Dark matter searches with cryogenic detectors

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FAKT Workshop 2022, 25th February 2021

Dark matter direct detection

Relic dark matter particle scattering off detector material nuclei.

Expected differential recoil rate:

$$\frac{dR}{dE_{\mathrm{nr}}} = \frac{\rho_0 M}{m_N m_\chi} \int_{v_{\mathrm{min}}}^{v_{esc}} v f(v) \frac{d\sigma}{dE_{\mathrm{nr}}} dv$$

galactic escape velocity

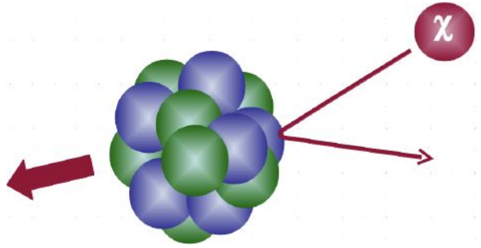
velocity distribution

minimal velocity to produce a recoil above E_{nr}

DM-nucleon cross section ~ A^2 , ~ form factor

Astro physics: Velocity distribution, escape velocity

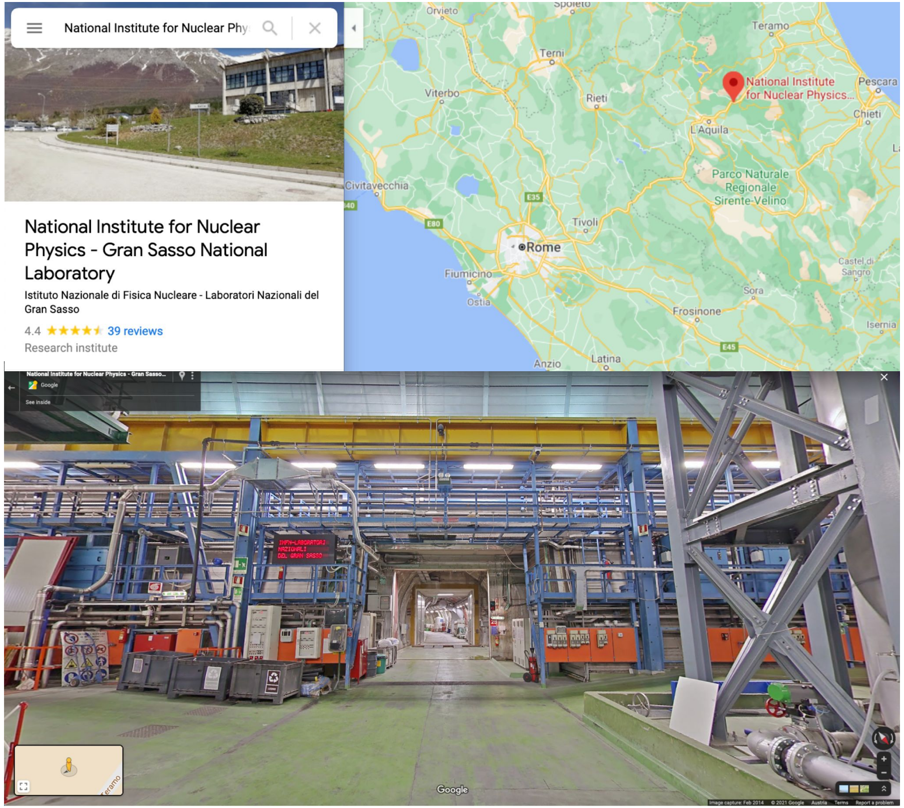
Particle physics: Form factor, energy threshold, detector material, dark matter mass



Laboratori Nazionali del Gran Sasso (LNGS)

Low background necessary for rare event searches to achieve sensitive measurements, e.g. in underground laboratories as the LNGS:

- 120 km from Rome
- 6000 m^2 floor space
- 1400 m rock (3600 m.w.e.)



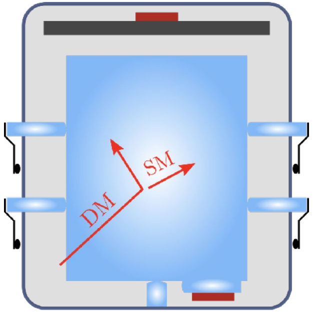
Cryogenic detectors

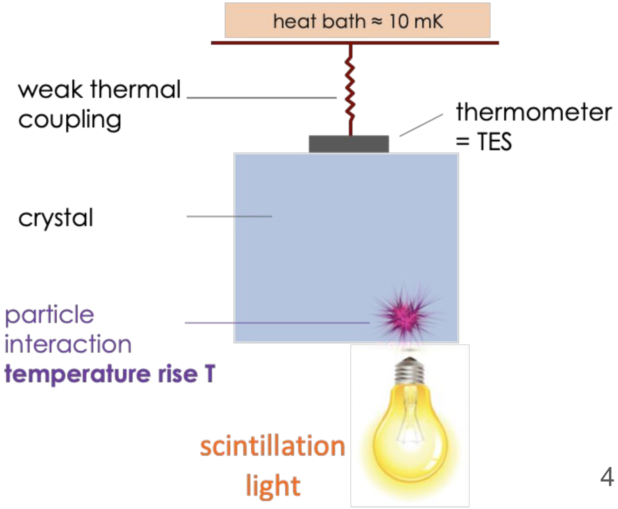
Small scintillating crystals (~50 g), operated at *cryogenic temperatures* (~10-20 mK).

A particle recoil in the crystal produces *heat* and *scintillation light*.

Amount of emitted light depends on particle type: *Light quenching*.

Sensitive *thermometers (TES - transition edge sensors)* measure the heat signal of the detector crystal.





Light yield discrimination

Light Yield: Light Energy / Phonon Energy

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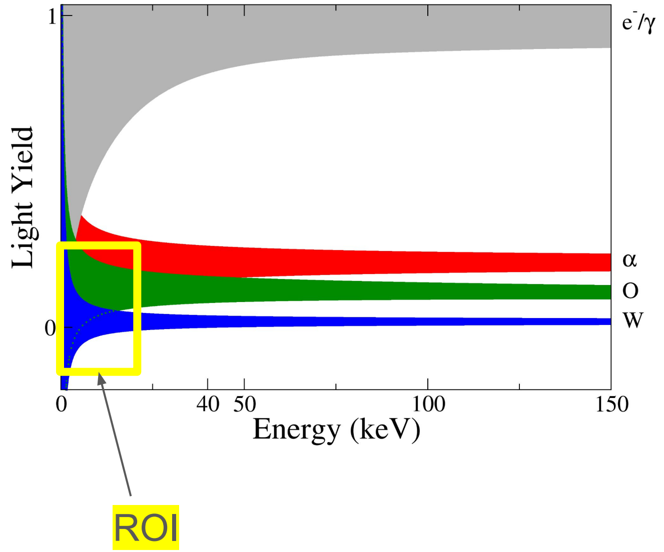

Transition edge sensor

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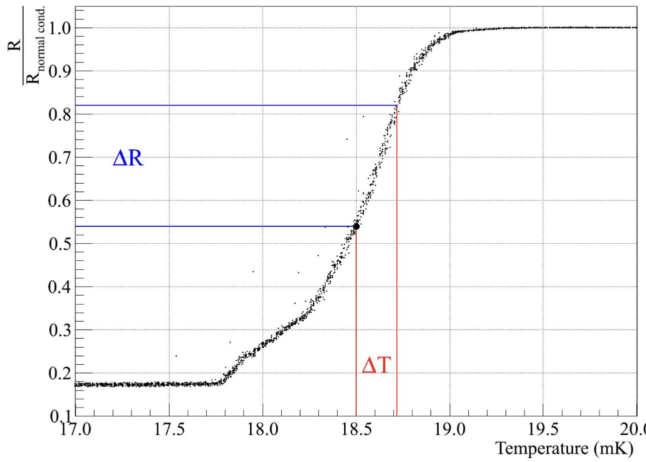
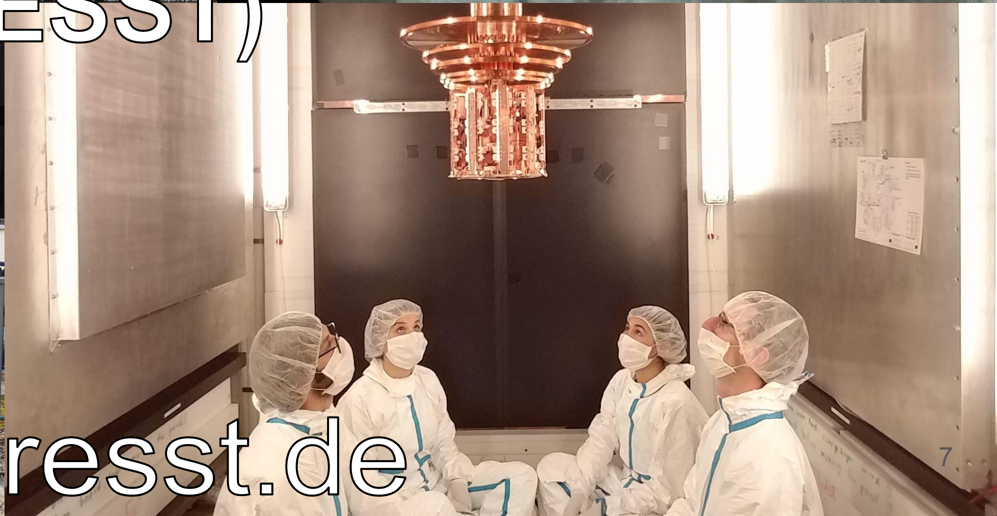


Cryogenic rare event search with superconducting thermometers (CRESST)





www.cresst.de

CRESST

Search for sub-GeV dark matter with scintillating crystals.

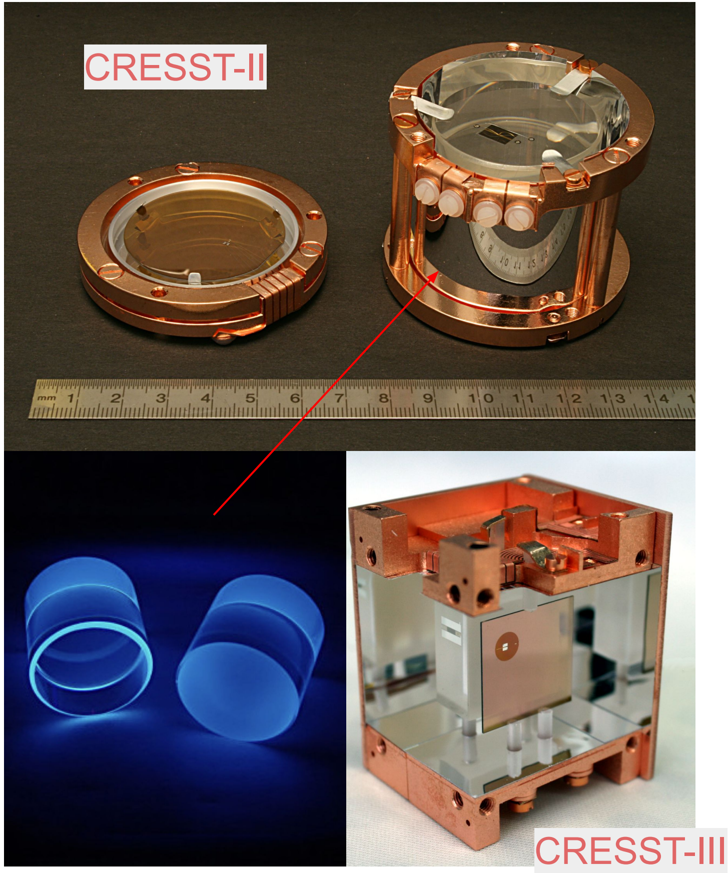
CRESST-II (2007-15):

- Calcium tungstate targets
- larger crystals ~ 250 g
- E_T > 0.4 keV

CRESST-III (since 2016):

- Multiple materials used as targets (also Lithium, Sapphire, Silicon)
- smaller crystals ~ 25 g
- E_T > 30 eV

unique CRESST feature



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Situation 2019

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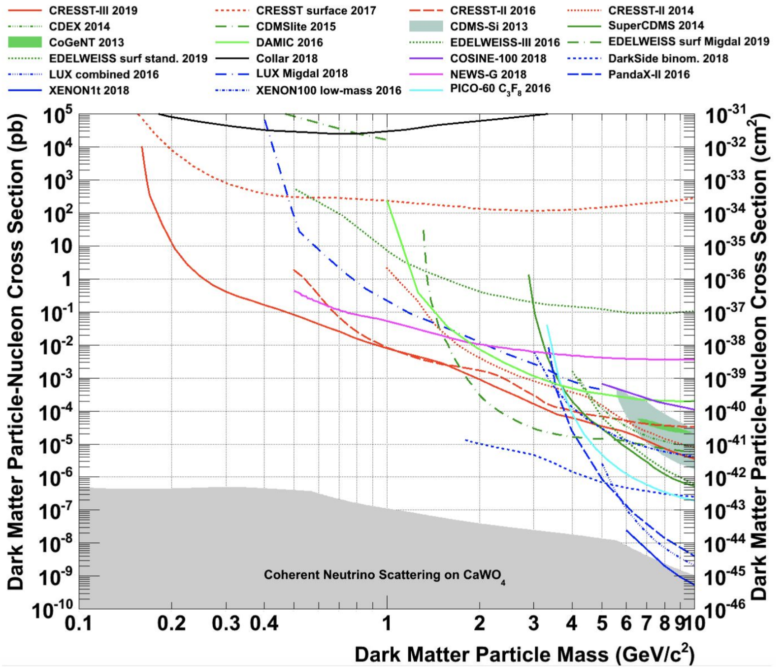

Phys. Rev. D 100, 102002 (2019), https://doi.org/10.1103/PhysRevD.100.102002

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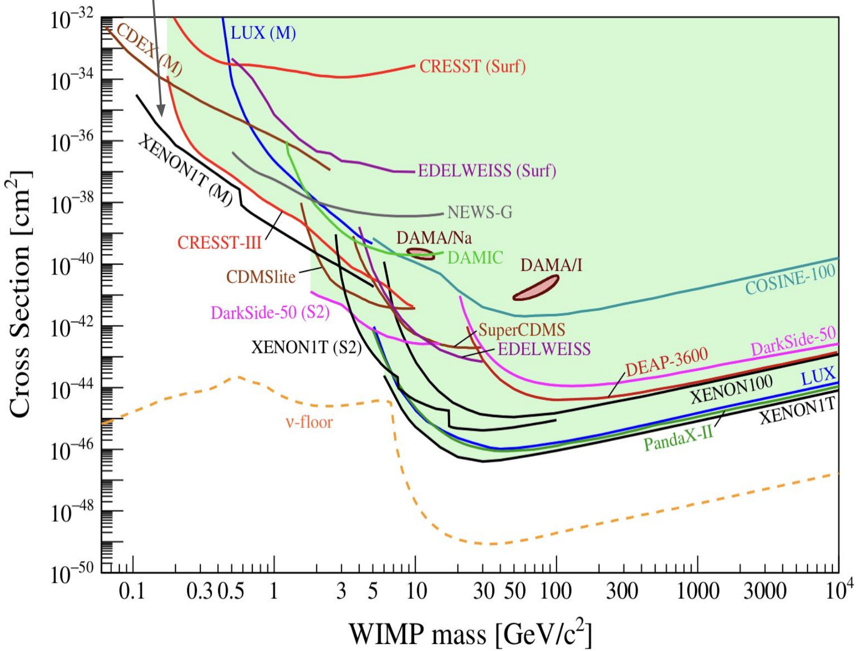
Migdal effect

Situation today



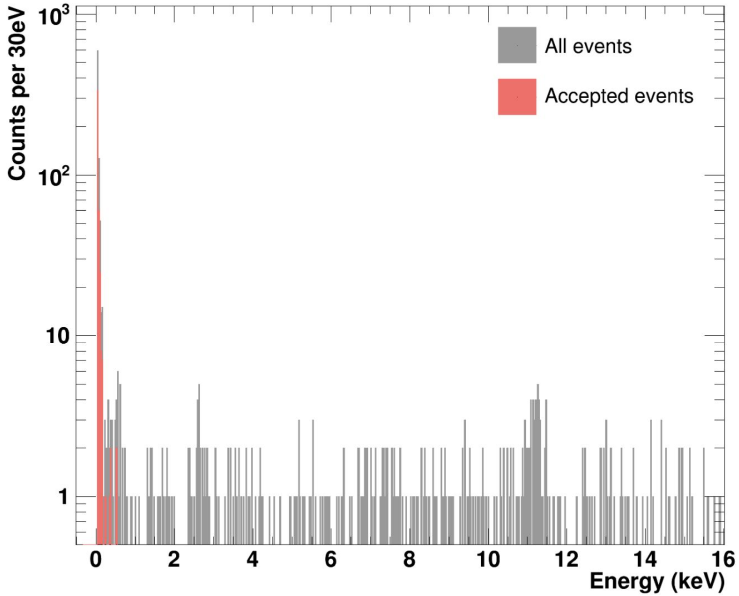
APPEC Committee Report, arXiv:2104.07634

Low energy excess

We observe a sharply rising event rate below 200 eV, an *excess* above known backgrounds.

Individual shape in detectors, therefore common nuclear recoil origin is unlikely.

Decaying time dependency points towards microfractures in the crystal, studying the excess is the main focus of current measurements.



https://arxiv.org/abs/1904.00498

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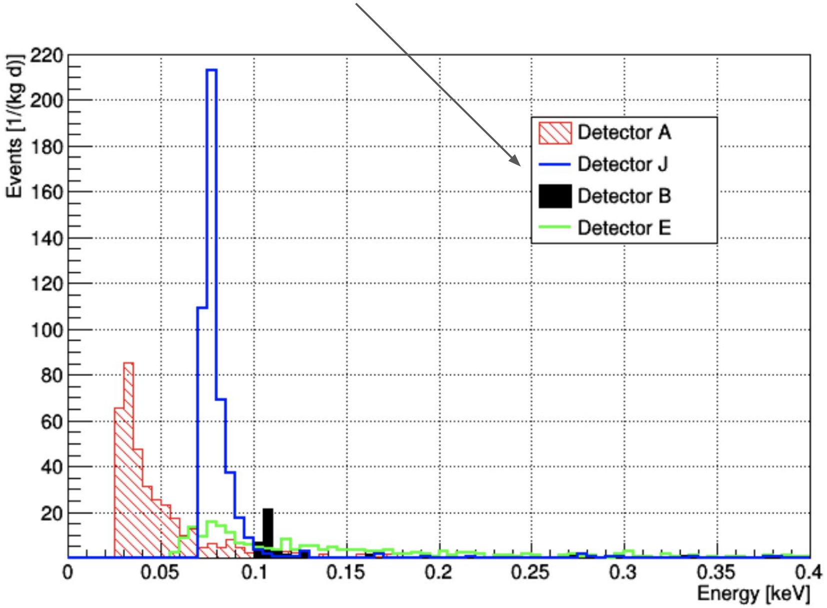
$CaWO_4$



https://doi.org/10.34726/hss.2021.45935

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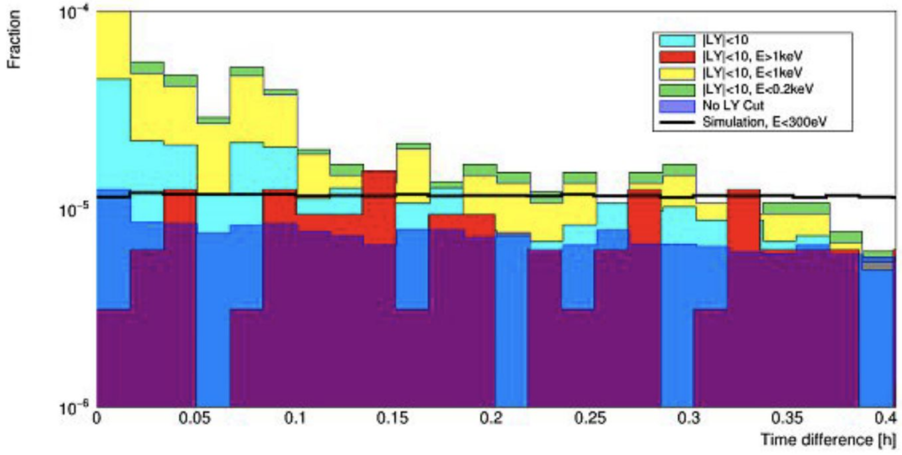


https://doi.org/10.34726/hss.2021.45935

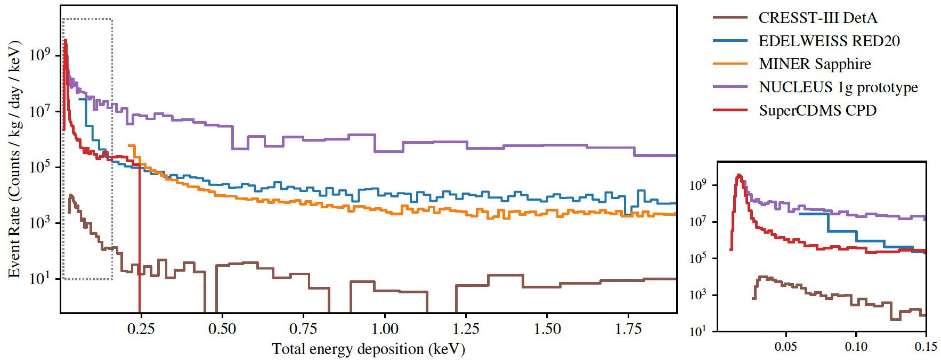
EXCESS workshop

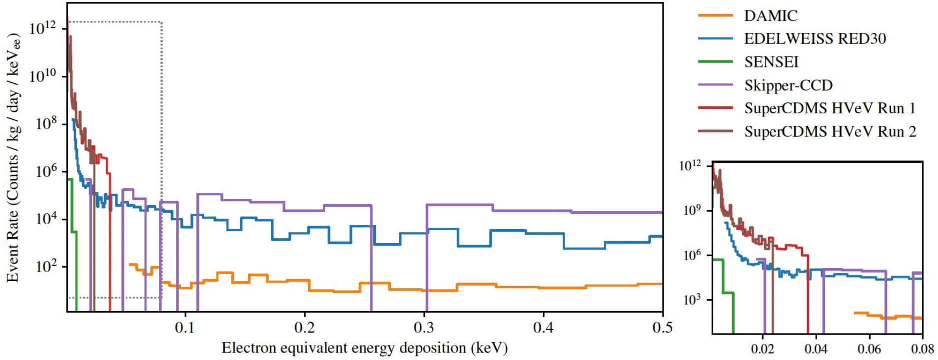
https://arxiv.org/abs/2202.05097

Multiple experiments observe similar excesses:

We organized a workshop (*EXCESS workshop*) with >100 participations to compare, study and interpret the excesses.

Preprint of a *summary white paper* online available, follow-up workshop as satellite of the IDM 2022 (Vienna).





EXCESS workshop

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Multiple e
excesses

We orga
worksho
compare
excesses

Preprint
online av
satellite

EXCESS workshop: Descriptions of rising low-energy spectra

P. Adari, A. Aguilar-Arevalo, D. Amidei, G. Angloher, E. Armengaud, C. Augier, L. Balogh, S. Banik, D. Baxter, C. Beaufort, G. Beaulieu, V. Belov, Y. Ben Gal, G. Benato, A. Benoît, A. Bento, L. Bergé, A. Bertolini, R. Bhattacharyya, J. Billard, I.M. Bloch, A. Botti, R. Breier, G. Bres, J.-.L. Bret, A. Broniatowski, A. Brossard, C. Bucci, R. Bunker, M. Cababie, M. Calvo, P. Camus, G. Cancelo, L. Canonica, F. Cappella, L. Cardani, J.-F. Caron, N. Casali, G.del Castello, A. Cazes, R. Cerulli, B.A. Cervantes Vergara, D. Chaize, M. Chapellier, L. Chaplinsky, F. Charlieux, M. Chaudhuri, A.E. Chavarria, G. Chemin, R. Chen, H. Chen, F. Chierchie, I. Colantoni, J. Colas, J. Cooley, J.-M. Coquillat, E.C. Corcoran, S. Crawford, M. Crisler, A. Cruciani, P. Cushman, A. D'Addabbo, J.C. D'Olivo, A. Dastgheibi-Fard, M. De Jésus, Y. Deng, J.B. Dent, E.L. Depaoli, K. Dering, S. Dharani, S. Di Lorenzo, A. Drlica-Wagner, L. Dumoulin, D. Durnford, B. Dutta, L. Einfalt, A. Erb, A. Erhart, R. Essig, J. Estrada, E. Etzion, O. Exshaw, F. Favela-Perez, F. v. Feilitzsch, G. Fernandez Moroni, N. Ferreiro Iachellini, S. Ferriol, S. Fichtinger, E. Figueroa-Feliciano, J.-B. Filippini, D. Filosofov, J. A. Formaggio, M. Friedl, S. Fuard, D. Fuchs, A. Fuss, R. Gaïor, A. Garai, C. Garrah, J. Gascon , G. Gerbier, M. Ghaith, V.M. Ghete, D. Gift, I. Giomataris, G. Giroux, A. Giuliani, P. Gorel, P. Gorla, C. Goupy, J. Goupy, C. Goy, M. Gros, P. Gros, Y. Guardincerri, C. Guerin, V. Guidi, O. Guillaudin, S. Gupta, E. Guy, P. Harrington, D. Hauff, S. T. Heine, S. A. Hertel, S.E. Holland, Z. Hong, E.W. Hoppe, T.W. Hossbach, J.-C. Ianigro, V. Iyer, A. Jastram, M. Ješkovský, Y. Jin, J. Jochum, J. P. Johnston, A. Juillard, D. Karaivanov, V. Kashyap, I. Katsioulas, S. Kazarcev, M. Kaznacheeva, F. Kelly, B. Kilminster, A. Kinast, L. Klinkenberg, H. Kluck, P. Knights, Y. Korn, H. Kraus, B. von Krosigk, A. Kubik, N.A. Kurinsky, J. Lamblin, A. Langenkämper, S. Langrock, T. Lasserre, H. Lattaud, P. Lautridou, I. Lawson, S.J. Lee, M. Lee, A. Letessier-Selvon, D. Lhuillier, M. Li, Y.-T. Lin, A. Lubashevskiy, R. Mahapatra, S. Maludze, M. Mancuso, I. Manthos, L. Marini, S. Marnieros, R.D. Martin, A. Matalon, J. Matthews, B. Mauri, D. W. Mayer, A. Mazzolari, E. Mazzucato, H. Meyer zu Theenhausen, E. Michielin, J. Minet, N. Mirabolfathi, K. v. Mirbach, D. Misiak, P. Mitra, J.-L. Mocellin, B. Mohanty, V. Mokina, J.-P. Mols, A. Monfardini, F. Mounier, S. Munagavalasa, J.-F. Muraz, X.-F. Navick, T. Neep, H. Neog, H. Neyrial, K. Nikolopoulos, A. Nilima, C. Nones, V. Novati, P. O'Brien, L. Oberauer, E. Olivieri, M. Olmi, A. Onillon, C. Oriol, A. Orly, J.L. Orrell, T. Ortmann, C.T. Overman, C. Pagliarone, V. Palušová, P. Pari, P. K. Patel, L. Pattavina, F. Petricca, A. Piers, H. D. Pinckney, M.-C. Piro, M. Platt, D. Poda, D. Ponomarev, W. Potzel, P. Povinec, F. Pröbst, P. Privitera, F. Pucci, K. Ramanathan, J.-S. Real, T. Redon, F. Reindl, R. Ren, A. Robert, J.Da Rocha, D. Rodrigues, R. Rogly, J. Rothe, N. Rowe, S. Rozov, I. Rozova, T. Saab, N. Saffold, T. Salagnac, J. Sander, V. Sanglard, D. Santos, Y. Sarkis, V. Savu, G. Savvidis, I. Savvidis, S. Schönert, K. Schäffner, N. Schermer, J. Schieck, B. Schmidt, D. Schmiedmayer, C. Schwertner, L. Scola, M. Settimo, Ye. Shevchik, V. Sibille, I. Sidelnik, A. Singal, R. Smida, M. Sofo Haro, T. Soldner, J. Stachurska, M. Stahlberg, L. Stefanazzi, L. Stodolsky, C. Strandhagen, R. Strauss, A. Stutz, R. Thomas, A. Thompson, J. Tiffenberg, C. Tomei, M. Traina, S. Uemura, I. Usherov, L. Vagneron, W. Van De Pontseele, F.A. Vazquez de Sola Fernandez, M. Vidal, M. Vignati, A.L. Virto, M. Vivier, T. Volansky, V. Wagner, F. Wagner, J. Walker, R. Ward, S.L. Watkins, A. Wex, M. Willers, M.J. Wilson, L. Winslow, E. Yakushev, T.-T. Yu, M. Zampaolo, A. Zaytsev, V. Zema, D. Zinatulina, A. Zolotarova
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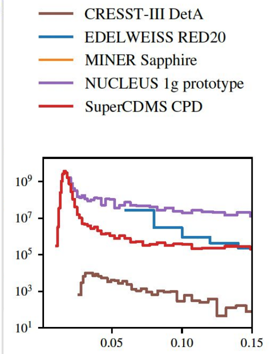
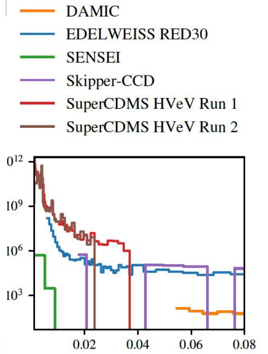




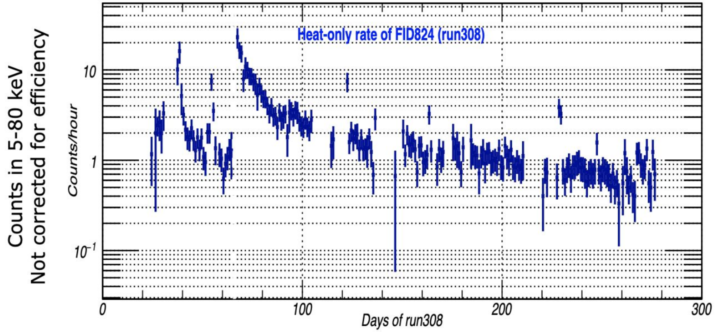
Run36 status and perspectives

Currently measurements ongoing at LNGS. Dark matter data sets are finalized and *unblinded* - publications are planed.

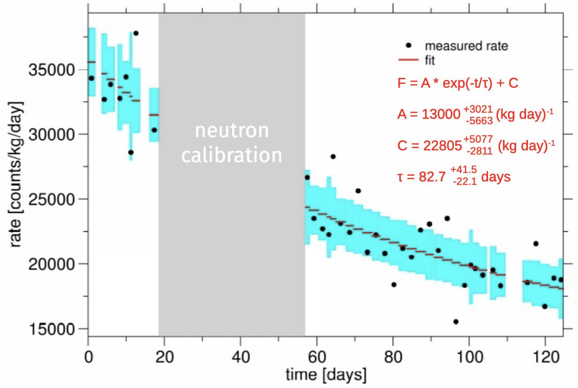
Tests of the excess's time dependency through *cryostat warm ups* (ongoing).

For *run 37*: Further studies of the excess planed.

After run 37 major upgrade to 288 channels (currently ~30). Development a *new DAQ* in Vienna.



EDELWEISS warm up test



CRESST run 35 decaying event rate

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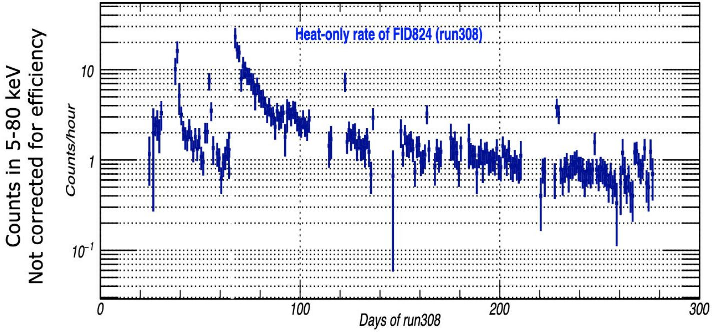

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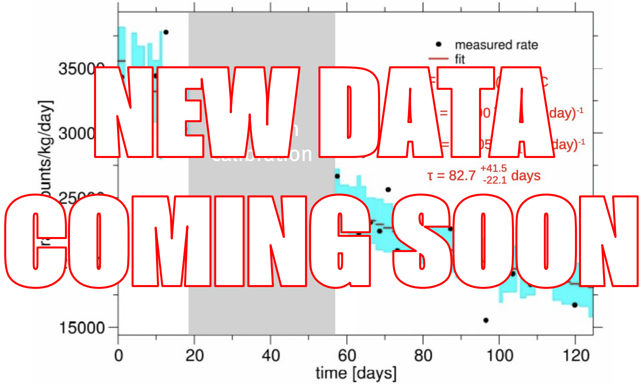


CRESST run 35 decaying event rate

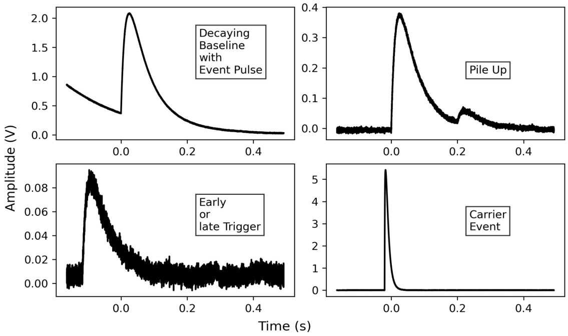
Analysis and control with machine learning

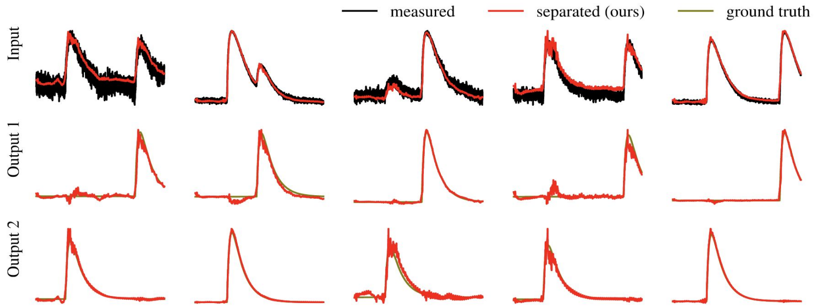
Cait (Cryogenic Artificial Intelligence Tools): Python Package for machine learning-based raw data analysis.

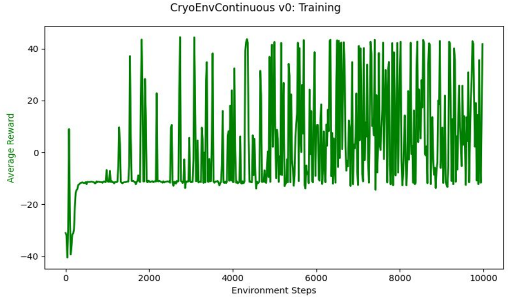
Analysis: Identification, classification and reconstruction of particle recoil events, optimization of acceptance regions through tree- and net-based learners and data augmentation.

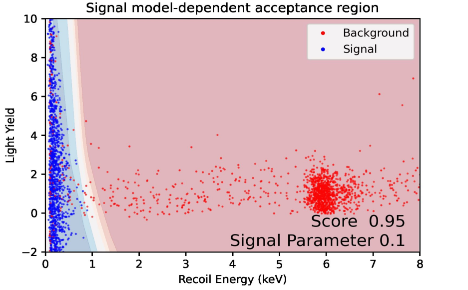
Control: Fine tuning of detector parameters through deep reinforcement learning.

cait









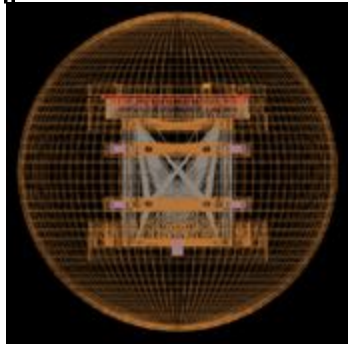
https://doi.org/10.5281/zenodo.5091416

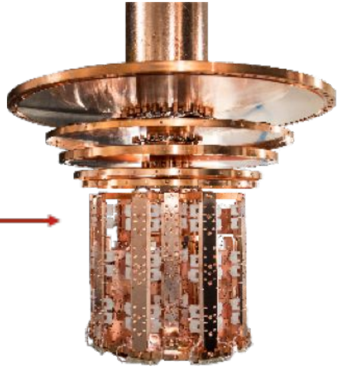
https://arxiv.org/abs/2112.06792

CRESST background (bkg) simulation

Single TUM40 module in a shell

start

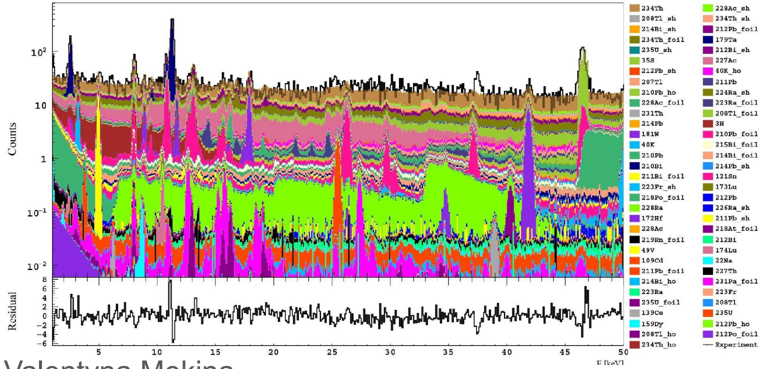




- multiple detectors, different Runs implemented
- extended geometry (till 50mK mantle), next - shield
- work on parametric fit to extend data range for verification of bkg model
- use of Likelihood method to fit simulated templates
- more materials included, more isotopes
- screening and use these values as priors in the fit

- CaWO$_4$, Cu materials
- intrinsic, cosmogenics
- 3 data sets to verify
- no info about radiopurity

First results -
work is in progress!



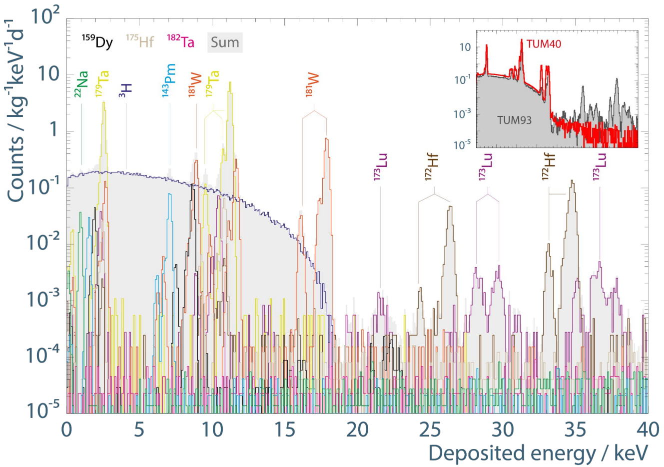
Reproduction of bkg up to (68.2±15.8)% → (98.1±0.8)%

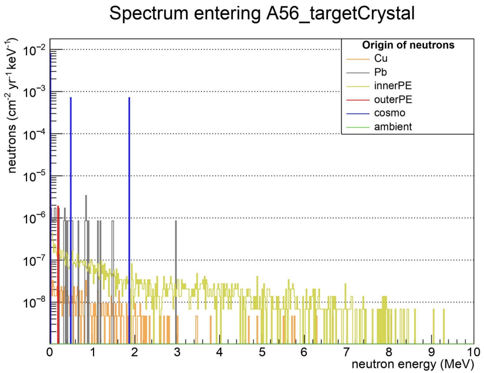
preliminary

EPJ-C 79 (2019) 881

CRESST background simulation

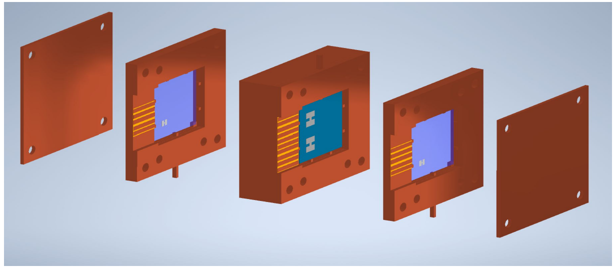
Extensive study of cosmic activation of $CaWO_4$

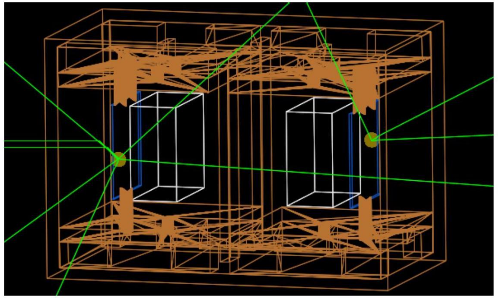




Neutron and muon simulation

Direct read into code CAD drawings of also future detectors to test them





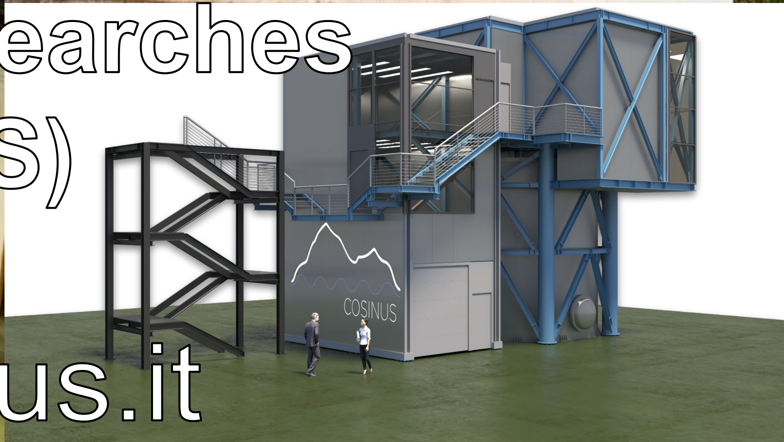
Investigation of calibration influence of data spectra

and much more…

The code is maintained and extended for use by CRESST and COSINUS.

COSINUS

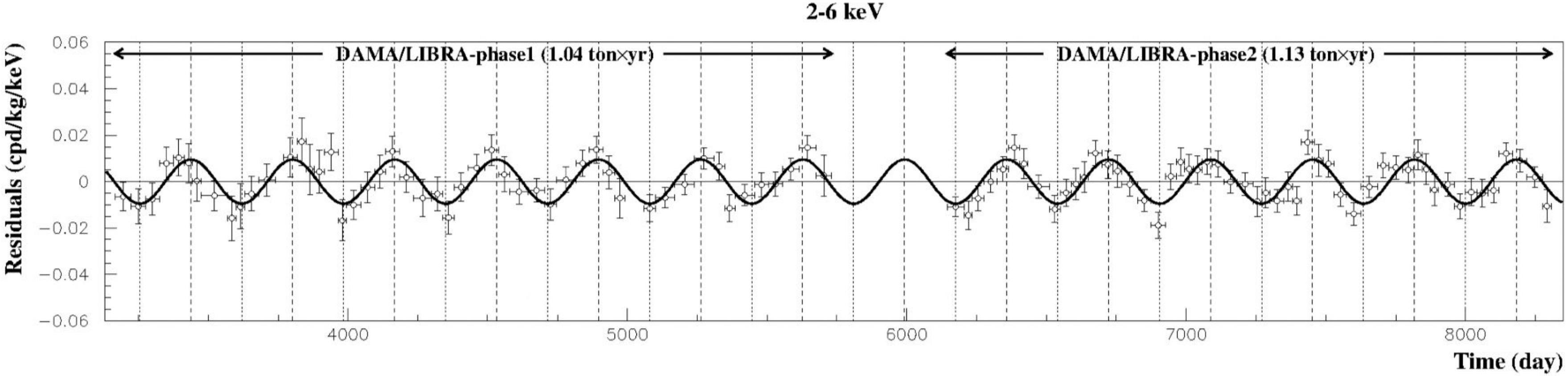
Cryogenic Observatory for SIgnatures seen in Next-generation Underground Searches (COSINUS)



www.cosinus.it

The DAMA/LIBRA results

R. Bernabei et al. (2018), DOI: 10.15407/jnpae2018.04.307

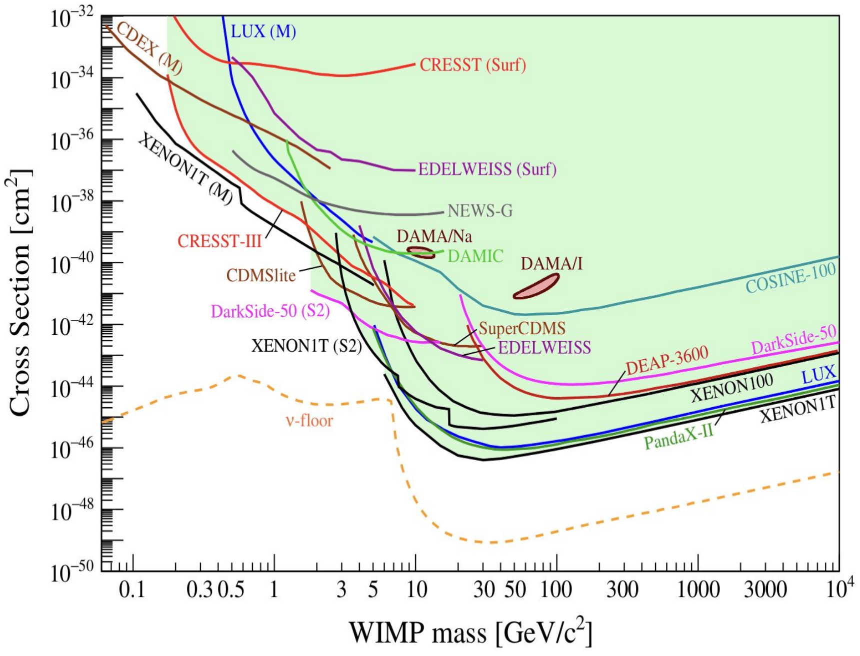


Modulation Amplitude: S_m= (0.0103±0.0008) /(keV×kg×day)

Exposure: 2.46 t×year over 20 annual cycles in 2-6 keV

***C.L.:* 12.9 σ**

Dark Matter Landscape



[arXiv:2104.07634](https://arxiv.org/abs/2104.07634)

Other experiments with NaI targets:

Anais. https://arxiv.org/abs/2103.01175

Cosine. https://arxiv.org/abs/1903.10098

Sabre. https://arxiv.org/abs/1806.09340

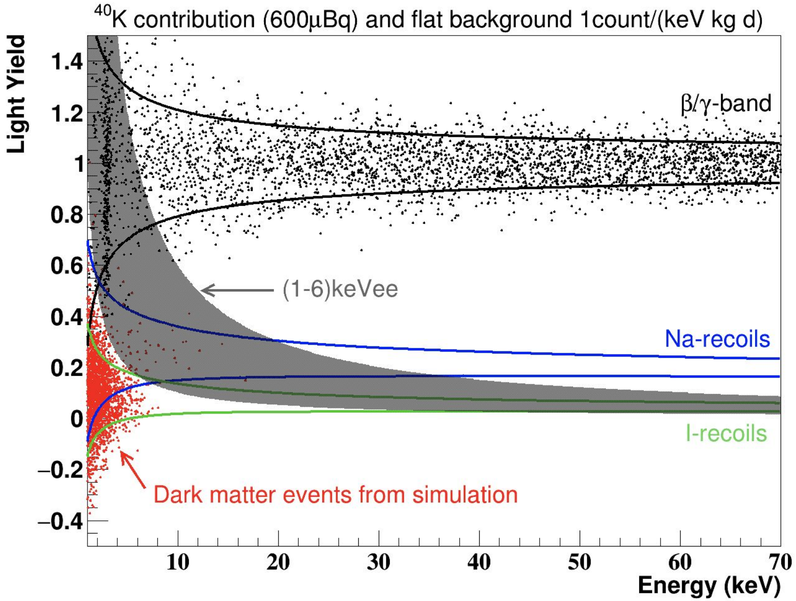
still in construction

… all of them measure scintillation light, but no total energy deposition.

The COSINUS Experiment

Light Yield: Light Energy / Phonon Energy

- *Two channel approach (heat, light):* In-situ measurement of nuclear energy scale.
- NaI as target material: Immune against *material dependence.*
- Operation as *cryogenic detector*: <1 keV nuclear recoil energy threshold.



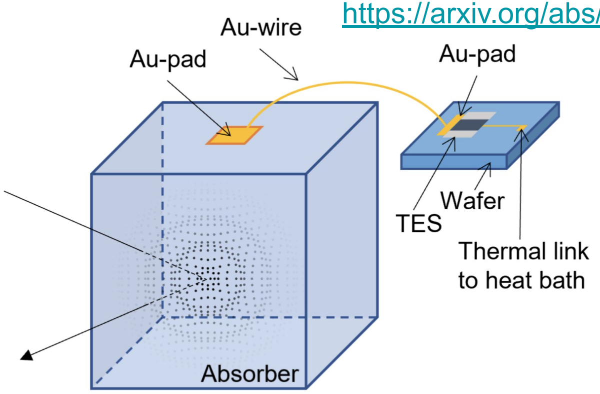
G. Angloher et al. (2016), DOI: 10.1140/epjc/s10052-016-4278-3

First measurement of remoTES

remoTES idea first suggested by M. Pyle et al. in 2015, https://arxiv.org/abs/1503.01200

NaI has to be exclusively handled in controlled atmosphere:

- avoid the carrier crystal, thus avoid that phonons have to
- pass through another material except of NaI
- avoid the amorphous interface (e.g. glue, grease, oil, …)
- instead: profit from good e-ph coupling of Au



https://arxiv.org/abs/2111.00349

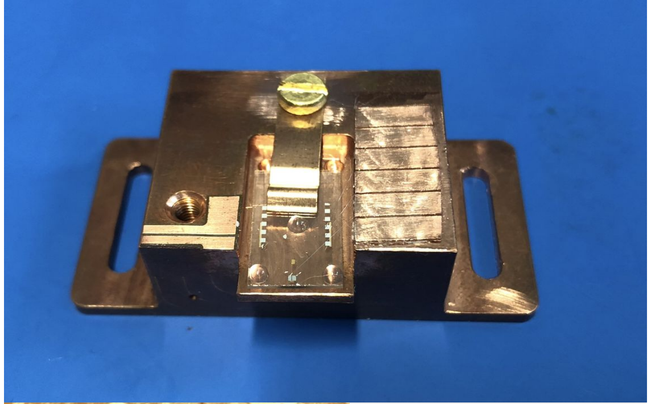
Previous prototype measurement: Phonon threshold of 8.23 keV.

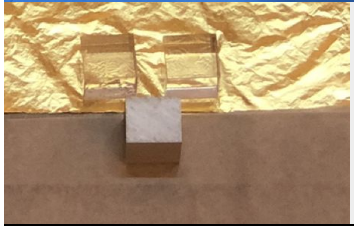
G. Angloher et al. JINST 12 P11007 (2017)
F. Reindl et al., J. Phys. Conf. Ser. 1342 012099 (2020)
Schäffner, K. et al. J Low Temp Phys (2018)

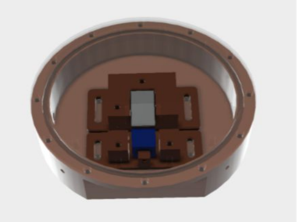
First measurement of remoTES

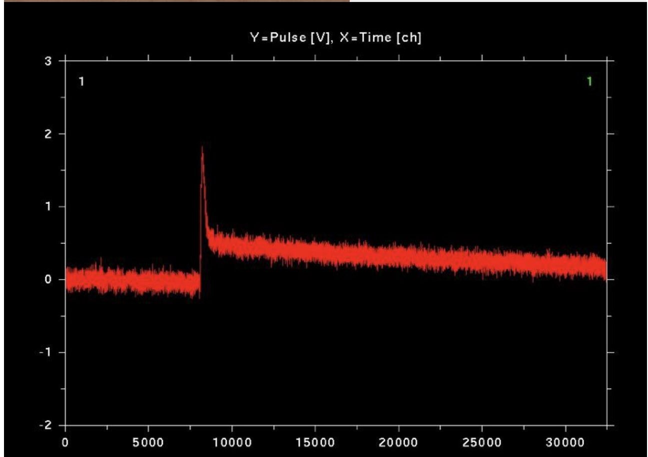
Two above ground R&D runs (autumn 2022) with NaI remoTES:

- Operation as cryogenic detector possible (first pulse shown right).
- Promising *energy resolution*.
- Basis for the *final detector design*.









First measurement of remoTES

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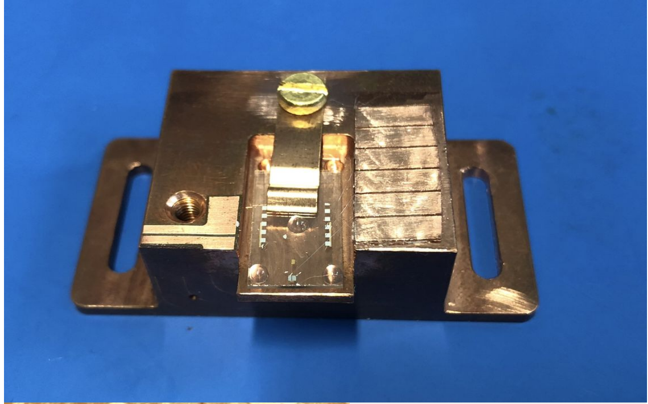

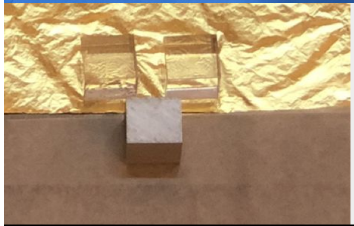

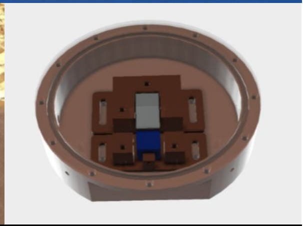

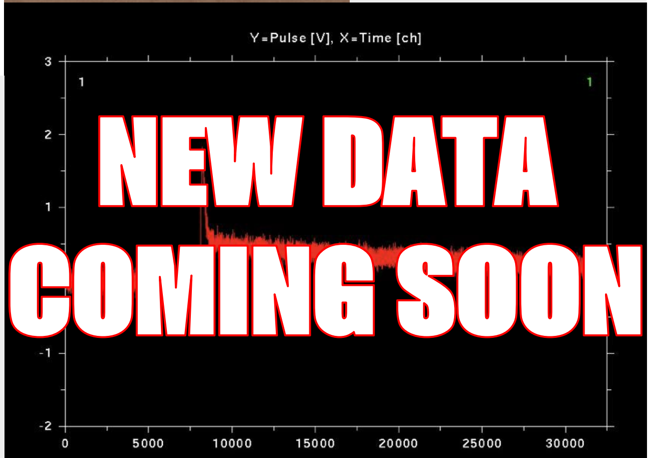

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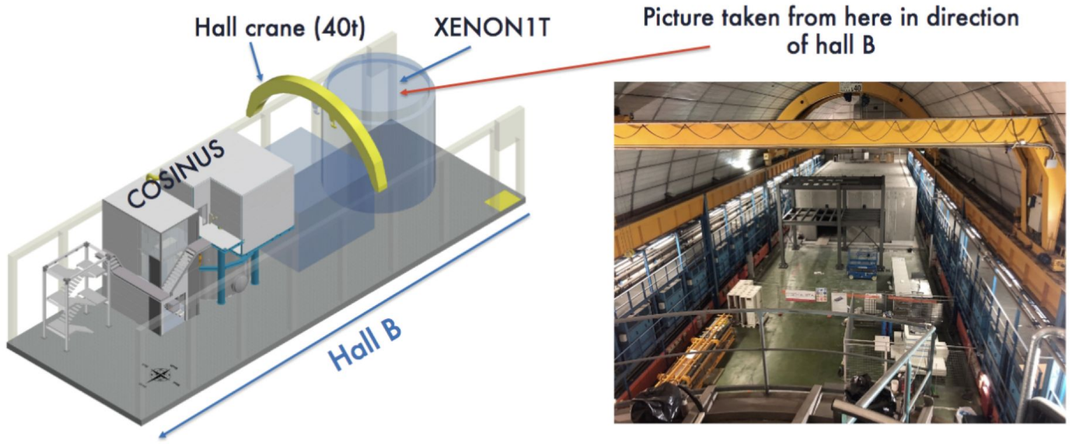
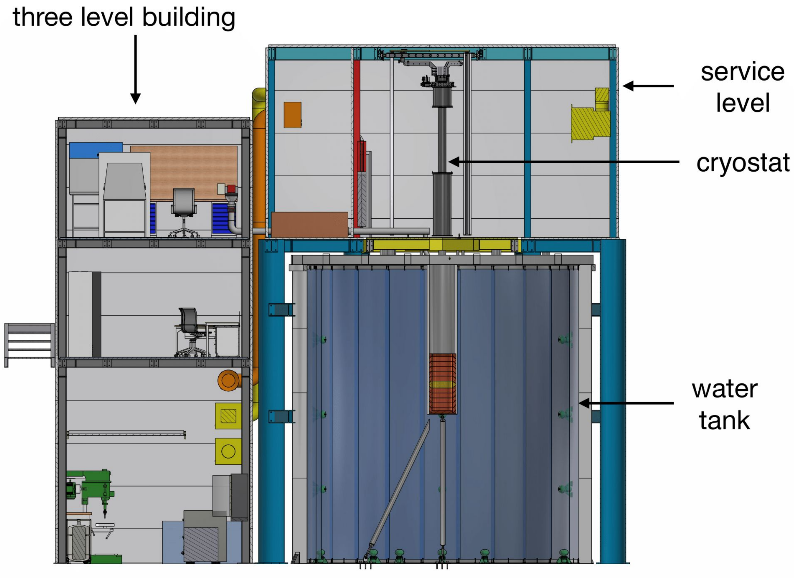
Setup @ LNGS


Hall crane (40t)
XENON1T
Picture taken from here in direction of hall B
COSINUS
Hall B


three level building
service level
cryostat
water tank

Setup @ LNGS

Summary

CRESST …

- tests sub-GeV dark matter with $CaWO_4$, $LiAlO_2$, Si, Al_2O_3 targets.
- achieved one of the best cross section upper limits down to 140 MeV.
- studies a low energy excess signal.

COSINUS …

- cross-checks the DAMA signal claim with NaI targets.
- will finish construction in 2022/23.

CRESST & COSINUS

only CRESST

only COSINUS

The people behind HEPHY RES

Simulation


Jochen Schieck
(Group leader)


Vasile Mihai Ghete
(scientist)


Holger Kluck
(Postdoc)


Valentyna Mokina
(Postdoc)


Samir Banik
(Postdoc)


Alexander Fuß
(PhD)


Rituparna Maji
(PhD)


Jens Burkhart
(MSc)
(PhD soon!)

Analysis


Florian Reindl
(tenured)


Daniel Schmiedmayer
(PhD)


Shubham Gupta
(PhD)

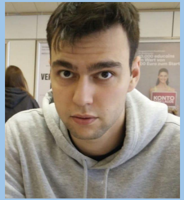
Theory

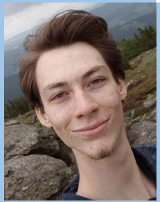

Leonie Einfalt
(PhD)

Machine Learning


Felix Wagner
(PhD)


Daniel Bartolot
(MSc)


Damir Rizvanovic
(MSc)


Moritz Lackner
(MSc)

Data acquisition


Stephan
Fichtinger
(technician)


Christoph
Schwertner
(technician)

DANAE


Wolfgang
Treberspurg
(Scientist)

Backup

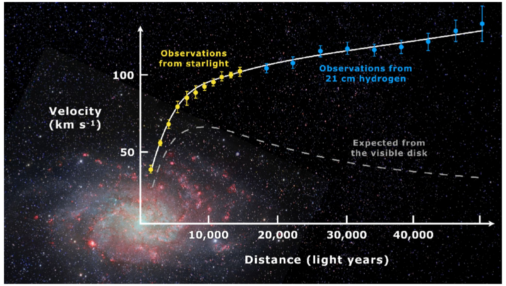
Dark matter

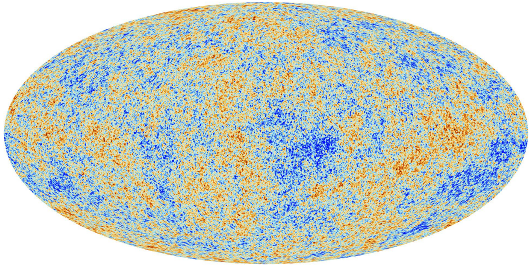
Today we observe 5 times more dark matter than visible matter in the universe.

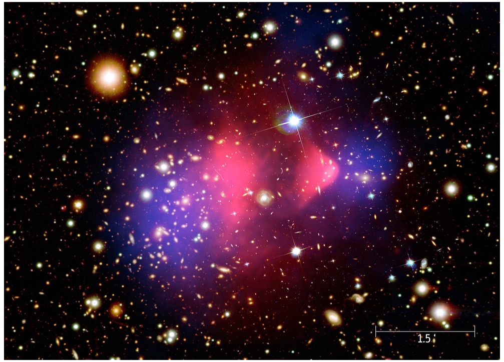
Observations: Galactic rotation curves, CMB, gravitational lensing, …

Open question: What is the *nature* of dark matter?

Hypothesis: A yet unknown non-luminous, non-baryonic, cold, stable particle.







Dark matter direct detection

Movement of the earth w.r.t. the sun introduces an annual modulation in the expected signal:

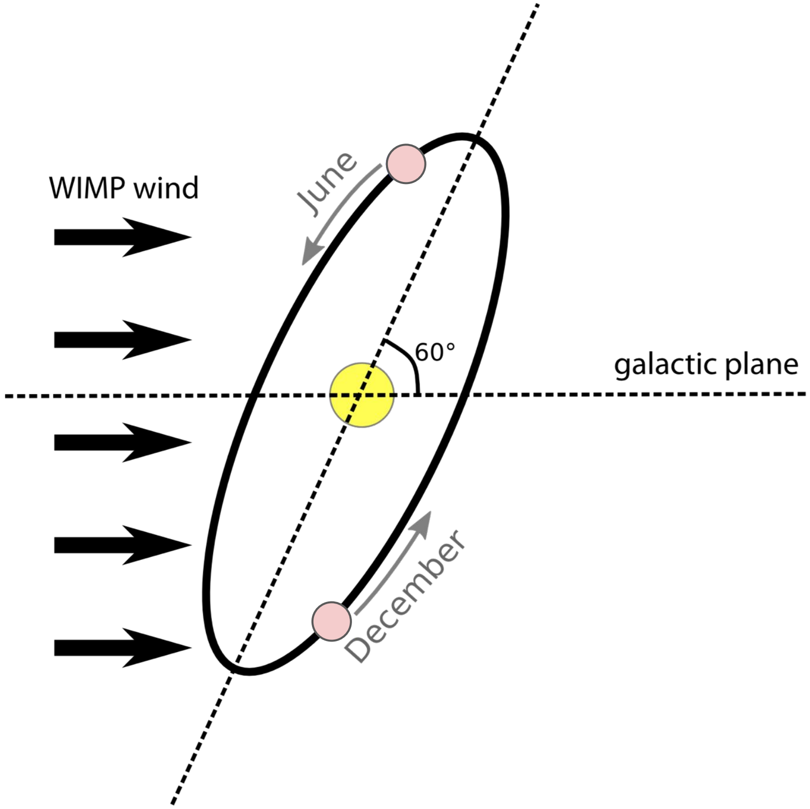
$$S(t) = B(t) + S_0 + S_m \cos\left[\omega(t - t_0)\right]$$

B(t) … Background

S_0 … Constant signal share

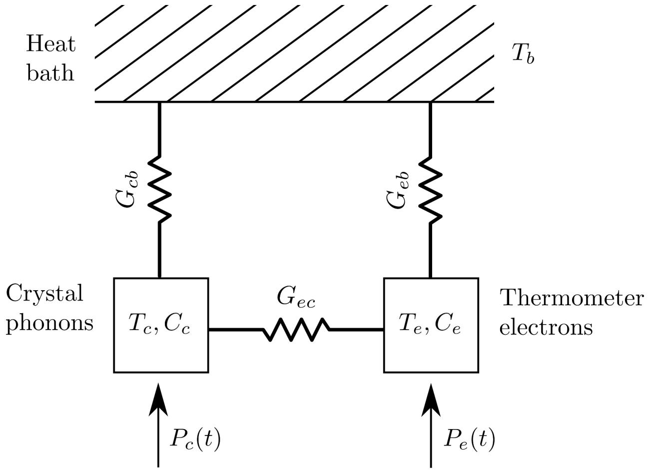
S_m … Modulating signal share (~ 0.05 S_0)*

*J. Billard et al. (2021), arXiv:2104.07634, p. 21



F. Pröbst et al., J. Low Temp. Phys. 100, 69 (1995)

Detector Response Model

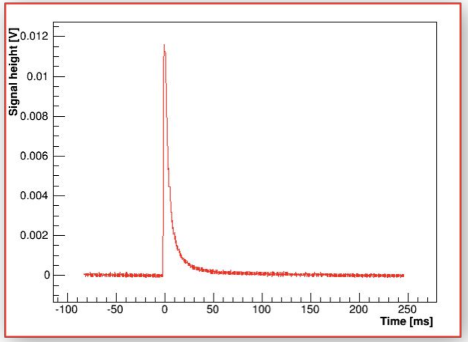


Equivalent thermal circuit of the detector components provides matrix-valued differential equation for all temperatures:

$$C_i \frac{dT_i}{dt} + G_{ib}(T_i - T_b) + \sum_j G_{ji}(T_j - T_i) = P_i$$

Solution for thermometer temperature after *particle recoil* in the crystal:

$$\Delta T_e(t) = \Theta(t)\left[A_n\left(\mathrm{e}^{-t/\tau_n} - \mathrm{e}^{-t/\tau_{in}}\right) + A_t\left(\mathrm{e}^{-t/\tau_t} - \mathrm{e}^{-t/\tau_n}\right)\right]$$



Baseline Design

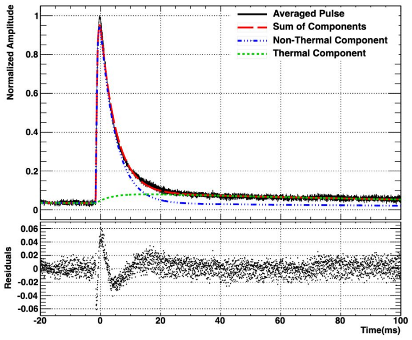
Measurement at LNGS (2017).

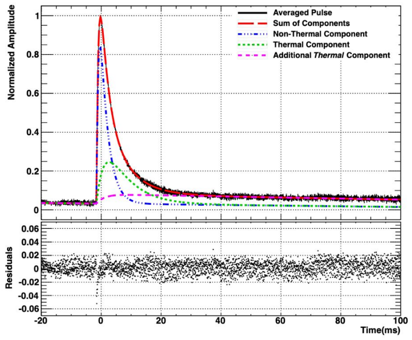
66 g NaI crystal, 1.32 kg days exposure.

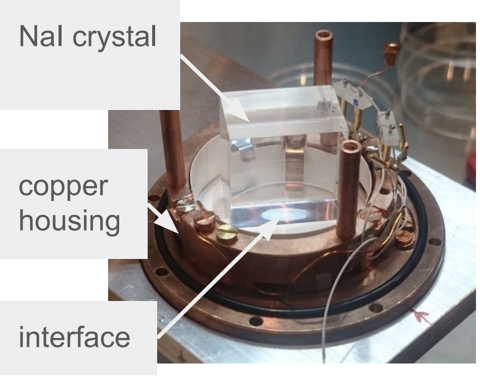
^{241}Am source (~60 keV).

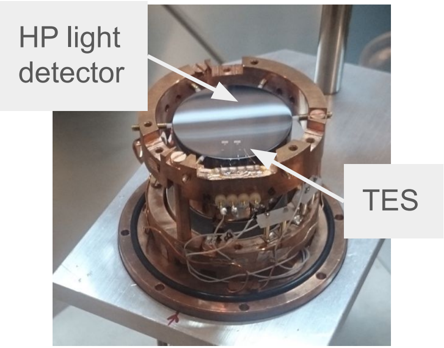
Beaker-shaped light detector (Si).

Three thermal components: Absorber crystal, thermometer and carrier crystal.









F. Reindl et al., J. Phys. Conf. Ser. 1342 012099 (2020)
Schäffner, K. et al. J Low Temp Phys (2018)

Baseline Design

Challenges:

- hygroscopicity
- high Debye temperature
- potassium (K) contamination

Energy Threshold NaI:

8.26 +/- 0.02 keV

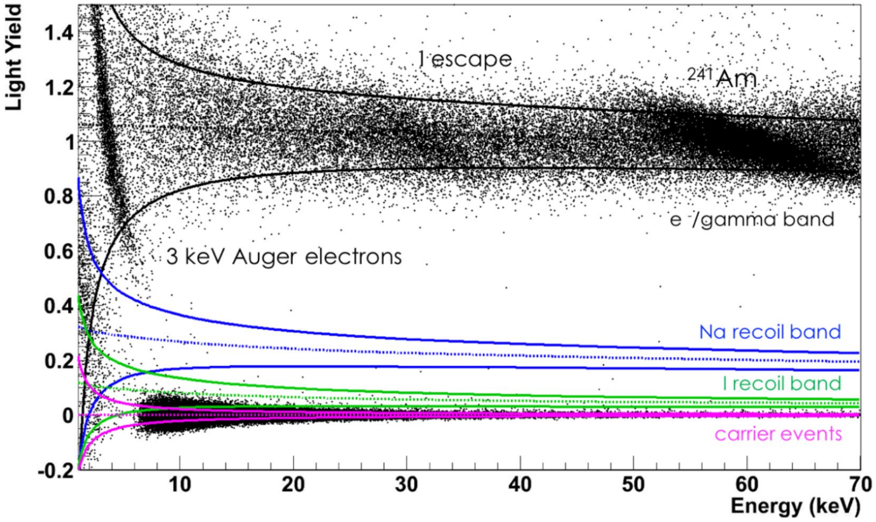
Energy Resolution NaI:

1.1 keV (baseline) - 4.5 keV (60 keV)

Energy Resolution Light:

~0.6 keVee

Pulse shape identification of carrier events.



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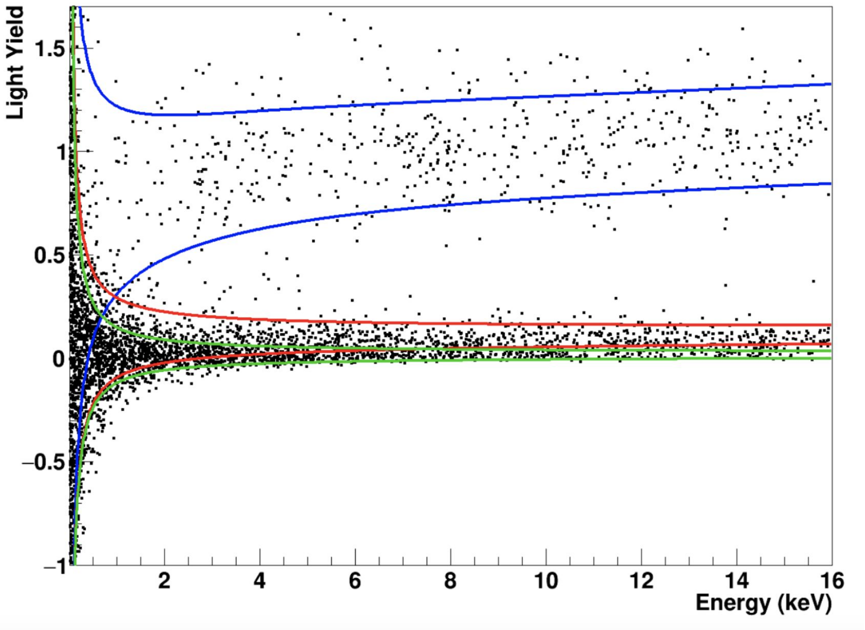
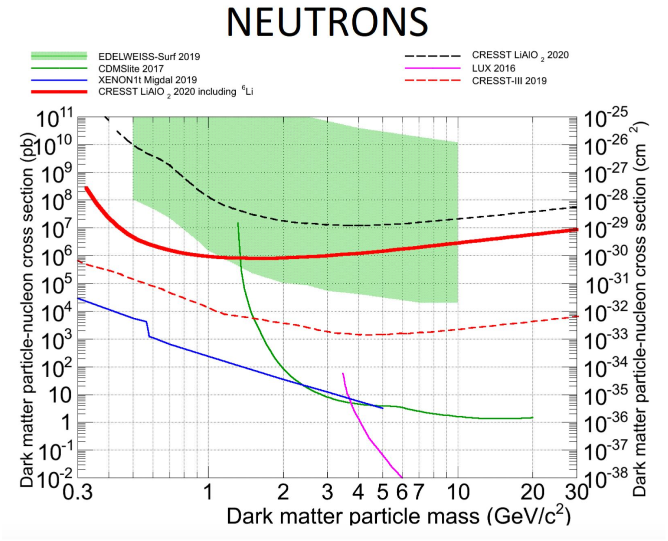
CRESST-III DetA neutron calibration

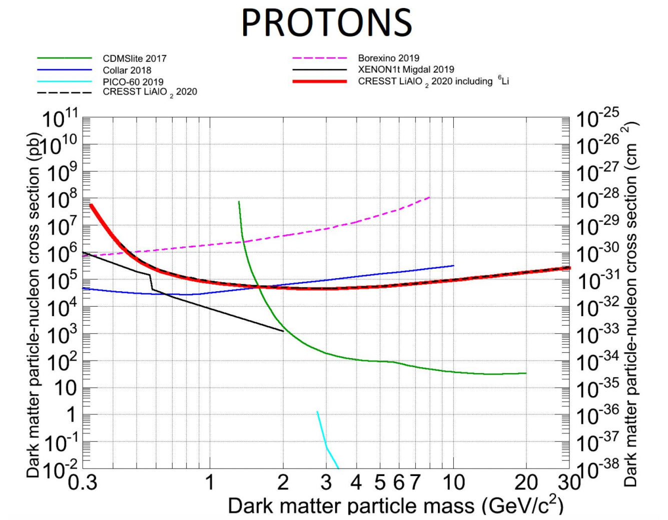


Lithium 6 Limits (above ground)

New best CRESST limits for spin-dependent dark matter with above ground lithium measurements.

Improvement expected from Run 36 data.





https://arxiv.org/abs/2201.03863

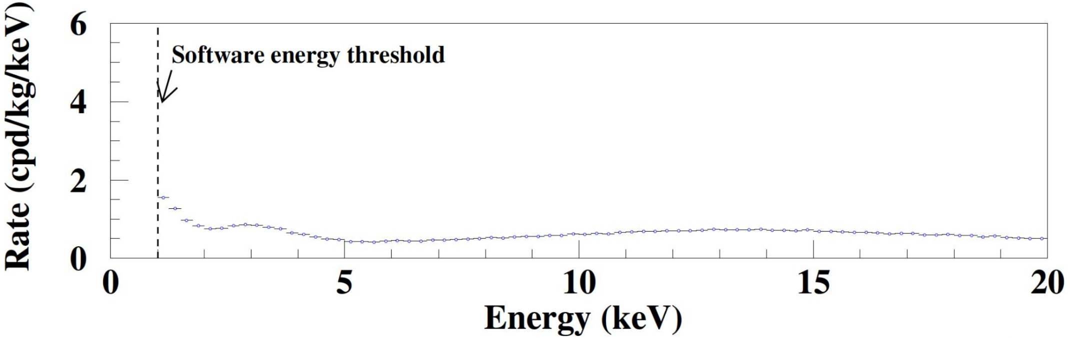
The DAMA/LIBRA results

Observation of positive evidence for the presence of dark matter particles via *annual modulation*.

Target: 250 kg sodium iodide NaI(Tl) crystals.

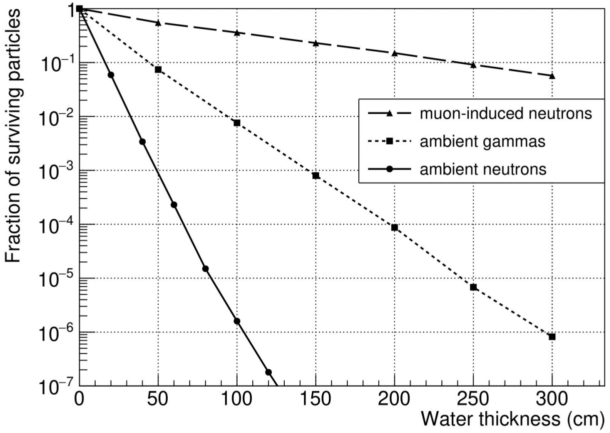
R. Bernabei et al. (2018), DOI: 10.15407/jnpae2018.04.307

Location	LNGS
Material	250 kg NaI(Tl)
Signal(s)	Light (PMTs)
Particle Discrimination	no
Energy Threshold	1keVee
Data taking	since 1996



Setup @ LNGS

https://arxiv.org/abs/2106.07390

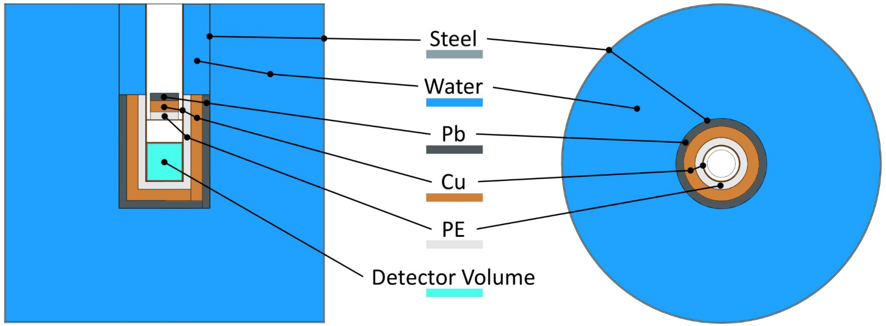


Construction @ LNGS (3600 mwe), started 2021.

A PMT-equipped water tank acts as passive shielding and active veto.

Result of simulation studies:

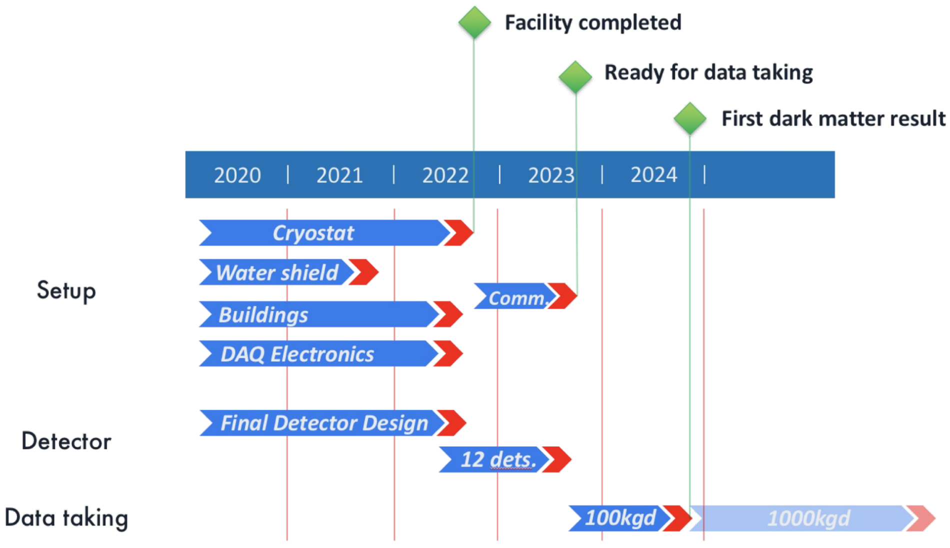
- Cylindrical water tank, 7 m height and diameter.
- 8 cm Cu.
- No lead (Pb) layer: Water provides enough shielding against gammas, less muon-induced events in Cu.
- No polyethylen (PE) layer: Contaminations could cause additional neutrons.



Time Scale

COSINUS – 1π (2022-2025)
Exclude or confirm nuclear recoil origin of DAMA, independent of dark matter halo, for any interaction of dark matter with nuclei.

COSINUS – 2π (≥2026)
Investigate annual modulation signature with COSINUS.



"It has been evaluated that if COSINUS excludes a DM scattering rate of about 0.01 events/(kg×day), with an energy threshold of 1.8keV, it will rule out the explanations of DAMA/LIBRA in terms of DM scattering off sodium and/or iodine." - 2021 APPEC Committee Report

https://arxiv.org/abs/2104.07634
https://arxiv.org/abs/1802.10175

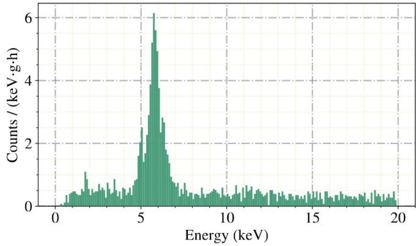
First measurement of remoTES

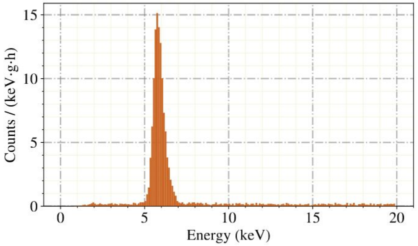
[Submitted on 30 Oct 2021]

First measurements of remoTES cryogenic calorimeters: easy-to-fabricate particle detectors for a wide choice of target materials

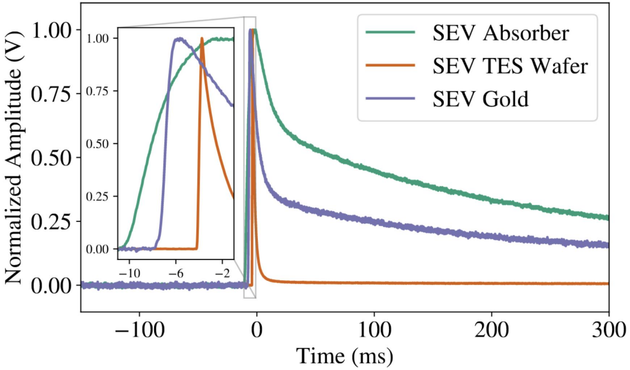
COSINUS Collaboration: G. Angloher, M.R. Bharadwaj, I. Dafinei, N. Di Marco, L. Einfalt, F. Ferroni, S. Fichtinger, A. Filipponi, T. Frank, M. Friedl, A. Fuss, Z. Ge, M. Heikinheimo, K. Huitu, M. Kellermann, R. Maji, M. Mancuso, L. Pagnanini, F. Petricca, S. Pirro, F. Proebst, G. Profeta, A. Puiu, F. Reindl, K. Schaeffner, J. Schieck, D. Schmiedmayer, C. Schwertner, M. Stahlberg, A. Stendahl, F. Wagner, S. Yue, V. Zema, Y. Zhu, A. Bento, L. Canonica, A. Garai

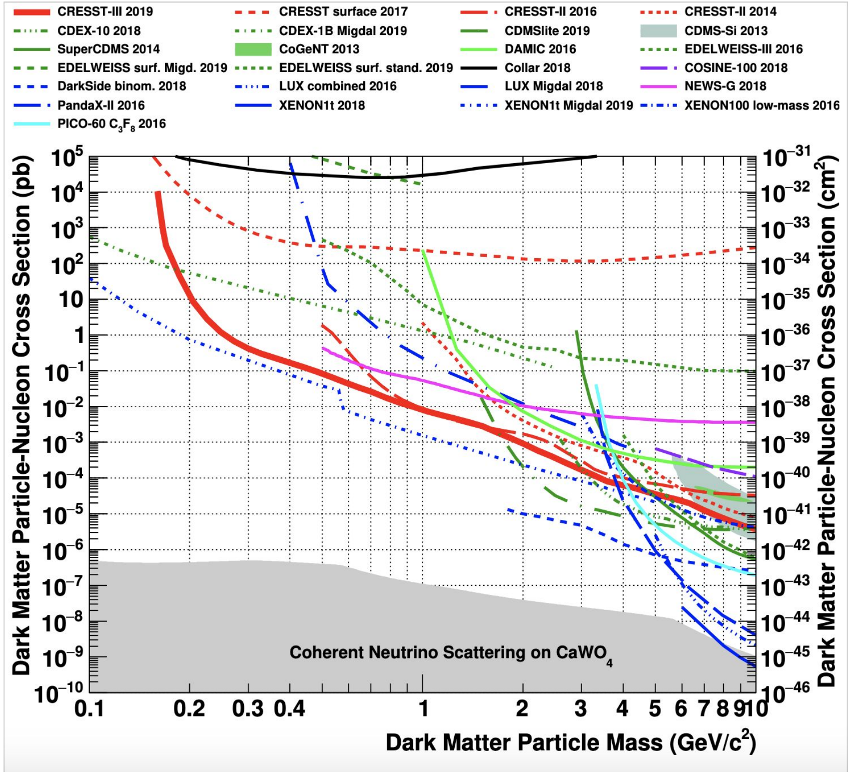
Low-temperature calorimeters based on a readout via transition edge sensors (TESs) and operated below 100 mK are well suited for rare event searches. We present first experimental results from two detector prototypes using a novel thermometer design denoted remoTES. This design facilitates the use of TESs in combination with absorber materials which, due to their physical and chemical properties, as e.g. hygroscopicity, low hardness and low melting point, prevent the direct deposition of the TES onto their surface. In a remoTES detector, the TES is fabricated onto a separate wafer. The absorber crystal is then equipped with a gold pad that transmits the phonon signal created from an interaction in the absorber to the thermometer via a gold bonding wire. With recent prototype detectors operated in an above-ground R&D facility, we achieve energy resolutions of sigma=87.8 eV for a silicon absorber and $\sigma = 193.5$ eV for an alpha-TeO_2 absorber, respectively. RemoTES calorimeters offer - besides the wider choice of absorber materials - a simpler production process combined with a higher reproducibility for large detector arrays and an enhanced radiopurity standard, which is of particular interest for rare event searches.





Absorber material	Absorber volume (mm^3)	Au-pad properties	Au-wire properties	TES	Energy resolution (eV)
Si	20x10x5	200nm sputtered RRR=3.79	17 µm glued on pad	W-TES on Al_2O_3	87.8 ± 5.6
TeO_2	20x10x2	400nm foil glued RRR=15	17 µm 2 wedge bonds	W-TES on Al_2O_3	193.5 ± 3.1




CRESST-III 2019
CRESST surface 2017
CRESST-II 2016
CRESST-II 2014
CDEX-10 2018
CDEX-1B Migdal 2019
CDMSlite 2019
CDMS-Si 2013
SuperCDMS 2014
CoGeNT 2013
DAMIC 2016
EDELWEISS-III 2016
EDELWEISS surf. Migd. 2019
EDELWEISS surf. stand. 2019
Collar 2018
COSINE-100 2018
DarkSide binom. 2018
LUX combined 2016
LUX Migdal 2018
NEWS-G 2018
PandaX-II 2016
XENON1t 2018
XENON1t Migdal 2019
XENON100 low-mass 2016
PICO-60 C3F8 2016
Dark Matter Particle-Nucleon Cross Section (pb)
Dark Matter Particle-Nucleon Cross Section (cm2)
Coherent Neutrino Scattering on CaWO4
Dark Matter Particle Mass (GeV/c2)