Direct Detection of Dark Matter

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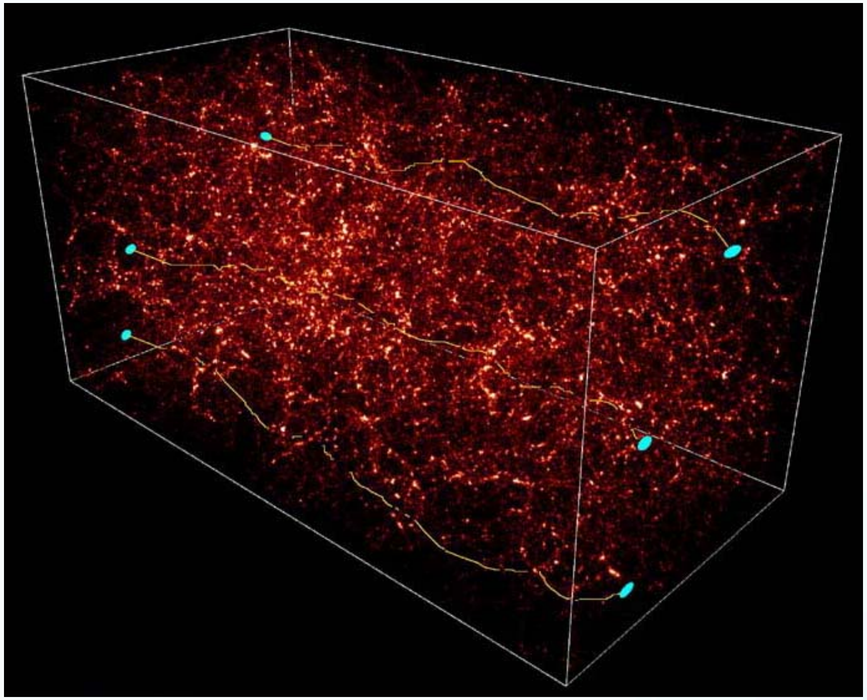
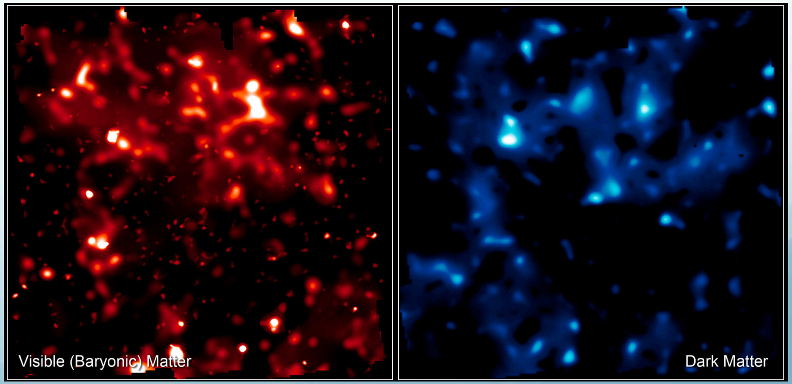
The Dark Matter in the Universe

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





Relic DM particles from primordial Universe

SUSY
(as neutralino or sneutrino
in various scenarios)

the sneutrino in the Smith
and Weiner scenario

sterile ν

electron interacting dark matter

a heavy ν of the 4-th family

even a suitable particle not
yet foreseen by theories

etc…

axion-like (light pseudoscalar
and scalar candidate)

self-interacting dark matter

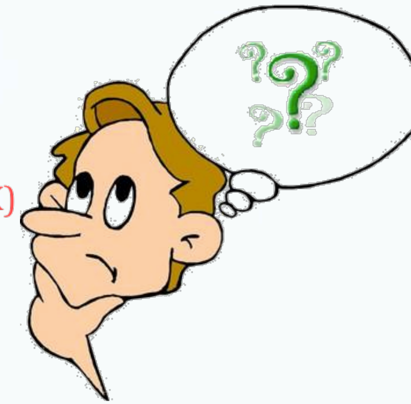
mirror dark matter

Kaluza-Klein particles (LKK)

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

Elementary Black holes,
Planckian objects, Daemons

invisible axions, ν's



What accelerators can do:

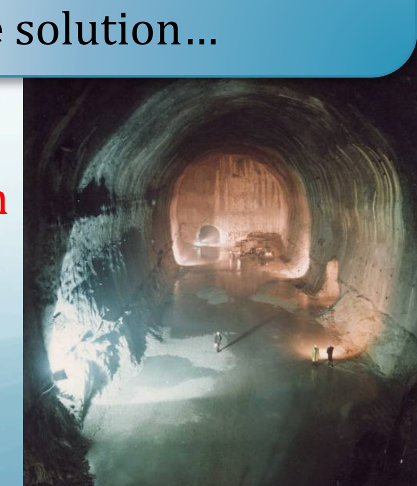
to demostrate the existence of some of the possible DM candidates

What accelerators cannot do:

to credit that a certain particle is the Dark Matter solution or the "single" Dark Matter particle solution…

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

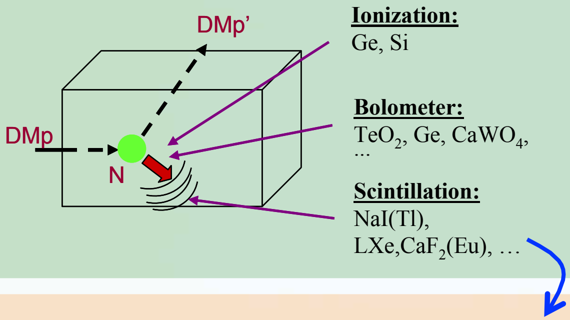
DM direct detection method using a model independent approach and a low-background widely-sensitive target material



Some direct detection processes:

- Scatterings on nuclei

  → detection of nuclear recoil energy



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

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

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

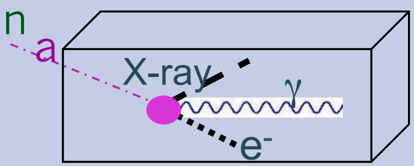
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

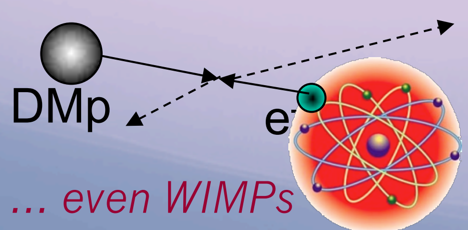
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

  → detection of e.m. radiation

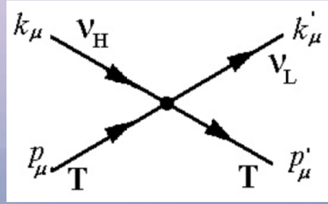


… even WIMPs

- Interaction of light DMp (LDM) on e^- or nucleus with production of a lighter particle

  → detection of electron/nucleus recoil energy

  e.g. sterile ν



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

… also other ideas …

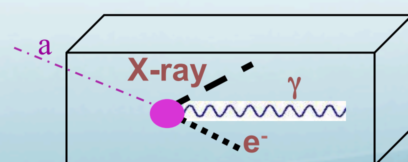
- **… and more**

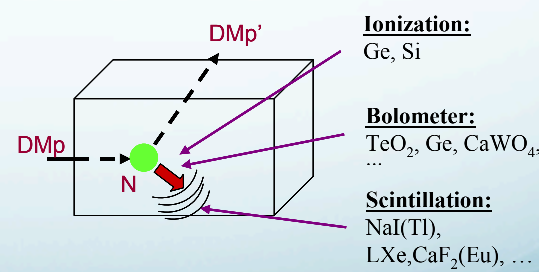
Direct detection experiments

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

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

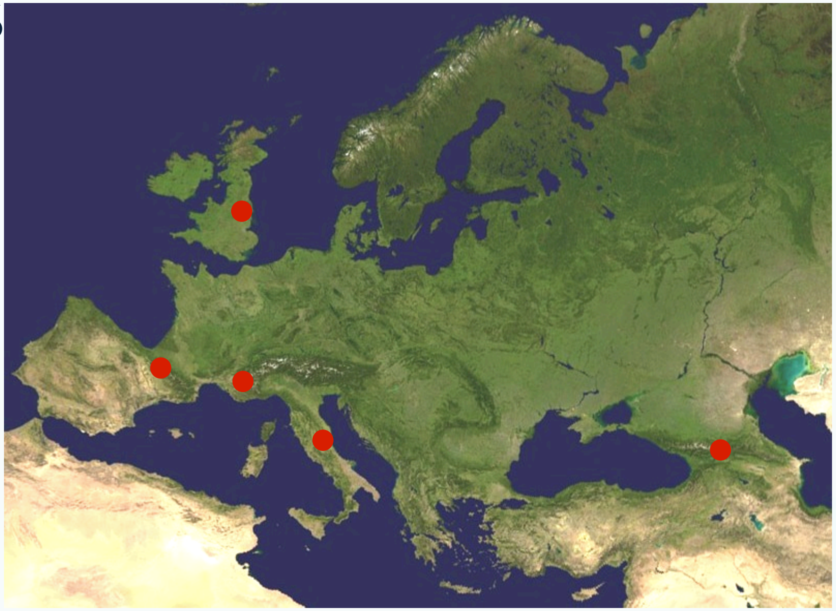
2. on the use of uncertain techniques of statistical **subtractions** of the e.m. component **of the counting rate** (adding systematical effects and lost of candidates with pure electromagnetic productions)





Dark Matter direct detection activities in underground labs

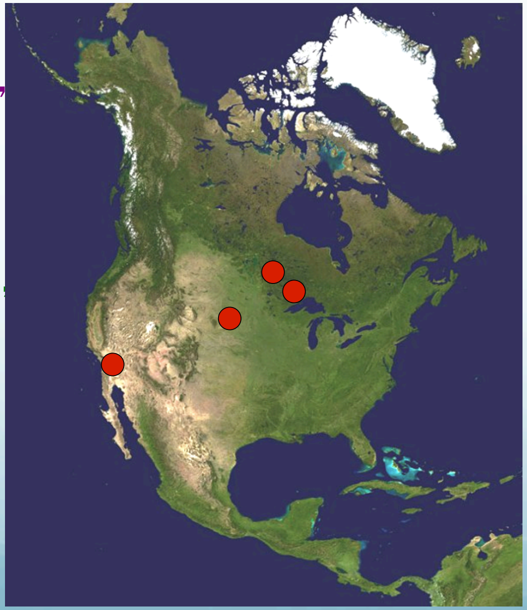
- Various approaches and techniques
- Various different target materials
- Various different experimental site depths
- Different radiopurity levels, etc.

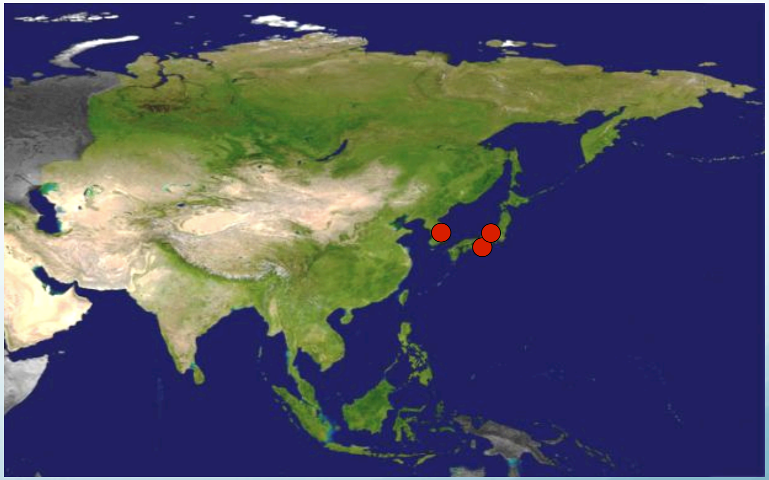


- **Gran Sasso (depth ~ 3600 m.w.e.): DAMA/NaI, DAMA/LIBRA, DAMA/LXe, HDMS, WARP, CRESST, Xenon, DarkSide**
- **Boulby (depth ~ 3000 m.w.e.): DRIFT, Zeplin, NAIAD**
- **Modane (depth ~ 4800 m.w.e.): Edelweiss**
- **Canfranc (depth ~ 2500 m.w.e.): ANAIS, Rosebud, ArDM**

- **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**

Experiments using liquid noble gases

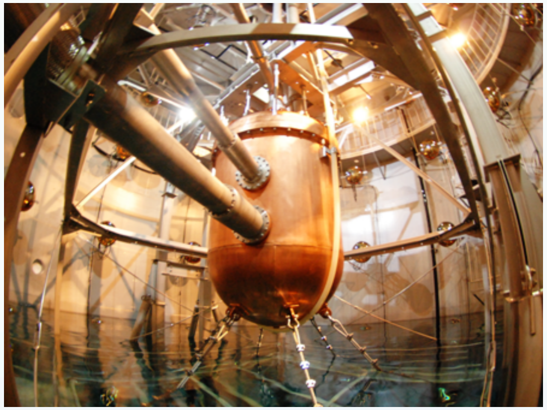
- Single phase: LXe, LAr, LNe → scintillation, ionization
- Dual phase liquid /gas → prompt scintillation + secondary scintillation

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

in single phase detector:

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

DAMA/LXe

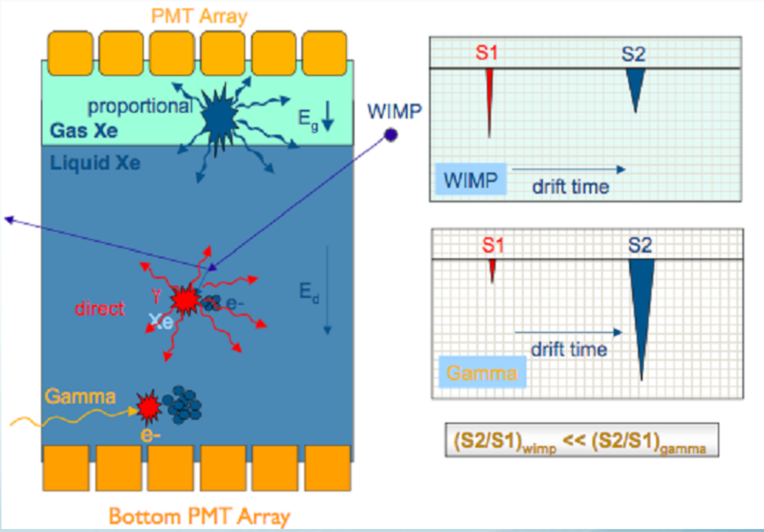


XMASS

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

in dual phase detector:

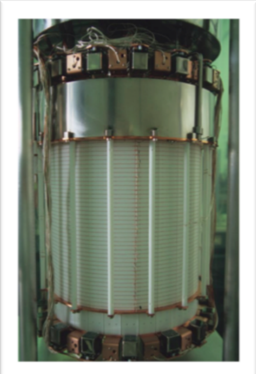
- prompt signal (S1): UV photons from excitation and ionization
- delayed signal (S2): e^- drifted into gas phase and secondary scintillation due to ionization in electric field



XENON10, 100, WARP, Dark Side, LUX

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

XENON100 results

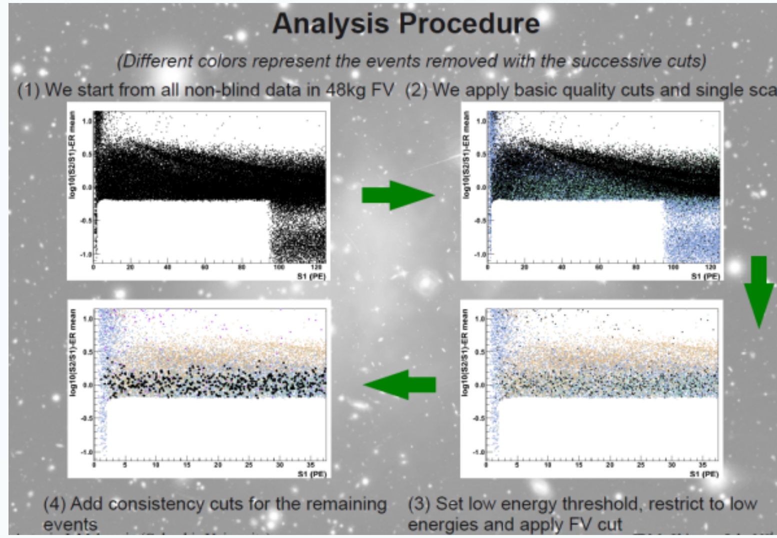


Experimental site: Gran Sasso (1400 m depth)

Target material: ^{nat}Xe

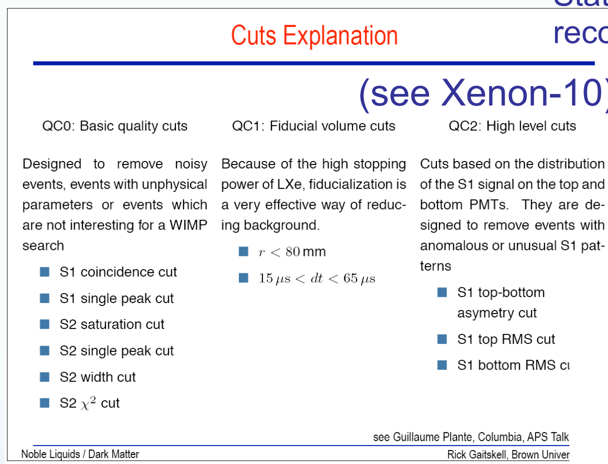
Target mass: ≈161 kg (fiducial: 34 kg)

Used exposure: 224.6 days



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

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



Cuts Explanation

QC0: Basic quality cuts	QC1: Fiducial volume cuts	QC2: High level cuts
Designed to remove noisy events, events with unphysical parameters or events which are not interesting for a WIMP search	Because of the high stopping power of LXe, fiducialization is a very effective way of reducing background.	Cuts based on the distribution of the S1 signal on the top and bottom PMTs. They are designed to remove events with anomalous or unusual S1 patterns
■ S1 coincidence cut ■ S1 single peak cut ■ S2 saturation cut ■ S2 single peak cut ■ S2 width cut ■ S2 χ^2 cut	■ $r < 80\,\mathrm{mm}$ ■ $15\,\mu s < dt < 65\,\mu s$	■ S1 top-bottom asymmetry cut ■ S1 top RMS cut ■ S1 bottom RMS cu

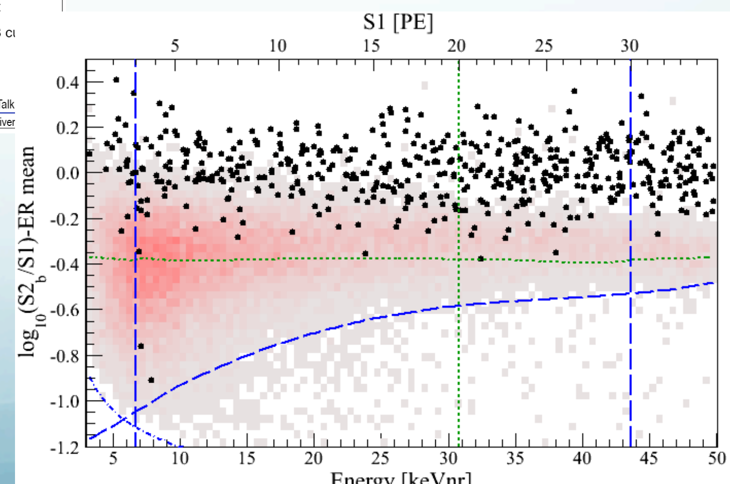
see Guillaume Plante, Columbia, APS Talk

Noble Liquids / Dark Matter — Rick Gaitskell, Brown Univer

(see Xenon-10)

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

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



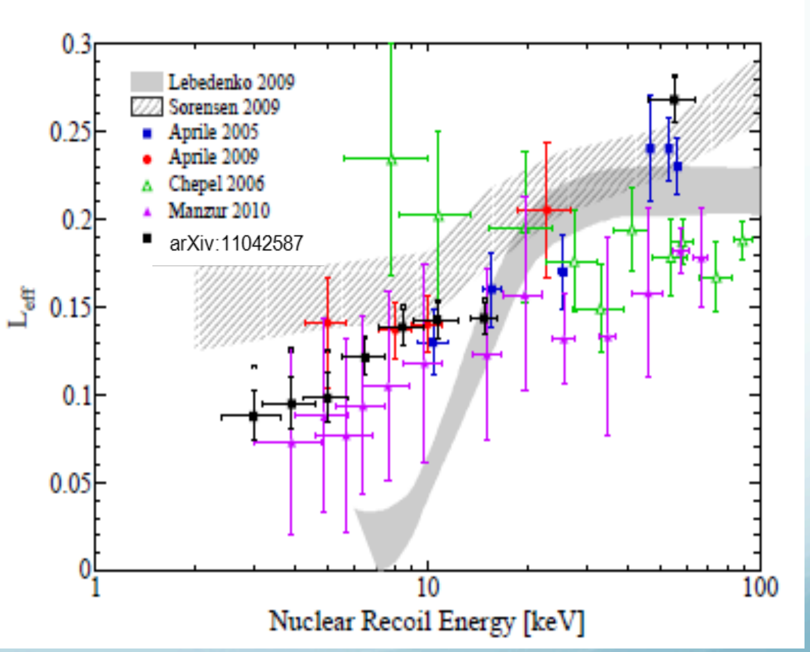
For example: what about the response of LXe set-ups at low-energy recoils?

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

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

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

  - L_{eff} drastically drops at lower energy?
  - Kinematic cutoff?
  - More precise measurements and/or more reliable theoretical evaluations required.



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

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

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

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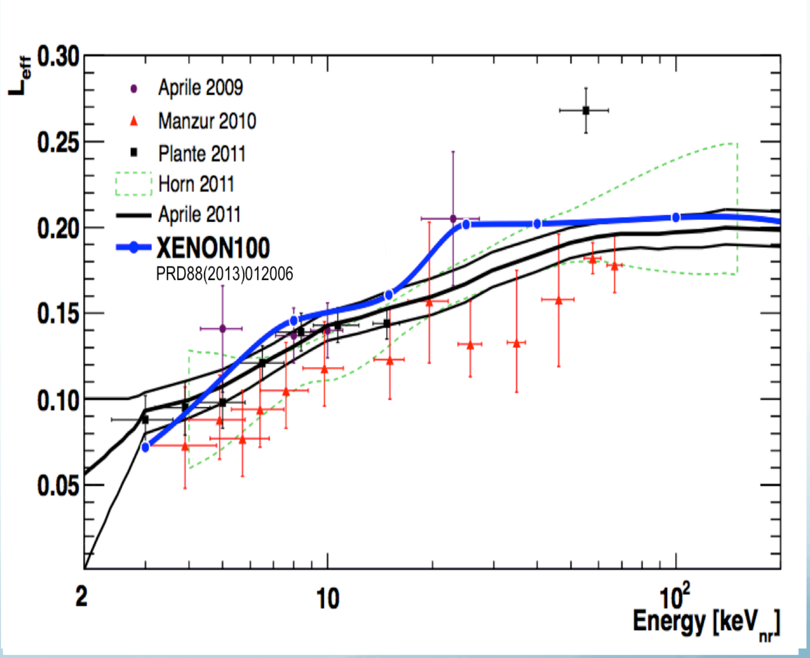

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LXe and LAr at LNGS

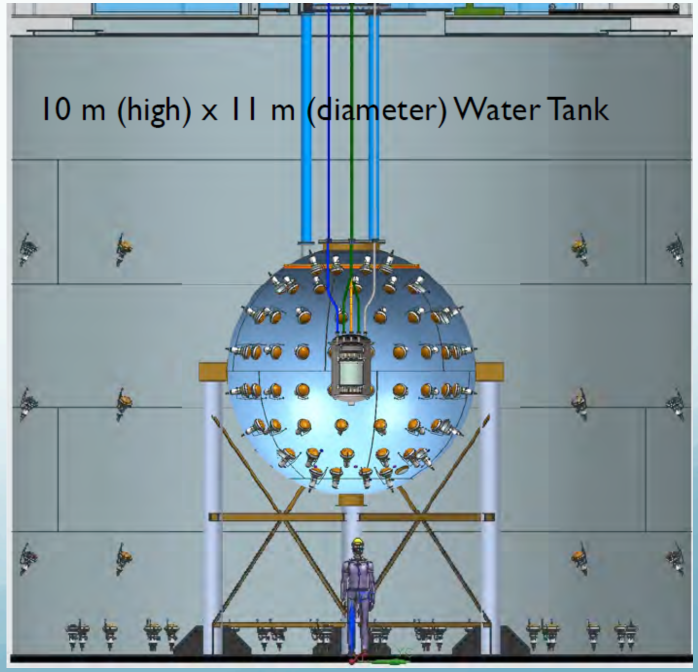
Technical comments similar as for XENON are expected (see above)

- > 3 t LXe (1 m³ detector)
- 1 t fiducial mass => 20x larger than XENON100
- 1m drift
- lower radioactivity components: 100x lower background
- Water Cerenkov Muon Veto system
- background goal: <1 background event in 2 years

XENON1T

DARKSIDE

- Operated DarkSide-10 prototype for 1 year
- Constructed as part of DarkSide-50:
  - 1000 tonnes water Cherenkov muon veto
  - 30 tonnes organic liquid scintillator neutron veto
  - two Rn-free clean rooms for final preparation of the detector
  - argon recirculation, purification, and recovery systems
- All facilities built sized to house DarkSide-G2



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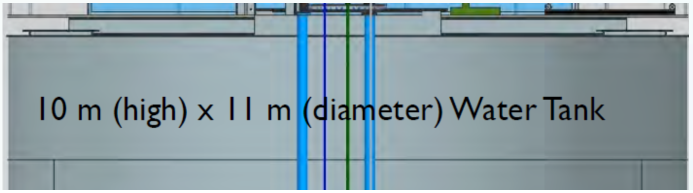
XENON1T



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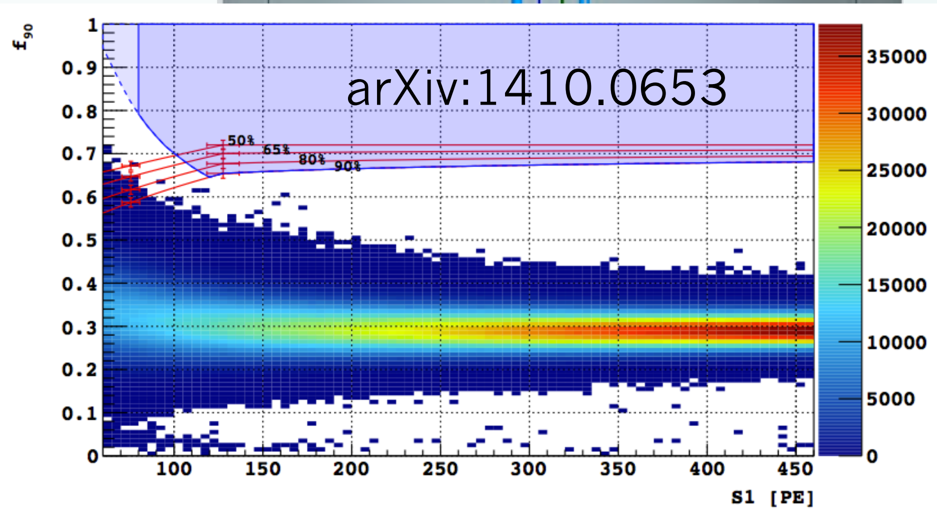
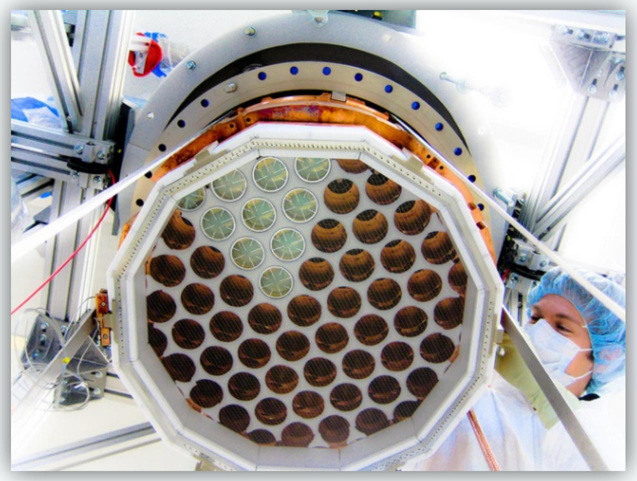


Results from LUX

PRL112(2014)091303



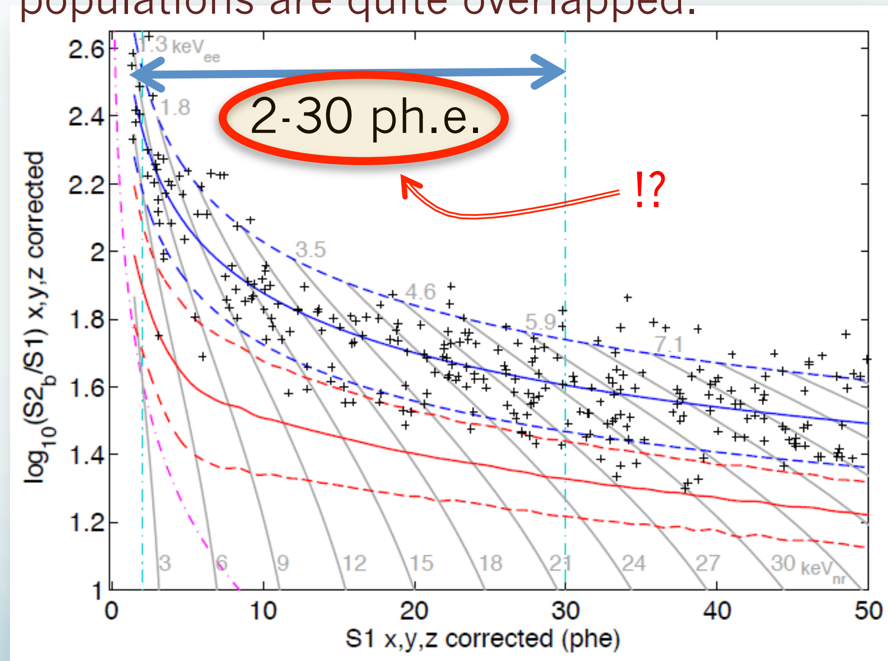
Experimental site: Sanford Underground Research Facility (SURF, 4300 m.w.e.)

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

Live time: 85.3 days

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

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



ER band ($\pm 1.28\sigma$)
NR band ($\pm 1.28\sigma$)
Approx. location of the minimum S2 cut

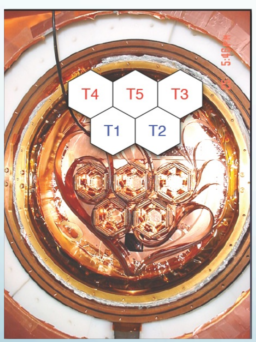
All NR band events assumed to be due to ER bkg events

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

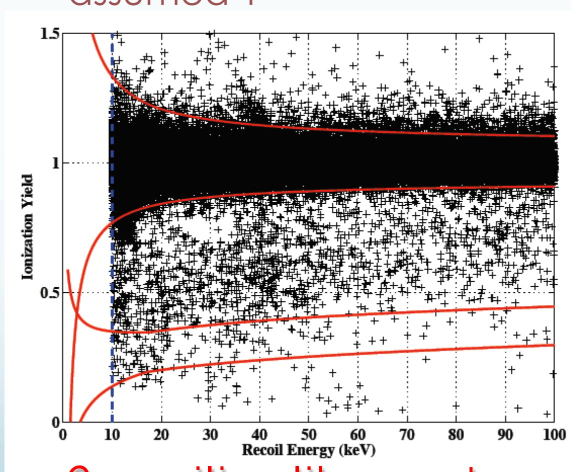
Results from double read-out bolometric technique (ionization vs heat)

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

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



PRL102,011301(2009), arXiv:0912.3592



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

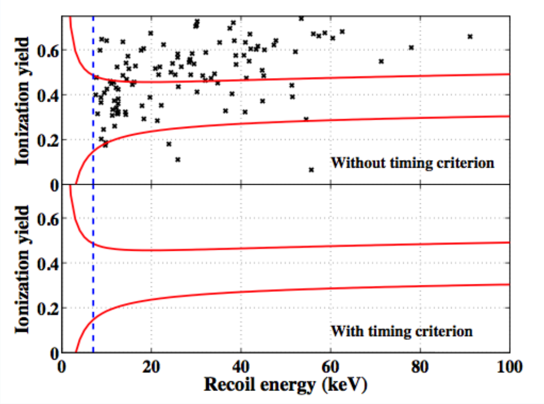
5 events observed (4 with E<22.5keV$_{recoil}$; 1 with E=172keV$_{recoil}$)

PLB702,5 (2011) 329

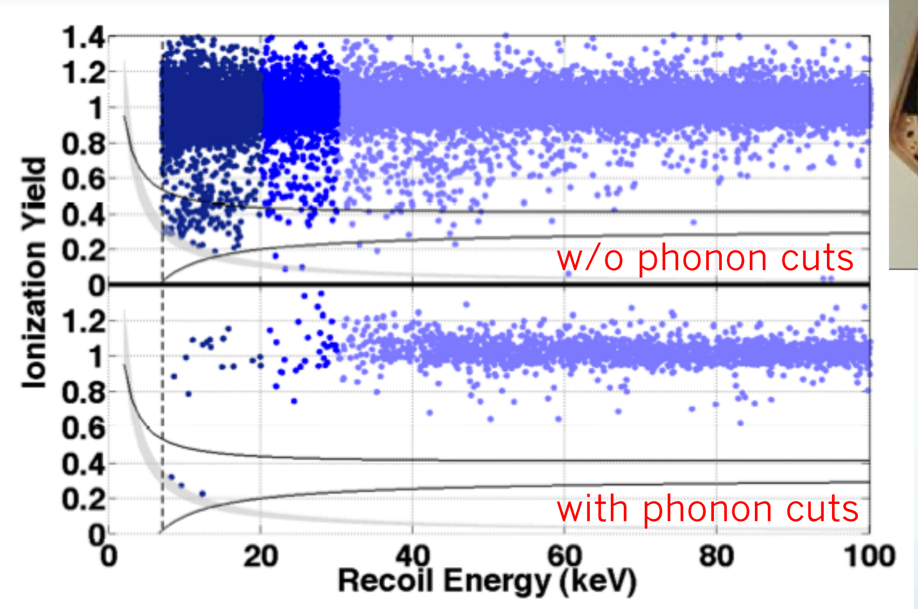
Results from double read-out bolometric technique (ionization vs heat): CDMS–Si

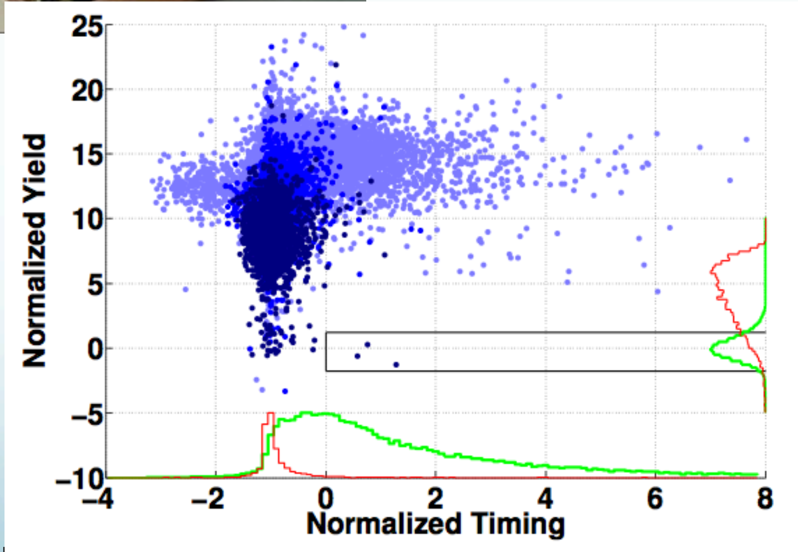
Results of CDMS-II with the Si detectors published in two close-in-time data releases:

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



arXiv:1304.3706
arXiv:1304.4279



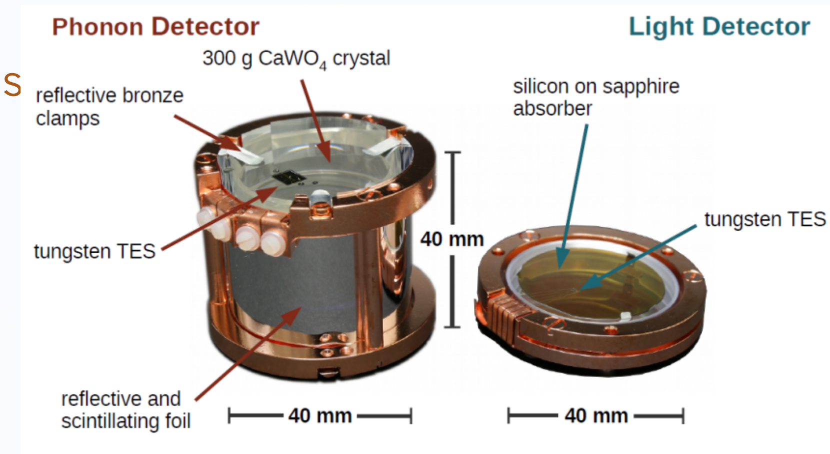


after many data selections and cuts, 3 Si recoil-like candidates survive in an exposure of 140.2 kg x day. Estimated residual background 0.41

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

Positive hint from CRESST (scintillation vs heat) ?

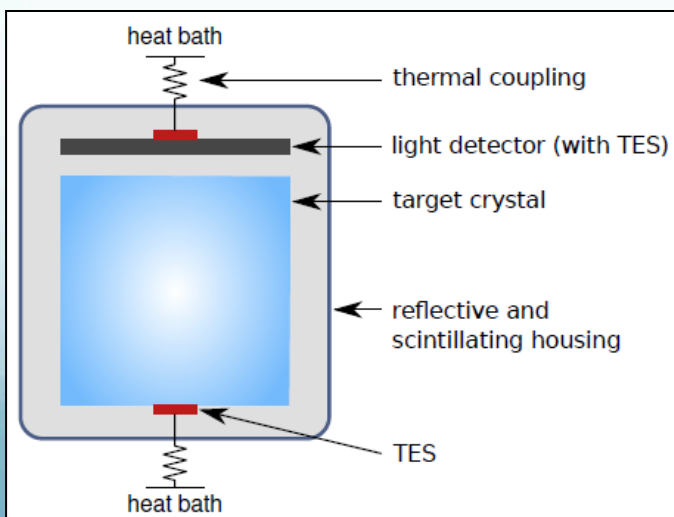
Experimental site: Gran Sasso (LNGS)
Detector: 33 $CaWO_4$ crystals (10 kg mass
data from 8 detectors
Exposure: ≈ 730 kg x day

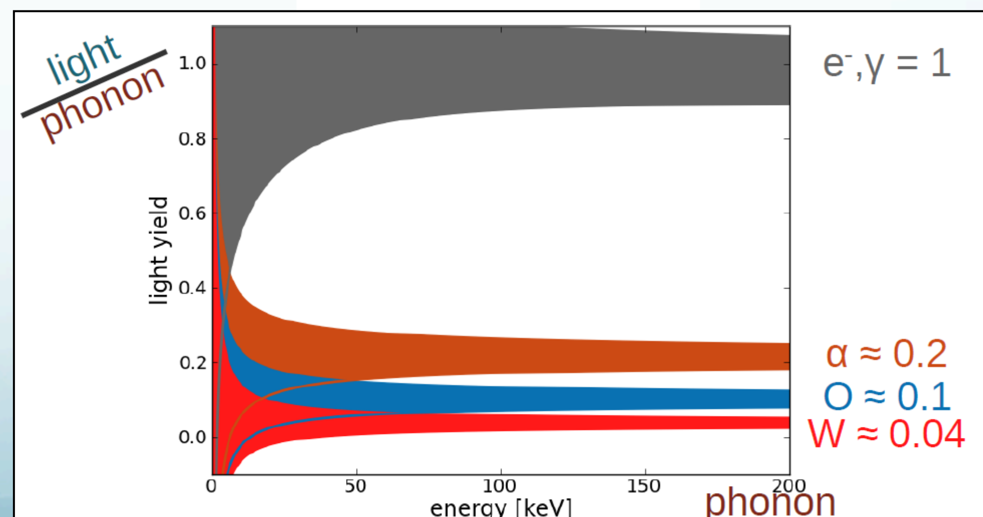


Discrimination of nuclear recoils from radioactive backgrounds by simultaneous measurement of phonons and scintillation light:

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

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





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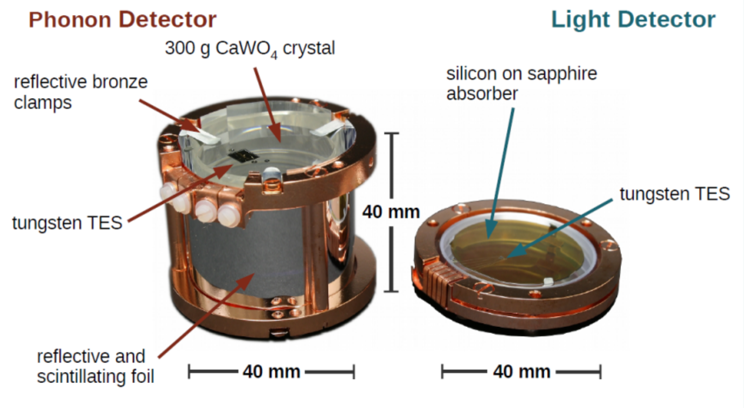
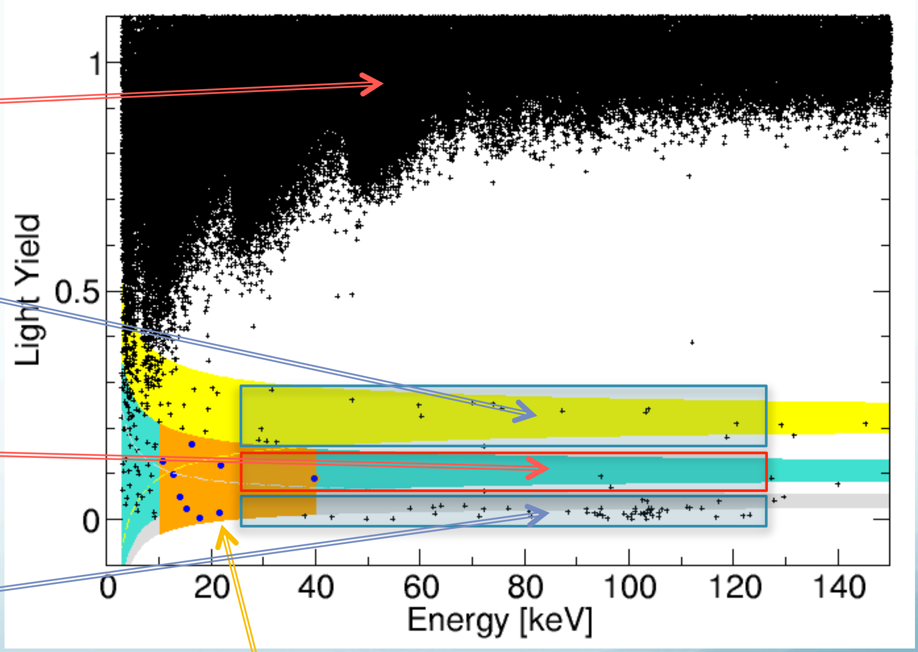


Typical Detector Module - Backgrounds

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



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

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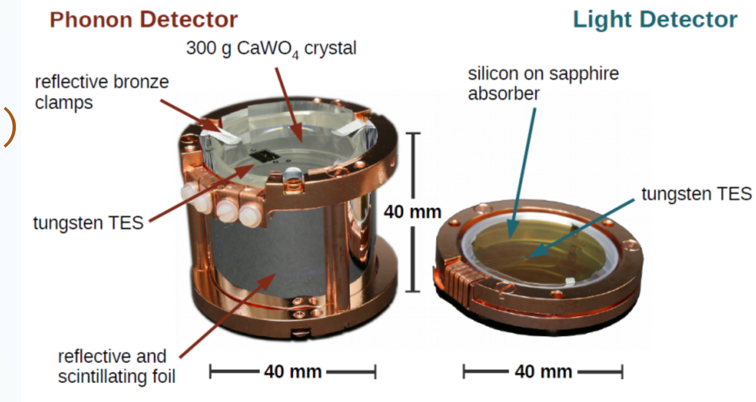
Exposure: ≈ 730 kg x day

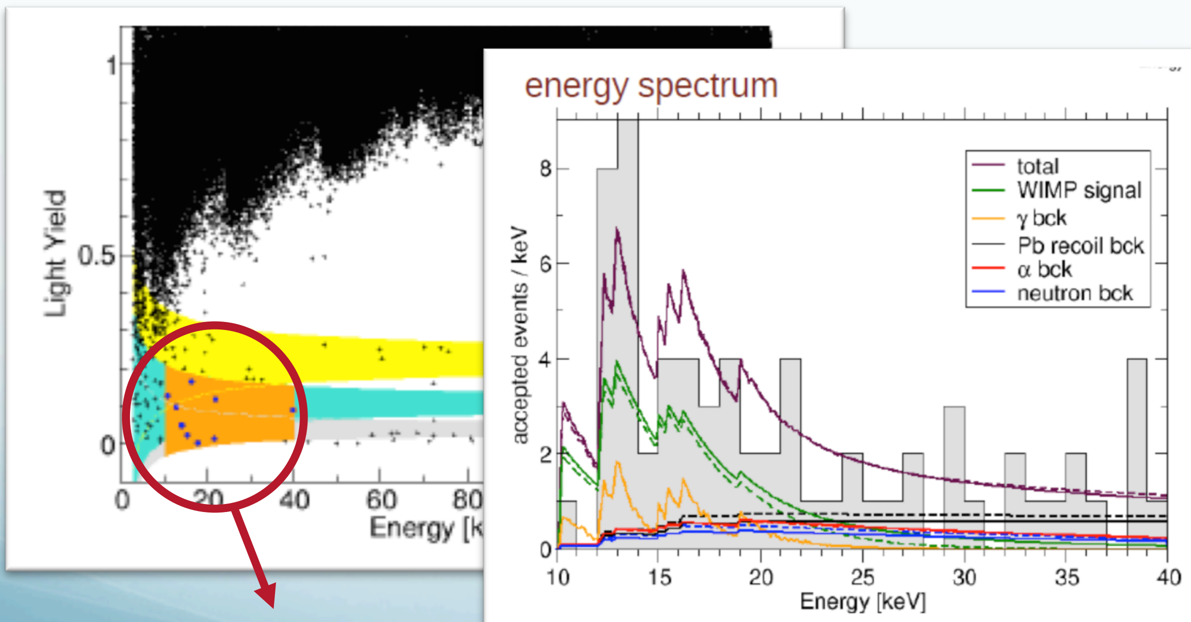


Discrimination of nuclear recoils from radioactive backgrounds by simultaneous measurement of phonons and scintillation light

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



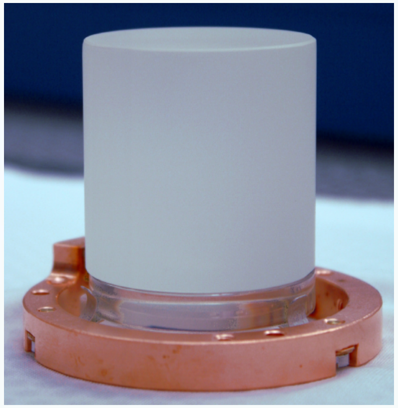
67 total events observed in O-band;

Future Run with improvement in preparation

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

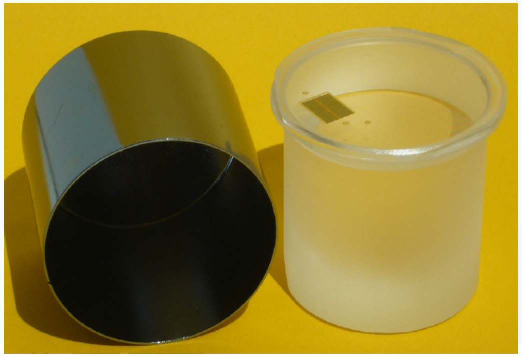
Efficiencies + stability + calibration, crucial role

Positive hint from CRESST (scintillation vs heat) ?



Last run highest priority: reduction of the overall background level

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

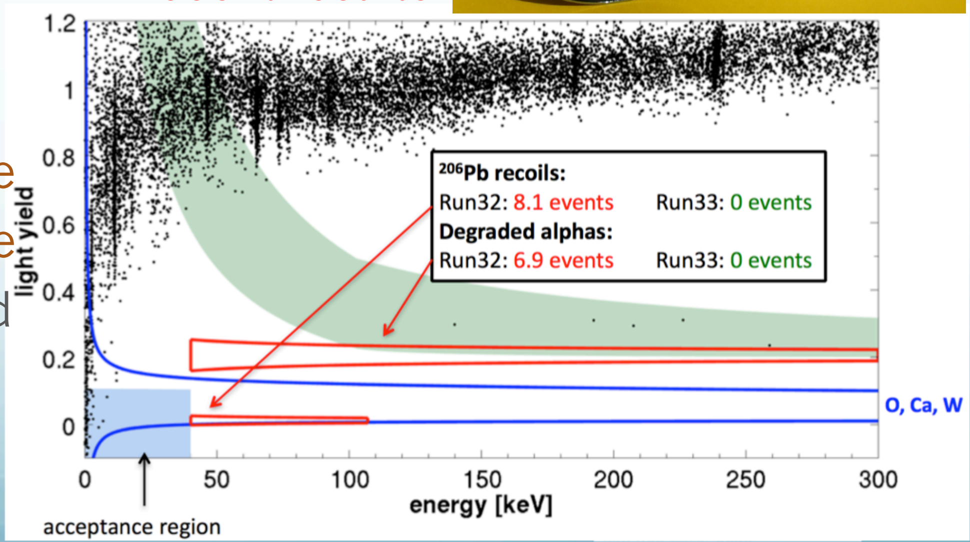


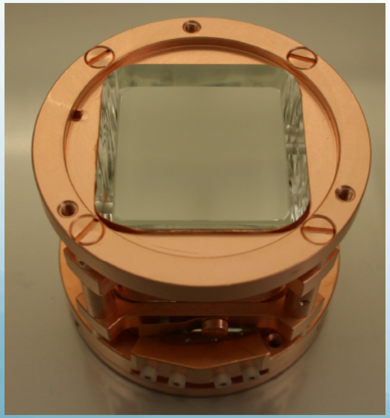
18 modules installed (~5.4 kg): 12 conventional detector modules + 6 active Pb recoil discriminating modules (3 different designs tested)

Data taking since July 2013

Expect ~2000 kg-days of data within 2 years

Recent results





Zero event in ≈ 29 kg x day (exposure 25 times lower than the previous run). Expected from previous run: < 1 event.

Still premature!

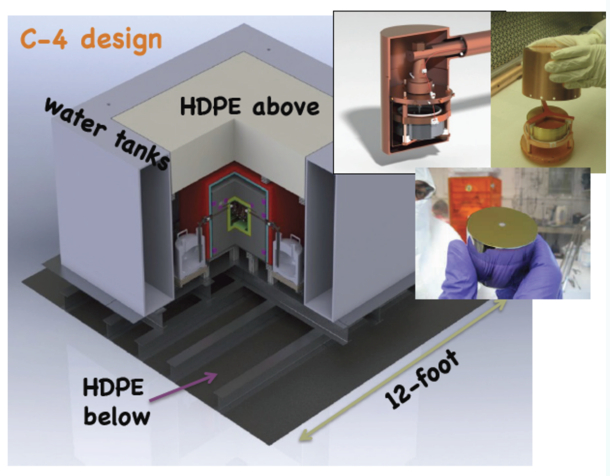
Positive hints from CoGeNT (ionization detector)

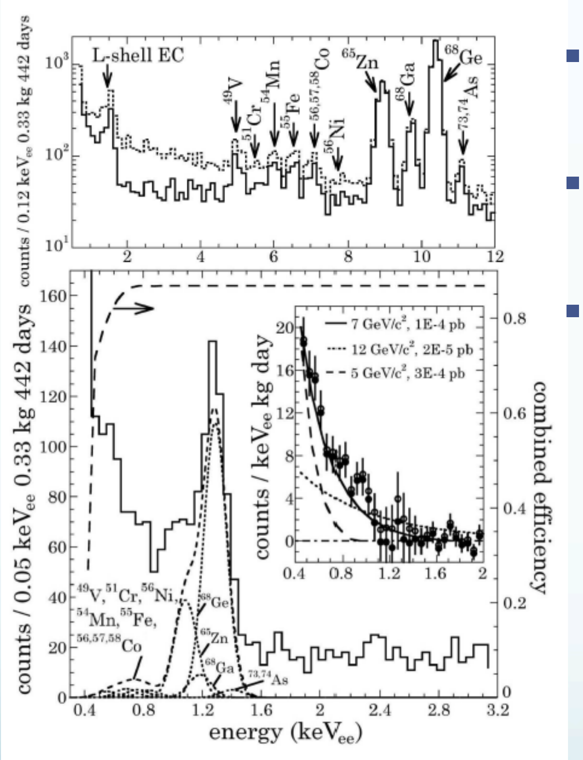
PRL107(2011)141301

Experimental site: Soudan Underground Laboratory (2100 mwe)

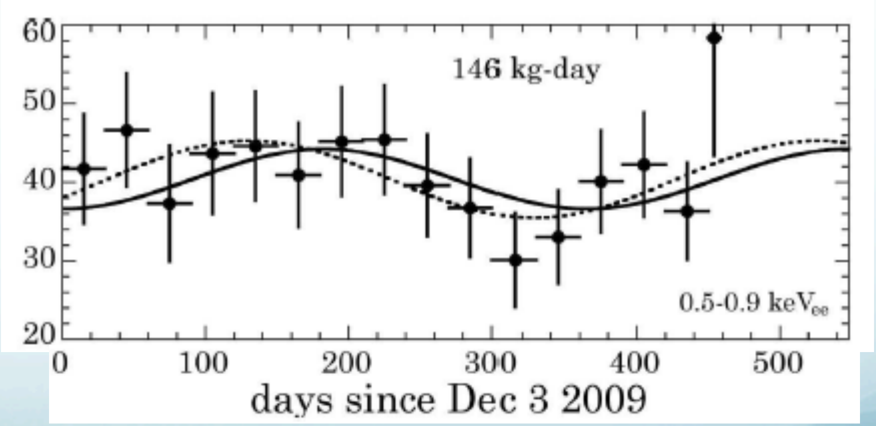
Detector: 440 g, p-type point contact (PPC) Ge diode 0.5 keVee energy threshold

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





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



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

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

In data taking since July 2011 after the fire in Soudan

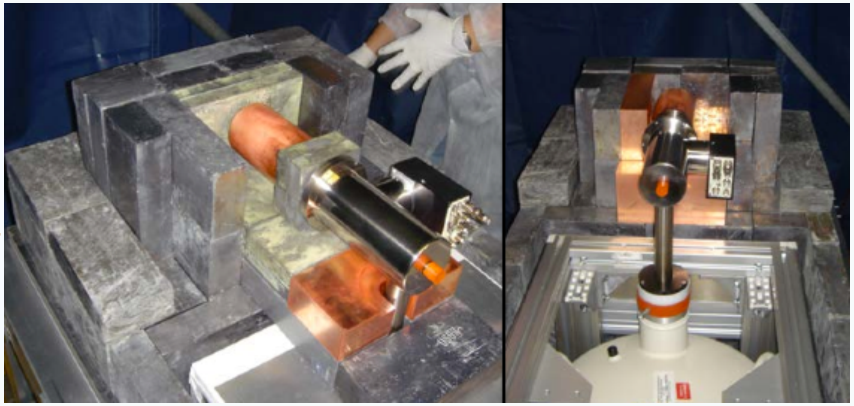
Positive hints from CoGeNT (ionization detector)

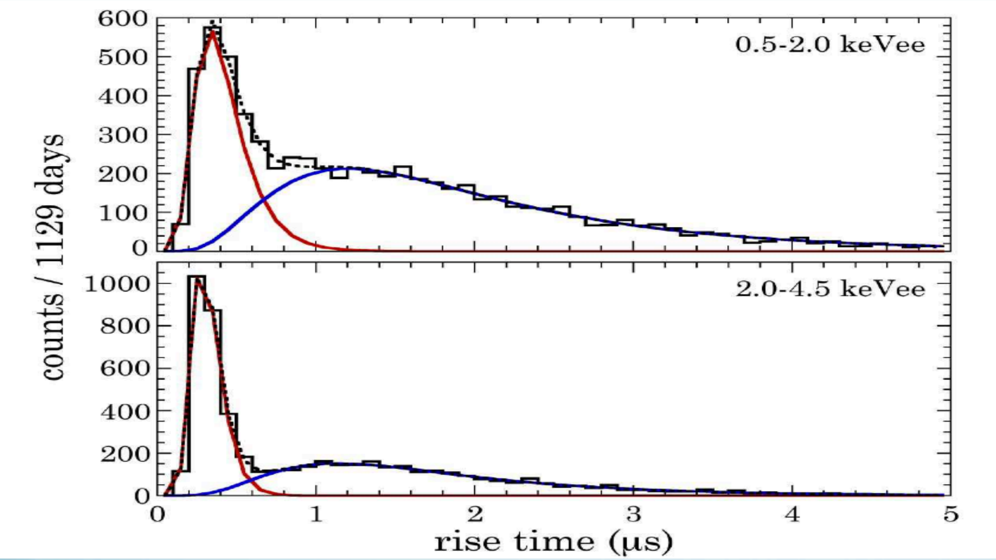
New data: arXiv:1401.3295

Experimental site: Soudan Underground Laboratory (2100 mwe)

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

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





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

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

Positive hints from CoGeNT

New data: arXiv:1401.3295

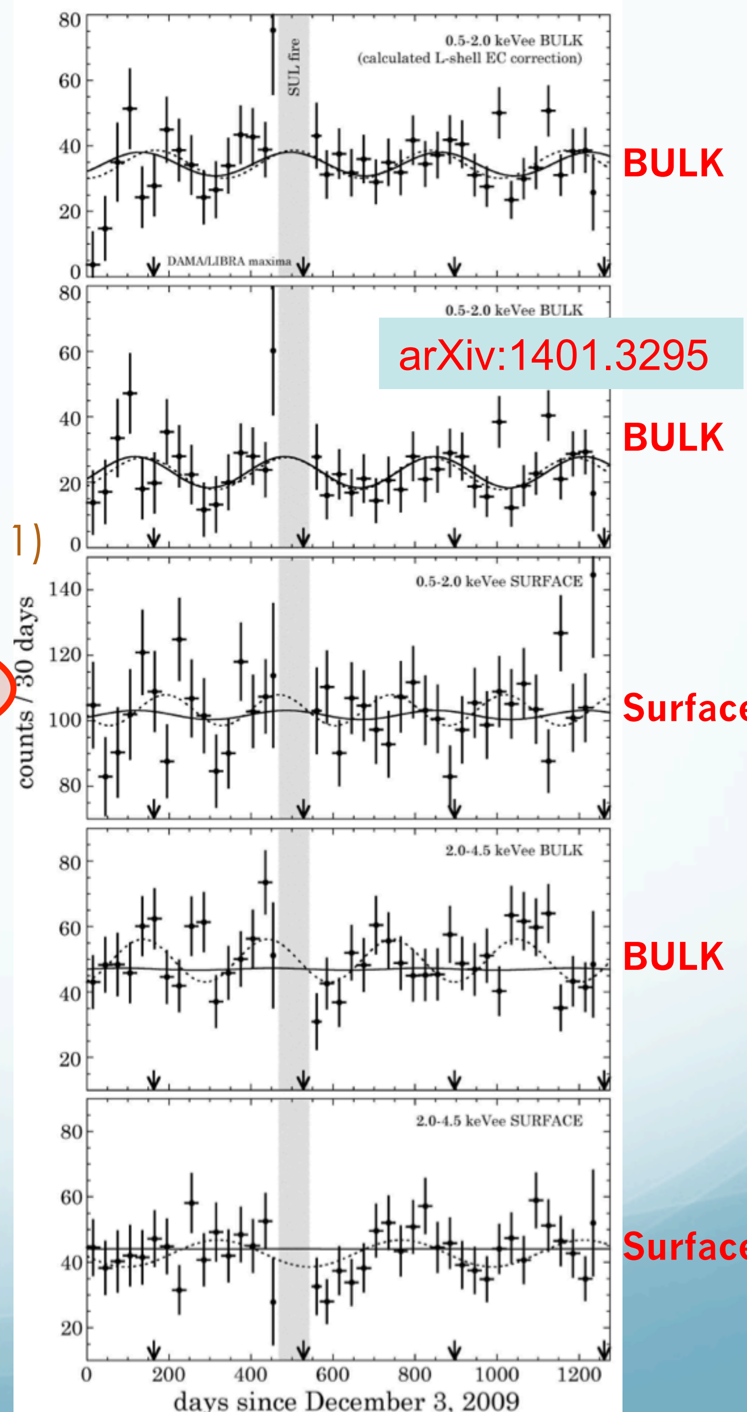
Experimental site: Soudan Underground Laboratory (2100 mwe)

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

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

- A straightforward analysis indicates a persistent annual modulation exclusively at low energy and for bulk events. Best-fit phase consistent with DAMA/LIBRA (small offset may be meaningful). Similar best-fit parameters to 15 mo dataset, but with much better bulk/surface separation (~90% SA for~90% BR)

  Unoptimized frequentist analysis yields ~2.2σ preference over null hypothesis. This however does not take into account the possible relevance of the modulation amplitude found...



CoGeNT upgrade: C-4 is coming up very soon

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

Even very small **systematics** in the data selections and statistical discrimination and rejection procedures can be difficult to estimate;

e.m. component of the rate can contain the signal or part of it

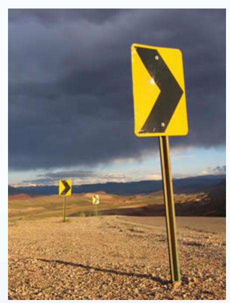
Even assuming pure recoil case and ideal discrimination on an event-by-event base, the result will NOT be the identification of the presence of WIMP elastic scatterings as DM signal, because of the well **known existing recoil-like indistinguishable background**

*Therefore, even in the ideal case the "excellent suppression of the e.m. component of the counting rate" can **not** provide a "signal identification"*

A model independent signature is needed

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

very hard to realize, it holds for some DM candidates

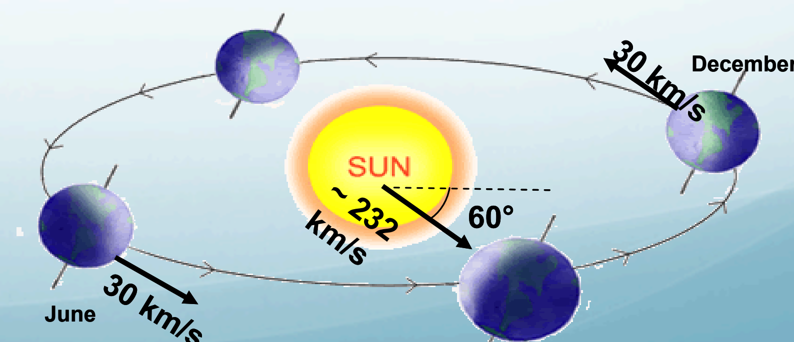


Diurnal modulation Daily variation of the interaction rate due to different Earth depth crossed by the Dark Matter particles

only for high σ

Annual modulation Annual variation of the interaction rate due to Earth motion around the Sun

at present the only feasible one, sensitive to many DM candidates and scenarios



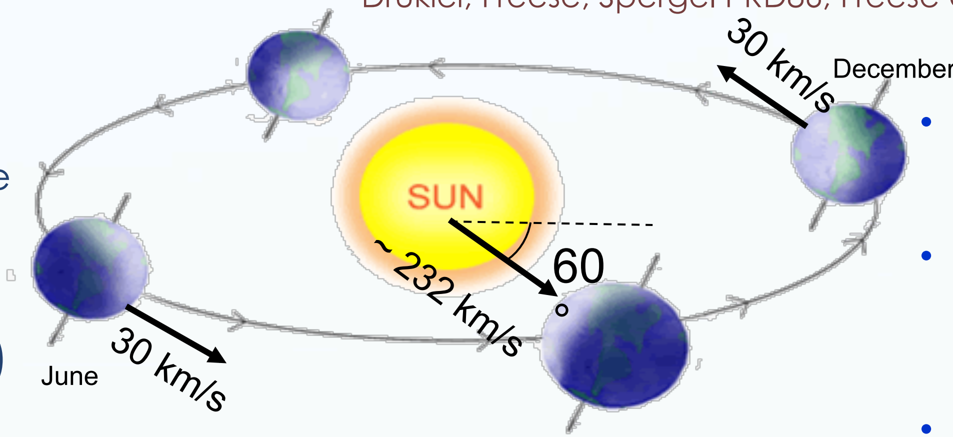
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

With the present technology, the annual modulation is the main model independent signature for the DM signal. Although the modulation effect is expected to be relatively small a suitable large-mass, low-radioactive set-up with an efficient control of the running conditions can point out its presence.

Requirements of the annual modulation

1) Modulated rate according cosine
2) In a definite low energy range
3) With a proper period (1 year)
4) With proper phase (about 2 June)
5) Just for single hit events in a multi-detector set-up
6) With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions, but it can be larger in case of some possible scenarios

Drukier, Freese, Spergel PRD86; Freese et al. PRD88



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

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

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

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

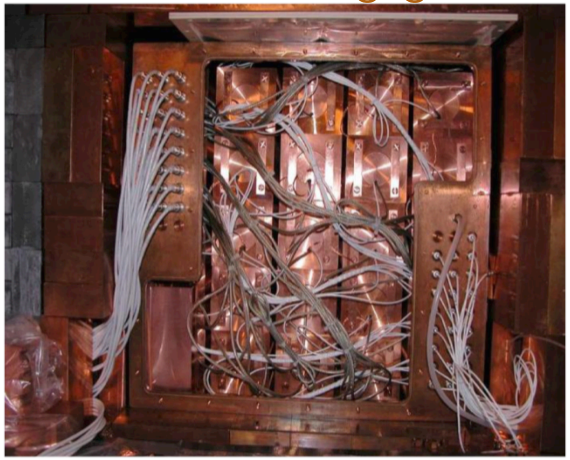
To mimic this signature, spurious effects and side reactions must not only - obviously - be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

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)

See R. Cerulli's talk

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



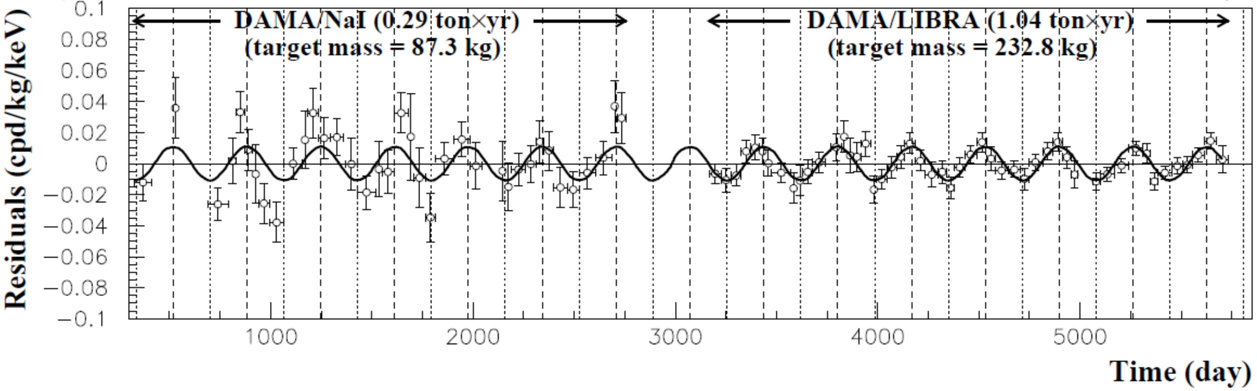
- Radiopurity, performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
- Results on DM particles, Annual Modulation Signature: EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648.
  Related results: PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022, EPJC74(2014)2827, arXiv:1409.3516.
- Results on rare processes: PEP violation: EPJC62(2009)327; CNC in I: EPJC72(2012)1920; IPP in ^{241}Am decay: EPJA49(2013)64

Model Independent Annual Modulation Result

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

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

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



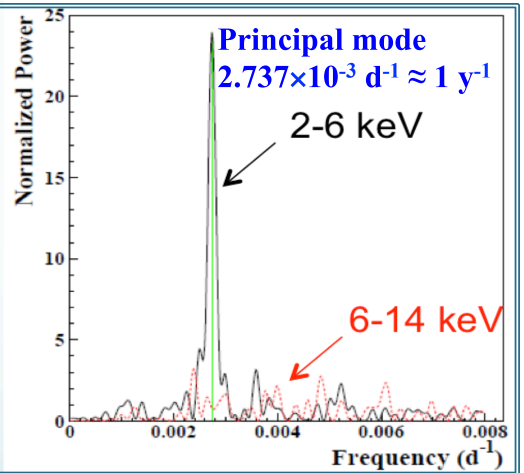
continuous line: t_0 = 152.5 d, T = 1.0 y

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

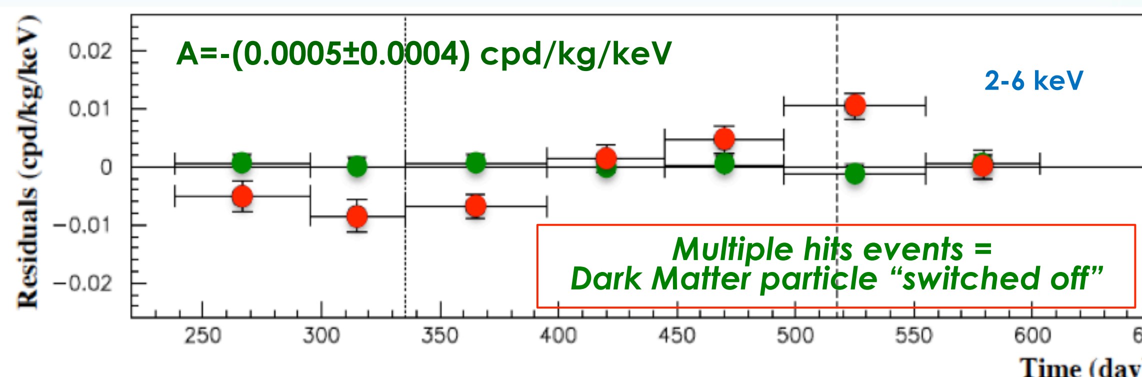
Absence of modulation? No
χ^2/dof=154/87 P(A=0) = 1.3×10^{-5}

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

Power spectrum



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

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 9.2σ C.L.

•Contributions to the total neutron flux at LNGS;
•Counting rate in DAMA/LIBRA for *single-hit* events, in the (2 – 6) keV energy region induced by:

- neutrons,
- muons,
- solar neutrinos.

$$\Phi_k = \Phi_{0,k}\left(1+\eta_k cos\omega\left(t-t_k\right)\right)$$
$$R_k = R_{0,k}\left(1+\eta_k cos\omega\left(t-t_k\right)\right)$$

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

arXiv:1409.3516

Modulation amplitudes

Source		$\Phi_{0,k}^{(n)}$ (neutrons cm^{-2} s^{-1})	η_k	t_k	$R_{0,k}$ (cpd/kg/keV)		$A_k = R_{0,k}\eta_k$ (cpd/kg/keV)	A_k/S_m^{exp}
SLOW neutrons	thermal n ($10^{-2} - 10^{-1}$ eV)	1.08×10^{-6} [15]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 8 \times 10^{-6}$	[2, 7, 8]	$\ll 8 \times 10^{-7}$	$\ll 7 \times 10^{-5}$
	epithermal n (eV-keV)	2×10^{-6} [15]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 3 \times 10^{-3}$	[2, 7, 8]	$\ll 3 \times 10^{-4}$	$\ll 0.03$
FAST neutrons	fission, $(\alpha, n) \to$ n (1-10 MeV)	$\simeq 0.9 \times 10^{-7}$ [17]	$\simeq 0$ however $\ll 0.1$ [2, 7, 8]	–	$< 6 \times 10^{-4}$	[2, 7, 8]	$\ll 6 \times 10^{-5}$	$\ll 5 \times 10^{-3}$
	$\mu \to$ n from rock ($>$ 10 MeV)	$\simeq 3 \times 10^{-9}$ (see text and ref. [12])	0.0129 [23]	end of June [23, 7, 8]	$\ll 7 \times 10^{-4}$	(see text and [2, 7, 8])	$\ll 9 \times 10^{-6}$	$\ll 8 \times 10^{-4}$
	$\mu \to$ n from Pb shield ($>$ 10 MeV)	$\simeq 6 \times 10^{-9}$ (see footnote 3)	0.0129 [23]	end of June [23, 7, 8]	$\ll 1.4 \times 10^{-3}$	(see text and footnote 3)	$\ll 2 \times 10^{-5}$	$\ll 1.6 \times 10^{-3}$
	$\nu \to$ n (few MeV)	$\simeq 3 \times 10^{-10}$ (see text)	0.03342 *	Jan. 4th *	$\ll 7 \times 10^{-5}$	(see text)	$\ll 2 \times 10^{-6}$	$\ll 2 \times 10^{-4}$
	direct μ	$\Phi_0^{(\mu)} \simeq 20$ μ m^{-2}d^{-1} [20]	0.0129 [23]	end of June [23, 7, 8]	$\simeq 10^{-7}$	[2, 7, 8]	$\simeq 10^{-9}$	$\simeq 10^{-7}$
	direct ν	$\Phi_0^{(\nu)} \simeq 6 \times 10^{10}$ ν 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) can mimic the DM annual modulation signature since some of the **peculiar requirements of the signature** would fail, such as the neutrons would induce e.g. variations in all the energy spectrum, variation in the multiple hit events,… which were not observed.

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

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

Neutralino as LSP in various SUSY theories

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

a heavy ν of the 4-th family

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

WIMP with preferred inelastic scattering

Mirror Dark Matter

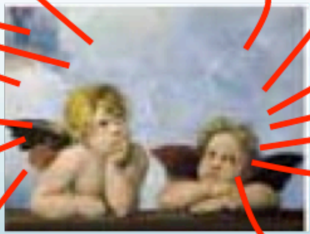
Light Dark Matter

Self interacting Dark Matter

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

Sterile neutrino

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



Elementary Black holes such as the Daemons

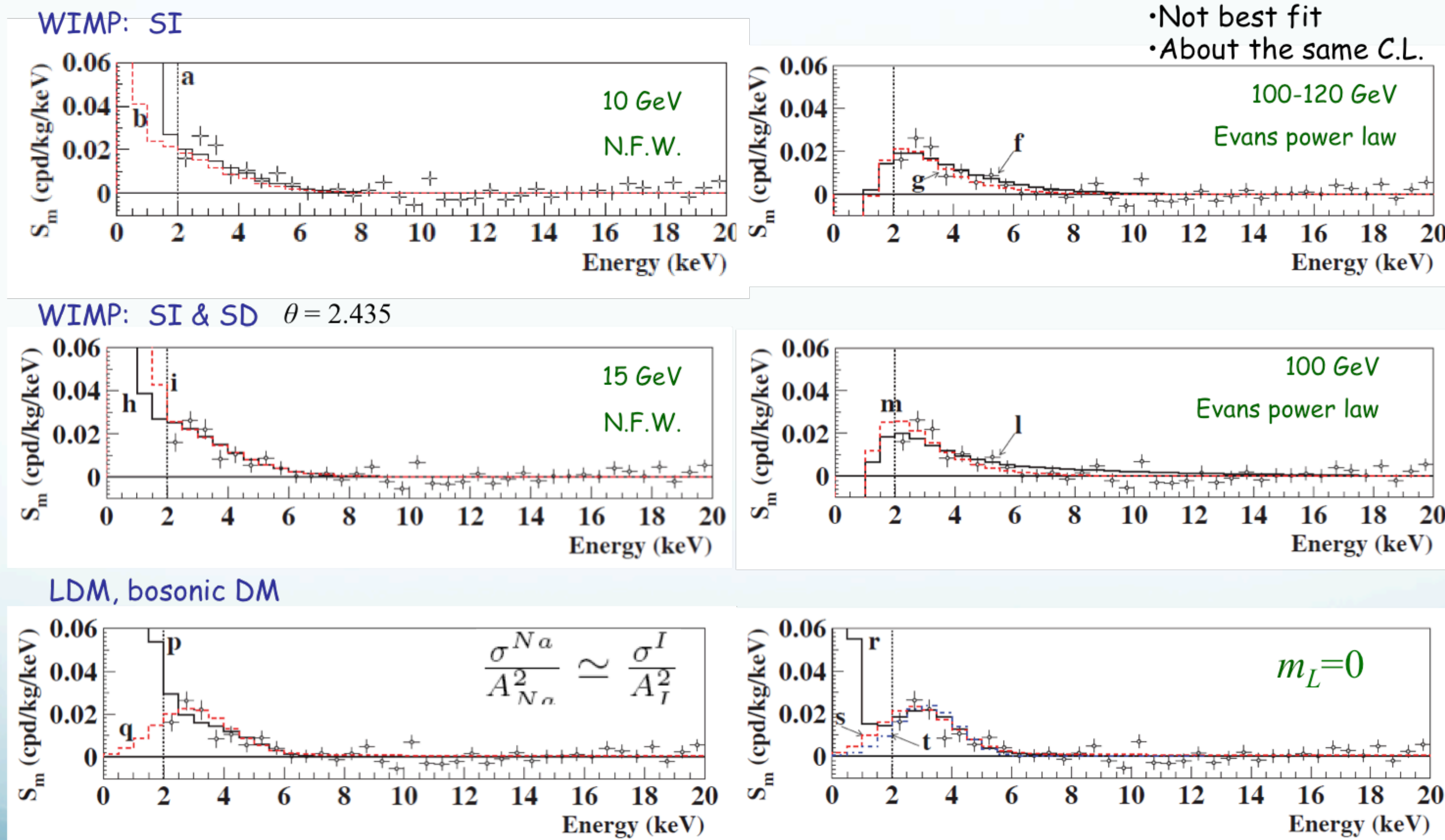
Kaluza Klein particles

... and more

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

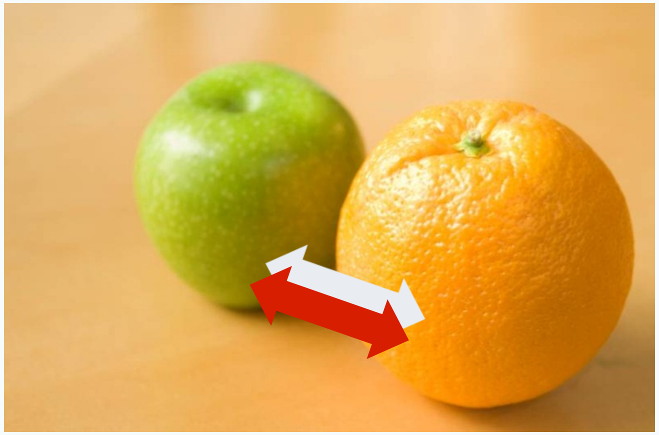
well compatible with several candidates in many astrophysical, nuclear and particle physics scenarios

Just few examples of interpretation of the annual modulation in terms of candidate particles in some scenarios



Compatibility with several candidates; other ones are open

EPJC56(2008)333
IJMPA28(2013)1330022



About interpretation

See e.g.: Riv.N.Cim.26 n.1(2003)1, IJMPD13(2004)2127, EPJC47(2006)263, IJMPA21(2006)1445, EPJC56(2008)333, PRD84(2011)055014, IJMPA28(2013)1330022

…models…

- Which particle?
- Which interaction coupling?
- Which Form Factors for each target-material?
- Which Spin Factor?
- Which nuclear model framework?
- Which scaling law?
- Which halo model, profile and related parameters?
- Streams?
- …

…and experimental aspects…

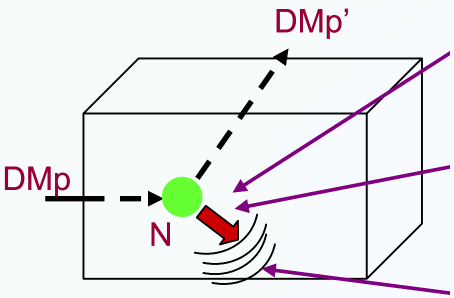
- Exposures
- Energy threshold
- Detector response (phe/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities
- Efficiencies
- Definition of fiducial volume and non-uniformity
- Quenching factors, channeling, …
- …

Uncertainty in experimental parameters, as well as necessary assumptions on various related astrophysical, nuclear and particle-physics aspects, affect all the results at various extent, both in terms of exclusion plots and in terms of allowed regions/volumes. Thus comparisons with a fixed set of assumptions and parameters' values are intrinsically strongly uncertain.

No experiment can be directly compared in model independent way with DAMA

... an example in literature...

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



Regions in the nucleon cross section vs DM particle mass plane

- Some velocity distributions and uncertainties considered.
- The DAMA regions represent the domain where the likelihood-function values differ more than 7.5σ from the null hypothesis (absence of modulation).
- For CoGeNT a fixed value for the Ge quenching factor and a Helm form factor with fixed parameters are assumed.
- The CoGeNT region includes configurations whose likelihood-function values differ more than 1.64σ from the null hypothesis (absence of modulation). This corresponds roughly to 90% C.L. far from zero signal.

Including the Migdal effect
→Towards lower mass/higher σ

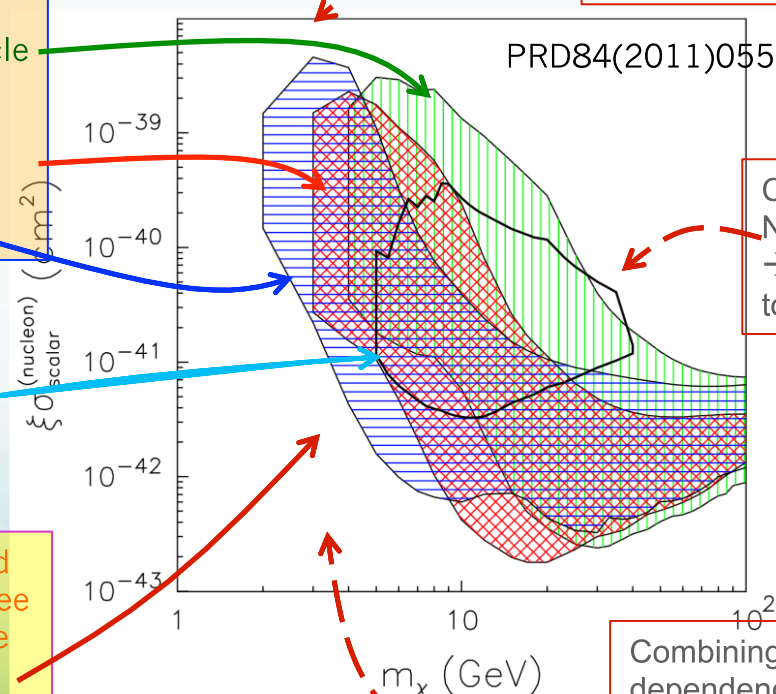
DAMA allowed regions for a particular set of astrophysical, nuclear and particle Physics assumptions without (green), with (blue) channeling, with energy-dependent Quenching Factors (red);

7.5 σ C.L.

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

CoGeNT; qf at fixed assumed value

1.64 σ C.L.



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

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

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

DAMA →

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

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

Velocity of the detector in the terrestrial laboratory:

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

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

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

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

Annual modulation term:

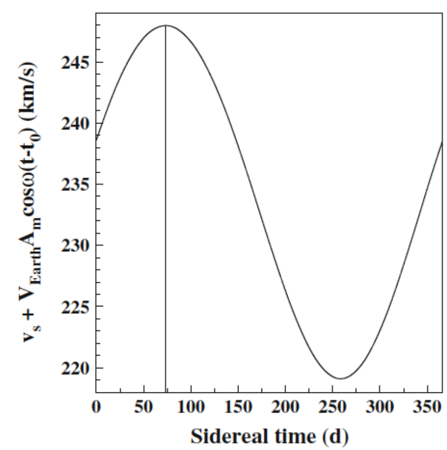
$$\hat{v}_s \cdot \vec{v}_{rev}(t) = V_{Earth} B_m \cos(\omega(t - t_0))$$

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

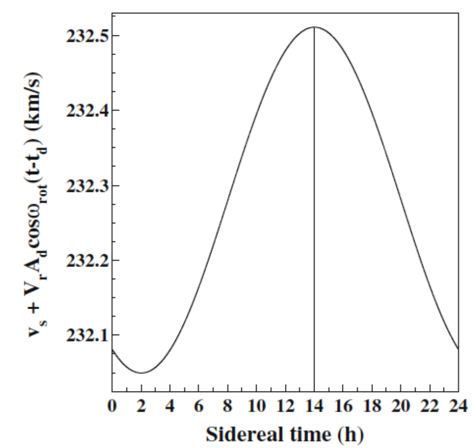
Diurnal modulation term:

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

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



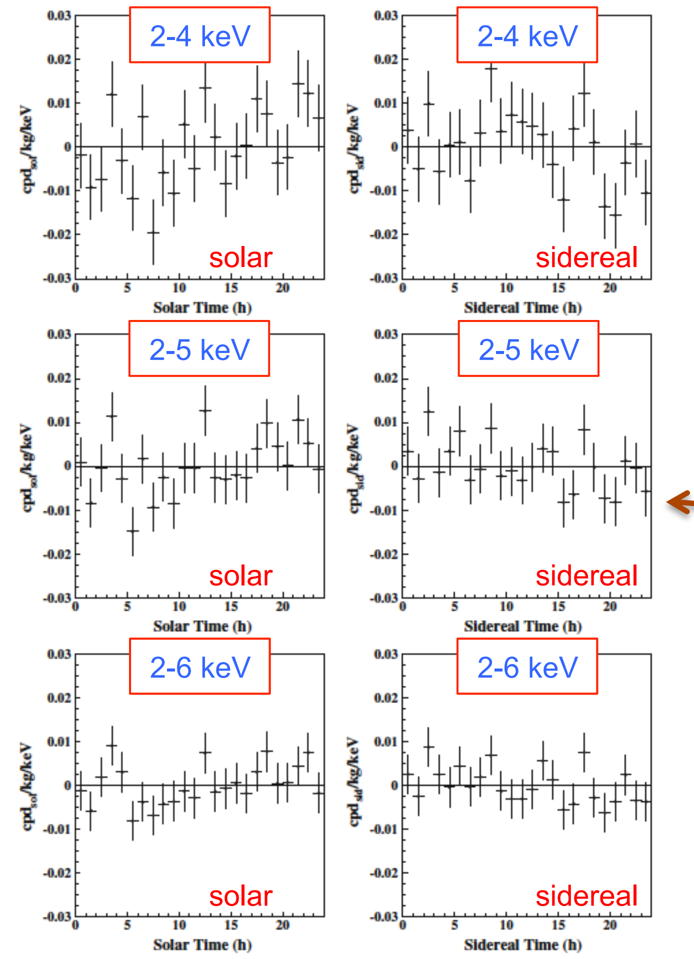
Velocity of the Earth in the galactic frame as a function of the sidereal time, with starting point March 21 (around spring equinox). The contribution of diurnal rotation has been dropped off. The maximum of the velocity (vertical line) is about 73 days after the spring equinox.



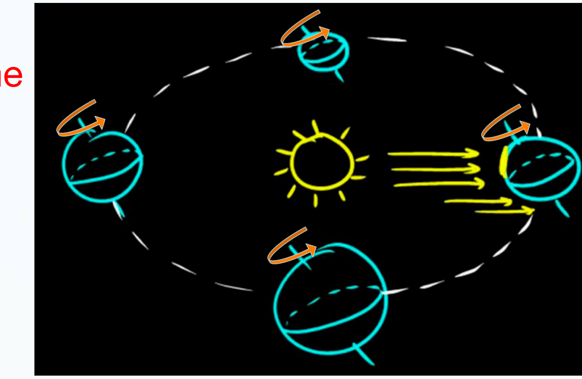
Sum of the Sun velocity in the galactic frame (v_s) and of the rotation velocity of a detector at LNGS ($\mathbf{v}_s \cdot \mathbf{v}_{rot}(t)$) as a function of the sidereal time. The maximum of the velocity is about at 14 h (vertical line).

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

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

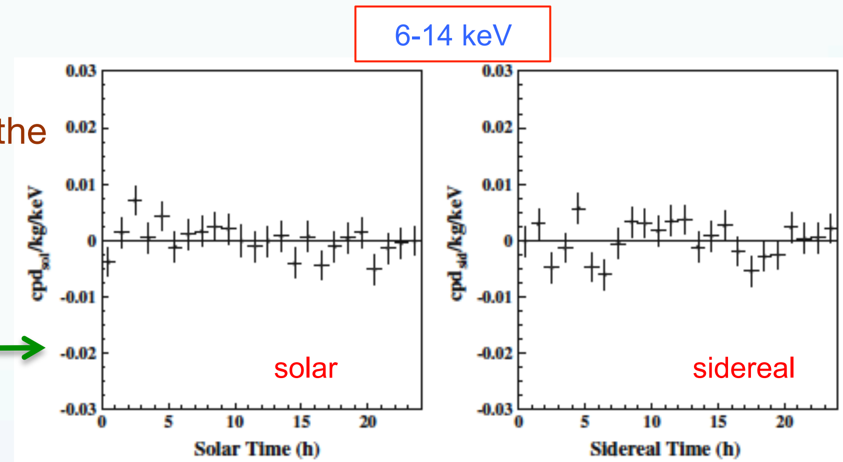


- Experimental *single-hit* residuals rate vs either sidereal and solar time and vs energy.
- These residual rates are calculated from the measured rate of the *single-hit* events after subtracting the constant part



Energy region where the annual modulation is observed.

Energy region just above.



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

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

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

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

The time dependence of the counting rate

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

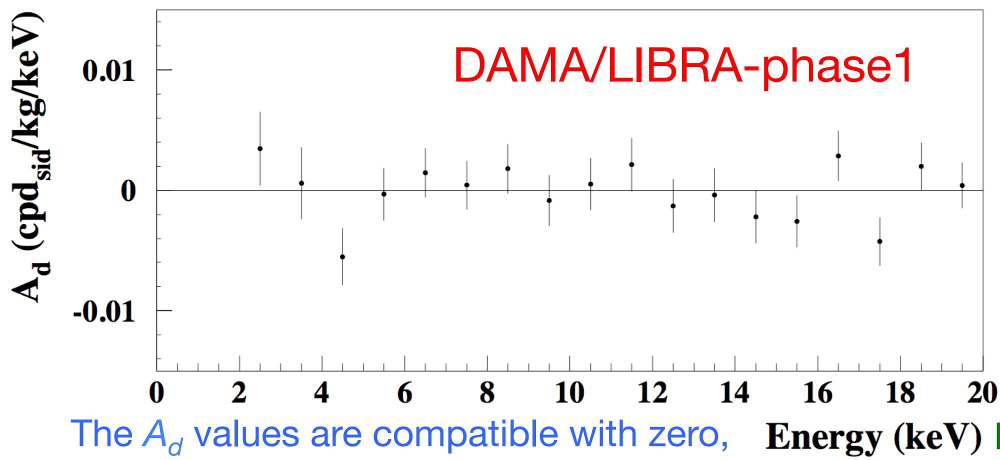
$$S_k\left[v_{lab}(t)\right] \simeq S_k\left[v_s\right] + \left[\frac{\partial S_k}{\partial v_{lab}}\right]_{v_s}\left[V_{Earth}A_m\cos\omega(t-t_0) + V_r A_d \cos\omega_{rot}(t-t_d)\right]$$

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

The ratio R_{dy} of the diurnal over annual modulation amplitudes is a model independent constant

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

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



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

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

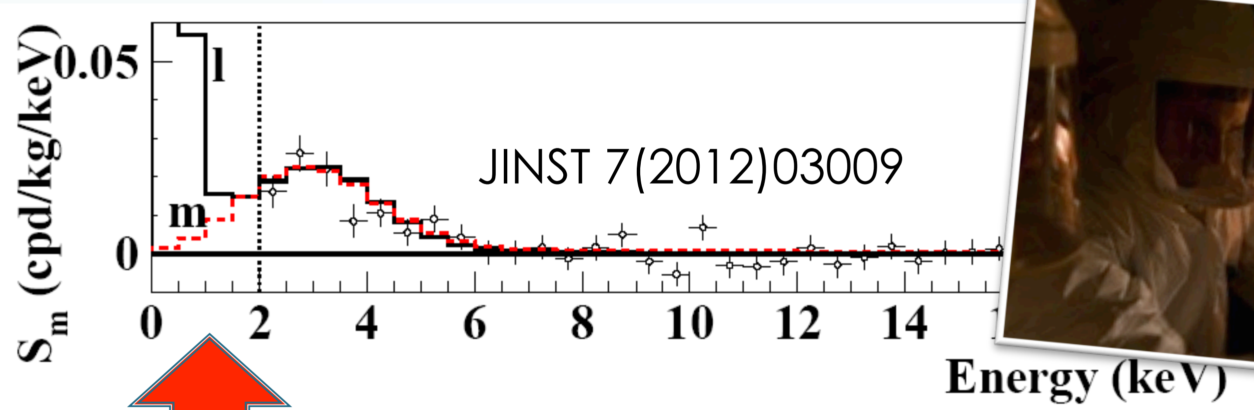
The A_d values are compatible with zero, having random fluctuations around zero with χ^2 equal to 19.5 for 18 dof

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

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

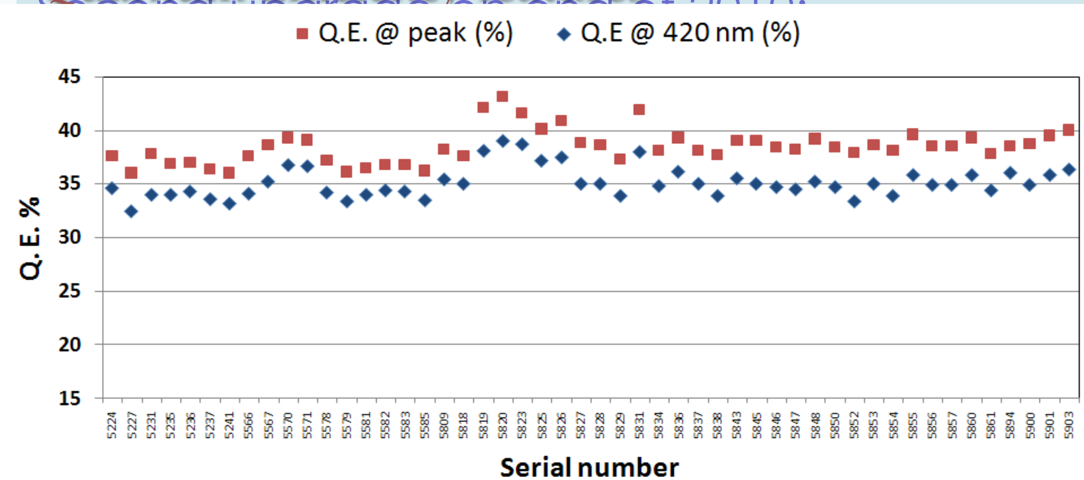
DAMA/LIBRA phase2 - running

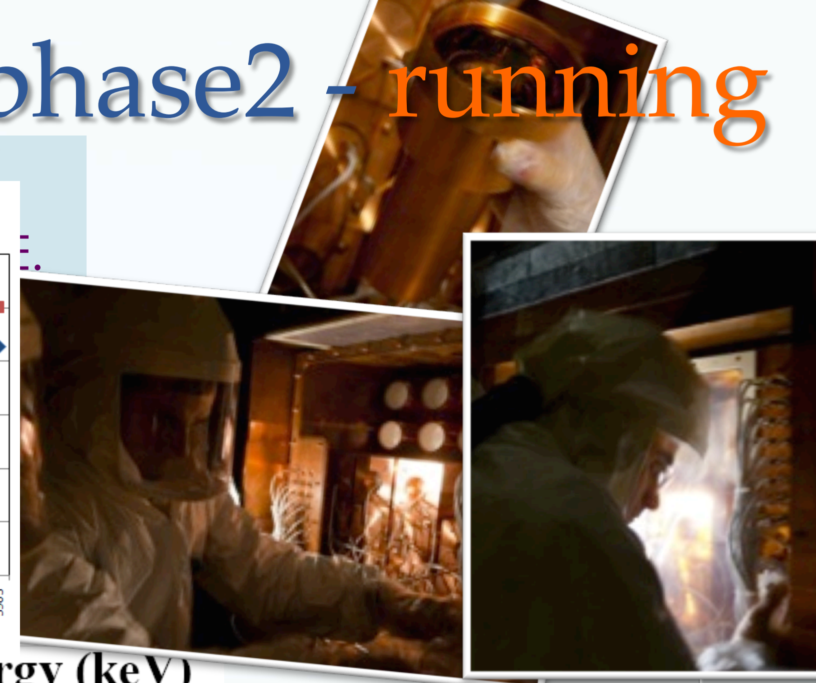
Second upgrade on end of 2010:
all PMTs replaced with new ones of higher Q.E.



DAMA/LIBRA phase2 - running

Quantum Efficiency features



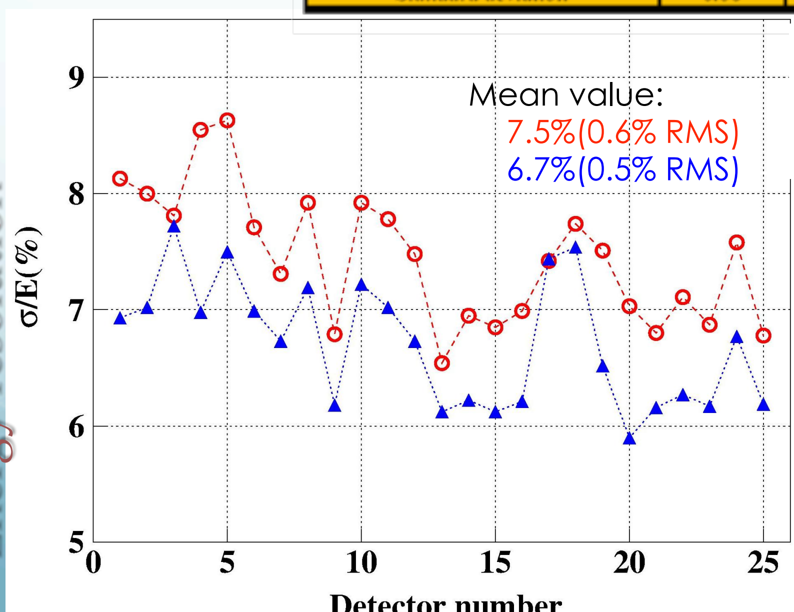


Residual Contamination

The limits are at 90% C.L.

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

Energy resolution



σ/E @ 59.5 keV for each detector with new PMTs with higher quantum efficiency (blu points) and with previous PMT EMI-Electron Tube (red points).

The light responses

Previous PMTs: 5.5-7.5 ph.e./keV

New PMTs: up to 10 ph.e./keV

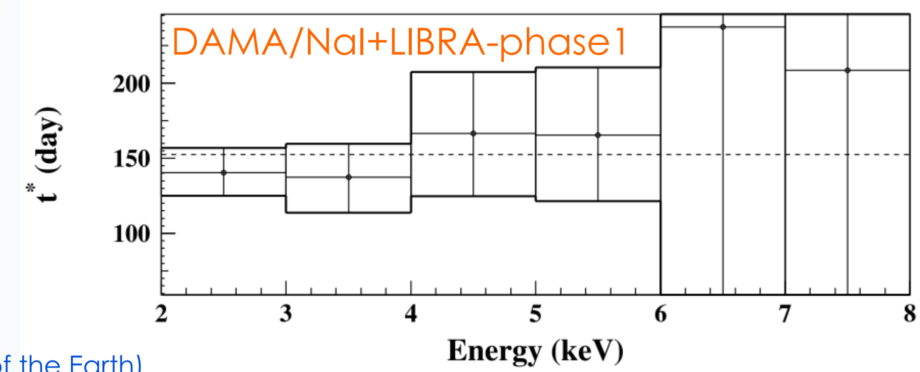
- To study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects, and to investigate second order effects
- Special data taking for *other rare processes*

Features of the DM signal

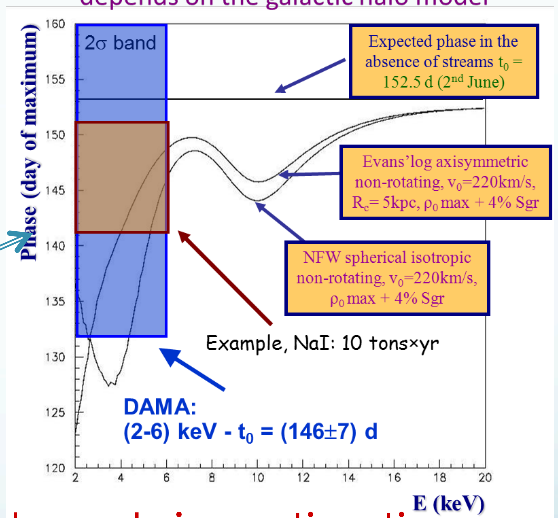
The importance of studying second order effects and the annual modulation phase

High exposure and lower energy threshold can allow further investigation on:

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

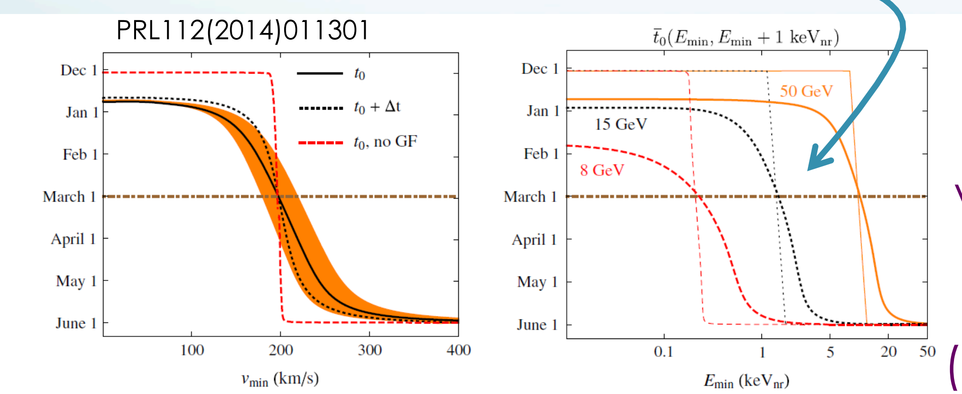


The effect of the streams on the phase depends on the galactic halo model



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



A step towards such investigations:

➔**DAMA/LIBRA-phase2**

with lower energy threshold and larger exposure

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

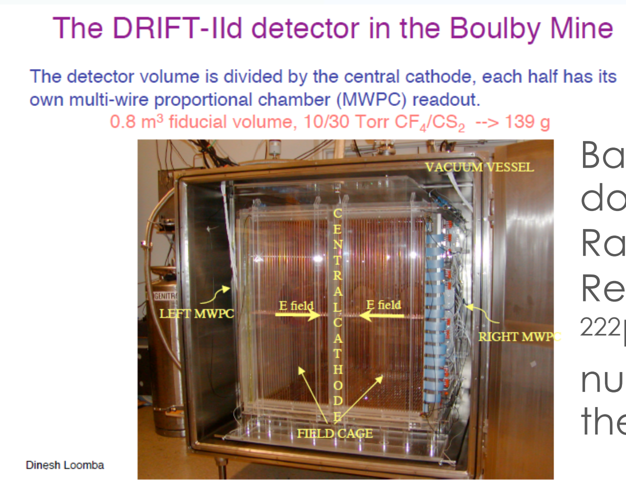
- *Other signatures?*
- *Diurnal effects*
- *Second order effects*
- *Directionality*
- *…*

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

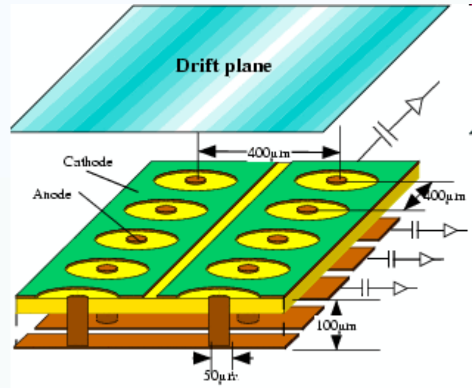
Anisotropic scintillators: DAMA, UK, Japan

DRIFT-IId



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

NEWAGE

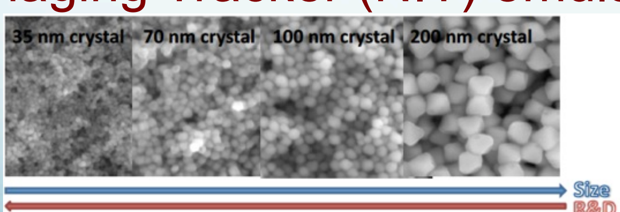


μ-PIC(Micro Pixel Chamber) is a two dimensional position sensitive gaseous detector

	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!

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

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

Not yet competitive sensitivity

Directionality technique

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

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

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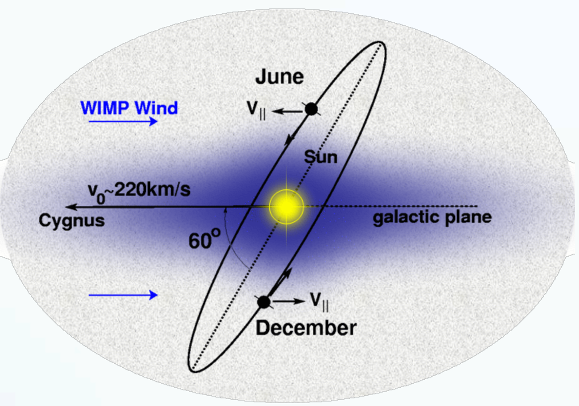
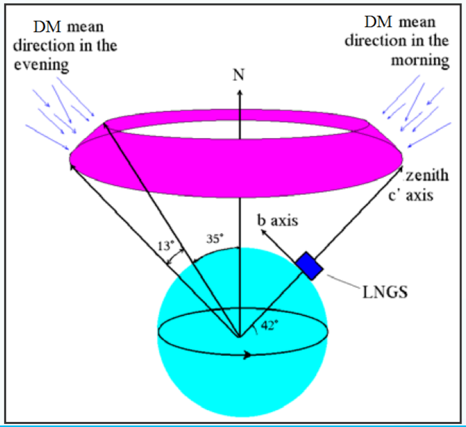


The dynamics of the rotation of the Milky Way galactic disc through the halo of DM causes the Earth to experience a wind of DM particles apparently flowing along a direction opposite to that of solar motion relative to the DM halo …but, because of the Earth's rotation around its axis, the DM particles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

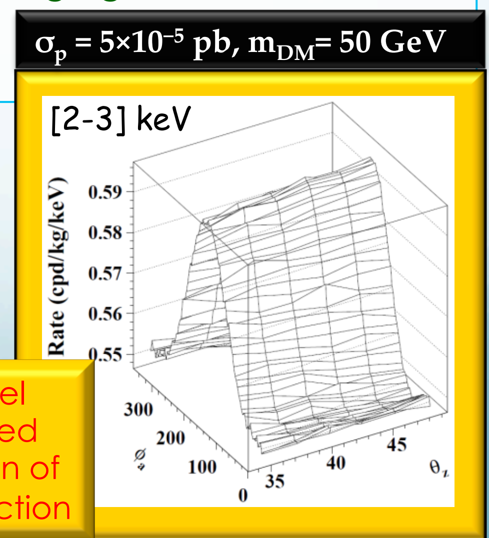


Nuclear recoils are expected to be strongly correlated with the DM impinging direction
This effect can be pointed out through the study of the variation in the response of anisotropic scintillation detectors during sidereal day

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



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

Conclusions

DARK MATTER investigation with direct detection approach

- Different **solid** techniques can give complementary results
  - Some further efforts to demonstrate the **solidity** of some techniques are needed

    - Higher exposed mass not a synonymous of **higher sensitivity**
      - **DAMA** positive evidence (9.2σ C.L.). The modulation parameters determined with **better precision**
        - **DAMA: full sensitivity** to many kinds of DM candidates and interactions both inducing recoils and/or e.m. radiation.

          - Possible positive hints in direct searches are compatible with DAMA in many scenarios; null searches not in robust conflict. Consider also the experimental and theoretical uncertainties.

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