Upgrade and perspectives of DAMA/LIBRA

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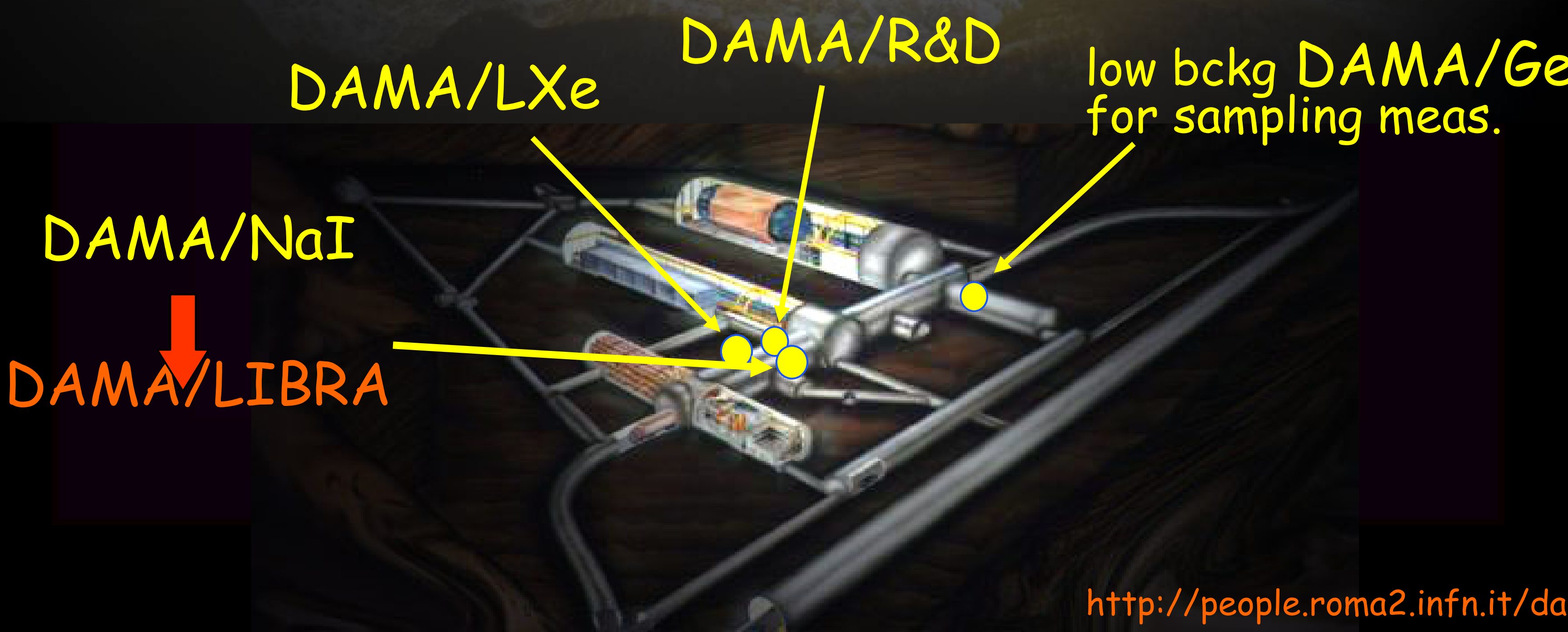
INFN-LNGS

Hot topics in Modern Cosmology
Spontaneous Workshop IV
10 - 15 May 2010 Cargèse

DAMA: an observatory for rare processes @LNGS



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

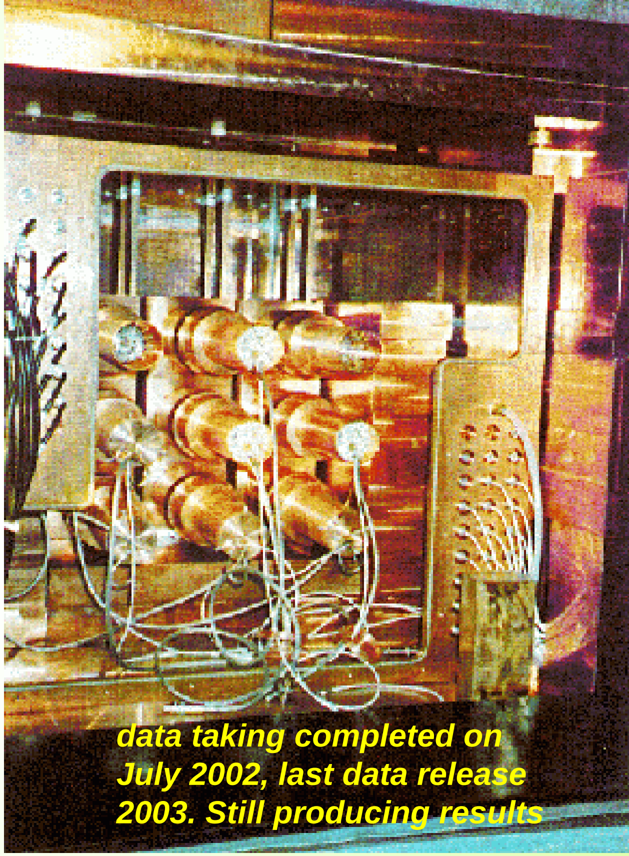
Competitiveness of ULB NaI(Tl) set-up

- Well known technology
- High duty cycle
- Large mass possible
- "Ecological clean" set-up; no safety problems
- Cheaper than every other considered technique
- Small underground space needed
- High radiopurity by selections, chem./phys. purifications, protocols reachable
- Well controlled operational condition feasible
- Neither re-purification procedures nor cooling down/warming up (reproducibility, stability, ...)
- High light response (5.5 -7.5 ph.e./keV)
- Effective routine calibrations feasible down to keV in the same conditions as production runs
- Absence of microphonic noise + noise rejection at threshold (τ of NaI(Tl) pulses hundreds ns, while τ of noise pulses tens ns)
- Sensitive to many candidates, interaction types and astrophysical, nuclear and particle physics scenarios on the contrary of other proposed target-materials (and approaches)
- Sensitive to both high (mainly by Iodine target) and low mass (mainly by Na target) candidates
- Effective investigation of the annual modulation signature feasible in all the needed aspects
- Fragmented set-up
- Etc.

A low background NaI(Tl) also allows the study of several other rare processes : possible processes violating the Pauli exclusion principle, CNC processes in ^{23}Na and ^{127}I, electron stability, nucleon and di-nucleon decay into invisible channels, neutral SIMP and nuclearites search, solar axion search, ...

High benefits/cost

DAMA/NaI: ≈100 kg NaI(Tl)



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

Results on rare processes:

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

Results on DM particles:

- PSD — PLB389(1996)757
- Investigation on diurnal effect — N.Cim.A112(1999)1541
- Exotic Dark Matter search — PRL83(1999)4918
- Annual Modulation Signature

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

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

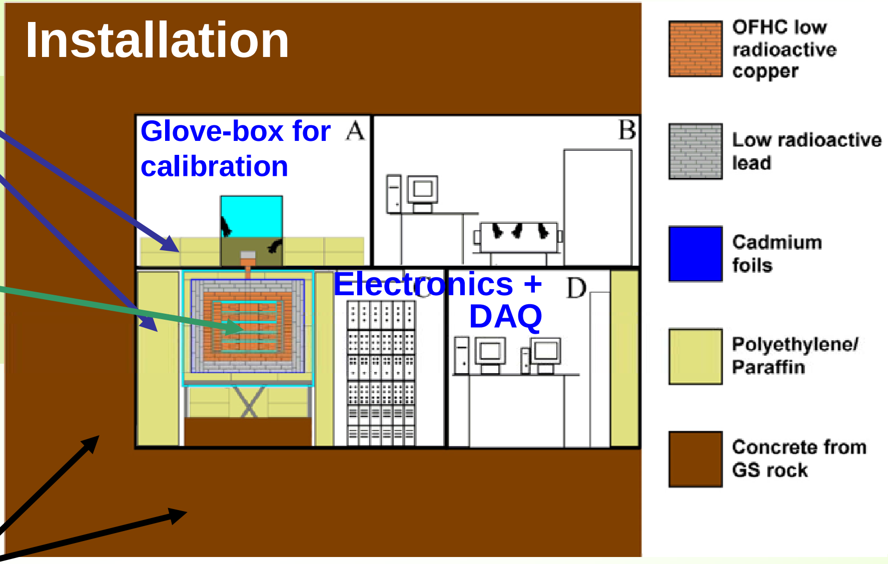
total exposure (7 annual cycles) 0.29 ton x yr

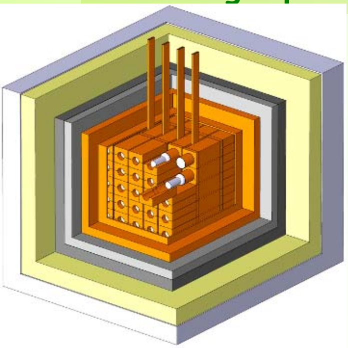
The DAMA/LIBRA set-up

For details, radiopurity, performances, procedures, etc.
NIMA592(2008)297

Polyethylene/
paraffin

- 25 x 9.7 kg NaI(Tl) in a 5x5 matrix
- two Suprasil-B light guides directly coupled to each bare crystal
- two PMTs working in coincidence at the single ph. el. threshold





5.5-7.5 phe/keV

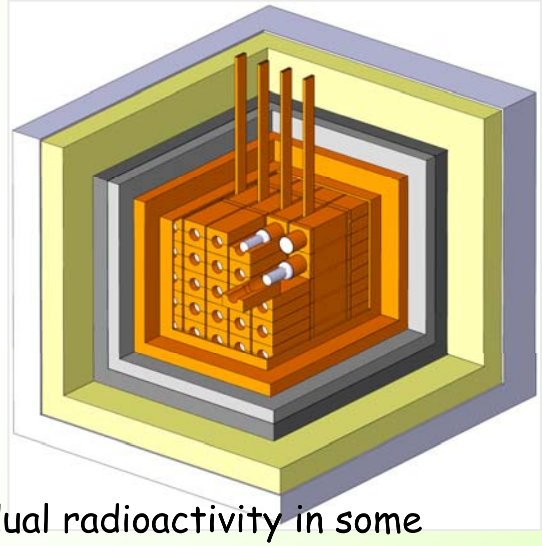
~ 1m concrete from GS rock

- Dismounting/Installing protocol (with "Scuba" system)
- All the materials selected for low radioactivity
- Multicomponent passive shield (>10 cm of Cu, 15 cm of Pb + Cd foils, 10/40 cm Polyethylene/paraffin, about 1 m concrete mostly outside the installation)
- Three-level system to exclude Radon from the detectors
- Calibrations in the same running conditions as production runs
- Installation in air conditioning + huge heat capacity of shield
- Monitoring/alarm system; many parameters acquired with the production data
- Pulse shape recorded by Waveform Analyzer Acqiris DC270 (2chs per detector), 1 *Gsample/s,* 8 bit, bandwidth 250 MHz
- Data collected from low energy up to MeV region, despite the hardware optimization was done for the low energy

DAMA/LIBRA passive shield

Heavy passive shield:

- Cu/Pb/Cd-foils/polyethylene/paraffin shield
- PMTs surrounded by shaped low-radioactive copper shields
- Materials selected for low radioactivity, underground since many years
- Pb and Cu etching and handling in clean room
- Multi-level system to exclude Radon (and flux with HP N_2 gas)



Materials	^{238}U (ppb)	^{232}Th (ppb)	^{nat}K (ppm)
Cu	< 0.5	< 1	< 0.6
feedthroughs	—	< 1.6	< 1.8
Neoprene	—	< 54	< 89
boliden Pb	< 8	< 0.03	< 0.06
boliden2 Pb	< 3.6	< 0.027	< 0.06
polish Pb	< 7.4	< 0.042	< 0.03
polyethylene	< 0.3	< 0.7	< 2
plexiglass	< 0.64	< 27.2	< 3.3

Residual radioactivity in some components of the DAMA/LIBRA passive shield (95% C.L.)

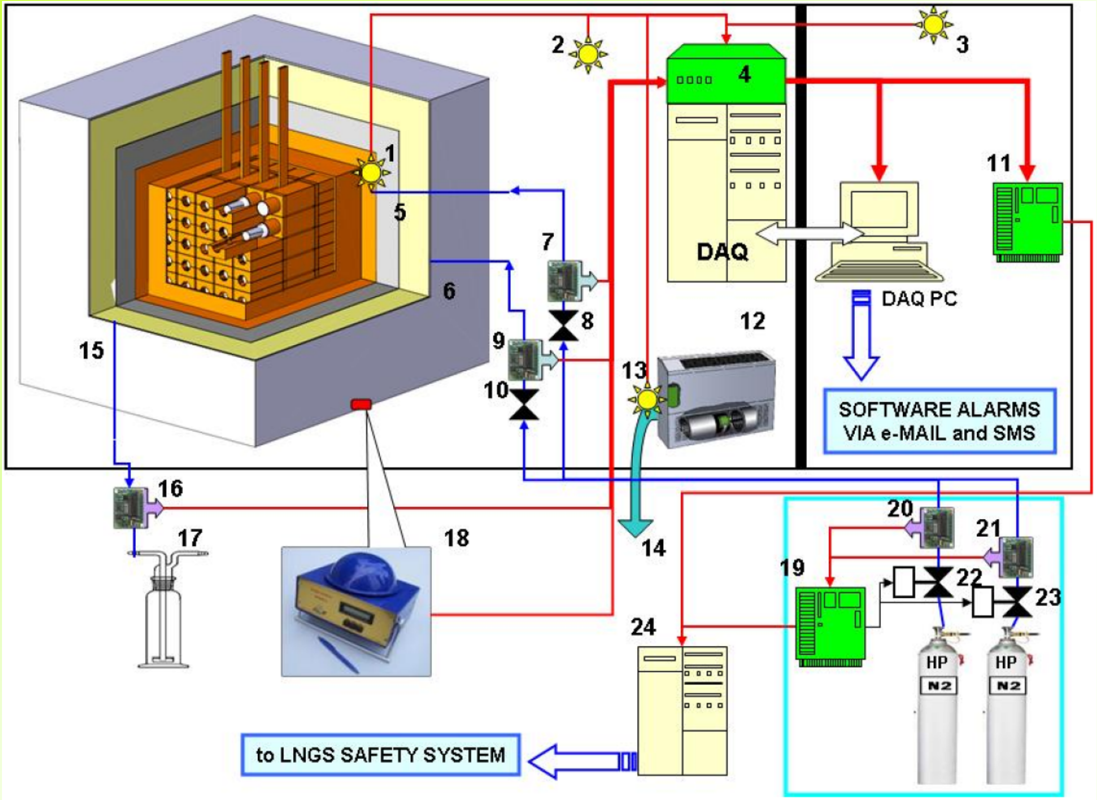
Advantages

- Compact, stable on long term, with fixed conditions on radiopurity and costs
- Fixed shielding efficiency
- Easily to manage in case of crystal scintillators for calibrations etc...
- A detector's array already works as an active shield
- Cosmic muons give negligible contribution in the very low energy region and can be identified in a system with many detectors.
- Similar arguments still hold also for environmental neutrons

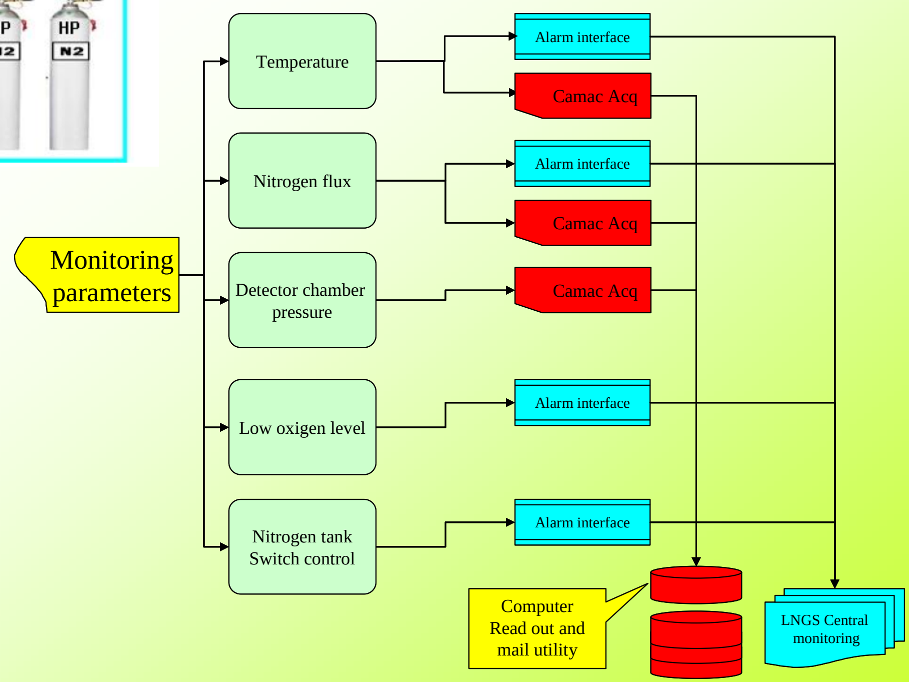
Active liquid shields in future experiments?

Not competitive, suitable running conditions not assured for DM annual modulation, high costs etc...

The monitoring/alarm system



+ Rn meter inside the first (of three) insulation level (where the Rn is at level of sensitivity of the Rn meter, that is few Bq/m^3)
+ several other acquired parameters.
& software alarms



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

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

installing DAMA/LIBRA detectors

assembling a DAMA/ LIBRA detector

filling the inner Cu box with further shield

detectors during installation; in the central and right up detectors the new shaped Cu shield surrounding light guides (acting also as optical windows) and PMTs was not yet applied

- *Radiopurity,performances, procedures, etc.:* NIMA592(2008)297
- *Results on DM particles: Annual Modulation Signature:* EPJC56(2008)333, EPJC67(2010)39.
- *Results on rare processes: Possible processes violating the Pauli exclusion principle in Na and I:* EPJC62(2009)327

closing the Cu box housing the detectors

view at end of detectors' installation in the Cu box

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

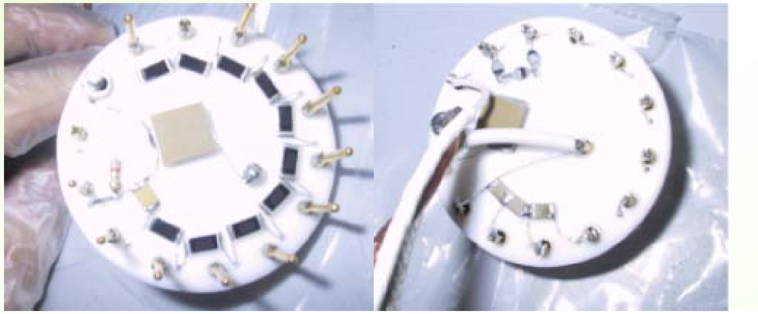
The DAMA/LIBRA calibration system

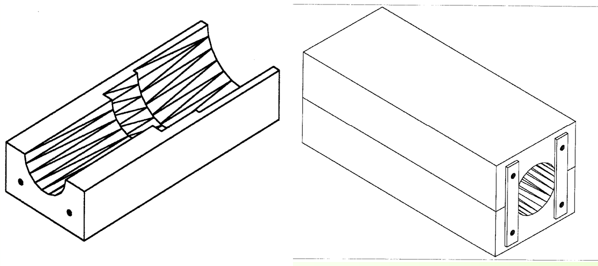
•***PMTs***: stored underground since 2001

•**Voltage dividers**: low bckg materials stored and assembled underground

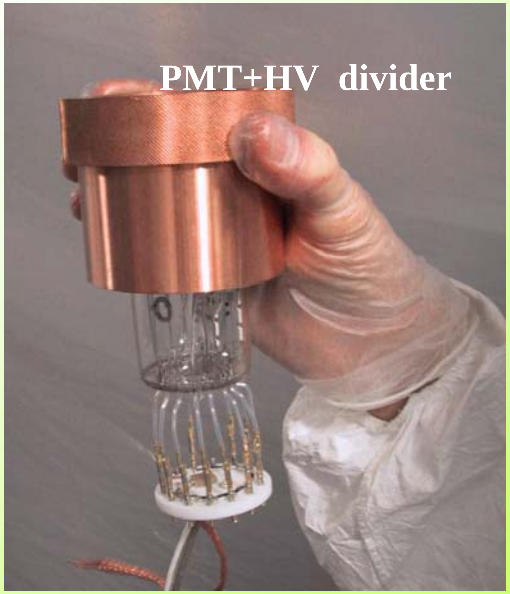
•**Wiring**: new and conceptually modified

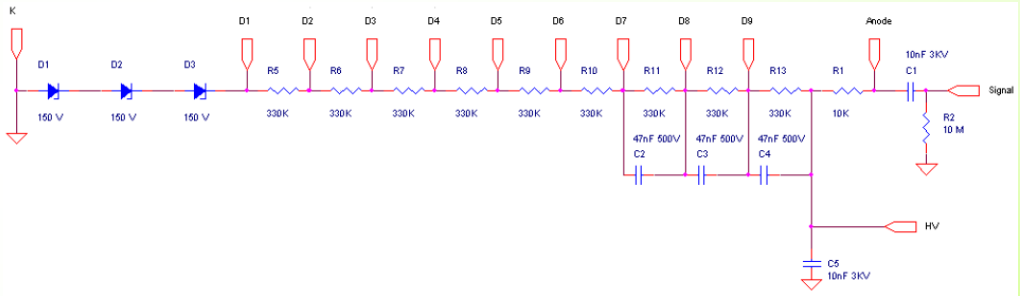
•**New low bckg Cu shield for PMTs** : improved etching and handling protocol



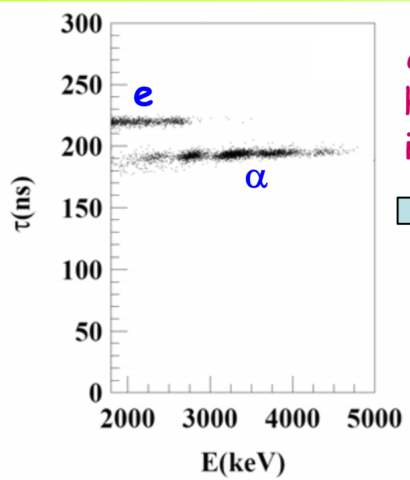


- 3" window PMTs
- Low radioactive glass
- Flying leads directly connected to voltage dividers made of miniaturized SMD components mounted on thin teflon sockets (all selected for low bckg)
- Solders performed by low radioactive Boliden lead and low radiactive resin
- 3" diameter and 10 cm long UV Suprasil-B light guides used, acting also as optical windows of the detectors
- The PMTs have 9 high gain, high stability dynodes of linear focused design, high quantum efficiency (30% at 380 nm), good pulse height resolution for single photoelectron pulses (peak/valley $\geq$ 2), low dark noise rate (0.1 kHz), and a gain of $\approx 10^6$





Some on residual contaminants in NaI(Tl) detectors



α/e pulse shape discrimination has practically 100% effectiveness in the MeV range

The measured α yield in the new DAMA/LIBRA detectors ranges from 7 to some tens α/kg/day

Second generation R&D for new DAMA/LIBRA crystals: new selected powders, physical/chemical radiopurification, new selection of overall materials, new protocol for growing and handling

^{232}Th residual contamination

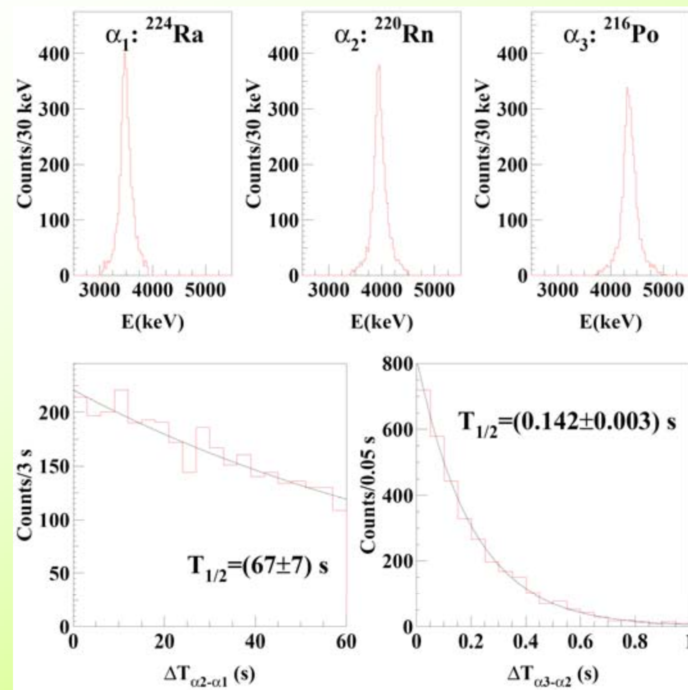
Time-amplitude method: arrival time and energy of each event used for selection of fast decay chains in ^{232}Th family

^{224}Ra (Q_α=5.8 MeV, $T_{1/2}$=3.66 d) → ^{220}Rn (Q_α=6.4 MeV, $T_{1/2}$=55.6 s) → ^{216}Po (Q_α=6.9 MeV, $T_{1/2}$=0.145 s) → ^{212}Pb

α peaks as well as the distributions of the time intervals between the events are in a good agreement with those expected

$$\alpha / \beta = 0.467(6) + 0.0257(10) \times E_\alpha [MeV]$$

Example: 3310 triple delayed coincidences in 8100 kg×day → (9.0±0.4) μBq/kg



⇒ ^{228}Th activity ranging from 2 to about 30 μBq/kg in the DAMA/LIBRA detectors (in agreement with Bi-Po analysis)

If ^{232}Th chain at equilibrium: ^{232}Th contents in new detectors typically range from 0.5 ppt to 7.5 ppt

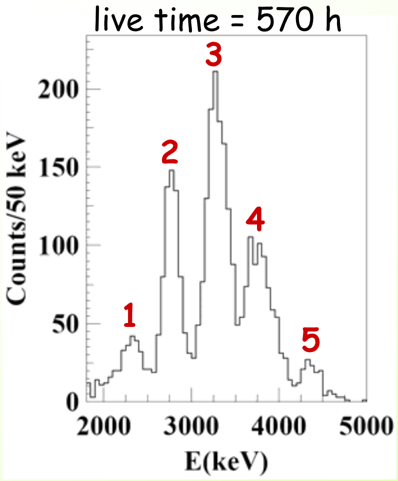
^{238}U residual contamination

First estimate: considering the measured α and ^{232}Th activity, if ^{238}U chain at equilibrium $\Rightarrow$ ^{238}U contents in new detectors typically range from 0.7 to 10 ppt

But, hypothesis of equilibrium is not confirmed by the study of the α particles energy distributions:

Example: 5 α peaks

1. ^{232}Th(Q_α=4.08 MeV) + ^{238}U(4.27 MeV)
2. ^{234}U(4.86 MeV) + ^{230}Th(4.77 MeV) + ^{226}Ra(4.87 MeV)
3. ^{210}Po(5.41 MeV) + ^{228}Th(5.52 MeV) + ^{222}Rn(5.59 MeV) + ^{224}Ra(5.79 MeV)
4. ^{218}Po(6.12 MeV) + ^{212}Bi(6.21 MeV) + ^{220}Rn(6.41 MeV)
5. ^{216}Po(6.91MeV)



^{238}U chain splitted into 5 subchains: $^{238}U \rightarrow {}^{234}U \rightarrow {}^{230}Th \rightarrow {}^{226}Ra \rightarrow {}^{210}Pb \rightarrow {}^{206}Pb$

Thus, in this case: (2.1±0.1) ppt of ^{232}Th; (0.35 ±0.06) ppt for ^{238}U and: (15.8±1.6) μBq/kg for ^{234}U + ^{230}Th subchain; (21.7±1.1) μBq/kg for ^{226}Ra subchain; (24.2±1.6) μBq/kg for ^{210}Pb subchain.

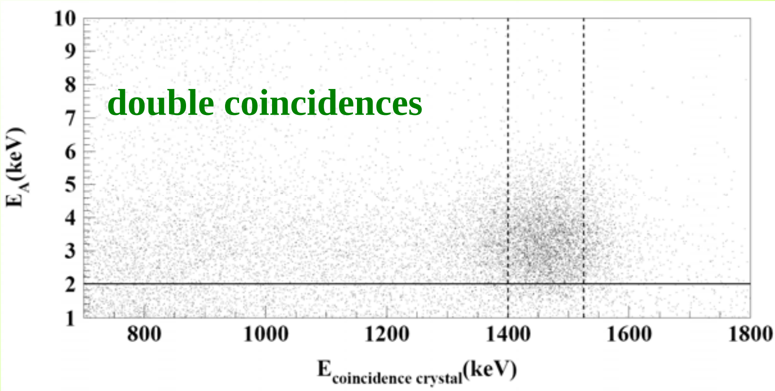
^{nat}K residual contamination

^{40}K (δ=0.0117%)

EC: (1461 keV γ) + (3.2 keV X-rays/Auger electrons); b.r.=10.66%

The 1461 keV γ can escape from one detector (*A*) and hit another one causing a double coincidence. X-rays/Auger electrons give rise in *A* to a 3.2 keV peak

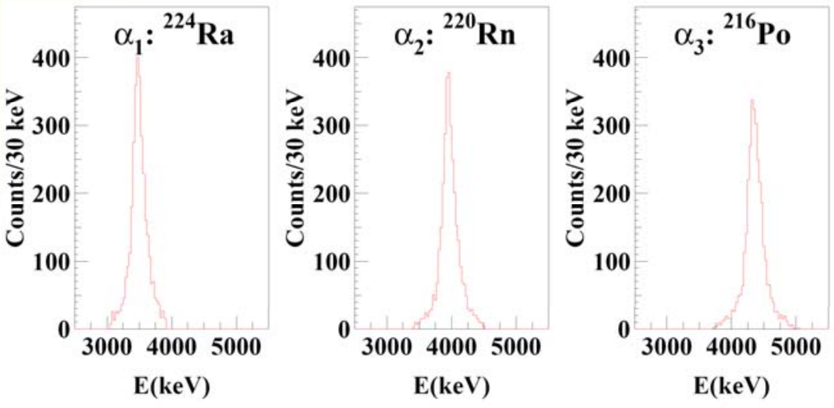
The 3.2 keV peak offers also the proof of the physical threshold of the detectors and an intrinsic calibration for each one in the lowest energy region



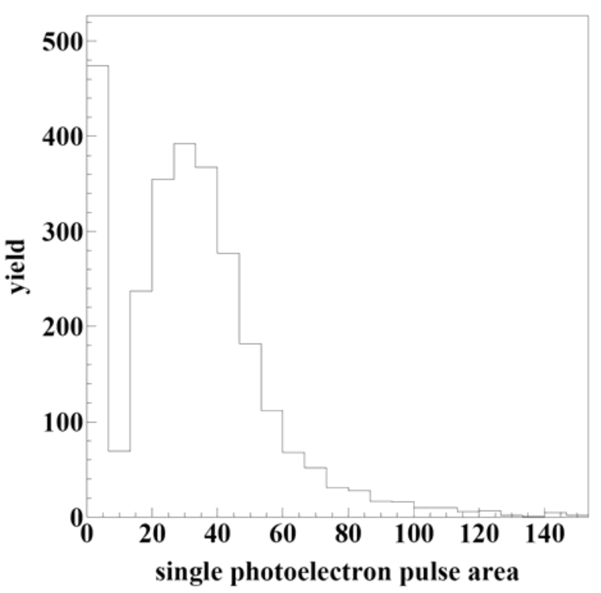
The analysis has given for the ^{nat}K content in the crystals values not exceeding about 20 ppb

Uniformity of the light collection

- Absence of dead spaces in the light collection: no significant variations of the peak position and energy resolution when irradiating the whole detector with high-energy γ sources (e.g., ^{137}Cs) from different positions.
- α peaks at high energy and their energy resolutions are well compatible with those expected considering γ calibration (ex: energy resolution σ = (75$\pm$3) keV for α_1, for γ's is 72 keV).
- All this supports the uniformity of the light collection within 0.5%.



Photoelectrons/keV



A clean sample of photoelectrons can be extracted from the end part of the Waveform Analyser time window (2048 ns) where afterglow single photoelectron signals can be present.

Typical experimental distribution of the area of the single photoelectron's pulses for a DAMA/LIBRA detector

The relative peak value can be compared with the peak position of the distribution of the areas of the pulses corresponding to a full energy deposition from the 59.5 keV of the ^{241}Am

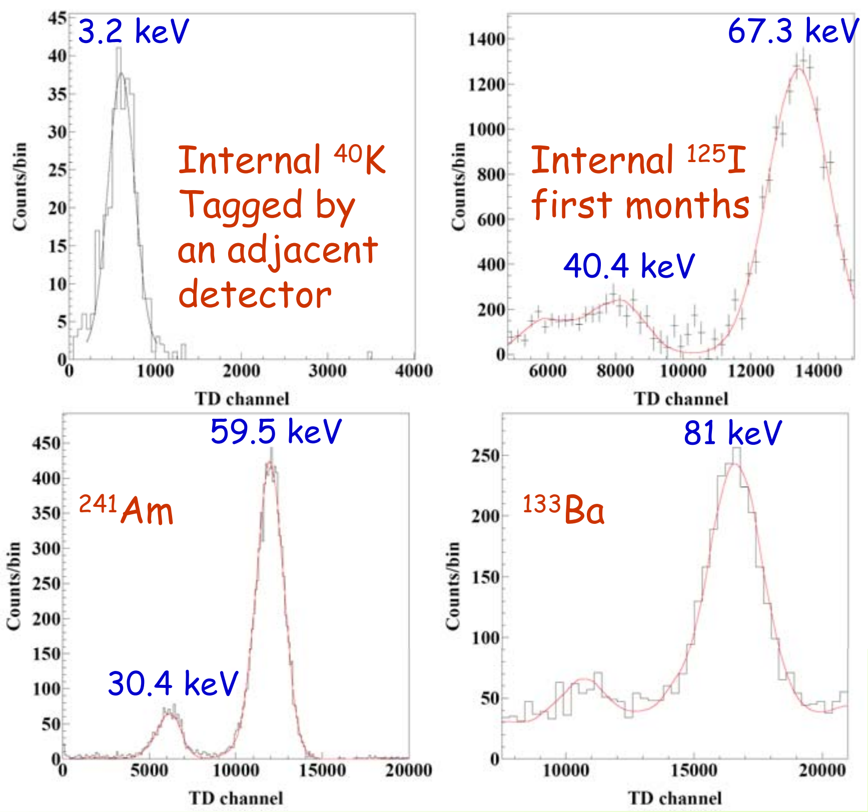
$\Rightarrow$ the number of photoelectrons/keV ranges from 5.5 to 7.5 depending on the detector

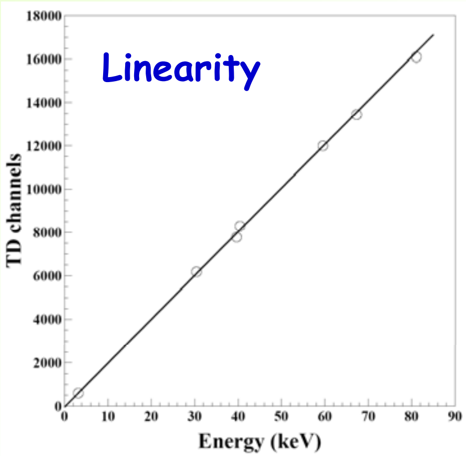
DAMA/LIBRA: calibrations at low energy

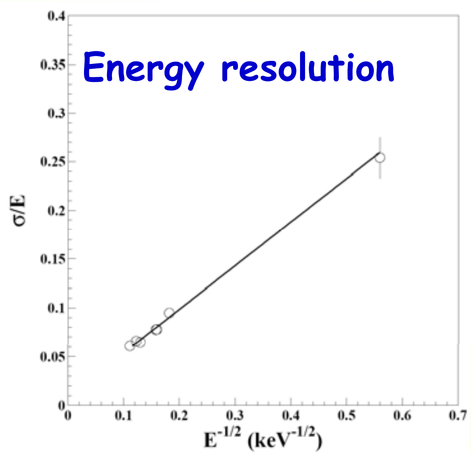
Studied by using various external gamma sources (^{241}Am, ^{133}Ba) and internal X-rays or gamma's (^{40}K, ^{125}I, ^{129}I)

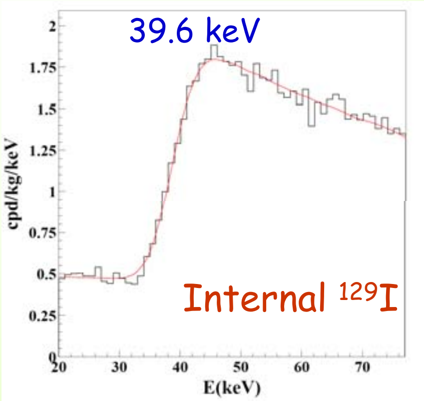
The curves superimposed to the experimental data have been obtained by simulations

- **Internal ^{40}K:** 3.2 keV due to X-rays/Auger electrons (tagged by 1461 keV γ in an adiacent detector).
- **Internal ^{125}I:** 67.3 keV peak (EC from K shell + 35.5 keV γ) and composite peak at 40.4 keV (EC from L,M,.. shells + 35.5 keV γ).
- **External ^{241}Am source:** 59.5 keV γ peak and 30.4 keV composite peak.
- **External ^{133}Ba source:** 81.0 keV γ peak.
- **Internal ^{129}I:** 39.6 keV structure (39.6 keV γ + β spectrum).









Routine calibrations with ^{241}Am

$$\frac{\sigma_{LE}}{E} = \frac{(0.448 \pm 0.035)}{\sqrt{E(keV)}} + (9.1 \pm 5.1) \cdot 10^{-3}$$

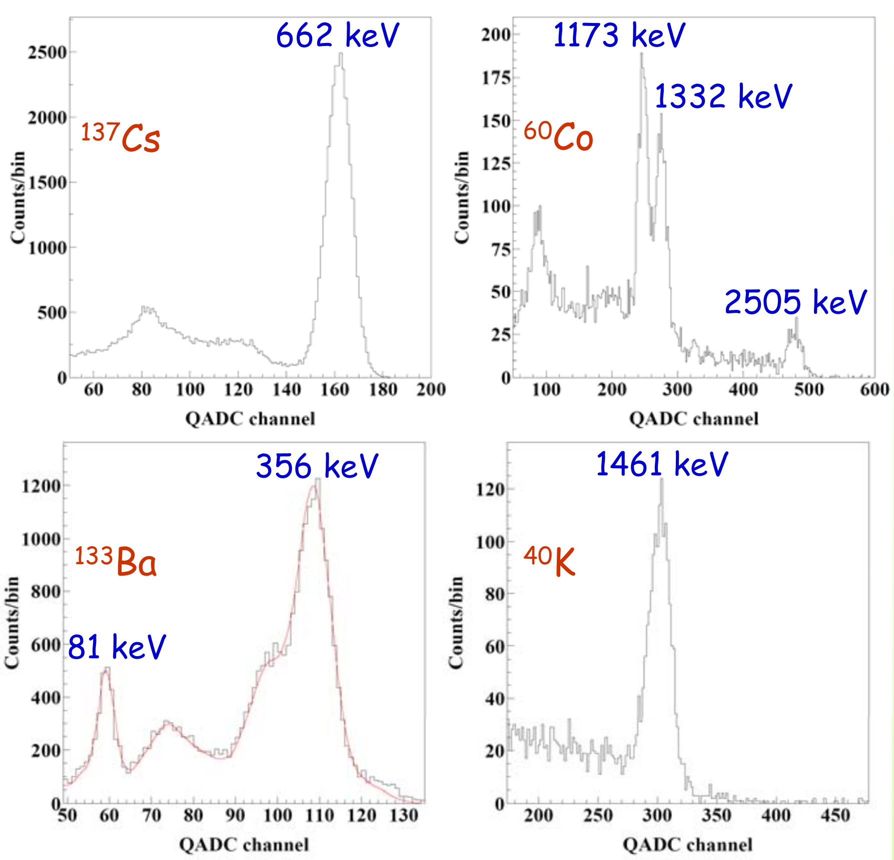
Thus, here and hereafter keV means keV electron equivalent

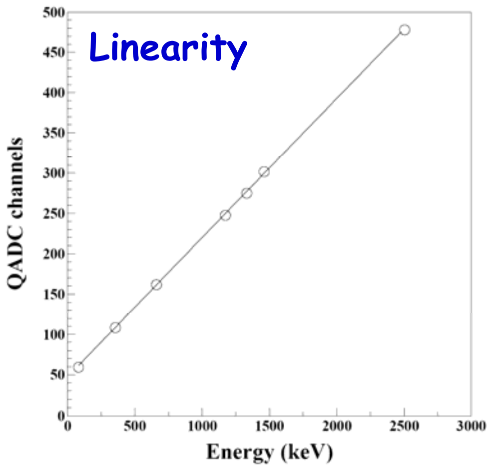
DAMA/LIBRA: calibrations at high energy

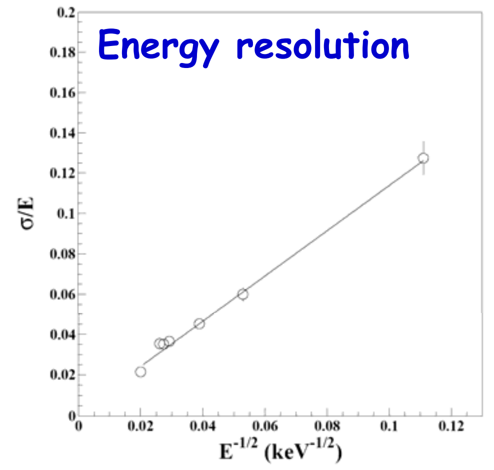
The data are taken on the full energy scale up to the MeV region by means QADC's

Studied by using external sources of gamma rays (e.g. ^{137}Cs, ^{60}Co and ^{133}Ba) and gamma rays of 1461 keV due to ^{40}K decays in an adjacent detector, tagged by the 3.2 keV X-rays

$$\frac{\sigma_{HE}}{E} = \frac{(1.12 \pm 0.06)}{\sqrt{E(keV)}} + (17 \pm 23) \cdot 10^{-4}$$







The signals (unlike low energy events) for high energy events are taken only from one PMT

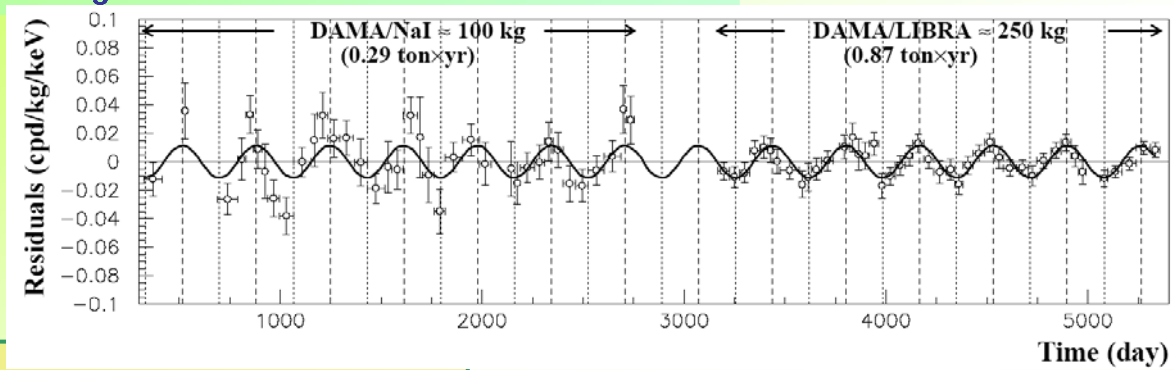
Thus, here and hereafter keV means keV electron equivalent

Dark Matter investigation by model-independent annual modulation signature

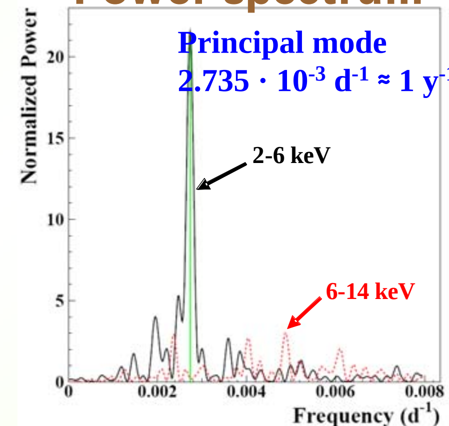
DAMA/NaI (7 years) + DAMA/LIBRA (6 years). Total exposure: **1.17 ton×yr** (the **largest** exposure ever collected in this field)

EPJC 56(2008)333, EPJC67(2010)39

Experimental single-hit residuals rate *vs* time in 2-6 keV



Power spectrum



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

continuous lines: t_0 = 152.5 d, T = 1.00 y

A=(0.0114±0.0013) cpd/kg/keV

χ^2/dof = 64.7/79 8.8 σ C.L.

Absence of modulation? No

χ^2/dof=140/80 P(A=0) = 4.3×10^{-5}

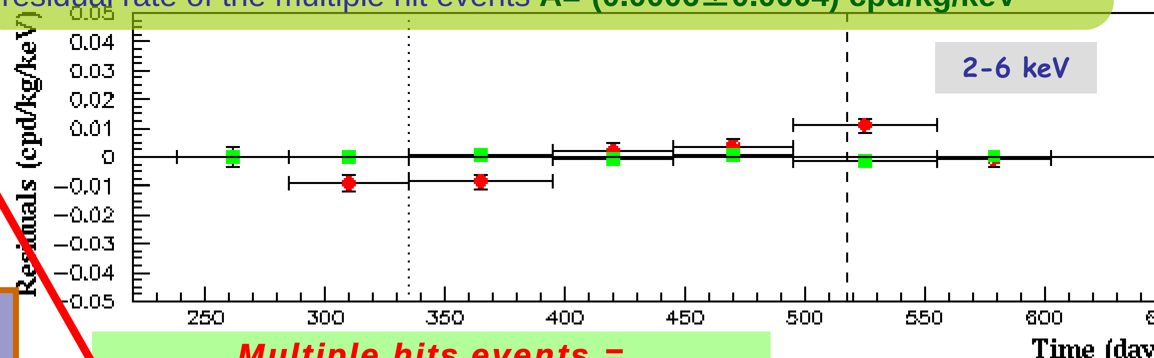
fit with all the parameters free:

A = (0.0098 ± 0.0015) cpd/kg/keV

t_0 = (146±9) d

T = (0.999±0.002) y

Comparison between **single hit residual rate (red points)** and **multiple hit residual rate (green points)** for (DAMA/LIBRA 1-6); Clear modulaion in the single hit events **A=(0.0091±0.0014) cpd/kg/keV**; No modulation in the residual rate of the multiple hit events **A=-(0.0006±0.0004) cpd/kg/keV**



Multiple hits events = Dark Matter particle "switched off"

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

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 9σ C.L.

The first upgrade in fall 2008

Phase 1

- Mounting of the "clean room" set-up in order to operate in HP N_2 atmosphere
- Opening of the shield of DAMA/LIBRA set-up in HP N_2 atmosphere
- Replacement of some PMTs in HP N_2 atmosphere
- Closing of the shield

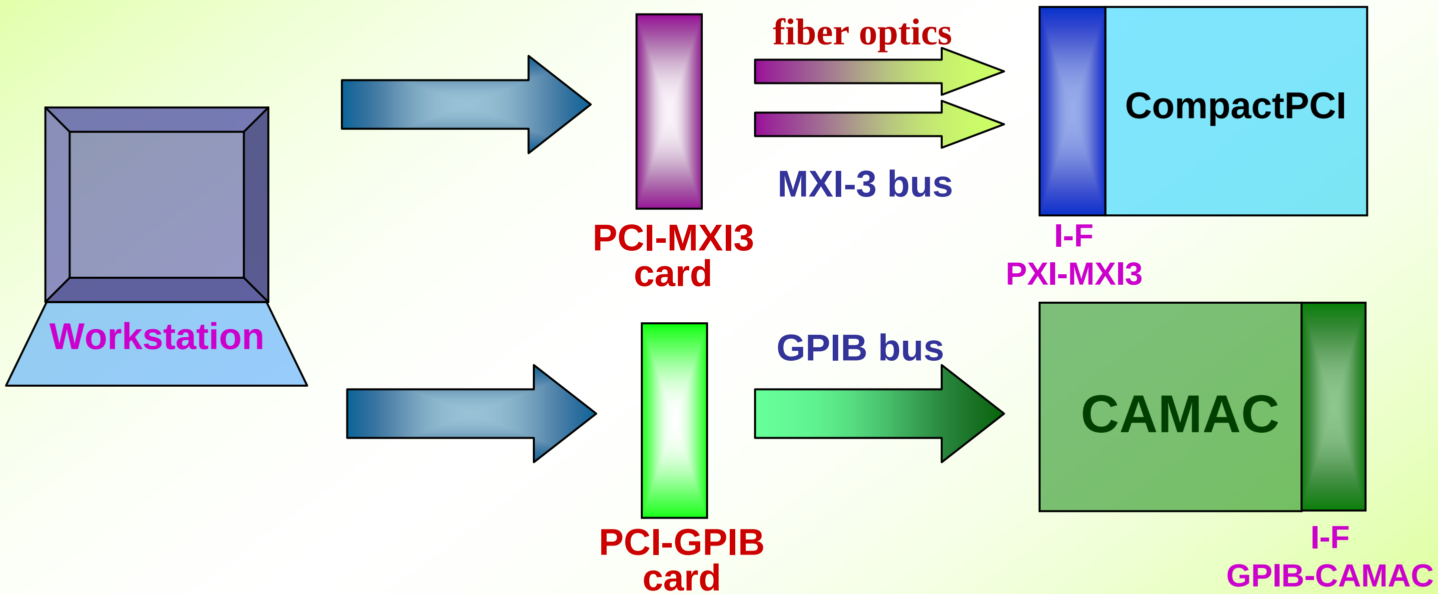
Phase 2

- Dismounting of the Tektronix TDs (Digitizers + Crates)
- Mounting of the new Acqiris TD (Digitizers + Crate)
- Mounting of the new DAQ system with optical read-out
- Test of the new TDs (*hardware*) and of the new required DAQ system (*software*)

Since Oct. 2008 again in data taking

Future improvements in the DAMA/LIBRA DAQ + new TDs

- **Computer:** HP Workstation with Intel processor (3.4 GHz) with Red-Hat Linux operating system
- **Bus:** MXI-3 and GPIB
- **Mainframe:** CompactPCI and CAMAC



New Transient Digitizers: Quad-Channel CompactPCI Digitizer Acqiris DC270

- ✓ improving in the performances
- ✓ semplifying trigger system
- ✓ data transfer on fiber optics (+ TD electrically decoupled from PC)
- ✓ increasing the duty cycle and the daq live-time
- ✓ hardware and software supports from company (on the contrary of the Tektronix Waveform Analizers)

DC270 Acqiris Digitizers:

- 4 channels
- 250 MHz bandwidth
- 1 GS/s sampling rate simultaneously on all 4 channels
- Acq memory = 2 Mpoints
- Full front-end amplification with internal calibration
- < 1% DC accuracy for precise voltage measurement (typical)
- Complete pre and post triggering
- ±2 ppm clock accuracy
- Low dead-time sequential recording with time stamps for up to 4000 segments
- Built-in 5 ps Trigger Time Interpolator (TTI) for accurate timing measurements
- 1 GHz Auto-Synchronization-Bus (ASBus) for trigger and clock signal distribution
- Modular, 6U CompactPCI standard
- Low power (< 40 W)
- Very high data transfer rate to host PC
- Device drivers for Linux

Acquisition and transfer time (=dead-time of ACQ), as measured by us:

$$T \approx 60\mu s + N_{chns} \cdot 85\mu s$$

Crate Acqiris CC121

- 21-slot cPCI Crate can host up to 80 channels
- Houses 21 6U modules in a compact 9U-high 19" rack-mounted crate
- 1260 W (60 W/slot) useable power
- Optimized cross-flow air circulation
- Separate cooling for modules and power supply with full protection against over-temperature
- High-quality power supply with universal AC input, power factor correction, auto-voltage and auto-frequency ranging
- 20 peripheral slots plus system slot on the left
- Accepts both 6U and 3U cPCI and PXI modules
- Systems compatible with cPCI extension interfaces or embedded processor boards

Next upgrade of DAMA/LIBRA

- Continuously running

- *Next upgrade*: replacement of all the PMTs with higher Quantum Efficiency (Q.E.) PMTs.

- New PMTs with higher Q.E. in production: 20 PMTs already ready;

- Continuing data taking in the new configuration to investigate also the data below the present 2 keV energy threshold

- Reaching very high C.L. for the model independent result and determing very precisely all the modulation parameters to disentangle among the many possible scenarios for DM candidates, interactions, halo models, nuclear/atomic properties, etc..

- Investigation ondark matter peculiarities and second order effect

- Special data taking for other rare processes.

Examples of previous developments of PMTs

Examples of residual radioactivity in PMTs and light guides

DAMA/LIBRA (Suprasil B):

<0.012 Bq/kg ^{238}U; <0.008 Bq/kg ^{232}Th; <0.041 Bq/kg ^{40}K

DAMA/LIBRA PMTs (Il Nuov.Cim.A112(1999)545):

≈0.37 Bq/kg ^{238}U; ≈0.12 Bq/kg ^{232}Th; ≈1.9 Bq/kg ^{40}K

R&D for new concept PMTs

low background PMTs without any glass & ceramics

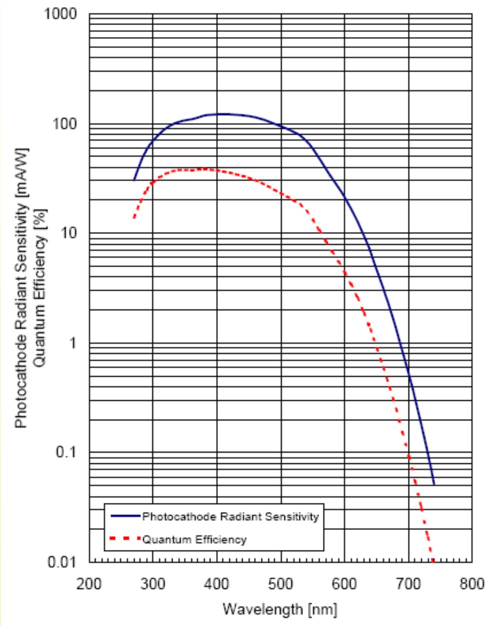
material selection and assembling techniques, 2 prototypes built and qualified:

	first prototype:		second prototype:
^{40}K:	< 0.032 Bq/kg	^{40}K:	< 0.003 Bq/kg
^{238}U:	(0.062 ± 0.012) Bq/kg	^{238}U:	(0.248 ± 0.012) Bq/kg
^{232}Th:	(3.6 ± 0.8) mBq/kg	^{232}Th:	(8.9 ± 0.8) mBq/kg

but electric performances not satisfactory

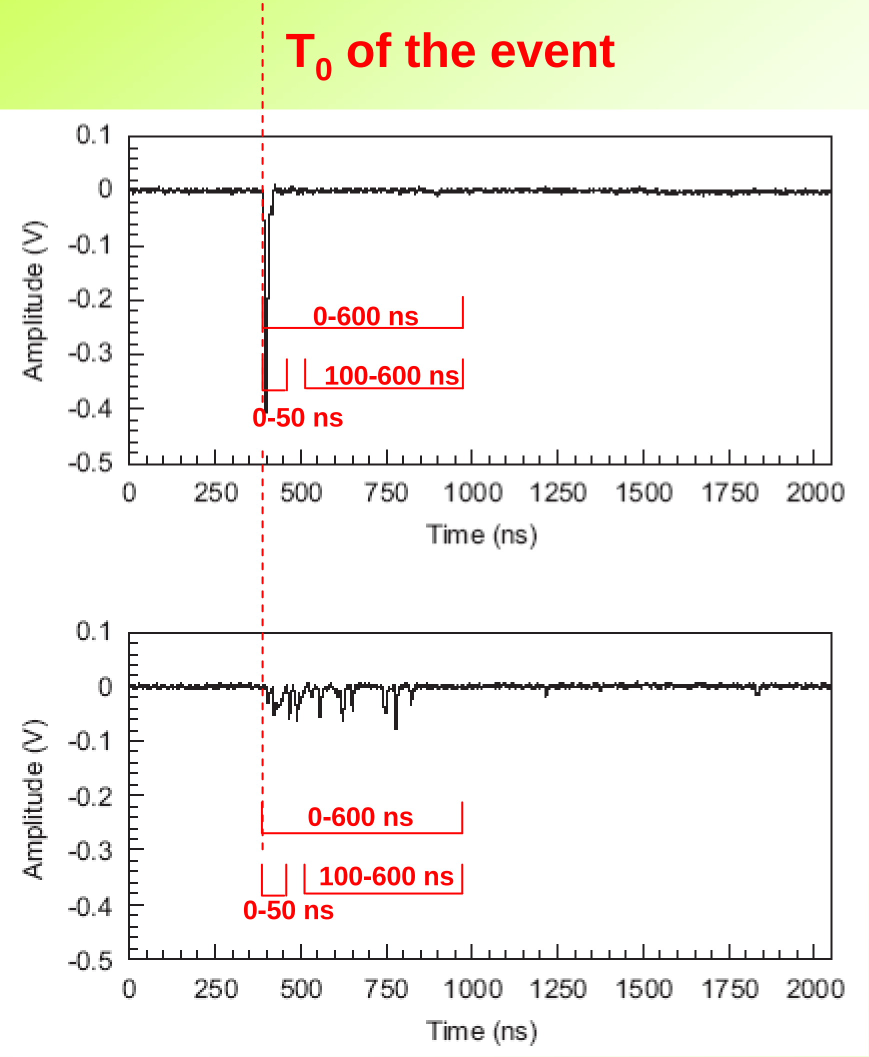
New DAMA/LIBRA selected High Q.E. PMTs (from Hamamatsu):

^{238}U:	<0.40 Bq/kg
^{232}Th:	<0.08 Bq/kg
^{40}K:	< 0.35 Bq/kg



New DAMA/LIBRA selected High Q.E. PMTs (from Hamamatsu): ≈40 % @ peak

Noise rejection near the energy threshold



- **Examples of variables that can be used:**

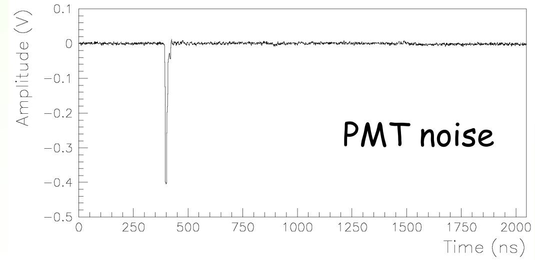
X1 = Area[100-600 ns] / Area [0-600 ns]

X2 = Area[0-50 ns] / Area [0-600 ns]

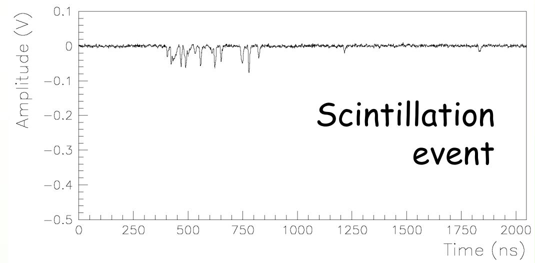
Noise:	**X1 ≈ 0.** **X2 ≈ 1.**
Scintillation:	**X1 ≈ 0.70** **X2 ≈ 0.25**

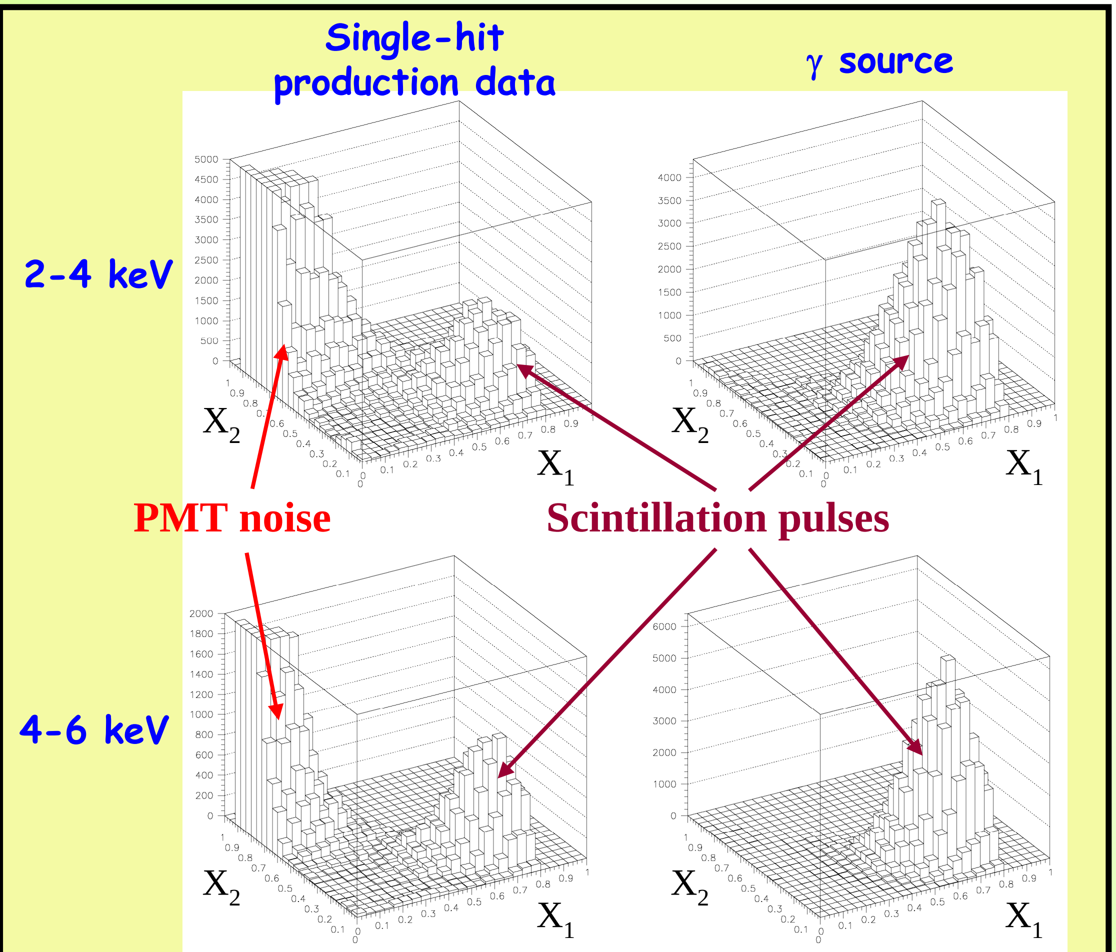
Noise rejection near the energy threshold

Typical pulse profiles of PMT noise and of scintillation event with the same area, just above the energy threshold of 2 keV



The different time characteristics of PMT noise (decay time of order of tens of ns) and of scintillation event (decay time about 240 ns) can be investigated building several variables





From the Waveform Analyser 2048 ns time window:

$$X_1 = \frac{\text{Area (from 100 ns to 600 ns)}}{\text{Area (from 0 ns to 600 ns)}};$$

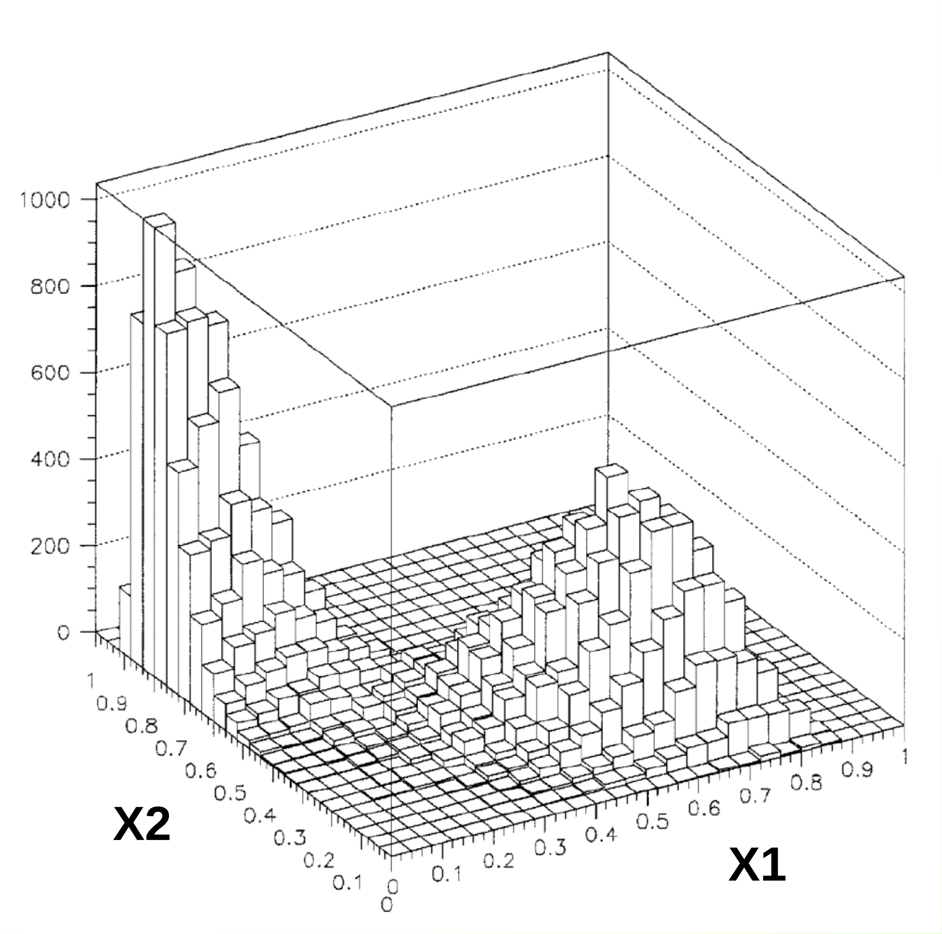
$$X_2 = \frac{\text{Area (from 0 ns to 50 ns)}}{\text{Area (from 0 ns to 600 ns)}}$$

- The separation between noise and scintillation pulses is very good.
- Very clean samples of scintillation events selected by stringent acceptance windows.
- The related efficiencies evaluated by calibrations with ^{241}Am sources of suitable activity in the same experimental conditions and energy range as the production data (efficiency measurements performed each ~10 days; typically 10^4–10^5 events per keV collected)

This is the only procedure applied to the analysed data

Towards the <≈1 keV energy threshold in future data by the new high Q.E. PMTs

E = 1–2 keV (Expected)



There is the possibility to decrease the energy threshold keeping high the acceptance window efficiency

Program of DAMA/LIBRA set-up in incoming years

Program of DAMA/LIBRA set-up in incoming years

see ApPEC document: R. Bernabei spokesperson

Goals of high-mass and high-sensitivity NaI detector:

- Extremely high C.L. for the model independent signal and precise determination of all the signature parameters
- Model independent investigation on other peculiarities of the signal
- High exposure: investigation & test of different astrophysical, nuclear, particle physics models

- **Further investigation on Dark Matter candidates (further on neutralino, bosonic DM, mirror DM, inelastic DM, neutrino of 4th family, etc.):**

✓ **high exposure can better disentangle among the different astrophysical, nuclear and particle physics models (nature of the candidate, couplings, inelastic interaction, particle conversion processes, …, form factors, spin-factors and more on new scenarios)**

✓ **scaling laws and cross sections**

✓ **multi-component DM particles halo?**

+

- **Further investigation on astrophysical models:**

✓ **velocity and position distribution of DM particles in the galactic halo**

✓ **effects due to:**

i) satellite galaxies (as Sagittarius and Canis Major Dwarves) tidal "streams";

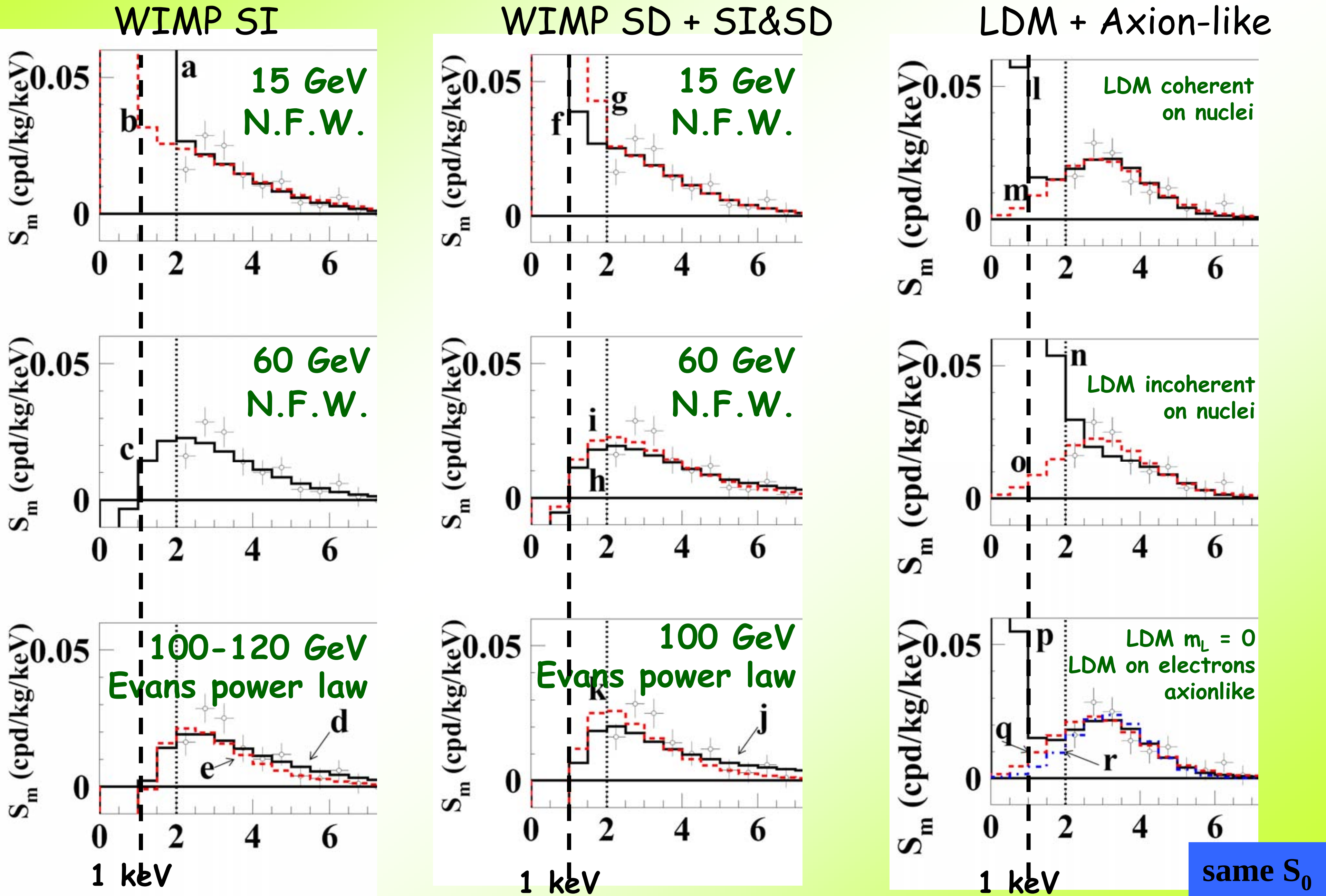
ii) caustics in the halo;

iii) gravitational focusing effect of the Sun enhancing the DM flow ("spike" and "skirt");

iv) possible structures as small scale size clumpiness;

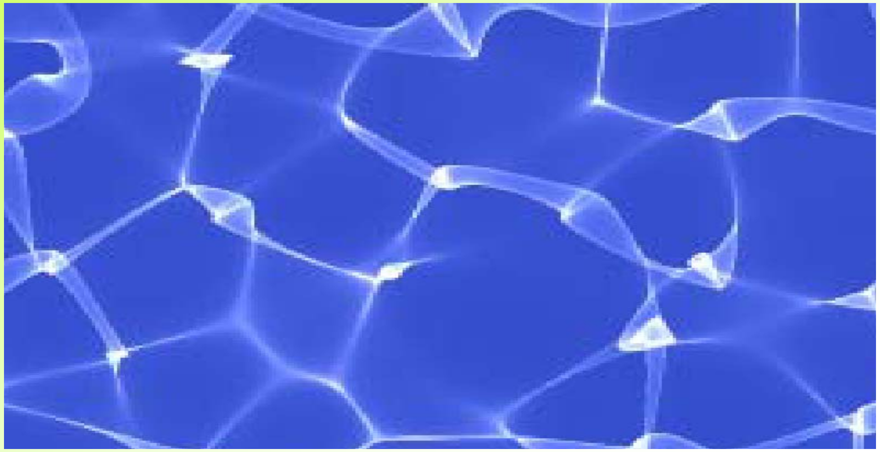
Also high sensitivities investigation on other rare processes: *possible PEP violating processes, various possible CNC processes in ^{23}Na and ^{127}I, nucleon and di-nucleon decay into invisible channels with new approach in ^{23}Na and ^{127}I, exotic particles (e.g. SIMPs, neutral nuclearities, Q-balls), 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.*

Some examples of the discrimination power of 1keV threshold on few of the many possible scenarios superimposed to the measured modulation amplitues $S_{m,k}$ *(EPJC56(2008)333)*



… other astrophysical scenarios?

Possible other (beyond SagDEG) non-thermalized component in the galactic halo?
In the galactic halo, fluxes of Dark Matter particles with dispersion velocity relatively low are expected :



Possible presence of caustic rings

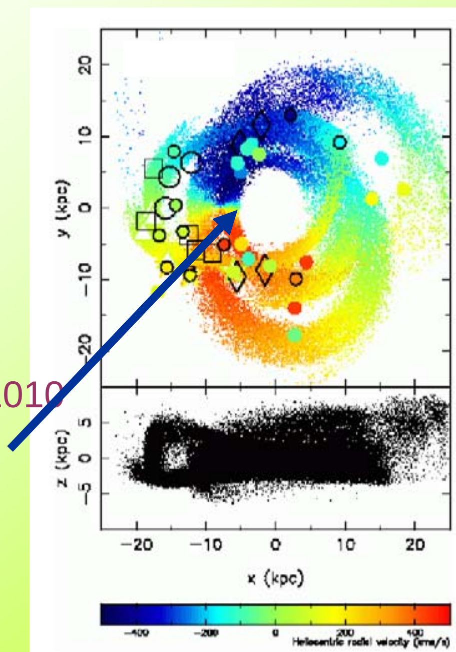
⇒ streams of Dark Matter particles

P. Sikivie, Fu-Sin Ling et al. astro-ph/0405231

Interesting scenarios for DAMA

Effect on $|S_m/S_o|$ respect to "usually" adopted halo models?

Effect on the phase of annual modulation signature?



Canis Major simulation:
astro-ph/0311010

Position of the Sun: (-8,0,0) kpc

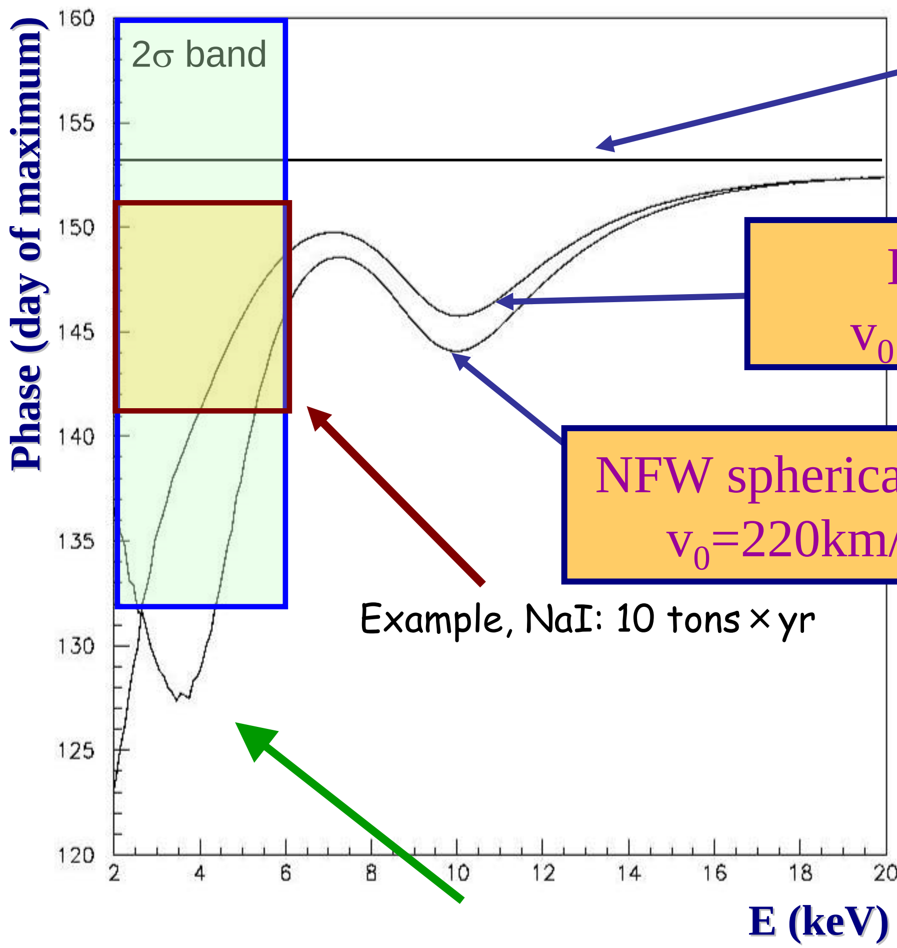
Other dark matter stream from satellite galaxy of Milky Way close to the Sun?

.....very likely....

Can be guess that spiral galaxies like Milky Way have been formed capturing close satellite galaxy as Sgr, Canis Major, etc…

An example of possible signature for the presence of streams in the Galactic halo

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



Expected phase in the absence of streams t_0 = 152.5 d (2nd June)

Evans'log axisymmetric non-rotating, v_0=220km/s, R_c= 5kpc, ρ_0 max + 4% Sgr

NFW spherical isotropic non-rotating, v_0=220km/s, ρ_0 max + 4% Sgr

High sensitivity will allow the further investigation of possible contribution of streams in the galactic halo

DAMA/NaI+DAMA/LIBRA results:

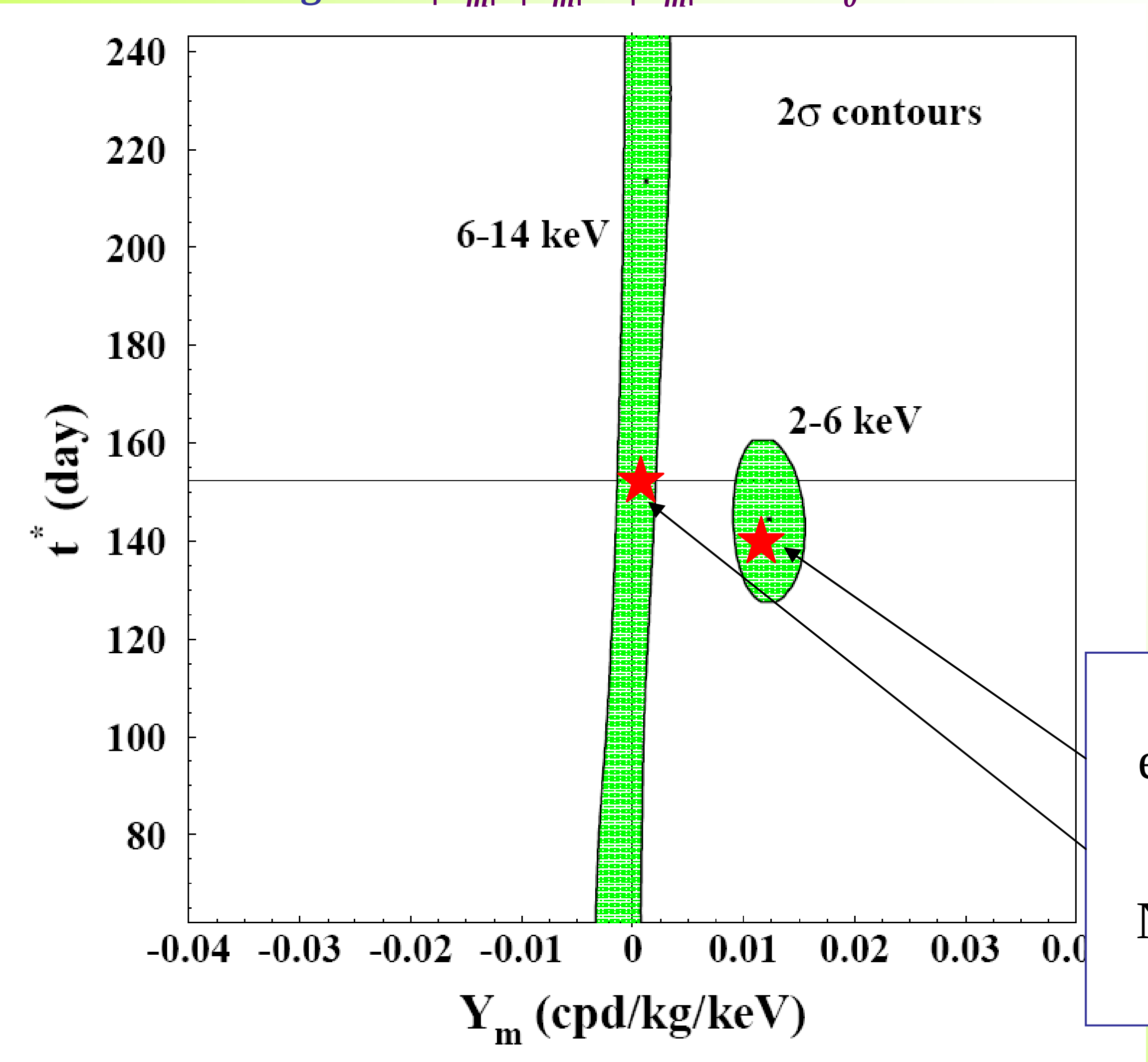
(2-6) keV **t_0 = (146±7) d**

Eur. Phys. J. C 47(2006) 263

Examples of the effect of SagDEG tail on the phase of the signal annual modulation

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

For Dark Matter signals: $|Z_m| \ll |S_m| \approx |Y_m|$ - $t^* \approx t_0 = 152.5d$



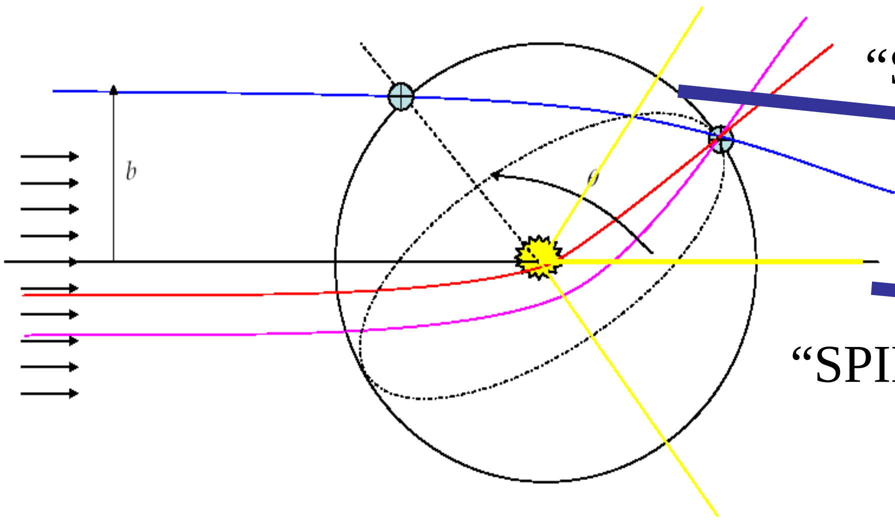
Slight differences from 2nd June are expected in case of contributions from non thermalized DM components (as e.g. the SagDEG stream)

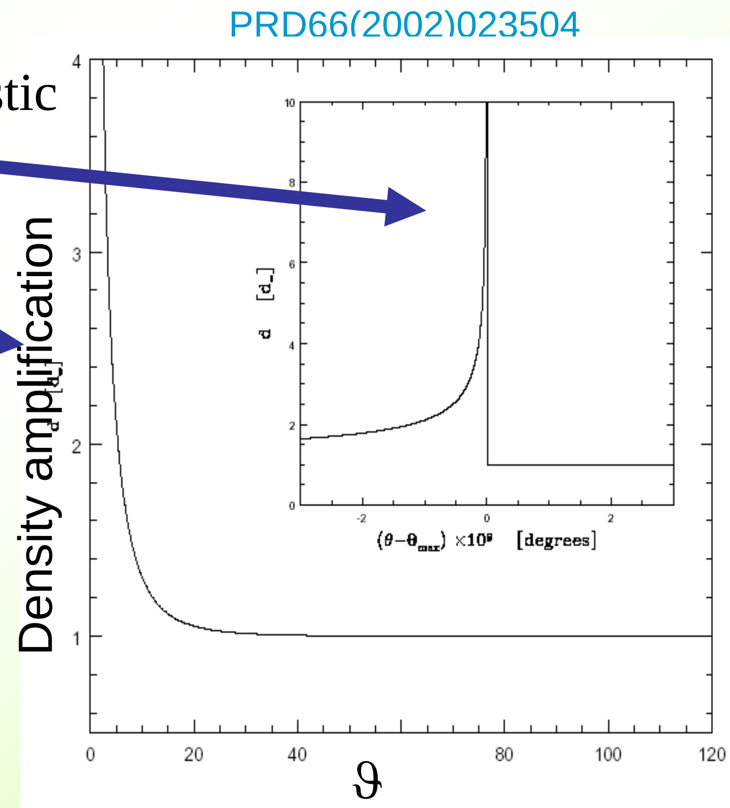
Examples of SagDEG expectations in the given energy bin

NFW, V0=220km/s ρ_0 max + 4% Sgr

Effect of Solar gravity for DM streams

The Sun gravity can focus the DM flux producing two type of enhancements in the density: “spike” collinear to the direction of incidence between DM flux and Sun, “skirt” divergence on a cone of angle θ max





The presence of SKIRT can be investigated by observing an increase in the counting rate in a time interval of 1 day

With large exposure and low energy threshold you can be sensitive to small fraction (10^{-3}-10^{-5}) of flow density with respect to the halo density

an example:

V_{flux} ~ 300 km/s ; σ_V ~70km/s

Earth orbit within 10° from “spike”

sensibility to ρ_{flux} > few % ρ_0

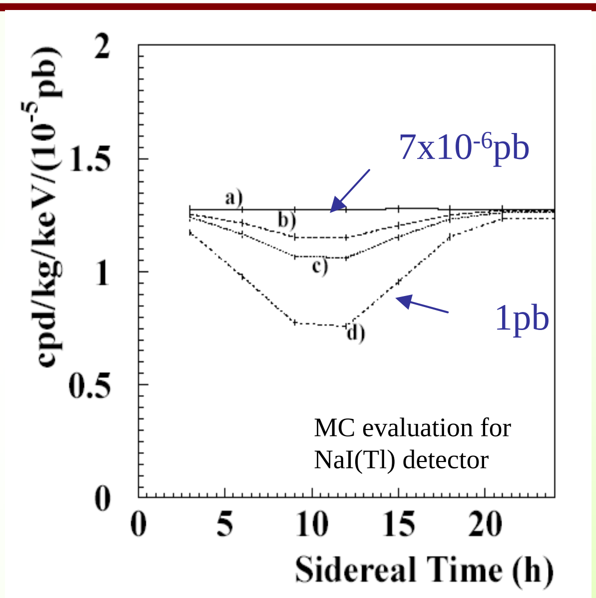
INVESTIGATION OF POSSIBLE DIURNAL EFFECTS

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

DIURNAL EFFECTS

daily effect on the sidereal time: high cross section DM candidates (shadow of the Earth)

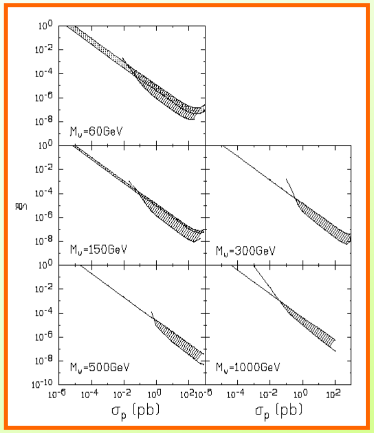
Daily variation of the interaction rate due to different Earth depth crossed by the DMp



Study on diurnal variation in the rate with suitable exposure and stability can allow to investigate:

high σ_p DMp component (with small ξ) in the dark halo and decouple ξ from σ_p

Investigation in DAMA/NaI-2 data (N.Cim. A112(1999)1541): 14962 kg d



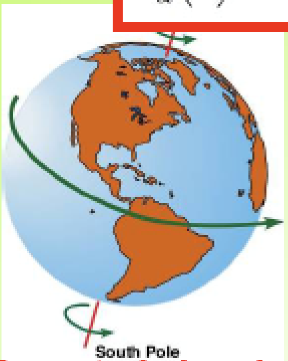
Limits on halo fraction (ξ) vs σ_p for SI case in the given scenario

DIURNAL EFFECTS

daily modulation on the sidereal time: due to the Earth rotation velocity contribution (wide range of DM candidates) Phys. Atom. Nucl. 72 (2009)2076

Velocity of the detector in the galactic frame:

$$v_d(t) = v_\odot + v_\oplus cos\gamma cos\omega(t-t_0) + v_{rot} cos\zeta sin\beta cos\Omega(t-t_d)$$



annual modulation term

diurnal modulation term

$v_{rot} \simeq 0.46$ km/s

$\beta \simeq 42^o$ angle beetwen the Earth axis and the DM flux

$\Omega = 2\pi/d_s$ $d_s = 1$ sideral day

t_d = phase depending on detector longitude

$\zeta \simeq 42.5^o$ LNGS latitude

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

$$S_k[\eta(t)] \simeq S_k[\eta_0] + [\frac{\partial S_k}{\partial \eta}]_{\eta_0} (\Delta\eta cos\omega(t-t_0) + \delta\eta cos\Omega(t-t_d))$$

$$\delta\eta = \frac{v_{rot} cos\zeta sin\beta}{v_0}$$

$$R_{dy} = \frac{\delta\eta}{\Delta\eta} = \frac{v_{rot} cos\zeta sin\beta}{v_\oplus cos\gamma} \simeq 0.015$$

The ratio of the diurnal modulation amplitude over the annual modulation amplitude is a fully model-independent constant

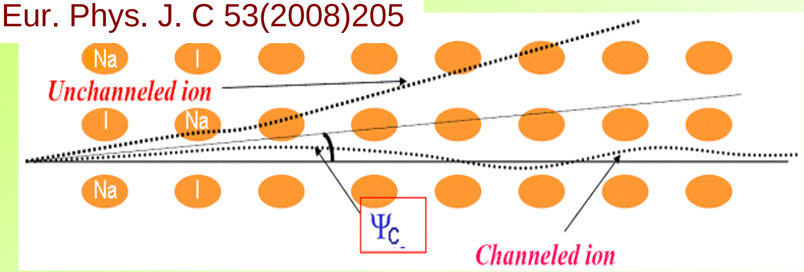
- **Considering the annual modulation amplitude observed in DAMA in the 2-6 keV energy interval, the expected diurnal modulation amplitude in the same energy interval requires larger exposure**

- **The decreasing of the energy threshold will also improve the experimental sensitivity to such an effect**

DIURNAL EFFECTS

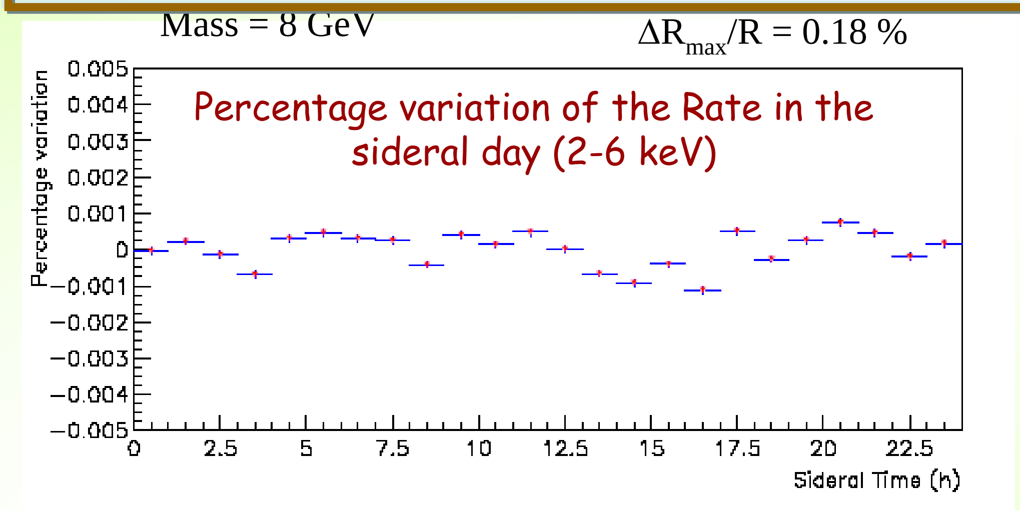
daily effect on the sidereal time: due to the channeling in case of DM candidates inducing just nuclear recoils.

Eur. Phys. J. C 53(2008)205

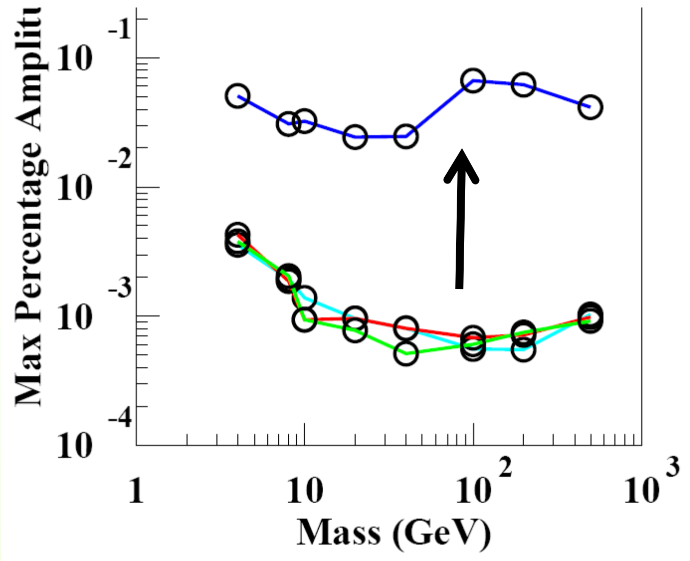


- **Due to the Earth daily rotation with respect to the Galactic Frame, the orientations of the crystallographic axes (c.a.) changes during sideral day**
- **The DM signal varies during the day depending on the orientation of the c.a.**

In case of those DM candidates, considering DAMA annual modulation result a rate not exceeding about 10^{-3} cpd/kg/keV can be expected in the 2-6 keV energy interval for various scenarios, but it can be larger in other cases



Few examples of maximum percentage within the sidereal day in (2-6 keV)



- **for some candidates and scenarios, this amplitude can be investigated in the 2-6 keV energy interval when a larger exposure will be available. Obviously, much better sensitivities are reachable if the energy threshold is decreased and/or in other cases: in particular for the Mirror DM candidates**

Conclusions

- Upgrade in fall 2010 substituting all the PMTs with new ones having higher Q.E. to lower the experimental energy threshold, improve general features and disentangle among at least some of the possible scenarios

- 20 PMTs ready

- Collect a very large exposure in the new running conditions

- Reaching extremely high C.L., very high precise determination of all the running parameters and S_m shape as a function of energy, etc.; investigating the many possible corollary scenarios and second order effects

(+ some R&Ds towards a possible 1 ton ULB NaI(Tl) set-up DAMA proposed in 1996 in light of a 100 ton highly radiopure NaI(Tl) set-up for high-resolution full-spectroscopy solar neutrinos (Astrop.Phys.4(1995)45) also carried out)