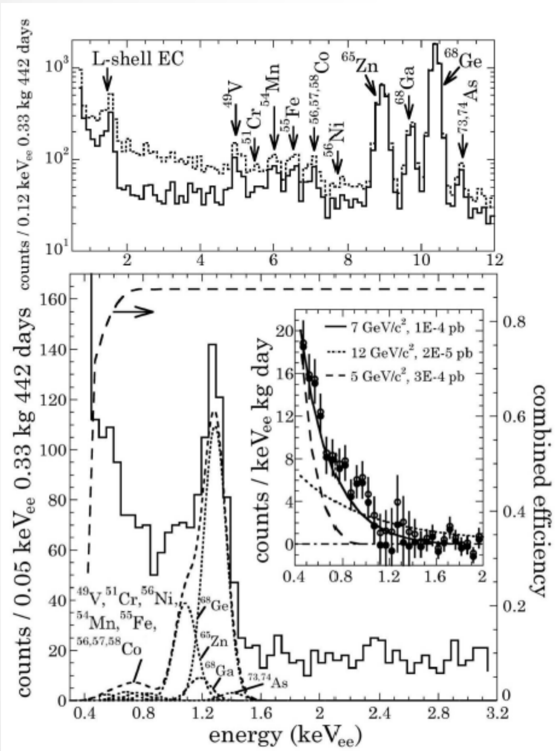
- Future Run with improvment in preparation

Positive hints from CoGeNT (ionization detector)

PRL107(2011)141301

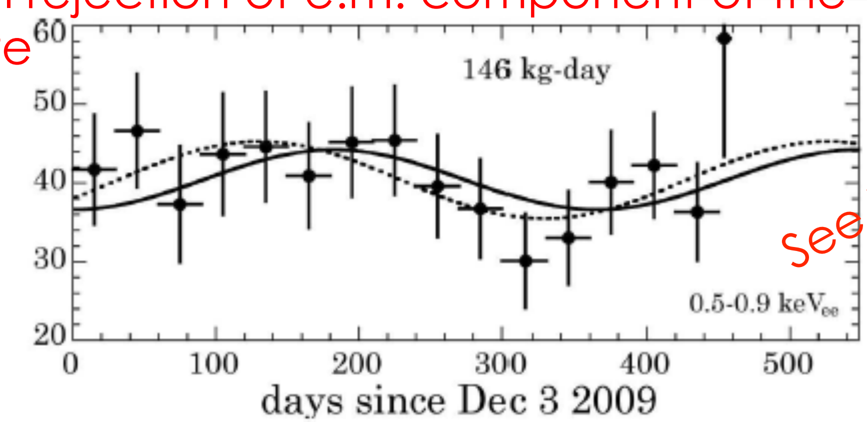
Experimental site: Soudan Underground Laboratory (2100 mwe)
Detector: 440 g, p-type point contact (PPC) Ge diode 0.4 keVee energy threshold
Exposure: 146 kg x day (dec '09 - mar '11)





- Energy region for DM search (0.4-3.2 keVee)
- Efficiencies for cumulative data cut applied

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



See later

✓ **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

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 undistinguishable 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

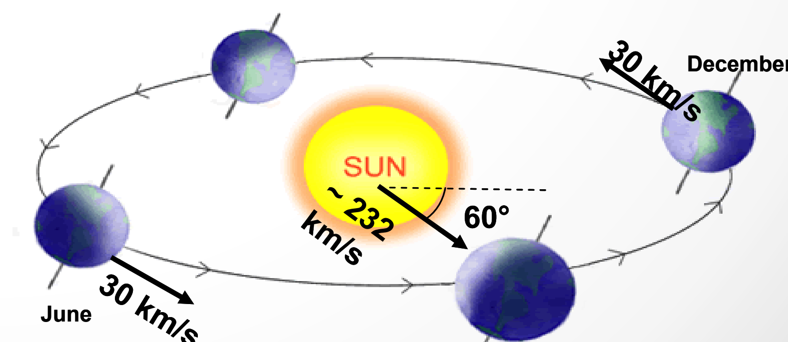
very hard to realize, it holds for some DM candidates

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



Directionality technique (at R&D stage)

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

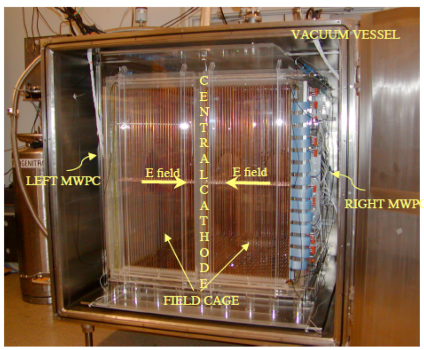
Anisotropic scintillators: DAMA, UK, Japan

DRIFT-IId

The DRIFT-IId detector in the Boulby Mine

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

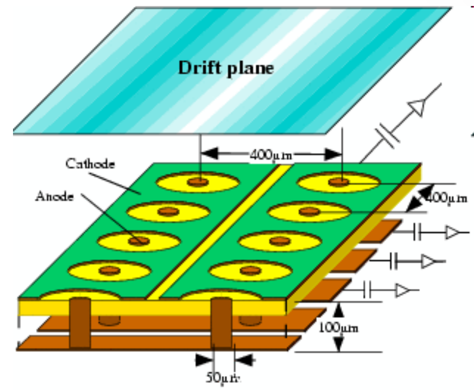
0.8 m³ fiducial volume, 10/30 Torr CF_4/CS_2 --> 139 g



Dinesh Loomba

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

NEWAGE

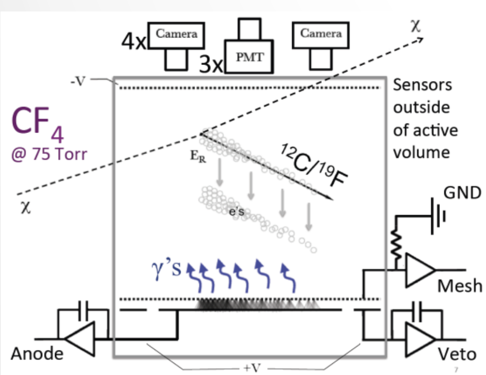


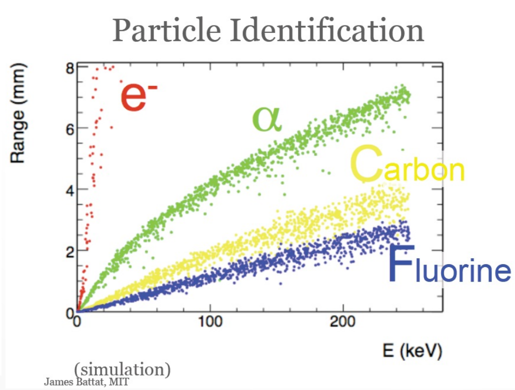
μ-PIC(Micro Pixel Chamber) is a two dimensional position sensitive gaseous detector

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

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

DM-TPC



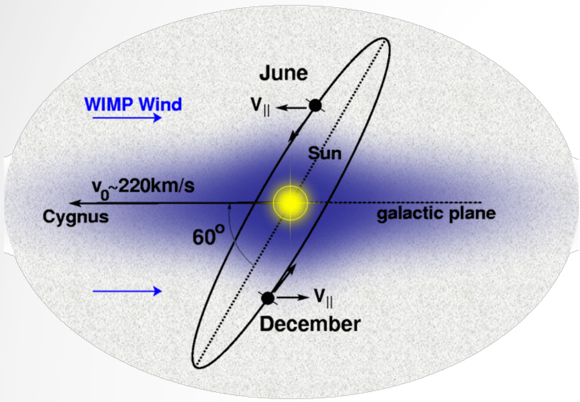


- The "**4---Shooter**" 18L (6.6 gm) TPC 4xCCD, Sea-level@MIT
- moving to WIPP
- Cubic meter funded, design underway

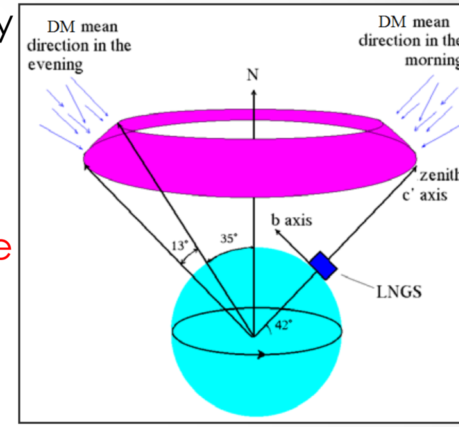
Not yet competitive sensitivity

The ADAMO project: Study of the directionality approach with ZnWO4 anisotropic detectors

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



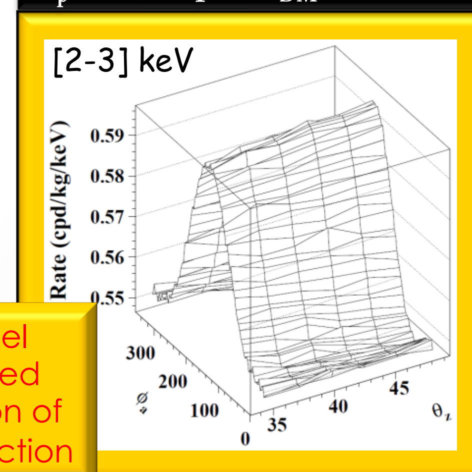
Nuclear recoils are expected to be strongly correlated with the DM impinging direction
This effect can be pointed out through the study of the variation in the response of anisotropic scintillation detectors during sidereal day

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

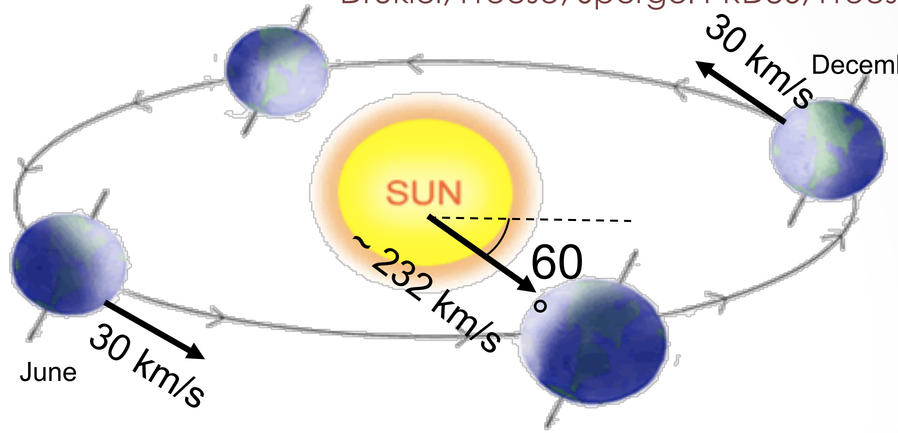
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

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 = 2[nd] June (when $v_\oplus$ is maximum)

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

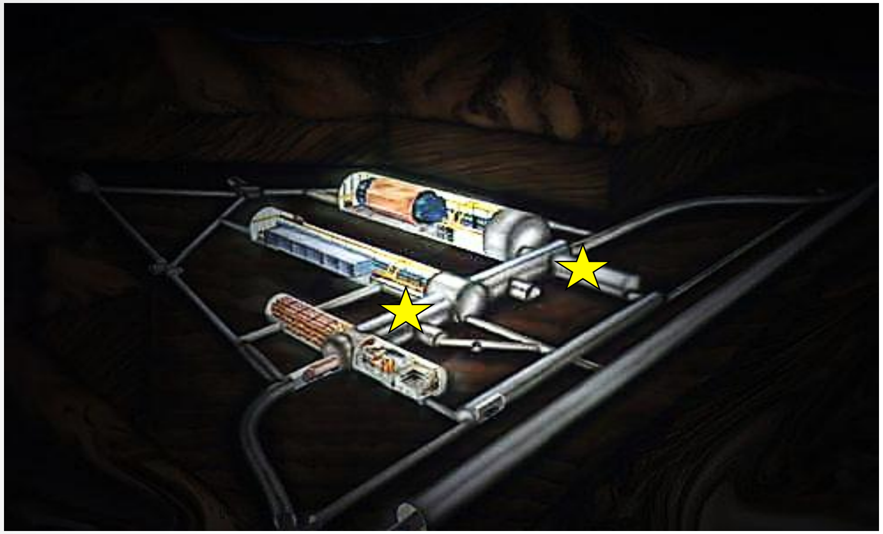
$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \cong S_{0,k} + S_{m,k} \cos[\omega(t-t_0)]$$

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

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

DAMA set-ups

an observatory for rare processes @ LNGS



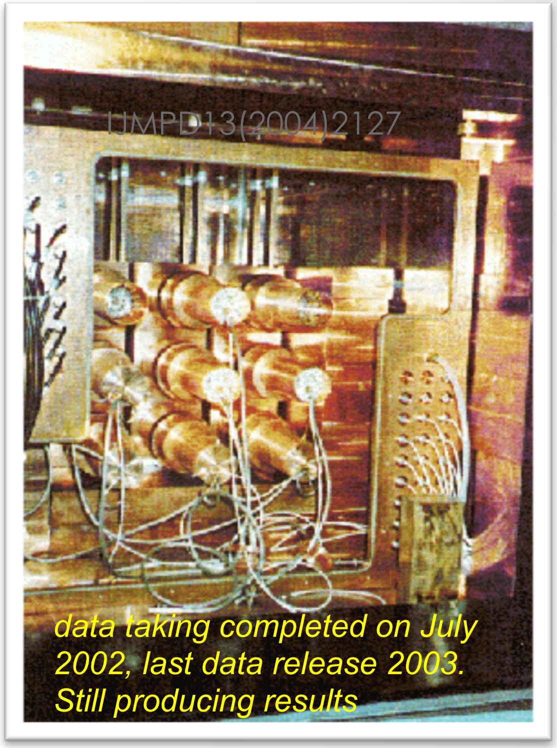
- DAMA/LIBRA (DAMA/NaI)
- DAMA/LXe
- DAMA/R&D
- DAMA/Crys
- DAMA/Ge

Collaboration:

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

Web Site: http://people.roma2.infn.it/dama

The pioneer DAMA/NaI: ≈100 kg highly radiopure NaI(Tl)



Performances:

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

Results on rare processes:

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

Results on DM particles:

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

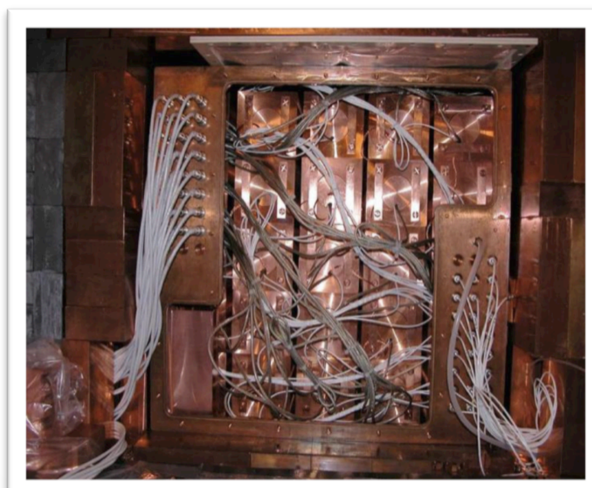
Model independent evidence of a particle DM component in the galactic halo at 6.3 σ C.L.

total exposure (7 annual cycles) 0.29 ton×yr

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

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

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

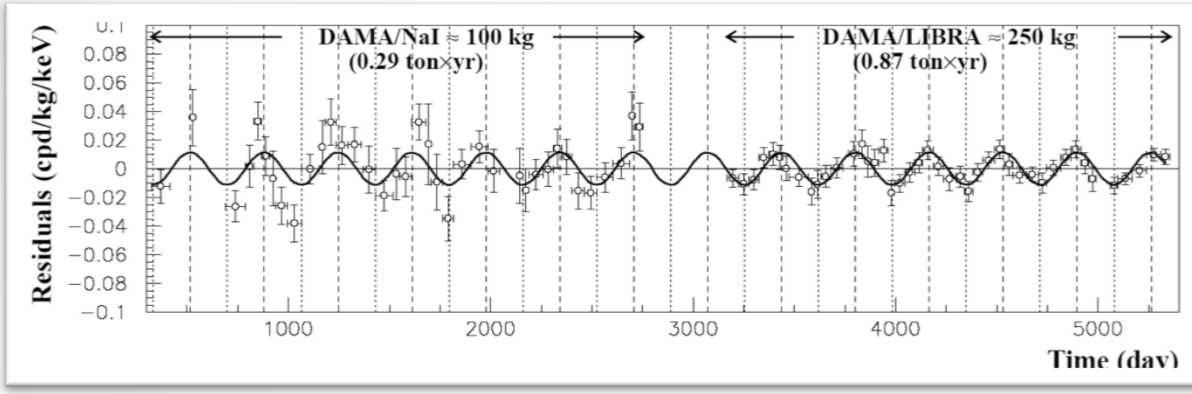


Radiopurity, performances, procedures, etc.: **NIMA592(2008)297, JINST 7 (2012) 03009**
Results on DM particles, Annual Modulation Signature: **EPJC56(2008)333, EPJC67(2010)39**
Results on rare processes: PEP violation **EPJC62(2009)327** CNC in I **EPJC72(2012)1920**

Model Independent Annual Modulation Result

DAMA/NaI (7 years) + **DAMA/LIBRA** (6 years) Total exposure: 425428 kg×day = **1.17 ton×yr**

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



EPJC 56(2008)333, EPJC 67(2010)39

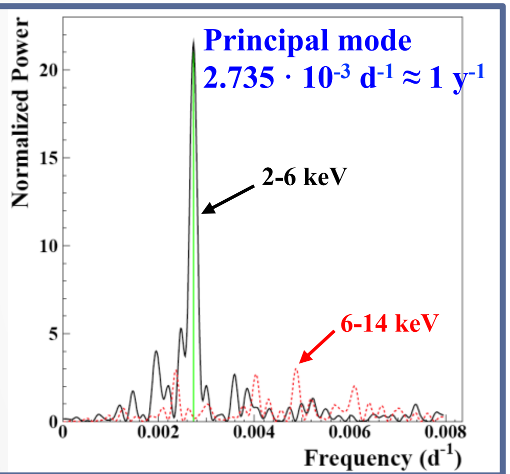
continuous line: t_0 = 152.5 d, T =1.0 y

A=(0.0114±0.0013) cpd/kg/keV
χ^2/dof = 64.7/79 8.8 σ C.L.

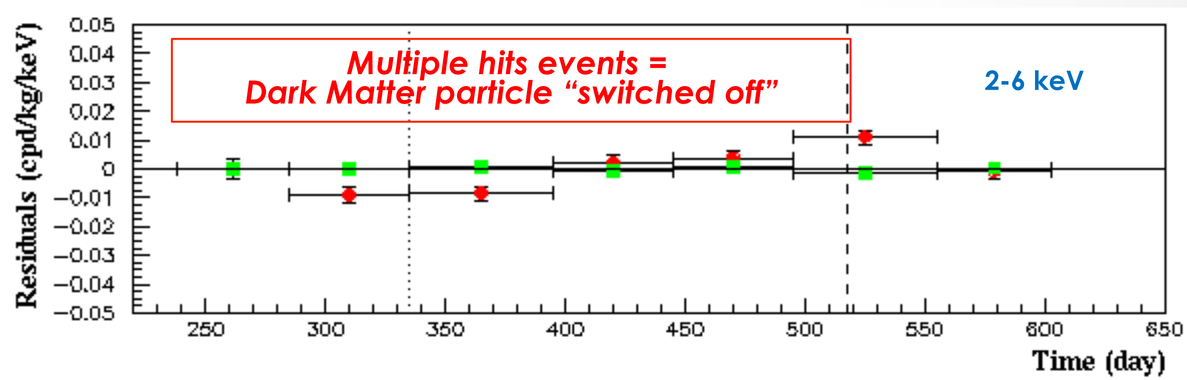
Absence of modulation? No
χ^2/dof=140/80 P(A=0) = 4.3×10^{-5}

fit with all the parameters free:
A = (0.0116 ± 0.0013) cpd/kg/keV
t_0 = (146±7) d - T = (0.999±0.002) y

Power spectrum



Comparison between **single hit residual rate (red points)** and **multiple hit residual rate (green points)**; Clear modulation in the single hit events; No modulation in the residual rate of the multiple hit events
A=-(0.0006±0.0004) cpd/kg/keV



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

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

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

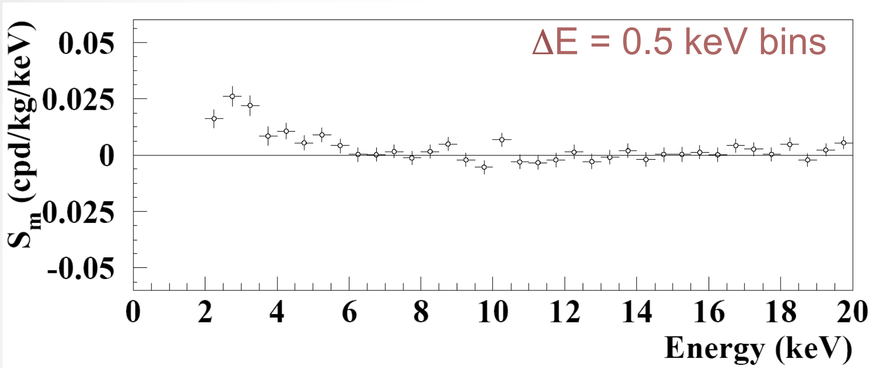
Model Independent Annual Modulation Result

DAMA/NaI (7 years) + **DAMA/LIBRA** (6 years)   Total exposure: 425428 kg×day = **1.17 ton×yr**

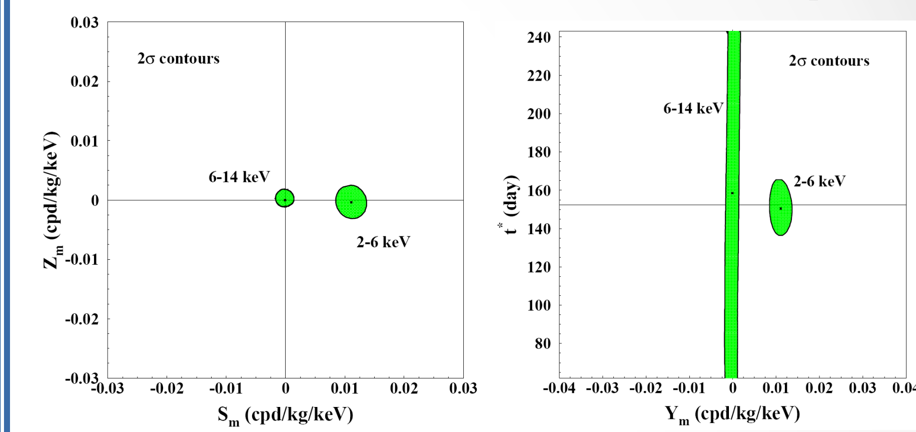
EPJC 56(2008)333, EPJC 67(2010)39

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

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

Summary of the results obtained in the additional investigations of possible systematics or side reactions

(NIMA592(2008)297, EPJC56(2008)333, arXiv:0912.0660, Can. J. Phys. 89 (2011) 11, S.I.F.Atti Conf.103 (211) (arXiv:1007.0595), PhysProc37(2012)1095, EPJC72(2012)2064 and refs therein)

Source	Main comment	Cautious upper limit (90%C.L.)
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	**$<2.5\times10^{-6}$ cpd/kg/keV**
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	**$<10^{-4}$ cpd/kg/keV**
NOISE	Effective full noise rejection near threshold	**$<10^{-4}$ cpd/kg/keV**
ENERGY SCALE	Routine + intrinsic calibrations	**$<1\text{-}2\times10^{-4}$ cpd/kg/keV**
EFFICIENCIES	Regularly measured by dedicated calibrations	**$<10^{-4}$ cpd/kg/keV**
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV *multiple-hits* events; this limit includes all possible sources of background	**$<10^{-4}$ cpd/kg/keV**
SIDE REACTIONS	Muon flux variation measured at LNGS	**$<3\times10^{-5}$ cpd/kg/keV**

+ they cannot satisfy all the requirements of annual modulation signature

→ **Thus, they cannot mimic the observed annual modulation effect**

No role for μ in DAMA annual modulation result

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

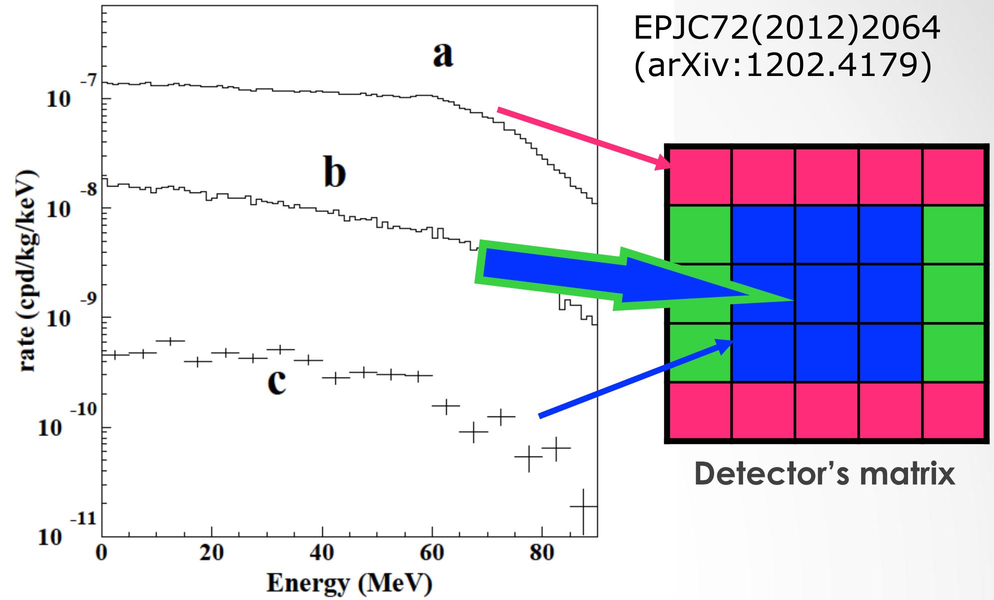
DAMA/LIBRA surface ≈0.13 m^2
μ flux @ DAMA/LIBRA ≈2.5 μ/day

MonteCarlo simulation:

- muon intensity distribution
- Gran Sasso rock overburden map
- Single hit events

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

EPJC72(2012)2064
(arXiv:1202.4179)



Detector's matrix

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

$$R_n = (\text{fast n by } \mu)/(\text{time unit}) = \Phi_\mu \, Y \, M_{eff}$$

- Φ_μ @ LNGS ≈ 20 μ $m^{-2}d^{-1}$ (±1.5% modulated)
- Measured neutron Yield @ LNGS:

$Y=1\div7 \; 10^{-4}$ n/μ/(g/cm^2)

Annual modulation amplitude at low energy due to **μ modulation**:

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

g = geometrical factor;
ε = detection eff. by elastic scattering
f_{DE} = energy window (E>2keV) effic.;
f_{single} = single hit effic.

Hyp.: M_{eff} = 15 tons; $g \approx \varepsilon \approx f_{\Delta E} \approx f_{single} \approx 0.5$ (cautiously)
Knowing that: M_{setup} ≈ 250 kg and ΔE=4keV

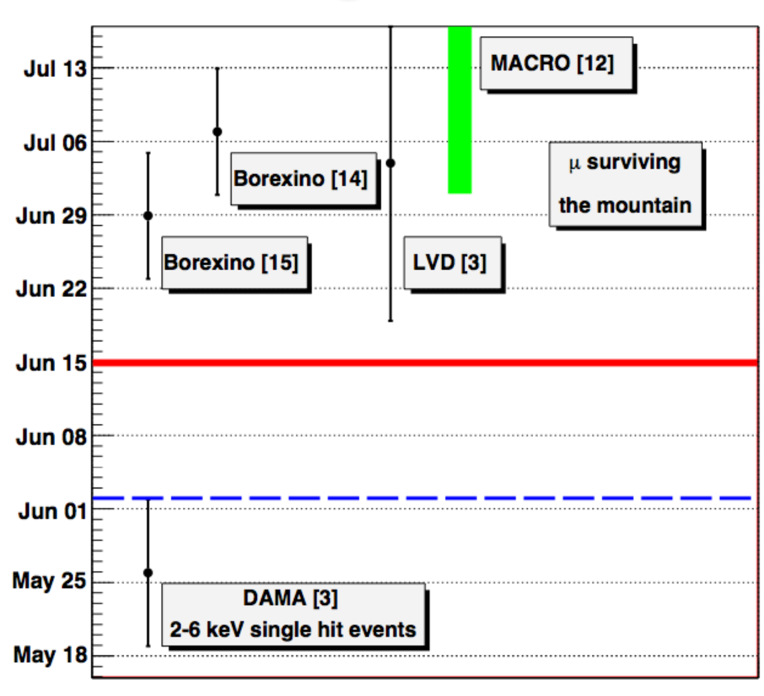
$S_m^{(m)} < (0.3\text{-}2.4) \times 10^{-5}$ cpd/kg/keV

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

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

Example: inconsistency of the phase between DAMA signal and μ modulation

For many others arguments EPJC72(2012)2064



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

but

- the muon phase differs from year to year (error no purely statistical); LVD/BOREXINO value is a "mean" of the muon phase of each year
- The DAMA: modulation amplitude 10^{-2} cpd/kg/keV, in 2-6 keV energy range for single hit events; phase:
  May 26 ± 7 days (stable over 13 years)

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

considering the seasonal weather al LNGS, quite impossible that the max. temperature of the outer atmosphere (on which μ flux variation is dependent) is observed e.g. in June 15 which is 3 σ from DAMA

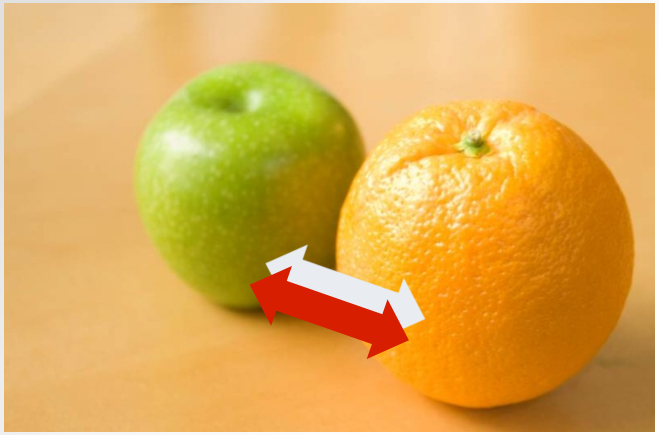
Can (whatever) hypothetical cosmogenic products be considered as side effects, assuming that they might produce:

- only events at low energy,
- only *single-hit* events,
- no sizable effect in the *multiple-hit* counting rate
- pulses with time structure as scintillation light

But, its phase should be (much) larger than μ phase, t_μ :

- if $\tau \ll T/2\pi$: $t_{side} = t_\mu + \tau$
- if $\tau \gg T/2\pi$: $t_{side} = t_\mu + T/4$

It cannot mimic the signature: different phase



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

…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?
- ...

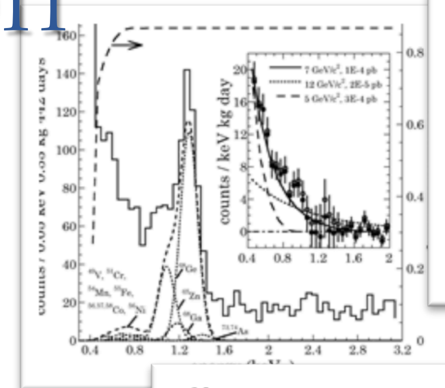
…and experimental aspects…

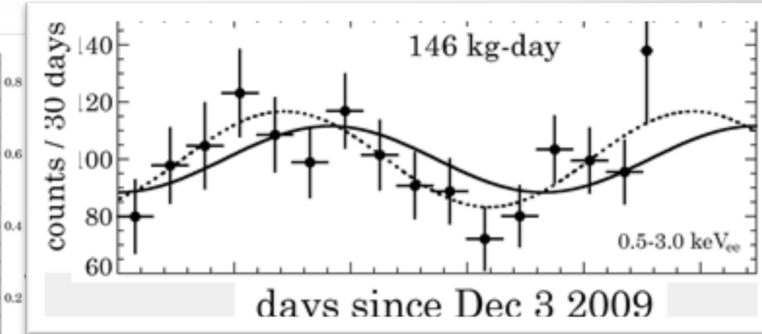
- Exposures
- Energy threshold
- Detector response (phe/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities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

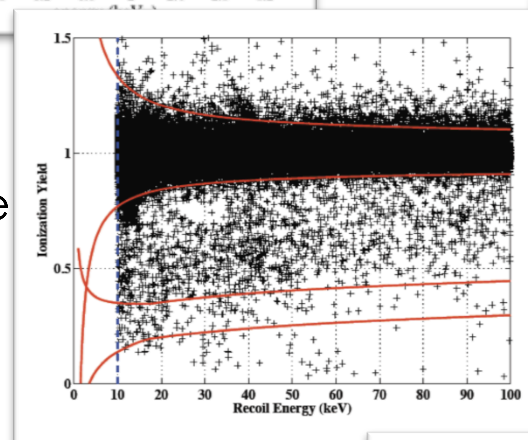
DAMA/NaI & DAMA/LIBRA vs recent possible positive hints 2010/2011

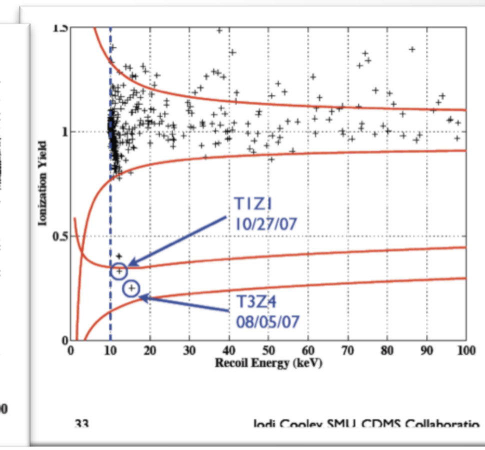




CoGeNT:

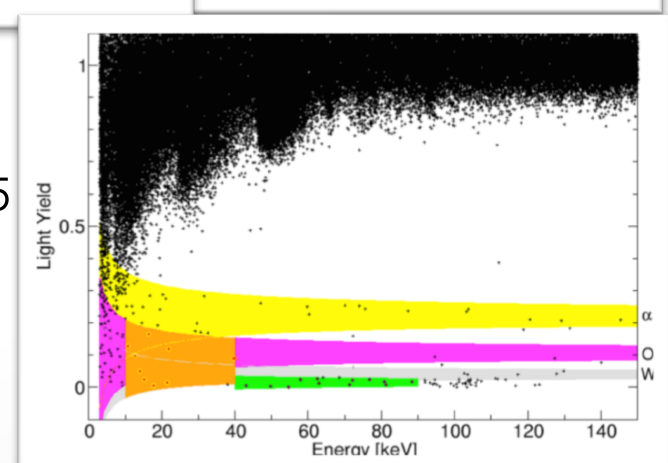
low-energy rise in the spectrum (irreducible by the applied background reduction procedures)
+ annual modulation





CDMS:

after many data selections and cuts, 2 Ge candidate recoils survive in an exposure of 194.1 kg x day (0.8 estimated as expected from residual background)



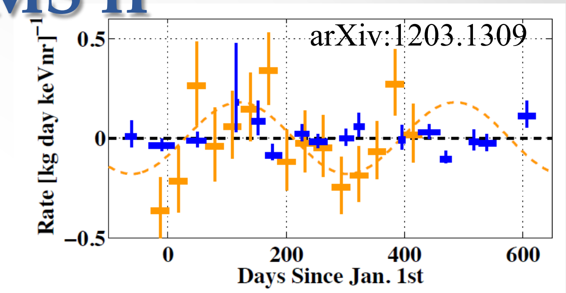
CRESST:

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

All those excesses are compatible with the DAMA 8.9σ C.L. annual modulation result in various scenarios

Comparison between CoGeNT and CDMS II

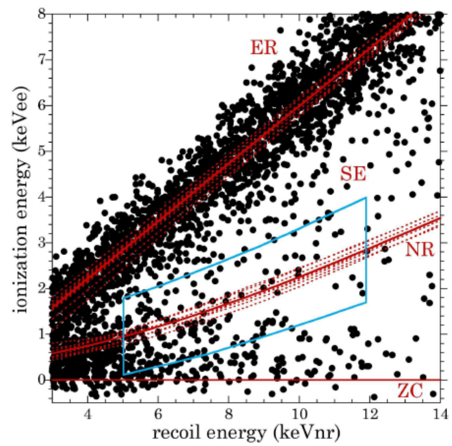
Same target material, germanium, but orthogonal background cuts



The CDMS exposure starts in late 2007, while the CoGeNT exposure starts in late 2009.

Remarks:

- **modulation by CoGeNT in 0.50-3.0 keVee, corresponding ~ 2.3-11.2 keVnr**
- **CDMS data in 5.0-11.9 keVnr**
  Just a part of the CoGeNT data can be compared with CDMS
- **detectors used by CDMS in this analysis are 8 over 30**
- **CDMS data are not continuous over the nearly two years of exposure and not involved for the whole annual periods**



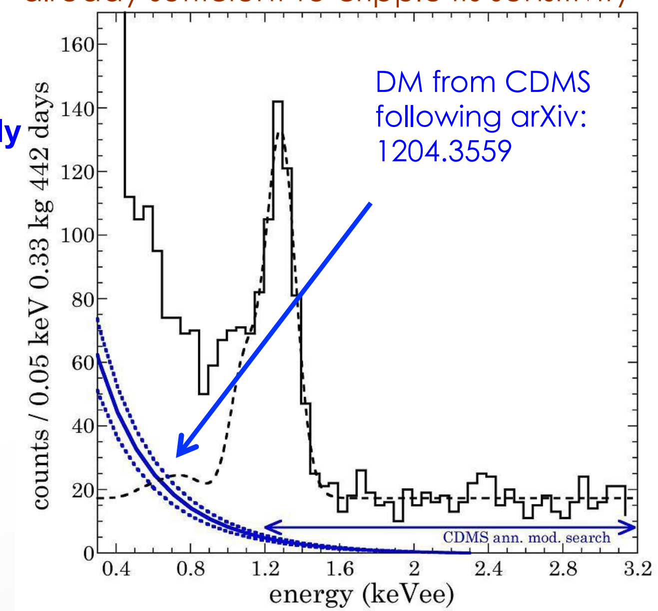
CDMS II rate in nuclear-recoil band for 5.0-11.9 keVnr interval after subtracting the best-fit unmodulated rate for each detector

CoGeNT rate (assuming a nuclear-recoil energy scale) and maximum-likelihood modulation model in this energy range. Energy bin = 1.21-3.20 keVee

Important additional concerns (see e.g. arXiv:1204.3559):

- **non-overlapping time periods from detectors spanning an order of magnitude in background rate within the signal box**
- **Negligible overlap with the CoGeNT region containing excess**
- **unresolved issues related to CDMS's energy scales.**

the choice of signal box boundaries (poor signal-to- background ratio) is already sufficient to cripple its sensitivity



CDMS data strongly support (5.7 σ C.L.) the presence of a family of low-energy events in the nuclear recoil band. An origin in neutron scattering is highly unlikely

Data quality cuts reduce the usable live-time of CDMS detectors to less than 50% of the already discontinuous detector-specific live periods. In the extreme case of T3Z2, just 10% of the exposure was used for the analysis. Operational stability of detectors is an important prerequisite for a modulation search.

… recent search for an annual modulation signal by the CDMS collaboration is insufficiently sensitive to exclude a dark matter origin for this excess, due to an inadequate selection of analysis region. Unsupported quantitative statements made in about background composition in CDMS detectors are not compatible with CoGeNT findings.

If this excess is interpreted as a WIMP signal, it is compatible with DAMA, CoGeNT and CRESST

From talk by Collar IDM2012

"À la guerre comme à la guerre"

CDMS Q&A, yesterday's afternoon funfest:

- "No, we never looked at the data from the eight detectors overlapped"
- "No, we never performed an annual modulation search at lower energy"

(Third time I get the same replies, from different CDMS speakers)

> From: [redacted]
> Date: Thu, 12 May 2011 10:14:04 -0500
> To: [redacted]
> Cc: CDMS Analysis <cdms_analysis@fnal.gov>
> Subject: Radon variation at Soudan
>
> As I mentioned at the meeting yesterday, Radon concentrations also vary seasonally (and also daily) at Soudan. Our own measurements (figure attached) use a well-calibrated sensitive instrument (Rad7), but our sampling has not been thorough enough to pin down the phase accurately. MINOS has been using a less precise instrument, but they have kept it automatically sampling every hour since Nov 2007 (only partly overlapping our data sets). It is clear that the Radon seasonal variation has a phase that drifts somewhat between early August and early September, and that the curve is not purely sinusoidal. If this is the cause of the variation [redacted] sees in our low threshold NR region, it should show up more clearly when we look at ER's. Both we and Cogent do have Radon purges, but it is possible that neither is quite good enough.

Orthogonal axis:

That is a remarkably taut ship, but I worry about the values we are instilling in our students, and the general (mental) health of this field.

"All is fair in love and war"

Interpretation of the model independent DAMA results in the case of a DM candidate with SI coupling

Comparison of allowed regions and supersymmetric expectations (points and light blue region) in MSSM where:

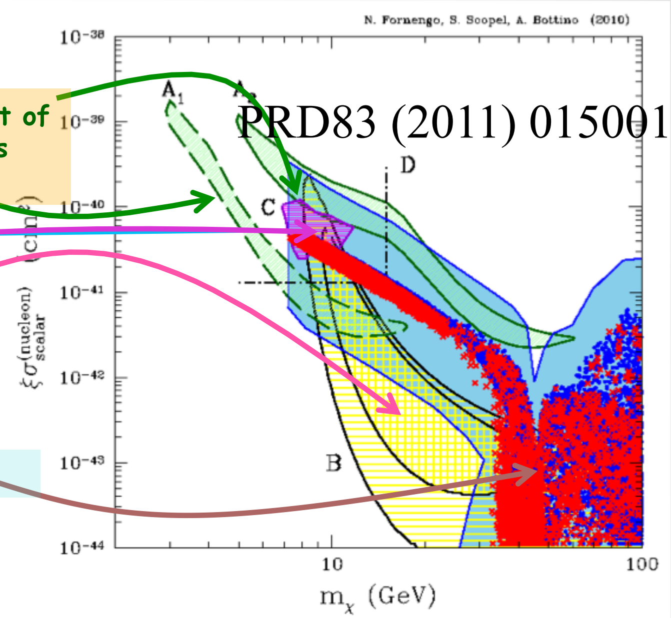
- for the neutralino a dominant purely SI coupling is assumed
- the gaugino mass unification at GUT scale: $M_1/M_2 \neq 0.5$ (<) is released (where M_1 and M_2 U(1) and SU(2) gaugino masses)

DAMA allowed regions for a particular set of astrophysical, nuclear and particle Physics assumptions with and without channeling

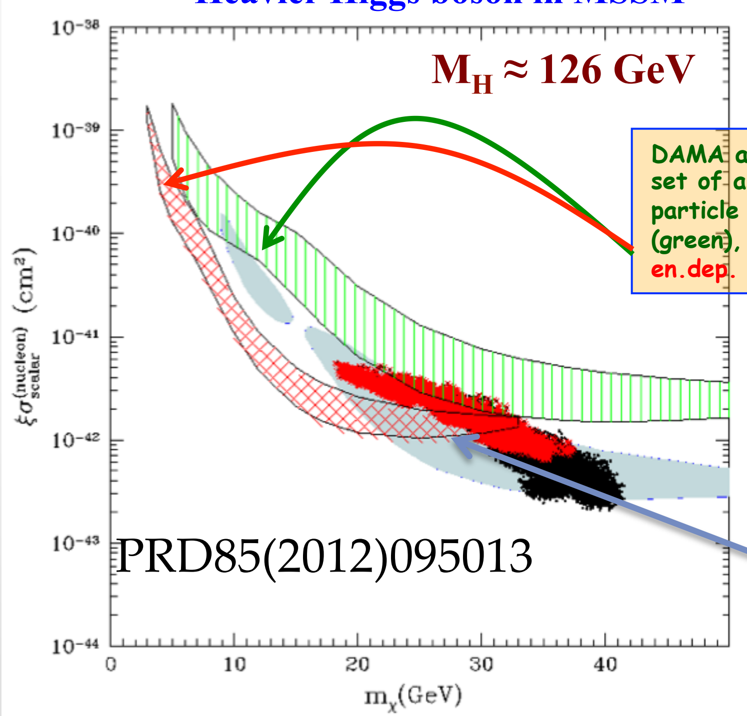
CoGeNT and CRESST

If the two CDMS events are interpreted as relic neutralino interactions

Relic neutralino in effMSSM



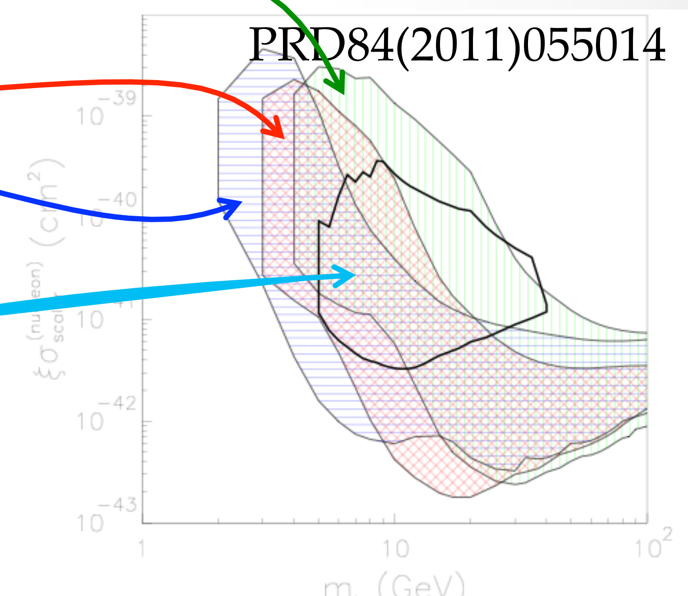
Heavier Higgs boson in MSSM



DAMA allowed regions for a particular set of astrophysical, nuclear and particle Physics assumptions without (green), with (blue) channeling, with en.dep. Q.F.(red)

CoGeNT

CRESST



Another example of compatibility

DM particle with preferred inelastic interaction

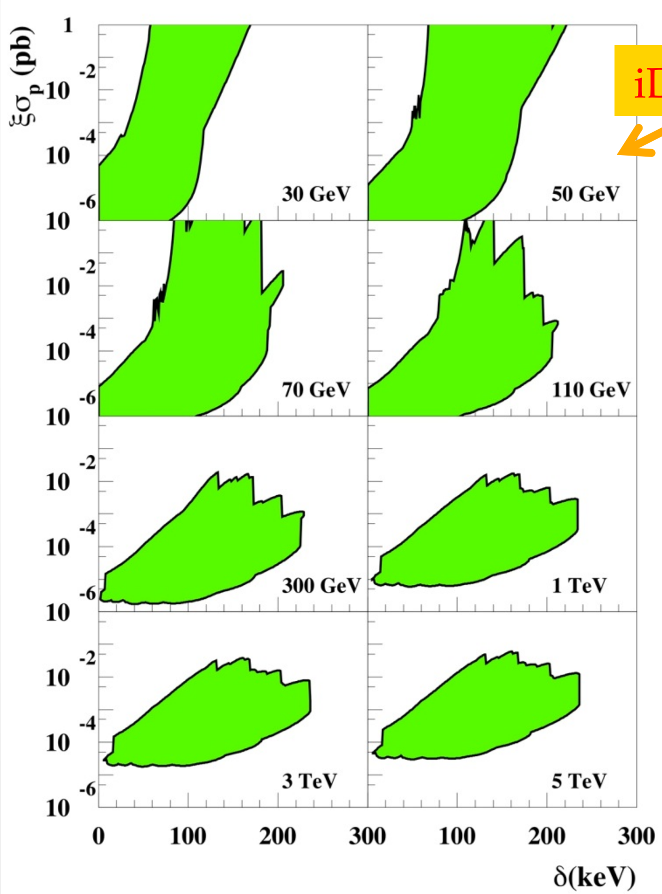
In the Inelastic DM (iDM) scenario, WIMPs scatter into an excited state, split from the ground state by an energy comparable to the available kinetic energy of a Galactic WIMP.

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

- 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

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

well compatible with several candidates

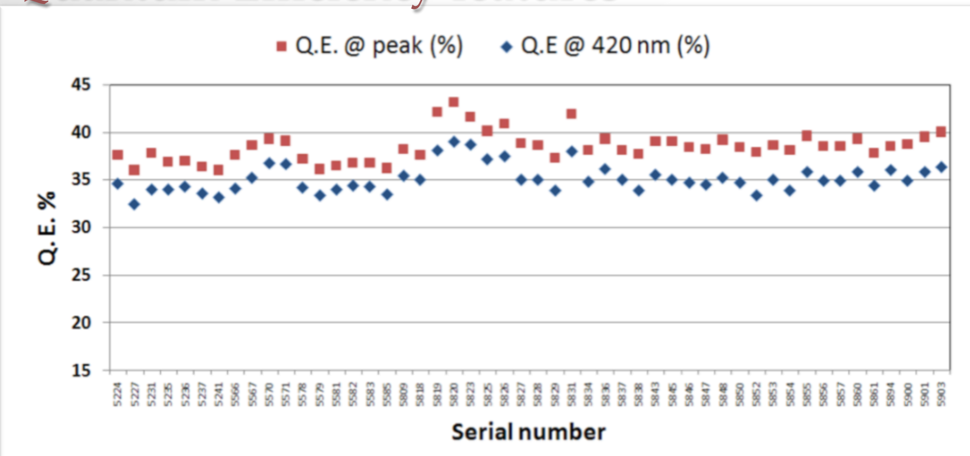
(in many possible astrophysical, nuclear and particle physics scenarios)

- Low mass neutralino (PRD81(2010)107302, PRD83(2011)015001, arXiv:1003.0014,arXiv:1007.1005, arXiv:1009.0549, PRD84(2011)055014, arXiv:1112.5666, PRD85(2012)095013)
- Next-to-minimal models (JCAP0908(2009)032, PRD79(2009)023510, JCAP0706(2007)008, arXiv:1009.2555,1009.0549)
- Mirror DM in various scenarios (arXiv:1001.0096, 1106.2688, PRD82(2010)095001, JCAP1107(2011)009, JCAP1009(2010)022, arXiv:1203.2387)
- Light scalar WIMP through Higgs portal (PRD82(2010)043522, JCAP0810(2010)034)
- Isospin-Violating Dark Matter (JCAP1008(2010)018, arXiv:1102.4331,1105.3734)
- Sneutrino DM (JHEP0711(2007)029, arXiv:1105.4878)
- Inelastic DM (PRD79(2009)043513, arXiv:1007.2688)
- Resonant DM (arXiv:0909.2900)
- DM from exotic 4th generation quarks (arXiv:1002.3366)
- Cogent results (arXiv:1002.4703, 1106.0650)
- DM from exotic 4th generation quarks (arXiv:1002.3366)
- Composite DM (IJMPD19(2010)1385)
- iDM on Tl (arXiv:1007:2688)
- Specific two higgs doublet models (arXiv:1106.3368)
- exothermic DM (arXiv:1004.0937)
- Secluded WIMPs (PRD79(2009)115019)
- Asymmetric DM (arXiv:1105.5431)
- Leptophobic Z0 models (arXiv:1106.0885)
- SD Inelastic DM (arXiv:0912.4264)
- Complex Scalar Dark Matter (arXiv:1005.3328)
- Singlet DM (JHEP0905(2009)036, arXiv:1011.6377)
- Specific GU (arXiv:1106.3583)
- **Long range forces** (arXiv:1108.4661)

… and more (JCAP1008(2010)018, arXiv:1105.5121,1011.1499, arXiv:1108.1391, arXiv:1109.2722, arXiv:1110.5338, arXiv:1112.5457, …)

The new PMTs

Quantum Efficiency features

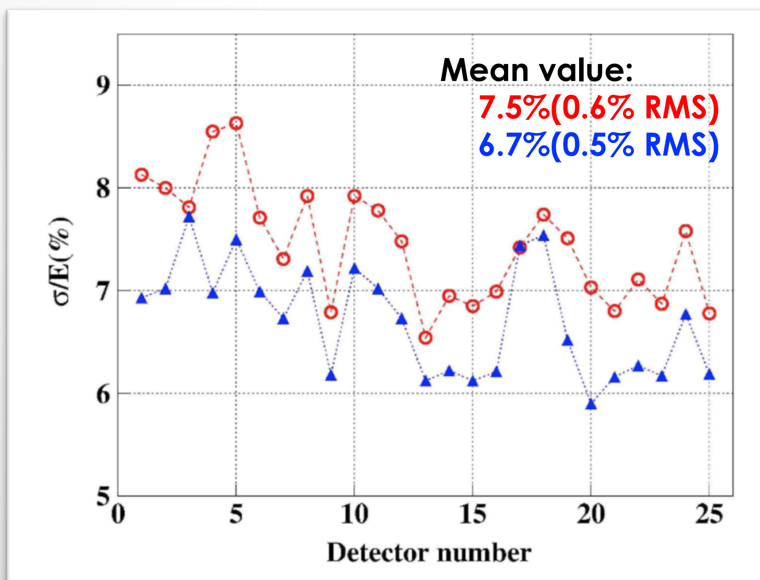


Residual Contamination

The limits are at 90% C.L.

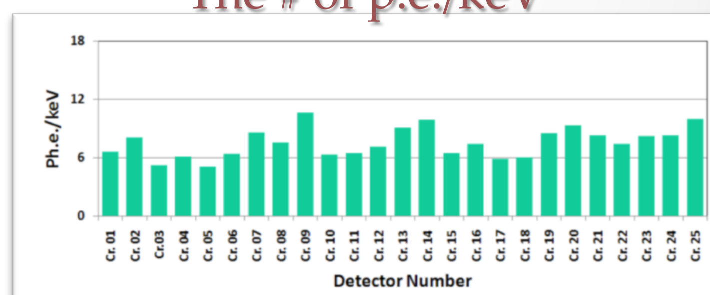
PMT	Time (s)	Mass (kg)	^{226}Ra (Bq/kg)	^{234m}Pa (Bq/kg)	^{235}U (mBq/kg)	^{228}Ra (Bq/kg)	^{228}Th (mBq/kg)	^{40}K (Bq/kg)	^{137}Cs (mBq/kg)	^{60}Co (mBq/kg)
Average			*0.43*	*-*	*47*	*0.12*	*83*	*0.54*	*-*	*-*
Standard deviation			*0.06*	*-*	*10*	*0,02*	*17*	*0.16*	*-*	*-*

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 # of p.e./keV



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

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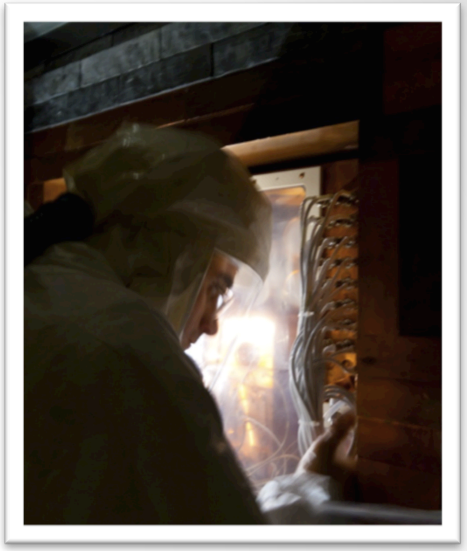
DAMA/LIBRA perspectives

Continuously running

- Replacement of all the PMTs with higher Q.E. ones done



- New PMTs with higher Q.E. :

- Continuing data taking in the new configuration with lower software energy threshold (below 2 keV).
- New preamplifiers and trigger modules realized to further implement low energy studies.
- Suitable exposure planned in the new configuration to deeper study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects.
- Investigation on dark matter peculiarities and second order effect
- Special data taking for other rare processes.

Conclusions

- Different **solid** techniques can give complementary results

- Some further efforts to demonstrate the solidity of some techniques are needed

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

- Positive evidence for the presence of DM particles in the galactic halo at 8.9 σ C.L. (cumulative exposure 1.17 ton × yr – 13 annual cycles DAMA/NaI and DAMA/LIBRA)

- Positive hints from CoGeNT and CRESST in direct searches – due to excesses above an evaluated background – are compatible with DAMA in many scenarios; null searches not in robust conflict, considering also the experimental and theoretical uncertainties.

- DAMA/LIBRA running in new configuration to collect very large exposure