DarkSide-20k: Status & Prospects

ECFA-UK Meeting on UK Studies for the European Strategy Particle Physics Update,
Durham University,
23rd - 26th September 2024

Science and Technology Facilities Council
Particle Physics

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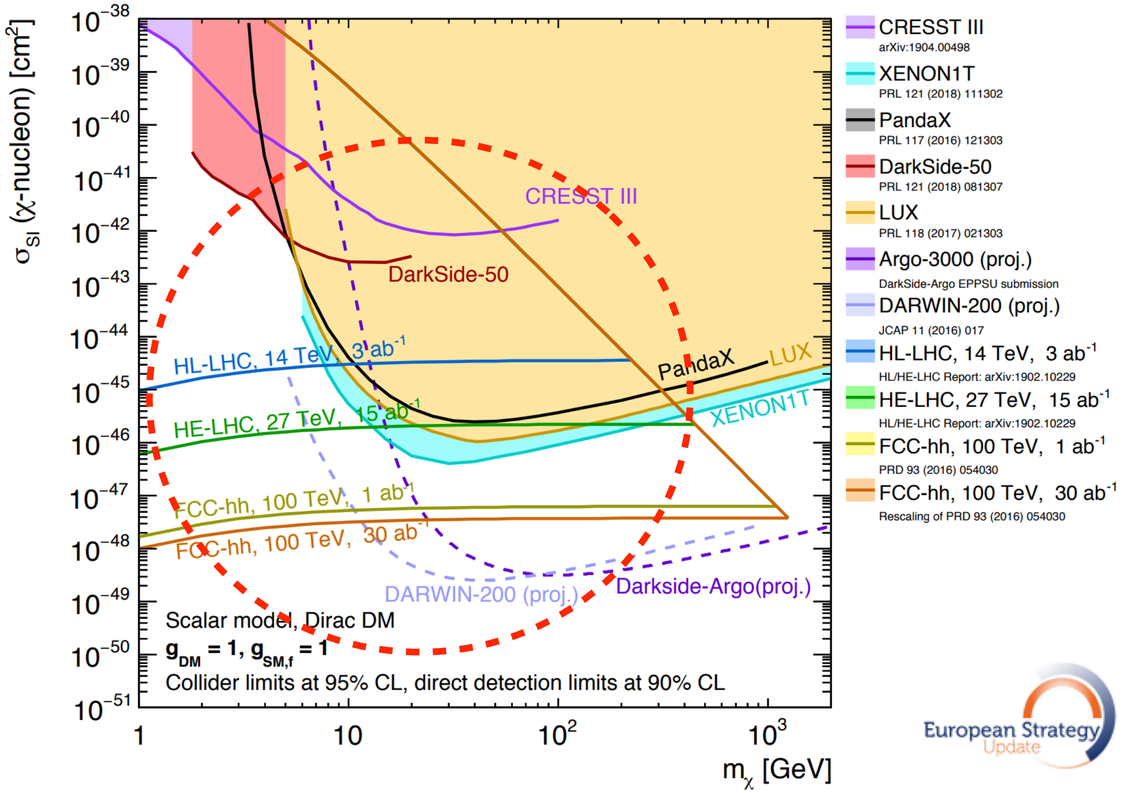
Direct Dark Matter Detection in ESPP Update 2020

Ellis et al.,"European Strategy for Particle Physics Preparatory Group: Physics Briefing Book." arXiv preprint arXiv:1910.11775 (2019).

> **In consideration of the strong synergy between direct dark matter detection and the programme for its production and discovery in high-energy collisions at accelerators as well as in accelerator-based fixed target experiments, discussions at the Open Symposium in Granada highlighted that CERN's support for selected direct dark matter search programmes that can take critical advantage of technology developed at CERN can deliver a decisive boost of their sensitivity.**



European Strategy Update

Direct dark matter detection has important complementarity with future accelerators.

Accelerators can probe what the dark matter particle is; direct detection can tell us if the interaction really originates from our DM halo.

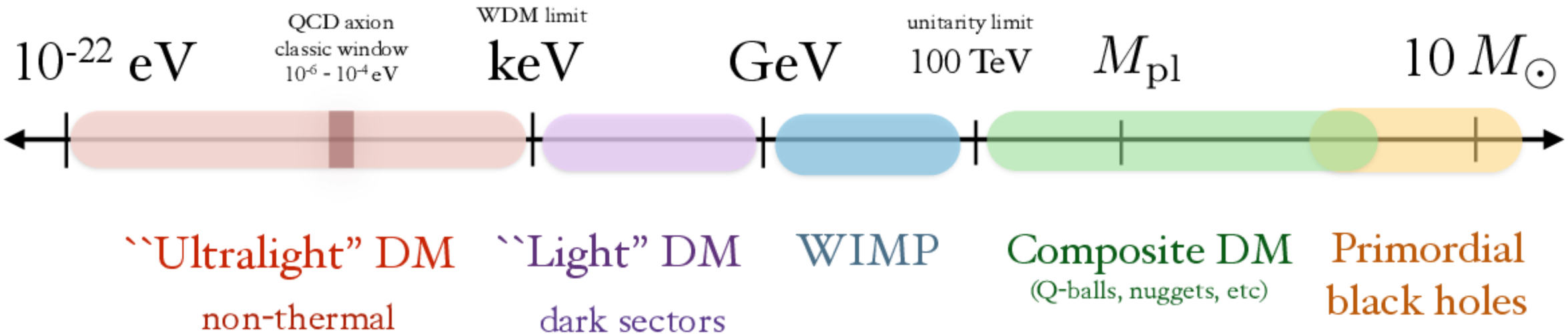
Happy region of overlap where accelerators can confirm direct detection discovery (and vice versa).

Courtesy of S Shaw.

The Challenge

Mass Scale of Dark Matter (Not to Scale)

Lin, Tongyan. "TASI lectures on dark matter models and direct detection." arXiv preprint arXiv:1904.07915 4 (2019).



Dark Matter can span over 80 orders of magnitude!

Patience is a Virtue

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should

It took 50 years after prediction for CEνNS to be discovered!

the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

There is recent experimental evidence[1] from CERN and NAL which suggests the presence of a neutral current in neutrino-induced interactions. A primary goal of future neutrino experiments is to confirm the present findings and to investigate the properties of the weak neutral current, for important to interpret experimental results in a very broad theoretical framework.[4] We assume a general current-current effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \frac{1}{\sqrt{2}} G l^{\mu} \mathcal{J}_{\mu} , \qquad (1)$$

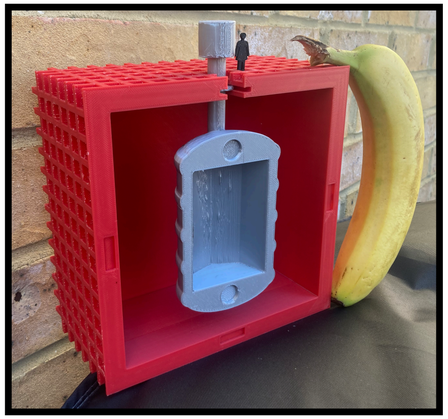
DarkSide-20k: Overview

Global Argon Dark Matter Collaboration (GADMC) comprised of 400+ people across 14 countries.

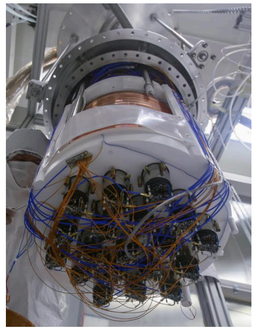
June 2023 DarkSide-20k Collaboration Meeting at LNGS

DarkSide-20k: Overview

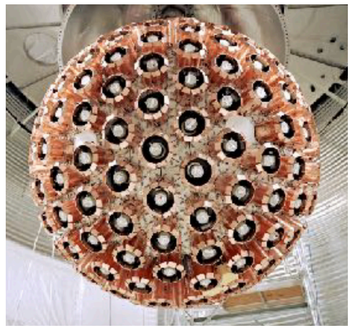
Global Argon Dark Matter Collaboration (GADMC) comprised of 400+ people across 14 countries.



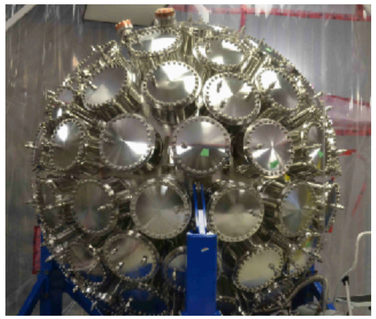
3D printed model by T. Covella (Banana for Scale).



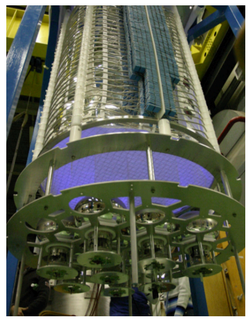
DarkSide-50



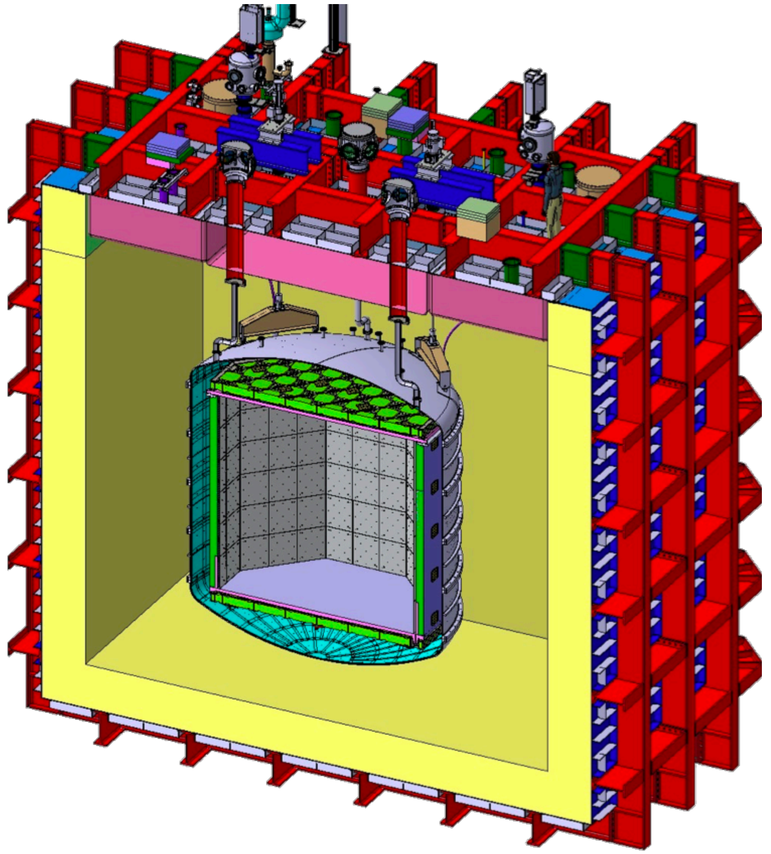
DEAP-3600



MiniCLEAN



ArDM



Under Construction: DarkSide-20k @ LNGS!

- Leverages ProtoDUNE Cryostat Technology.

- 50t of Underground Argon (UAr) in Dual-Phase TPC.

- Viewed by 27 m^2 Silicon Array Sensors.

- Nominal Runtime of 10 yrs.

DarkSide-20k: Overview

UK groups building 25% of Silicon Detector Readout, Production, and Installation.

Construction at LNGS well underway:

- ✓ Cryostat and infrastructures in LNGS Hall C complete.
- ✓ Cryogenics system operating in Hall C.
- ✓ TPC components in production.
- ✓ Installation of UK photodetectors starting 2025; construction complete 2026.

DarkSide-20k located in Hall C at LNGS, Italy (3400 m.w.e)

June 2023

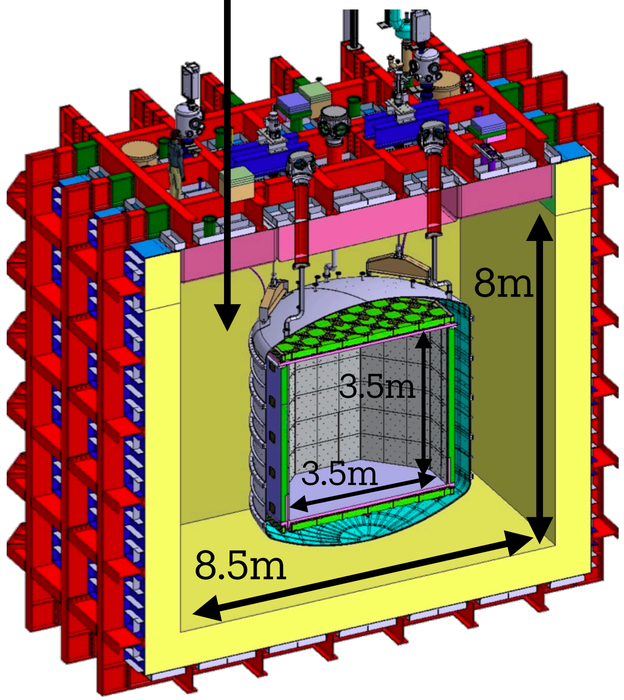
March 2024

June 2024

DarkSide-20k: Detector Structure

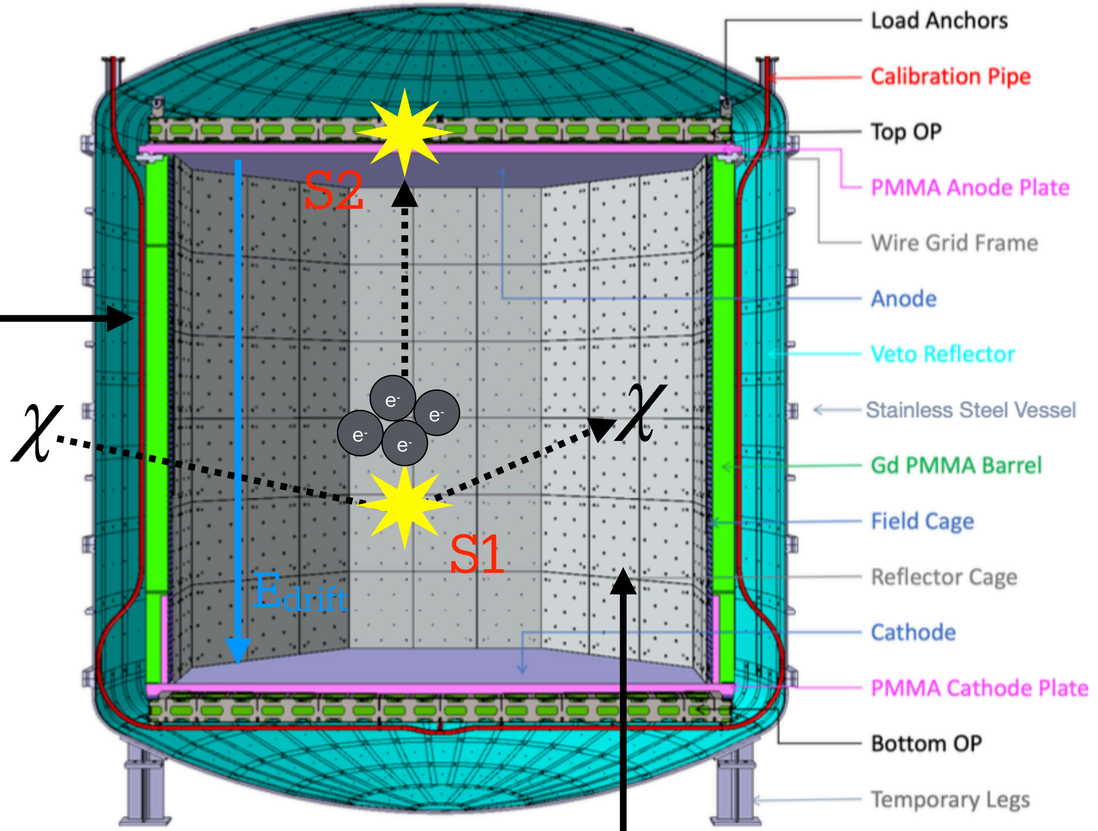
Cosmogenic (Outer) Veto:

- 650t Atmospheric Ar.
- Instrumented with Silicon Photomultipliers (SiPMs) with sparse coverage.



Neutron (Inner) Veto:

- Enclosed in Stainless Steel vessel; HDPE neutron shield surrounding vessel.
- 35t UAr.
- (Gd) PMMA barrel.
- Instrumented with SiPMs; UK building 7 m^2.
- Light yield: 2 PE/keV.

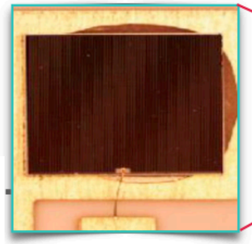


Dual-Phase TPC:

- 50t UAr; Instrumented with 2x Optical Plates of SiPM arrays with 21 m^2 coverage; Light yield for S1 scintillation [S2 charge] is 10 PE/keV [20 PE/e^-].

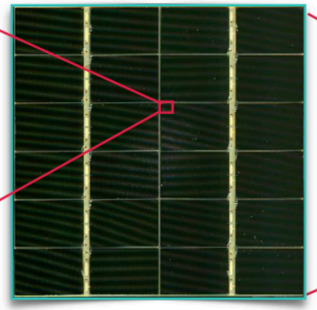
DarkSide-20k: Light Readout with SiPMs

Silicon Photomultiplier (SiPM)



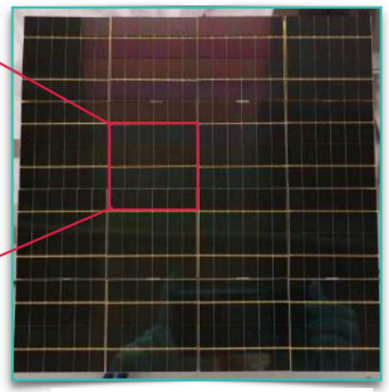
1 cm^2
95k Single Photon Avalanche Diodes

Photodetector Module (PDM)



5x5 cm^2; 24 SiPMs + Front-End Electronics

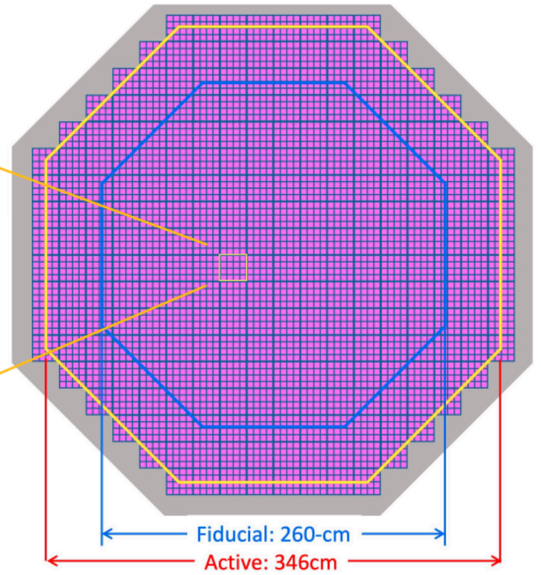
Photodetector Unit (PDU)



20 x 20 cm^2; 16 PDMs + Motherboard

~ 21 m^2
518 PDUs

TPC Optical Plane



First dark matter experiment to be fully instrumented with SiPMs!

SiPMs boast lower noise, lower radioactivity, and higher photon detection efficiency compared to PMTs.

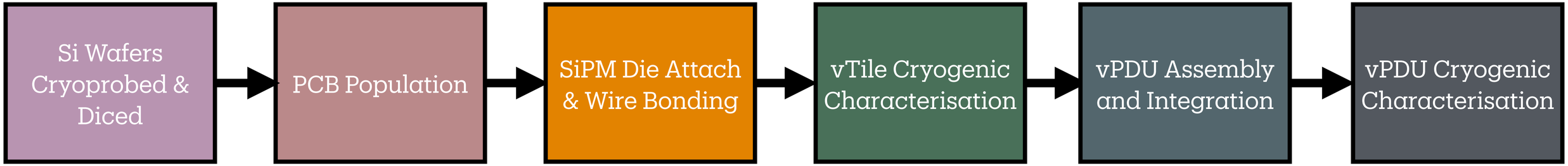
518 PDUs in TPC; 120 PDUs in Neutron Veto; 30 PDUs in Cosmogenic Veto.

1 large PCB enables/disables and biases individual tiles, and sums signals from each quadrant (4 quadrants per PDU = 4 readout channels).

✓ 1/4 less cables/feedthroughs means lower radioactivity!

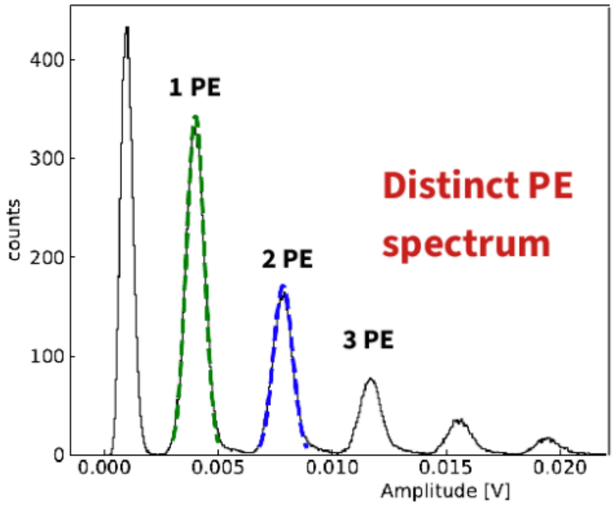
DarkSide-UK Project

Delivery of DarkSide-20k Veto Photodetectors

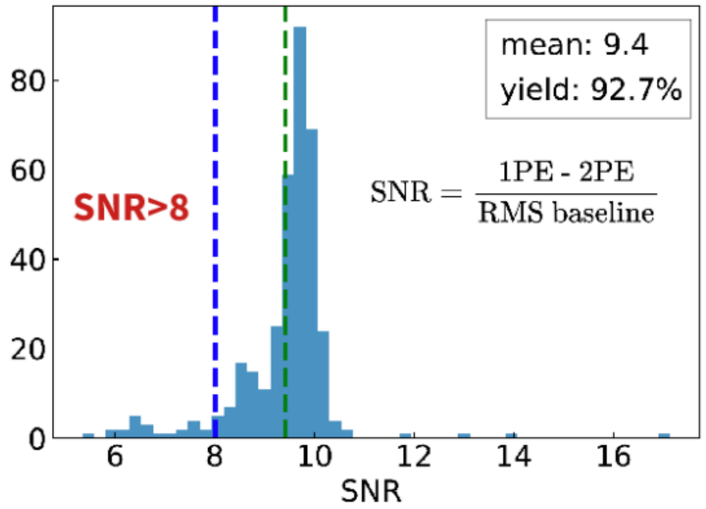


vTile Assembly/Testing:

- 1.4k SiPM wafers cryoprobed in Italy (94% yield).
- PCB population in **Birmingham** (Component selection from **Boulby** radioassay).
- SiPM die attach at **Liverpool** & **STFC Interconnect.**
- Cryogenic characterisation using laser calibration at **Oxford** & **STFC**.
- QA/QC for dust counting, signal-to-noise, charge response, breakdown voltage, noise.



Figures courtesy of P. Franchini.



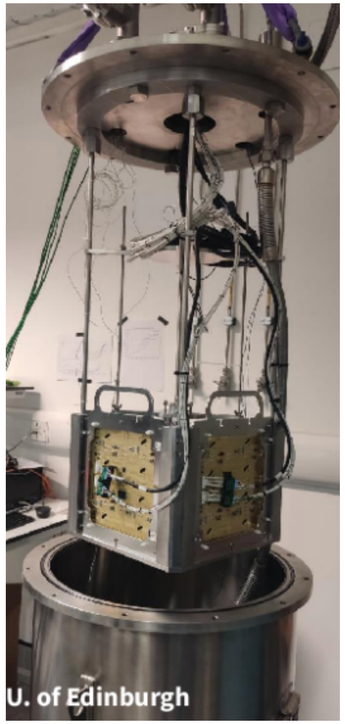
DarkSide-UK Project

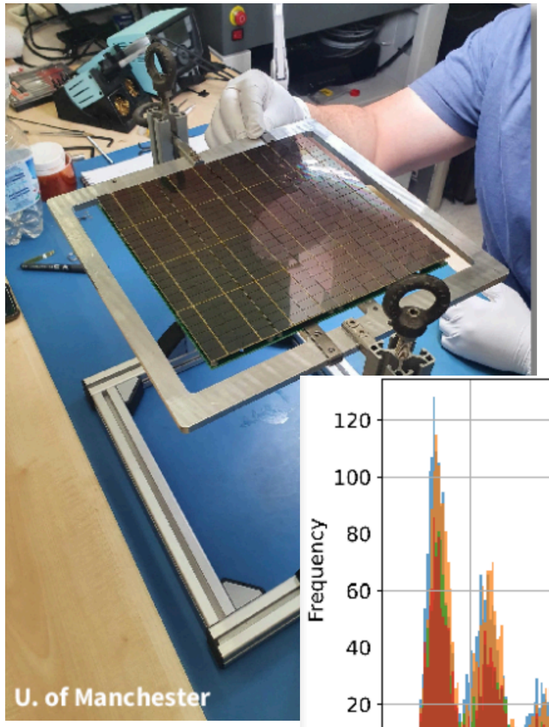
Delivery of DarkSide-20k Veto Photodetectors

Si Wafers Cryoprobed & Diced → PCB Population → SiPM Die Attach & Wire Bonding → vTile Cryogenic Characterisation → vPDU Assembly and Integration → vPDU Cryogenic Characterisation

vPDU Assembly/Testing:

- vPDU assembly in **Manchester** & **Warwick**, electrical characterisation & dust counting.
- Cryogenic characterisation of each 10 cm x 10 cm channel using laser calibration in PDU test stands at **Edinburgh**, **Liverpool**, **Lancaster,** and **AstroCeNT (Poland)**.
- QA/QC for dust counting, signal-to-noise, charge response, breakdown voltage, noise.
- **Production > 40% complete meeting yield requirement!**





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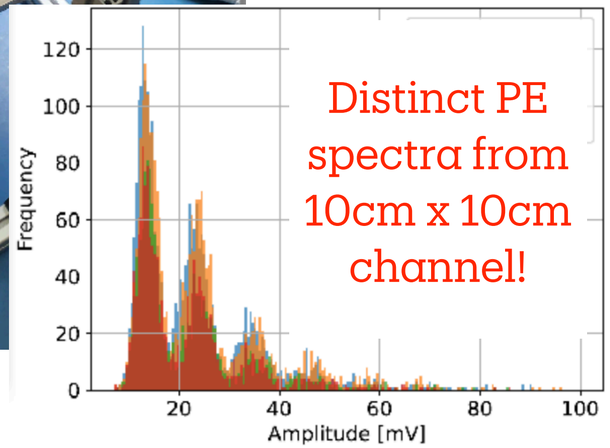
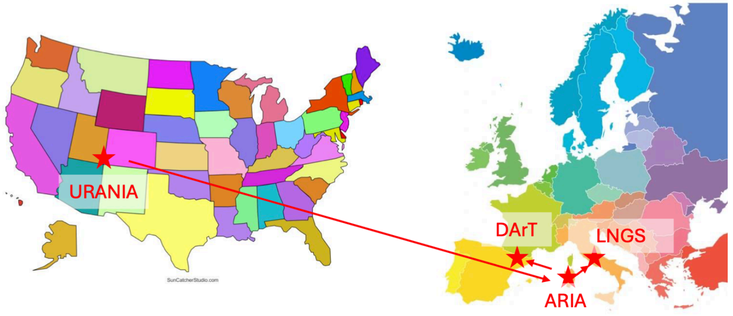


DarkSide-20k: Background Mitigation Strategies

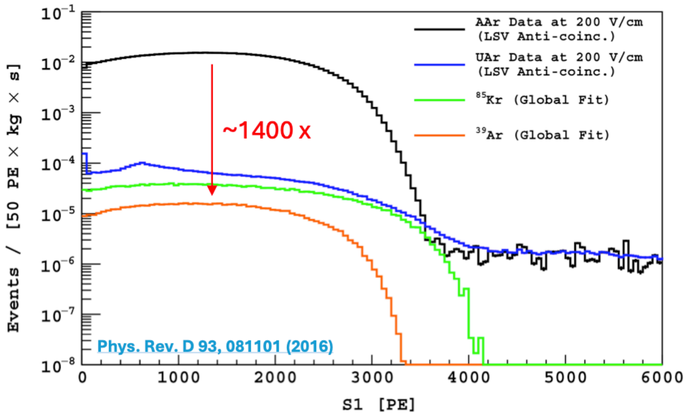
Goal: Instrumentally Background-Free over 200 Tonne-Year Exposure

1) Use of UAr

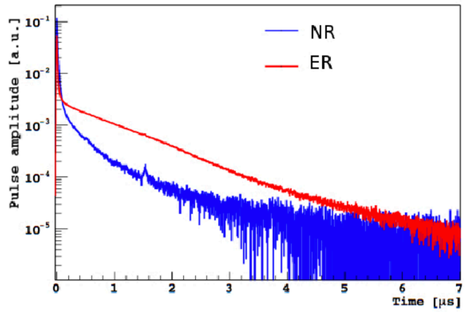


Global effort: Extraction in Urania (99.9% pure); Purification in ARIA (99.999% pure); ^{39}Ar depletion factor measured in DArT.

Depletion factor ~1400!



2) Pulse-Shape Discrimination (PSD)

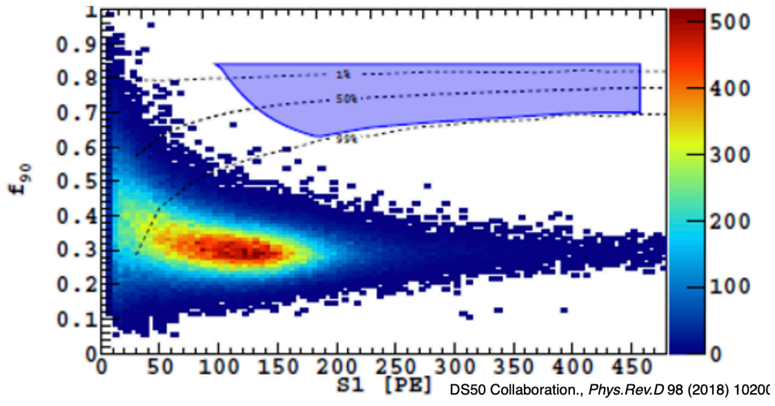


Major Ar advantage: Strong ER discrimination via PSD.

ER/NRs produce different # of singlet/triplet states with well-separated decay times (~1000).

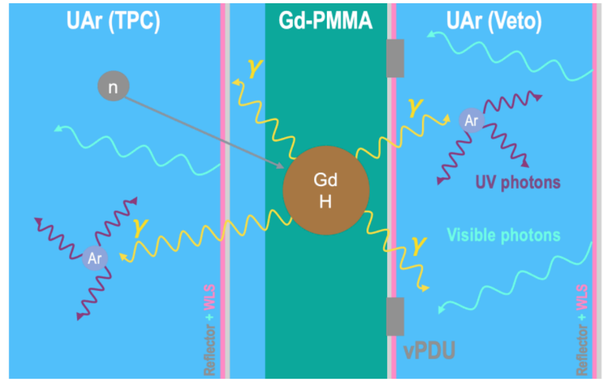
Ratio of prompt light to (prompt + late) light is PSD parameter.

World-leading PSD demonstrated by DEAP-3600: 10^{-10} ER leakage probability at 50% NR acceptance. *PRD 100 (2019) 2, 022004.*



DS50 Collaboration., *Phys.Rev.D* 98 (2018) 1020(

3) Neutron Tagging: TPC-Veto Coincidence



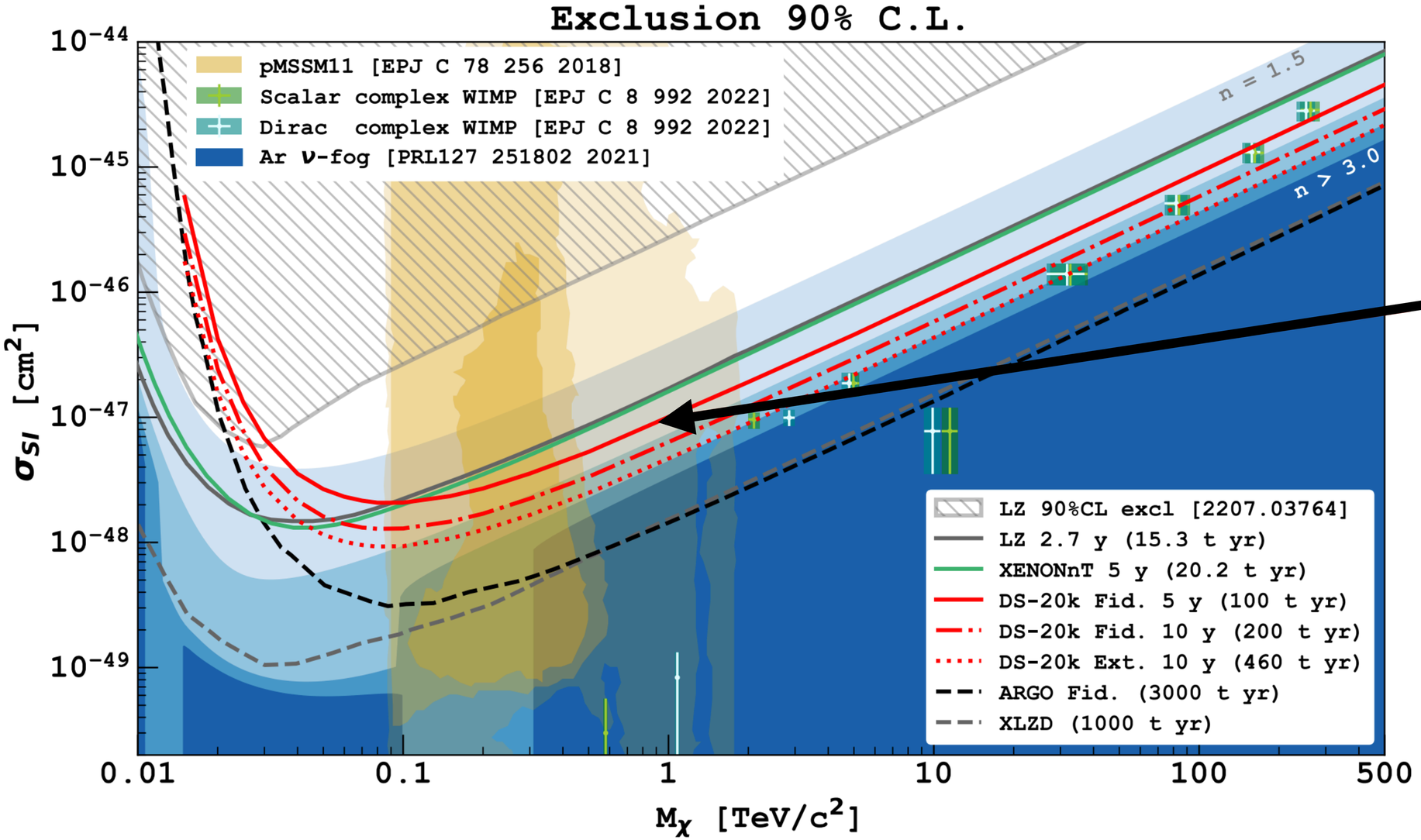
15 cm of Gd-PMMA surrounding TPC: neutron moderator.

1% Gd concentration; n-capture on Gd (65%) c.f. H (10%) and Ar (19%). Look for 8 MeV γ in TPC/veto in 800 us coincidence window with single NR in TPC.

Considering Pure PMMA option (no Gd); 2.1 MeV from H capture (53%) in TPC/veto.

<0.1 neutron WIMP-like event in 200 tonne-years (Gd-PMMA) option.

DarkSide-20k: High-Mass WIMP Sensitivity

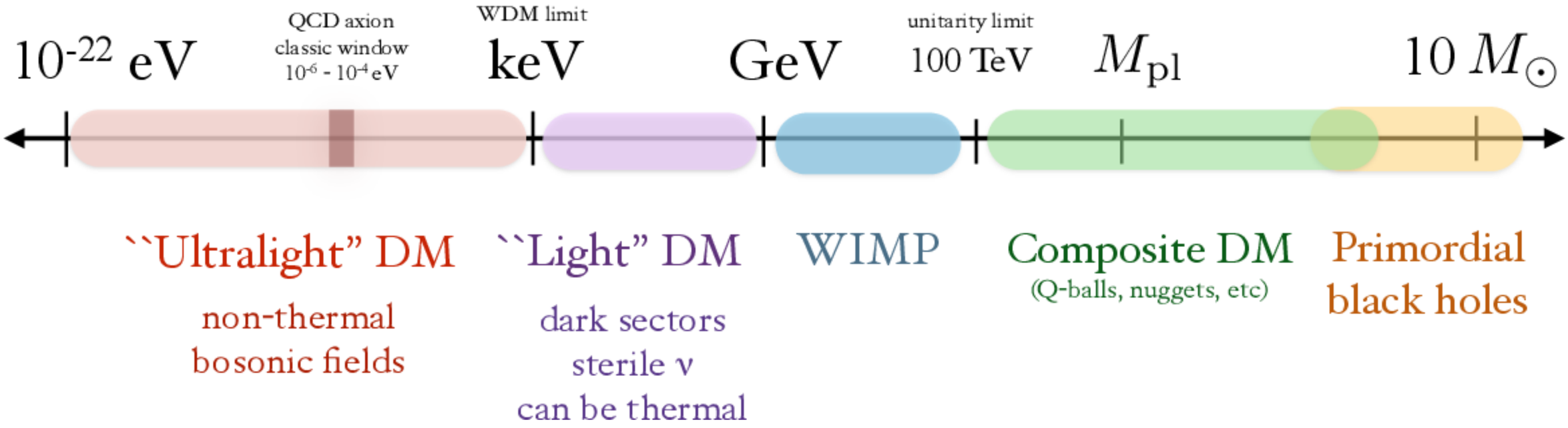


Projected sensitivity to spin-independent WIMP-nucleon scattering cross section: 7.4 x 10^{-48} cm^2 for a 1 TeV/c^2 WIMP.

200 tonne-years exposure.

It's not all about WIMPs...

DarkSide-20k has potential to search for **both** lighter and heavier dark matter candidates!



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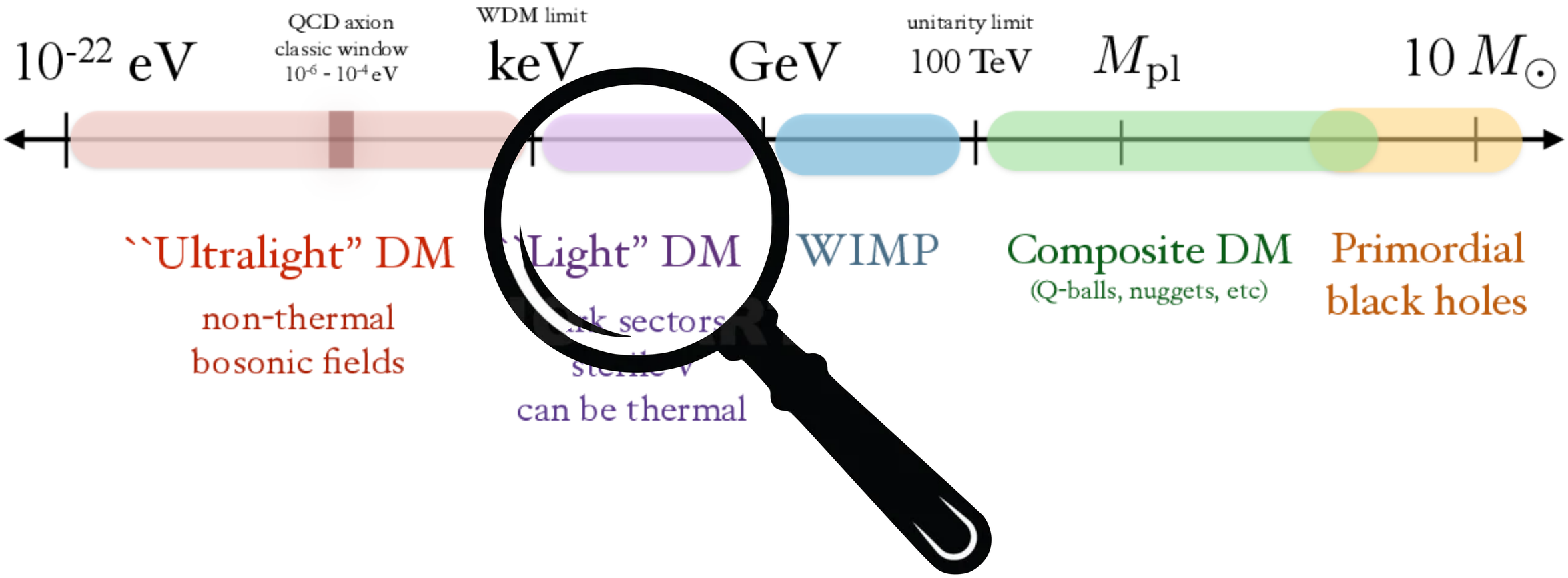


Low-Mass WIMPs

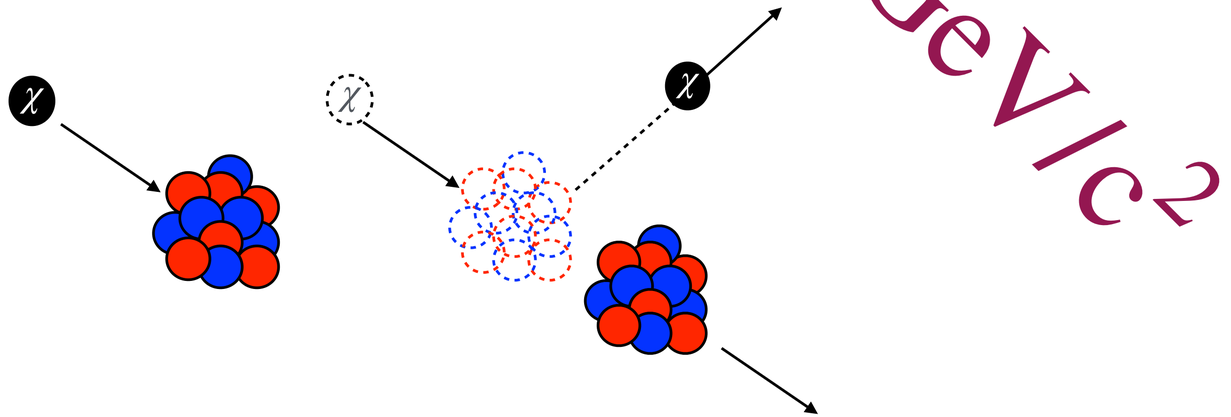
Ionisation Signal (S2)-Only Analysis

Dual-phase TPC design drifts and extracts single ionisation electrons in gas with near-100% efficiency—signal amplified a further x20 exploiting electroluminescence in the gas phase.

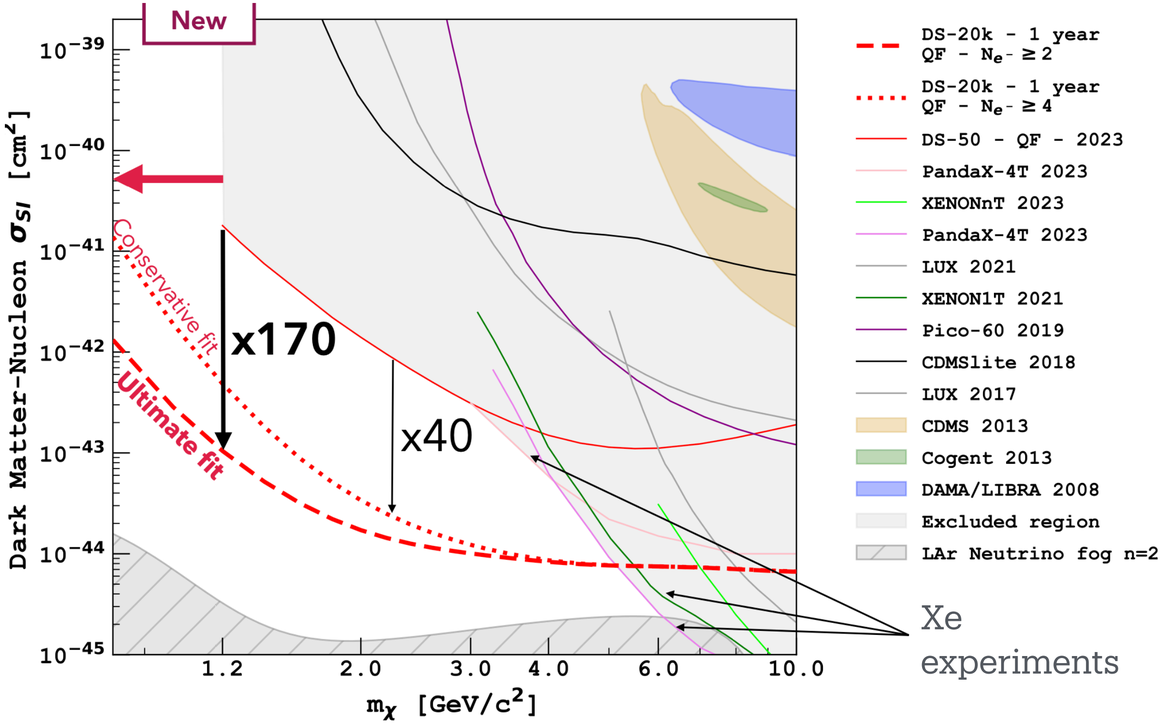
By exploiting ionisation signal (S2) alone, DarkSide-20k can reach sub-keV recoil energy thresholds.

Sensitivity projections based on 1-year livetime show a potential **improvement of two orders of magnitude** on current leading results (DarkSide-50).

After 10-years of livetime, DarkSide-20k projected to **reach neutrino fog** at ~5 GeV/c^2!



GeV/c2



Acerbi, F., et al. "DarkSide-20k sensitivity to light dark matter particles." arXiv preprint arXiv:2407.05813 (2024).

Low-Mass WIMPs

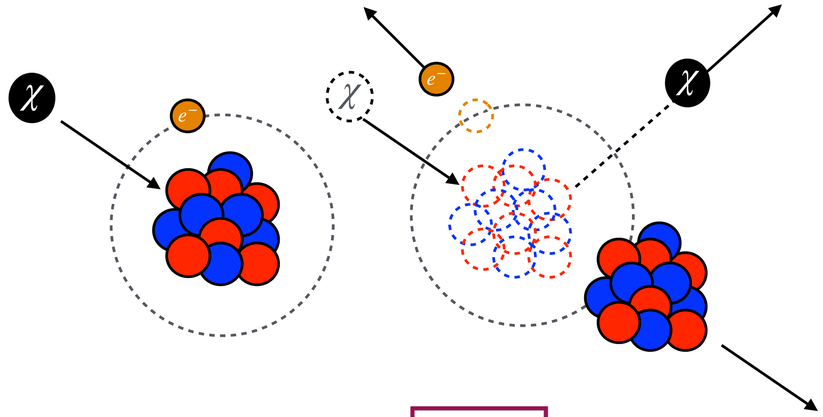
Including Migdal Effect

After nuclear recoil, surrounding electron cloud gets accelerated, releases de-excitation ionisation.

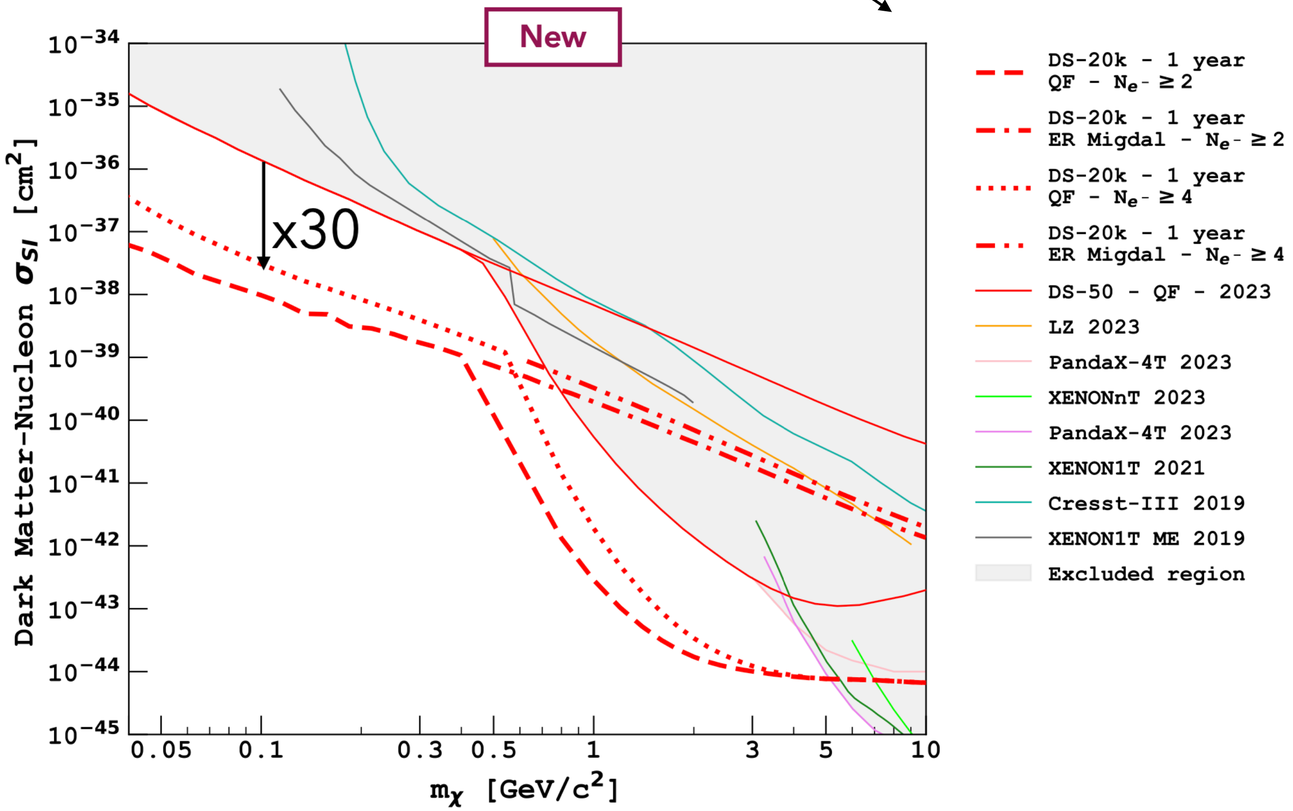
- Additional ionisation signal results in even lower energy threshold!

Including Migdal: most stringent limits between 40 MeV/c^2 and 5 GeV/c^2.

Project **>1 order of magnitude improvement** with respect to current experiments with only a **1-year livetime!**



GeV/c2



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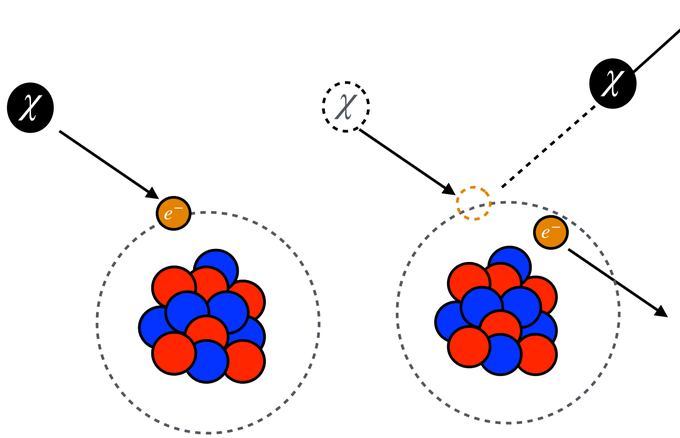
Light Dark Matter

Elastic Scattering off Atomic Electrons

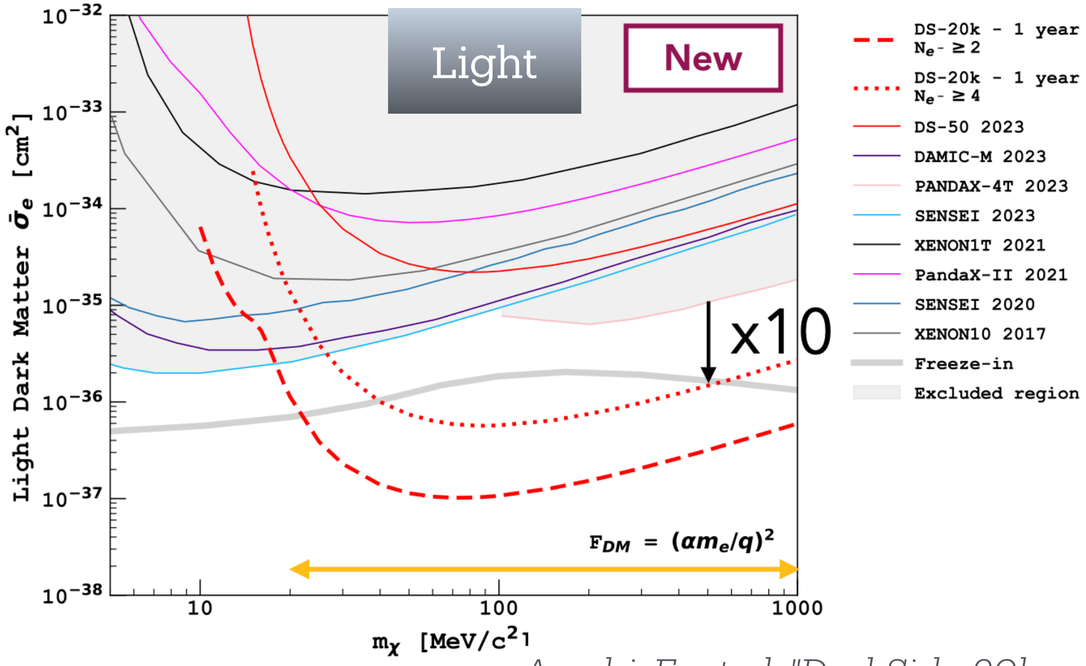


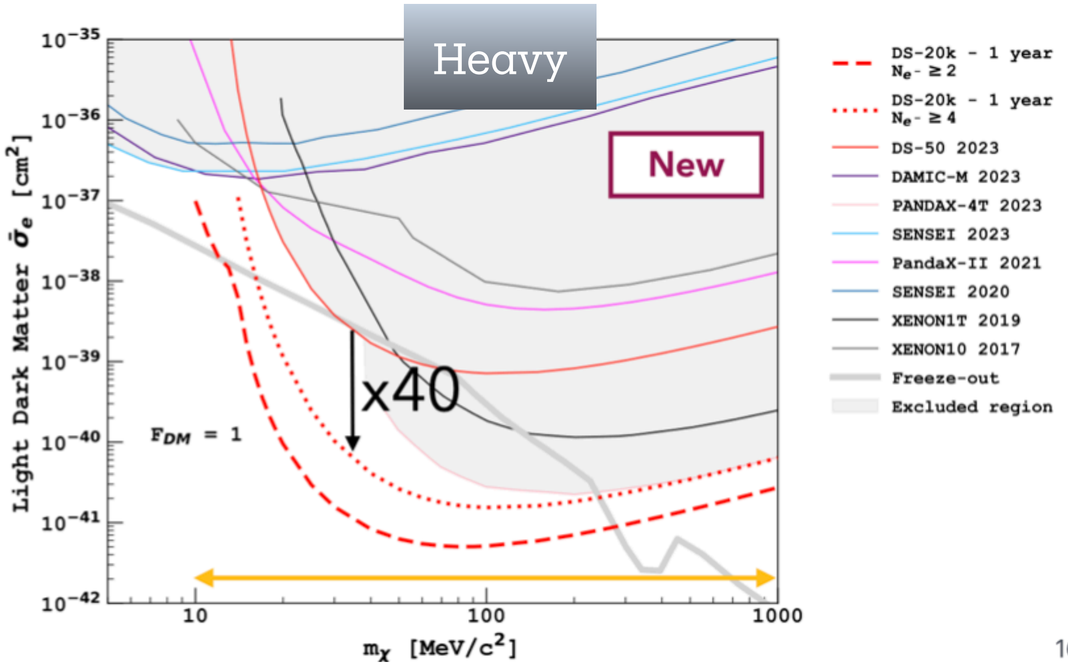
MeV/c2

Light dark matter can be sub-GeV fermion or scalar boson, interacting with atomic electrons via a vector mediator.

Mediator can be light $(m_{\mathrm{med}} \ll m_{\chi})$ or heavy $(m_{\mathrm{med}} \gg m_{\chi})$.

Project **>1 order of magnitude improvement** with respect to current experiments with only a **1-year livetime!**





Acerbi, F., et al. "DarkSide-20k sensitivity to light dark matter particles." arXiv preprint arXiv:2407.05813 (2024).

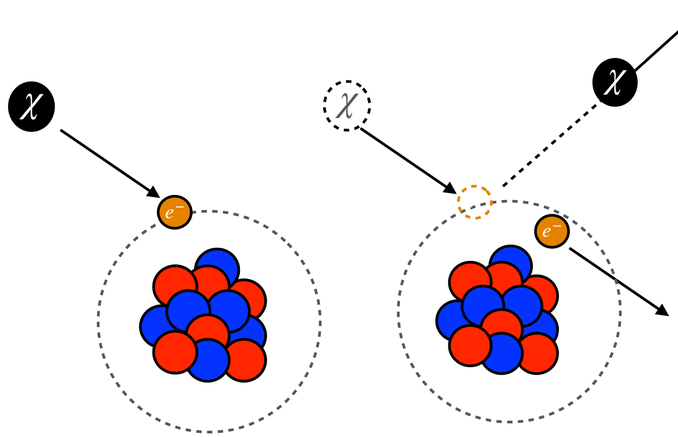
Warm Dark Matter: Sterile Neutrinos

keV/c2

Inelastic Scattering off Atomic Electrons

Sterile neutrinos mixing with an active neutrino state by an angle $|U_{e4}|^2$ could inelastically scatter off a bound electron.

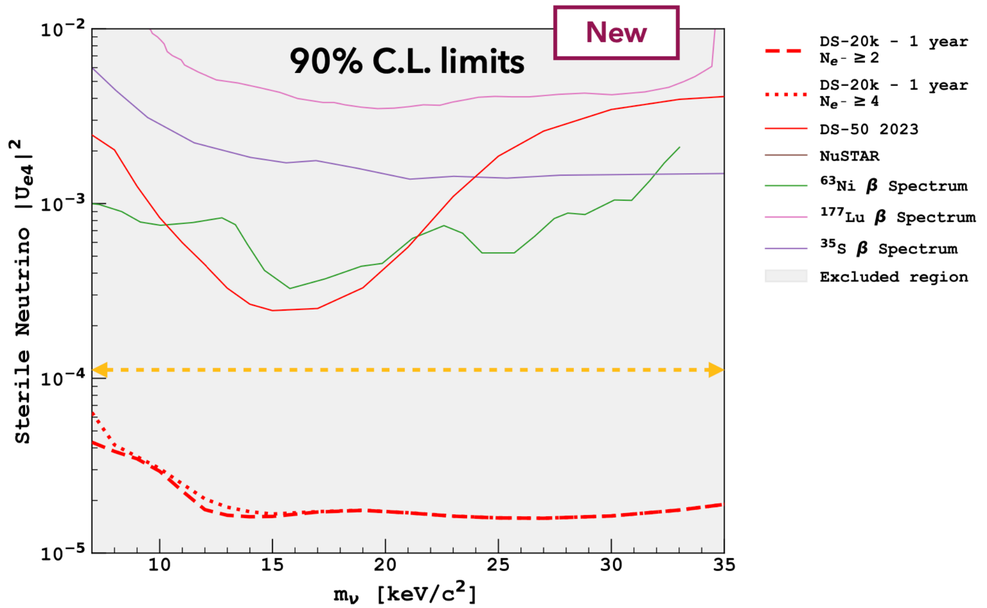
$$\nu_s + e \rightarrow \nu_e + e$$



Predecessor DarkSide-50 **first direct detection experiment** to set limits on sterile neutrino mixing angle!

Strongest direct limits after 1-year livetime...

... Phase space already ruled out from NuSTAR indirect measurements.



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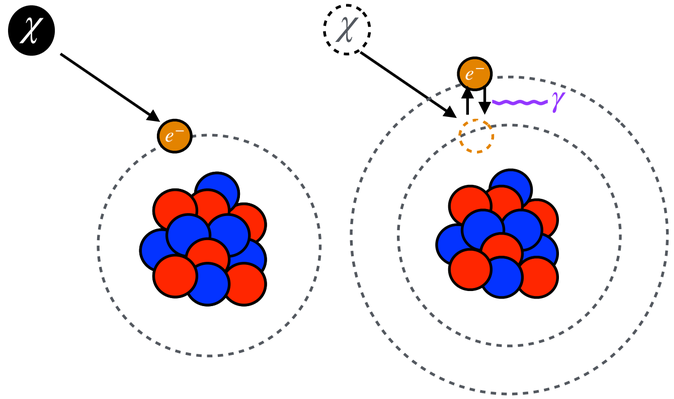
Axion-Like Particles & Dark Photons

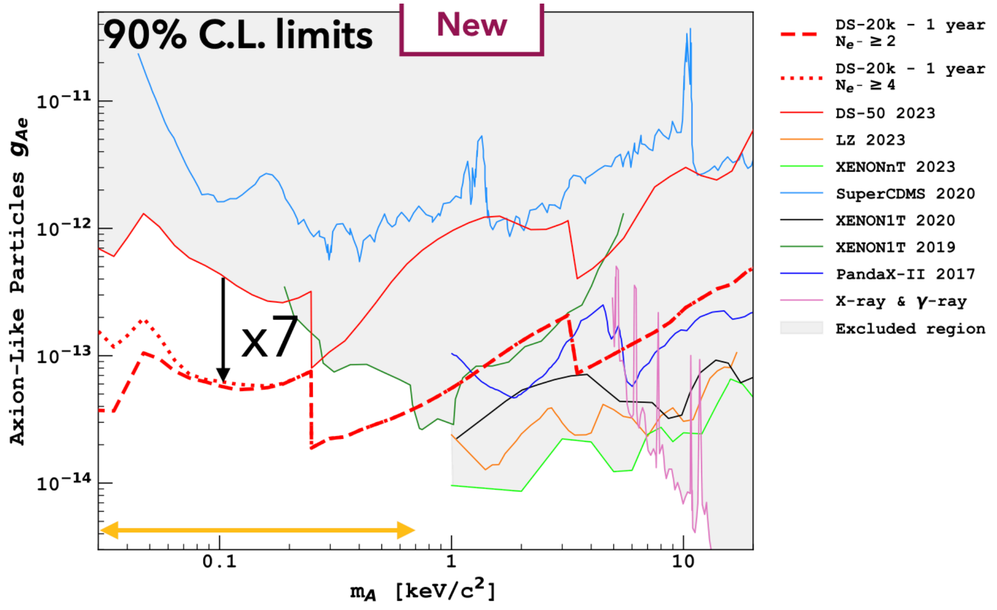
keV/c2

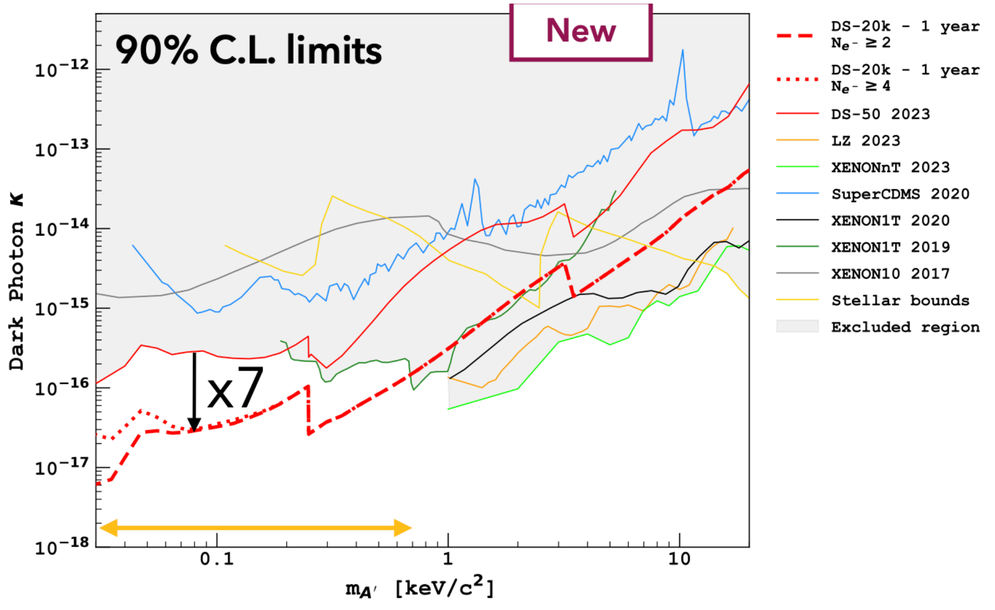
Absorption by Atomic Electrons

Non-relativistic ALPs [DPs] interact with electrons via axioelectric effect [kinetic mixing]: constrain ALP-e- coupling g_{Ae} and DP kinetic mixing strength κ.

Mono-energetic signal at m_χ.





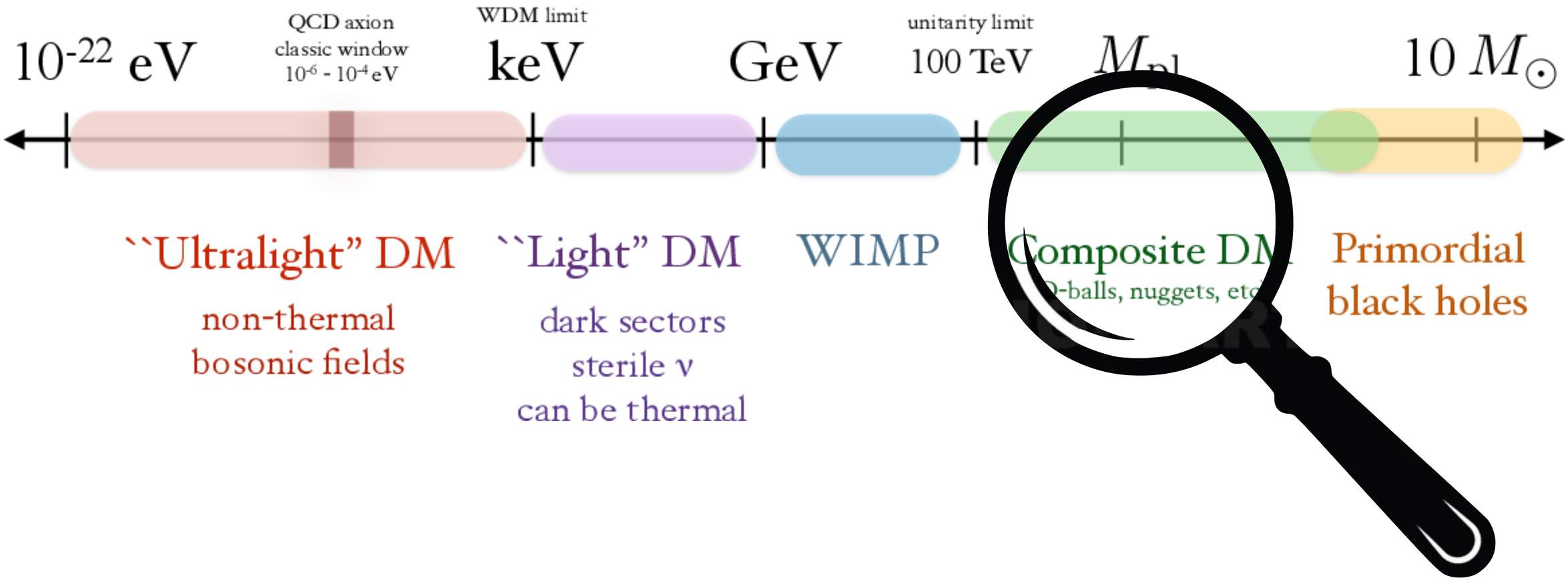


Project **x7 improvement** with respect to current experiments with only a **1-year livetime!**

Acerbi, F., et al. "DarkSide-20k sensitivity to light dark matter particles." arXiv preprint arXiv:2407.05813 (2024).

It's not all about WIMPs...

DarkSide-20k has potential to search for **both** lighter and heavier dark matter candidates!



Very Heavy Dark Matter

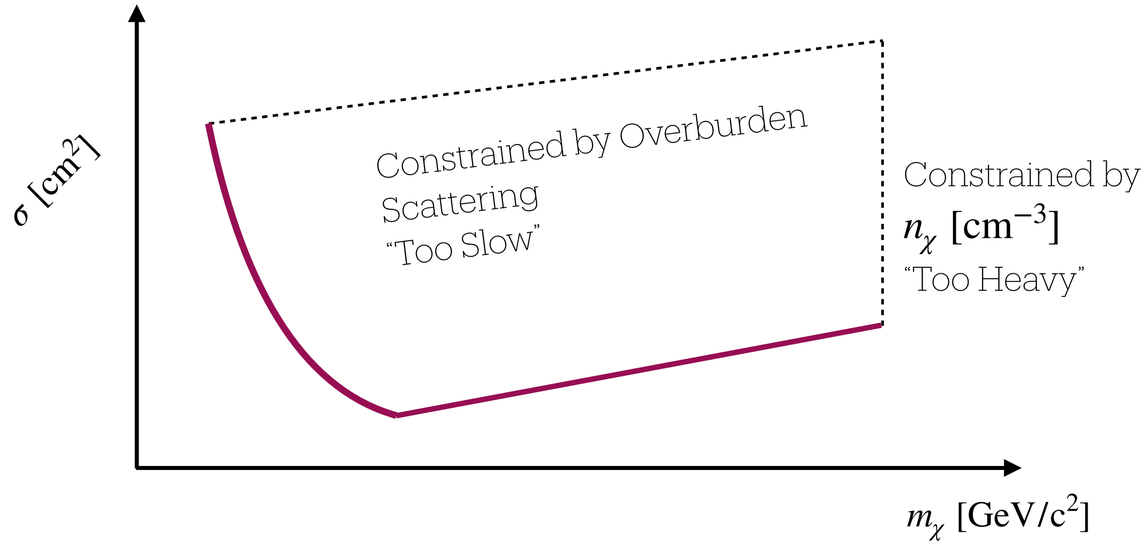
Planck-Scale Masses

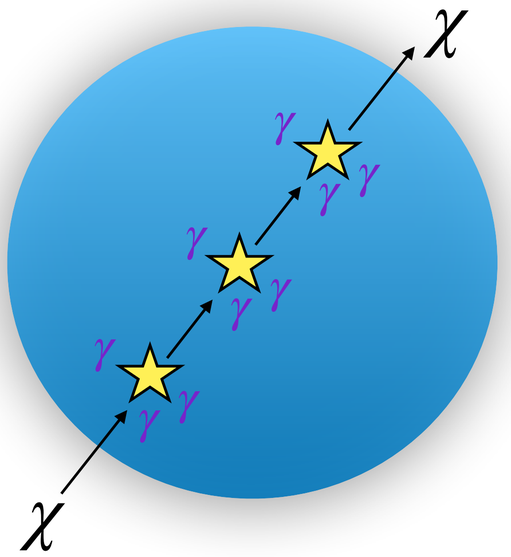
May be produced non-thermally through GUTs, primordial black hole radiation, or extended thermal production in a dark sector.

Unlike standard WIMPs, Planck-scale DM has a high enough mass to scatter multiple times as it traverses a detector: multiple co-linear nuclear recoils.

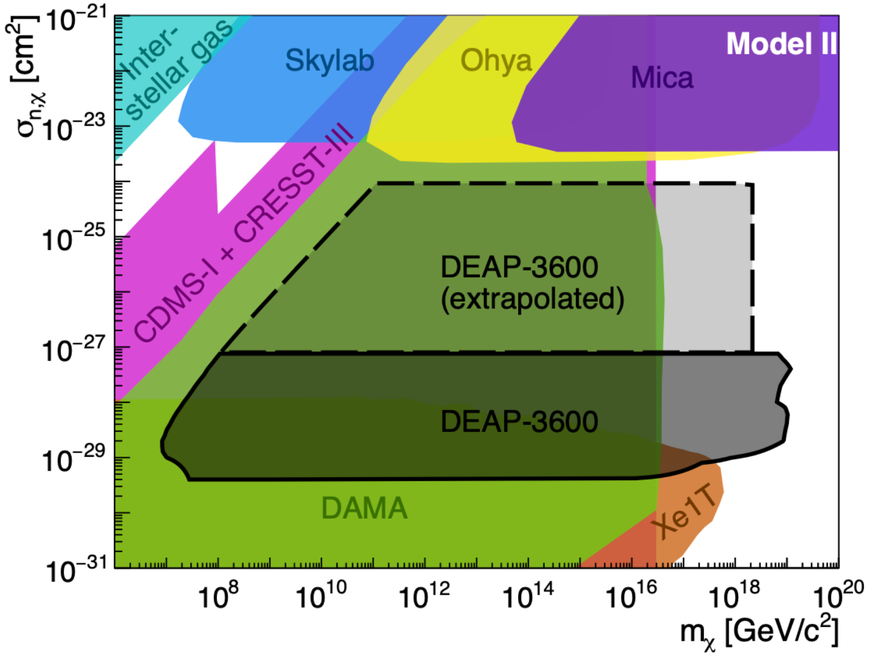
DarkSide-20k is an excellent target: large detector area normal to DM flux and large "thickness"...

- Sensitivity paper in preparation.





10^{19} GeV/c^2



Physical Review Letters 128.1 (2022): 011801.

Conclusions

DarkSide-20k is making **exciting progress** and should be acquiring **first physics data in 2027**.

DarkSide-20k has **huge potential** for dark matter discovery, from **keV-scale up to Planck-scale** masses.

- Within 1-year of data-taking, DarkSide-20k projected to probe **unchartered parameter space** for light dark matter candidates from keV to GeV range.

DarkSide-UK: **Strong synergy** with UK involvement in ECFA Liquid Detectors Collaboration ("DRD2") now established at CERN.

P5 endorsement and long term running: DarkSide-20k **prioritised on P5 baseline** programme for a **decade** of operations from 2027. Consistent with recent DarkSide-UK Consolidated Grant submission

Thanks for listening! Questions?