(Particle) Dark Matter Direct Detection

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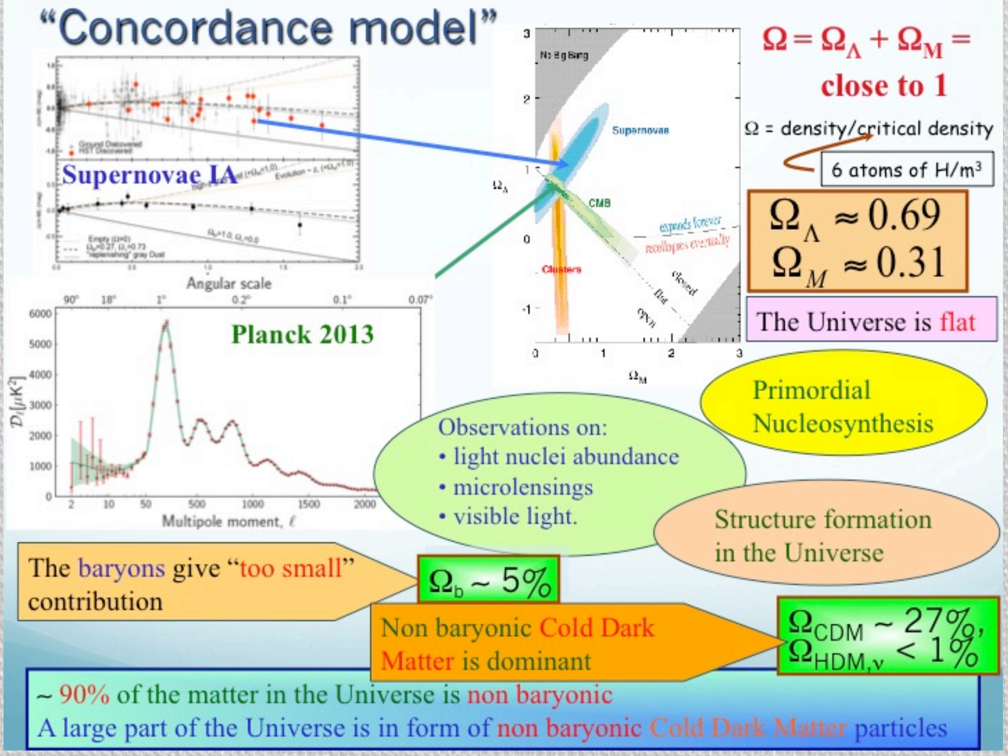
Dark Matter in the Universe

- A large part of the Universe is made of Dark Matter and Dark Energy
- The Dark Matter is fundamental for the formation of the structures and galaxies in the Universe
- The "baryonic" matter is only ≈5% of the total budget
- Concordance model and precision cosmology
- Non-baryonic Dark Matter is the dominant component (≈27%) in the matter.
- DM particles, possibly relics from Big Bang, with no e.m. and color charges → beyond the SM



"Concordance model"

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

Ω = density/critical density

6 atoms of H/m^3

$\Omega_\Lambda \approx 0.69$
$\Omega_M \approx 0.31$

The Universe is flat

Primordial Nucleosynthesis

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

Structure formation in the Universe

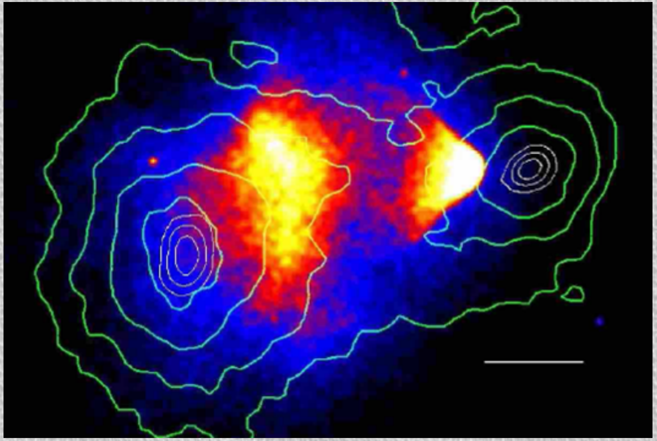
The baryons give "too small" contribution

$\Omega_b \sim 5\%$

Non baryonic Cold Dark Matter is dominant

$\Omega_{CDM} \sim 27\%$, $\Omega_{HDM,\nu} < 1\%$

~ 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



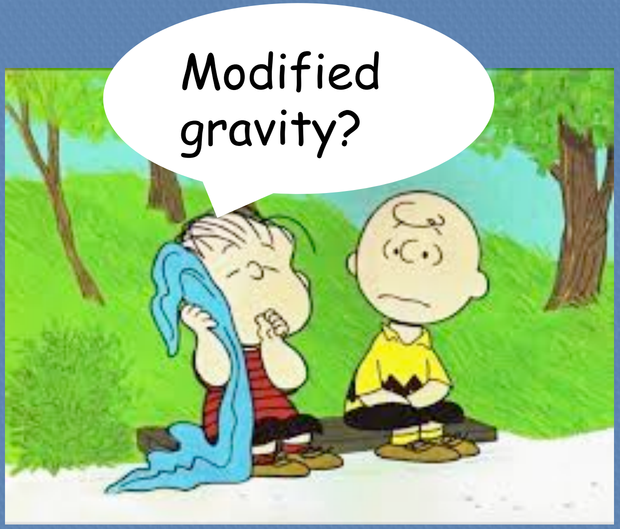
Efforts to find alternative explanations to DM proposed e.g.:

- ✓ Modified Gravity Theory (MOG)
- ✓ Modified Newtonian Dynamics (MOND) theory

They hypothesize that the theory of gravity is incomplete and that a new gravitational theory might explain the experimental observations:

- ✓ MOG modifies the Einstein's theory of gravitation to account for an hypothetical fifth fundamental force in addition to the gravitational, electromagnetic, strong and weak ones.

- ✓ MOND modifies the law of motion for very small accelerations



BUT

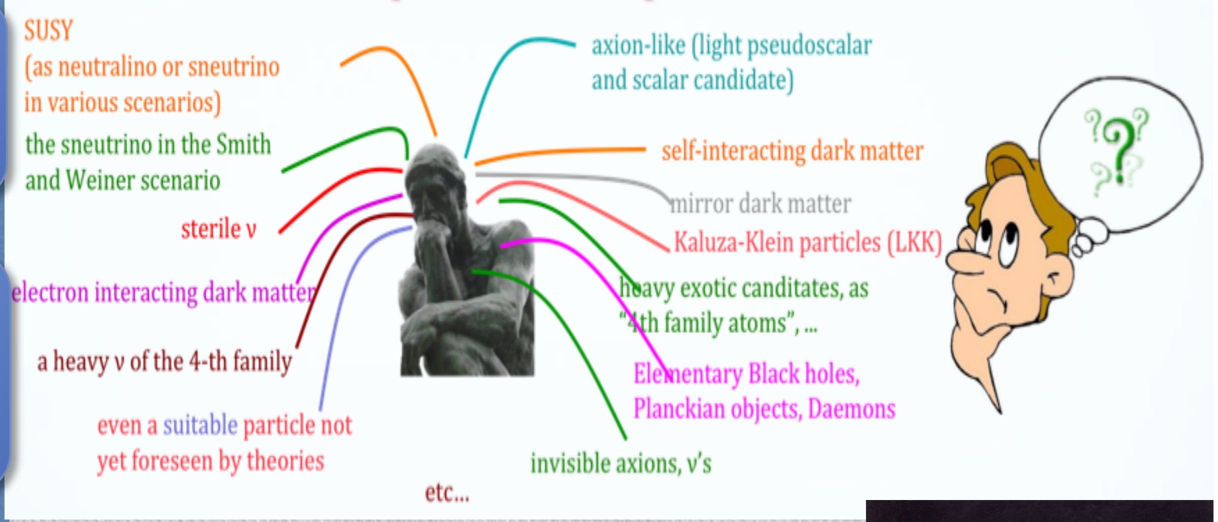
- ✓ no general underlying principle;
- ✓ generally unable to account for all small and large scale observations;
- ✓ fail to reproduce accurately the Bullet Cluster;
- ✓ generally require some amount of DM particles as seeds for the structure formation.

Relic DM particles from primordial Universe

What accelerators can do:
to demostrate the existence of some of the DM candidates

What accelerators cannot do:
to credit that a certain particle is a DM solution or the “only” DM particle solution…

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



SUSY
(as neutralino or sneutrino
in various scenarios)

the sneutrino in the Smith
and Weiner scenario

sterile ν

electron interacting dark matter

a heavy ν of the 4-th family

even a suitable particle not
yet foreseen by theories

etc…

axion-like (light pseudoscalar
and scalar candidate)

self-interacting dark matter

mirror dark matter

Kaluza-Klein particles (LKK)

heavy exotic canditates, as
“4th family atoms”, …

Elementary Black holes,
Planckian objects, Daemons

invisible axions, ν’s

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

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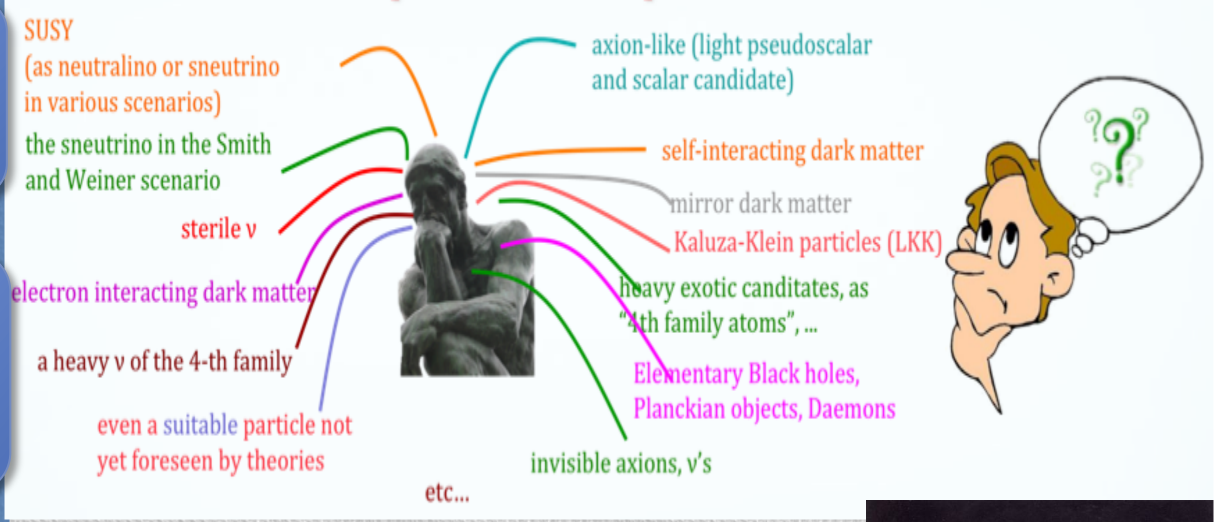

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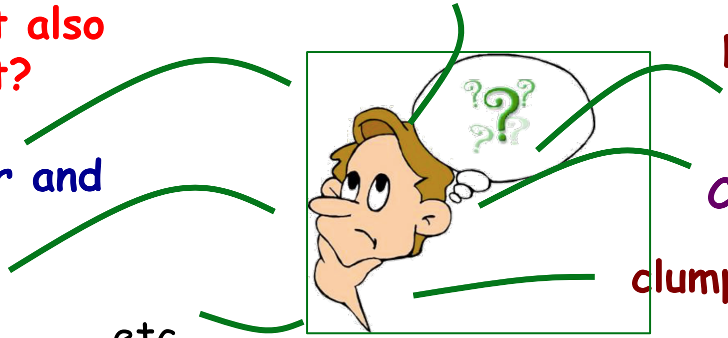


Right halo model and parameters?

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

etc

Non thermalized components?

Caustics?

clumpiness?

2 different questions:

✓ Are there Dark Matter particles in the galactic halo?

e.g.: The exploitation of the DM annual modulation signature with highly radiopure NaI(Tl) as target material can permit to answer to this question by direct detection and in a way largely independent on the nature of the candidate and on the astrophysical, nuclear and particle Physics assumptions → DAMA/NaI and DAMA/LIBRA

✓ Which is exactly the nature of the DM particle(s) and the related astrophysical, nuclear and particle Physics scenarios?

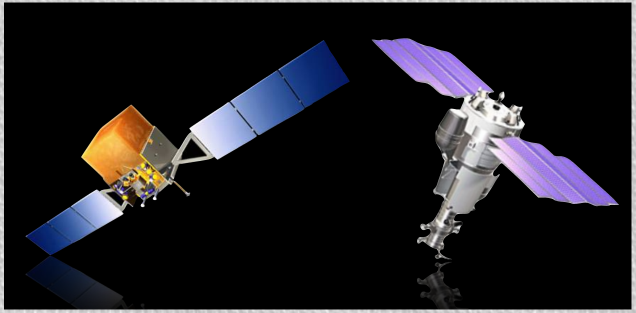
Always model-dependent corollary analyses required

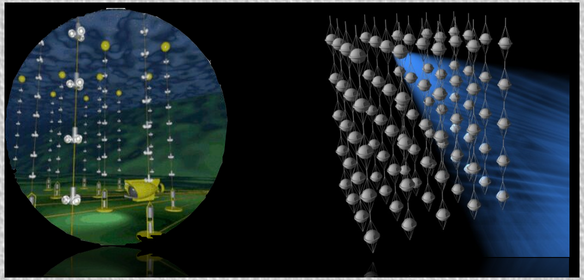
↓

REMARK: It does not exist any approach to investigate the nature of the candidate in the direct and indirect DM searches, which can offer this latter information independently on assumed astrophysical, nuclear and particle Physics scenarios...

Overcoming the problems of the indirect detection

- Indirect detection: measurement of secondary particles (ν's, γ's, antiparticles,...) may be produced by annihilation of some DM candidate in celestial bodies provided several assumptions are fulfilled (approach: continuous radiation damage + subtraction of unknown competing background + strongly model dependent + can require very high boost factor, ...)

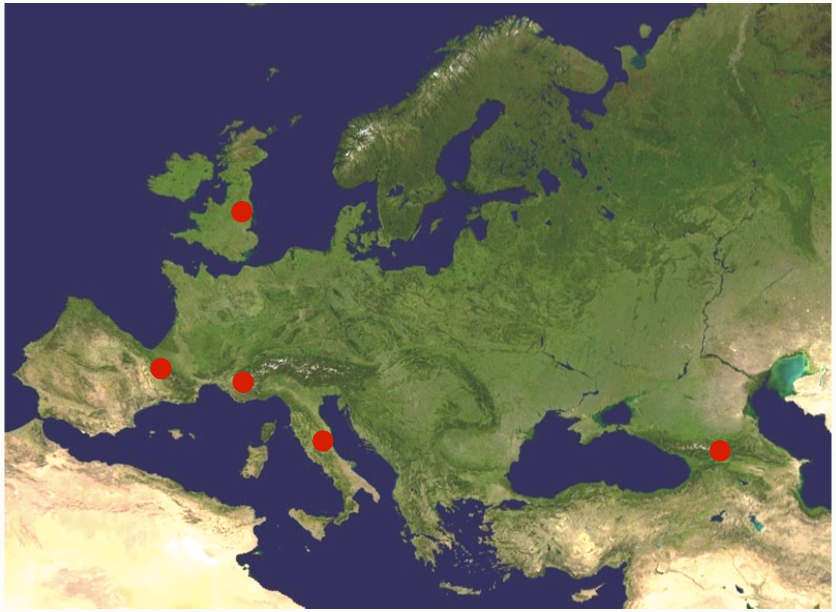




→ No direct model independent comparison possible with direct detection and accelerators

Dark Matter direct detection activities in underground labs

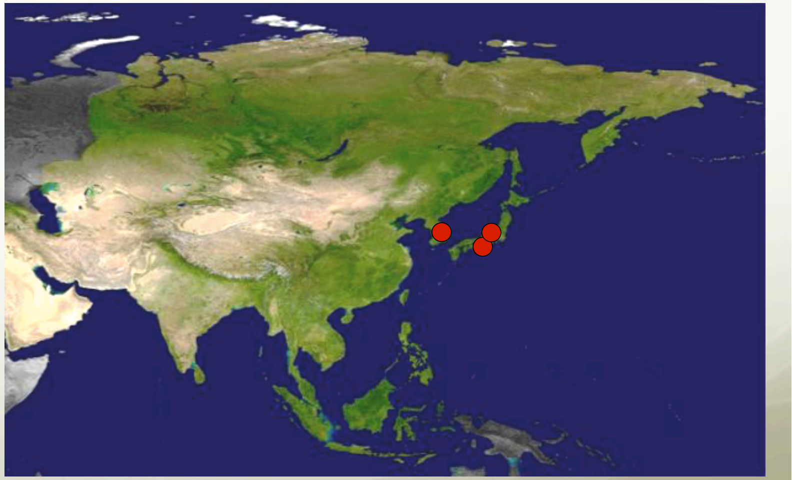
- Various approaches and techniques
- Various different target materials
- Various different experimental site depths
- Different radiopurity levels, etc.



- **Gran Sasso (depth ~ 3600 m.w.e.): DAMA/NaI, DAMA/LIBRA, DAMA/LXe, HDMS, WARP, CRESST, Xenon, DarkSide**
- **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, COUPP, DEAP, CLEAN, SuperCDMS**
- **Stanford (~10 m): CDMS I**
- **Soudan (~ 2000 m.w.e.): CDMS II, CoGeNT**
- **SURF (~4400 m.w.e.): LUX**
- **WIPP (~1600 m.w.e.): DMTPC**

- **South Pole: DM-ICE**



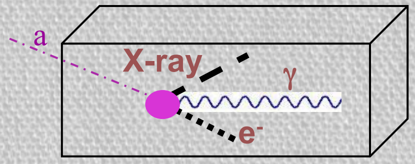
- **Y2L (depth ~ 700 m): KIMS**
- **Oto (depth ~ 1400 m.w.e.): PICO-LON**
- **Kamioka (depth ~2700 m.w.e.): XMASS, NEWAGE**

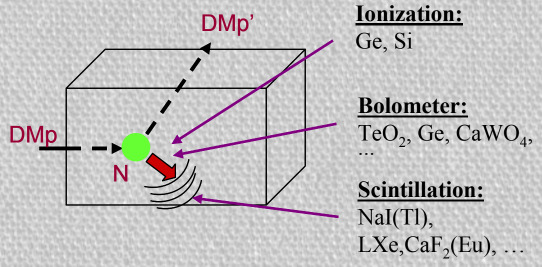
Direct detection experiments

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 electromagnetic productions)

→ Various different experimental observables





+ detection of "invisible" axions: ADMX; see Van Bibber talk in DM2 section

Some direct detection processes:

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

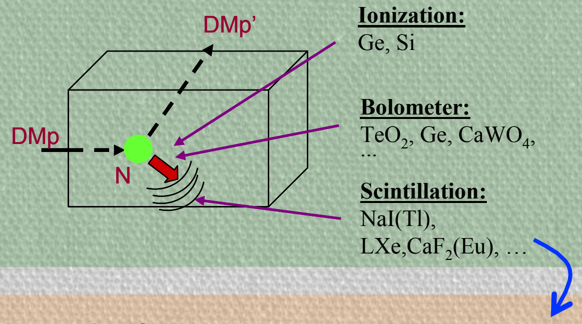
→ W has 2 mass states $\chi+$, $\chi-$ with δ mass splitting

→ Kinematic constraint for the inelastic scattering of $\chi-$ on a nucleus

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

- Elastic scatterings on nuclei

→ detection of nuclear recoil energy

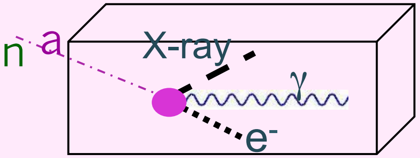


- Excitation of bound electrons in scatterings on nuclei

→ detection of recoil nuclei + e.m. radiation

- Conversion of particle into e.m. radiation

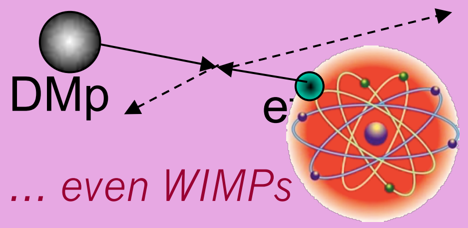
→ detection of γ, X-rays, e^-



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

- Interaction only on atomic electrons

→ detection of e.m. radiation

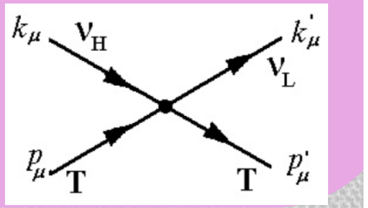


... even WIMPs

- 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

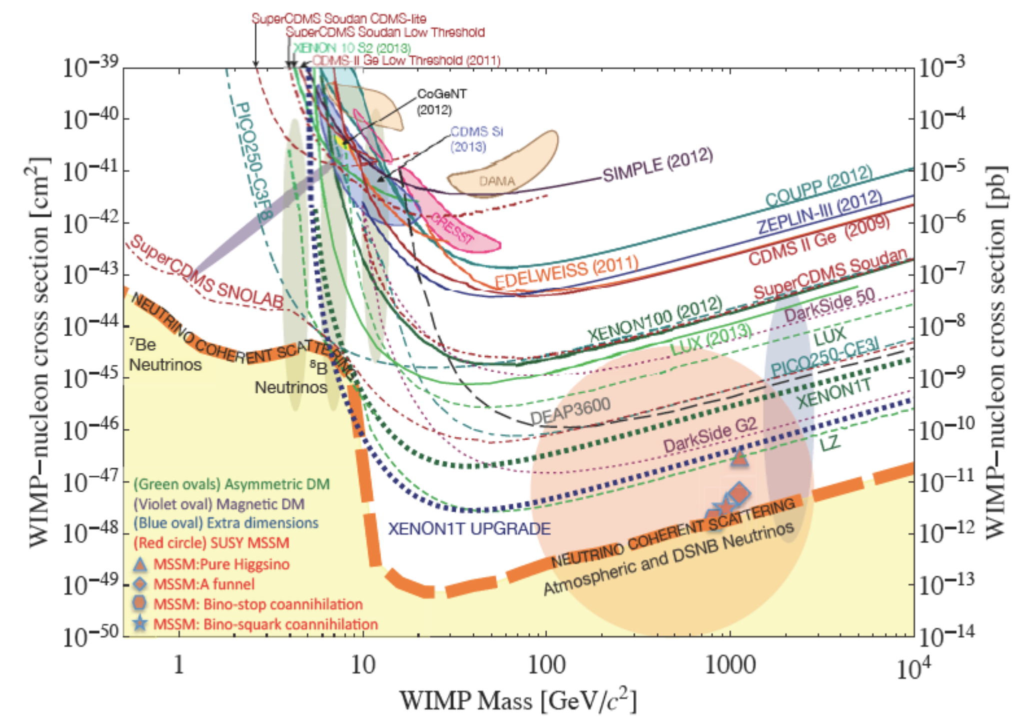


... also other ideas ...

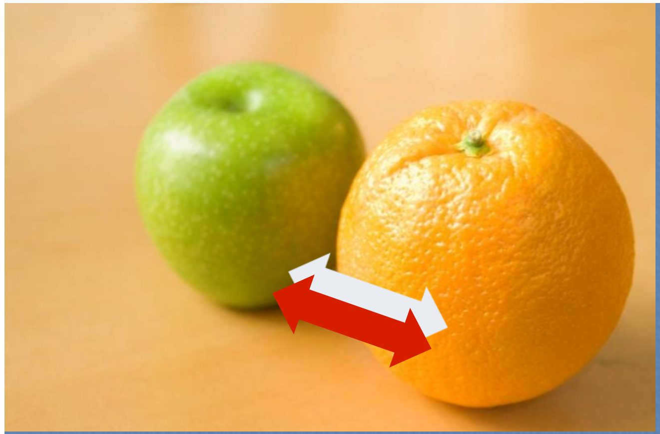
- ... and more

Is this an "universal" and "correct" way to approach the problem of DM, comparisons and perspectives?

- Has this anything to do with the nature and with a correct approach to the DM problem?
- Are the comparisons definitively right?
- Larger masses (in most cases is quoted much larger than fiducial one) do not imply automatically an increase of sensitivities! Generally assumed zero background! The sensitivity depends on many parameters and procedures! All of them must be suitably proved.
- Etc. etc.



This is just a largely arbitrary/partial/incorrect exercise



…models…

- Which particle?
- Which interaction?
- 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.

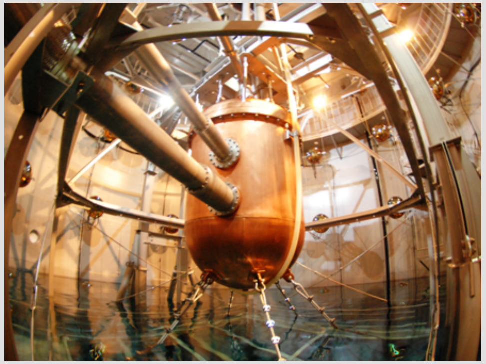
No direct model independent comparison possible among experiments using different target materials and/or approaches

Experiments using liquid noble gases

in single phase detector:

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

DAMA/LXe



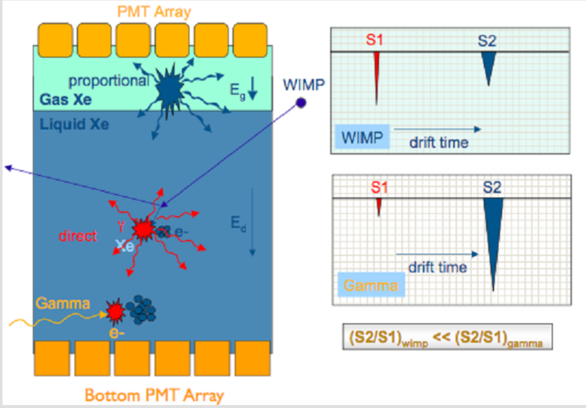
XMASS

in dual phase detector:

- prompt signal (S1): UV photons from excitation and ionization
- delayed signal (S2): e^- drifted into gas phase and secondary scintillation due to ionization in electric field

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

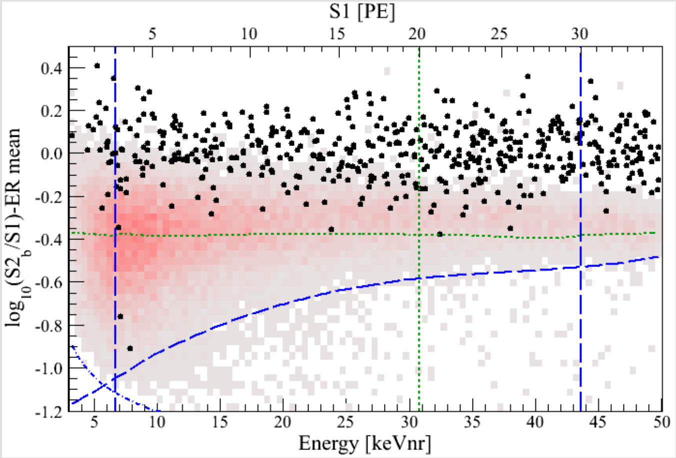
XENON10, 100, 1ton, WARP, DarkSide, LUX



- **Non-uniform** response of detector: intrinsic limit
- **UV light**, **unlinearity** (more in larger volumes)
- **Correction** procedures applied
- **Systematics**
- **Small light responses** (2.2 ph.e./keVee) ⇒ energy threshold at few keV unsafe
- Physical **energy threshold unproved** by source calibrations
- Poor energy **resolution**; resolution at threshold **unknown**
- **Light responses** for electrons and recoils at low energy
- **Quenching factors** measured with a much-more-performing detector **cannot be used** straightforward
- Etc.

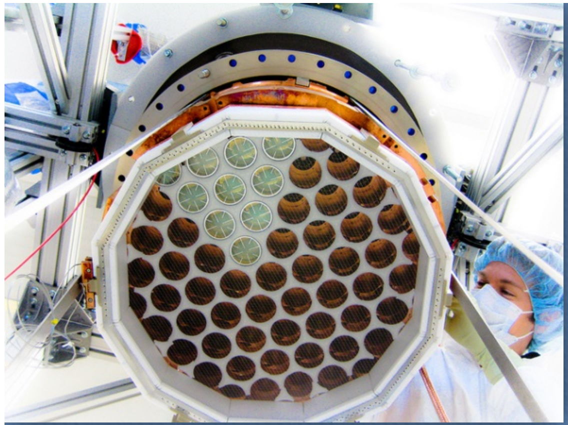
Many cuts applied, each of them can introduce systematics. The systematics can be variable along the data taking period; can they and the related efficiencies be suitably evaluated in short period calibration?

After many cuts few (two in XENON100) events survive: intrinsic limit reached?



Results from LUX

PRL112(2014)091303



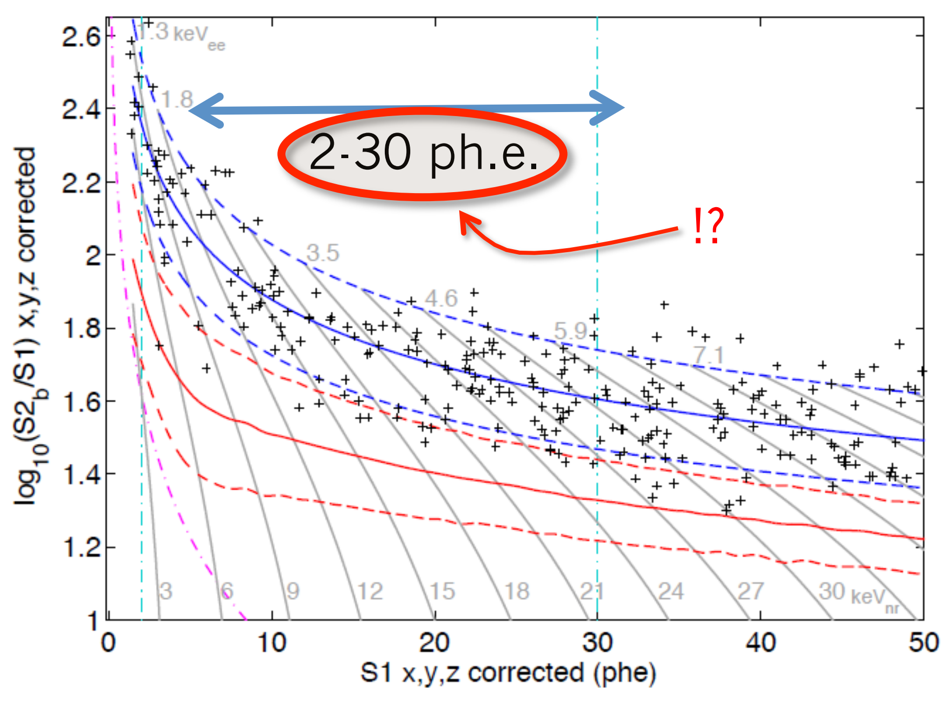
- Response: 8.8 phe/keV at 122 keV (and at low energy ? Low T?)
- Analysis applied after data cuts ("high" acceptance ?)
- Data events subtractions (efficiency ?)
- "WIMP" S1 and S2 expected reference distributions obtained by simulations
- Threshold: 2 phe ≈ 3 keV$_r$ (!?)
- 160 events after the cuts

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

Experimental site:	Sanford Underground Research Facility (SURF, 4300 m.w.e.)
Target mass:	(118.3±6.5) kg fiducial of 370 kg LXe (≈250 kg dual phase)
Live time:	85.3 days

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



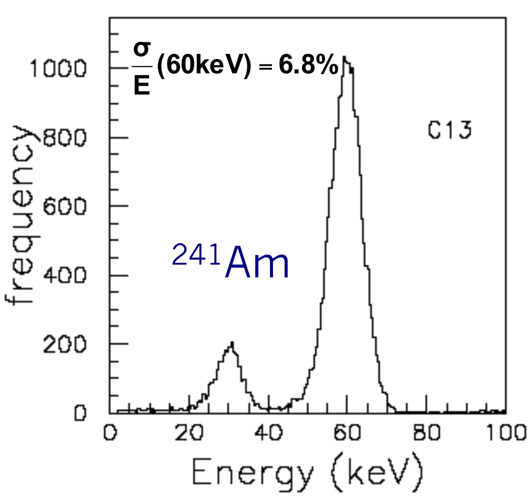
2-30 ph.e.

!?

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

Examples of energy resolutions

DAMA/LIBRA ULB NaI(Tl)



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

^{241}Am

ZEPLIN-II

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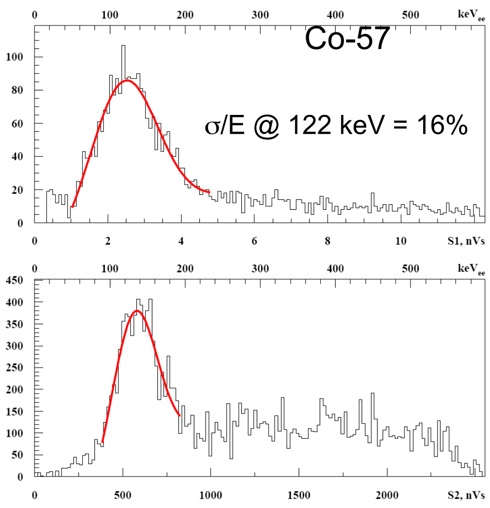

Co-57

σ/E @ 122 keV = 16%

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

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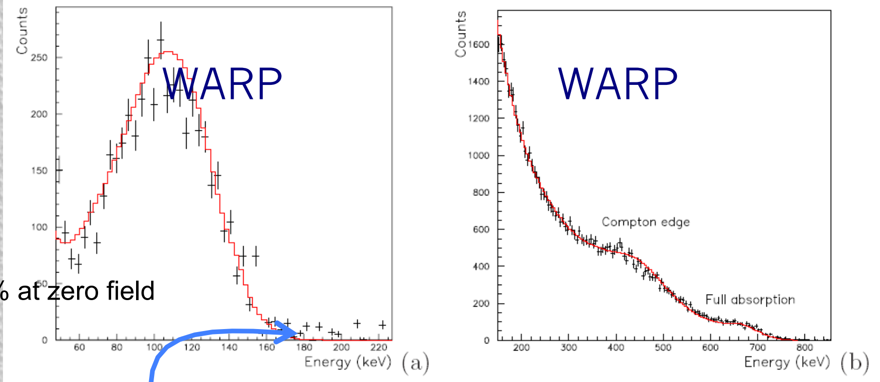
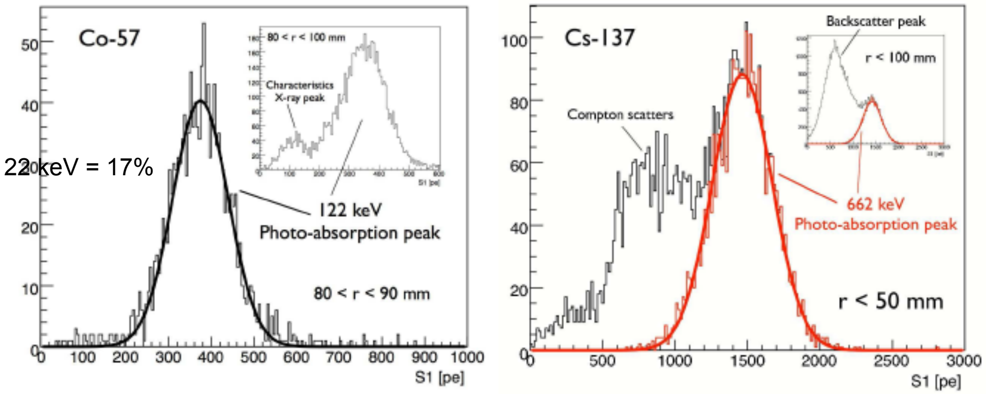


Fig. 2. Energy spectra taken with external γ-ray sources, superimposed with the corresponding Monte Carlo simulations. (a) ^{57}Co source ($E = 122$ keV, B.R. 85.6%, and 136 keV, B.R. 10.7%), (b) ^{137}Cs source ($E = 662$ keV).

σ/E @ 122 keV = 13% at zero field

subtraction of the spectrum ?

XENON10



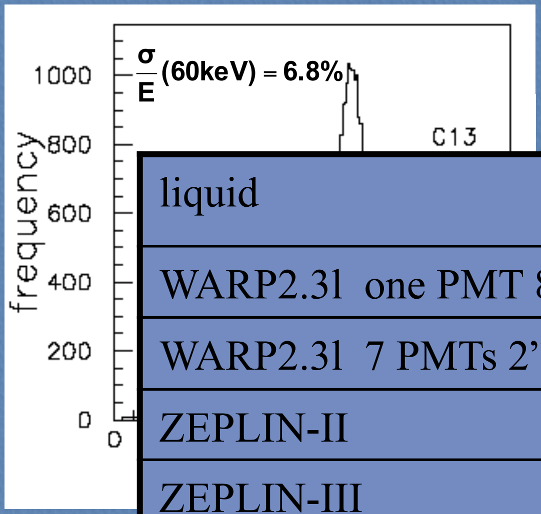
σ/E @ 122 keV = 17%

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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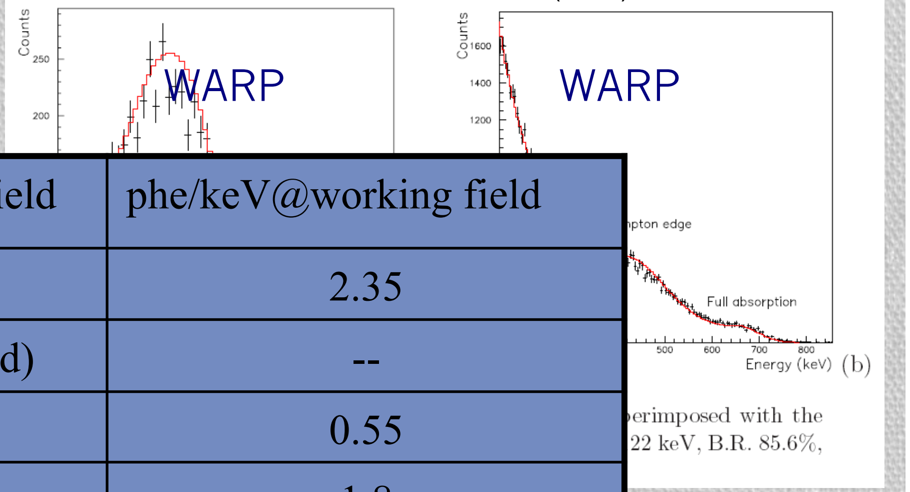

perimposed with the
22 keV, B.R. 85.6%,

rum ?

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

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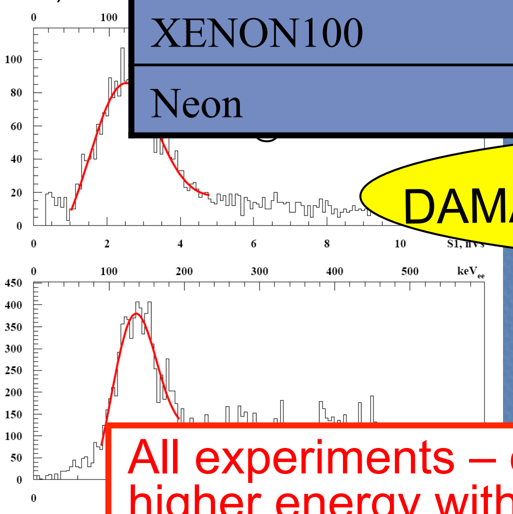

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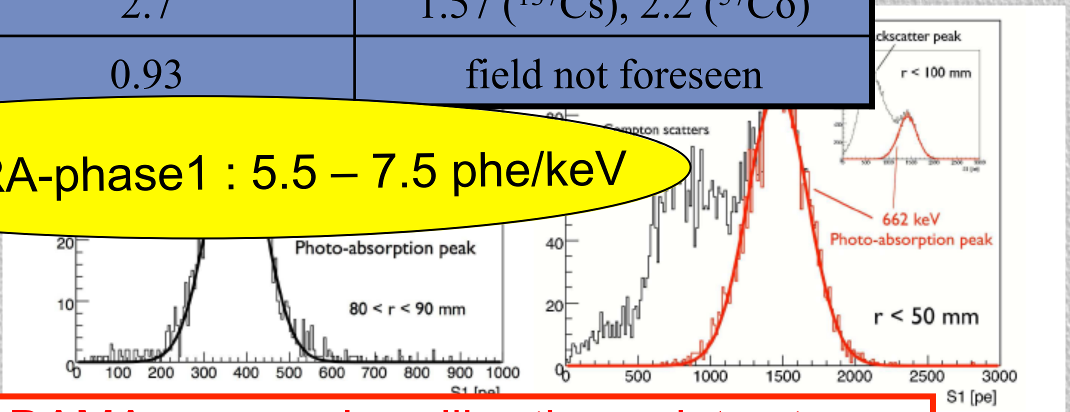
DAMA/LIBRA-phase1 : 5.5 – 7.5 phe/keV



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

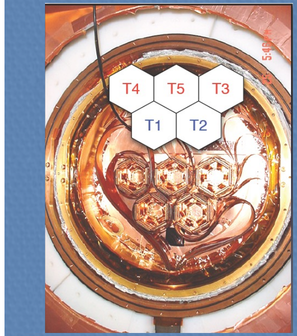
he 122 keV
ation. The
light yield for the 662 keV photo-absorption peak is 2.2 p.e./keV.

JoP: Conf. Ser. 65 (2007) 012015

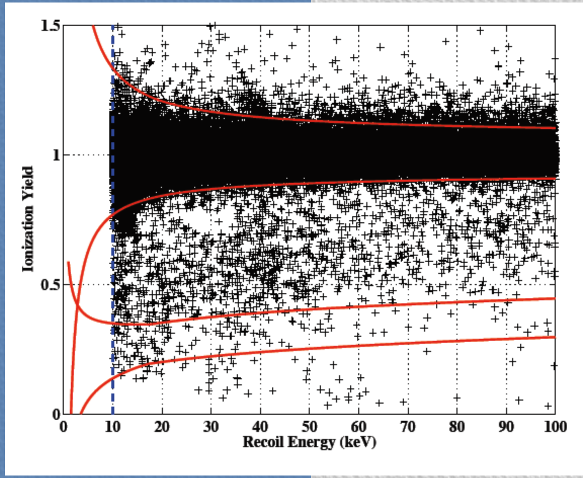
Results from double read-out bolometric technique (ionization vs heat)

	CDMS-II	Edelweiss II
Experimental site:	Soudan	Lab. Souterrain de Modane (LSM)
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 + subtractions**	**nuclear recoils + subtractions**
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



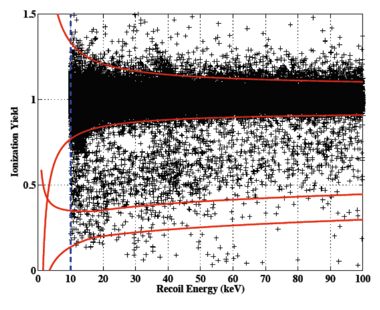
2 recoiling-like events "survived " (exp. bckg = 0.8)

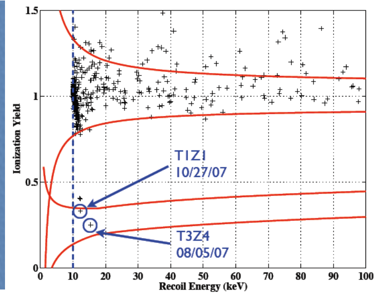
PLB702,5 (2011) 329

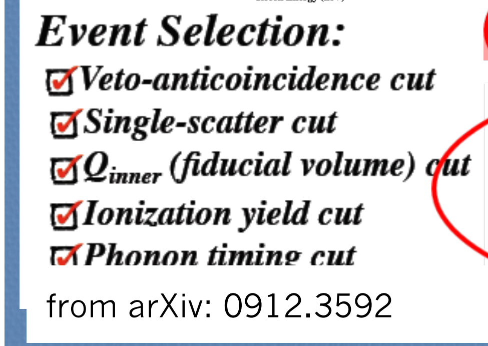
5 events observed (4 with $E<22.5\,\mathrm{keV}_{recoil}$; 1 with $E=172\,\mathrm{keV}_{recoil}$)

Data selection, handling and e.m. rejection procedures

CDMS-II



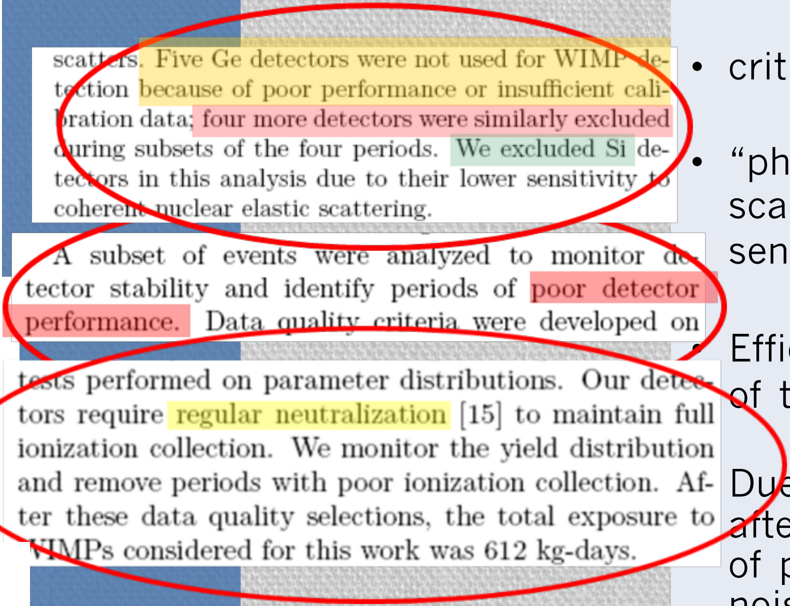




Event Selection:

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

from arXiv: 0912.3592



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.

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
- “physical” energy threshold, energy scale, Y scale, quenching factor, sensitive volumes, efficiencies, ...
- 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

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

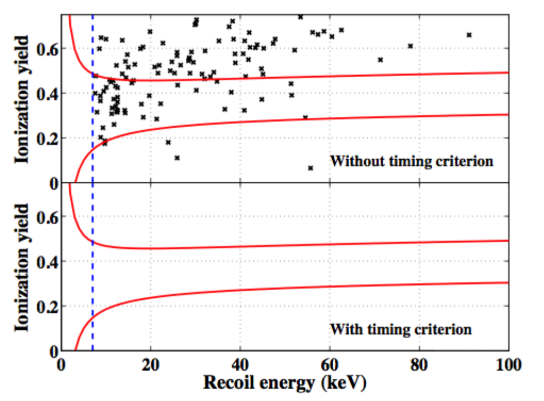
Results from double read-out bolometric technique (ionization vs heat): CDMS–Si

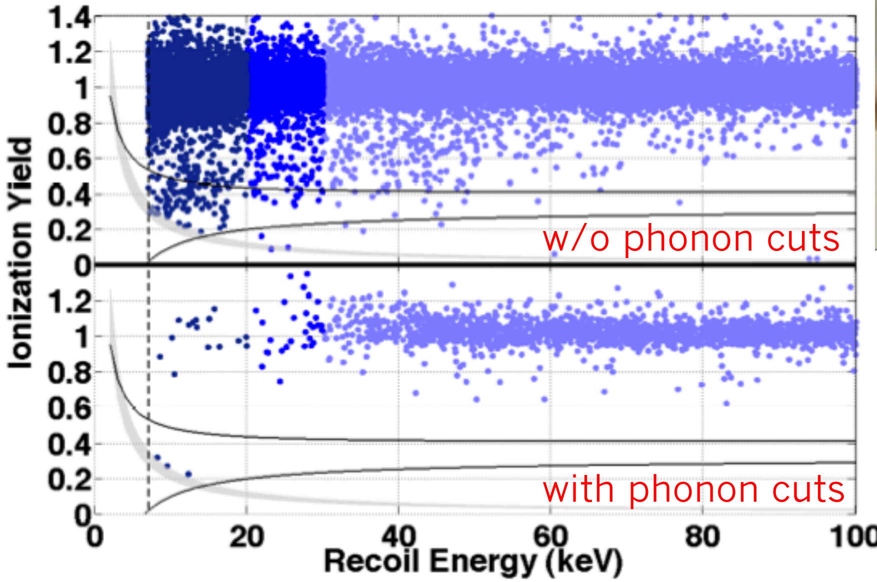
Si excluded in previous analysis.

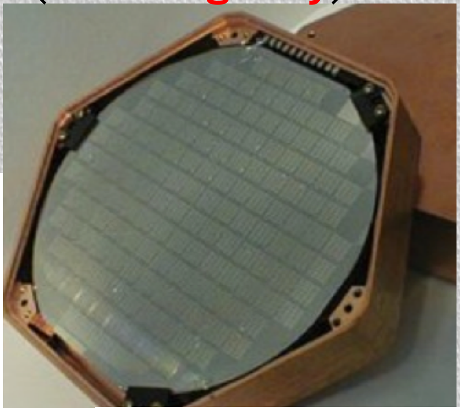
Results of CDMS-II with the Si detectors published in two close-in-time data releases:

- *no events* in six detectors (**55.9 kg×day**)
- *three events* in eight (over 11) detectors (**140.2 kg×day**)

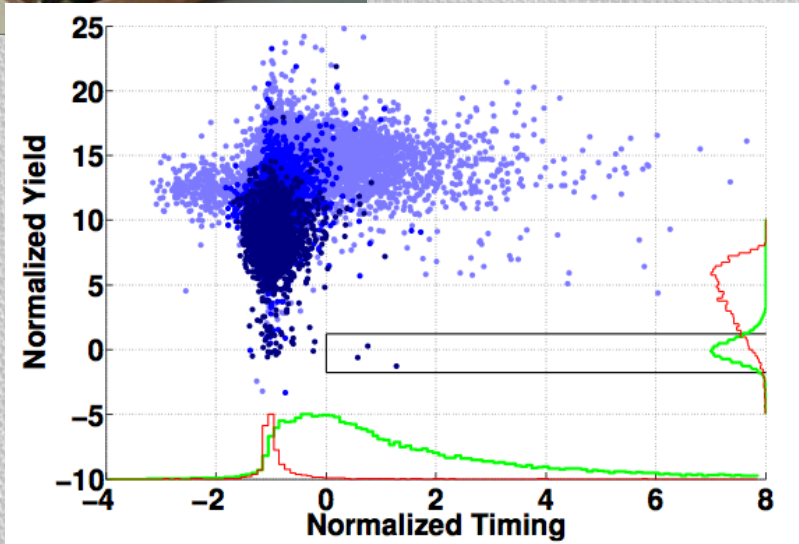
- 1.2 kg Si (11 x 106g)
- July 2007- September 2008







arXiv:1304.3706
arXiv:1304.4279



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

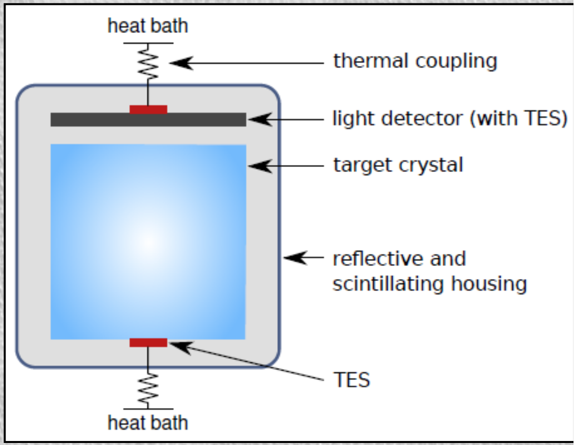
A profile likelihood analysis favors a signal hypothesis at 99.81% CL (~3σ, p-value: 0.19%).

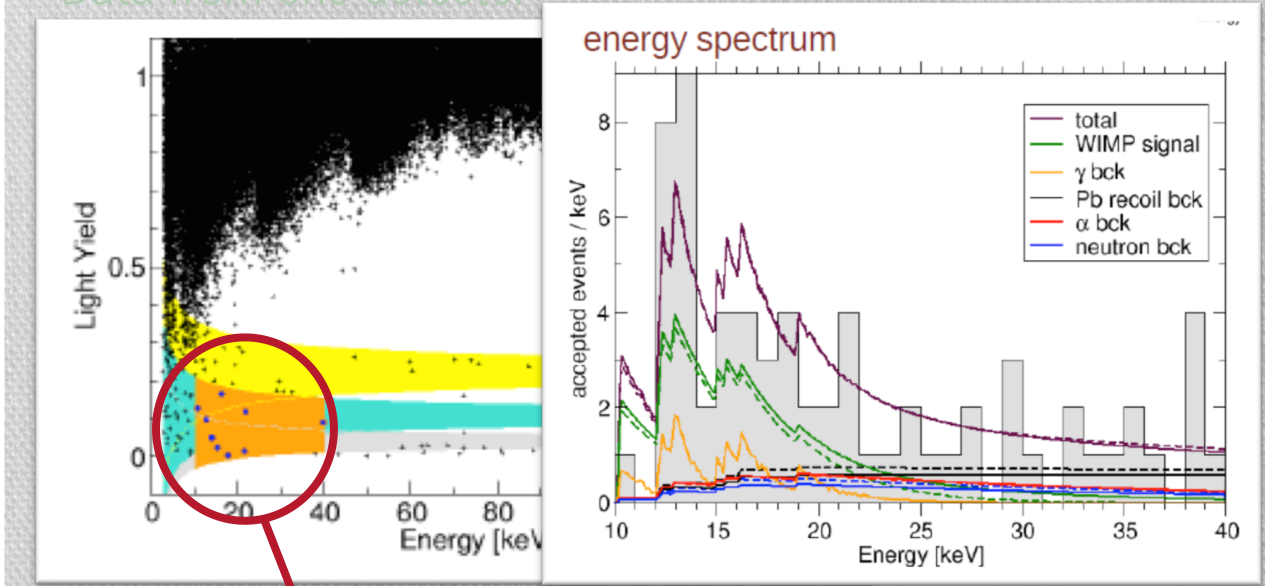
Double read-out bolometric technique (scintillation vs heat)

CRESST at LNGS: 33 $CaWO_4$ crystals (10 kg mass)

data from 8 detectors. Exposure: ≈ 730 kg x day

Data from one detector

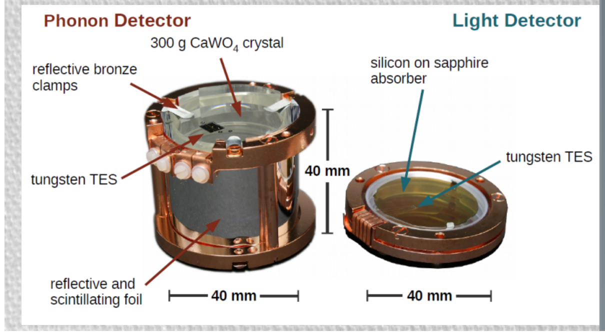




background-only hypothesis rejected with high statistical significance → **additional source of events needed (DM?)**

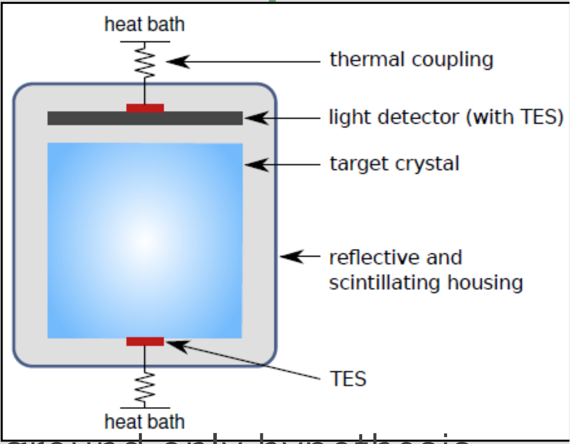
crucial role: Efficiencies + stability + calibrations

67 total events observed in O-band;



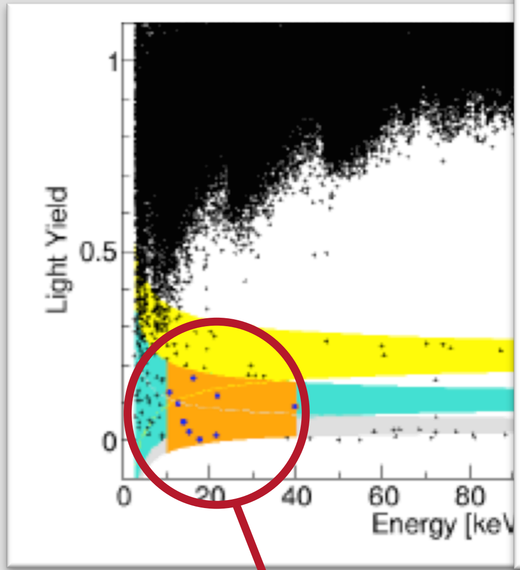
Latest run with lower energy threshold, smaller exposure does not confirm the previous 4 σ excess?! Large systematics in previous runs ? Wait for larger exposure?

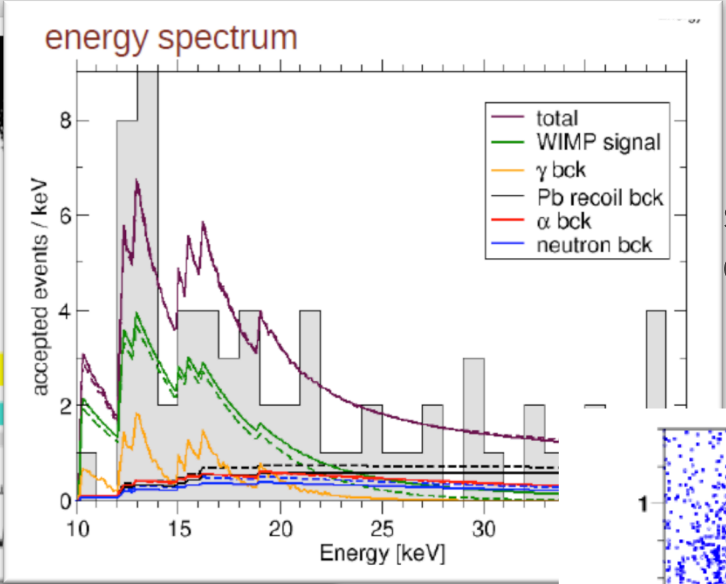
Double read-out bolometric technique (scintillation vs heat)



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

Data from one detector





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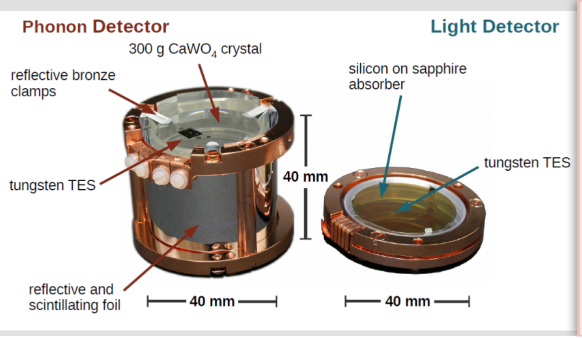
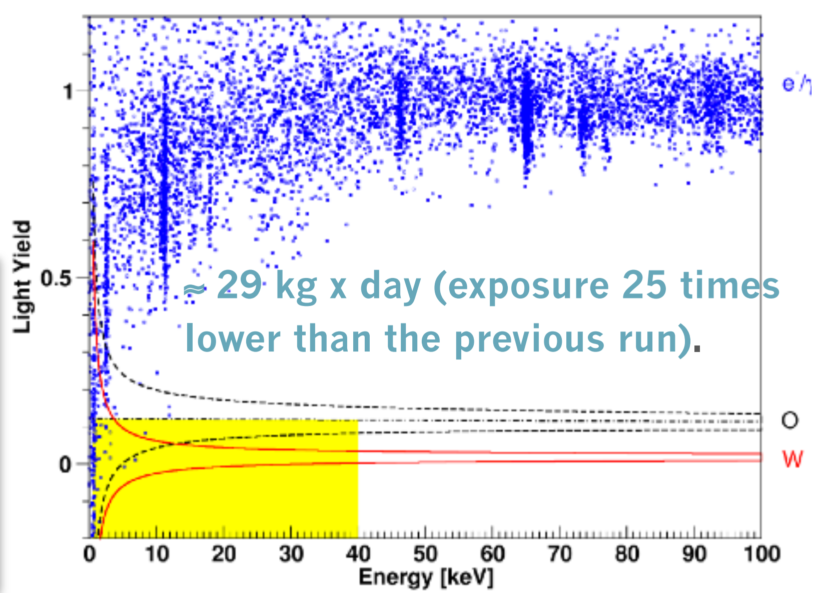


Latest run with lower energy threshold, smaller exposure does not confirm the previous 4 σ excess?! Large systematics in previous runs ? Wait for larger exposure?

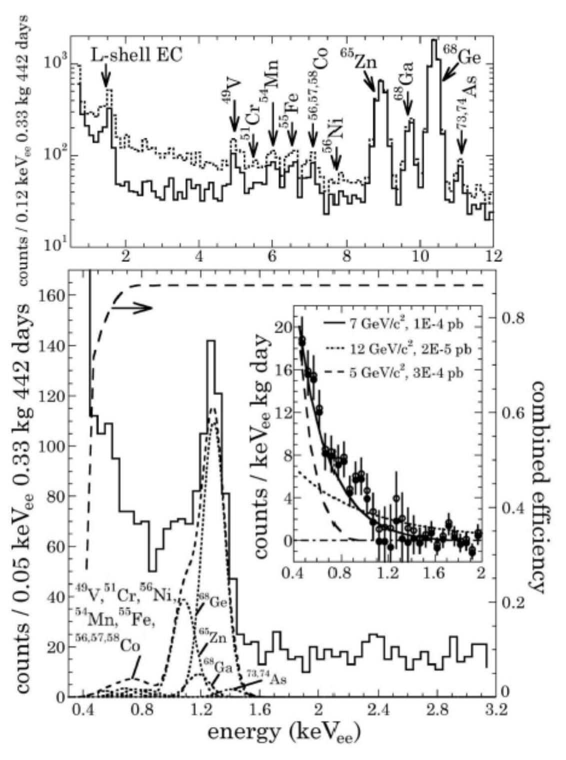


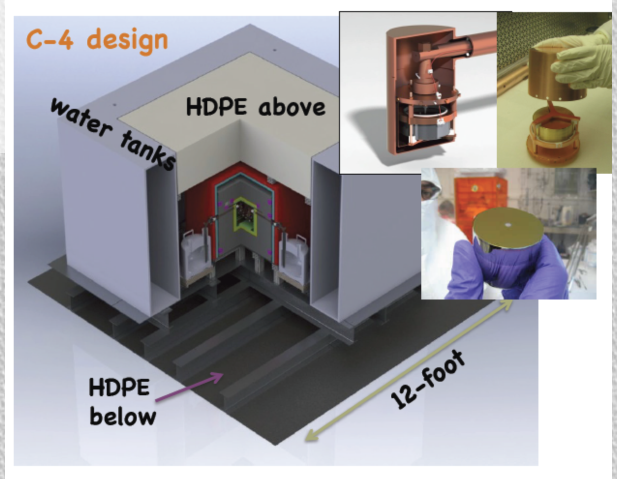
≈ 29 kg x day (exposure 25 times lower than the previous run).

Positive hints from CoGeNT (ionization detector)

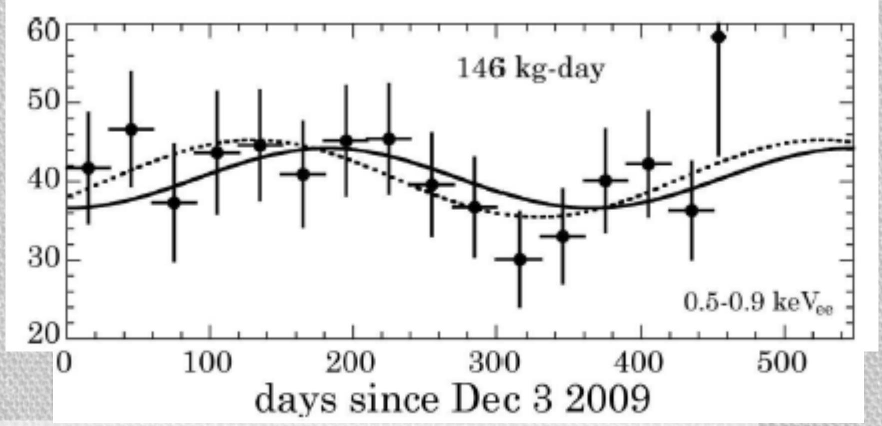
Experimental site: Soudan Underground Laboratory (2100 mwe)
Detector: 440 g, p-type point contact (PPC) Ge
diode 0.5 keVee energy threshold
Exposure: **146 kg x day** (dec '09 - mar '11)

PRL107(2011)141301





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

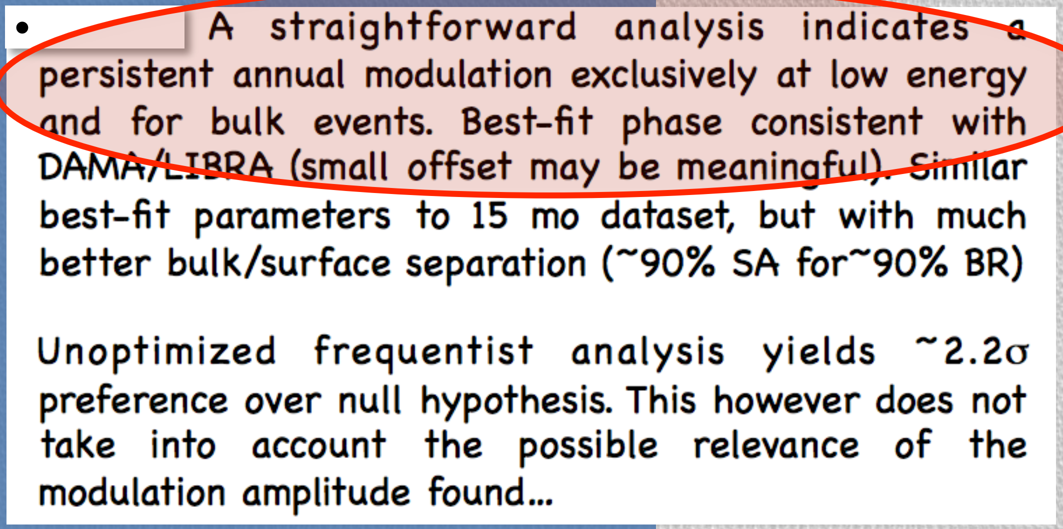


✓ **Irreducible excess** of bulk-like events below 3 keVee observed;
✓ **annual modulation** of the rate in 0.5-3 keVee at ~2.8σ C.L.

In data taking since July 2011 after the fire in Soudan

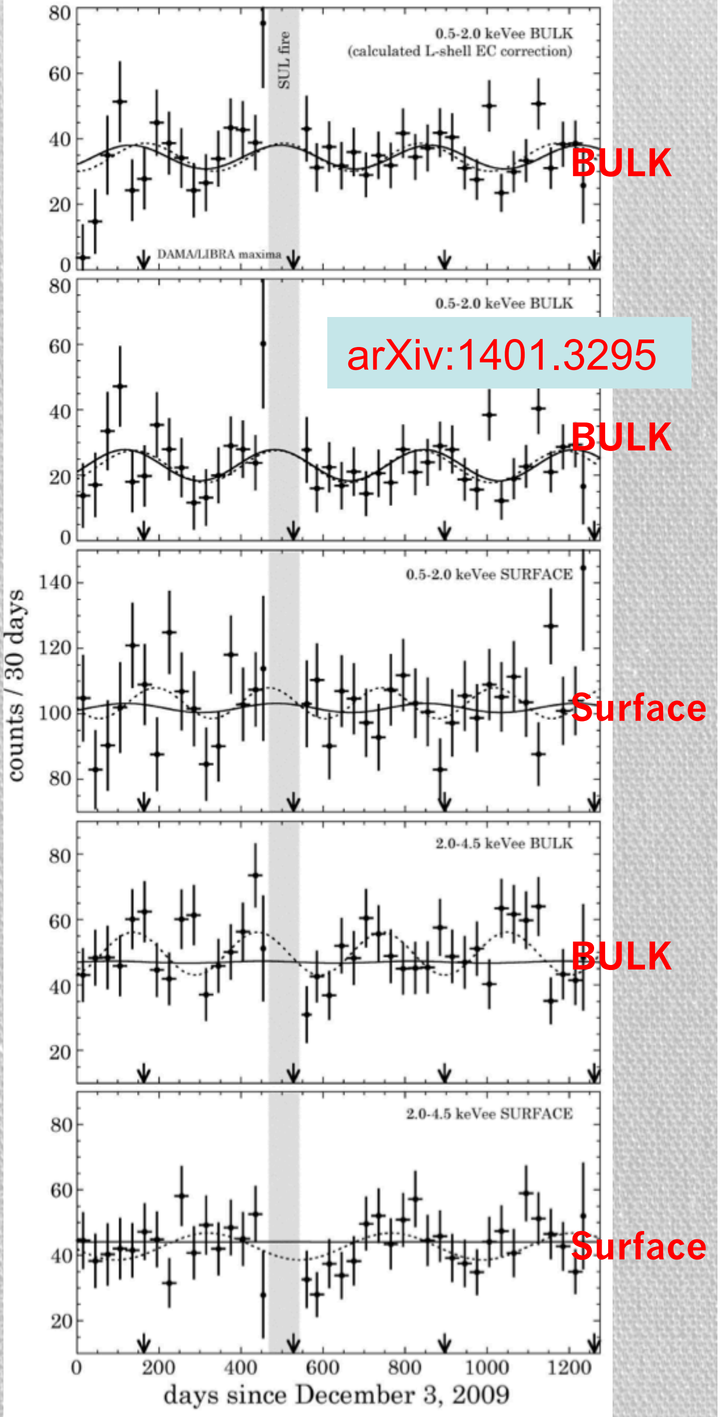
Positive hints from CoGeNT

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



- 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...



arXiv:1401.3295

CoGeNT upgrade: C-4 is coming up very soon

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

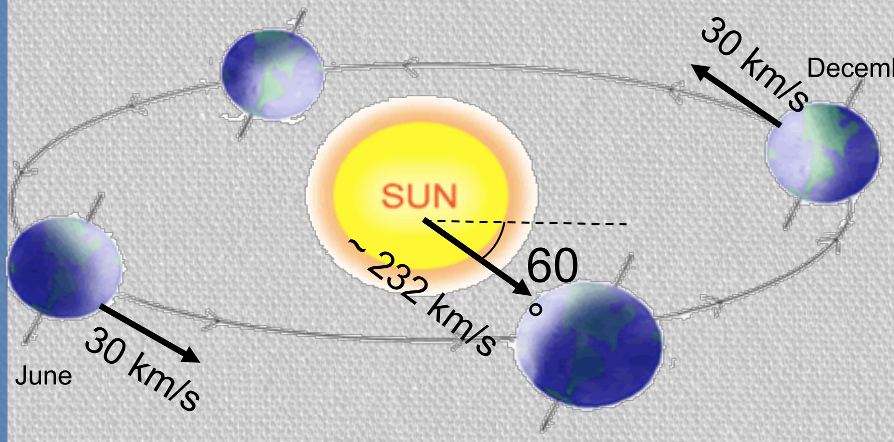
The DM annual modulation: a model independent signature to investigate the DM particles component in the galactic halo

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 DM 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)

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

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

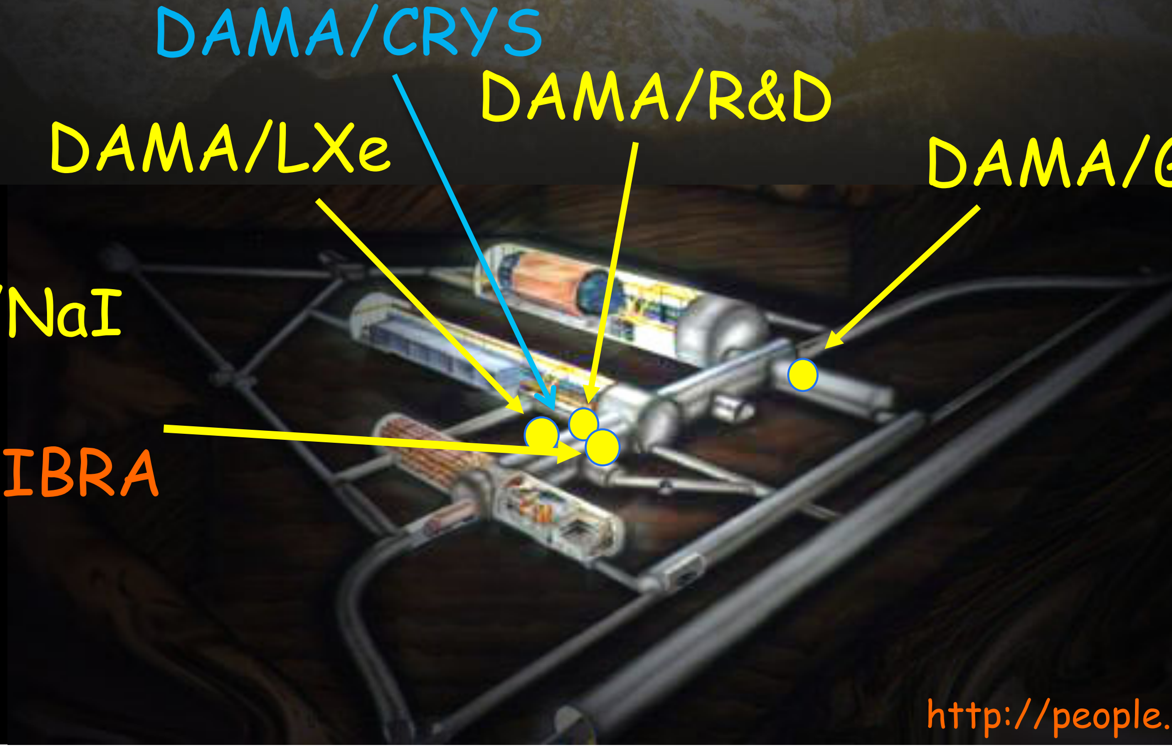
the DM annual modulation signature has a different origin and peculiarities (e.g. the phase) than those effects correlated with the seasons

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

Roma2,Roma1,LNGS,IHEP/Beijing

+ by-products and small scale expts.: INR-Kiev and others
+ neutron meas.: ENEA-Frascati
+ in some studies on $\beta\beta$ decays (DST-MAE project): IIT Kharagpur, India

DAMA: an observatory for rare processes @LNGS



DAMA/CRYS

DAMA/R&D

DAMA/LXe

DAMA/Ge

DAMA/NaI

↓

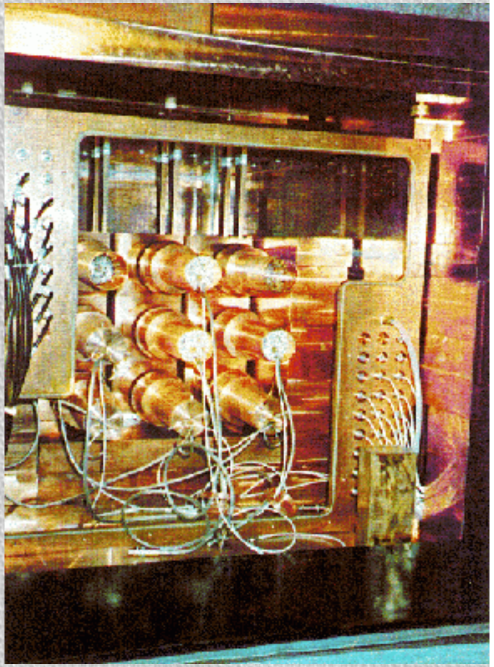
DAMA/LIBRA

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

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

PLB424(1998)195, PLB450(1999)448, PRD61(1999)023512, PLB480(2000)23, EPJC18(2000)283, PLB509(2001)197, EPJC23(2002)61, PRD66(2002)043503, Riv.N.Cim.26 n.1 (2003)1, IJMPD13(2004)2127, IJMPA21(2006)1445, EPJC47(2006)263, IJMPA22(2007)3155, EPJC53(2008)205, PRD77(2008)023506, MPLA23(2008)2125.

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

total exposure (7 annual cycles) 0.29 ton × yr

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

As a result of a second generation R&D for more radiopure NaI(Tl)
by exploiting new chemical/physical radiopurification techniques
(all operations involving crystals and PMTs - 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

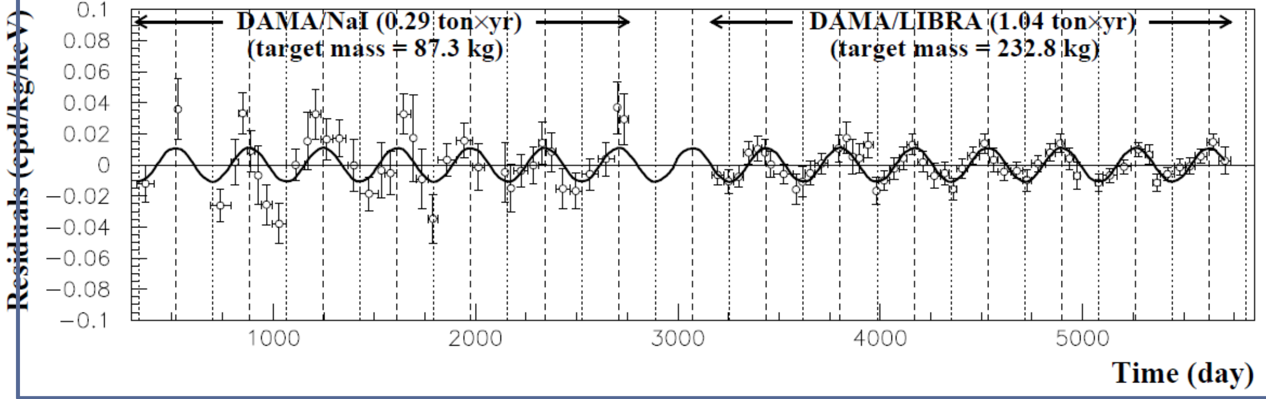
- *Radiopurity, performances, procedures, etc.:* NIMA592(2008)297, JINST 7 (2012) 03009
- *Results on DM particles: Ann. Mod. Signature:* EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648
- *related results:* PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022, EPJC74(2014)2827, EPJC75 (2015) 239, arXiv:1507.04317
- *Results on rare processes: PEP violation in Na, I:* EPJC62(2009)327, *CNC in I:* EPJC72(2012)1920
  IPP in ^{241}Am: EPJA49(2013)64

Model Independent Annual Modulation Result

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

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

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

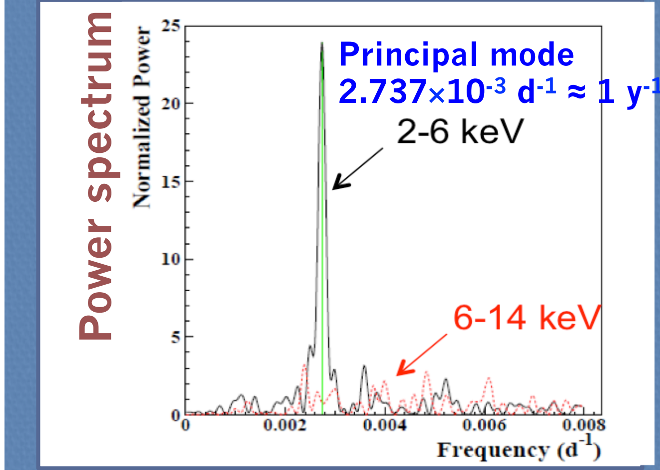


continuous line: t_0 = 152.5 d, T =1.0 y

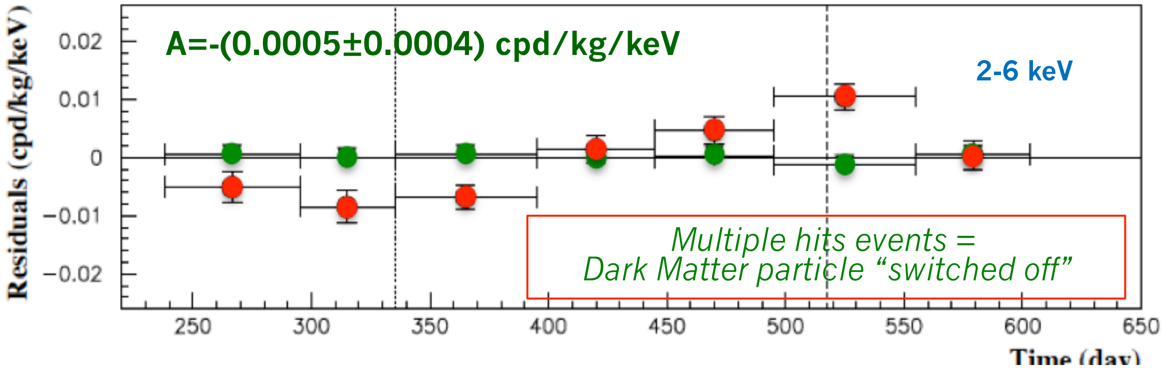
A=(0.0110±0.0012) cpd/kg/keV
χ^2/dof = 70.4/86 9.2 σ C.L.

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

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



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



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 more than 9 σ C.L.

Model Independent Annual Modulation Result

DAMA/NaI + DAMA/LIBRA-phase1

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

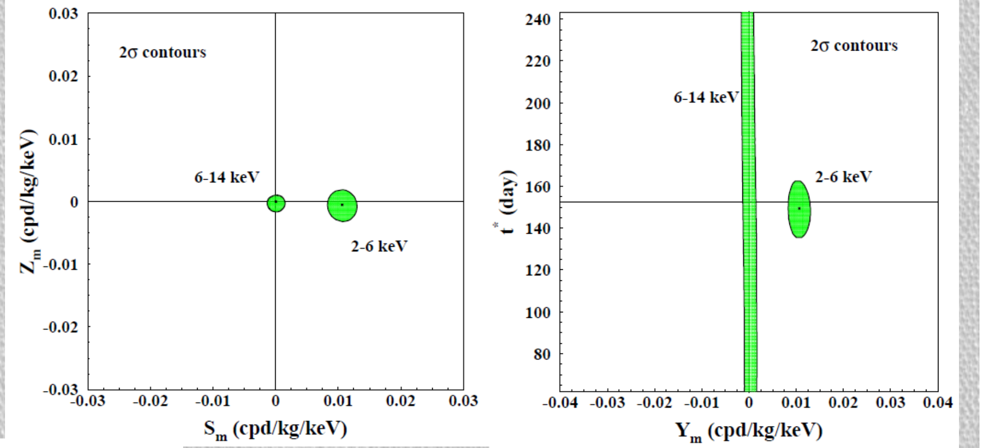
EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648

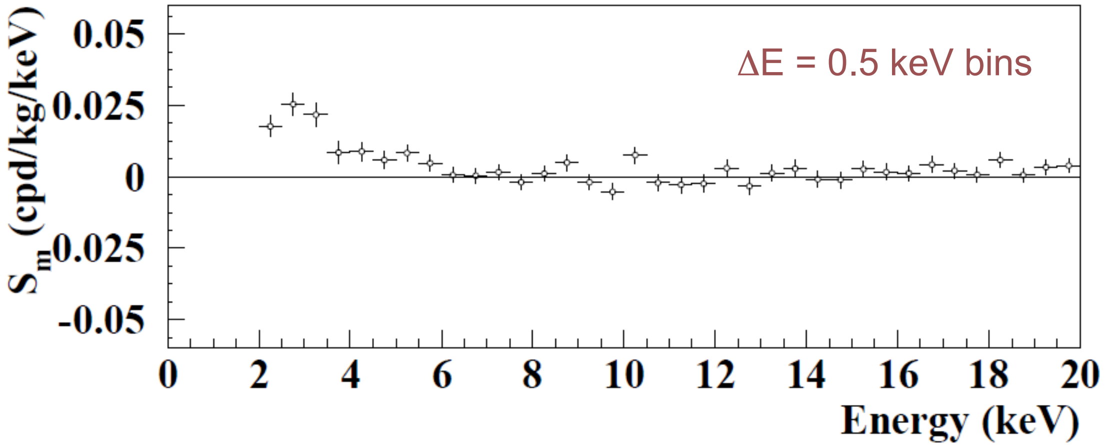
- **No modulation above 6 keV**
- **No modulation in the whole energy spectrum**
- **No modulation in the 2-6 keV multiple-hit events**

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

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

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





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

- Contributions to the total neutron flux at LNGS; → $\Phi_k = \Phi_{0,k}\left(1 + \eta_k cos\omega\left(t - t_k\right)\right)$
- Counting rate in DAMA/LIBRA for *single-hit* → $R_k = R_{0,k}\left(1 + \eta_k cos\omega\left(t - t_k\right)\right)$

events, in the (2 – 6) keV energy region induced by:

  - neutrons,
  - muons,
  - solar neutrinos.

(See e.g. also EPJC 56 (2008) 333, EPJC 72(2012) 2064, IJMPA 28 (2013) 1330022)

EPJC74(2014)3196

Modulation amplitudes

Source		$\Phi^{(n)}_{0,k}$ (neutrons cm^{-2} s^{-1})	η_k	t_k	$R_{0,k}$ (cpd/kg/keV)		$A_k = R_{0,k}\eta_k$ (cpd/kg/keV)	A_k/S_m^{exp}
SLOW neutrons	thermal n (10^{-2} – 10^{-1} eV)	1.08×10^{-6} [15]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 8 \times 10^{-6}$	[2, 7, 8]	$\ll 8 \times 10^{-7}$	$\ll 7 \times 10^{-5}$
	epithermal n (eV-keV)	2×10^{-6} [15]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 3 \times 10^{-3}$	[2, 7, 8]	$\ll 3 \times 10^{-4}$	$\ll 0.03$
FAST neutrons	fission, $(\alpha, n) \rightarrow$ n (1-10 MeV)	$\simeq 0.9 \times 10^{-7}$ [17]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 6 \times 10^{-4}$	[2, 7, 8]	$\ll 6 \times 10^{-5}$	$\ll 5 \times 10^{-3}$
	$\mu \rightarrow$ n from rock (> 10 MeV)	$\simeq 3 \times 10^{-9}$ (see text and ref. [12])	0.0129 [23]	end of June [23, 7, 8]	$\ll 7 \times 10^{-4}$	(see text and [2, 7, 8])	$\ll 9 \times 10^{-6}$	$\ll 8 \times 10^{-4}$
	$\mu \rightarrow$ n from Pb shield (> 10 MeV)	$\simeq 6 \times 10^{-9}$ (see footnote 3)	0.0129 [23]	end of June [23, 7, 8]	$\ll 1.4 \times 10^{-3}$	(see text and footnote 3)	$\ll 2 \times 10^{-5}$	$\ll 1.6 \times 10^{-3}$
	$\nu \rightarrow$ n (few MeV)	$\simeq 3 \times 10^{-10}$ (see text)	0.03342 *	Jan. 4th *	$\ll 7 \times 10^{-5}$	(see text)	$\ll 2 \times 10^{-6}$	$\ll 2 \times 10^{-4}$
	direct μ	$\Phi^{(\mu)}_0 \simeq 20\ \mu$ m^{-2}d^{-1} [20]	0.0129 [23]	end of June [23, 7, 8]	$\simeq 10^{-7}$	[2, 7, 8]	$\simeq 10^{-9}$	$\simeq 10^{-7}$
	direct ν	$\Phi^{(\nu)}_0 \simeq 6 \times 10^{10}\ \nu$ cm^{-2}s^{-1} [26]	0.03342 *	Jan. 4th *	$\simeq 10^{-5}$	[31]	3×10^{-7}	3×10^{-5}

* The annual modulation of solar neutrino is due to the different Sun-Earth distance along the year; so the relative modulation amplitude is twice the eccentricity of the Earth orbit and the phase is given by the perihelion.

All are negligible w.r.t. the annual modulation amplitude observed by DAMA/LIBRA and they cannot contribute to the observed modulation amplitude.

+ In no case neutrons (of whatever origin), muon or muon induced events, solar ν can mimic the DM annual modulation signature since some of the **peculiar requirements of the signature** would fail (and – in addition - quantitatively negligible amplitude with respect to the measured effect).

Summary of the results obtained in the additional investigations of possible systematics or side reactions – DAMA/LIBRA-phase1

(NIMA592(2008)297, EPJC56(2008)333, J. Phys. Conf. ser. 203(2010)012040, arXiv:0912.0660, S.I.F.Atti Conf. 103(211), Can. J. Phys. 89 (2011) 11, Phys.Proc.37(2012)1095, EPJC72(2012)2064, arxiv:1210.6199 & 1211.6346, IJMPA28(2013)1330022, EPJC74(2014)3196)

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

+ they cannot satisfy all the requirements of annual modulation signature

Thus, they cannot mimic the observed annual modulation effect

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

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

Neutralino as LSP in various SUSY theories

Various kinds of WIMP candidates with several different kind of interactions
Pure SI, pure SD, mixed + Migdal effect
+channeling,… (from low to high mass)

a heavy ν of the 4-th family

Pseudoscalar, scalar or mixed light bosons with axion-like interactions

WIMP with preferred inelastic scattering

Mirror Dark Matter

Light Dark Matter

Dark Matter (including some scenarios for WIMP) electron-interacting

Sterile neutrino

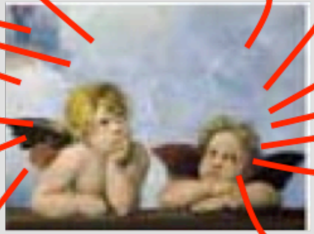
Self interacting Dark Matter

heavy exotic canditates, as “4th family atoms”, ...

Elementary Black holes such as the Daemons

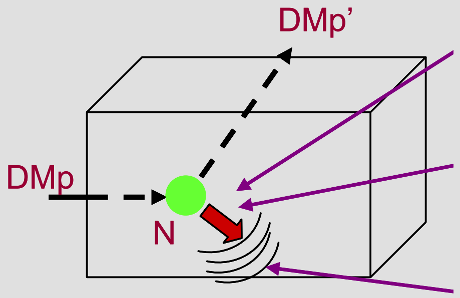
Kaluza Klein particles

… and more



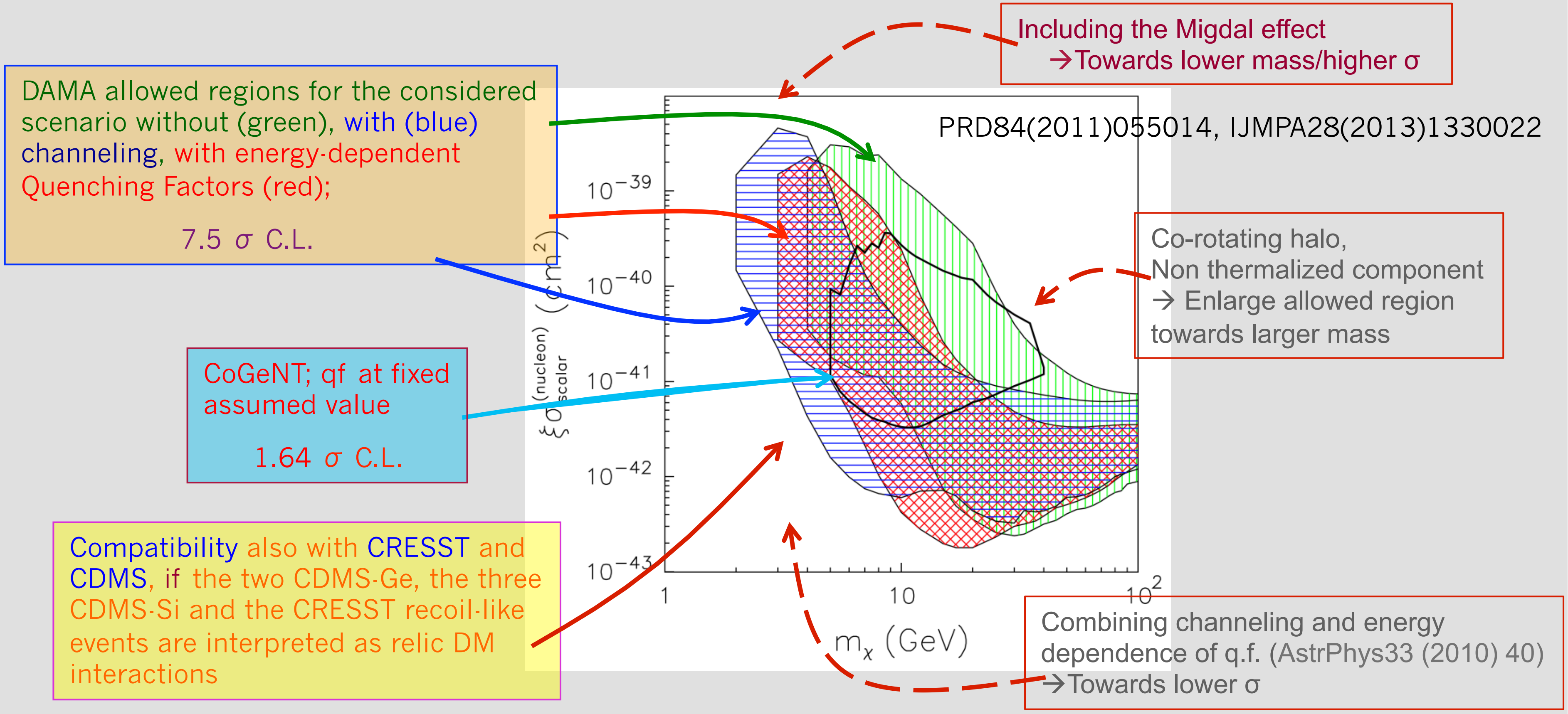
... an example in literature...

Case of DM particles inducing elastic scatterings on target-nuclei, Spin-Independent 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.



PRD84(2011)055014, IJMPA28(2013)1330022

Including the Migdal effect
→Towards lower mass/higher σ

DAMA allowed regions for the considered scenario without (green), with (blue) channeling, with energy-dependent Quenching Factors (red);

7.5 σ C.L.

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

CoGeNT; qf at fixed assumed value

1.64 σ C.L.

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

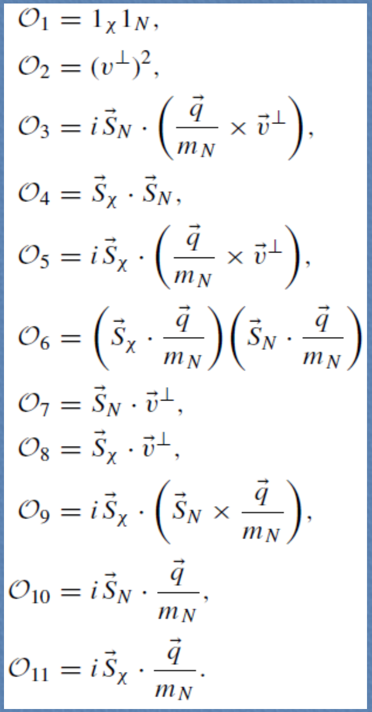
Combining channeling and energy dependence of q.f. (AstrPhys33 (2010) 40)
→Towards lower σ

Scratching Below the Surface of the Most General Parameter Space

(S. Scopel talk in DM2 session)

Most general approach: consider ALL possible NR couplings, including those depending on velocity and momentum

- A much wider parameter space opens up
- First explorations show that indeed large rooms for compatibility can be achieved



$\mathcal{O}_1 = 1_\chi 1_N,$

$\mathcal{O}_2 = (v^\perp)^2,$

$\mathcal{O}_3 = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right),$

$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N,$

$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right),$

$\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$

$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp,$

$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp,$

$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right),$

$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N},$

$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}.$

… and much more considering experimental and theoretical uncertainties

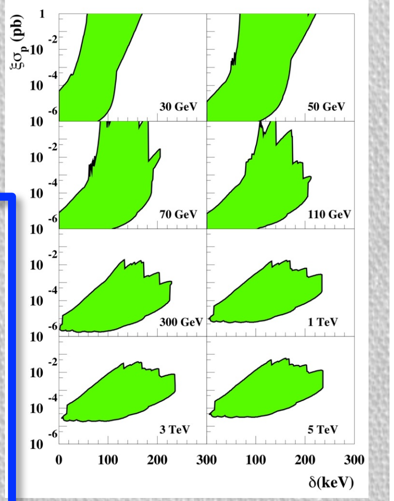
Other examples

DMp with preferred inelastic interaction: $\chi^- + N \rightarrow \chi^+ + N$

- iDM mass states χ^+, χ^- with δ mass splitting
- Kinematic constraint for iDM:

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

DAMA slices from the 3D allowed volume in given scenario



Fund. Phys. 40(2010)900

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

PRL106(2011)011301

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

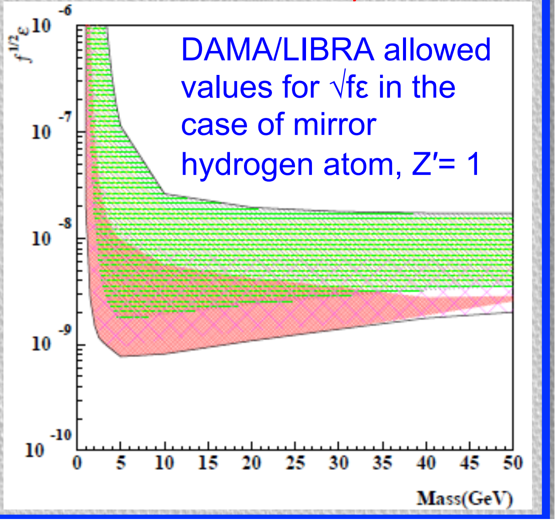
Mirror Dark Matter

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

(See Z. Berezhiani's talk in DM2 session and arXiv:1507.04317)

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

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



DAMA/LIBRA allowed values for √fε in the case of mirror hydrogen atom, Z′= 1

Other signatures?

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

The importance of studying second order effects and the annual modulation phase

Higher exposure and lower threshold can allow further investigation on:

- the nature of the DMp
  - ✓ to disentangle among the different astrophysical, nuclear and particle physics models (nature of the candidate, couplings, form factors, spin-factors ...)
  - ✓ scaling laws and cross sections
  - ✓ multi-component DMp halo?

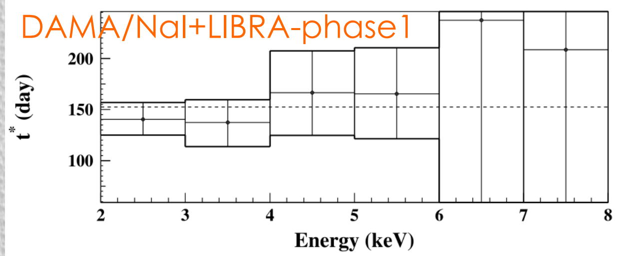
possible diurnal effects in sidereal time

- ✓ expected in case of high cross section DM candidates (shadow of the Earth)
- ✓ due to the Earth rotation velocity contribution (it holds for a wide range of DM candidates)
- ✓ due to the channeling in case of DM candidates inducing nuclear recoils.

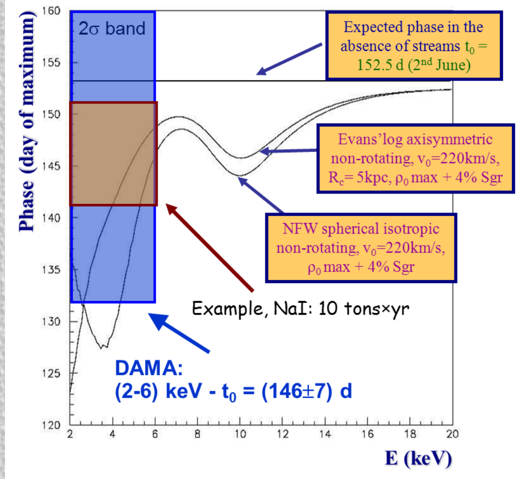
- astrophysical models
  - ✓ velocity and position distribution of DMp in the galactic halo, possibly due to:
    - satellite galaxies (as Sagittarius and Canis Major Dwarves) tidal "streams";
    - caustics in the halo;
    - gravitational focusing effect of the Sun enhancing the DM flow ("spike" and "skirt");
    - possible structures as clumpiness with small scale size
    - Effects of gravitational focusing of the Sun

A step towards such investigations:

➔**DAMA/LIBRA-phase2 running with lower energy threshold**

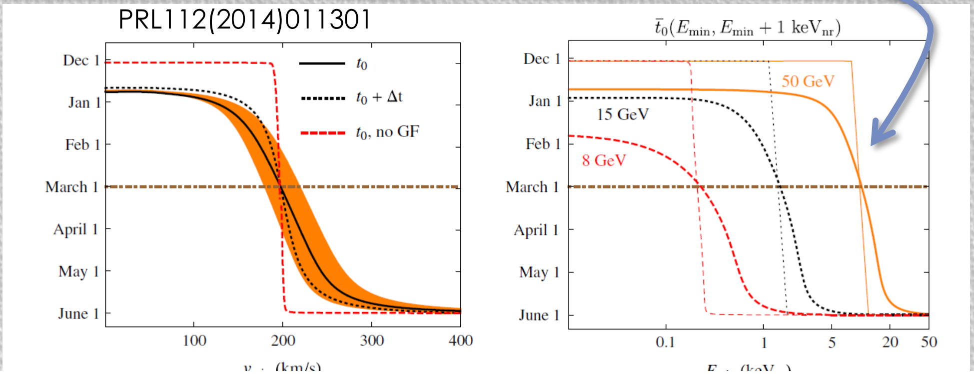


The effect of the streams on the phase depends on the galactic halo model



The annual modulation phase depends on :

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


PRL112(2014)011301

Diurnal effects

EPJC 74 (2014) 2827

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

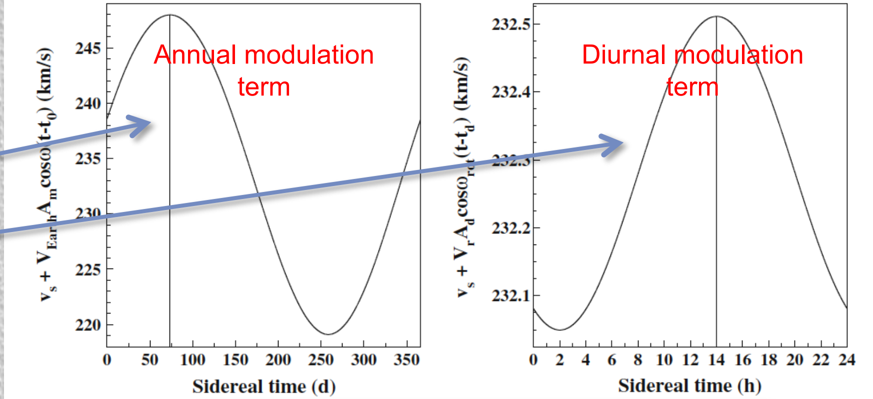
Velocity of the detector in the terrestrial laboratory:

$$\vec{v}_{lab}(t) = \vec{v}_{LSR} + \vec{v}_{\odot} + \vec{v}_{rev}(t) + \vec{v}_{rot}(t),$$

Since:

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

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



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

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

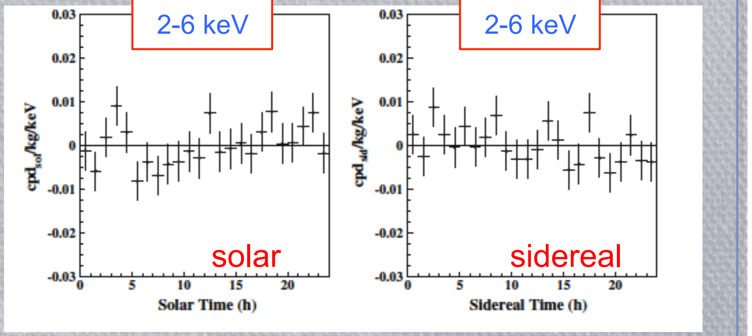
The ratio R_{dy} is a model independent constant:

$$R_{dy} = \frac{S_d}{S_m} = \frac{V_r B_d}{V_{Earth} B_m} \simeq 0.016$$ at LNGS latitude

- Observed annual modulation amplitude in DAMA/LIBRA–phase1 in the (2–6) keV energy interval: (0.0097 ± 0.0013) cpd/kg/keV
- Thus, the expected value of the diurnal modulation amplitude is ≃1.5 × 10^{-4} cpd/kg/keV.
- When fitting the *single-hit* residuals with a cosine function with amplitude A_d as free parameter, period fixed at 24 h and phase at 14 h: all the diurnal modulation amplitudes are compatible with zero.

A_d (2-6 keV) < 1.2 × 10^{-3} cpd/kg/keV (90%CL)

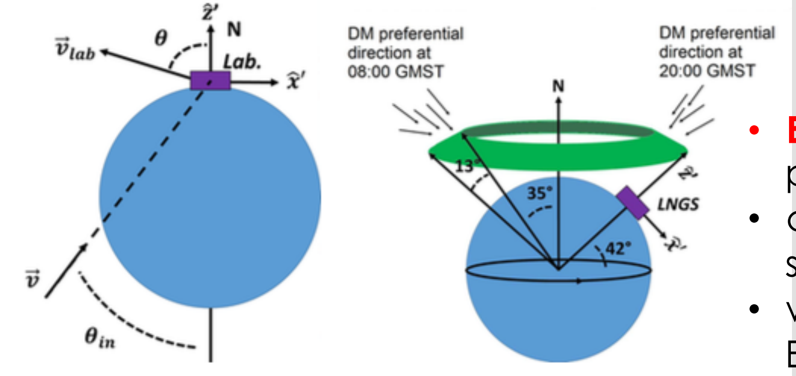
Model-independent result on possible diurnal effect in DAMA/LIBRA–phase1



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

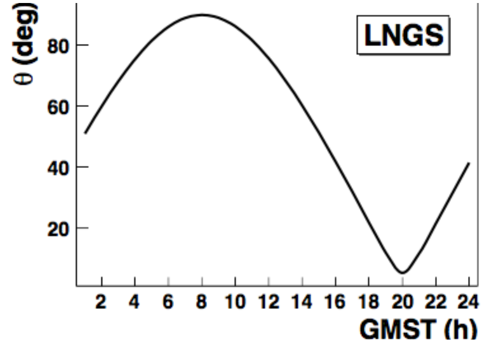
larger exposure DAMA/LIBRA–phase2 with lower energy threshold offers increased sensitivity to such an effect

Earth shadowing effect with DAMA/LIBRA–phase1

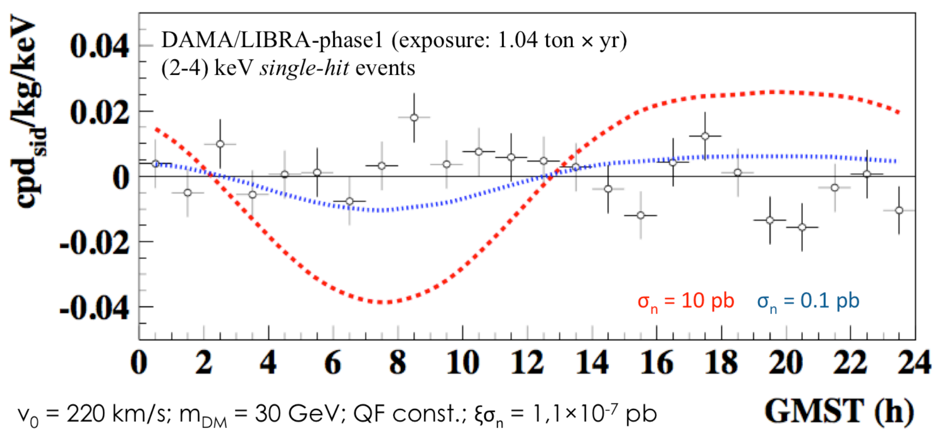


EPJC75 (2015) 239

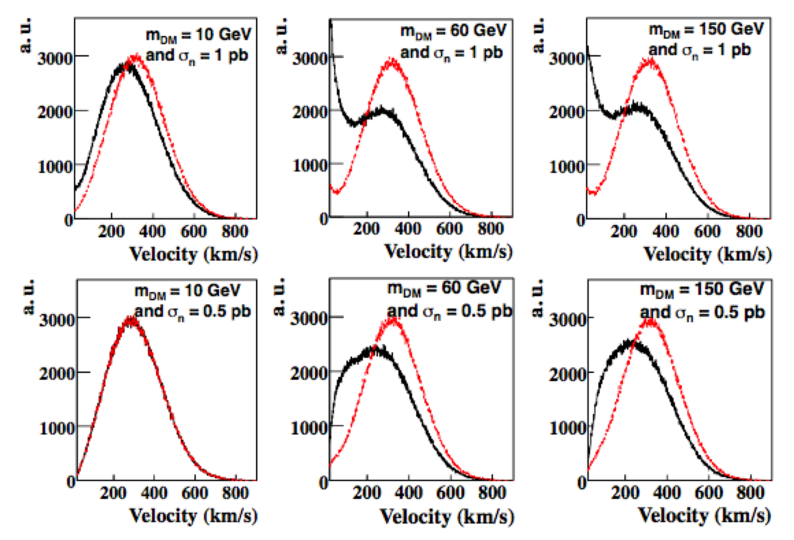
- **Earth Shadow Effect** could be expected for DM candidate particles inducing just nuclear recoils
- can be pointed out only for candidates with high cross-section with ordinary matter (low DM local density)
- would be induced by the variation during the day of the Earth thickness crossed by the DM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



- DM particles crossing Earth lose their energy
- DM velocity distribution observed in the laboratory frame is modified as function of time (**GMST 8:00 black**; **GMST 20:00 red**)



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



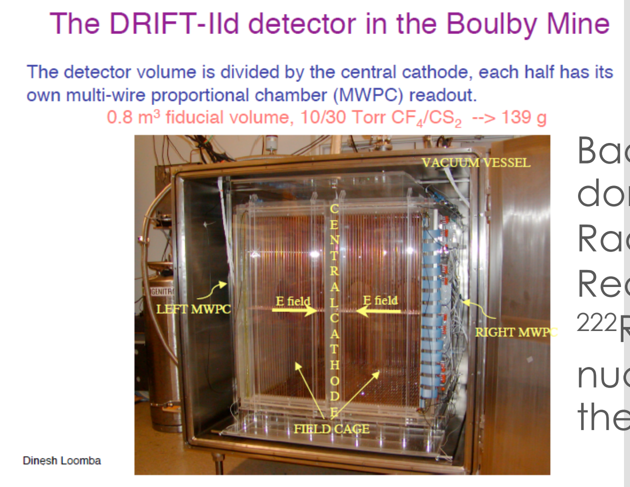
Taking into account the DAMA/LIBRA DM annual modulation result, allowed regions in the ξ vs σ_n plane for each m_{DM}.

Directionality technique (at R&D stage)

- Only for candidates inducing just nuclear 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

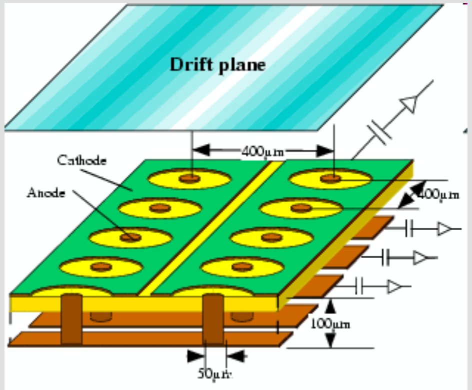
The detector volume is divided by the central cathode, each half has its own multi-wire proportional chamber (MWPC) readout.

0.8 m^3 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

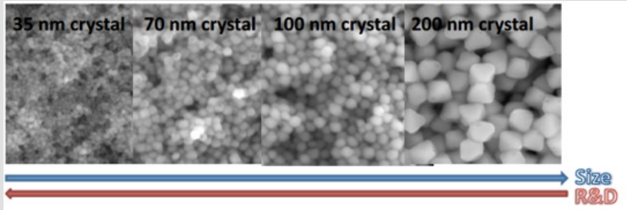


μ-PIC(Micro Pixel Chamber) is a two dimensional position sensitive gaseous detector

	Current	Plan
Detection Volume	30 × 30 × 31cm^3	>1m^3
Gas	CF_4 152Torr	CF_4 30 Torr
Energy threshold	100keV	35keV
Energy resolution(@ threshold)	70%(FWHM)	50%(FWHM)
Gamma-ray rejection(@threshold)	8 × 10^{-6}	1 × 10^{-7}
Angular resolution (@ threshold)	55° (RMS)	30° (RMS)

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

Nano Imaging Tracker (NIT) emulsions



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

DM-TPC

- TPC 4xCCD
- Sea-level@MIT
- moving to WIPP
- Cubic meter funded, design underway

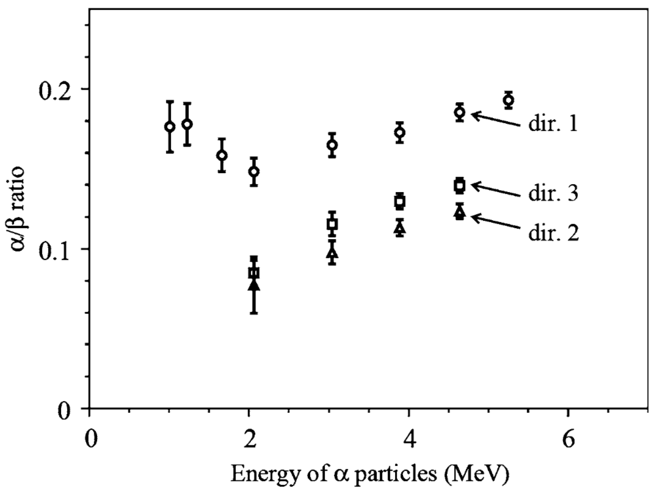
Not yet competitive sensitivity

Directionality technique

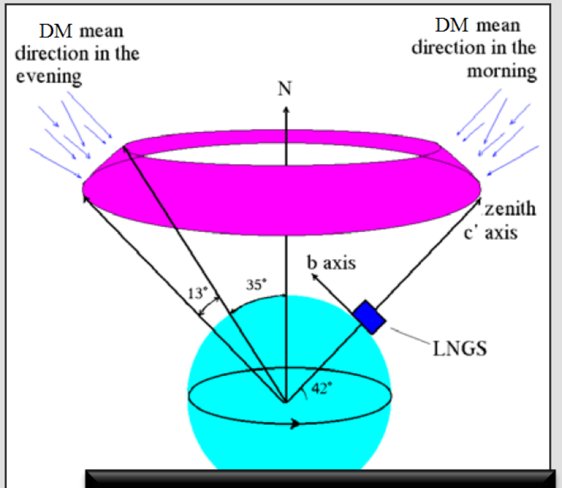
EPJ C73 (2013) 2276

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

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



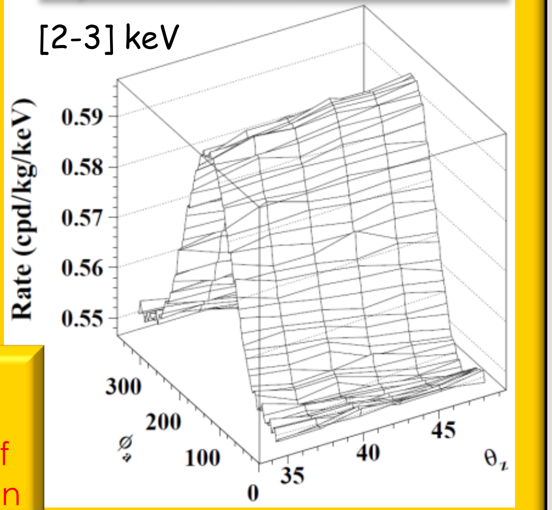
Nuclear recoils are expected to be strongly correlated with the DM impinging direction
This effect can be pointed out through the study of the variation in the response of anisotropic scintillation detectors during sidereal day



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

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



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

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

New laboratories ?

Developments about new kinds of detectors and – if successful – a new kind of DM experimental activities and other applications as well

Do need new ideas !

An intriguing one which could hold for low mass DM candidates inducing just nuclear recoils is the exploitation of a new class of nano-booms and biological DM detectors, taking advantage of new signatures with low atomic number targets.

- ✓ Nano-explosives detectors (nano-booms): each explosives grain is "independent" room-temperature bolometer.

  Advantages:
  - Use very low mass targets – Li, Be, B, C, N, O
  - Large choice of compounds to select from;
  - Each explosives grain is "independent" bolometer;
  - Amplification of signal from 0.1 keV to 1 MeV possible;
  - dE/dx (nuclei) >> dE/dx (electrons)

    => expected advantages

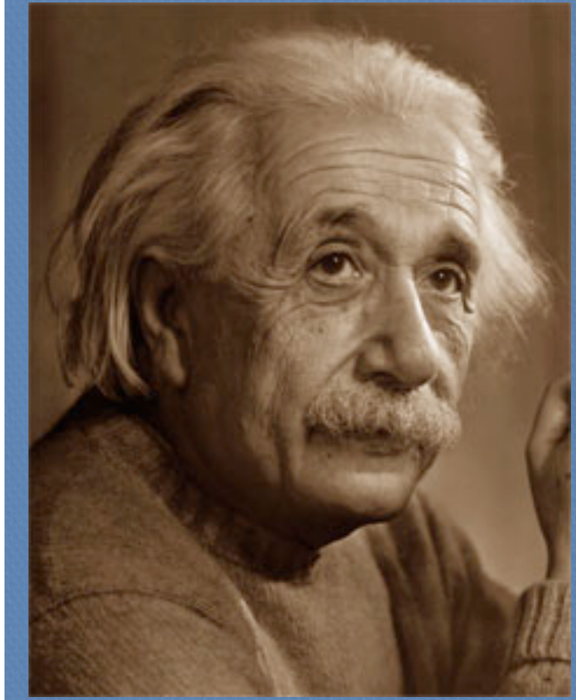
- ✓ Two types of biological DM detectors: DNA-based detectors and enzymatic reactions (ER) based detectors.

See **A.K. Drukier talk in DM2 session** and IJMPA 29 (2014) 1443008

Conclusions

- Different solid techniques can give complementary results
- Some further efforts to demonstrate the solidity of some techniques and developments are needed
- Higher exposed mass not a synonymous of higher sensitivity
- DAMA model-independent positive evidence at 9.3σ C.L. & full sensitivity to many kinds of DM, of interactions both inducing recoils and/or e.m. radiation, of scenarios
- Possible positive hints in direct and indirect searches compatible with DAMA in various scenarios; null searches not in robust conflict. Consider also the experimental and theoretical uncertainties.

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



"… The one who follows the crowd will usually get no further than the crowd. The one who walks alone, is likely to find himself in places no one has ever been."

Thanks for attention