Studio e investigazione di DM tramite una marcatura *model-independent*

Spokesperson: R. Bernabei

Past:

- Annual Modulation: DAMA/NaI and DAMA/LIBRA-phase1

Present:

- Annual Modulation: DAMA/LIBRA-phase2

Towards WN:

- Studies at second order with very high sensitivity
- …

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DAMA/LIBRA-phase2
↓
DAMA/LIBRA/phase3
↓
DAMA/1ton

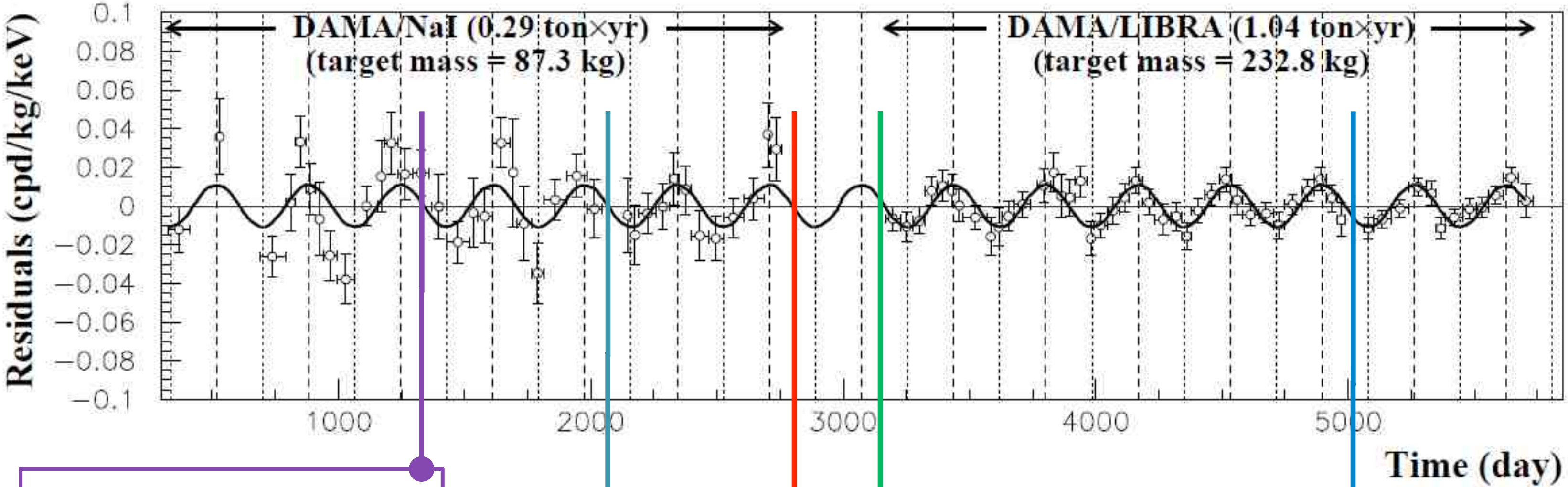
- Directionality

see Cerulli's talk

WN – Ottobre 2014

P. Belli
INFN-Roma Tor Vergata

DAMA/NaI & DAMA/LIBRA experiments main upgrades and improvements



PHASE2

Minimal upgrade in Fall

On 2003 DAMA/LIBRA has begun first operations

July 2000 new DAQ and new electronic chain installed (MULTIPLEXER removed, now one TD channel for each detector):

- (i) TD VXI Tektronix;
- (ii) Digital Unix DAQ system;
- (iii) GPIB-CAMAC.

Sept.-Oct. 2008 – DAMA/LIBRA upgrade:

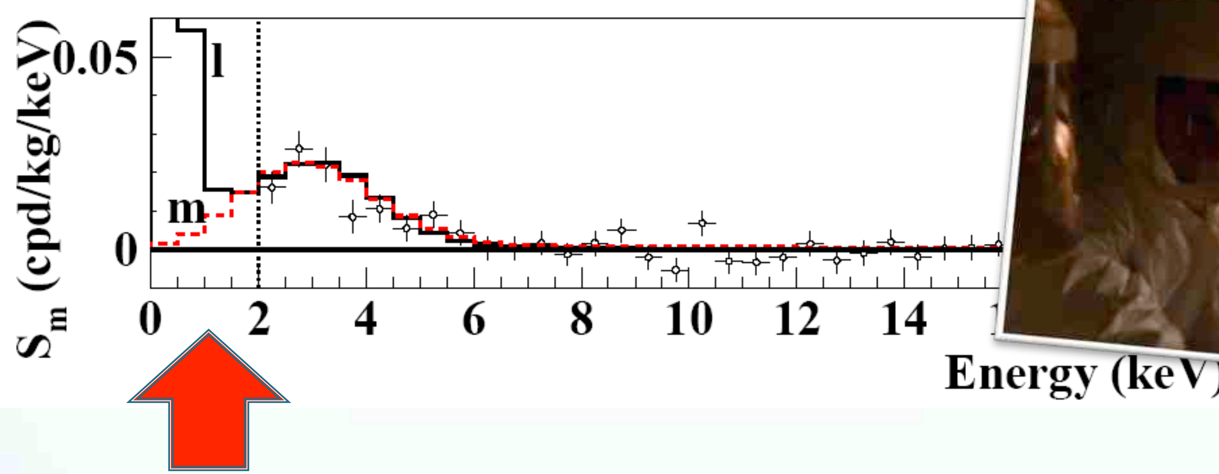
1. one detector recovered by replacing a broken PMT
2. a new optimization of some PMTs and HVs performed
3. all the TD replaced with new ones (U1063A Acqiris 8-bit 1GS/s DC270 High-Speed cPCI Digitizers)
4. a new DAQ with optical read-out installed.

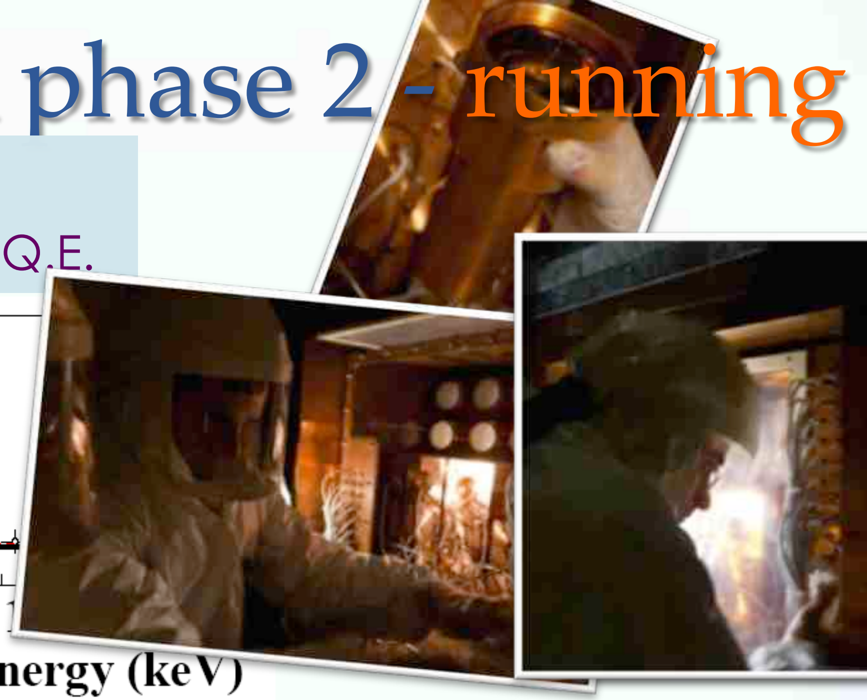
July 2002 DAMA/NaI data taking completed

The second DAMA/LIBRA upgrade in Fall 2010:
Replacement of all the PMTs with higher Q.E. ones from dedicated developments
(+new preamp in Fall 2012 and other developments in progress)
DAMA/LIBRA-phase2 *in data taking*

DAMA/LIBRA phase 2 - running

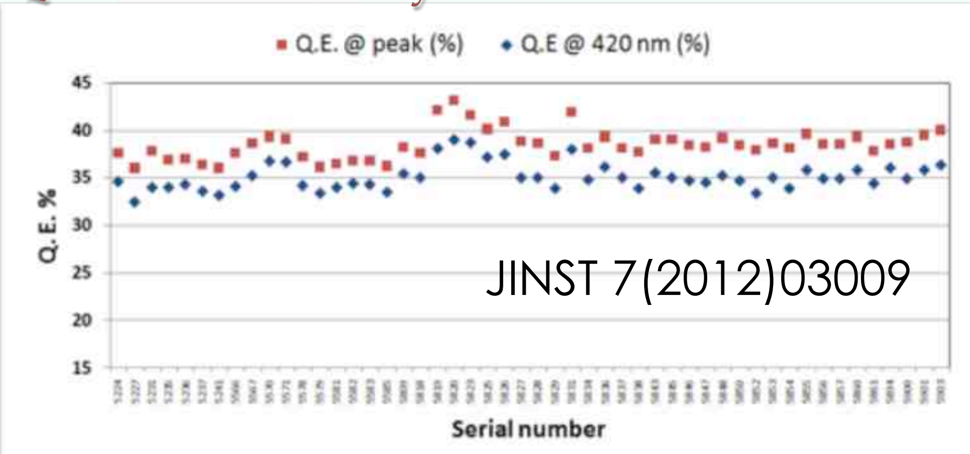
Second upgrade on end of 2010:
all PMTs replaced with new ones of higher Q.E.





DAMA/LIBRA phase 2 - running

Quantum Efficiency features

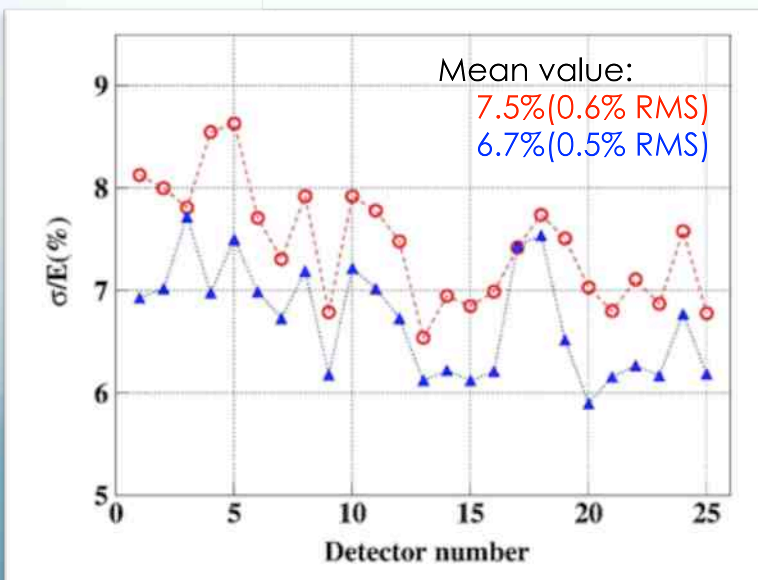


Residual Contamination

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



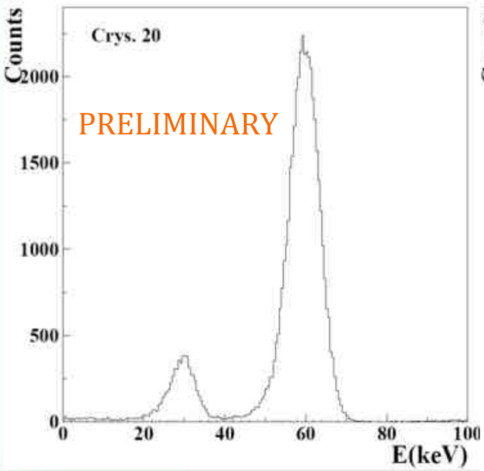
σ/E @ 59.5 keV for each detector with new PMTs with higher quantum efficiency (blu points) and with previous PMT EMI-Electron Tube (red points).

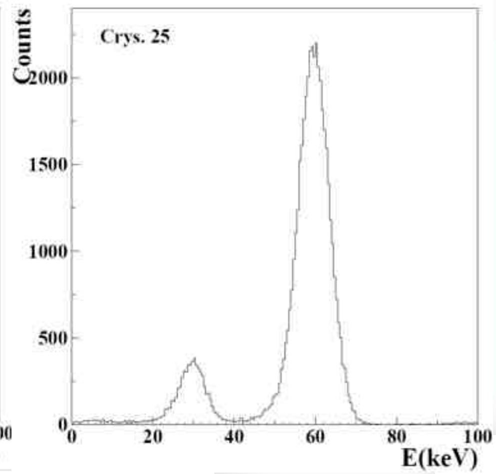
The light responses

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

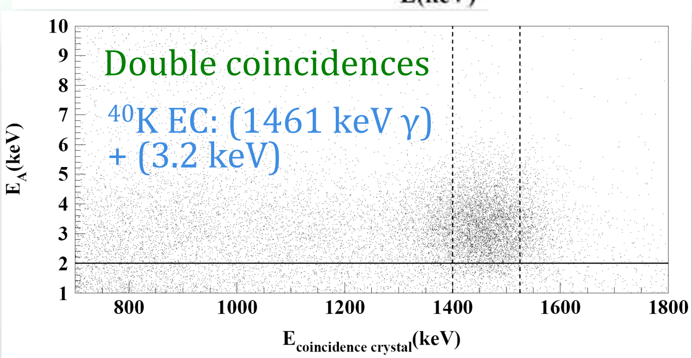
- To study the nature of the particles and features of related astrophysical, nuclear and particle physics aspects, and to investigate second order effects
- Special data taking for *other rare processes*

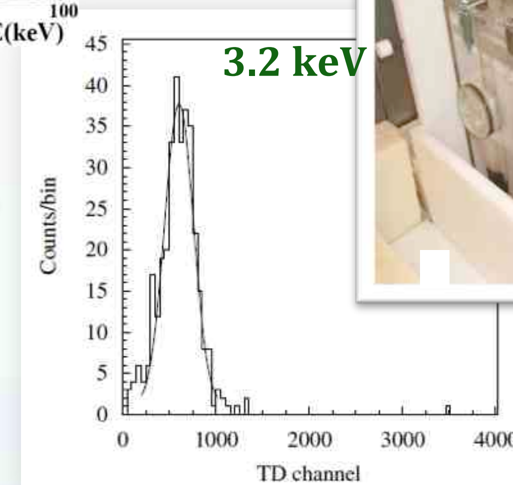
Low-energy calibrations and spectrum in DAMA/LIBRA-phase2

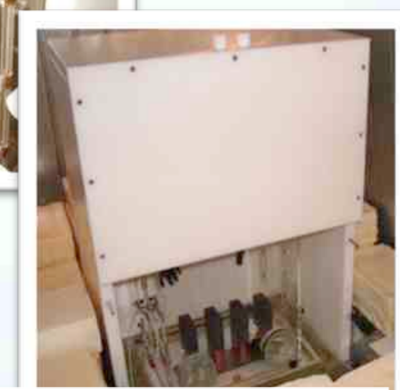




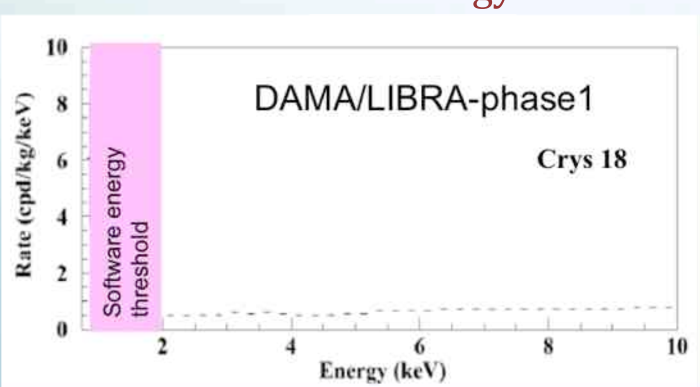
Routine calibrations with ^{241}Am sources every ≈10 days in the same running conditions



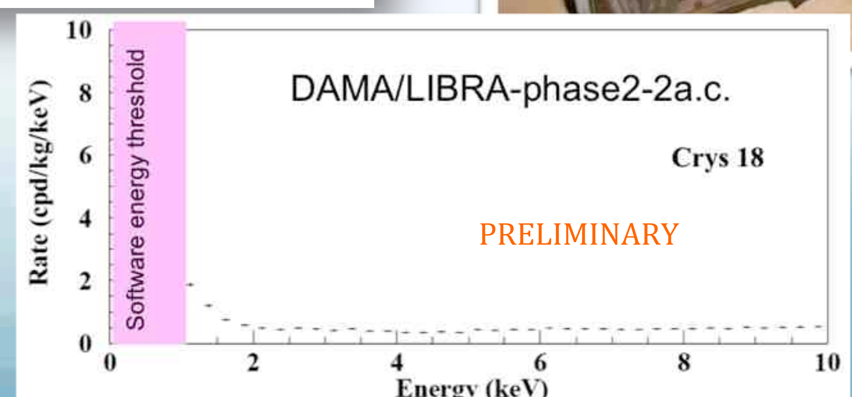




DAMA/LIBRA is the only set-up calibrated near the software energy threshold



Ex. of low-energy distribution of the *single-hit* scintillation events



Towards DAMA/LIBRA-phase3

- The light collection of the detectors can futher be improved.
- Thus, the light yields and the energy thresholds will improve too.

The strong interest in the low energy range suggests the possibility of a new development of **high Q.E. PMTs** with **increased radiopurity** to directly couple them to the DAMA/LIBRA crystals, **removing** the special radio-pure quartz (Suprasil B) light guides (10 cm long), which act also as optical window.

The presently-reached PMTs features, but not for the same PMT mod.:

- Q.E. around 35-40% @ 420 nm (NaI(Tl) light)
- radiopurity at level of 5 mBq/PMT (^{40}K), 3-4 mBq/PMT (^{232}Th), 3-4 mBq/PMT (^{238}U), 1 mBq/PMT (^{226}Ra), 2 mBq/PMT (^{60}Co).

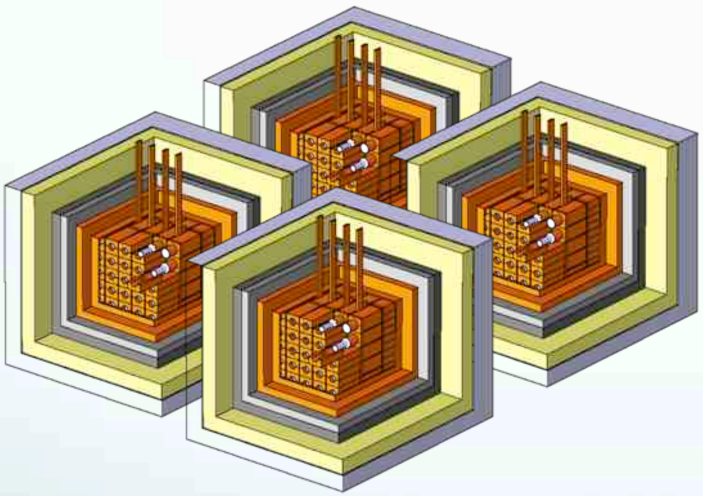
R&D efforts to obtain PMTs matching the best performances… feasible

No longer need for light guides (a 30-40% improvement in the light collection is expected)

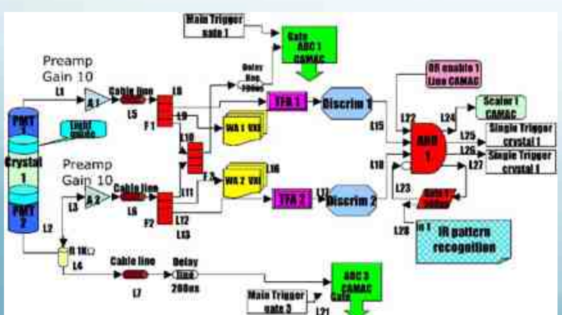
Towards a possible multi-purpose DAMA/1ton

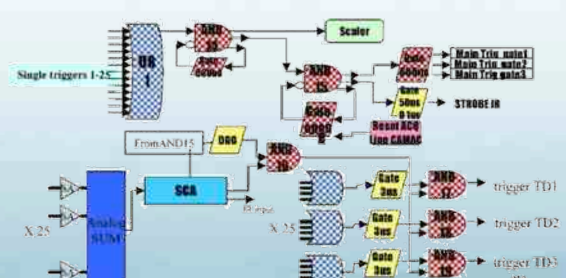
1) Proposed since 1996 (DAMA/NaI and DAMA/LIBRA intermediate steps)
2) Technology largely at hand (large experiences and fruitful collaborations among INFN and companies/industries)
3) Still room for further improvements in the low-background characteristics of the set-up (NaI(Tl) crystals, PMTs, shields, etc.)
4) 1 ton detector: the cheapest, the highest duty cycle, the clear signature, fast realization in few years

A possible design: DAMA/1 ton can be realized by four replicas of DAMA/LIBRA:



- the detectors could be of similar size than those already used
- the features of low-radioactivity of the set-up and of all the used materials would be assured by many years of experience in the field
- electronic chain and controls would profit by the previous experience and by the use of compact devices already developpped, tested and used.
- new digitizers will offer high expandibility and high performances
- the daq can be a replica of that of DAMA/LIBRA





Electronic chain and example of the trigger system

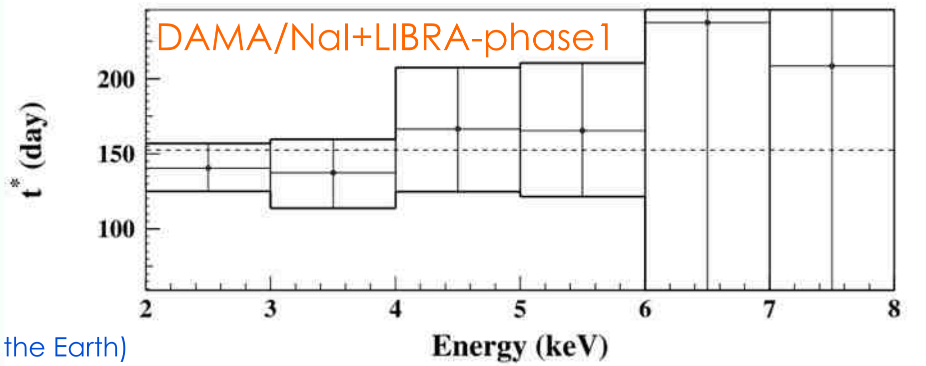
- Some R&Ds on PMTs and on crystals carried out
- Other ideas

Features of the DM signal

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

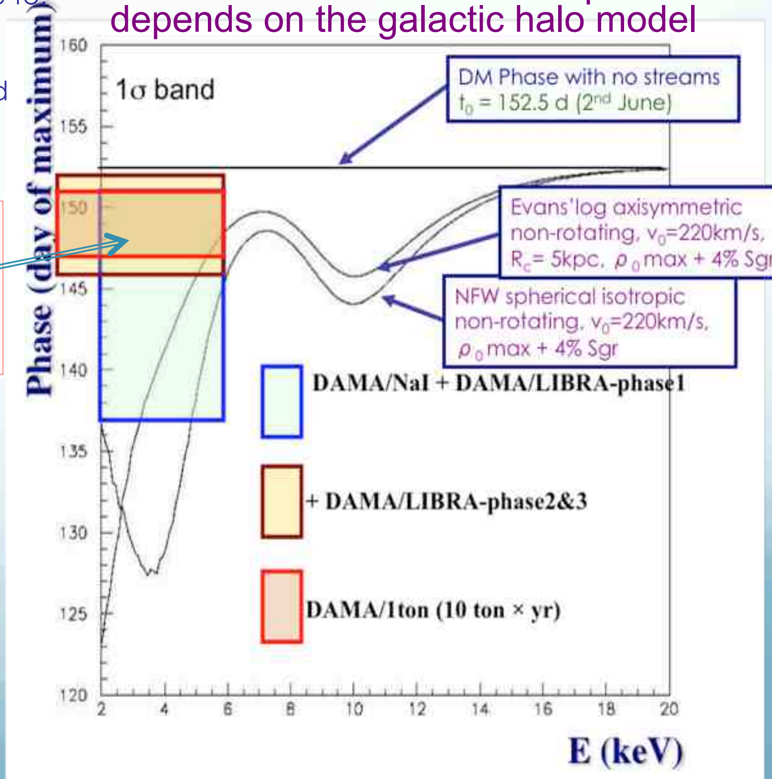
High exposure and lower energy threshold can allow further investigation on:

- 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 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 annual modulation phase depends on :
- Presence of streams (as SagDEG and Canis Major) in the Galaxy
- Presence of caustics
- Effects of gravitational focusing of the Sun

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



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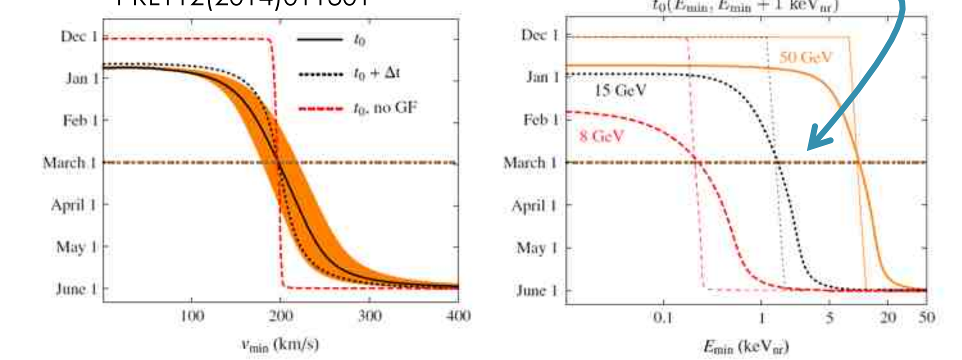


- *Other signatures?*
- *Other second order effects*
- *Diurnal effects*
- *Directionality (see Cerulli's talk)*
- *…*

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:

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

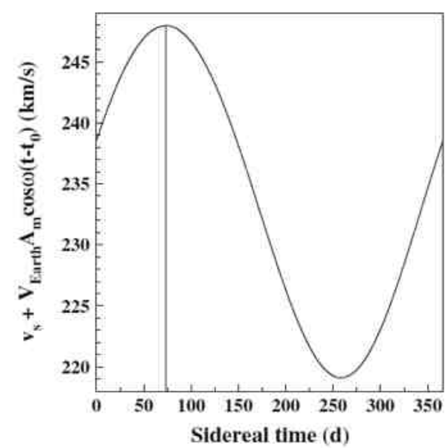
$$\hat{v}_s \cdot \vec{v}_{rev}(t) = V_{Earth} B_m \cos(\omega(t - t_0))$$

- 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

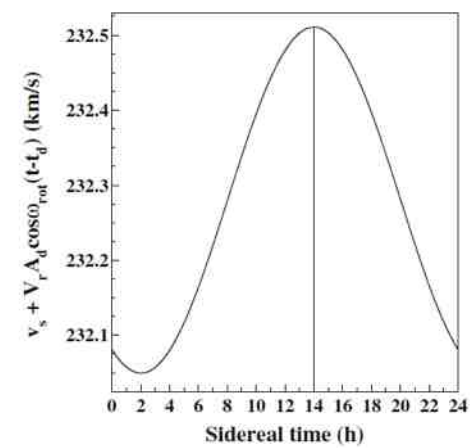
Diurnal modulation term:

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

- 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

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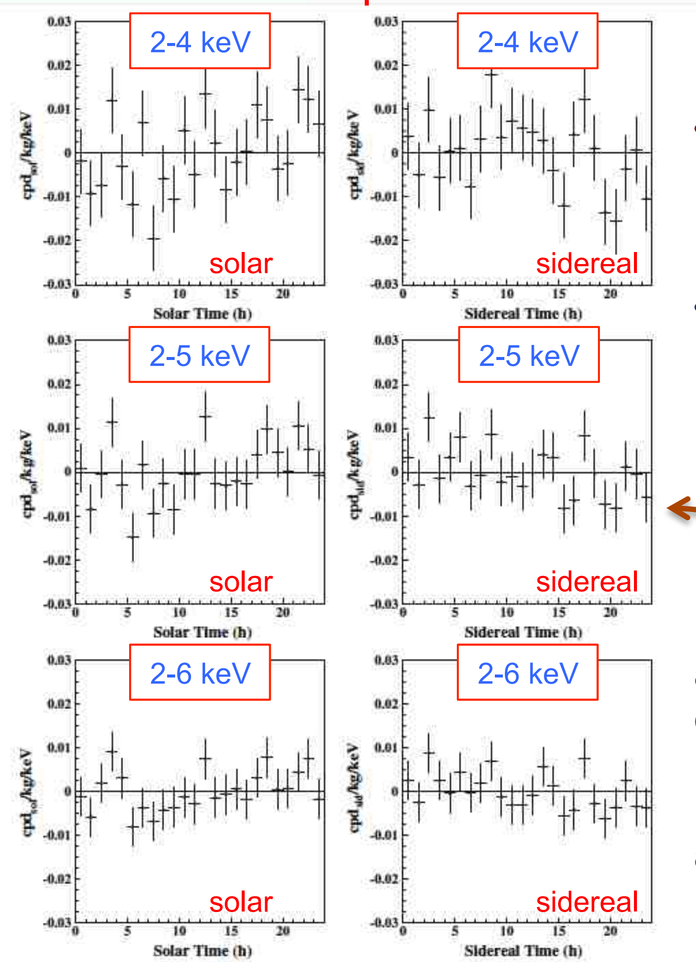
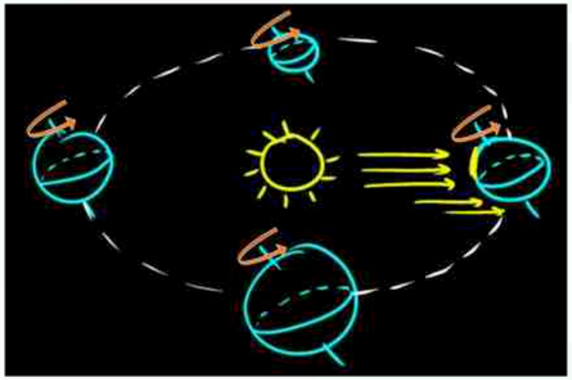
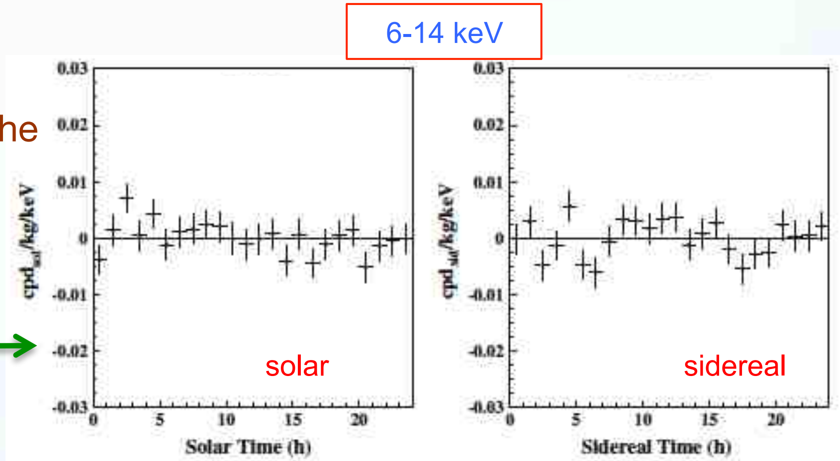


- Experimental *single-hit* residuals rate vs either sidereal and solar time and vs energy.
- These residual rates are calculated from the measured rate of the *single-hit* events after subtracting the constant part



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:

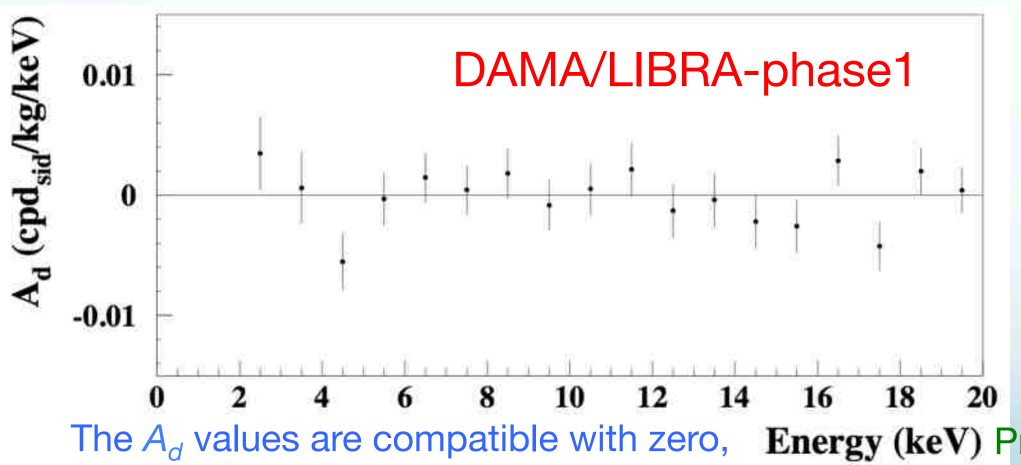
$$S_k\left[v_{lab}(t)\right] \simeq S_k\left[v_s\right] + \left[\frac{\partial S_k}{\partial v_{lab}}\right]_{v_s}\left[V_{Earth}A_m \cos\omega(t-t_0) + V_r A_d \cos\omega_{rot}(t-t_d)\right]$$

- 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&3 and/or DAMA/1ton (+lower energy threshold) offers increased sensitivity to such an effect

DAMA/LIBRA-phase2 also allows:

high sensitivities investigation on other rare processes:
possible PEP violating processes, various possible CNC processes in ^{23}Na and ^{127}I, nucleon and di-nucleon decay into invisible channels with new approach in ^{23}Na and ^{127}I, exotic particles (e.g. SIMPs, neutral nuclearities, Q-balls), solar axions by Primakoff effect in NaI(Tl), rare nuclear processes in ^{23}Na, ^{127}I, hypothesized neutral particles (new QED phase) in ^{241}Am decays, etc.

+ DAMA/LIBRA-phase3 and/or DAMA/1ton with higher sensitivities

... towards a 100 ton highly radiopure NaI(Tl) set-up for high-resolution full-spectroscopy solar neutrinos (Astrop.Phys.4(1995)45)