Dark Matter Search – 2

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The Dark Matter Particles

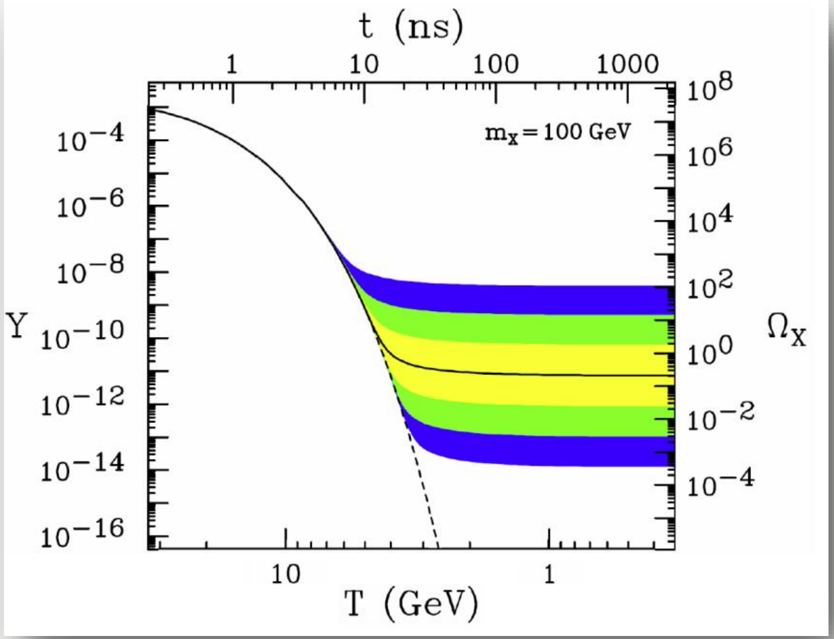
- WIMP a particle many candidates (sub GeV to multi TeV): neutral, massive, non-relativistic, stable, weakly interacting

- Axion, ALPs: pseudoscalar particles with interaction given by

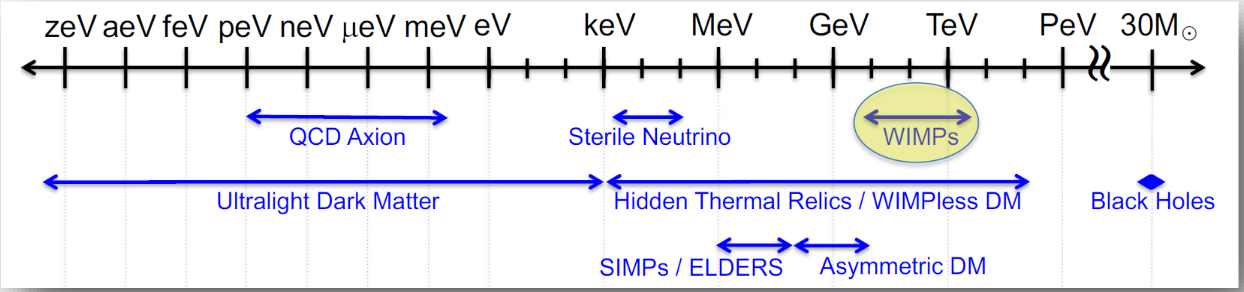
$$-\sum_{f=e,p,n} g_{af}\, a \bar{\psi}_f \gamma_5 \psi_f - \frac{1}{4} g_{a\gamma}\, a\, F_{\mu\nu} \tilde{F}^{\mu\nu}$$

- Others: Heavy neutrino, Mirror particles, sterile-ν, sneutrino, Kaluza-Klein particles, Elementary Black holes, Planckian objects, Daemons, electron interacting

The "WIMP miracle" (new physics for M ~m_W and g~1)



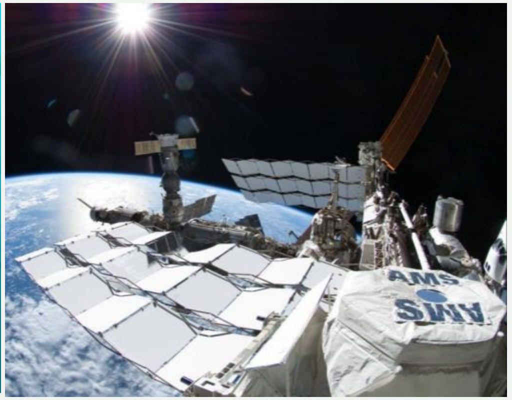
J.L. Feng, arXiv:2212.02479



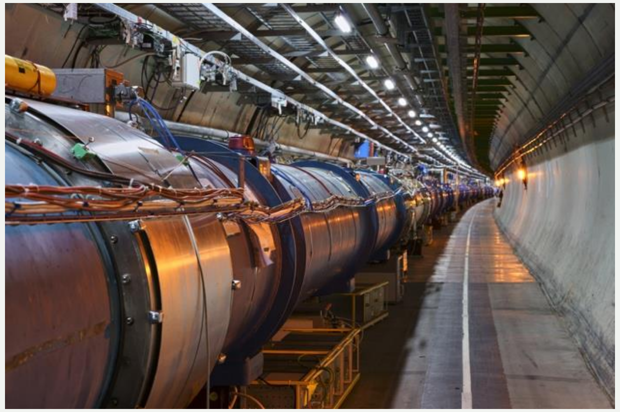
Hunting the Dark Matter particles

Direct: interaction of particle with target nuclei

Indirect: flux of secondary particles produced in annihilation of DM particles in Sun or in space

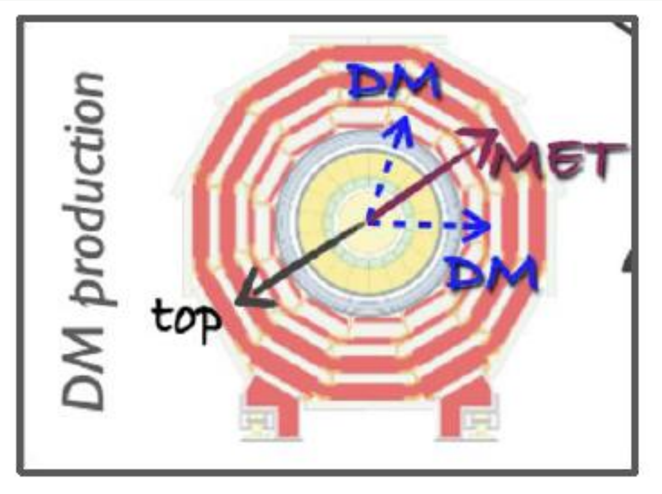


Accelerator: production of new particles



DM search at accelerator

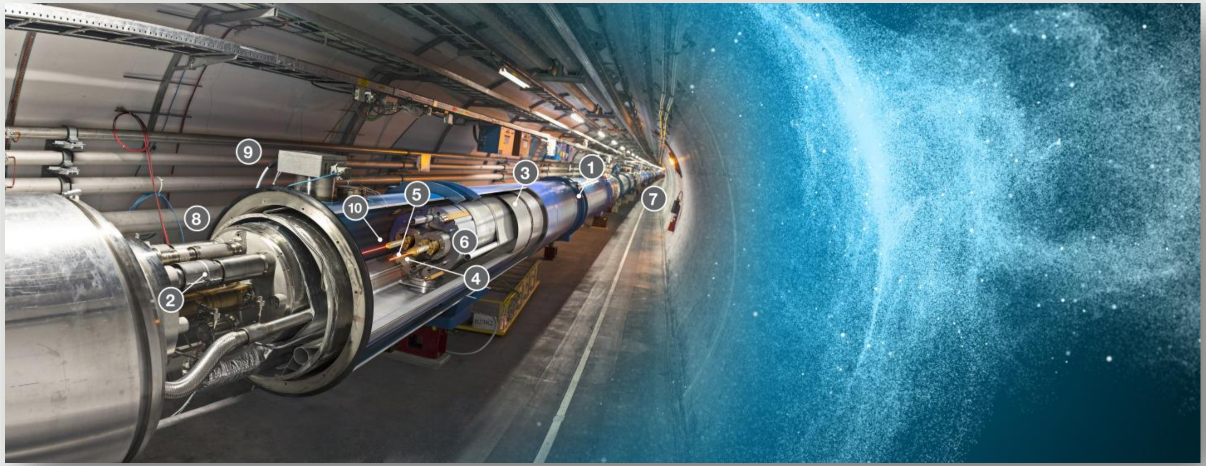
- Search for events in Missing Transverse Energy (MET) tail wrt SM
- No signature: search of excess above background in region with significant signal



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

Complementary information from accelerator

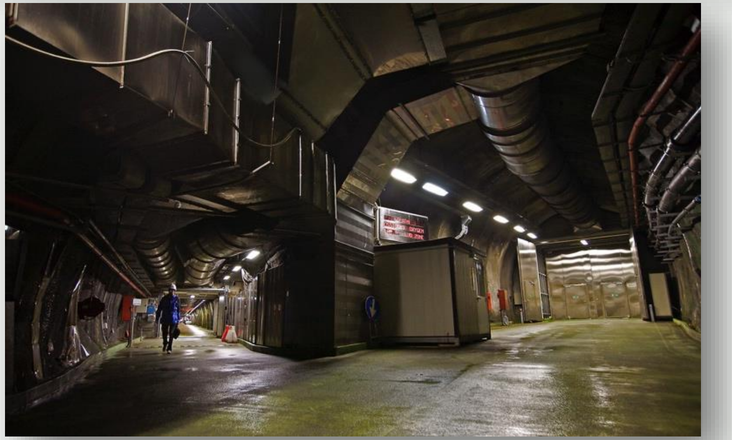


What can accelerators do?

- to demonstrate the existence of some possible DM candidates

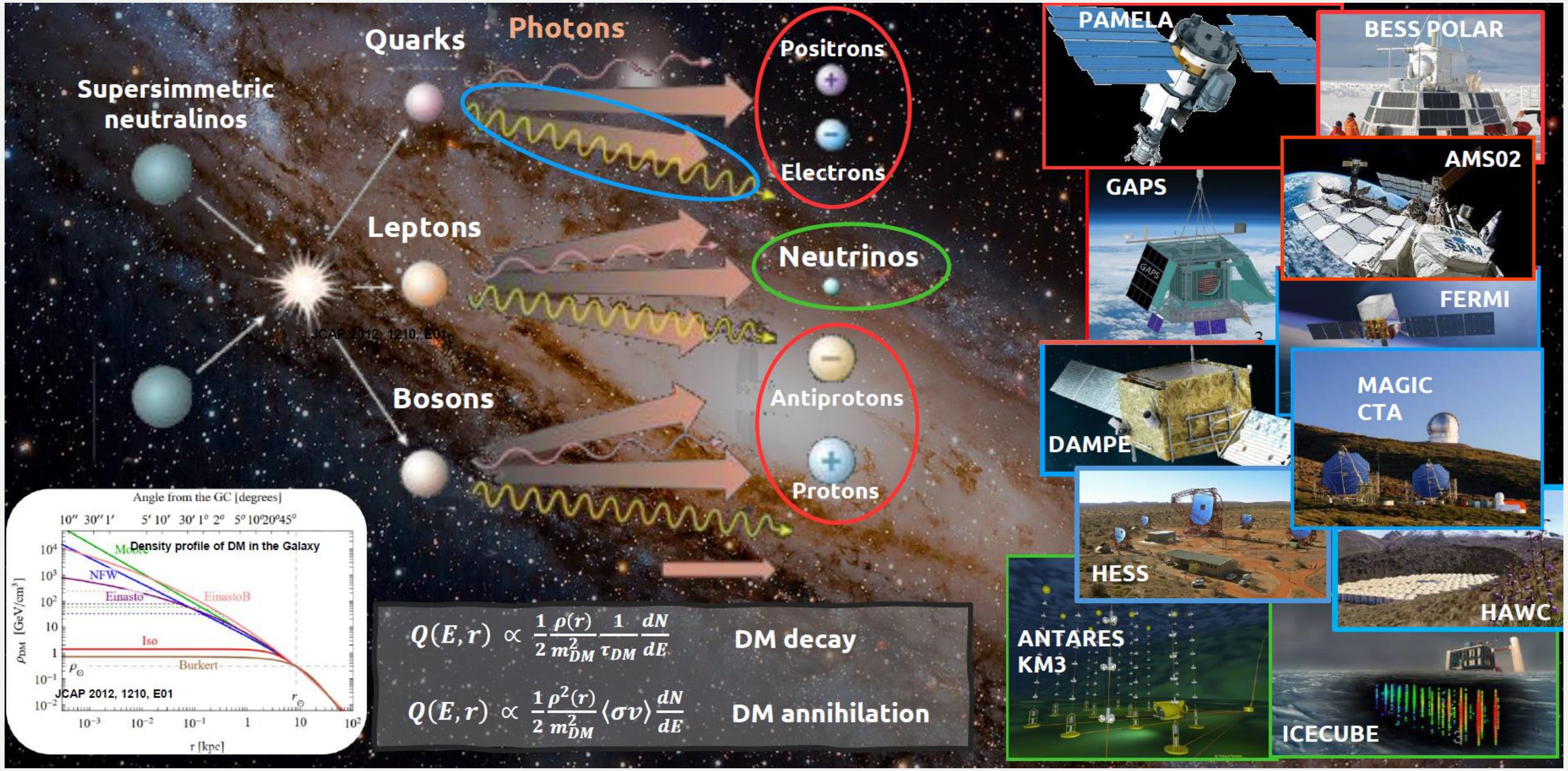
What can accelerators not do?

- to credit that a certain particle is the DM solution or the “single” DM particle solution …
- DM candidates exist (even for neutralino) on which accelerators cannot give any information



Indirect Dark Matter search

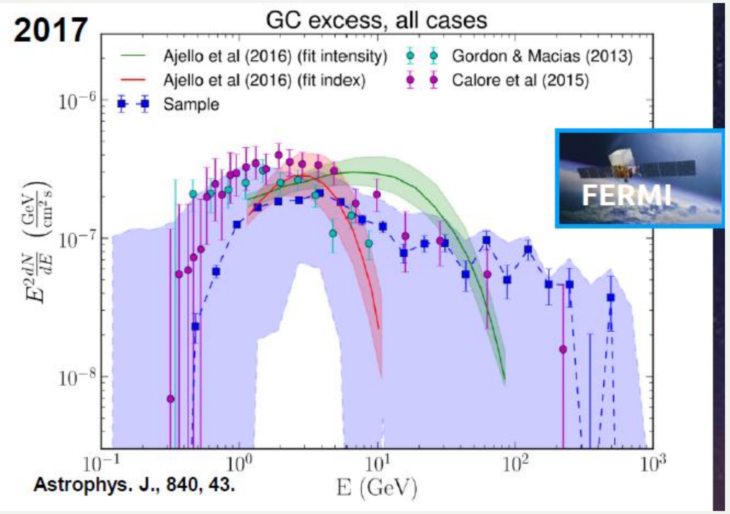
- High-energy neutrinos
- Gamma-rays
- Antimatter in the space (anti-protons, positrons, …)
- Effects of DM on astrophysical objects

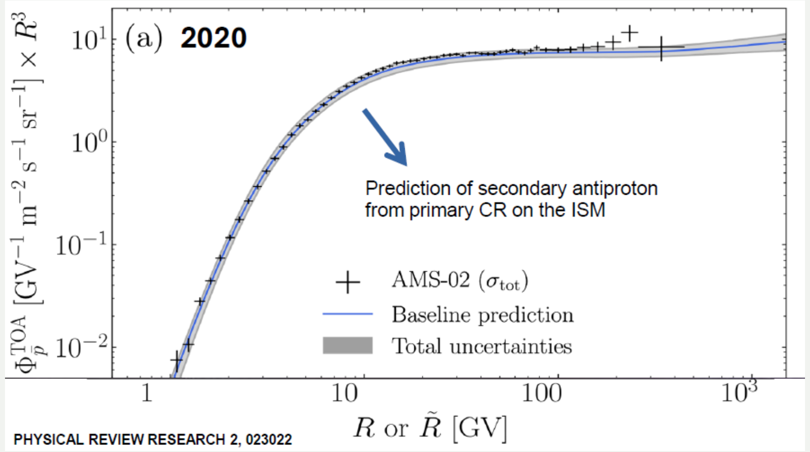


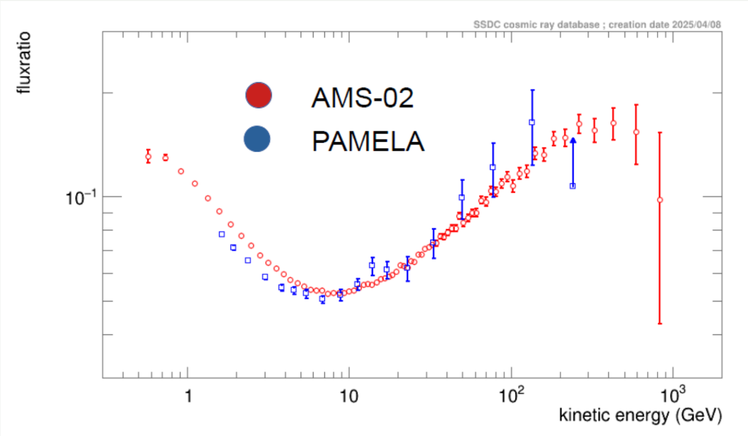
Indirect Dark Matter search

Observed excess:

- Gamma-ray from galactic center
- Positron excess
- Anti-protons (mass 30-100 GeV)



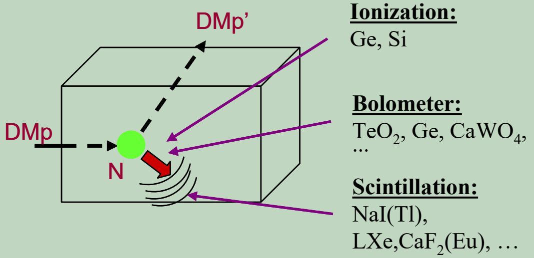




Indirect searches have so far not provided conclusive evidence of Dark Matter and the reported excesses can be interpreted in terms of background from astrophysical sources

DM direct detection processes:

- Scatterings on nuclei
  → detection of nuclear recoil energy (NR)

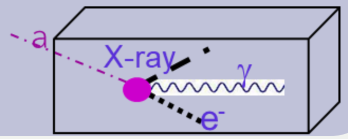


- Inelastic Dark Matter: W + N → W* + N
  → W has 2 mass states χ+ , χ− with δ mass splitting
  → Kinematical constraint for the inelastic scattering of χ− on a nucleus

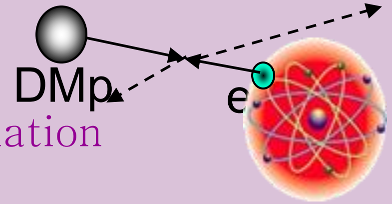
$$\frac{1}{2}\mu v^2 \geq \delta \Leftrightarrow v \geq v_{thr} = \sqrt{\frac{2\delta}{\mu}}$$

- Excitation of bound electrons in scatterings on nuclei (Migdal effect)
  → detection of recoil nuclei + e.m. radiation

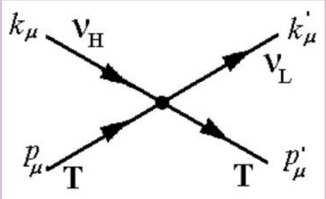
- Conversion of particle into e.m. radiation
  → detection of γ, X-rays, e^-



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



- Interaction of light DMp (LDM) on e^- or nucleus with production of a lighter particle
  → detection of electron/nucleus recoil energy
  e.g. sterile ν



e.g. signals from these candidates are **completely lost** in experiments based on "rejection procedures" of the e.m. component of their rate

… also other ideas …

DM particle–nucleus elastic scattering

Differential energy distribution:

Case of flux of monoenergetic particles: $R = N_B\, n_W\, \sigma\, v$

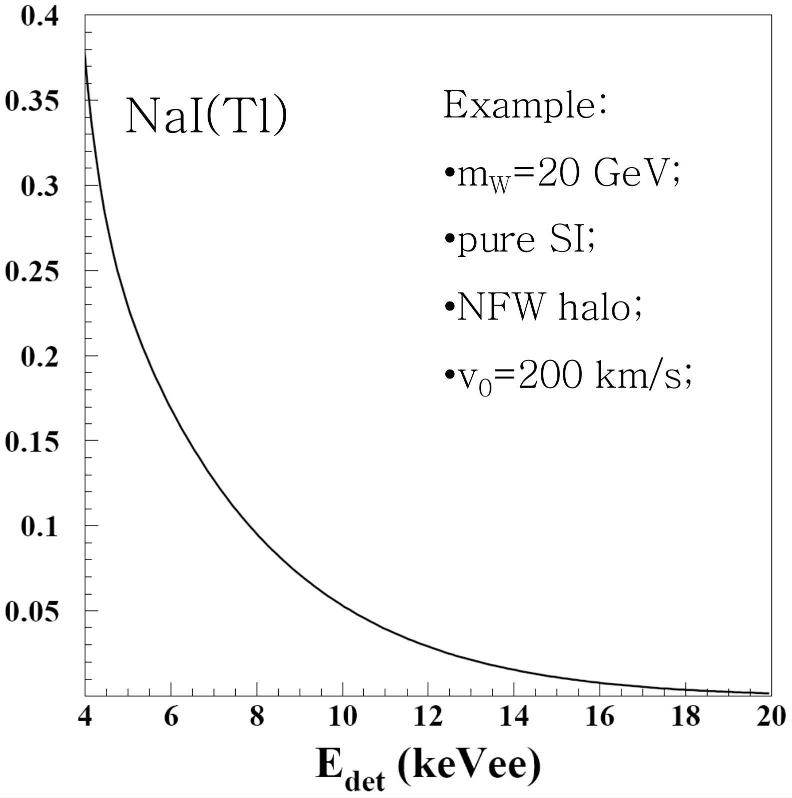
Dark Matter in the galactic halo has a velocity distribution f(v) : $R = N_B\, n_W \int v\, f(v)\, \sigma\, dv$

$$n_W = \frac{\rho_W}{m_W} = \frac{\xi\rho_0}{m_W}$$

ξ is the halo fraction; ρ_0 is the halo density

$$\frac{dR}{dE_R} = N_T \frac{\rho_W}{m_W} \int_{v_{\min}(E_R)}^{v_{\max}} \frac{d\sigma}{dE_R}(v, E_R) v f(v) dv = N_T \frac{\rho_W m_N}{2 m_W m_{Wp}^2} \cdot \Sigma(E_R) \cdot I(E_R)$$

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



$N_{T,B}$: number of target nuclei

f(v): DM particle velocity distribution in the Earth frame (it depends on v_e)

v_{max}: maximal DM particle velocity in the Earth frame

$$v_e = v_{Sun} + v_{orb} \cos \omega t$$

$$I(E_R) = \int_{v_{\min}(E_R)}^{v_{\max}} \frac{f(v)}{v} dv$$

Nuclear Form Factor

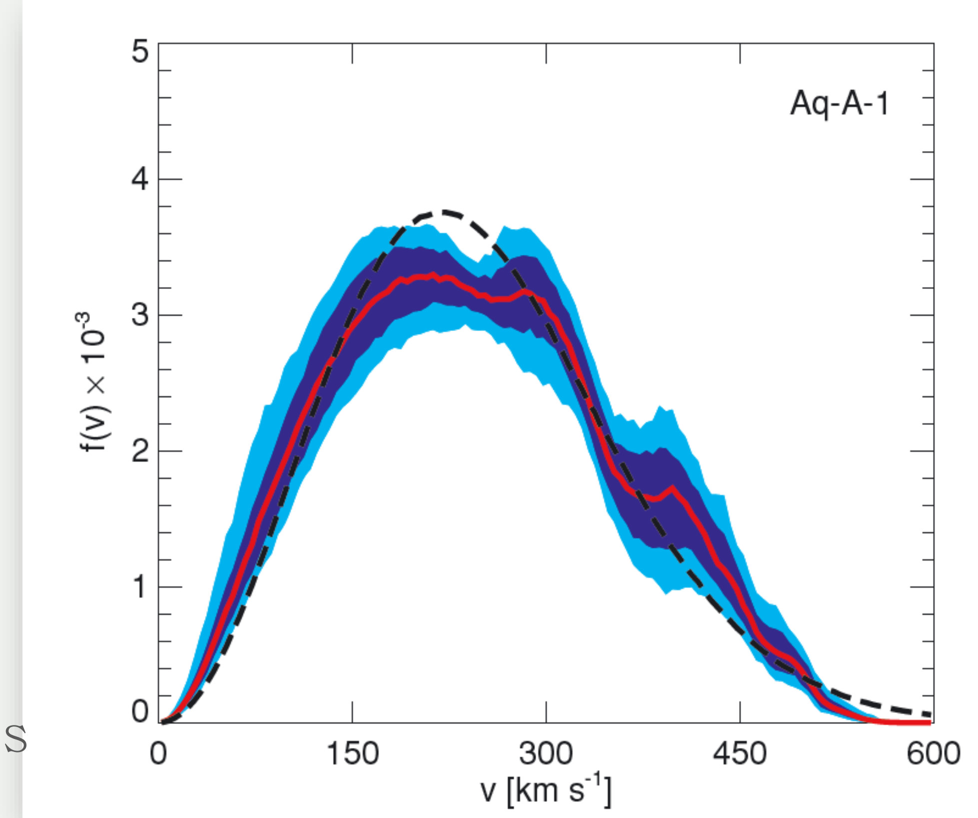
$$\frac{d\sigma}{dE_R}(v, E_R) = \frac{d\sigma}{dE_R}(v, 0) \cdot F^2(E_R)$$

Dark Matter in the Galactic halo

Dark Matter particles form a halo in the Galaxy with velocity of order of 200 km/s

The spatial and velocity distribution of Dark Matter particle in the Galactic halo is an open issue:

- Different halo models (isotropic/anisotropic halo, rotational halo, etc..)
- Maxwellian velocity distribution not satisfactory (from spherical “unphysical” halo)
- DM Multicomponents?
- Possible presence of non thermalized components
- Clumpiness?
- …



Mon. Not. R. Astron. Soc. **395**, 797–811 (2009)

Halo modeling

PHYSICAL REVIEW D 66, 043503 (2002)

- Needed quantities for Dark Matter direct searches:

→ DM local density $\rho_0 = \rho_{DM}(R_0 = 8.5\ \text{kpc})$

→ local velocity $v_0 = v_{rot}(R_0 = 8.5\text{kpc})$

→ velocity distribution

Isothermal sphere: the most widely used model only in the "WIMP" direct search (but not correct)

density profile: $\rho_{DM}(r) \propto r^{-2}$

gravitational potential: $\Psi_0 \propto \log(r^2)$

→ Maxwellian velocity distribution

Spherical ρ_{DM}, isotropic velocity dispersion

Evans' logarithmic

$$\rho_{DM}(r) = \frac{v_0^2}{4\pi G}\frac{3R_c^2 + r^2}{(R_c^2 + r^2)^2} \qquad \Psi_0(r) = -\frac{v_0^2}{2}\log(R_c^2 + r^2) \qquad v_{rot}^2(r) = v_c^2 \frac{r^2}{(R_c^2 + r^2)}$$

Evans' power-law

$$\rho_{DM}(r) = \frac{\beta \Psi_a R_c^\beta}{4\pi G}\frac{3R_c^2 + r^2(1-\beta)}{(R_c^2 + r^2)^{(\beta+4)/2}} \qquad \Psi_0(r) = \frac{\Psi_a R_c^\beta}{(R_c^2 + r^2)^{\beta/2}},\ (\beta \neq 0) \qquad v_{rot}^2(r) = \frac{\beta \Psi_a R_c^\beta r^2}{(R_c^2 + r^2)^{(\beta+2)/2}}$$

Others:

$$\rho_{DM}(r) = \rho_0 \left(\frac{R_0}{r}\right)^\gamma \left[\frac{1 + (R_0/a)^\alpha}{1 + (r/a)^\alpha}\right]^{(\beta-\gamma)/\alpha}$$

If spherical ρ_{DM} with non-isotropic velocity dispersion →

$$\beta_0 = 1 - \frac{\overline{v_\phi^2}}{\overline{v_r^2}}$$

If Axisymmetric ρ_{DM} → *q* flatness

$$\Psi_0(r,z) = -\frac{v_0^2}{2}\log\left(R_c^2 + r^2 + \frac{z^2}{q^2}\right)$$

Triaxial ρ_{DM} → p, q, δ

$$\Psi_0(x,y,z) = -\frac{v_0^2}{2}\log\left(x^2 + \frac{y^2}{p^2} + \frac{z^2}{q^2}\right)$$

δ = free parameter → in spherical limit (p=q=1) quantifies the anisotropy of the velocity dispersion tensor

$$\frac{\overline{v_\phi^2}}{\overline{v_r^2}} = \frac{2+\delta}{2}$$

Constraining the models

$$v_0 = (220 \pm 50)\,km \cdot s^{-1}$$

$$1 \cdot 10^{10} M_\oplus \le M_{vis} \le 6 \cdot 10^{10} M_\oplus$$

$$0.8 \cdot v_0 \le v_{rot}(r = 100kpc) \le 1.2 \cdot v_0$$

Examples of uncertainties in models and scenarios

Nature of the candidate and couplings

- WIMP class particles (neutrino, sneutrino, etc.): SI, SD, mixed SI&SD, preferred inelastic
  + e.m. contribution in the detection
- Light bosonic particles
- Kaluza-Klein particles
- Mirror dark matter
- Heavy Exotic candidate
- …etc. etc.

Halo models & Astrophysical scenario

- Isothermal sphere ⇒ very simple but unphysical halo model
- Many consistent halo models with different density and velocity distribution profiles can be considered with their own specific parameters (see e.g. PRD61(2000)023512)
- Caustic halo model
- Presence of non-thermalized DM particle components
- Streams due e.g. to satellite galaxies of the Milky Way (such as the Sagittarius Dwarf)
- Multi-component DM halo
- Clumpiness at small or large scale
- Solar Wakes
- …etc. …

Instrumental quantities

- Energy resolution
- Efficiencies
- Quenching factors
- Channeling effects
- Their dependence on energy
- …

Scaling laws

of cross sections for the case of recoiling nuclei

- Different scaling laws for different DM particle:

$\sigma_A \propto \mu^2 A^2 (1+\varepsilon_A)$

$\varepsilon_A = 0$ *generally assumed*

$\varepsilon_A \approx \pm 1$ *in some nuclei? even* for neutralino candidate in MSSM (see Prezeau, Kamionkowski, Vogel et al., PRL91(2003)231301)

Form Factors

for the case of recoiling nuclei

- Many different profiles available in literature for each isotope
- Parameters to fix for the considered profiles
- Dependence on particle-nucleus interaction
- In SD form factors: no decoupling between nuclear and Dark Matter particles degrees of freedom + dependence on nuclear potential

Spin Factors for the case of recoiling nuclei

- Calculations in different models give very different values also for the same isotope
- Depend on the nuclear potential models
- Large differences in the measured counting rate can be expected using: either SD not-sensitive isotopes or SD sensitive isotopes depending on the unpaired nucleon (compare e.g. odd spin isotopes of Xe, Te, Ge, Si, W with the ^{23}Na and ^{127}I cases).

Quenching Factor

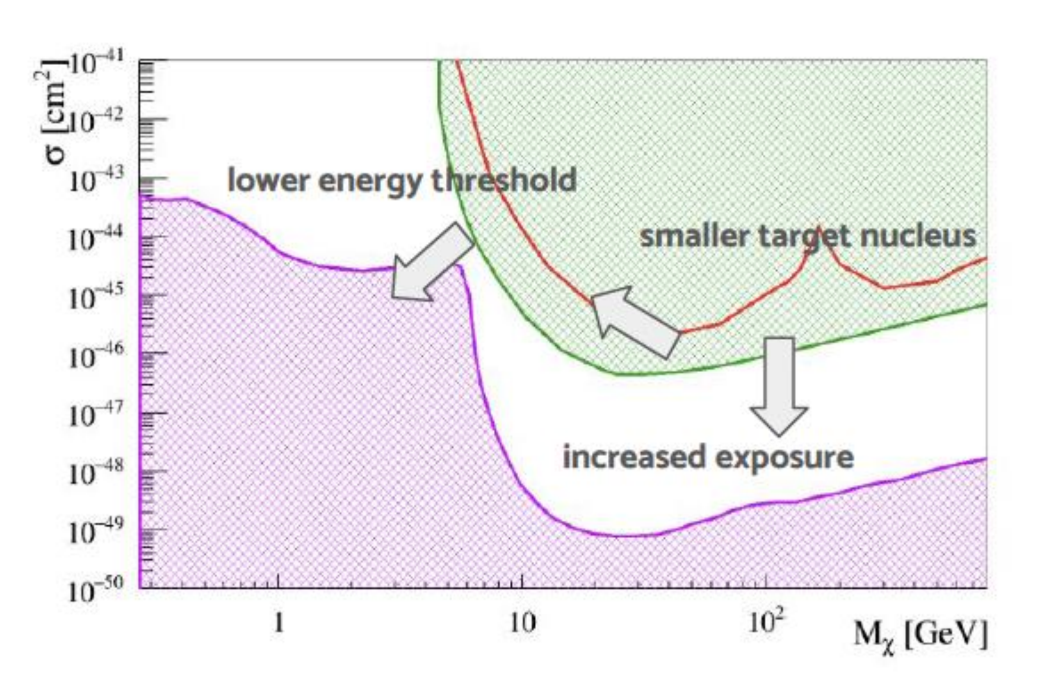
- differences are present in different experimental determinations of *q* for the same nuclei in the same kind of detector depending on its specific features (e.g. *q* depends on dopant and on the impurities; in liquid noble gas e.g.on trace impurities, on presence of degassing/releasing materials, on thermodynamical conditions, on possibly applied electric field, etc); assumed 1 in bolometers
- channeling effects possible increase at low energy in scintillators (dL/dx)
- possible larger values of *q* (AstropPhys33(2010) 40)

→ energy dependence

Model-dependent approach for DM search

- searching for excess produced by nuclear recoils events (NR)
- use of discriminating variables to disantagle between NR and electron/gamma background (ER)
- excluding cross section (σ) and masses (M_W) regions giving a counting rate larger than measured
- many assumptions required for the calculations (see previous slides)

→ **no signal identification**



Even very small systematics in the data selections and statistical discrimination and rejection procedures can be difficult to estimate;

e.m. component of the rate can contain the signal or part of it

Even assuming pure recoil case and ideal discrimination on an event-by-event base, the result will NOT be the identification of the presence of WIMP elastic scatterings as DM signal, because of the well known existing recoil-like indistinguishable background

Model-independent approach for DM search

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

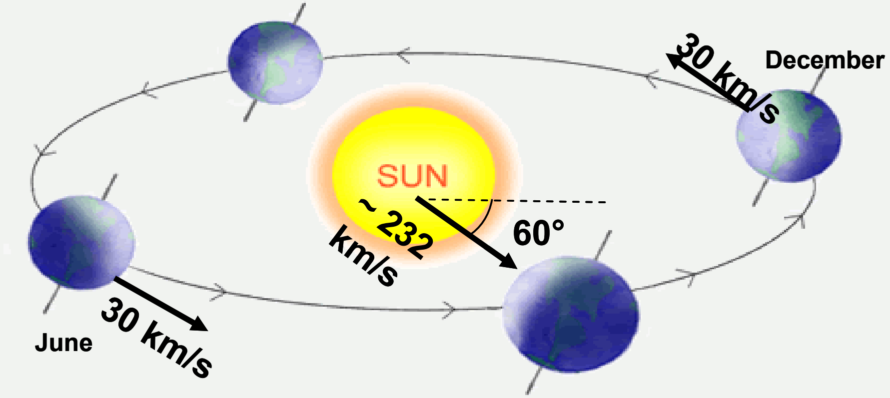
very hard to realize

Diurnal modulation Daily variation of the interaction rate due to different Earth depth crossed by the Dark Matter particles

only for high σ

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

at present the only feasible one, sensitive to many DM candidates and scenarios



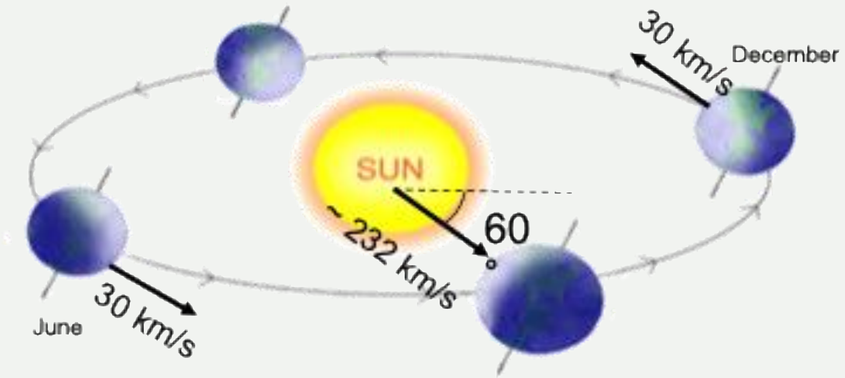
The annual modulation

With the present technology, the annual modulation is the main model independent signature for the DM signal. Although the modulation effect is expected to be relatively small a suitable large-mass, low-radioactive set-up with an efficient control of the running conditions can point out its presence.

Requirements of the annual modulation

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

Drukier, Freese, Spergel PRD86; Freese et al. PRD88



- v_{sun} ~ 232 km/s (Sun vel in the halo)
- v_{orb} = 30 km/s (Earth vel around the Sun)
- $\gamma = \pi/3$, $\omega = 2\pi/T$, T = 1 year
- $t_0 = 2^{nd}$ June (when $v_\oplus$ is maximum)

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

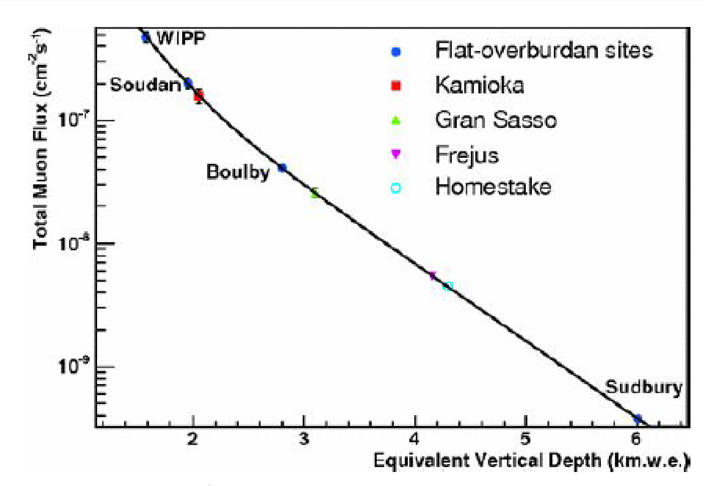
$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \cong S_{0,k} + S_{m,k} \cos[\omega(t-t_0)]$$

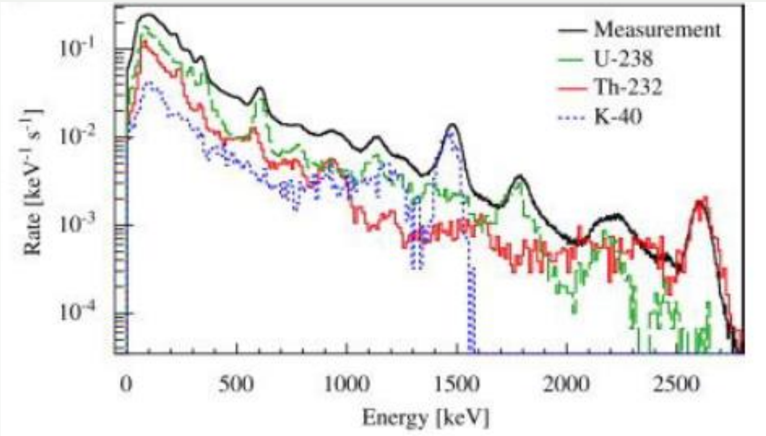
the DM annual modulation signature has a different origin and peculiarities (e.g. the phase) than those effects correlated with the seasons

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

Background for Dark Matter search

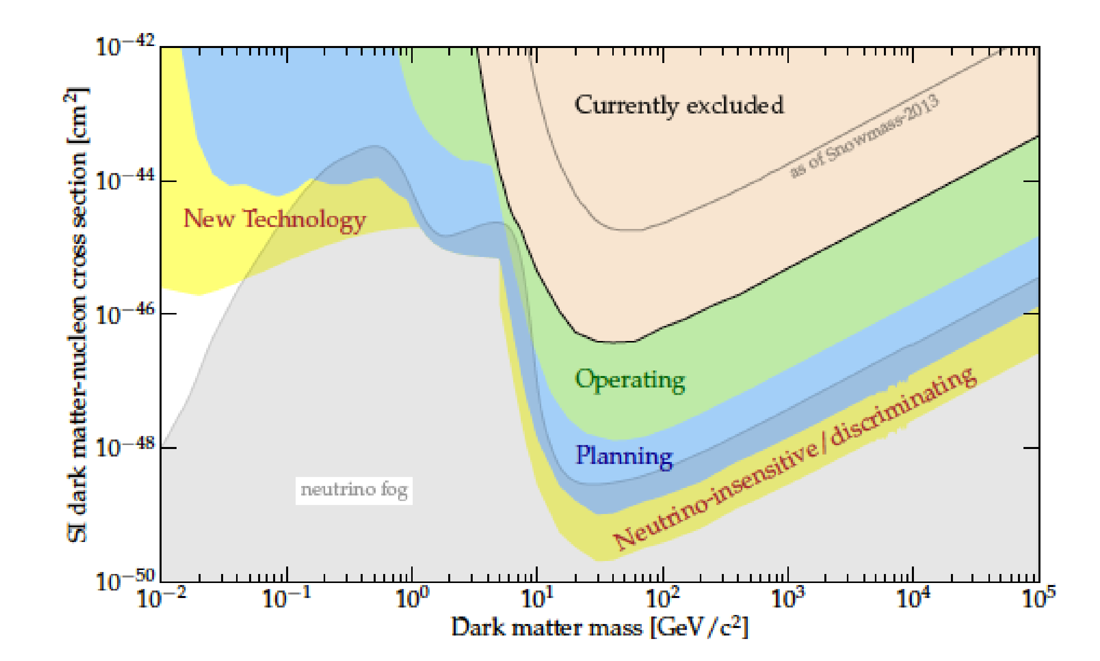
- Cosmic particles hitting the laboratory (muons)
- Natural radioactivity in the experimental environment (gamma, neutrons, …)
- Radioactive isotopes present in trace close to the detector (U, Th and K radioactive chains, Radon,…)
- Radioactive isotopes in trace in the target material
- Cosmogenic activation





Neutrino floor (fog)

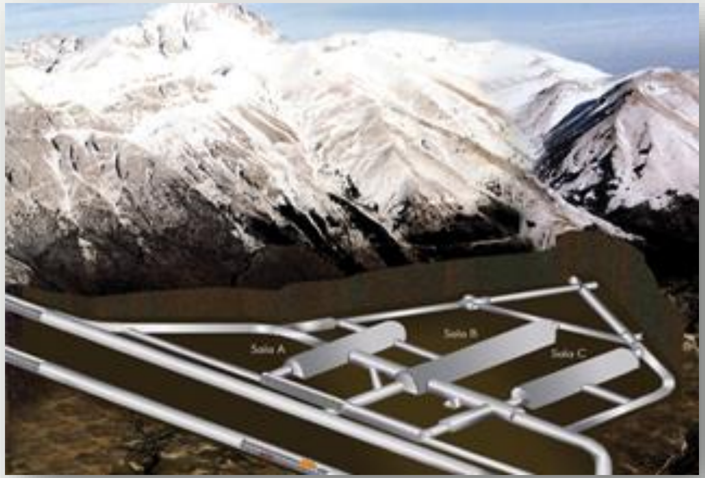
- Coherent scattering of neutrinos off target nuclei (CEvNS) produce NRs indistinguishable from WIMPs
- Sources: solar neutrino, atmospheric neutrinos, diffuse supernovae neutrinos
- Ultimate background for direct WIMP searches

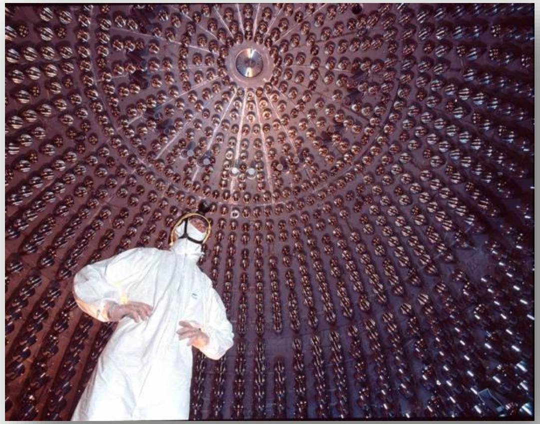


Strategies for Direct Dark Matter Search

DM is weakly interacting → Extremely low counting rate experiments:

- Underground laboratory
- High radiopurity target detectors, materials and surrounding environment
- Background suppression with passive and active shields
- Discrimination techniques and methods
- Signature (model-independent if possible)

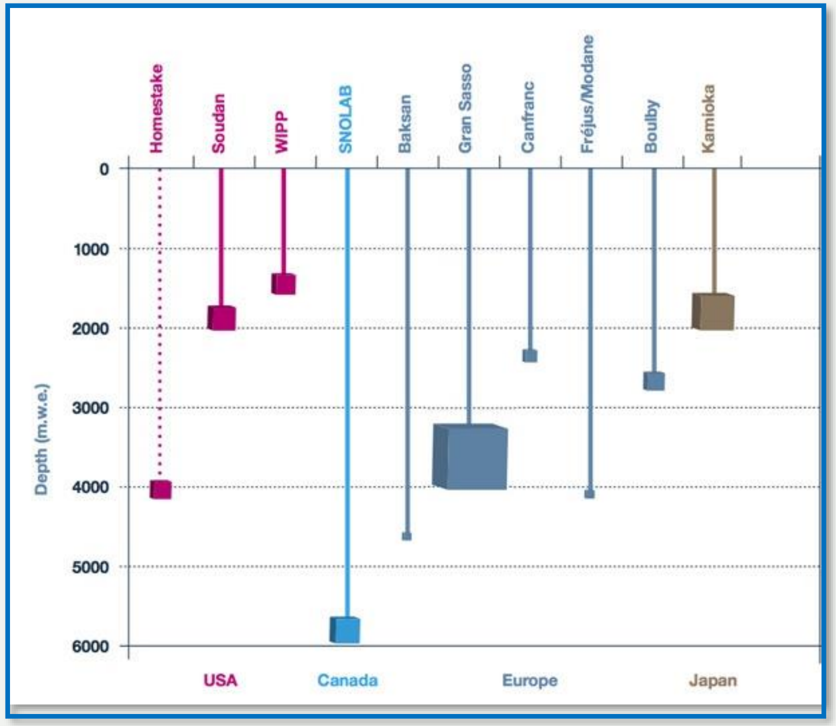




Underground Laboratories

LNGS:

- muons → 0.6 m/(m^{2}h)
- gamma → 0.5 gamma/(cm^{2}s)
- neutrons → $1.08\cdot10^{-6}$ n/(cm^{2}s) thermal
  $1.98\cdot10^{-6}$ n/(cm^{2}s) epithermal
  $0.09\cdot10^{-6}$ n/(cm^{2}s) fast (>2.5 MeV)
- Radon in the hall → ≈30 Bq/m^3



Reduction is not enough and experiments need additional passive and active shielding

Material selection and radiopurity

Radioactive assay with different technique (ICP-MS, HPGe,AA,…)

Supporting facilities to improve cleaness (protocolos to enter lab, clean room for assemblying procedures, radon removal system,…)

Example of low background Lead selection

Measurement of lead with GeMPI

lead sample	weight	time	specific activity [μBq/kg]				
	[kg]	[d]	^{226}Ra	^{228}Th	^{40}K	^{207}Bi	^{210}Pb
DowRun	144.6	101.7	< 29	< 22	440 ± 140	98 ± 24	$(2.7 \pm 0.4) \times 10^7$
Boliden	144.3	75.0	< 46	< 31	460 ± 170	< 13	$(2.3 \pm 0.4) \times 10^7$
roman	22.1	37.2	< 45	< 72	< 270	< 19	$< 1.3 \times 10^6$
	bolometric measurement: Allesandrello et al. NIM B142 (1998) 163						$< 4 \times 10^3$

The knowledge of radioactive contamination of the material of the set-up is an important information for experiment background model being a fundamental ingredient for Monte Carlo simulation

Shielding from background

Passive shield:

- high Z material to suppress gamma bg component
- polyethylene/paraffine + Cd for neutrons
- water (large volume)
- radon removal system (Nitrogen atmosphere for the set-up, radon removal system for liquid or gas detector)

Active shield:

- using a detector system to discriminate and reject bg events
- outer detector to shield
- segmented set-up
- anticoincidence techniques

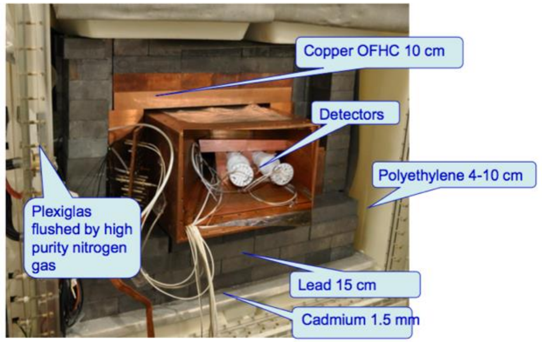
Fiducialization:

- using a fiducial volume of the detector

Discrimination:

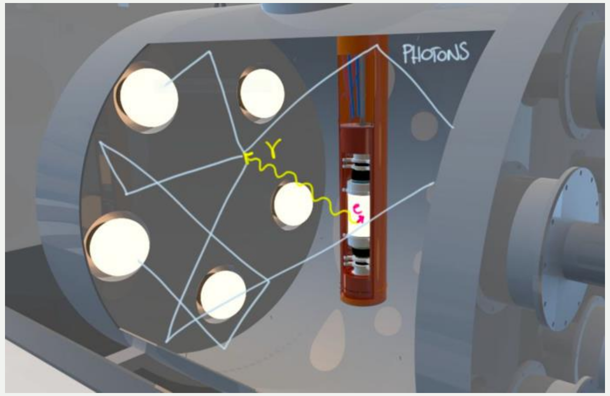
- Nuclear recoil vs Electron recoils with different techniques
- PSD

DAMA R&D passive shield

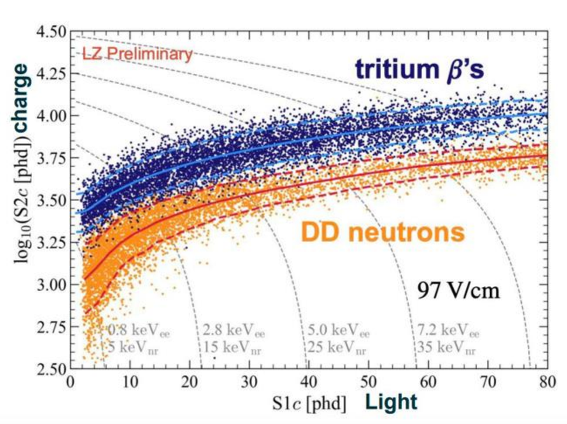


Passive shield typically is made of a few layers to shield against gamma and neutrons, sealing from radon, and to minimize cost

SABRE PoP LS active veto



LZ discrimination plot



Direct Dark Matter Detection

- **Search for DM particles with liquid noble gas**: DARK SIDE, XENON, PANDA-X, LZ, DEAP
- **DM particles search with low threshold detectors**: CRESST, CDMS, Edelweiss, Tesseract, DAMIC, SENSEI, …
- **Investigation DM with the Annual Modulation using NaI(Tl) crystal scintillators** : DAMA, SABRE, COSINUS, COSINE, ANAIS
- **Directionality**: CYGNO, MIMAC, $ZnWO_4$
- **Other techniques**: PICO (Bubble chamber), Supercooled Liquid
- **Axion, ALPs**: e.g. QUAX, ADMX, HAYSTAC, ORGAN, CULTASK, KLASH

Table of DM past/present/future activities from Snowmass 2021

Name	Detector	Target	Active Mass	Location of Experiment	Status	Start_Ops	End_Ops
XMASS	Scintillator	LXe	832 kg	Kamioke	Ended	2010	2019
XENON10	TPC	LXe	62 kg	LNGS	Ended	2006	2008
XENON100	TPC	LXe	62 kg	LNGS	Ended	2012	2016
XENON1T	TPC	LXe	"1,995 kg"	LNGS	Ended	2017	2019
XENON1T (Ionization)	TPC Ioniz.-only	LXe	"1,995 kg"	LNGS	Ended	2017	2019
XENONnT	TPC	LXe	"7,000 kg"	LNGS	Construction/Run	2021	2025
LUX	TPC	LXe	250 kg	SURF	Ended	2013	2016
LUX (Ionization)	TPC Ioniz.-only	LXe	250 kg	SURF	Ended	2017	2019
LZ	TPC	LXe	"8,000 kg"	SURF	Construction/Run	2021	2025
PandaX-II	TPC	LXe	580 kg	CJPL	Ended	2016	2018
PandaX-4T	TPC	LXe	"4,000 kg"	CJPL	Running	2021	2025
LZ HydroX	TPC	LXe+H2	"8,000 kg"	SURF	R&D	2026	
Darwin / US G3	TPC	LXe	"50,000 kg"	LNGS/SURF/Boulby	Planning	2028	2033
DEAP-1	Scintilator	LAr			Ended	2007	2011
DEAP-3600	Scintillator	LAr	"3,300 kg"	SNOLAB	Running	2016	202X
DarkSide-50	TPC	LAr	46 kg	LNGS	Ended	2013	2019
Darkside-LM (Ionization)	TPC Ioniz.-only	LAr	46 kg	LNGS	Ended	2018	2019
Darkside-20k	TPC	LAr	30 t	LNGS	Planning/Construct	2025	2030
ARGO	TPC or Scintillator	LAr	300 t	SNOLAB	Planning	2030	2035
GADMC	TPC	LAr			Planning	2030	
DAMA/LIBRA	Scintillator	NaI	250 kg	LNGS	Running	2003	
ANAIS-112	Scintillator	NaI	112 kg	Canfranc	Running	2017	2022
COSINE-100	Scintillator	NaI	106 kg	YangYang	Running	2016	2021
COSINE-200	Scintillator	NaI	200 kg	YangYang	Construction	2022	2025
COSINE-200 South Pole	Scintillator	NaI	200 kg	South Pole	Planning	2023	?
COSINUS	Bolometer Scintillator	NaI	?	LNGS	Planning	2023	?
SABRE PoP	Scintillator	NaI	5 kg	LNGS	Construction	2021	2022
SABRE (North)	Scintillator	NaI	50 kg	LNGS	Planning	2022	2027
SABRE (South)	Scintillator	NaI	50 kg	SUPL	Planning	2022	2027
CDEX-10	Ionization (77K)	Ge	10 kg	CJPL	Running	2016	?
CDEX-100 / 1T	Ionization (77K)	Ge	100-1000 kg	CJPL	Planning	202X	
SuperCDMS	Cryo Ionization	Ge	9 kg	Soudan	Ended	2011	2015
CDMSLite (High Field)	Cryo Ionization	Ge	1.4 kg	Soudan	Ended	2012	2015
CDMSLite (High Field)	Cryo Ionization	Ge	1.4 kg	Soudan	Ended	2012	2015
CDMS-HVeV Si	Cryo Ionization HV	Si	0.9 g	Surface Lab	Ended	2018	2018
SuperCDMS CUTE	Cryo Ionization / HV	Ge/Si	5 kg/1 kg	SNOLAB	Running	2020	2022
SuperCDMS SNOLAB	Cryo Ionization / HV	Ge/Si	11 kg/3 kg	SNOLAB	Construction	2023	2028
EDELWEISS III	Cryo Ionization	Ge	20 kg	LSM	Ended	2015	2018
EDELWEISS III (High Field)	Cryo Ionization HV	Ge	33 g	LSM	Running	2019	
CRESST-II	Bolometer Scintillation	CaWO4	5 kg	LNGS	Ended	2012	2015
CRESST-III	Bolometer Scintillation	CaWO4	240 g	LNGS	Ended	2016	2018
CRESST-III (HW Tests)	Bolometer Scintillation	CaWO4		LNGS	Running	2020	
COUPP	Bubble Chamber	CF3I	4 kg	SNOLAB / Fermilab	Ended	2011	2012
PICASSO	Superheated Droplet	C4F10	3 kg	SNOLAB	Ended		2017
PICO-2	Bubble Chamber	C3F8	2 kg	SNOLAB	Ended	2013	2015
PICO-40	Bubble Chamber	C3F8	35 kg	SNOLAB	Running	2020	
PICO-60	Bubble Chamber	"CF3I,C3F8"	52 kg	SNOLAB	Ended	2013	2017
PICO-500	Bubble Chamber	C3F8	430 kg	SNOLAB	Construction/Run	2021	
DRIFT-II	Gas Directional	CF_4	0.14 kg	Boulby	Ended		
NEWAGE-03b'	Gas Directional	CF4	14 g	Kamioka	Running	2013	2023
MIMAC	Gas Directional	$CF_4+CHF_3+C_4H_{10}$		LSM (Modane)	Running	2012	
CYGNO	Gas Directional	$He + CF_4$	0.5 - 1 kg	LNGS	Planning	2024	
CYGNUS	Gas Directional	$He + SF_6/CF_4$		Multiple sites	Planning		
NEWS-G	Gas Drift	CH4		LSM	Ended	2017	2019
NEWS-G	Gas Drift	CH4		SNOLAB	Construction/Run	2020	2025
DAMIC	CCD	Si	2.9 g	SNOLAB	Ended	2015	2015
DAMIC	CCD	Si	40 g Si	SNOLAB	Ended	2017	2019
DAMIC100	CCD	Si	100 g Si	SNOLAB	Not Built		
DAMIC-M	CCD Skipper	Si	1 kg Si	LSM	Construction/Run	2021	2024
SENSEI	CCD Skipper	Si	2 g Si	Fermilab u/g	Running	2019	2020
SENSEI	CCD Skipper	Si	100 g Si	SNOLAB	Construction/Run	2021	2023
Oscura	CCD Skipper	Si	10 kg Si	SNOLAB	Planning	2024	2028
SNOWBALL	Supercooled Liquid	H2O			Planning		
ALETHEIA	TPC	He		China Inst. At. Energy	R&D		
TESSERACT	Cryo TES	He		LBNL	R&D		

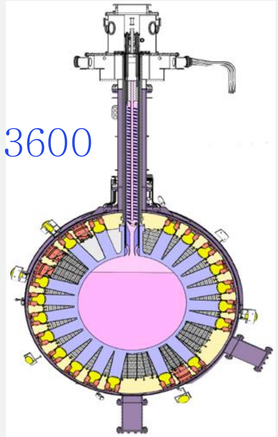
arXiv:2203.08084

Liquid Noble Gases Experiments

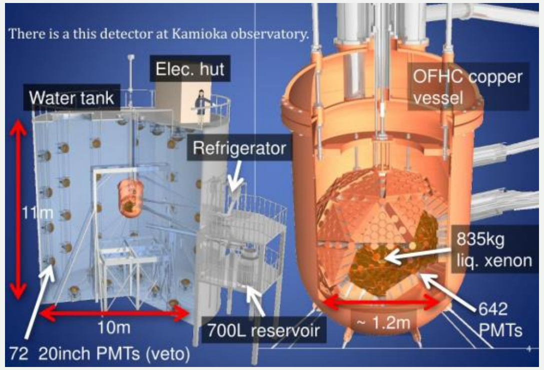
Single phase (XMASS, DAMA/LXe, DEAP-3600, miniCLEAN):

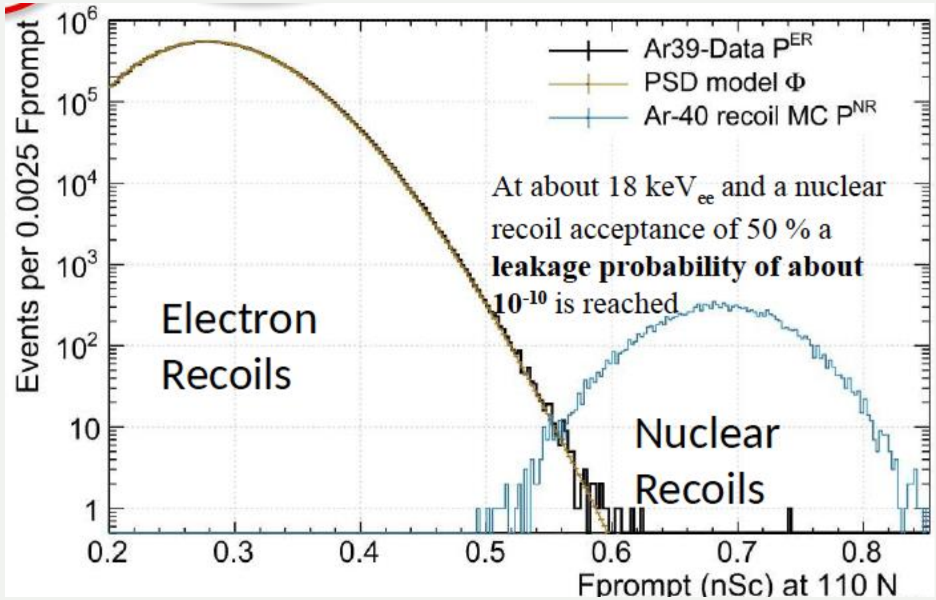
- LXe, LAr, LNe scintillation, ionization
- pulse shape discrimination γ/recoils from the UV scintillation photons

DEAP-3600



XMASS





DEAR-3600: Eur. Phys. J. C 81,823 (2021)

Statistical rejection of background component of the counting rate

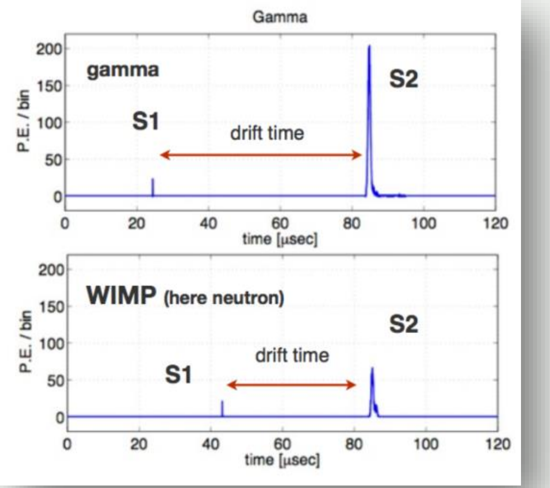
Some issues:

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

Liquid Noble Gases Experiments

Dual phase liquid /gas (TPC) (XENON10, -100, -1T, -nT, LUX, LZ, PANDAX, DarkSide-50, -2K):

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

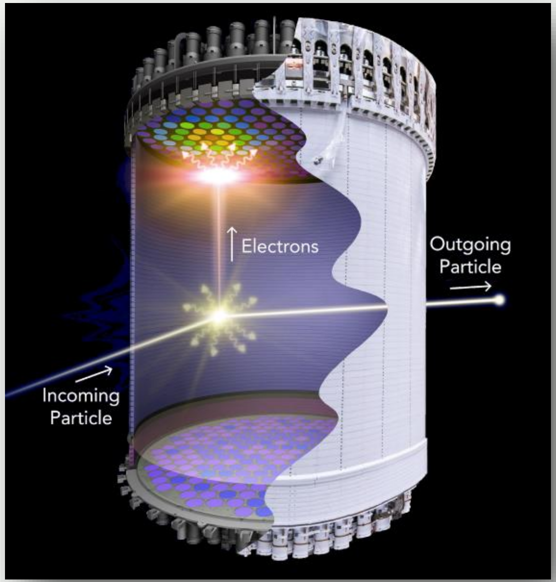


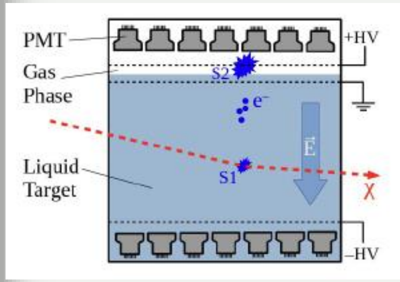
$(S2/S1)_{WIMP} << (S2/S1)_{\gamma}$

3D reconstruction:

(x,y) ⇒ hit pattern of S2

(z) ⇒ drift time





Some issues:

- **Non-uniform** response of detector: intrinsic limit
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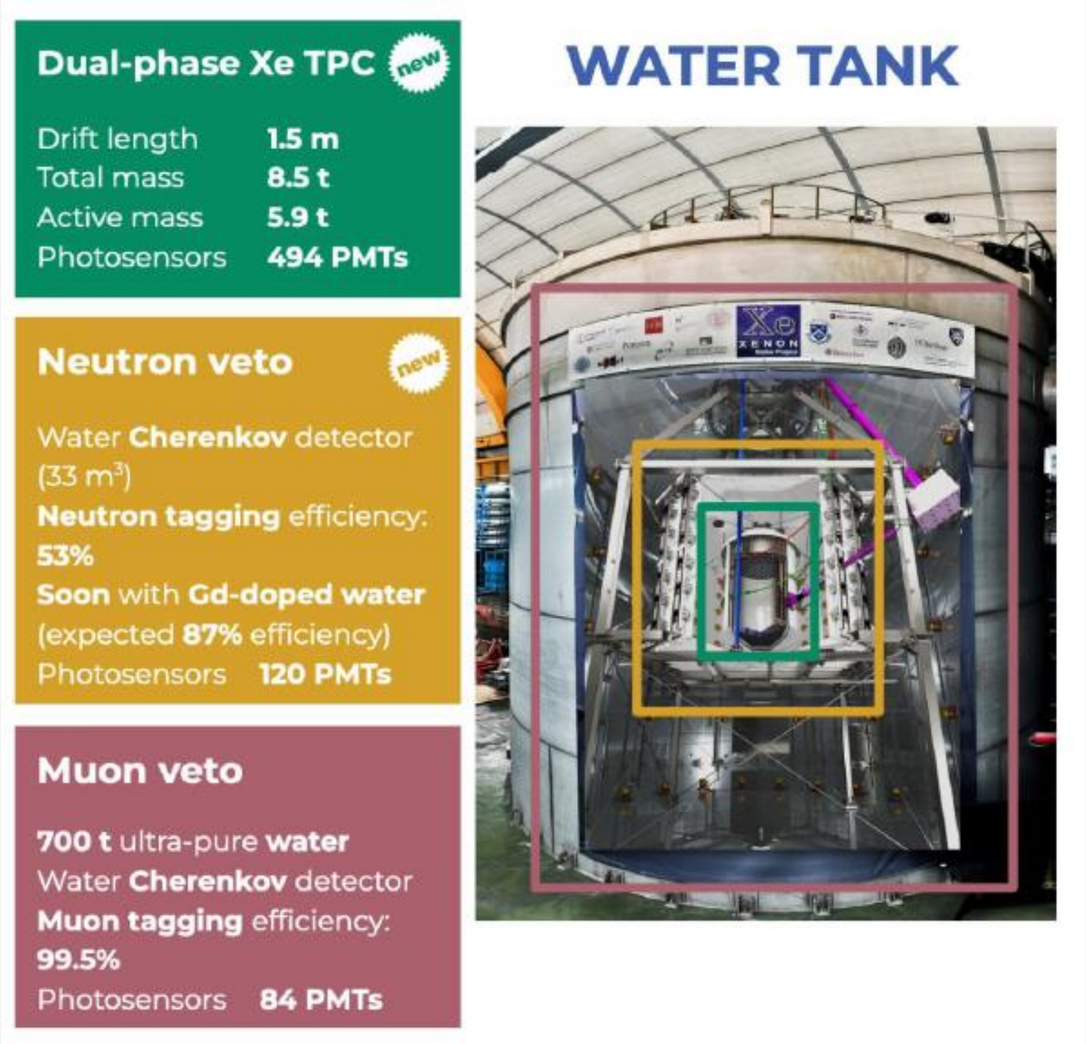
- **Correction** procedures applied (**systematics**)
- Poor energy **resolution**
- **Light responses** for electrons and recoils at low energy
- **Quenching factors** measured with a much-more-performing detector **cannot be used** straightforward

Statistical rejection of background component of the counting rate

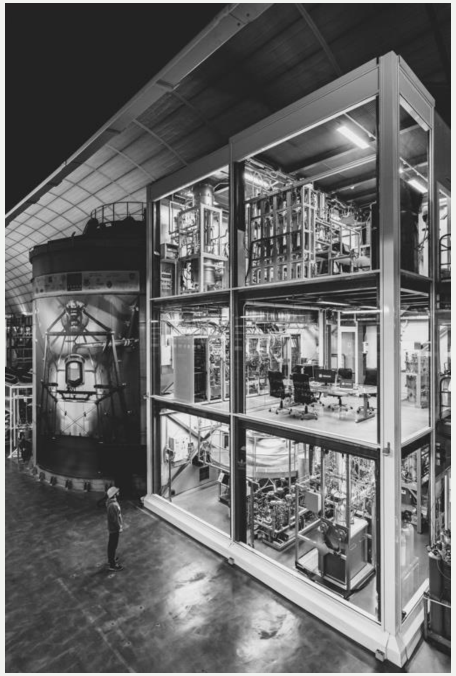
XENONnT Experiment at LNGS

Set-up:

- upgrade of XENON1T
- Stainless-Steel Cryostat with 8.5 t of LXe (5.9 t active mass)
- 700 t water Cherenkov muon veto tank
- 4m × 3m water (Gd in near future) Cherenkov detector as neutron veto enclosing the TPC, tagging neutrons through their capture on H (2.22 MeV ɣ-ray emitted), ~68% efficiency
- new materials and high-flow radon removal
- number of PMTs 494, light detection efficiency 36%



XENONnT Experiment at LNGS



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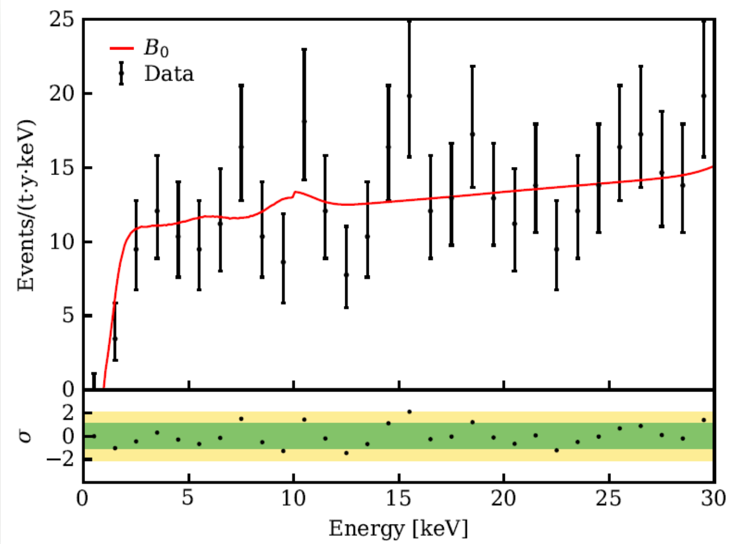
- new materials and high-flow radon removal
- number of PMTs 494, light detection efficiency 36%

Electron Recoil Spectrum:

- fiducial mass 4.37 ton
- Exposure: 1.16 ton × yr
- Rate: 15.8±1.3 ev/ton/yr/keV
- ROI; (3.1-60.0) keV
- No excess of event observed
- Bacground dominated by 2beta decay of ^{136}Xe and ^{214}Pb



- No significant excess above the background
- Very stringent limits on:
  - Solar Axions
  - Neutrino magnetic moment
  - ALPs DM
  - Dark Photon

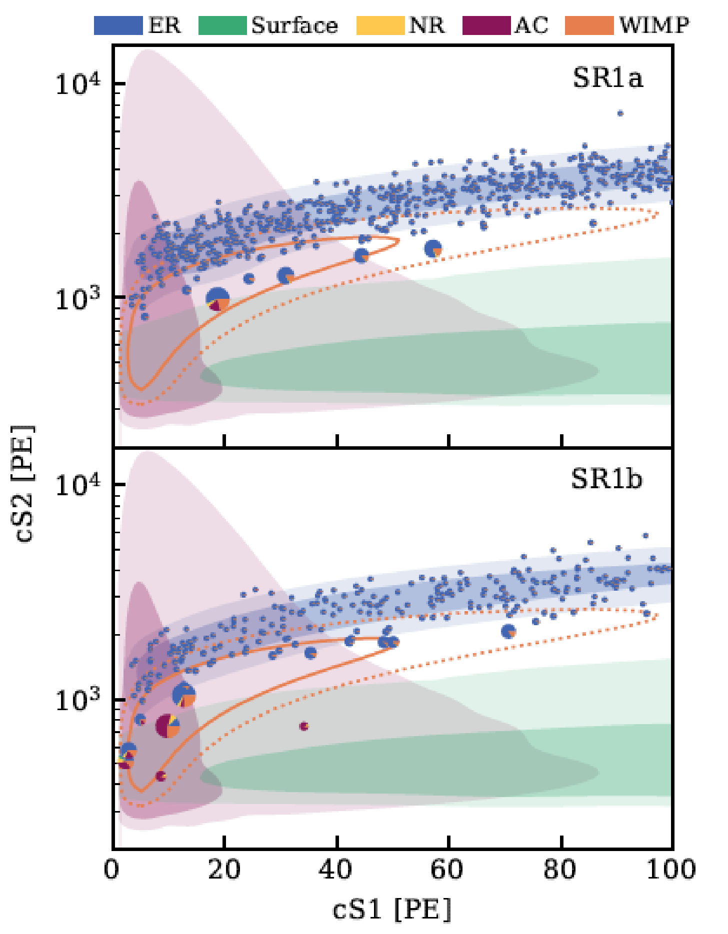
PRL 129, 161805 (2022)

Results from XENONnT

WIMP search (SI coupling):

- Exposure: 3.1 ton × yr
- ROI: (3.8–60.0) keV
- No excess of event observed
- $\sigma_n < 1.7\ 10^{-47}\ cm^2$ for 30 GeV mass (90% C.L.)

	SR0		SR1a		SR1b	
	Nominal	Best fit	Nominal	Best fit	Nominal	Best fit
ER (flat)	134	136 ± 12	430 ± 30	450 ± 20	151 ± 11	154 ± 10
ER (^{3}H-like)	–	–	62	40 ± 30	101	80^{+18}_{-17}
ER (^{37}Ar)	–	–	58 ± 6	55 ± 5	–	–
Neutron	0.7 ± 0.3	0.6 ± 0.3	0.47 ± 0.19	0.45 ± 0.19	0.7 ± 0.3	0.7 ± 0.3
CEνNS (solar)	0.16 ± 0.05	0.16 ± 0.05	0.010 ± 0.003	0.010 ± 0.003	0.019 ± 0.006	0.019 ± 0.006
CEνNS (atm.+DSNB)	0.04 ± 0.02	0.04 ± 0.02	0.024 ± 0.012	0.024 ± 0.012	0.05 ± 0.02	0.05 ± 0.02
AC	4.3 ± 0.9	$4.4^{+0.9}_{-0.8}$	2.12 ± 0.18	2.10 ± 0.18	3.8 ± 0.3	3.8 ± 0.3
Surface	13 ± 3	11 ± 2	0.43 ± 0.05	0.42 ± 0.05	0.77 ± 0.09	0.76 ± 0.09
Total background	152	152 ± 12	553	550 ± 20	257	239 ± 15
WIMP (200 GeV/c^2)	–	1.8	–	1.1	–	2.1
Observed	152		560		245	



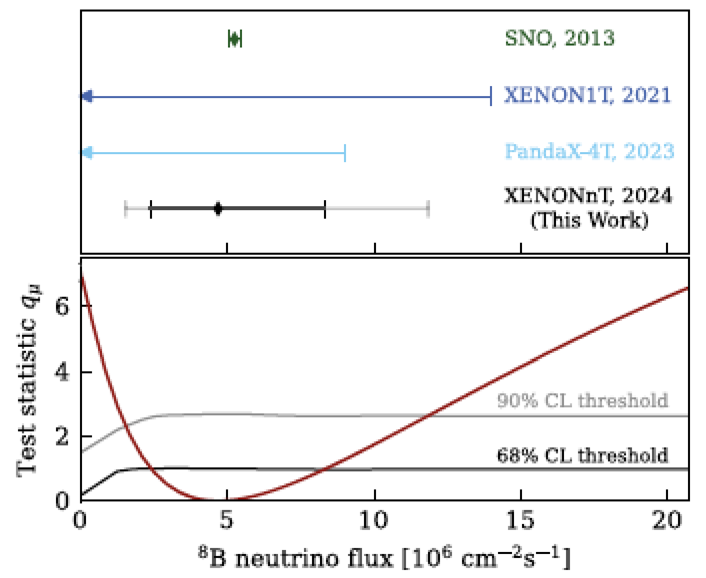
No excess of events observed wrt the estimated background

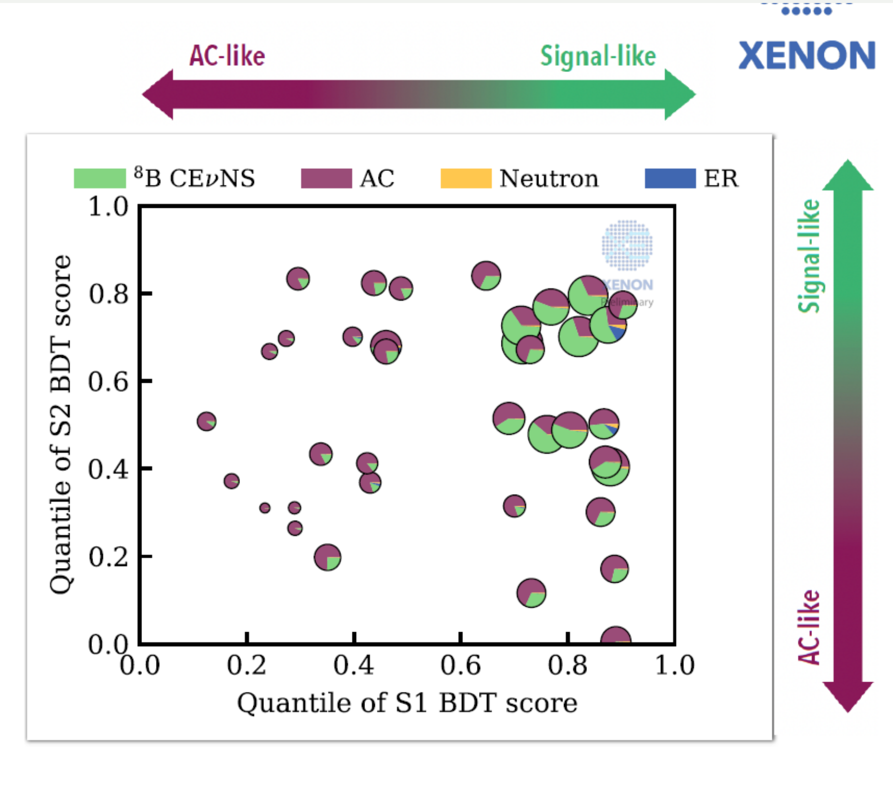
arXiv:2502.18005

Results from XENONnT

Solar ^{8}B neutrino:

- Exposure: 3.1 ton × yr
- ROI: (3.8–60.0) keV
- No excess of event observed
- First indication of solar ^{8}B neutrino detection (CEvNS) PRL133(2024)191002



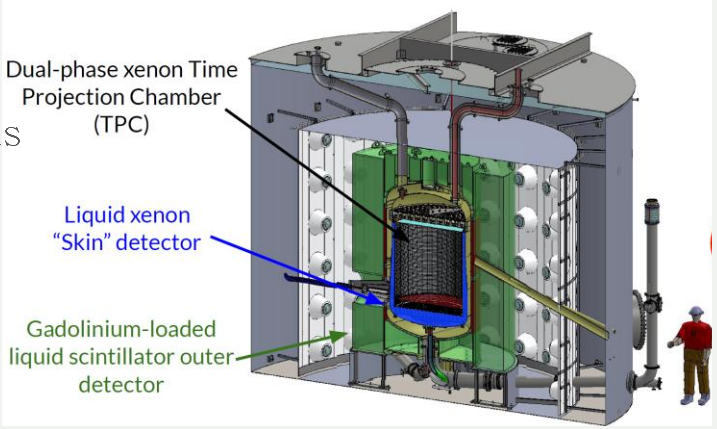


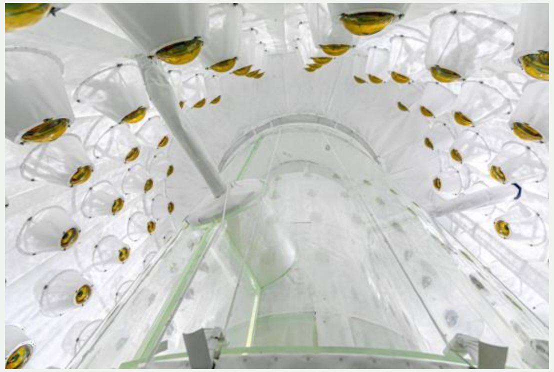
From TAUP 2025:
Expected background: 26.4 ± 1.5
Expected signal: ± 12 3
Oserved: 37

LZ Experiment at SURF (South Dakota, 4300 m.w.e.)

Set-up:

- 10 t of LXe (7 t active mass)
- 2 t LXe “skin detector“ for anticoincidence γ
- 17 t Gd-loaded liquid scintillator in acrylic vessels as anti-coincidence det. for ɣ & n
- ext shield tank filled by 238 t ultra-pure water
- data until 2028





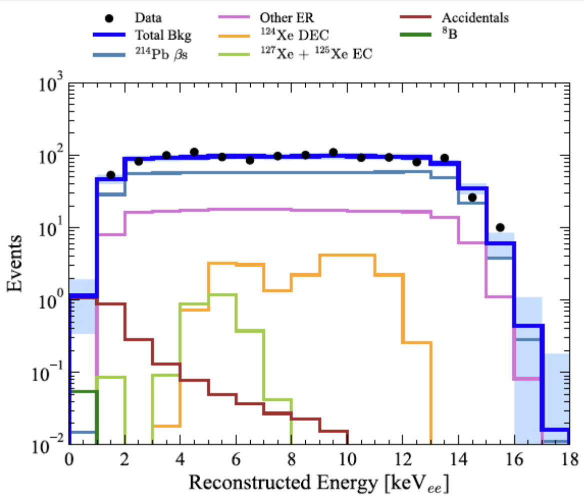
First WIMP search (SI coupling):

- Exposure: 3.3 t × yr
- Rate ER: 276 ev/ton/yr/keV
- ROI; (3.1-60.0) keV
- 1220 events survive cuts
- σ_n<5.1 10^{-48} cm^2 for 40 GeV mass (90% C.L.)

Component	Expected Events	Best Fit Events
^{214}Pb β decays	743 ± 88	733 ± 34
^{85}Kr + ^{39}Ar +detector γs	162 ± 22	161 ± 21
Solar ν ERs	102 ± 6	102 ± 6
^{212}Pb + ^{218}Po β decays	62.7 ± 7.5	63.7 ± 7.4
^{3}H + ^{14}C β decays	58.3 ± 3.3	59.7 ± 3.3
^{136}Xe 2νββ decay	55.6 ± 8.3	55.9 ± 8.2
^{124}Xe DEC	19.4 ± 2.5	20.4 ± 2.4
^{127}Xe + ^{125}Xe EC	3.2 ± 0.6	2.7 ± 0.6
Atm. ν CEνNS	0.12 ± 0.02	0.12 ± 0.02
^{8}B + *hep* ν CEνNS	0.06 ± 0.01	0.06 ± 0.01
Det. Neutrons		$0.0^{+0.2}$
Accidentals	2.8 ± 0.6	2.6 ± 0.6
Total	1210 ± 91	1202 ± 41

10^6 factor of selection!

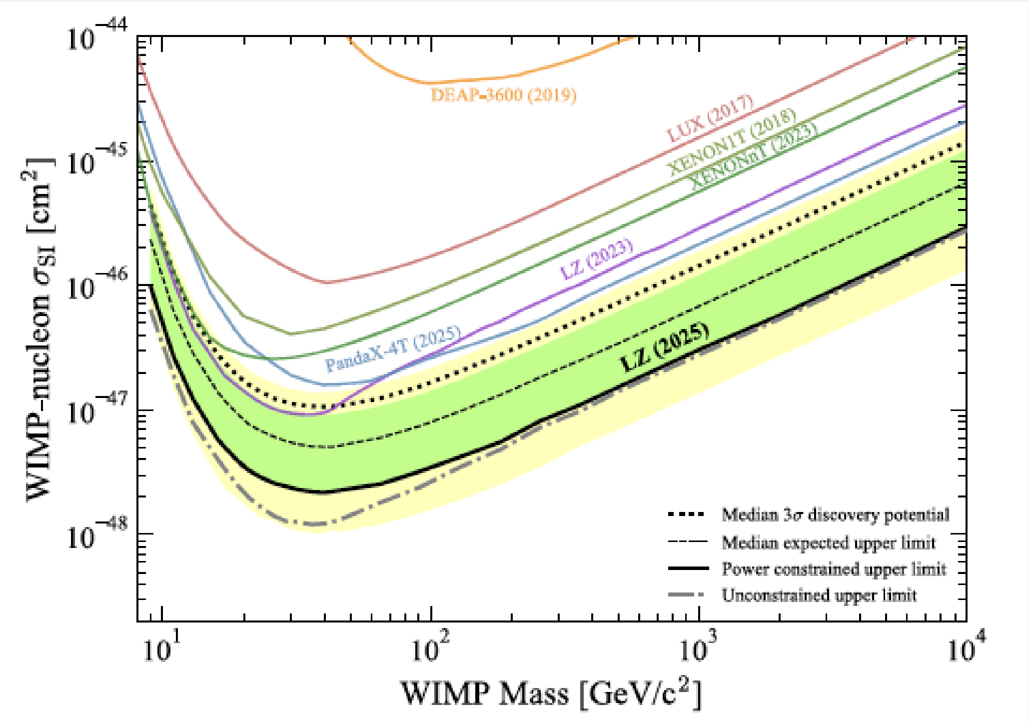
Selection description	Events after selection
All triggers	1.1×10^8
Analysis time hold-offs	6.0×10^7
Single scatter	1.0×10^7
Region-of-interest	1.8×10^5
Analysis cuts for accidentals	3.1×10^4
Fiducial volume	416
OD and Skin vetoes	335



PRL35(2025)1802

WIMP-SI limits from LXe Experiments

- Exclusion plots calculated under specific assumptions and model framework
- Neutrino fog zone still not covered
- Survived events in agreement with expectation of the background model
- Validation of the background model difficult to be performed (intrinsic limitation of this approach)



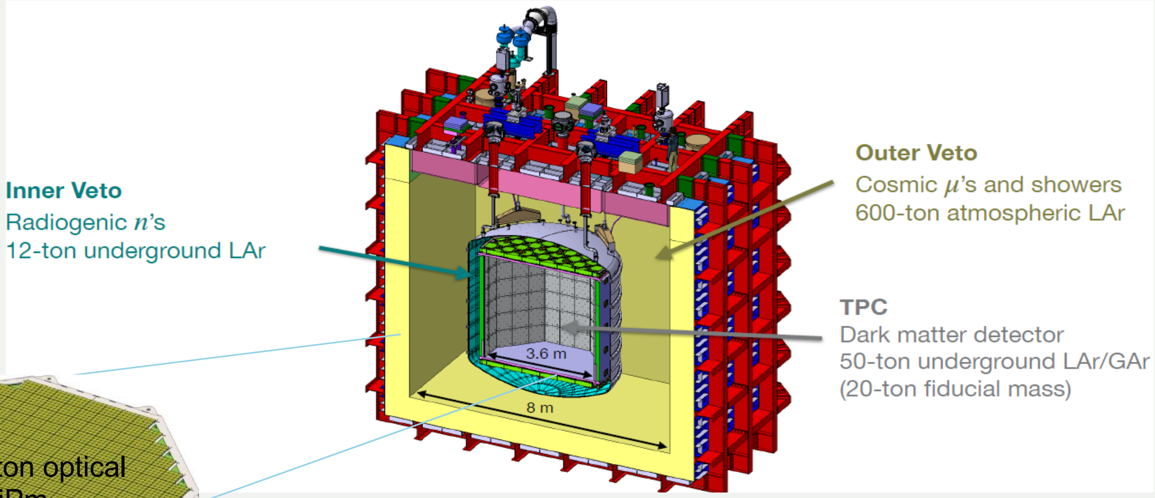
toward an ultimate LXe experiment (XLZD – XENON LUX ZEPLIN DARWIN)

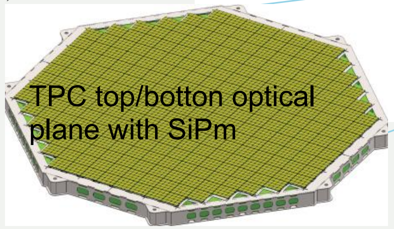
DARKSIDE-20k

EPJ Plus (2018) 133:131

Set-up:

- Fiducial volume of ≈ 20 ton, underground argon (50 tons in total of UAr), depleted in ^{39}Ar
- Active neutron veto integrated in TPC, Gd-loaded PMMA TPC and inner veto sealed inside a stainless steel
- SiPM based photon detection (total area ≈ 26 m^2)
- 650 ton Outer Veto in atmospheric argon (AAr)
- To be deployed in Hall-C of INFN-LNGS
- Start of operations in 2028





Goals:

- SI sensitivity up to ≈ 10^{-48} cm^2 for 0.1 TeV DM mass
- Exposure expected: 1000 ton × yr
- Expect > 10^8 discrimination using PSD with argon
- Background: 0.1 background events over 200 t×y in the ROI (30-200 keVnr)

Many activities ongoing:

- production of UAr (URANIA in USA and ARIA in Sardinia)
- Cryogenic System, Readout, etc.
- Mechanical mockup test in progress
- The NOA clean room for SiPM packaging and assembly @ LNGS is ready
- Installation started

DS @ LNGS

DarkSide-50 S2-only some results

Full dataset analysis published:

a) Nuclear Recoil: Phy. Rev. D 107 (2023), 063001

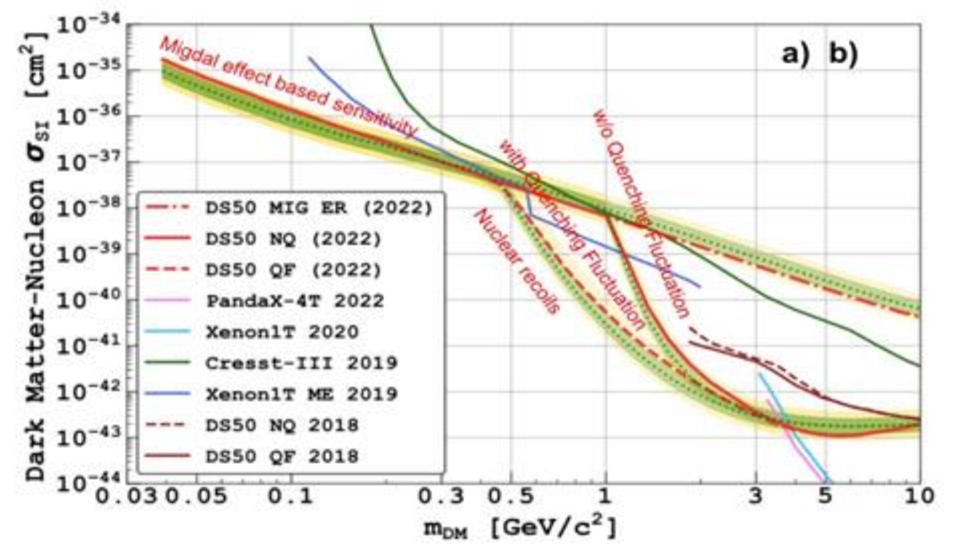
b) Nuclear Recoil + Migdal: Phys. Rev. Lett. 130 (2023),101001

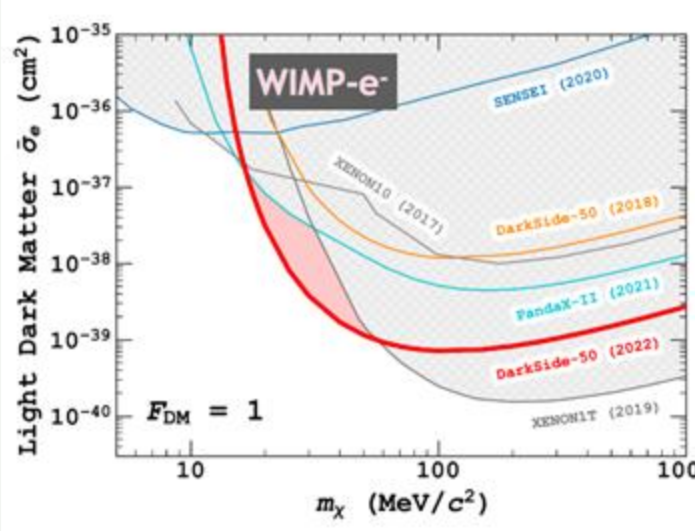
c) Electron Recoil: Phys.Rev. Lett. 130 (2023),101002

d) Bayesian analysis accepted to EPJC

Improved sensitivity for WIMPs in the few GeV/c² mass range

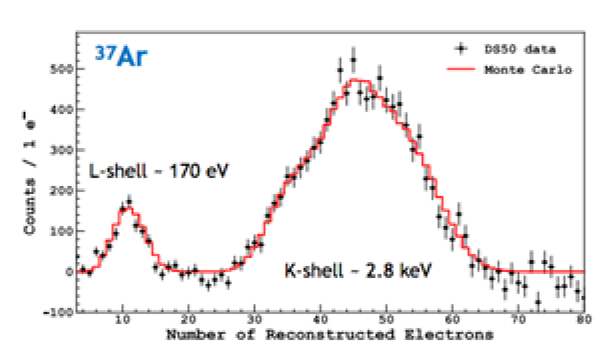
World best limit as low as 40 MeV/c² including Migdal effect

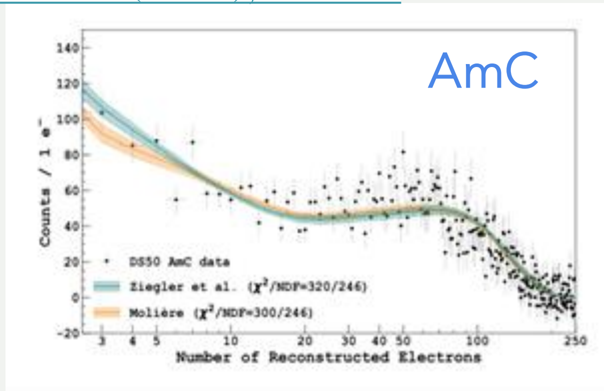




c)

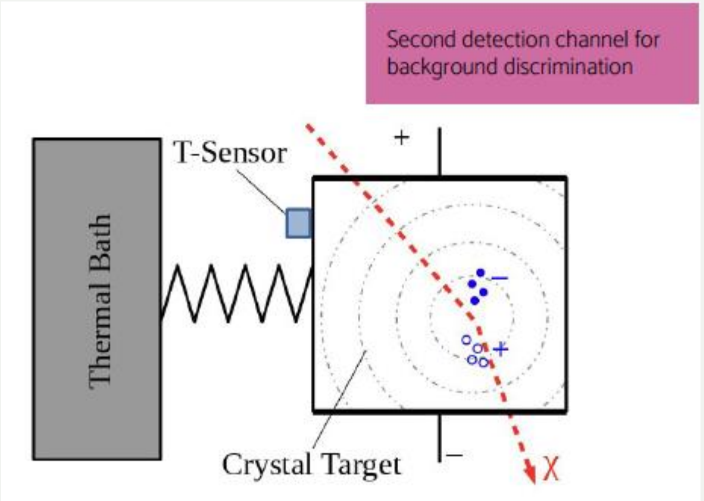
ER/NR charge yield from global fit of DS-50 calibration data + external dataset: Phys.Rev.D 104 (2021), 082005

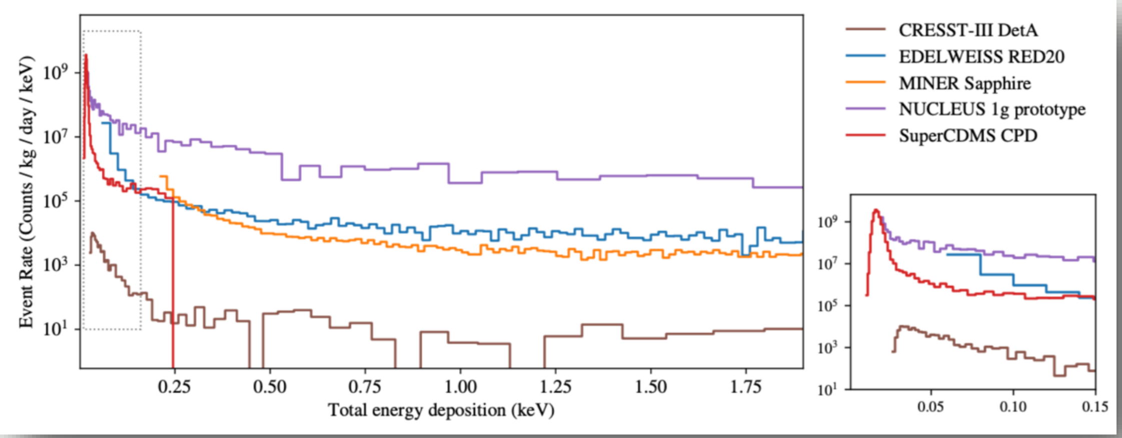




Low threshold detectors

- Low temperature operation (mK)
- Threshold well below keV, up to tens of eVee
- Extended sensitive to DM mass ~0.1-10 GeV
- ~ kg mass scale detector
- Strong background suppression
- Energy calibration challenging (CRAB)
- Migdal effect enhancement (?) [firstly proposed by DAMA in IJMPA22(2007) 3155]
- Unexpected background excess whose origin is unknown



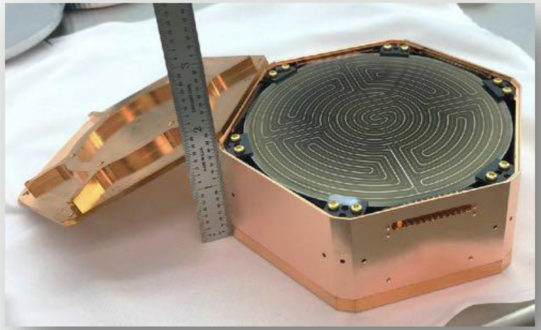


→ CEvNS physics

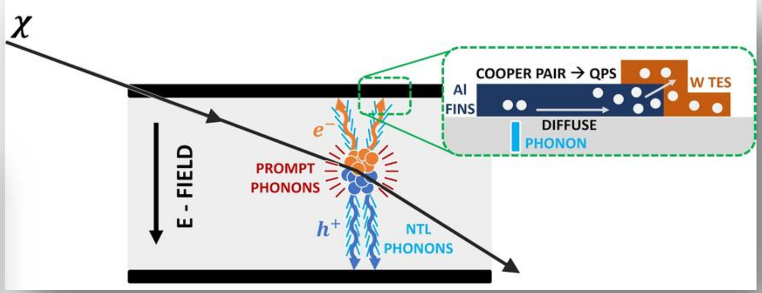
Super-CDMS at SNOLAB

From M. Wilson, IDM 2022

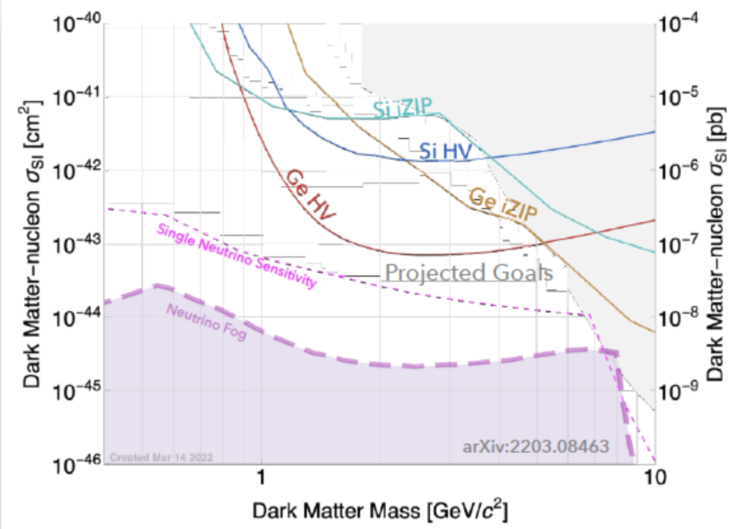
- Cryogenic with double read-out technique (CDMS-I, CDMS-II, SUPER-CDMS at Soudan [iZip, CDMS-Lite])
- Target materials: Si (0.6 kg), Ge (1.4 kg); **phonon** (Quasi-particle trap and Electrothermal feedback Transition Edge Sensors) and **charge** measured; **12 iZIP** (⌀100 mm x 33.3 mm) + **12 HV** (no ionization sensors)
- iZIP detector: 12 phonon channels, 4 charge channels, Low bias voltage (~ 6 V), ER/NR discrimination
- HV Detector: 12 phonon chns, high bias (~ 100 V), low threshold

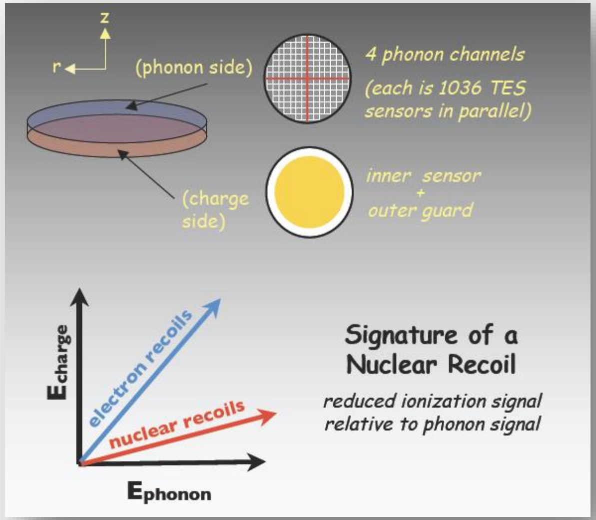


iZip detector



Projected Sensitivity



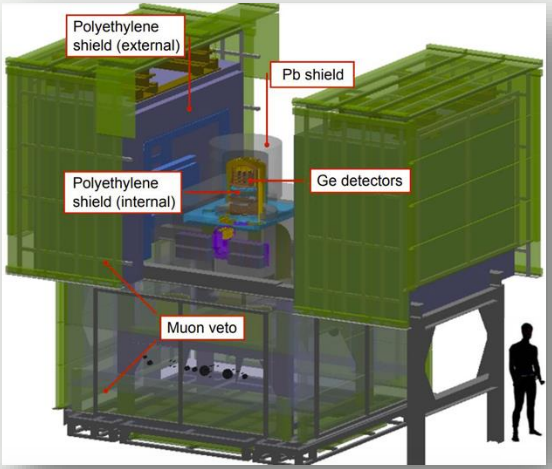


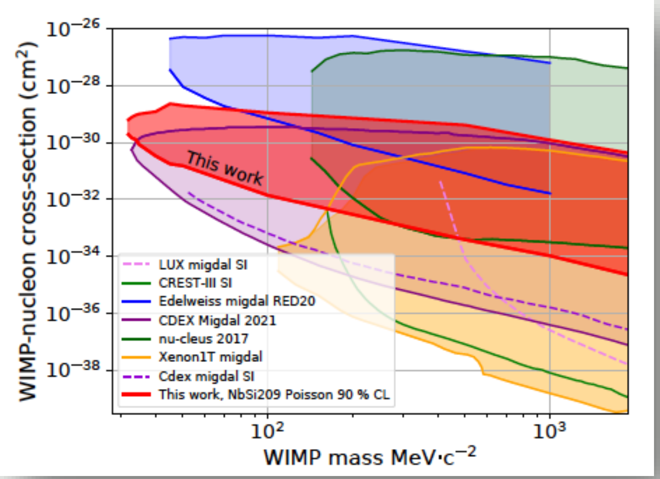
- Installation in progress at SNOLAB
- Commissioning in late 2025

PRD111,012006 (2025)

Edelweiss for sub-GeV DM

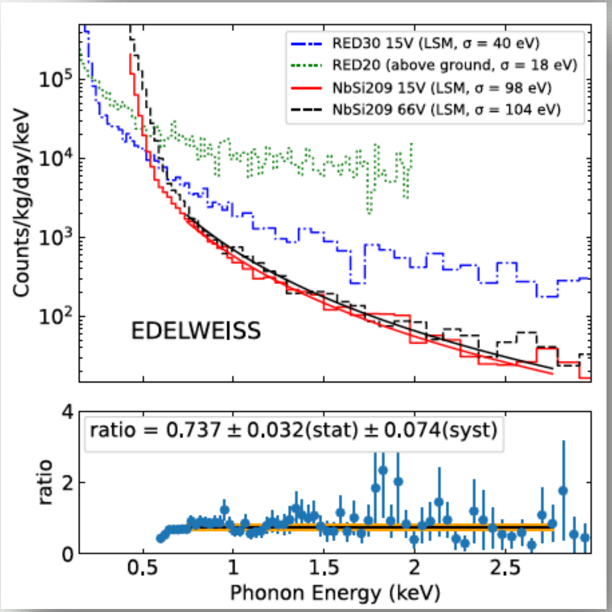
- Focused on the study the ≲ 1 GeV DM mass range by developing **cryogenic low threshold detector**
- First low mass results with Ge-NTD detector with only phono readout (2019)
- Ge detector based on Neganov-Luke-Trofimov (NTL) effect to amplify phonon signal by applying a high bias voltage (66V) (2022)
- Experiments at LSM (4800 m.w.e.); NbSi TES for heat signal, Al electrodes for ionization; ; 30 eVee threshold





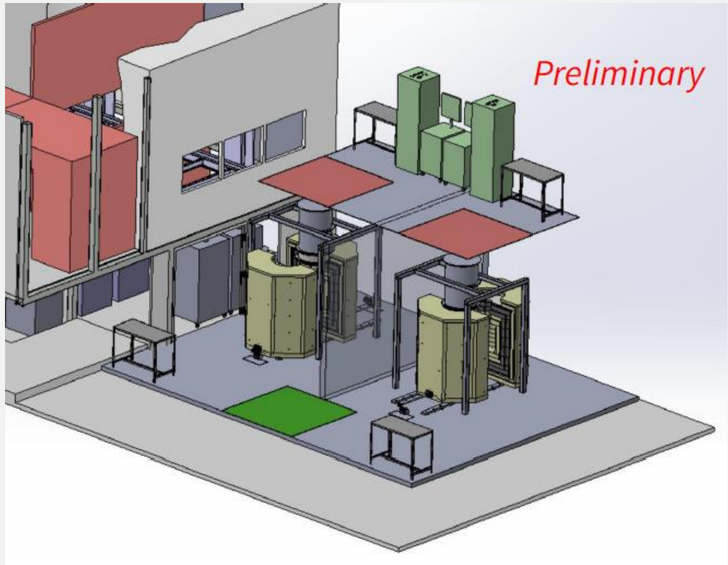
Phys. Rev. D 106, 062004 (2022)

- Limits in sub-GeV mass region
- Enhancement of the sensitivity due to the Migdal effect
- Excess of background with phonon only signal (Excess) is the limiting factor (HO events)

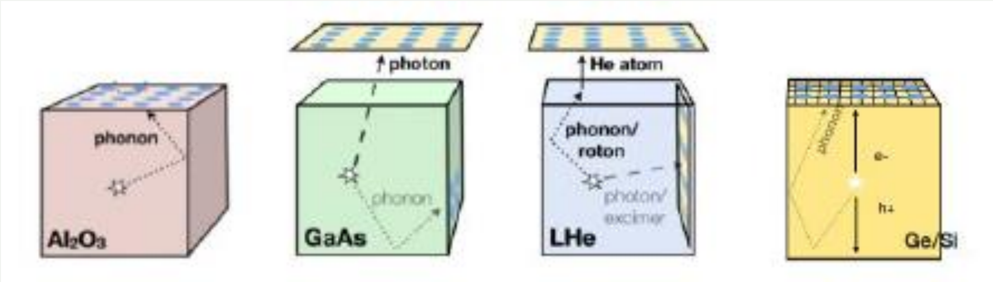


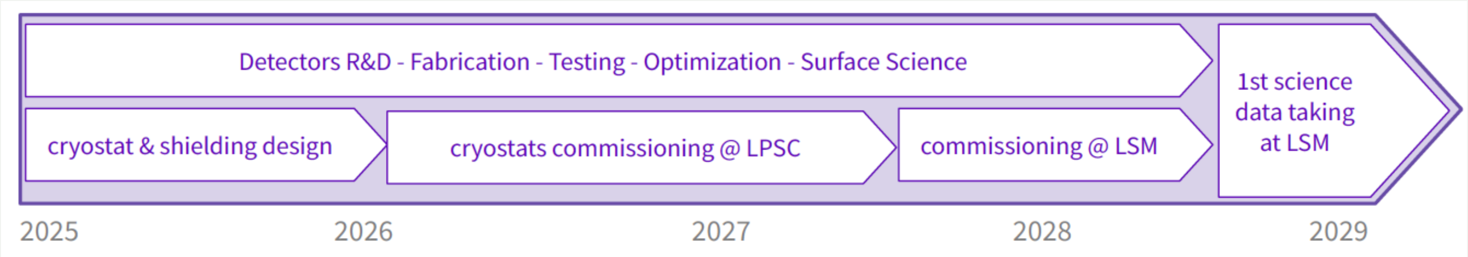
Tesseract

Transition Edge Sensor with Sub-Ev Resolution And Cryogenic Targets



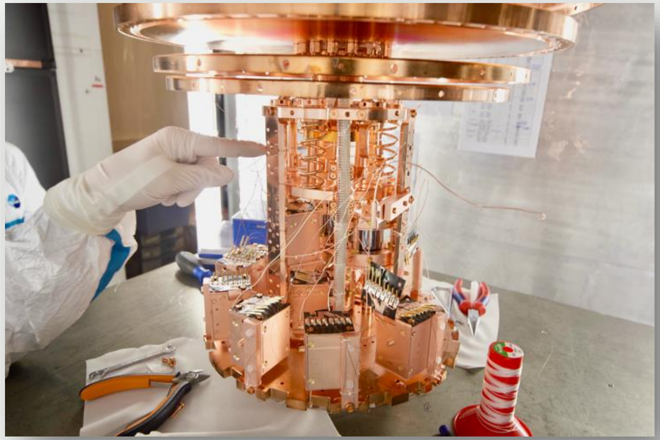
- Experimental set-up to host several target equipped with new generation TES
- At Modane Laboratory in France
- developing technology to reject LEE events
- Use ultra-low threshold

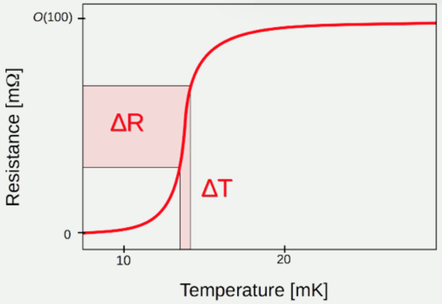


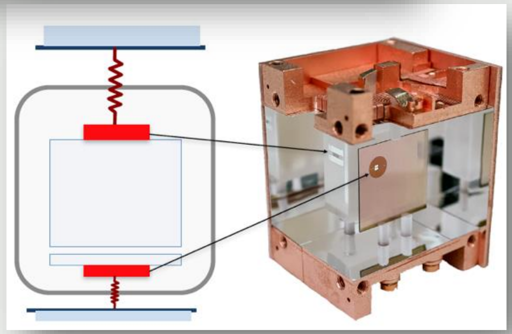


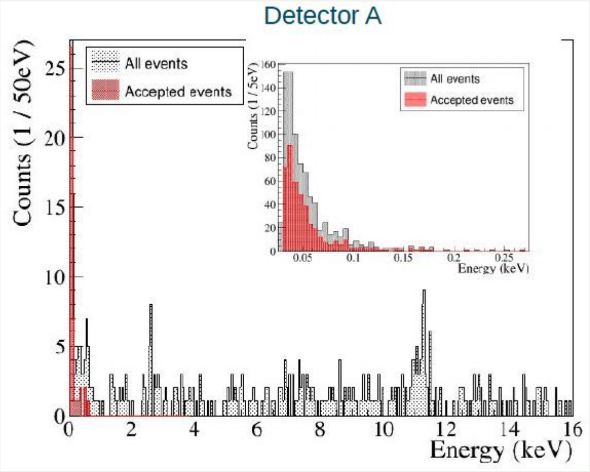
CRESST

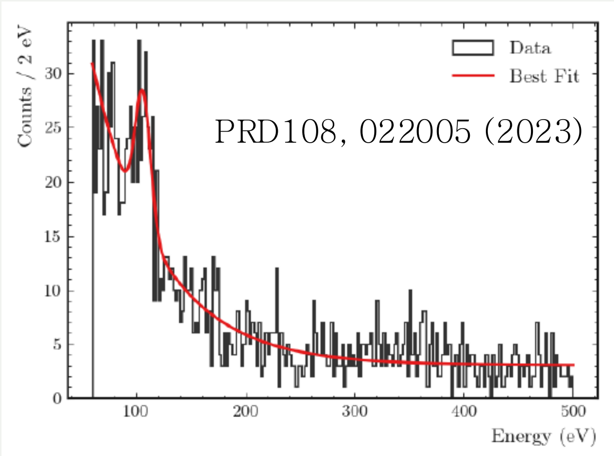
- Simultaneous measurement of phonons (W-TES) and light (Si or SOS sensor) to discriminate ER vs NR
- Target crystals (2x2x1): $CaWO_4$ (24 g), Al_2O_3 (16g), $LiAlO_2$ (10g), Si (9g)
- Results:
  - 23.6 g $CaWO_4$, 5.698 kg × d, 30.1 eV threshold (2019)
  - 0.35g Si wafer, 55.6 g × d, 10.0 eV threshold (2022)
  - calibration of W recoil response at 100 eV scale (2023)







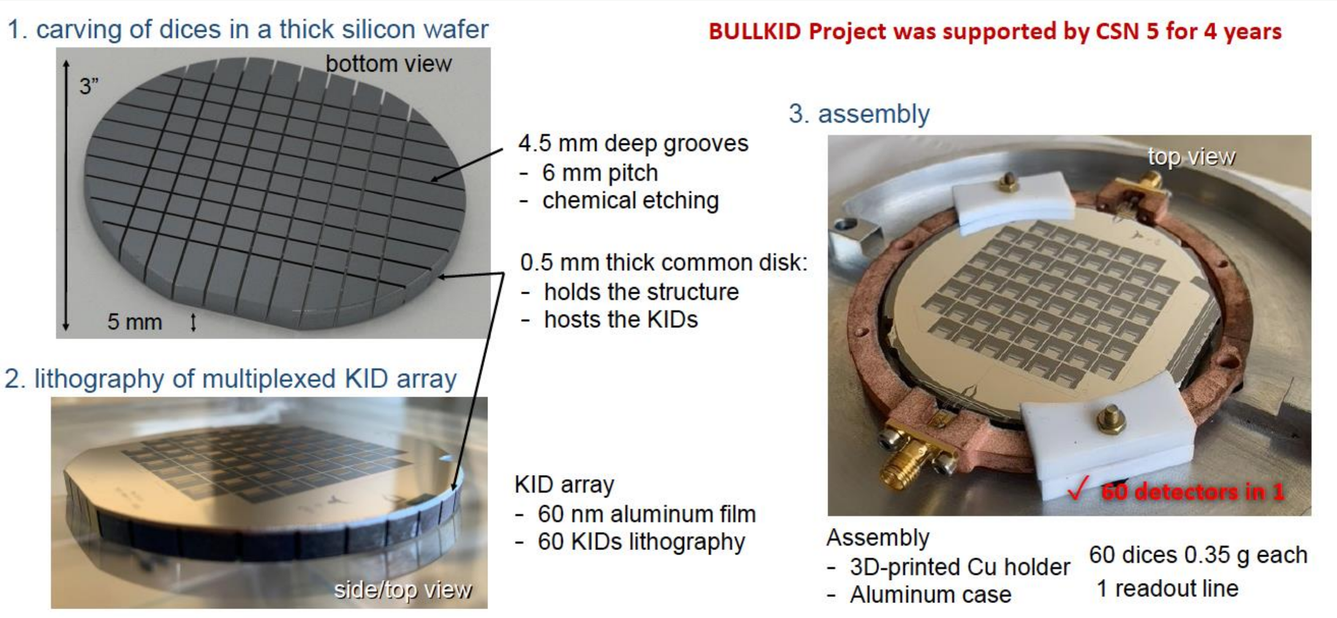


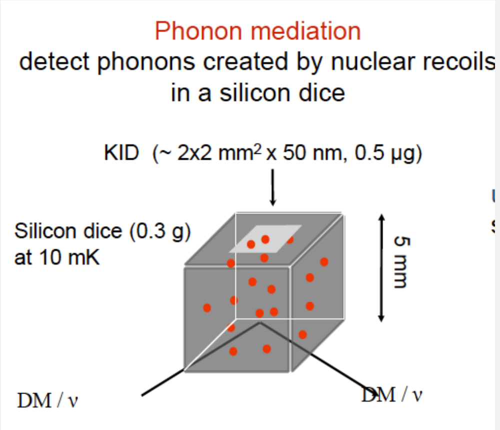


- Limit on WIMP cross-section at few 10^{-42} cm^2 level at 10 GeV [PRD100, 102002 (2019)]
- Best WIMP sensitivity below 1.7 GeV
- Presence of unexplained rise in the counting rate at low energy (LEE) (arXiv:2207.09375)
- Measurements campaign to study LEE

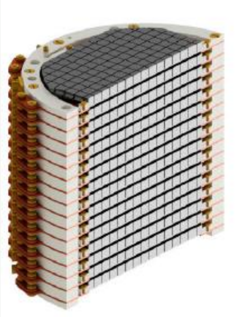
BULLKID-DM

- Detector based on an array of Si-dices equipped with KIDs (Kinetic Inductance Detectors) for multiplexing readout
- 16 wafer hosting each 5 KIDs (800g mass, fiducial 600g)
- Energy threshold: 50-200 eV
- Located at LNGS

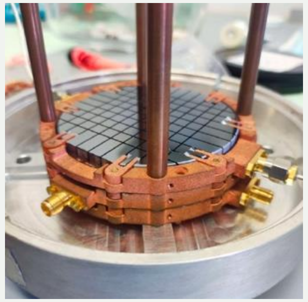


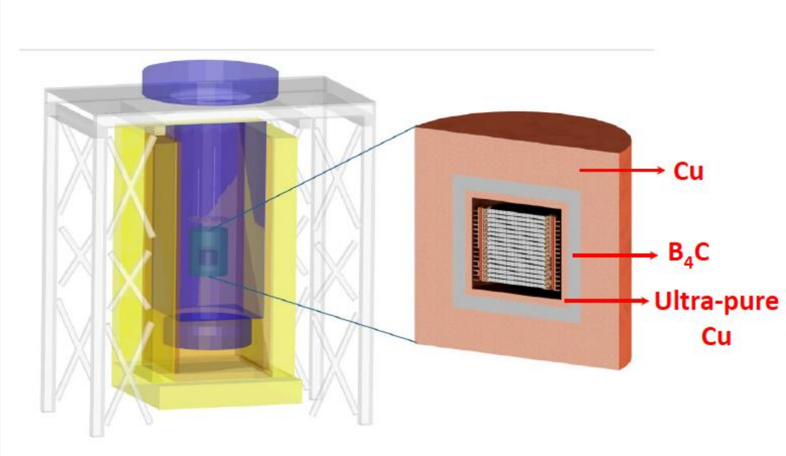


Design of the experiment



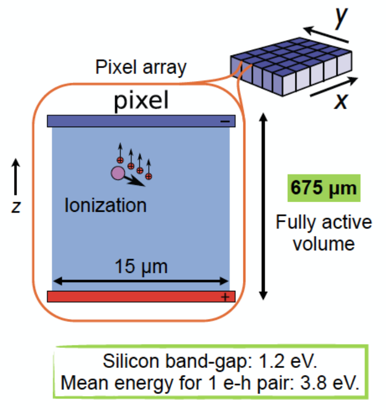
Demonstrator

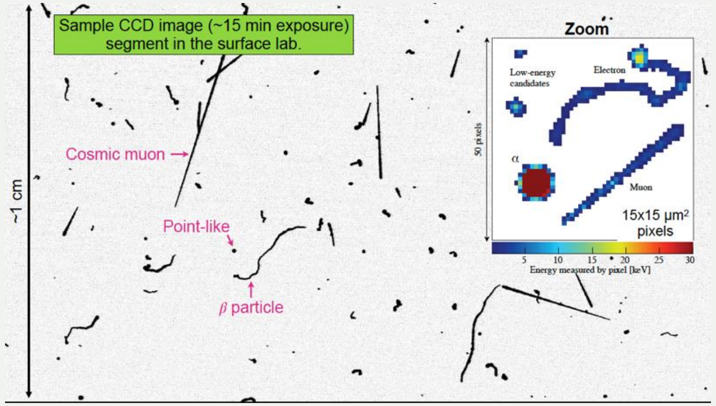




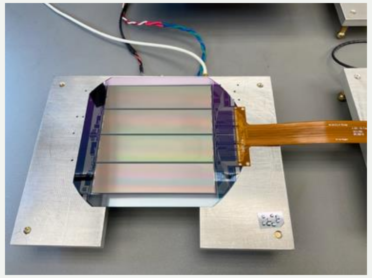
CCD for sub-GeV DM

- **Exploiting DM interaction with electrons**
- Electron recoil signal (electron are light!) + possible additional e- (Migdal effect) or γ
- No coherent enhancement and probing **DM-e interaction** cross-section.
- Sensitive to bosonic particle that couples to e⁻ (hidden or dark photon)



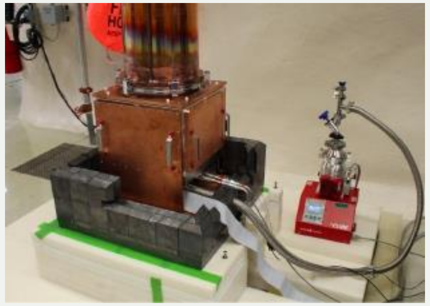


DAMIC: CCD at SNOLAB in 2022, now DAMIC-M in commissioning at LSM



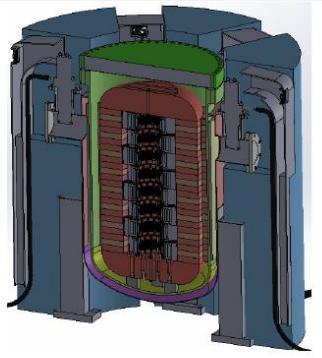
arXiv:2302.02372

Sensei: Skipper CCD



PRD106,075004 (2022)

OSCURA: 10 kg CCD scale

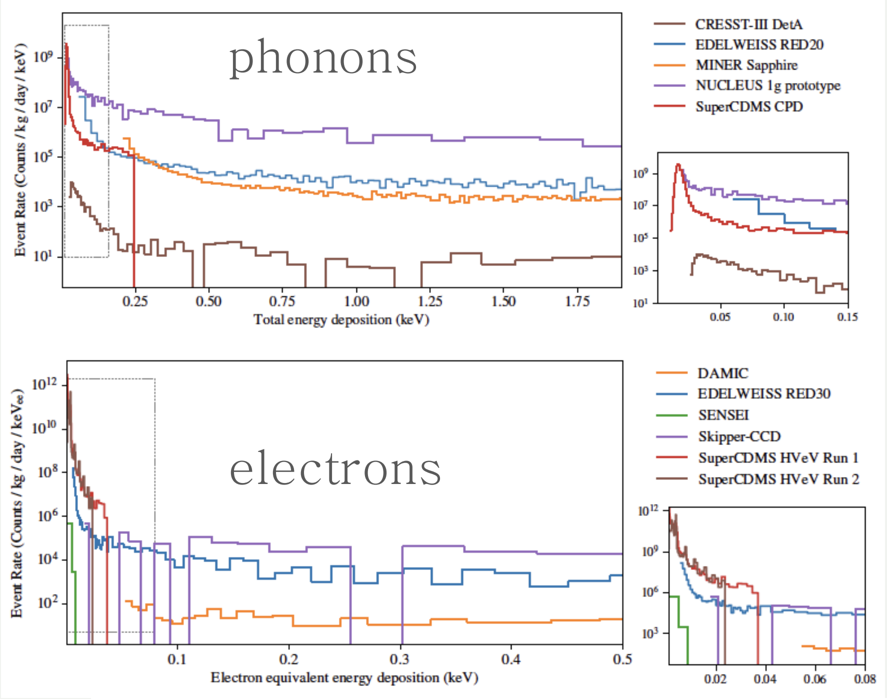


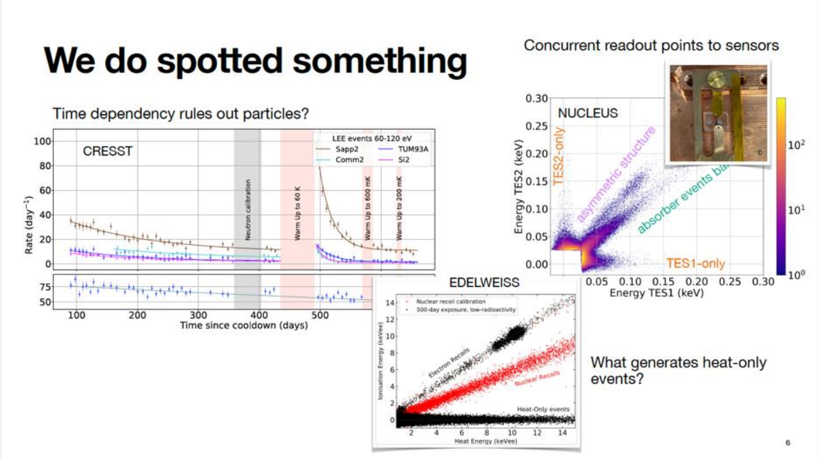
arXiv:2202.10518

- The goal is to reach a cross section on electrons of order of 10^{-39}–10^{-42} cm^2 for 10 MeV DM mass

The excess problem

- Low mass DM experiment and CEvNS experiment observed an excess of events in the low energy region (below 0.5 keV)
- Observed in:
  - cryogenic detector (CRESST, Edelweiss, MINER, SUPER-CDMS, NUCLEUS)
  - in CCDs experiment (DAMIC, SENSEI, SKIPPER)
  - in different experimental condition (under/above ground)
  - in different techniques and materials
  - different in rate in the different experiment
  - time dependent effect (CRESST)
- Origin of this effect(s) is at present unknown; many hypothesis under studies: unknown particle background, stress from crystal, sensor or holding, unknown detector response (calibration)
- At present excess limit the sensitivity for low-mass detector





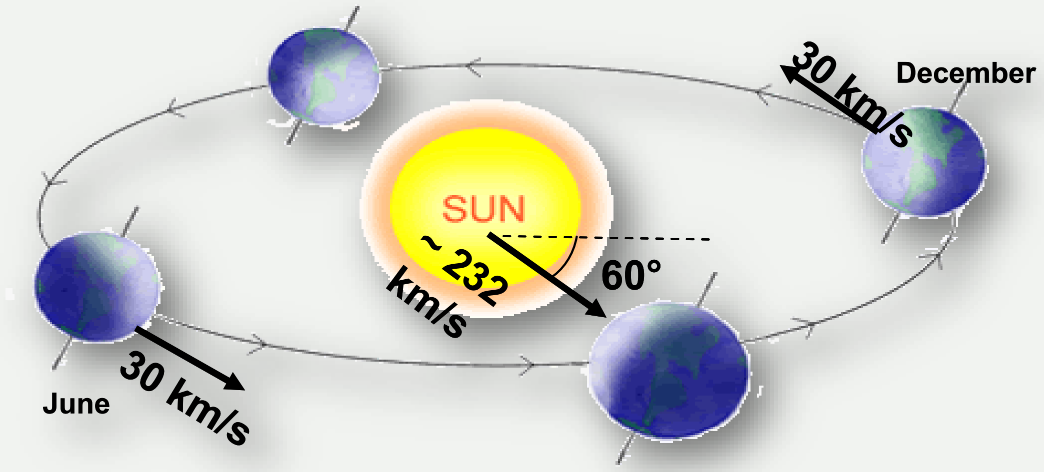
→ EXCESS initiative: common effort in the low threshold detectors to understand the excess

https://agenda.infn.it/event/39007/

Annual Modulation Signature

Annual modulation: annual variation of the interaction rate due to Earth motion around the Sun; sensitive to many DM candidates and scenarios

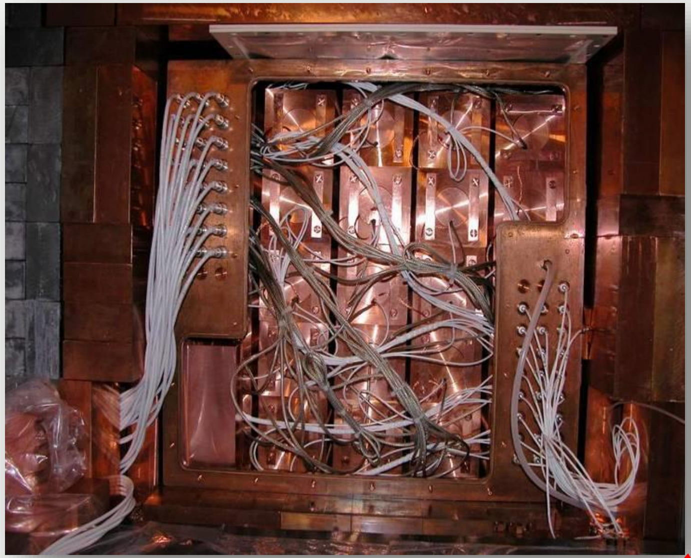
1) Modulated rate according cosine
2) In a definite low energy range
3) With a proper period (1 year)
4) With proper phase (about 2 June)
5) Just for single hit events in a multi-detector set-up
6) With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions,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



It doesn't depend on the nature and interaction of the DM candidate

DAMA/LIBRA Experiment

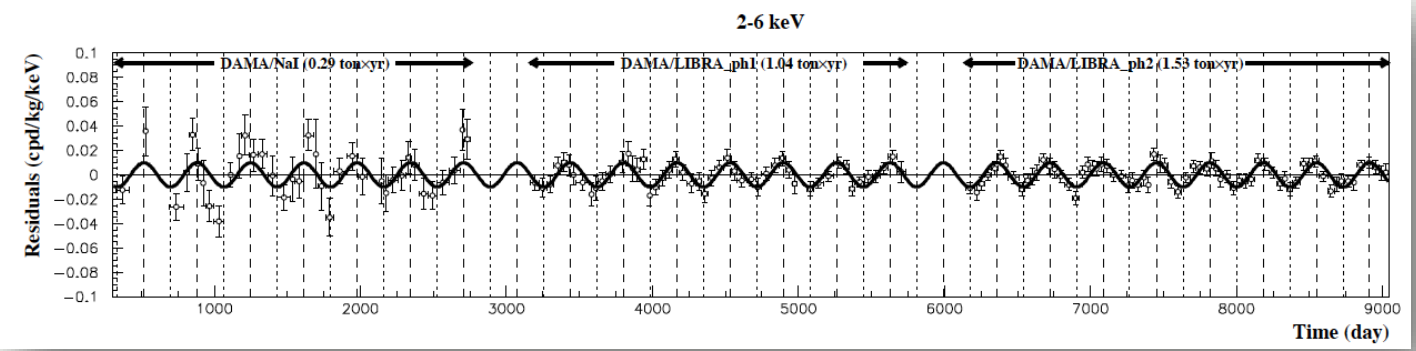
- ULB 25 x 9.7 kg **NaI(Tl)** in a 5x5 matrix + Suprasil-B light guides directly coupled to each bare crystal + 2 high Q.E. PMTs (40% at peak) for each crystal working in coincidence at the single ph. el. threshold
- Software energy threshold: 2 keV in phase1; 1 keV in phase2 (new PMTs, 6-10 phe/keV); 0.5 keV in phase2 empowered
- Multiton-multicomponent passive shield (>10 cm of OFHC Cu, 15 cm of boliden Pb + Cd foils, 10/40 cm Polyethylene/paraffin, about 1 m concrete, mostly outside the installation)
- Three-level system to exclude Radon from the detectors
- Calibrations in the same running conditions as prod runs
- Fragmented set-up: single-hit events = each detector has all the others as anticoincidence
- DAMA/LIBRA-ph2 empowered: Dec 2021 – Dec 2024



Concluded in 2024

DAMA/LIBRA annual modulation result

- Experimental residuals of the single-hit scintillation events rate vs time and energy (in DAMA/LIBRA-phase2 1 keV thershold)
- Exposure: 2.86 ton × yr (DAMA/NaI + DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2)

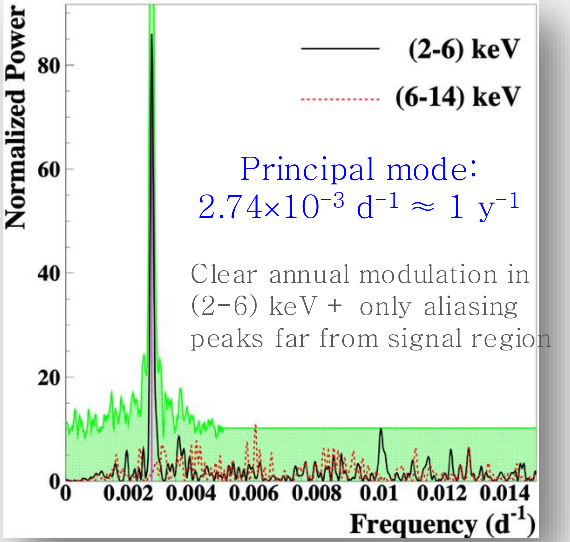


- Absence of modulation? No – $\chi2$/dof=311/156 ⇒ P(A=0) =2.3×10^{-12}
- *A=(0.00996±0.00074) cpd/kg/keV – $\chi2$/dof = 130/155* ***13.4σ C.L.***

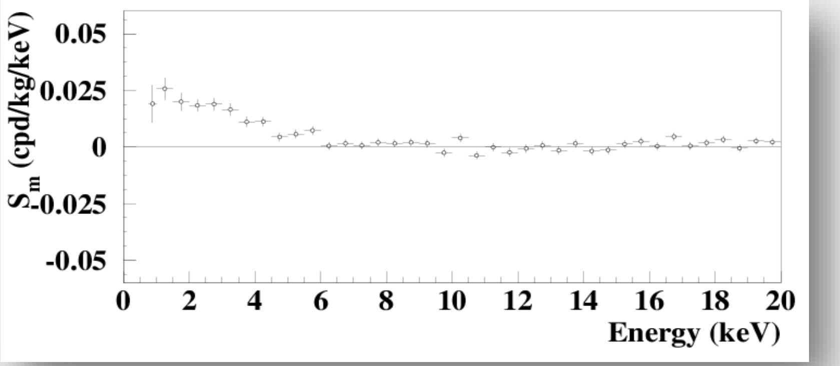
- DAMA/NaI + DAMA/LIBRA-phase1 + phase2 favor the presence of a modulated behavior with proper features at 13.7 σ C.L.
- No systematics or side reaction able to mimic the exploited DM signature (i.e. to account for the whole measured modulation amplitude and to simultaneously satisfy all the requirements of the signature), has been found

IJMPA37(2022)2240015

- The analysis in frequency



- Modulation amplitudes vs Energy

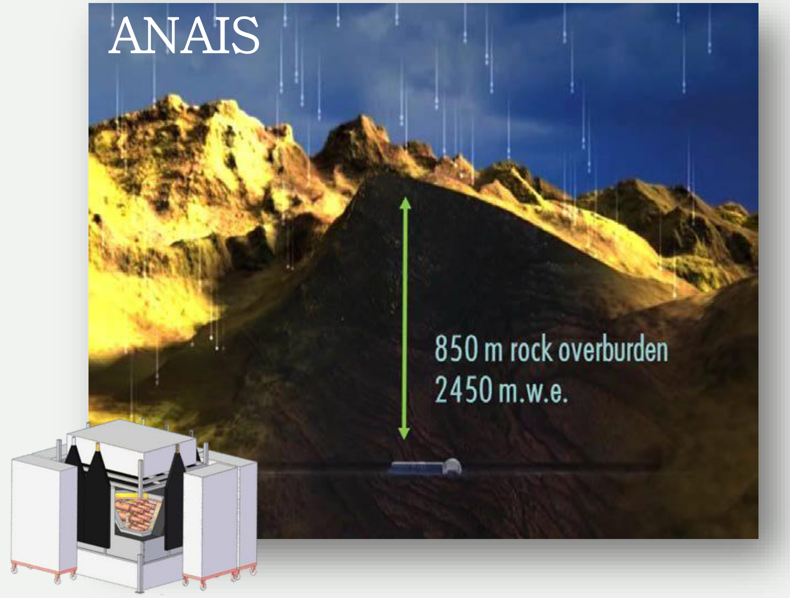


COSINE-100 and ANAIS experiments

- NaI(Tl) experiment aiming to reproduce the annual modulation results of DAMA
- COSINE-100: in Yang Yang Underground Lab in Korea (700 m rock overburden), 8 NaI(Tl) crystals (106 kg) in liquid scintillator, in data taking since Sept. 2016
- ANAIS: in Canfranc Underground Laboratory in Spain (2450 m.w.e.), 9 NaI(Tl) crystals (112.5 kg) in a 3x3 matrix; light collection in all the nine modules ~ 15 p.e./keV (12.7-15.8 p.e./keV), in data taking data since August 2017
- Experiments in progress, preliminary results not yet a sensitive comparable with DAMA/LIBRA

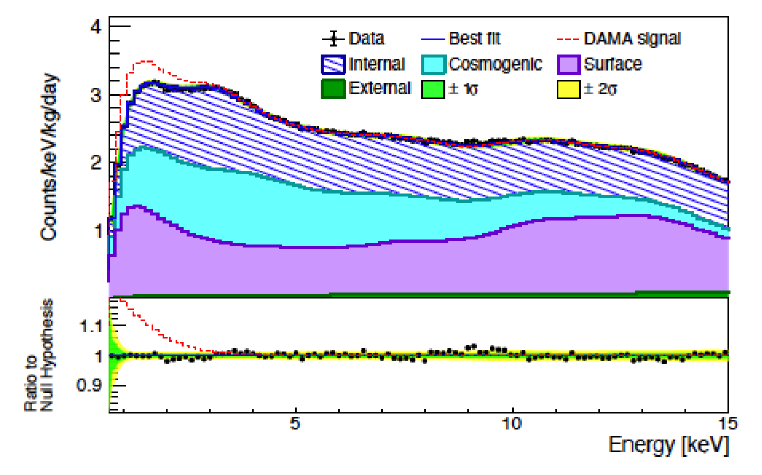
Experiment	Location	Target	Mass [kg]	Status
DAMA/LIBRA	LNGS	NaI(Tl)	250	running
ANAIS-112	LSC	NaI(Tl)	112.5	running
COSINE-100	Y2L	NaI(Tl)	106/61.3	upgrading
COSINE-200	Yemilab	NaI(Tl)	~200	in preparation
SABRE North / South	LNGS + SUPL	NaI(Tl)	~50	in preparation
COSINUS	LNGS	NaI	~1	in preparation
PICOLON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

credit: A. Ianni - IDM 2024



COSINE-100

- Last data released: Oct 2016-Nov 2019 (3 crystals not used)
- Background subtraction for comparing experimental data with WIMP signal (model dependent analysis and result!)
- Experimental counting rate at keV higher than DAMA/LIBRA
- Different QF wrt DAMA crystals



Components	Background 2-6 keV (dru)
Internal ^{210}Pb	1.50 +/- 0.07
Internal ^{40}K	0.05 +/- 0.01
Surface ^{210}Pb	0.38 +/- 0.21
^{3}H (Cosmogenic)	0.58 +/- 0.54
^{109}Cd (Cosmogenic)	0.09 +/- 0.09
Other cosmogenic	0.05 +/-0.03
External	0.03 +/- 0.02
Total expected	2.70 +/- 0.59
Data	2.64 +/- 0.05

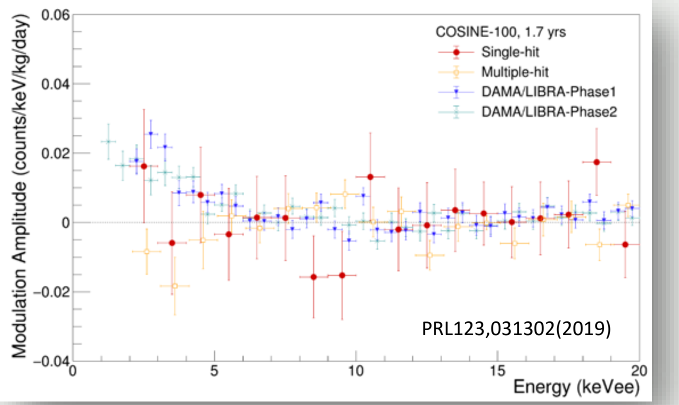
Eur.Phys.J.C(2018)78:490

[Unit: Counts/keV/kg/day]		Crystal 7
Data		2.492 ± 0.009
Total simulation		2.504 ± 0.210
Internal	^{210}Pb	0.999 ± 0.008
	^{40}K	0.046 ± 0.004
	Others	0.0048 ± 0.0001
Surface ^{210}Pb	Crystal	0.513 ± 0.131
	Teflon	0.051 ± 0.004
Cosmogenic	^{3}H	0.798 ± 0.164
	^{113}Sn	0.020 ± 0.002
	^{109}Cd	0.022 ± 0.002
	Others	0.015 ± 0.004
External ($\times 10^{-2}$)		3.374 ± 0.062

Eur.Phys.J.C(2021)81:837

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

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

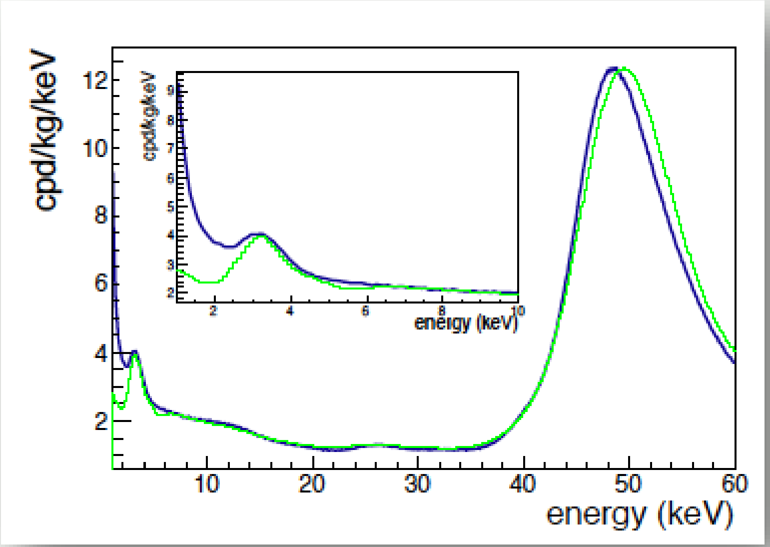


Crystal #2, #3, #4, #6, #7
$\langle$data−model$\rangle_{crystals}$ [1−6 keV] = −0.04±0.21 cpd/kg/keV
→ S_0[1−6 keV]<0.31 cpd/kg/keV 90%CL
Compatible with DAMA result

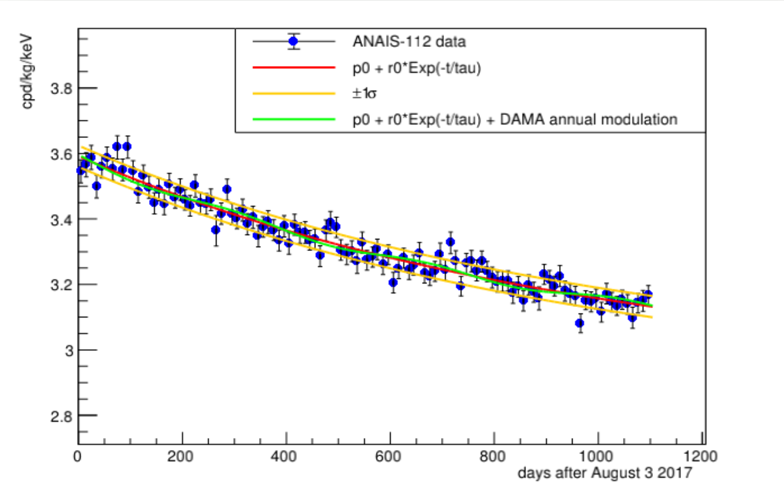
If the model of background is not correct the exclusion limits are meaningless

ANAIS

Phys. Rev. D 103, 102005 (2021)



- Last data release: 6 years annual cycles, exposure 625.75 kg×y
- Time dependent background
- Data analysis to extract modulation signal in the time dependent rate: robust background model mandatory
- No annual modulation observed
- Claimed incompatibility with DAMA at 4.0 (3.5) σ (PRL 135, 051001 (2025))



- ≈5 times larger rate in [1,2] keV wrt DAMA/LIBRA-phase2
- **High** counting rate in **ROI** explained as populations, other than background, "which could be leaking at the lowest energies in the ROI" being the trigger rate "dominated by other events, some of them with origin in the PMTs, others still **unexplained**"
- Detection efficiencies of cuts not periodically evaluated with dedicated calibrations as in DAMA/LIBRA

Even a 0.3% instability of the ANAIS rate in the [1-6] keV is enough to hide the annual modulation signal detected by DAMA: A≈0.01 cpd/kg/keV (green line in the plot)

SABRE: Sodium Iodide with Active Background REjection

Twin experiments at Gran Sasso Laboratory (LNGS) and SUPL (a future underground laboratory in Australia).

Goal:

- independent test of DAMA using NaI(Tl) detectors with background level lower than DAMA
- two location to study seasonal effect

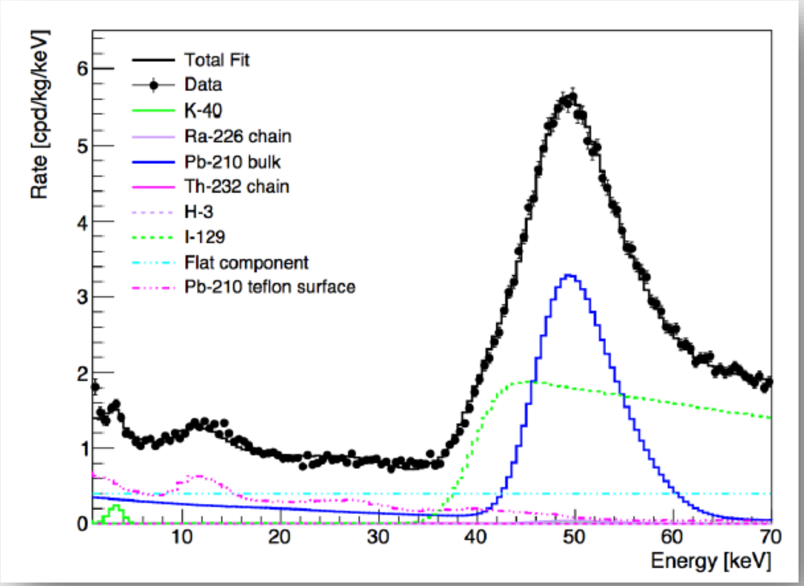
Results:

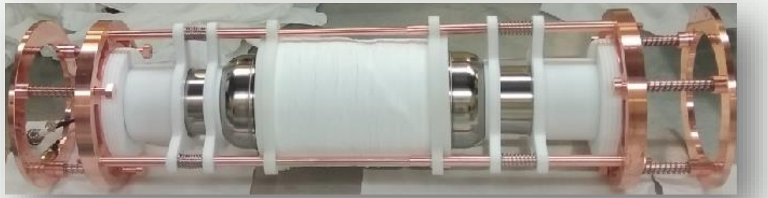
- Breakthrough background level: ~1 count/day/kg/keV in the 1-6 keV ROI ⇒ aim to reach ~0.5 count/day/kg/keV
- Active veto no longer required, need radiopure reflector

Strategy:

- Produce highly radipure NaI(Tl) crystal using zone-refining to purify powders and Bridgman technique for crystal growth
- Not yet ready for production not the final crystals

→ Demonstrate feasibility of a full-scale experiment without active veto and finalize the design of crystal array + shielding

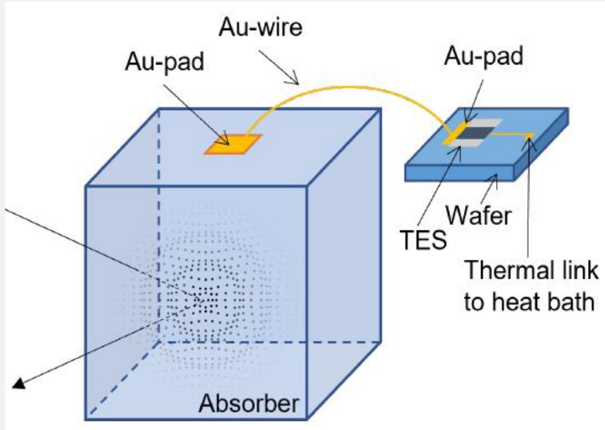




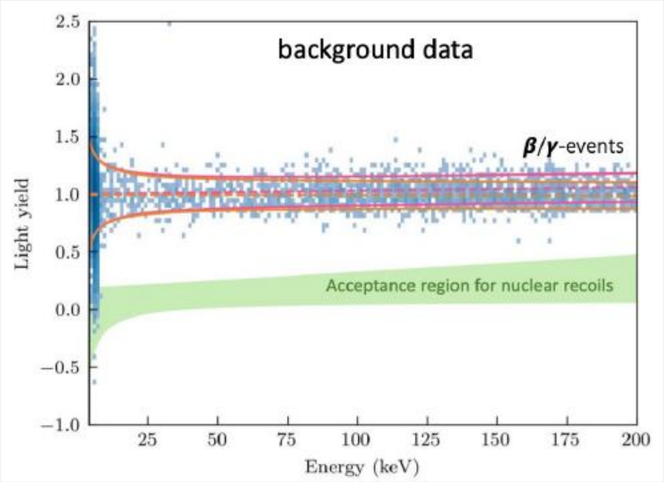
Eur. Phys. J. C 82, 1158 (2022)

COSINUS

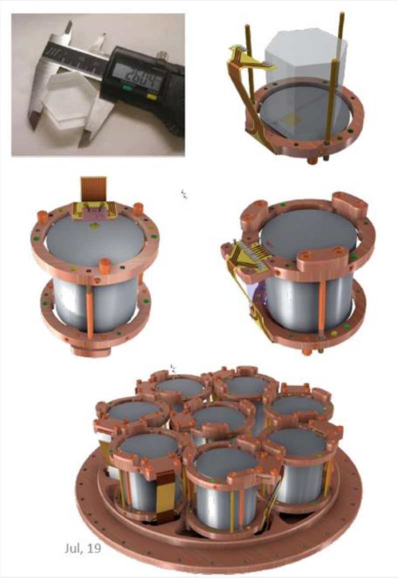
- NaI crystal as a bolometer to study the DAMA signal
- Difficulties in NaI: hygroscopic, high radiopurity to reach, low debye temperature (adapted remoteTES)
- First UG measurement performed, $E_{th} < 2$keV
- Facility at LNGS in completation



- separate wafer hosts the W-TES
- Au-pad on absorber: phonons propagate in NaI and couple to the electron system of the Au pad
- Au bond wire connection to the temperature sensor



K. Schäffner, UCLA DM 2025



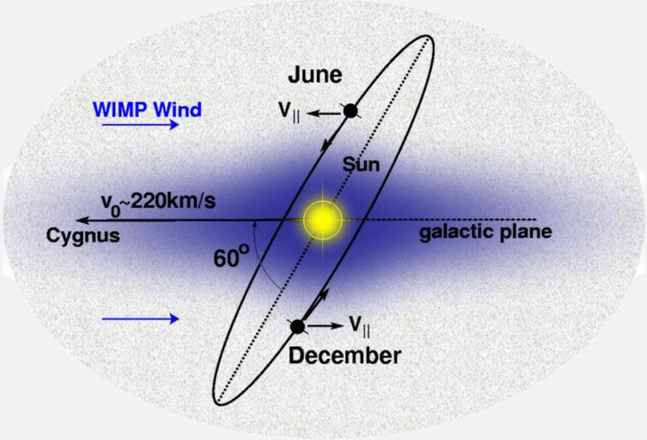
- Si-beaker for 4π active surrounding of the crystal
- First 8 modules (35g mass) will be installed before the end of 2025 to be in data taking in 2026

LNGS facility installed in 2024-2025

EPJ C 82, 2022

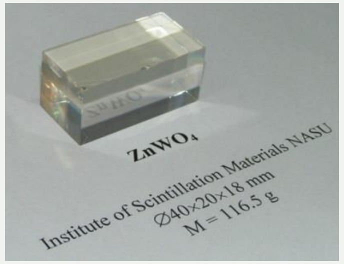
Directionality technique

- Based on the study of the correlation between the Earth motion in the galactic rest frame and the arrival direction of the Dark Matter (DM) particles
- A good signature but difficult to exploit
- Only for candidates inducing recoils
- It can help to identify solar neutrino coherent scattering entering in the neutrino fog zone
- Still at R&D stage



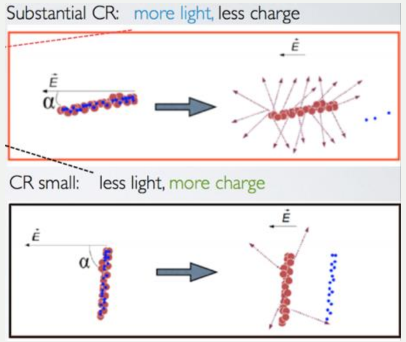
Low Pressure Gas TPC

Anisotropic scintillator ($ZnWO_4$)

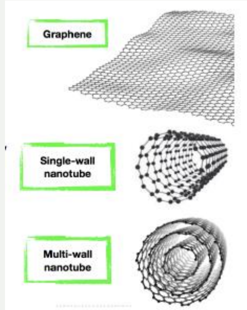


Nanometric tracking with nulcear emulsion

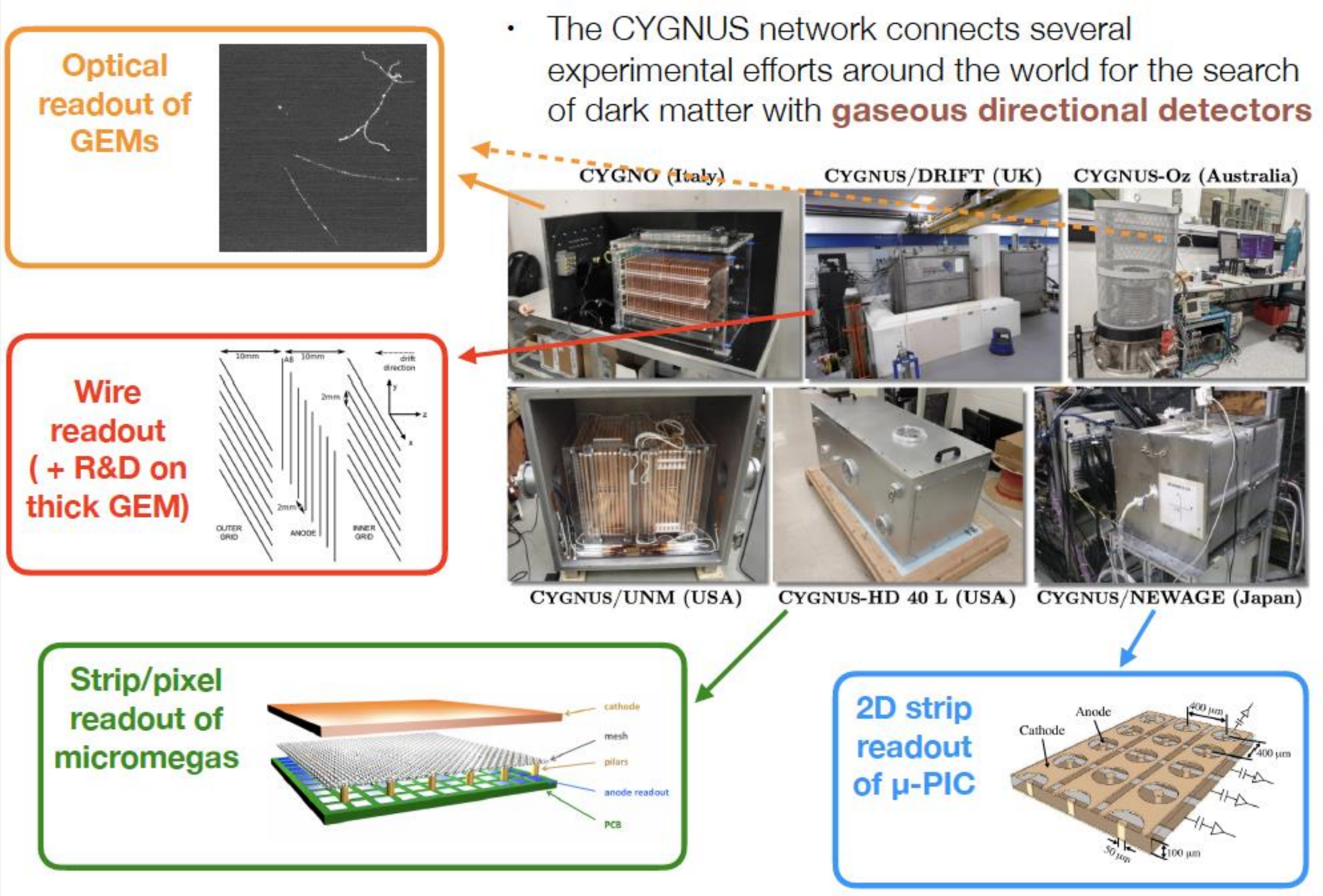
Columnar recombination in Liquid Ar TPC



Ptolemy, graphene target in nanotubes

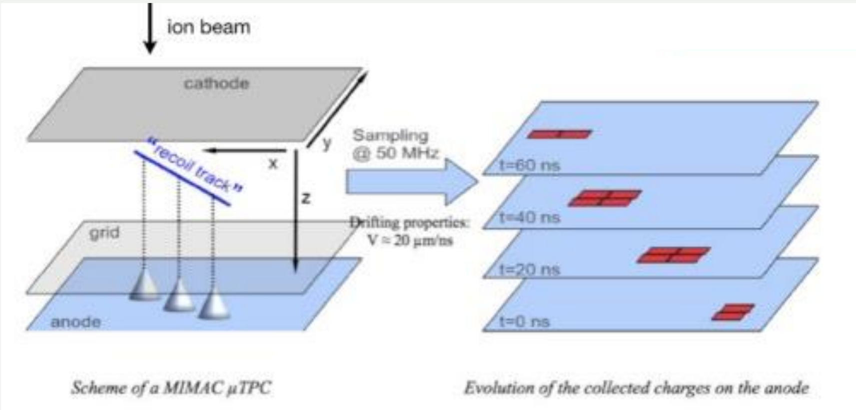


Gaseous TPC

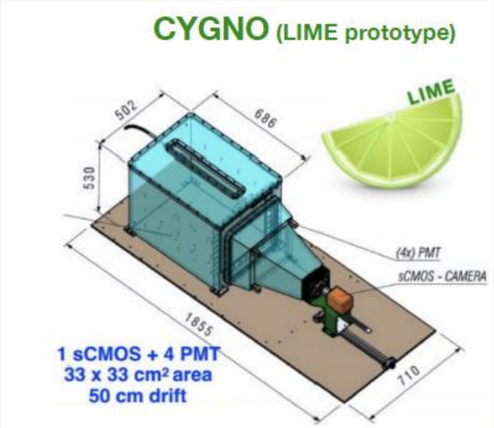


E. Baracchini, IDM2022

- MIMAC micro TPC exploits electron and ions signal

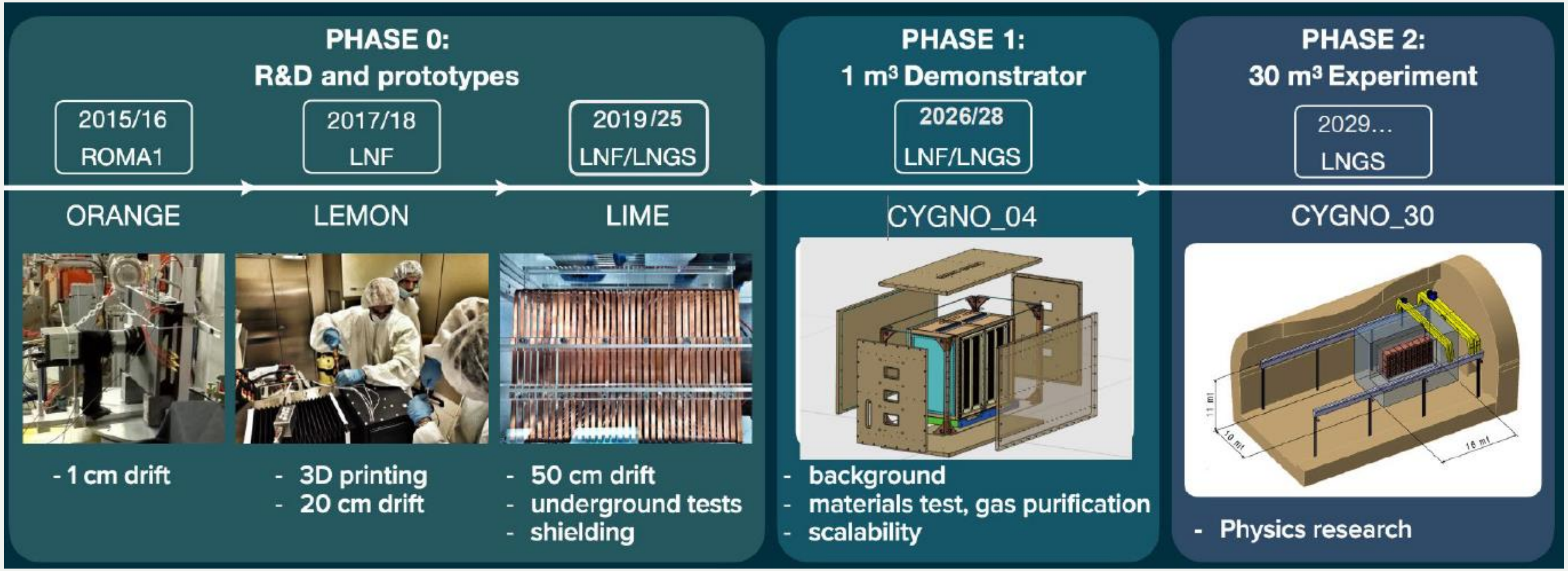


- CYGNO (LIME) at LNGS

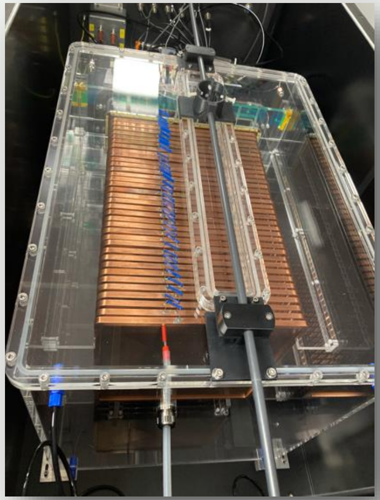


CYGNO

high-precision triple-GEM TPC at atmospheric pressure with optical readout



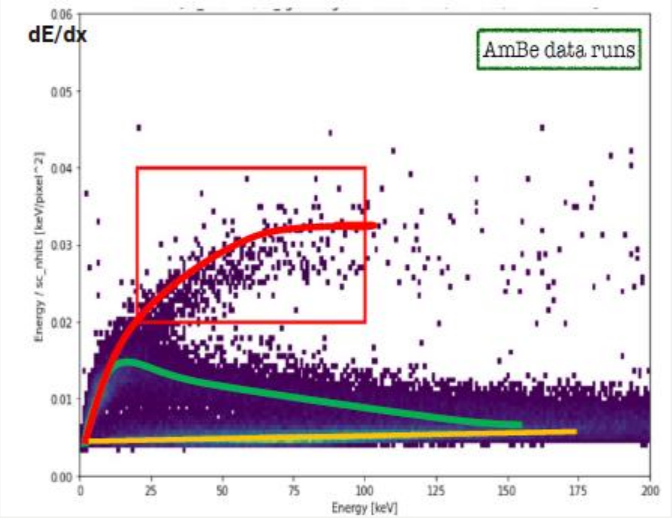
CYGNO



LIME detector (a demonstrator):

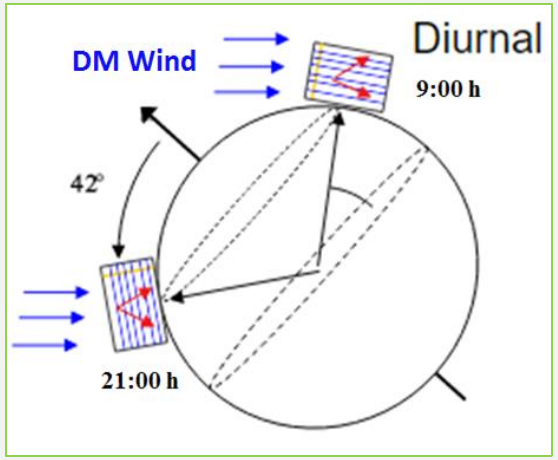
- high-precision triple-GEM TPC at atmospheric pressure with optical readout
- 50 litre prototype in operation at LNGS
- data collected with no shielding and with 4 cm Cu shielding
- measurement performed
- background model validation in progress
- not directionality
- concluded in May 2025

NR discrimination



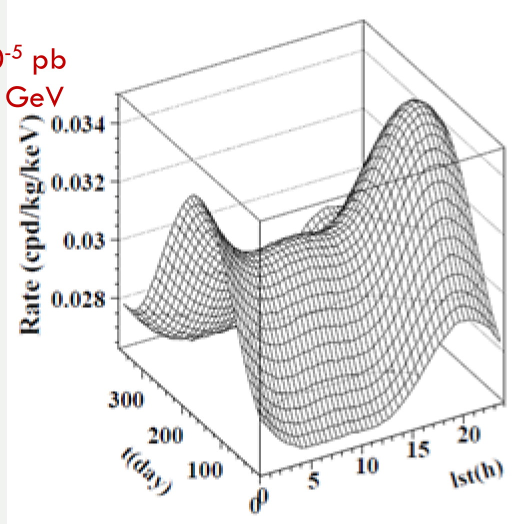
$ZnWO_4$

Eur. Phys. J. C (2013) 73:2276
Eur. Phys. J. A 56 (2020) 83



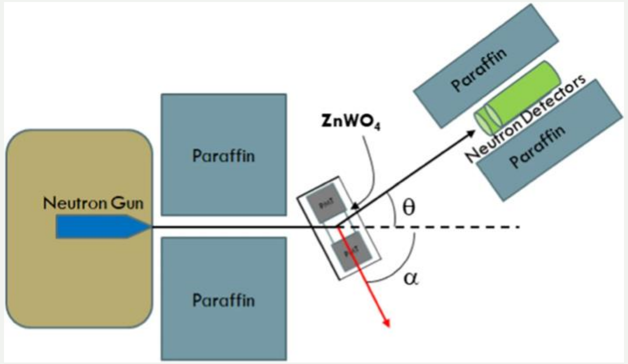
- Anisotropic Scintillator (proposed by DAMA Coll.):
  - for heavy particles the light output and the pulse shape depends on the particle impinging direction wrt crystal axes
  - for γ/e isotropic light output and pulse shape
- The observation of an anisotropy in the distribution of nuclear recoil direction could give evidence for such DM candidates

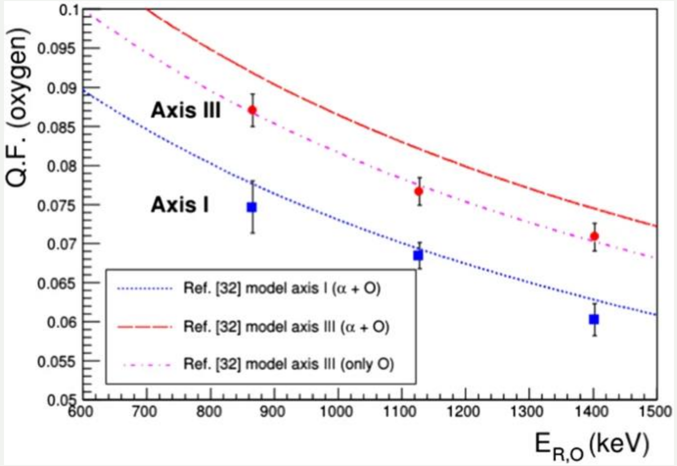
[2-3] keV
$\sigma_p = 5\times10^{-5}$ pb
$m_{DM} = 10$ GeV



The signature is very distinctive and cannot be mimicked by background

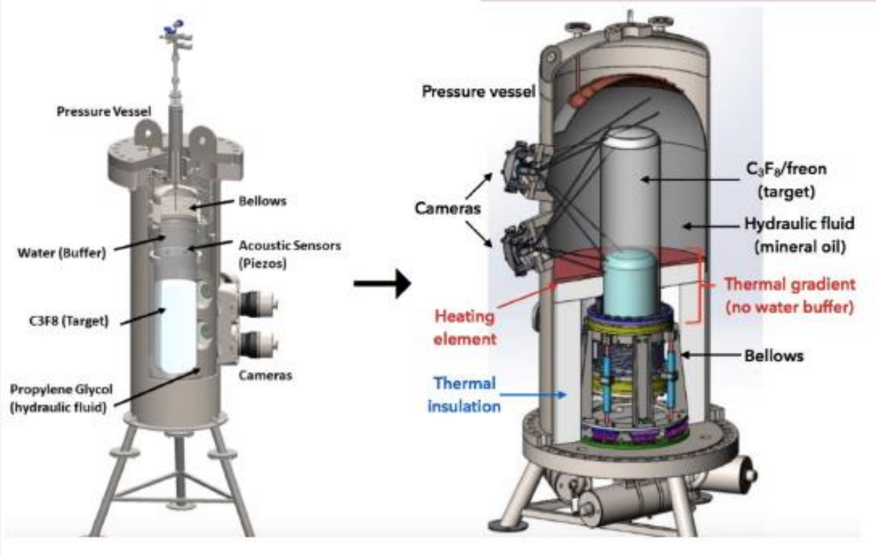
First evidence for anisotropy on the response of $ZnWO_4$ for nuclear recoils

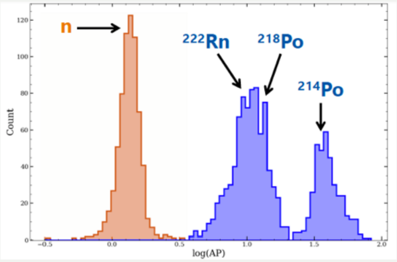


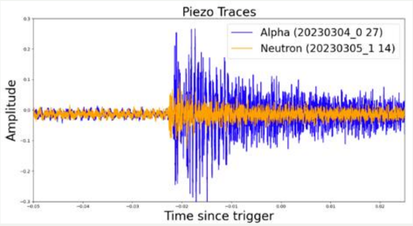


Bubble Chamber (PICO Experiment)

- Superheated fluid (CF_3I, C_3F_8, C_4F_{10})
- Particles interacting ($E>E_{th}$) evaporate a small amount of material: bubble nucleation
- Readout: camera and piezo-electric acoustic sensor
- Insensitive to electron and gammas
- PICO40L commissioning and data taking 2024-2025; analysis in progress

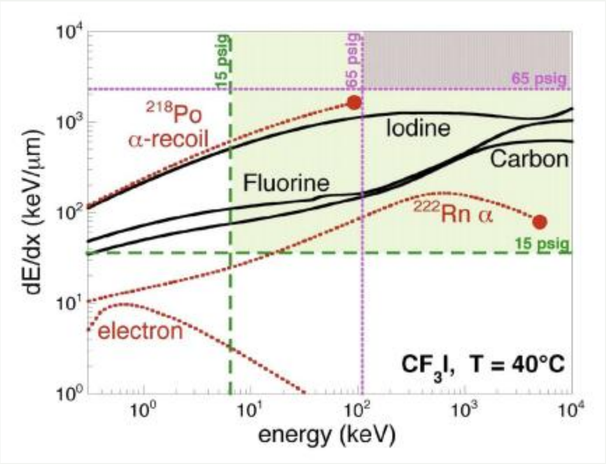






- Alphas deposit their energy over tens of microns
- Nuclear recoils deposit theirs over tens of nanometers

Phys. Rev. D 100, 022001 (2019)



CONCLUSIONS

- DM direct detection is an eclectic field: very different solid techniques can give complementary results
- Ideal zero background experiment is vanishing
- Validation of background more and more challenging
- Neutrino fog zone at the horizon
- Further scaling in mass requires enormous investments
- The model independent signature is the only strategy to point out the presence of Dark Matter particle component(s) in the Galactic halo
- DAMA positive evidence the only DM signal, many attempts to study the annual modulation in NaI(Tl)