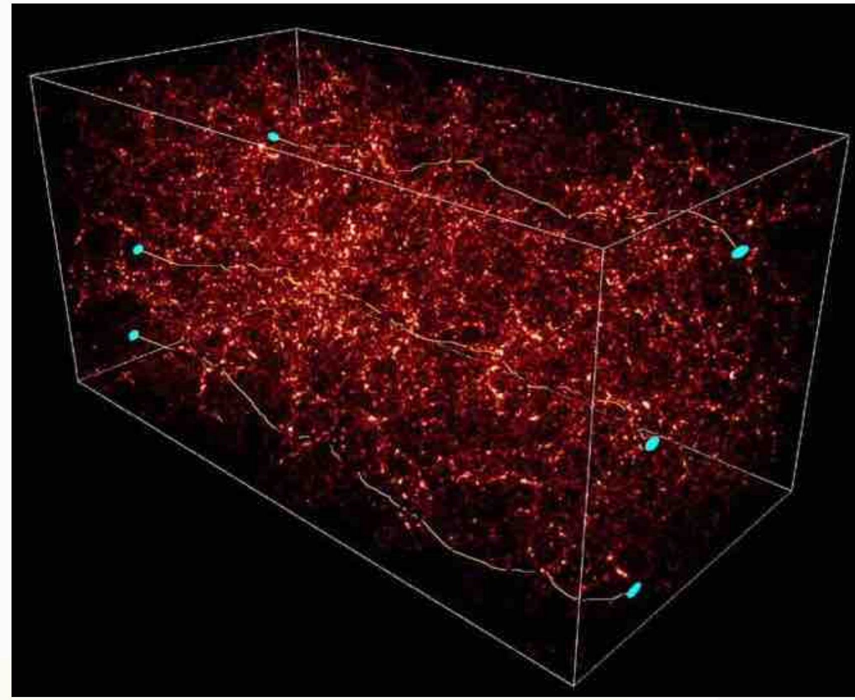
# Results and Strategies for Dark Matter Investigations

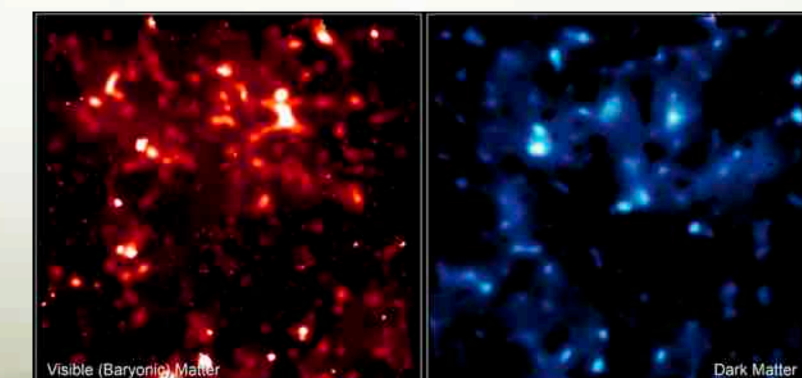
P. Belli
INFN – Roma Tor Vergata

NDM15
Jyväskylä, Finland,
June 1-5, 2015

# 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

axion-like (light pseudoscalar
and scalar candidate)

self-interacting dark matter

mirror dark matter

Kaluza-Klein particles (LKK)

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

Elementary Black holes,
Planckian objects, Daemons

invisible axions, ν's

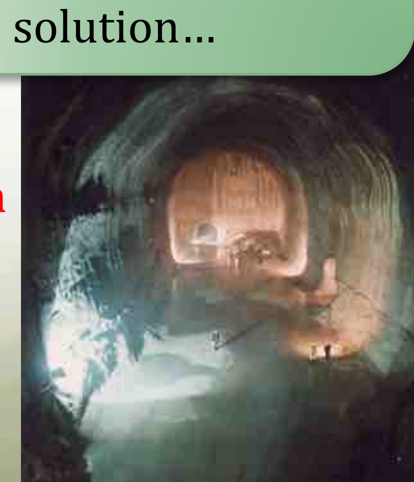
etc...


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

What accelerators cannot do:
to credit that a certain particle is the
Dark Matter solution or the "single"
Dark Matter particle solution…

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

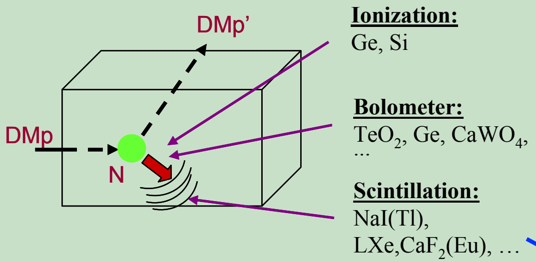
DM direct detection method using a model
independent approach and a low-background
widely-sensitive target material



# Some direct detection processes:

- Scatterings on nuclei

  → detection of nuclear recoil energy




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

  → W has 2 mass states χ+ , χ- with δ mass splitting

  → Kinematical constraint for the inelastic scattering of χ- on a nucleus

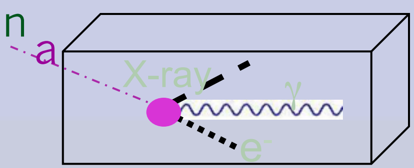
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

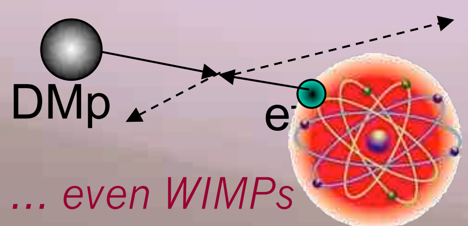
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, $e^-$




- Interaction only on atomic electrons

  → detection of e.m. radiation

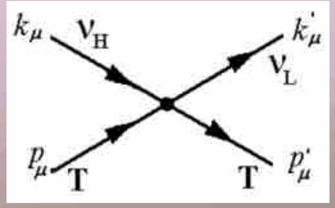



*… even WIMPs*

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

  → detection of electron/nucleus recoil energy

  *e.g. sterile ν*




… also other ideas …

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

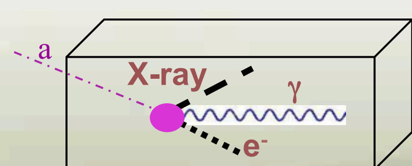
- **… and more**

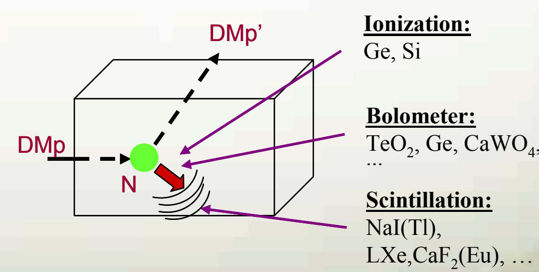
# Direct detection experiments

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**

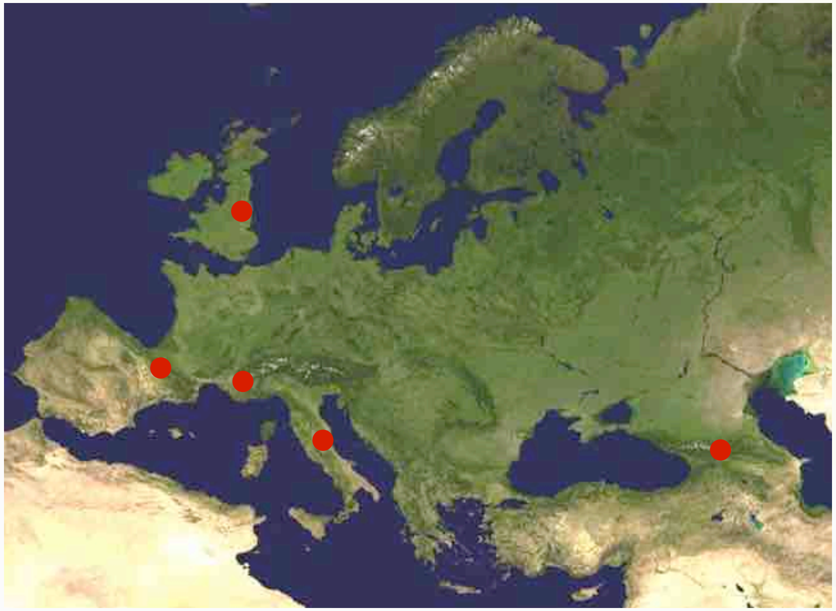
2. on the use of uncertain techniques of statistical **subtractions** of the e.m. component **of the counting rate** (adding systematical effects and lost of candidates with pure electromagnetic productions)



# Dark Matter direct detection activities in underground labs

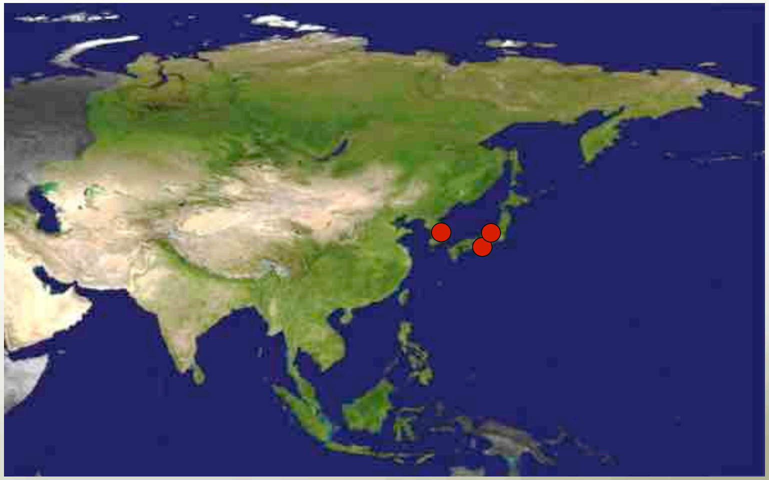
- Various approaches and techniques
- Various different target materials
- Various different experimental site depths
- Different radiopurity levels, etc.



- **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

**in single phase detector:**

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

DAMA/LXe

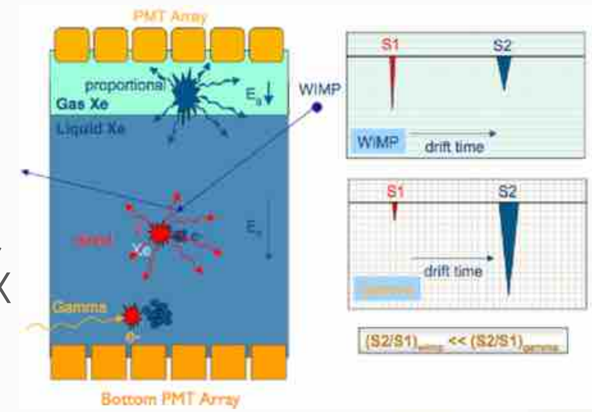
XMASS

**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

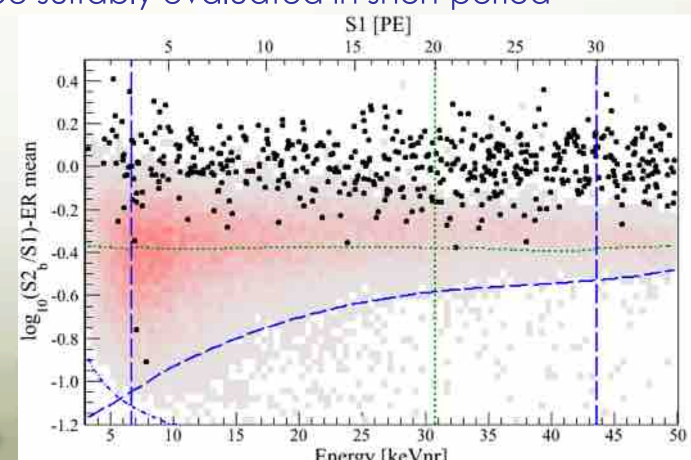
XENON10, 100, 1ton, WARP, DarkSide, LUX



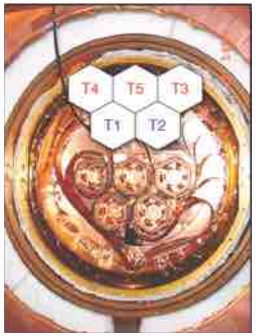

- **Non-uniform** response of detector: intrinsic limit
- **UV light**, **unlinearity** (more in larger volumes)
- **Correction** procedures applied
- **Systematics**
- **Small light responses** (2.2 ph.e./keVee) ⇒ energy threshold at few keV unsafe
- Physical **energy threshold unproved** by source 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?



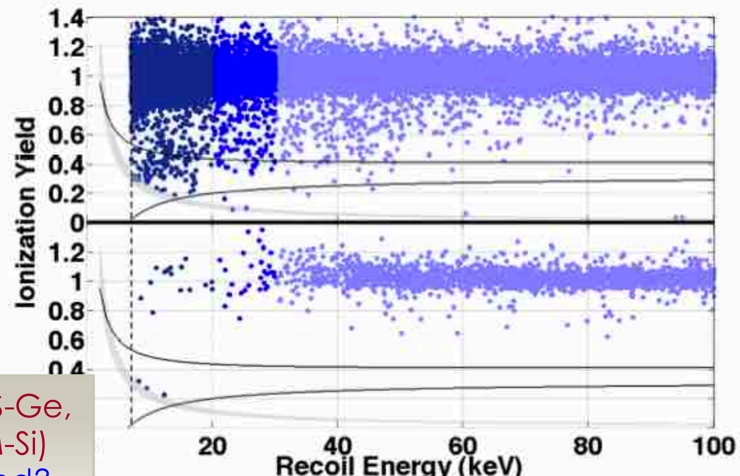
# Double read-out bolometric technique (ionization vs heat)

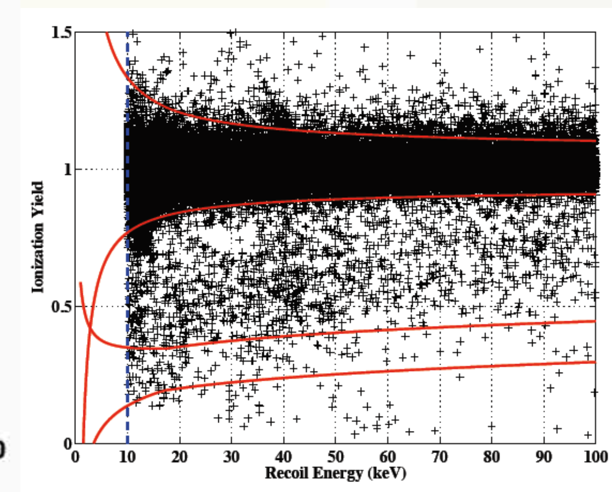



- CDMS-Ge: Soudan, 3.22 kg Ge, 194.1 kg x day; $E_{th}$=10 keV + other attemps at lower $E_{th}$
- Edelweiss: LSM, 3.85 kg Ge, 384 kg x day; $E_{th}$=20 keV
- CDMS-Si: 1.2 kg Si, 140.2 kg x day; $E_{th}$=7 keV

- **Many cuts on the data:** how about systematics?
- **Low duty cycle:** (selected exposure) / (data taking time x mass) about 10%
- The **systematics** can be variable along the data taking period; can they and the related efficiencies be suitably evaluated in short period calibration?
- **Phonon timing cut:** time and energy response vary across the detector ⇒look-up table used (stability, robustness of the reconstruction procedure, efficiency and uncertainties)
- **Poor detector performances:** many detectors excluded in the analysis
- **Critical stability of the performances**
- **Non-uniform** response of detector: intrinsic limit
- **Surface electrons:** PSD needed with related uncertainty

- 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
- **Efficiencies** of both signals



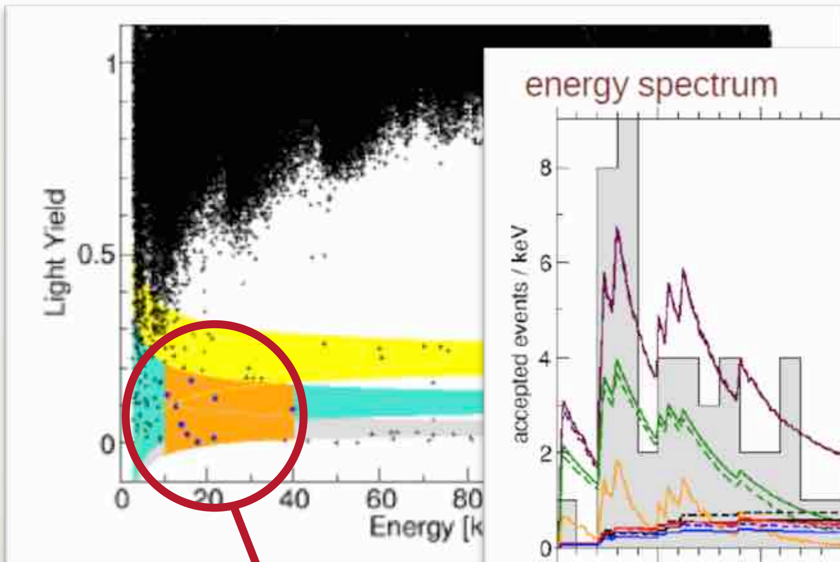

After many cuts few (two in CDMS-Ge, five in Edelweiss and three in CDM-Si) events survive: intrinsic limit reached?

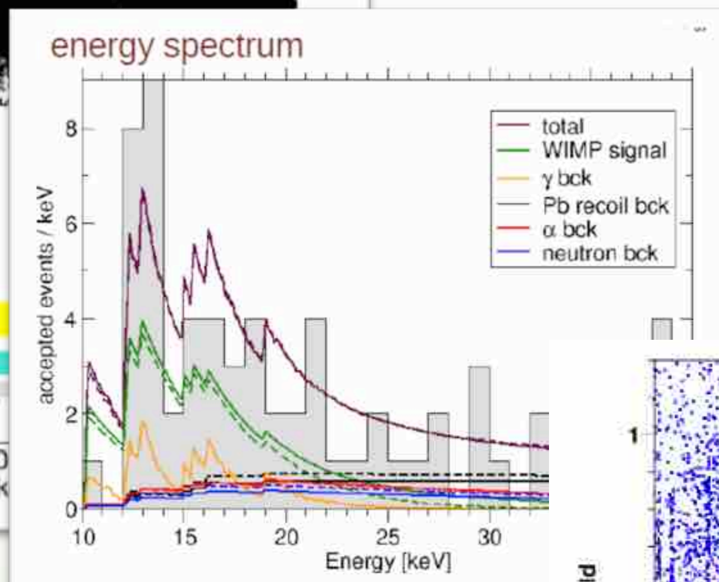
# Double read-out bolometric technique (scintillation vs heat)

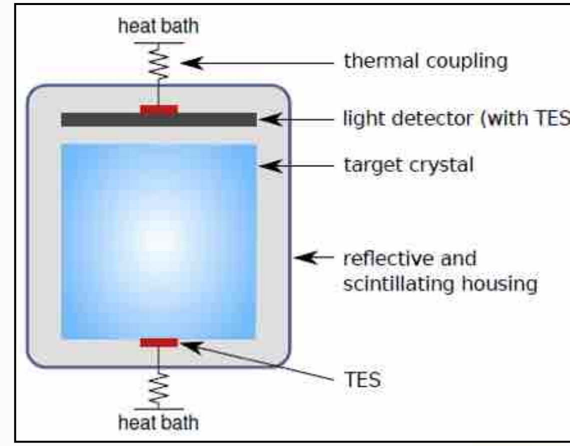
CRESST at LNGS: 33 $CaWO_4$ crystals (10 kg mass)

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

Data from one detector



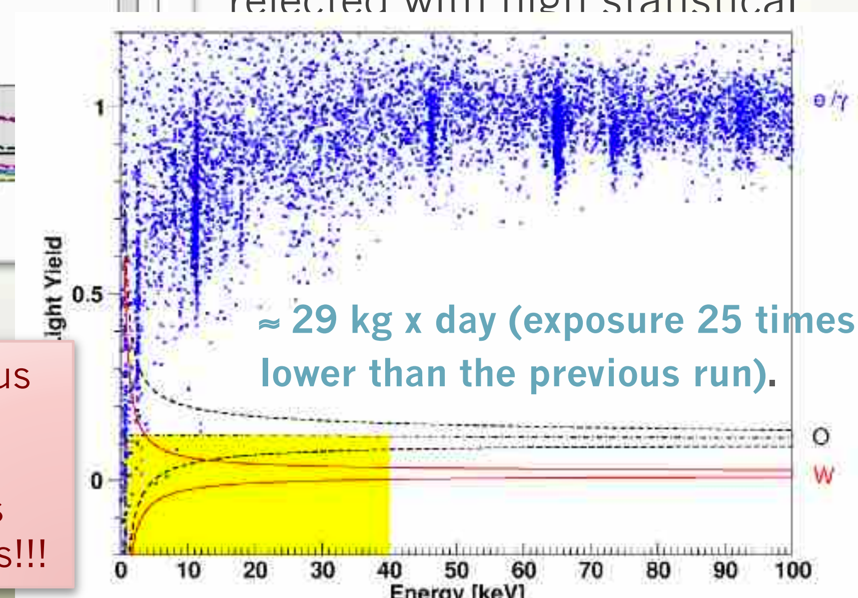




background-only hypothesis rejected with high statistical

67 total events observed in O-band;


Systematics in previous runs (?):
Latest run with lower energy threshold does not confirm the excess!!!

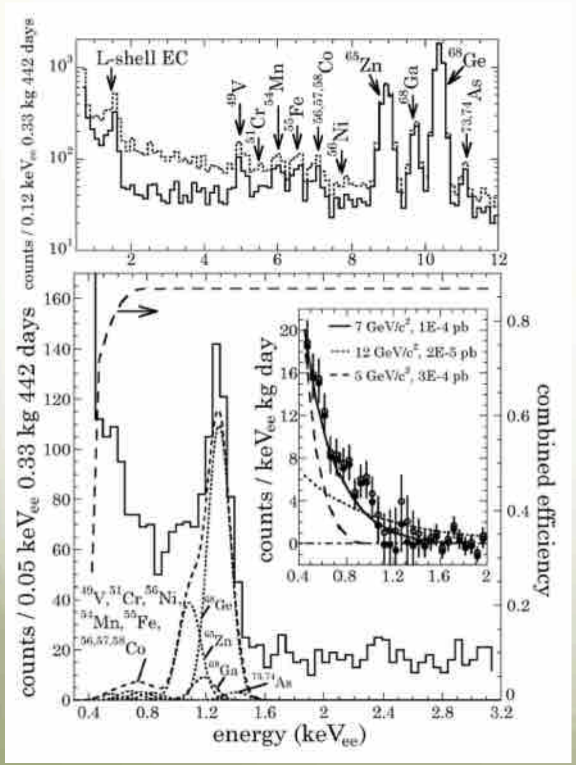


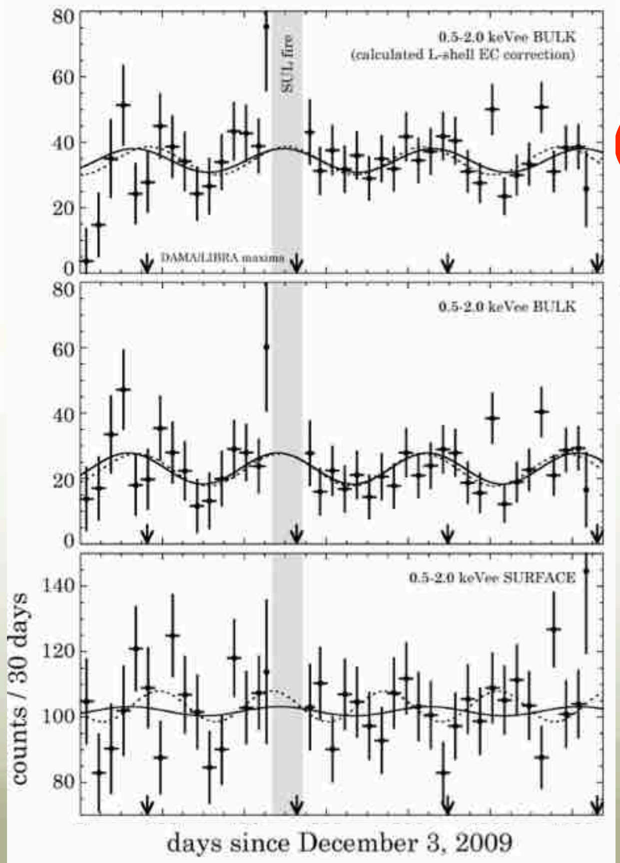

≈ 29 kg x day (exposure 25 times lower than the previous run).

# Positive hints from CoGeNT (ionization detector)

Experimental site: Soudan Underground Lab (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)

- ✓ **Irreducible excess** of bulk-like events below 3 keVee observed;
- ✓ **annual modulation** of the rate in 0.5-4.5 keVee at ~2.2σ C.L.




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

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

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

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

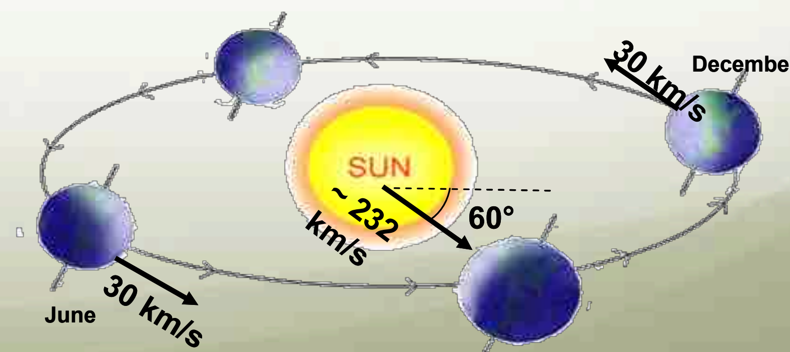
Directionality Correlation of Dark Matter impinging direction with Earth's galactic motion due to the distribution of Dark Matter particles velocities

very hard to realize

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

only for high $\sigma$

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



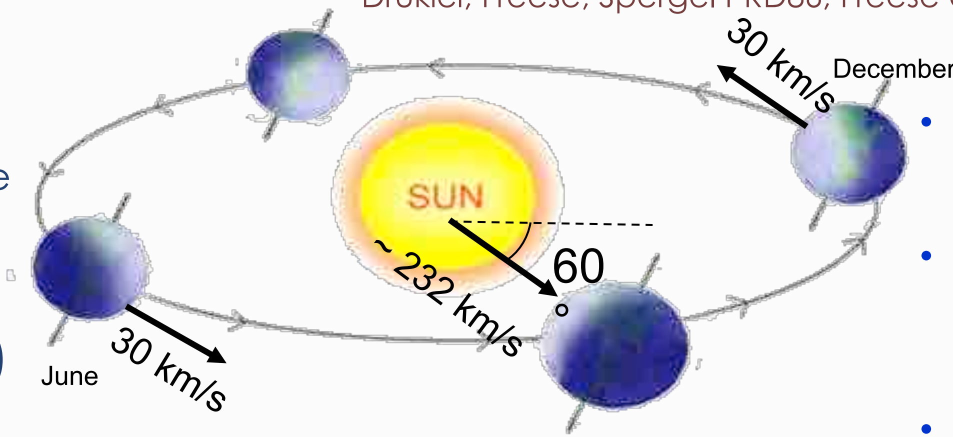
# The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

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)

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

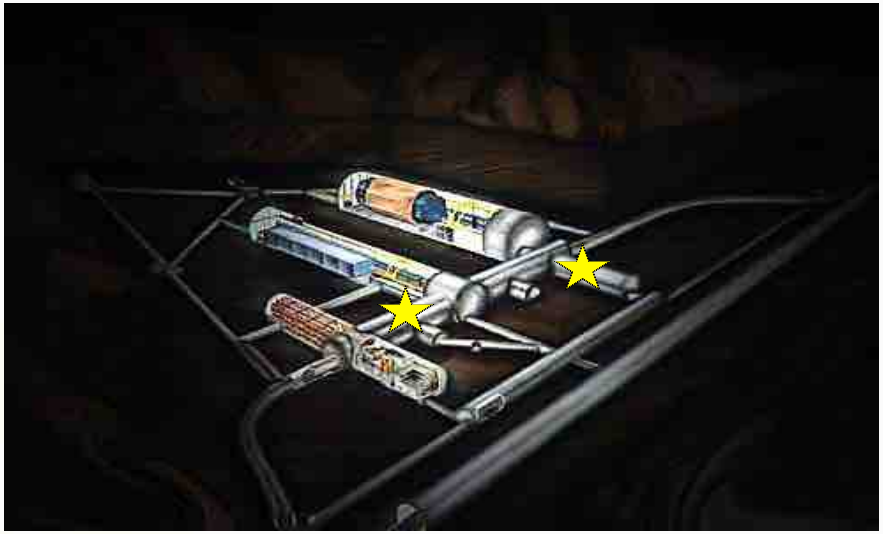
$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \cong S_{0,k} + S_{m,k} \cos[\omega(t-t_0)]$$

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

# DAMA set-ups

an observatory for rare processes @ LNGS



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

see Cerulli's talk

## Collaboration:

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

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

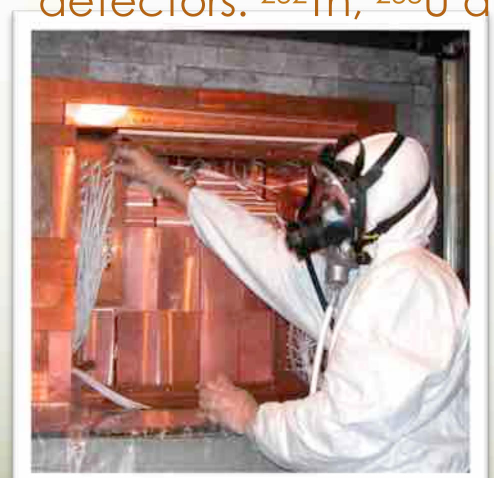
+ neutron meas.: ENEA-Frascati

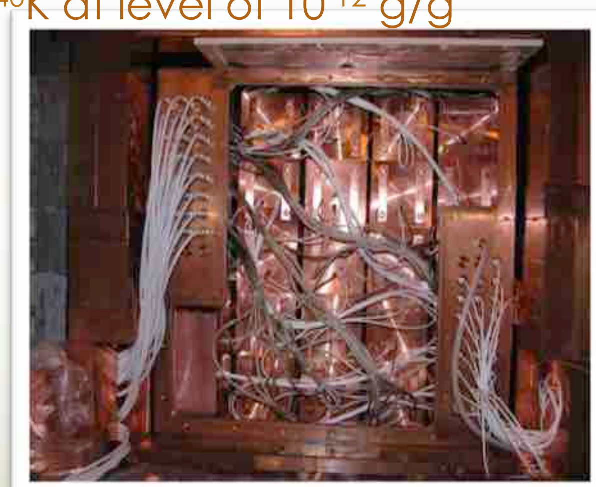
+ in some studies on ββ decays (DST-MAE and Inter-Universities project): IIT Kharagpur and Ropar, India

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

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

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





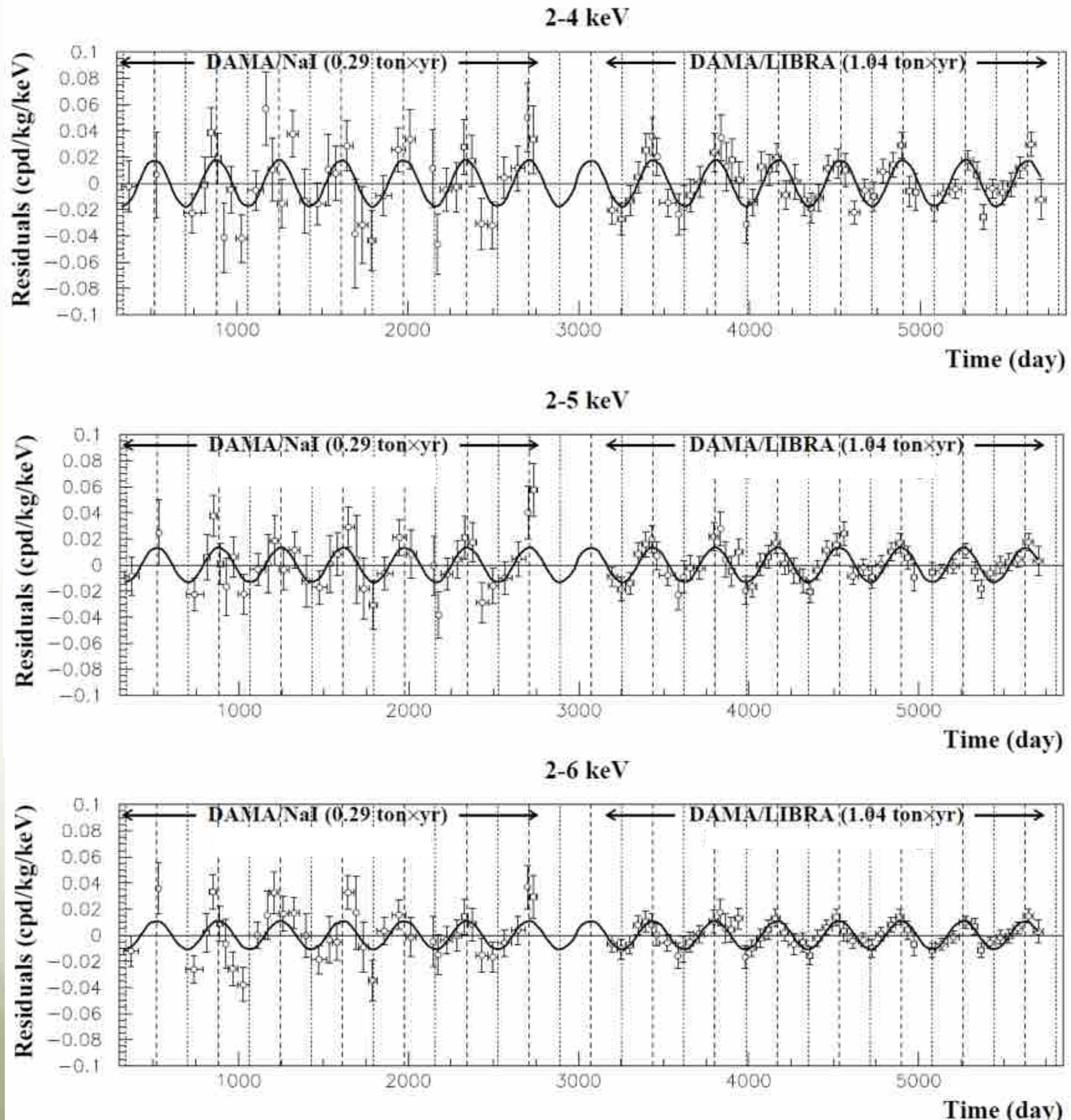
- Radiopurity, performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
- Results on DM particles, Annual Modulation Signature: EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648.
  Related results: PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022, EPJC74(2014)2827, EPJC74(2014)3196, arXiv:1505.05336
- Results on rare processes: PEPv: EPJC62(2009)327; CNC: EPJC72(2012)1920; IPP in $^{241}$Am: EPJA49(2013)64

# Model Independent DM Annual Modulation Result

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

DAMA/NaI + DAMA/LIBRA-phase1

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




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

**2-4 keV**

A=(0.0179±0.0020) cpd/kg/keV

$\chi^2$/dof = 87.1/86 **9.0 σ C.L.**

Absence of modulation? No

$\chi^2$/dof=169/87 ⇒ P(A=0) = $3.7\times10^{-7}$

**2-5 keV**

A=(0.0135±0.0015) cpd/kg/keV

$\chi^2$/dof = 68.2/86 **9.0 σ C.L.**

Absence of modulation? No

$\chi^2$/dof=152/87 ⇒ P(A=0) = $2.2\times10^{-5}$

**2-6 keV**

A=(0.0110±0.0012) cpd/kg/keV

$\chi^2$/dof = 70.4/86 **9.2 σ C.L.**

Absence of modulation? No

$\chi^2$/dof=154/87 ⇒ P(A=0) = $1.3\times10^{-5}$

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

# Model Independent Annual Modulation Result

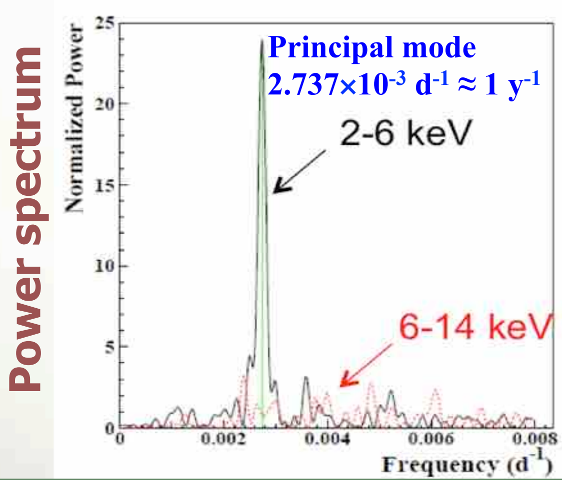
**DAMA/NaI** + **DAMA/LIBRA-phase1** Total exposure: 487526 kg×day = **1.33 ton×yr**

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

The measured modulation amplitudes (A), period (T) and phase ($t_0$) from the single-hit residual rate vs time

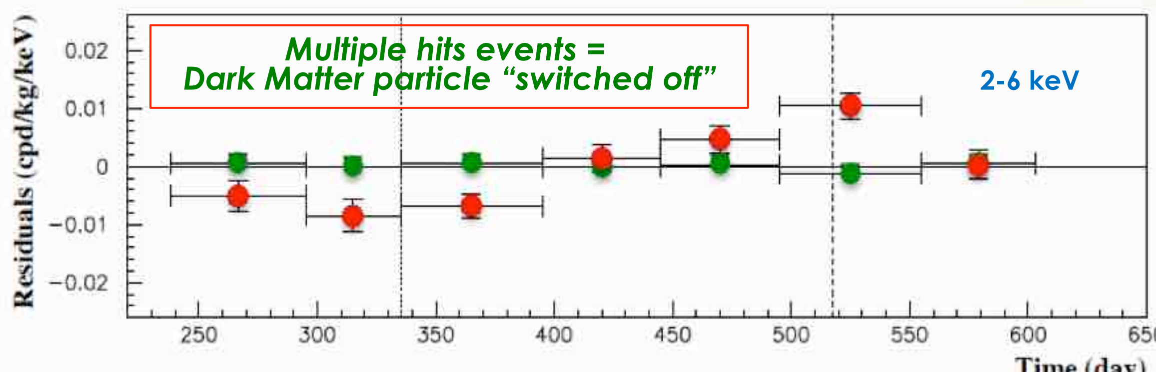
| | A(cpd/kg/keV) | $T=2\pi/\omega$ (yr) | $t_0$ (day) | C.L. |
|---|---|---|---|---|
| DAMA/NaI+DAMA/LIBRA-phase1 | | | | |
| (2-4) keV | 0.0190 ±0.0020 | 0.996 ±0.0002 | 134 ± 6 | 9.5σ |
| (2-5) keV | 0.0140 ±0.0015 | 0.996 ±0.0002 | 140 ± 6 | 9.3σ |
| (2-6) keV | 0.0112 ±0.0012 | 0.998 ±0.0002 | 144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

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




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

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




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

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

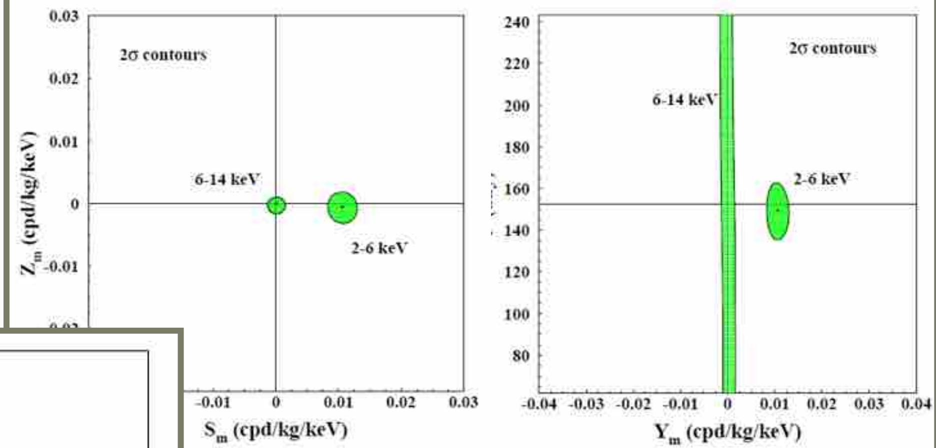
# Model Independent Annual Modulation Result

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

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

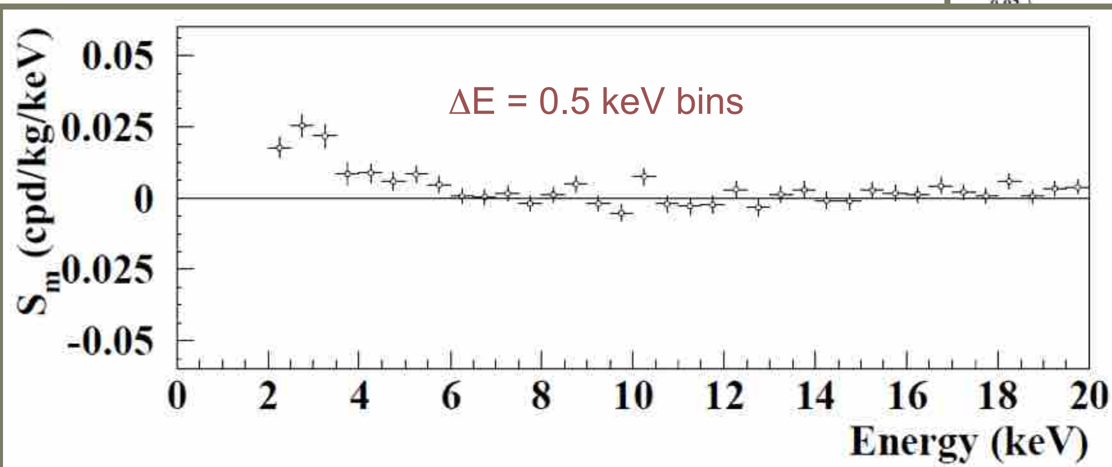
- No modulation above 6 keV
- No modulation in the whole energy spectrum
- No modulation in the 2-6 keV multiple-hit events

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




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

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




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

- 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* events, in the (2 – 6) keV energy region induced by: → $R_k = R_{0,k}\left(1 + \eta_k cos\omega\left(t - t_k\right)\right)$
  - neutrons,
  - muons,
  - solar neutrinos.

EPJC 74 (2014) 3196 (also EPJC 56 (2008) 333, EPJC 72 (2012) 2064,IJMPA 28 (2013) 1330022)

Modulation amplitudes

| Source | | $\Phi^{(n)}_{0,k}$ (neutrons cm$^{-2}$ s$^{-1}$) | $\eta_k$ | $t_k$ | $R_{0,k}$ (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) | $1.08 \times 10^{-6}$ [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) | $2 \times 10^{-6}$ [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 $\mu$ | $\Phi^{(\mu)}_0 \simeq 20\ \mu$ 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 $\nu$ | $\Phi^{(\nu)}_0 \simeq 6 \times 10^{10}\ \nu$ cm$^{-2}$s$^{-1}$ [26] | 0.03342 * | Jan. 4th * | $\simeq 10^{-5}$ | [31] | $3 \times 10^{-7}$ | $3 \times 10^{-5}$ |

* 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

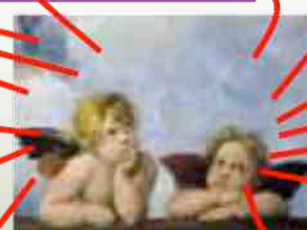
Self interacting Dark Matter

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



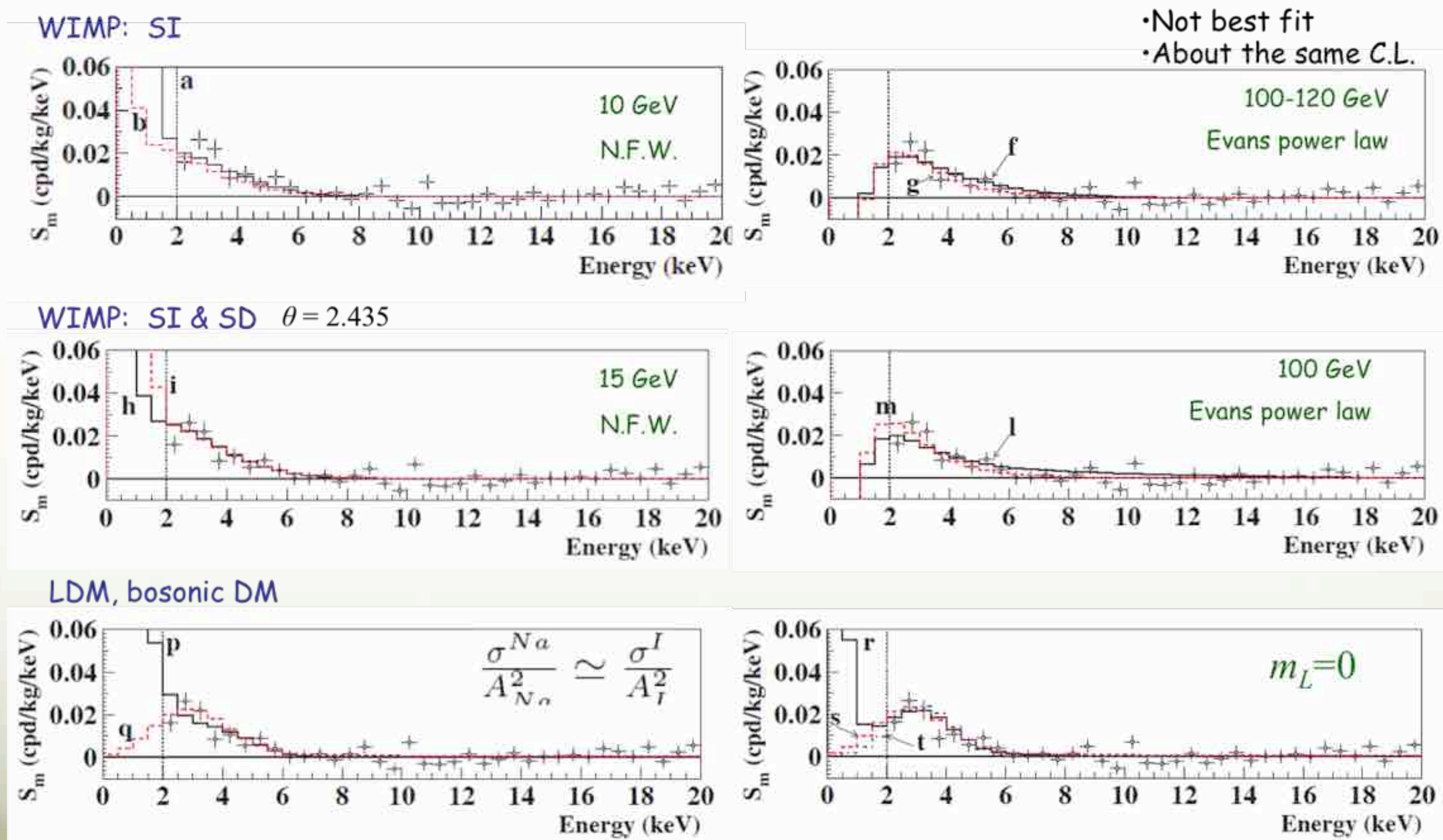
Kaluza Klein particles

… and more

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

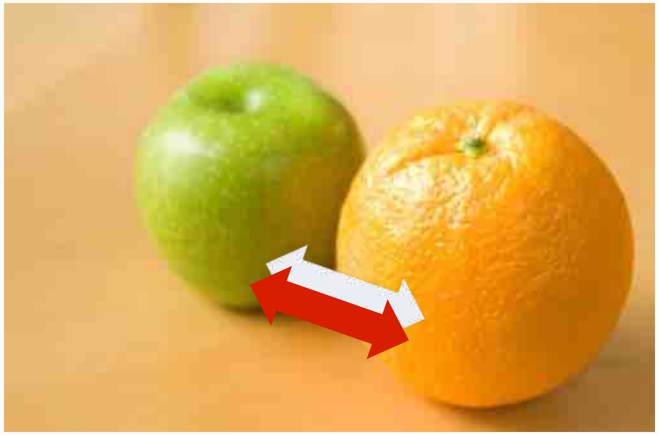
well compatible with several candidates in many astrophysical, nuclear and particle physics scenarios

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




Compatibility with several candidates;
other ones are open

EPJC56(2008)333
IJMPA28(2013)1330022



# 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…

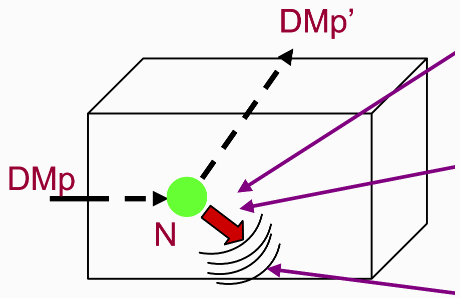
- Exposures
- Energy threshold
- Detector response (phe/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities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

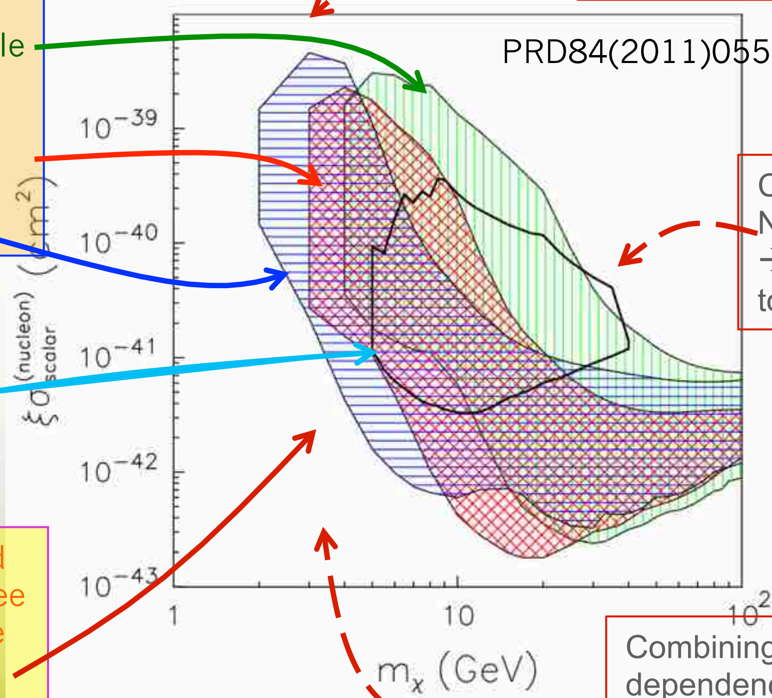
- Some velocity distributions and uncertainties considered.
- The DAMA regions represent the domain where the likelihood-function values differ more than 7.5σ from the null hypothesis (absence of modulation).
- For CoGeNT a fixed value for the Ge quenching factor and a Helm form factor with fixed parameters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

PRD84(2011)055014, IJMPA28(2013)1330022




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

CoGeNT; qf at fixed assumed value

1.64 σ C.L.

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

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

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

DAMA →

# Diurnal effects

EPJC 74 (2014) 2827

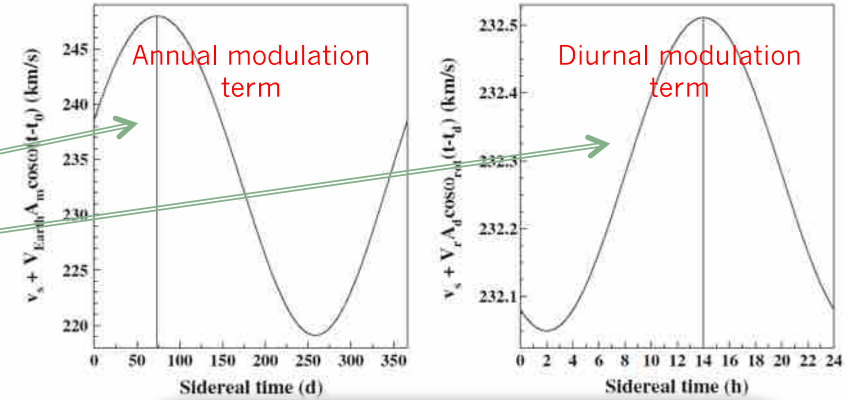
A diurnal effect with the sidereal time is expected for DM because of Earth rotation

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:

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

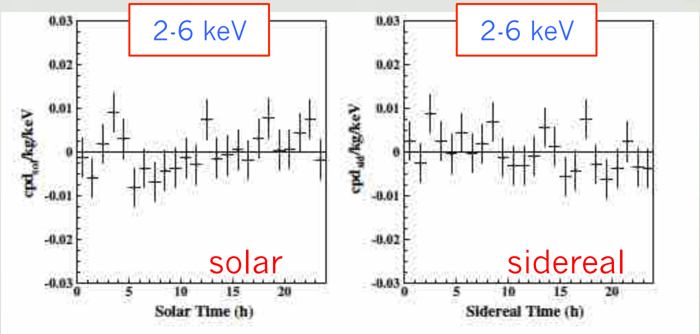
The ratio $R_{dy}$ is a model independent constant:

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

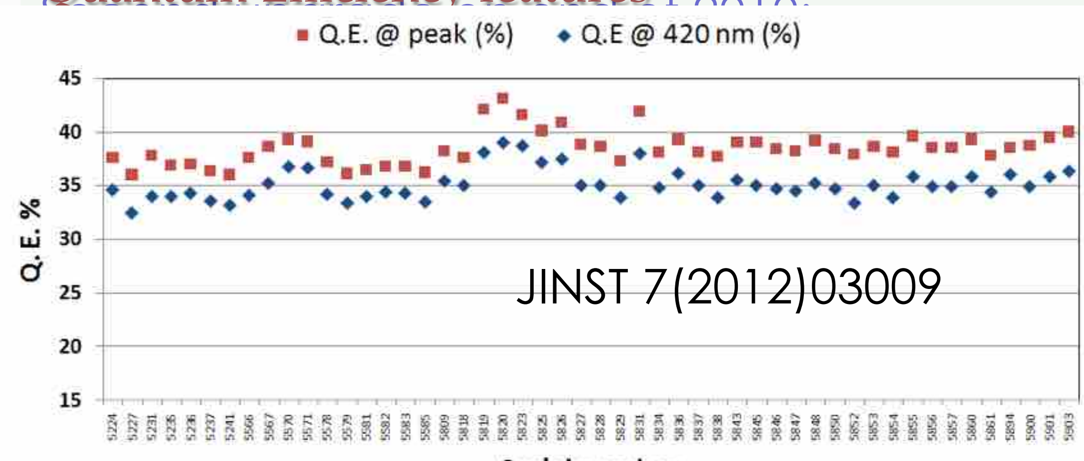



Present experimental sensitivity more modest than the expected diurnal modulation amplitude derived from the DAMA/LIBRA–phase1 observed effect.

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

# DAMA/LIBRA phase2 - running

## Quantum Efficiency features



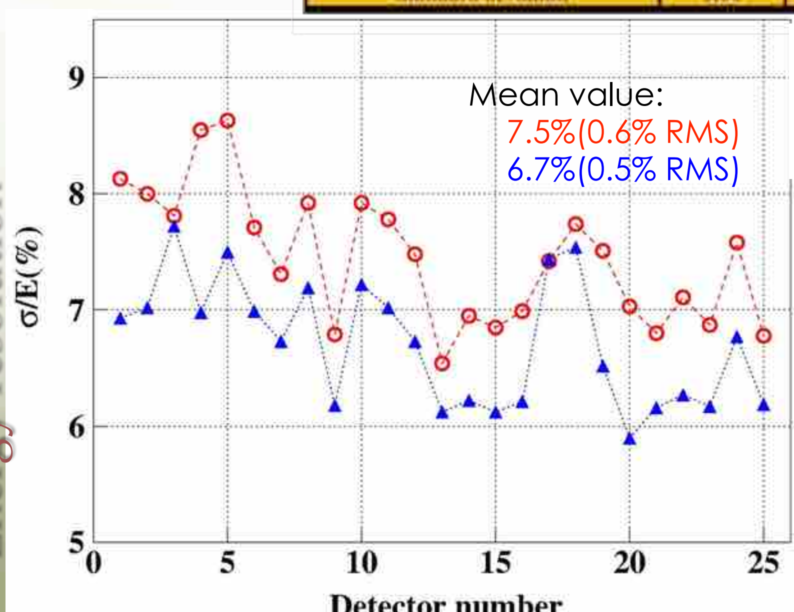

## Residual Contamination

The limits are at 90% C.L.

Energy (keV)

| PMT | Time (s) | Mass (kg) | $^{226}$Ra (Bq/kg) | $^{234m}$Pa (Bq/kg) | $^{235}$U (mBq/kg) | $^{228}$Ra (Bq/kg) | $^{228}$Th (mBq/kg) | $^{40}$K (Bq/kg) | $^{137}$Cs (mBq/kg) | $^{60}$Co (mBq/kg) |
|---|---|---|---|---|---|---|---|---|---|---|
| *Average* | | | *0.43* | - | *47* | *0.12* | *83* | *0.54* | - | - |
| *Standard deviation* | | | *0.06* | - | *10* | *0.02* | *17* | *0.16* | - | - |

## Energy resolution




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

**The light responses**

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

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

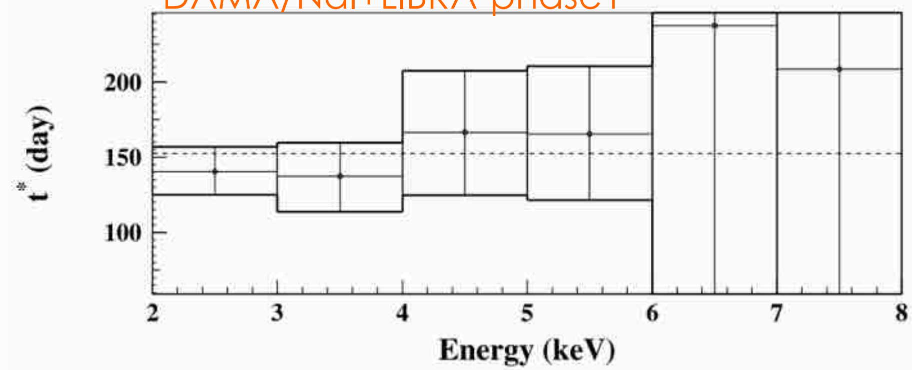
# Features of the DM signal

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

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

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

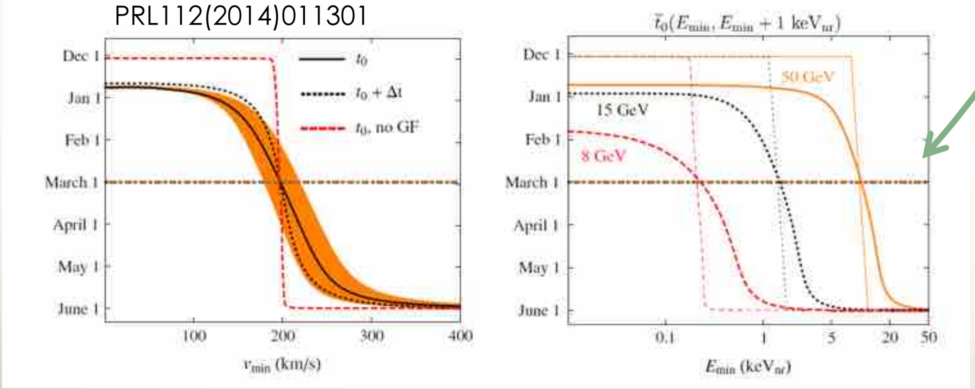
DAMA/NaI+LIBRA-phase1



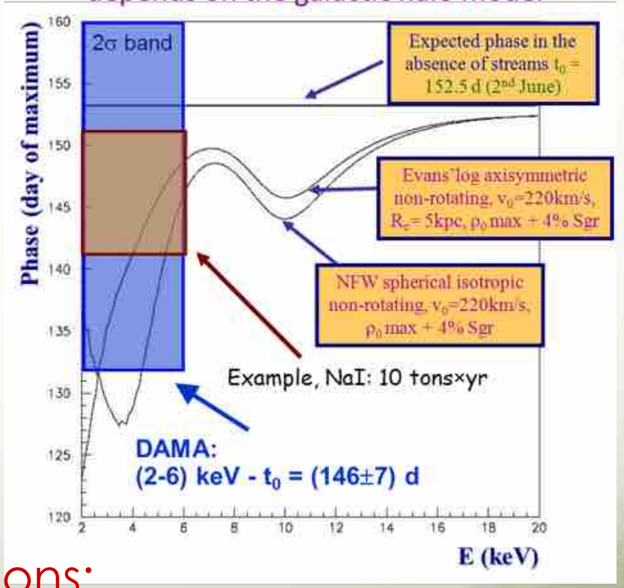

The annual modulation phase depends on :

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

PRL112(2014)011301




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




A step towards such investigations:

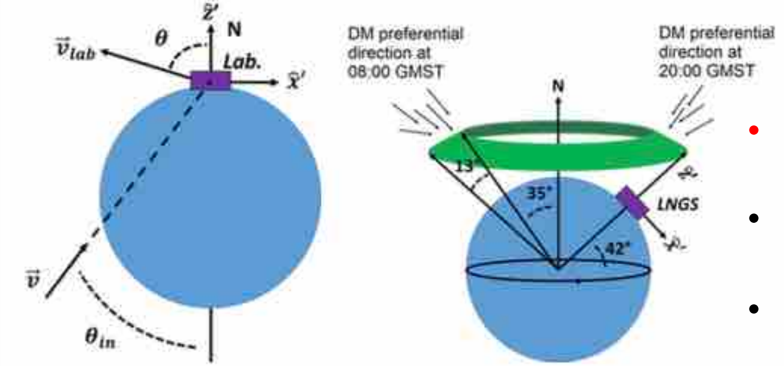
➔**DAMA/LIBRA-phase2**

with lower energy threshold and larger exposure

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

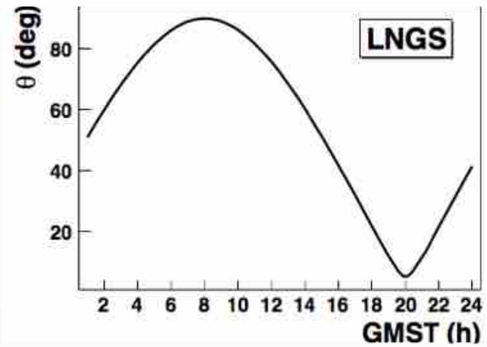
- *Other signatures?*
- *Diurnal effects*
- *Second order effects*
- *Shadow effects*
- *Directionality*
- *…*

# Earth shadowing effect with DAMA/LIBRA–phase1

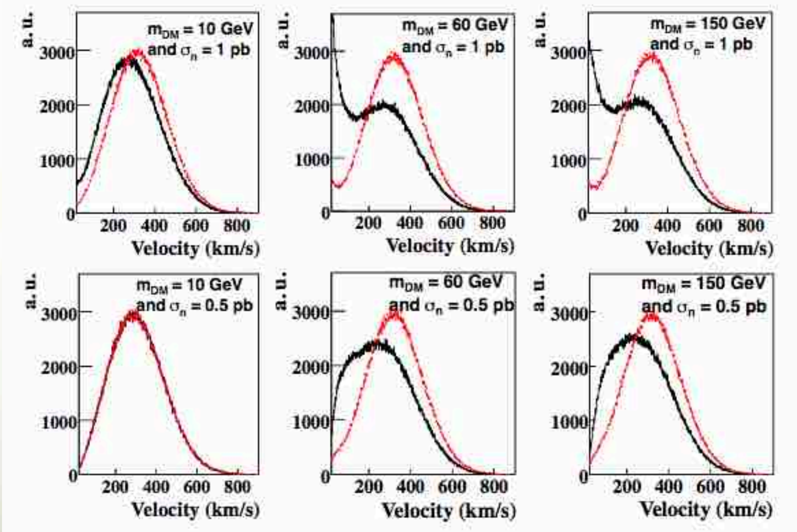


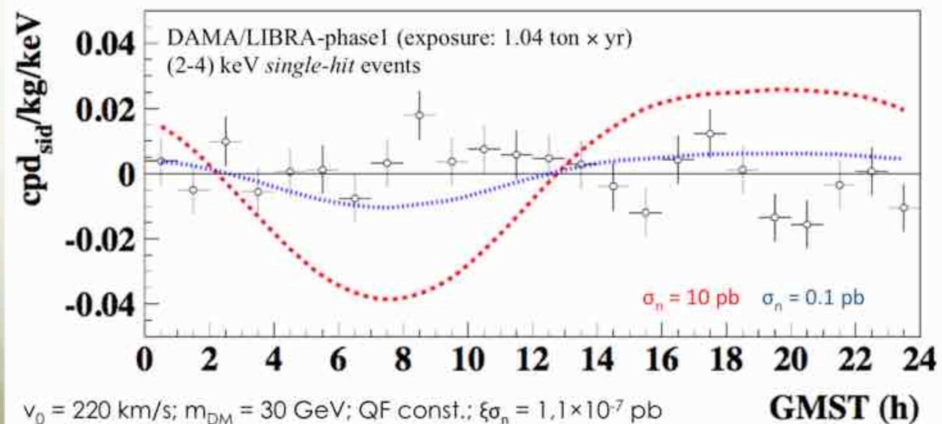

arXiv:1505.05336 (EPJC)

- **Earth Shadow Effect** could be expected for DM candidate particles inducing 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**)




Taking into account the DAMA/LIBRA DM annual modulation result, allowed regions in the $\xi$ vs $\sigma_n$ plane for each $m_{DM}$.

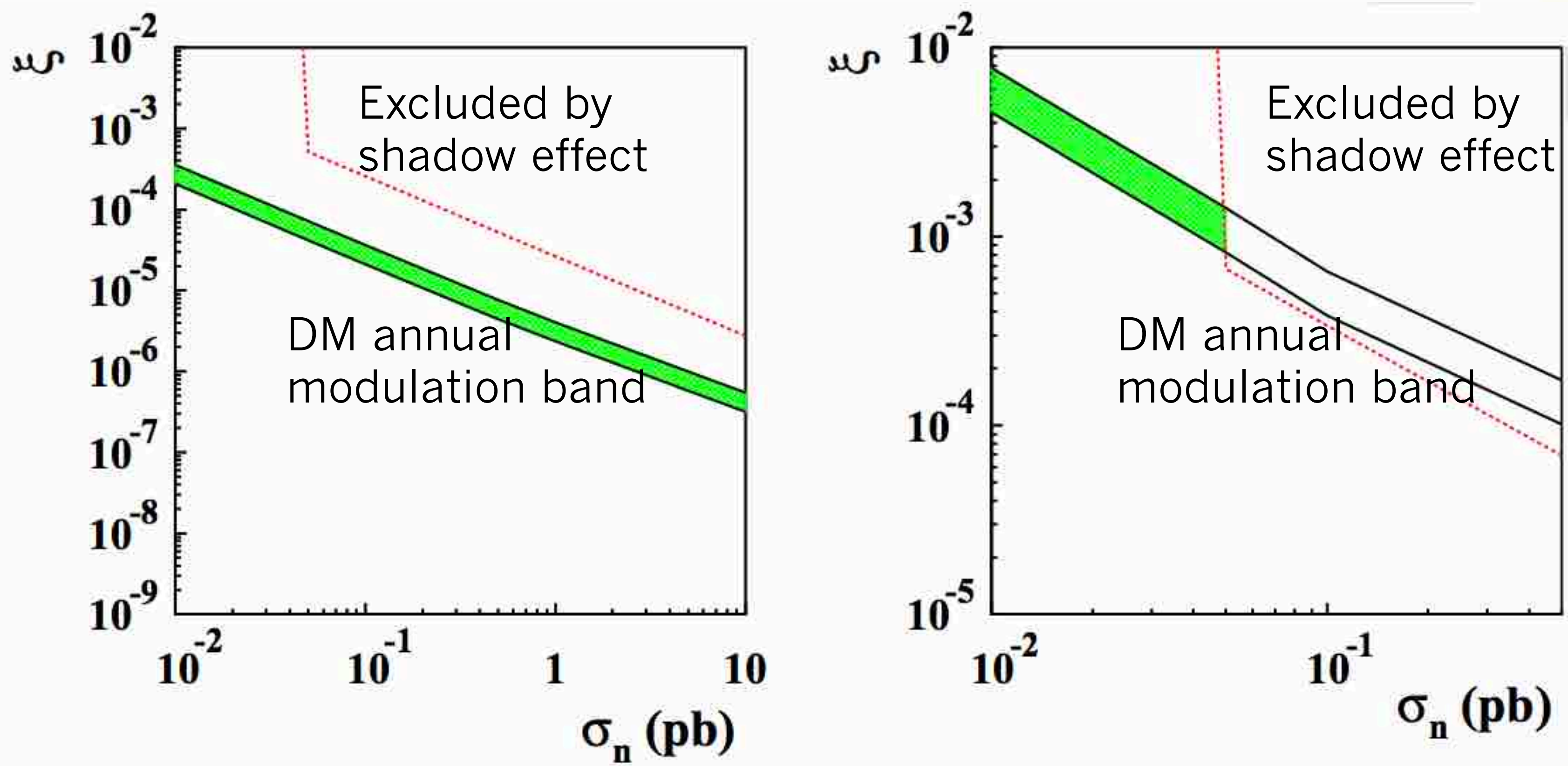
# Earth shadowing effect with DAMA/LIBRA–phase1

arXiv:1505.05336 (EPJC)

Two examples for a given model:

- *Left* $m_{DM}$=10 GeV, the upper limits on $\xi$ do not constrain the results of annual modulation.
- *Right* $m_{DM}$=60 GeV, the upper limits on $\xi$ do exclude the band with $\sigma_n > 0.05$ pb and $\xi > 10^{-3}$ for the considered model framework.

The combined allowed regions are reported as *shaded–green on-line–area*



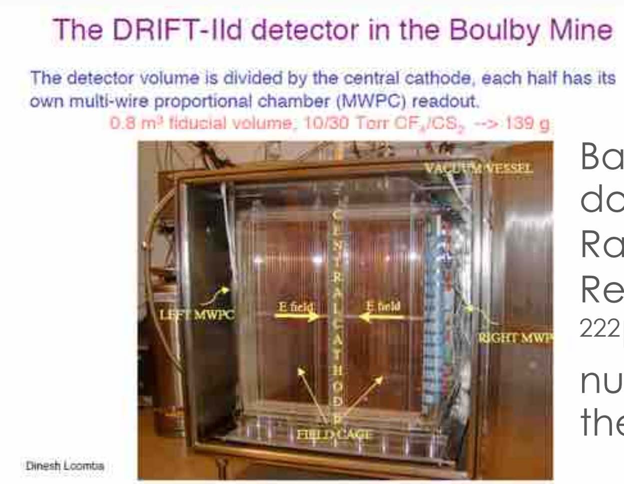
- *Other signatures?*
- *Diurnal effects*
- *Second order effects*
- *Shadow effects*
- *Directionality*
- *…*

# 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

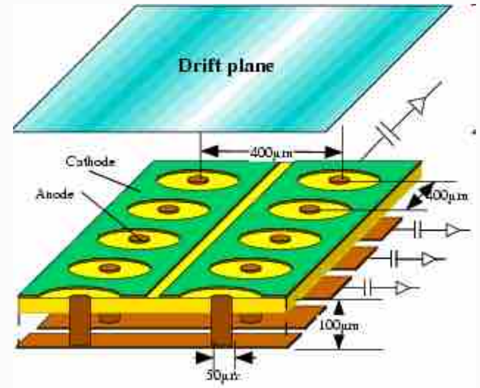
## Anisotropic scintillators: DAMA, UK, Japan

## DRIFT-IId




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

## NEWAGE

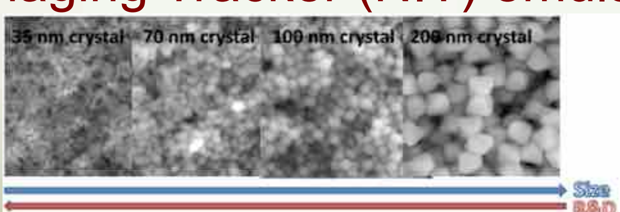



μ-PIC(Micro Pixel Chamber) is a two dimensional position sensitive gaseous detector

| | 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) | $8\times10^{-6}$ | $1\times10^{-7}$ |
| 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

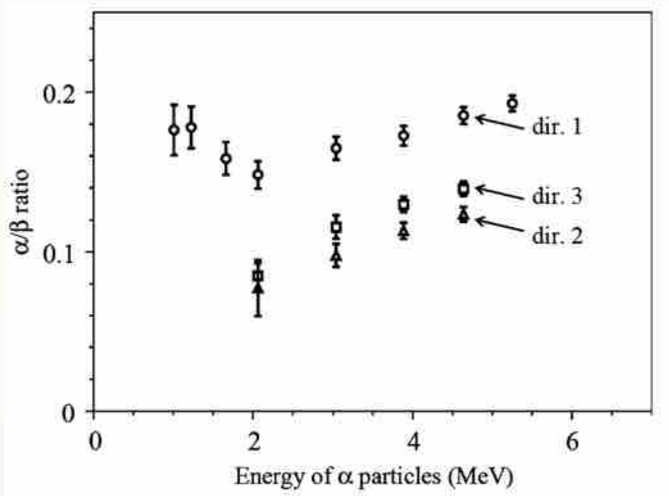
Not yet competitive sensitivity

# Directionality technique

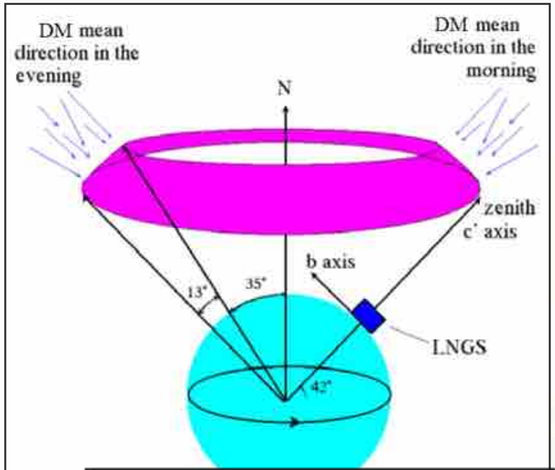
EPJ C73 (2013) 2276

- 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



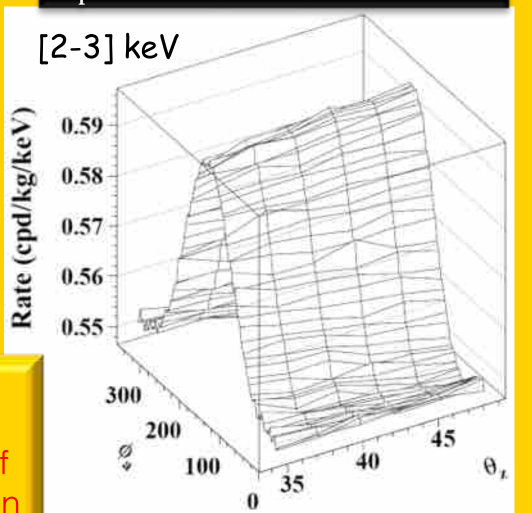

Nuclear recoils are expected to be strongly correlated with the DM impinging direction
This effect can be pointed out through the study of the variation in the response of anisotropic scintillation detectors during sidereal day




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

# 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 (9.2$\sigma$ 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