WIMP search programme introduction

Direct Dark Matter Detection Report Community Feedback Meeting

February 2, 2021

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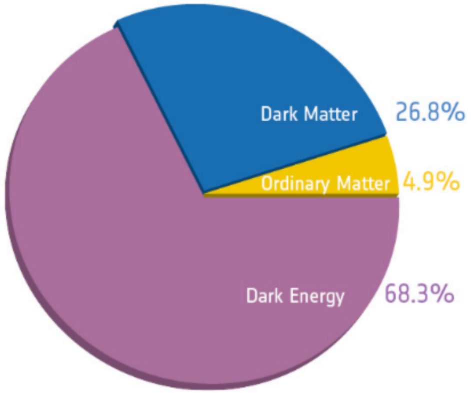
Search for dark matter

We believe that dark matter exists but we do not know what it is and how it interacts



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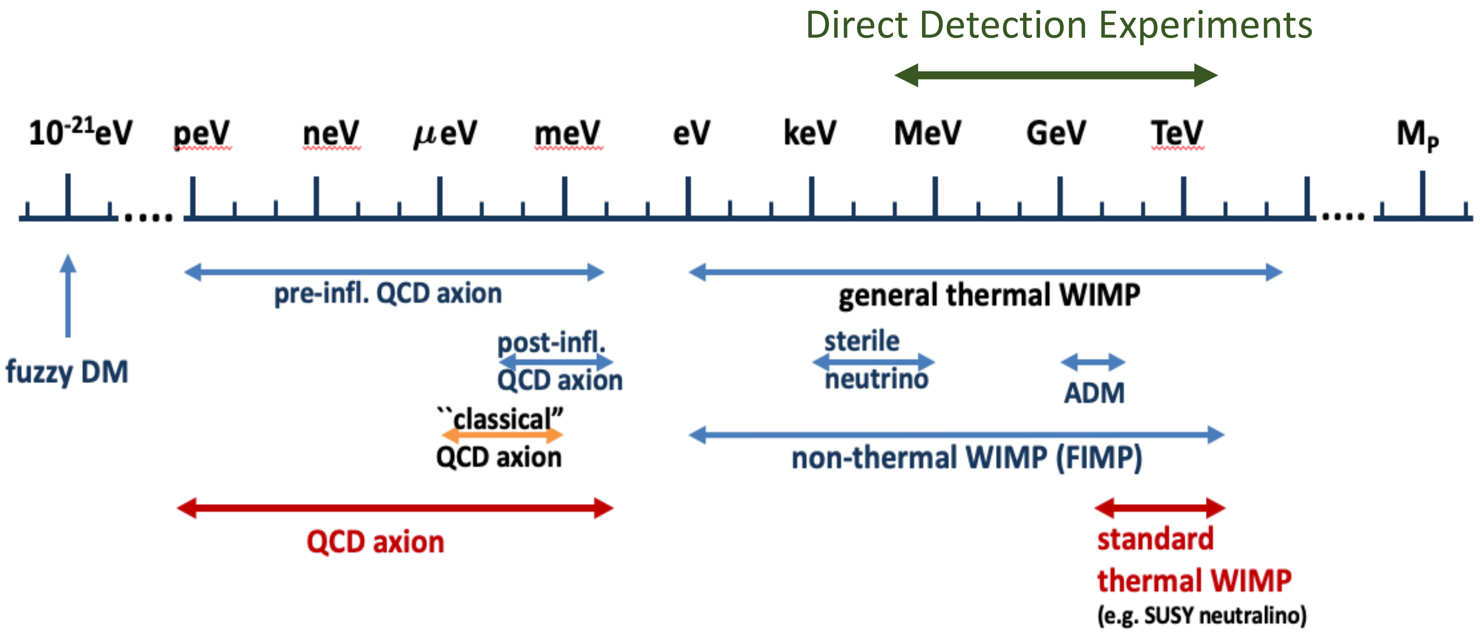


Need experients to probe the broadest experimentally accessible ranges of particle mass, couplings and interaction channels!

Dark matter direct detection

Search for signals induced by dark matter from the Galactic DM halo in terrestrial detectors

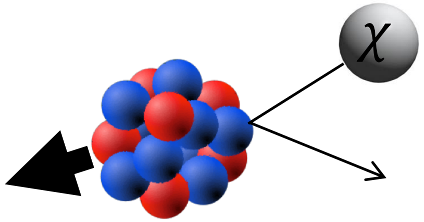
Basic idea

Dark matter is made of particles
which interact with Standard Model particles

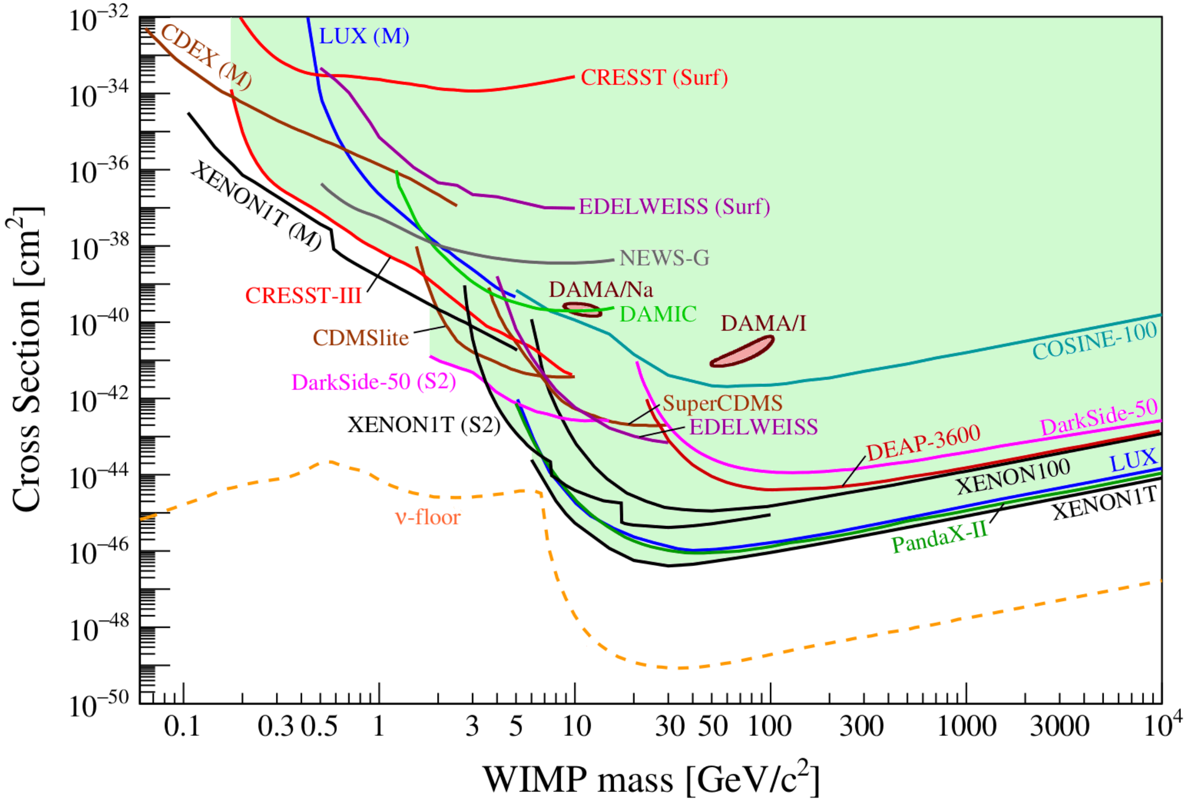
Most common scenario

- (in)elastic scattering off a target nucleus
- momentum transfer gives rise to a nuclear recoil

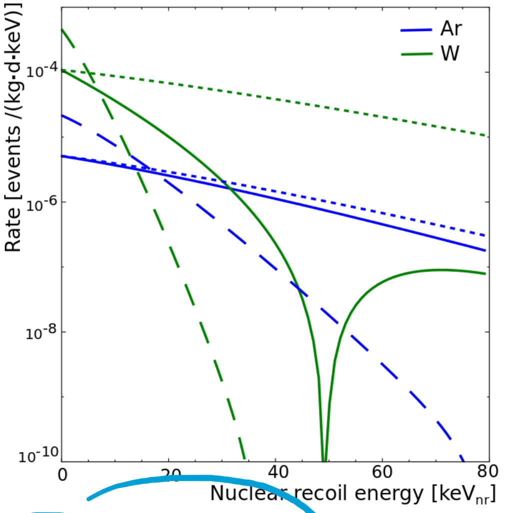
$$\frac{dR}{dE_r} \propto \frac{\rho_0}{m_\chi \mu^2} \sigma_0 F^2(E_r) \int_{v_{min}(E_r)=\sqrt{\frac{E_r m_N}{2\mu^2}}}^{v_{esc}} d^3v \, \frac{f(\bar{v})}{v}$$



Dark matter direct detection



J. Phys. G43 (2016) no.1, 013001



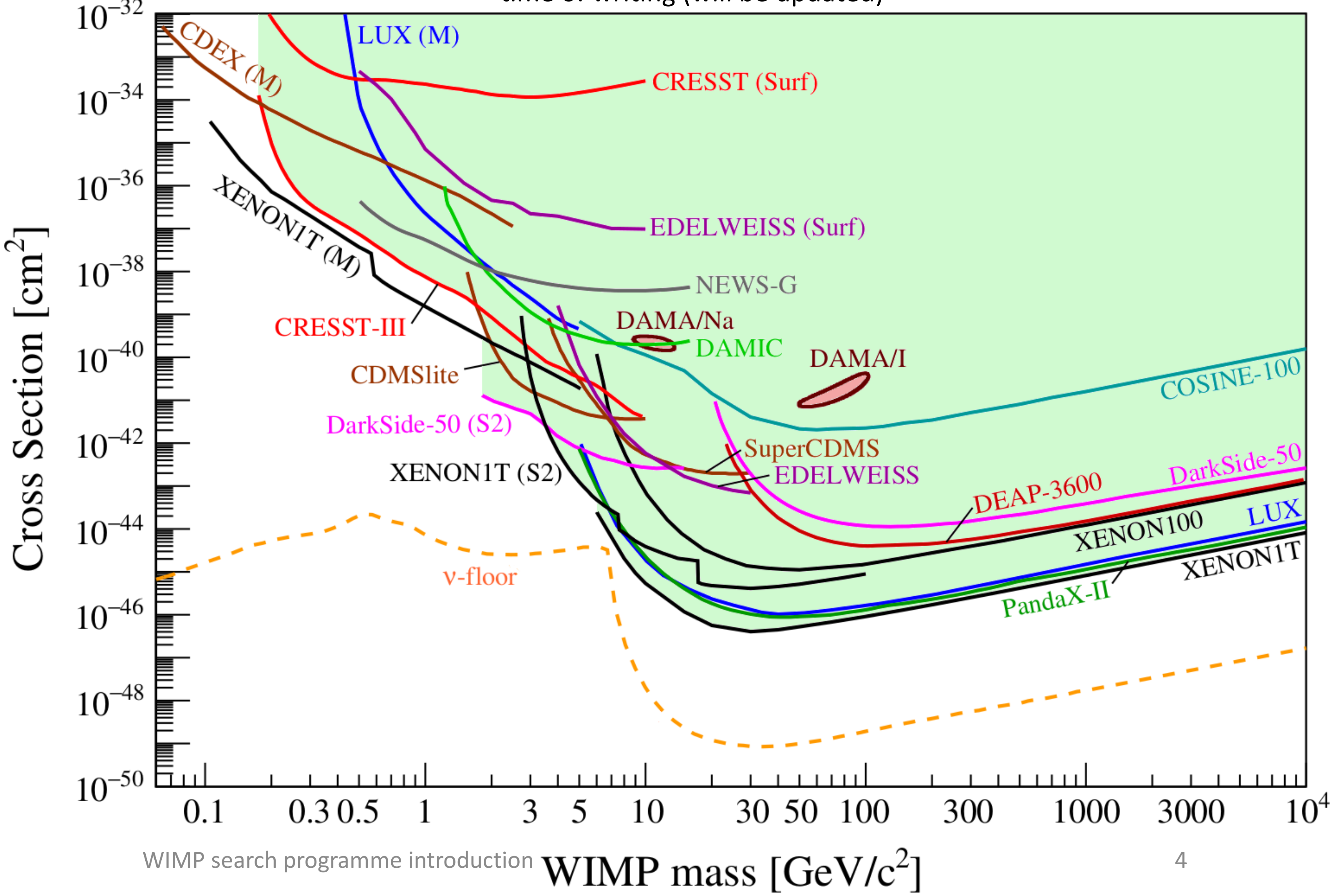
$$\frac{dR}{dE_r} \propto \frac{\rho_0}{m_\chi \mu^2} \sigma_0 F^2(E_r) \int_{v_{min}(E_r)=\sqrt{\frac{E_r m_N}{2\mu^2}}}^{v_{esc}} d^3v \frac{f(\bar{v})}{v}$$

Credit: ESO/L. Calçada

Dark matter direct detection – Current status*

* Published in a peer reviewed journal at the time of writing (will be updated)

Current status of searches for spin-independent elastic WIMP-nucleus scattering assuming the standard parameters for an isothermal WIMP halo: ρ_0 = 0.3 GeV/cm^3, v_0 = 220 km/ s, v_{esc} = 544 km/s. Results labelled "M" were obtained assuming the Migdal effect. Results labelled "Surf" are from experiments not operated underground. The ν-floor shown here for a Ge target is a discovery limit defined as the cross section σ_d at which a given experiment has a 90% probability to detect a WIMP with a scattering cross section $\sigma > \sigma_d$ at ≥3 sigma.

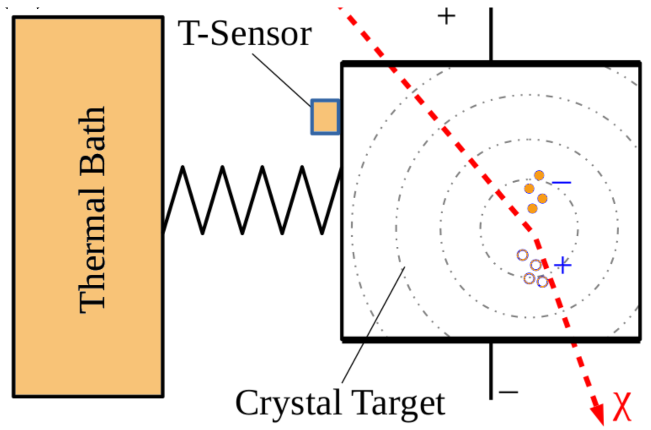


European leadership in highest-sensitivity experiments is very strong.

<u>Diversity allows to be in the best position for high-impact results!</u>

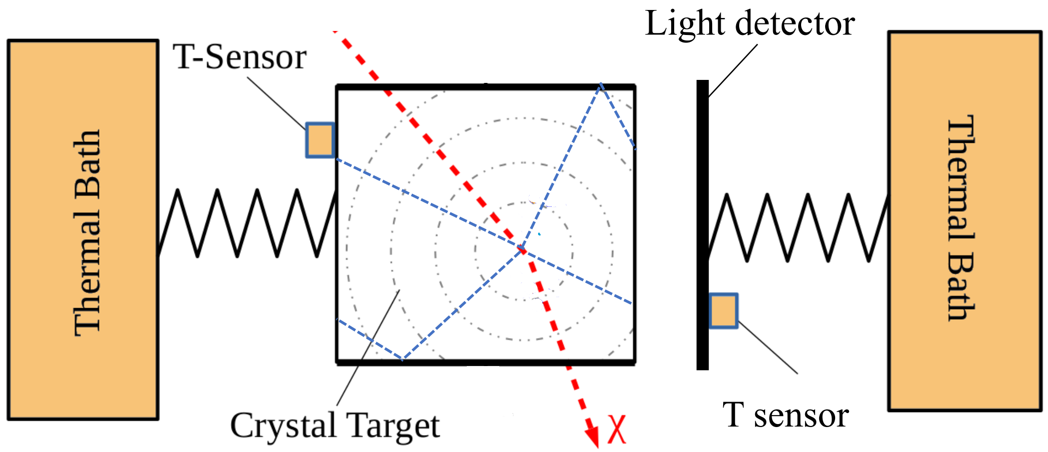
Cryogenic Experiments

- Direct measurement of the (almost) full energy deposition
- Low (< 100eV) nuclear recoil energy thresholds
- Background rejection down to low energy
- mK operating temperature



Phonon + Ionization

- Phonon and charge sensors on the target crystal
- Particle identification via ratio of ionization to primary phonon



Phonon + Light

- Phonon sensor on the target crystal, separate cryogenic detector for light signal
- Particle identification via ratio of light to primary phonon

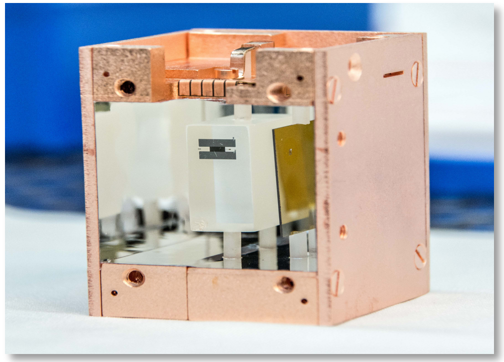
Cryogenic Experiments

In recent years have consolidated their role as the leading technology in the GeV/c^2 and sub–GeV/c^2 mass region.

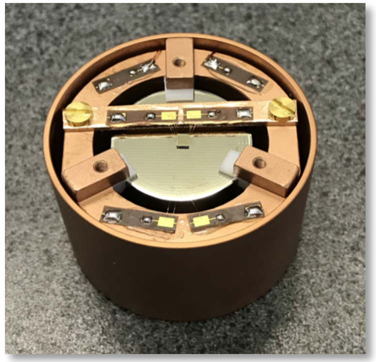
European leadership is very strong two out of three most sensitive cryogenic experiments (CRESST, EDELWEISS) being fully European.

- Unique in exploring the low mass range down to the MeV/c^2 regime
- Possibility of using different target materials – complementary sensitivities to different models
- Slow scalability to large exposures
- Technology being exploited for CEvNS

CRESST



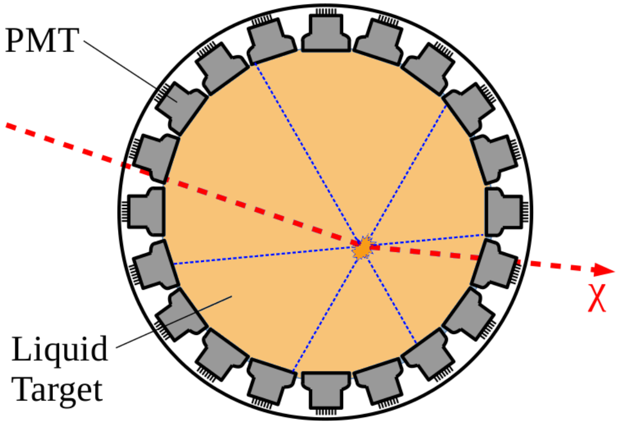
EDELWEISS

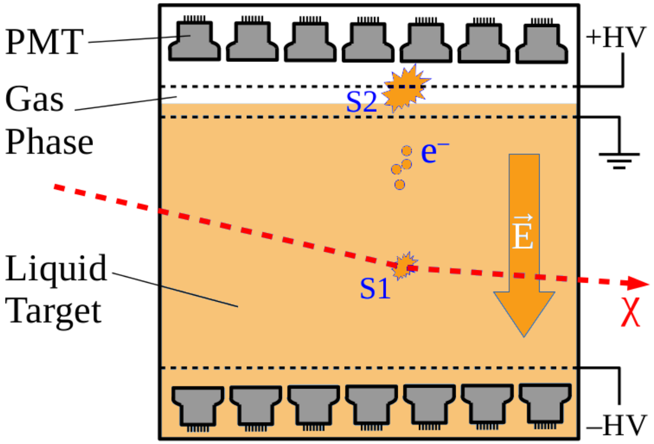


<u>Ten-year perspective and beyond:</u>
The cryogenic technology to access low mass DM is already mature enough to start the planning on a tonne-scale experiment to reach down to the solar neutrino floor.

Liquid Noble Gas Experiments

Noble gases Ar and Xe are excellent scintillators and can be ionized easily
Used to build massive, dense and compact DM targets





Single-phase liquid noble gas detectors

- measure only the scintillation signal
- interaction position can be reconstructed via photon timing and signal distribution with few cm resolution
- Ar detectors employ PSD for background reduction

Dual-phase time projection chambers

- measure the primary scintillation signal (S1) in the liquid and ionisation electrons via secondary scintillation (S2) in the gas
- reconstruction of the interaction position with mm-precision
- multi-scatter rejection
- ratio S2/S1 used to distinguish electronic from nuclear recoils
- Ar detectors employ PSD for background reduction

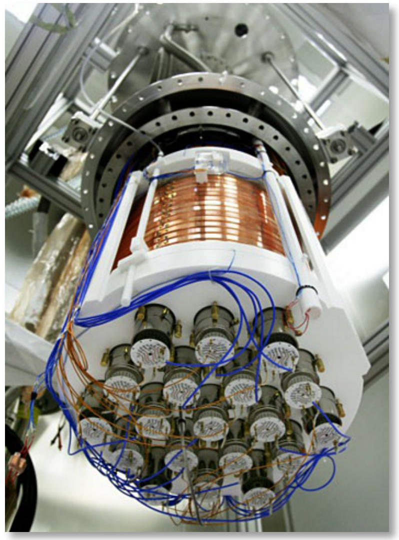
Liquid Noble Gas Experiments

In the last decades liquid noble gas experiments have consolidated their role as the leading technology in the mass range from few GeV/c^2 to the TeV/c^2 scale.

Strong European leadership, providing key contributions, including innovative technologies, extensive research and development effort, and also significant funding

- Easily scalable to very large masses (multi-tonne)
- Limited E threshold in standard operating mode
- Very effective in the WIMP-like scenario and for heavy dark matter

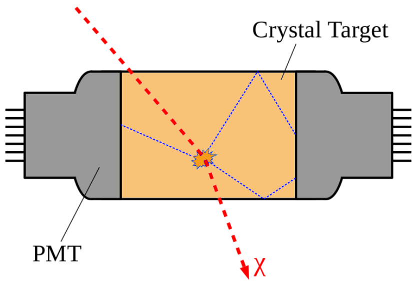
DarkSide



XENON

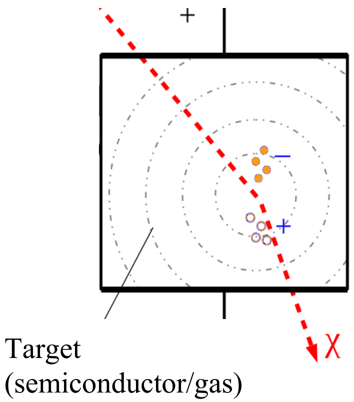
Ten-year perspective and beyond:
While the solar neutrino floor is in reach by the upcoming generation of detectors, substantial innovative R&D for both LAr and LXe programmes will be needed to get down to the atmospheric neutrino floor. The LAr groups have formed the Global Argon DM Collaboration to build DarkSide-20k and its successor, the 300t detector ARGO. On the xenon side, R&D is ongoing to build the next generation detector DARWIN and towards multi-tonne liquid xenon detectors in general.

NaI(Tl) Scintillators, Ionization Experiments and Bubble Chambers



Arrays of high-purity scintillator crystals

- measure only scintillation signal
- simple design
- long time stability
- relatively high background level
- absence of fiducialisation and electronic recoil rejection
- concentrate on exploiting the annual modulation signature



p-type point contact HPGe

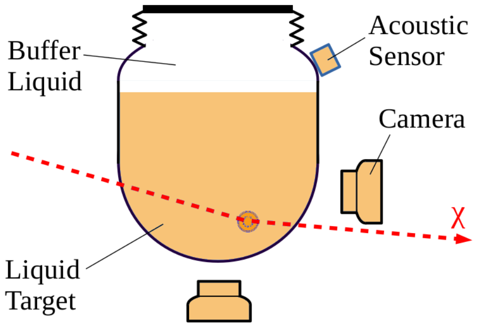
- low thresholds thanks to a very small capacitance in combination with a rather large detector mass

Si – CCDs

- high sensitivity to single-electron signals and very low ionization energy
- 3D position reconstruction and effective particle identification for background rejection

Spherical proportional counters

- Light target (Ne, He, H)
- Pulse shape discrimination against surface events down to low energy
- Low threshold thanks to very low capacitance



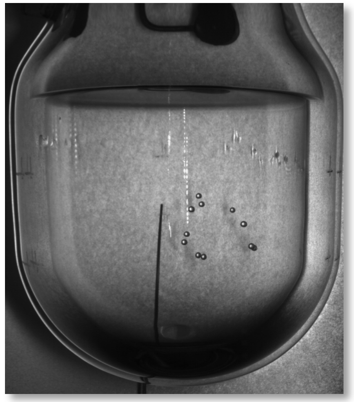
Bubble chambers

- fluid in a metastable state which can be quenched by energy depositions
- threshold device with integrating response, no information on the energy of the event
- can be tuned to be immune to Ers
- alpha-particles can be rejection based on acoustics of bubble explosion
- highest sensitivity for SD couplings to protons thanks to F-targets

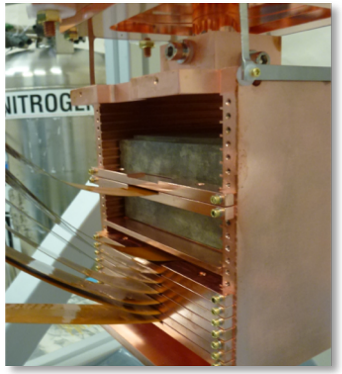
NaI(Tl) Scintillators, Ionization Experiments and Bubble Chambers

ANAIS

PICO



DAMIC



CDEX

NEWS-G

- NaI scintillators: unique opportunity to prove the NaI modulation anomaly
- Ionization detectors: very sensitive to DM-electron interactions with very low threshold, lightest nuclei in gas targets
- Bubble chambers: very sensitive spin dependent limits

<u>Ten-year perspective and beyond:</u>

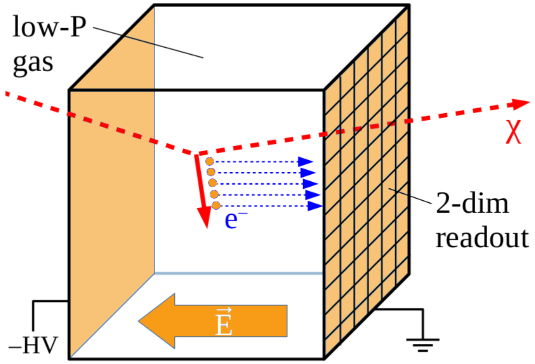
NaI scintillators experiments will focus on the necessary test of the DAMA/LIBRA annual modulation signal. Depending on the outcome in some two years, the community will likely be in a position to outline their longer-term plans.

Detectors with single-electron sensitivity are uniquely sensitive to hidden sector DM, through DM-electron interactions.

Intense R&D on proportional counters towards increasingly radiopure and large detectors.

Bubble chambers following a staged approach to test the technology for future tonne scale detector.

Directional Experiments



Directional detectors aiming at reconstructing the direction and energy of the WIMP-induced nuclear recoil offer an unambiguous way of confirming the Galactic origin of a WIMP signal.

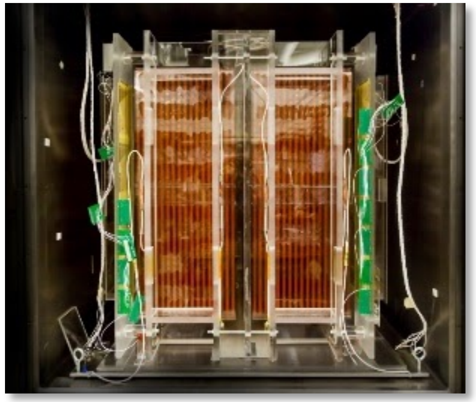
Ten-year perspective and beyond:

Several efforts worldwide, including European-led projects, are underway. Currently lagging behind conventional detectors in terms of sensitivity, due to technological challenges and significantly lower target masses.

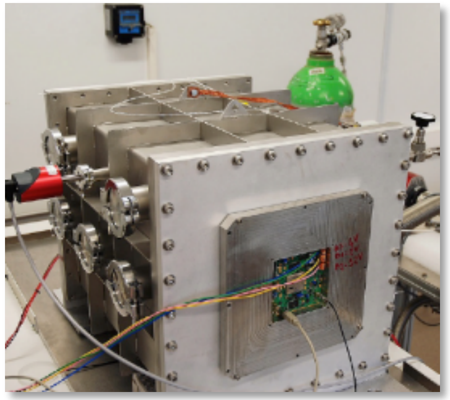
CYGNUS proto-collaboration formed carrying out R&D to determine the optimum configuration for a large target mass directional detector.

- Aim at reconstructing the direction of the WIMP-induced nuclear recoil
- Low-pressure gas targets (~40 – 100 mbar) with photographic or fine-granularity 2- 3D track readout in a TPC geometry
- Very promising technology for unambiguous signature and halo exploration (in case of positive signal)
- Immune to neutrino floor
- Still very far from competitive exposure
- Highest sensitivity for SD couplings to protons thanks to F-targets

DRIFT



MIMAC



Comparison of Different Experimental Efforts

Many different technologies and experimental efforts:

- The low-mass region, from $\sim$100 MeV/c^2 to $\sim$5 GeV/c^2, will be best explored by the cryogenic bolometers (CRESST, EDELWEISS, SuperCDMS) with their extremely low-energy thresholds and background rejection capabilities down to the lowest energies.
- Interactions of DM particles in the mass range of 1 − 100 MeV/c^2 will be best searched for by detectors with a sensitivity to single electrons.
- The exploration of the medium to high-mass range requires very large exposures and will be dominated by the massive LAr (DarkSide-20k, ARGO) and LXe TPCs (XENONnT, LZ, PandaX-4T, DARWIN).

Different targets/technologies are sensitive to different interactions (SI, SD, DM-e)

The combination of data from different targets can significantly improve the reconstruction of WIMP mass and cross section.

Diversified approach needed to probe the broadest experimentally accessible ranges of particle mass and interactions!

Comparison of Different Experimental Efforts

The discovery potential of DM experiments at their limit of sensitivity is strongly affected by exposure, threshold, uncertainties and the level of background events.

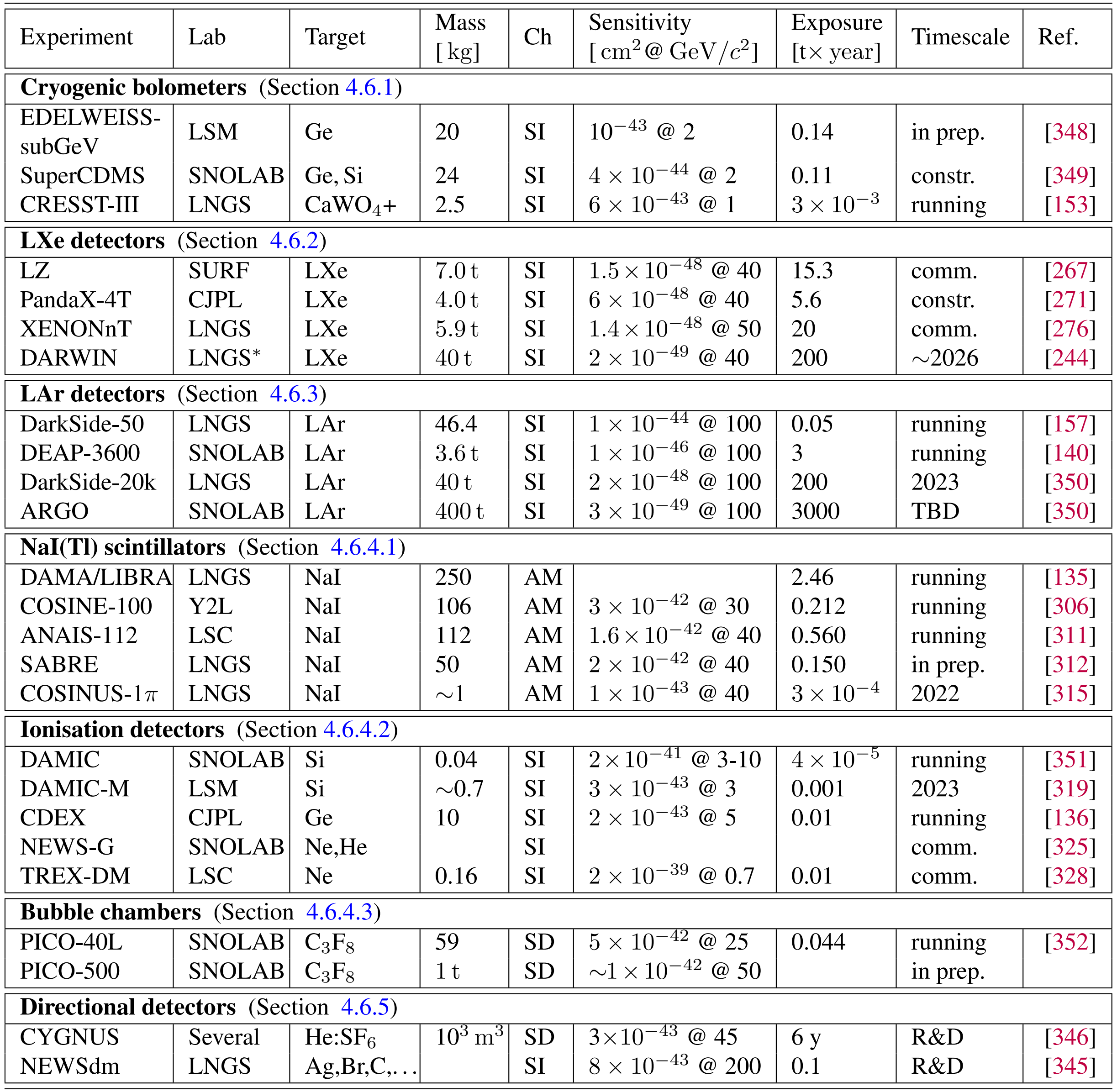
Next-generation DM experiments will observe neutrino-induced background events via both ν-e elastic scattering and CEvNS, generating ER and NR events, respectively.

If a putative DM discovery is made in any experiment, a confirmation using a second target and possibly even a second technology is required

- to rule out potentially mis-identified experimental backgrounds or artefacts
- to start confining the relevant DM particle properties.

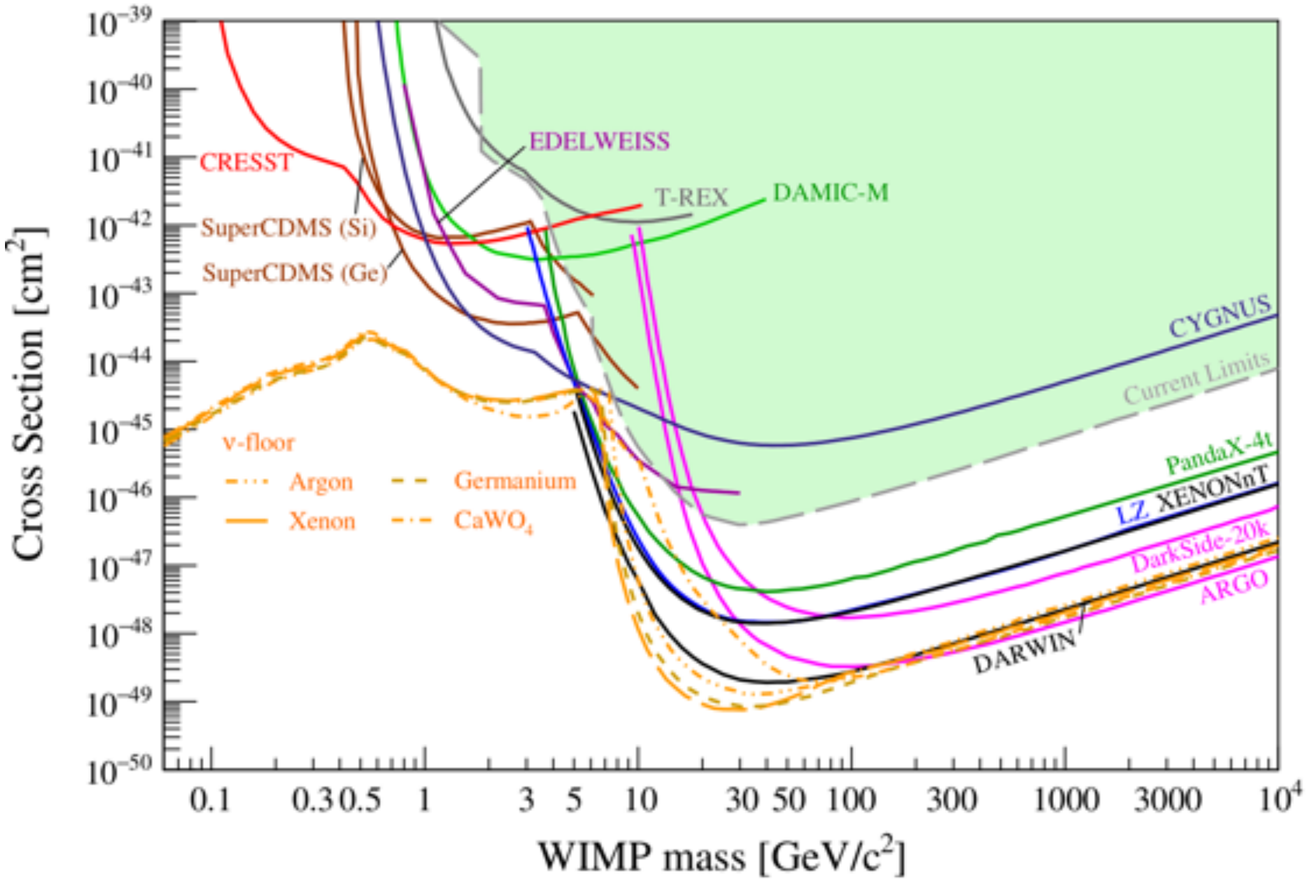
<u>We need experiments that can test each other!</u>

Dark matter direct detection – Projections*



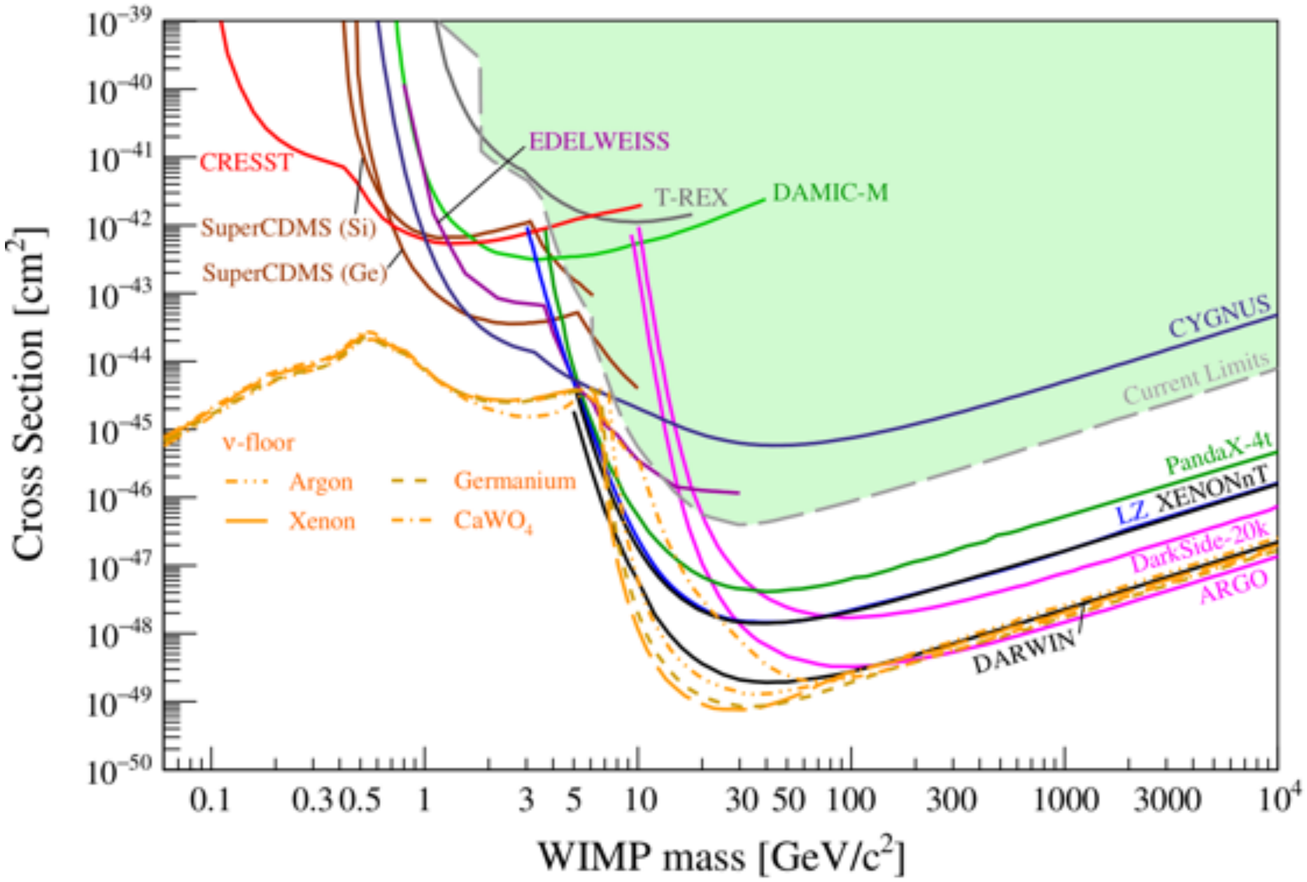
Experiment	Lab	Target	Mass [kg]	Ch	Sensitivity [cm^2@ GeV/c^2]	Exposure [t× year]	Timescale	Ref.
Cryogenic bolometers (Section 4.6.1)								
EDELWEISS-subGeV	LSM	Ge	20	SI	10^{-43} @ 2	0.14	in prep.	[348]
SuperCDMS	SNOLAB	Ge, Si	24	SI	4×10^{-44} @ 2	0.11	constr.	[349]
CRESST-III	LNGS	$CaWO_4$+	2.5	SI	6×10^{-43} @ 1	3×10^{-3}	running	[153]
LXe detectors (Section 4.6.2)								
LZ	SURF	LXe	7.0 t	SI	1.5×10^{-48} @ 40	15.3	comm.	[267]
PandaX-4T	CJPL	LXe	4.0 t	SI	6×10^{-48} @ 40	5.6	constr.	[271]
XENONnT	LNGS	LXe	5.9 t	SI	1.4×10^{-48} @ 50	20	comm.	[276]
DARWIN	LNGS*	LXe	40 t	SI	2×10^{-49} @ 40	200	∼2026	[244]
LAr detectors (Section 4.6.3)								
DarkSide-50	LNGS	LAr	46.4	SI	1×10^{-44} @ 100	0.05	running	[157]
DEAP-3600	SNOLAB	LAr	3.6 t	SI	1×10^{-46} @ 100	3	running	[140]
DarkSide-20k	LNGS	LAr	40 t	SI	2×10^{-48} @ 100	200	2023	[350]
ARGO	SNOLAB	LAr	400 t	SI	3×10^{-49} @ 100	3000	TBD	[350]
NaI(Tl) scintillators (Section 4.6.4.1)								
DAMA/LIBRA	LNGS	NaI	250	AM		2.46	running	[135]
COSINE-100	Y2L	NaI	106	AM	3×10^{-42} @ 30	0.212	running	[306]
ANAIS-112	LSC	NaI	112	AM	1.6×10^{-42} @ 40	0.560	running	[311]
SABRE	LNGS	NaI	50	AM	2×10^{-42} @ 40	0.150	in prep.	[312]
COSINUS-1π	LNGS	NaI	∼1	AM	1×10^{-43} @ 40	3×10^{-4}	2022	[315]
Ionisation detectors (Section 4.6.4.2)								
DAMIC	SNOLAB	Si	0.04	SI	2×10^{-41} @ 3-10	4×10^{-5}	running	[351]
DAMIC-M	LSM	Si	∼0.7	SI	3×10^{-43} @ 3	0.001	2023	[319]
CDEX	CJPL	Ge	10	SI	2×10^{-43} @ 5	0.01	running	[136]
NEWS-G	SNOLAB	Ne,He		SI			comm.	[325]
TREX-DM	LSC	Ne	0.16	SI	2×10^{-39} @ 0.7	0.01	comm.	[328]
Bubble chambers (Section 4.6.4.3)								
PICO-40L	SNOLAB	C_3F_8	59	SD	5×10^{-42} @ 25	0.044	running	[352]
PICO-500	SNOLAB	C_3F_8	1 t	SD	$\sim1\times10^{-42}$ @ 50		in prep.	
Directional detectors (Section 4.6.5)								
CYGNUS	Several	He:SF_6	10^3 m^3	SD	3×10^{-43} @ 45	6 y	R&D	[346]
NEWSdm	LNGS	Ag,Br,C,...		SI	8×10^{-43} @ 200	0.1	R&D	[345]

* Predictions for the (far) future come with some uncertainty. Based on best-guess assumptions but include quite some extrapolation.



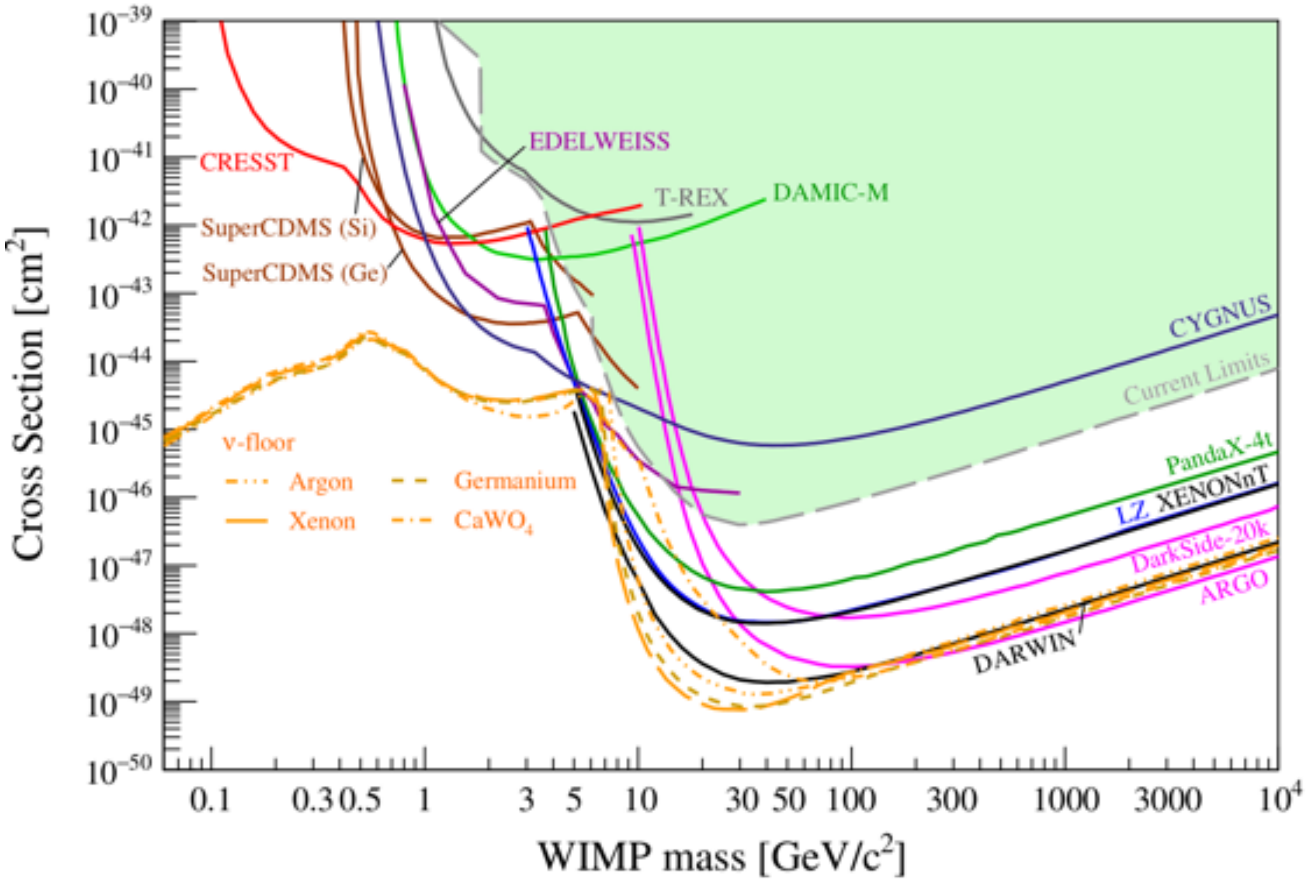
Dark matter direct detection – Future

Recommendation 2. The diversified approach to probe the broadest experimentally accessible ranges of particle mass and interactions is needed to ensure the most conservative and least assumption-dependent exploration of hypothetical candidates for cosmological dark matter or subdominant relics.



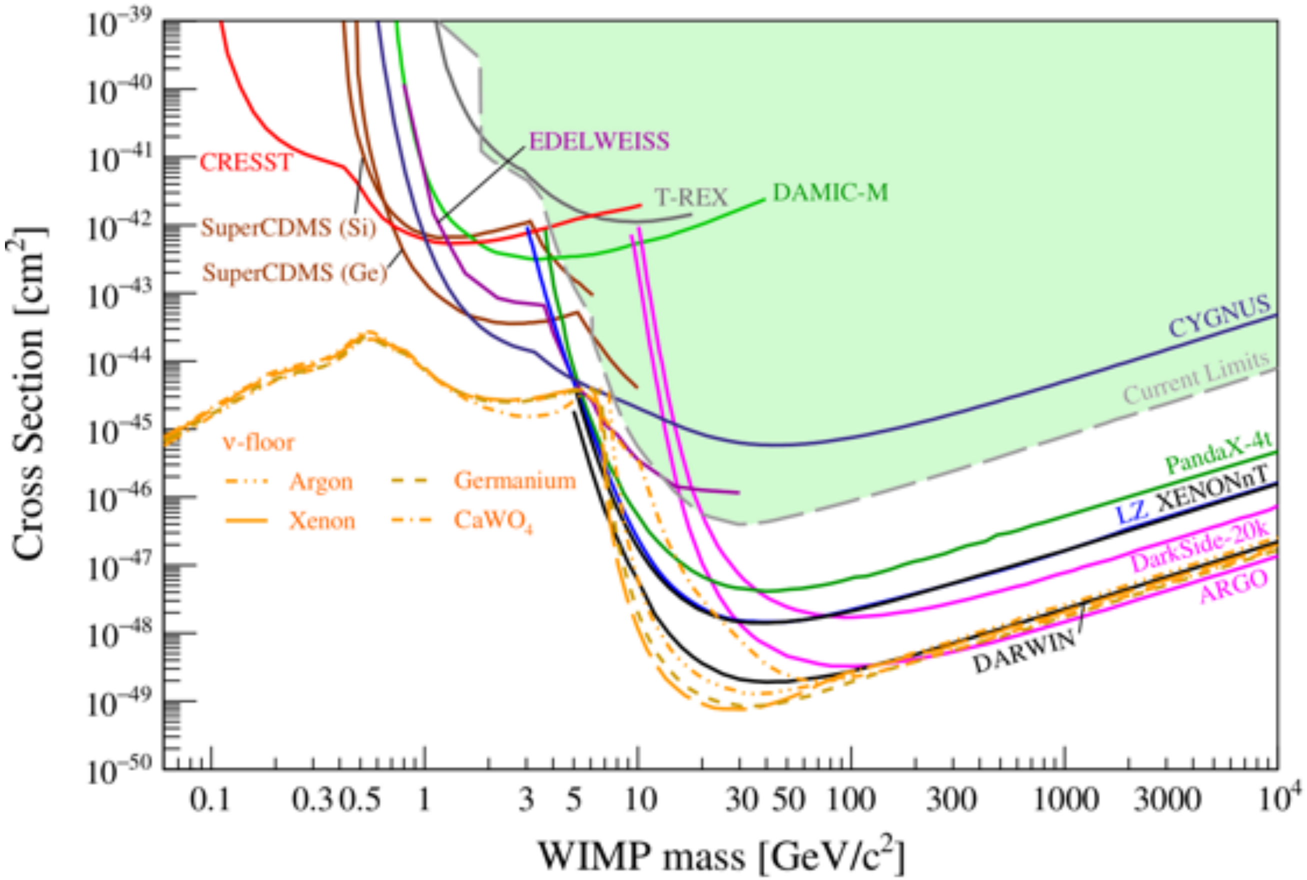
Dark matter direct detection – Future

Recommendation 3. The experimental underground programmes with the best sensitivity to detect signals induced by dark matter scattering off the target should receive enhanced support to continue efforts to reach down to the so-called neutrino floor on the shortest possible timescale.



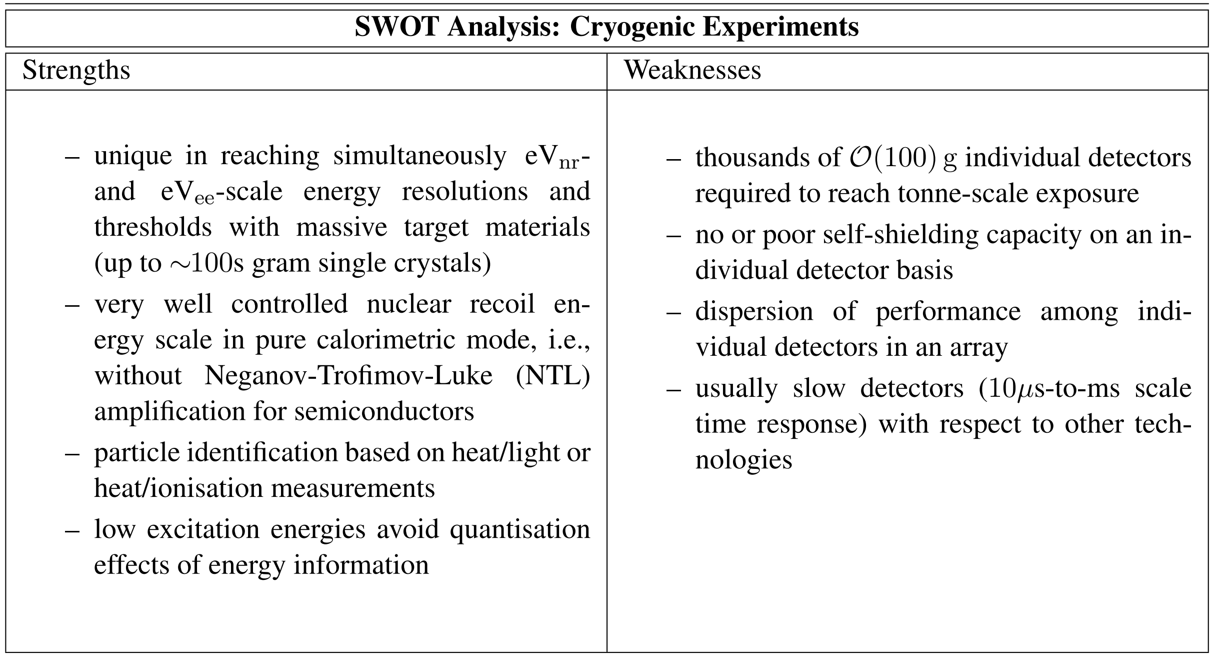
Dark matter direct detection – Future

Recommendation 4. <u>European participation in DM search programmes and associated, often novel, R&D efforts, that currently do not offer the biggest improvement in sensitivity should continue and be encouraged with view of a long-term investment in the field and the promise of potential interdisciplinary benefits.</u>



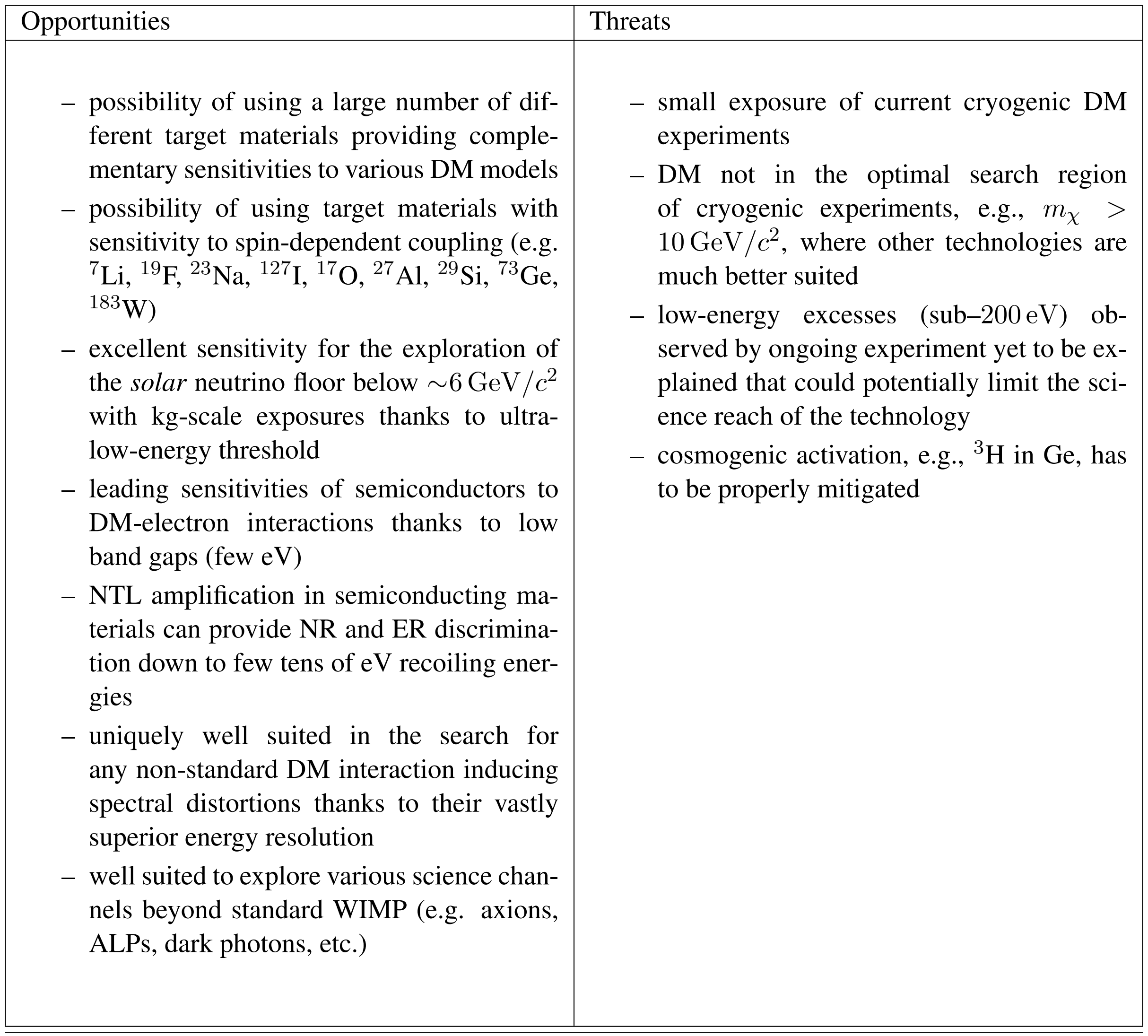
Additional material

Cryogenic Experiments



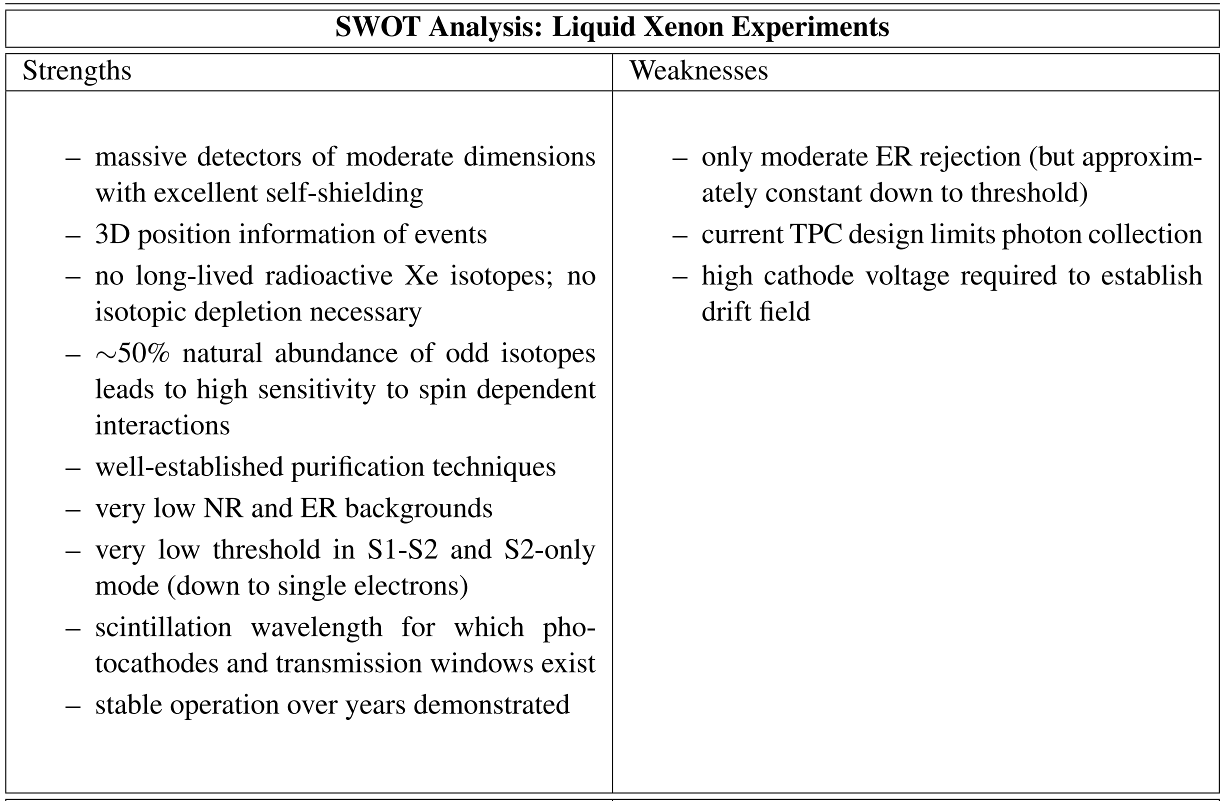
SWOT Analysis: Cryogenic Experiments

Strengths	Weaknesses
– unique in reaching simultaneously $\mathrm{eV_{nr}}$- and $\mathrm{eV_{ee}}$-scale energy resolutions and thresholds with massive target materials (up to $\sim$100s gram single crystals) – very well controlled nuclear recoil energy scale in pure calorimetric mode, i.e., without Neganov-Trofimov-Luke (NTL) amplification for semiconductors – particle identification based on heat/light or heat/ionisation measurements – low excitation energies avoid quantisation effects of energy information	– thousands of $\mathcal{O}(100)\,\mathrm{g}$ individual detectors required to reach tonne-scale exposure – no or poor self-shielding capacity on an individual detector basis – dispersion of performance among individual detectors in an array – usually slow detectors (10μs-to-ms scale time response) with respect to other technologies



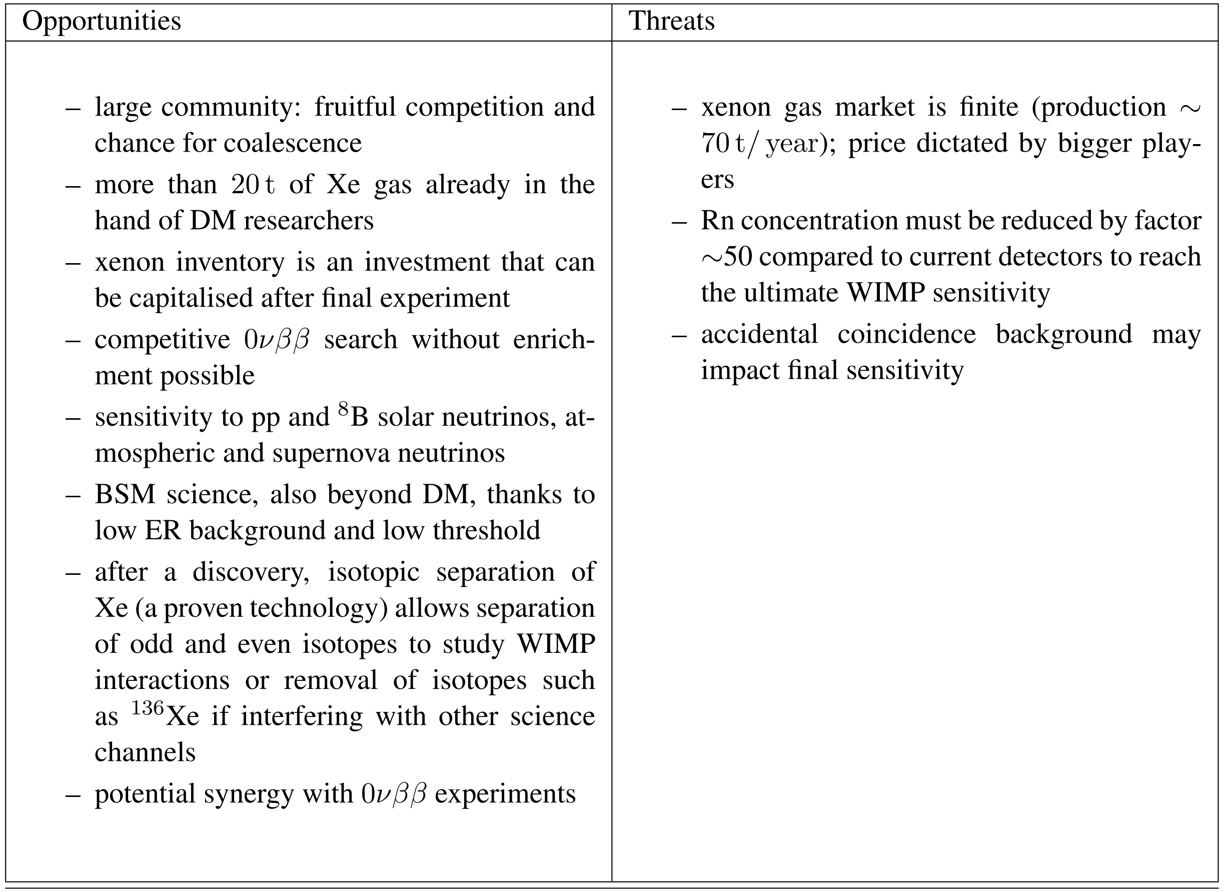
Opportunities	Threats
– possibility of using a large number of different target materials providing complementary sensitivities to various DM models – possibility of using target materials with sensitivity to spin-dependent coupling (e.g. ^{7}Li, ^{19}F, ^{23}Na, ^{127}I, ^{17}O, ^{27}Al, ^{29}Si, ^{73}Ge, ^{183}W) – excellent sensitivity for the exploration of the *solar* neutrino floor below $\sim 6\,\mathrm{GeV}/c^2$ with kg-scale exposures thanks to ultra-low-energy threshold – leading sensitivities of semiconductors to DM-electron interactions thanks to low band gaps (few eV) – NTL amplification in semiconducting materials can provide NR and ER discrimination down to few tens of eV recoiling energies – uniquely well suited in the search for any non-standard DM interaction inducing spectral distortions thanks to their vastly superior energy resolution – well suited to explore various science channels beyond standard WIMP (e.g. axions, ALPs, dark photons, etc.)	– small exposure of current cryogenic DM experiments – DM not in the optimal search region of cryogenic experiments, e.g., $m_\chi > 10\,\mathrm{GeV}/c^2$, where other technologies are much better suited – low-energy excesses (sub–$200\,\mathrm{eV}$) observed by ongoing experiment yet to be explained that could potentially limit the science reach of the technology – cosmogenic activation, e.g., ^{3}H in Ge, has to be properly mitigated

Liquid Xenon Experiments



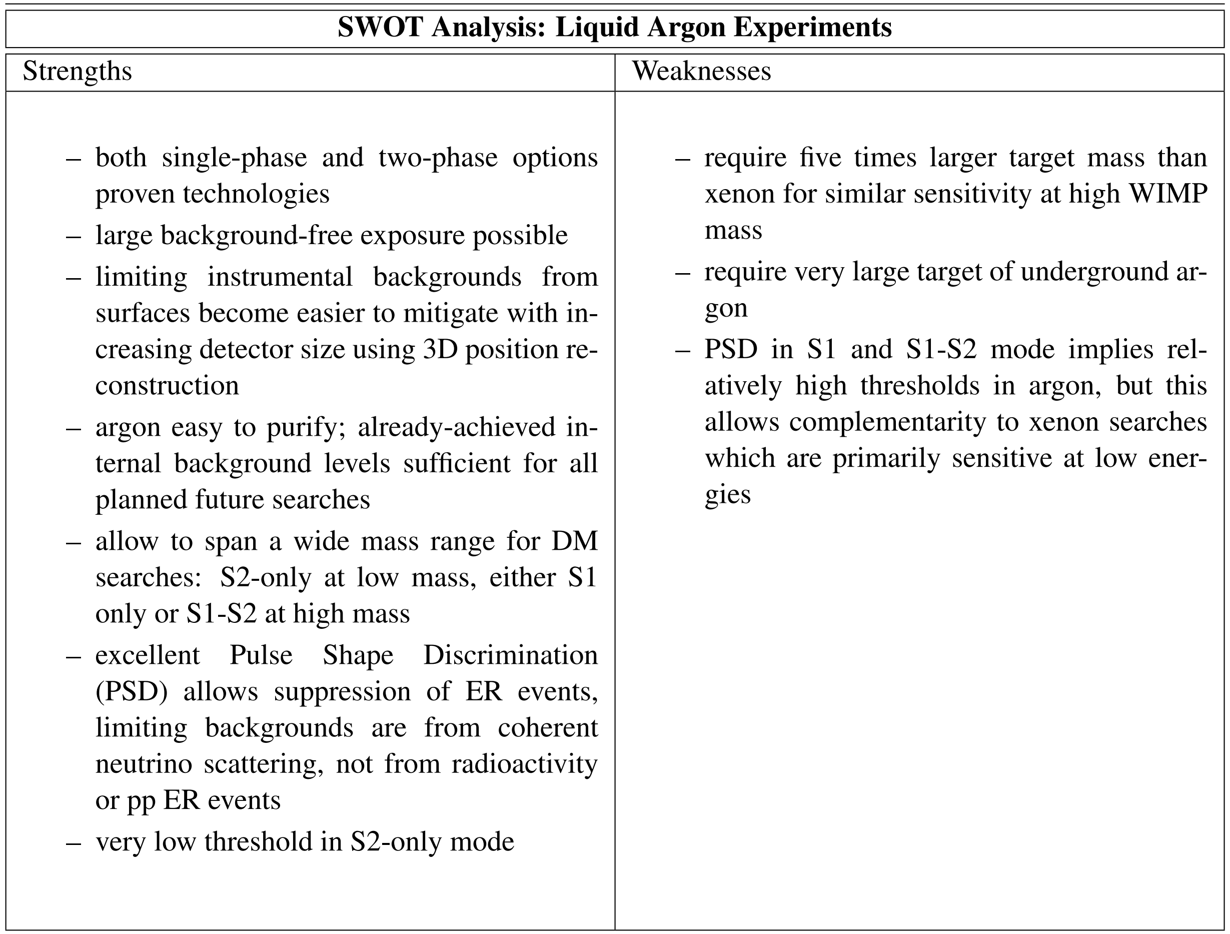
SWOT Analysis: Liquid Xenon Experiments

Strengths	Weaknesses
– massive detectors of moderate dimensions with excellent self-shielding – 3D position information of events – no long-lived radioactive Xe isotopes; no isotopic depletion necessary – $\sim$50% natural abundance of odd isotopes leads to high sensitivity to spin dependent interactions – well-established purification techniques – very low NR and ER backgrounds – very low threshold in S1-S2 and S2-only mode (down to single electrons) – scintillation wavelength for which photocathodes and transmission windows exist – stable operation over years demonstrated	– only moderate ER rejection (but approximately constant down to threshold) – current TPC design limits photon collection – high cathode voltage required to establish drift field

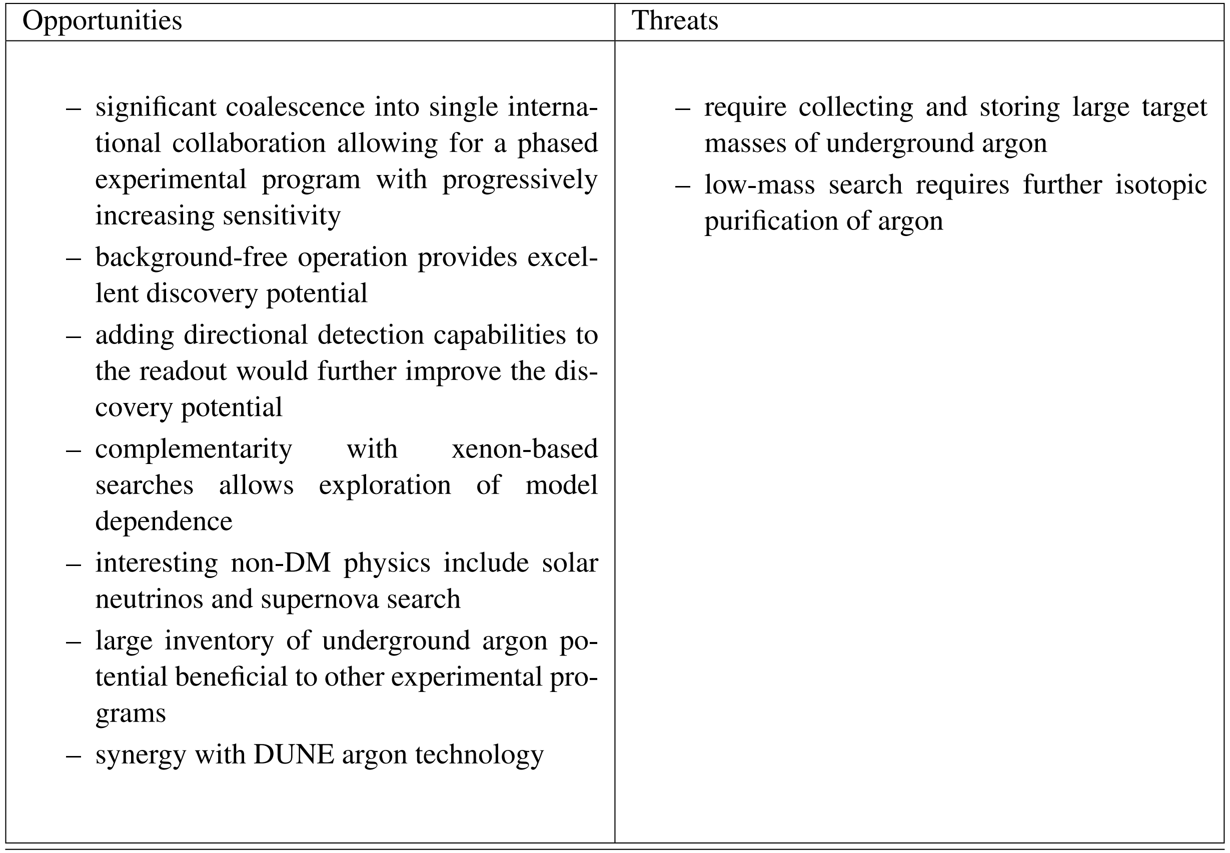


Opportunities	Threats
– large community: fruitful competition and chance for coalescence – more than $20\,\mathrm{t}$ of Xe gas already in the hand of DM researchers – xenon inventory is an investment that can be capitalised after final experiment – competitive $0\nu\beta\beta$ search without enrichment possible – sensitivity to pp and ^{8}B solar neutrinos, atmospheric and supernova neutrinos – BSM science, also beyond DM, thanks to low ER background and low threshold – after a discovery, isotopic separation of Xe (a proven technology) allows separation of odd and even isotopes to study WIMP interactions or removal of isotopes such as ^{136}Xe if interfering with other science channels – potential synergy with $0\nu\beta\beta$ experiments	– xenon gas market is finite (production $\sim 70\,\mathrm{t}/\,\mathrm{year}$); price dictated by bigger players – Rn concentration must be reduced by factor $\sim$50 compared to current detectors to reach the ultimate WIMP sensitivity – accidental coincidence background may impact final sensitivity

Liquid Argon Experiments

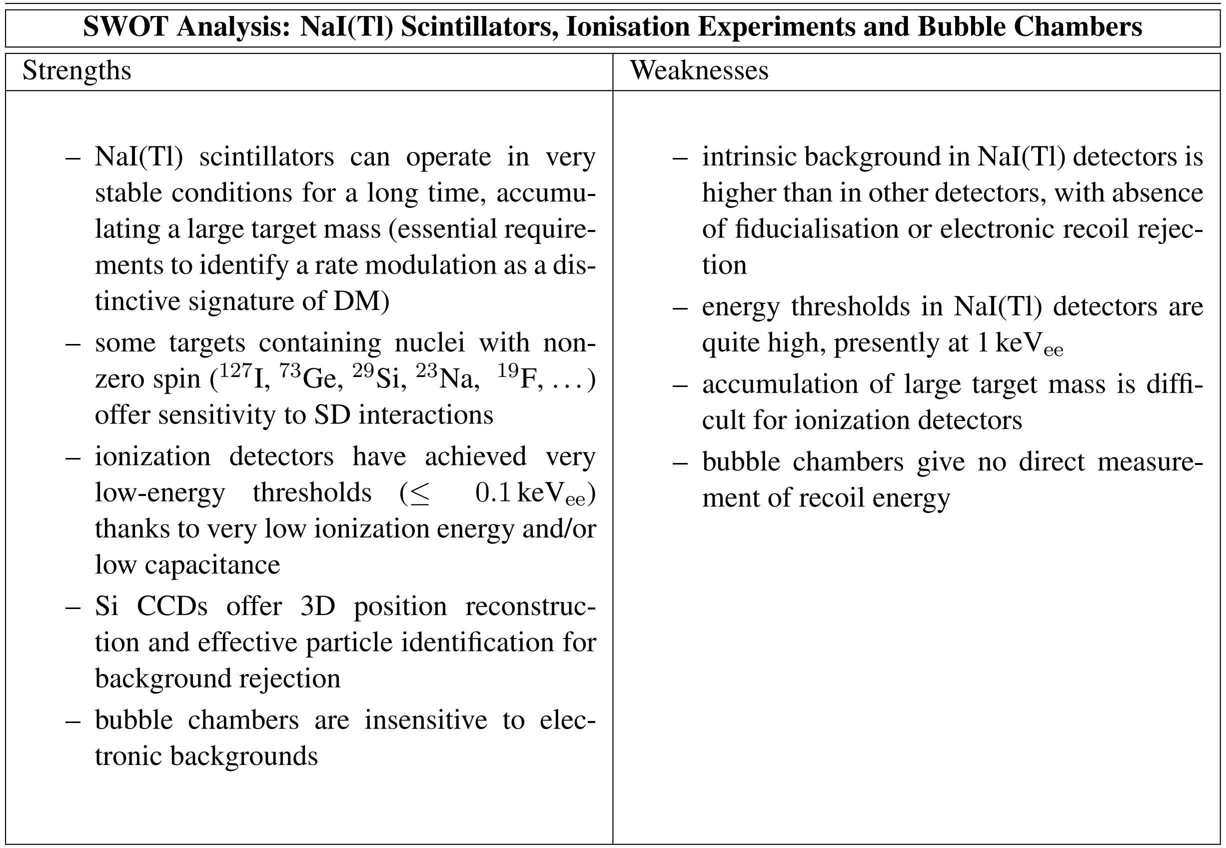


SWOT Analysis: Liquid Argon Experiments	
Strengths	**Weaknesses**
– both single-phase and two-phase options proven technologies – large background-free exposure possible – limiting instrumental backgrounds from surfaces become easier to mitigate with increasing detector size using 3D position reconstruction – argon easy to purify; already-achieved internal background levels sufficient for all planned future searches – allow to span a wide mass range for DM searches: S2-only at low mass, either S1 only or S1-S2 at high mass – excellent Pulse Shape Discrimination (PSD) allows suppression of ER events, limiting backgrounds are from coherent neutrino scattering, not from radioactivity or pp ER events – very low threshold in S2-only mode	– require five times larger target mass than xenon for similar sensitivity at high WIMP mass – require very large target of underground argon – PSD in S1 and S1-S2 mode implies relatively high thresholds in argon, but this allows complementarity to xenon searches which are primarily sensitive at low energies



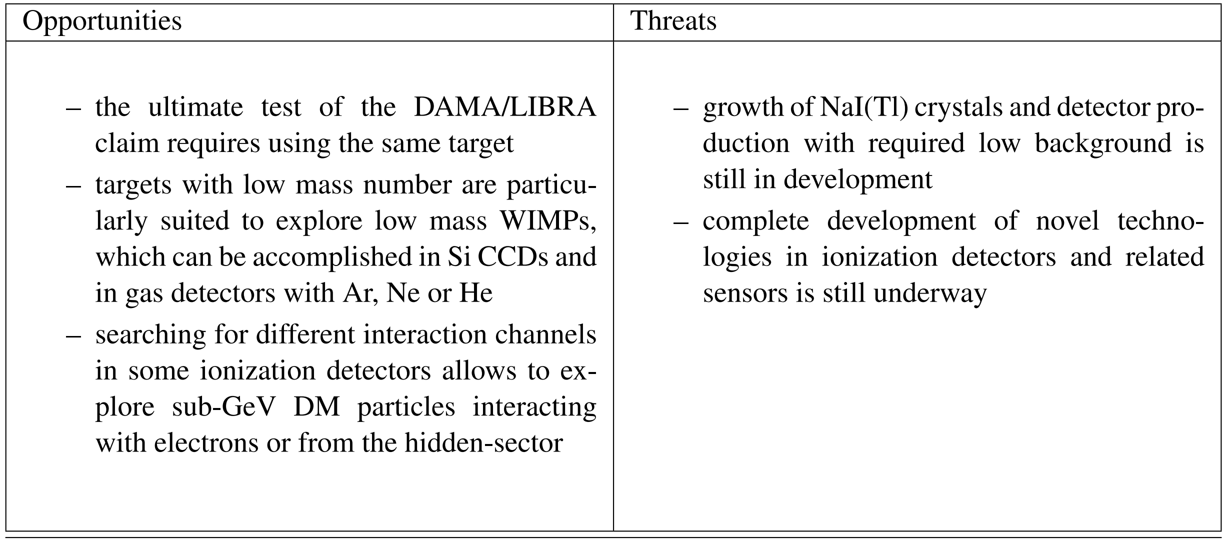
Opportunities	Threats
– significant coalescence into single international collaboration allowing for a phased experimental program with progressively increasing sensitivity – background-free operation provides excellent discovery potential – adding directional detection capabilities to the readout would further improve the discovery potential – complementarity with xenon-based searches allows exploration of model dependence – interesting non-DM physics include solar neutrinos and supernova search – large inventory of underground argon potential beneficial to other experimental programs – synergy with DUNE argon technology	– require collecting and storing large target masses of underground argon – low-mass search requires further isotopic purification of argon

NaI(Tl) Scintillators, Ionization Experiments and Bubble Chambers



SWOT Analysis: NaI(Tl) Scintillators, Ionisation Experiments and Bubble Chambers

Strengths	Weaknesses
– NaI(Tl) scintillators can operate in very stable conditions for a long time, accumulating a large target mass (essential requirements to identify a rate modulation as a distinctive signature of DM) – some targets containing nuclei with non-zero spin (^{127}I, ^{73}Ge, ^{29}Si, ^{23}Na, ^{19}F, …) offer sensitivity to SD interactions – ionization detectors have achieved very low-energy thresholds ($\leq$ 0.1 keV$_{\mathrm{ee}}$) thanks to very low ionization energy and/or low capacitance – Si CCDs offer 3D position reconstruction and effective particle identification for background rejection – bubble chambers are insensitive to electronic backgrounds	– intrinsic background in NaI(Tl) detectors is higher than in other detectors, with absence of fiducialisation or electronic recoil rejection – energy thresholds in NaI(Tl) detectors are quite high, presently at 1 keV$_{\mathrm{ee}}$ – accumulation of large target mass is difficult for ionization detectors – bubble chambers give no direct measurement of recoil energy



Opportunities	Threats
– the ultimate test of the DAMA/LIBRA claim requires using the same target – targets with low mass number are particularly suited to explore low mass WIMPs, which can be accomplished in Si CCDs and in gas detectors with Ar, Ne or He – searching for different interaction channels in some ionization detectors allows to explore sub-GeV DM particles interacting with electrons or from the hidden-sector	– growth of NaI(Tl) crystals and detector production with required low background is still in development – complete development of novel technologies in ionization detectors and related sensors is still underway