Review on Direct Searches for Dark Matter

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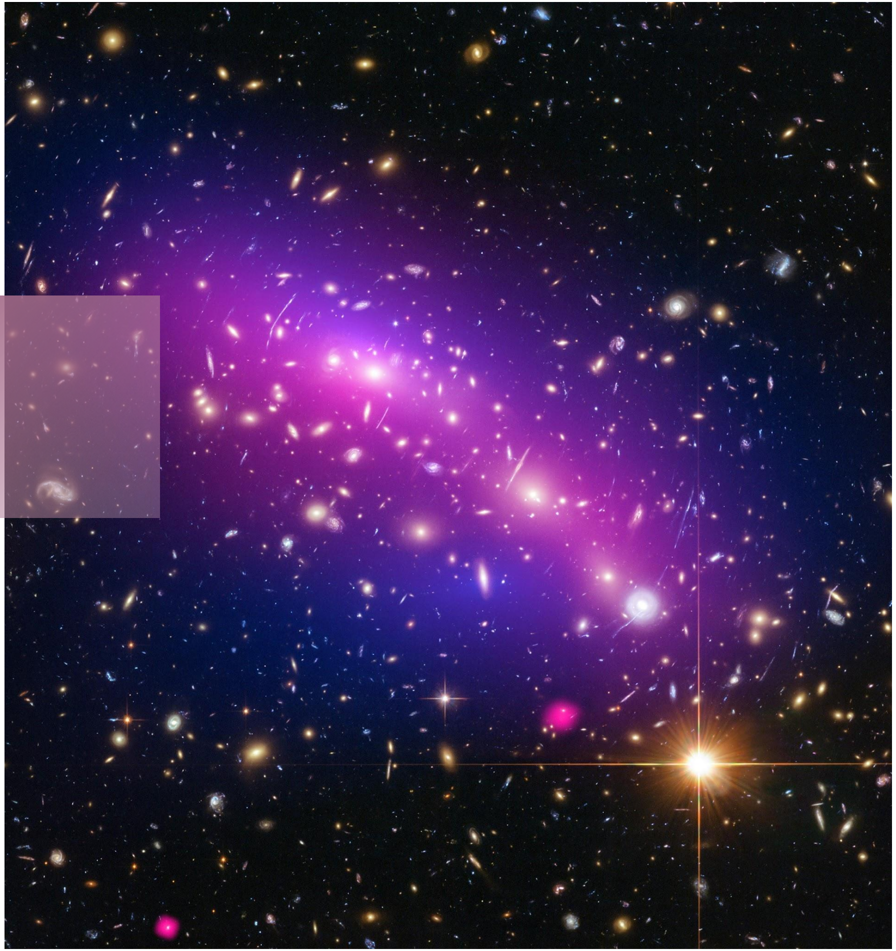
INFN

Riunione CSN2 - Venezia, 7 - 9 aprile 2025



GRAZIE

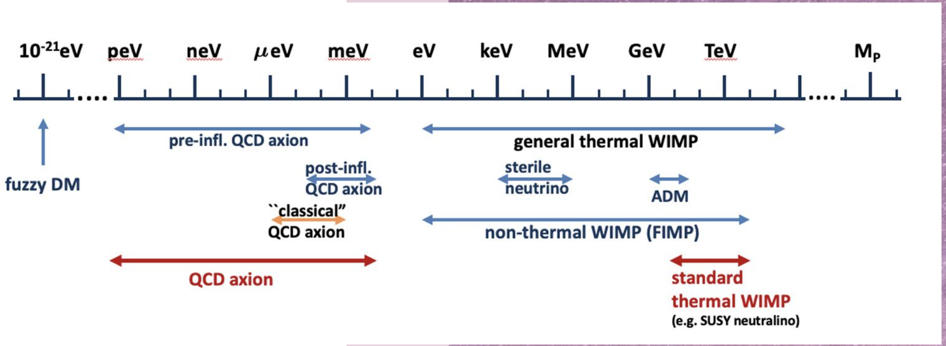
Fabio Bellini, Riccardo Cerulli, Giulia D'Imperio, Angelo Esposito, Paolo Gorla, Aldo Ianni, Eric Vazquez Jauregui, Lorenzo Pagnanini, Davide Pinci, Marco Selvi, Livia Soffi, Marco Vignati, Lindley Winslow.

also slides from **UCLA DM 2025, 15th Symposium**
March 24 - 27, 2025

DARK MATTER PARTICLES

Diverse astronomical and cosmological observations, on scales ranging from galaxies to the entire Universe, provide powerful evidence that 85% of the matter in the Universe is in the form of cold, non baryonic dark matter (CDM)

APPEC Committee Report 2021



PROPERTIES

neutral, stable, interacts only gravitationally and via weak force

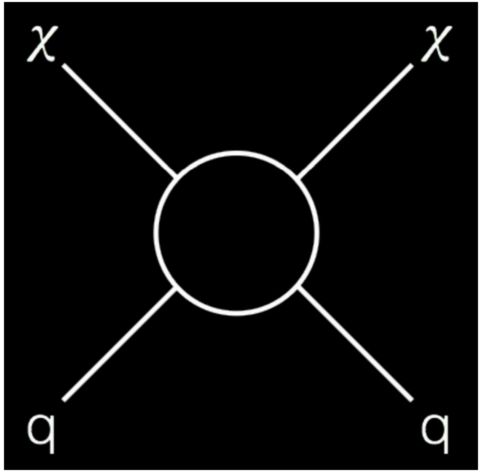
huge discovery space: drives the scientific interest and the technological development

DM SEARCHES

- Direct searches
  - rare events searches in underground laboratories
  - searches with quantum sensors → see talk from Caterina Braggio
- Searches at accelerators
- Indirect searches → see talk from Riccardo Munini

Indirect detection experiments: look for cosmic messengers resulting from dark matter interactions

Direct detection searches: focus on detecting dark matter’s interactions in a detector on Earth



accelerators-based experiments: attempt to produce dark matter particles

DM and nuclear recoil - NR

NR rate vs. Energy

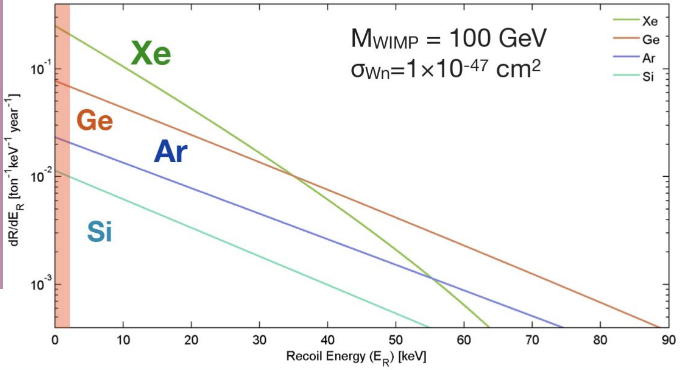
$$\frac{dR}{dE_{nr}}(E_{nr}) = \frac{\rho_0}{M_\chi M_N}\int_{v_{min}}^{v_{max}} d^3\vec{v}\, vF(\vec{v}+\vec{v}_e)\frac{d\sigma_{\chi-N}}{dE_{nr}}(v, E_{nr}, A)$$

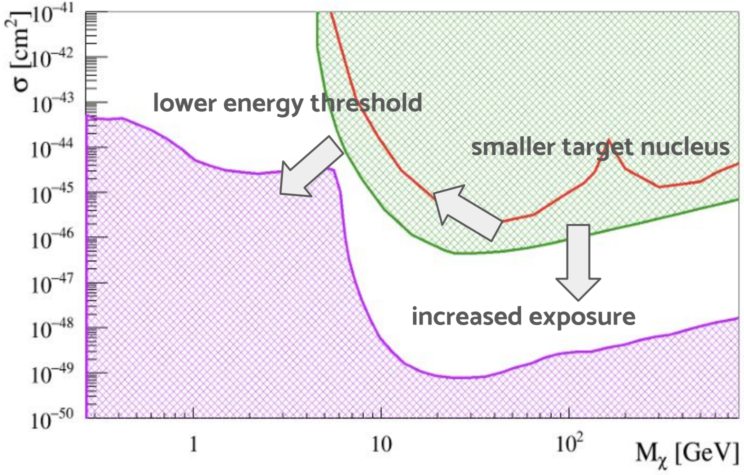
$$v_{min}(E_{nr}, M_\chi, A) = \sqrt{\frac{M_N E_{nr}}{2\mu_N^2}}$$

Model-dependent approach: assumptions on **dark matter velocity distribution, local density in the Galaxy, etc**... are necessary

Ex. Flux = ~10^5 cm^{-2} s^{-1} - M_W= 100 GeV - density 0.3 GeV/cm^3

The measurement of the recoil energy is translated into the plane dark matter-nucleon scattering cross section vs. mass



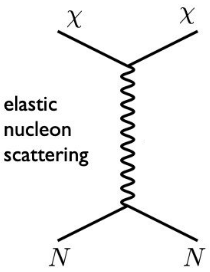


Use of **discriminating variables** to disentangle possible dark matter events from electron/gamma backgrounds.

If no excess of events over the expected background is observed, a limit in the plane is derived.

DM interactions

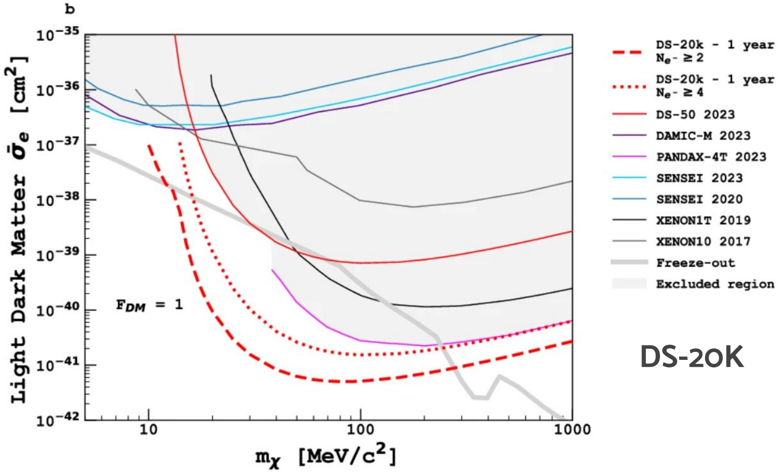
SPIN-INDEPENDENT (SI)



the rate is converted to a WIMP-nucleon cross section to allow the comparison between different target nuclei. A^2 dependence favours heavy target nuclei.

SPIN-DEPENDENT (SD)

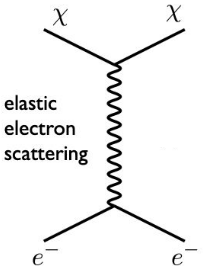
the rate depends on the total nuclear spin of the target.
SD-results are quoted assuming that WIMPs couple either only to neutrons (nuclei with an odd number of neutrons, ex. ^{17}O, ^{29}Si, ^{73}Ge, ^{129}Xe, ^{131}Xe) or to protons (nuclei with an odd number of protons, ex. ^{7}Li, ^{23}Na, ^{127}I).



DS-20K

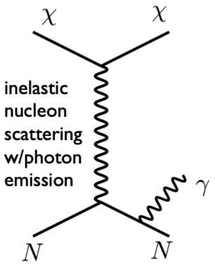
ELECTRONIC RECOIL (ER)

WIMPs in the MeV/c^2 range and below do not transfer sufficient momentum to the target nucleus to generate NRs of detectable size.
WIMP-electron scattering will create very small ionisation signals of ER type.



INELASTIC SCATTERING (iDM)

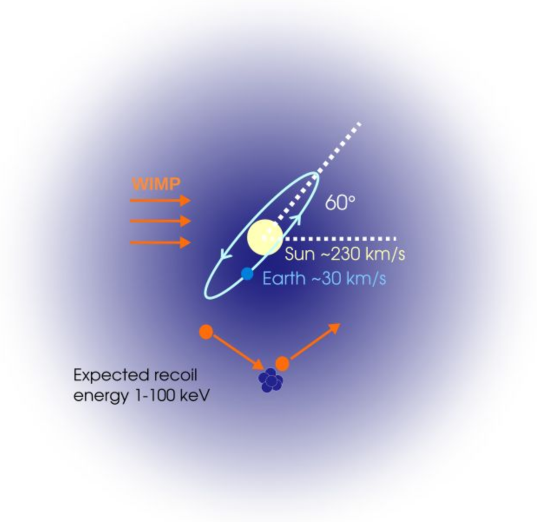
nuclear recoil followed by an electronic de-excitation of either the WIMP or the target nucleus.
MIGDAL effect.



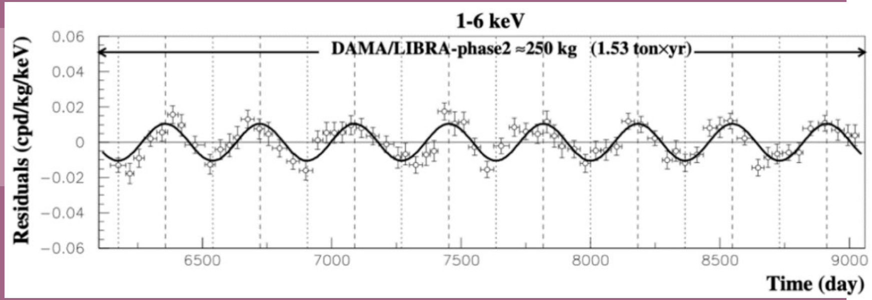
Dark Matter with annual modulation

$$R = S_0 + S_m \cos\left(\frac{2\pi}{T}(t - t_0)\right)$$

The modulation observed by DAMA/LIBRA satisfies the criteria expected of a DM-induced signal.

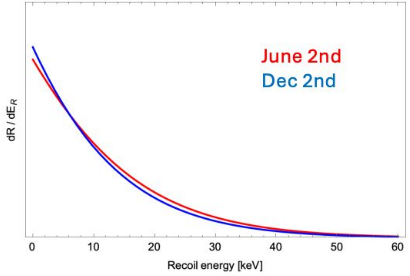


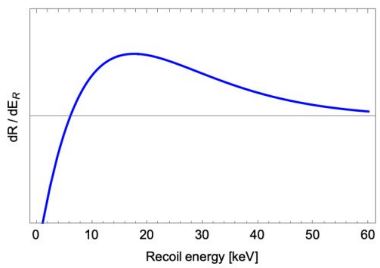
DAMA/LIBRA 11.6 σ in [1-6] keV



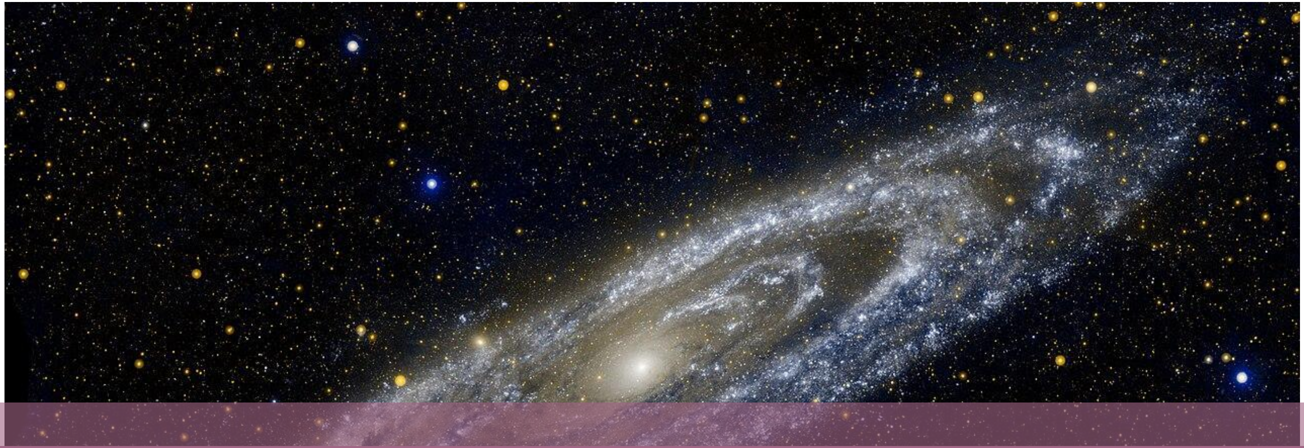
Nucl. Phys. At. Energy 22 (2021) 329-342

- **Expected rate in an Earth-based detector is modulated**
- Small modulation fraction S_m/S_0 = O(~few %)
- Region of interest in NaI: [1-6] keV





DIRECTIONAL DM SEARCHES



WHY

Expectation is for the DM flux to peak in a given direction (towards the constellation Cygnus).

HOW

The direction of the induced NR is correlated with that of the impinging DM particle.
An observed anisotropy in the distribution of NR directions could give evidence for a galactic origin of the signal.

DETECTOR

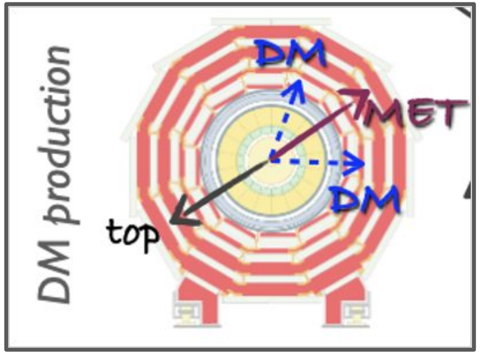
A direction sensitive detector is needed, but not only:

- high mass
- low threshold
- low background
- stable

Directionality: use the angular information to discriminate interactions of DM particles against background.

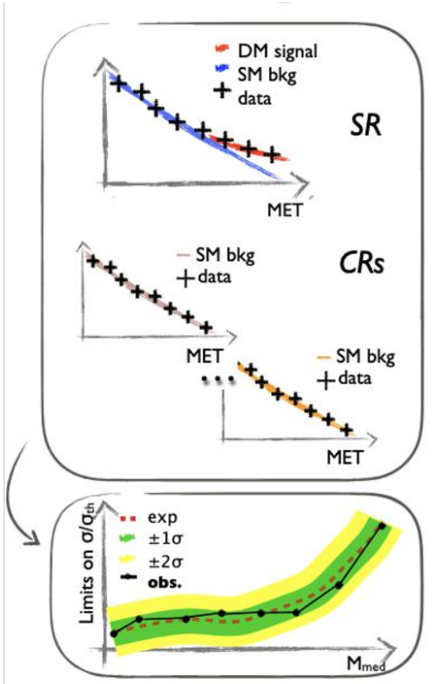
DARK MATTER AT ACCELERATORS

Selection: DM appears as excess of events in MET tail wrt SM (or peak)



Background: precise modeling, evaluation of SM processes in SR essential, achieved through use of multiple control regions (CRs)

Results: Compare SM predictions with data
- excess of events in data. Did we find DM?
- no excess, interpret result in terms of theory model parameters



invisible: no striking signature, eg. mass peak, mT kinematic endpoint

look for excess in region enriched in signal (signal region - SR)

Complementarity with direct-detection essential:

- accelerator-based directly characterize particle properties of produced DM, explore relativistic DM production
- direct detection explores a combination of DM properties with their cosmological abundance, probe non- relativistic scattering

INTERNAL BACKGROUND

NEAR CONTAMINATIONS

sources of radioactivity that are within or in close contact with the sensitive elements of the experimental setup contribute with alpha, beta and gamma events

FAR CONTAMINATIONS

sources of radioactivity that are within the experimental setup but not in close contact with the sensitive elements contribute with beta/gamma events examples: U/Th in the shields

Main culprits (are everywhere) :

- ^{238}U, ^{232}Th chains, ^{40}K
- ^{210}Pb, cosmogenic isotopes, but also radioactive isotopes of the material used as target (ex. ^{39}Ar in atmospheric Ar, etc…)

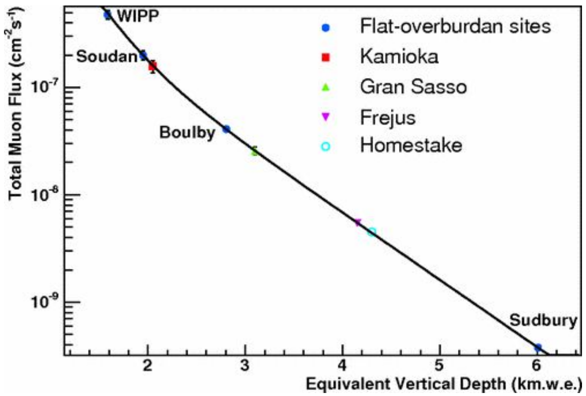
COSMOGENIC ACTIVATION

Avoid material exposure to cosmic rays, sea level transportation, underground cooling from cosmogenic activity (order of months, 1 year), underground growth/extraction.

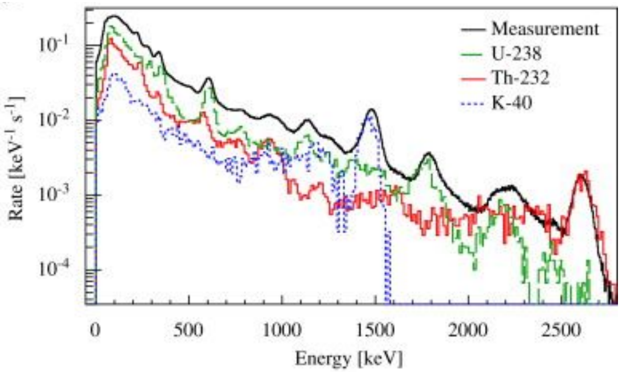
RADIOGENIC NEUTRONS

arise from (α, n) and spontaneous fission reactions

MUONS FROM COSMIC RAYS

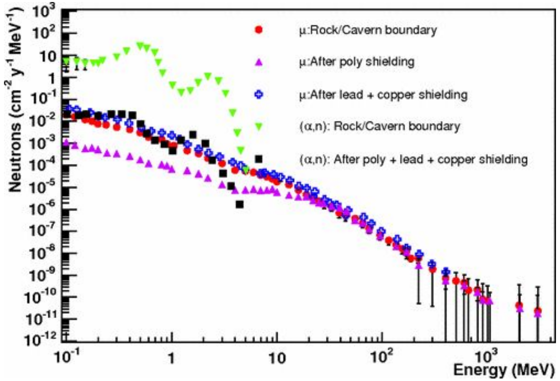


ENVIRONMENTAL GAMMAS



https://doi.org/10.1016/j.nima.2011.04.027

EXTERNAL BACKGROUND



NEUTRINOS

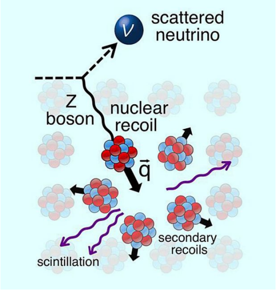
see next slide

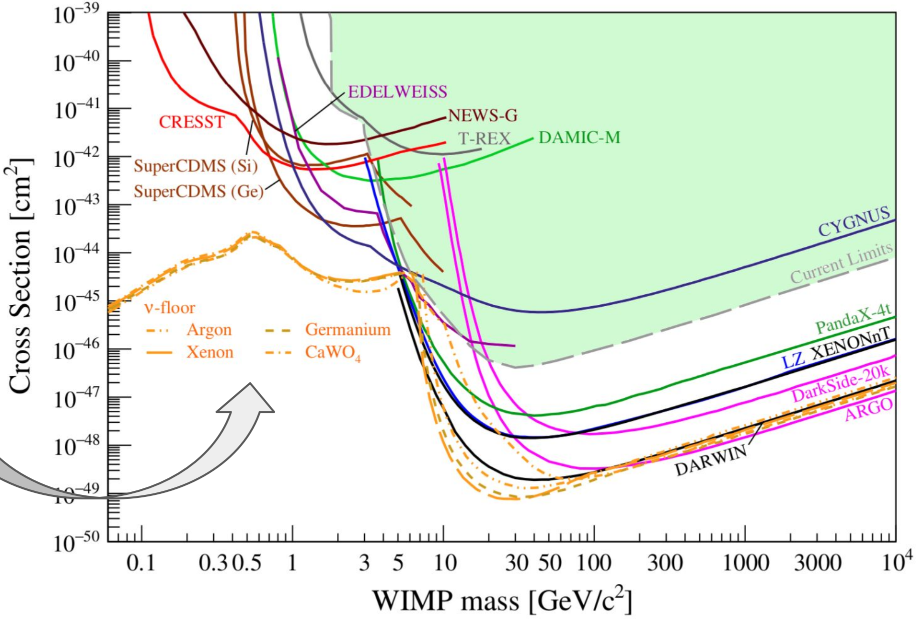
NEUTRONS FROM THE ENVIRONMENT OR MUON-INDUCED

D. Mei and A. Hime, Phys. Rev. D 73, 053004 (2006).

NEUTRINO FLOOR (FOG)

Coherent scattering of neutrinos off target nuclei (CEvNS) produce NRs indistinguishable from WIMPs on an event-by-event basis.
Ultimate background for direct WIMP searches





Solar Neutrinos produced via fusion reactions in the core of the sun

Atmospheric neutrinos: produced through cosmic ray collisions in the earth's atmosphere

Diffuse supernova neutrinos: accumulated flux from all supernova explosions in the history of the universe

disentangling the neutrino background from WIMP signal:
- Better understand the neutrino background
- Advancements in detector technology

STRATEGIES TO COPE WITH RADIOACTIVE BACKGROUND

underground laboratories
passive shielding

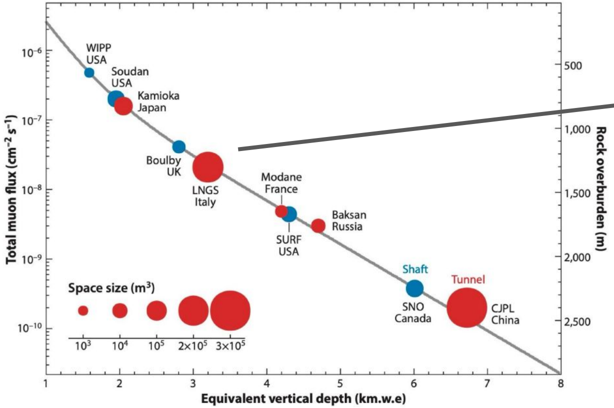
select low radioactivity materials clean/purify materials

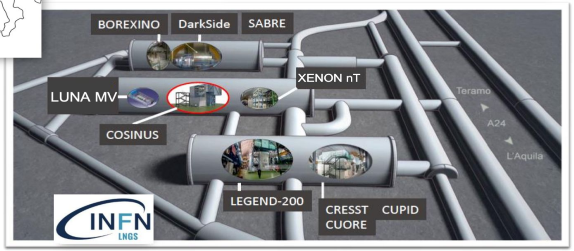
accurate Monte Carlo simulations of known background sources

active shielding, veto, fiducialization

discrimination and rejection techniques

UNDERGROUND LABORATORIES



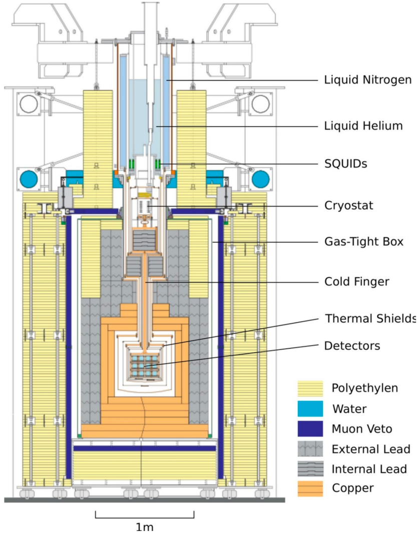


Muons: ~3 x 10^{-8}/cm^2/s

Environmental gamma flux about 0.5 gammas/cm^2/s

Neutrons: about 10^{-6} n/cm^2/s

Reducing muons is not enough, experiments need passive shieldings to reduce the gamma and neutron fluxes at the underground location



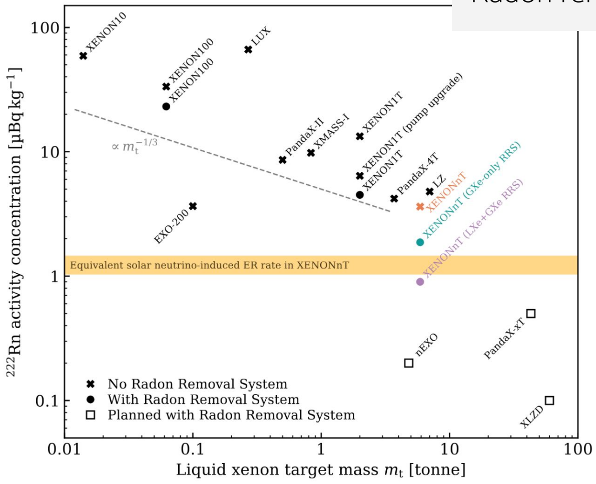
Ex. CRESST passive shieldings
High-Z elements for gammas
Neutron moderators/absorbers

PASSIVE SHIELDINGS

SELECT/PURIFY MATERIALS

MONTE CARLO SIMULATIONS

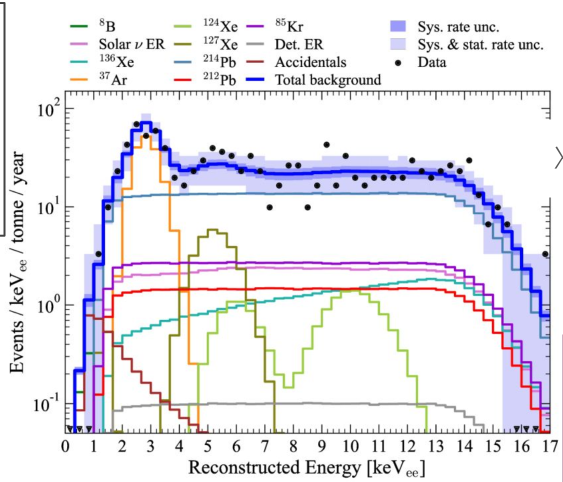
Radon removal system in XENON



A precise reconstruction of the background spectrum of an experiment (Background Model, BM) allows to account for the observed events as due to known sources.
This improves the DM sensitivity as the limits are derived from data-bkg rather than from data alone.

Systematics:

- precise modeling of the geometry of the experimental apparatus
- location of the bkg sources in the setup

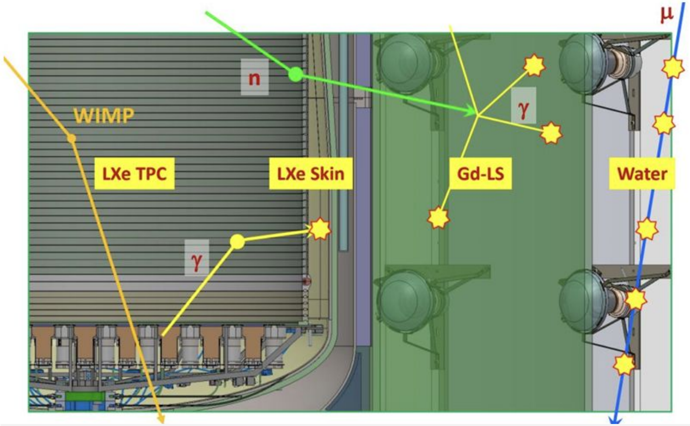


XENON BM

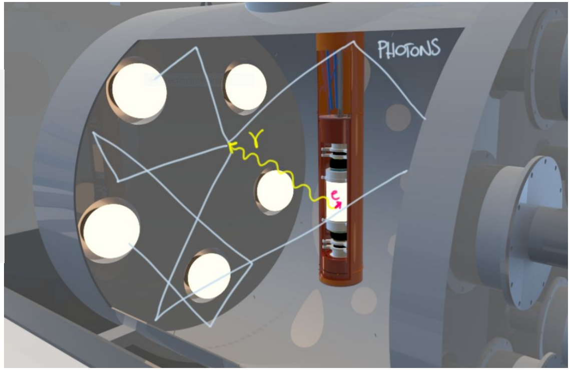
Radioactive assay of materials using different techniques (HPGe, ICP-MS, NAA, etc...)

ACTIVE SHIELDING, FIDUCIALIZATION

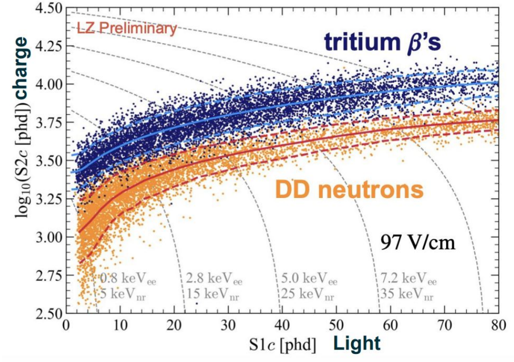
DISCRIMINATION, REJECTION TECHNIQUES



SABRE PoP LS active veto, now used in COSINE-100

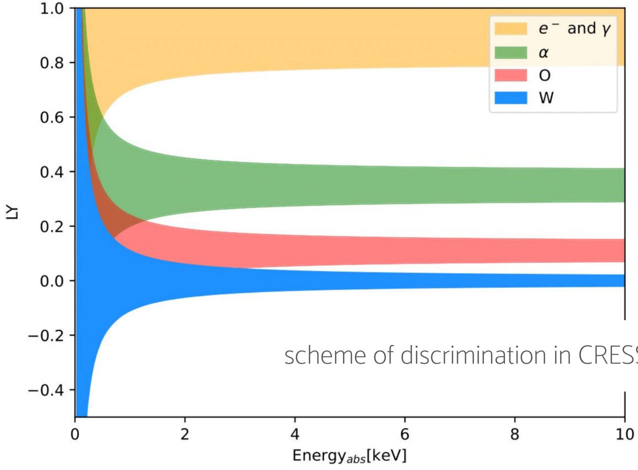


LZ experiment: Xe Skin + Outer Detector (OD) with Gd-loaded LS to characterize and reject γ + neutron backgrounds



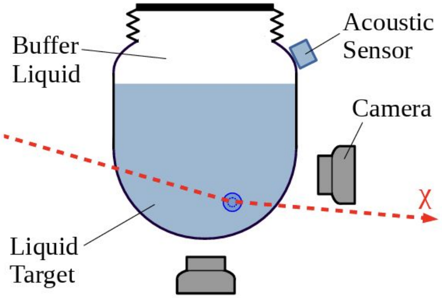
Discrimination between potential signal events (NR) and dominant radioactive background (ER).

Discrimination power decreases at low energies and needs to be calibrated accurately for efficiency.

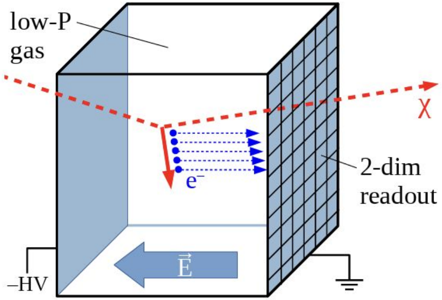


scheme of discrimination in CRESST

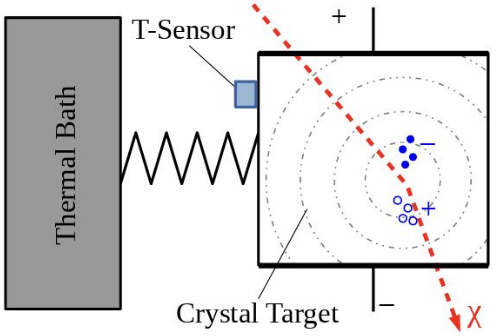
EXPERIMENTAL TECHNIQUES



Superheated liquid detectors

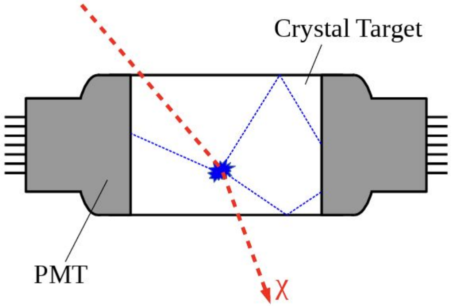


Directional detectors

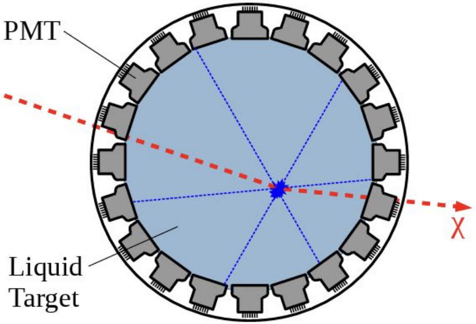


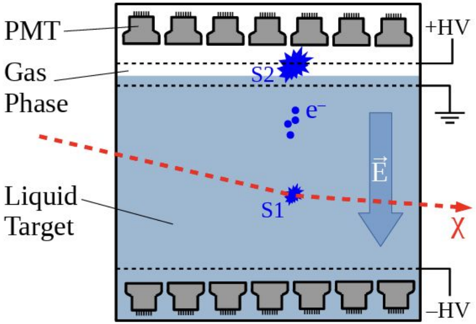
Solid-state cryogenic detectors

Room temperature scintillators



Single and double-phase noble liquids





Marc Schumann (2019) *J. Phys. G: Nucl. Part. Phys.* 46 103003

EXPERIMENTAL LANDSCAPE

DM particles search with low threshold solid-state detectors: CRESST, CDMS, DAMIC, SENSEI, TESSERACT, BULLKID-DM

Search for DM particles with liquid noble gases: XENON, PANDA-X, LZ, DARK SIDE

Investigation DM with the Annual Modulation using NaI(Tl) crystal scintillators : DAMA, ANAIS, COSINE, SABRE, COSINUS

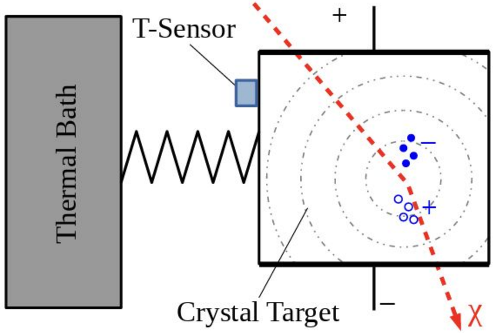
Other techniques: PICO (Bubble chamber)

Directionality: CYGNO

DISCLAIMER: I'll try to focus on the characteristics and complementarities of different experimental techniques, not on results.

DM particles search with low threshold solid-state detectors

Second detection channel for background discrimination

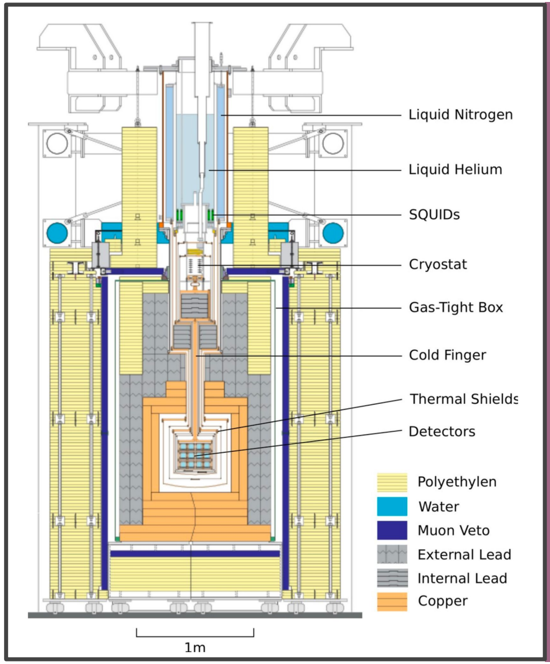


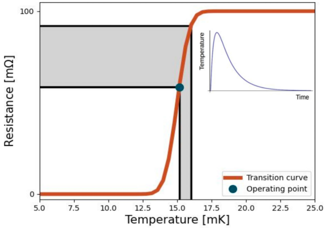
Due to their extremely low thresholds well below 1keV$_{NR}$, the cryogenic experiments with ionisation/scintillation and phonon readout are very sensitive to low-mass WIMPs.

Ionization detectors: SuperCDMS, DAMIC, SENSEI, Tesseract
Cryogenic bolometers: CRESST, BULLKID-DM

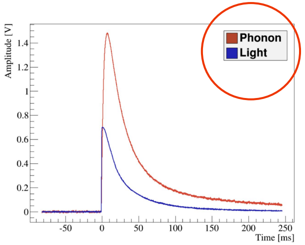
Features:
Conversion of the collected energy into a thermal signal (phonons). All the released energy is eventually converted into heat, resulting in a non-quenched signal.
Energy to produce an elementary excitation (phonon) is extremely small O (10 meV), fluctuation of the number of elementary excitations is not limiting the resolution, limited by vibrational and electronic noise.
Double readout (heat + light, heat + charge) allows for particle discrimination.
Low operating temperatures: 10-20mK
Exposure into the range of kg day (to be compared with tonne day, or multi-tonne day, in noble liquid TPCs): not competitive in terms of exposure.

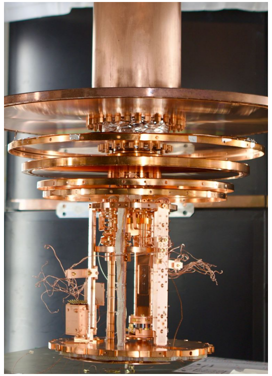
CRESST @ LNGS

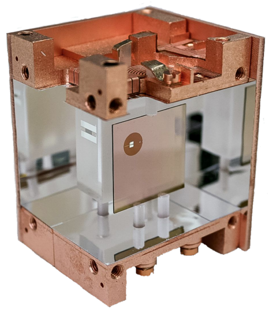




Sensor: W-TES at 15 mK

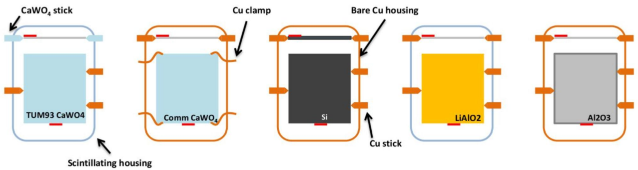


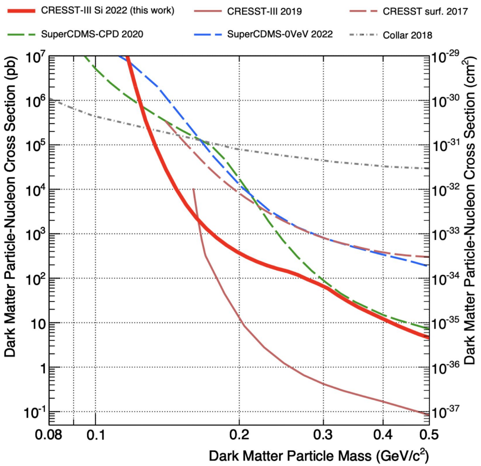




2x2x0.4 cm³ thin film
Si or silicon-on-sapphire (SOS) as light detector for scintillating absorbers

Target: 2x2x1 cm³ crystal
various crystal materials CaWO4, Al2O3, LiAlO2, Si





intense studies on detector design to address the LEE

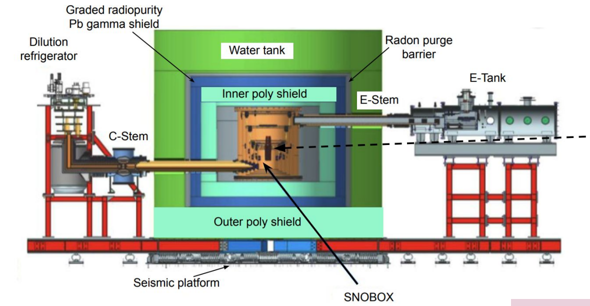
- Energy threshold of O (10 eV)
  - 30 eV in 2019 (24 g CaWO4 crystals, exposure 6 kg days)
  - 10 eV in 2022 (55 g days)
- Calibration from recoils induced by radiative capture of thermal neutrons allows calibration of CaWO4 detectors without introducing contaminants in the CRESST setup
- **CRESST collaboration is preparing to increase the number of channels to enhance exposure**

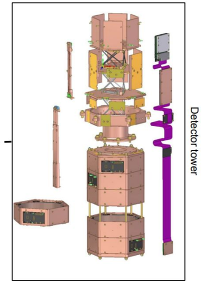
SuperCDMS @ SNOLAB

Cryogenic experiment: 15 mK

Layered shielding : ultra-low background

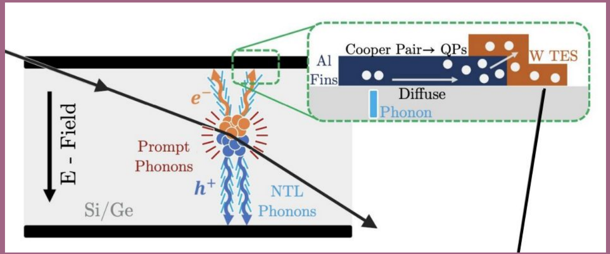
Vibration isolation



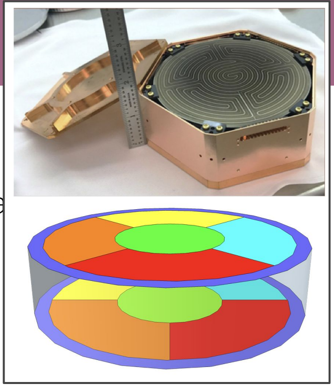


SNOBOX: Detectors housed in Copper cans

Array of ultra-pure silicon and germanium detectors to search for low-mass DM (< 10 GeV/c²)



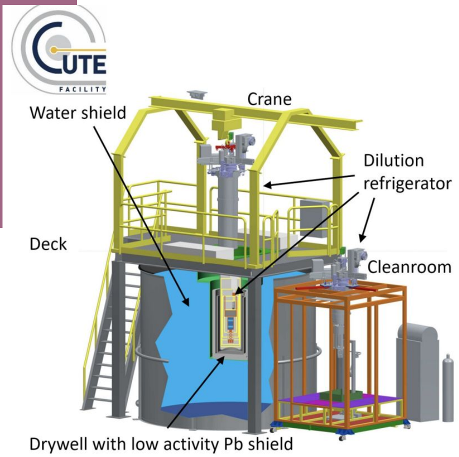
- Particle interaction in the crystal produces prompt phonons and e-h pairs
- Charges drifting through applied E-field produce additional phonons (Neganov-Trofimov-Luke effect)
- Phonons are measured with TES
- Charges are measured with interleaved electrodes



Commissioning set to start late 2025

Successfully tested HV detector tower at CUTE

Validated detector performance.



Phonon + charge particle discrimination

iZIP detector: measures both charge and phonon signa[l] for NR/ER discrimination

HV detector: measures phonon-only signal for lower threshold (demonstrated sub-eV σ_{phonon} with 1 cm^3 Si device)

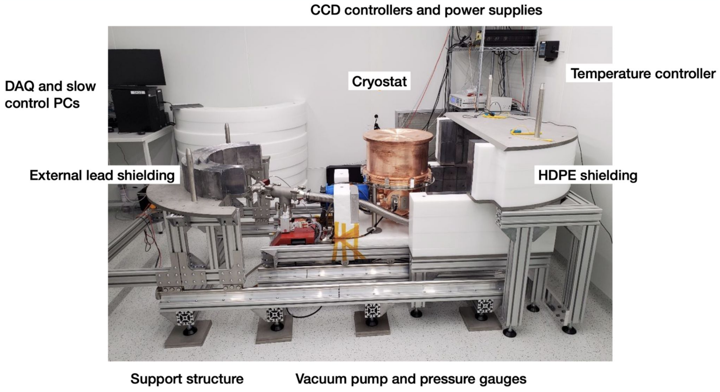
DAMIC-M @ LSM

Conventional CCDs read out each pixel once
- **best achieved RMS noise of ~2e- (~10eV).**

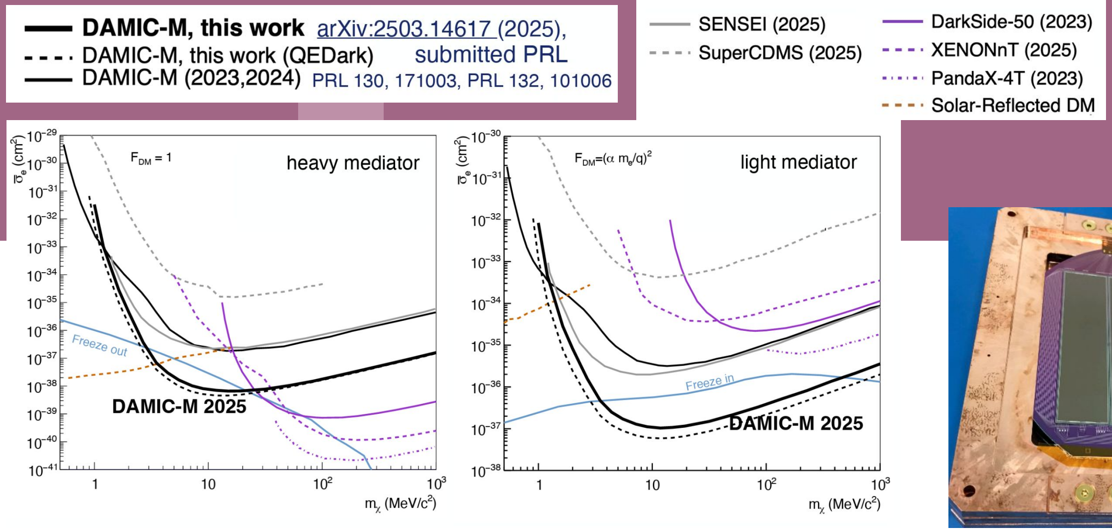
CCDs with "skipper" amplifiers move charge on and off sense node to make multiple non-destructive charge measurements.
- **reduces readout noise by 1/sqrt(Nskips).**

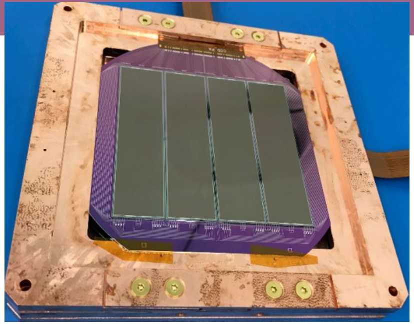
DAMIC-M prototype at LSM operating since February 2022 in the LBC (Low Background Chamber)

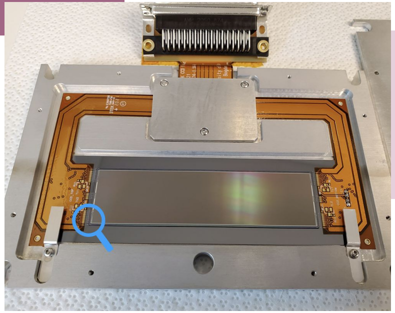
Temperature: ~130 K



2x DAMIC-M modules (8 CCDs for 26g)
electroformed copper boxes
reduced dark current: ~10^{-4} e-/pixel/day
background: ~7 dru + shield partly open
resolution: 0.16e- (0.6 eV) with 500 skips
data set exposure: 1.3 kg-day

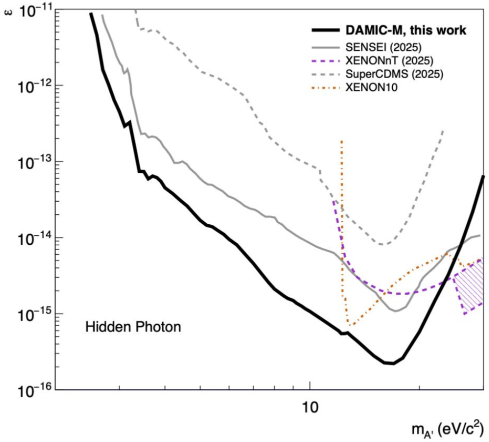


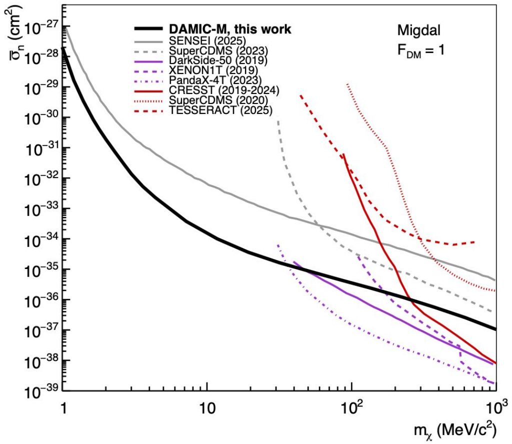




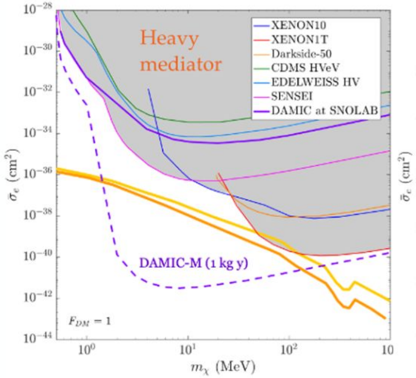
DAMIC-M @ LSM

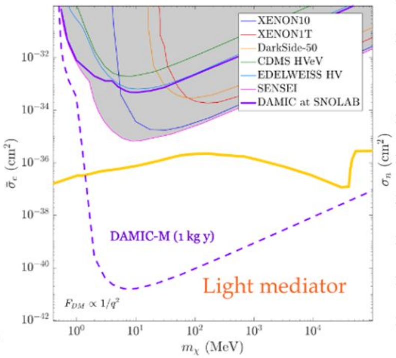
- array of 208 skipper CCDs for kg-scale mass
- thick (675um), massive (~3.3g), 9Mpixel CCDs
- “skipper” amplifier readout for single electron resolution and self-calibration
- pixelization for background rejection
- 1 kg-year exposure to probe hidden-sector benchmarks over a wide range of masses

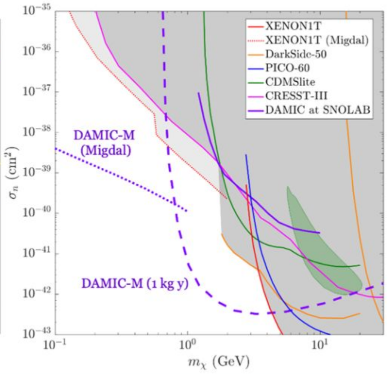


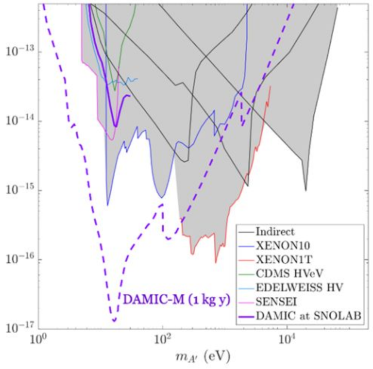


Coming soon, online by end 2025. Currently in the construction phase on-site at LSM.









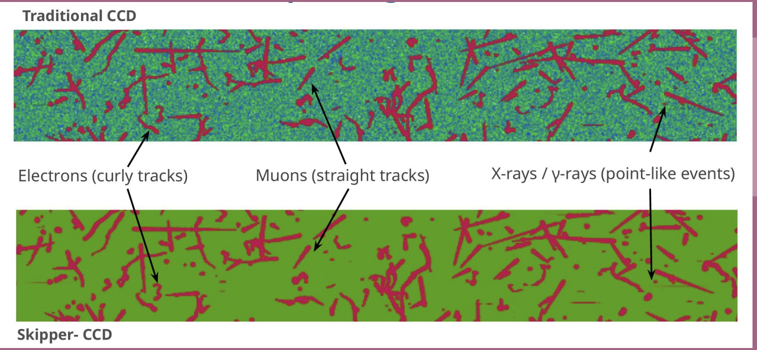
SENSEI @ SNOLAB

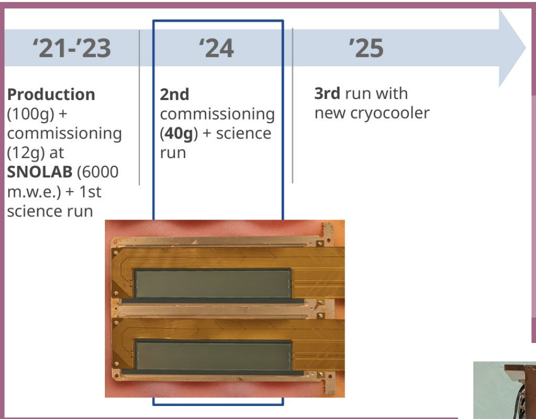
A. M. Botti at UCLA DM 2025

SENSEI implements silicon skipper CCDs to search for DM. Skipper-CCDs can resolve single electrons in each of millions of pixels, which allows for the low energy threshold required to detect sub-GeV dark matter interacting with electrons.

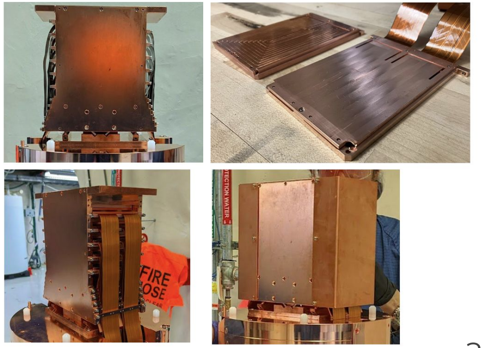
Sub-Electron-Noise Skipper-CCD Experimental Instrument
New generation Charge Coupled Devices (CCD)
Energy threshold ~ 1.1 eV
Readout noise ~ 0.1 e-

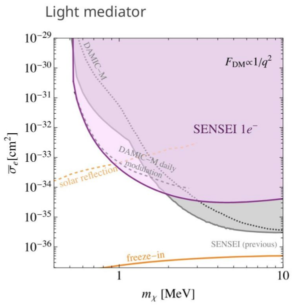
ProtoSENSEI@Surface: 2018
ProtoSENSEI@MINOS: 2019
SENSEI@MINOS: 2020
SENSEI@SNOLAB: 2023

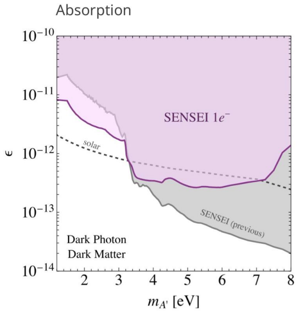




two science runs at SNOLAB
about 50 g of CCD
0, 2, 6, 20 hour exposures



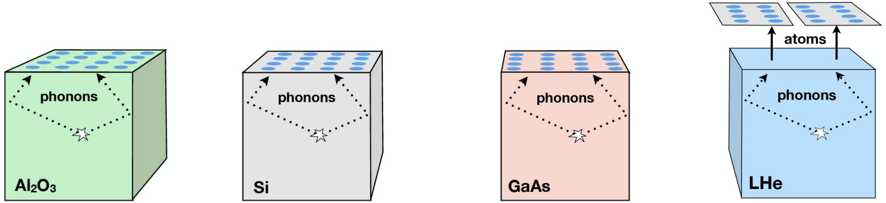




SENSEI recently measured the lowest event rates containing one electron in silicon detectors: $(1.4 \pm 0.1) \times 10^{-5}$ e-/pix/day
resulting in **world-leading sensitivity**

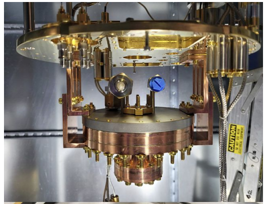
TESSERACT

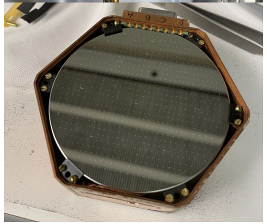
S. Hertel at UCLA DM 2025

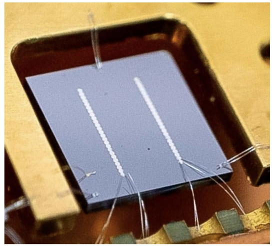


TESSERACT: Transition Edge Sensors with Sub-EV Resolution And Cryogenic Targets

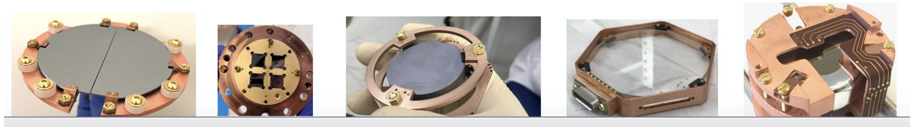
1. Apply diverse TES-based methods to the low-mass regime
2. Push phonon sensors to sub-eV thresholds
3. Apply those sensors to diverse target materials (with diverse DM couplings)
4. Attack the Low Energy Excess (LEE) challenge with complementary approaches
5. Deploy underground @ LSM

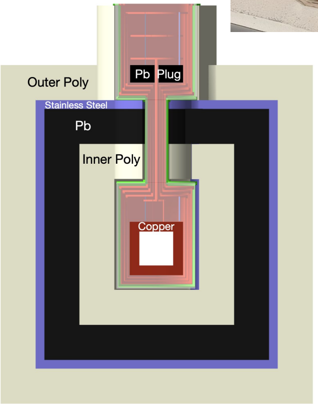






1cm^2 X 1mm “pixel” calorimeter made of silicon (0.233 g mass of Si)
Tungsten-Aluminum sensors fabricated directly on Si
World-leading resolution of 361 meV





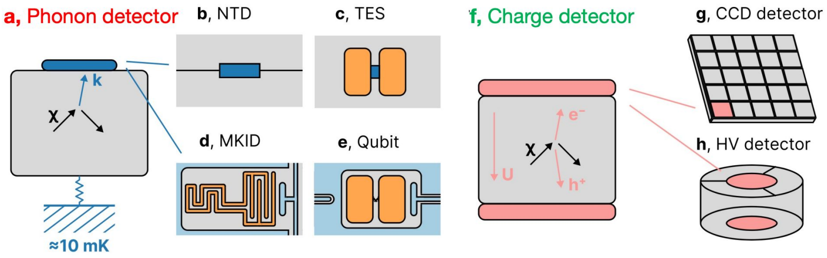
Designed around commercial cryostat and vertical layout

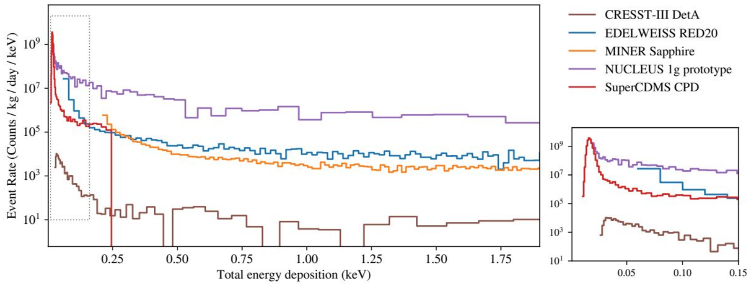
Simulations predict
~1 DRU (ER)
<1e-3 DRU (NR)

(possible future upgrade: cold veto)

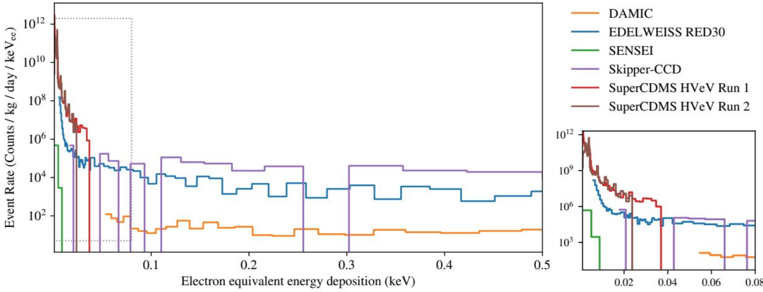
The low energy excess: LEE

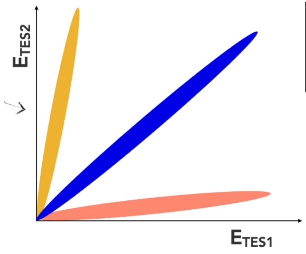
EXCESS Workshop yearly since 2021.
This year satellite of LTD 2025.



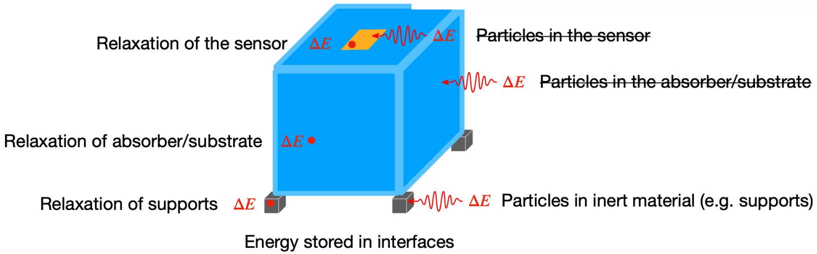


Observations
- Rise in the keV region, steeper in the 100 eV region
- Shape: multiple exponentials or power-laws
- Rate decays with time since cooldown
- Phonon excess is not ionizing (heat-only)
- No coincidences between adjacent detectors





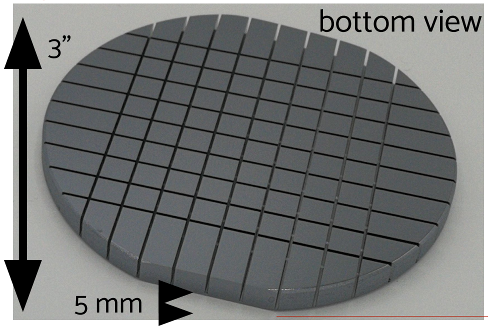
Basic idea: instrument the absorber with 2 TES



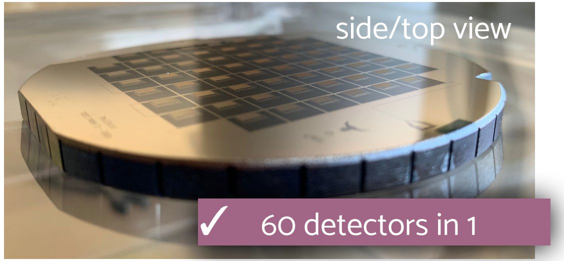
M. Vignati, EXCESS 2024

BULLKID-DM prototype

target dice carved in a thick silicon



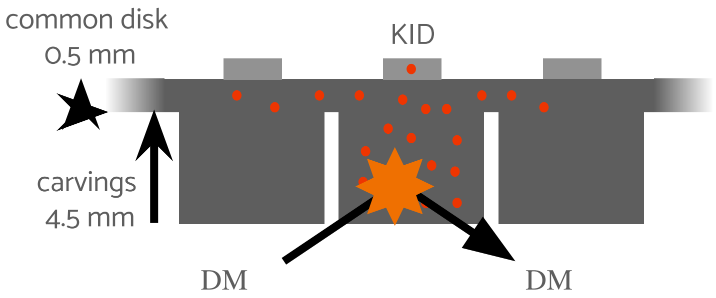
lithography of cryogenic KID sensors

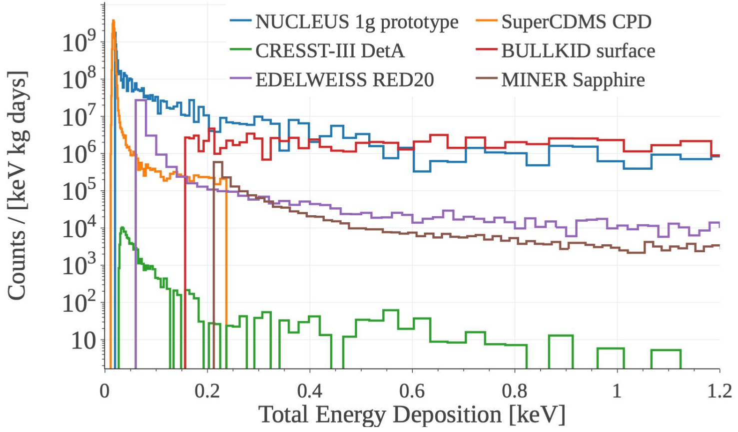


Fully multiplexed (single readout channel)

A. Cruciani, et al, Appl. Phys. Lett. 121, 213504 (2022)

monolithic target helps in excess bkg reduction





D. Delicato et al, Eur. Phys. J. C 84 (2024) 353

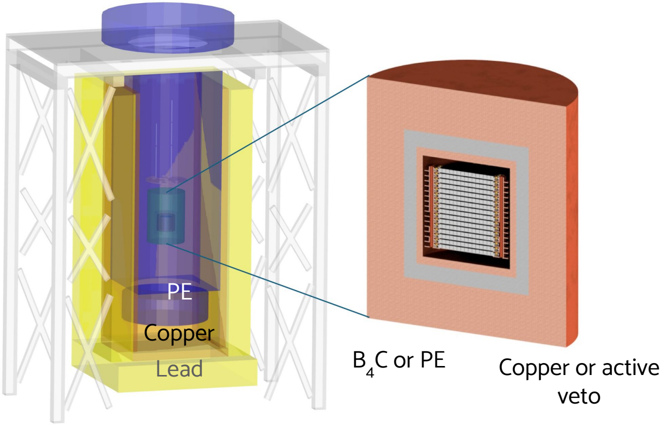
INFN Sezioni di Rm, Fe, Pi, LNGS

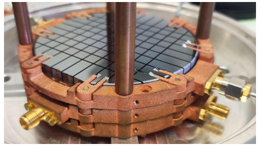
BULLKID-DM towards the experiment

Collaboration formed in 2024

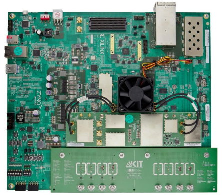
CDR approved in 2024, TDR in 2026

Simulation of LNGS CryoPlatform ongoing
external shield concluded

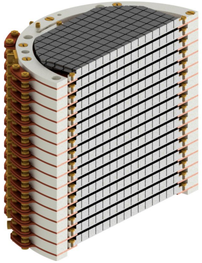




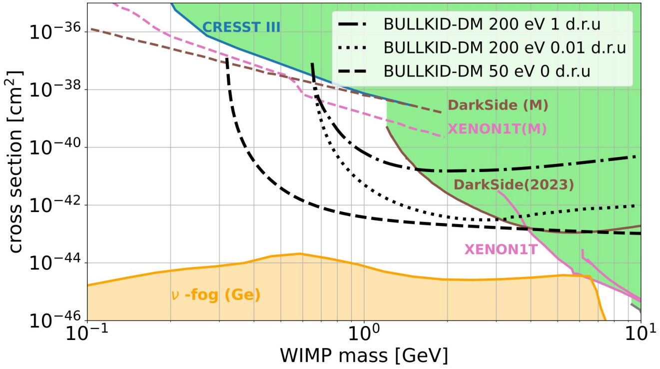
Demonstrator - 180 dice = 60 g
3-layer stack of 3” wafers
operations ongoing



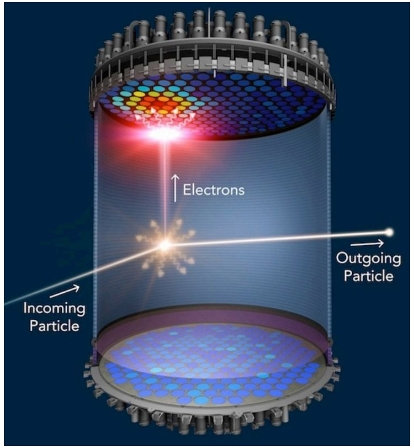
Electronics - 150 dice / channel
ZCU216 board with 16 channels
customisation ongoing



Full target - 2300 dice = 800 g
16-layer stack of 100 mm wafers
commissioning in 2026 at Sapienza



Noble liquids (Xe, Ar) TPC



Target: argon and xenon, exploited in single (liquid) or double (liquid+gas) phase TPC

Strengths: mass scalability, radiopurity, 3D reconstruction (allows fiducialisation and the identification of multiple scatter events), NR/ER discrimination

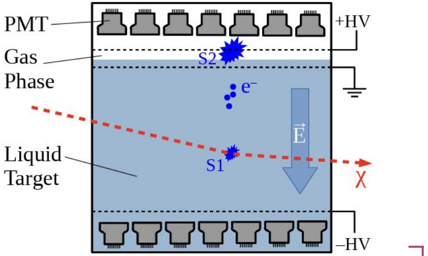
- **S1: light signal** → prompt scintillation photons in liquid phase
- **S2: charge signal** → secondary scintillation photons from electroluminescence in gaseous phase due to drifted electrons

3D reconstruction (mm precision):

- X,Y: hit pattern of S2
- Z drift time (S2 - S1)

NR/ER discrimination:

- S2/S1 → larger for ER than for NR in Xenon
- $S_1(t)$ → in Argon



XENON				ARGON			
Signal	Threshold NR	Threshold ER	Discrimination NR/ER	Signal	Threshold NR	Threshold ER	Discrimination NR/ER
S2/S1	3.3 keV NR	1 keVee	YES	PSD (S1)	13 keV NR	0.6 keVee	YES
S2	0.7 keV NR	190 eVee	NO	S2	0.6 keV NR	0.05 keVee	NO

XENONnT @ LNGS

The most stringent limit on the cross-section is 1.7×10^{-47} cm^2 for a WIMP mass of 30 GeV/c^2

Dual-phase Xe TPC new

Drift length	**1.5 m**
Total mass	**8.5 t**
Active mass	**5.9 t**
Photosensors	**494 PMTs**

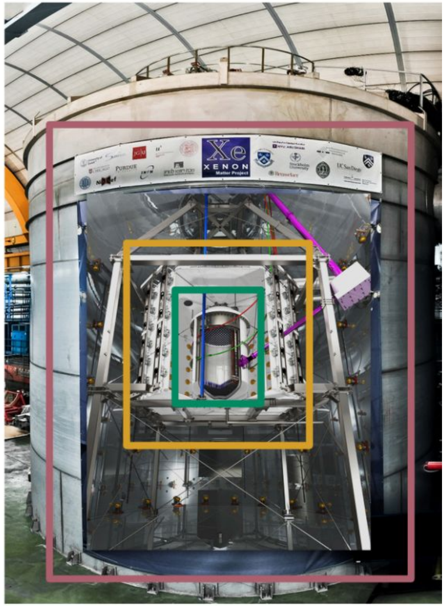
Neutron veto new

Water **Cherenkov** detector (33 m^3)
Neutron tagging efficiency: **53%**
Soon with **Gd-doped water** (expected **87%** efficiency)
Photosensors **120 PMTs**

Muon veto

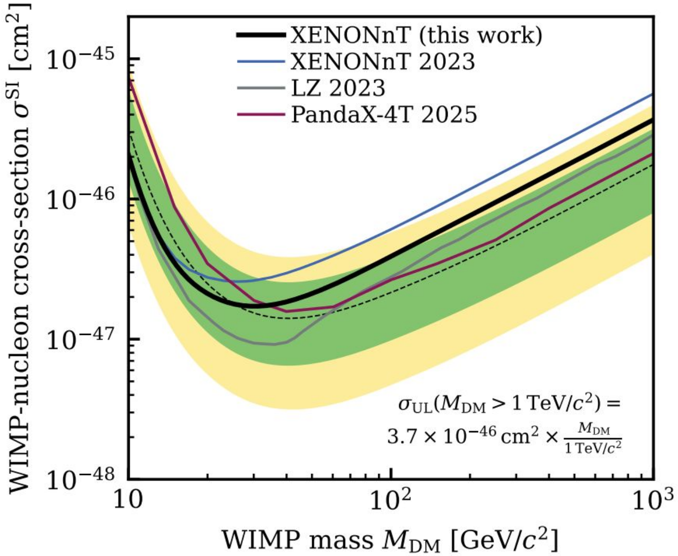
700 t ultra-pure **water**
Water **Cherenkov** detector
Muon tagging efficiency: **99.5%**
Photosensors **84 PMTs**

WATER TANK



Emptying of the water tank already started on March 2025.

total exposure of 3.1 tonne x year



Neutron Veto with demi-water: **neutron tagging efficiency of 53% in 250 us** (68% in 600 us), best result in a water Cherenkov detector.
With 500 ppm of GdSO, **efficiency up to 77%**, reducing the neutron background by a factor 2.
Started the campaign to replace the TPC electrodes, to improve on WIMP search by increasing the separation between ER and NR.

XENONnT sees through neutrino fog

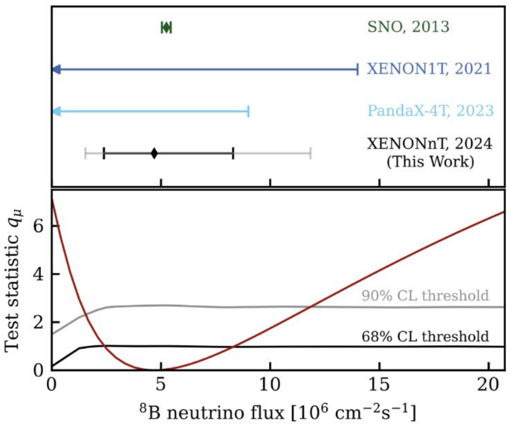
APS Highlight of the year 2024: detection of ^{8}B solar neutrinos

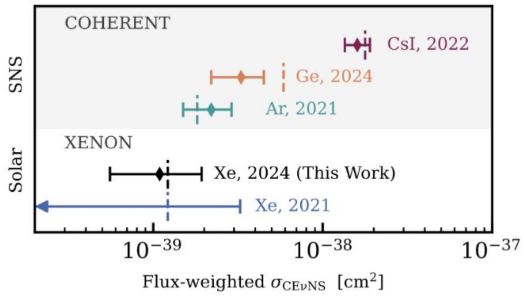
Phys.Rev.Lett. 133 (2024) 19, 191002

- entered neutrino fog for the first time
- DM experiments can study neutrinos

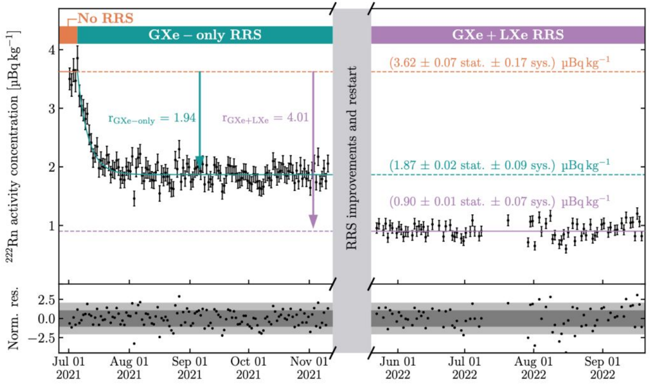
The background-only hypothesis is rejected with a statistical significance of 2.73σ

Component	Expectation	Best-fit
AC (SR0)	7.5 ± 0.7	7.4 ± 0.7
AC (SR1)	17.8 ± 1.0	17.9 ± 1.0
ER	0.7 ± 0.7	$0.5^{+0.7}_{-0.6}$
Neutron	$0.5^{+0.2}_{-0.3}$	0.5 ± 0.3
Total background	$26.4^{+1.4}_{-1.3}$	26.3 ± 1.4
^{8}B	$11.9^{+4.5}_{-4.2}$	$\boxed{10.7^{+3.7}_{-4.2}}$
Observed	37	





unprecedented reduction of ^{222}Rn in Xe (liquid and gas)

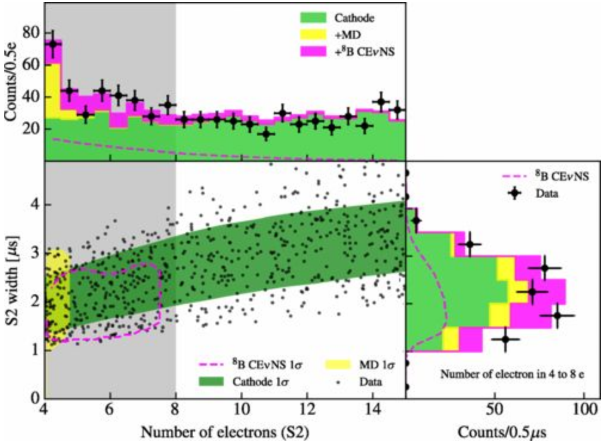


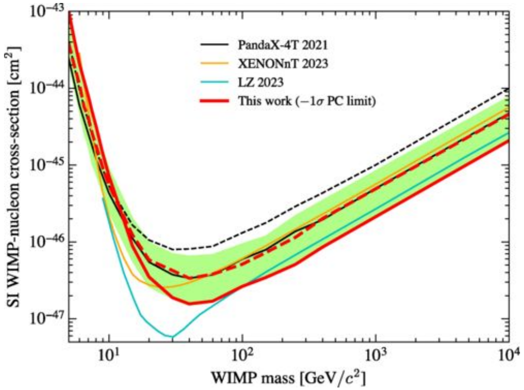
flux-weighted cross section for CEvNS in agreement with the SM
^{8}B flux in agreement with SNO

PandaX @ CJPL

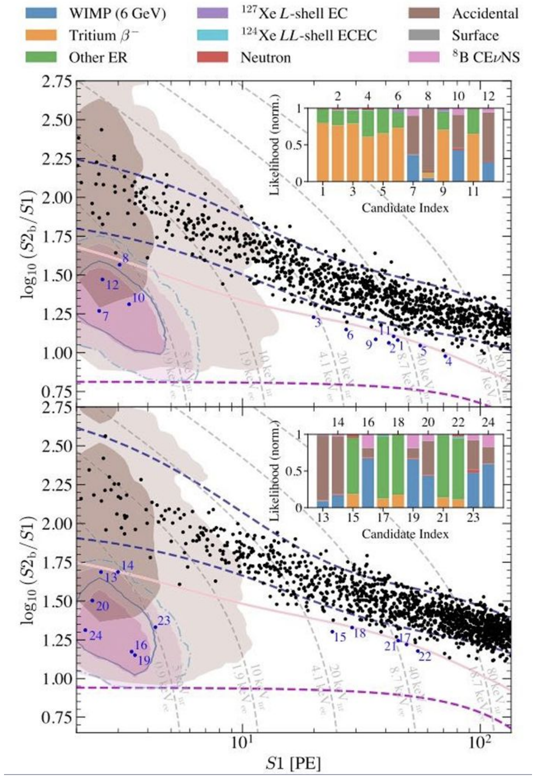
From 2009 to 2021 went from:
PandaX-I (120 kg) to PandaX-4 (3.7 ton)

APS Highligt 2024:
First indication of solar ^{8}B CEvNS signal
Significance: 2.64 sigma
Fitted flux (8.4 ±3.1) x 10^6 cm^{-2} s^{-1}
PRL 133, 191001 (2024)

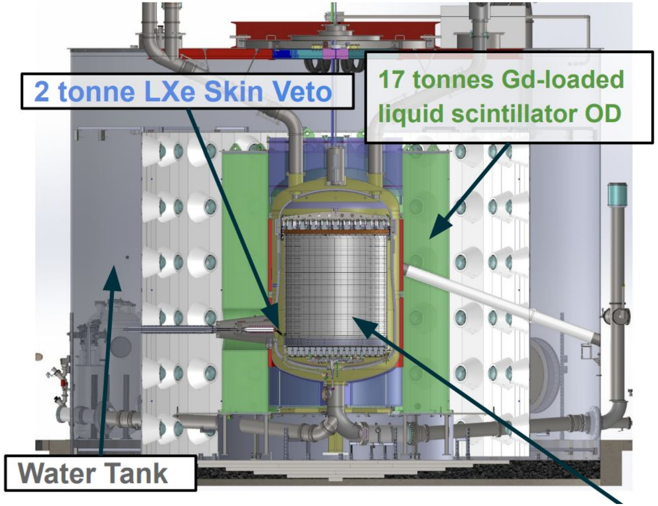




Leading constraints for DM mass above 100 GeV
Lowest exclusion reaches 1.6x10^{-47}cm^2

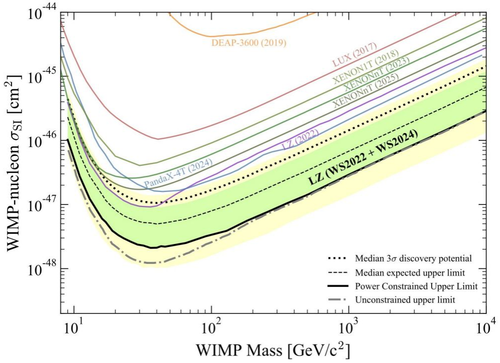


LUX-ZEPLIN (LZ) @ SURF



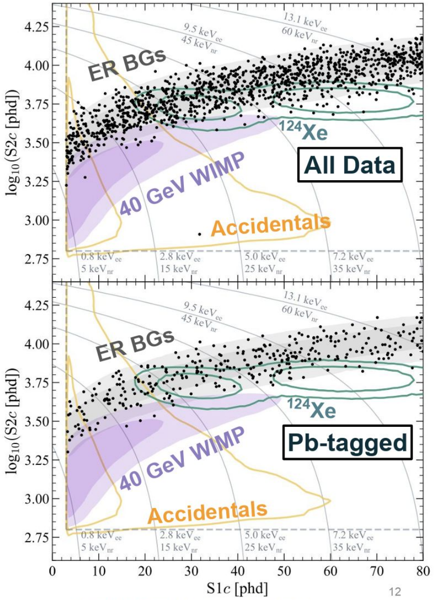
Xe Skin & Outer Detector (OD) characterize and reject γ + neutron backgrounds!

7 tonnes active liquid Xenon in Dual Phase Time Projection Chamber

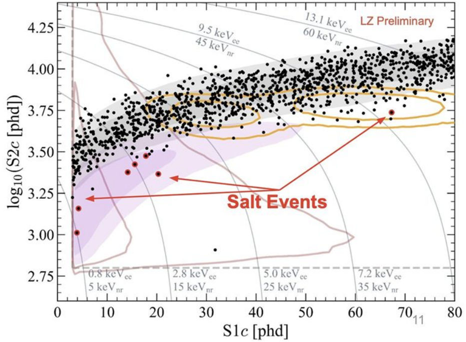


arXiv:2410.17036 [submitted to PRL]

LZ is the world's most sensitive WIMP direct detection experiment with combined total exposure of 4.2 tonne-years



arXiv:2410.17036 [submitted to PRL]



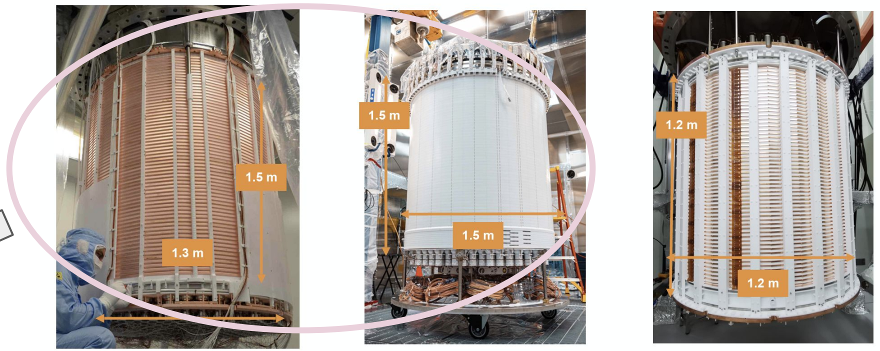
LZ continues to take quality science data with 'salt' events injected for active bias mitigation
Data collection continues to 2028.

Current and future LXe two-phase TPCs

- PandaX-4T: ongoing data taking since detector upgrade completed 12/2023
- XENONnT: data taking will soon end to upgrade TPC with new electrodes
- LZ: ongoing data taking

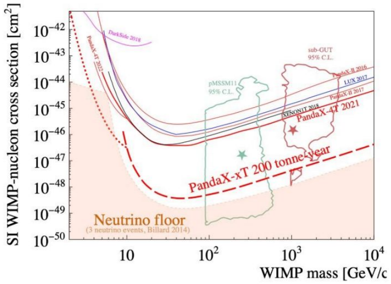
XLZD: see next slide

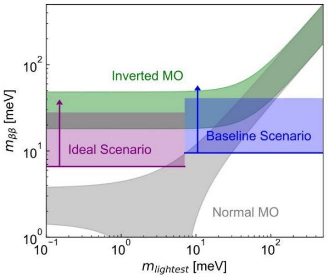
XENONnT | LUX-ZEPLIN | PandaX-4T

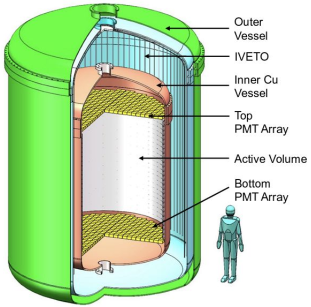


LNGS, 8.6(5.9)t	SURF, 10(7)t	JinPing, 5.6(3.7)t
23 V/cm	97 V/cm	93 V/cm

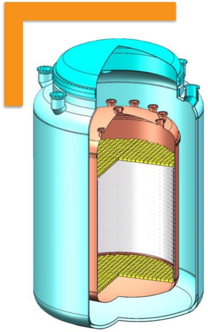
~40 tonne sensitive volume
Letter-of-interest sent to Chinese funding agency
Key tests on WIMP and Dirac/Majorana neutrino







PandaX-20T

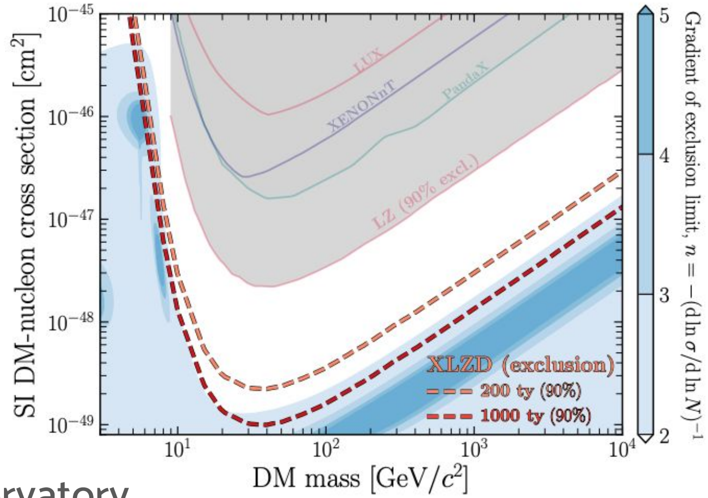


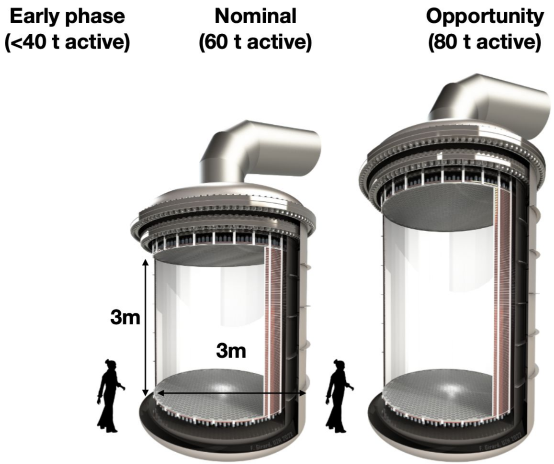
PandaX-20T with timeline:

- 2026: move to CJPL and assembling
- 2027: commissioning

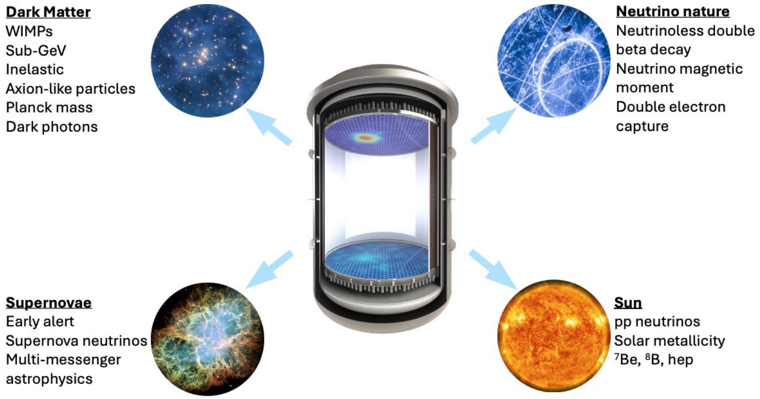
XLZD

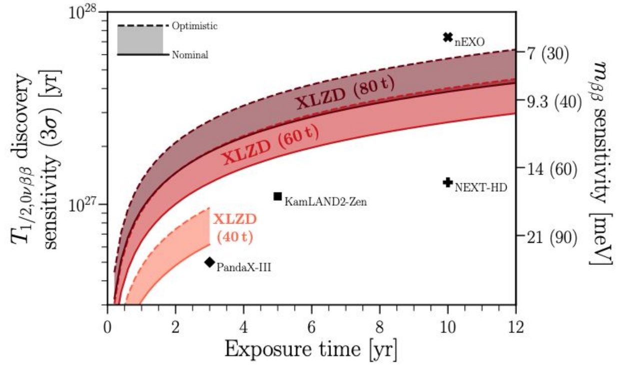
XENON-LUX-ZEPLIN-DARWIN (XLZD) is now a Collaboration: site selection ongoing (decision by 2026).





Next-generation Xenon Observatory



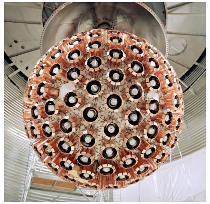


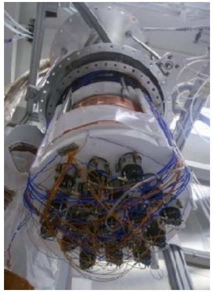
8.9% abundance of ^{136}Xe in natural, non-enriched xenon → 5.3 tonnes of isotope

Depth of the host laboratory important to mitigate activation of ^{137}Xe (beta decay).

DarkSide-20k @LNGS

Since 2017 DEAP-3600 (SNOLAB), DarkSide-50, MiniCLEAN and ARDM joined in the Global Argon Dark Matter Collaboration (GADMC)

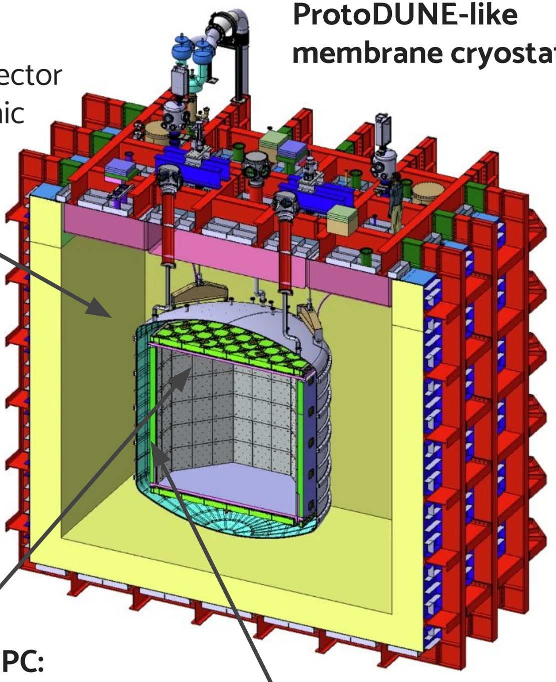




Custom SiPM-based photosensors.
Packaging and assembly at Nuova Officina Assergi (NOA) at LNGS.

Outer Veto: 650 tons atmospheric argon (AAr): shield and outer veto detector for muons and cosmogenic neutrons

ProtoDUNE-like membrane cryostat



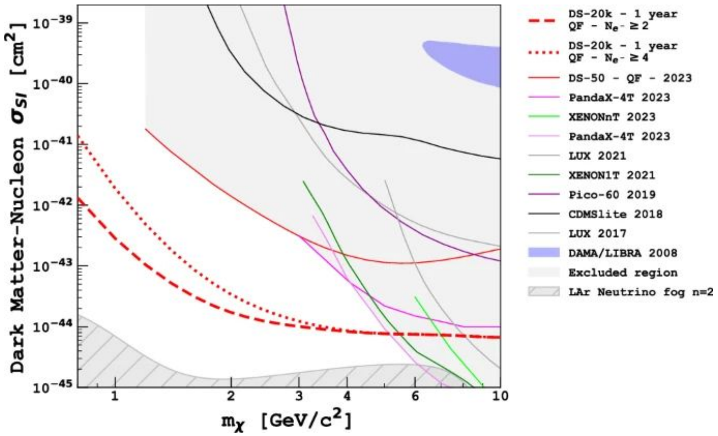
Dual-phase UAr TPC:
50 ton active mass UAr
Two planes of cryogenic SiPMs covering the top and the bottom faces of the TPC
~200 k SiPMs gathered in 5 x 5 cm^2 arrays, called Photo Detector Modules (PDMs)

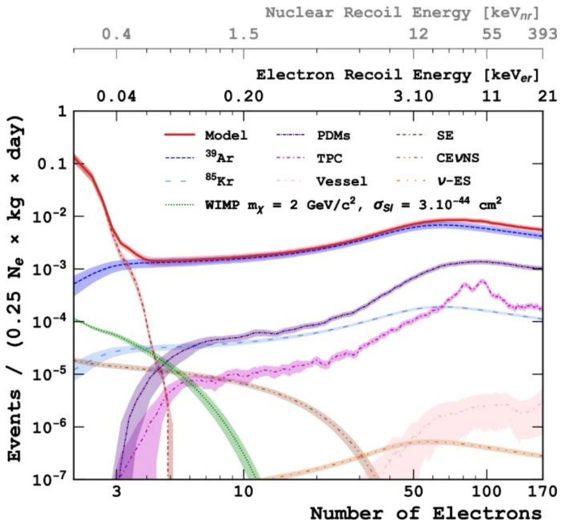
Inner Veto:
SS vessel, **32 ton UAr**
480 photo detector channels
tag radiogenic neutrons by detecting gammas from their capture

DarkSide-20k sensitivity

One of the leading technologies to search for dark matter particles with masses below 10 GeV/c^2. DarkSide-50 (DS-50) demonstrated the capability of the technology and obtained world best sensitivities to light DM particles using only the S2 signal.

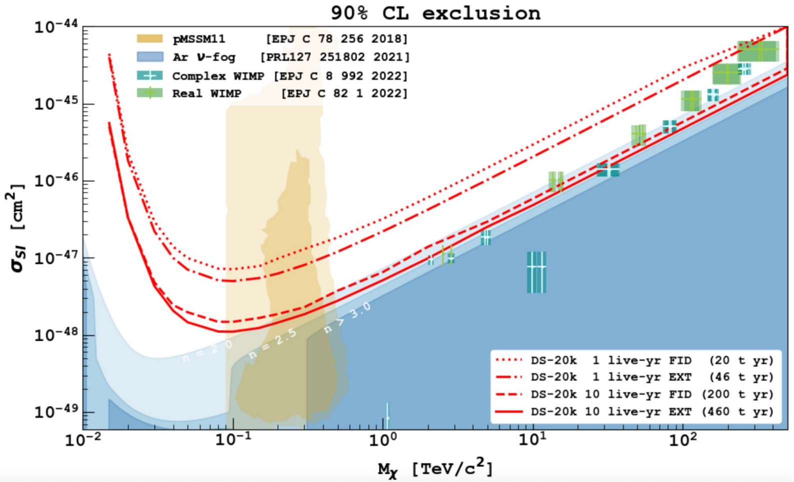
DS-20k aims for <0.1 background events with an exposure of 200 ton · year





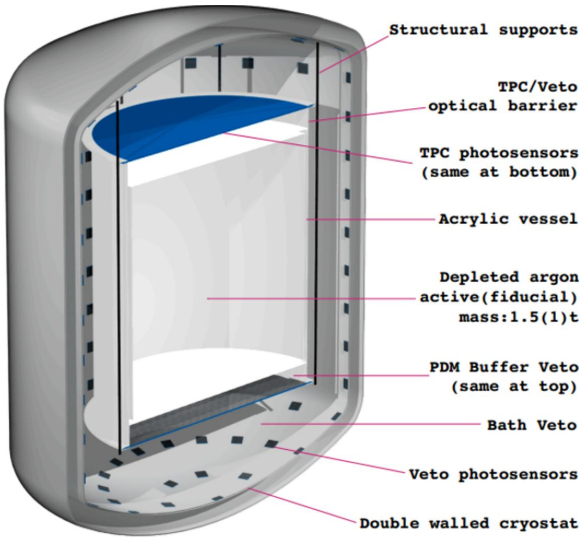
Low energy threshold < 10 keV
Discrimination: multi-scatter vs single-scatter
PSD bkg discrimination > 10^8

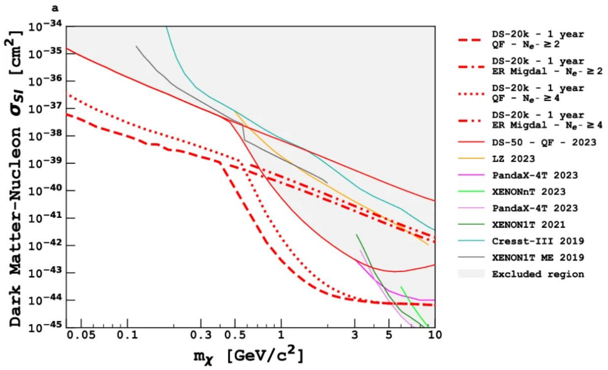
- **FID:** low instrumental background rate < 0.3 events in ROI (30-200 keVnr) with 200 t-yr exposure
- **EXT:** background dominated by radiogenic neutrons from photosensors and experimental Hall



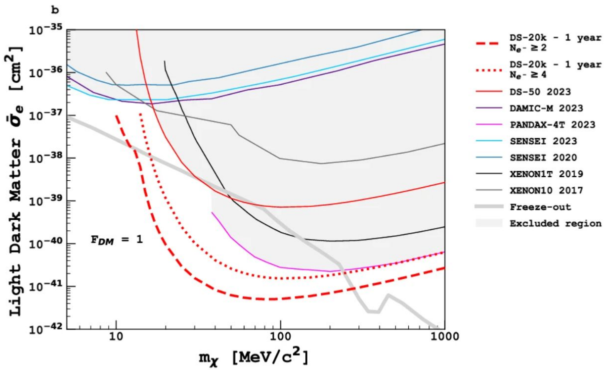
Commun Phys 7, 422 (2024). https://doi.org/10.1038/s42005-024-01896-z

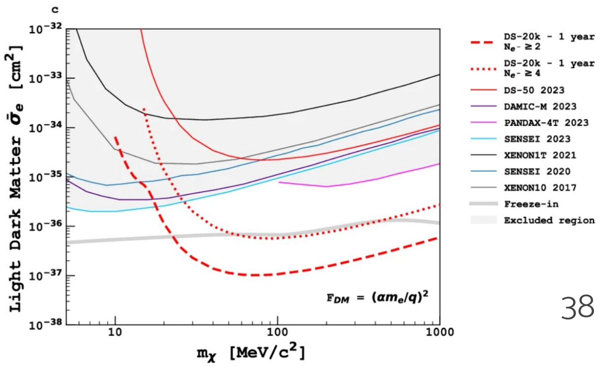
DarkSide-20k and more





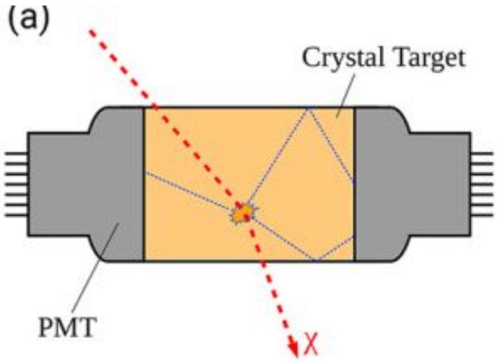
Spin-independent WIMP-nucleon cross-section when considering the Migdal effect (a) and with quenching fluctuations (QF) for the NR signal. Light dark matter cross-section for an heavy (b) and light (c) mediator, respectively.





C. Galbiati at UCLA DM 2025

NaI-based DM experiments



Experiment	Location	Target	Mass [kg]	Status
DAMA/LIBRA	LNGS	NaI(Tl)	250	running
ANAIS-112	LSC	NaI(Tl)	112.5	running
COSINE-100	Y2L	NaI(Tl)	106/61.3	upgrading
COSINE-200	Yemilab	NaI(Tl)	~200	in preparation
SABRE North / South	LNGS + SUPL	NaI(Tl)	~50	in preparation
COSINUS	LNGS	NaI	~1	in preparation
PICOLON	Kamioka	NaI(Tl)	~50	in preparation

credit: A. Ianni - IDM 2024

- well-known experimental technique, scalability
- possibility to grow large (~10 kg) crystals
- high duty cycle, high light output and good alpha/beta PSD
- possibility to carry on routine calibration in the keV range
- sensitivity to different DM scenarios and interactions

Disadvantages:

- hygroscopic crystals
- **growing large crystals with the required radio purity has proven very challenging**

So far DM-Ice, NaIAD, DAMA/LIBRA, ANAIS-112, and COSINE-100 have deployed arrays of NaI(Tl) detectors to search for DM.

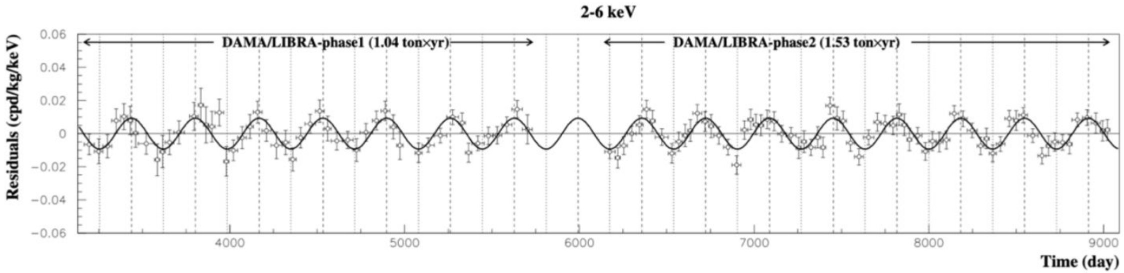
New programs are under development: COSINE-100+, COSINE-200, SABRE, COSINUS, and PICOLON.

R&D: ANAIS+, ASTAROTH.

DAMA @ LNGS

Nucl. Phys. At. Energy 22 (2021) 329-342

DAMA/LIBRA 13.7 σ in [2-6] keV



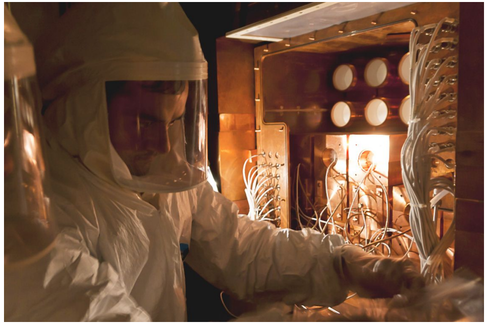
DAMA/NaI - 100 kg

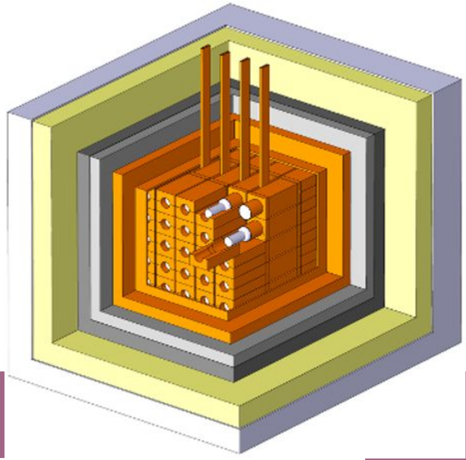
Ended in July 2002 7 annual cycles collected (0.29 tonxy) AM evidence at 6.3σ C.L. + many results on other rare processes

DAMA/LIBRA - 250 kg (new detectors with better radiopurity)

phase1: 7 annual cycles (1.04 tonxyr) - AM evidence at 9.3σ C.L.
phase2: lowering software energy thr below 2 keV
8 annual cycles (1.53 tonxyr)
Upgrade on Nov/Dec 2010: PMTs replaced with new ones of higher Q.E. ⇒ 1 keV thr
Empowered new stage in 2021 ⇒ 0.5 keV thr
Data release expected soon.

Gamma shielding: ≥10 cm of OFHC Cu + 15 cm of Pb
Anti-Rn: Plexiglas box fluxed with N2 gas
Neutron shielding: 10/40 cm Polyethylene/paraffin + 1.5 mm Cd foils



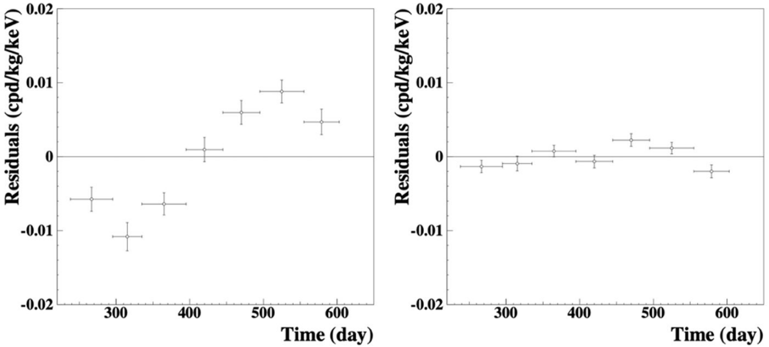


Model-independent evidence for a signal that satisfies all the requirements of the DM annual modulation signature at 13.7σ C.L. (22 independent annual cycles with 3 different set-ups: 2.86 ton x yr). Modulation parameters determined with high precision.

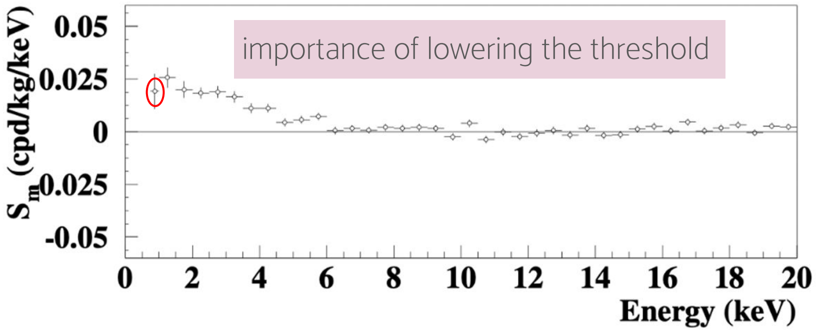
Decommissioning in 2025

Evidence from DAMA and comparison with DM expectations

No modulation at higher energy, no modulation in the whole energy spectrum



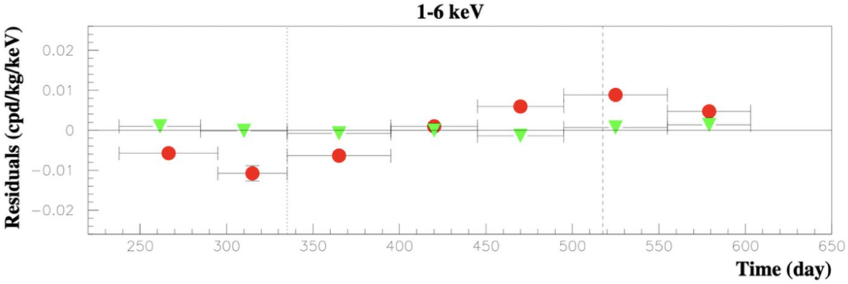
lower (1-6) vs higher (10-20) energy single-hit events



Modulation parameters determined with high precision

E, keV	A, cpd/kg/keV	$T = 2\pi/\omega$, yr	t_0, d	C.L.
DAMA/LIBRA-phase2:				
1 – 3	(0.0191 ± 0.0020)	1.0	152.5	9.7 σ
1 – 6	(0.01048 ± 0.00090)	1.0	152.5	11.6 σ
2 – 6	(0.00933 ± 0.00094)	1.0	152.5	9.9 σ
1 – 3	(0.0191 ± 0.0020)	(0.99952 ± 0.00080)	149.6 ± 5.9	9.6 σ
1 – 6	(0.01058 ± 0.00090)	(0.99882 ± 0.00065)	144.5 ± 5.1	11.8 σ
2 – 6	(0.00954 ± 0.00076)	(0.99836 ± 0.00075)	141.1 ± 5.9	12.6 σ
DAMA/LIBRA-phase1 + phase2:				
2 – 6	(0.00941 ± 0.00076)	1.0	152.5	12.4 σ
2 – 6	(0.00959 ± 0.00076)	(0.99835 ± 0.00069)	142.0 ± 4.5	12.6 σ
DAMA/NaI + DAMA/LIBRA-phase1 + phase2:				
2 – 6	(0.00996 ± 0.00074)	1.0	152.5	13.4 σ
2 – 6	(0.01014 ± 0.00074)	(0.99834 ± 0.00067)	142.4 ± 4.2	13.7 σ

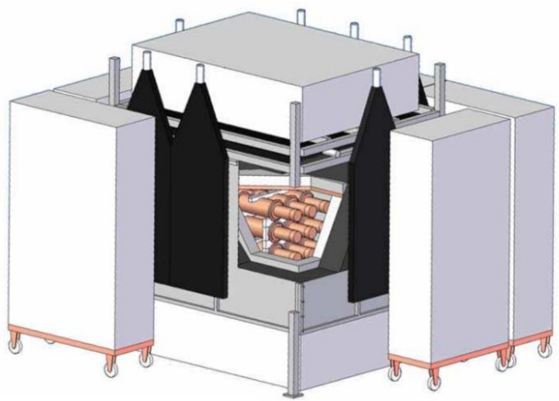
No modulation in multiple-hit events



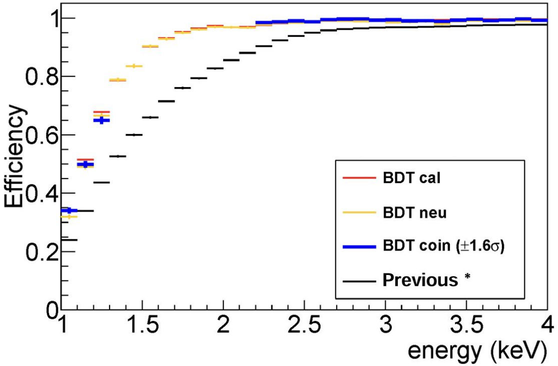
single-hit (red) vs multiple-hit (green) events

ANAIS-112 @ CANFRANC, SPAIN

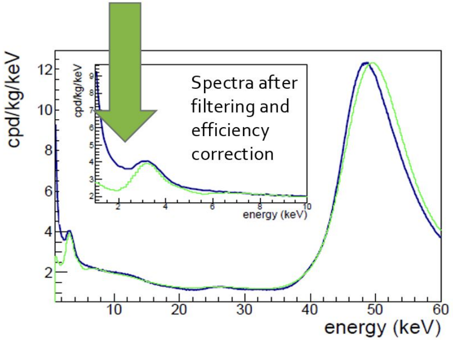
Start data taking in 2017.
Gamma shielding: 10 cm of ancient Pb + 20 cm of Pb
Anti-Rn: metallic box fluxed with N2 gas
Neutron shielding: 40 cm Polyethylene/water tanks
Active muon veto: 16 plastic scintillator



9 ultrapure NaI(Tl) crystals 12.5 kg (112.5 kg) in 3 x 3 cylindrical modules coupled to 2 high QE PMTs (~40%).



improved analysis efficiency



currently improving their BM

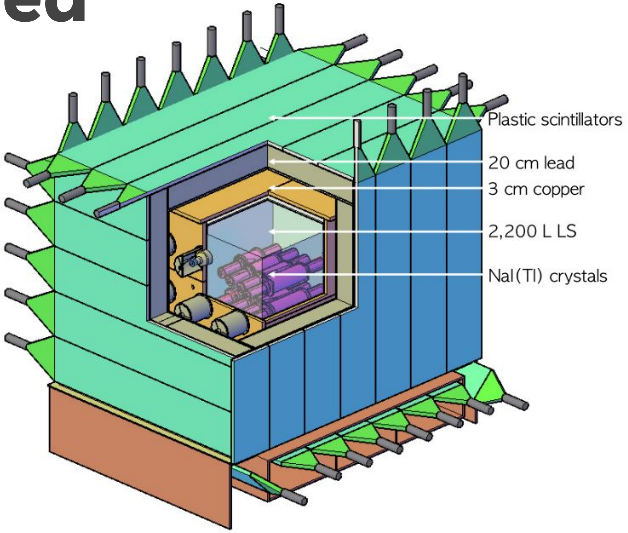
Sensitivity with 6 years data:
4.2 (4.1) σ for [1-6] ([2-6]) keV
ANAIS most sensitive search to date with the same target material of DAMA/LIBRA.

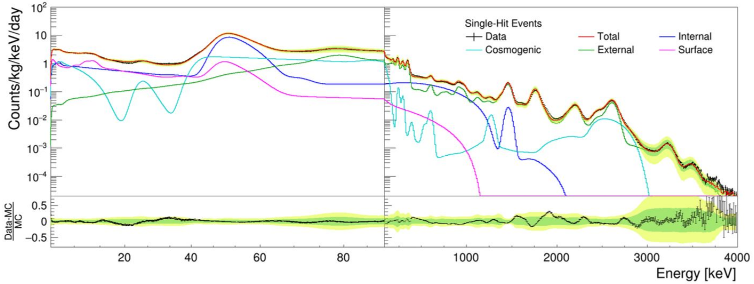
M.L. Sarsa at UCLA DM 2025

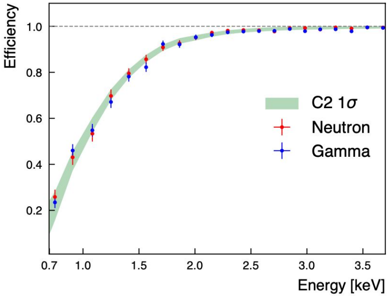
COSINE-100 @ Y2L, South Korea

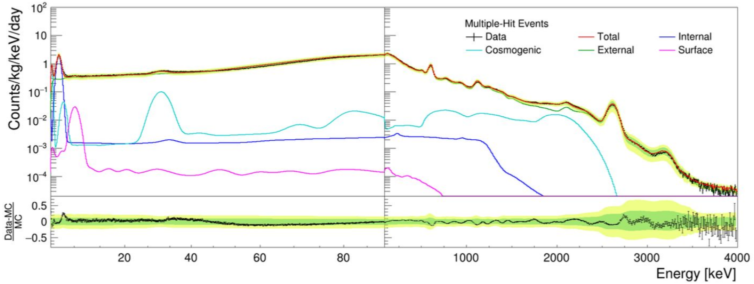
Start data taking in 2016.
100 kg of NaI(Tl) detectors for a total active mass of 61.3 kg (some detectors with high rate excluded)
Gamma shielding: 3 cm Copper + 20 cm Pb
LS Veto: 2200 l
Active muon veto: plastic scintillator

2024 New Deeper Site
Yemilab

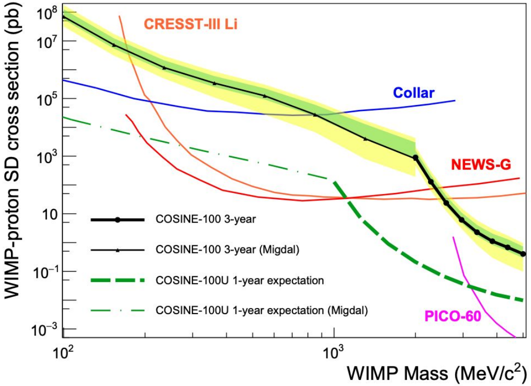








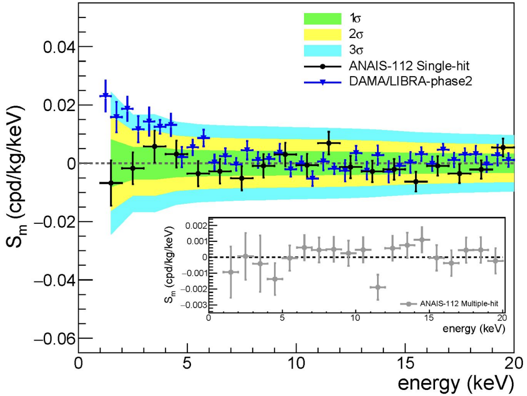
COSINE-100U upgraded version of COSINE-100
~40% enhancement in LY

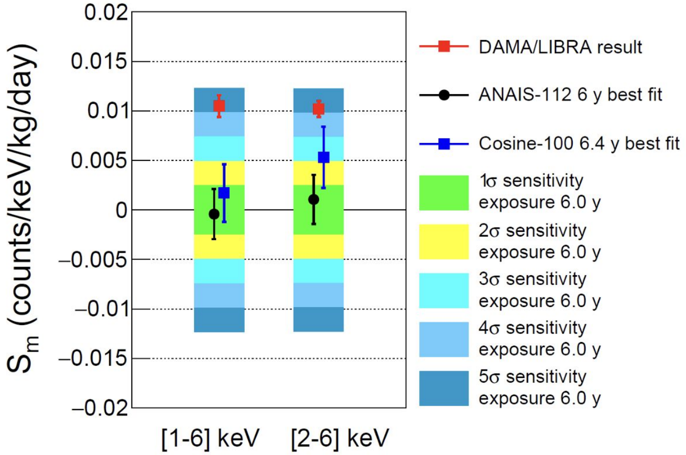


COSINE-100 BM

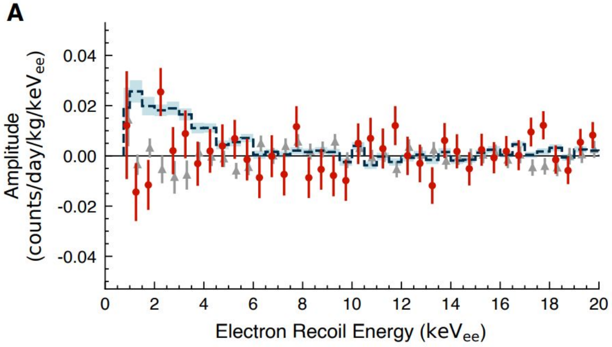
ANAIS and COSINE - 6y dataset

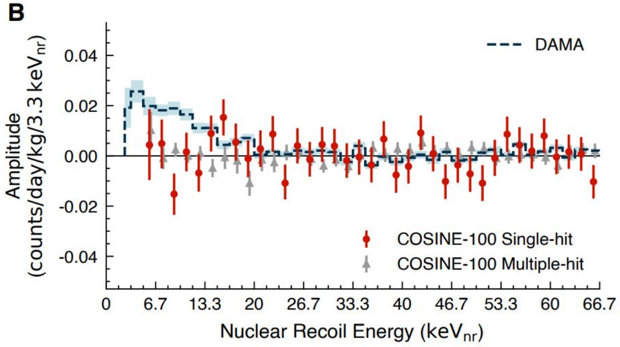
ANAIS best fits are incompatible with DAMA/LIBRA result at 4.0 and 3.5 σ in [1-6] and [2-6] keV energy regions while compatible with the full dataset COSINE-100 results at 1 σ.





Comparison valid for ER events and in the case of NR signals, when assuming QF for NR is an intrinsic property.





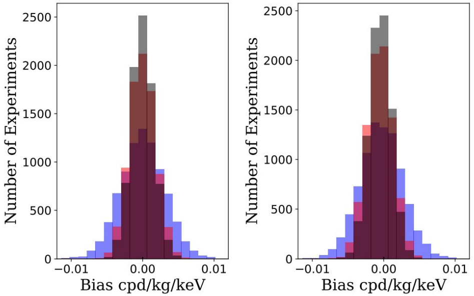
https://arxiv.org/pdf/2409.13226

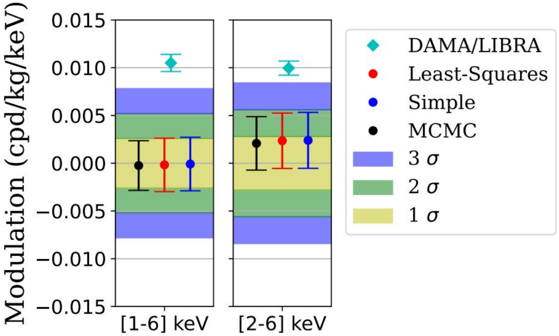
https://arxiv.org/pdf/2502.01542

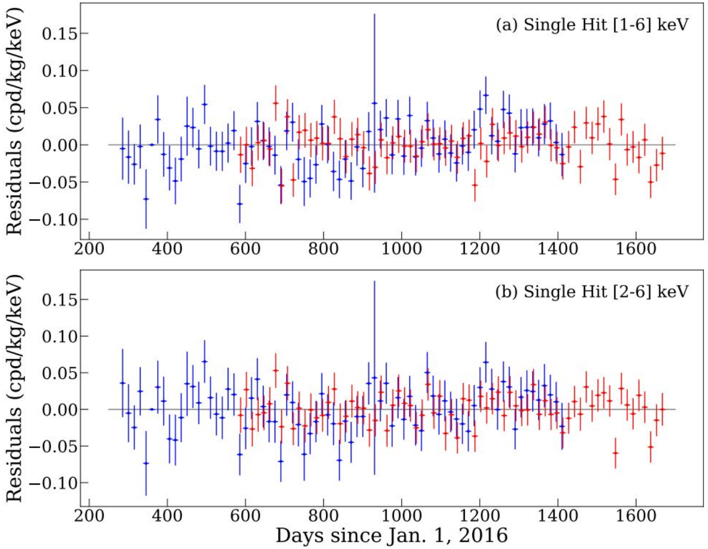
ANAIS and COSINE - combined

https://arxiv.org/pdf/2503.19559

Due to the numerous factors each experiment must individually account for,
the best way to directly combine datasets is to compute the residuals of each crystal detector for each experiment







Configuration	1–6 keV	2–6 keV
COSINE-100 (this)	0.0052 ± 0.0042	0.0067 ± 0.0047
ANAIS-112 (this)	-0.0040 ± 0.0037	-0.0002 ± 0.0037
Combined MCMC	-0.0002 ± 0.0026	0.0021 ± 0.0028
Combined LS	-0.0002 ± 0.0028	0.0023 ± 0.0029
Combined Simple	-0.0001 ± 0.0028	0.0024 ± 0.0029

near 1 ton·yr COMBINED EXPOSURE

	Tot mass kg	crystal mass kg	exp ton y	PMT	light guides	LY phe/keV	veto	BM	bkg rejection	Rate in ROI dru
DAMA	250	10	2.86	R6233MOD	yes	8	no	yes	cuts	1-0.7
COSINE	106 (61.3)	8 - 18	0.35	R12669SEL	quartz, now removed	12.4 - 14.8	LS, muon	yes	BDT	3
ANAIS	112	12.5	0.62	R12669SEL	no	14.5	muon	yes	BDT	3

- Both ANAIS and COSINE include time dependent background model from MC simulations in the chisquare fit
- An accurate background model is crucial.
- Both ANAIS and COSINE discuss the bias distribution of fitted Sm.
- **ANAIS+** → Replace PMTs by SiPM, operation at low T (~100K)
- **COSINE-200:** Ultra-pure NaI(Tl)

$$\mu_{i,d} = [R_{0,d}(1 + f_d \phi^{MC}_{bkg,d}(t_i)) + S_m cos(\omega(t_i - t_0))] M_d \Delta E \Delta t,$$

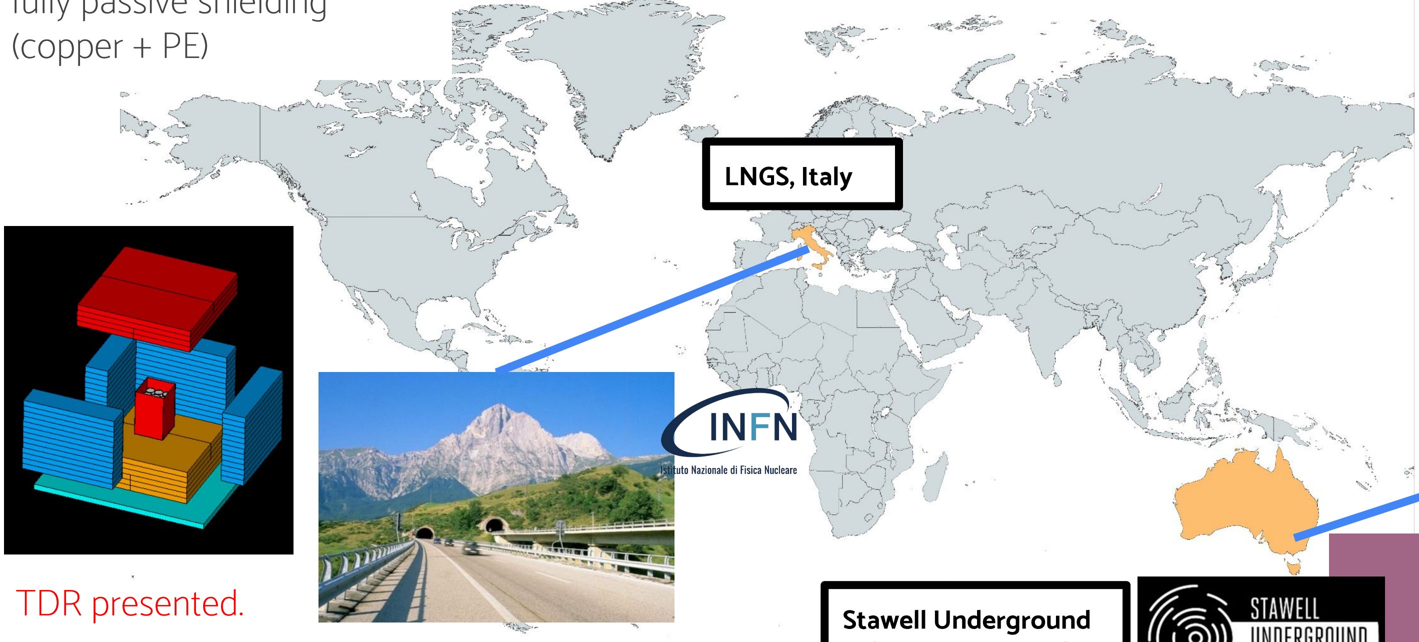
The SABRE project

- Two similar arrays of NaI(Tl) scintillating crystals to search for DM via annual modulation.
- R&D on ultra-radiopure crystals to reach a lower background than competing experiments.

SABRE North

9 crystals each ~5 kg

fully passive shielding (copper + PE)



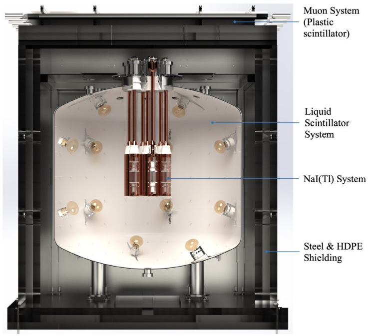
INFN
Istituto Nazionale di Fisica Nucleare

TDR presented.

Entering full scale experiment phase.

SABRE South

7 crystals, each ~5-7 kg



Stawell Underground Laboratory, Australia

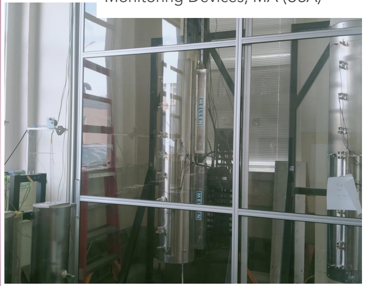
STAWELL UNDERGROUND PHYSICS LAB

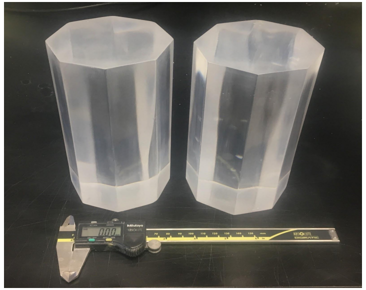
How to grow a radiopure NaI(Tl) crystal:

Clean precursors: NaI powder, Tl dopant → Powder drying → Doping → Clean growth → Cutting & polishing

Clean NaI powder Astrograde by Sigma Aldrich now Merck, Germany

Crystals grown by RMD - Radiation Monitoring Devices, MA (USA)





Currently working on NaI-42 grown after Zone Refining

SABRE Proof-of-principle (PoP) and PoP-dry achieved a background of ~1 dru

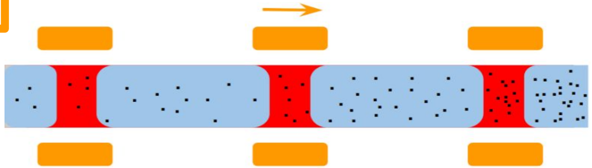
add extra step Zone Refining to further purify the powder

Clear segregation visible for K and Rb (both contributing to bkg in DM ROI).

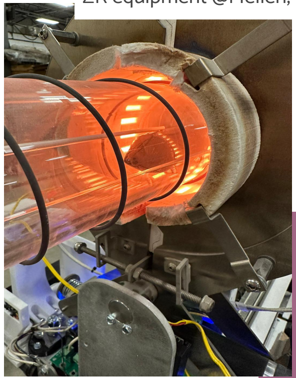
heating elements (furnaces)

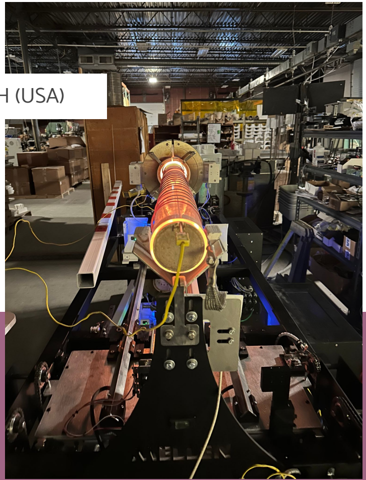
molten zone

solid zone



ZR equipment @Mellen, NH (USA)

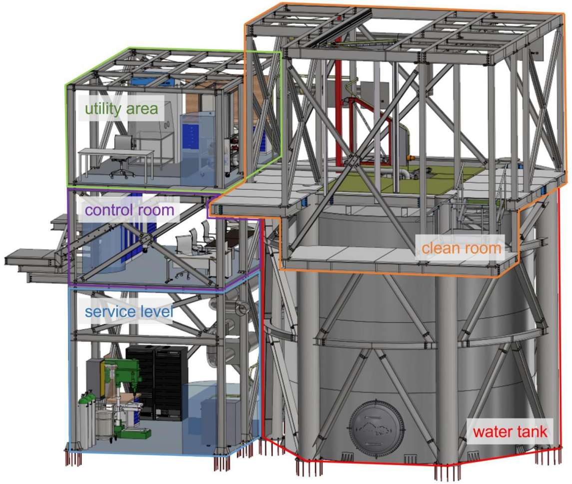




COSINUS

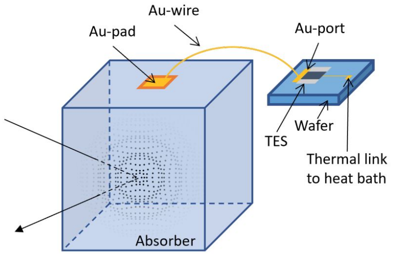
Same target material of DAMA/LIBRA
First NaI experiment operated as low-temperature scintillating calorimeter with light + phonon channels

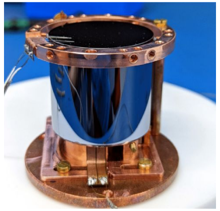
- Highly radiopure crystals
- No need of QF knowledge
- Rate search instead of modulation
- Same underground lab as DAMA/LIBRA (LNGS)
- Active muon veto



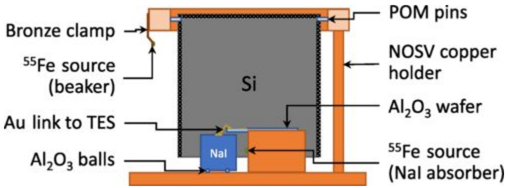
Muon veto filled February 2025
DAQ running

Radiopure NaI crystals 2x2x2 cm^3 grown at SICCAS with Astrograde powder, at LNGS beginning 2025



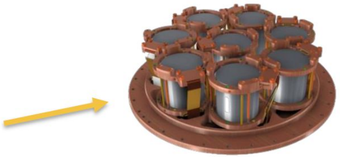


remoTES design



3 Boxes with 8 Detector Modules each

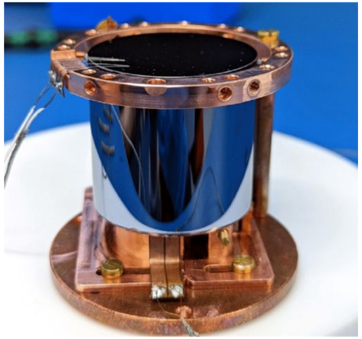
30 g

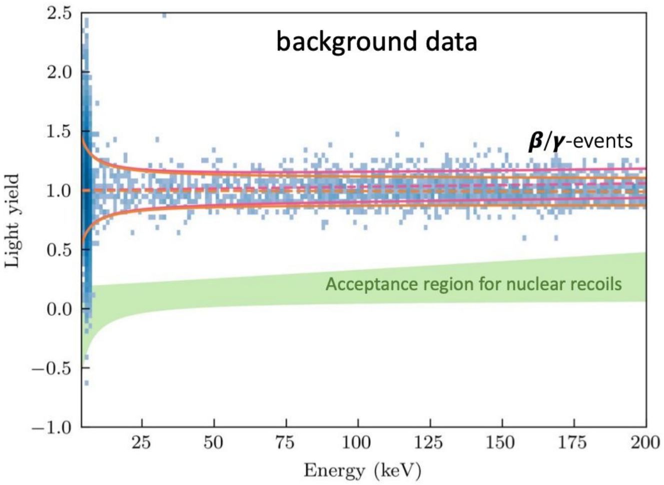


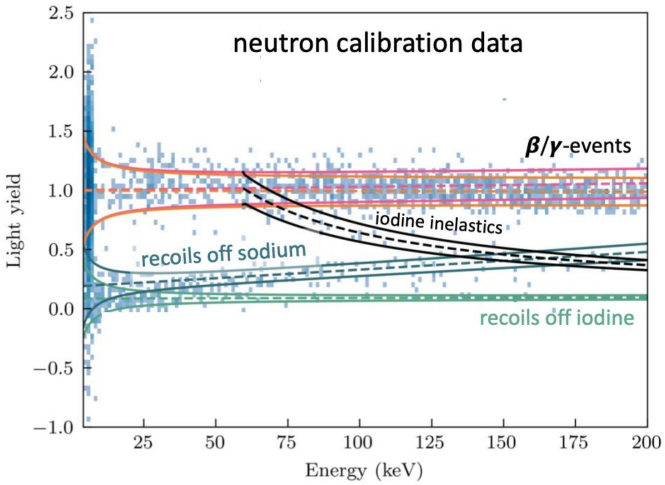
COSINUS

Test at the CRESST facility @LNGS

K. Schaeffner at UCLA DM 2025







First underground measurement of a NaI cryogenic calorimeter readout via the novel remoTES scheme demonstrated discrimination in NaI

3.67 g NaI absorber with an improved silicon light detector design, exposure of only 11.6 g d

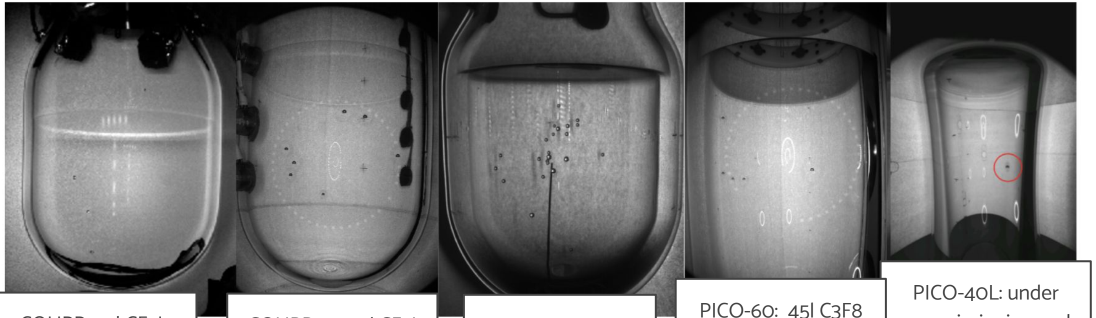
σNaI = (0.441 ± 0.011) keV - nuclear recoil threshold Ethr < 2 keV → performance goal reached !

Bubble chambers - PICO

Target material: superheated CF3I and C3F8 (spin-dependent/independent)

1. Particles interacting evaporate a small amount of material (bubble nucleation).
2. Cameras record bubbles.
3. Piezo-electric acoustic sensors detect sound.
4. Recompression after each event

PICO-500: future ton-scale experiment 2024-2026



COUPP4: 2l CF3I SNOLAB 2010-2012

COUPP60: 40l CF3I SNOLAB 2013-14

PICO-2L: 2l C3F8 SNOLAB 2013-14 and 2015-16

PICO-60: 45l C3F8 SNOLAB 2016-17

PICO-40L: under commissioning and data taking.

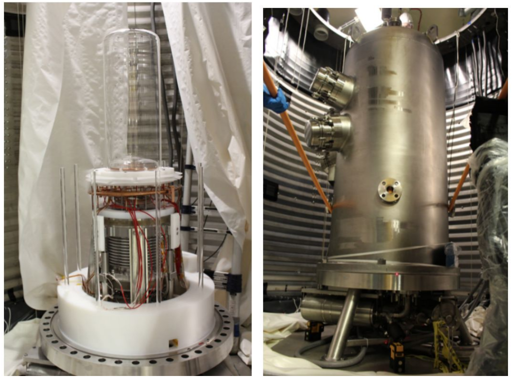
Characteristics:

- Zero background
- Large target mass
- Low energy threshold (a few keV, and down to eV for some fluids)
- Multiple target nuclei: test expected cross section dependences on atomic number and nuclear spin
- (Fluorine, Iodine, Chlorine, Xenon, Argon, Bromine, Hydrogen...)
- Measure nuclear recoil energies (by varying threshold)
- No measure of nuclear recoil direction

PICO-40L @SNOLAB

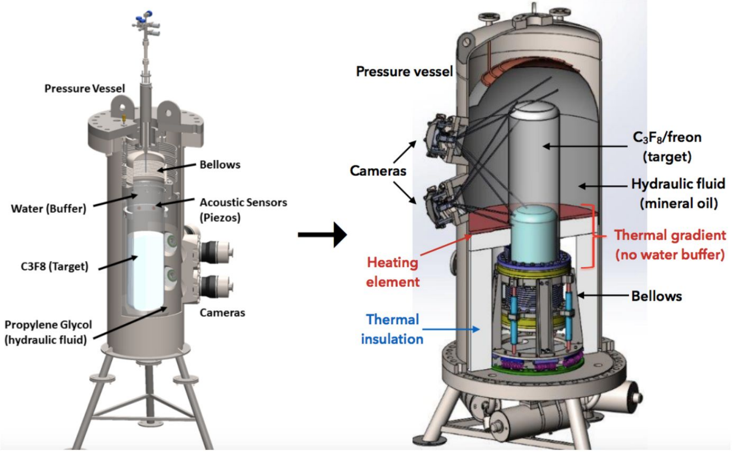
PICO-40L Commissioning and data taking: 2024-2025

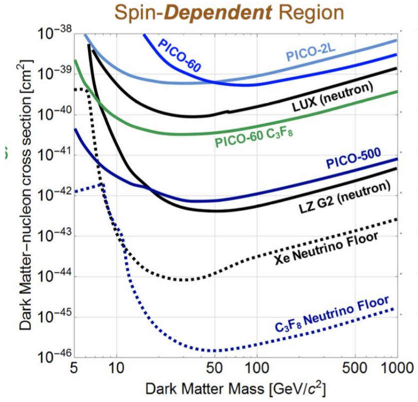
Engineering:
demonstrate background reduction and technology improvements for PICO-500
focus on (neutron) background reduction
confirm "RSU" design used in prototype chambers
Science:
acquire one-year background-free exposure
order of magnitude improvement on PICO-60 limits

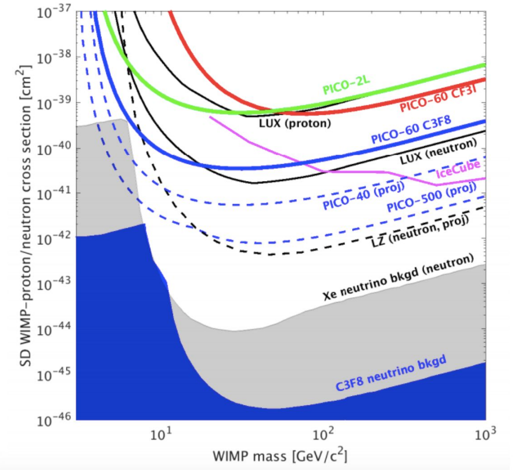


PICO-500 coming soon: 2026

PICO-60 to PICO-40L RSU (right side up)





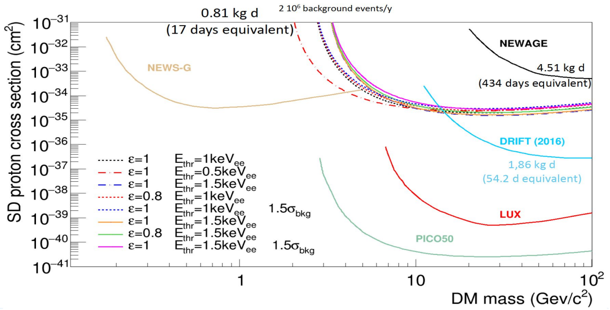


The CYGNO project

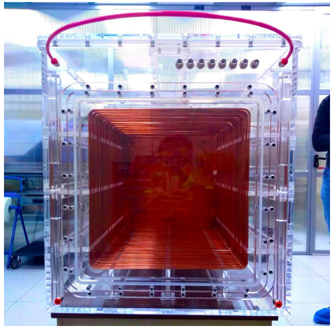
Gaseous Time Projection Chamber (TPC) with a GEM amplification stage operated with an He/CF_4 mixture at atmospheric pressure and room temperature

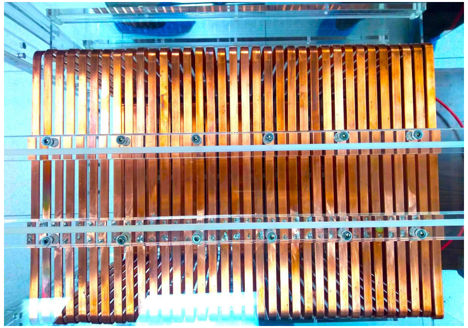
- low energy events in 1 atm gas visible tracks
- He, F (possibly H) in the mixture sensitive to sub-GeV DM and spin dependent interactions (F, possibly H);
- Allows the measurement of position, direction, total released energy, dE/dx (head/tail), PID

The group revived the optical readout of gaseous TPCs by pioneering the use of cameras equipped with Active Pixel Sensors based on ultra-low noise scientific-CMOS.

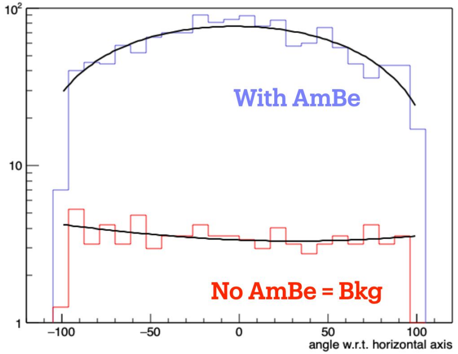


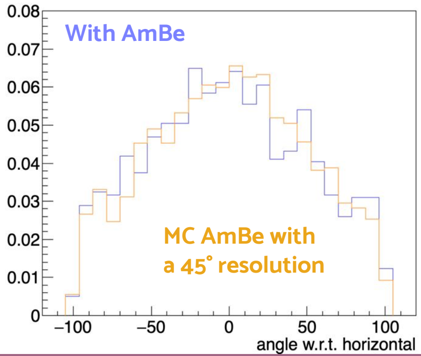
LIME not meant to provide limits (no solid background model) just exercise to estimate where the exposure of the detector can lead and to practice with analysis tools





The Large Imaging ModulE (LIME): 50 l sensitive volume (67 g of gas) operated at LNGS with an uninterrupted data taking of 15 months total exposure of 0.024 kg x year



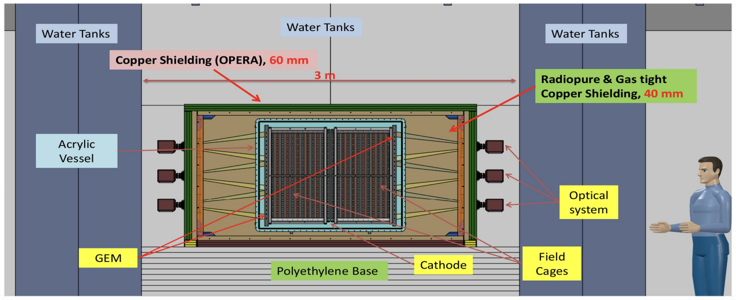


CERN-THESIS-2024-211

https://prodotti.dsi.infn.it/#/product/thesis/67eee8f3ee92a428e0ac4d4b

CYGNO04 @ LNGS

CYGNO 0.4 m^3 demonstrator to be tested in Hall-F at LNGS starting from 2026.



Experimental infrastructure and Control Room completed in Hall-F

Main aim is the demonstration of the scalability of the performance with a modular readout approach and a clear control of the background with properly scrutinised materials.

Experiment	Where	Amplification + Readout	Gas Pressure [mbar]	Volume [L]	Energy Thr [keV_{ee}]	Active Mass [gr]
DRIFT	UK	MWPC	55	800	20	33
NEWAGE	Japan	1 GEM +muPIC	100	37	20	11.5
MIMAC	France	Micromegas	50	5.8	2	1.2
D3	Australia	2 GEM + pixelated RO	1000	40	5	60
CYGNO	Italy	3 GEMs + sCMOS + PMT	900	400	1	600

Conclusive remarks (1)

Different but complementary experiments are crucial to probe the nature of DM and its interaction.

Spin-independent searches with noble liquid TPCs have entered the neutrino fog, while confirming the null results in the standard WIMP scenario.

It is necessary to extend the search to different mass ranges: large region of parameters still to be explored

- limits in the sub-GeV mass range from current experiments
- new technologies for thresholds lower than O (10 eV)

Observation of LEE is currently limiting the sensitivity to DM (and CEvNS). Initiated a common effort to address this issue.

Conclusive remarks (2)

Challenges/opportunities:

High DM mass and neutrino floor/fog: future DS-20k (Argo) and XLZD will face this

Low DM mass and LEE: a community which extends across fields (DM, CEvNS) is addressing this issue

Interpretation of the DAMA result : COSINUS and SABRE at LNGS, NaI network.

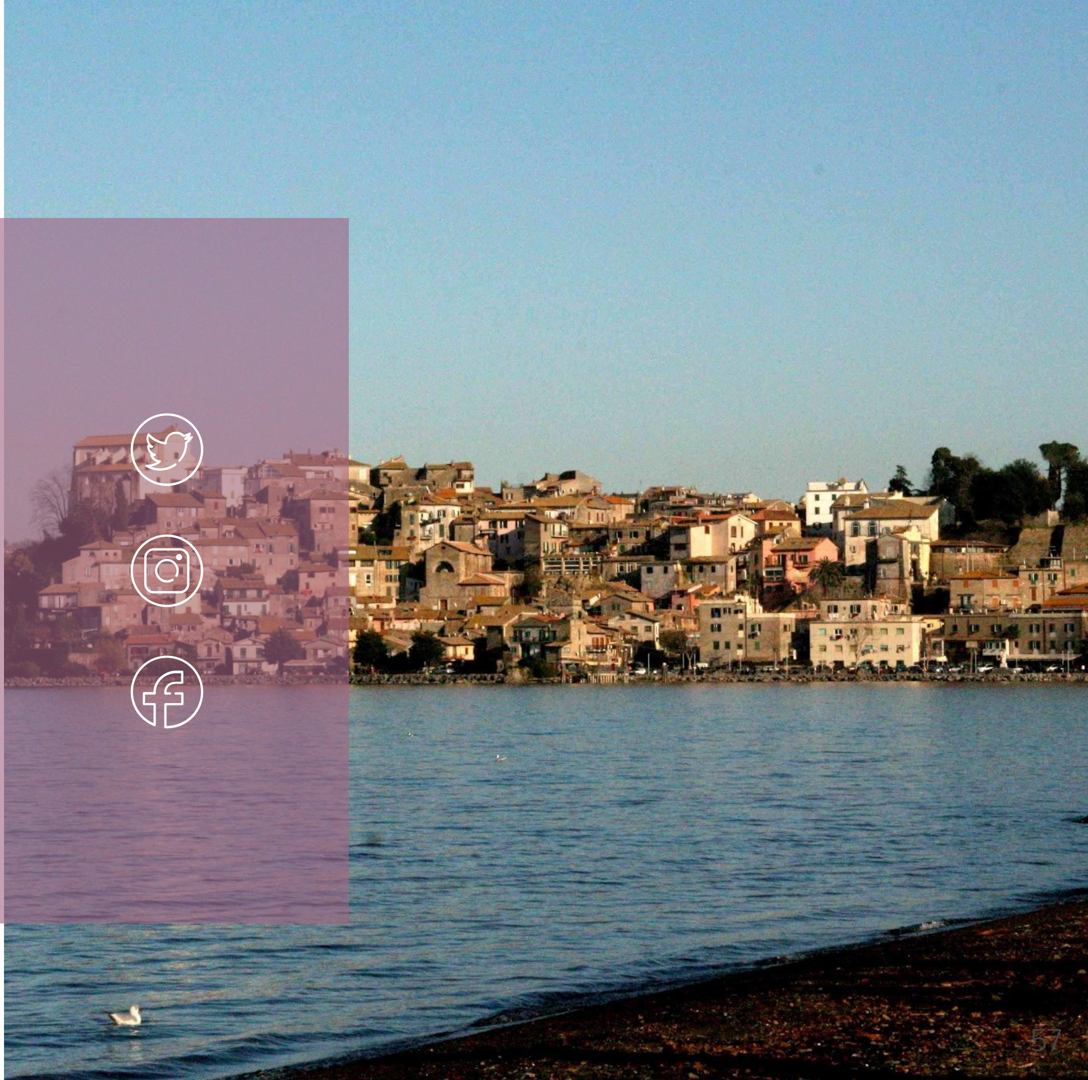
Directionality: CYGNO will demonstrate scalability and background.

High mass, low mass, annual modulation, directionality … INFN experiments are well in the game.

THANKS

Does anyone have any questions?

claudia.tomei@roma1.infn.it



CREDITS

This is where you give credit to the ones who are part of this project.

- Presentation template by Slidesgo
- Icons by Flaticon
- Infographics by Freepik
- Images created by Freepik

DARK MATTER HALO

In the commonly hypothesized scenario, DM particles are distributed in a spherically symmetric (?) halo surrounding each galaxy, with a certain:

- radial dependence
- velocity distribution
- density

STANDARD HALO MODEL

Isotropic, isothermal sphere with density profile $\rho(r) \propto r^{-2}$.

Maxwellian velocity distribution

Astrophysical parameters

v0 = 233 kms
vesc = 528 kms
rho = 0.3 - 0.5 GeV/cm3

Where are DM particles?

DM CANDIDATES

neutralino: lightest state in models of low-energy SUSY, promising detection rates. As a Majorana fermion coupled to the SM via EW-strength interactions (however, suppressed by mixing angles), its mass range as CDM is between a few GeV and a few TeV, with the exact depending on a specific SUSY model and its assumed parameter ranges. The neutralino is arguably the most popular example of the standard (thermal) WIMP class of CDM candidates.

effective field theories (EFTs): an EFT includes only a minimal set of particles (for instance SM nucleons and the DM particles) and interactions.

In the context of DM searches, **simplified models** typically contain the SM as one (visible) sector, a DM candidate, often as part of a dark sector, and a messenger sector– often called "portal"– containing one or more states that mediate SM–DM interactions. Ex. Higgs portal where DM particle can be either a scalar or a fermion and DM–SM interactions are mediated by a SM Higgs doublet. The viable parameter space of the simplest Higgs portal models has been almost fully probed, with the most important constraints arising from direct detection experiments.

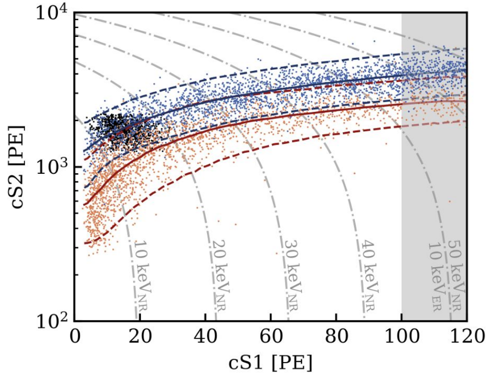
The **dark photon** portal is another recently popular class of models in which a light thermal WIMP (either fermion or scalar), in the MeV mass range, interacts with the SM sector via a dark photon (a new dark sector gauge boson) that mixes with the usual photon via kinetic mixing. Direct detection experiments are also increasing their sensitivity to these type of models by exploiting the DM-electron scattering mode.

In another scenario called **asymmetric DM** (ADM) an asymmetry between the DM particle and its antiparticle is generated. Since in the ADM scenario the DM is not its own antiparticle and the abundance of and particles can be highly asymmetric at present, the expected indirect detection rates from annihilations are typically suppressed while elastic scattering of DM with nuclei can in some model be even larger than for usual WIMPs.

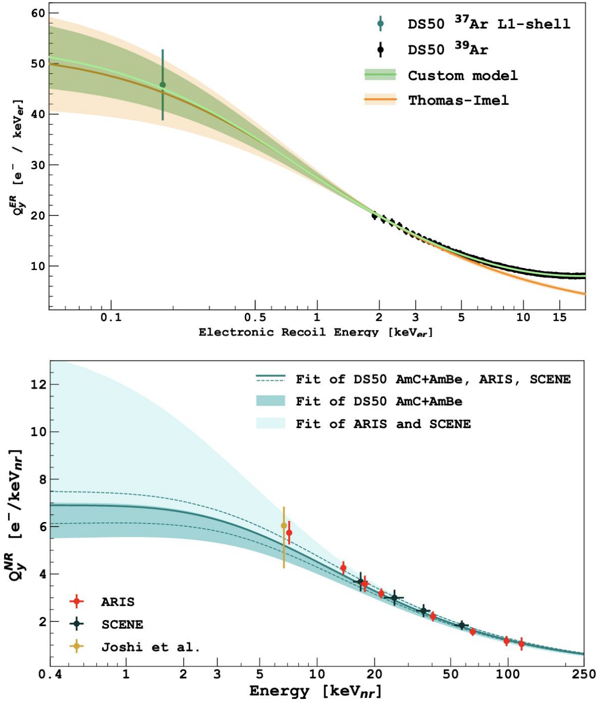
QUENCHING FACTOR

Energy Calibrations are usually performed using gamma sources

XENONnT, Phys.Rev.Lett. 129 (2022) 16, 161805



NR and ER calibration data from ^{241}AmBe (orange), ^{220}Rn (blue) and ^{37}Ar (black).



DarkSide-50, Phys. Rev. D 104, 082005 (2021)

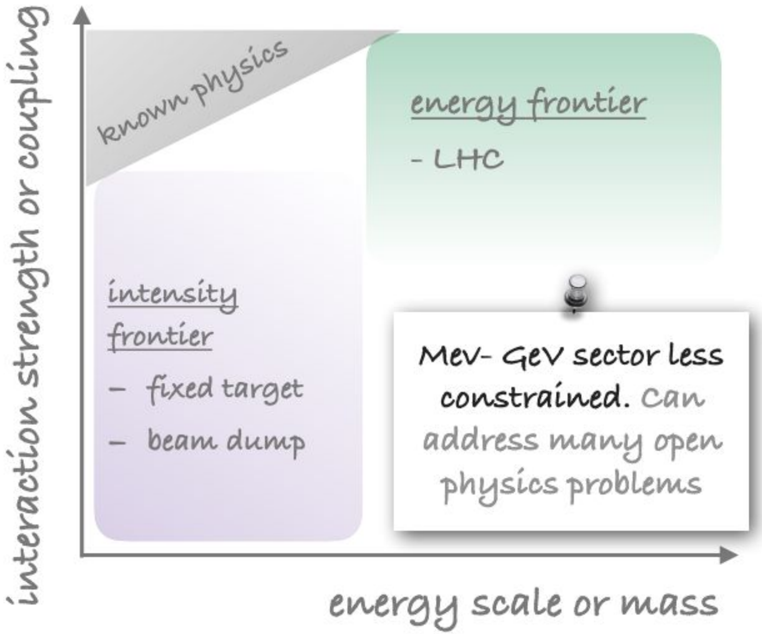
The relative calibration of nuclear recoils (keV$_{ee}$ ➡ keV$_{NR}$), the quenching factor (QF), must be known with accuracy

Dark Matter at the energy frontier

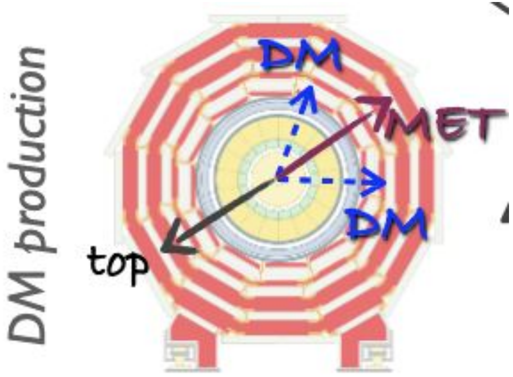
- Complementarity with direct-detection essential:

  - accelerator-based directly characterize particle properties of produced DM, explore relativistic DM production

  - direct detection explores a combination of DM properties with their cosmological abundance, probe non- relativistic scattering



- DM could be produced at colliders (rare process):
  - invisible signature: no direct trace in the detector, but …
  - can be inferred from pT imbalance (MET)
  - need visible particle to which DM particle recoils against "mono-X"



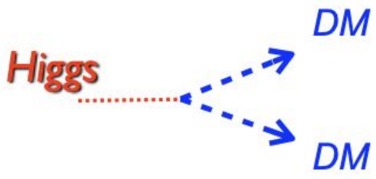
Example of complementary to direct detection: Higgs portal

- DM-SM interactions mediated by Higgs boson: coupling to DM enhance H invisible decays (SM ~0.1%)
- Higgs production as in SM

  - gluon fusion (MET+j)

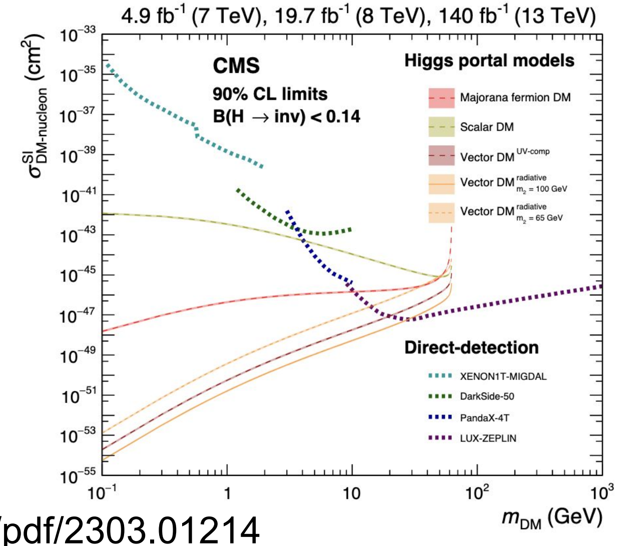
  - associated VH (MET+V), ttH (MET+tt)

  - vector-boson fusion (MET+2jets)



mDM < mH/2

- Results: combination of results from various Higgs production, translated into a spin-independent DM-nucleon elastic scattering xsec limit:



https://arxiv.org/pdf/2303.01214

SuperCDMS SNOLAB payload

Ultra pure semiconductor (Ge, Si) crystals as target
- Ge → better suited for low cross-section DM
- Si → better kinematic coverage for low mass DM

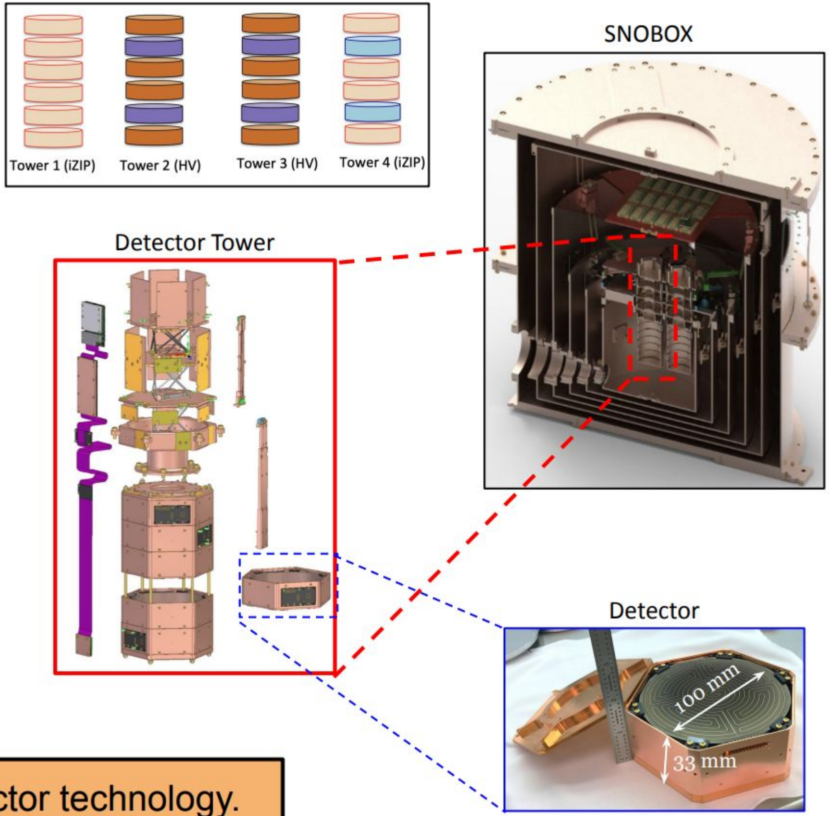
Cylindrical in shape: Ø = 100 mm, h = 33 mm

Payload: 24 detectors in 4 stacks ("towers")
- 2 iZIP towers & 2 HV towers
- Total mass ~ 30 kg

Cool the detectors down to **mK**
- Athermal phonon measurements with TES
- Ionization measurement with electrodes + HEMTs

iZIP detectors gives **background discrimination.**

HV detectors allows **low threshold operation.**

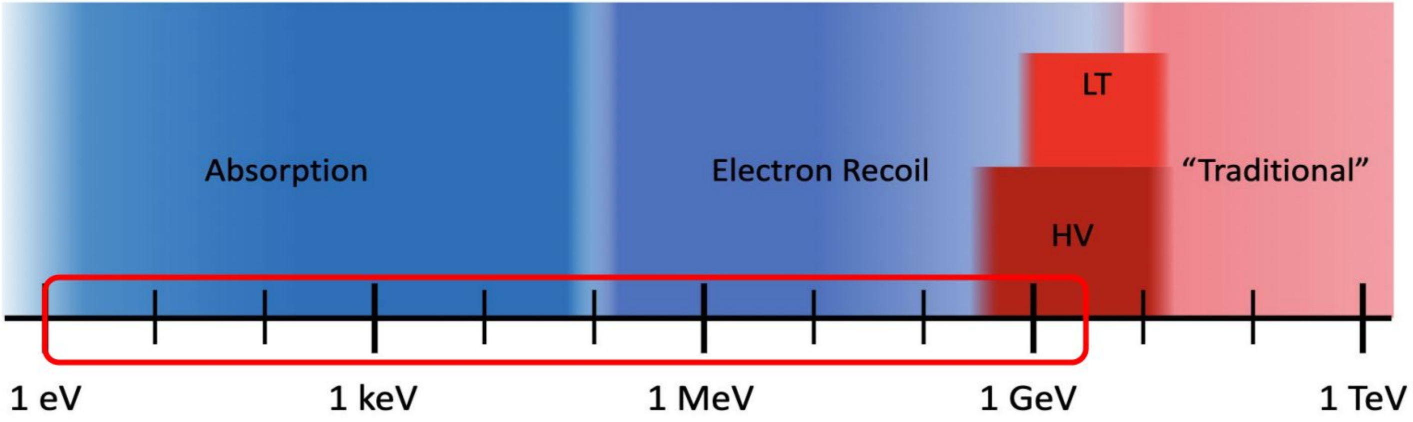


Maximum use of complementary detector technology.

SuperCDMS science reach : DM mass scale

Dark Matter mass ranges:

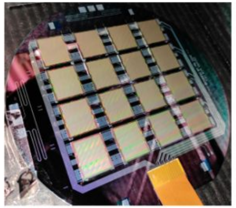
○ Traditional NR	iZIP, Full discrimination	$\gtrsim$ 5 GeV
○ Low threshold NR	iZIP, limited discrimination	$\gtrsim$ 1 GeV
○ HV NR	HV, no discrimination	~ 0.3 - 10 GeV
○ Electron recoil	HV, no discrimination	~ 0.5 MeV - 10 GeV
○ Absorption (dark photons, ALPs)	HV, no discrimination	~ 1 eV - 500 keV “peak search”

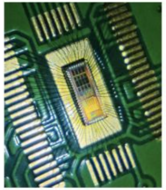


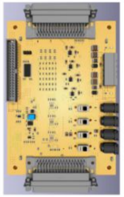
Shubham Pandey, UCLA DM 2025

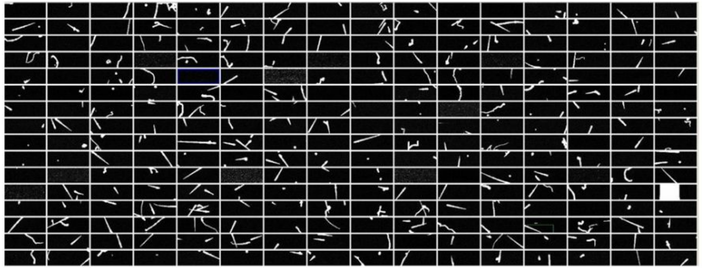
Skipper-CCD program: light dark matter

SENSEI 100g — DAMIC-M 1kg — OSCURA 10kg









10% (1kg) integration test soon!

IEEE Transactions vol. 70, no. 6, pp. 2306-2316
JINST 18 P01040 arxiv:2004.07599
JINST 16 P11012 IEEE Sensors,25, 5, 8813-8822

Current largest CCD camera (in # of CCDs) in the world !

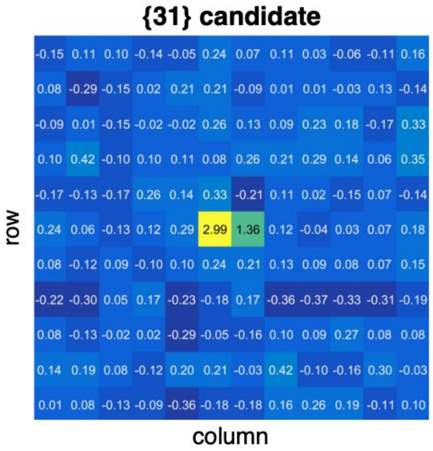
Pixel pattern analysis

Blind analysis
- Data set 1 (D1): selection sample (130 g-day)
- Data set 2 (D2): blinded analysis set (1.3 kg-day)

Candidate selection
- look for horizontal cluster patterns from diffusion (previously used single pixel spectra)
- select 2 or 3 horizontally adjacent pixels (due to row binning) with total charge 2, 3, or 4e-
- exclude single pixels with ≥ 2e-

Patterns
- identify rows: {11}, {21}, {111}, {31}, {22}, {211}
- calculate probability to obtain pixel values from background smeared with charge resolution (σ_{ch})

Backgrounds
- estimate radiogenic/cosmogenic background by scaling measured high energy events (2.5 to 7.5 keV) with Geant4
- random coincidences of single pixels next to each other evaluated from measurements + toy MC



	Pattern p		
	{11}	{21}	{111}
D_p	144	0	0
B_p^{rc}	141.4	0.111	0.042
B_p^{rad}	0.039	0.039	0.016
	{31}	{22}	{211}
D_p	1	0	0
B_p^{rc}	0.019	$2.5 \cdot 10^{-5}$	$5.8 \cdot 10^{-5}$
B_p^{rad}	0.052	0.011	0.035

TABLE I. The number of candidates D_p in the D2 data set, and the number expected from backgrounds due to random coincidences, B_p^{rc}, and to radioactive decays, B_p^{rad}.

Luminance of Dark Matter

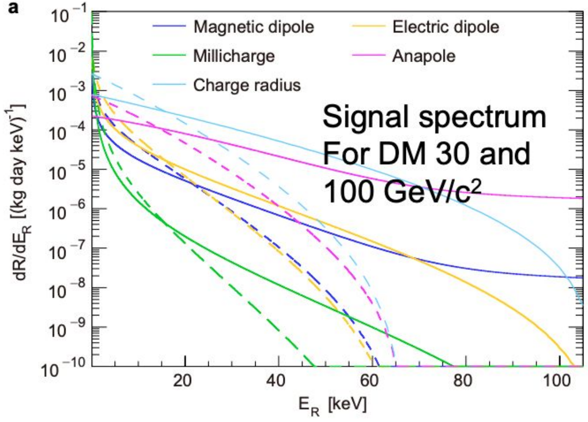
Run0 Data

- **Residual weak EM properties through EFT**

$$\mathcal{L} = Qe\bar{\chi}\gamma^{\mu}\chi A_{\mu} + \frac{\mu_{\chi}}{2}\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu} + i\frac{d_{\chi}}{2}\bar{\chi}\sigma^{\mu\nu}\gamma^{5}\chi F_{\mu\nu} + b_{\chi}\bar{\chi}\gamma^{\mu}\chi\partial^{\nu}F_{\mu\nu} + a_{\chi}\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\partial^{\nu}F_{\mu\nu}$$

millicharge | magnetic dipole | electric dipole | charge radius | anapole

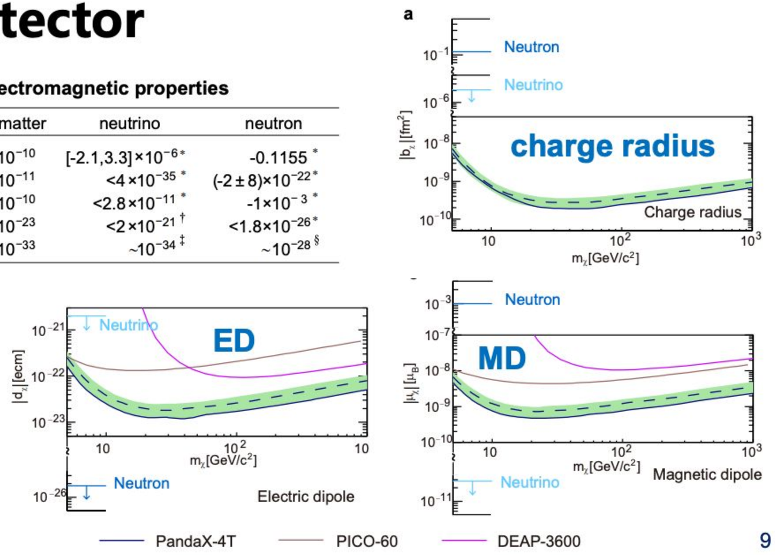
- **Dedicated searches in xenon detector**



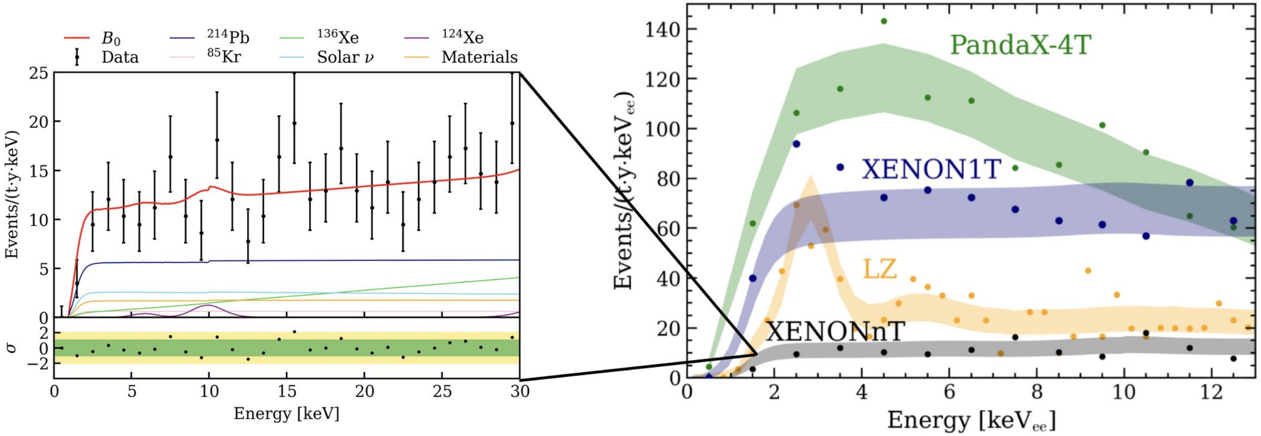
Nature 618, 7963, 47-50 (2023)

Table 1 | Comparison of electromagnetic properties

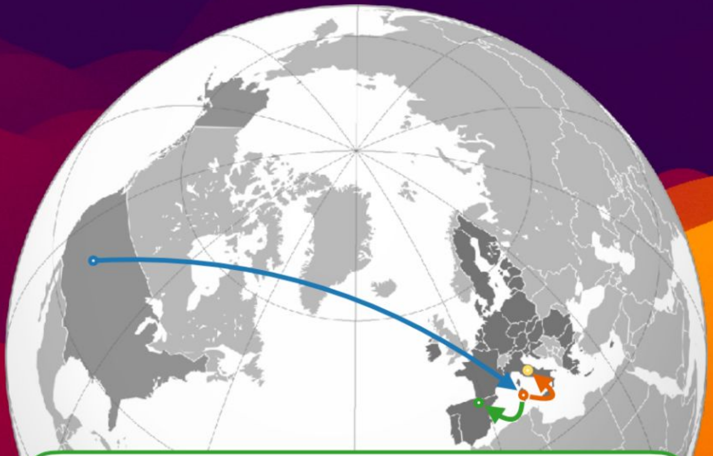
	dark matter	neutrino	neutron
Charge radius (fm^2)	$<1.9\times10^{-10}$	$[-2.1,3.3]\times10^{-6}$ *	-0.1155 *
Millicharge (e)	$<2.6\times10^{-11}$	$<4\times10^{-35}$ *	$(-2\pm8)\times10^{-22}$ *
Magnetic dipole (μ_B)	$<4.8\times10^{-10}$	$<2.8\times10^{-11}$ *	-1×10^{-3} *
Electric dipole (ecm)	$<1.2\times10^{-23}$	$<2\times10^{-21}$ †	$<1.8\times10^{-26}$ *
Anapole (cm^2)	$<1.6\times10^{-33}$	$\sim10^{-34}$ ‡	$\sim10^{-28}$ §



XENONnT ER background



Industrial Scale UAr Production



Production

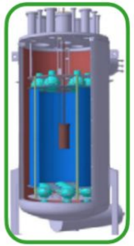
URANIA Site
Cortez, CO, US

- Industrial-scale extraction plant
- Extraction rate of $(250 - 330)\,\mathrm{kg/day}$
- Production capability of $\approx 120\,\mathrm{t}$ over two years for Darkside
- UAr purity of $99.99\,\%$

Qualification

DArT
Canfranc, Spain

- Single-phase detector to measure $^{39}\mathrm{Ar}$ depletion factor
- Sensitive to $^{39}\mathrm{Ar}$ down to a reduction factor of 1400 with 7% accuracy
  https://doi.org/10.1088/1748-0221/15/02/P02024
- DArT soon to be installed inside ArDM

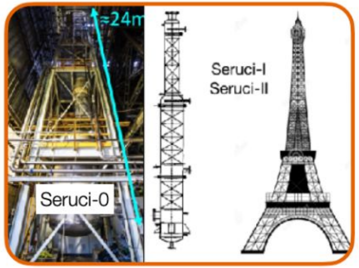


Purification

ARIA Site
Sardinia, Italy

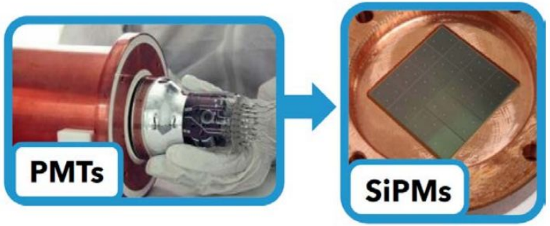
- Seruci-0 demonstrator tested
- $350\,\mathrm{m}$ long cryogenic distillation column
- $\mathcal{O}(1\,\mathrm{tonne/day})$ purification throughput
- Resulting UAr purity of $99.999\,\%$

https://doi.org/10.1140/epjc/s10052-021-09121-9
https://arxiv.org/abs/2301.09639



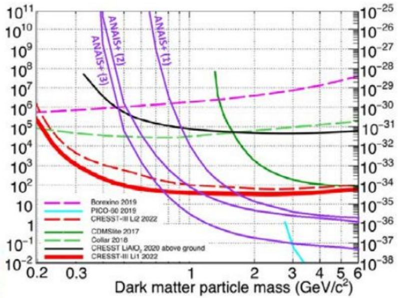
XENON				ARGON			
Signal	Threshold NR	Threshold ER	Discrimination NR/ER	Signal	Threshold NR	Threshold ER	Discrimination NR/ER
S2/S1	3.3 keV NR	1 keVee	YES	PSD (S1)	13 keV NR	0.6 keVee	YES
S2	0.7 keV NR	190 eVee	NO	S2	0.6 keV NR	0.05 keVee	NO

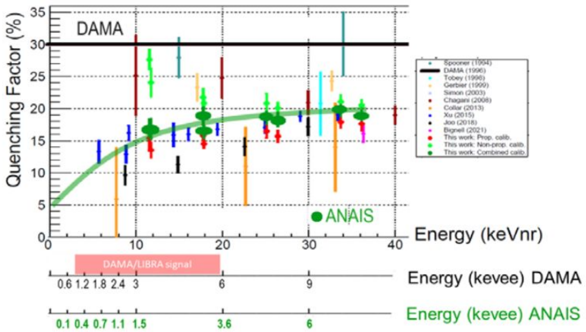
We are moving forward to a new technological approach **ANAIS+**

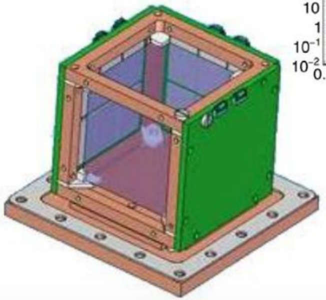


Replace PMTs by SiPM and operation at low T (∼100K)

- Reduce “light noise” coming from the PMT
- Increase light collection and then, reduced threshold
- Allow the operation inside a LAr active veto to fight backgrounds







First prototype in construction

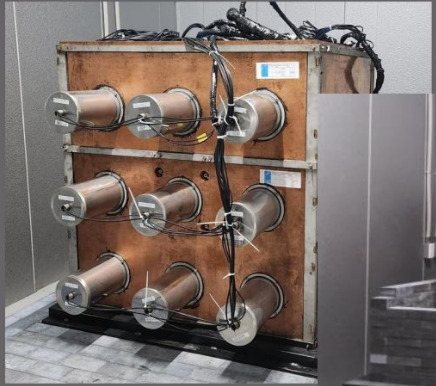
CAPA Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza

INFN LNGS

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

COSINE-100Upgrade

Lower Threshold | **New Deeper Site; Yemilab**

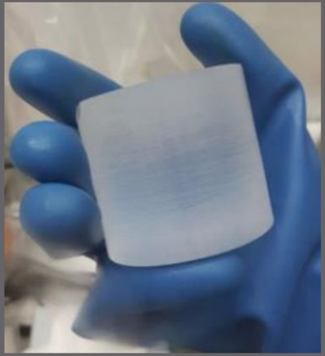


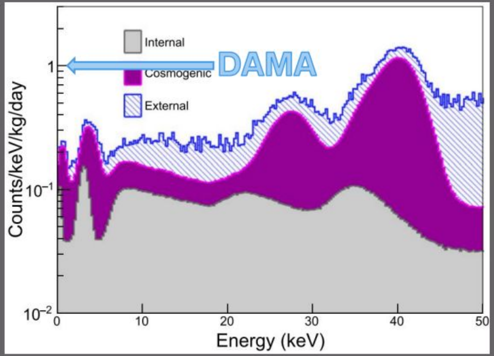
Ultra-pure NaI(Tl) Development for COSINE-200

- 400 kg of ultra-pure NaI powder is ready.
  - J. Rad. Nucl. Chem. 317, 1329 (2018), JINST 15, C07031 (2020)
  - EPJC 80, 814 (2020), Front. Phys. 11, 1142849 (2023)

(ppb)	K	Pb	U	Th
Initial	248	19.0	<0.01	<0.01
Purified	<16	0.4	<0.01	<0.01

- We grew 0.7 kg of crystal with 0.2 counts/day/kg/keV.
- Further R&D to grow large crystals within the safety regulation is ongoing.

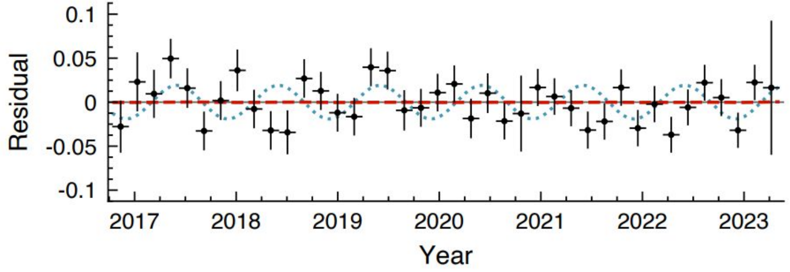


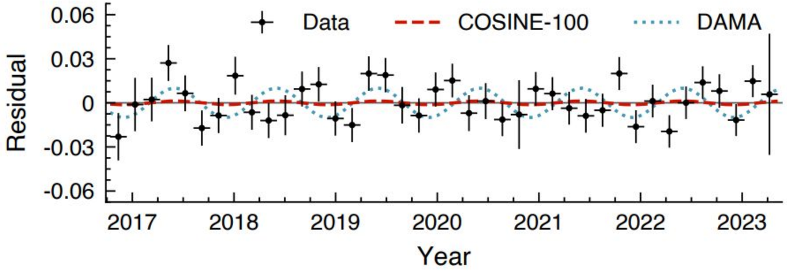


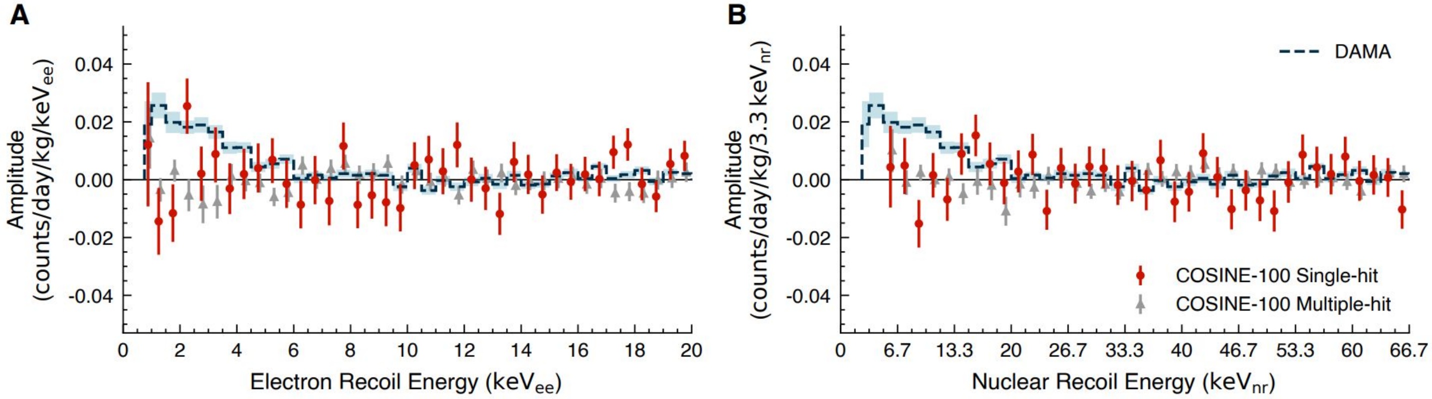
ANAIS and COSINE - 6y dataset

https://arxiv.org/pdf/2409.13226

https://arxiv.org/pdf/2502.01542





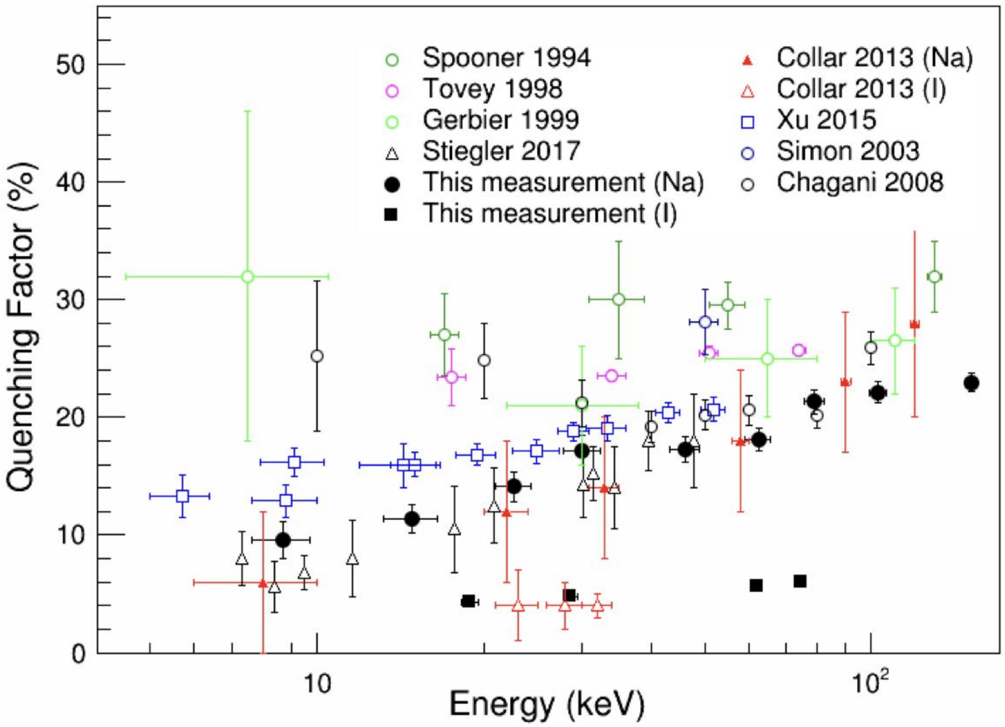


NaI quenching factors

relevant systematics in the DAMA testing

Sodium and iodine scintillation QF have been measured by several authors and results do not fully agree.

- dependence on the particular crystal properties (impurities, defects, growth method, etc.)
- systematics in the calculation of the quenching factors.



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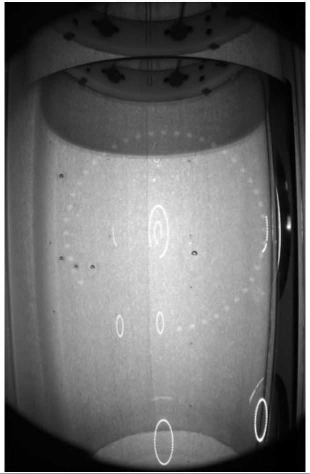
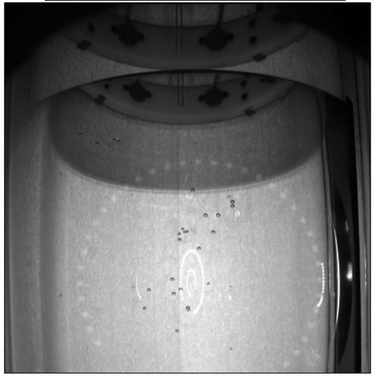
Bubble chambers: signal

- Alpha decays:
  Nuclear recoil and
  40 μm alpha track
  1 bubble

- Neutrons:
  Nuclear recoils
  mean free path ~20 cm
  3:1 multiple-single ratio
  in PICO-60

- Neutrinos or WIMPs:
  Nuclear recoil
  mean free path $> 10^{10}$ cm
  1 bubble





slide from Eric Vázquez Jáuregui (UNAM)

The CYGNO project

CYGNO Experiment

Direct Detection of Dark Matter – APPEC Committee Report *

DRIFT-II	Gas Directional	CF_4	0.14 kg	Boulby
NEWAGE-03b'	Gas Directional	CF4	14 g	Kamioka
MIMAC	Gas Directional	$CF_4+CHF_3+C_4H_{10}$		LSM (Modane)
CYGNO	Gas Directional	He + CF_4	0.5 - 1 kg	LNGS
CYGNUS	Gas Directional	He + SF_6/CF_4		Multiple sites

DRIFT (Directional Recoil Identification From Tracks) was the pioneer of directional detectors, using MWPCs attached to a TPC with a large conversion volume ($1\,\mathrm{m}^3$, corresponding to a target mass of 140 g) filled with electronegative gas; in this way, the formed ions (not electrons) are drifted to the readout, to reduce diffusion and optimise track resolution. Electronic recoil background can be rejected to high levels based on their longer range and lower ionization density but alpha background is still problematic. It operated at Boulby, UK, over more than a decade, using a $CS_2+CF_4+O_2$ mixture. Directional nuclear recoils (from ^{252}Cf neutrons) quantifying the head-tail asymmetry parameter have been measured [347] and the best limits for SD WIMP-proton interaction from directional detectors ($\sigma < 2.8 \times 10^{-37}\,\mathrm{cm}^2$ at $m_\chi \approx 100\,\mathrm{GeV}/c^2$) were derived from 54.7 live-days [348].

NEWAGE (NEw generation WIMP search with an Advanced Gaseous tracker Experiment) uses a simplified system with amplification structure and readout in a monolithic detector with a TPC and a micro-pixel chamber. After first operation in surface, long runs at Kamioka in Japan have been made using CF_4. The head/tail effect above $100\,\mathrm{keV}$ has also been confirmed. After the release of first results for SD proton interaction [351], a low background detector is running since 2018 and very first new limits have been presented from 108 days and an exposure of $1.1\,\mathrm{kg} \times$ day [352].

MIMAC (MIcro-tpc MAtrix of Chambers) also operates a dual TPC with a common cathode, but equipped with pixelized bulk Micromegas (micromesh gas structures), at the Modane Underground Laboratory in France since 2012. MIMAC works with $CHF_3+CF_4+C_4H_{10}$ and 3D tracks of radon progeny nuclear recoils have been registered [349]. A competitive low threshold of $2\,\mathrm{keV_{ee}}$ has been achieved in prototypes, lower than typical thresholds in other directional detectors. First observation of ^{19}F ion tracks at ion beam facilities with angular resolution at 10-20^o has been reported [350] and quenching factors of He and F with an ion source in Grenoble have been measured. A $1\,\mathrm{m}^3$ detector is

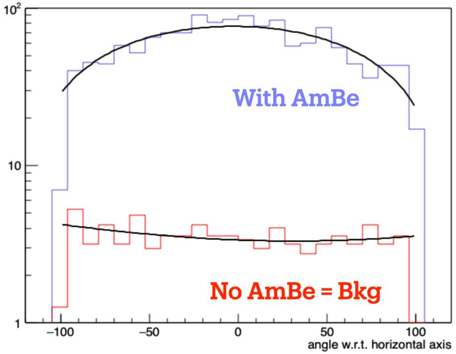
DMTPC (Dark Matter Time-Projection Chamber) is based on a TPC equipped with external optical (CCD, PMTs) and charge readouts. Several prototypes have been developed since 2007, operated first at MIT and then underground at WIPP in the USA, working now also for the $1\,\mathrm{m}^3$ scale (corresponding to $\sim 150\,\mathrm{g}$ at 30 Torr). First limits on SD WIMP-proton cross section were obtained from a 10-litre detector [353]. The measurement of the direction of recoils has been reported and the sensitivity to directionality was estimated for the first time [354].

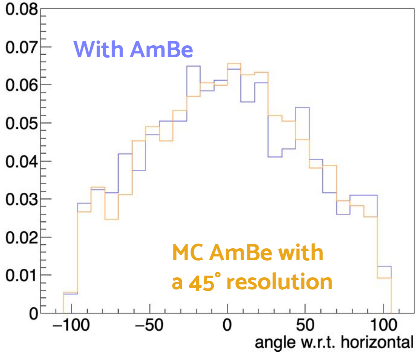
slide from Davide Pinci (INFN Roma)

Main LIME performance

slide from Davide Pinci (INFN Roma)

The CYGNO project aims at a large detector for high precision 3D tracking of low energy (down to few keVs) nuclear recoils from rare interactions (as for example WIMPs)





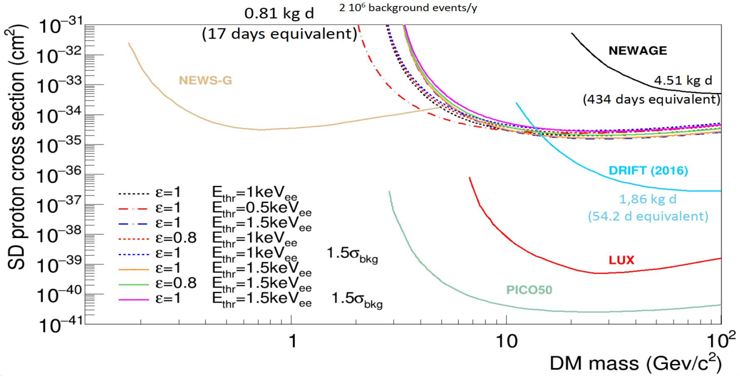
The analysis of data taken with an AmBe calibration source shows a clear sensitivity to the direction of NR induced by neutron scattering with an evaluated 2D angular resolution of 45°

Best results for a O(0.1 kg) mass target

Room for large improvements with more sophisticated directional and rejection algorithms under development

An exercise was performed to evaluate from a with a subsample of 17 days, the DM sensitivity with a Bayesian fit procedure to estimate Credible Interval Limit (BAT toolkit used)

LIME is not able to provide limits yet: no solid background model (LIME was not meant for this), however, it can be used to estimate where the exposure of the detector can lead and to get practice with the analysis tools



NEWS-DM

Direction sensitive dark matter search with nano-tracking technologies for super resolution nuclear emulsion.

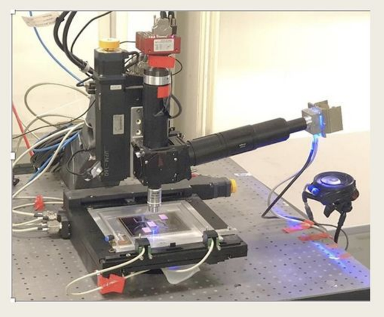
Nano Imaging Tracker (NIT) developed for NEWSdm

		Mass fraction	Atomic Fraction
Heavier DM	Ag	0.44	0.10
	Br	0.32	0.10
	I	0.019	0.004
Lighter DM	C	0.101	0.214
	O	0.074	0.118
	N	0.027	0.049
neutron	H	0.016	0.410
	S, Na + others	~ 0.001	~ 0.001

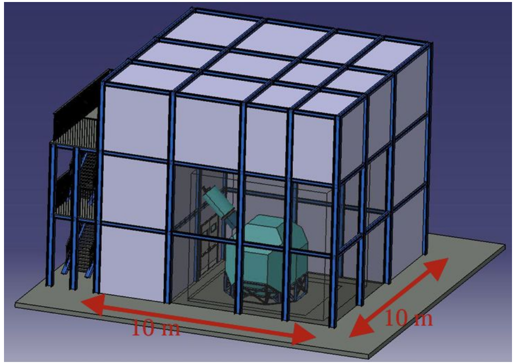
Solid-state detector - Density: 3.1 g/cm3

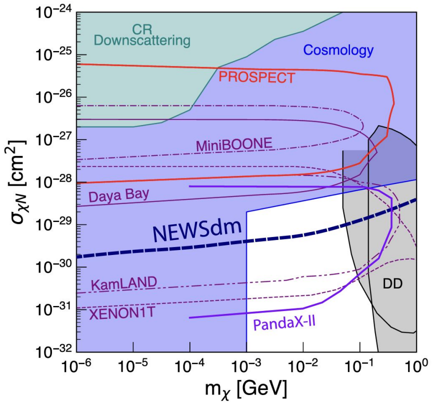
Proposed search:

a module of the NEWSdm experiment, a stack of emulsion films placed on an equatorial telescope to compensate for the Earth's rotation, could search for Dark Matter boosted forward when scattered by cosmic-ray nuclei.
The boosted Dark Matter flux at the edge of the Earth's atmosphere is expected to be pointing to the Galactic Center, with a flux 15 to 20 times larger than in the transverse direction.



Optical image readout



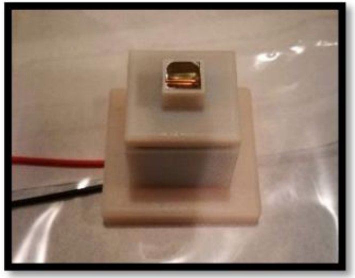


A 10 kg module of the NEWSdm experiment exposed for one year at the Gran Sasso surface laboratory can probe Dark Matter masses between 1 keV/c2 and 1 GeV/c2 and cross-section values down to 10-30 cm2 with a directional sensitive search.

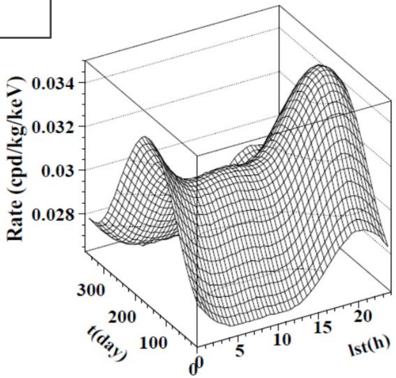
Anisotropic crystals - ZnWO4

200 kg of ZnWO4 • 5 years • 2 keVee thr
Allowed regions (green, red, blue) from the DAMA model independent result in terms of DM candidates considered here.

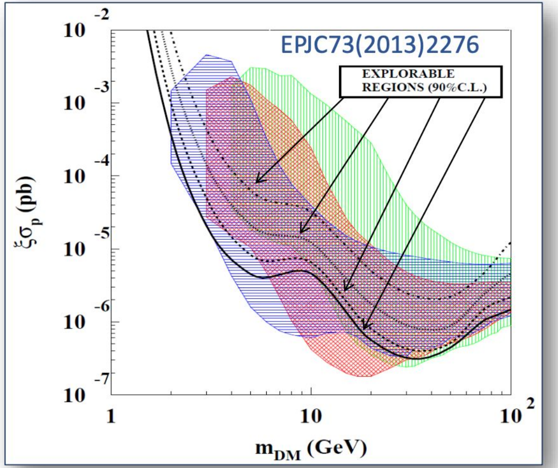
- **heavy particles (p, α, nuclear recoils):** light output and pulse shape depends on the particle impinging direction with respect to the crystal axes
- **γ/e:** light output and pulse shape responses are isotropic



Expected rate as a function of sidereal time and days of the year.
It is possible to arrange the crystal to obtain the maximum range of variability of the anisotropic detector response during a sidereal day.



- 10^{-4} cpd/kg/keV
- 10^{-3} cpd/kg/keV
- 10^{-2} cpd/kg/keV
- 0.1 cpd/kg/keV



ADAMO: small ZnWO4 crystal (10 x 10 x 10 mm3, 7.99 g), irradiated by a collimated beam of α particles from an **241Am source** and a **neutron beam** of 14 MeV at ENEA Casaccia (Oxygen recoils).

Confirmed anisotropic response of ZnWO4 crystal scintillator to α particles in the MeV energy region and Oxygen nuclear recoils at hundreds keV.