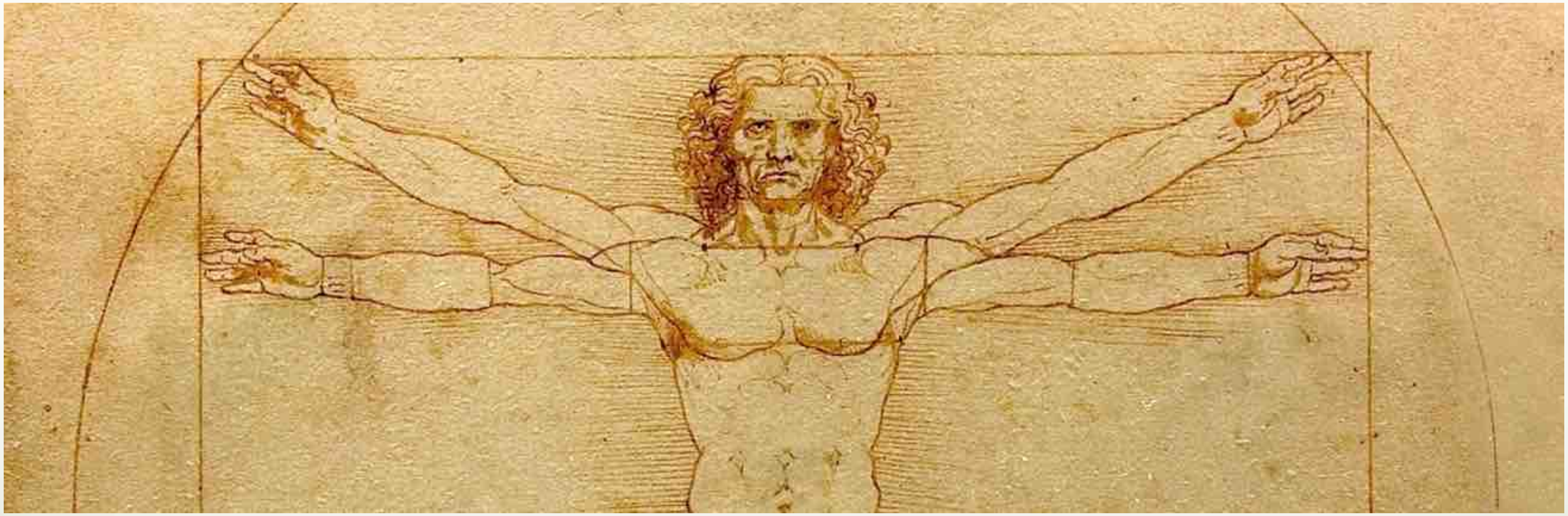
Direct Detection of Dark Matter particles



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INFN – Roma Tor Vergata

ICNFP 2019
8th Int. Conf. on New Frontiers in Physics
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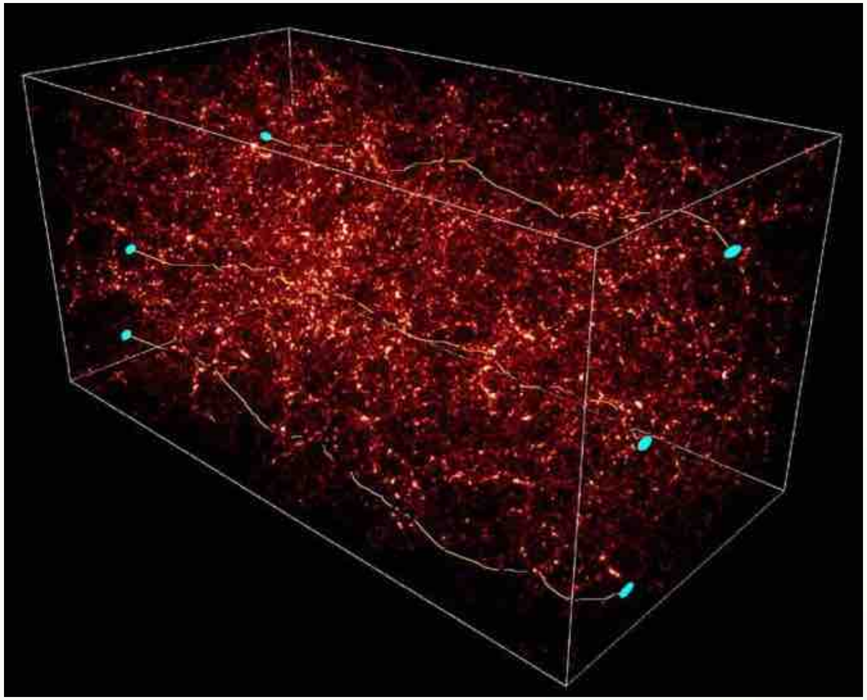
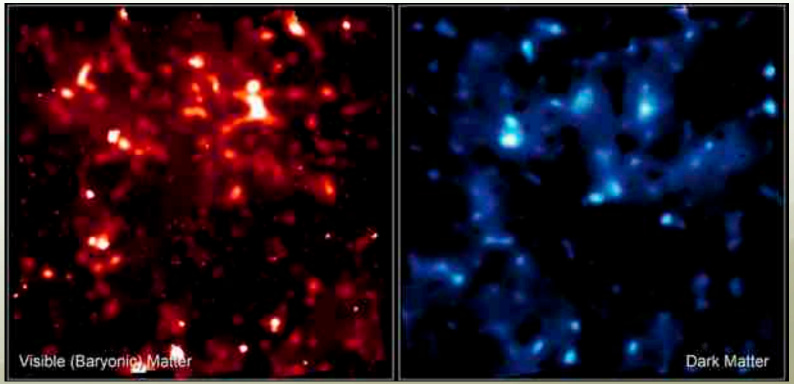
21-29 August 2019

The Dark Matter in the Universe

- A large part of the Universe is made of Dark Matter and Dark Energy
- The so-called "baryonic" matter is only ≈5% of the total budget
- (Concordance) ΛCDM model and precision cosmology
- The Dark Matter is fundamental for the formation of the structures and galaxies in the Universe
- Non-baryonic Cold Dark Matter is the dominant component (≈27%) among the matter.
- CDM particles, possibly relics from Big Bang, with no em and color charges → beyond the SM





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

etc...

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

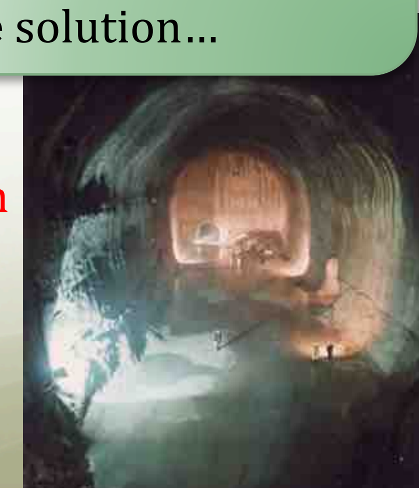
invisible axions, ν’s

What accelerators can do:
to demostrate the existence of
some of the possible DM candidates

What accelerators cannot do:
to credit that a certain particle is the
Dark Matter solution or the “single”
Dark Matter particle solution…

+ DM candidates and scenarios exist (even for neutralino
candidate) on which accelerators cannot give any information

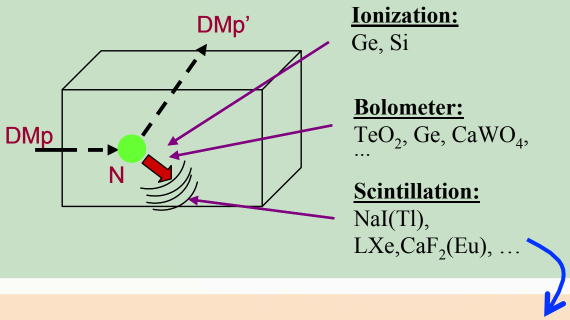
DM direct detection method using a model
independent approach and a low-background
widely-sensitive target material



Some direct detection processes:

- Scatterings on nuclei

  → detection of nuclear recoil energy



- Inelastic Dark Matter: **W + N → W* + N**

  → W has 2 mass states $\chi+$, $\chi-$ with δ mass splitting

  → Kinematical constraint for the inelastic scattering of $\chi-$ on a nucleus

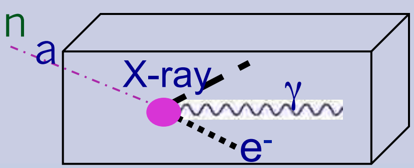
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei

  → detection of recoil nuclei + e.m. radiation

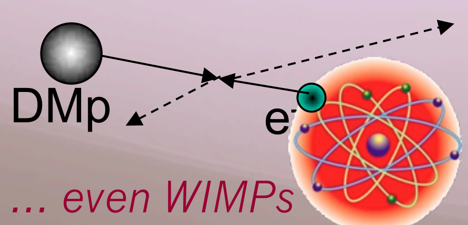
- Conversion of particle into e.m. radiation

  → detection of γ, X-rays, e^-



- Interaction only on atomic electrons

  → detection of e.m. radiation

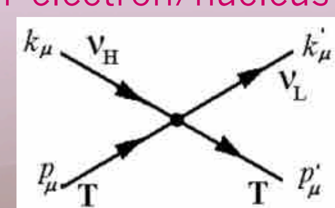


… even WIMPs

- 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 …

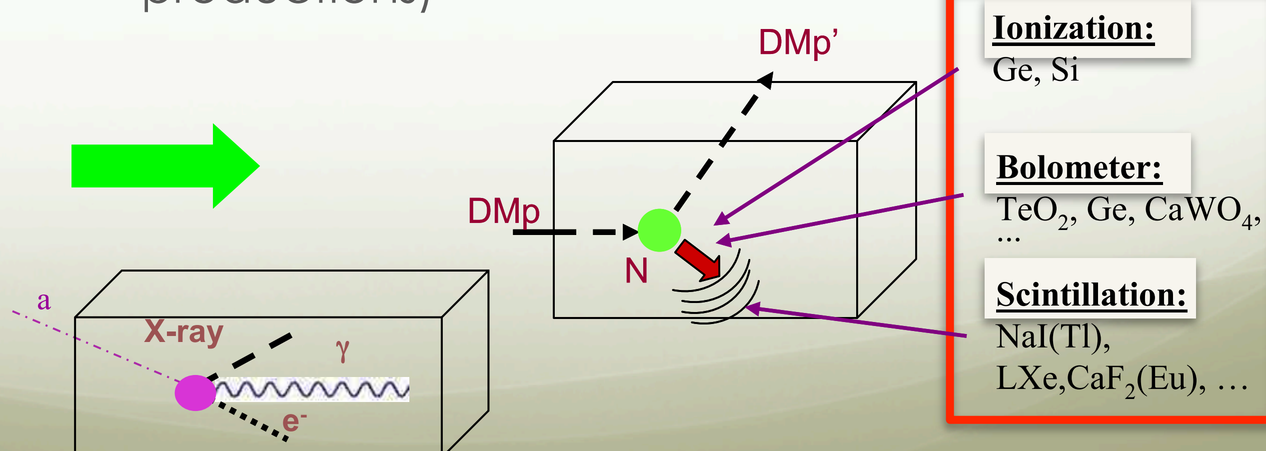
- **… and more**

Direct detection experiments

The direct detection experiments can be classified in **two classes**, depending on what they are based:

1. on the recognition of the signals due to Dark Matter particles with respect to the background by using a ***model-independent*** **signature**

2. on the use of uncertain techniques of statistical **subtractions** of the e.m. component **of the counting rate** (adding systematical effects and lost of candidates with pure electromagnetic productions)



Direct detection experiments

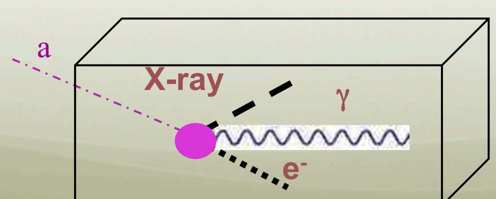
Summarizing, the detectors for DM:

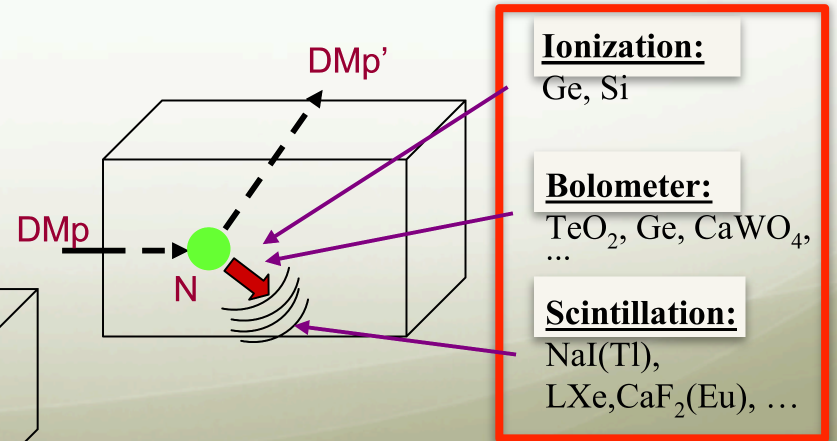
- must have very low-energy thresholds (order of keV at least)
- must have very low intrinsic bckg
- must be well shielded by external environmental radiation (muons, neutrons, gammas, ...)
- must be stable with time
- must have very good experimental features (energy resolution, check of the energy scale, uniformity of the detector, and many others)

Many techniques/experiments on the market:

- Scintillation detectors: NaI(Tl) ...
- Liquid noble gases: LXe, LAr, LNe
- Bolometers (heat vs ionization): Ge, Si
- Bolometers (heat vs scintillation): $CaWO_4$
- Ionization detectors: Ge
- and others…

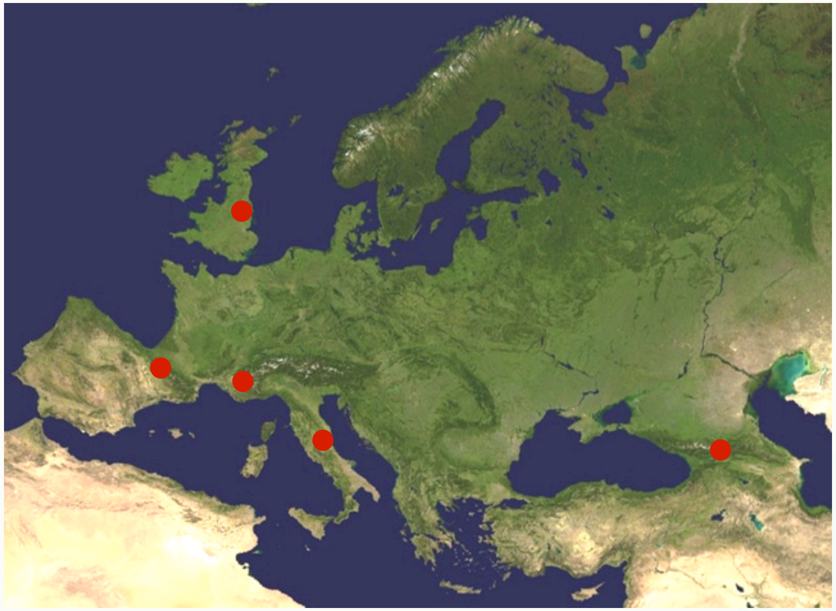
For some other novel techniques see the next talk of A. Drukier





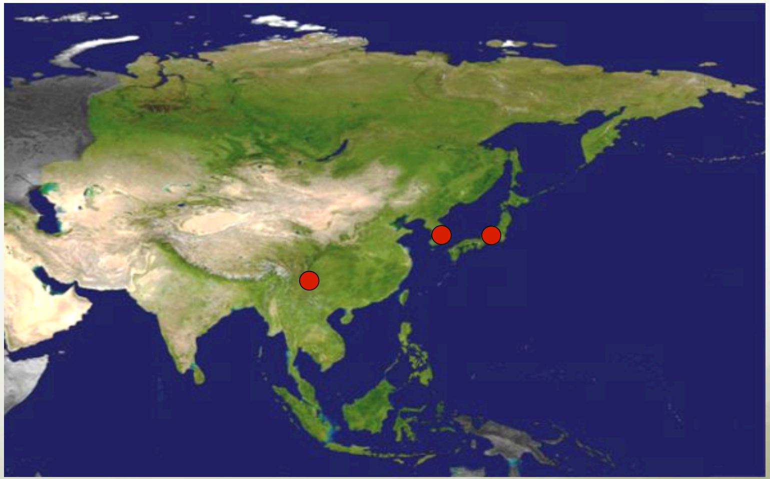
Dark Matter direct detection activities in underground labs

- Various approaches and techniques
- Various different target materials
- Various different experimental site depths
- Different radiopurity levels, etc.



- **Gran Sasso (depth ~ 3600 m.w.e.): DAMA/NaI, DAMA/LIBRA, DAMA/LXe, HDMS, WARP, CRESST, CUORE, XENON, DarkSide, SABRE, Cosinus, NEWSdm, CYGNO**
- **Boulby (depth ~ 3000 m.w.e.): DRIFT, Zeplin, NAIAD**
- **Modane (depth ~ 4800 m.w.e.): Edelweiss, DAMIC-M**
- **Canfranc (depth ~ 2500 m.w.e.): ANAIS, Rosebud, ArDM**

- **SNOlab (~ 6000 m.w.e.): Picasso, Coupp, PICO, DEAP, CLEAN, SuperCDMS, DAMIC, NEWS-G**
- **Stanford (~10 m): CDMS I**
- **Soudan (~ 2000 m.w.e.): CDMS II, SuperCDMS, CoGeNT**
- **SURF (~4400 m.w.e.): LUX-Zeplin, MALBEK**
- **WIPP (~1600 m.w.e.): DMTPC**
- **South Pole: DM-ICE**



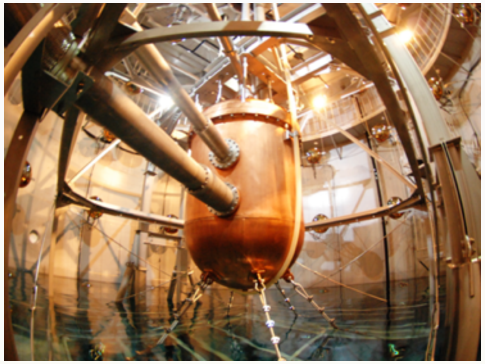
- **Y2L (depth ~ 700 m): COSINE-100/KIMS**
- **KAMIOKA: PICO-LON, NEWAGE, XMASS**
- **CJPL (depth ~6700 m.w.e.): Texono, CDEX, PANDAX**

Experiments using liquid noble gases

PSD in single phase detector:

- pulse shape discrimination γ/recoils from the UV scintillation photons

DAMA/LXe

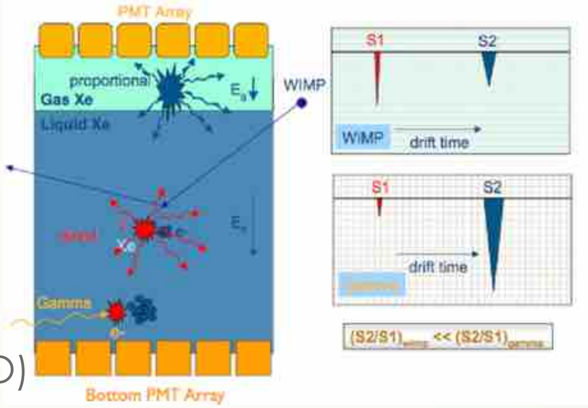


XMASS

in dual phase detector:

- prompt signal (S1): UV photons from excitation and ionization
- delayed signal (S2): e^- drifted into gas phase and secondary scintillation due to ionization in electric field

Statistical rejection of e.m. component of the counting rate

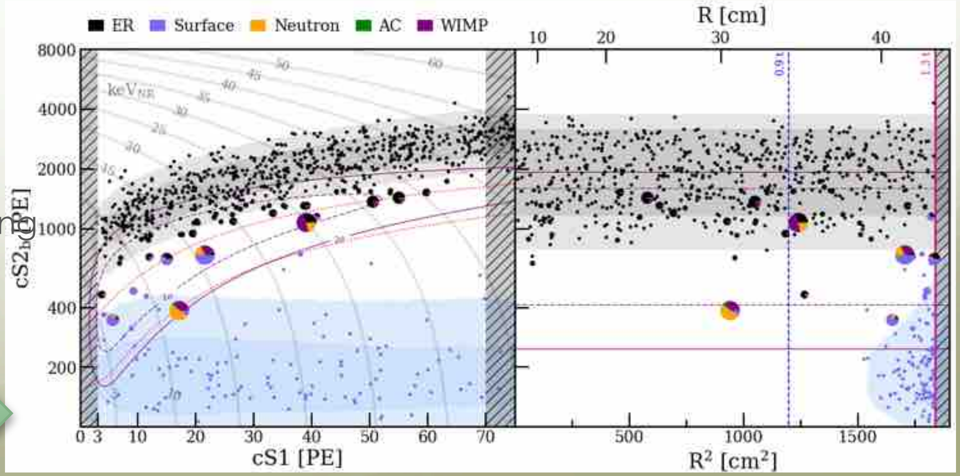


WARP, XENON10, -100, -1T, -nT, LUX, PANDAX, DarkSide-50, DEAP-3600, CLEAN, ArDM ➔ towards larger target masses (LZ, Darwin, DS-20k, ARGO)

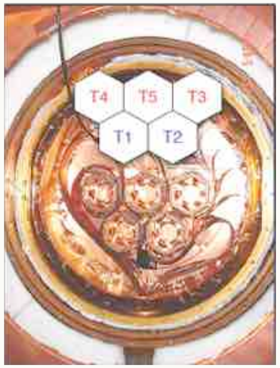
- **Non-uniform** response of detector: intrinsic limit
- **UV light**, **unlinearity** (more in larger volumes)
- **Correction** procedures applied; **Systematics**
- Physical **energy threshold not robust**
- Poor energy **resolution**
- **Light responses** for electrons and recoils at low energy
- **Quenching factors** measured with a much-more-performing detector **cannot be used** straightforward
- Etc.

Many cuts applied, each of them can introduce systematics. The systematics can be variable along the data taking period; can they and the related efficiencies be suitably evaluated in short period calibration?

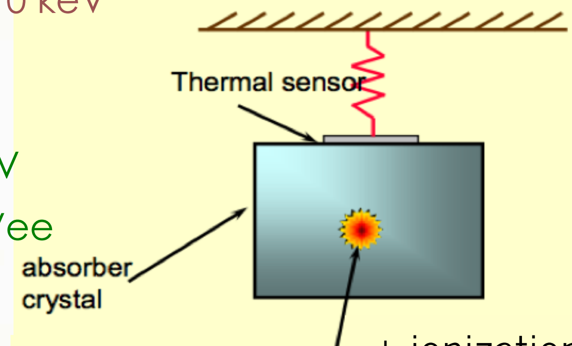
After many cuts few events survive: intrinsic limit reached?



Double read-out bolometric technique (ion. vs heat)



- CDMS-Ge: Soudan, 3.22 kg Ge, 194.1 kg x day; E_{th}=10 keV + other attemps at lower E_{th}
- SuperCDMS: Soudan, 9 kg Ge, 577 kg x day
- Edelweiss: LSM, 3.85 kg Ge, 384 kg x day; E_{th}=20 keV + search for low-mass WIMPs, ; E_{th}~1 keVee
- CDMS-Si: 1.2 kg Si, 140.2 kg x day; E_{th}=7 keV



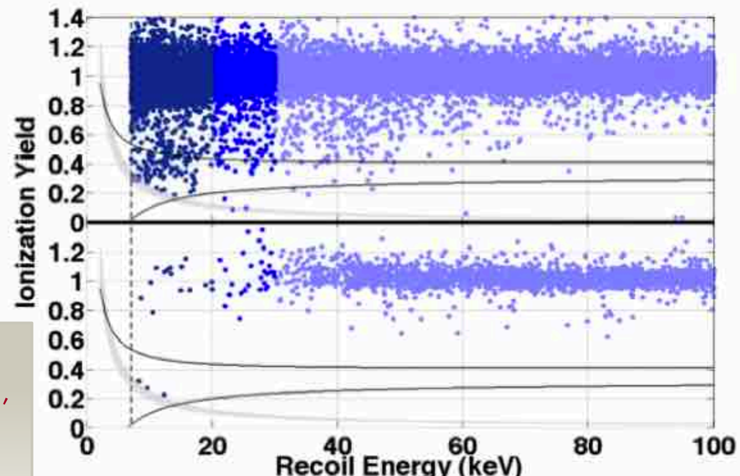
$$\Delta T = \frac{Q}{C_V}$$

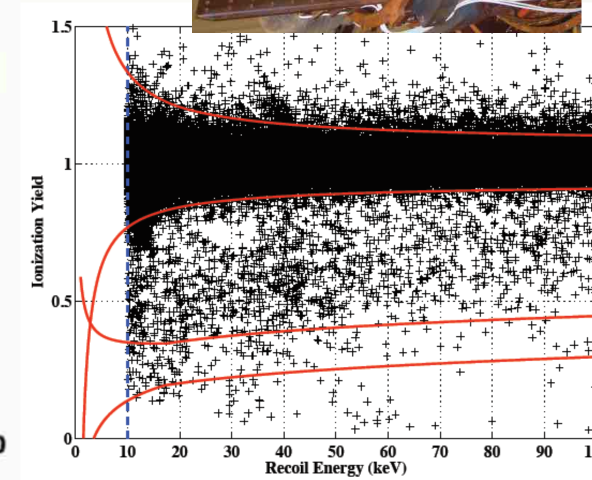
$$C_V = 1944 \frac{V}{V_m} \left(\frac{T}{\Theta}\right)^3 \text{ J/K}$$

Thermal sensors:
- superconductor thermistors (highly doped SC): NTD Ge → **EDELWEISS**
- superconducting transition sensors: TES → **CDMS**, **CRESST**

Towards low energy thresholds → **CDMSlite** (no charge collection, HV enhancement of the phonon signal (Neganov-Luke effect)

- **Many cuts on the data:** how about systematics?
- The **systematics** can be variable along the data taking period;
- **Poor detector performances:** many detectors excluded in the analysis
- **Critical stability of the performances**
- **Non-uniform** response of detector: intrinsic limit
- **Surface electrons:** PSD needed with related uncertainty

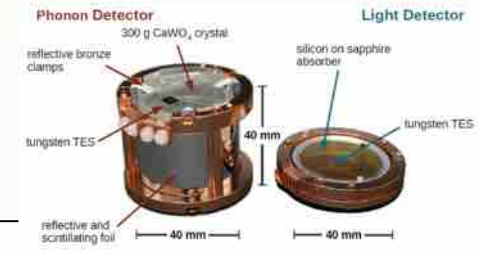


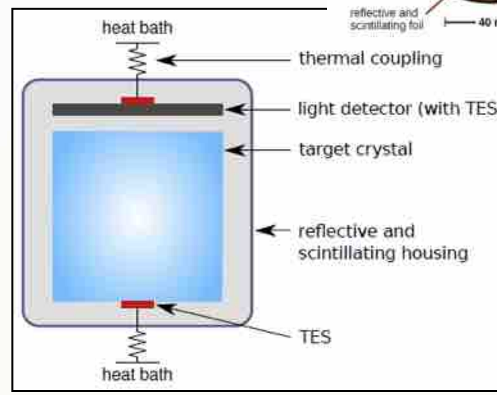


Anyhow, after many cuts few (two in CDMS-Ge, eleven in SuperCDMS, five in Edelweiss and three in CDMS-Si) events survive: positive hints or intrinsic limit reached?

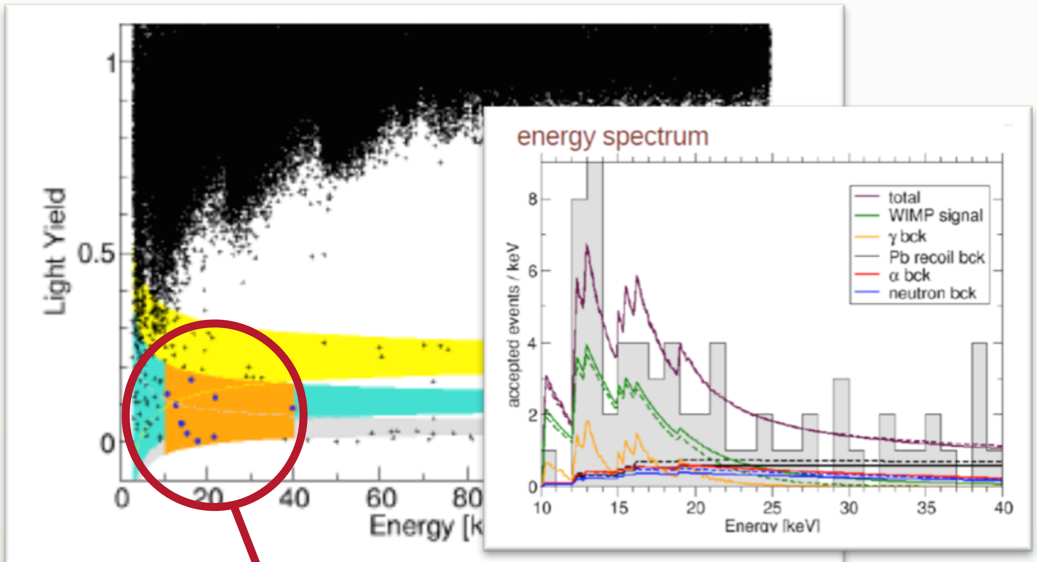
Double read-out bolometric technique (scintillation vs heat)

CRESST at LNGS: 33 $CaWO_4$ crystals (10 kg mass)
data from 8 detectors. Exposure: ≈ 730 kg x day





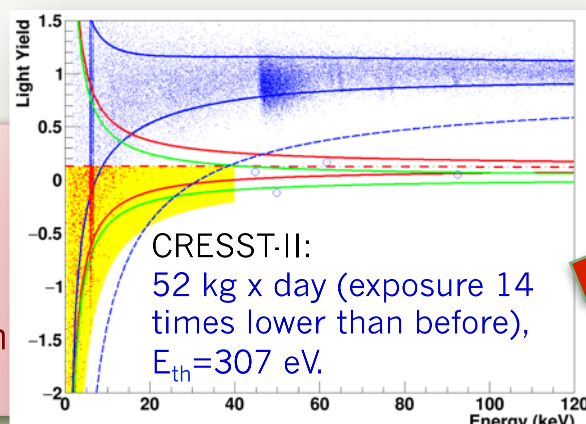
Data from one detector



Efficiencies + stability + calibration, crucial role

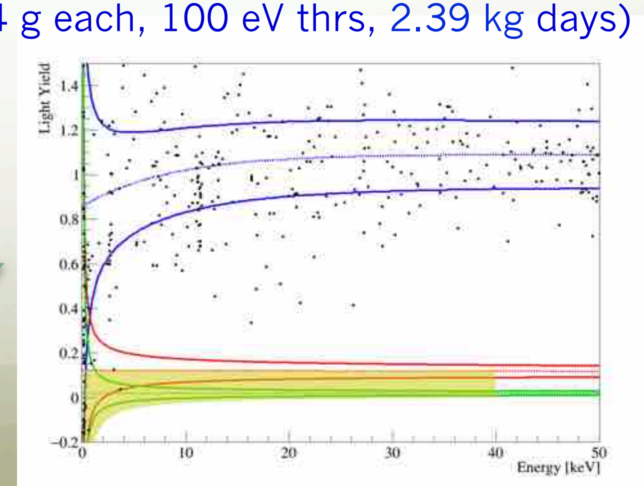
67 total events observed in O-band

Systematics in previous runs (?):
Following run with lower exposure and lower energy threshold does not confirm this 3.5σ excess!!!



CRESST-II:
52 kg x day (exposure 14 times lower than before), E_{th}=307 eV.

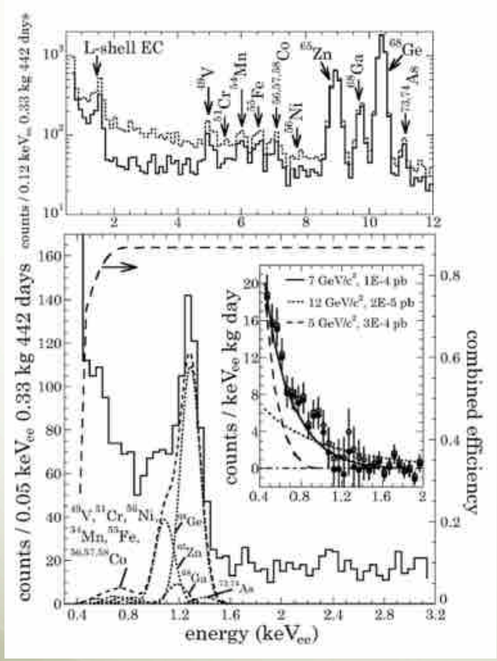
CRESST-III (new detector modules, 24 g each, 100 eV thrs, 2.39 kg days)



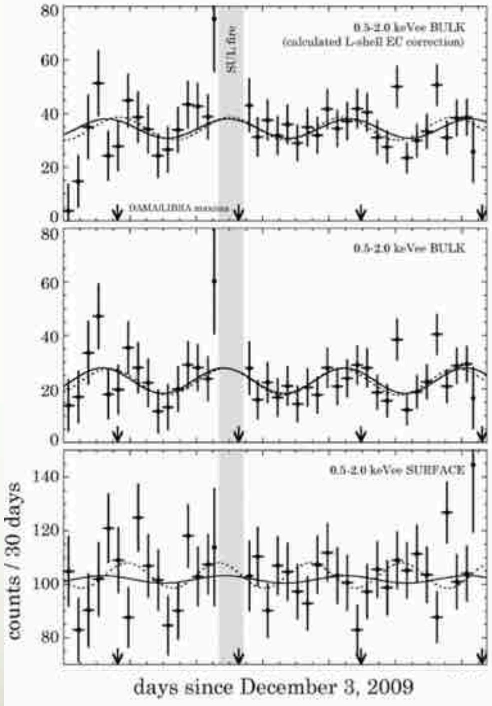
Positive hints from CoGeNT (ionization detector)

Experimental site:	Soudan Underground Lab (2100 mwe)
Detector:	440 g, p-type point contact (PPC) Ge diode 0.5 keVee energy threshold
Exposure:	146 kg x day (dec '09 - mar '11)

✓ **Irreducible excess** of bulk-like events below 3 keVee observed;



✓ **annual modulation** of the rate in 0.5-4.5 keVee at ~2.2σ C.L.



format. A straightforward analysis indicates a persistent annual modulation exclusively at low energy and for bulk events. Best-fit phase consistent with DAMA/LIBRA (small offset may be meaningful). Similar best-fit parameters to 15 mo dataset, but with much better bulk/surface separation (~90% SA for ~90% BR)

Unoptimized frequentist analysis yields ~2.2σ preference over null hypothesis. This however does not take into account the possible relevance of the modulation amplitude found...

Other Ge activity:
Texono, CDEX @ CJPL

- CoGeNT upgrade: C-4
- C-4 aims at x4 total mass increase, bckg decrease, and substantial threshold reduction. Soudan is still the lab

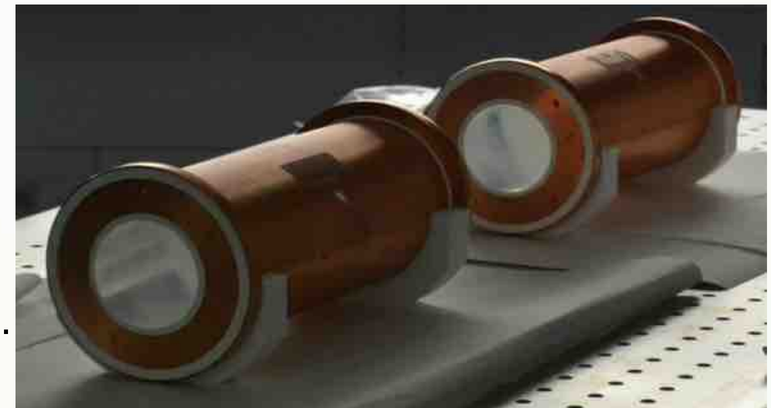
NaI(Tl) scintillating detectors

These experiments were motivated to reproduce the more-than-20-years DAMA results with its ULB NaI(Tl). They are at well different R&D stages. Intrinsically not enough sensitivity

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)

KIMS: CsI(Tl) crystals since 2000 at Yangyang (Y2L), Korea. Afterwards, KIMS-NaI joining Cosine

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

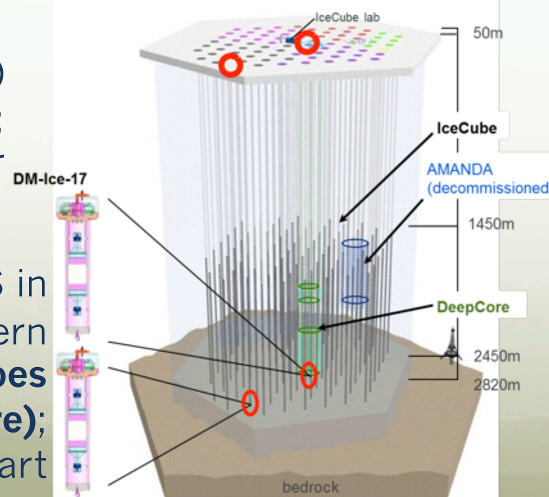


Warning: PSD with CsI(Tl), NaI(Tl), ... sometimes overestimated sensitivity; claimed high rejection power, but existing systematics drastically limit the reachable sensitivity.

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 effect does not depend on hemisphere)**; PoP (5 kg) ready to start



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.

+ picoLON

DAMA/LIBRA-phase3: R&D under completion

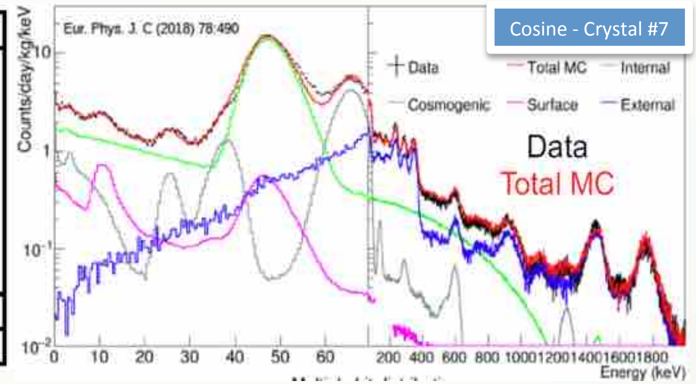
An example: how not to do to get a result (exclusion limits)
The case of COSINE-100

- The methodology of the background subtraction, used for example 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.

Very important discrepancies in the reconstruction of the structure at ≈ 45 keV, due to:

1. Missing contribute of ^{129}I (emended in a later paper, but not in the exclusion limits))
2. Overestimate contribute of ^{210}Pb

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**



- ✓ 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!

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<0.18 cpd/kg/keV in (2-4) keV (DAMA/LIBRA-phase2).

Cosine-100 low energy analysis is wrong and the exclusion limits are meaningless (published on Nature!!)

In conclusion: the methodology of the background subtraction is a **dangerous** way to claim sensitivities by the fact not supported by large counting rate

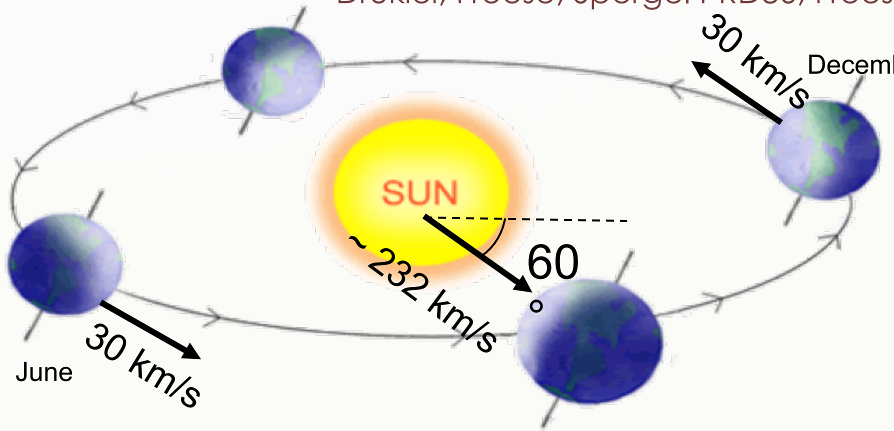
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

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.

Requirements of the 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

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)

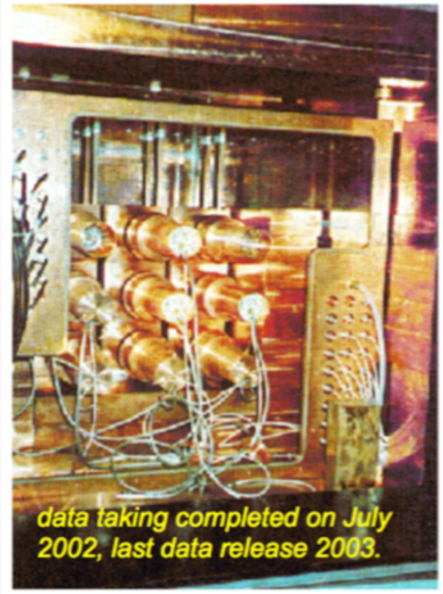
$$v_\oplus(t) = v_{sun} + v_{orb}\cos\gamma\cos[\omega(t-t_0)]$$

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

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 - obviously - be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

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



Performances:

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

Results on rare processes:

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

Results on DM particles:

- PSD — PLB389(1996)757
- Investigation on diurnal effect — N.Cim.A112(1999)1541
- Exotic Dark Matter search — PRL83(1999)4918
- **Annual Modulation Signature** — PLB424(1998)195, PLB450(1999)448, PRD61(1999)023512, PLB480(2000)23, EPJC18(2000)283, PLB509(2001)197, EPJC23(2002)61, PRD66(2002)043503, Riv.N.Cim.26 n.1 (2003)1, IJMPD13(2004)2127, IJMPA21(2006)1445, EPJC47(2006)263, IJMPA22(2007)3155, EPJC53(2008)205, PRD77(2008)023506, MPLA23(2008)2125

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

total exposure (7 annual cycles) 0.29 ton×yr

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

Perform

Results

- Poss
- CNC
- Elect
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- Sear
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- Sear
- Sear

Results

- PSD
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- **Ann**

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)

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

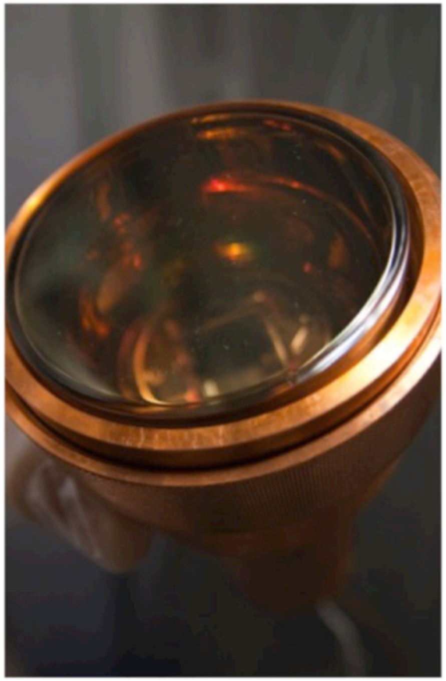
- Radiopurity, performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
- Results on DM particles,
  - Annual Modulation Signature: EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648.
  - Related results: PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022, EPJC74(2014)2827, EPJC74(2014)3196, 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

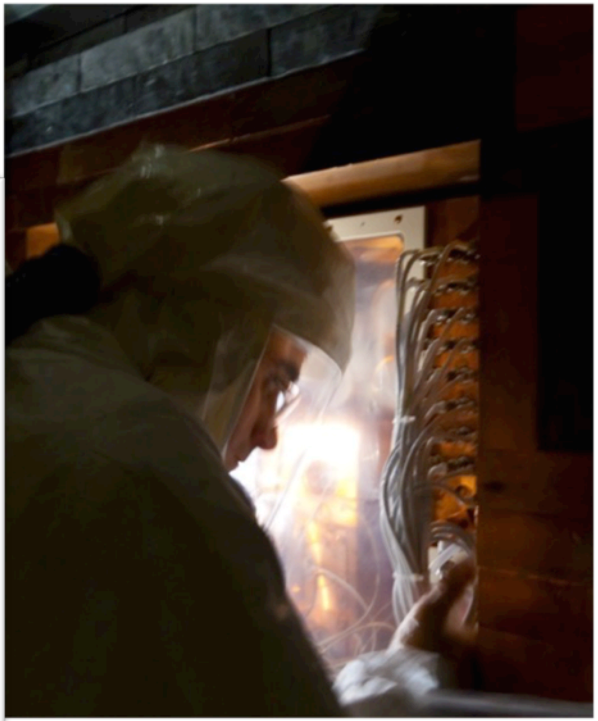
DAMA/LIBRA–phase1 (7 annual cycles, 1.04 ton×yr) confirmed the model-independent evidence of DM: reaching 9.3σ C.L.

DAMA/LIBRA–phase2

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

JINST 7(2012)03009
Universe 4 (2018) 116
NPAE 19 (2018) 307
Bled W. in Phys. 19, 2 (2018) 27
arXiv:1907.06405





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

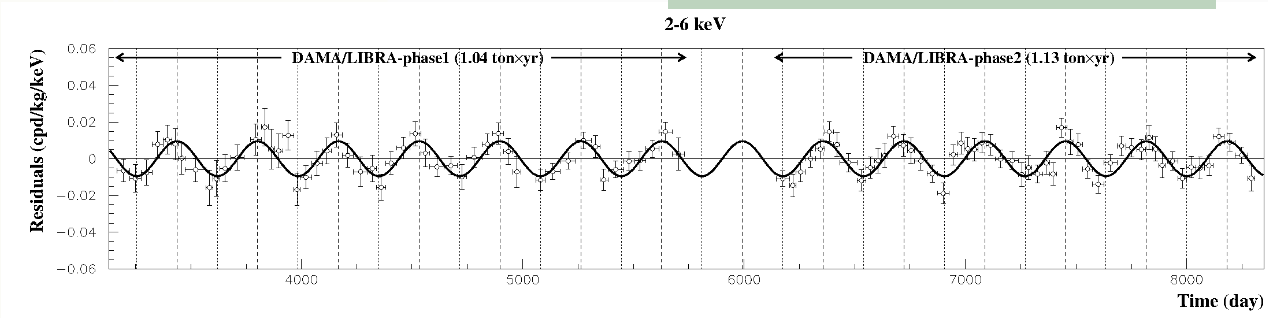
Model Independent Annual Modulation Result

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

Universe 4 (2018) 116; NPAE 19 (2018) 307

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

See Caracciolo's talk



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.

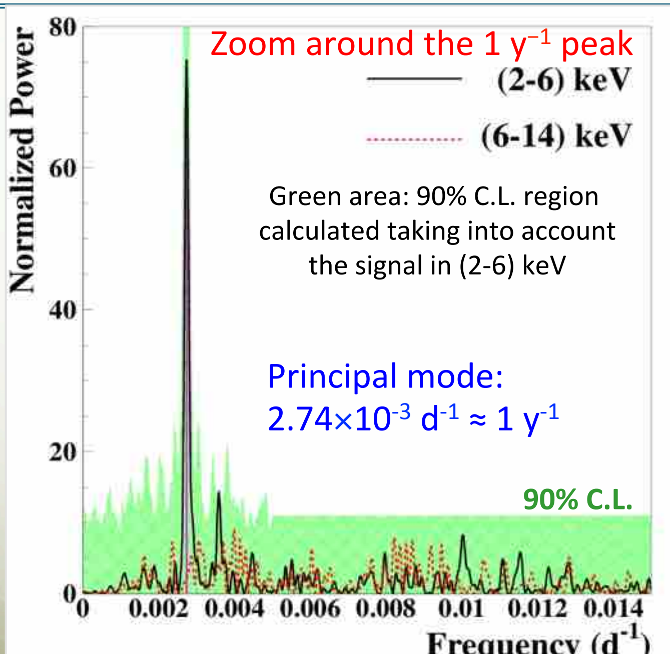
Absence of modulation? No

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

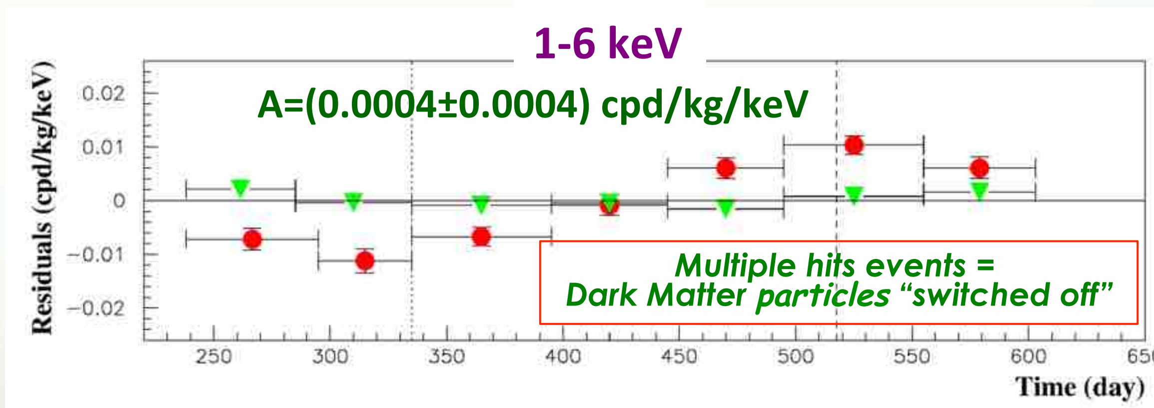
Fit with all the parameters free:

A = (0.0096 ± 0.0008) cpd/kg/keV

t_0 = (145±5)d - T = (0.9987±0.0008)y



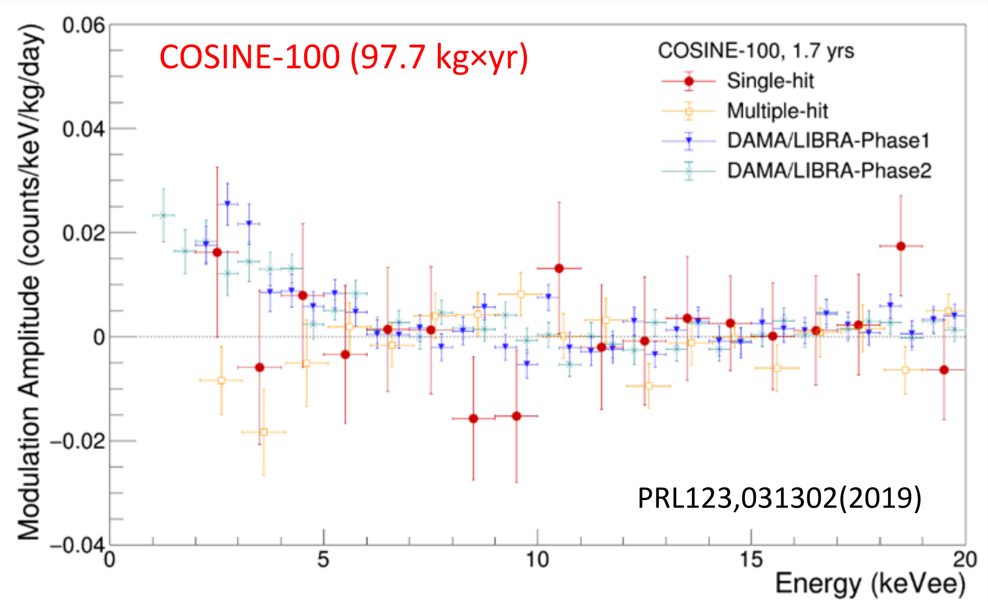
Comparison between **single hit residual rate (red points)** and **multiple hit residual rate (green points)**; Clear modulation in the single hit events; No modulation in the residual rate of the multiple hit events

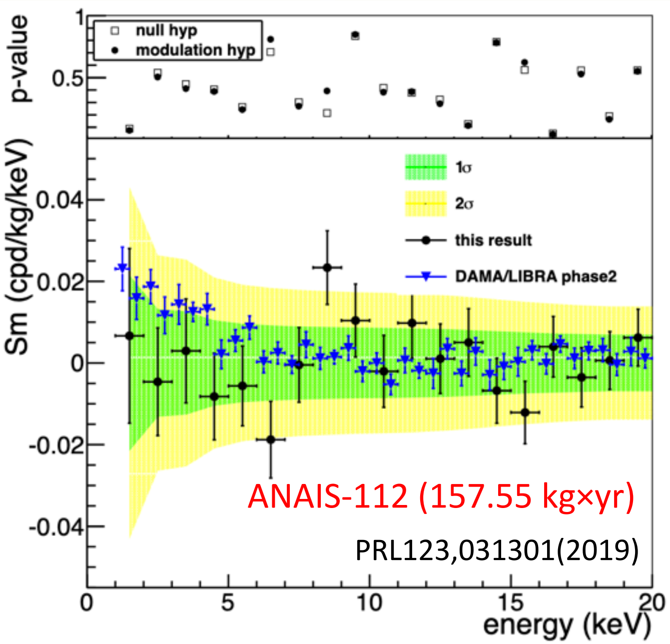


This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from bckg

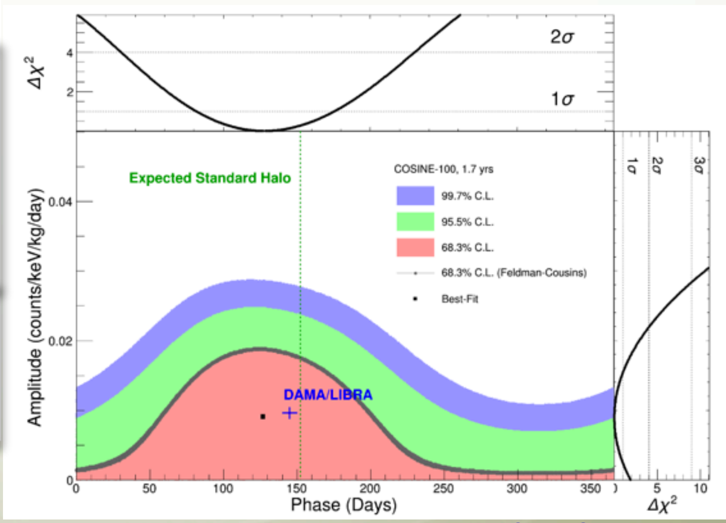
The data favour the presence of a modulated behaviour with all the proper features of DM particles in the galactic halo at high C.L.: 12.9 σ C.L. when including DAMA/NaI
+ No systematics or side processes able to mimic the signal available

Other annual modulation results with NaI(Tl)





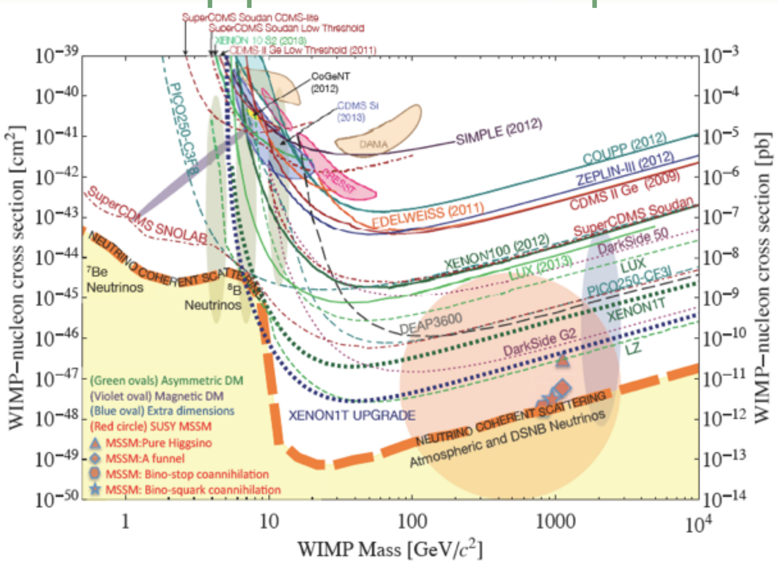
Energy interval	Experiment	Exposure ton x yr	Rate (cpd/ kg/keV)	Amplitude (cpd/ kg/keV)
(2,6) keV	DAMA/LIBRA (ph1 + ph2)	2.17	0.8	0.0095 ± 0.0008
	COSINE-100	0.098	3.0	0.0083 ± 0.0068
	ANAIS-112	0.16	3.2	- 0.0044 ± 0.0058
(1,6) keV	DAMA/LIBRA-phase2	1.13	0.7	0.0105 ± 0.0011
	ANAIS-112	0.16	3.6	- 0.0015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



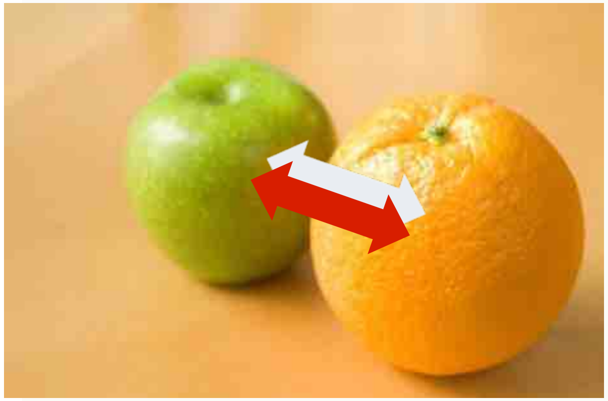
DAMA-LIBRA is still much better than any other NaI experiment for exposure time, for exposed mass, for background, and for energy threshold

COSINE & ANAIS sensitivity far from DAMA: data are compatible with DAMA, but also with null hypothesis

About Interpretation: is an “universal” and “correct” way to approach the problem of DM and comparisons?



No, it isn’t. This is just a largely arbitrary/partial/incorrect exercise



see e.g.: Riv.N.Cim.26 n. 1(2003)1, IJMPD 13 (2004) 2127, EPJC 47 (2006) 263, IJMPA 21 (2006) 1445, EPJC 56 (2008) 333, PRD 84 (2011) 055014, IJMPA 28 (2013) 1330022, arXiv: 1907.06405

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

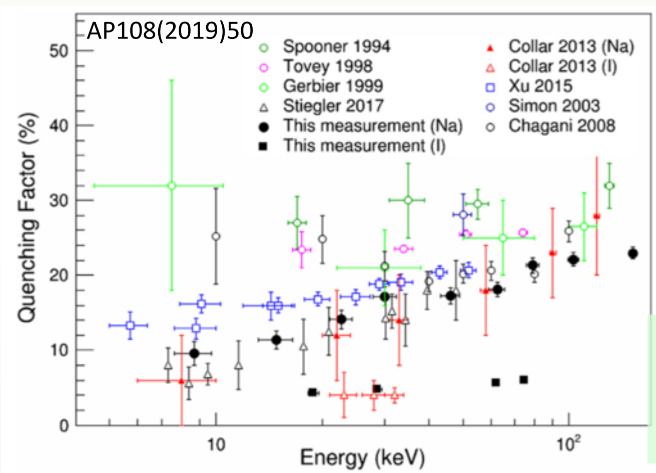
Uncertainty in experimental parameters, and necessary **assumptions** on various related astrophysical, nuclear and particle-physics aspects, affect all the results at various extent, both in terms of exclusion plots and in terms of allowed regions/volumes. Thus comparisons with **a fixed set** of assumptions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

No direct model-independent comparison among expts with different target-detectors and different approaches

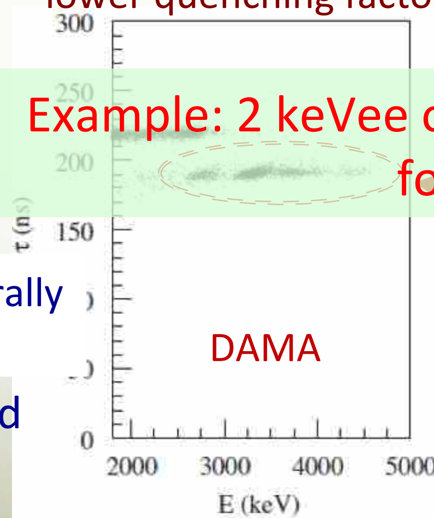
The case of the NaI(Tl) quenching factors (QF)

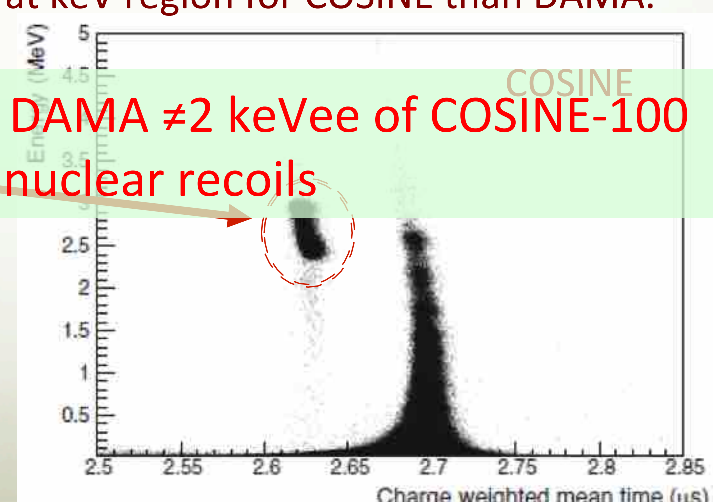
- ✓ The QFs are a property of the specific detector and not general property, particularly in the very low energy range.
- ✓ For example in NaI(Tl), QFs depend on the adopted growing procedures, on Tl concentration and uniformity in the detector, on the specific materials added in the growth, on the 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 NaI(Tl)
- This is also confirmed by the different α/β light ratio measured with DAMA and COSINE crystals. This implies much lower quenching factors at keV region for COSINE than DAMA.





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

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.

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

Examples of model-dependent analyses

DM particles elastically interacting with target nuclei - SI interaction

DAMA/NaI, DAMA/LIBRA-ph1 and ph2

arXiv:1907.06405

- A large (but not exhaustive) class of halo models is considered;
- Local velocity v_0 in the range [170,270] km/s;
- Halo density ρ depending on the halo model;
- v_{esc} = 550 km/s (no sizable differences if v_{esc} in the range [550, 650]km/s);
- For DM candidates inducing nuclear recoils: three different sets of values for the nuclear form factor and quenching factor parameters.

σ_{SI} SI point-like DM-nucleon cross section

ξ fractional amount of local density in terms of the considered DM candidate

The point-like SI cross section of DM particles scattering off (A,Z) nucleus:

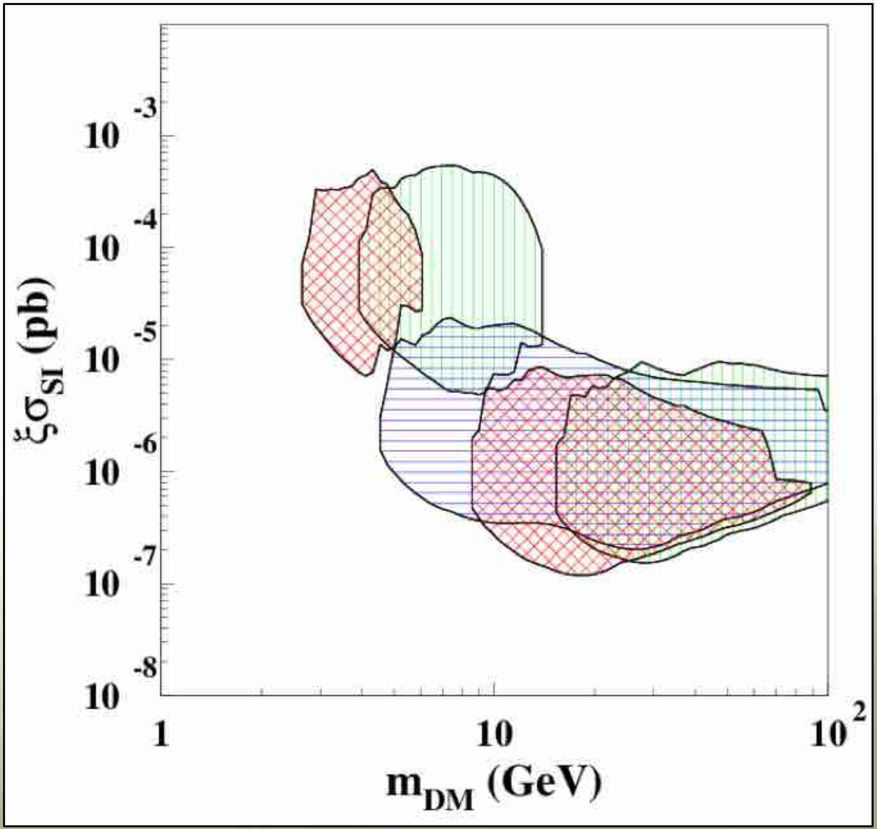
$$\sigma_{SI}(A,Z) \propto m_{red}^2(A,DM)\left[f_p Z + f_n(A-Z)\right]^2$$

where f_p, f_n are the effective DM particle couplings to protons and neutrons.

If $f_p=f_n$: $$\sigma_{SI}(A,Z) = \frac{m_{red}^2(A,DM)}{m_{red}^2(1,DM)} A^2 \sigma_{SI}$$

$\xi\sigma_{SI}$ vs m_{DM}

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



Allowed DAMA regions:
Domains where the likelihood-function values differ more than 10σ from absence of signal

Model-dependent analyses

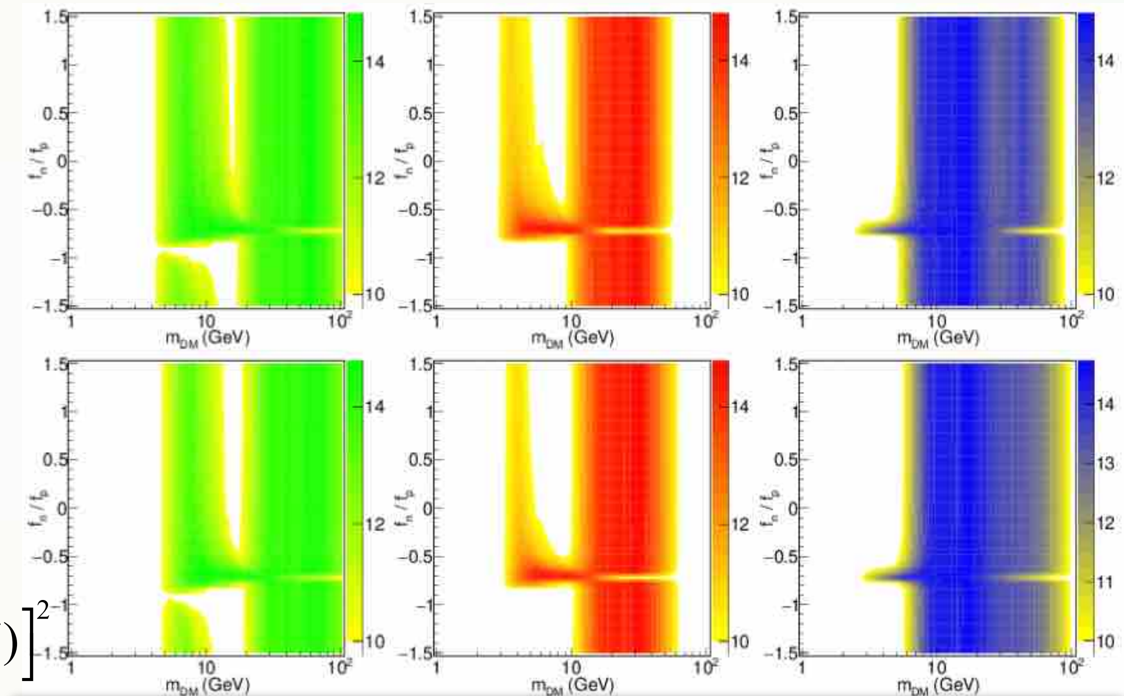
DM particles elastically interacting with target nuclei SI-IV interaction

DAMA/NaI, DAMA/LIBRA-ph1 and ph2

Case of isospin violating SI coupling:

$$f_p \neq f_n$$

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



f_n/f_p vs m_{DM}
marginalizing on $\xi\sigma_{SI}$

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

Allowed DAMA regions for A0 (isothermal sphere), B1, C1, D3 halo models (top to bottom)

- 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).
- Contrary to what was stated in Ref. [PLB789,262(2019), JCAP07,016(2018), JCAP05,074(2018)] where the low mass DM candidates were disfavored for f_n/f_p = 1 by DAMA data, the inclusion of the uncertainties related to halo models, quenching factors, channeling effect, nuclear form factors, etc., can also support 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.

Model-dependent analyses: other examples

arXiv:1907.06405

DM particles elastically interacting with target nuclei - purely SD interaction

Only possible for target nuclei with spin≠0 $\tan\vartheta = \dfrac{a_n}{a_p}, \quad \vartheta \text{ in } [0,\pi]$

a_p and a_n are the effective DM-nucleon coupling strengths for SD int.

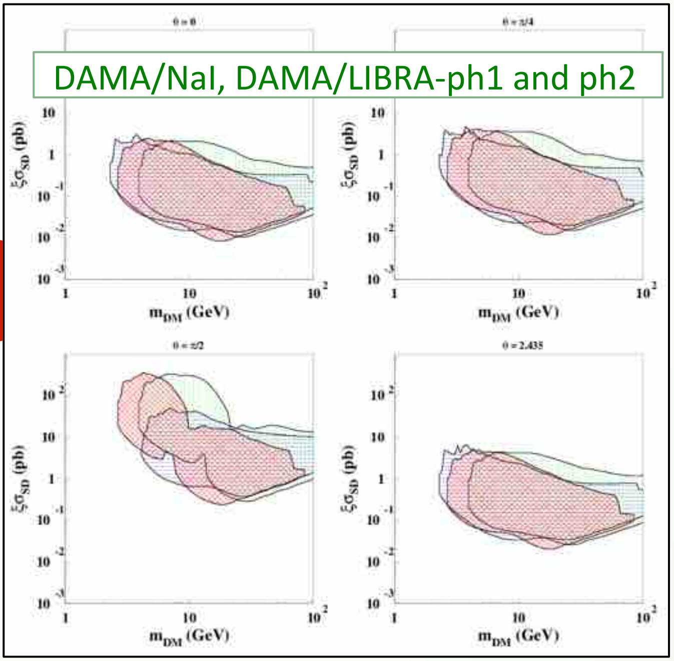
$\theta = 0 \Rightarrow a_n=0,\ a_p\neq 0$ or $|a_p|>>|a_n|$;

$\theta = \pi/4 \Rightarrow a_n=a_p$;

$\theta = \pi/2 \Rightarrow a_p=0,\ a_n\neq 0$ or $|a_n|>>|a_p|$;

$\theta = 2.435\text{rad} \Rightarrow a_n/a_p=-0.85$, pure Z_0 coupling

$\xi\sigma_{SD}$ vs m_{DM}

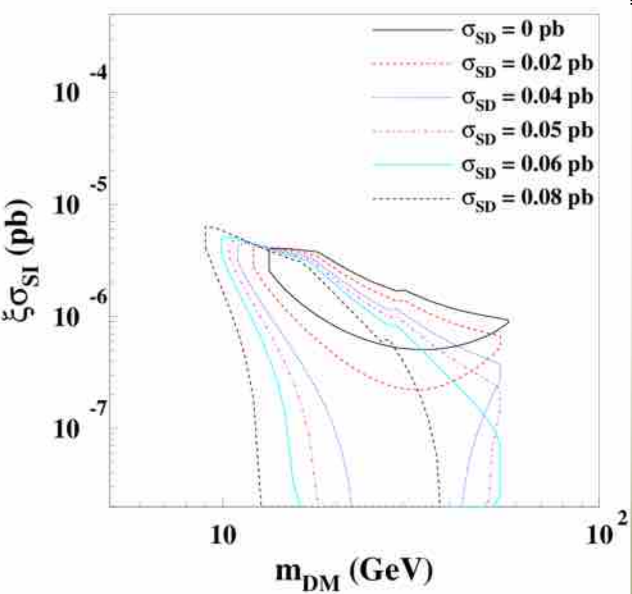


1. Constants q.f.

2. Varying q.f.(E_R)

3. With channeling effect

Effect induced by the inclusion of a SD component on allowed regions in the plane $\xi\sigma_{SI}$ vs m_{DM}



- Even a relatively small SD (SI) contribution can drastically change the allowed region in the (m_{DM}, $\xi\sigma_{SI(SD)}$) plane;
- The model-dependent comparison plots between exclusion limits at a given C.L. and regions of allowed parameter space do not hold e.g. for mixed scenarios when comparing experiments with and without sensitivity to the SD component of the interaction.
- The same happens when comparing regions allowed by experiments whose target-nuclei have unpaired proton with exclusion plots quoted by experiments using target-nuclei with unpaired neutron when the SD component of the interaction would correspond either to $\theta\approx 0$ or $\theta\approx\pi$

Perspectives for the future

Other signatures?

- *Diurnal effects*
- *Shadow effects*
- *Second order effects*
- *Directionality*
- *...*

Diurnal effects

EPJC 74 (2014) 2827

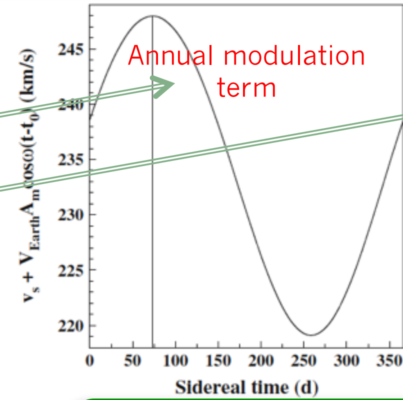
A diurnal effect with the sidereal time is expected for DM because of Earth rotation

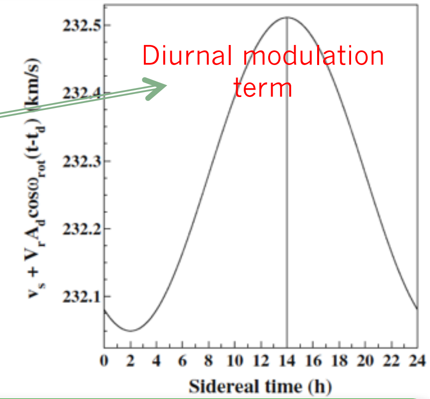
Velocity of the detector in the terrestrial laboratory: $\vec{v}_{lab}(t) = \vec{v}_{LSR} + \vec{v}_{\odot} + \vec{v}_{rev}(t) + \vec{v}_{rot}(t),$

Since:

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

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





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

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

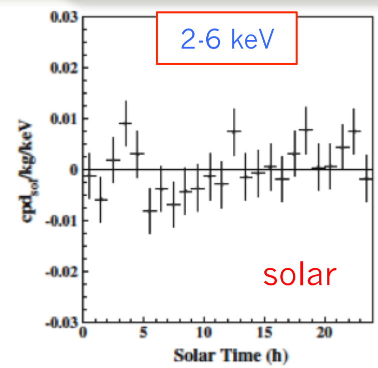
The ratio R_{dy} is a model independent constant:

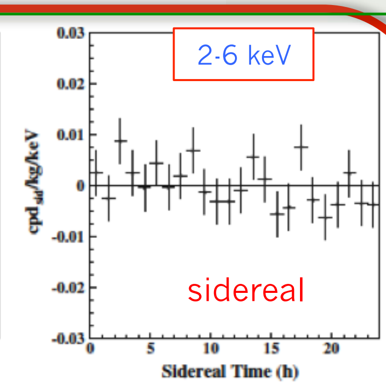
$$R_{dy} = \frac{S_d}{S_m} = \frac{V_r B_d}{V_{Earth} B_m} \simeq 0.016 \quad \text{at LNGS latitude}$$

A practical example: the case of DAMA/LIBRA–phase1

- Observed annual modulation amplitude in DAMA/LIBRA–phase1 in the (2–6) keV energy interval: (0.0097 ± 0.0013) cpd/kg/keV
- Thus, the expected value of the diurnal modulation amplitude is ≃1.5×10^{-4} cpd/kg/keV.
- When fitting the *single-hit* residuals with a cosine function with period fixed at 24 h and phase at 14 h: all the diurnal modulation amplitudes A_d are compatible with zero at the present level of sensitivity.

A_d (2-6 keV) < 1.2×10^{-3} cpd/kg/keV (90%CL)





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

larger exposure DAMA/LIBRA–phase2 (+lower energy threshold) offers increased sensitivity to such an effect

Perspectives for the future

Other signatures?

- *Diurnal effects*
- *Shadow effects*
- *Second order effects*
- *Directionality*
- *...*

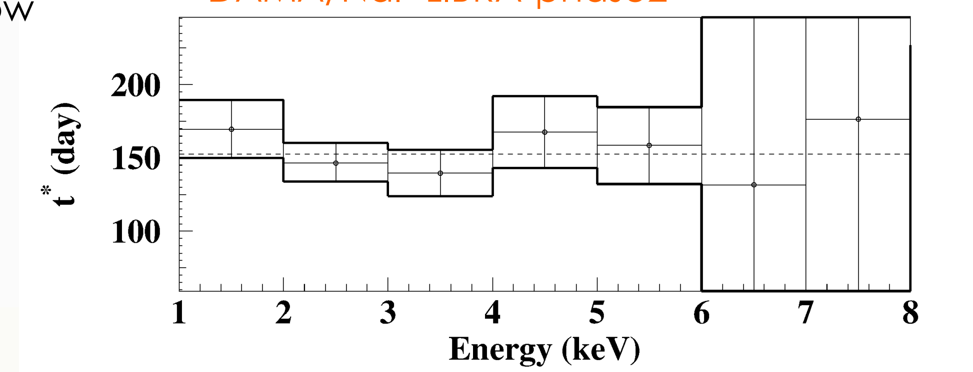
Features of the DM signal

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

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

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

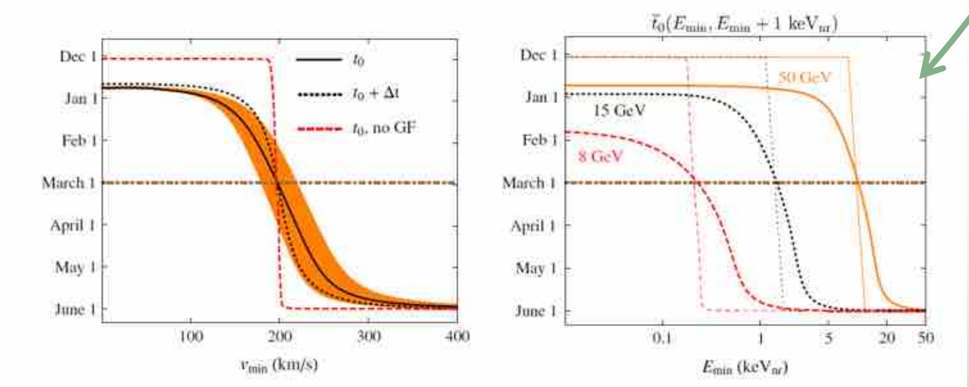
DAMA/NaI+LIBRA-phase2



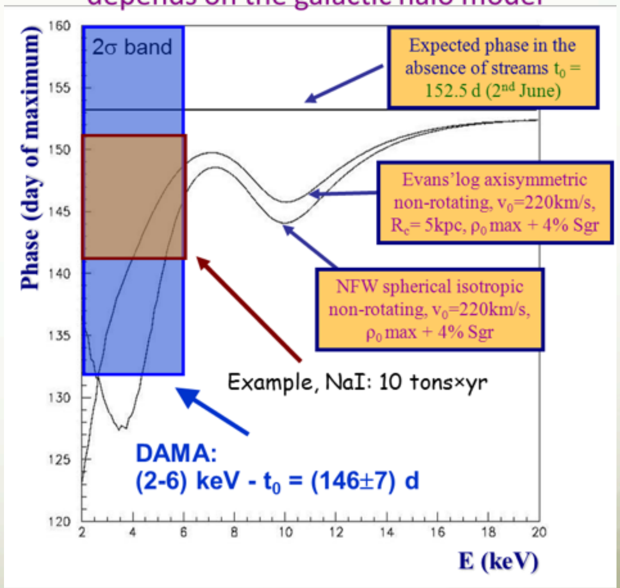
The annual modulation phase depends on :

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

PRL112(2014)011301



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

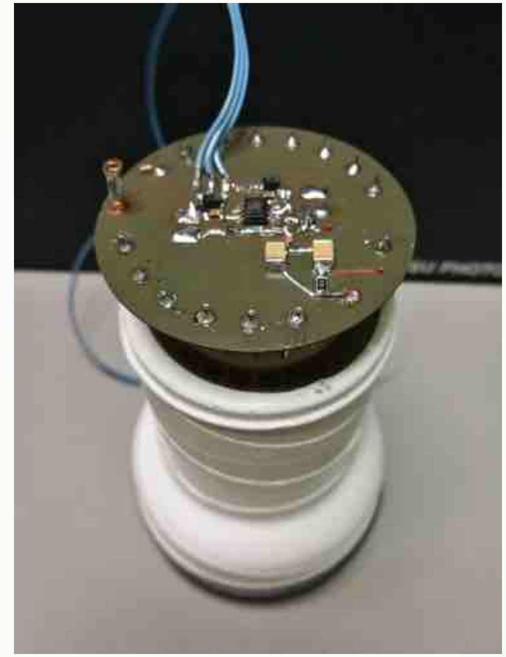


A step towards such investigations:

➔**DAMA/LIBRA-phase3**

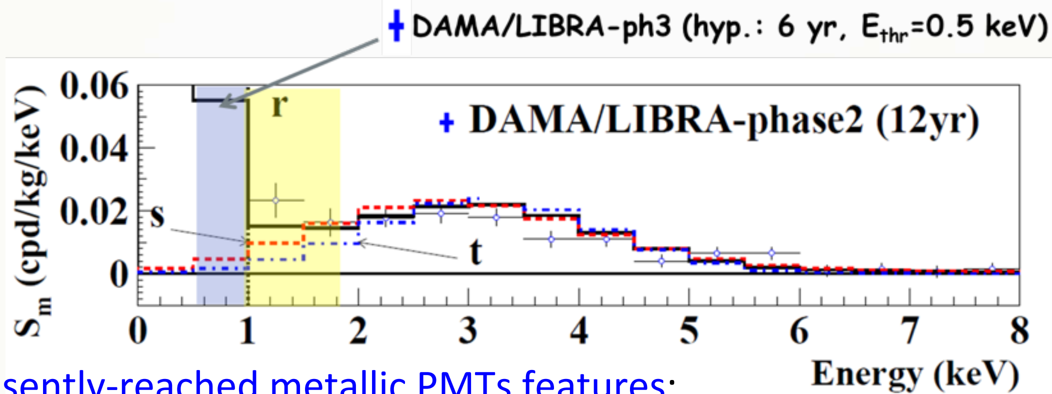
running with lower energy threshold and larger exposure

Toward DAMA/LIBRA-phase3



updating hardware to lower the 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).
- 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

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

Perspectives for the future

Other signatures?

- *Diurnal effects*
- *Shadow effects*
- *Second order effects*
- *Directionality*
- *...*

Directionality technique (at R&D stage)

- Only for candidates inducing recoils
- Identification of the Dark Matter particle by exploiting the non-isotropic recoil distribution correlated to the Earth position with to the Sun

Low pressure Gaseous TPC: DRIFT, MIMAC, DMTPC, NEWAGE, D3, CYGNO ⇒ CYGNUS TPC project

Exp.	V (L)	Gas	P (mbar)	Drift	Threshold (keV)	Location
DRIFT	800	73% CS_2 + 25% CF_4 + 2% O_2	55	ion, 50 cm	20 [24]	Boulby
MIMAC	5.8	70 % CF_4 + 28 % CHF_3 + 2 % C_4H_{10}	50	e^-, 20 cm	2	Modane
NEWAGE	37	CF_4	100	e^-, 41 cm	50	Kamioka
DMTPC	1000	CF_4	40	e^-, 27 cm	20	SNOLAB

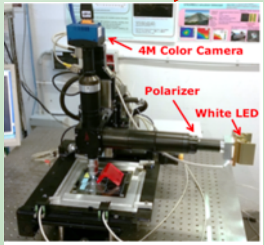
Physics Reports 627(2016)1

Anisotropic scintillators: DAMA, UK, Japan

R&D on other techniques

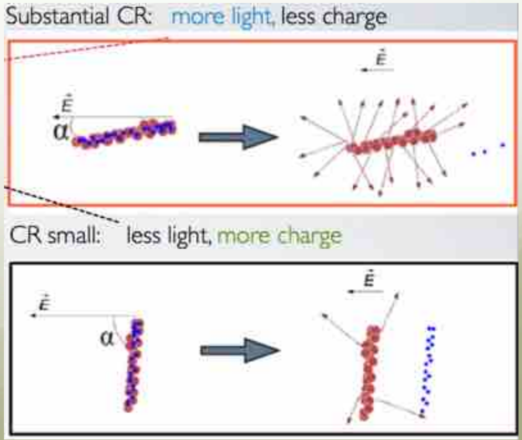
NEWSdm at LNGS

- Nanometric track direction measurement in nuclear emulsions;
- Exploit resonant light scattering using polarised light;
- Measurement of track beyond the optical resolution;
- Shape analysis: threshold 190 nm;
- Polarization analysis: threshold 120 nm



RED

Columnar Recombination (CR) in liquid argon TPC



PTOLEMY

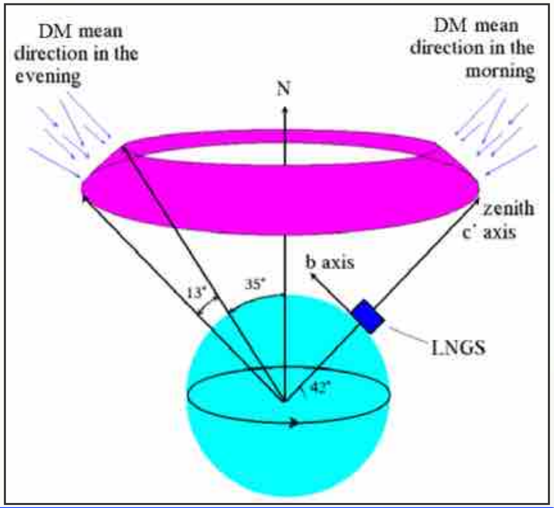
Graphene target (nanoribbon or nanotubes)

Development of detectors with anisotropic response

DAMA - Seminal paper: N.Cim.C15(1992)475; revisited: EPJC28(2003)203); more recently other suitable materials: EPJC73(2013)2276; now: work in progress

Anisotropic detectors are of great interest for many applicative fields, e.g.:

⇒ they can offer a unique way to study directionality for Dark Matter candidates that induce nuclear recoils by exploiting the non-isotropic recoil distribution correlated to the Earth velocity

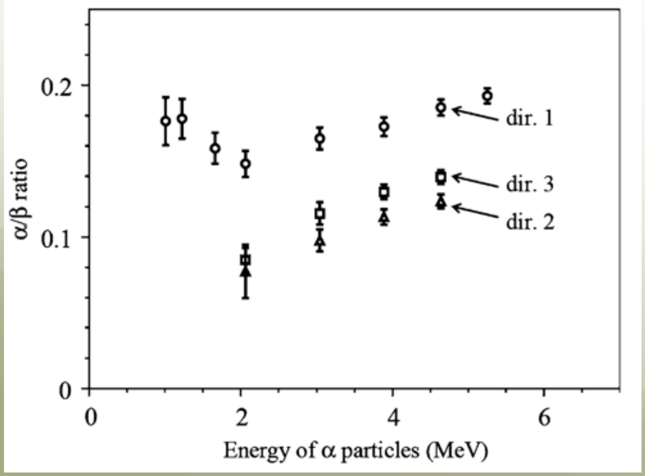


Taking into account:
- the correlation between the direction of the nuclear recoils and the Earth motion in the galactic rest frame;
- the peculiar features of anisotropic detectors;

the detector response is expected to vary as a function of the sidereal time

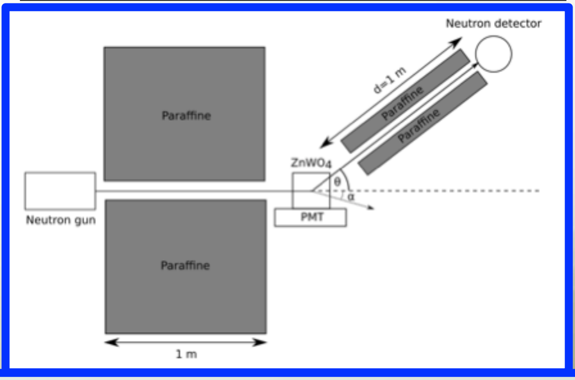
O → light masses
Zn, W → high masses

The ADAMO project: Development of $ZnWO_4$ anisotropic scintillators



The light output and pulse shape of $ZnWO_4$ depend on the direction of the impinging particles with respect to the crystal axes

Both these anisotropic features can provide two independent ways to exploit the directionality approach



Measurements of anisotropy in keV range by neutron generator on-going at ENEA-Casaccia

Conclusions

DARK MATTER investigation with direct detection approach

- Different **solid** techniques can give complementary results
- Some further efforts to demonstrate the **solidity** of some techniques are needed

- Higher exposed mass not a synonymous of **higher sensitivity**
- **DAMA** positive evidence (12.9σ C.L.). The modulation parameters determined with **better precision.**
  + **full sensitivity** to many kinds of DM candidates and interactions both inducing recoils and/or e.m. radiation.

- Possible positive hints are compatible with DAMA in many scenarios; null searches not in robust conflict. Also consider the experimental and theoretical uncertainties.

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