Rivelazione diretta di Dark Matter con gli esperimenti DAMA, prospettive per DAMA/LIBRA-fase3 e sviluppi di SABRE

Retreat Fisica Particelle Elementari
Assisi – 17 Giugno 2019

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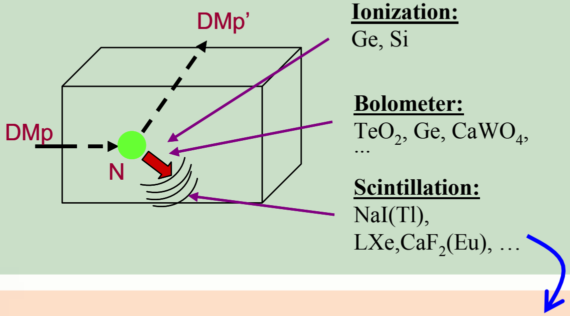
Some direct detection processes:

- 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

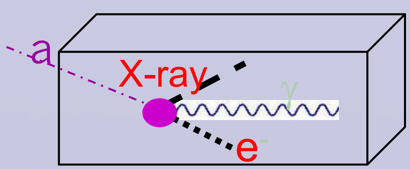
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

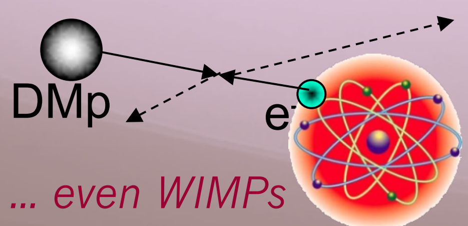
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

  → detection of e.m. radiation

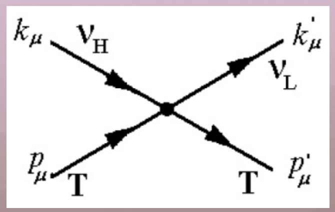


… even WIMPs

- 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



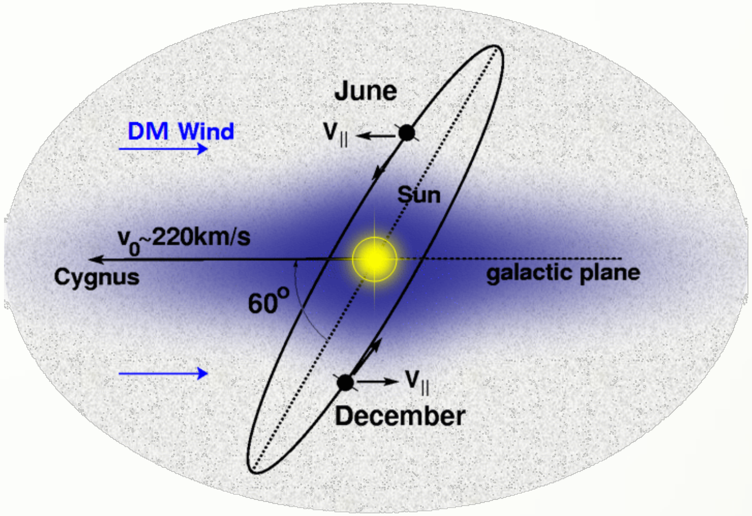
e.g. signals from these candidates are **completely lost** in experiments based on "rejection procedures" of the e.m. component of their rate

… also other ideas …

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*

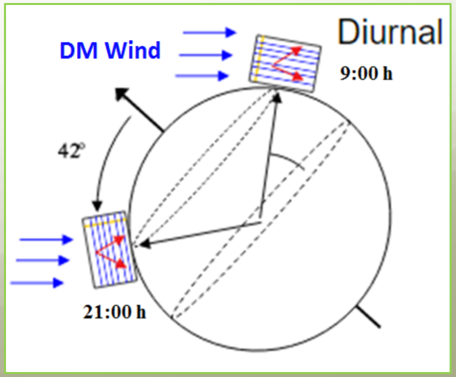


For these effects, the expected signature:

- *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*

Effects correlated with the Earth motion in the Dark Matter halo, but valid only for some DM candidates (i.e. model dependent) are:

- *Shadow effect*
- *Directionality*

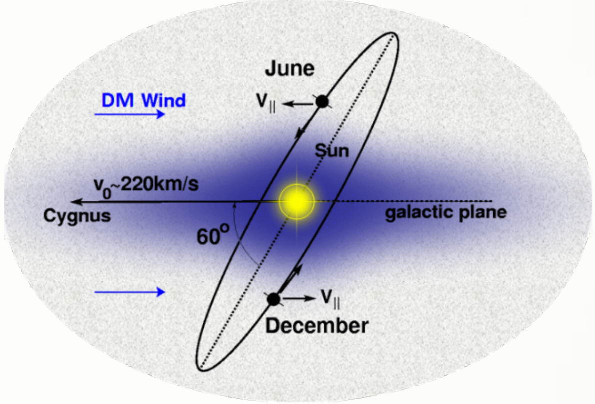


Velocity of a detector in a terrestrial laboratory

EPJC 74 (2014) 2827

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

$\vec{v}_{LSR}$	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:

$$\vec{v}_{rev}(t) = V_{Earth}\left(\hat{e}_1^{ecl} \sin\lambda(t) - \hat{e}_2^{ecl} \cos\lambda(t)\right)$$
$$\lambda(t) = \omega(t - t_{equinox}); \quad \omega = \frac{2\pi}{T}; \quad T=1y$$
$$(V_{Earth} \approx 29.8 \text{ km/s}; \quad t_{equinox} \approx \text{March 21})$$

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 $(\phi_0 = 42°27'N; \ \lambda_0 = 13°34'E)$

$$V_r = V_{eq} \cos\phi_0 = 0.3435 \text{ km/s}$$
$$(V_{eq} = 0.4655 \text{ km/s})$$

Annual and diurnal modulation term

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

$$\hat{v}_S \cdot \vec{v}_{rev}(t) = V_{Earth} A_m \cos[\omega(t - t_0)]$$

$A_m \approx 0.489$;

$t_0 = t_{equinox} + 73.25$ solar days

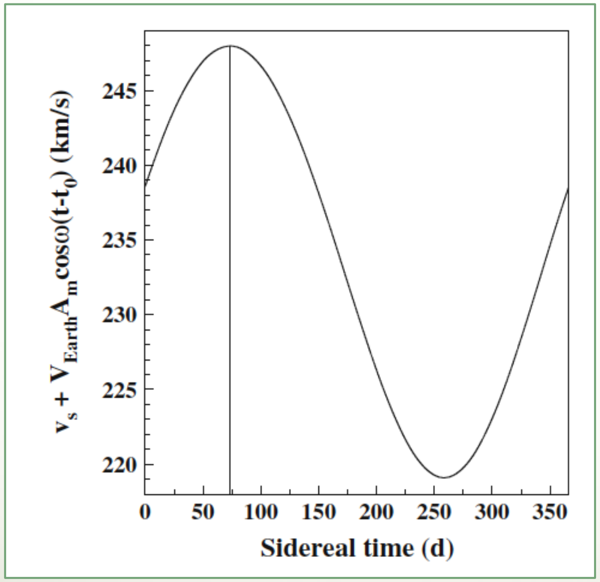
([71.8, 74.2] d when varying v_0 in [170,270] km/s)

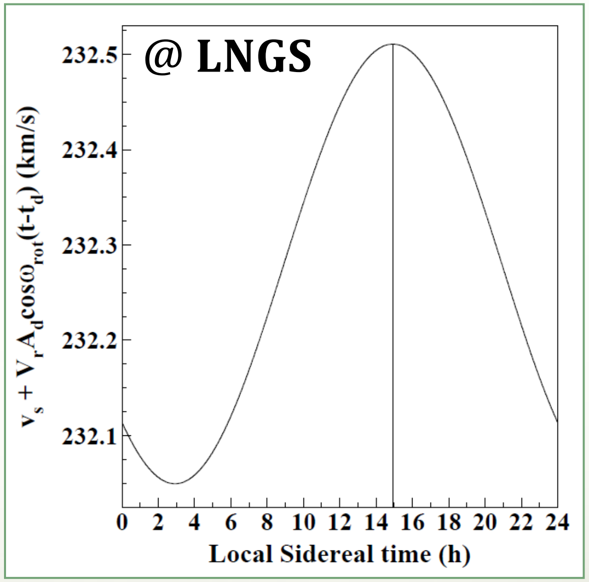
$$\hat{v}_S \cdot \vec{v}_{rot}(t) = V_r A_d \cos[\omega_{rot}(t - t_d)]$$

$A_d \approx 0.671$;

$t_d = 14.92$ h LST

([14.84, 14.97] h when varying v_0 in [170,270] km/s)





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

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

⇒ **The ratio R_{dy} is a model independent constant:** $R_{dy} = \frac{S_d}{S_m} = \frac{V_r A_d}{V_{Earth} A_m} \simeq 0.016$ **at LNGS latitude**

All the diurnal effects are based on sidereal time

- *Diurnal modulation effect due to Earth rotation*
- *Shadow effect*
- *Directionality*

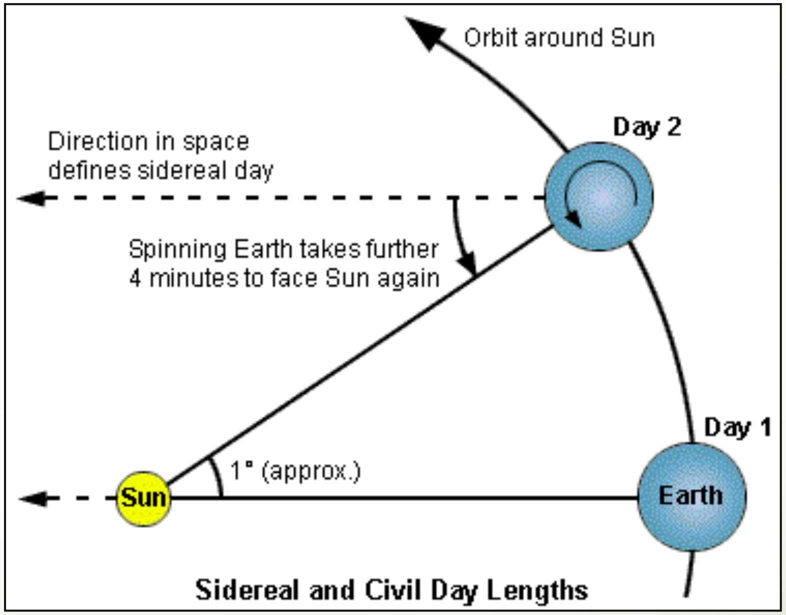
All effects with different phases but the same period:

T = 1 sidereal day

1 solar day ≅ 1.00274 sidereal days

(365.25 solar days ≅ 366.25 sidereal days)

Local sidereal time is 00:00 when the vernal equinox crosses the local meridian



⇒ Side effects related to ***solar* time**, even if with a similar phase, could not have any role in the interpretation of a possible signal

⇒ They would be completely blown away by taking an average of the data uniformly collected for 1 year

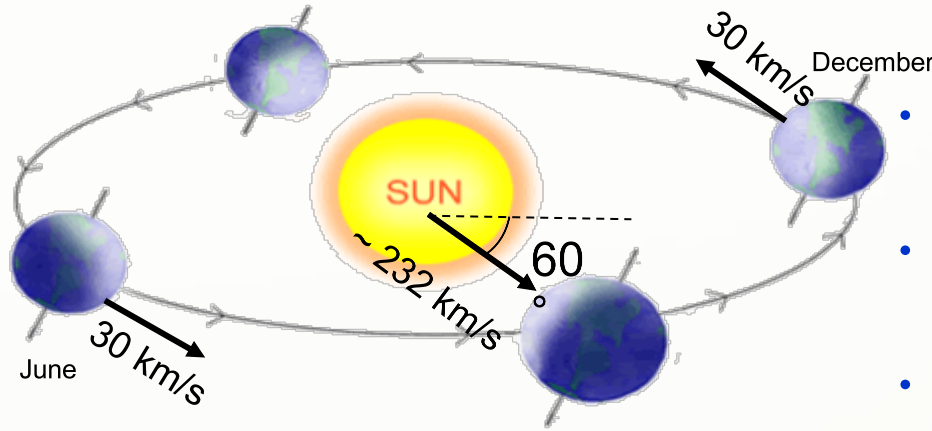
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

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 and low-radioactive set-up with an efficient control of the running conditions can point out its presence.

Requirements:

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

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_{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
- $t_0 = 2^{nd}$ June (when $v_\oplus$ is at maximum)

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

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

Avoided: data selections, subtractions and statistical discrimination procedure; and overall stability better than ~1%

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

DAMA Model Independent Annual Modulation Result

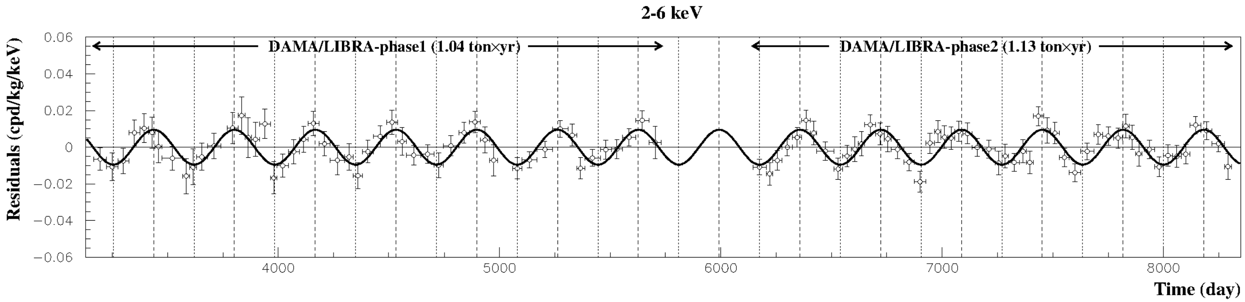
DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2 (2.17 ton×yr)

ULB detectors underground since suitable time

[Universe 4 (2018) 116; NPAE 19 (2018) 207]

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

(for each DAMA/LIBRA detector all the other ones in the set-up act as active veto)

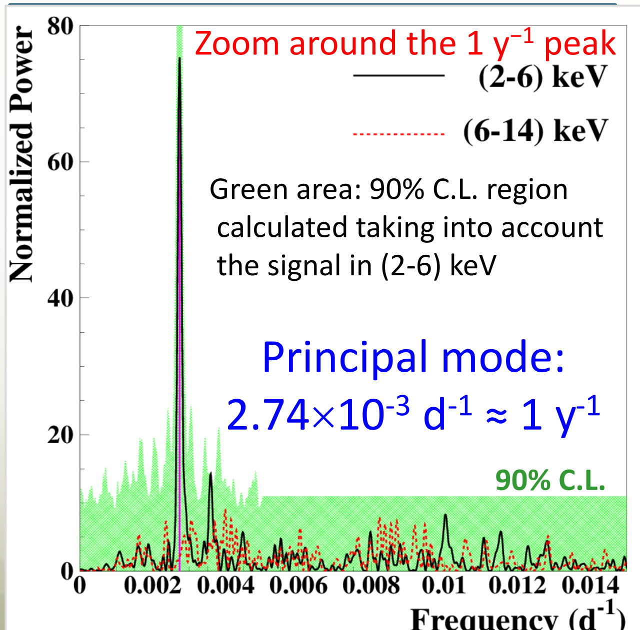


continuous line: t_0 = 152.5 d, T =1.0 y

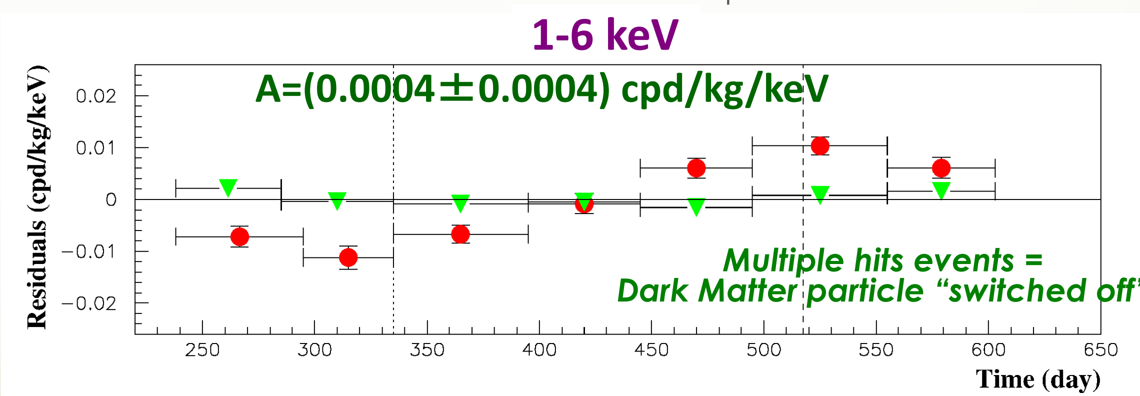
A=(0.0095±0.0008) cpd/kg/keV
χ^2/dof = 71.8/101 11.9 σ C.L.

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; No modulation in the residual rate of the multiple hit events



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

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.

Summary of the results obtained in the additional investigations of possible systematics or side reactions – DAMA/LIBRA

NIMA592(2008)297, EPJC56(2008)333, J. Phys. Conf. ser. 203(2010)012040, arXiv:0912.0660, S.I.F.Atti Conf.103(211), Can. J. Phys. 89 (2011) 11, Phys.Proc.37(2012)1095, EPJC72(2012)2064, arxiv:1210.6199 & 1211.6346, IJMPA28(2013)1330022, EPJC74(2014)3196, IJMPA31(2017)issue31, Universe4(2018)03009, Beld19,2(2018)27

Source	Main comment	Cautious upper limit (90%C.L.)
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	**$<2.5\times10^{-6}$ cpd/kg/keV**
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	**$<10^{-4}$ cpd/kg/keV**
NOISE	Effective full noise rejection near threshold	**$<10^{-4}$ cpd/kg/keV**
ENERGY SCALE	Routine + intrinsic calibrations	**$<1\text{-}2\times10^{-4}$ cpd/kg/keV**
EFFICIENCIES	Regularly measured by dedicated calibrations	**$<10^{-4}$ cpd/kg/keV**
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV *multiple-hits* events; this limit includes all possible sources of background	**$<10^{-4}$ cpd/kg/keV**
SIDE REACTIONS	Muon flux variation measured at LNGS	**$<3\times10^{-5}$ cpd/kg/keV**

+ they cannot satisfy all the requirements of annual modulation signature

→ **Thus, they cannot mimic the observed annual modulation effect**

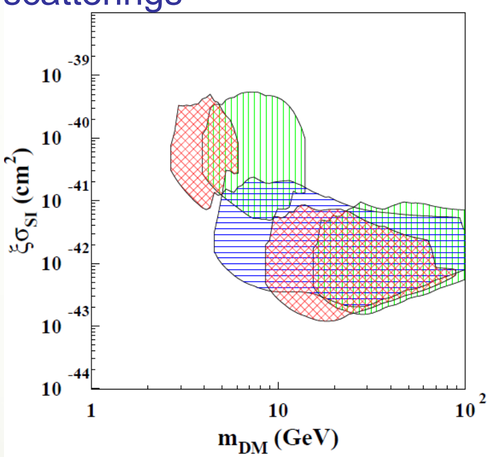
Few examples of model-dependent analyses including DAMA/LIBRA-phase2

to appear

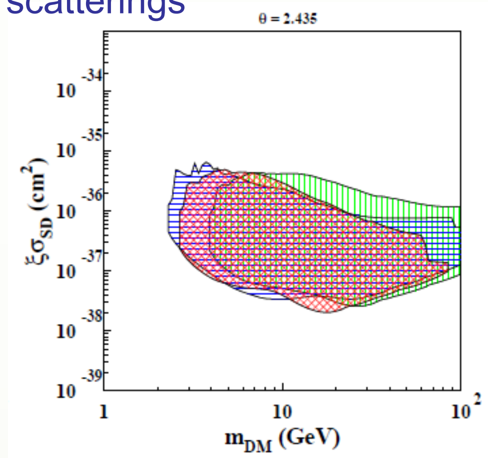
Some velocity distributions and uncertainties considered. Regions represent the domain where the likelihood-function values differ more than **10σ** from the null hypothesis (absence of modulation)

DAMA/NaI+DAMA/LIBRA-phase1+ DAMA/LIBRA-phase2

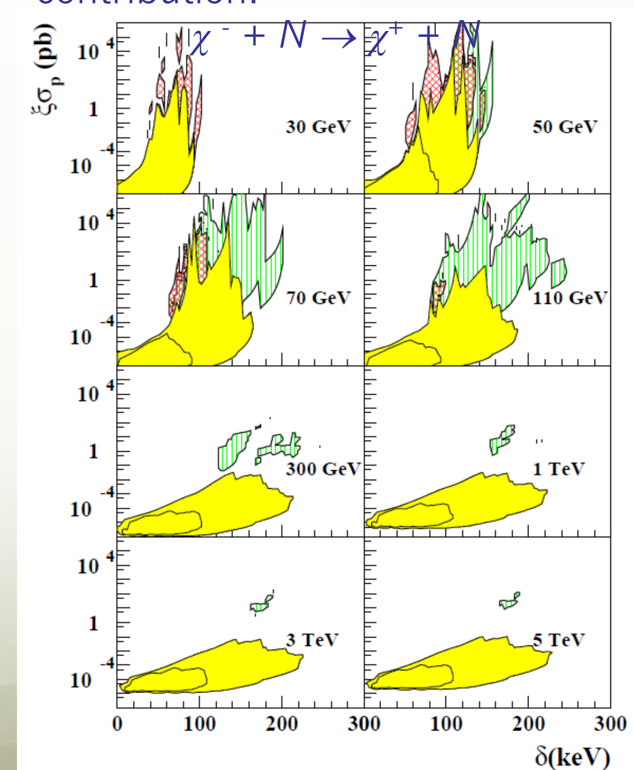
DM particles inducing SI elastic scatterings



DM particles inducing SD elastic scatterings

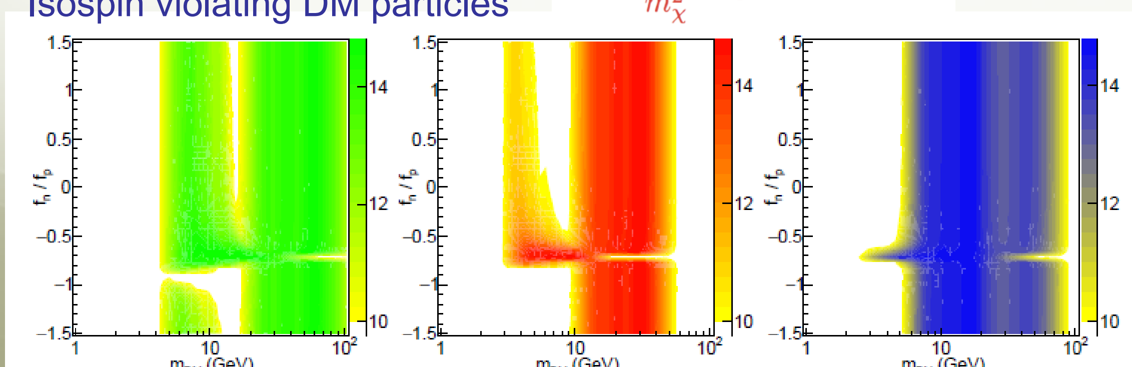


DM with preferred inelastic interaction including Tl contribution:



Isospin violating DM particles

$$\sigma_{SI} \sim \frac{\mu^2}{m_\chi^2}[Zf_p + (A-Z)f_n]^2$$



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 ≃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

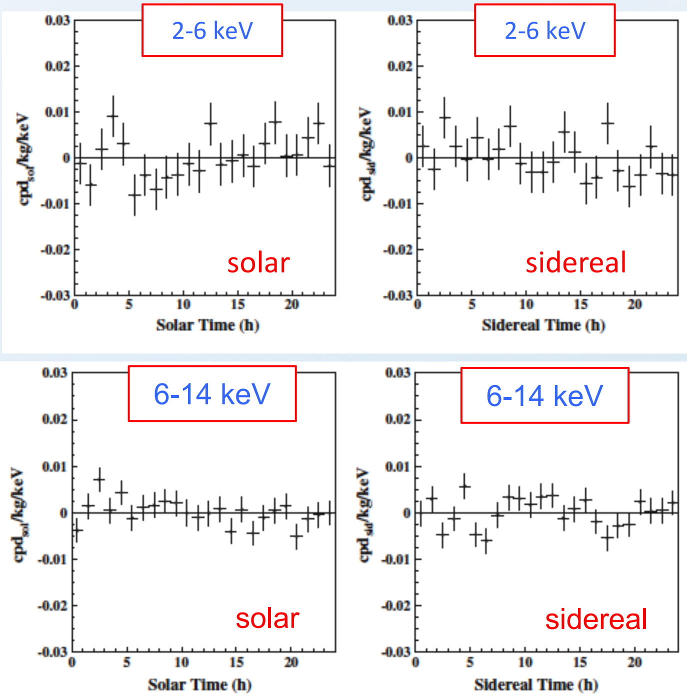
Energy	Solar Time	Sidereal Time
2–4 keV	χ^2/d.o.f. = 35.2/24 → P = 7%	χ^2/d.o.f. = 28.7/24 → P = 23%
2–5 keV	χ^2/d.o.f. = 35.5/24 → P = 6%	χ^2/d.o.f. = 24.0/24 → P = 46%
2–6 keV	χ^2/d.o.f. = 25.8/24 → P = 36%	χ^2/d.o.f. = 21.2/24 → P = 63%
6–14 keV	χ^2/d.o.f. = 25.5/24 → P = 38%	χ^2/d.o.f. = 35.9/24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

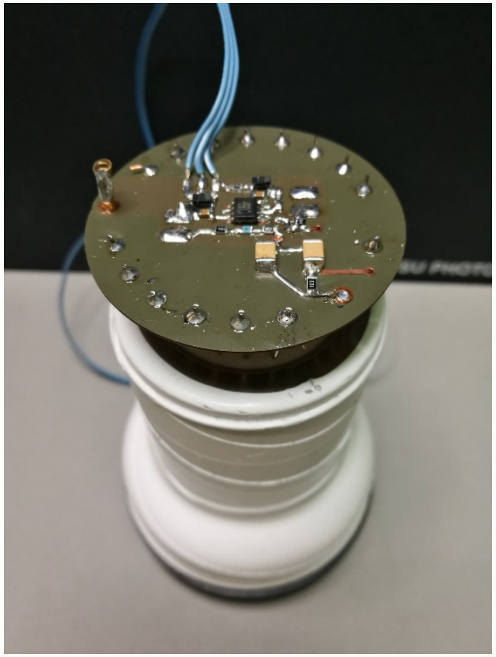
Present experimental sensitivity is not enough for the expected diurnal modulation amplitude derived from the DAMA/LIBRA–phase1 observed effect

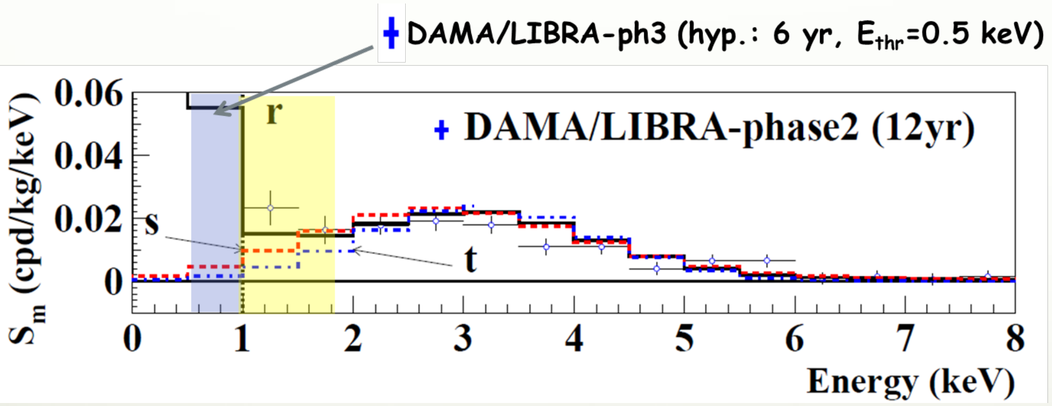
Larger exposure DAMA/LIBRA–ph2 (+lower energy threshold) is now under analysis and further improvements can be foreseen for DAMA/LIBRA-phase3

Toward DAMA/LIBRA-phase3

updating hardware to lower software energy threshold below 1 keV

new miniaturized low background **pre-amps** directly installed on the low-background supports of the **voltage dividers** of the new lower background high Q.E. **PMTs**





The presently-reached metallic PMTs features:

- Q.E. around 35-40% @ 420 nm (NaI(Tl) light)
- Radio-purity 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).

several prototypes from a dedicated R&D with HAMAMATSU at hand

Features of the DM signal investigated by DAMA at various levels; improvements foreseen with DAMA/LIBRA-phase3

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

High exposure and low energy threshold can allow investigation on:

- the nature of the DM candidates

- ✓ to disentangle among the different astrophysical, nuclear and particle physics models (nature of the candidate, couplings, inelastic interaction, form factors, spin-factors …)
- ✓ scaling laws and cross sections
- ✓ multi-component DM particles halo?

- possible diurnal effects on the sidereal time

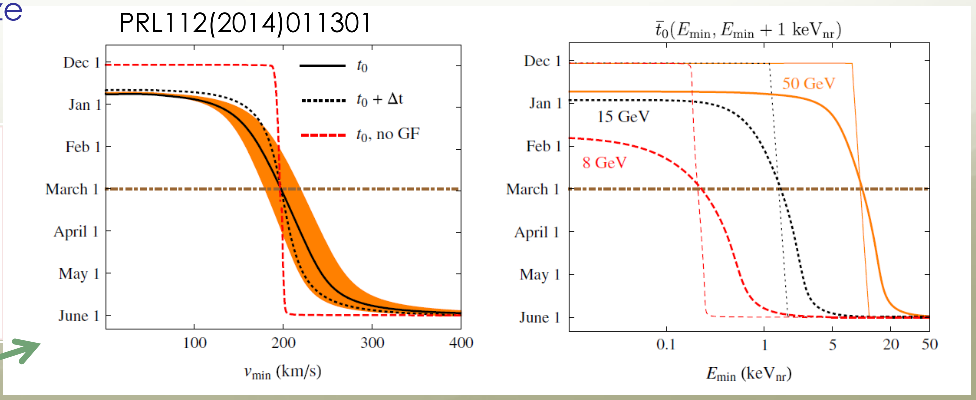
- ✓ expected in case of high cross section DM candidates (shadow of the Earth)
- ✓ due to the Earth rotation velocity contribution (it holds for a wide range of DM candidates)
- ✓ due to the channeling in case of DM candidates inducing nuclear recoils.

- astrophysical models

- ✓ velocity and position distribution of DM particles in the galactic halo, possibly due to:
  - satellite galaxies (as Sagittarius and Canis Major Dwarves) tidal "streams";
  - caustics in the halo;
  - gravitational focusing effect of the Sun enhancing the DM flow ("spike" and "skirt");
  - possible structures as clumpiness with small scale size
  - Effects of gravitational focusing of the Sun

The annual modulation phase depends on :

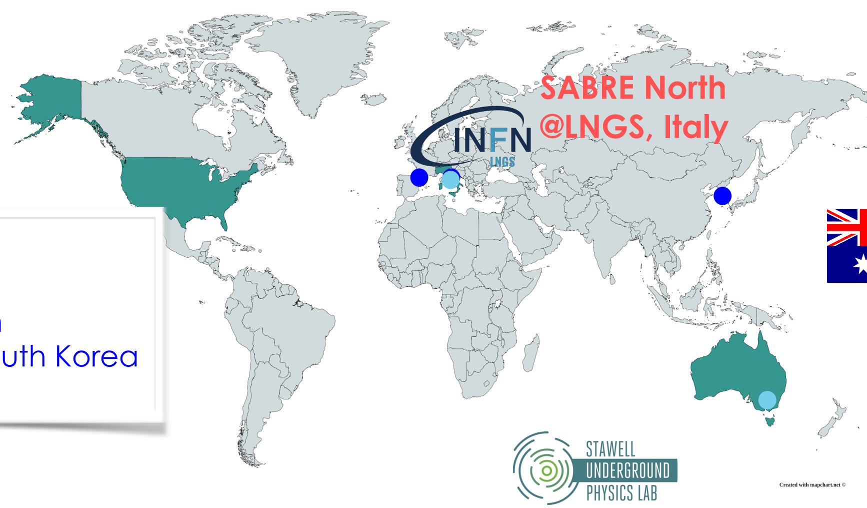
- Presence of **streams** (as SagDEG and Canis Major) in the Galaxy
- Presence of **caustics**
- Effects of gravitational **focusing of the Sun**



Slides kindly provided by SABRE Coll.

SABRE: Sodium-iodide with Active Background REjection

LLNL
PNNL
Princeton/University



Other NaI experiments:
- DAMA @LNGS, Italy
- ANAIS @Canfranc, Spain
- COSINE @Yang Yang, South Korea

LNGS & GSSI
INFN Roma & Sapienza University
INFN Milano and University of Milano

Adelaide University
Australian National University
Swinburne University
University of Melbourne

SABRE South
@SUPL, Stawell gold mine, Australia

SABRE
Key Features

1. **Development of ultra-high purity NaI(Tl) crystals**
   - High purity NaI powder
   - Clean crystal growth method
2. **Low energy threshold**
   - High QE Hamamatsu PMTs directly coupled to the crystal
3. **Passive shielding + active veto**
   - Unprecedented background rejection and sensitivity with a NaI(Tl) experiment
4. **Two identical detectors in northern and southern hemispheres**
   - seasonal backgrounds have opposite phase in northern and southern hemispheres
   - dark matter signal has same phase

Slides kindly provided by SABRE Coll.

Status of SABRE PoP : Crystals

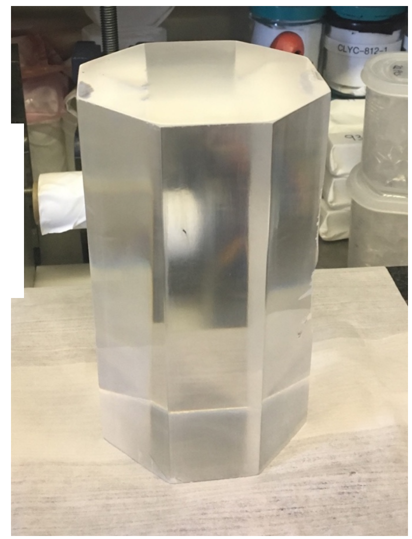
Ultra pure NaI(Tl) crystals

- Astro Grade powder (Sigma Aldrich, now Merck)
- Clean growth procedure: collaboration between Princeton and RMD, Boston

Crystal NaI-31, grown in a standard quartz crucible.
Mass: 3.7 kg after polishing.
Produced in June 2018.

Ready

Crystal NaI-31 was mounted with PMTs in LNGS enclosure and shipped to Italy



Crystal NaI-33, grown in a high purity crucible produced @ Princeton.
Mass: 3.4 kg after polishing
Produced in October 2018

Soon

ICP-MS measurements on samples from crystal tip and tail confirmed very low K content

Slides kindly provided by SABRE Coll.

Status of SABRE PoP: set-up @ LNGS

The SABRE PoP setup in Hall C @ LNGS is READY!

accomplished

Veto vessel ready in its final position. Passive shielding and all the Hall C accessory infrastructures: fluid handling, slow control, power plant, control room, safety plant are assembled.

upcoming

SABRE PoP set-up filling with scintillator is pending final approval from LNGS and external authorities.

If, as we expect, we meet the PoP requirements in coming months, we will then put forward a proposal for the full-scale experiment

Conclusions

With current technology, the annual modulation is the main model-independent signature for the DM signal, provided that a suitable setup and procedures are adopted

The DAMA model independent results favour the presence of a signal with all the proper features for DM particles in the galactic halo at 12.9σ C.L.
The result is compatible with many DM scenarios
The work towards DAMA/LIBRA-phase3 is ongoing

Information from SABRE: the PoP setup in Hall C at LNGS is ready
In coming months, if the PoP requirements will be satisfied, a proposal for the full-scale experiment will be presented by the SABRE Coll.

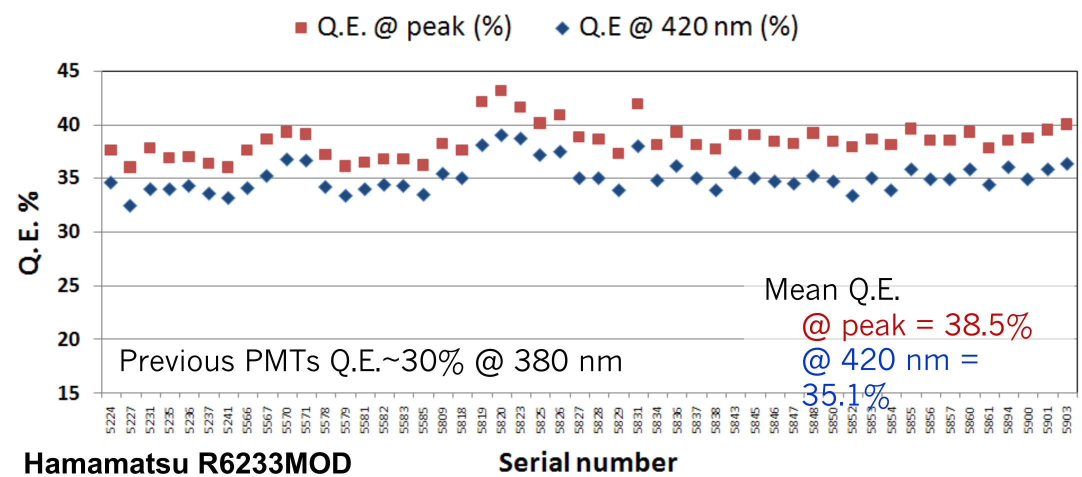
Other interesting approaches correlated with the Earth motion in the DM halo:

- ❑ Diurnal modulation effect due to Earth rotation (second order effect; model-independent)
- ❑ Shadow effect
- ❑ Directionality

JINST 7(2012)03009

New DAMA/LIBRA-phase2 PMTs

New High Quantum Efficiency PMTs installed at the end of 2010



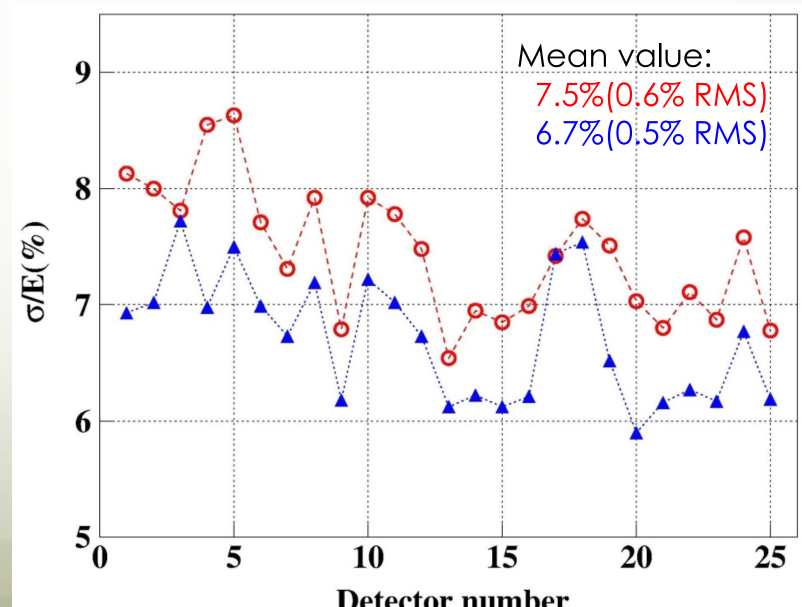
Light responses

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

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

Energy resolution

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



Residual Contamination

	Average	STD
^{226}Ra (Bq/kg)	0.43	0.06
^{235}U (mBq/kg)	47	10
^{228}Ra (Bq/kg)	0.12	0.02
^{228}Th (mBq/kg)	83	17
^{40}K (Bq/kg)	0.54	0.16

In the old PMTs:

- ≈0.37 Bq/kg for ^{238}U
- ≈120 mBq/kg for ^{232}Th
- ≈1.9 Bq/kg for ^{40}K

Sun velocity in the Equatorial coordinate system …

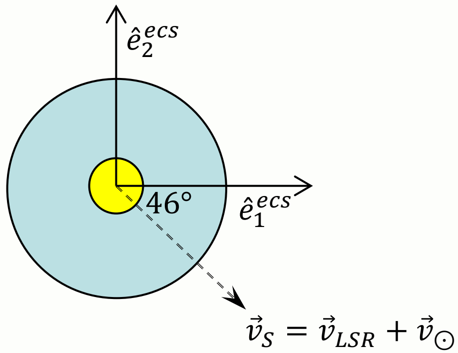
On equatorial plane:

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

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

$\Rightarrow \varphi = -46°$

$\Rightarrow$ t = 20.92 h (LST)

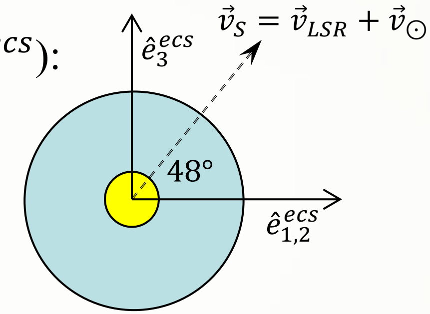


Angle w.r.t. North pole ($\hat{e}_3^{ecs}$):

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

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

$A_m \approx 0.489$;

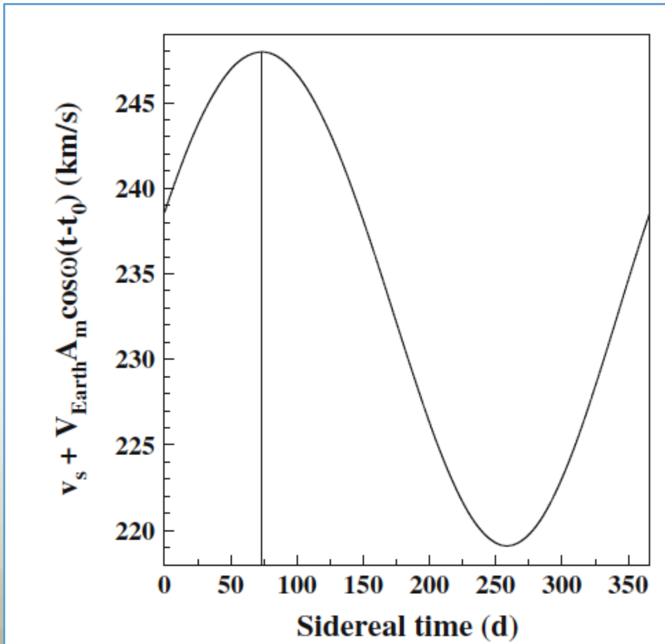
$t_0 = t_{equinox} + 73.25$ solar days

([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.



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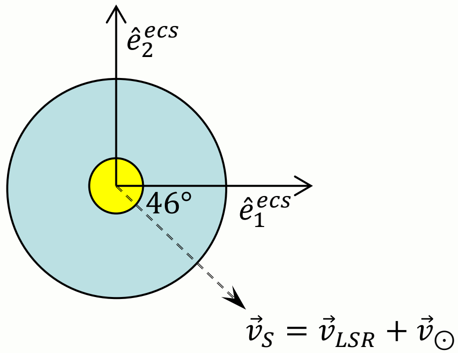

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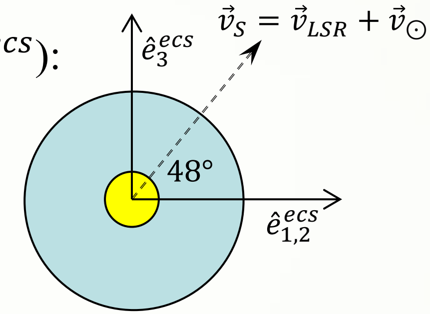


$$v_{lab}(t) \simeq v_S + \hat{v}_S \cdot \vec{v}_{rev}(t) + \hat{v}_S \cdot \vec{v}_{rot}(t)$$

… and diurnal modulation term

Based on DM flux annual variation due to Earth Rotation

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

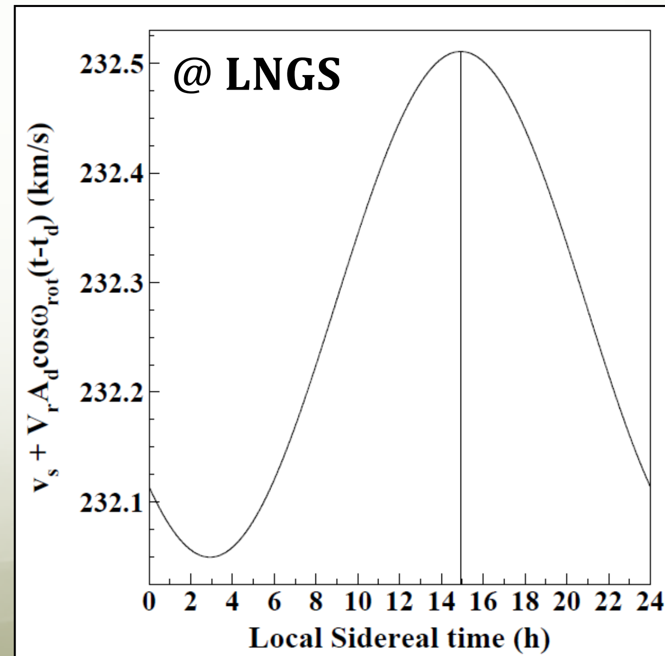
$A_d \approx 0.671;$

$t_d = 14.92$ 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:

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

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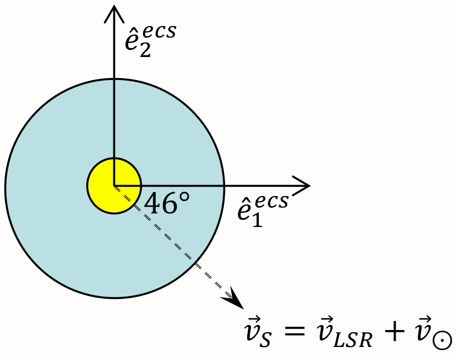

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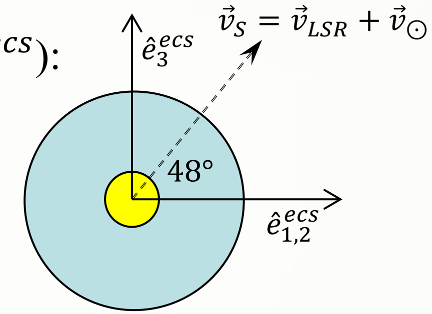


… and directionality

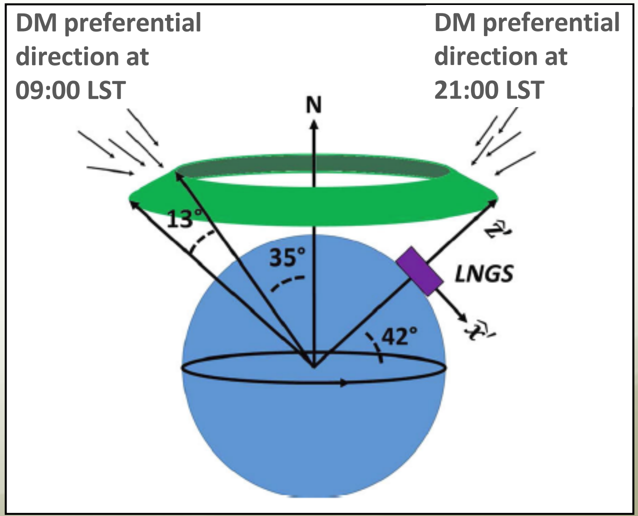
Based on diurnal variation of apparent DM wind arrival direction

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**



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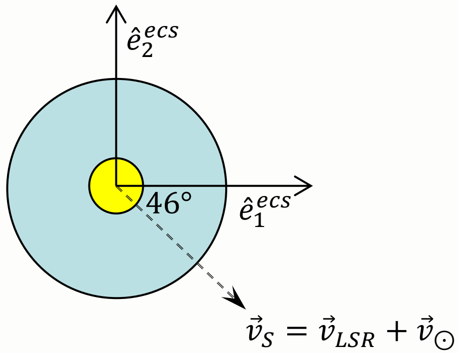

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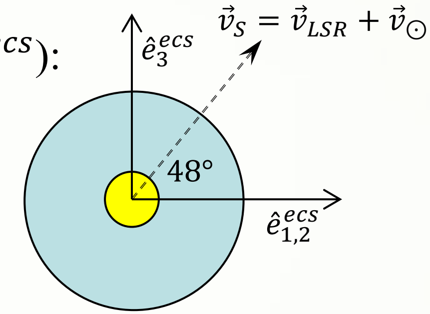
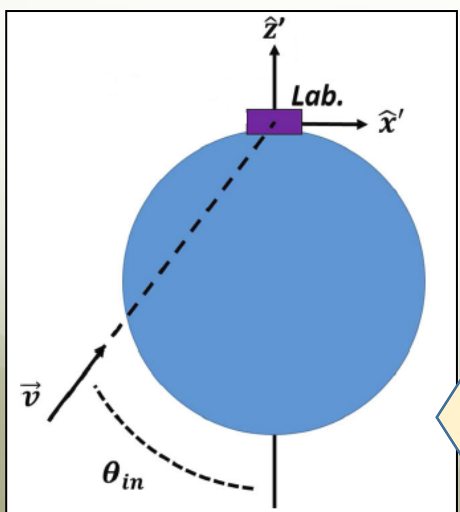


… and shadow effect

Based on diurnal variation of apparent DM wind arrival direction

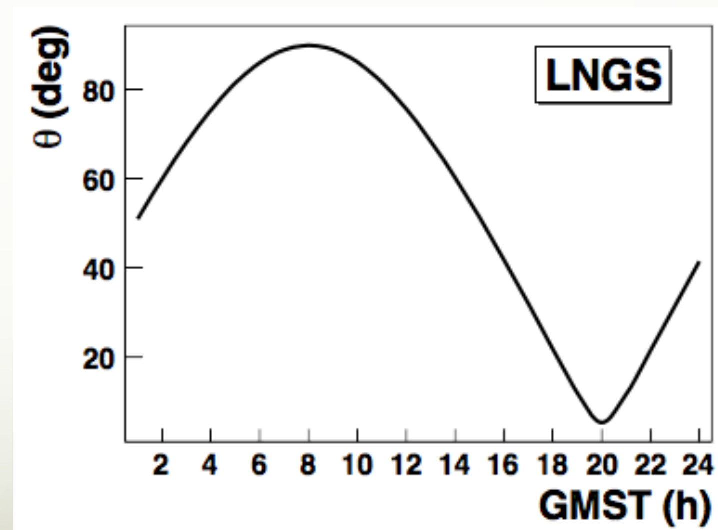
During a sidereal day the Earth shields a terrestrial detector with a varying thickness and this induces a variation of the flux of the DM candidates impinging the detector



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

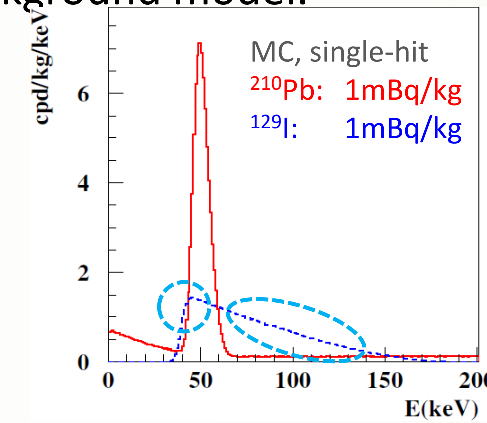
An example: the case of the latest COSINE-100

Several open problems: among them I will discuss a few.

- Results based only on the subtraction of what they consider the background model.
- The counting rate is three/four times that of DAMA.
- The background model has some faults. For example:
- ^{129}I completely forgotten in Cosine-100 data analysis
- Thus, ^{210}Pb significantly overestimated
- Others (^{3}H, …)

Very important discrepancies (note the log scale) in the reconstruction of the structure at ≈ 45 keV, due to:

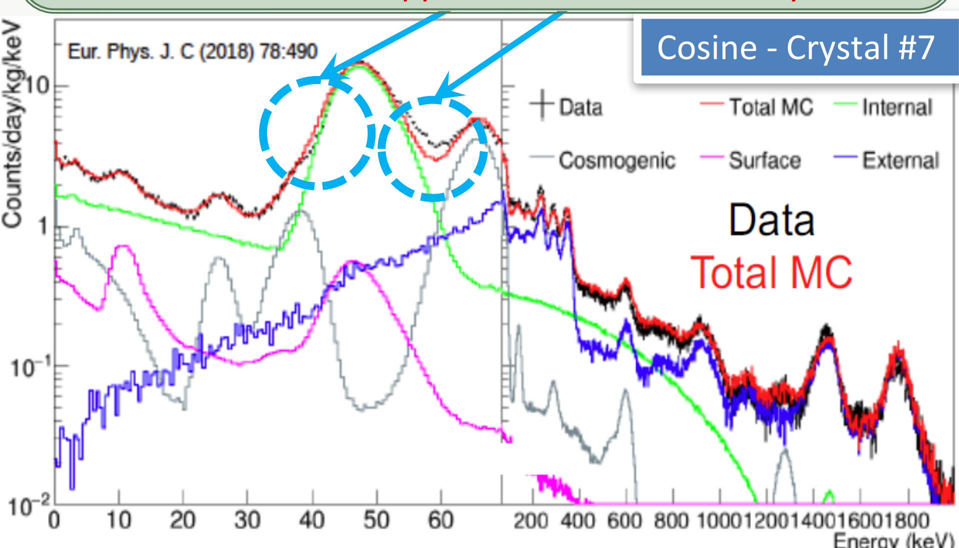
1. Missing contribute of ^{129}I
2. Overestimate contribute of ^{210}Pb



Internal ^{210}Pb seems to give the main (≈60%) contribution in 2-6 keV region, but , as shown, the assumed value is wrong: < 1.2 cpd/kg/keV

In green the spectrum, the ^{210}Pb peak height is ≈ 14cpd/kg/keV, that is ≈ 2mBq/kg

But the measured α rate in crystal 7 is (1.54±0.4) mBq/kg and this should be an upper limit for ^{210}Pb activity!



Cosine - Crystal #7

Components	Background 2-6 keV (dru)
Internal ^{210}Pb	1.50 +/- 0.07
Internal ^{40}K	0.05 +/- 0.01
Surface ^{210}Pb	0.38 +/- 0.21
^{3}H (Cosmogenic)	0.58 +/- 0.54
^{109}Cd (Cosmogenic)	0.09 +/- 0.09
Other cosmogenic	0.05 +/-0.03
External	0.03 +/- 0.02
Total expected	**2.70 +/- 0.59**
Data	**2.64 +/- 0.05**

To be revised

<< 2.4

- expected << observed
- Uncertainties per crystal: 0.6 cpd/kg/keV
- → Total uncer. ≈0.6/√6 = 0.25 cpd/kg/keV

Still large space for DM signal

… more on COSINE-100

- The methodology of the background subtraction, used by Cosine-100, is strongly discouraged and deprecated because of the impossibility to have a precise knowledge of the background contribution in particular at low energy, leading to large systematic uncertainties.
- Thus, it is a **dangerous** way to claim sensitivities by the fact not supported by large counting rate.
- Even considering the background model as correct, the analysis has fault.
- They get null residuals in each crystal (even always negative) starting from a wrong bckg hypothesis!

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Table 4 Fitted background events in units of dru (counts/day/keV/kg) in the (2–6) keV energy interval

	Crystal-1	Crystal-2	Crystal-3	Crystal-4	Crystal-6	Crystal-7
Internal						
^{40}K	0.10 ±0.02	0.20 ± 0.02	0.10 ± 0.01	0.10 ±0.01	0.05 ± 0.01	0.05 ±0.01
^{210}Pb	2.50 ± 0.10	1.69 ± 0.09	0.57 ± 0.05	0.71 ± 0.05	1.46 ± 0.07	1.50 ± 0.07
Other ($\times 10^{-4}$)	7.0±0.1	15±1	7.3±0.1	7.7±0.1	14±1	14±1
Cosmogenic						
^{3}H	2.35 ± 0.90	0.81 ± 0.40	1.54 ± 0.77	1.97 ± 0.66	0.69 ± 0.67	0.58 ± 0.54
^{109}Cd	0.05 ±0.04	0.009 ±0.009	0.13 ± 0.06	0.29 ± 0.15	0.08 ± 0.08	0.09 ± 0.09
Other	–	–	0.02 ± 0.01	0.09 ± 0.04	0.06 ± 0.03	0.05 ± 0.03
Surface						
^{210}Pb	0.64 ± 0.64	0.51 ± 0.51	1.16 ± 0.51	0.22 ± 0.16	0.34 ± 0.20	0.38 ± 0.21
External						
	0.03 ± 0.02	0.05 ± 0.04	0.03 ± 0.02	0.03 ± 0.02	0.04 ± 0.03	0.03 ± 0.02
Total simulation						
	5.68 ± 1.04	3.28 ± 0.67	3.57 ± 0.76	3.41 ± 0.75	2.74 ± 0.61	2.70 ± 0.51
Data						
	5.64 ± 0.10	3.27 ± 0.07	3.35 ± 0.07	3.19 ± 0.05	2.62 ± 0.05	2.64 ± 0.05
Data−model=	−0.04±1.04	−0.01±0.67	−0.22±0.76	−0.22±0.75	−0.12±0.61	−0.06±0.51

Data−model = −0.105±0.276 cpd/kg/keV

→ **S_0<0.36 cpd/kg/keV 90%CL in the (2-6) keV energy region**

Still large space for DM

Since time, by simple and direct determination in DAMA: S_0<0.25 cpd/kg/keV in (2-4) keV (DAMA/LIBRA-phase1), even less in phase2

In conclusion: Cosine-100 low energy analysis is **wrong** and the exclusion plot **meaningless**