Opportunities for light dark matter searches with the DarkSide-LowMass detector

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Opportunities for light dark matter searches with the DarkSide-LowMass detector

This talk is based on a recent publication:

P. Agnes *et al.* (Global Argon Dark Matter Collaboration)

Sensitivity projections for a dual-phase argon TPC

optimized for light dark matter searches through the ionization channel

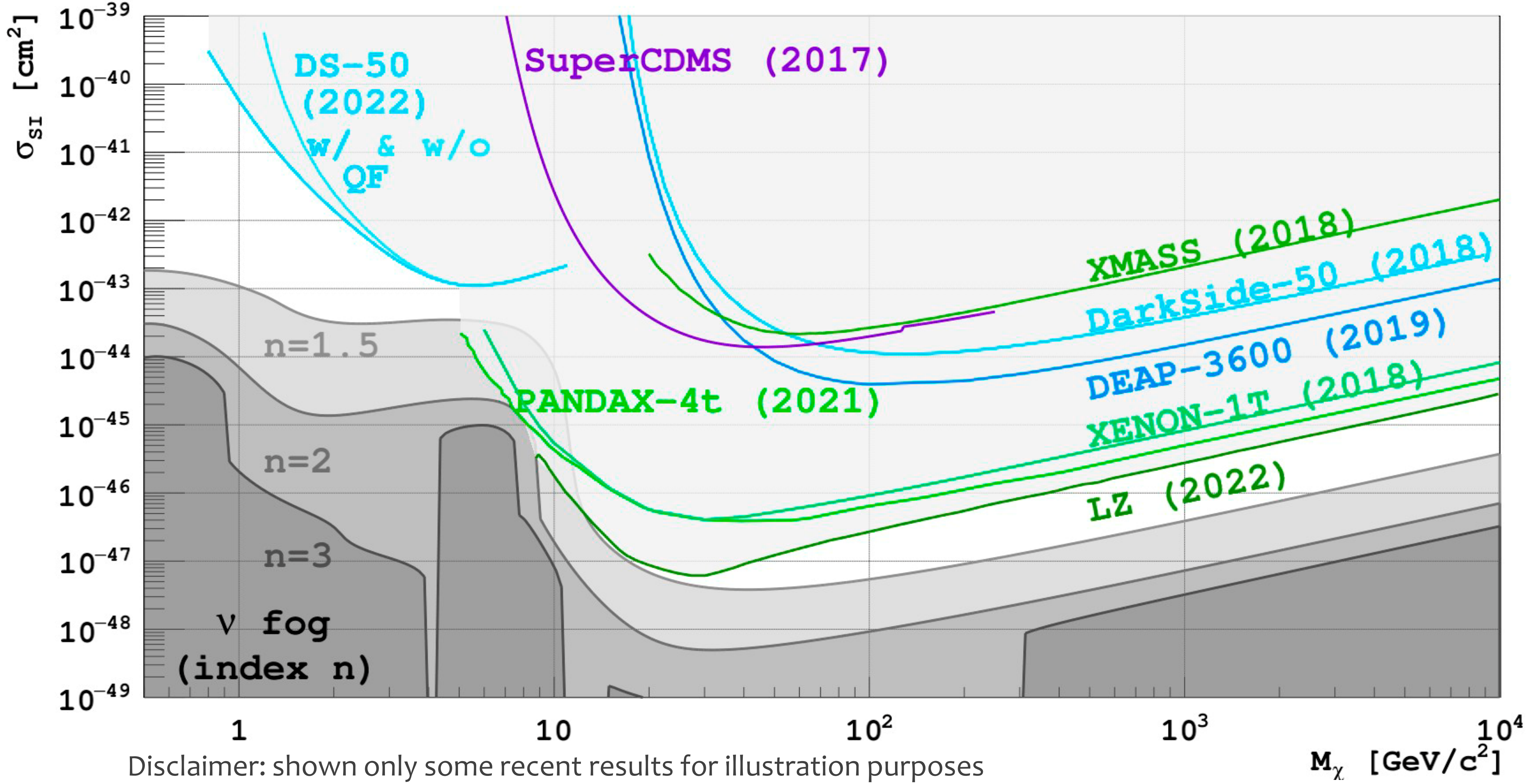
Phys. Rev. D 107, 112006

arXiv:2209.01177

In Search of the Klondike of Dark Matter

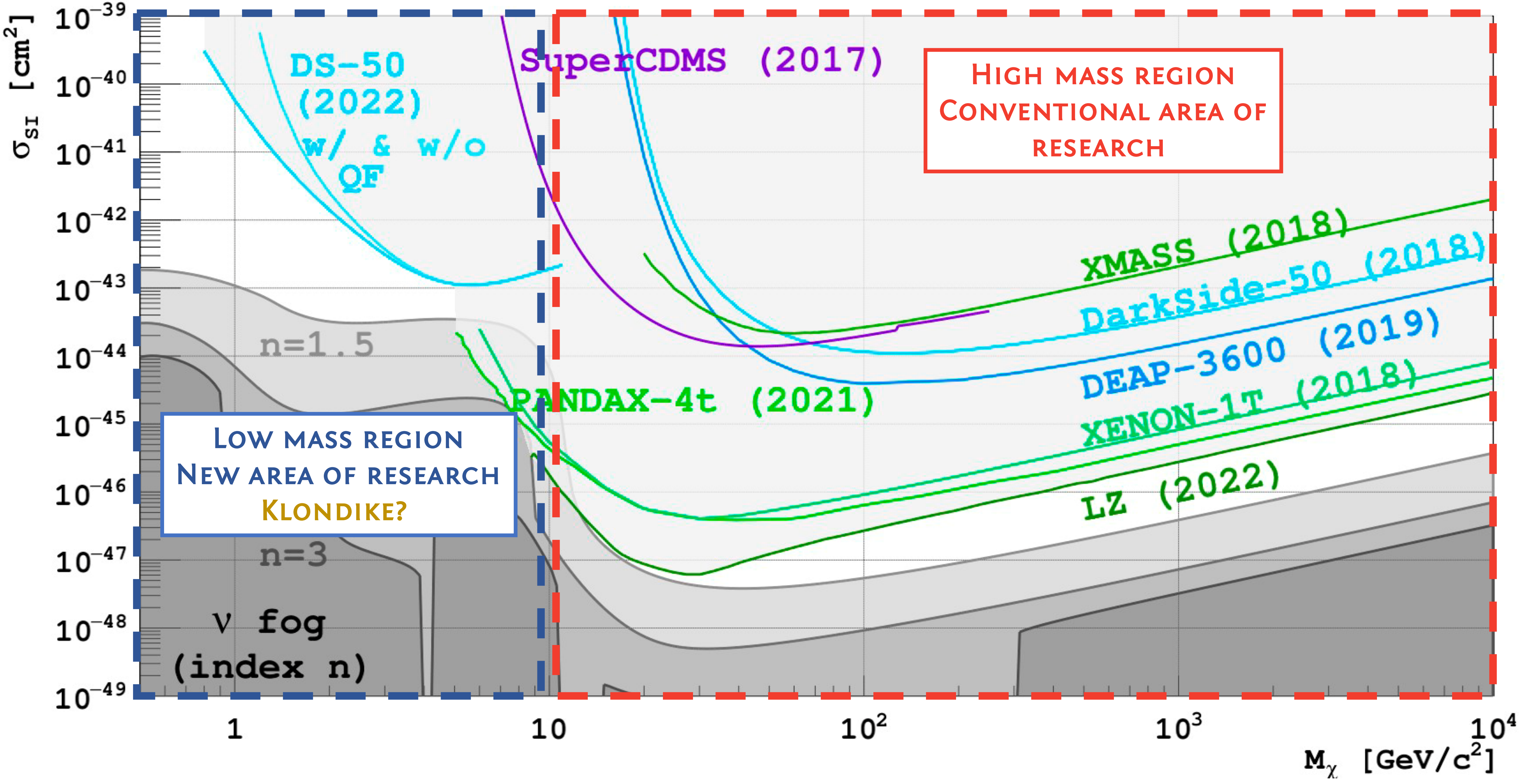
Where are we?

Current 90% C.L. upper limits on spin-independent DM-nucleon cross section



Disclaimer: shown only some recent results for illustration purposes

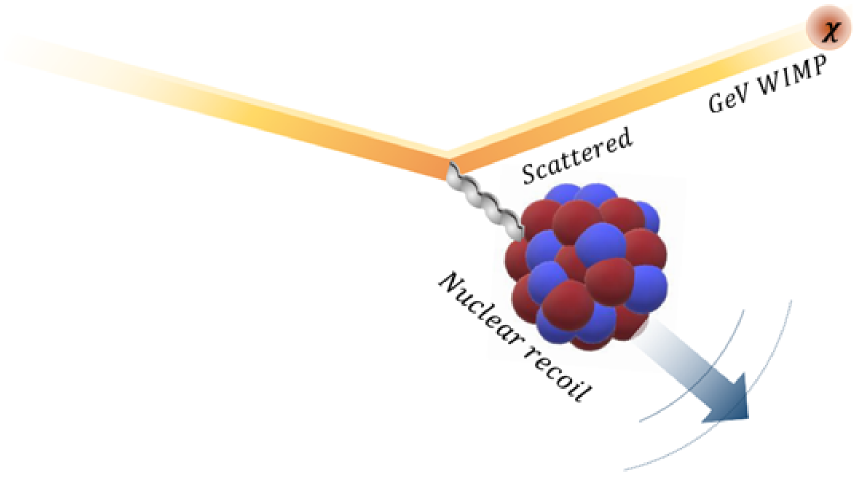
Two search directions



Possible detection channels overview

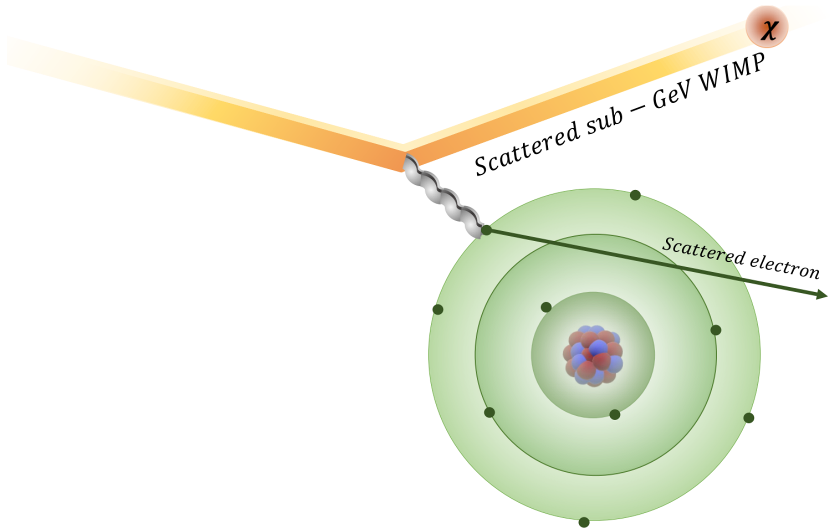
ELASTIC SCATTERING

Nuclear Recoil (NR)



DM high-mass range: ~5 GeV/c^2 to 10 TeV/c^2

Electron Recoil (ER)



DM low-mass range: ~30 MeV/c^2 to ~5 GeV/c^2

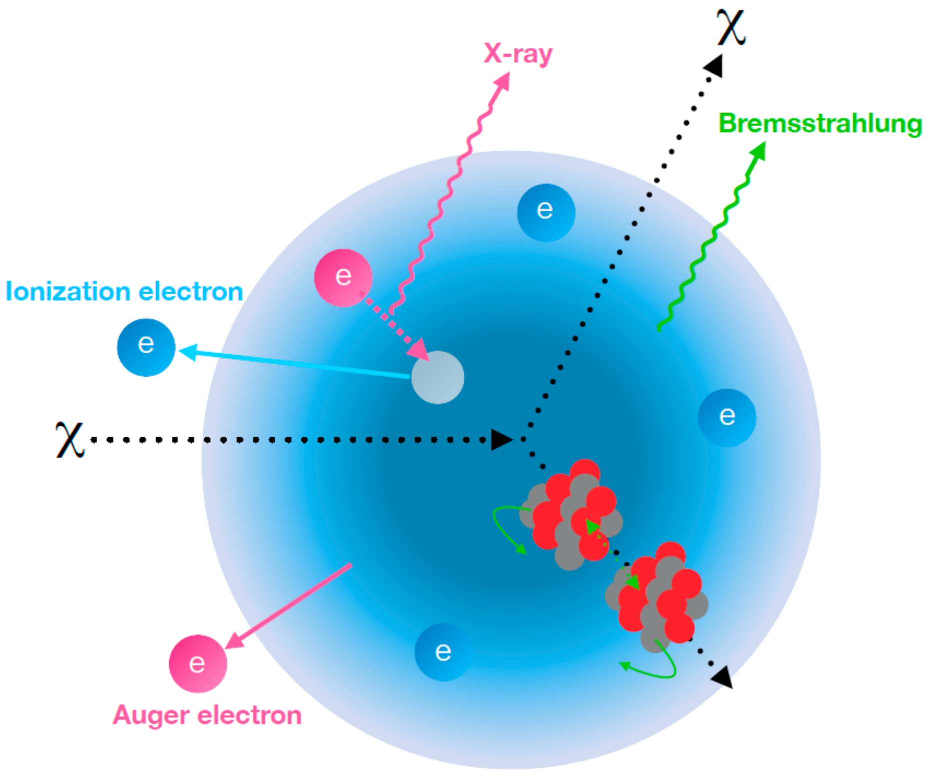
Possible detection channels overview

INELASTIC SCATTERING

DM-nucleus interactions produce polarized atoms. Then a few phenomena may occur

Migdal

keV-range
electron emission
X-ray
photon emission



Bremsstrahlung

X-ray
photon emission

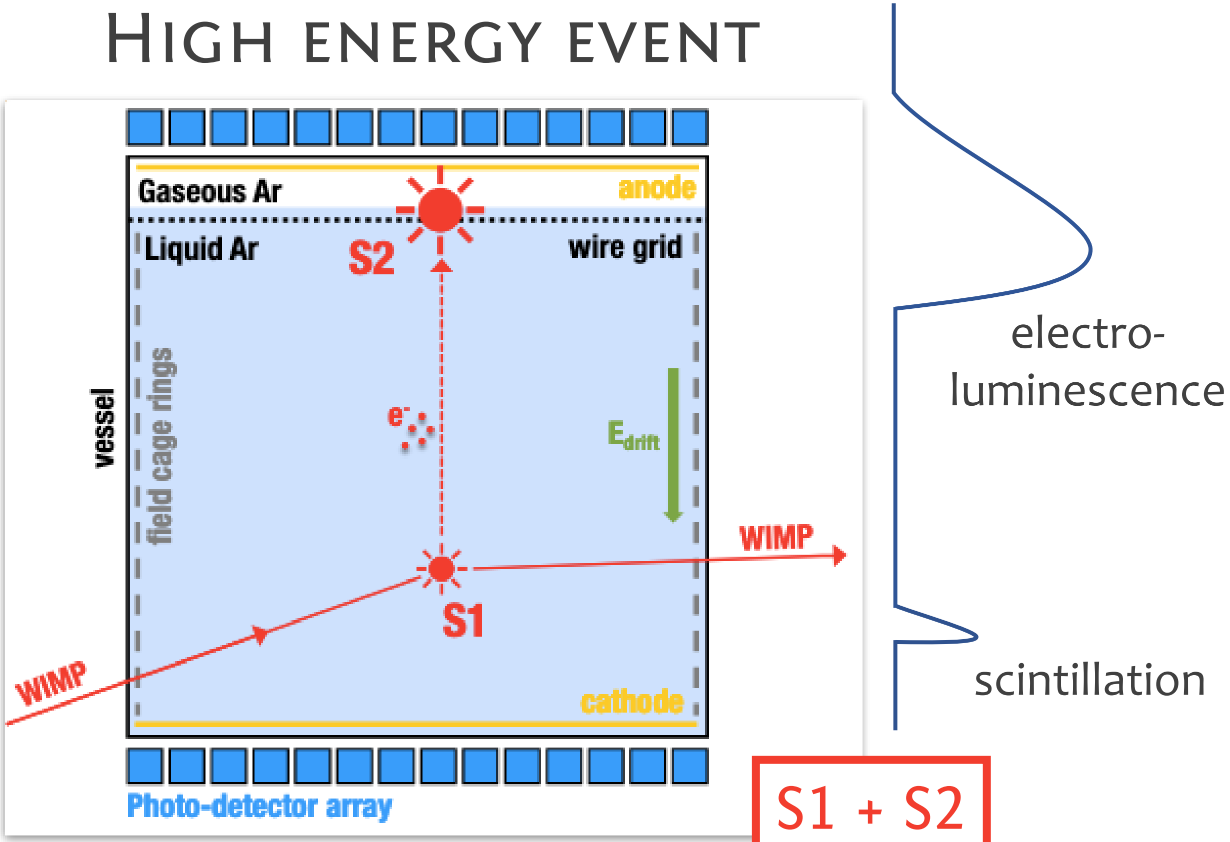
Problems:
weak effect, low sensitivity

DM low-mass range: ~30 MeV/c^2 to ~5 GeV/c^2

Image credit: XENON1T

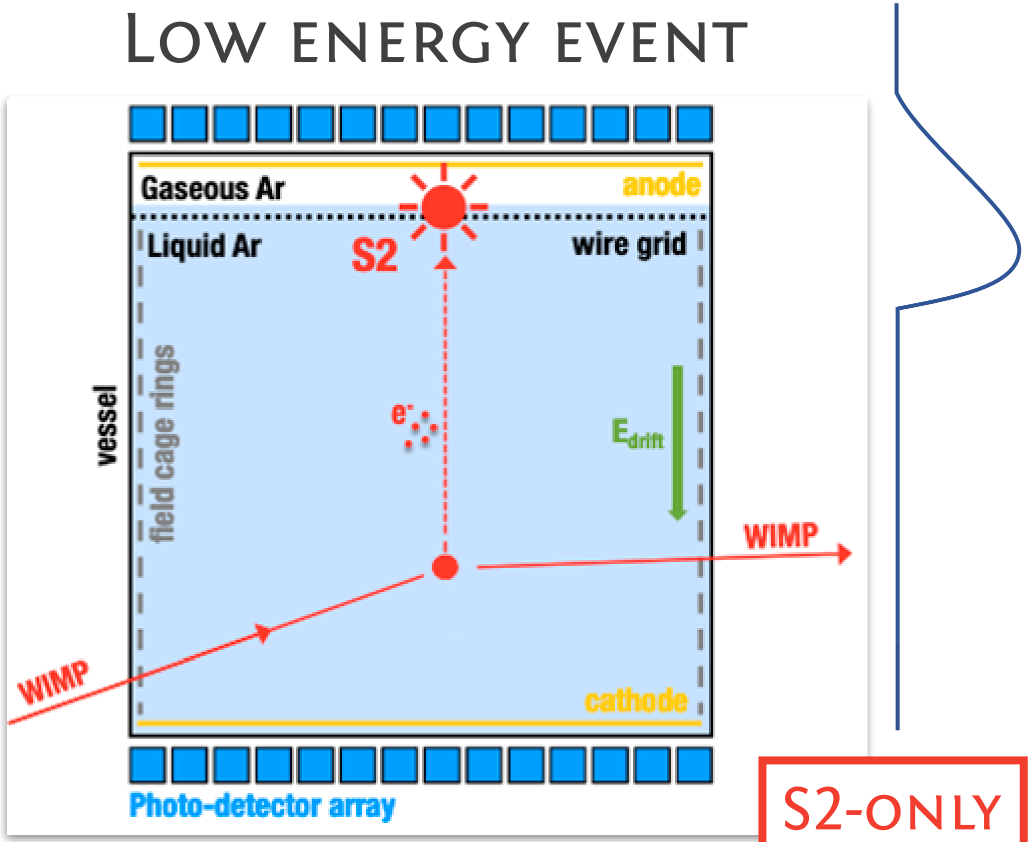
Dual-phase Time Projection Chamber (TPC)

High energy event



S1 + S2

Low energy event



S2-only

Energy dep. → scintillation photons & ionization e^-

~20% of photons detected → S1

e- drift to GAr, amplified, ~100% detected→S2

S1 gives particle identification, Z, energy resolution

Amplification in GAr lets us detect e^- with high efficiency above photoelectronic noise

→ Lower energy threshold

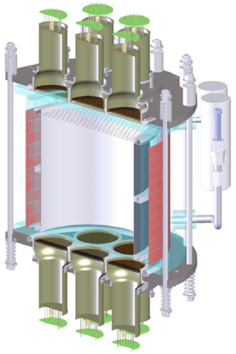
No pulse shape discrimination

No vertical position reconstruction

DarkSide Program: A multi-stage approach

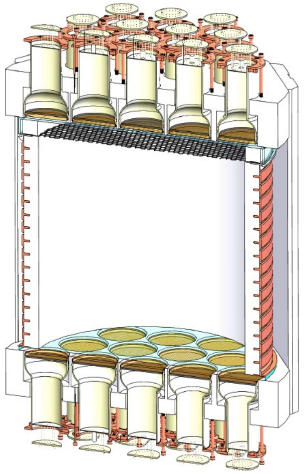
(Global Argon Dark Matter Collaboration participant)

2012 | 2013 - 2018 | 2025 - 2035 | 2030s - …



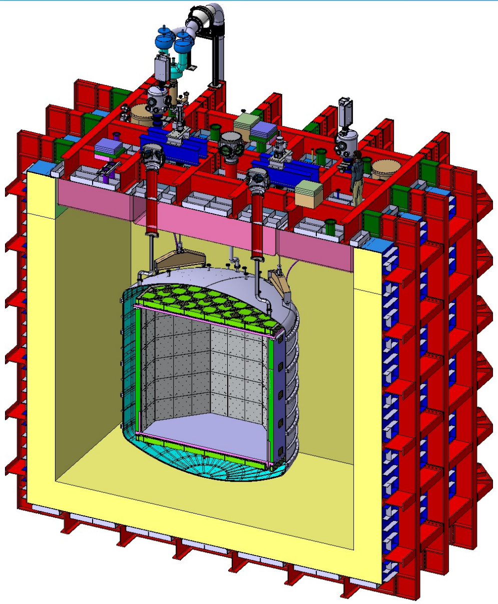
DarkSide-10

- First prototype
- Helped to refine TPC design
- Demonstrated a light yield >9PE/keV_{ee}



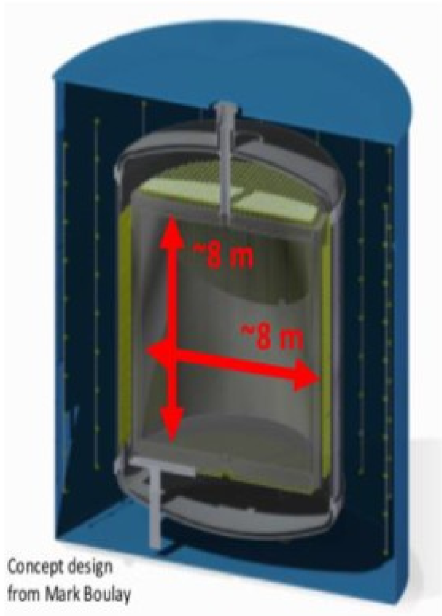
DarkSide-50

- Science detector
- Demonstrated the use of UAr
- First background-free results
- Best limits for low mass WIMP searches



DarkSide-20k @ LNGS

- Novel technologies
- First peek into the neutrino fog
- Nominal exposure: 200 t y

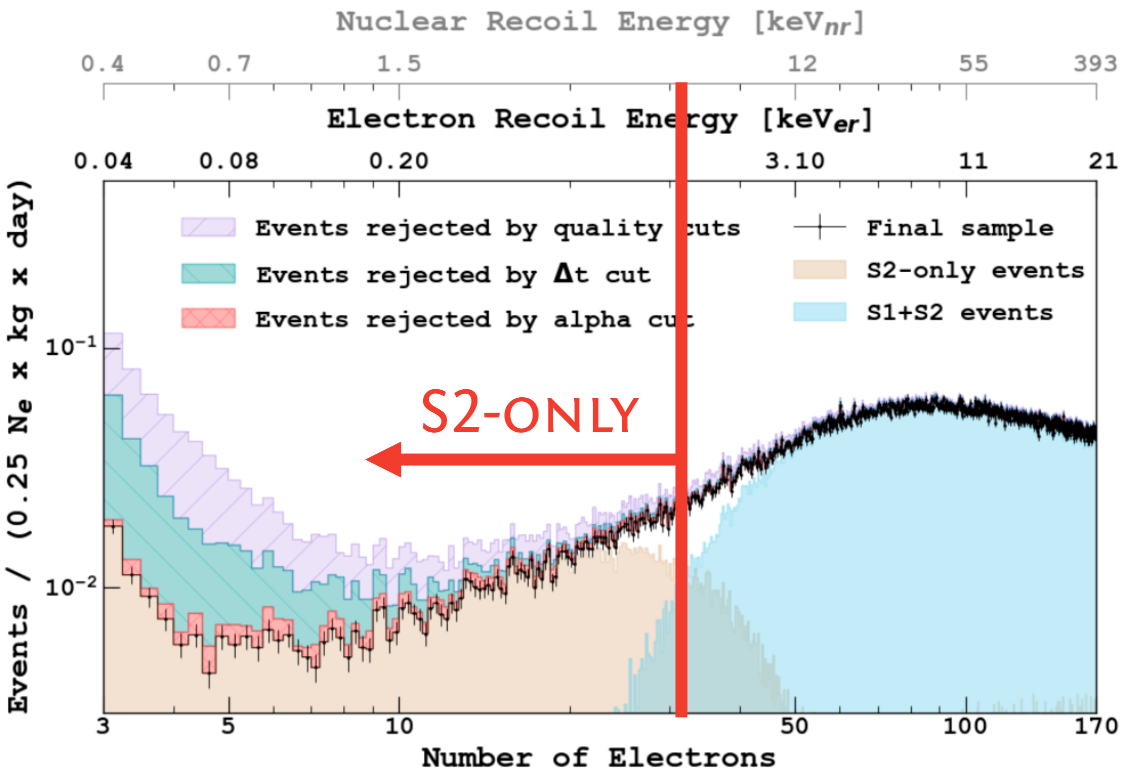


ARGO @ SNOLAB

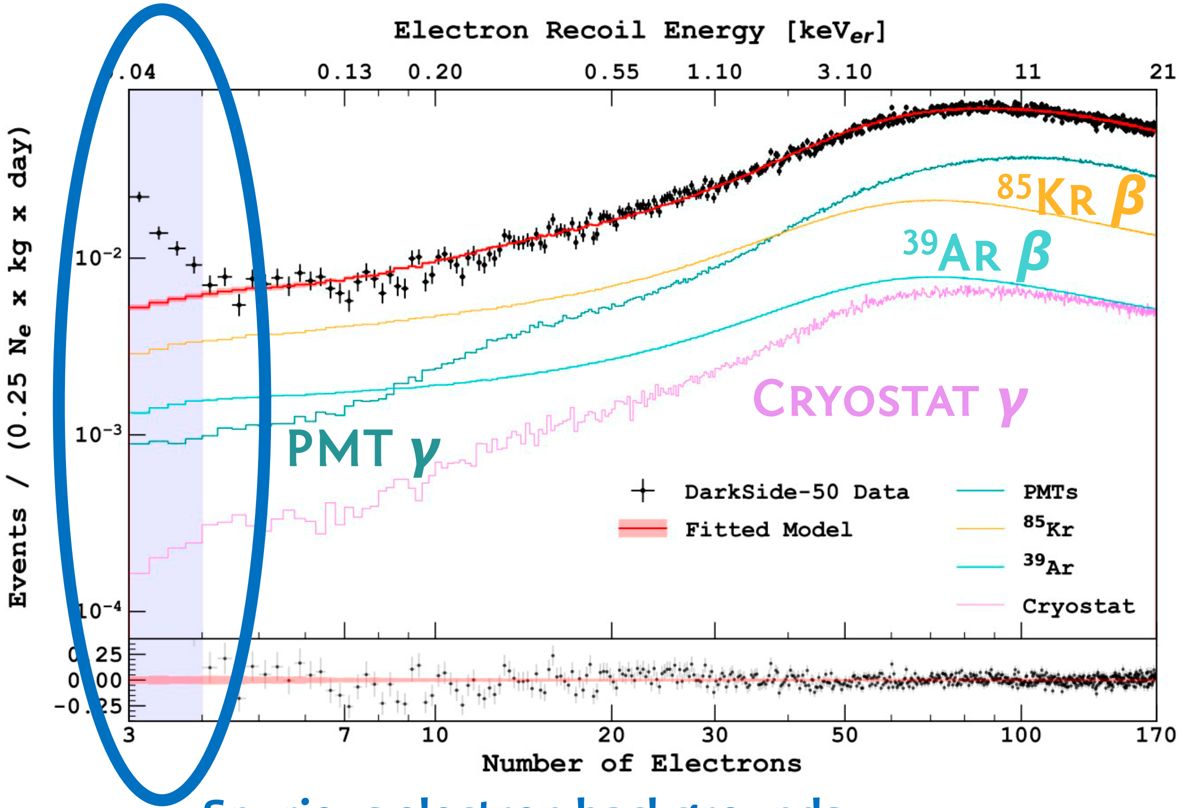
- Ultimate LAr DM detector
- Push well into the neutrino fog
- Nominal exposure: 3000 t y

Lessons from the DarkSide-50 experience

What limited DarkSide-50's sensitivity?



DarkSide-50 data

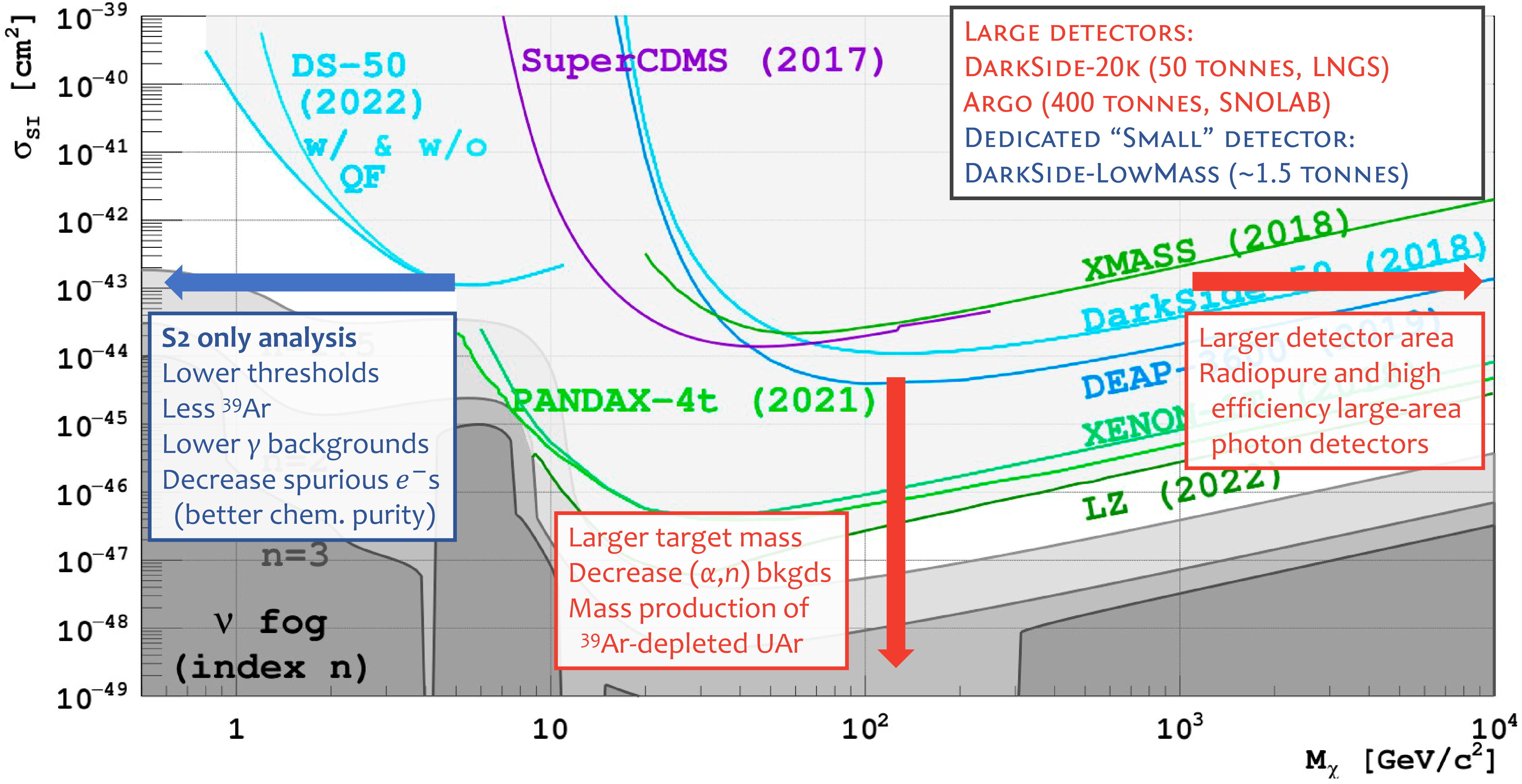


DarkSide Collaboration. "Search for low-mass dark matter WIMPs with 12 ton-day exposure of DarkSide-50" ***Phys. Rev. D 107, 063001 (2023)***

Spurious electron backgrounds

- Follow large S2 pulses
- Poorly understood
- Leading hypothesis: from drifting e^{-}'s interacting with impurities

Lessons from the DarkSide-50 experience



S2 only analysis
Lower thresholds
Less ^{39}Ar
Lower γ backgrounds
Decrease spurious e^-s (better chem. purity)

Larger target mass
Decrease (α,n) bkgds
Mass production of ^{39}Ar-depleted UAr

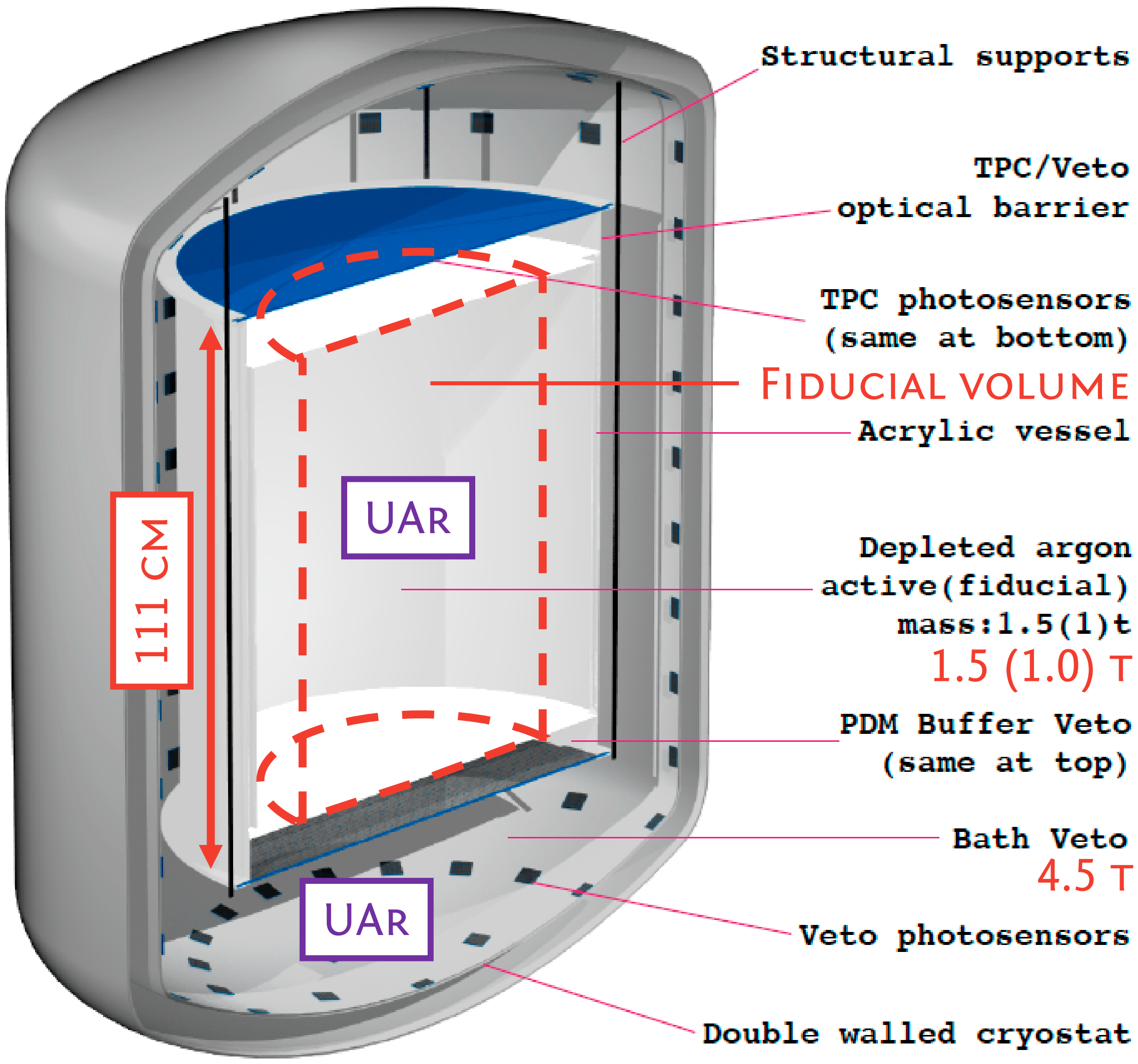
Large detectors:
DarkSide-20k (50 tonnes, LNGS)
Argo (400 tonnes, SNOLAB)
Dedicated "Small" detector:
DarkSide-LowMass (~1.5 tonnes)

Larger detector area
Radiopure and high efficiency large-area photon detectors

DarkSide-LowMass

- ➢ Conceptual design
- ➢ Detector response model
- ➢ Backgrounds

DarkSide-LowMass: A conceptual design



The cryostat is immersed in a water tank (not shown)

Underground argon low in ^{39}Ar and further depleted, using DS-20k's Urania & Aria plants, assayed at DArT in ArDM ^{39}Ar assay facility

Dominant γ sources (cryostat & photoelectronics) separated from TPC by **active vetoes**

SiPM photosensors developed for DS-20k

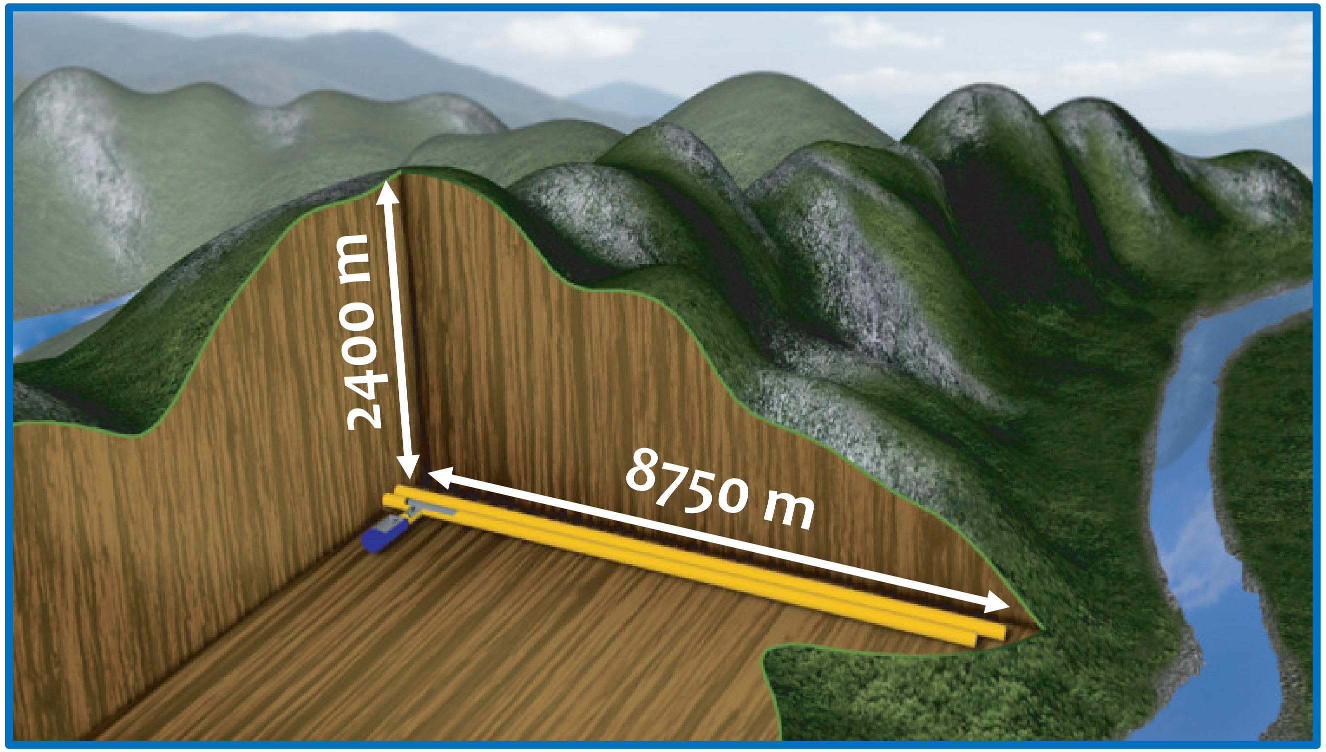
Much lower γ activity than PMTs

Materials assayed and carefully selected by DarkSide-20k and DEAP-3600

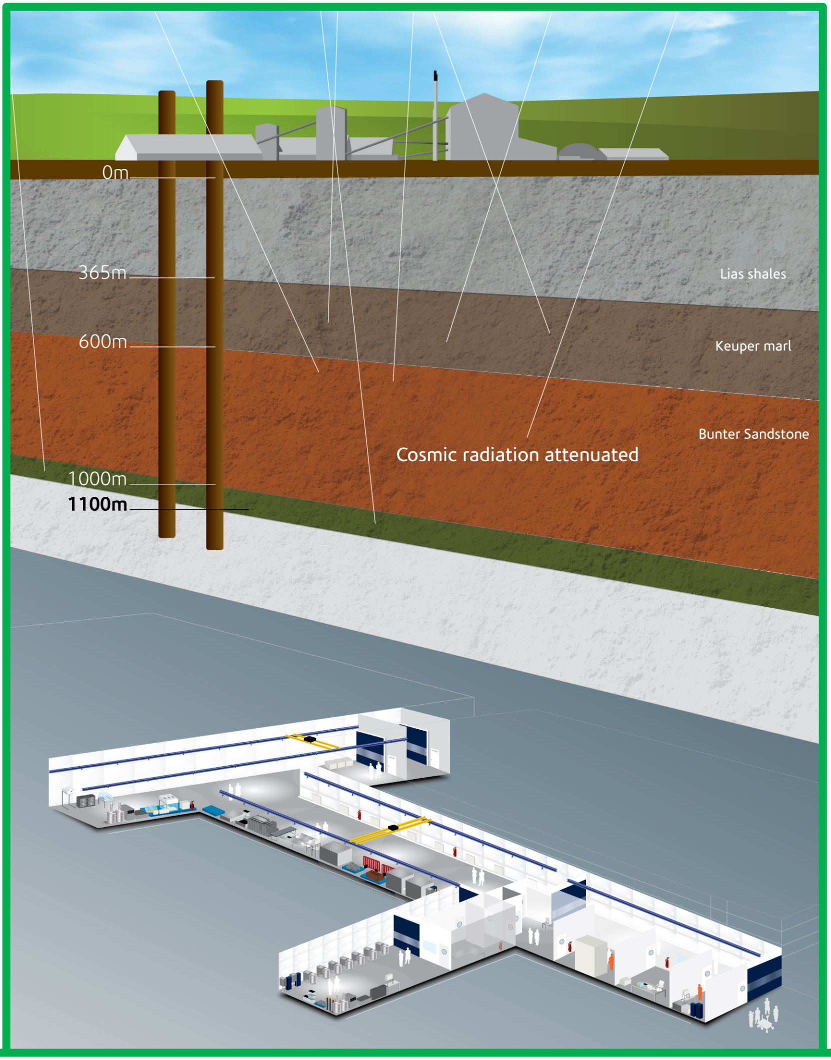
A double-walled stainless steel or **titanium cryostat, titanium structural supports** (radiopure and lightweight)

Titanium can be produced with a specified radiopurity

Possible detector locations



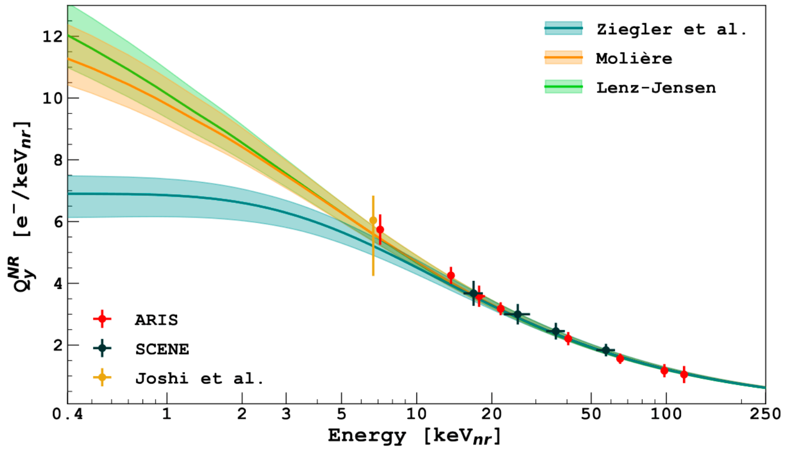
China Jinping Underground Laboratory
the Jinping Mountains of Sichuan,
the People's Republic of China



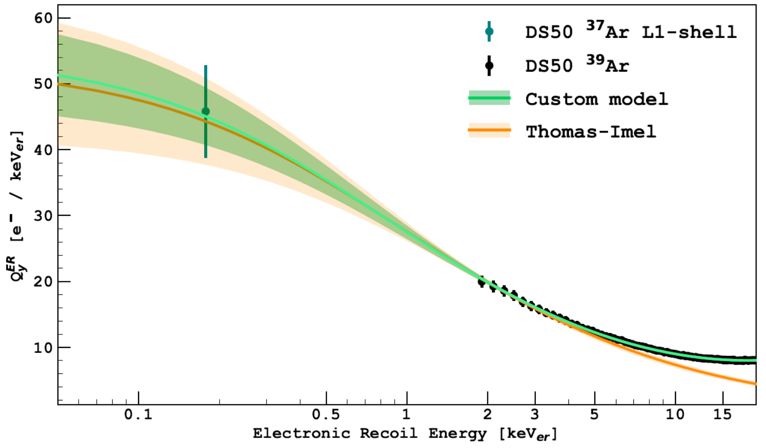
Boulby Underground Laboratory
between Saltburn and Whitby,
the United Kingdom

Realistic detector response model from DS-50 measurements

DarkSide-50



DarkSide-50



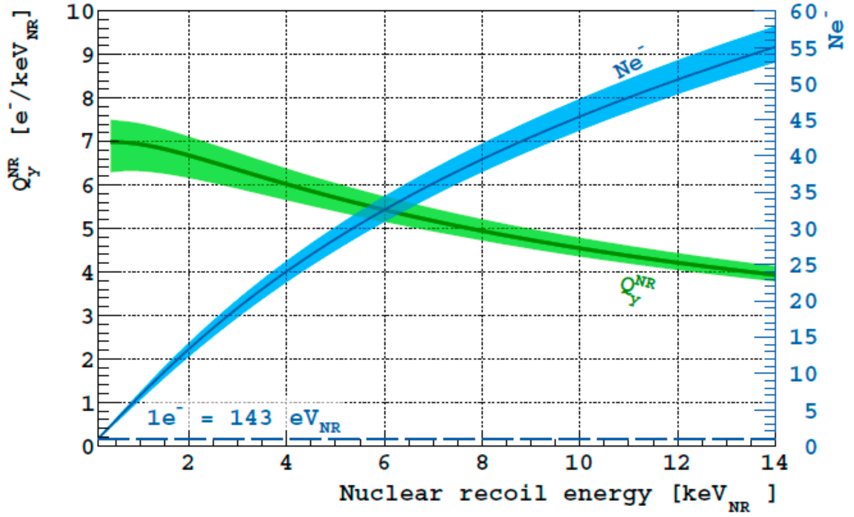
Ionization yield model fits to DS-50 ^{37}Ar, ^{39}Ar, neutron calibration data & ex situ measurements by ARIS, SCENE & Joshi *et al.*

DarkSide Collaboration. "Calibration of the liquid argon ionization response to low energy electronic and nuclear recoils with DarkSide-50".
Phys. Rev. D 104, 082005 (2021)

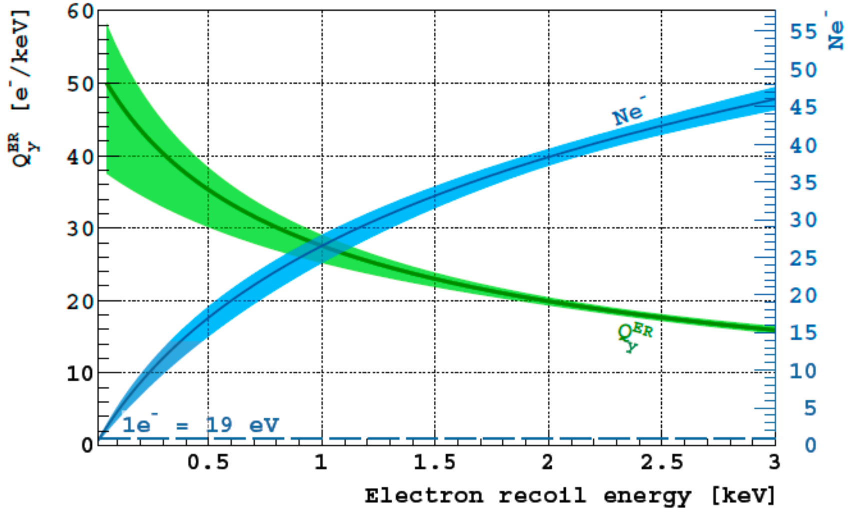
Non-parametric extrapolation uncertainties (e.g. stopping power screening function):
used lowest Q_y model (Ziegler et al.) for now

Uncertainties in N_e fluctuations around nominal value:
considered binomial quenching fluctuations and
no quenching fluctuations

DarkSide-LowMass

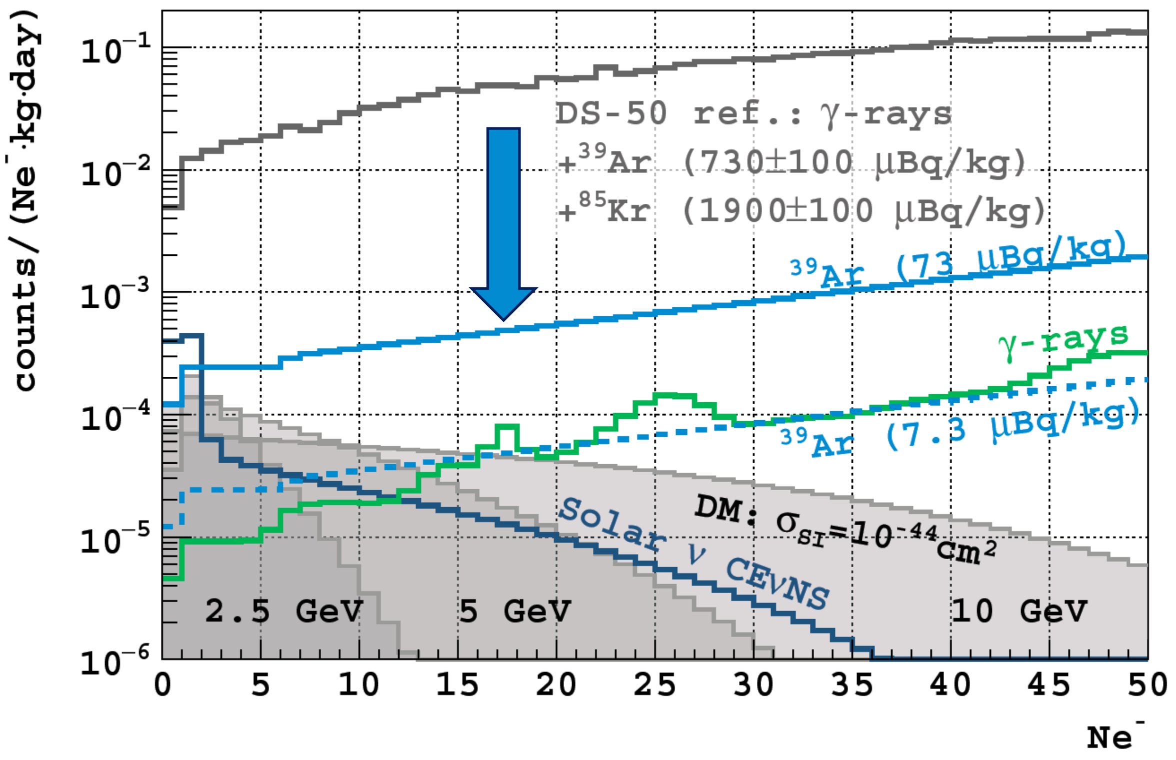


DarkSide-LowMass



Planning low-energy calibration measurements to improve these models

β-decay backgrounds



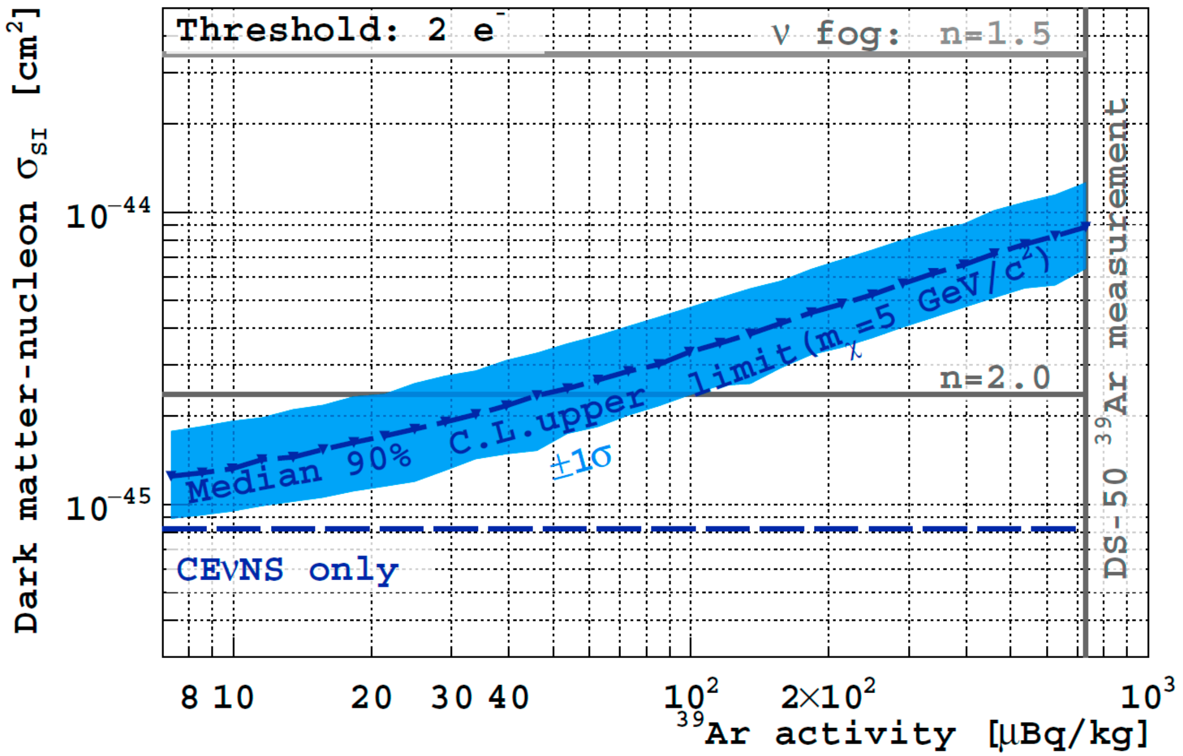
^{85}Kr: Expect to fully remove

^{39}Ar: Reduce by at least 10 times (Aria, 1 pass)

Up to 100 times reduction

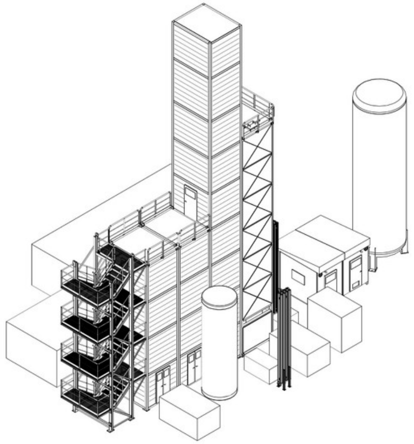
(2nd Aria pass, improvements to extraction)

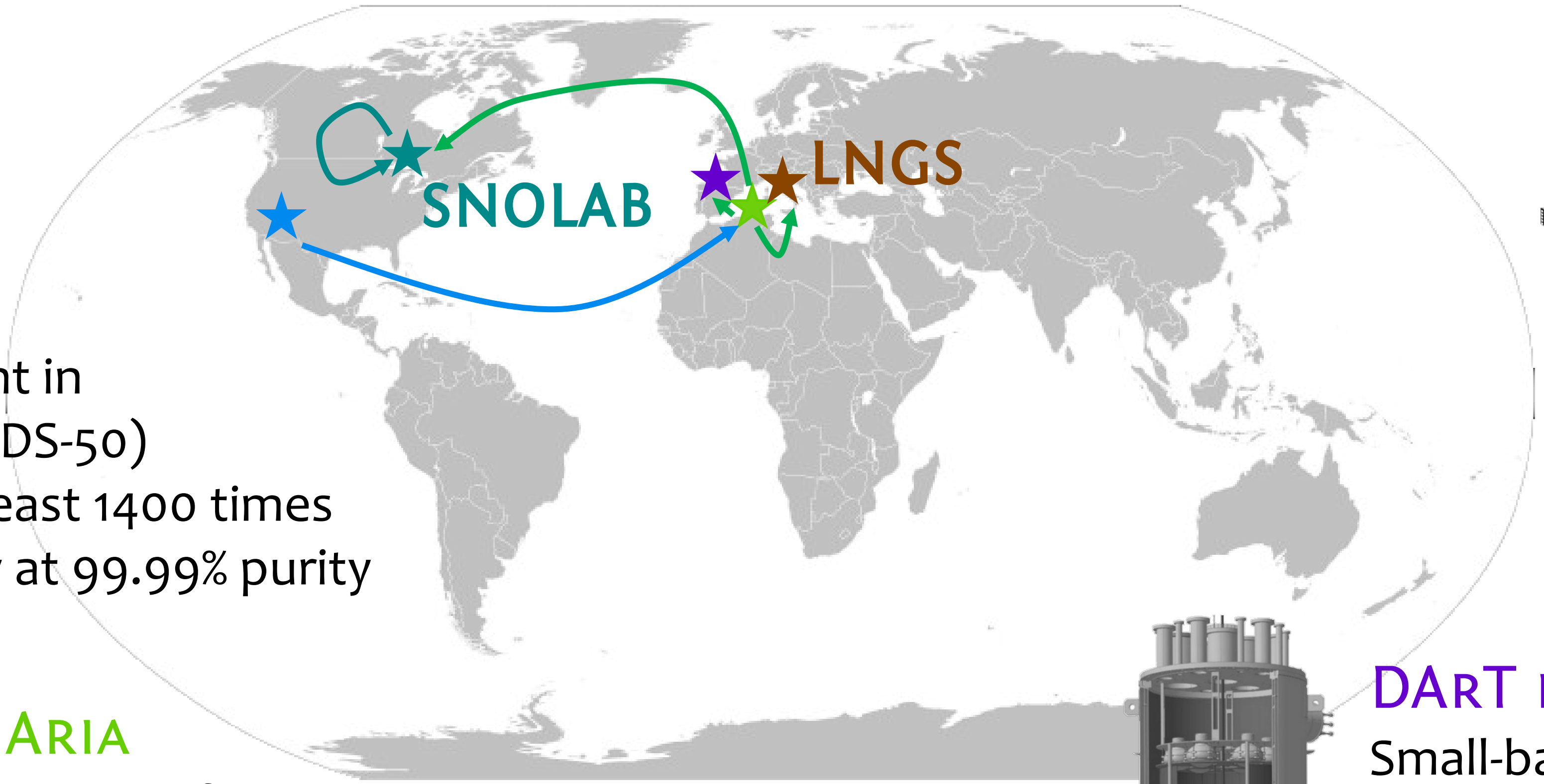
Expect to further reduce with improved UAr extraction and isotopic distillation

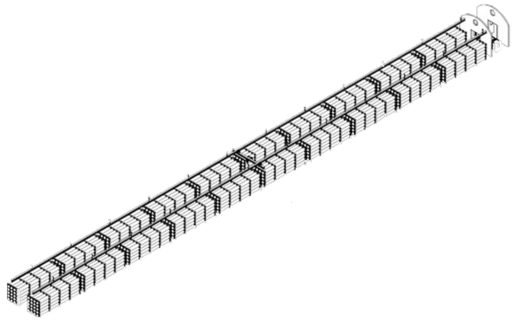


Sensitivity to 5 GeV/c² dark matter

UAr: Low radioactivity argon







Urania

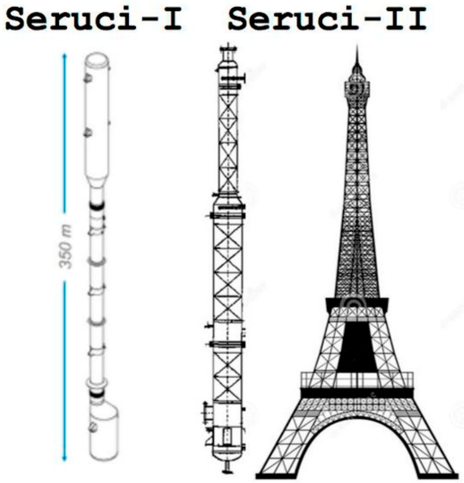
UAr extraction plant in Colorado (same as DS-50)

^{39}Ar depletion: at least 1400 times

Extract: 250 kg/day at 99.99% purity

ARGUS

Long-term Uar storage at SNOLAB



Aria

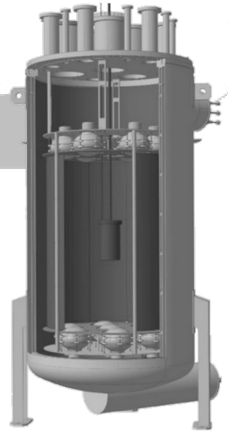
UAr purification in Sardinia

350 m-tall cryogenic distillation column

Chem. purification: 10^3 times reduction at O(1 tonne/day)

^{39}Ar depletion: 10 times reduction at O(10 kg/day)

DarkSide Collaboration. "Separating 39Ar from 40Ar by cryogenic distillation with Aria for dark matter searches". **Eur.Phys.J. C 81 (2021) 4, 359**



DArT in ArDM

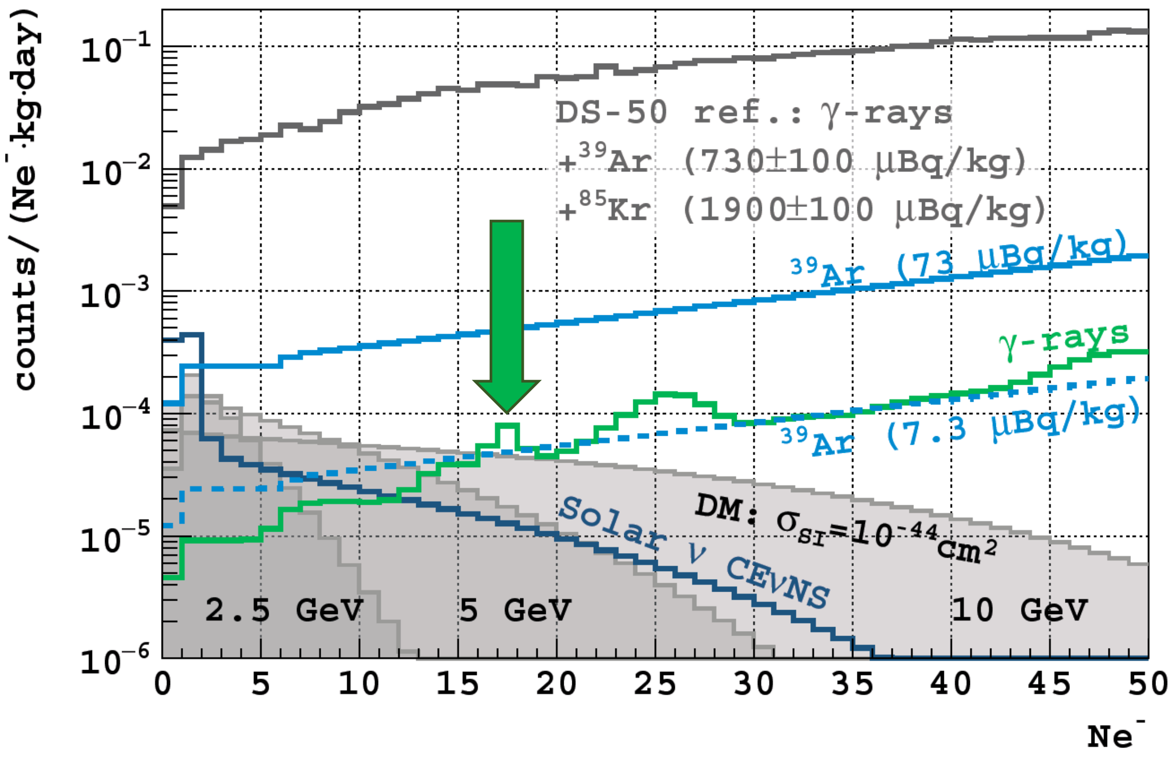
Small-batch ^{39}Ar assay facility in Canfranc Lab, Spain

Sensitivity: depletion factor U.L. of $6{\times}10^4$ at 90% C.L. in 1 week of counting time

DarkSide Collaboration. "Design and construction of a new detector to measure ultra-low radioactive-isotope contamination of argon". **JINST 15 P02024 (2020)**

γ-RAY BACKGROUNDS

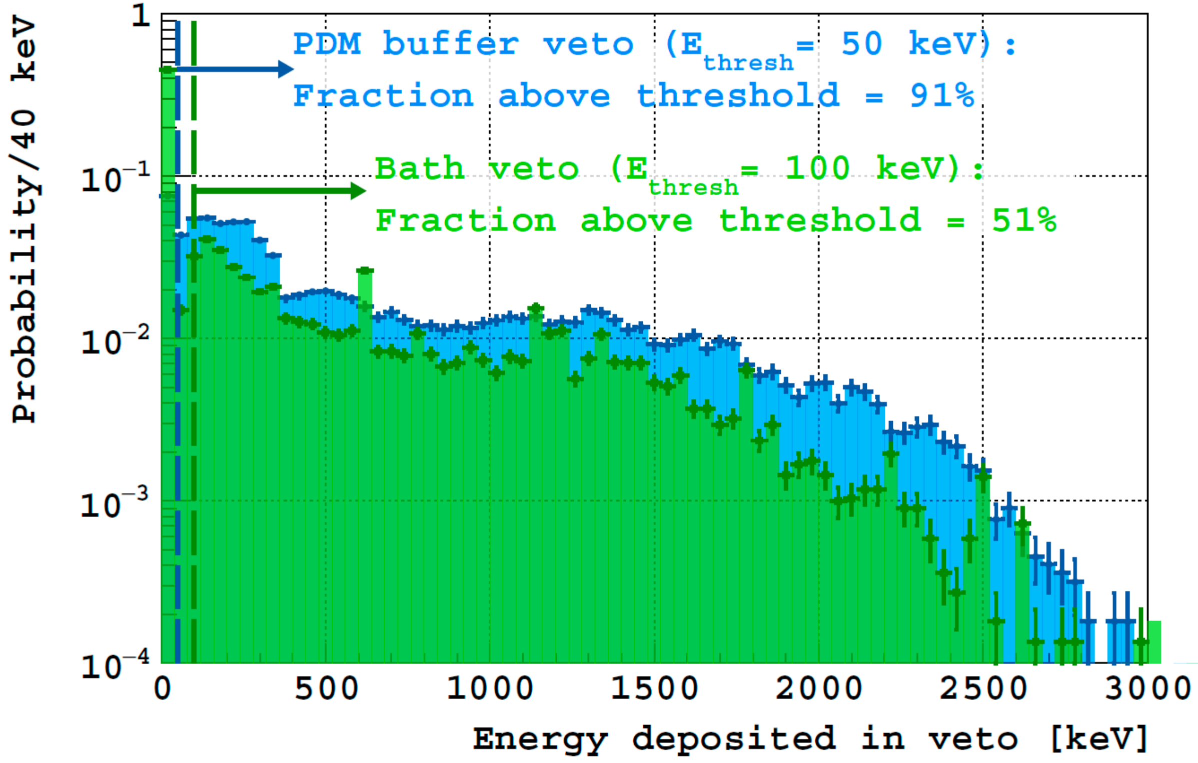
Two main sources: photoelectronics and cryostat



γ-ray background reduction
with improved radiopurity materials:

- SiPMs from DS-20k
- Acrylic from DEAP
- Ultra-pure stainless steel or titanium cryostat

For γ's from photoelectronics



Additional suppression
with 2-fold γ-ray veto system

Note: TPC in low-Z acrylic to avoid blocking γ's from veto

Size of cryostat chosen so that its γ's are subdominant to photoelectronics, after applying veto cuts

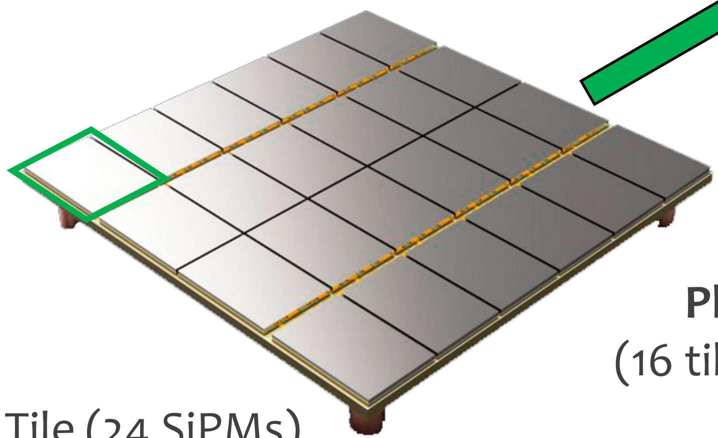
Low-background SiPMs developed for DarkSide-20k

Developed with Fondazione Bruno Kessler (FBK)

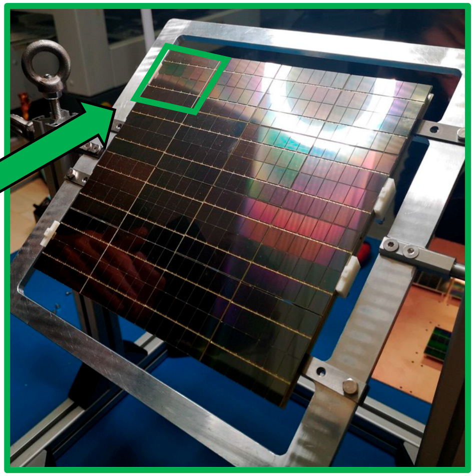
Photodetection efficiency: > 40% at 77 K
Dark count rate: <0.01 Hz/mm² at 77 K (7 VoV)
SNR: >8 (TPC)

SPAD

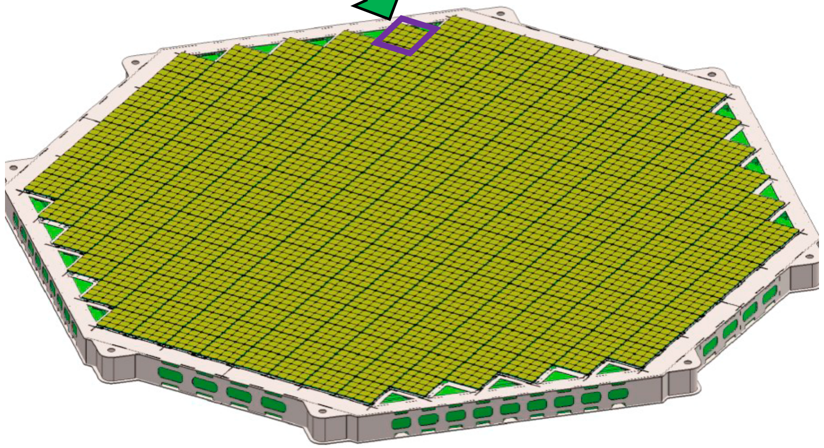
SiPMs
[8×12 mm²]



Tile (24 SiPMs)
[5×5 cm²]



Photo**D**etection **U**nit (PDU)
(16 tiles, arranged into 4 channels)
[20×20 cm²]



Optical Plane
(264 PDUs)

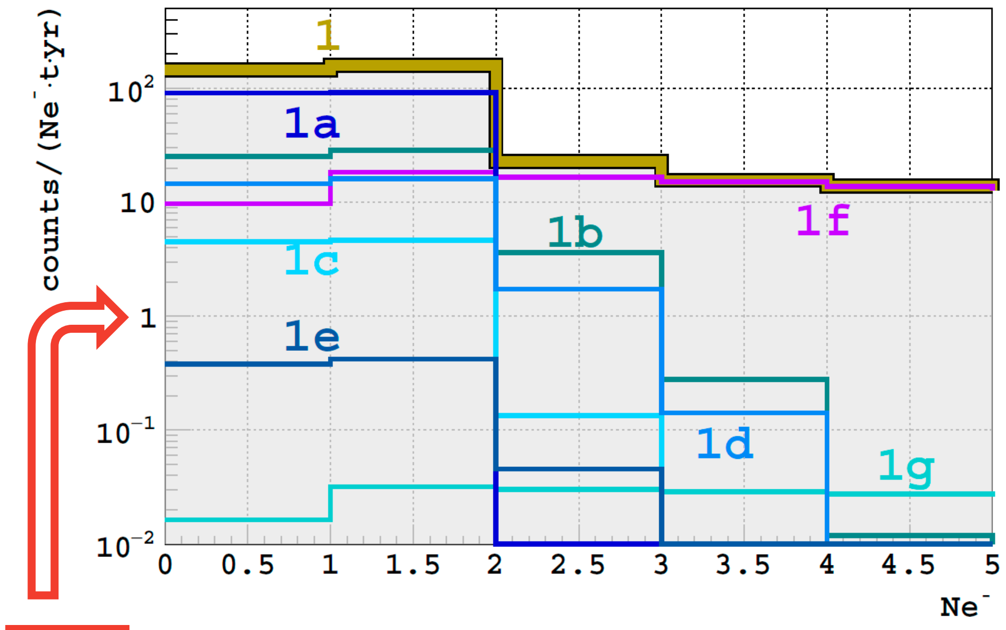
DarkSide Collaboration. "Cryogenic Characterization of FBK RGB-HD SiPMs". **JINST 12 P09030 (2017)**

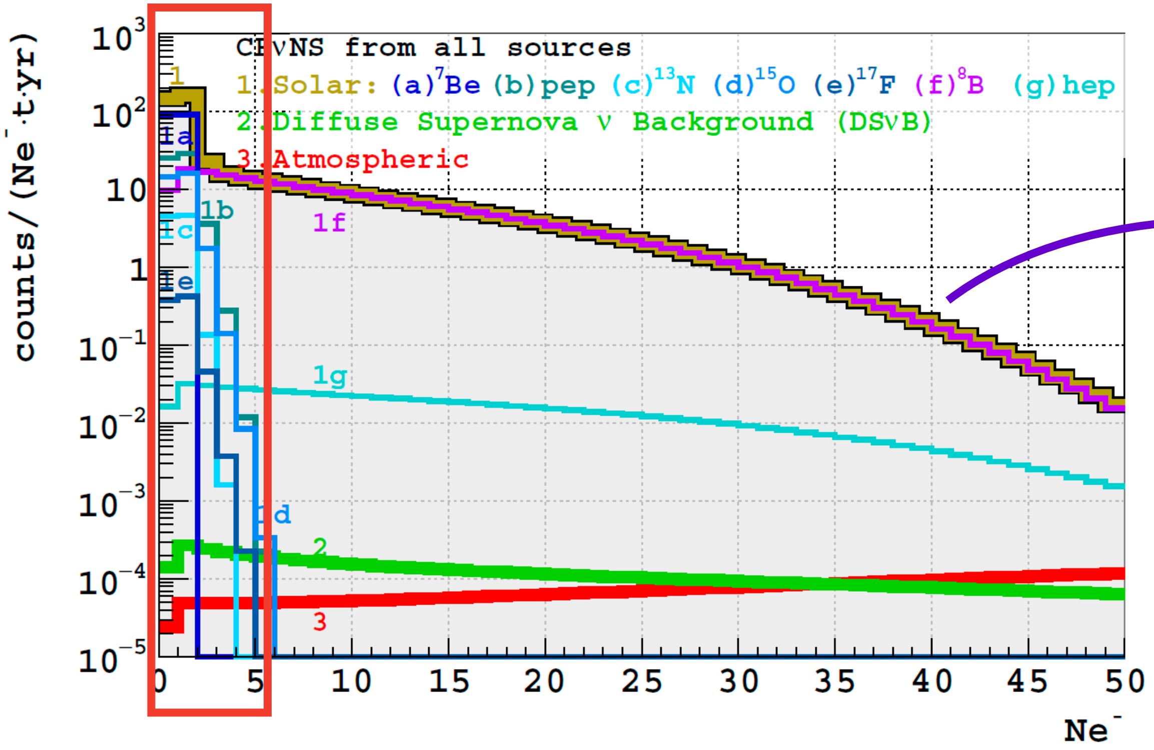
A. Gola *et al.* "NUV-Sensitive Silicon Photomultiplier Technologies Developed at Fondazione Bruno Kessler". **Sensors19(2), 308 (2019)**

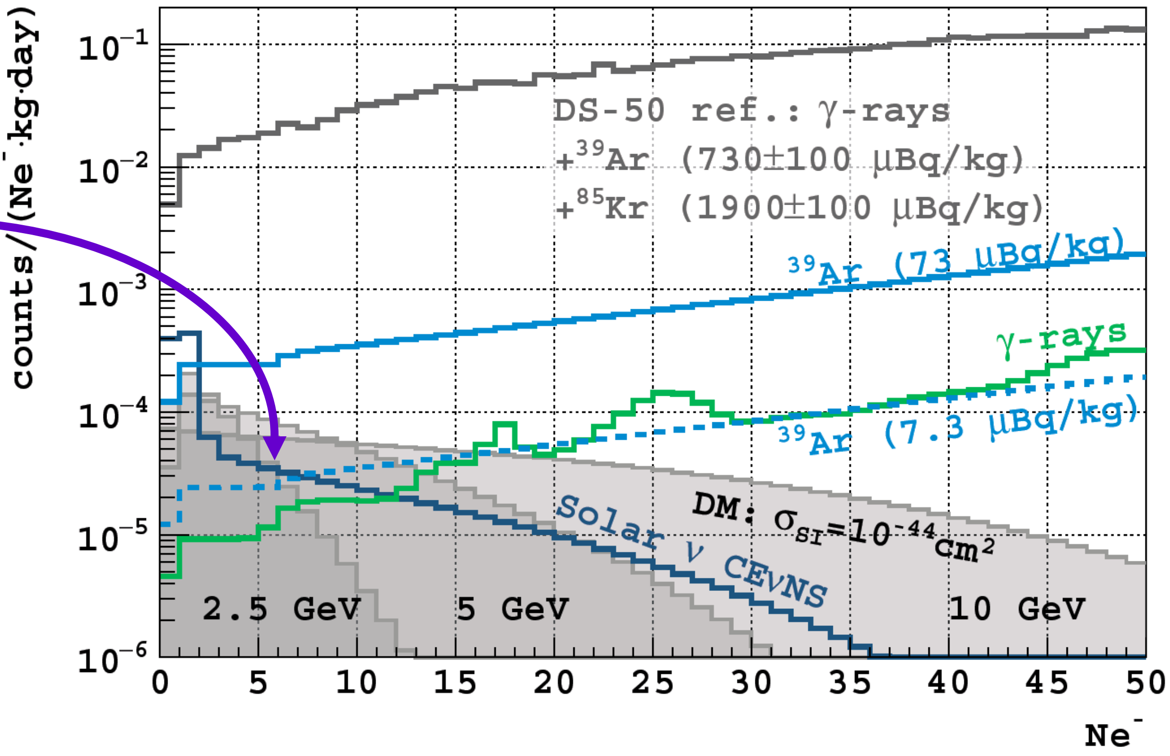
PDU production pipeline

SiPM production at LFoundry (Italy) → PDU packaging and assembly at Nuova Officina Assergi (NOA) at LNGS → Testing at the Naples Test Facility

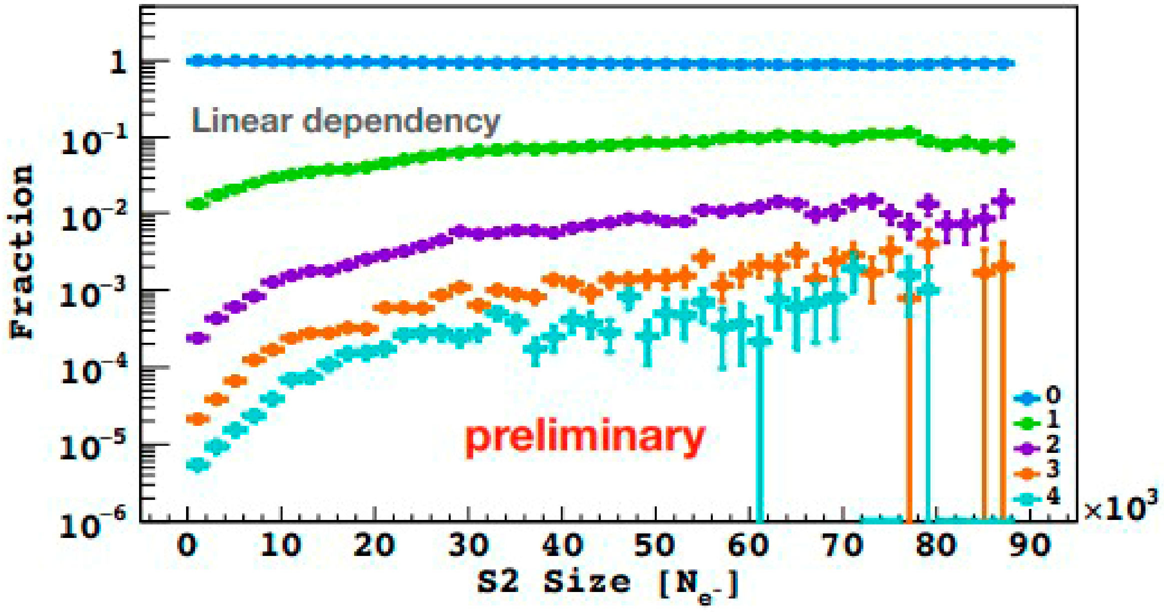
IRREDUCIBLE SOLAR ν CEνNS MAY CONTRIBUTE COMPARABLY TO OTHER BACKGROUND SOURCES

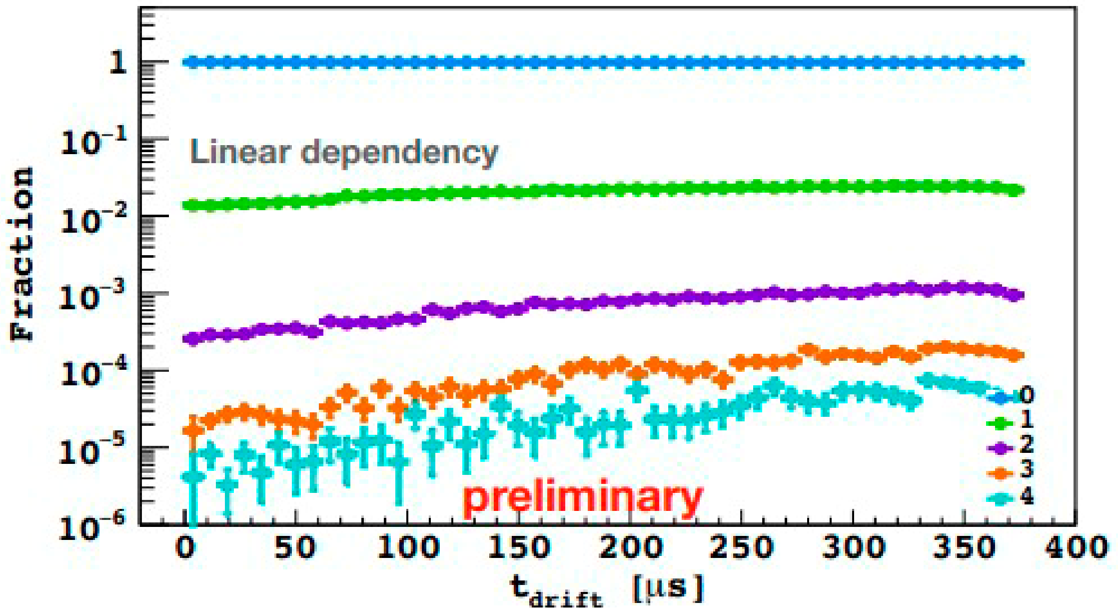






Spurious electron backgrounds

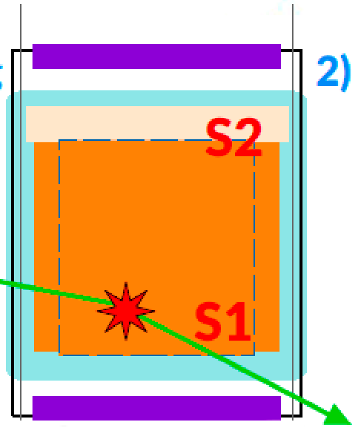




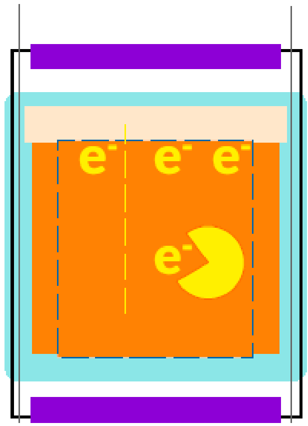
Linear correlation between SE probability and preceding S2 size & t_{drift}

SE & parent channels strongly correlated

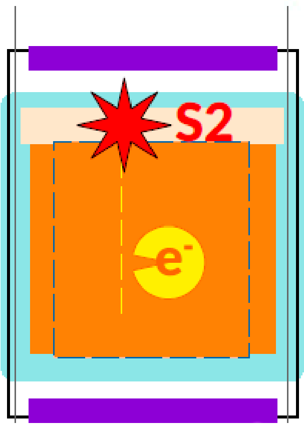
1) Something scatters in LAr→S1



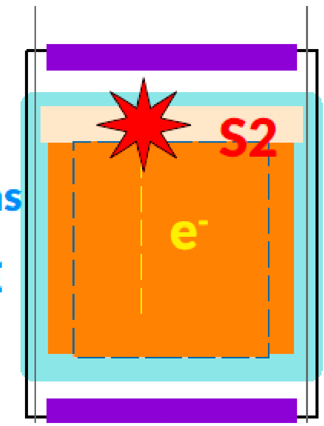
2) Most ionization electrons dirft to gas pocket; one captures on impurity



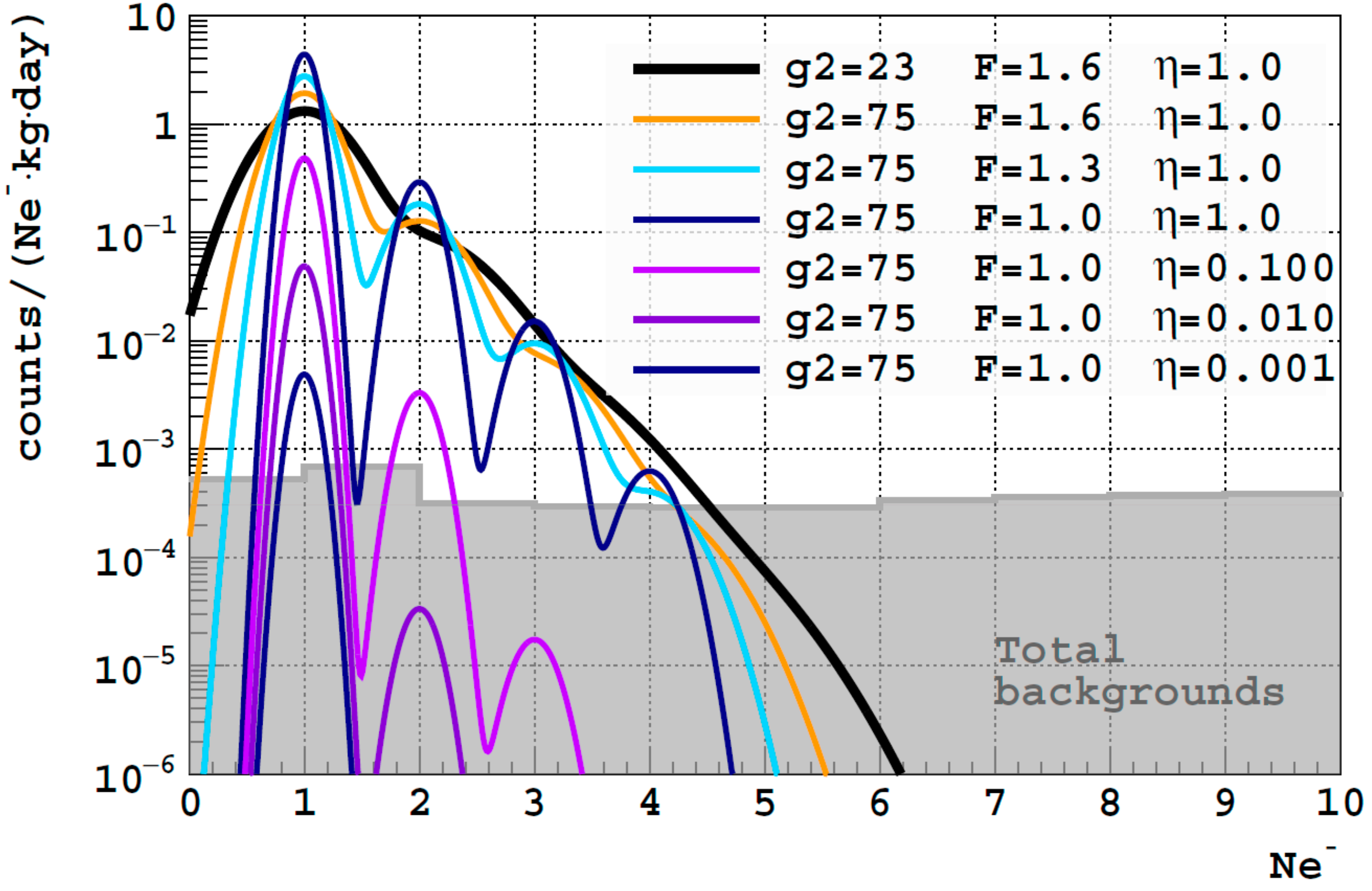
3) Drifted electrons produce S2; captured electron stays captured



4) Captured elecctron released & drifts to gas pocket→ delayed SE



Toy SE model motivated by DS-50 data: smeared Poissonian SE Ne distribution from SE pileup



$$\mathrm{SE}(n) = R \sum_{k=0} \mathrm{P}(k;p) G\left(n; k+1, F\sqrt{\frac{k+1}{g_2}}\right)$$

$$\mathrm{P}(k;p) = \frac{1}{k!}\left(\frac{p^k}{k+1} - \frac{p^{k+1}}{k+2}\right),$$

$$R \propto R_{\mathrm{trig}} \times L_{\mathrm{drift}}^{\mathrm{max}} \times \eta / M_{\mathrm{fid.}}$$

$$p \propto L_{\mathrm{drift}}^{\mathrm{max}} \times \eta$$

g2: Electron amplification in gas pocket

***F*:** Excess noise factor beyond Poisson

***η*:** Impurity concentration rel. to DS-50

Model consistent w/ DS-50; not definitive

Most projections here assume we can't model SEs; consider effect $2e^-$ and $4e^-$ thresholds like DS-50

This model is used to explore sensitivity gains from modeling SEs — currently active R&D toward this

Other backgrounds: subdominant and manageable

Cosmogenic backgrounds:

A) Material activation in transit limits ^{39}Ar reduction

Main isotopes expected in UAr
(other isotopes short-lived, removed in purification)

	^{39}Ar	^{37}Ar [μBq/kg]	^{3}H
Urania→Aria	14.7 ± 1.3	806 ± 73	58 ± 12
Aria (1 mo., surface)	2.57 ± 0.33	294 ± 39	9.0 ± 2.8
Aria→LNGS	0.86 ± 0.11	118 ± 15	3.00 ± 0.95
Aria→N. America	5.73 ± 0.73	483 ± 64	20.0 ± 6.3

^{37}Ar: $t_{1/2}$ = 35 days → Good calibration, removes itself
^{3}H: $t_{1/2}$ = 12.3 years → Remove w/ chem. Purification
^{39}Ar: $t_{1/2}$ = 269 years → Sets floor: Hard to go below ~1 μBq/kg; for reference, DS-50 had 730 μBq/kg

Material activation is not included in sensitivity projections

B) Muon-induced signals during operation @ underground lab: **negligible**

Surface activity

ACHIEVABLE

For S2-only analyses, fiducialization only in horizontal plane

Threshold surface activities of ^{222}Rn and ^{210}Pb decay chains needed to contribute <10% of the γ-ray background rate, A_{thr}

Isotope	$\mathcal{A}_{thr}$	DarkSide-50 [mBq/m^2]	DEAP-3600
^{222}Rn	6.01 ± 0.25	—	$< 5 \times 10^{-3}$
^{210}Pb	2.21 ± 0.05	2.51 ± 0.01	0.26 ± 0.02

These backgrounds are not considered

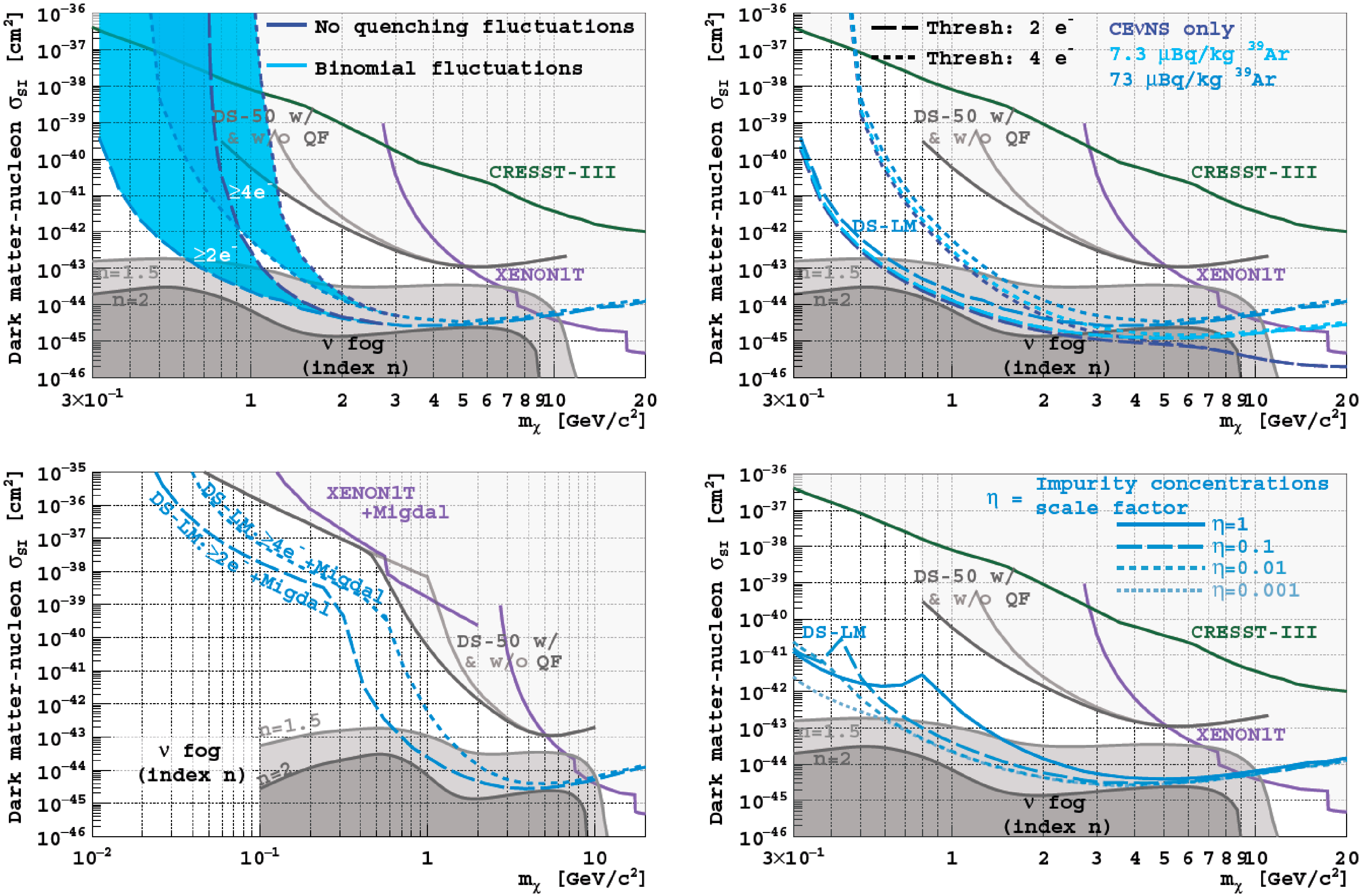
Radiogenic neutrons from (α,n) reactions

If all detector's materials are radiopure as in DS-20k, neutron bkgds are expected to be subdominant to those from γ-rays

Not included in this study

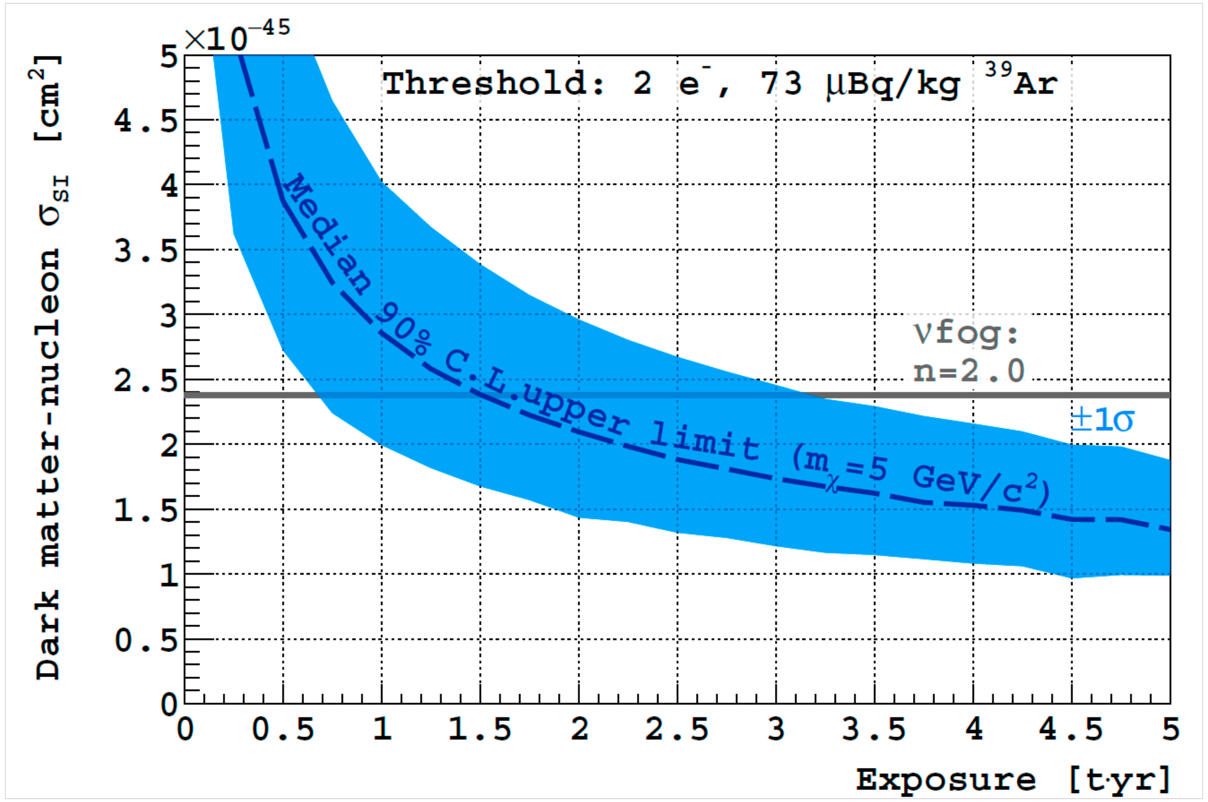
DarkSide-LowMass Sensitivity projections

Projected 90% C.L. upper limits on the spin-independent DM-nucleon scattering cross section for 1 t yr exposure

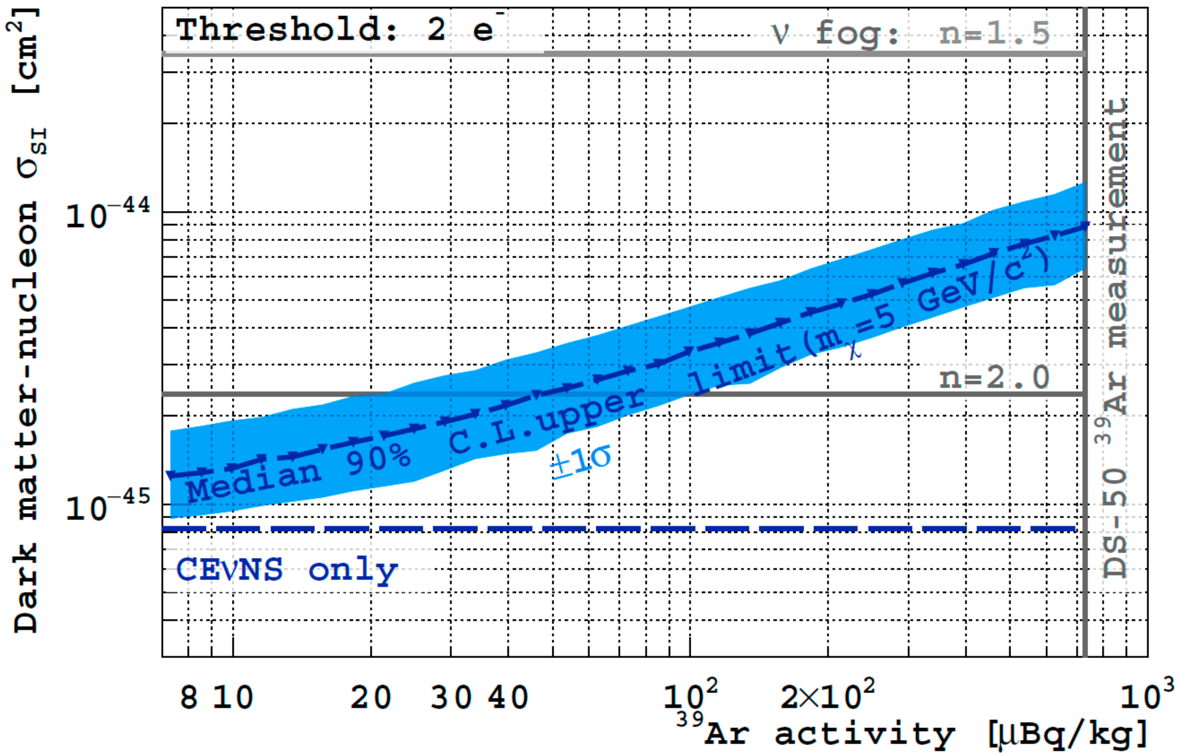


Required exposure and ^{39}Ar depletion

Projected sensitivity at 5 GeV/c2 (90% CL)



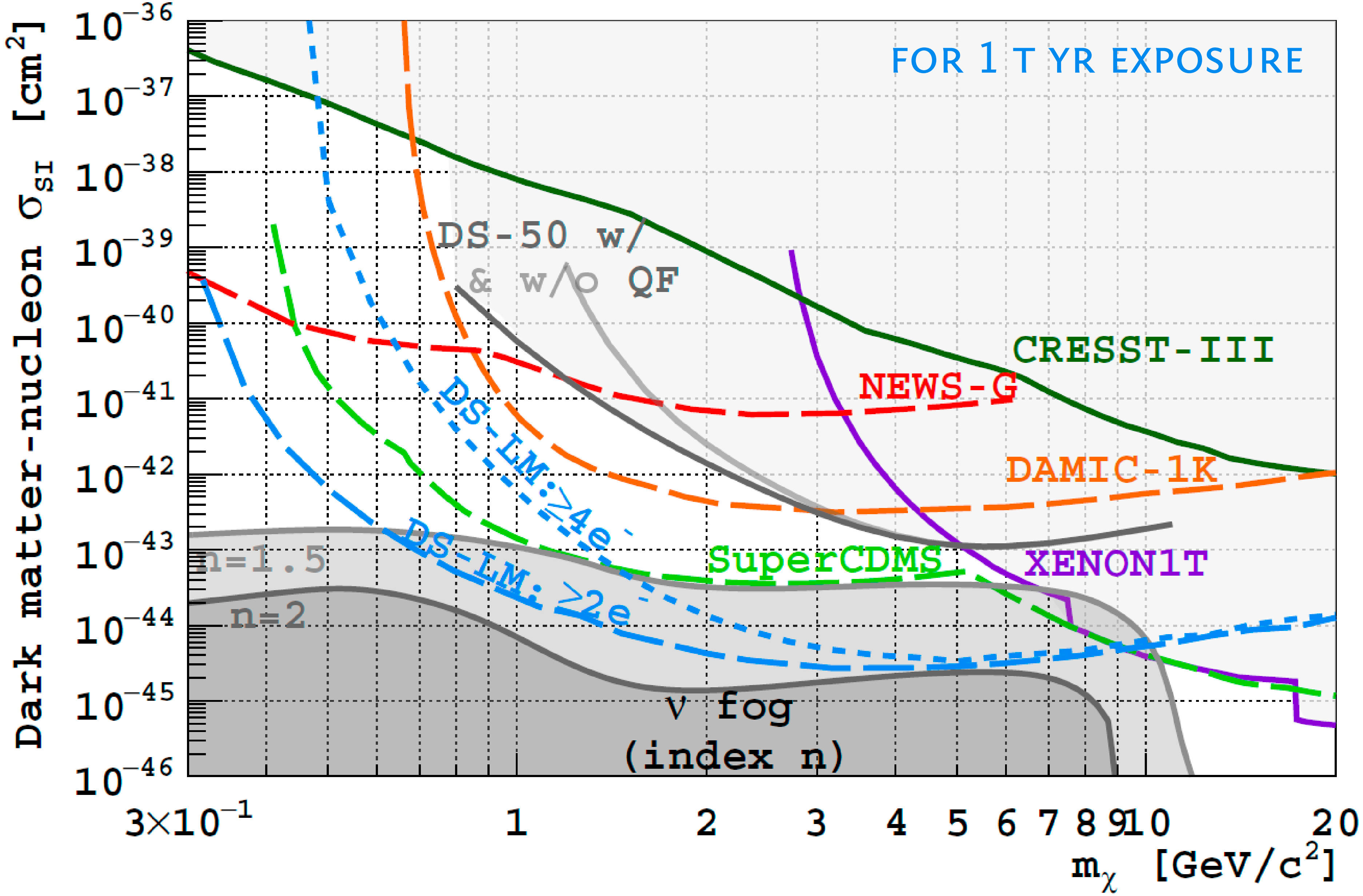
FOR 1 T YR EXPOSURE



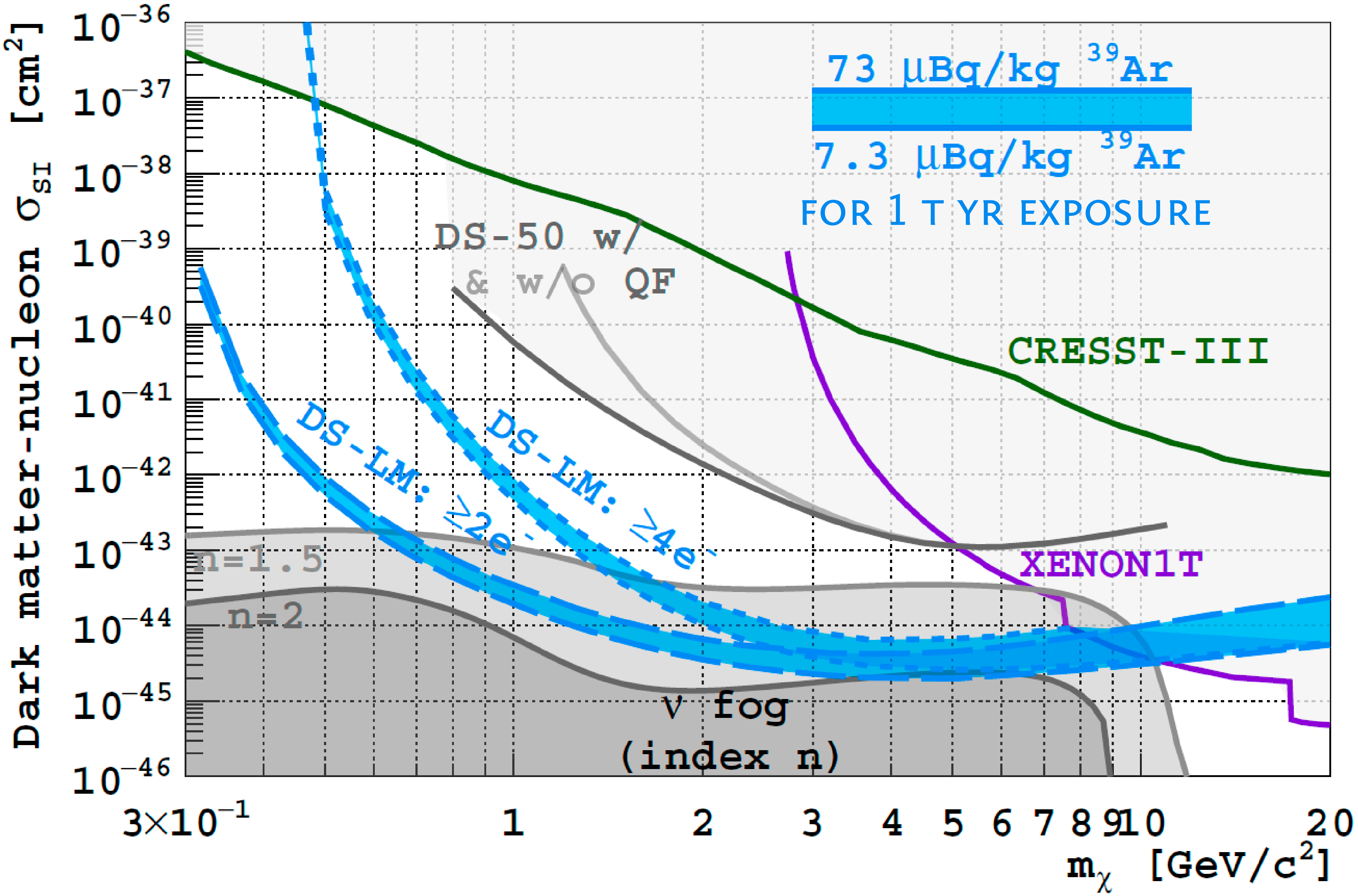
Marginal gain for >1.5-2.0 t yr exposure

Significant gains for ^{39}Ar depletion

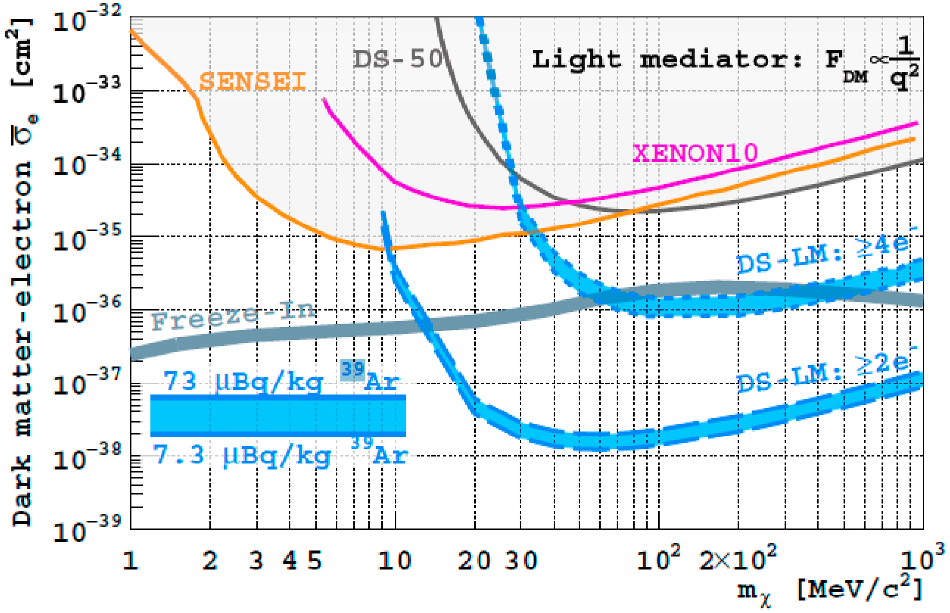
Projected and current 90% C.L. upper limits on spin-independent DM-nucleon scattering



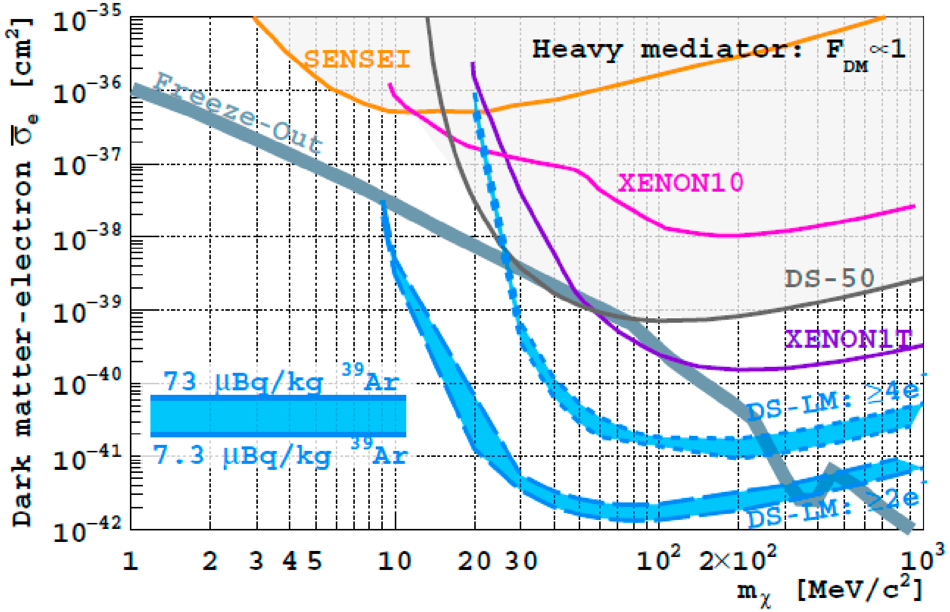
3σ evidence contours varying threshold and ^{39}Ar activity

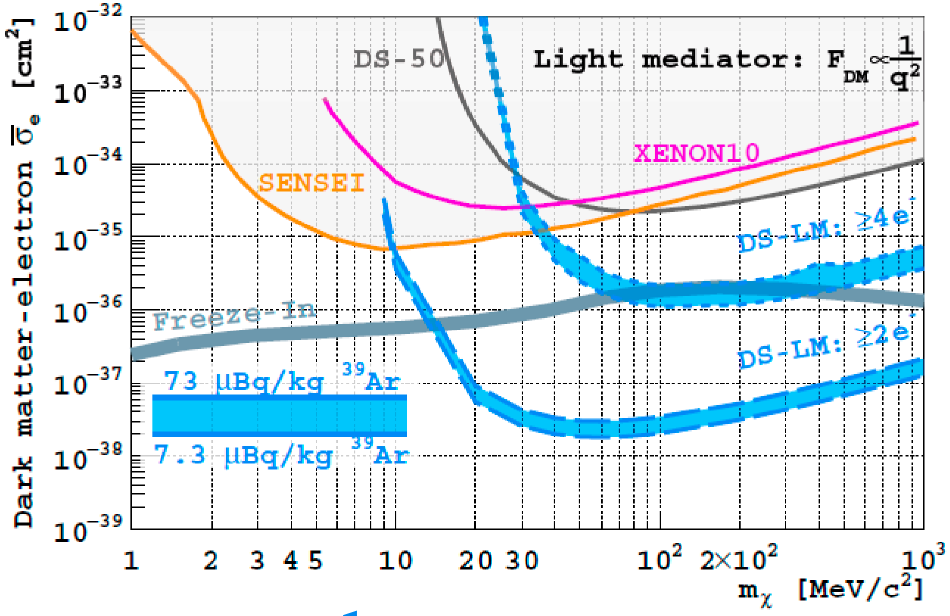


Projected & current 90% C.L. upper limits & 3σ evidence contours for DM-e^- scattering

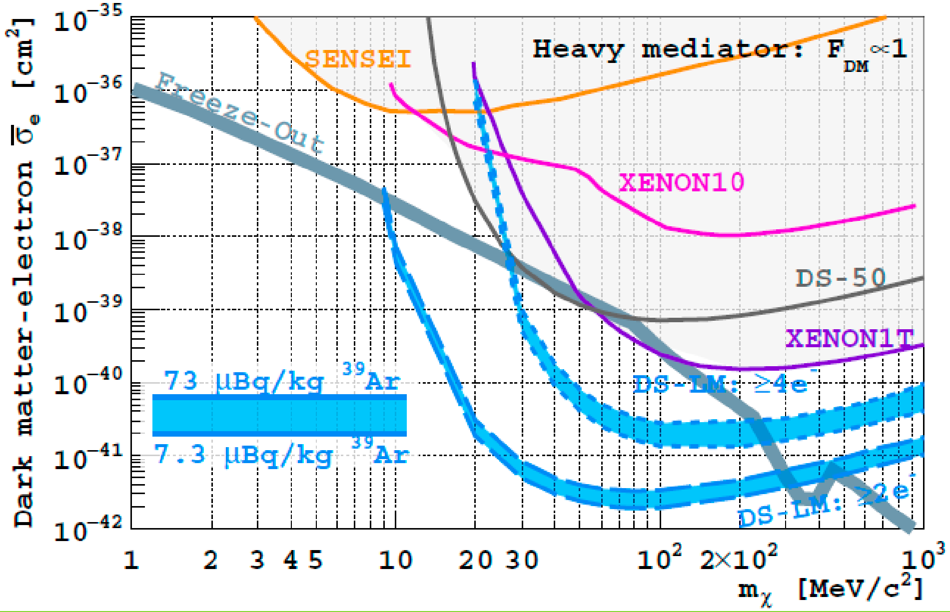


FOR 1 T YR EXPOSURE





FOR 1 T YR EXPOSURE



Conclusions

- A **well-optimized LArTPC** will significantly increase the search capabilities for light DM particles
- DarkSide-LowMass is **complementary** to other detectors constructing or operating by the Global Argon Dark Matter Collaboration
- Need multiple targets (e.g. LAr, LXe, Ge in SuperCDMS) to check each other and complement each other's DM searches
- **Several years of data taking** are enough to achieve main physical results
- Almost all technologies and methods are developed and available*

*R&D + potential improvements & upgrades

- Charge yield calibration measurements of LAr to low-energy recoils → improve response models
- Identify SE sources & develop mitigation strategies → targeted SE reduction
- Dope LAr with Xe or hydrogenous (photo-ionizing?) dopants to
  - Enhance charge yield / lower energy threshold
  - Add kinematically favorable or spin-dependent targets (at high concentration)

From words to deeds: join us, build and run it together!

Thank you for your attention!

DarkSide

DEAP 3600

ArDM

MiniCLEAN

DarkSide-LowMass

BACKUP SLIDES

Projected & current 90% C.L. upper limits