European Strategy for Particle Physics

PARALLEL 8 / **DARK MATTER AND DARK SECTOR**

Direct Detection: status and prospects for the ESPP

Paolo Agnes (Gran Sasso Science Institute)

23-27 JUNE 2025 Lido di Venezia

Input received

Submissions

Mainly from **large collaborations** (Xe and Ar communities) addressing, as main goal, **traditional WIMPs**

 # 175 -- XLZD: The low-background observatory for astroparticle physics

 # 268 -- Dark Matter Searches with Low-Radioactivity Argon

+ Networks and National inputs, National Laboratories

The paradigm in the community *IS* shifting.

Technological advancement (***lower*** thresholds) enables to turn attention to lower mass candidates.

In this region of parameter space, the higher flux of lighter DM candidates enables ***small*** exposures to be competitive.

(…Next couple of slides are not meant to be an exhaustive review…)

Principles of Direct Detection (**DD**)

Model independent approach, with assumptions on Standard Halo Model (DM local density, v distribution)

Spin-Independent (SI) or **spin-dependent (SD)**

Predicted flux: ~10^{-5} cm^{-2} s^{-1} (M_W= 100 GeV/c^2 - density 0.3 GeV/cm^3) at terrestrial detectors and predicted rate:
- **scales as A^2**
- **energy recoil < 100 keV**

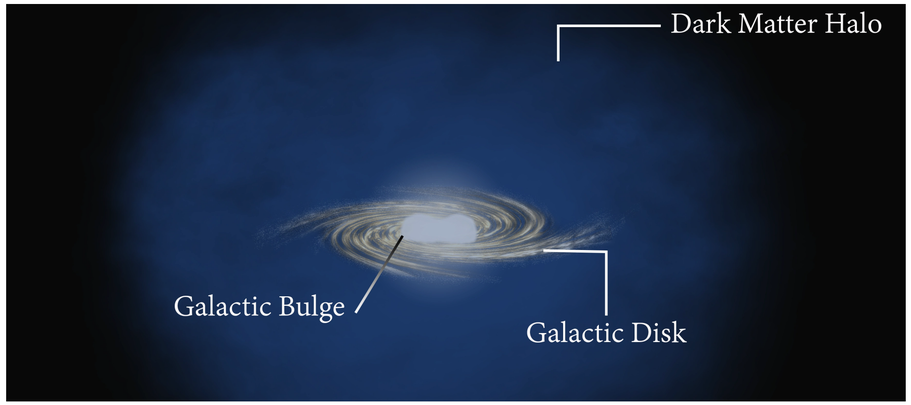
Annual and diurnal event rate **modulations** are **signature** (large number of signal events)

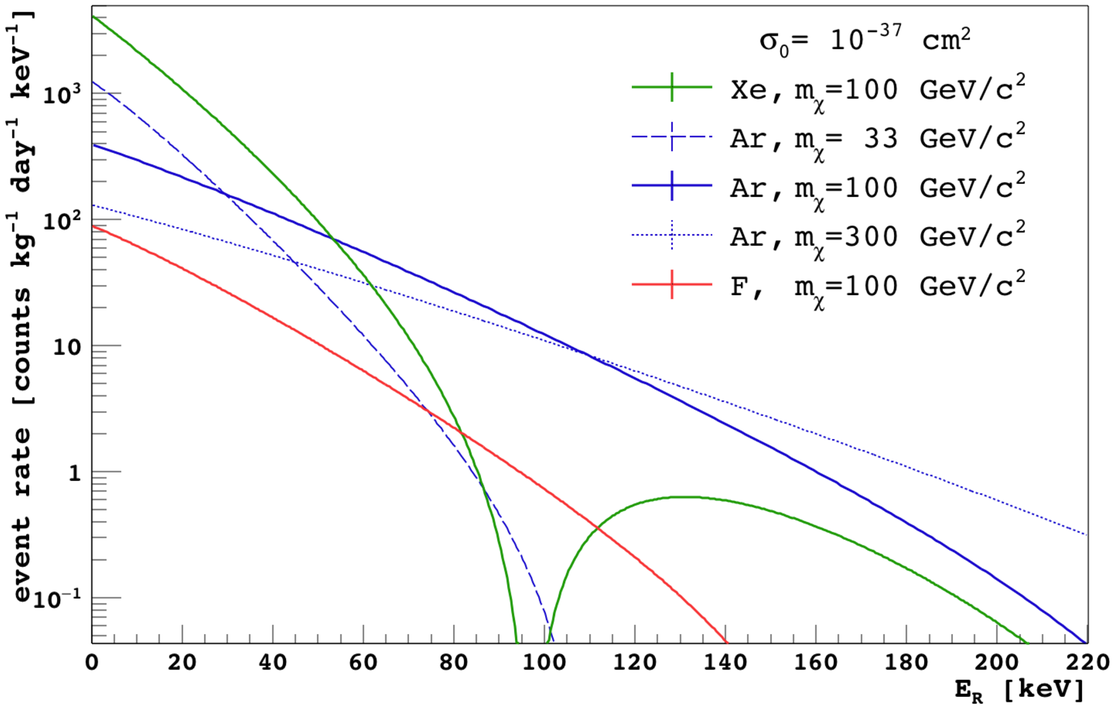
If no event is observed in a given exposure, experiments can put **a limit on the interaction strength**

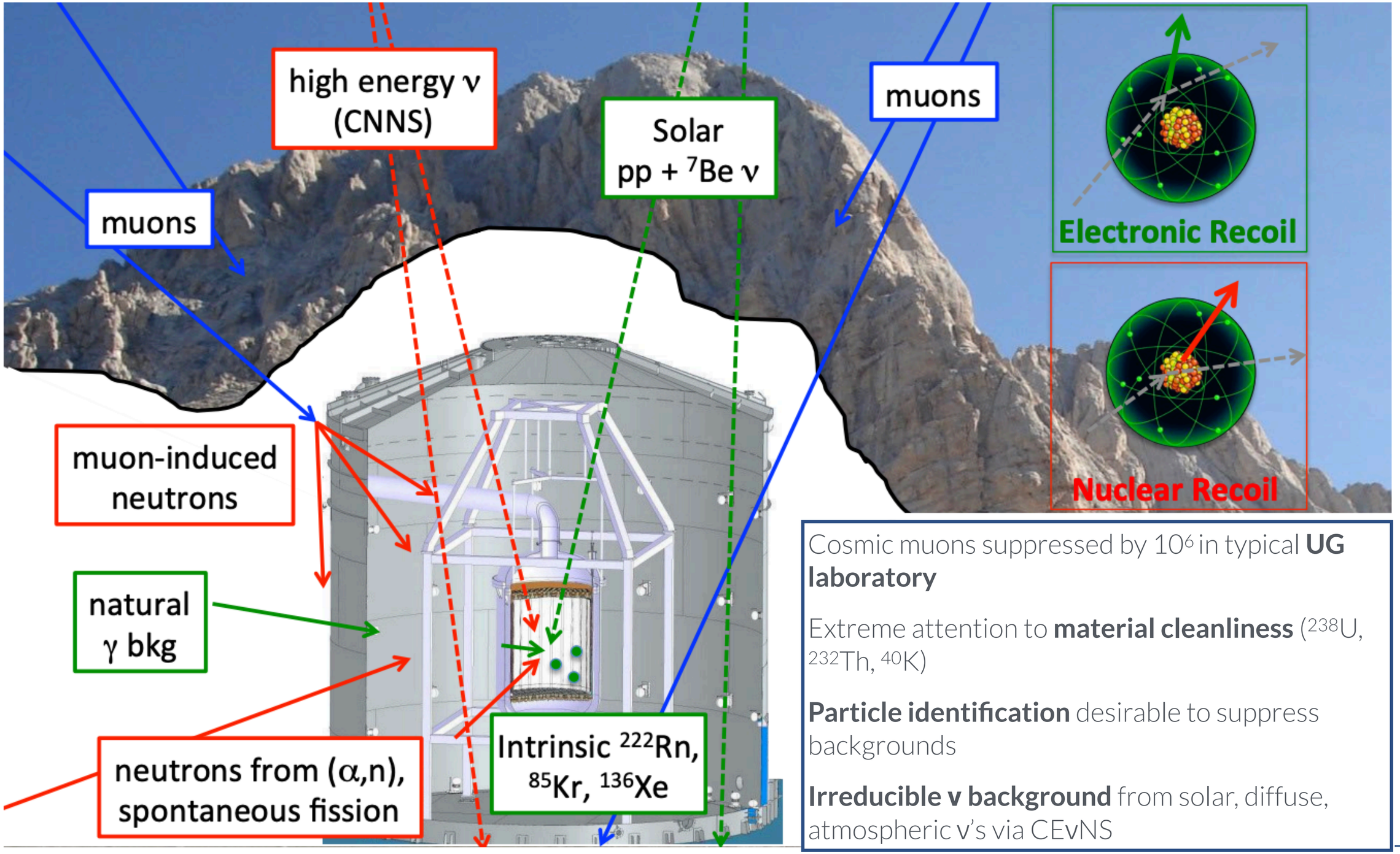
Cross section — Nuclear Form Factor — Astrophysics

$$\frac{dR^{NR}}{dE_R} = \sigma_n \frac{\rho_\chi}{M_\chi} \frac{m_A}{2\mu_{n\chi}^2} A^2 F_A(q)^2 \int_{v_{min}(E_R)}^{v_{esc}} d^3v \frac{f(v, v_E)}{v}$$

Dark Matter Properties — Target







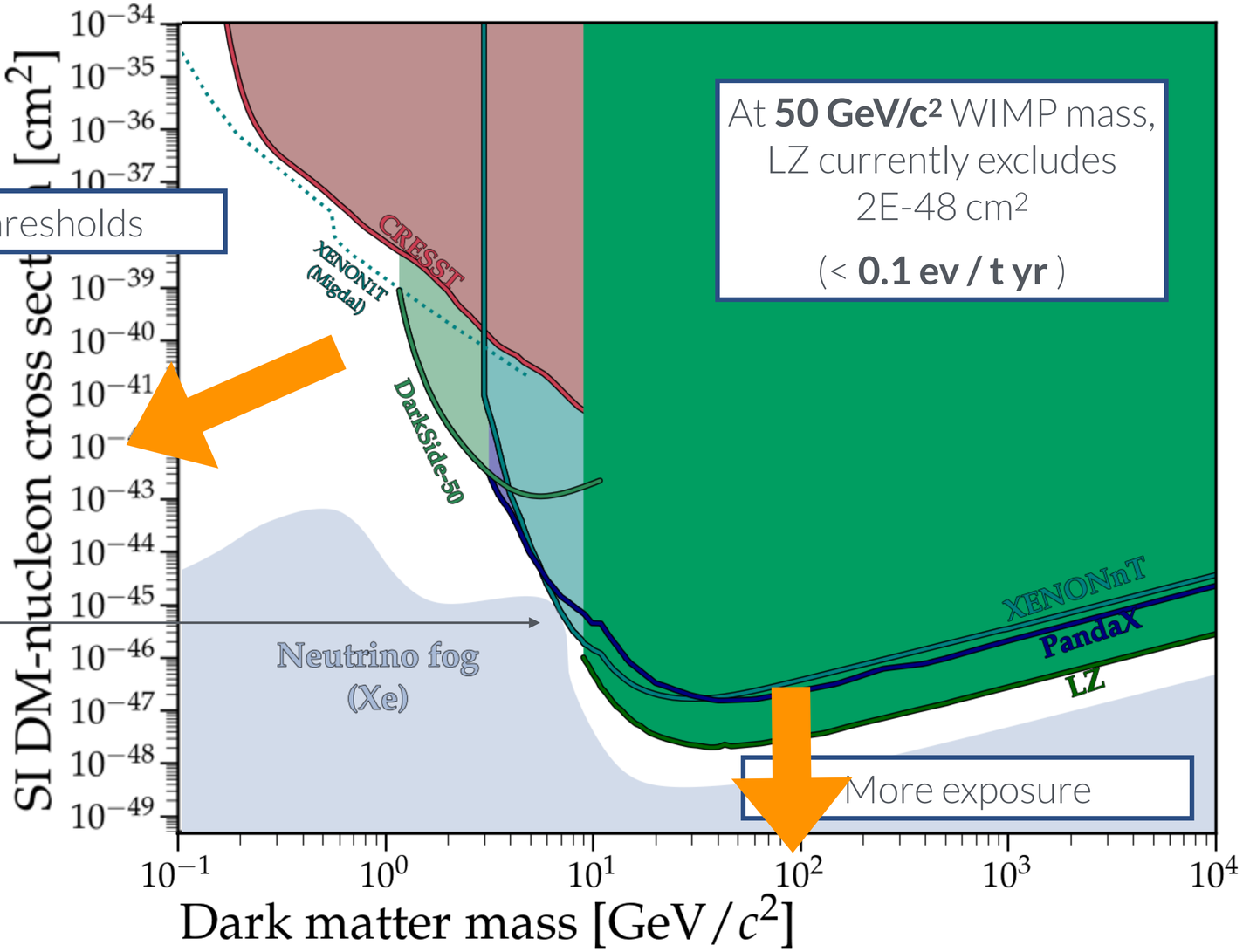
Cosmic muons suppressed by 10^{6} in typical **UG laboratory**

Extreme attention to **material cleanliness** (^{238}U, ^{232}Th, ^{40}K)

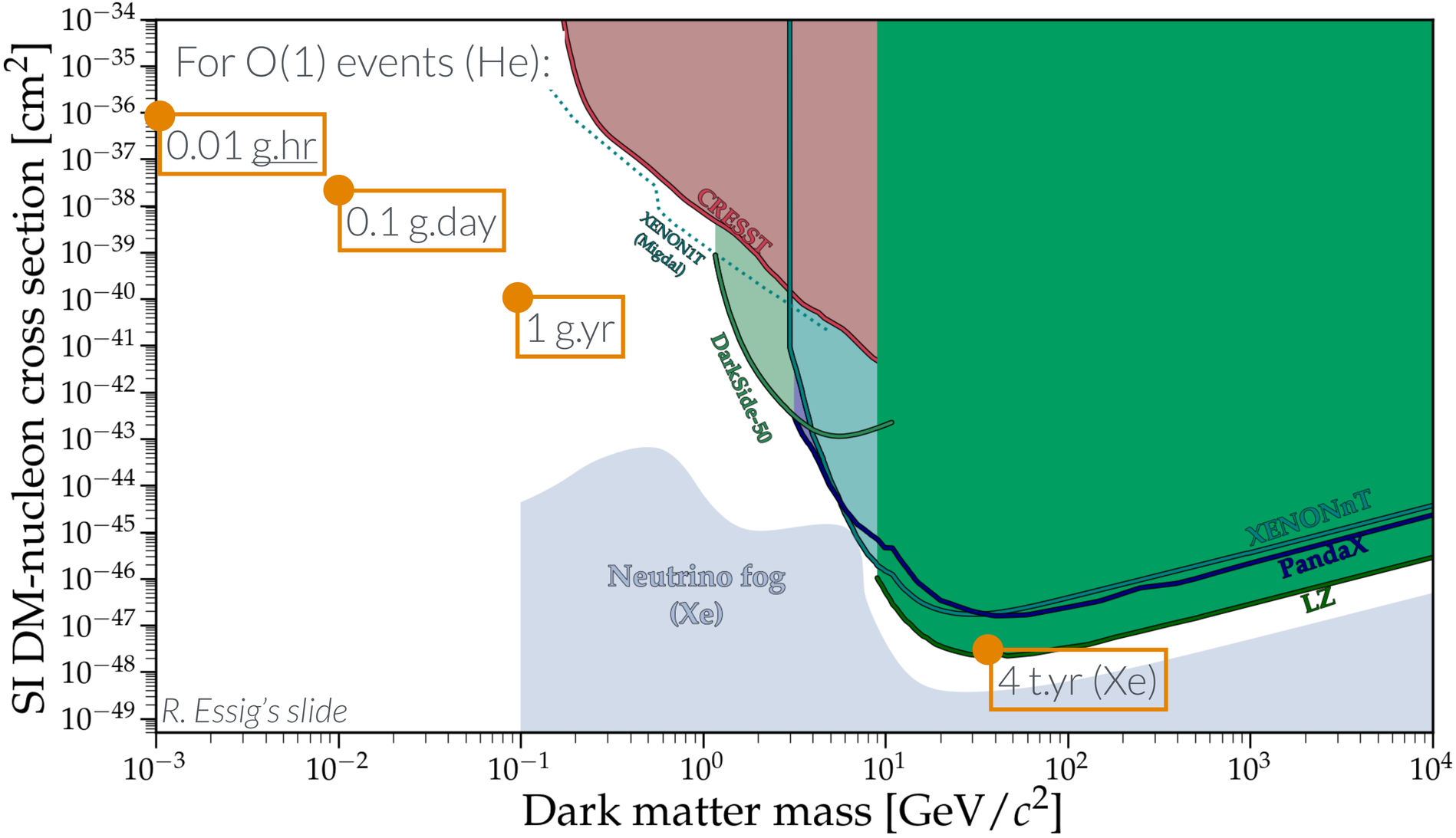
Particle identification desirable to suppress backgrounds

Irreducible ν background from solar, diffuse, atmospheric ν's via CEvNS

Exclusion


SI DM-nucleon cross sect [cm²]
Dark matter mass [GeV/c²]
CRESST
XENON1T (Migdal)
DarkSide-50
XENONnT
PandaX
LZ
Neutrino fog (Xe)
At 50 GeV/c² WIMP mass, LZ currently excludes 2E-48 cm²
(< 0.1 ev / t yr)
Lower thresholds
More exposure
Neutrino fog, irreducible background from CEvNS
! First hints of 8B neutrino observation by XENONnT/PandaX (2.6-2.7σ). XS in agreement with SM !

Exclusion


For O(1) events (He):
0.01 g.hr
0.1 g.day
1 g.yr
4 t.yr (Xe)
CRESST
XENON1T (Migdal)
DarkSide-50
Neutrino fog (Xe)
XENONnT
PandaX
LZ
R. Essig's slide
SI DM-nucleon cross section [cm^2]
Dark matter mass [GeV/c^2]

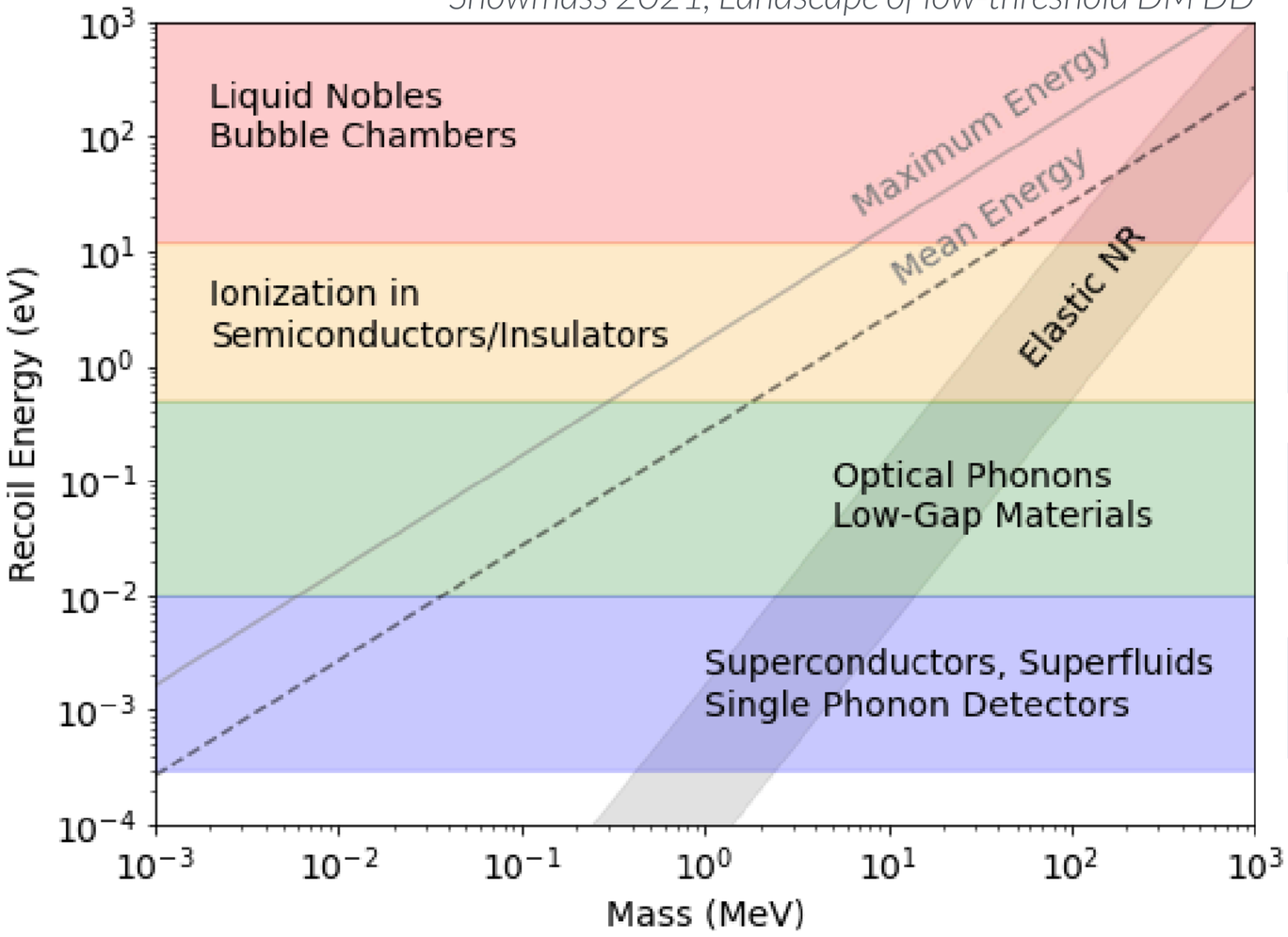
Technological advance and novel strategies

Limited potential of elastic scattering for light DM

Inelastic processes:

1) DM scattering with bound electrons,
2) DM scattering with nuclei boosted by Migdal effect (or accompanied by a photon from bremsstrahlung)
3) DM-target scattering that produces a collective excitations

Snowmass 2021, Landscape of low-threshold DM DD



Binding energy in NL : **10 eV**

Binding energy in SC : **1 eV**

Binding energy in L-G Materials : **~ meV**

Phonon modes : **~ meV**

$m_\chi > 10\ GeV/c^2$

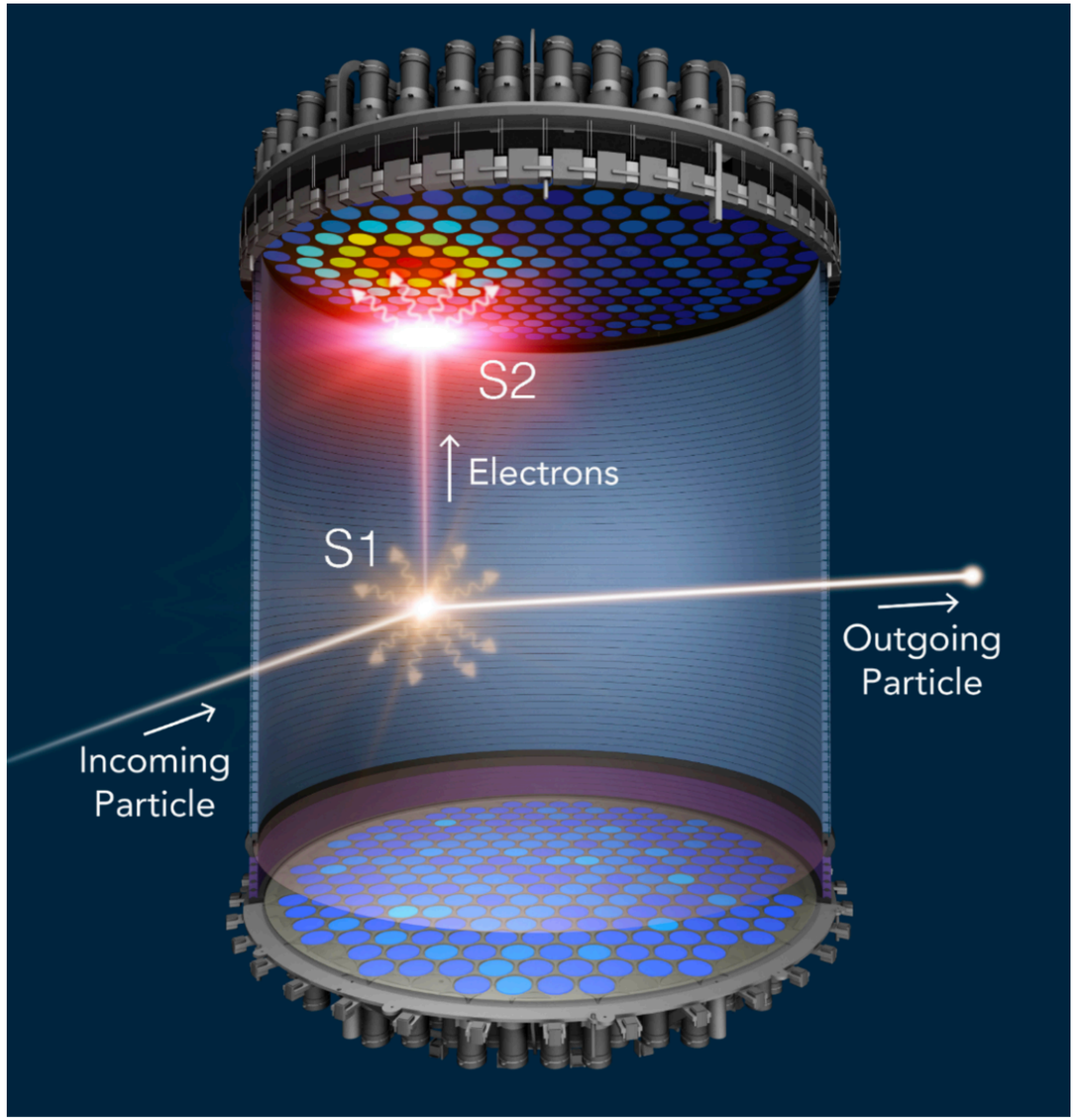
Several efforts to test the claim by **DAMA**, now excluded at >3.5σ
(ANAIS-112, COSINE-100, SABRE, COSINUS) — not covered in this presentation

Noble liquid experiments are providing the most stringent constraints and are the most promising technique to reach the neutrino fog

175 -- XLZD: The low-background observatory for astroparticle physics

268 -- Dark Matter Searches with Low-Radioactivity Argon

Current status, m_χ >10 GeV/c^2, SI



Dual-phase TPC to detect prompt de-excitation (S1) and delayed electroluminescence (S2) — typical drift times ~ ms

3D vertex reconstruction (< cm)

Noble liquids particularly suitable (purity, scalability, transparency)

— ionisation energy ~ 10 eV

— background discrimination based on S2/S1 and pulse shape discrimination (PSD) using time profile of scintillation pulse

Typically operated in combination with anti-coincidence external veto systems for radiogenic and cosmogenic background sources

- Threhsold at 5 keV_{NR} (LXe) or 50 keV_{NR} (LAr)
- Large exposures achievable

Xenon programme

Three large experiments are currently running

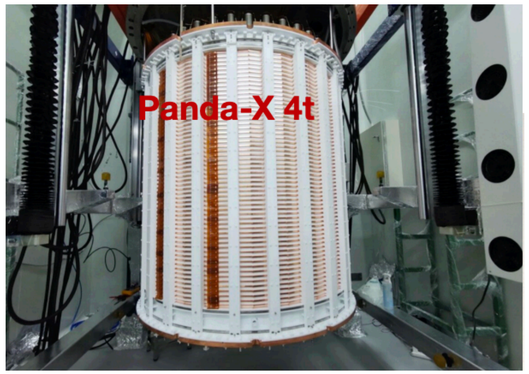
LZ (SURF, 7 t active mass)

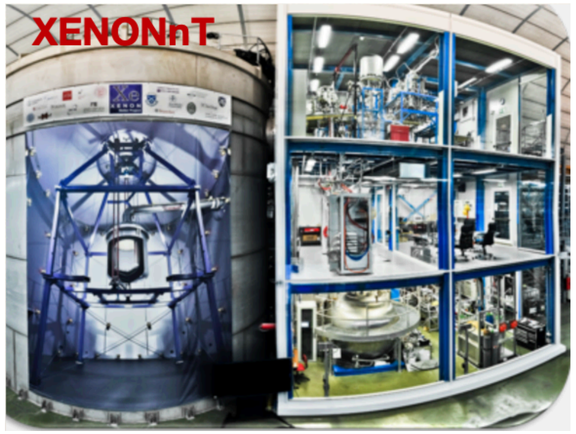
PandaX (CJPL, 3.7 t active)

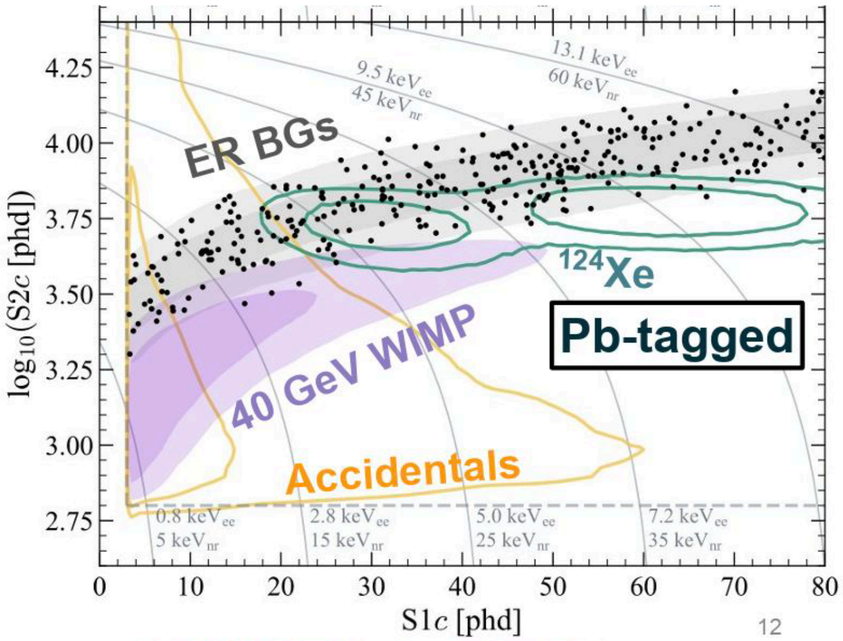
XENONnT (LNGS, 5.9 t active mass)

ER background mainly due to internal Rn, successfully reached unprecedented **0.9 μBq/kg**

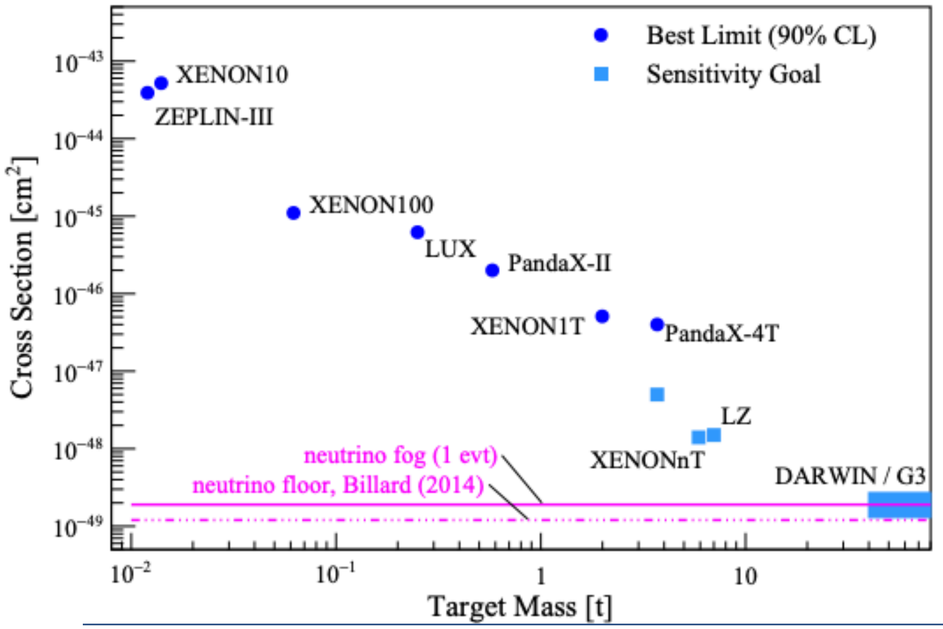
Plans to reach **15-20 t.yr** exposures

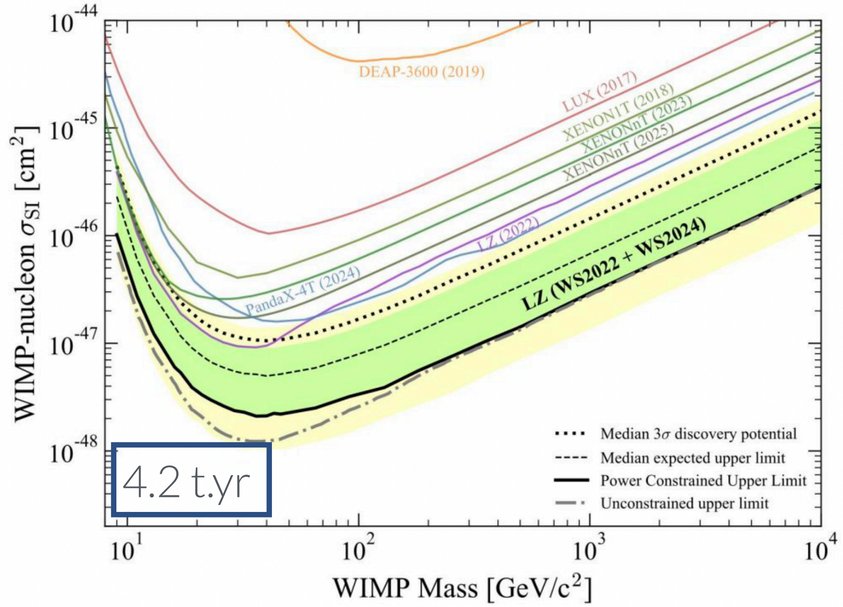






arXiv:2410.17036 [submitted to PRL]





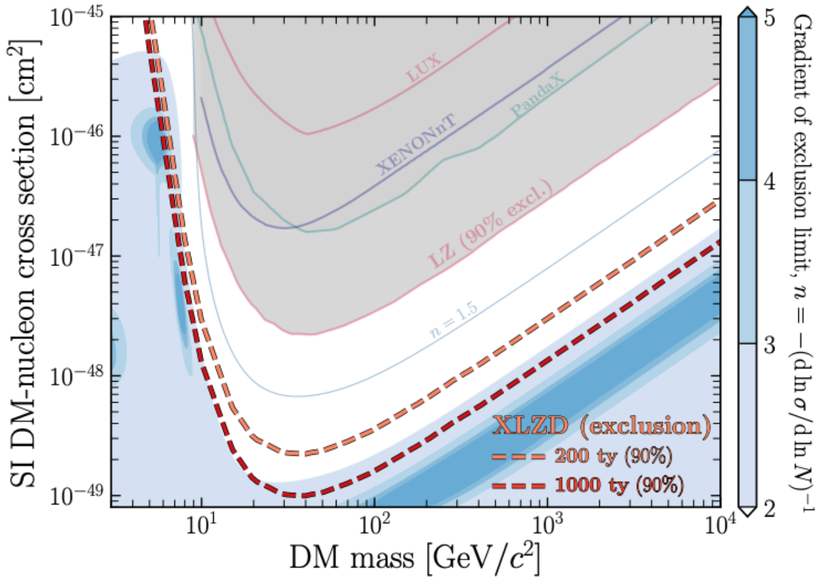
Xenon programme XLZD

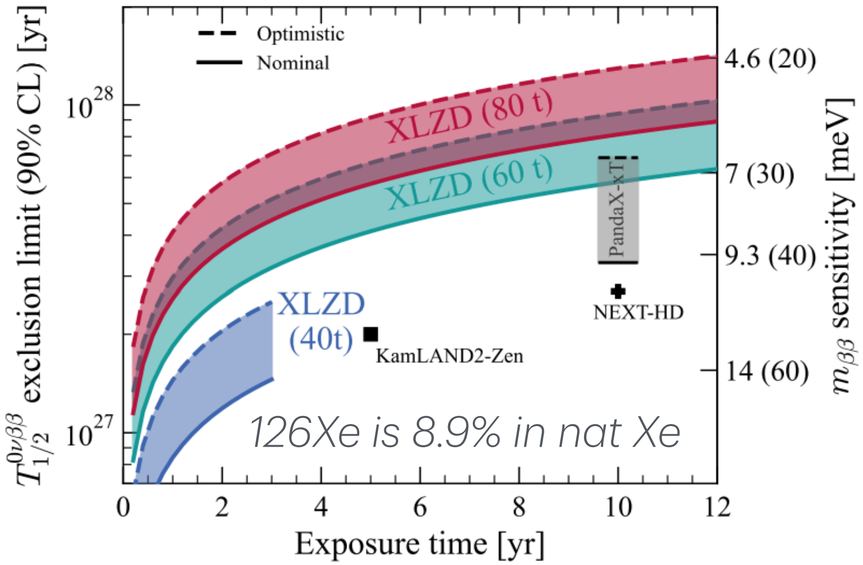
XENONnT+LZ (440 members from 74 institutions)

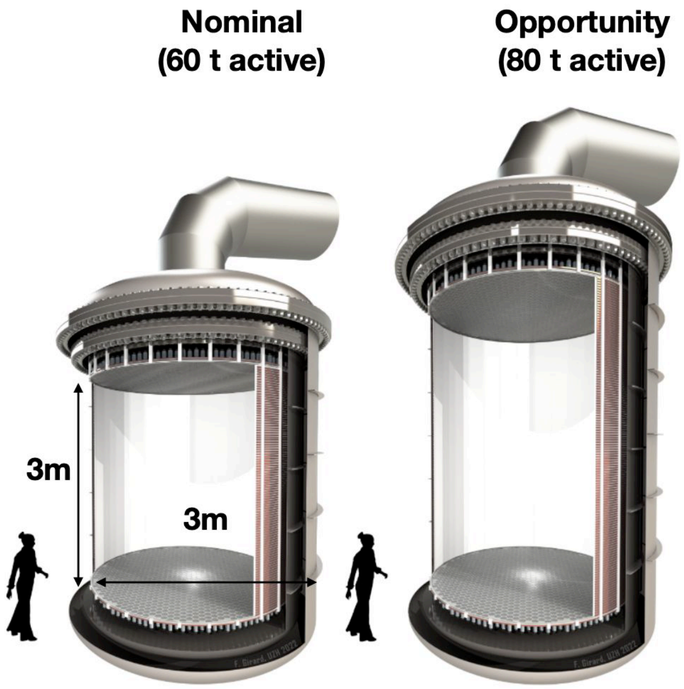
Reach physics reach, including **DM**, **0νββ (136Xe),** SN and solar neutrinos, double electron capture…

R&D ongoing for drift field (3 m), internal 222Rn contamination (target: 0.1 μBq/kg), could benefit from synergy with CERN NP (cryoplatform, HV)

Selection of hosting underground site (LNGS, Boulby) in 2026,
TDR expected in 2027







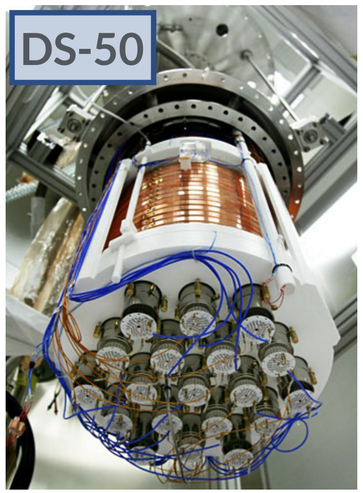
Argon programme

Global Argon Dark Matter Collaboration (400 members, 65 institutes)
(DarkSide, DEAP-3600, MiniCLEAN, ArDM)

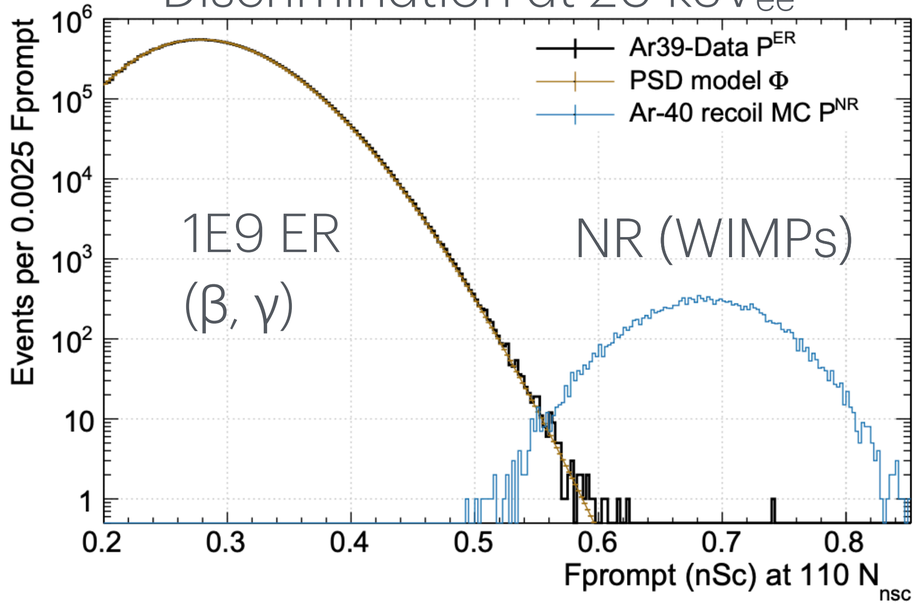
DEAP-3600 (3.3 t active), single phase

DarkSide-50 (50 kg active), dual-phase

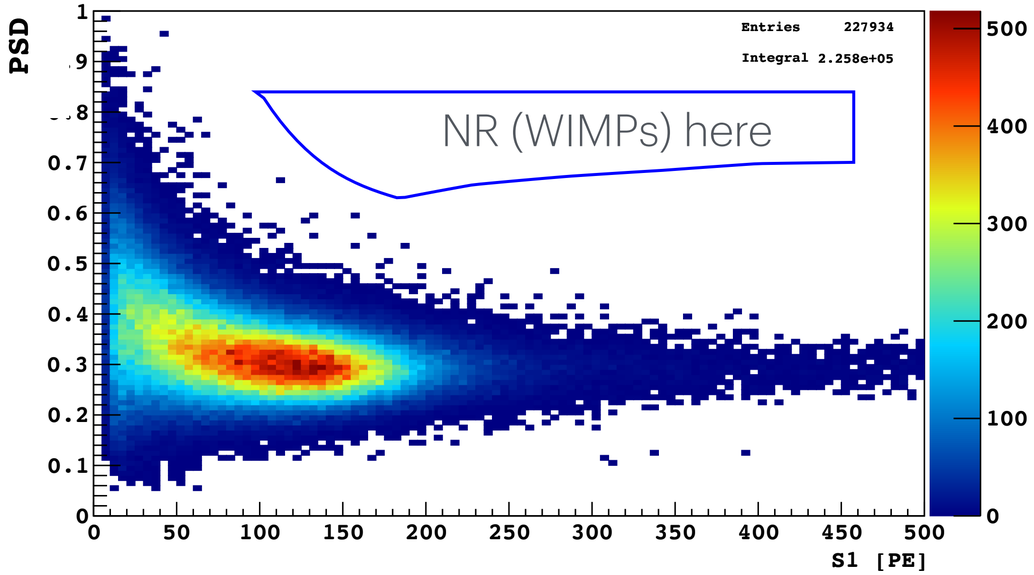
— Builds upon excellent **bg-rejection** capability of LAr (1E9, DEAP3600) to separate electronic recoils (ER) from nuclear recoils (NR) - **DarkSide-50** demonstrated **background-free** operation over 500 days in dual-phase



Discrimination at 20 keV$_{ee}$



DarkSide-50 — 17.103 kg.d, bg free



Argon programme: DarkSide-20k

DarkSide-20k, currently in construction at LNGS (**50 t active**)

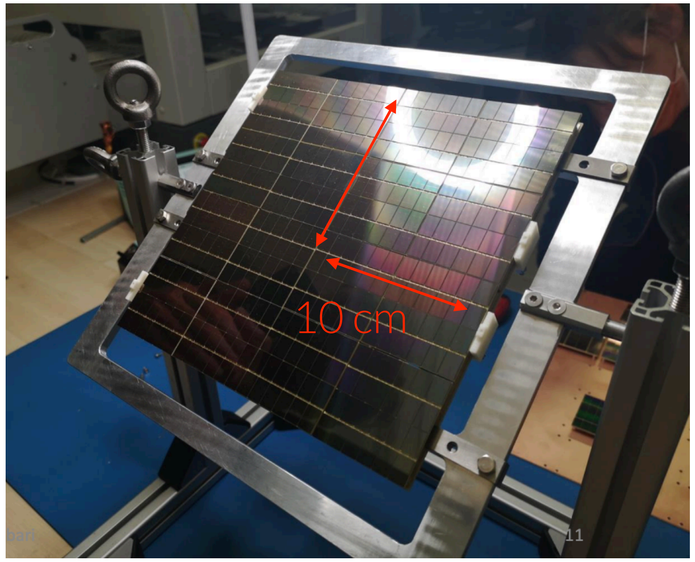
— **protoDUNE**-like cryostat delivered by **CERN**, already built underground

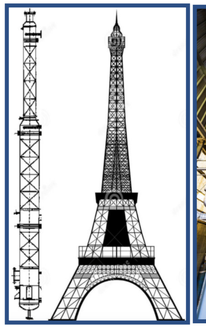
— will use need extraction and purification of **100 t** of argon from underground CO2 well (depleted from radioactive 39Ar **by >10^3**)

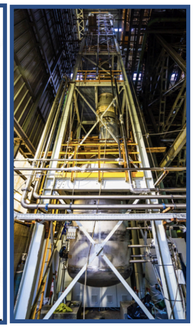
— pioneers large area, low-noise **SiPM arrays** for light detection (25 m^2)
achieved 10^3 reduction of dark counts
400 m^2 ISO6 clean room at LNGS for the assembly


Hall C LNGS

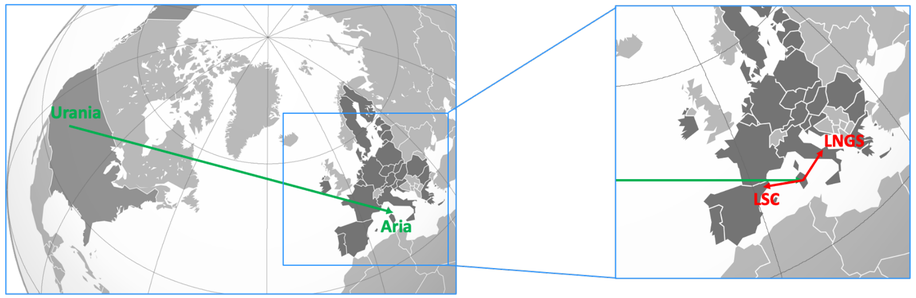

NOA at LNGS



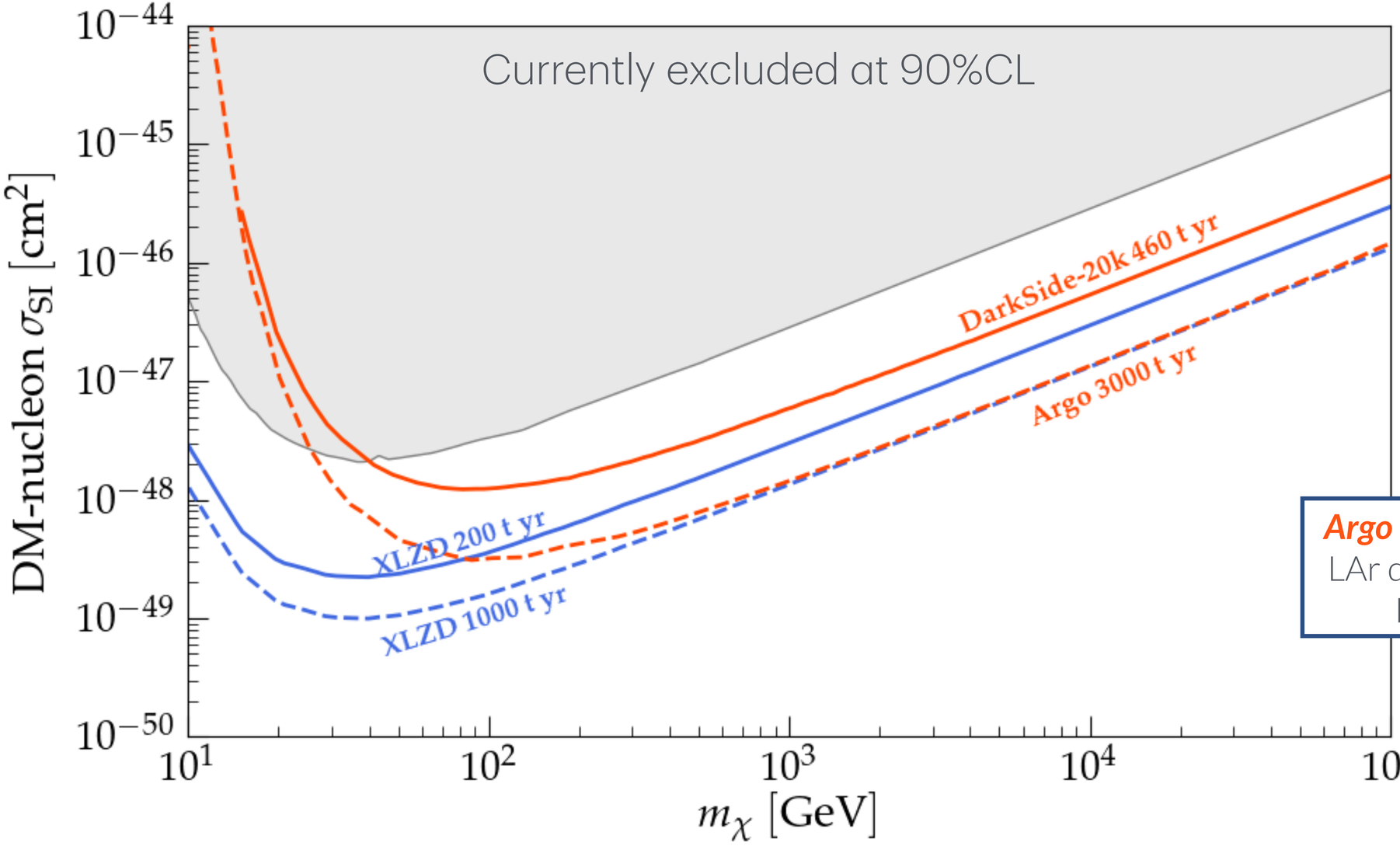




UAr from URANIA (Colorado) to ARIA (Sardinia)



Sensitivity projections



Both targets ≲ 2040

Argo is a foreseen future LAr detector, 500 t (10x DarkSide-20k)

~0.1 GeV/c^2 < m_χ < 10 GeV/c^2

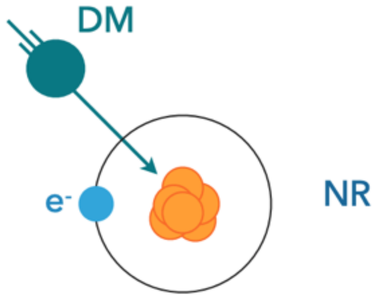
A lot of complementary activities, exploiting different techniques and targets

Summary for **DM-nucleon** scattering:

Thresholds goal at < ~100 eV

Light targets have more favourable kinematics

Backgrounds (radiological are no more dominant)



+ inelastic (Migdal)

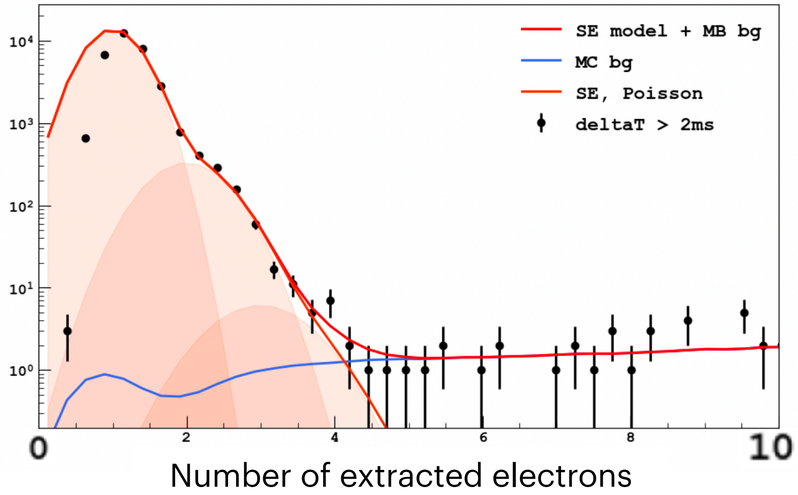
Ionisation only searches in noble liquids

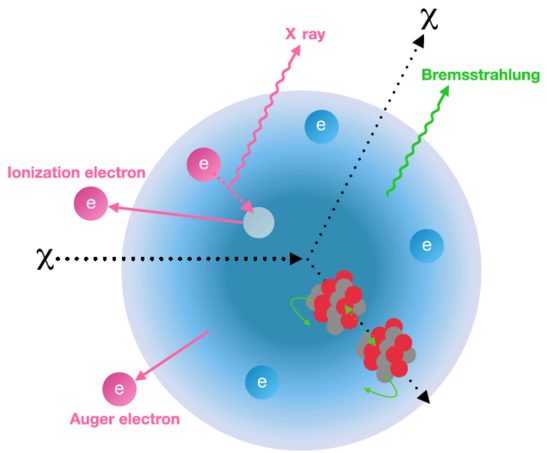
Lower the threshold, exploiting **single electron** sensitivity (**10-20 eV**) to lower analysis threshold down to 100 eV

Limited background discrimination and no vertical fiducialisation

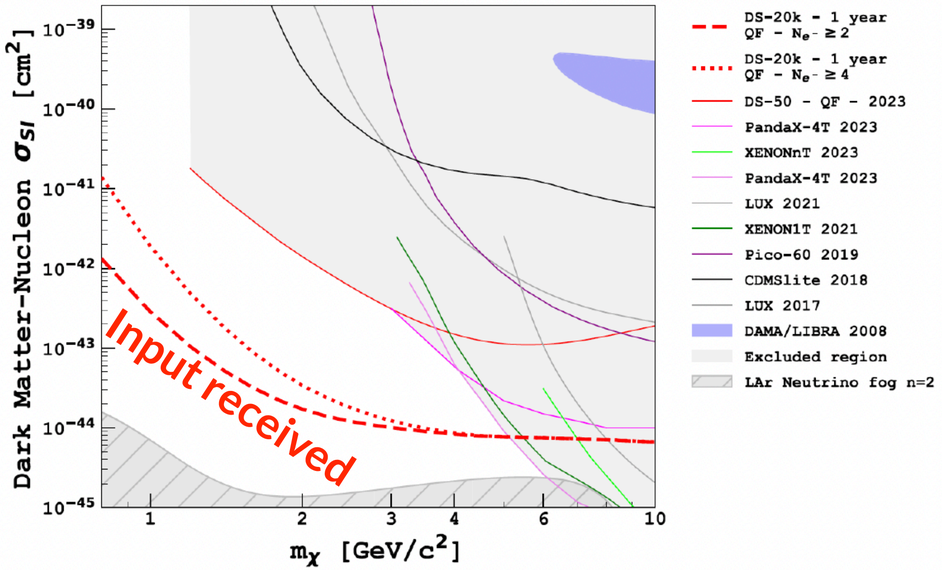
Background due to **spurious electrons** (trapping/release on impurities, delayed extraction, fluorescence - timescale up to O(1) s) to be understood.

Currently **most stringent exclusion for GeV** scale dark matter





+ Migdal effect (inelastic): exploit ionization which follows the sudden acceleration of atom struck by DM to boost the signal



Wide range of targets and technologies

Gaseous detectors

NEWS-G (Ne, CH4, He) —> DarkSPHERE (single channel spere, He:i-C4H10, 90%:10% @5bar, 3 m)

CYGNO (optical TPC directionality, He:CH4 at room T and pressure). LIME at LNGS

ALETHEIA, liquid He TPC

He-Superfluid + phonon readout

DeLight, **QUEST-DMC, HeRALD** (TESSERACT)

Cryogenic solid-state detectors

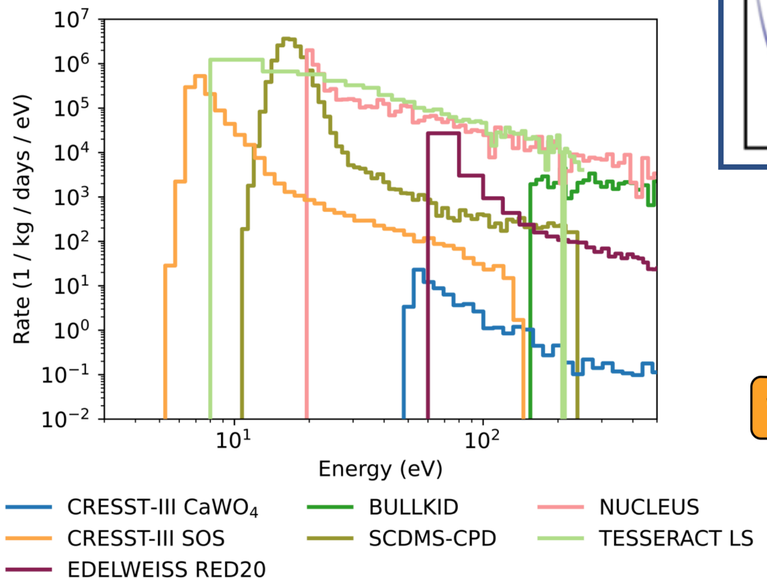
Ionization detectors: **SuperCDMS, EDELWEISS, DAMIC/SENSEI**

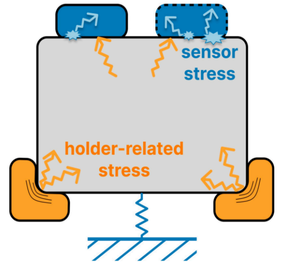
Cryogenic bolometers: **CRESST, BULLKID-DM**

+ SPICE (TESSERACT)

Dual-observable enables particle identification => **bg rejection**

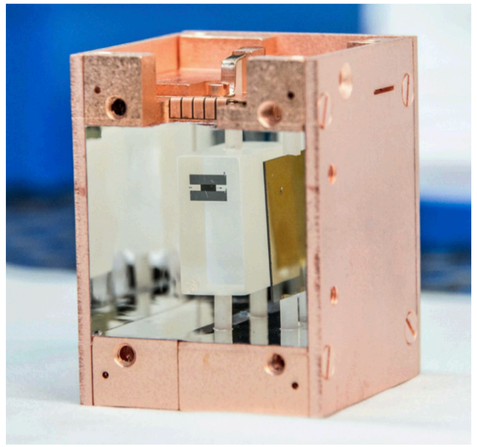
Series of workshops to tackle bg of Low-Energy Events (LEE).

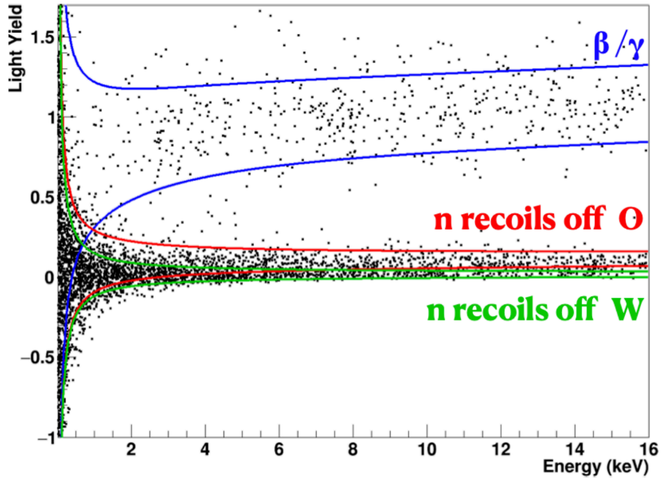




CRESST-III (LNGS)

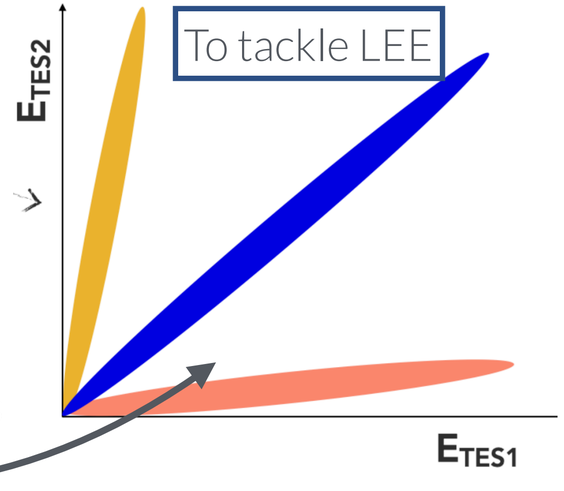
Detect **thermal phonons** (Transition edge Sensors, **TES**) and **light** (Silicon On Sapphire, **SOS**), various target crystals: **$CaWO_4$**, Al_2O_3, $LiAlO_2$, Si

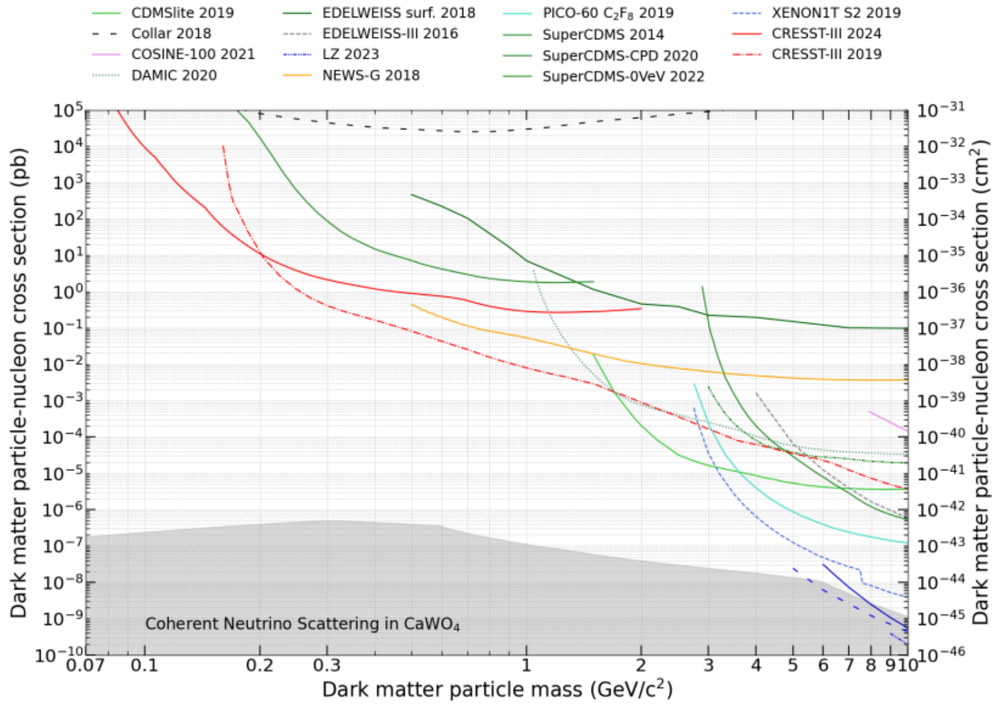




CRESST-III
- Probed down to 160 MeV/c^2
- 6 kg day exposure search
- 24 g crystals $CaWO_4$
- 30.1 eV threshold

Currently preparing **upgrade**, to increase target mass and lower even further the threshold (smaller crystals)
+ implementing **dual-TES** readout to suppress LEE





Potential to improved current limits at 100 MeV/c^2 by orders of magnitude

Current exclusions and projections

For **SI DM-nucleon** interaction

Current limits from

6 kg.day CRESST

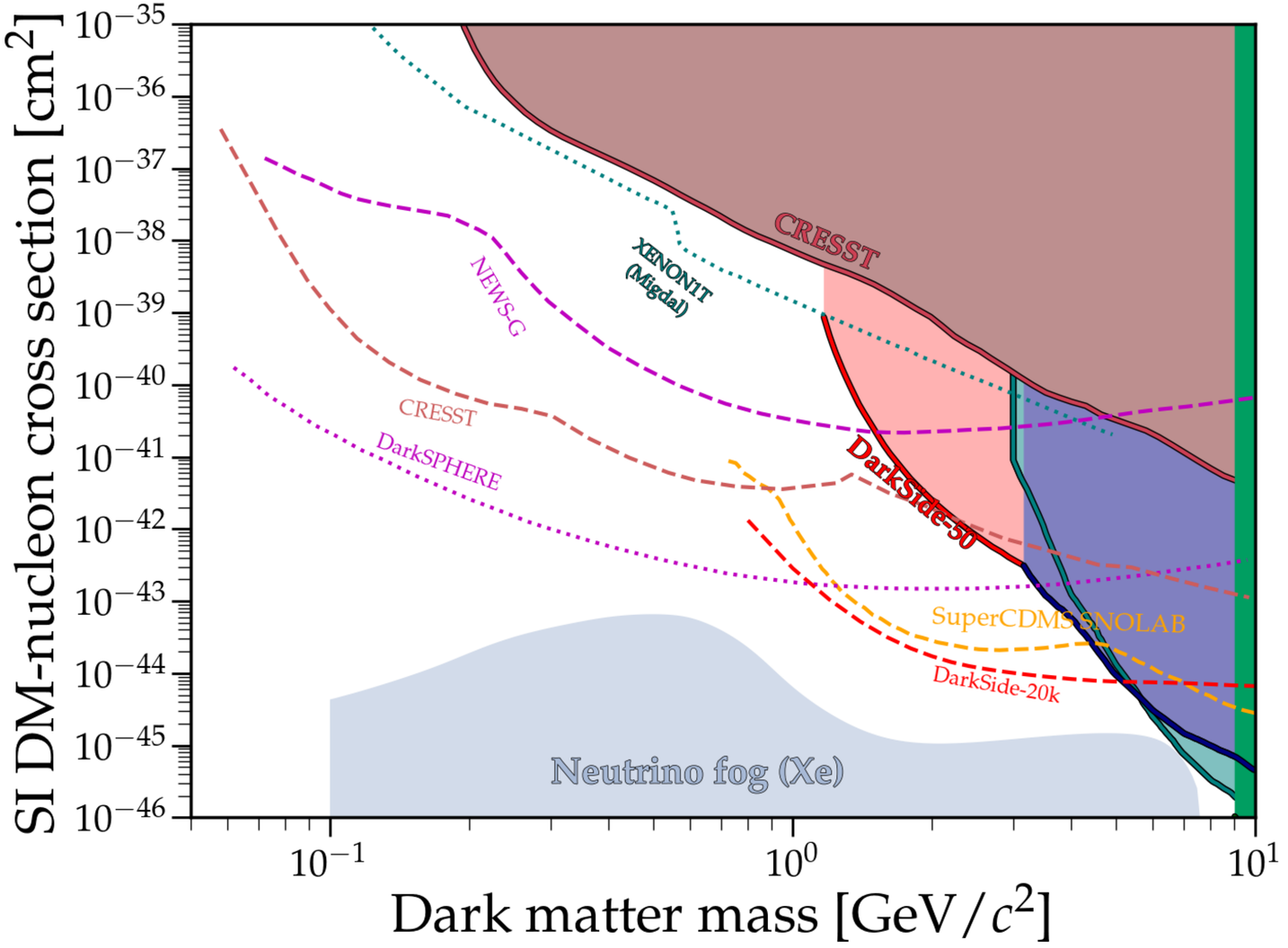
12 t.day DarkSide-50

XENON1T based on Inelastic (MIGDAL)

Some representative projections

DarkSPHERE
CRESST 500 kg.day (**$CaWO_4$** at 5 eV threshold)
DarkSide-20k 18 t.yr

Not a complete overview



$m_\chi < 0.1\ GeV/c^2$

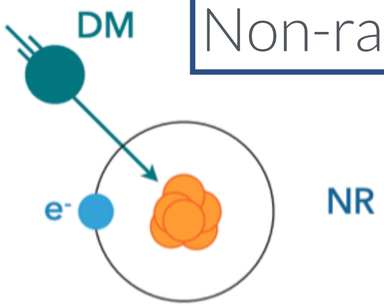
Small exposure can be competitive

Large number of new ideas and techniques

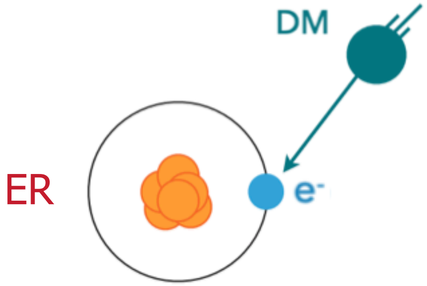
DM-nucleon

Push threshold at the eV and below

Non-radiological backgrounds

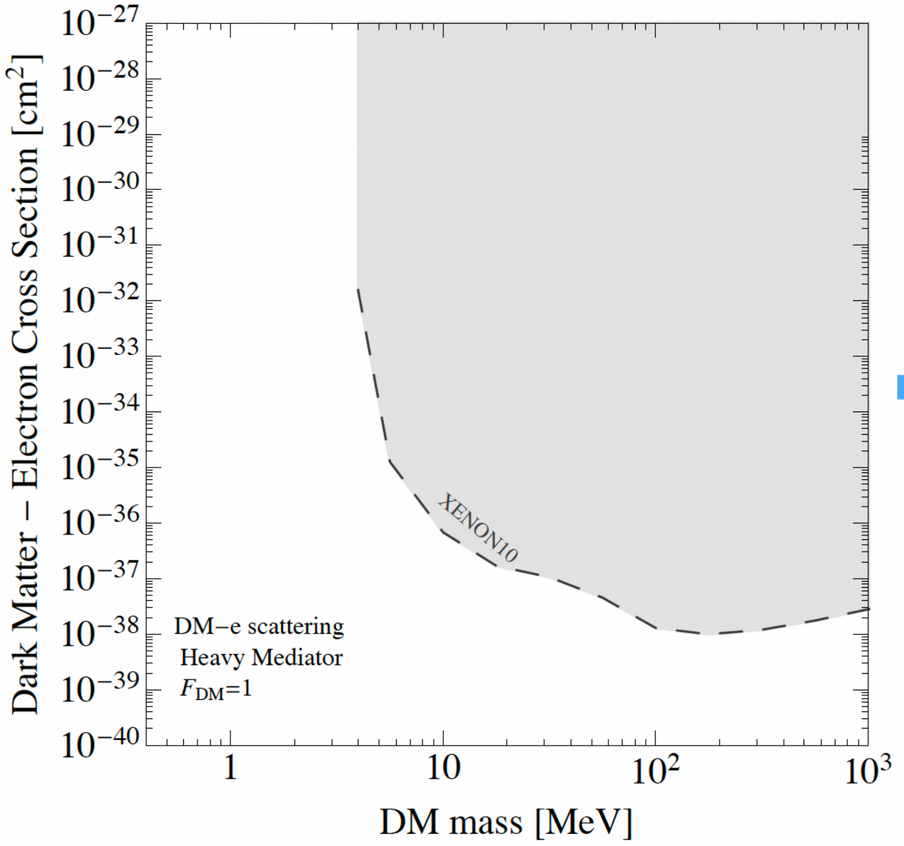


DM-electron

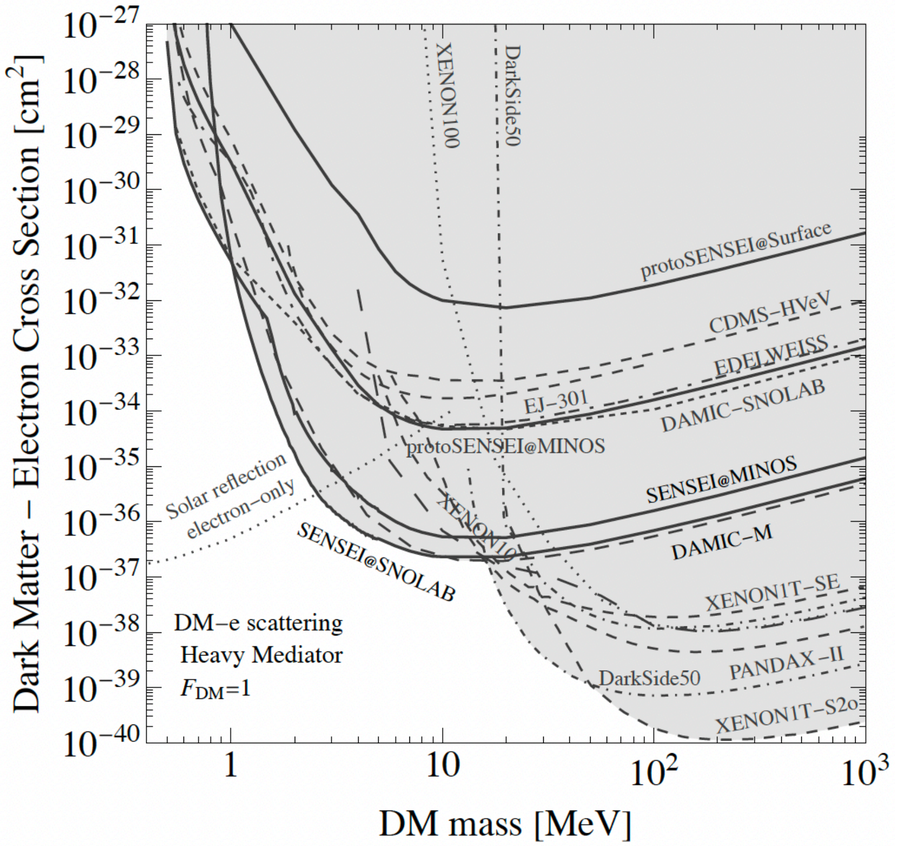


DM electron

2012

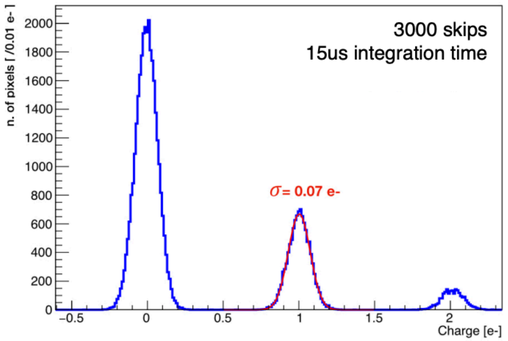


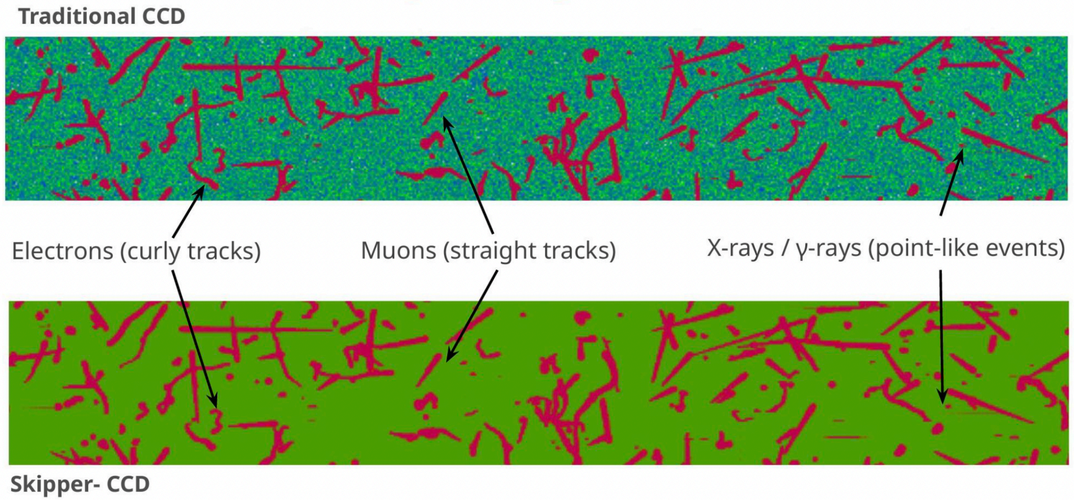
2024



R. Essig's slide

Skipper CCDs





SENSEI (SNOLAB), **DAMIC-M** (LSM) —> **skipper CCDs** (pixellated silicon sensors, readout each pixel multiple times to reduce the electronics noise)

Thick pixels (DAMIC-M: 675 um), exploit diffusion for fiducialisation and discrimination

Long exposures and slow readout

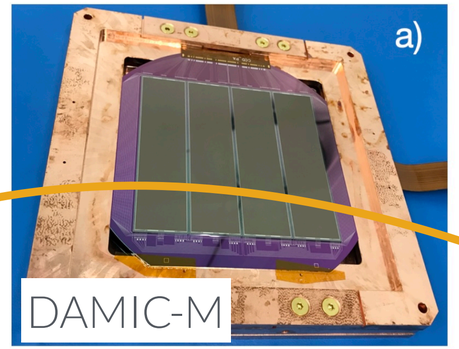
Energy threhsold: **1.1 eV**

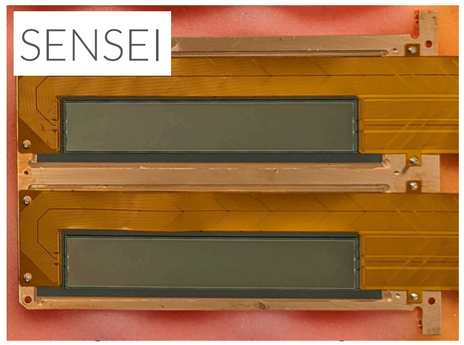
Readout noise: < 0.2 eV

Low dark noise (**~1.4E-5 e-/pixel/day**)

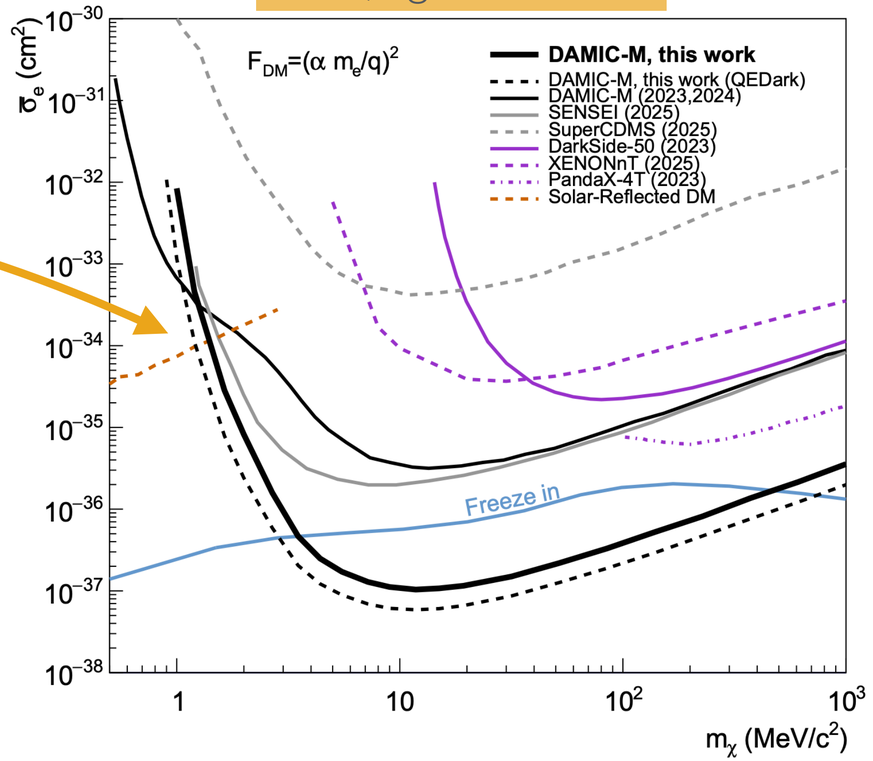
DAMIC-M exposure: **1.3 kg-day**

OSCURA is the proposed next phase: 10 kg of Si, 700 μm thick pixels, aiming at 30 kg.yr exposure and 2 e- threshold (target: ~1E−6 e-/pix/day)



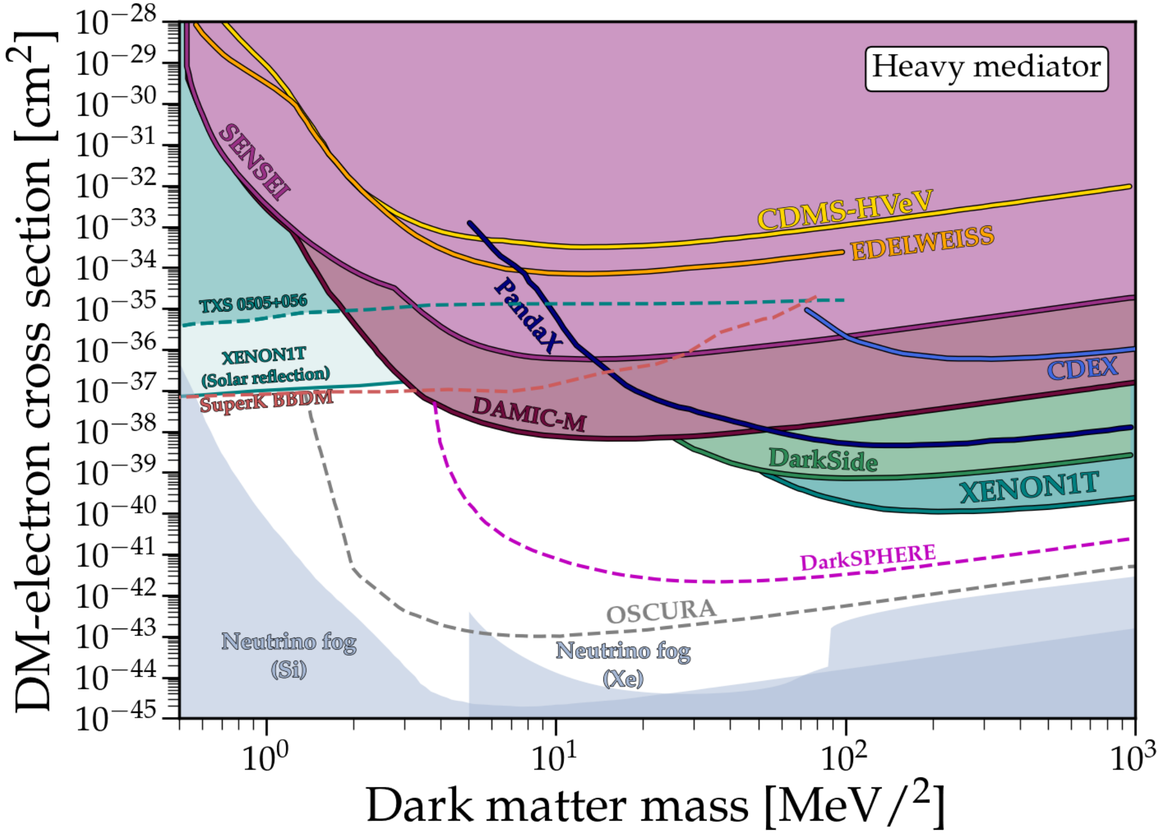


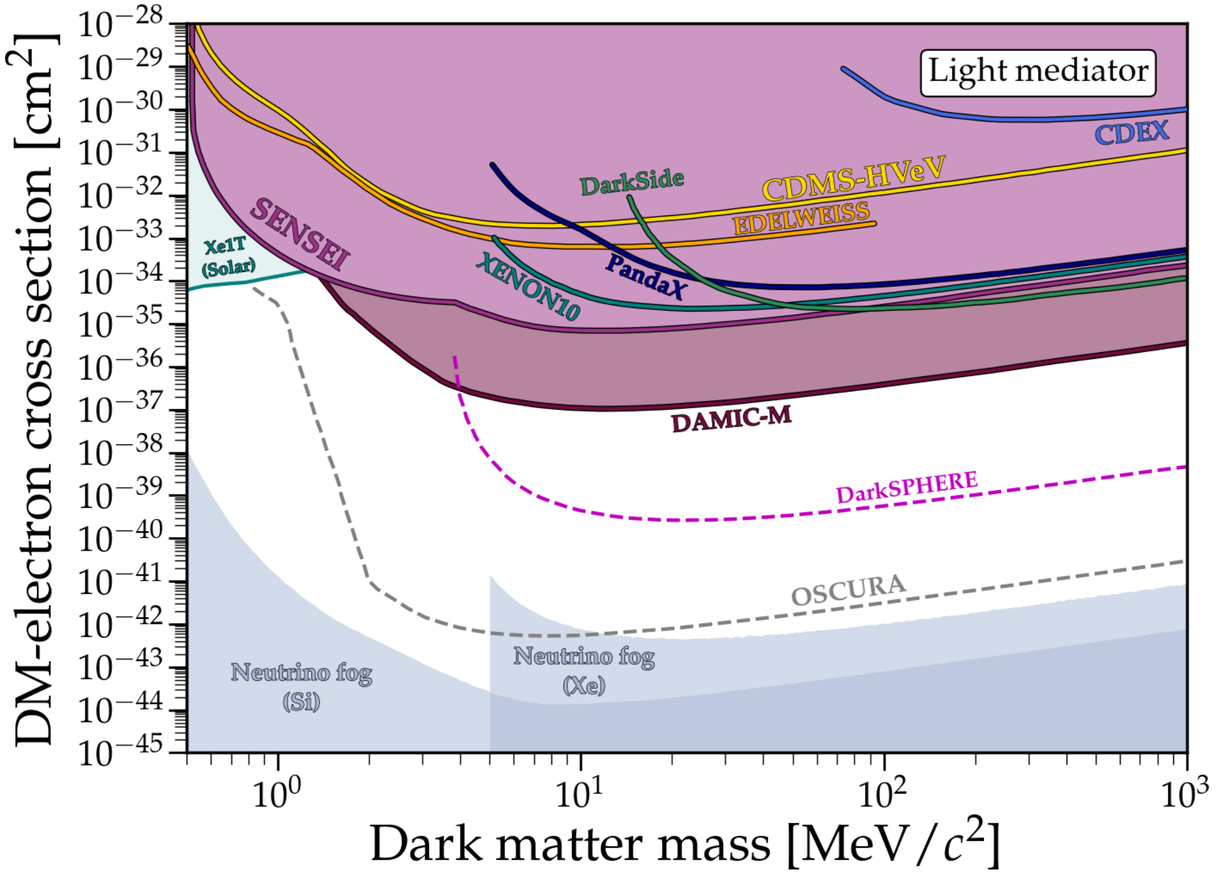
DM-e, light mediator



DM-electron — scattering

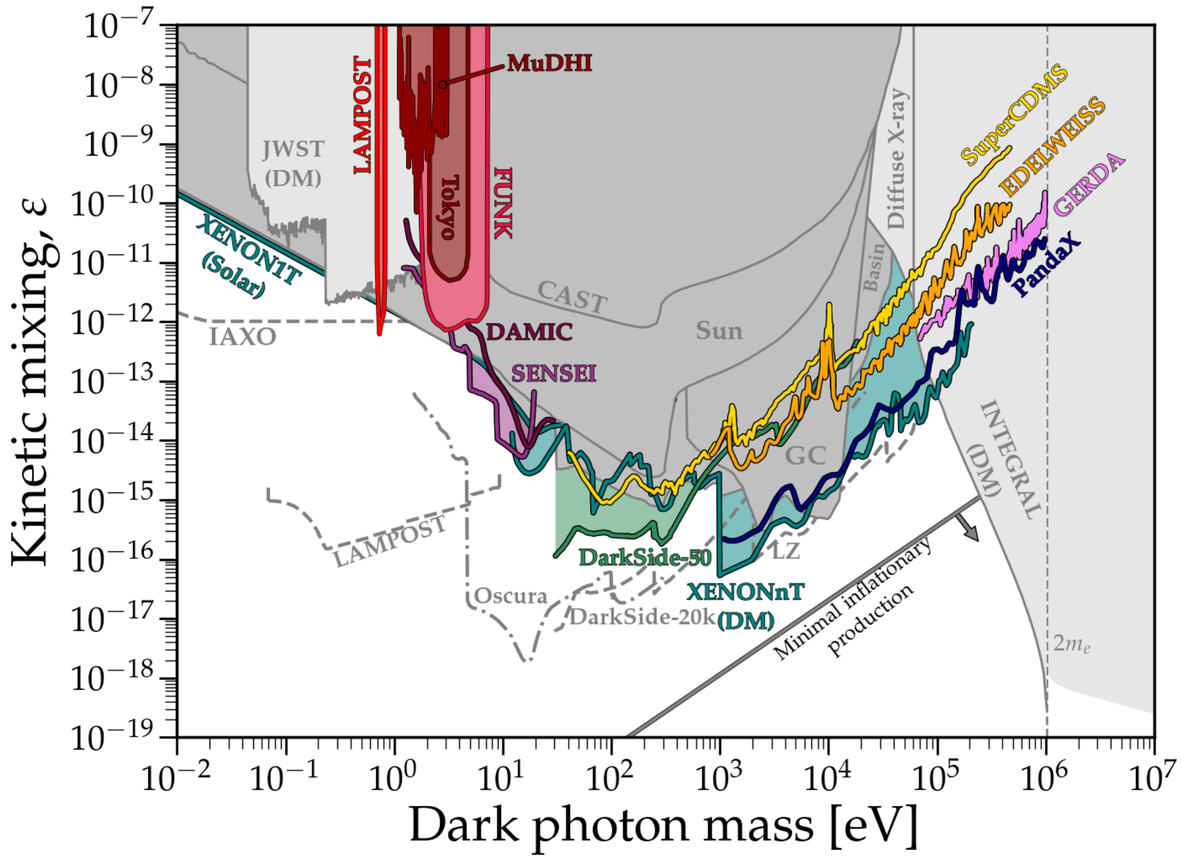
DM electron SI scattering (**heavy** mediator and **light** mediator)

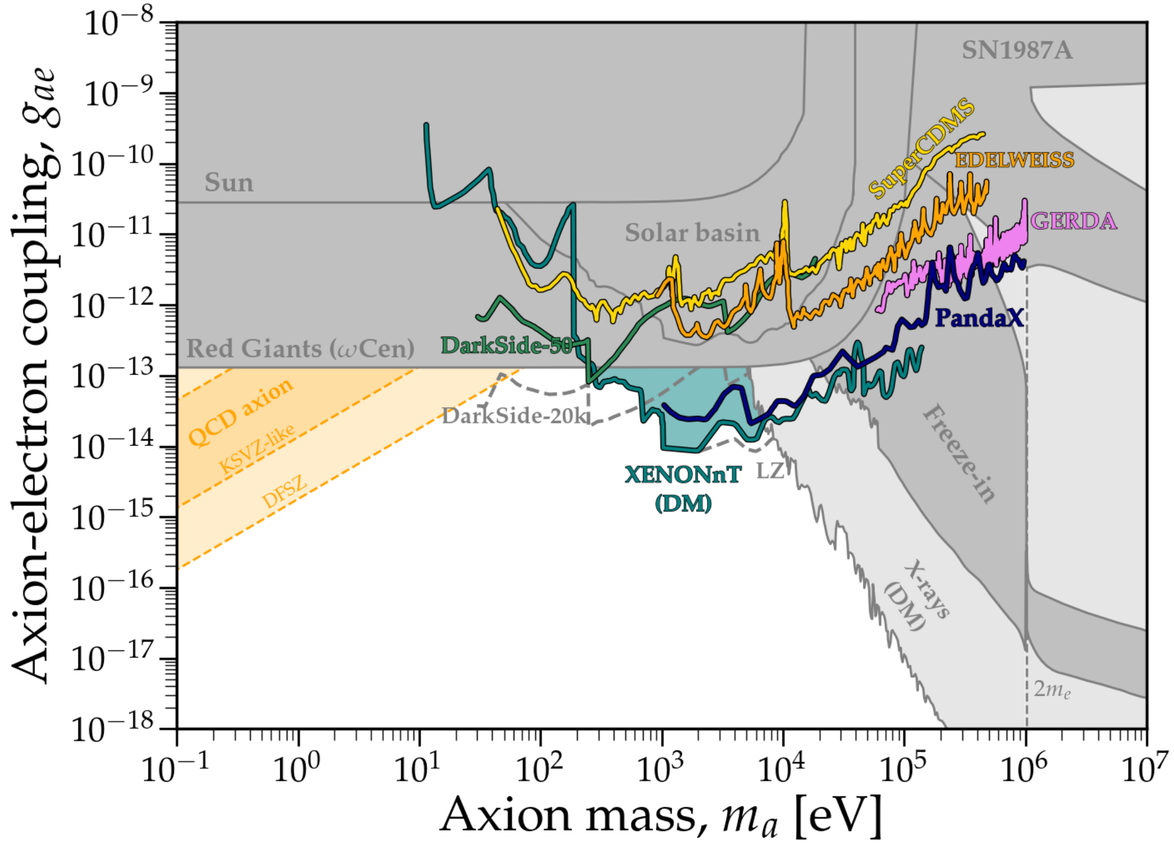




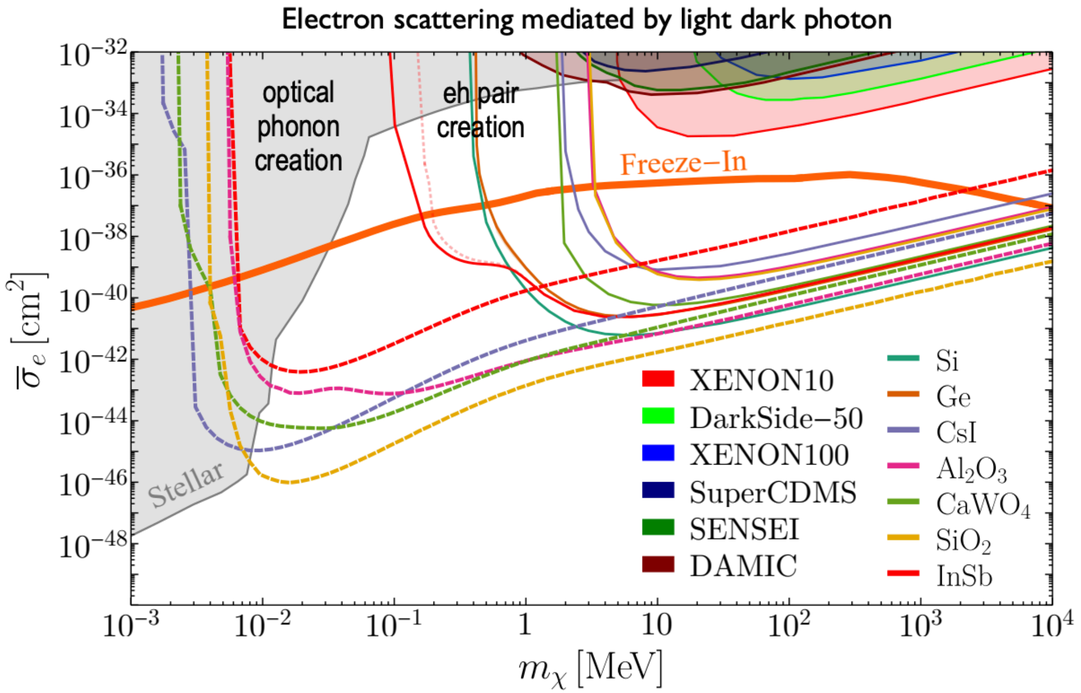
DP and ALP absorption

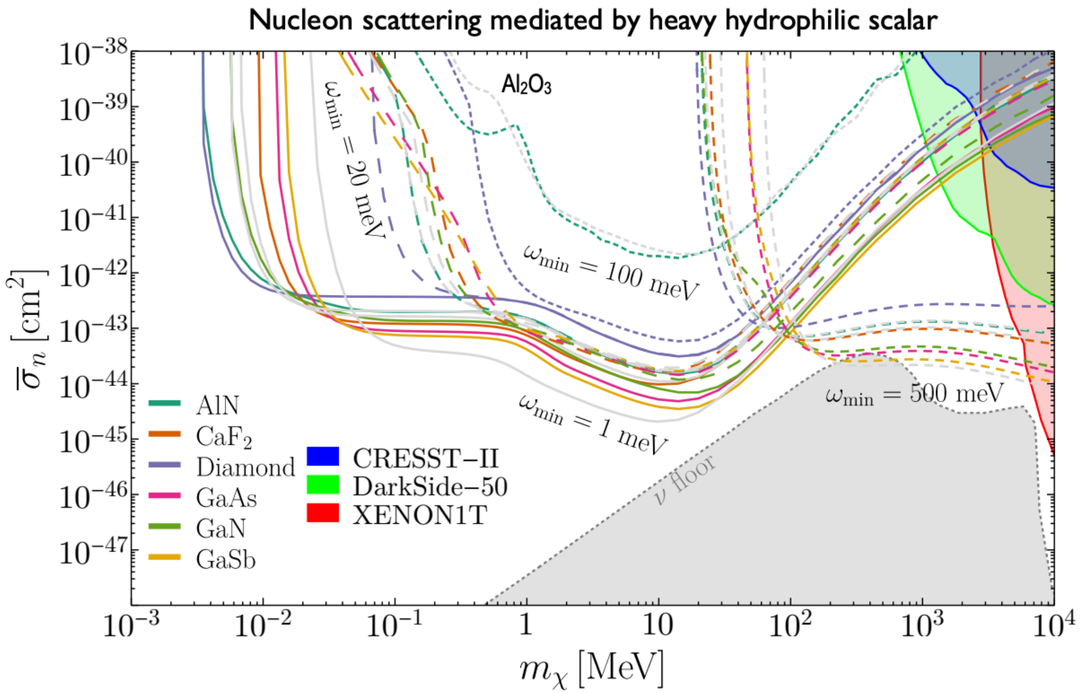
Well understood datasets enable searches for different signal models. DP and ALP absorptions result in mono-energetic peaks at E = m; and can **probe DM candidates from 1 eV to MeV**





Wide range of *opportunities*





Griffin et al. PRD 101, 055004 (2020)

DM-electron (optical phonons) and DM-nucleon (acoustic phonons)

Several combinations of target, detector technology and readout

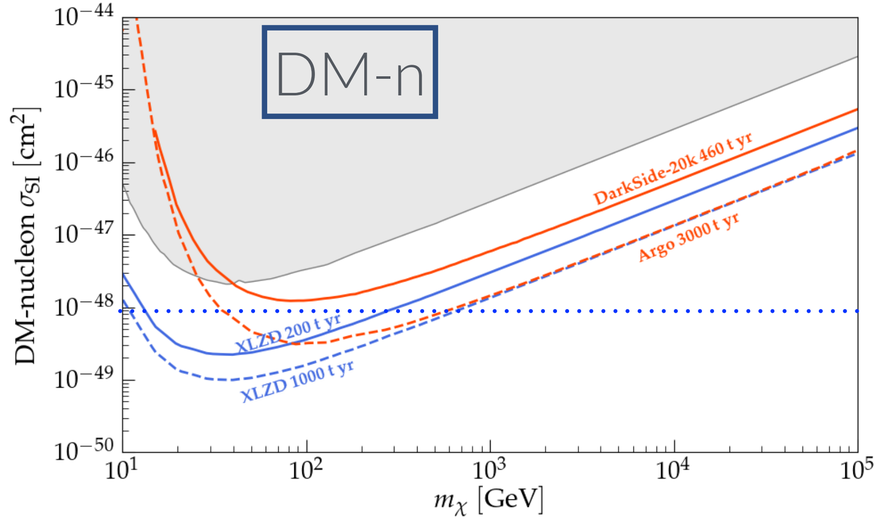
Several R&D programmes with the ultimate goal of single phonon sensitivity

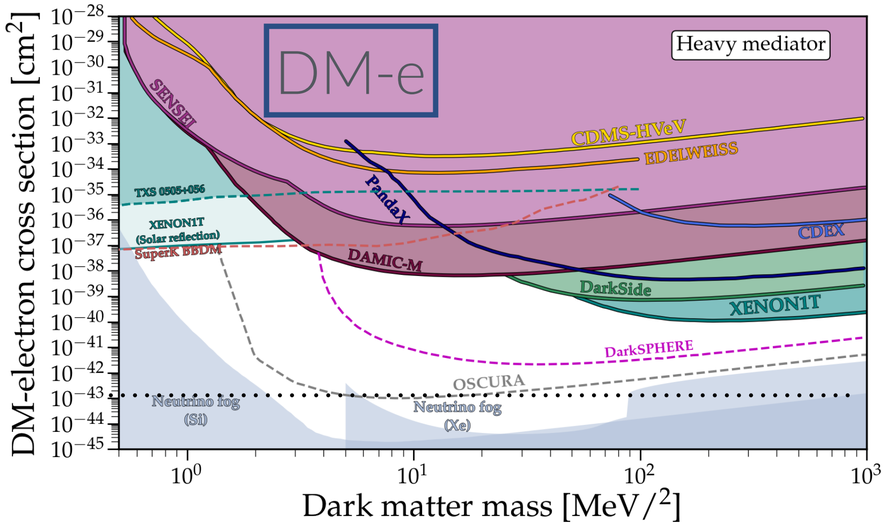
First step is to identify viable technologies, then characterise backgrounds and calibration strategies

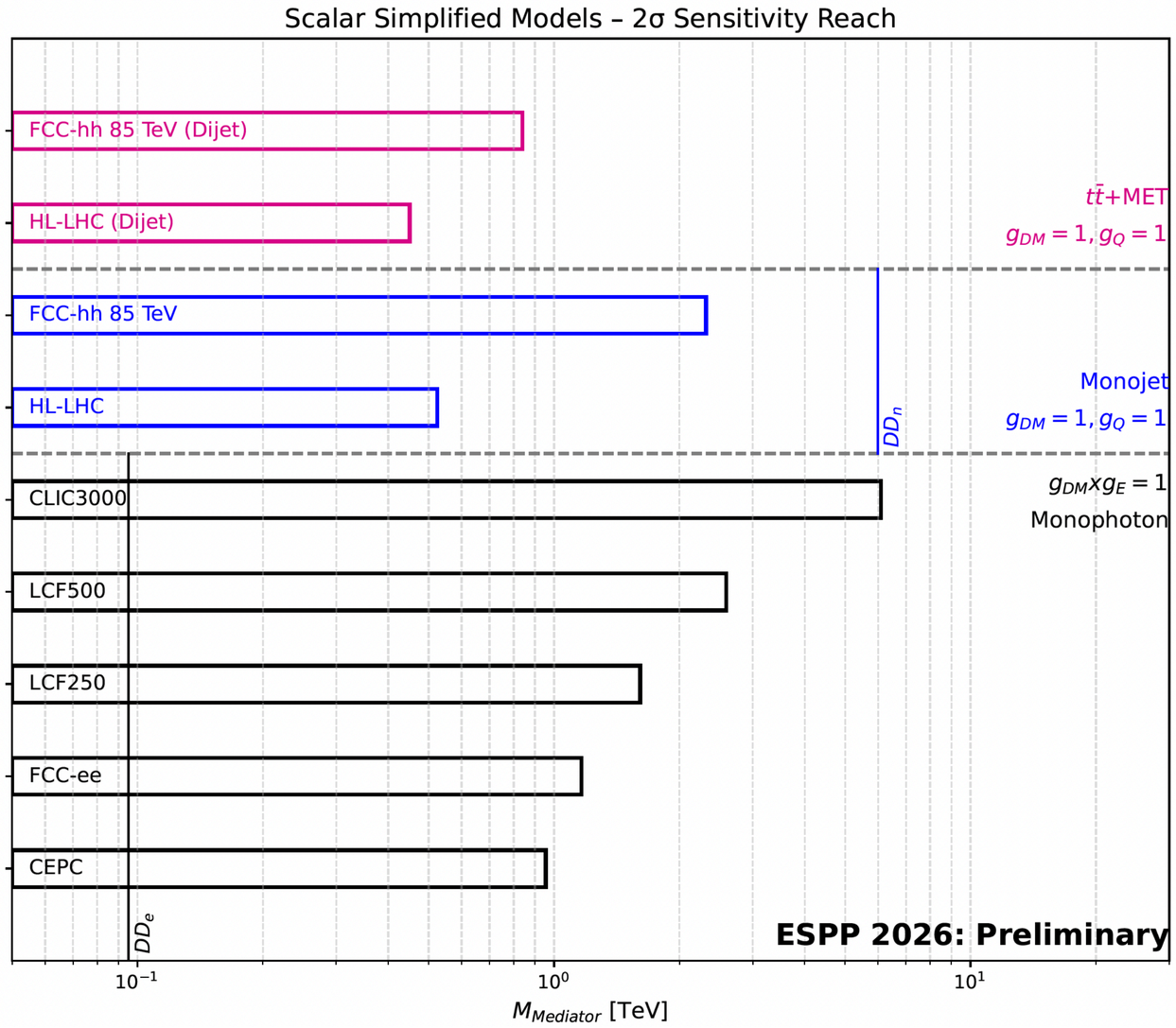
Complementarity (more in the next talk) and broader range of models

Comparison of maximum reach

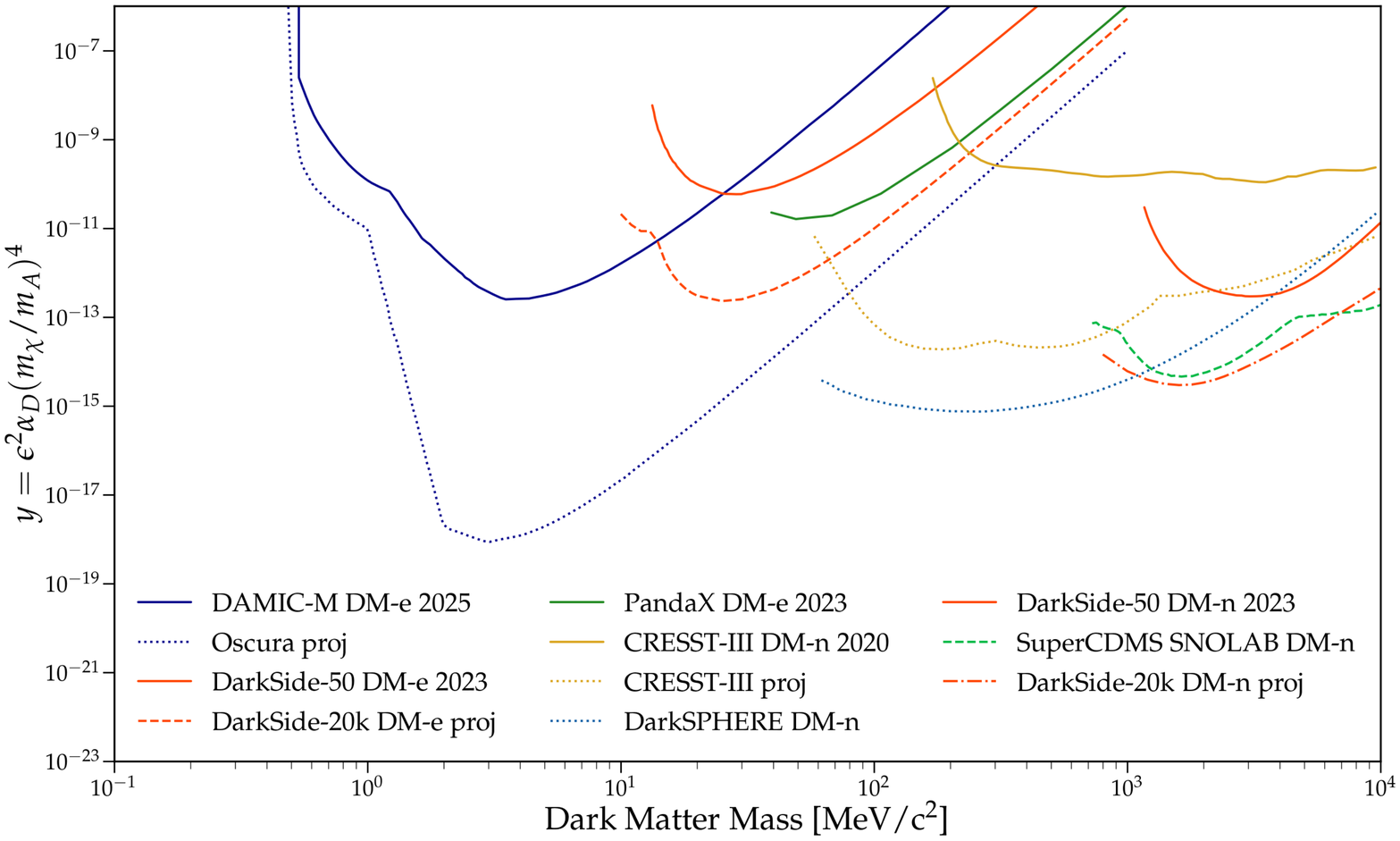
Simplified model with scalar mediator







Broader range of models



BC2 benchmark (from PBC): minimally coupled viable WIMP dark matter model can be constructed with a Dark Photon as light mediator (seen in the previous presentation).

Both **DM-nucleon** and **DM-e-** contribute to constraining the parameter space

DD can put constraints on broader range of models (not addressed in this talk)

Ultra-heavy, **effective operators, boosted DM**

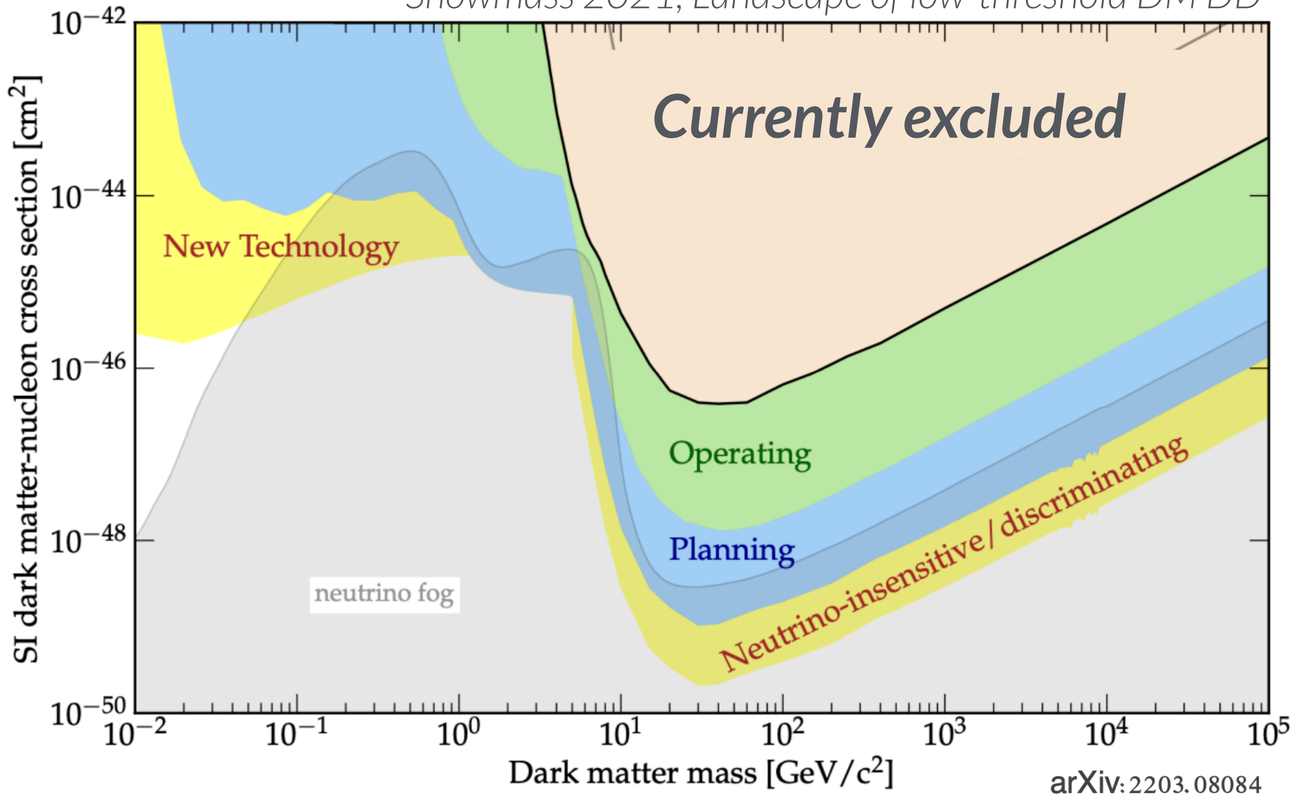
DD in the context of ESPP

Submission are mainly large collaborations
(Xe and Ar communities) addressing, as main goal,
traditional WIMPs + GeV range
+ Networks and National inputs, National Laboratories

Well established programmes (~2 decades) towards the neutrino fog > 10 GeV. Established **theoretical** (**complementarity**) and **technological** synergies.

Lots of activity at lower masses underpinned by novel technologies and techniques, exciting opportunities and new ideas which can grow and provide results in a short amount of time

Snowmass 2021, Landscape of low-threshold DM DD



Thanks

Thanks to C. J. O'Hare for providing and maintaining various tools to make many of the plots

Additional thanks for their recent review/ideas/material to R Essig, K Palladino, C Tomei