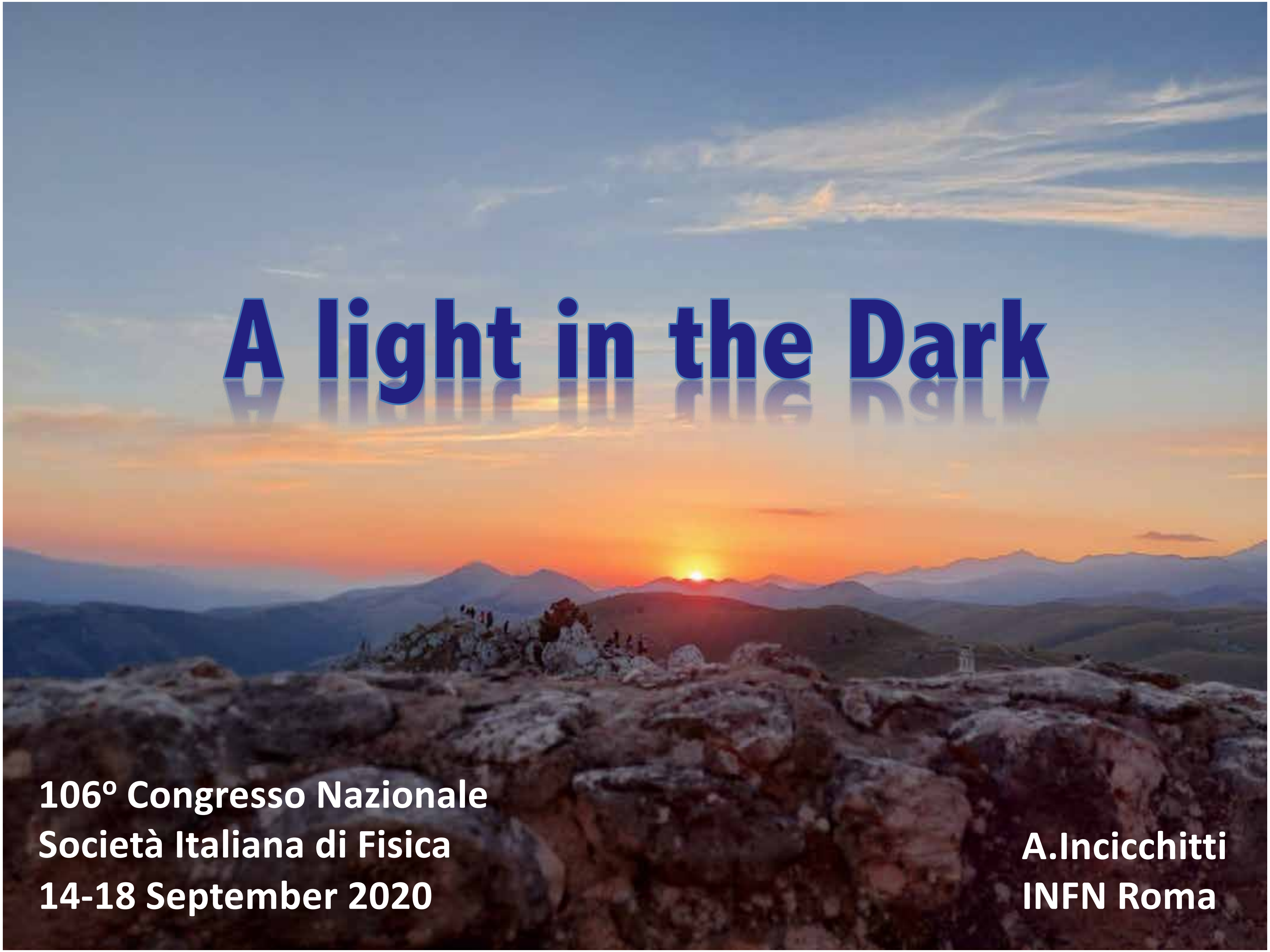


A light in the Dark

106º Congresso Nazionale
Società Italiana di Fisica
14-18 September 2020

A.Incicchitti
INFN Roma

Relic DM particles from primordial Universe

SUSY (as neutralino or sneutrino in various scenarios)

the sneutrino in the Smith and Weiner scenario

sterile ν

electron interacting dark matter

a heavy ν of the 4-th family

even a suitable particle not yet foreseen by theories

axion-like (light pseudoscalar and scalar candidate)

self-interacting dark matter

mirror dark matter

Kaluza-Klein particles (LKK)

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

Elementary Black holes, Planckian objects, Daemons

invisible axions, ν's

etc...

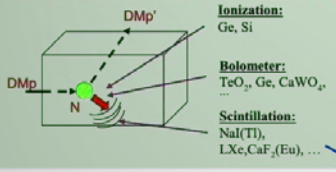
multi-component non-baryonic DM?

Accelerators:

- can demonstrate the existence of some possible DM candidates
- cannot credit that a certain particle is the Dark Matter solution or the "single" Dark Matter particle solution...

+ DM candidates and scenarios exist on which accelerators cannot give any information

- Scatterings on nuclei
  → detection of nuclear recoil energy



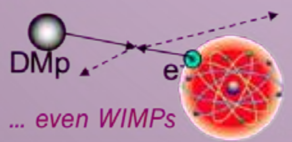
- Inelastic Dark Matter: **W + N → W* + N**
  → W has 2 mass states χ+ , χ- with δ mass splitting
  → Kinematical constraint for the inelastic scattering of χ- on a nucleus

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

- 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⁻

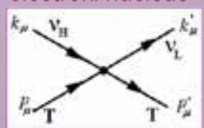
- Interaction only on atomic electrons
  → detection of e.m. radiation



... 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 ...

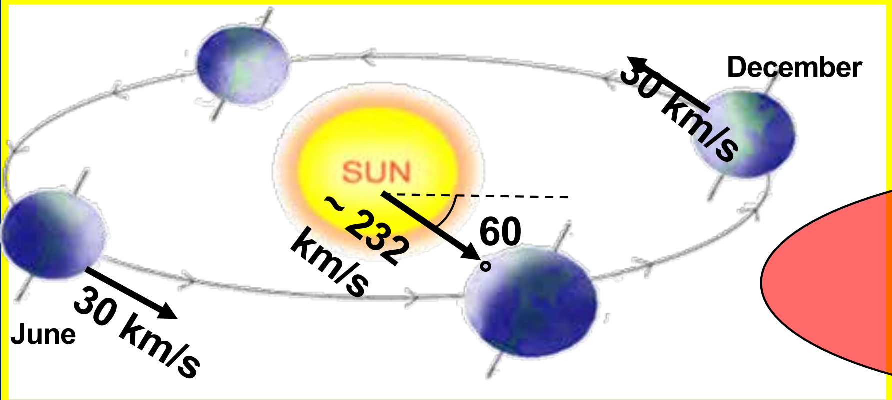
DM direct detection method using a model independent approach and a low-background widely-sensitive target material

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

A model independent signature is fundamental

A reliable technology to investigate a model independent signature:

- High duty cycle
- Well controlled operational conditions
- Reproducibility
- Long term stability
- Effective routine calibrations down to keV in the same conditions as production runs
- Sensitive to many candidates, interaction types and astrophysical, nuclear and particle physics scenarios



Annual modulation Annual variation of the interaction rate due to Earth motion around the Sun.

Model independent

Diurnal modulation Daily variation of the interaction rate due to Earth rotational velocity.

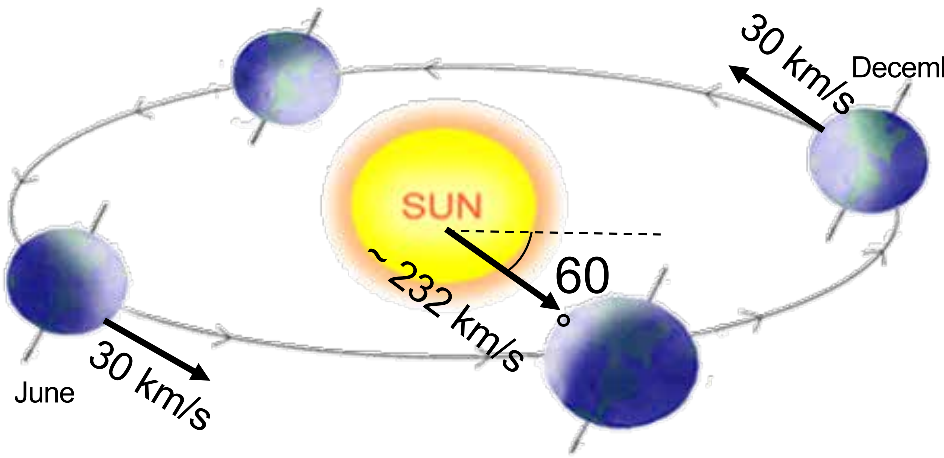
For some DM candidates →

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

The DM annual modulation: a model independent signature to investigate the 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



- 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 maximum)

Requirements of the DM annual modulation

1) Modulated rate according cosine
2) In a definite low energy range
3) With a proper period (1 year)
4) With proper phase (about 2 June)
5) Just for single hit events in a multi-detector set-up
6) With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions, but it can be larger in case of some possible scenarios

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

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

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

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

An example: the DM annual modulation on Mars

MARS:

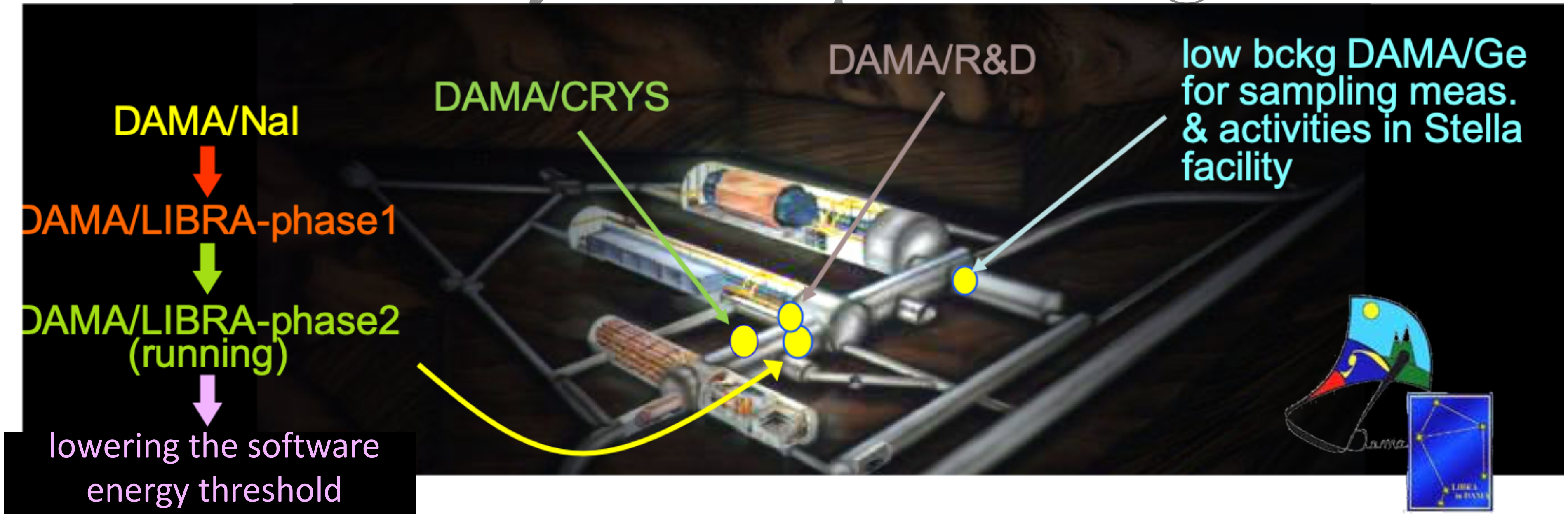
- semi-major axis of 1.524 A.U.
- average orbital speed of 24.1 km/s (26.5 km/s max and 22.0 km/s min).
- eccentricity of the orbit: difference between the aphelion and perihelion distances is 0.285 U.A.
- orbit inclined of 1.85^0 with respect to the ecliptic.
- tilted axis, inclined 25.19^0 to its orbital plane (Earth's axial tilt of approx. 23.44^0)
- period T_M = 668.6 Sols.

Expected DM annual modulation with period T_M, phase ≃ 354 Sols in the Mars calendar and an amplitude ≃ 5% (i.e. the S_m/S_0 value) for usually adopted halo distributions.
(Mars parameters evaluated by Starlink Project)

The measurement of DM modulation signature both on Earth and on Mars would strongly improve our knowledge on astrophysical parameters and therefore on corollary data analyses, once the experimental parameters and the other uncertainties were fully under control, on both the planets, with the needed sensitivity.

DAMA

an observatory for rare processes @ LNGS



Collaboration:

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

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

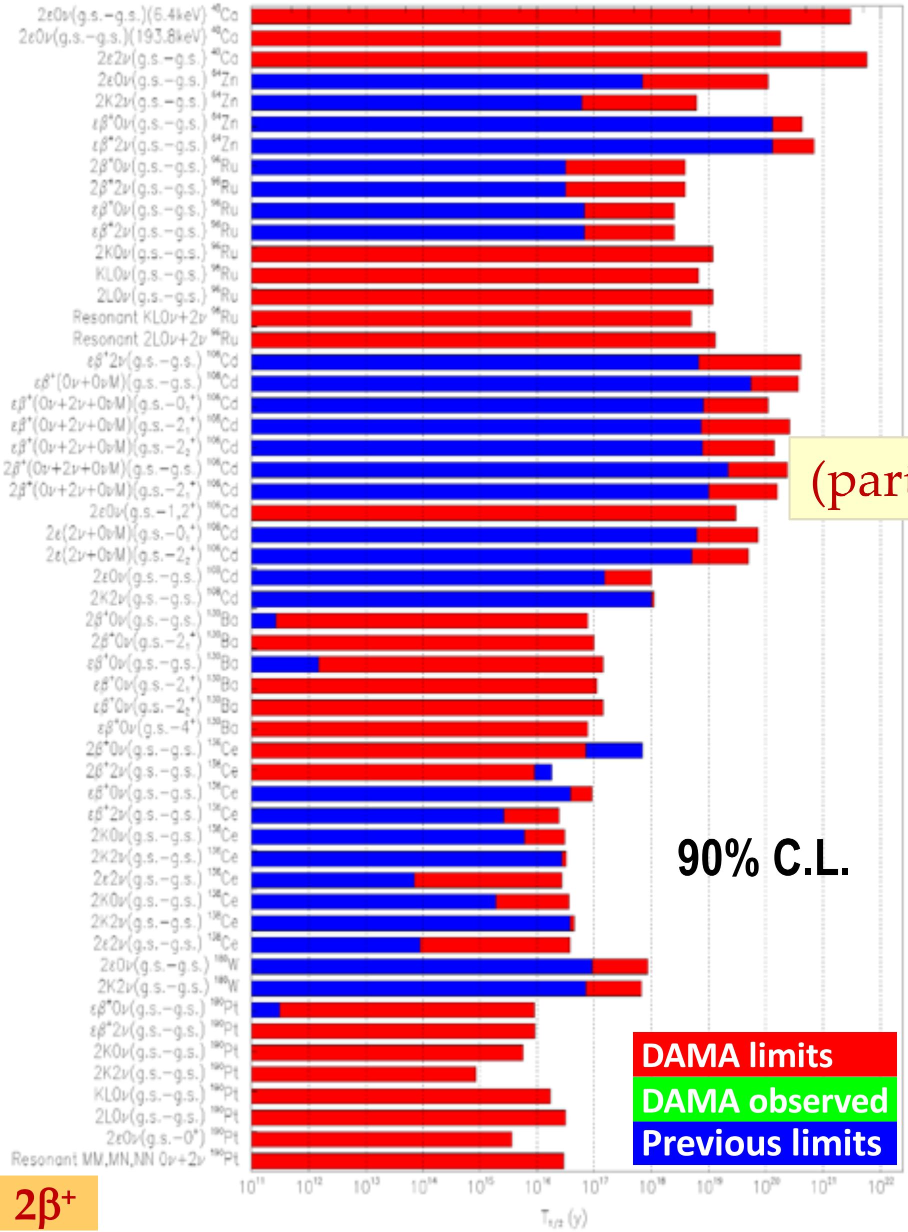
+ neutron meas.: ENEA-Frascati, ENEA-Casaccia

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

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

Search for ββ decay modes in various isotopes at DAMA and STELLA set-ups

DAMA and DAMA/Kiev

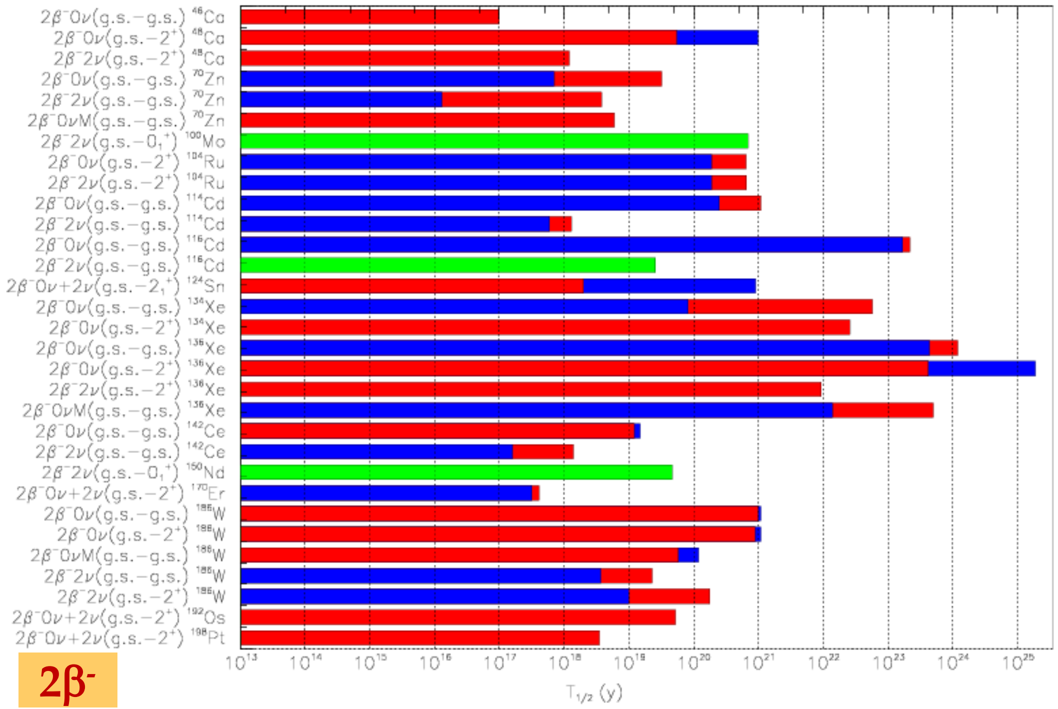


$2\beta^+$

New observations:

ARMONIA:	$2\nu2\beta^-$ decay	$^{100}Mo \rightarrow ^{100}Ru(0_1^+)$	NPA846(2010)143
AURORA:	$2\nu2\beta^-$ decay	$^{116}Cd \rightarrow ^{116}Sn$	PRD98(2018)092007
Nd_2O_3-HPGe:	$2\nu2\beta^-$ decay	$^{150}Nd \rightarrow ^{150}Sm(0_1^+)$	NPAE19(2018)95

(partial list)



$2\beta^-$

- Many competitive limits obtained on lifetime of $2\beta^+$, $\varepsilon\beta^+$ and 2ε processes (^{40}Ca, ^{64}Zn, ^{96}Ru, ^{106}Cd, ^{108}Cd, ^{130}Ba, ^{136}Ce, ^{138}Ce, ^{180}W, ^{190}Pt, ^{184}Os, ^{156}Dy, ^{158}Dy, …).
- First searches for resonant $0\nu2\varepsilon$ decays in some isotopes

The pioneer DAMA/NaI: ≈100 kg highly radiopure NaI(Tl)

Perform

Results
- Poss
- CNC
- Elect in lo
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- Sear

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

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

- Radiopurity, performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
- Results on DM particles,
  - Annual Modulation Signature: EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648.
  - Related results: PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022, EPJC74(2014)2827, EPJC74(2014)3196, EPJC75(2015)239, EPJC75(2015)400, IJMPA31(2016) dedicated issue, EPJC77(2017)83
- Results on rare processes:
  - PEPv: EPJC62(2009)327, arXiv1712.08082;
  - CNC: EPJC72(2012)1920;
  - IPP in ^{241}Am: EPJA49(2013)64

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

DAMA/LIBRA–phase1 (7 annual cycles, 1.04 ton×yr) confirmed the model-independent evidence of DM: reaching 9.3σ C.L.

DAMA/LIBRA–phase2

JINST7(2012)03009,Universe 4(2018)116,NPAE19(2018)307, Bled works. in Phys.19(2018)27 and20(2019)1,NPAE20(4)(2019)317,AracneEd.,Roma(2019),pagg. 200,ISBN:978-88-255-2940-1, N.Cim. C 43(2020)23, PPNP 114 (2020) 103810

Upgrade on Nov/Dec 2010: all PMTs replaced with new ones of higher Q.E.

Fulfilled goal: software energy threshold down to 1 keV

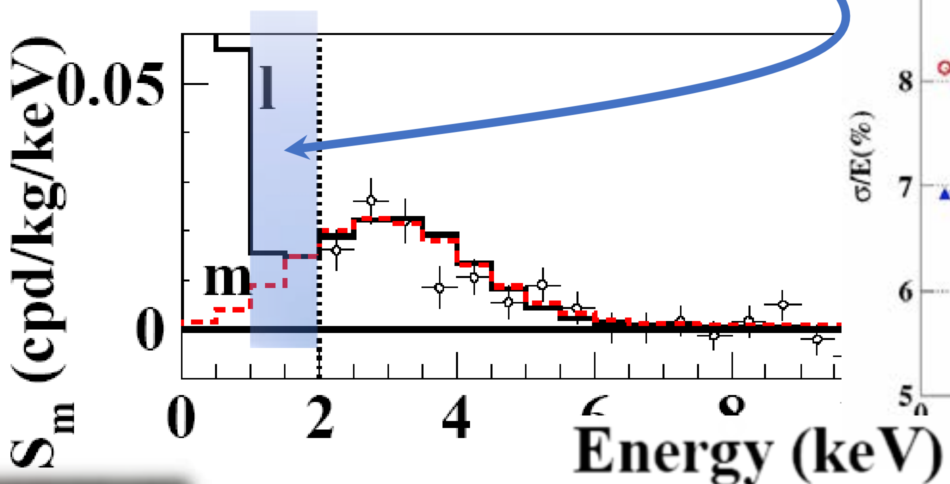
Q.E. of the new PMTs:
33 – 39% @ 420 nm
36 – 44% @ peak

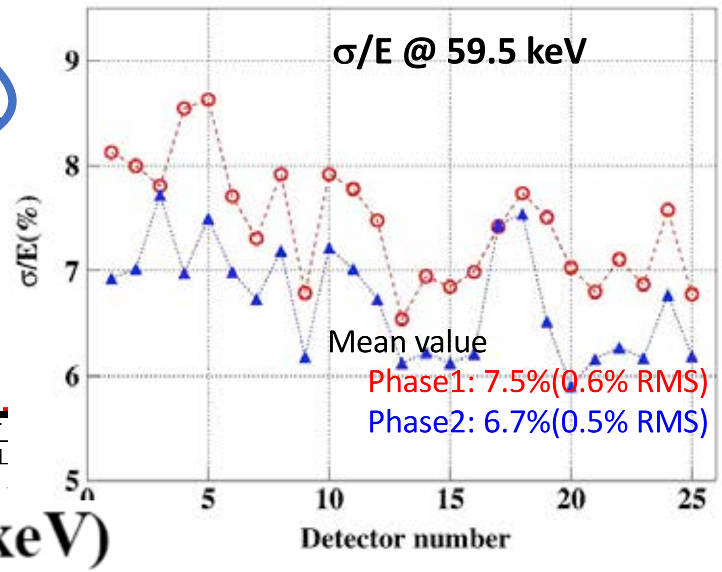
DAMA/LIBRA–phase2

JINST 7 (2012) 03009, Universe 4 (2018) 116, NPAE 19 (2018) 307, Bled works. in Phys. 19 (2018) 27 and 20 (2019) 1, NPAE 20(4)(2019)17, Aracne Ed., Roma (2019), pagg. 200, ISBN:978-88-255-2940-1, PPNP 114 (2020) 103810

Lowering software energy threshold below 2 keV:

- to study the nature of the particles and features of astrophysical, nuclear and particle physics aspects, and to investigate 2nd order effects
- special data taking for *other rare processes*





The contaminations:

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

The light responses:

DAMA/LIBRA-phase1: 5.5 – 7.5 ph.e./keV
DAMA/LIBRA-phase2: 6-10 ph.e./keV

DAMA/LIBRA-phase2 data taking

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

Energy resolution @ 60 keV mean value:

prev. PMTs	7.5%	(0.6% RMS)
new HQE PMTs	6.7%	(0.5% RMS)

- ✓ Fall 2012: new preamplifiers installed + special trigger modules.
- ✓ Calibrations 6 a.c.: ≈ 1.3 × 10^8 events from sources
- ✓ Acceptance window eff. 6 a.c.: ≈ 3.4 × 10^6 events (≈ 1.4 × 10^5 events/keV)

Annual Cycles	Period	Mass (kg)	Exposure (kg × d)	(α-β²)
I	Dec 23, 2010 – Sept. 9, 2011	commissioning		
II	Nov. 2, 2011 – Sept. 11, 2012	242.5	62917	0.519
III	Oct. 8, 2012 – Sept. 2, 2013	242.5	60586	0.534
IV	Sept. 8, 2013 – Sept. 1, 2014	242.5	73792	0.479
V	Sept. 1, 2014 – Sept. 9, 2015	242.5	71180	0.486
VI	Sept. 10, 2015 – Aug. 24, 2016	242.5	67527	0.522
VII	Sept. 7, 2016 – Sept. 25, 2017	242.5	75135	0.480

Exposure first data release of DAMA/LIBRA-phase2: **1.13 ton × yr**

Exposure DAMA/NaI+DAMA/LIBRA-phase1+phase2: **2.46 ton × yr**

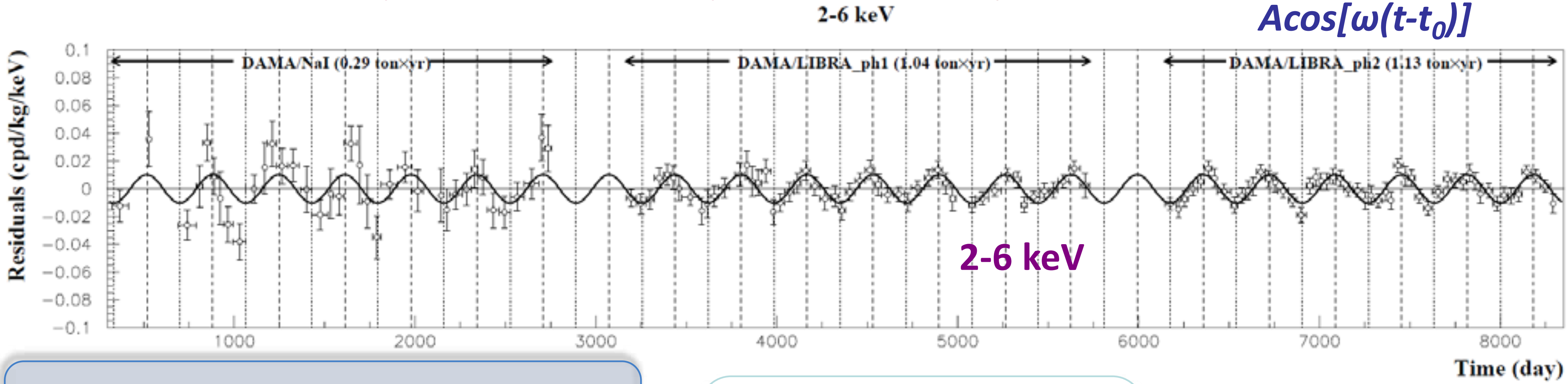
DM model-independent Annual Modulation Result

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

DAMA/NaI+DAMA/LIBRA-phase1+DAMA/LIBRA-phase2 (2.46 ton × yr)

NPAE 19 (2018) 307
N.Cim. C 43 (2020) 23
PPNP 114(2020)103810

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



Absence of modulation? No

χ^2/dof=272.3/142 ⇒ P(A=0) =3.0×10^{-10}

DAMA/NaI (0.29 ton x yr)
DAMA/LIBRA-ph1 (1.04 ton x yr)
DAMA/LIBRA-ph2 (1.13 ton x yr)

total exposure = 2.46 ton×yr

phase2: software energy threshold down to 1 keV

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

A=(0.0102±0.0008) cpd/kg/keV

χ^2/dof = 113.8/138 **12.8 σ C.L.**

Releasing period (*T*) and phase (*t_0*) in the fit

	ΔE	A(cpd/kg/keV)	T=2π/ω (yr)	t_0 (day)	C.L.
DAMA/LIBRA-ph2	(1-3) keV	0.0184±0.0023	1.0000±0.0010	153±7	8.0σ
	(1-6) keV	0.0106±0.0011	0.9993±0.0008	148±6	9.6σ
	(2-6) keV	0.0096±0.0011	0.9989±0.0010	145±7	8.7σ
DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2	(2-6) keV	0.0096±0.0008	0.9987±0.0008	145±5	12.0σ
DAMA/NaI + DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2	(2-6) keV	0.0103±0.0008	0.9987±0.0008	145±5	12.9σ

The data of DAMA/NaI + DAMA/LIBRA-phase1 +DAMA/LIBRA-phase2 favor the presence of a modulated behavior with proper features at 12.9 σ 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)116, Bled works. In Phys.19(2018)27 and 20(2019)1, NPAE19(2018)307, NPAE 20(4)(2019)17, Aracne ed. Roma (2019) ISBN:978-88-255-2940-1, PPNP114(2020)103810

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**

NaI(Tl) scintillating detectors

These experiments were motivated to reproduce the more-than-20-years DAMA results. They are at well different R&D stages, not at the same sensitivity and with marginal exposureswith respect to the total one released by DAMA so far.

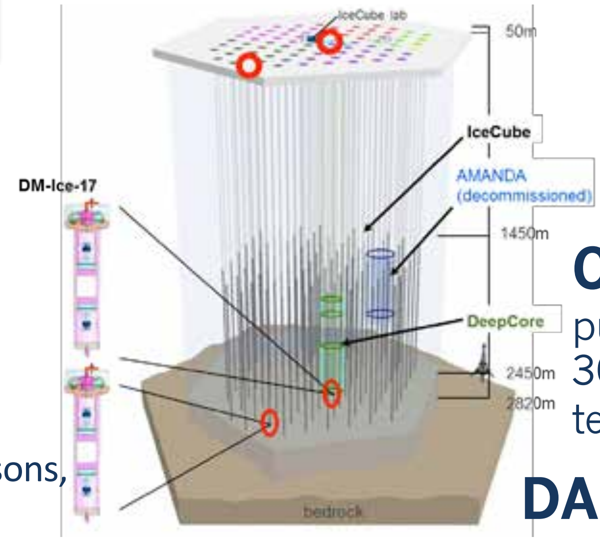
ANAIS-112: 3×3 matrix of NaI(Tl) scintillators 12.5 kg each to study DM annual modulation at Canfranc (LSC); 1.5 yr of data taking released (exposure: 157.55 kg x yr)

COSINE-100: Yangyang (Y2L), Korea, after KIMS, joining COSINE ≈100 kg NaI in Y2L, released 1.7 years collected with five of the eight crystals (60 kg) ⇒ 97.7 kg x yr.

COSINE-200: plan for a 200 kg set-up in progress.

Warning: PSD with CsI(Tl), NaI(Tl), … sometimes overestimated sensitivity; claimed high rejection power, but existing systematics drastically limit the realistic reachable sensitivity.

Key points: not only residual contaminants but also long-term/high-level stability, etc.



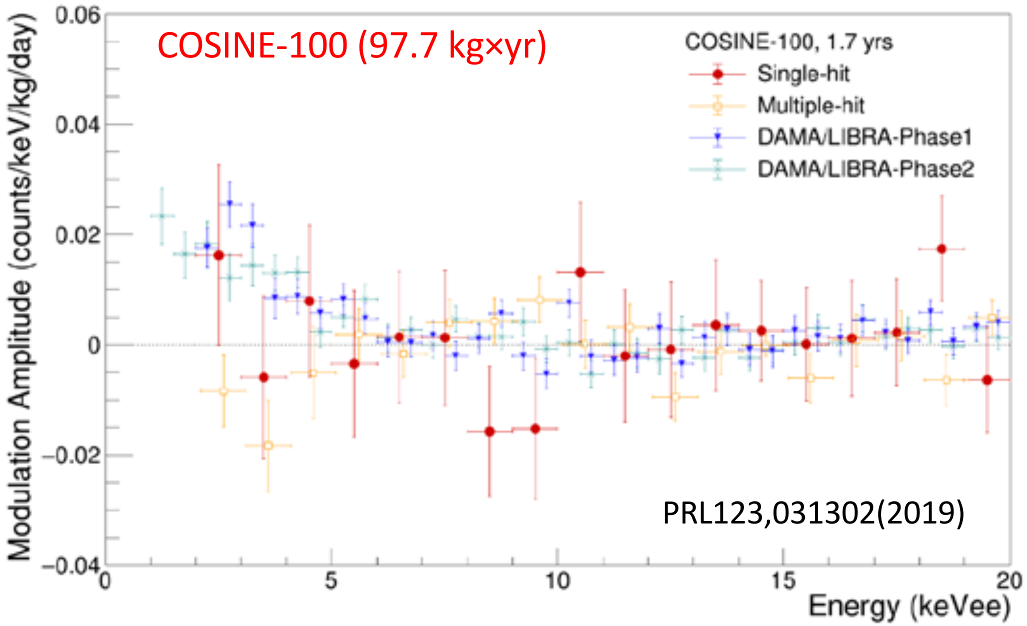
DM-ICE: NaI(Tl) deployed at the South Pole; exposure: 60.8 kg x yr

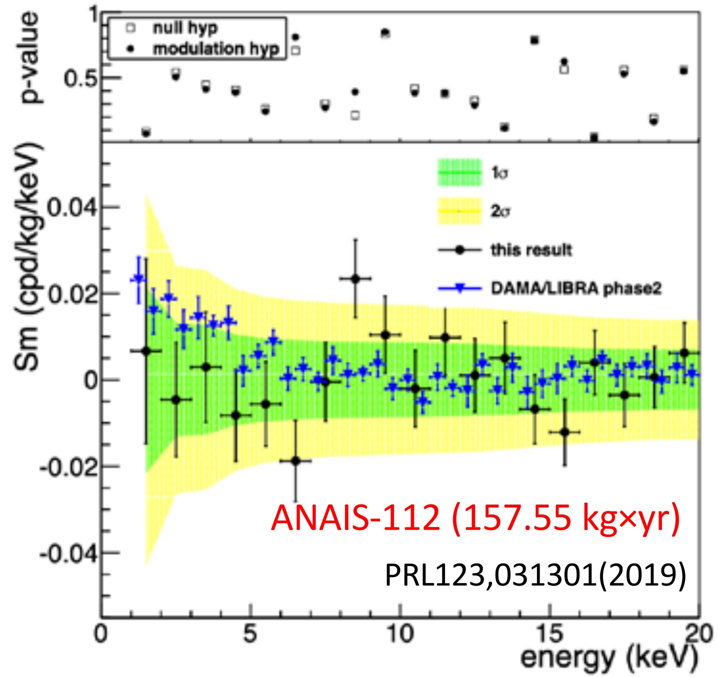
SABRE: two sites: LNGS in Northern and SUPL in Southern hemisphere (but the DM annual modulation does not depend on seasons, i.e. on the hemisphere); Proof of Principle (PoP) taking data

COSINUS: cryogenic calorimeters with pure NaI; dual readout; R&D phase 50 g to 300 g but scintillation different from standard temperature and doped conditions.

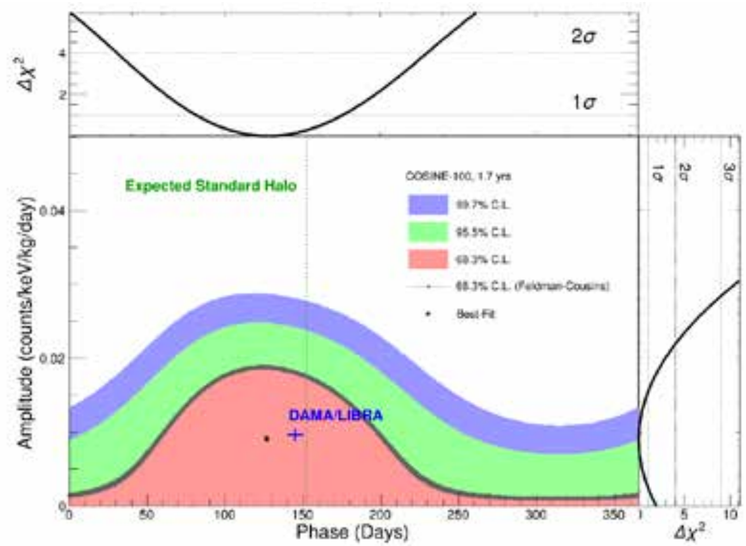
DAMA/LIBRA: towards further lowering the software energy threshold

Other annual modulation results with NaI(Tl)





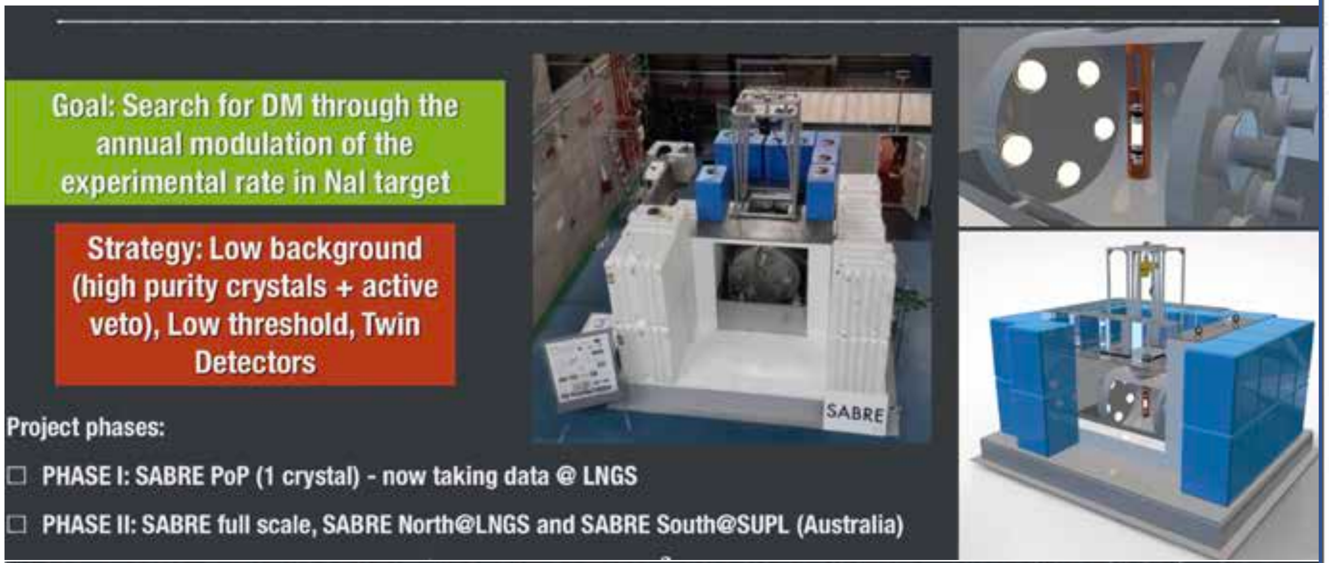
Energy interval	Experiment	Exposure ton x yr	Rate (cpd/kg/keV)	Amplitude (cpd/kg/keV)
(2,6) keV	DAMA/LIBRA (ph1 + ph2)	2.17	0.8	0.0095 ± 0.0008
	COSINE-100	0.098	3.0	0.0083 ± 0.0068
	ANAIS-112	0.16	3.2	- 0.0044 ± 0.0058
(1,6) keV	DAMA/LIBRA-phase2	1.13	0.7	0.0105 ± 0.0011
	ANAIS-112	0.16	3.6	- 0.0015 ± 0.0063



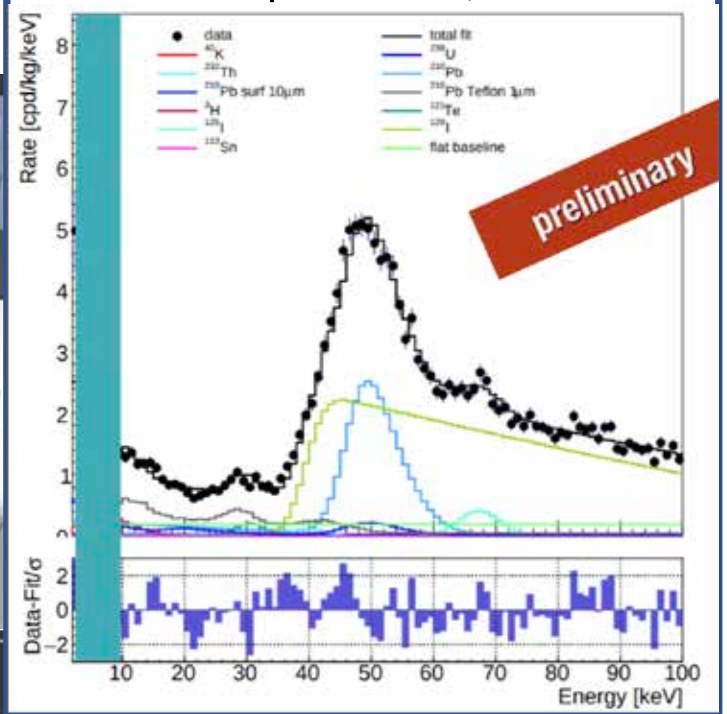
DAMA-LIBRA is still much better than any other NaI experiment for exposure time, for exposed mass, for background, and for energy threshold and control of all the experimental parameters

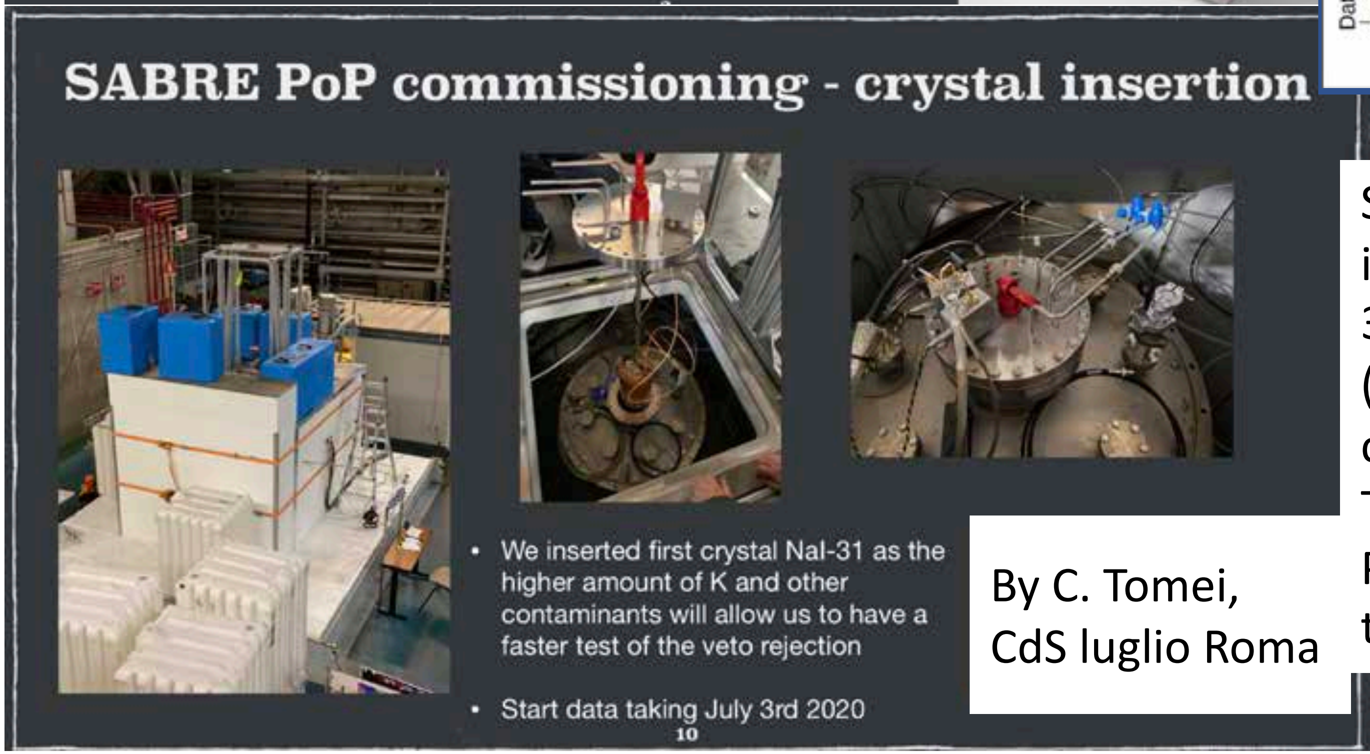
COSINE & ANAIS have not sufficient sensitivity to DAMA signal

SABRE



Test set-up in hall B, NaI-31





By C. Tomei, CdS luglio Roma

SABRE crystals: NaI-31(grown in a standard quartz crucible, 3.5 kg after polishing), NaI-33 (grown in a high purity crucible, 3.4 kg after polishing). They are are directly coupled to PMTs and mounted in a air-tight copper enclosure.

About interpretation

See e.g.: Riv.N.Cim.26 n.1(2003)1, IJMPD13(2004)2127, EPJC47(2006)263, IJMPA21(2006)1445, EPJC56(2008)333, PRD85(2012)095013,IJMPA28(2013)1330022, NPAE 20(2019)317, PPNP 114 (2020)103810

…models…

- Which particle?
- Which interaction coupling?
- Which Form Factors for each target-material?
- Which Spin Factor?
- Which nuclear model framework?
- Which scaling law?
- Which halo model, profile and related parameters?
- Streams?
- ...

…and experimental aspects…

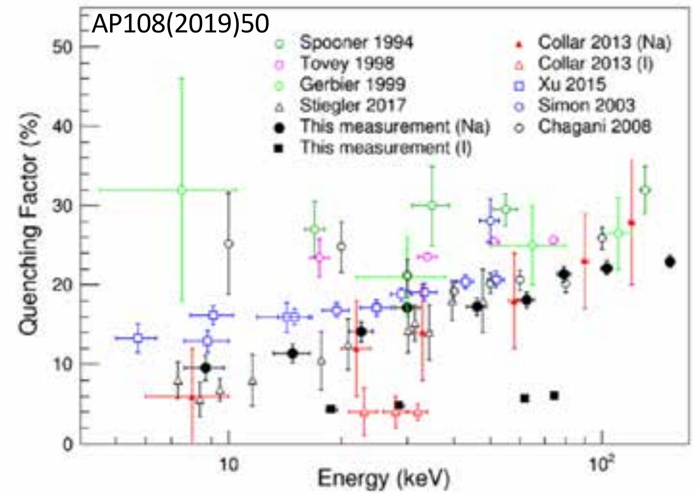
- Exposures
- Energy threshold
- Detector response(phe/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities
- Efficiencies
- Definition of fiducial volume and non-uniformity
- Quenching factors, channeling
- …

Uncertainty in experimental parameters, and necessary assumptions on various related astrophysical, nuclear and particle-physics aspects, affect all the results at various extent, both in terms of exclusion plots and in terms of allowed regions/volumes. Thus comparisons with a fixed set of assumptions and parameters' values are intrinsically strongly uncertain.

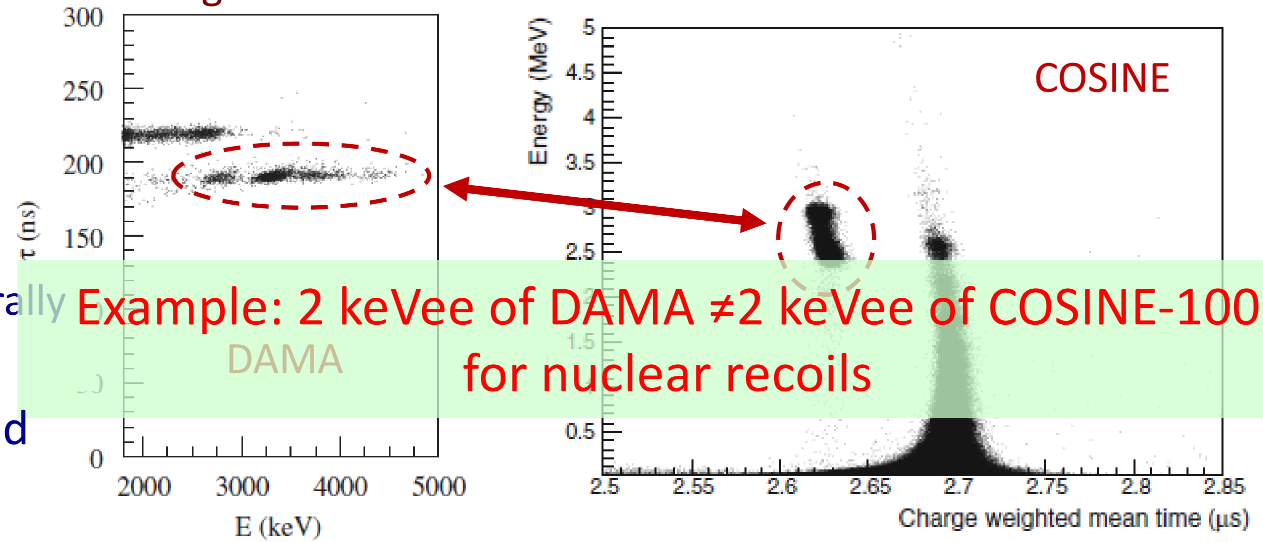
The case of the NaI(Tl) quenching factors (QF)

- ✓ The QFs are a property of the specific detector, particularly in the very low energy range.
- ✓ For example in NaI(Tl), QFs depend on the adopted growing procedures, on Tl concentration and uniformity in the detector, on the specific materials added in the growth, on the mono-crystalline or poly-crystalline nature of the detector, etc.
- ✓ Their measurements are difficult and always affected by significant experimental uncertainties.
- ✓ All these aspects are always relevant sources of uncertainties when comparing whatever results in terms of DM candidates inducing nuclear recoils.

+ QF depending on energy + channeling effects
+ Migdal effect



- A wide spread existing in literature for different NaI(Tl) productions
- This is also confirmed by the different α/β light ratio measured with DAMA and COSINE crystals. This implies much lower QFs at keV region for COSINE than DAMA.



Example: 2 keVee of DAMA ≠2 keVee of COSINE-100 for nuclear recoils

Alphas from ^{238}U and ^{232}Th chains span from 2.6 to 4.5 MeVee in DAMA, while from 2.3 to 3.0 MeVee in COSINE

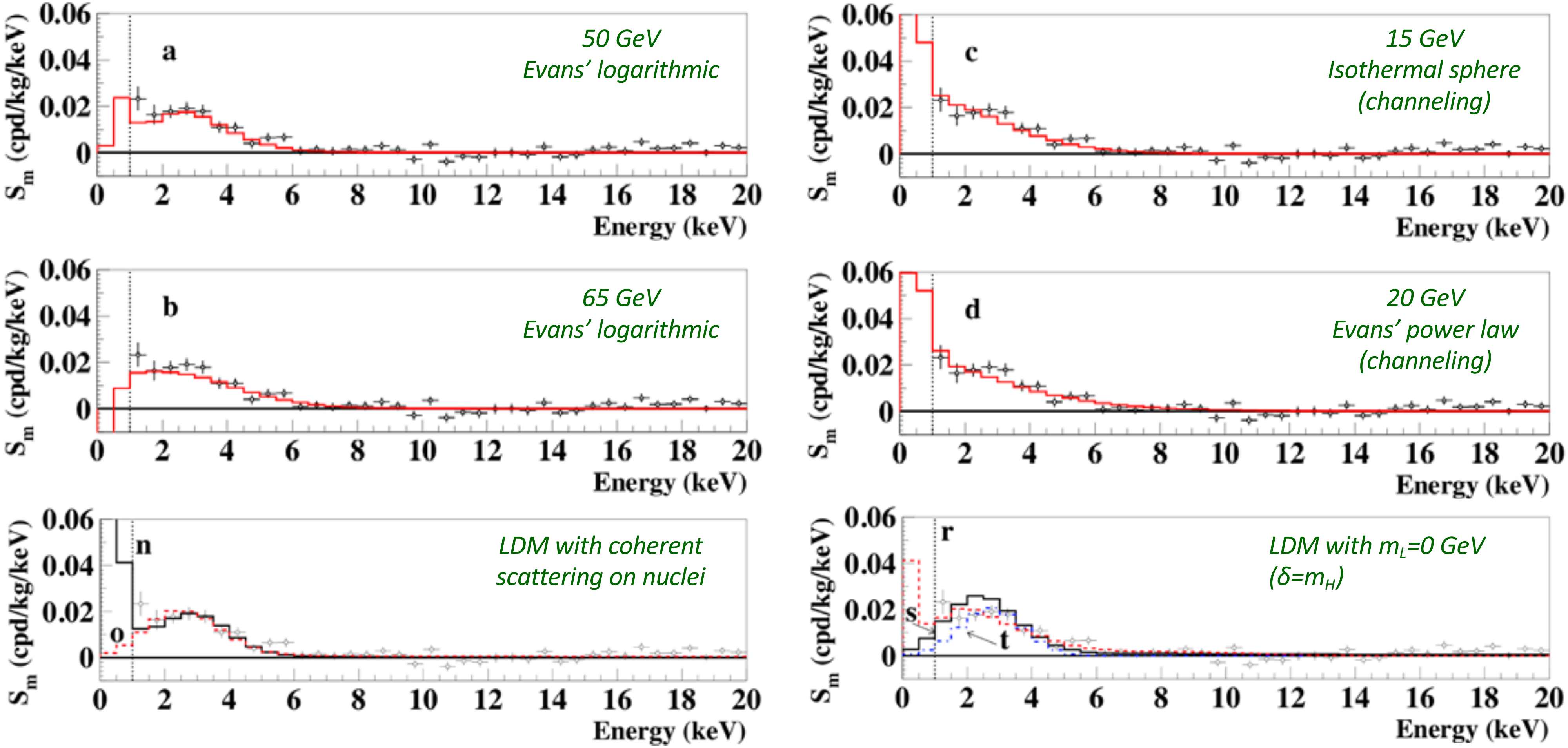
CURIOSITY: Recent productions (generally by Bridgman growth) yields low QF…

The model dependent analyses and comparisons must be performed using the QF **measured** for each detector.

Model-independent evidence by DAMA/NaI and DAMA/LIBRA-ph1, -ph2

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

Just few examples of interpretation of the annual modulation in terms of candidate particles in some model dependent scenarios



Examples of model-dependent analyses

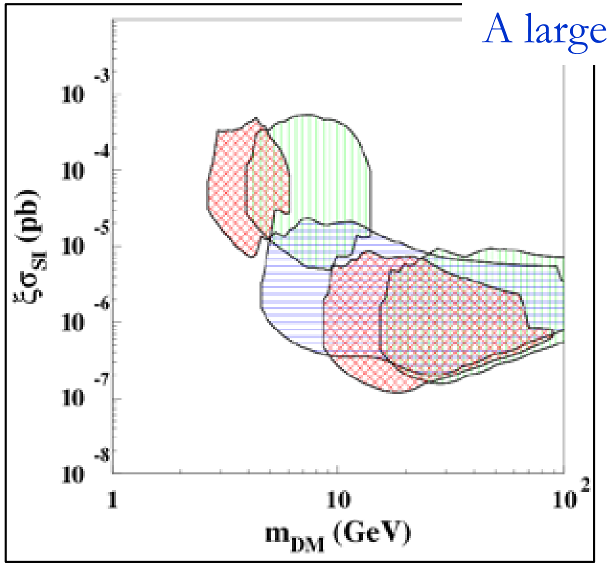
(after recent DAMA/LIBRA-ph2 data release

NPAE 20(4) (2019) 317, Bled works. in Phys. 20(2019)1, N. Cim. C 43 (2020) 23, PPNP 114 (2020)103810

A large (but not exhaustive) class of halo models and uncertainties are considered

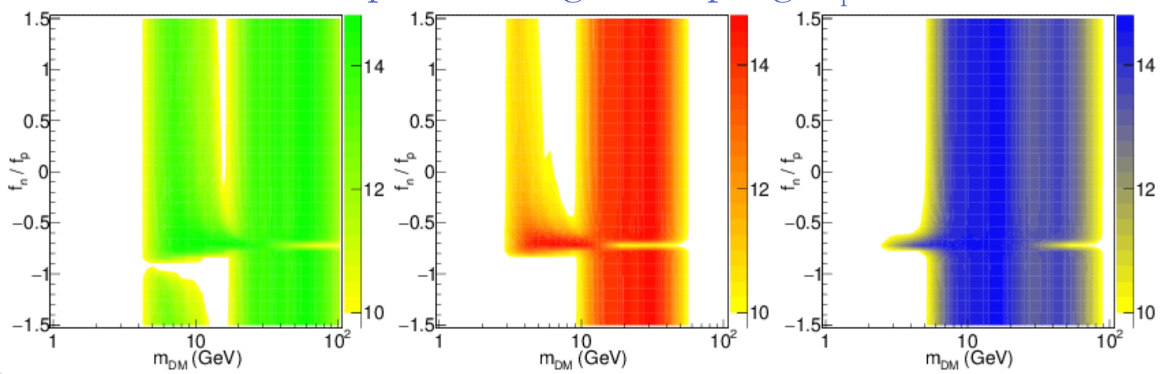
DM particles elastically scattering off target nuclei – SI interaction

$$\sigma_{SI}(A,Z) \propto m_{red}^{2}(A,DM)\left[f_p Z + f_n(A-Z)\right]^2$$

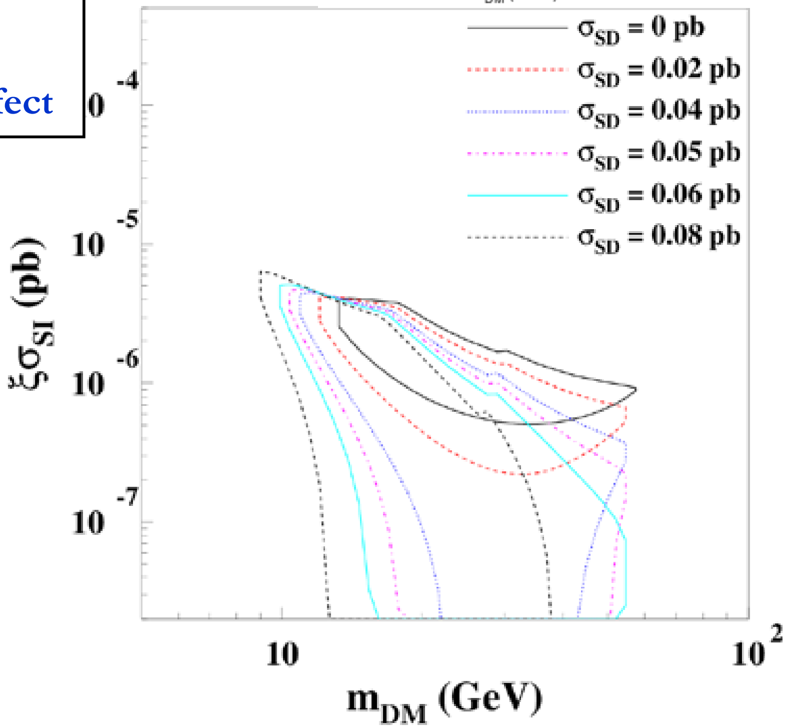


1. Constants q.f.
2. Varying q.f.(E_R)
3. With channeling effect

Case of isospin violating SI coupling: $f_p \neq f_n$



Even a relatively small SD (SI) contribution can drastically change the allowed region in the (m_{DM}, $\xi\sigma_{SI(SD)}$) plane



- Two bands at low mass and at higher mass;
- Good fit for low mass DM candidates at $f_n/f_p \approx -53/74 = -0.72$ (signal mostly due to ^{23}Na recoils).
- The inclusion of the uncertainties related to halo models, quenching factors, channeling effect, nuclear form factors, etc., can also support for $f_n/f_p=1$ low mass DM candidates either including or not the channeling effect.
- The case of isospin-conserving $f_n/f_p=1$ is well supported at different extent both at lower and larger mass.

DAMA/LIBRA: main last activities

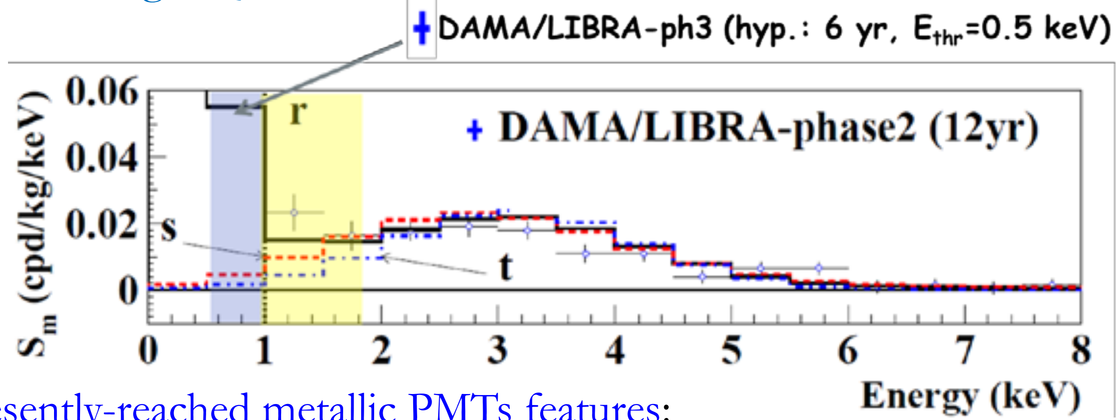
1) DAMA/LIBRA-phase2 is continuing its data taking.
2) Model dependent corollary analyses for DM particles also including DAMA/LIBRA-phase2 results published and presented at conferences/seminars.
3) New electronic modules to further improve the performance of the experiment at low energy developed.
4) R&D studies towards the lowering of the software energy threshold below 1 keV with high overall efficiency have been progressed:
   - The new system voltage divider with preamplifier on the same base has been applied.
   - 8 new metallic PMTs developed by HAMAMATSU: R11065-20MOD have been installed in DAMA/LIBRA set-up.
   - Tests are ongoing.
   - Alternative cheap possibilities in DAMA/LIBRA-phase2 are under study too.
5) Studies on other DM features or second order effects, and other rare processes (also with dedicated data taking) in progress.

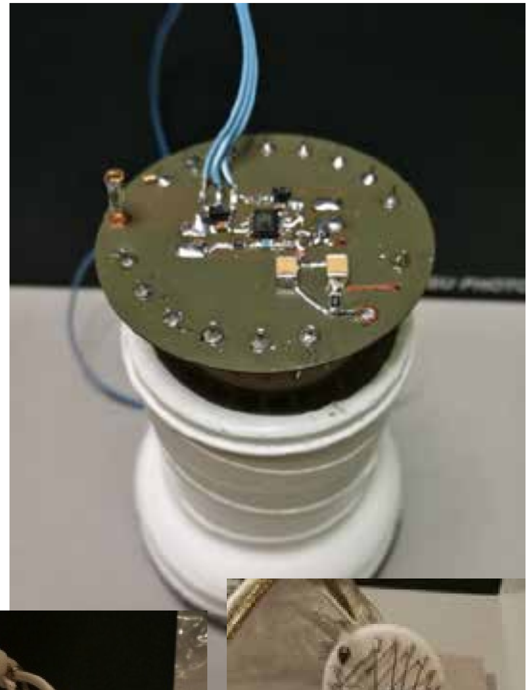
Upgraded DAMA/LIBRA can play an unique role in the future, both in the investigation of DM peculiarities and in the search for rare processes

On the R&D in progress

to lower the software energy threshold below 1 keV with high overall efficiency

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).
- Dark counts < 100 Hz

The features of the voltage divider+preamp system:

S/N improvement ≈3.0-9.0, discrimination of the single ph.el. from electronic noise: 3 – 8, the Peak/Valley ratio: 4.7 - 11.6; residual radioactivity much lower than that of the single PMT.

If the tests will be satisfactory we plan to replace all PMTs, otherwise the electronics (TD + voltage divider + preamp.) upgrade is planned

- several prototypes from a dedicated R&D with HAMAMATSU at hand
- 4 DAMA/LIBRA detectors equipped with the new PMTs as required by CSN2 referees

Features of the DM signal

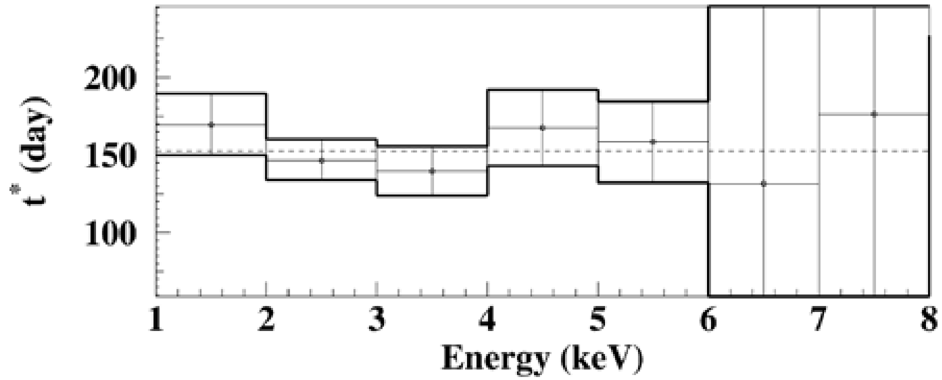
Investigated by the different stages of DAMA; advancements foreseen with further DAMA/LIBRA improvements

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

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

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

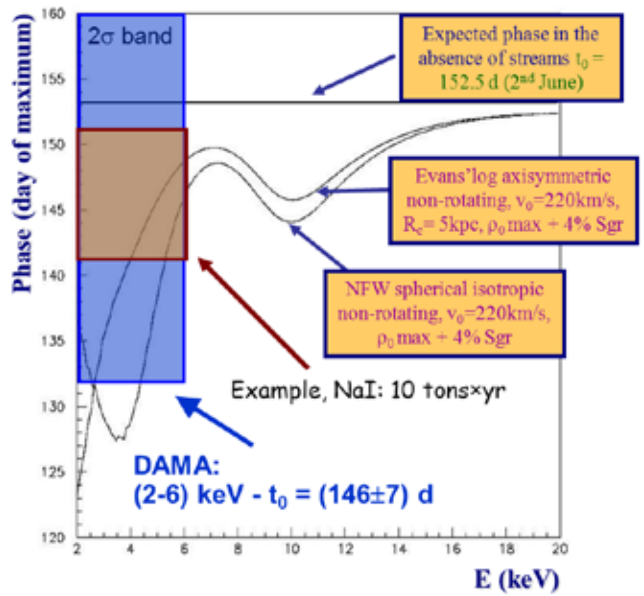
DAMA/NaI+LIBRA-phase2



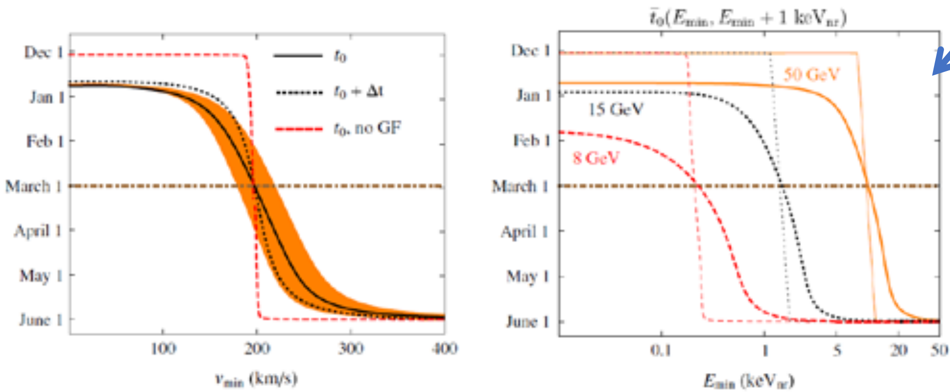
The annual modulation phase depends on :

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

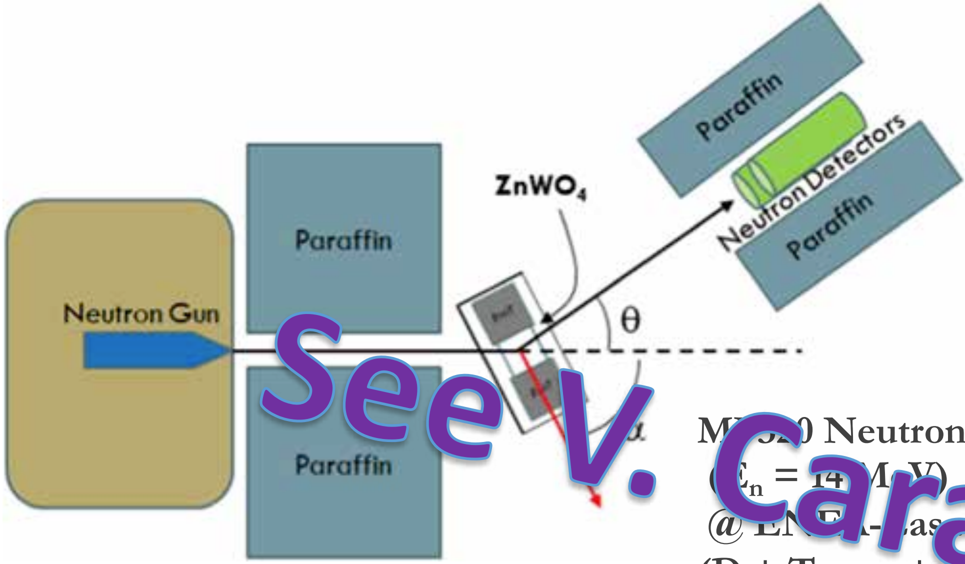
The effect of the streams on the phase depends on the galactic halo model



PRL112(2014)011301



Directionality: the ADAMO project



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

Eur. Phys. J. A 56 (2020) 83

Anisotropic scintillators can offer a unique possibility to exploit the directionality approach in order to investigate the presence of those Dark Matter candidates inducing nuclear recoils

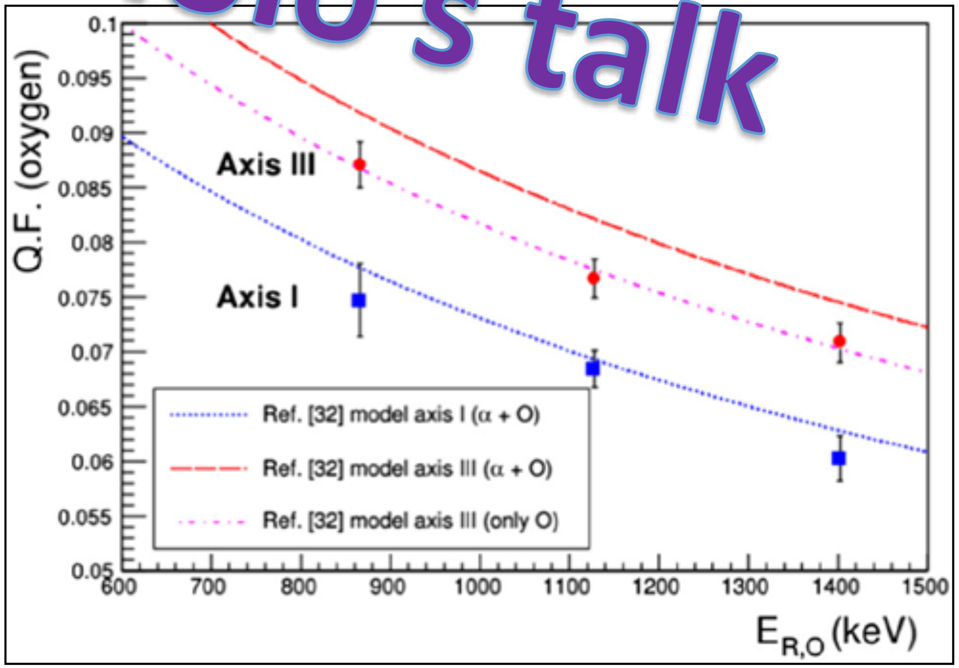
See V. Caracciolo's talk

A neutron generator at ENEA-CASACCIA Lab. and neutron detectors to tag the scattered neutrons have been used to measure the anisotropic response to nuclear recoils

Measure of quenching factors for nuclear recoils for different crystallographic axes and nuclear recoils energies

First measurement of anisotropy for recoils in energy region down to some hundreds keV (5.4 σ C.L.)

Further measurements with the same experimental set-up planned in the near future



Conclusions

- *DAMA model independent positive evidence further confirmed with full sensitivity to many kinds of DM candidates, interactions and overall scenarios*
- *DAMA/LIBRA phase-2 running and further R&D towards a lower energy threshold ongoing in order e.g. to determine modulation parameters with increased precision (in particular the phase wich carries important information) and to disentangle among different DM scenarios*
- *New investigations on different peculiarities of the DM signal exploited and in progress*

The model independent signature is the definite strategy to investigate the presence of Dark Matter component(s) in the Galactic halo