Sviluppo di scintillatori ad elevata radiopurezza per studi su Materia Oscura e processi rari

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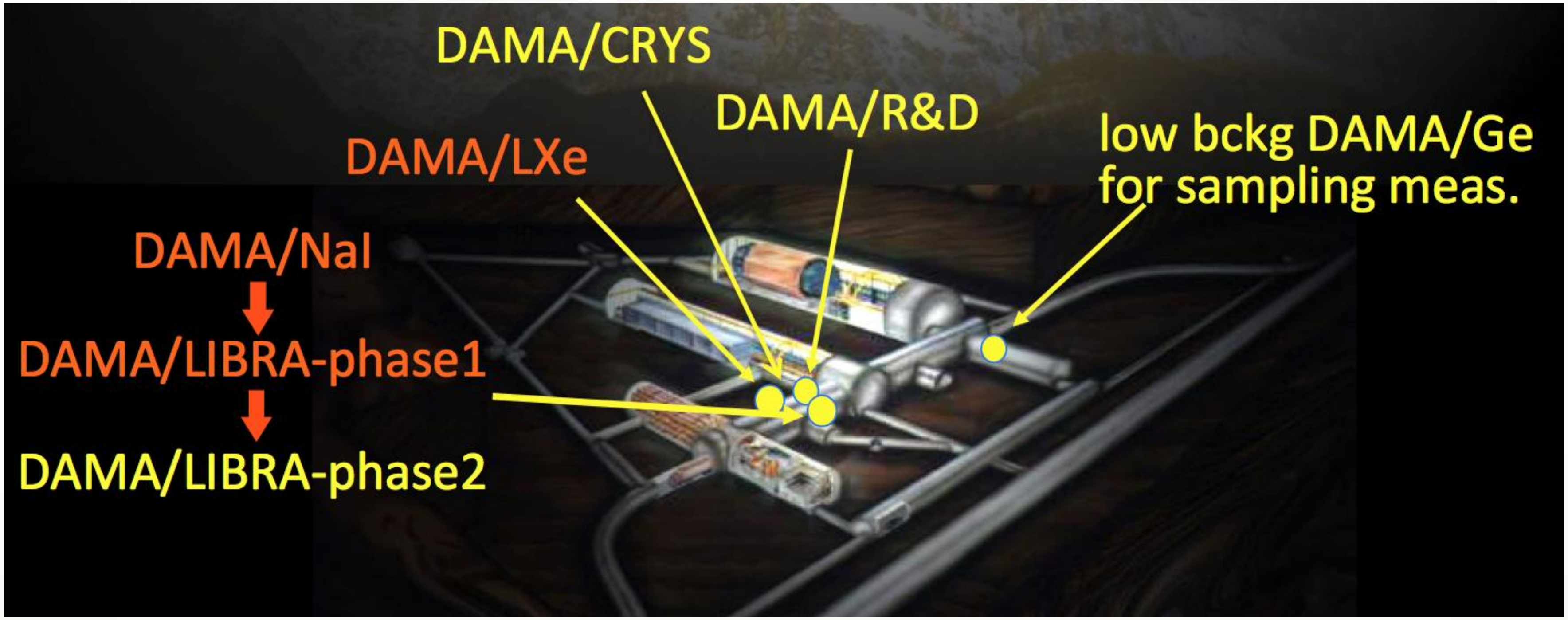
Univ. Roma La Sapienza
Jun 26, 2018

DAMA set-ups

an observatory for rare processes @ LNGS



Collaboration:

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

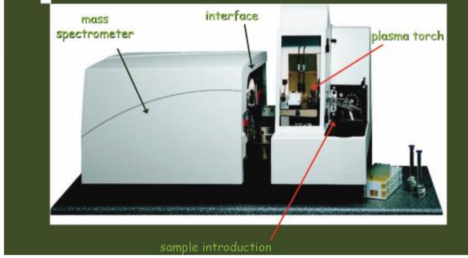
+ by-products and small scale expts.: INR-Kiev + other institutions

+ neutron meas.: ENEA-Frascati, ENEA-Casaccia

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

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

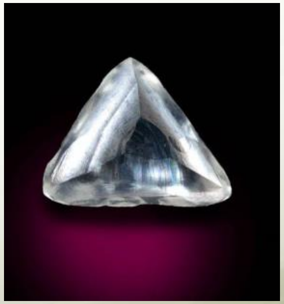
High radio-purity crystal scintillators



- Identification of materials sources
- All involved materials selection by:
  - Low background HPGe located deep underground
  - Mass and atomic spectrometry with high sensitivity
  - Neutron activation

- Devoted study of the presence of standard (U, Th, K) and non-standard contaminants
- Chemical/physical purification of the selected materials
- Selection of the more suitable growing process
- Additives selections
- Growing protocols
- Handling protocols
- Selection of the other materials (housing, optical grease, light guides, tools)
- Protocols for assembling, transport, storage, installation and maintenance in running conditions
- Prototypes tests deep underground

This kinds of development and measurements are themselves difficult experiments



NO

OK

Produce detectors for Physics and Astrophysics, but each one will have its own radio-purity + production differences....

Some of the crystal scintillators developed by DAMA

DAMA has developed and used many crystal scintillators to study several rare processes

	L.Y. % NaI(Tl)	τ (μs)	Rare Process	^{228}Th mBq/kg	^{226}Ra mBq/kg	^{227}Ac mBq/kg	^{40}K mBq/kg	α mBq/kg	Other Cont.
NaI(Tl)	100	0.23	DM, several rare processes	0.002	0.009		<0.6	0.08	
$ZnWO_4$	15	24	DM, $\beta\beta$ of ^{64}Zn, ^{70}Zn, ^{180}W, ^{186}W	0.002	0.002	<0.003	<0.02	0.2	^{65}Zn
$CdWO_4$	40	14	$\beta\beta$ of ^{106}Cd, ^{108}Cd, ^{114}Cd, ^{116}Cd	0.004	0.004	<0.002	0.3	0.3	^{113}Cd
LiF(W)	4	40	^{7}Li Solar axions	<0.6	<3.3		<5.1		
LiI(Eu)	35	1.4	^{7}Li Solar axions	<0.4	<1.1		<365		
$LaCl_3$(Ce)	120	0.026	Cluster decay, ^{139}La CNC decay	<0.4	<40	1800			^{138}La
$CeCl_3$	70	0.023 (70%)	$\beta\beta$ of ^{136}Ce, ^{138}Ce, ^{142}Ce	<0.16	<11	284			^{138}La
CeF_3	10	0.005, 0.027	$\beta\beta$ of ^{136}Ce, ^{138}Ce, ^{142}Ce	1000	<60	<20	<330	3400	
BaF_2	25	0.0006, 0.63	$\beta\beta$ of ^{130}Ba	400	1400				
CaF_2(Eu)	60	0.94	β,$\beta\beta$ of ^{48}Ca, α ^{151}Eu	0.13	1.3	0.011	5	8	^{152}Eu
SrI_2(Eu)	200-300	0.6, 2.4	$\beta\beta$ of ^{84}Sr, DM	6	100		<200		^{152}Eu

Main sources of radioactive contamination:

- naturally occurring radionuclides: ^{232}Th, ^{238}U, ^{235}U families and ^{40}K
- anthropogenic ^{60}Co, ^{90}Sr-^{90}Y, ^{137}Cs nuclides
- radioactive isotopes of the crystal elements, as e.g. ^{113}Cd in $CdWO_4$, ^{138}La in $LaCl_3$
- cosmogenic radionuclides as e.g. ^{65}Zn in $ZnWO_4$, ^{152}Eu in CaF_2(Eu), ^{113m}Cd in $CdWO_4$

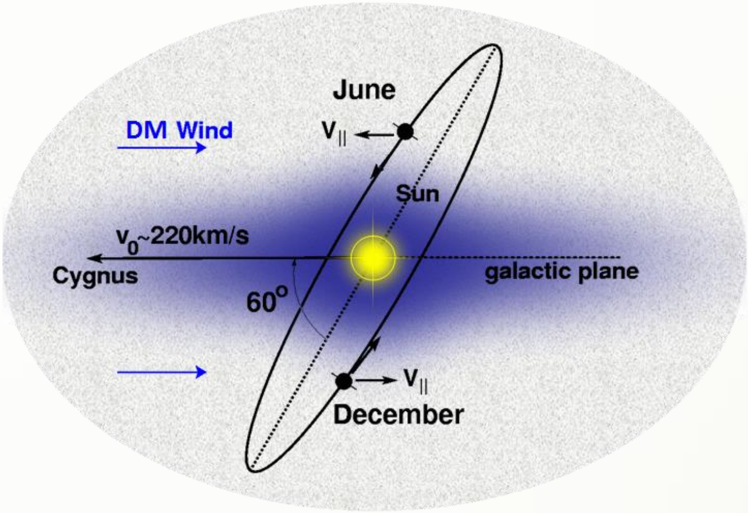
The highest sensitivity to measure internal contamination of crystal scintillators can be achieved in low background measurements where a scintillator is operating as a detector

- Time-amplitude analysis
- Pulse-shape discrimination
- Energy spectra analysis

Signatures for direct DM investigation

They are correlated with the Earth motion in the Dark Matter halo:

- *Annual modulation effect due to Earth revolution*
- *Diurnal modulation (second order) effect due to Earth rotation*

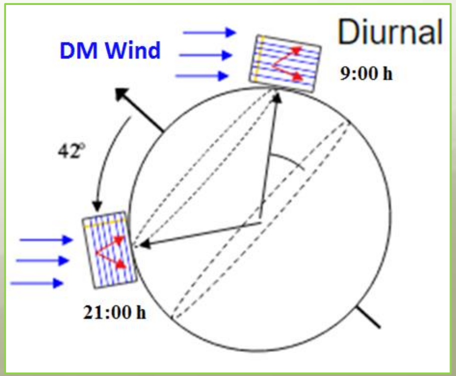


For these effects, the expected signature:

- *has to satisfy many requirements;*
- *with time varying periodic behavior;*
- *with peculiar period and phase;*
- *and avoids the large uncertainties associated to data selections, subtractions and statistical discrimination procedures which affect other approaches*

Other approaches correlated with the Earth motion in the Dark Matter halo, but valid only for some DM candidates are:

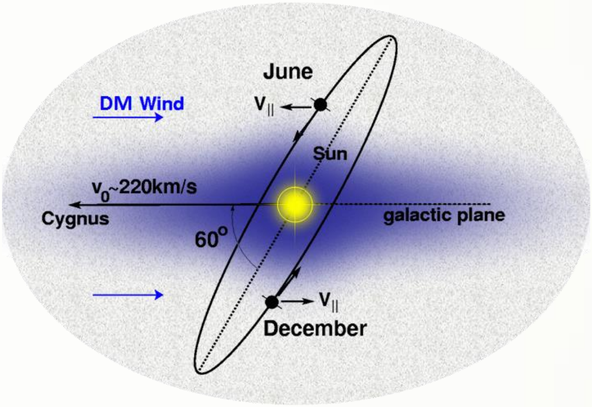
- *Shadow effect*
- *Directionality*



Velocity of a detector in a terrestrial laboratory

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

$\vec{v}_{LSR}$	Velocity of the Local Standard of Rest (LSR) due to Galaxy rotation
$\vec{v}_{\odot}$	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 @ lab (lat, lng)



The ***Sun velocity***, $\vec{v}_S$, in the *Galactic Coordinate system* is:

$$\vec{v}_{LSR} = (0, v_0, 0) \qquad (v_0 = 220 \pm 50 \text{ km/s})$$

$$\vec{v}_{\odot} = (9, 12, 7) \text{ km/s}$$

$$\Rightarrow \quad \vec{v}_S = \vec{v}_{LSR} + \vec{v}_{\odot} = (9, 232, 7) \text{ km/s}$$

The ***Earth revolution velocity*** in the *Ecliptic plane* $(\hat{e}_1^{ecl}, \hat{e}_2^{ecl})$ is:

$$\vec{v}_{rev}(t) = V_{Earth}\left(\hat{e}_1^{ecl} \sin\lambda(t) - \hat{e}_2^{ecl} \cos\lambda(t)\right)$$

$$\lambda(t) = \omega(t - t_{equinox}); \quad \omega = \frac{2\pi}{T}; \quad T\text{=1}y$$

$(V_{Earth} \approx 29.8$ km/s; $\;t_{equinox} \approx$ March 21)

The ***Earth rotation velocity*** in the *Equatorial plane* $(\hat{e}_1^{ecs}, \hat{e}_2^{ecs})$ is:

$$\vec{v}_{rot}(t) = -V_r(\hat{e}_1^{ecs} \sin\delta(t) - \hat{e}_2^{ecs} \cos\delta(t))$$

$$\delta(t) = \omega_{rot} t; \quad \omega_{rot} = \frac{2\pi}{T_d}; \quad T_d = 1 \text{ sidereal day}$$

(Here t is the local sidereal time, LST)

In *Galactic Coordinate System*:

$$\begin{cases} \hat{e}_1^{ecl} = (-0.05487, 0.49411, -0.86767) \\ \hat{e}_2^{ecl} = (-0.99382, -0.11100, -0.00035) \\ \hat{e}_3^{ecl} = (-0.09648, 0.86228, 0.49715) \end{cases}$$

$$\hat{e}_3^{ecl} \cdot (0, 0, 1) = 0.49715.$$

$\Rightarrow$ **60°** inclination w.r.t. galactic plane

$$\begin{cases} \hat{e}_1^{ecs} = (-0.05487, 0.49411, -0.86767) \\ \hat{e}_2^{ecs} = (-0.87344, -0.44483, -0.19808) \\ \hat{e}_3^{ecs} = (-0.48384, 0.74698, 0.45599) \end{cases}$$

@ LNGS $\;(\phi_0 = 42°27'\text{N}; \;\lambda_0 = 13°34'\text{E})$

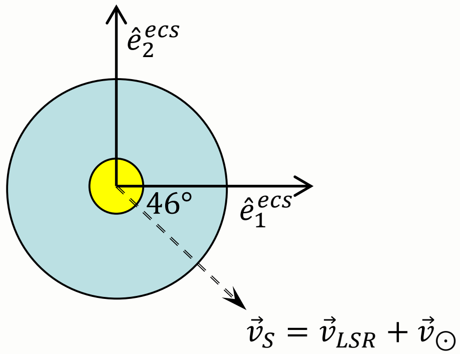
$V_r = V_{eq} \cos\phi_0 = 0.3435$ km/s

$(V_{eq} = 0.4655$ km/s$)$

Sun velocity in the Equatorial coordinate system …

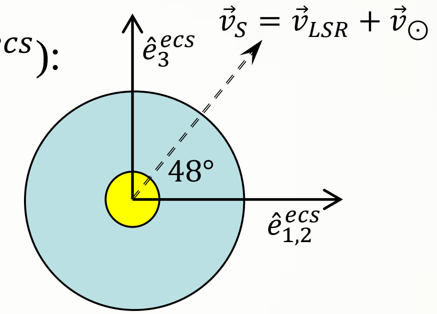
On equatorial plane:

$\hat{e}_1^{ecs} \cdot \vec{v}_S = 108.1$ km/s
$\hat{e}_2^{ecs} \cdot \vec{v}_S = -112.4$ km/s
$\Rightarrow \varphi = -46°$
$\Rightarrow$ t = 20.92 h (LST)



Angle w.r.t. North pole ($\hat{e}_3^{ecs}$):

$\hat{e}_3^{ecs} \cdot \vec{v}_S = 172.1$ km/s
$\Rightarrow \theta = 42°$
$\Rightarrow$ Lat = 48°



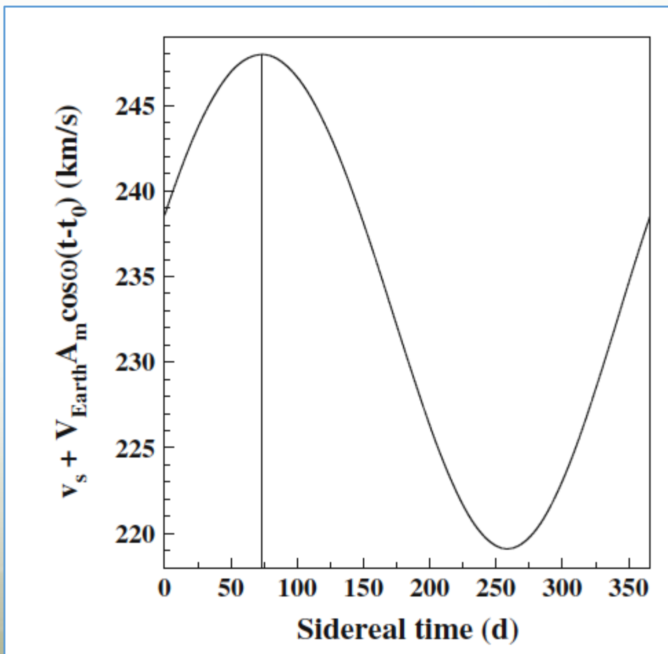
$$v_{lab}(t) \simeq v_S + \hat{v}_S \cdot \vec{v}_{rev}(t) + \hat{v}_S \cdot \vec{v}_{rot}(t)$$

… and annual modulation term

Based on DM flux annual variation due to Earth Revolution

$$\hat{v}_S \cdot \vec{v}_{rev}(t) = V_{Earth}\left(\hat{v}_S \cdot \hat{e}_1^{ecl} \sin\lambda(t) - \hat{v}_S \cdot \hat{e}_2^{ecl} \cos\lambda(t)\right) =$$
$$= V_{Earth} A_m \cos[\omega(t - t_0)]$$

$A_m \approx 0.489;$
$t_0 = t_{equinox} + 73.25$ solar days
([71.8, 74.2] d when varying v_0 in [170,270] km/s)



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 is about 73 days after the spring equinox.

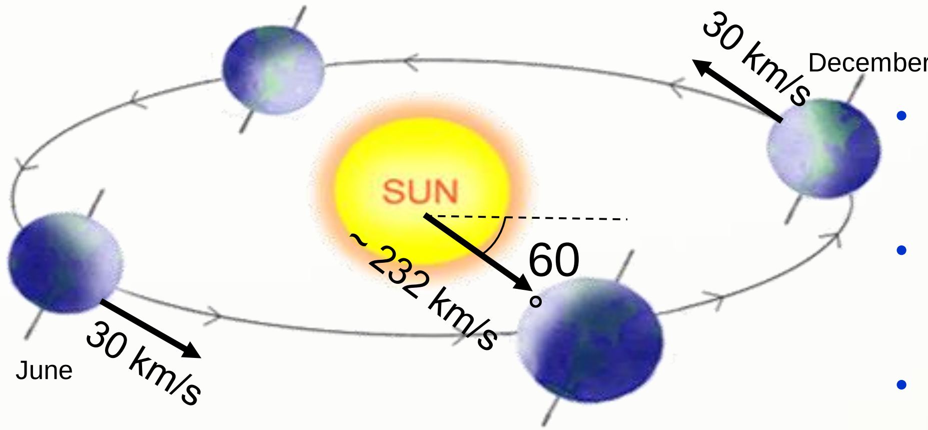
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

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.

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

Requirements:

1) Modulated rate according cosine
2) In 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



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

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

- 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 at maximum)

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

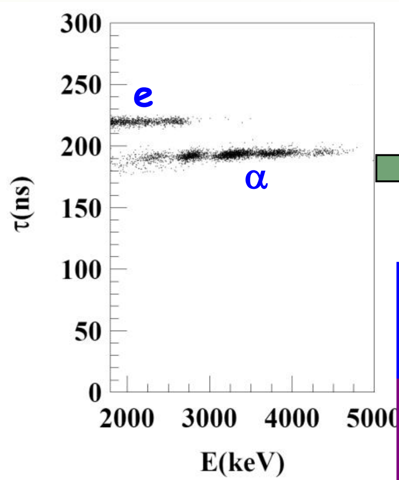
To mimic this signature, spurious effects and side reactions must not only be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

The relevance of ULB NaI(Tl) as target-material

- 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, ...)
- NaI(Tl) λ of the scintillation light well directly match PMTs sensitivity
- Uniform response in the realized detectors
- High light response (5.5-7.5 ph.e./keV phase1 and 6-10 ph.e./keV in phase2)
- Effective routine calibrations feasible down to keV in the same conditions as production runs
- No microphonic noise and noise rejection at threshold (τ of NaI(Tl) pulses >> τ of noise pulses)
- Sensitive to many candidates, interactions and astrophysical, nuclear and particle physics scenarios
- Sensitive to both high (I target) and low mass (Na target) DM and to DM inducing e.m. radiation
- Effective investigation of the annual modulation signature feasible in all the needed aspects
- Fragmented set-up

ULB NaI(Tl) also allows the study of several rare processes

Some on residual contaminants in new ULB NaI(Tl) detectors

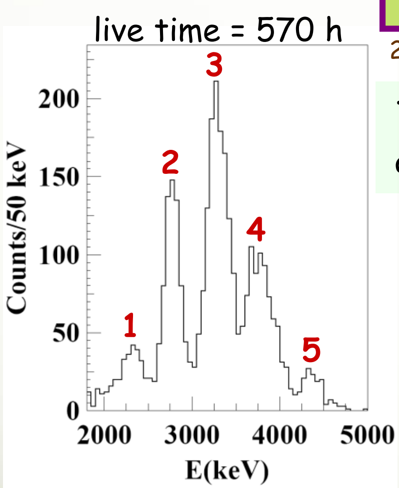


α/e pulse shape discrimination has practically 100% effectiveness in the MeV range

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	From time-amplitude method. If ^{232}Th chain at equilibrium: it ranges 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

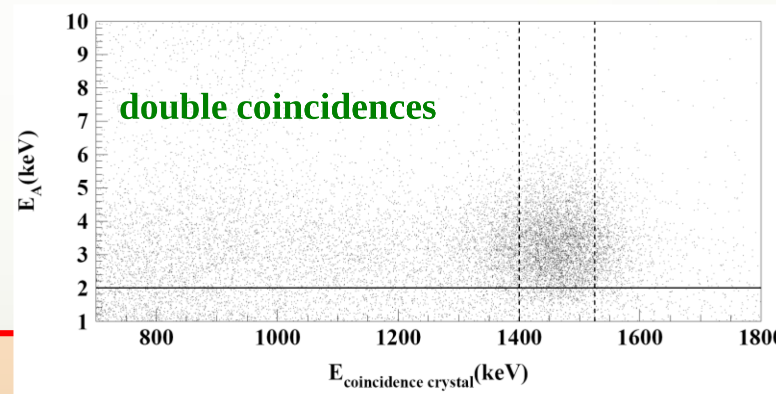


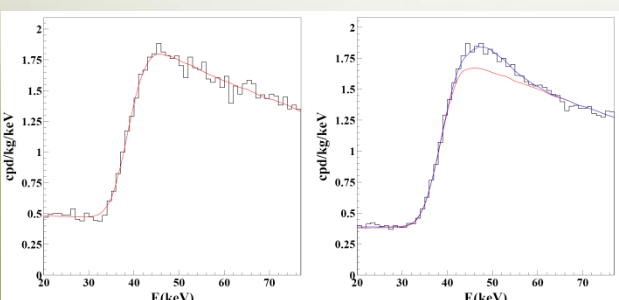
^{238}U chain split into 5 subchains: $^{238}U \rightarrow {}^{234}U \rightarrow {}^{230}Th \rightarrow {}^{226}Ra \rightarrow {}^{210}Pb \rightarrow {}^{206}Pb$

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; (21.7±1.1) μBq/kg for ^{226}Ra; (24.2±1.6) μBq/kg for ^{210}Pb.

^{40}K residual contamination

The analysis has given for the ^{40}K content in the crystals values not exceeding 2.4 ppt (<0.6 mBq/kg)





^{129}I and ^{210}Pb

$^{129}I/^{nat}I \approx 1.7\times10^{-13}$ for all the new detectors

^{210}Pb in the new detectors: (5 – 30) μBq/kg

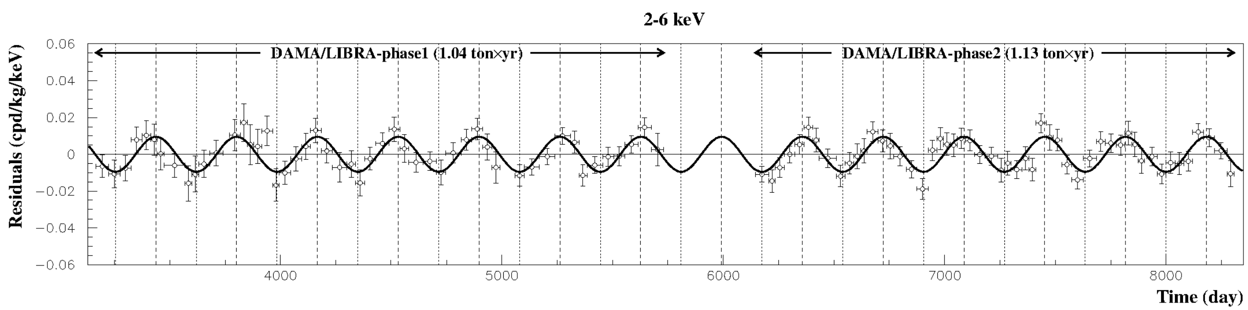
No sizable surface pollution by Radon daughters, thanks to the new handling protocols

... more on NIMA592(2008)297

Model Independent Annual Modulation Result

DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2 (2.17 ton×yr) https://arxiv.org/abs/1805.10486

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



2-6 keV

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

A=(0.0095±0.0008) cpd/kg/keV

χ^2/dof = 71.8/101 11.9 σ C.L.

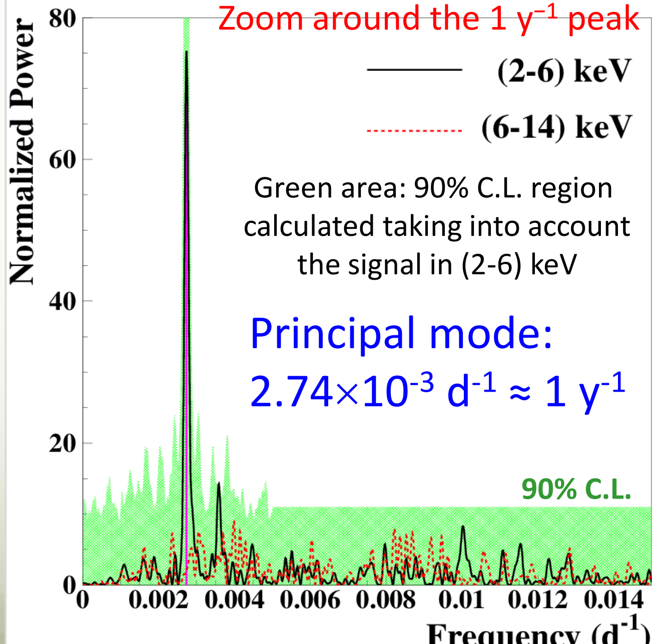
Absence of modulation? No

χ^2/dof=199.3/102 P(A=0) = 2.9×10^{-8}

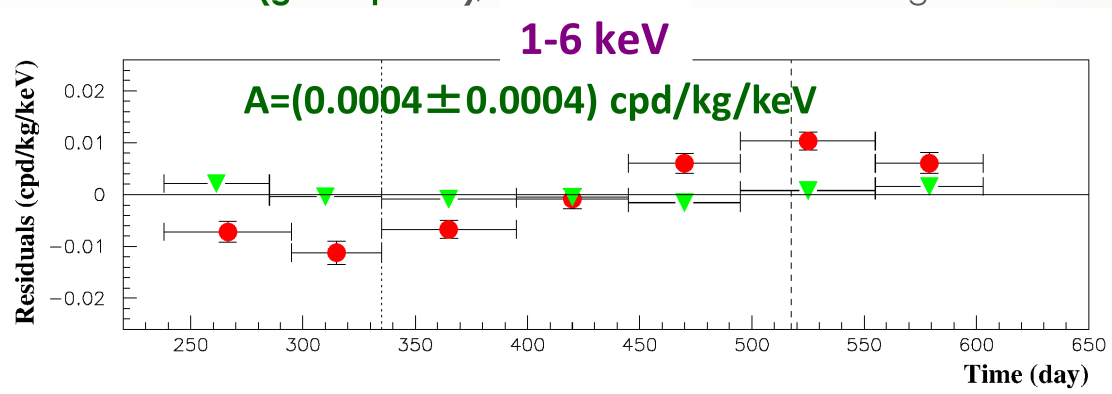
Fit with all the parameters free:

A = (0.0096 ± 0.0008) cpd/kg/keV

t_0 = (145±5)d - T = (0.9987±0.0008)y



Comparison between **single hit residual rate (red points)** and **multiple hit residual rate (green points)**; Clear modulation in the single hit events;



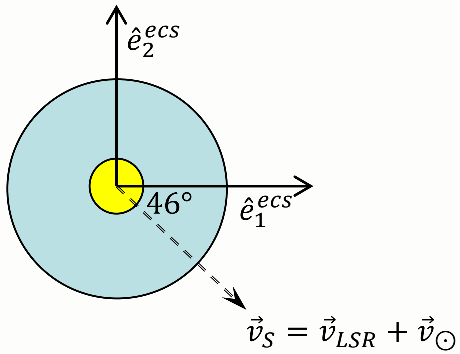
This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

The data favour the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at high C.L.

Sun velocity in the Equatorial coordinate system …

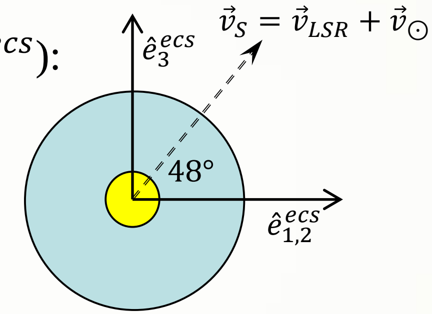
On equatorial plane:

$\hat{e}_1^{ecs} \cdot \vec{v}_S = 108.1$ km/s
$\hat{e}_2^{ecs} \cdot \vec{v}_S = -112.4$ km/s
$\Rightarrow \varphi = -46°$
$\Rightarrow$ t = 20.92 h (LST)



Angle w.r.t. North pole ($\hat{e}_3^{ecs}$):

$\hat{e}_3^{ecs} \cdot \vec{v}_S = 172.1$ km/s
$\Rightarrow \theta = 42°$
$\Rightarrow$ Lat = 48°



$$\boxed{v_{lab}(t) \simeq v_S + \hat{v}_S \cdot \vec{v}_{rev}(t) + \hat{v}_S \cdot \vec{v}_{rot}(t)}$$

… and diurnal modulation term

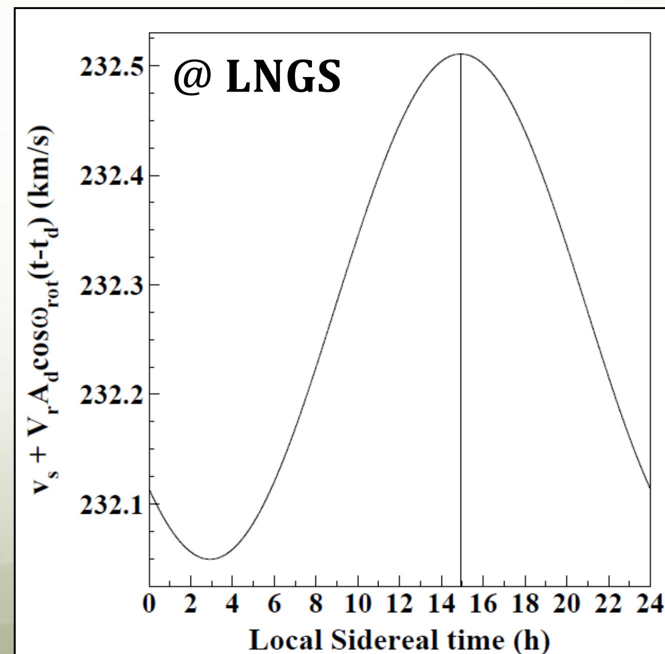
Based on DM flux annual variation due to Earth Rotation

$$\hat{v}_S \cdot \vec{v}_{rot}(t) = -V_r(\hat{v}_S \cdot \hat{e}_1^{ecs} \sin\delta(t) - \hat{v}_S \cdot \hat{e}_2^{ecs} \cos\delta(t)) =$$
$$= V_r A_d \cos[\omega_{rot}(t - t_d)]$$

$A_d \approx 0.671$;
$t_d = 14.92$ h LST
([14.84, 14.97] h when varying v_0 in [170,270] km/s)

$v_S + \hat{v}_S \cdot \vec{v}_{rot}(t)$ vs LST at LNGS

Maximum is about at 15 h LST



N.B.: The expected signal counting rate in a given k−th energy bin:

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

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

$$R_{dy} = \frac{S_d}{S_m} = \frac{V_r A_d}{V_{Earth} A_m} \simeq 0.016 \text{ at LNGS latitude}$$

Diurnal effects in DAMA/LIBRA-phase1

EPJC 74 (2014) 2827

- Observed annual modulation amplitude in DAMA/LIBRA–phase1 in (2–6) keV region: (0.0097 ± 0.0013) cpd/kg/keV
- Thus, the expected value of the diurnal modulation amplitude is $\simeq 1.5 \times 10^{-4}$ cpd/kg/keV.

Experimental *single-hit* residuals rate vs either sidereal and solar time

Test of null hypothesis ⇒
no diurnal variation with a significance of 95% CL

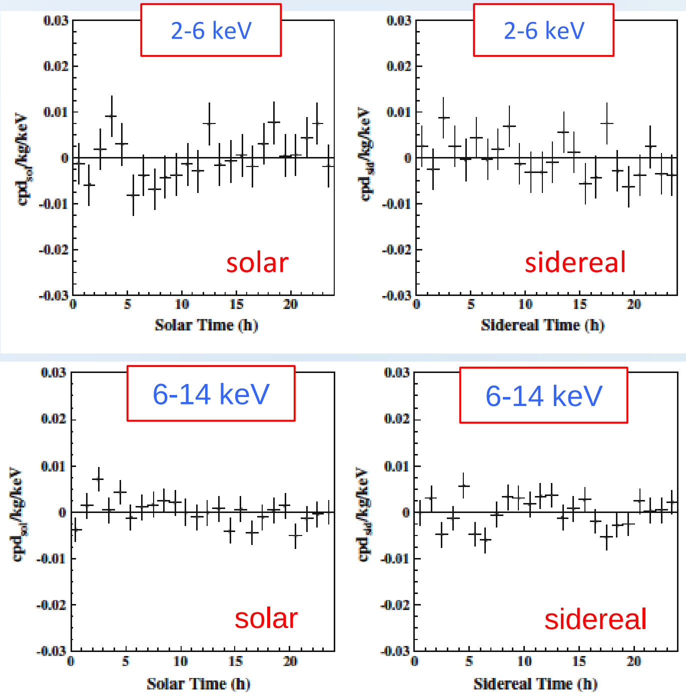
Energy	Solar Time	Sidereal Time
2–4 keV	χ^2/d.o.f. = 35.2/24 → P = 7%	χ^2/d.o.f. = 28.7/24 → P = 23%
2–5 keV	χ^2/d.o.f. = 35.5/24 → P = 6%	χ^2/d.o.f. = 24.0/24 → P = 46%
2–6 keV	χ^2/d.o.f. = 25.8/24 → P = 36%	χ^2/d.o.f. = 21.2/24 → P = 63%
6–14 keV	χ^2/d.o.f. = 25.5/24 → P = 38%	χ^2/d.o.f. = 35.9/24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

When fitting with a cosine function with T=24 h and t_d=15 h LST:
⇒ all the diurnal modulation amplitudes A_d 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 (2-6 keV) < 1.2×10^{-3} cpd/kg/keV (90%CL)

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



(here Sidereal Time = GMST)

Present experimental sensitivity is not enough for the expected diurnal modulation amplitude derived from the DAMA/LIBRA–phase1 observed effect

Larger exposure DAMA/LIBRA–ph2 (+lower energy threshold) offers increased sensitivity to such an effect

Sun velocity in the Equatorial coordinate system …

On equatorial plane:

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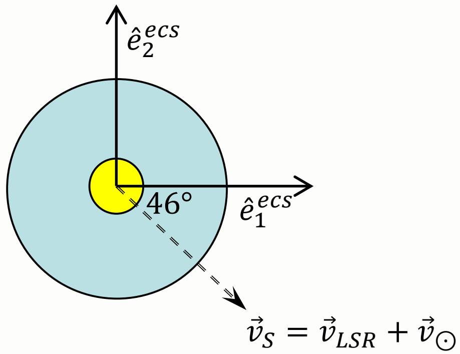

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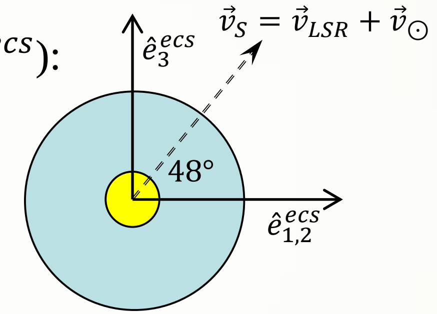
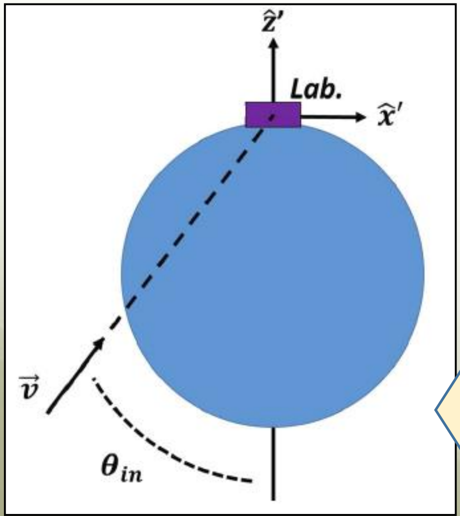
$\Rightarrow \ \theta = 42°$
$\Rightarrow$ Lat = 48°



… and shadow effect

Based on diurnal variation of apparent DM wind arrival direction

During a sidereal day the Earth shields a terrestrial detector with a varying thickness and this induces a variation of the flux of the DM candidates impinging the detector



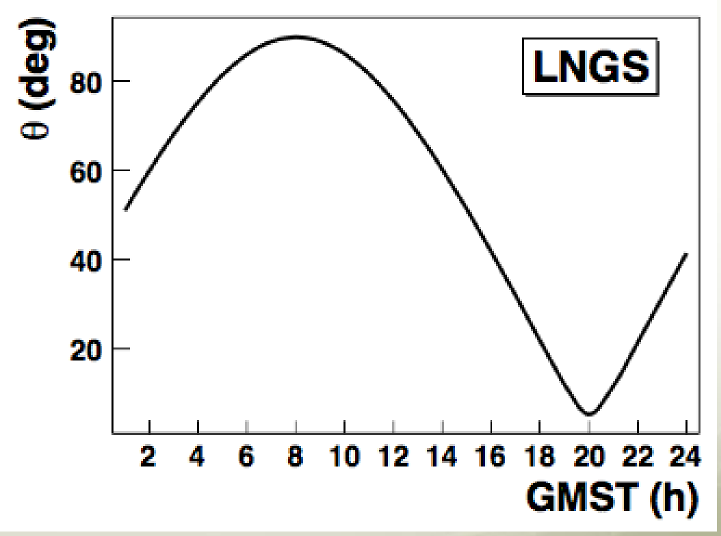
It depends on the **θ** angle: the "zenith distance" of $\vec{v}_{lab}(t)$

$\cos\theta = \hat{r}_{lab}(t) \cdot \hat{v}_{lab}(t)$

The thickness crossed before reaching a laboratory depends on the particle impinging angle θ_{in}

$\langle\theta_{in}\rangle = \pi - \langle\theta\rangle$

LNGS: ϕ_0 = **42°27′N**; λ_0 = **13°34′E**;
LST ~ GST + 0.904 h



The Earth shielding is Max at ~ 9:00 h LST and Min at ~ 21:00 h LST

Earth Shadow Effect with DAMA/LIBRA–phase1

- **Earth Shadow Effect** expected for DM candidate particles inducing nuclear recoils
- Only for candidates with **high cross-section** with ordinary matter (low DM local density)
- DM particles crossing Earth lose their energy and the distribution observed in the laboratory frame depends on time (**LST 9:00 black**; **LST 21:00 red**)

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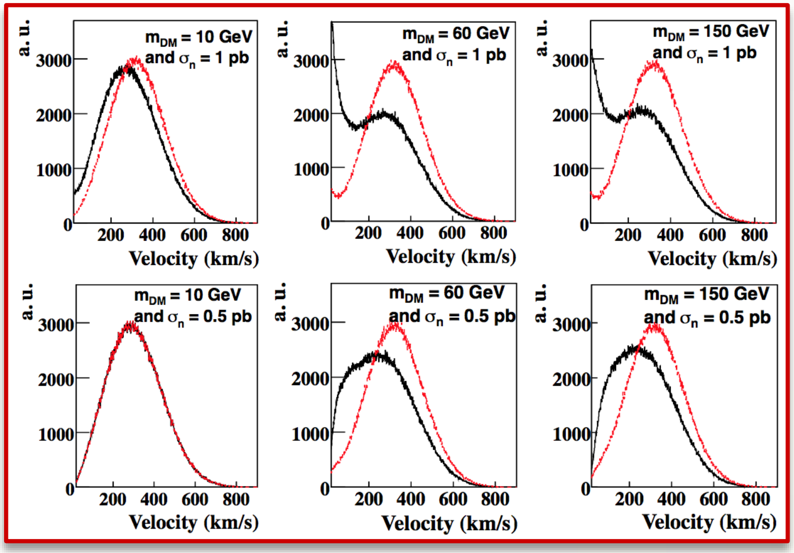
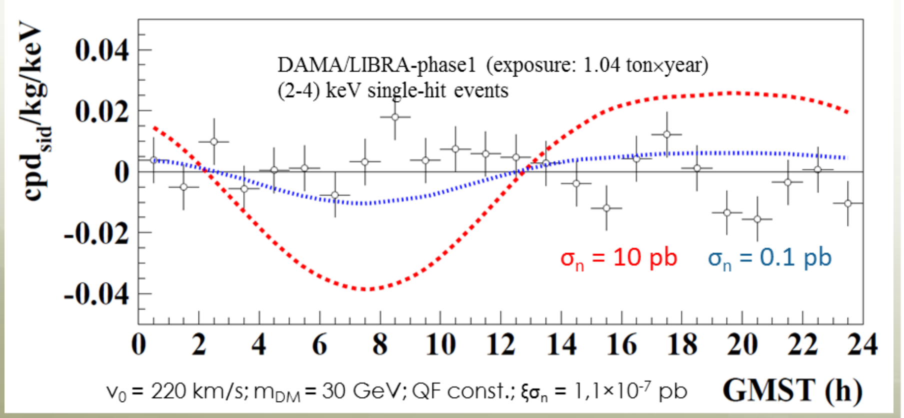


Expected counting rate for a given mass, cross section and scenario by MC:

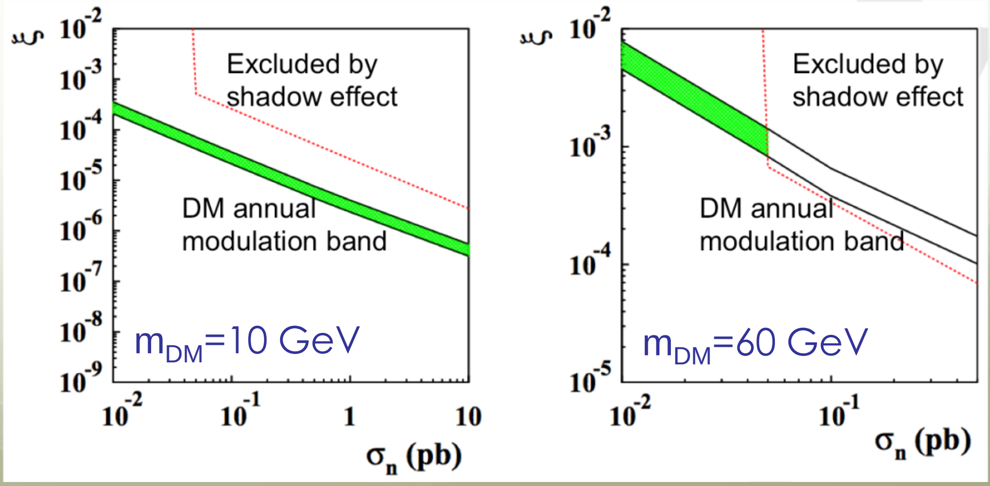
$$S_{d,sh}(t) = \xi\sigma_n \, S'_{d,sh}(t)$$

Expectations compared with diurnal residual rate of *single-hit* events of DAMA/LIBRA-phase1 in (2-4) keV

Minimizing χ^2, upper limits on ξ (relative abundance) can be evaluated



Constrain (red line) on DAMA/LIBRA DM annual modulation result from Earth Shadow Effect in the ξ vs σ_n plane for the considered model framework



Sun velocity in the Equatorial coordinate system …

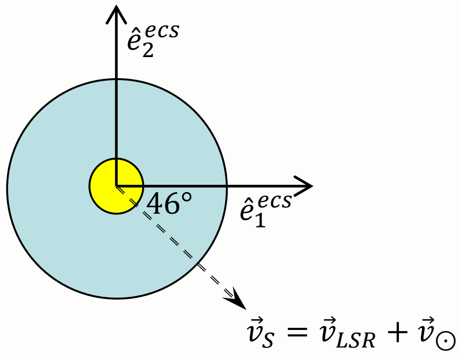
On equatorial plane:

$\hat{e}_1^{ecs} \cdot \vec{v}_S = 108.1$ km/s

$\hat{e}_2^{ecs} \cdot \vec{v}_S = -112.4$ km/s

$\Rightarrow \varphi = -46°$

$\Rightarrow$ t = 20.92 h (LST)

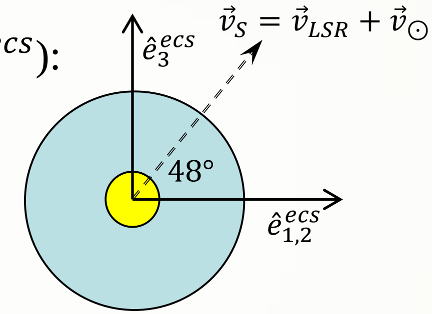


Angle w.r.t. North pole ($\hat{e}_3^{ecs}$):

$\hat{e}_3^{ecs} \cdot \vec{v}_S = 172.1$ km/s

$\Rightarrow \theta = 42°$

$\Rightarrow$ Lat $= 48°$



… and directionality

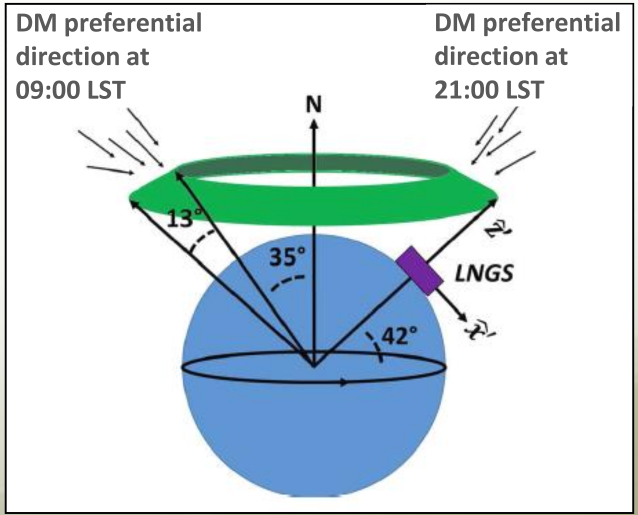
Based on diurnal variation of apparent DM wind arrival direction

Study of the correlation between the arrival direction of Dark Matter candidates inducing nuclear recoils and the Earth motion in the galactic frame

The direction of the induced nuclear recoil is strongly correlated with that of the impinging DM particle

The observation of an anisotropy in the distribution of nuclear recoil direction could give evidence for such candidates

direction-sensitive detector



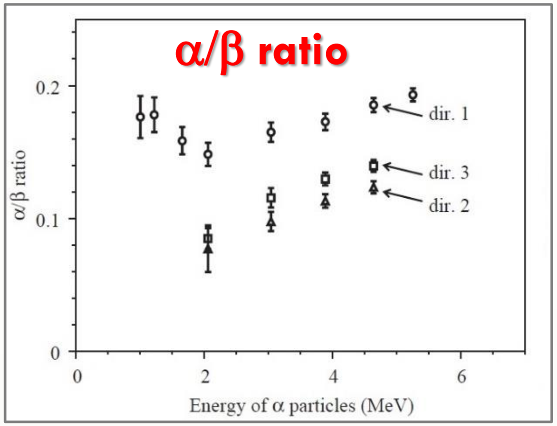
Directionality with anisotropic scintillators

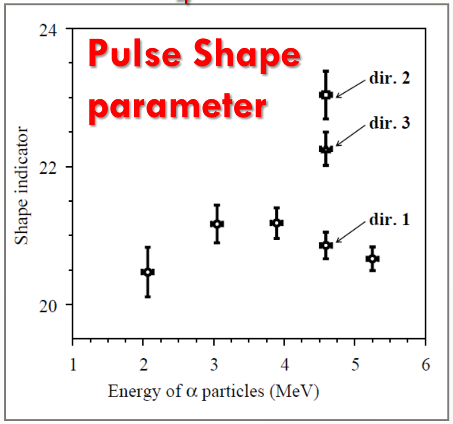
Firstly proposed in [P. Belli et al., Il Nuovo Cim. C 15 (1992) 475; R. Bernabei et al., EPJC28(2003)203]

Anisotropic Scintillator:

- for heavy particles *light output* and *pulse shape* depends on the particle impinging direction with respect to the crystal axes
- for γ/e *light output* and *pulse shape* are isotropic

α Particles in $ZnWO_4$

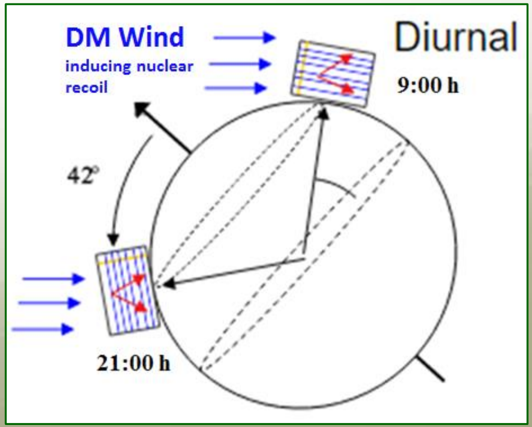




The variation of the response of an **anisotropic scintillator** during sidereal day can allow to point out the presence of a DM signal due to candidate inducing nuclear recoils

$ZnWO_4$ anisotropic scintillator: a very promising detector [EPJC73(2013)2276]

- ✓ Very good anisotropic features
- ✓ High level of radiopurity
- ✓ High light output, that is low energy threshold feasible
- ✓ High stability in the running conditions
- ✓ Sensitivity to small and large mass DM candidate particles
- ✓ Detectors with ~ kg masses



Radiopurity of the $ZnWO_4$ crystal scintillator

The measured radioactive contamination of $ZnWO_4$ approaches that of specially developed low background NaI(Tl)

- ~ 0.5 ppt for ^{232}Th
- ~ 0.2 ppt for ^{238}U
- < 0.02 mBq/kg for ^{40}K (0.6 ppb ^{nat}K)
- total α activity of 0.18 mBq/kg

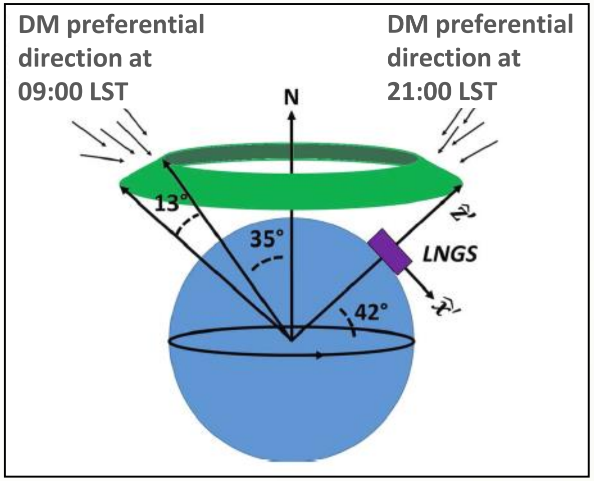
Improving radiopurity of $ZnWO_4$ crystal

- screening of zinc oxide to avoid cosmogenic ^{65}Zn
- protocol for the purification of the initial **zinc** (vacuum distillation and filtering) and **tungsten** (electron beam zone melting)
- low-thermal gradient Czochralski technique in a platinum crucible (very good results in producing large size crystals with high radiopurity levels)
- Segregation of radioactive elements (U, Th, Ra, K) expected (very similar compound to $CdWO_4$); recrystallization could further improve radiopurity level of $ZnWO_4$
- Detectors cut and assembled just after the growth of the crystalline bulk in a glove-box in controlled atmosphere.
- Selection of tools and abrasives for cutting and polishing the crystals

Example of expected signal

It is very convenient to consider an experiment performed at the LNGS latitude (**42°27′N**)

$\Rightarrow$ at 21:00 h LST the DM particles come mainly from the top, and 12 h later from the North and parallel to the horizon line

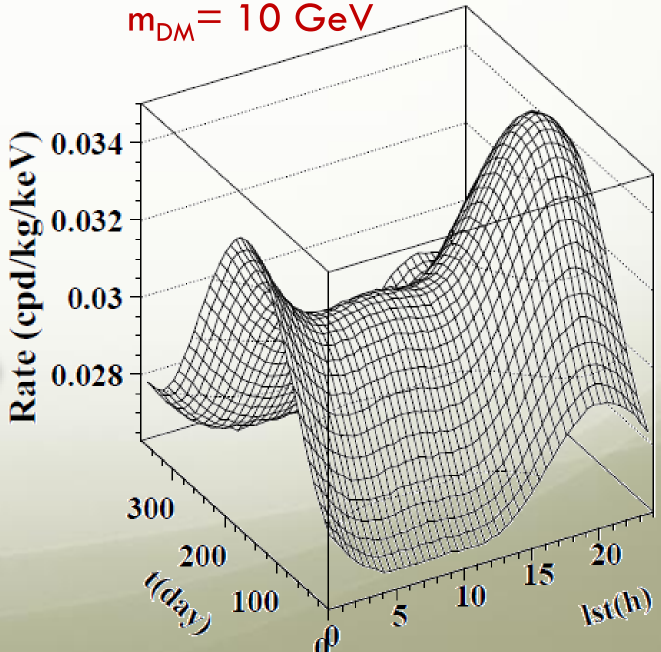


If we arrange the $ZnWO_4$ crystal axis so that:

- ➢ The one with the largest light output is vertical and
- ➢ the one with the smallest light output points north

$\Rightarrow$ range of variability of the anisotropic detector response during a sidereal day is at maximum)

[2-3] keV
$\sigma_p = 5\times10^{-5}$ pb
m_{DM}= 10 GeV



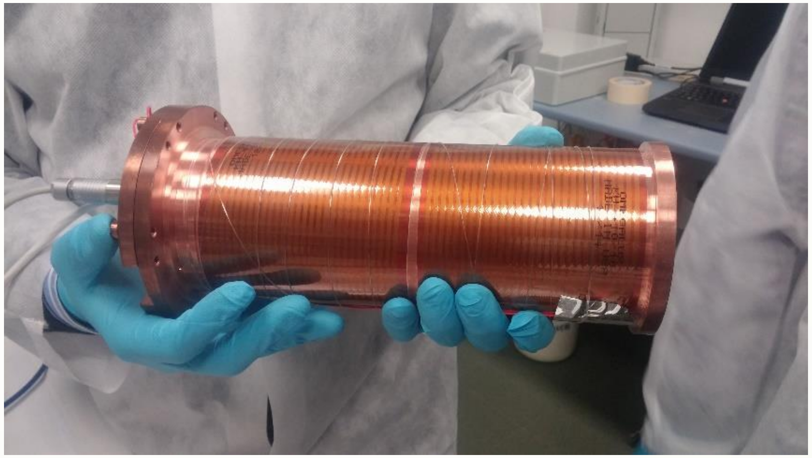
The diurnal effect refer to the sidereal day and not to the solar day

Absolute maximum rate is at day 152 and at 21h LST (when the DM flux is at maximum and the DM preferential arrival direction is near the zenith)

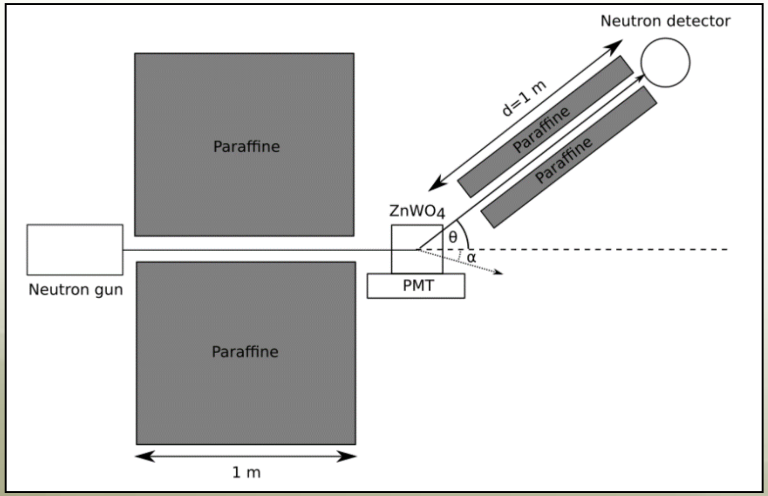
TEST: Identical sets of crystals placed in the same set-up with different axis orientation will observe consistently different time evolution of the rate

$ZnWO_4$ – work in progress…

- Cryostat for low temperature measurement with scintillation detectors realized



- Test of the Cryostat in progress
- Lowering the energy threshold (new PMT with higher QE, SiPM, APD, SDD, …)



- Measurements of anisotropy at low energy with MP320 Neutron Generator (E_n = 14 MeV) at ENEA-Casaccia lab
- Development of electronics

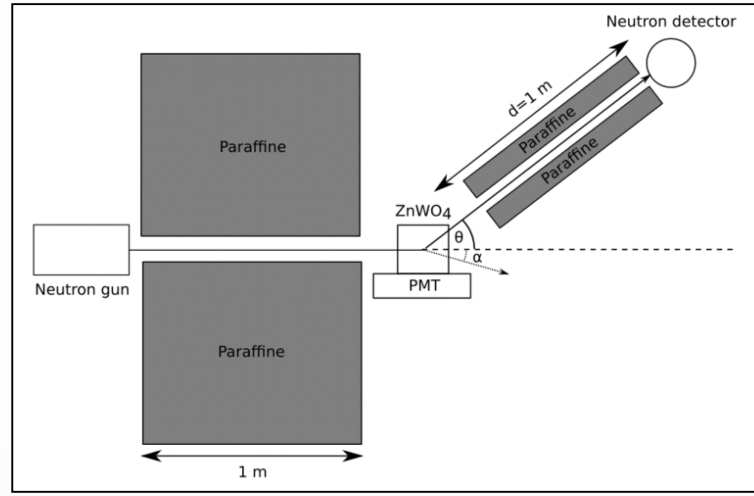
First measurement of anisotropy for low energy nuclear recoils in $ZnWO_4$

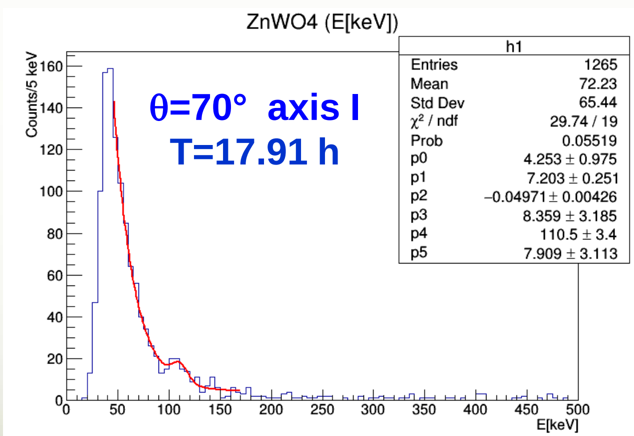
Preliminary
work in progress…

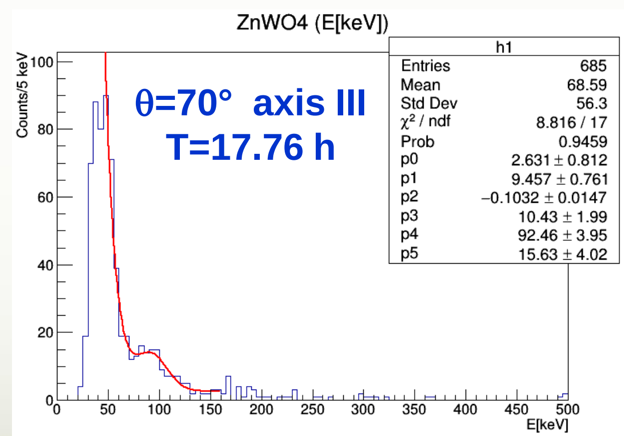
MP320 Neutron Generator ($E_n = 14$ MeV)
@ ENEA-Casaccia lab ($D + T \rightarrow n + {}^4He$)

Scattering angle of neutron [deg]: 70.0000

Nucl.	Target mass [GeV]	Erecoil [keV]	α lab. target
Zn	60.9	281.4	54.6
W	171.2	100.7	54.9
O	14.9	1115.7	53.3







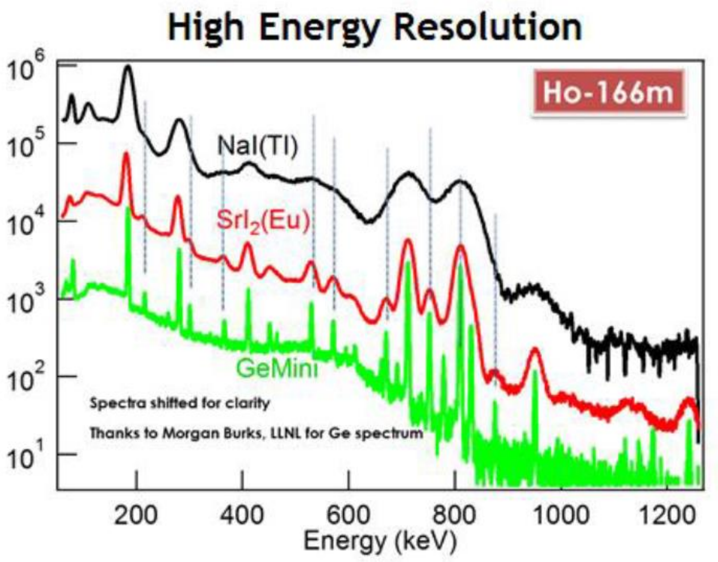
Angle	Axis	E_{peak} (keVee)	$E_{recoil,O}$ (keV)	Q	Q_I / Q_{III}
70	I	110.5±3.4	1116	0.099±0.003	1.20±0.06
70	III	92.5±3.9	1116	0.083±0.003	

Very high light output scintillators for rare processes: $SrI_2(Eu)$ and CaI_2

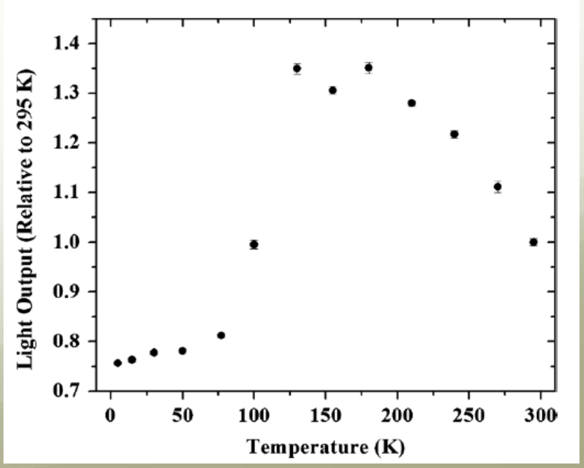
- Alkali earth metal iodide with very high light output:
  - 90000-120000 ph/Mev for $SrI_2(Eu)$
  - 110000 ph/Mev for CaI_2
- Energy threshold @ keV level feasible;
- Very good energy resolution: 3% @ 662 keV;
- No intrinsic long lifetime radioactivity;

⇒ Interesting detectors for searches on rare processes:
  - Dark Matter;
  - ββ decay (^{84}Sr, ^{48}Ca) with active-source technique

The development of $SrI_2(Eu)$ scintillator (studied by DAMA in [NIM A670 (2012) 10]) is also the subject of my INFN-Grant



… and improved features at low temperature for $SrI_2(Eu)$



… more about CaI_2

- Recent realizations of CaI_2 seems to have solved some trouble in crystal growth and degrade of its quality and performances (because of its high hygroscopy and of the presence of strong cleavage along the [001] plane) [Ceram. Int. 43 (2017) S423]
- CaI_2 not doped with Eu (no problem with cosmogenic ^{152}Eu)

Conclusions

DAMA is an observatory for rare processes, developing and using highly radiopure scintillators

Many crystal scintillators have been developed in the past years (NaI(Tl), $ZnWO_4$, $CdWO_4$, LiF(W), LiI(Eu), $LaCl_3$(Ce), CeF_3, BaF_2, $CeCl_3$, CaF_2(Eu), SrI_2(Eu), etc.), others will be soon explored

Personally, I will work on a project (INFN-Grant) for the development of SrI_2(Eu) scintillator

The DAMA strategy in the study of Dark Matter is based on the search for a signal that can be clearly distinguished from the unavoidable experimental background

Different opportunities are provided from the study on the correlation between the DM signal and the Earth motion in the DM halo:

- Annual modulation effect
- Diurnal modulation effect
- Shadow effect
- Directionality

The advantage of this strategy is avoiding the large uncertainties associated to data selections, subtractions or to statistical discrimination procedures which affect other approaches