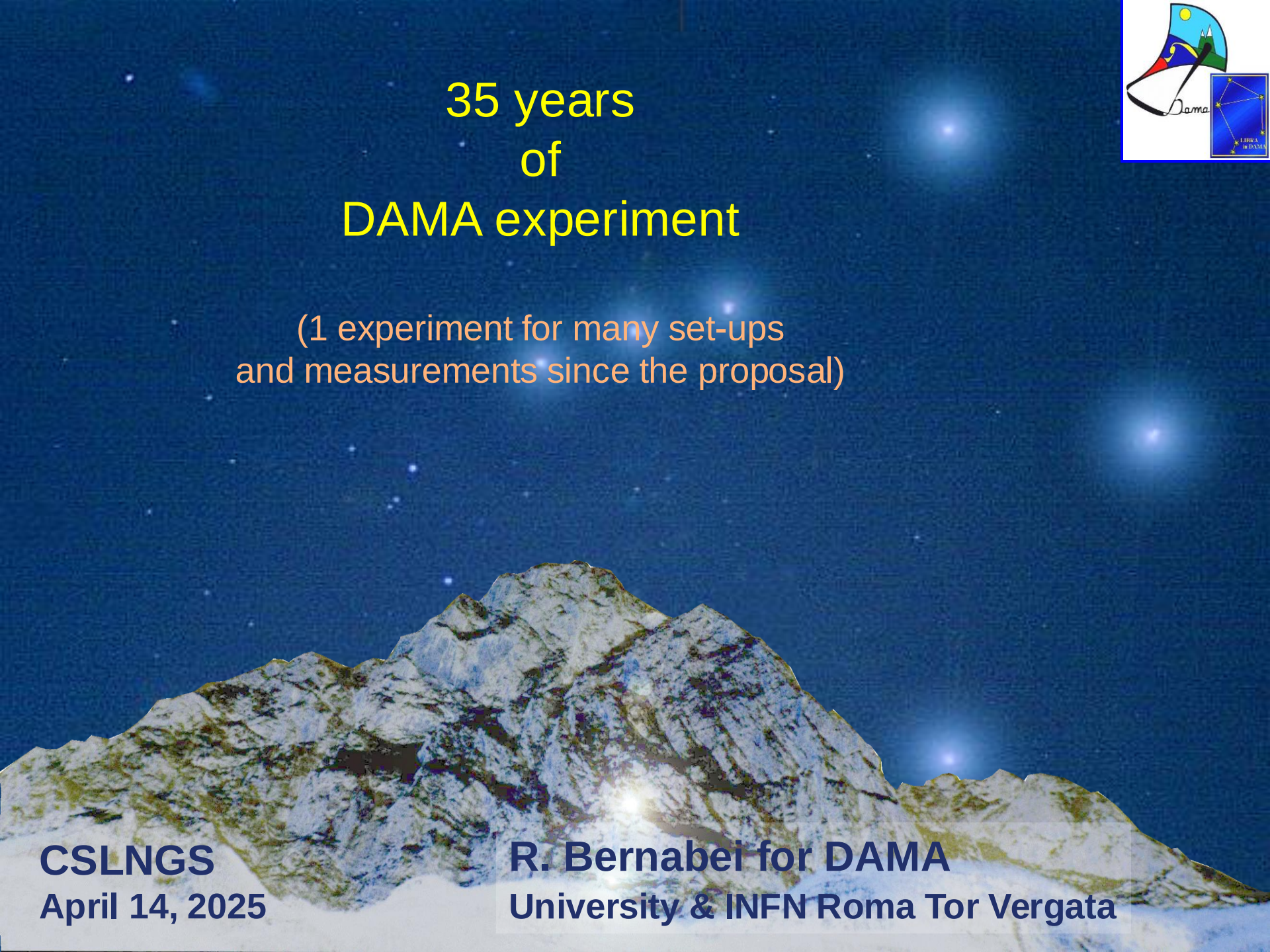


35 years of DAMA experiment

(1 experiment for many set-ups and measurements since the proposal)

R. Bernabei for DAMA
University & INFN Roma Tor Vergata

CSLNGS
April 14, 2025

To the memory of

- Prof. L. Paoluzi, Director of the INFN-Roma Tor Vergata and INFN vice president at time of starting/beginning this project
- Prof. D. Prosperi, one of the main proponents of the DAMA project
- Prof. S. d'Angelo, later in some DAMA meas; always fruitful scientific and human suggestions

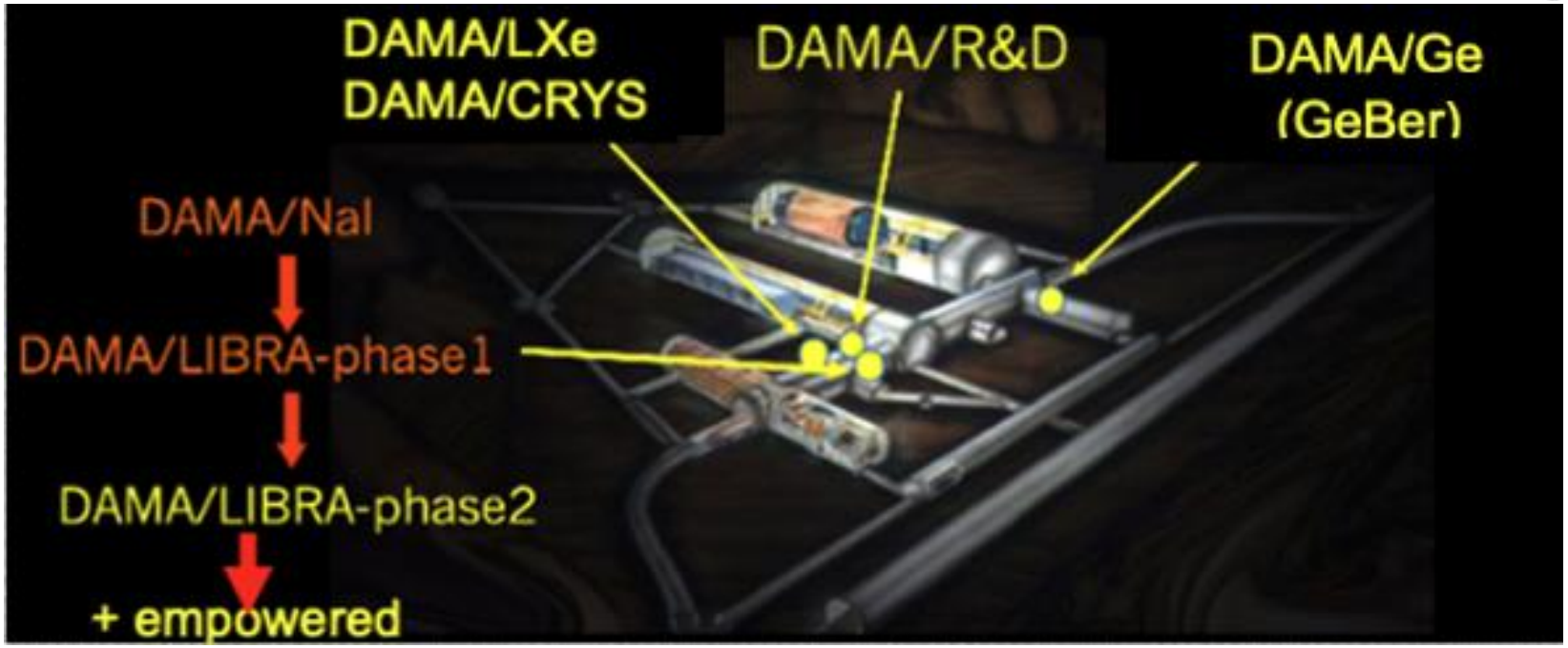
Grateful acknowledge to

- Prof. E. Bellotti, Director of LNGS at time of tests and setting up the experiment
- to the INFN Scientific Committee 2 in the various periods
- to the Tor Vergata Physics department
- to the INFN Roma Tor Vergata and Roma on whose annual budgets the DAMA set-ups were mainly realized (shields, R&Ds, detectors, etc. even the HPN_2)

Also, thanks to

- all the technical staffs and companies who supported the collaborative works along the time; in particular B. Meijler for interface in the about 5 yr efforts toward the joint developments of DAMA/NaI detectors and F. Kniest for interface in about 5 yr joint dev. toward the new DAMA/LIBRA detectors, R. McAlpine for the joint material selections for B53 PMTs and the HAMAMATSU company for various next realizations
- the colleagues who have contributed to the various searches on many processes other than DM with the DAMA low-background set-ups

Developing and using new and low background crystal scintillators & set-ups for rare events searches



https://dama.web.roma2.infn.it

In numbers:

- 350 (41 in the last five years) publications on international reviews
- 436 (66 in the last five years) talks at conf. and seminars
- DAMA h-index=63
- Theses (various levels): about 30

Time-line of ULB NaI(Tl) DAMA set-ups

end '80-beginning 90 — underground tests with commercial NaI(Tl) of the LADON 100 kg sphere; search for the best manufacture for ULB: Harshaw chosen, then acquired by Crismatec

24 April 1990 — only italians (Roma Tor Vergata & Roma La Sapienza): Proposal to INFN by R. Bernabei, P. Belli, C. Bacci, A. Incicchitti, R. Marcovaldi and D. Prosperi on large mass NaI(Tl) and liquid Xenon experiments for Dark Matter search, and first funding

1° experiment proposed and funded specifically for DM direct detection deep underground, with ULB NaI(Tl) and with LXe exploiting also the DM annual modulation signature

1990-end 1995 — R&D by a joint coll. between DAMA members and companies for crystal detectors and dedicated EMI-Thorn B53 PMTs realization

Chinese colleagues joined @LNGS in 1992

end 1995/96 to July 2002 — 100 kg DAMA/NaI installation + running +1998 minimal upgrade + July 2000 new DAQ and new electronic chain

Fall 1996 — Italian DAMA proposed (for insertion in the Piano Triennale) to INFN DAMA/1ton; get DAMA/LIBRA-pase1 as intermediate step and - with time - some additional R&Ds funded and carried out

1996/97 to 2003 — R&D and realization of the new DAMA/LIBRA detectors by Quartz & Silice (former Crismatec) → DAMA/R&D setup realized for tests of this R&D and then to be used for small scale expts.

Sept 2003 — start 250 kg DAMA/LIBRA-phase 1 + upgrade on Sept/Oct 2008

Fall 2010 — 2nd DAMA/LIBRA upgrade → DAMA/LIBRA-phase2 + preamp upgrade in Fall 2012

Dec 2010 – 2021 — DAMA/LIBRA-phase2 running

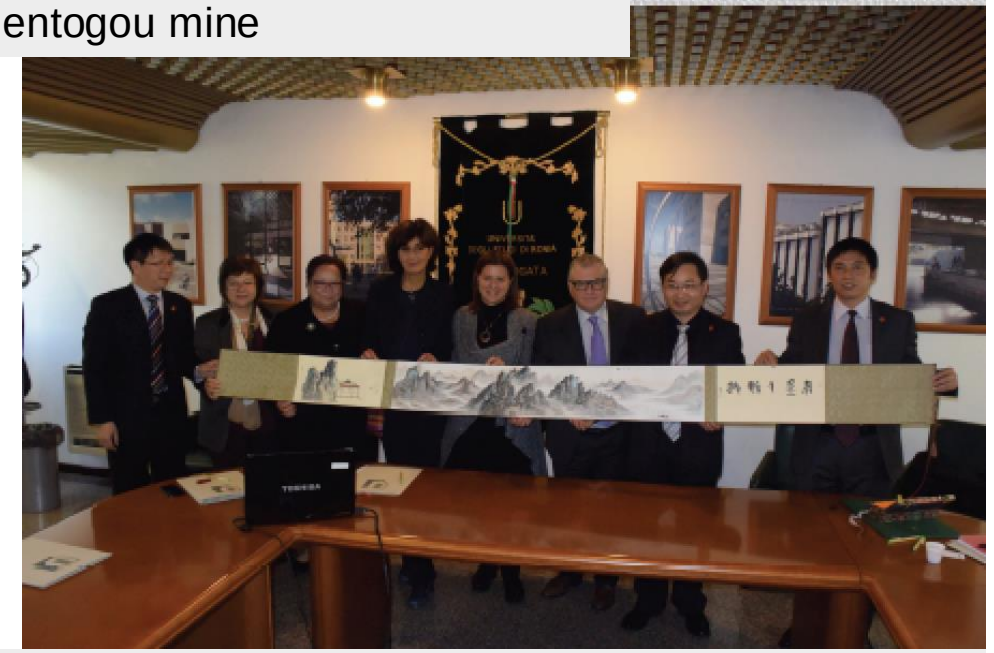
2019 – 2021 — R&Ds towards DAMA/LIBRA-phase2-empowered

Fall 2021 — Start DAMA/LIBRA-phase2-empowered

2021 – fall 2024 — DAMA/LIBRA-phase2-empowered running

Just two historical pictures from a long and fruitful collaboration and exchanges

1992: Visiting the Ge installation of the Chinese colleagues in the Mentogou mine



2015: Signing of a MOU by the two Rectors of the Rome Tor Vergata University and the Jinggangshan University

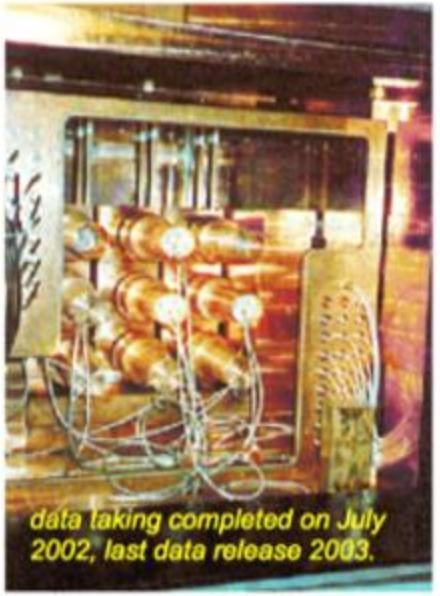
The pioneer DAMA/NaI: ≈100 kg highly radiopure NaI(Tl)

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:

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.

The pioneer DAMA/NaI:

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

As a result of a 2nd generation R&D for more radiopure NaI(Tl) by

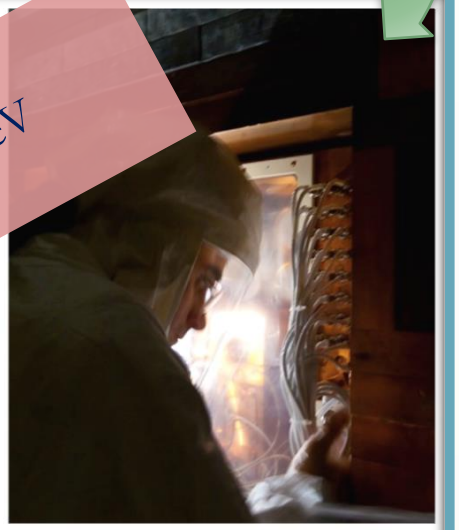
Residual
DAMA/LI
^{238}U and

DAMA/LIBRA–phase2

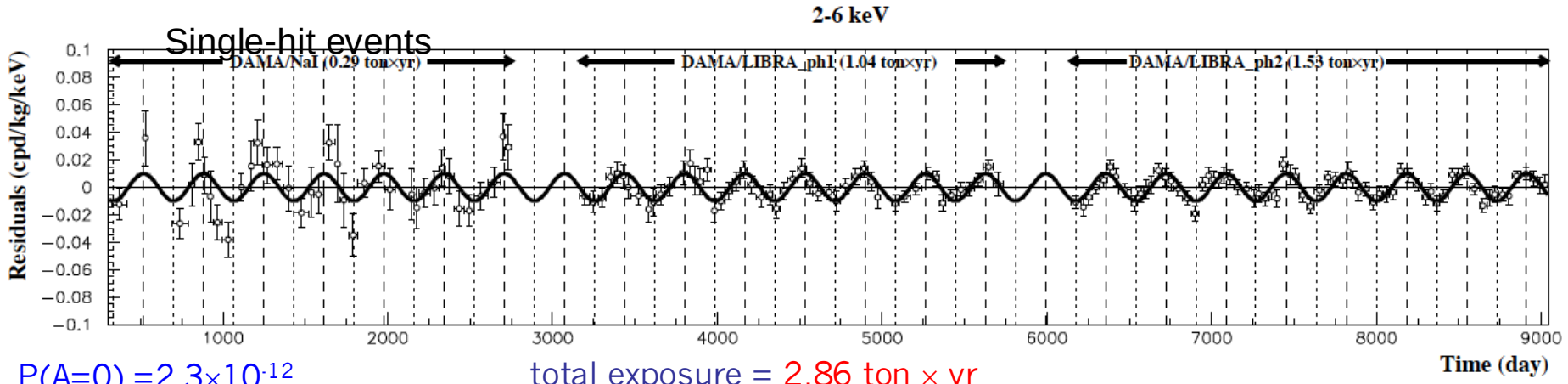
Upgrade on Nov/Dec 2010: all PMTs replaced with new ones of higher Q.E.

JINST 7(2012)03009
Universe 4 (2018) 116
NPAE 19 (2018) 307
Bled 19 (2018) 27
NPAE 20(4)(2019)
PPNP114(2020)

A new stage of the experiment:
DAMA/LIBRA-phase2- empowered with 0.5 keV
energy threshold from Dec 1, 2021 to 2024



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



$P(A=0) = 2.3 \times 10^{-12}$ total exposure = 2.86 ton × yr

phase and period well compatible with expectations for DM annual modulation

- Multiple different and independent analyses give completely consistent results
- All the many peculiarities of the DM annual modulation signature satisfied
- No competing systematics or reactions capable of mimicking the signature
- Result compatible with many different phenomenological scenarios

Further exposure and lower software thresholds increased with time the sensitivity and allowed a more precise determination of the parameters to investigate:

- The nature of Dark Matter particles
- Possible diurnal effects with sidereal time
- Astrophysical models

DAMA/LIBRA-phase2-empowered:
software energy threshold below 1 keV with suitable efficiency

Fall 2021, DAMA/LIBRA–phase2 heavily upgraded:

a. equipping all the PMTs with new low-background voltage dividers with pre-amps on the same board
b. the use of Transient Digitizers with higher vertical resolution (14 bits).

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 lower than that of single PMT

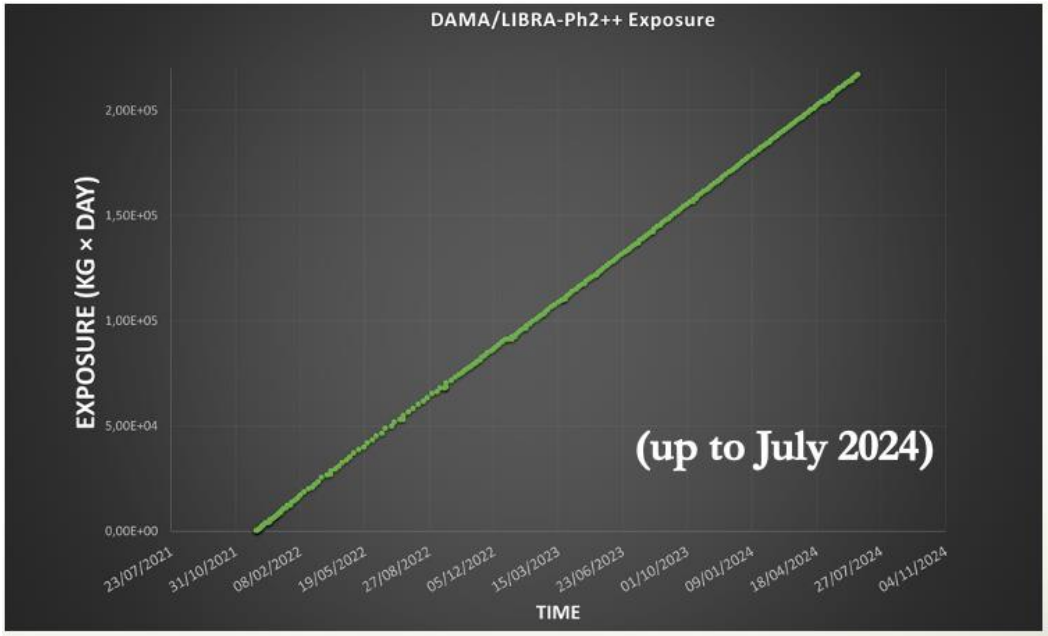
Data taking has been continued without interruptions, with regular calibration runs

✓Calibrations: $\approx 7.75 \times 10^7$ evts from sources

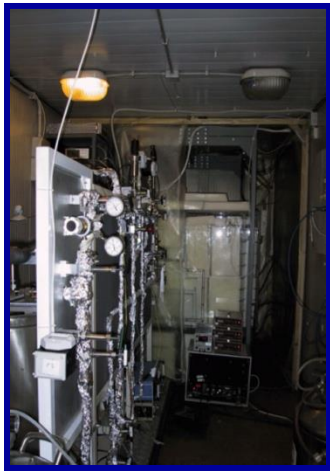
✓Acceptance window eff. per all crystals: $\approx 4.35 \times 10^7$ evts ($\approx 1.74 \times 10^6$ evts/keV)

Exposure of DAMA/LIBRA-phase2-empowered up to July 24:

$\mathbf{0.558\ ton \times yr}$ $\quad \mathbf{(\alpha - \beta^2) \approx 0.501}$



Time-line of DAMA/LXe set-up



end '80: Xelidon expt in CSN5 to develop LXe detectors - 1st prop. on such detectors in INFN

24 April 1990 Italian (Roma Tor Vergata & Roma La Sapienza) Proposal to INFN by R. Bernabei, P. Belli, C. Bacci, A. Incicchitti, R. Marcovaldi and D. Prosperi on large mass NaI(Tl) and liquid Xenon experiments

→ LXe only Italian + later C.J. Dai

1º experiment proposed and funded specifically for DM direct detection deep underground, and with LXe detector exploiting also the DM annual mod. Signature and other rare processes; mainly Xenon enriched in ^{129}Xe or ^{136}Xe, ^{134}Xe

1990- ~1994 prototypes for LB + installation deep underground of the LB set-up+ running ^{nat}Xe

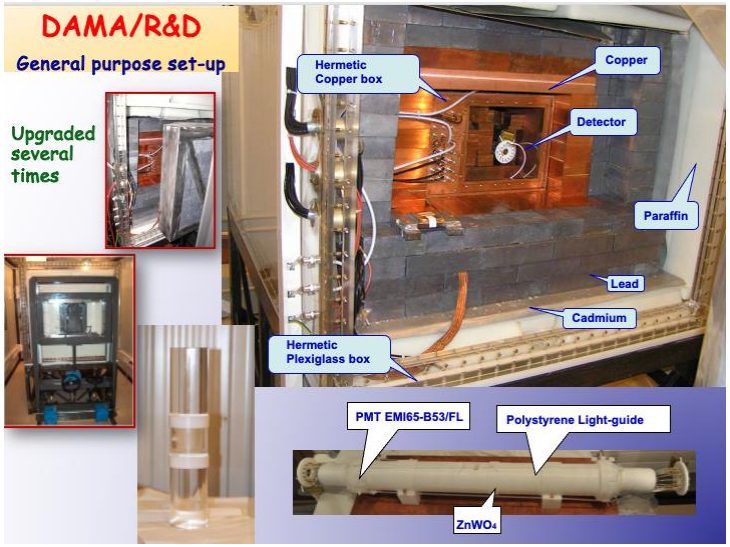
Around ~1995 we pointed out to the INFN-CSN2 the intrinsic limitations of this detector medium (see e.g. arguments in our 2 recent monographies) and agreed to pursue the activity with a set-up with a full block of Cu inner vessel by using ~ 6.5 kg Kr-free Xenon enriched either in ^{129}Xe at 99.5% or in ^{136}Xe at 68.8% and in ^{134}Xe at 17.1% (the largest LXe detector underground at time)

1996-2018 Several upgrades occurred with time + a period of stopping due to the Borexino accident that caused the stop of using liquids underground.

Published results on DM elastic- and inelastic-scattering, on response of a similar pure LXe scintillator to recoil nuclei as well as its pulse shape discrimination capability, on possible charge non-conserving processes, on nucleon and di-nucleon stability, on $\beta\beta$ decay modes: ^{136}Xe enriched at 68.8% or ^{134}Xe enriched at 17.1%, etc.+ detector details and performances

2018 Out of operation as in the plans

Time-line of DAMA/R&D set-up

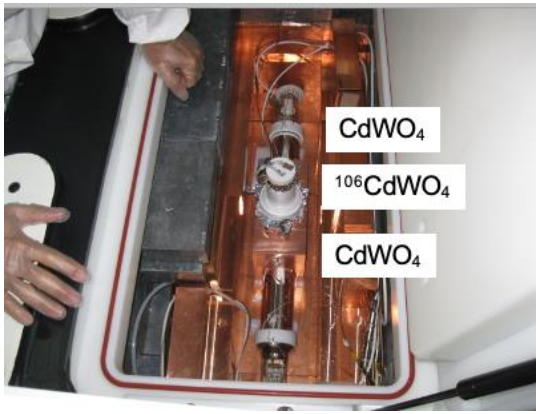


- proposed 1996-1997: setup for testing the prototypes of the R&D-I, -II for the new DAMA/LIBRA detectors and up to R&D-V for DAMA/1ton (proposed in 1996; other 3 replicas of DAMA/LIBRA) but abandoned later because: i) no similar materials and protocols (as e.g. no Pt crucibles and Kyropoulos growth); ii) possibility to increase DAMA/LIBRA sensitivity acting on other parameters

- to 2024: several measurements on various rare processes mainly within signed coll agreements INFN - INR-Kiev + others

Time-line of DAMA/CRYS set-up

- proposed end 2012: DAMA/CRYS set-up was installed in the same barrack of VIP. This set-up allowed the study of several rare processes in different low-bckg scintillators. The passive shield of the set-up was made of high purity copper, lead, cadmium, and polyethylene. Also this set-up was sealed and continuously flushed by HP-N2 gas to prevent the detector and other materials to be in contact with the environmental air.



- March 2020: DAMA/CRYS set-up moved to the inner part of the ground floor level of the dismounted DAMA/LXe; the previous DAMA/CRYS site was returned to LNGS

- to 2024: several measurements on small scale experiments and the $^{106}CdWO_4$ expt. whose final results have been published in last days

- Fruitful long collaboration since early 90 to 2025 (regular signed agreements) with INR-Kiev for measurements on many rare processes. (leader: Y. Zdesenko+, and then F. Danevich)

+ deceased on Sept. 2004

- & more coll. depending on the measurement.

Their first time visiting LNGS

V. Tretyak

Time-line of GEBER also indicated as DAMA/Ge set-up always sited in the Stella Laboratory

- end ’80- beginning ’90

Low Z window low-background HPGe realized by company with exchanges with R. Bernabei (suggestions from C. Arpesella and G. Heusser) with funding from Tor Vergata section other than DAMA

- 2003-2004

upgrade of shielding and protocol mainly coordinated by Roma La Sapienza

Measurements for qualifications of powders and samples, for materials for RD-I to RD-V, for other scintillator materials and for some of the RDs on PMTs and new scintillators + small scale experiments

Over all years also measurements in the HPGe of the LNGS Stella Laboratory (headed by Dr. M. Laubenstein)

In addition to ULB NaI(Tl): developments/measurements in the low-bckg DAMA set-ups

$ZnWO_4$	Ukraine	NIMA1029(2022)166400, J. of Lumin. 249 (2022) 119028, EPJA56(2020)83, NIMA935(2019)89, NIMA833(2016)77, PS90(2015)085301, EPJC73(2013)2276, JPG:NPP38(2011)115107, NIMA626-627(2011)31, NPA826(2009)256, PLB658(2008)193
$CdWO_4$	Ukraine	EPJA36(2008)167, PRC76(2007)064603
$^{106}CdWO_4$	Ukraine	Universe in publ. (2025), NPAE24(2023)193, Univ.6(2020)182, PRC93(2016)045502, PRC85(2012)044610, NIMA615(2010)301, AstroPhys10(1999)115
$^{116}CdWO_4$	Ukraine	Phys.Scr.97(2022)085302, PRD98(2018)092007, NIMA833(2016)77, JINST6(2011)08011
Cs_2HfCl_6	Canada (by S. Nagorny)	NPA1053(2025)122976, NPA1002(2020)121941
Cs_2ZrCl_6	Canada (by S. Nagorny)	JINST19(2024)P05037, EPJA59(2023)176
SrI_2	Ukraine, USA	NIMA670(2012)10, analysis in progress
CaF_2(Eu)	Bicron/Crismatec(Saint Gobain)	NPA789(2007)15, NPA705(2002)29, NPB563(1999)97, AstroPhys7 (1997)73
CeF_3	Crystal Clear coll. or China	NIMA498(2003)352, NCIM 110A (1997) 189
BaF_2	China or Bicron/Saint Gobain	EPJA50(2014) 134, NIMA525(2004)535
LiF(W)	Ukraine	NPA806(2008)388
^{7}LiI(Eu)	Ukraine	NIM704(2013)40
$LaCl_3$(Ce)	Saint Gobain	Ukr. J. of Phys.51(2006)1037, NIMA555(2005)270
$CeCl_3$	Iltis/Saint Gobain	JPG:NPP38(2011)015103, NPA824 (2009)101
Li_2MoO_4	Ukraine	NIMA607(2009)573
$Li_6Eu(BO_3)_3$	Ukraine	NIMA572(2007)734
$BaWO_4$	Canada (by S. Nagorny)	NIMA901(2018)150
Rb_2ZrCl_6	Canada (by S. Nagorny)	paper in preparation
GAGG:Ce	Epjc-crystal	analysis in progress
and polycrystalline powder:	ZnS(Ag)	Saint-Gobain MPLA27, No. 8 (2012)1250031

Main results obtained by DAMA in the search for rare processes

- First or improved results in the search for 2β decays of ~30 candidate isotopes: ^{40}Ca, ^{46}Ca, ^{48}Ca, ^{64}Zn, ^{70}Zn, ^{100}Mo, ^{96}Ru, ^{104}Ru, ^{106}Cd, ^{108}Cd, ^{114}Cd, ^{116}Cd, ^{112}Sn, ^{124}Sn, ^{134}Xe, ^{136}Xe, ^{130}Ba, ^{136}Ce, ^{138}Ce, ^{142}Ce, ^{144}Sm, ^{154}Sm, ^{150}Nd, ^{156}Dy, ^{158}Dy, ^{162}Er, ^{168}Yb, ^{180}W, ^{186}W, ^{184}Os, ^{192}Os, ^{190}Pt and ^{198}Pt (observed 2ν2β decay in ^{100}Mo, ^{116}Cd, ^{150}Nd)
- One of the best experimental sensitivities in the field for 2β decays with positron emission (^{106}Cd)

First observation of α decays of ^{151}Eu with a CaF_2(Eu) scintillator

First observation of α decay of ^{190}Pt to the first excited level (E_{exc} = 137.2 keV) of ^{186}Os

First observation of α decays of ^{174}Hf the measured half-life is in good agreement with the theoretical predictions

Investigations of rare β decays of ^{113}Cd and ^{113m}Cd with $CdWO_4$ scintillators and of ^{48}Ca with a CaF_2(Eu) detector

Observation of correlated e^+e^- pairs emission in α decay of ^{241}Am ($A_{e^+e^-}/A_\alpha \approx 5\times10^{-9}$)

Search for cluster decays of ^{127}I, ^{138}La and ^{139}La

Search for N, NN, NNN decay into invisible channels in ^{129}Xe and ^{136}Xe

Search for PEP violating processes in Sodium and in Iodine

Search for spontaneous transition of ^{23}Na and ^{127}I nuclei to superdense state

CNC processes, e.g. in ^{127}I, ^{136}Xe, ^{100}Mo and ^{139}La

Search for solar axions by Primakof effect

Search for ^{7}Li solar axions using resonant absorption in LiF crystal

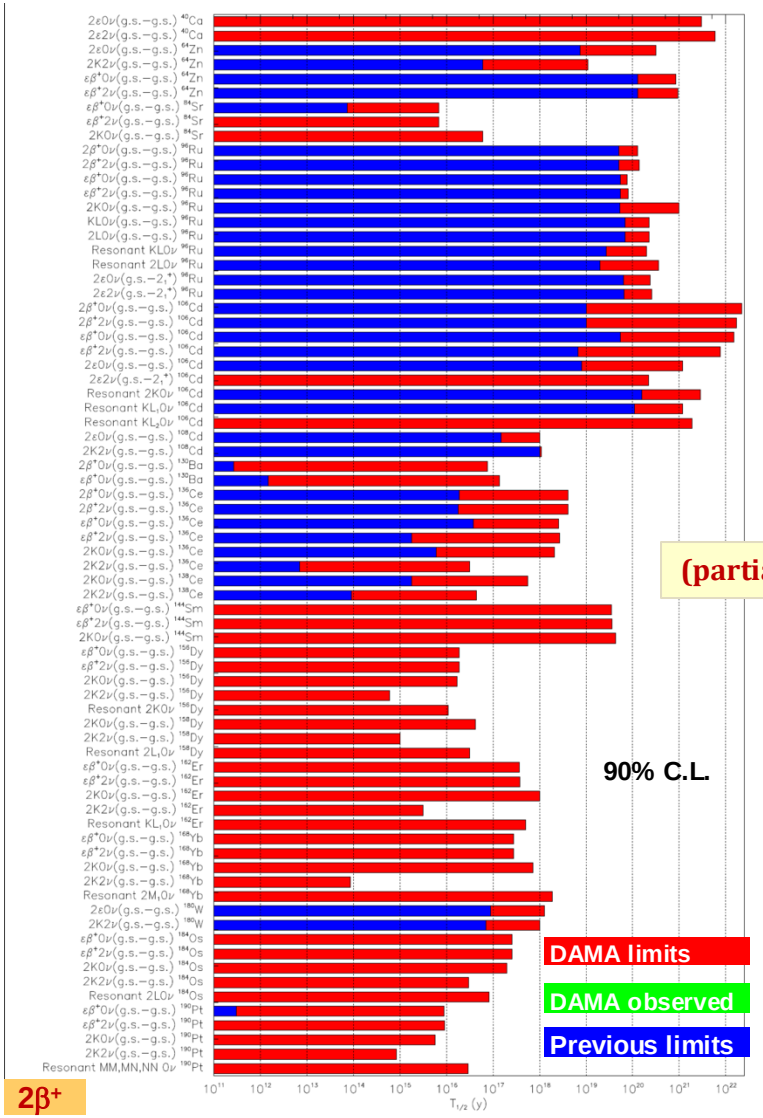
Search for long-lived super-heavy eka-tungsten with $ZnWO_4$ and $CdWO_4$

Best sensitive meas. of 2β decays of ^{150}Nd to 0^+ level and first observation to 2+ level.

Dark Matter model-indep & model-dep investigations with several methodologic approaches

… and many others

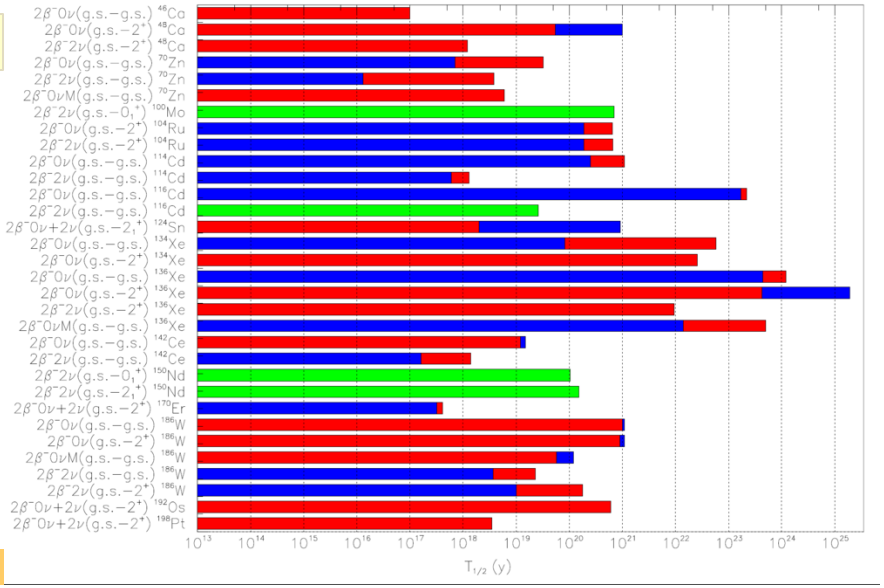
Searches for 2β decay modes in various isotopes at DAMA set-ups and in STELLA HPGe facility



(partial list)

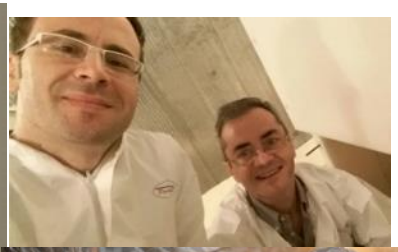
New observations:		DAMA and DAMA-Kiev
ARMONIA:	$2\nu2\beta^-$ decay $^{100}Mo \rightarrow {}^{100}Ru(0_1^+)$	NPA846(2010)143
AURORA:	$2\nu2\beta^-$ decay $^{116}Cd \rightarrow {}^{116}Sn$	PRD98(2018)092007
Nd_2O_3-HPGe:	$2\nu2\beta^-$ decay $^{150}Nd \rightarrow {}^{150}Sm(0_1^+)$	EPJC85(2025)174
	$2\nu2\beta^-$ decay $^{150}Nd \rightarrow {}^{150}Sm(2_1^+)$	EPJC85(2025)174

^{40}Ca, ^{48}Ca, ^{64}Zn, ^{70}Zn, ^{100}Mo, ^{96}Ru, ^{104}Ru, ^{106}Cd, ^{108}Cd, ^{114}Cd, ^{116}Cd, ^{112}Sn, ^{124}Sn, ^{134}Xe, ^{136}Xe, ^{130}Ba, ^{136}Ce, ^{138}Ce, ^{142}Ce, ^{148}Nd, ^{150}Nd, ^{144}Sm, ^{154}Sm, ^{156}Dy, ^{158}Dy, ^{162}Er, ^{170}Er, ^{168}Yb, ^{176}Yb, ^{180}W, ^{186}W, ^{184}Os, ^{192}Os, ^{190}Pt, ^{198}Pt

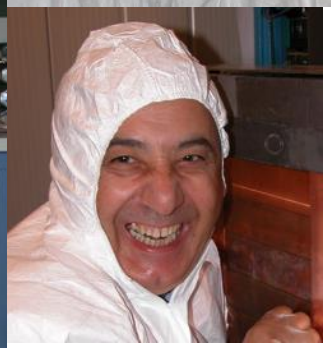
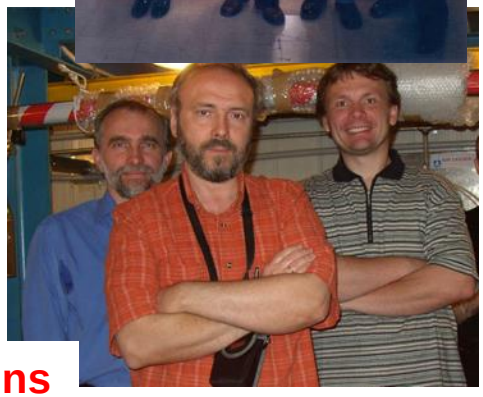


Thanks to the developments on **crystal scintillators**, **competitive results** obtained on lifetime of $2\beta^+$, $\varepsilon\beta^+$ and 2ε processes; **first searches** for **resonant $0\nu2\varepsilon$** decays in some isotopes





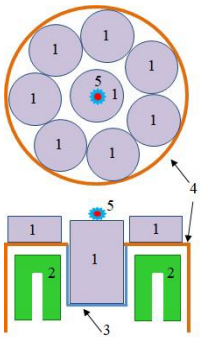







Few pictures of some of the people & occasions

Just the last results other than DM

The 2ν2β decay of ^{150}Nd to the first excited 740.5 keV 0_1^+ level of ^{150}Sm measured over 5.845 yr with the help of a 4-crystal low-background HPGe γ spectrometry system in the STELLA laboratory, with indication of 2ν2β decay the 2^+_1 excited level of ^{150}Sm



Expected γ's from the 0_1^+ level with 334.0 keV and 406.5 keV were observed both in one-dimensional spectrum and in coincidence data resulting in

$$\mathbf{T_{1/2} = \left[0.83^{+0.18}_{-0.13}(stat)^{+0.16}_{-0.19}(syst)\right] \times 10^{20}\ yr}$$

Interpreting the excess of the 334.0-keV peak area as an indication of the 2β decay of ^{150}Nd to the 334.0 keV 2_1^+ excited level of ^{150}Sm with a half-life of

$$\mathbf{T_{1/2} = \left[1.5^{+2.3}_{-0.6}(stat) \pm 0.4(syst)\right] \times 10^{20}\ yr}$$

the 2ν2β half-life of ^{150}Nd for the transition to the 0^+ level is

$$\mathbf{T_{1/2} = \left[1.03^{+0.35}_{-0.22}(stat)^{+0.16}_{-0.19}(syst)\right] \times 10^{20}\ yr}$$

in agreement with the previous experiments.

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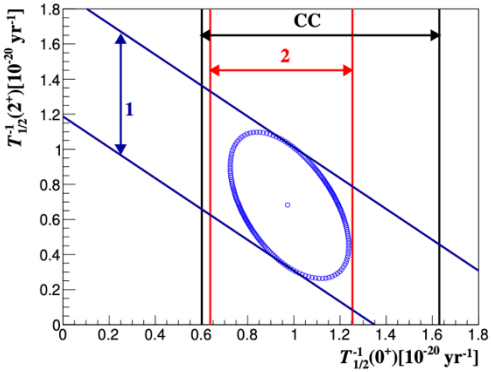
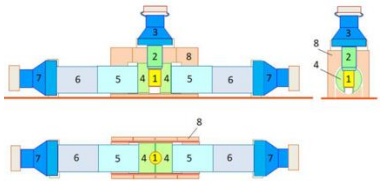


- 1-σ contour and best fit
- The 1-σ bands when considering only either the 334-keV (1), or 406.5-keV (2), or CC

Both $T_{1/2}$ reasonably agree with the theoretical calculations in the framework of proton-neutron QRPA with isospin restoration combined with like nucleon QRPA for description of excited states in the final nuclei (see paper).

For 2ν2β and 0ν2β transitions of ^{150}Nd and ^{148}Nd to several excited levels of ^{150}Sm and ^{148}Sm, limits were set at level of $T_{1/2} > 10^{20} - 10^{21}$ yr

The search for 2β decay of ^{106}Cd with a $CdWO_4$ scintillator enriched (66%) in stable isotope ^{106}Cd ($^{106}CdWO_4$) in coincidence and anticoincidence with two $CdWO_4$ scintillation counters scintillator at the DAMA/R&D set-up



New improved limits after 1075 days of data taking:

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$$T_{1/2}^{0\nu 2\beta^+} \geq 2.2 \times 10^{22}\text{yr}, \quad T_{1/2}^{0\nu EC\beta^+} \geq 1.5 \times 10^{22}\text{yr}$$

$$T_{1/2}^{2\nu EC\beta^+} \geq 7.7 \times 10^{21}\text{yr}$$

One of the most sensitive $2\beta^+$ experiments

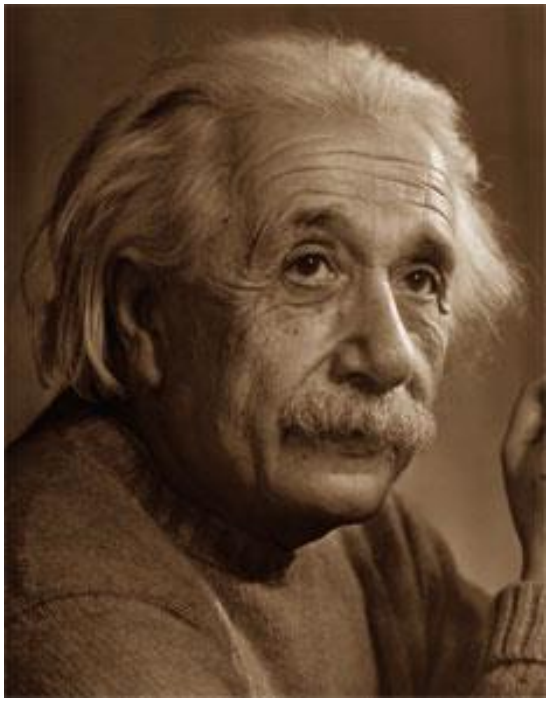
(theory: $T_{1/2} \sim 10^{21}$-10^{23} yr).
No event in the energy region >520 keV

… to be done

- Completing the decommissioning of all the DAMA set-ups and tests
- Completion of data analysis on available statistics of DAMA/LIBRA/phase2-empowered
- Other kinds of DM candidates and interactions
- Other processes investigated with available data
- Beta spectrum of ^{113}Cd and ^{113m}Cd (paper submitted)
- Final results on the last stage of the $^{106}CdWO_4$ expt. (published)
- Data analyses in progress on ^{87}Rb beta decay
- Data analyses in progress on several rare processes
- Phenomenological studies
- …

Main original ideas and/or legacy of DAMA

- Direct DM experiments:
  - First use of low-background scintillators (NaI, LXe, and others)
  - First exploitation of the DM annual mod. signature following Drukier et al. in 1986
  - First idea of use of anisotropic scintillators for directionality
  - First addressing of the Migdal effect in DM field
  - First addressing of the Channeling effect in DM field
  - E.m. signals due to DM interactions
  - Other kinds of DM candidates
  - Impact of Galactic and SagDEG streams
  - Diurnal modulation
  - Shadow effects
  - First measurements of anisotropic response to nuclear recoils in anisotropic scintillators ($ZnWO_4$)
  - R&D of several scintillators, even of novel concept
  - Many nuclides available for 2β decay investigations
  - Many nuclear, rare, exotic, processes studied
  - Axions investigation in underground expts
  - …



"… The one who follows the crowd will usually get no further than the crowd. The one who walks alone, is likely to find himself in places no one has ever been."

Thanks for attention