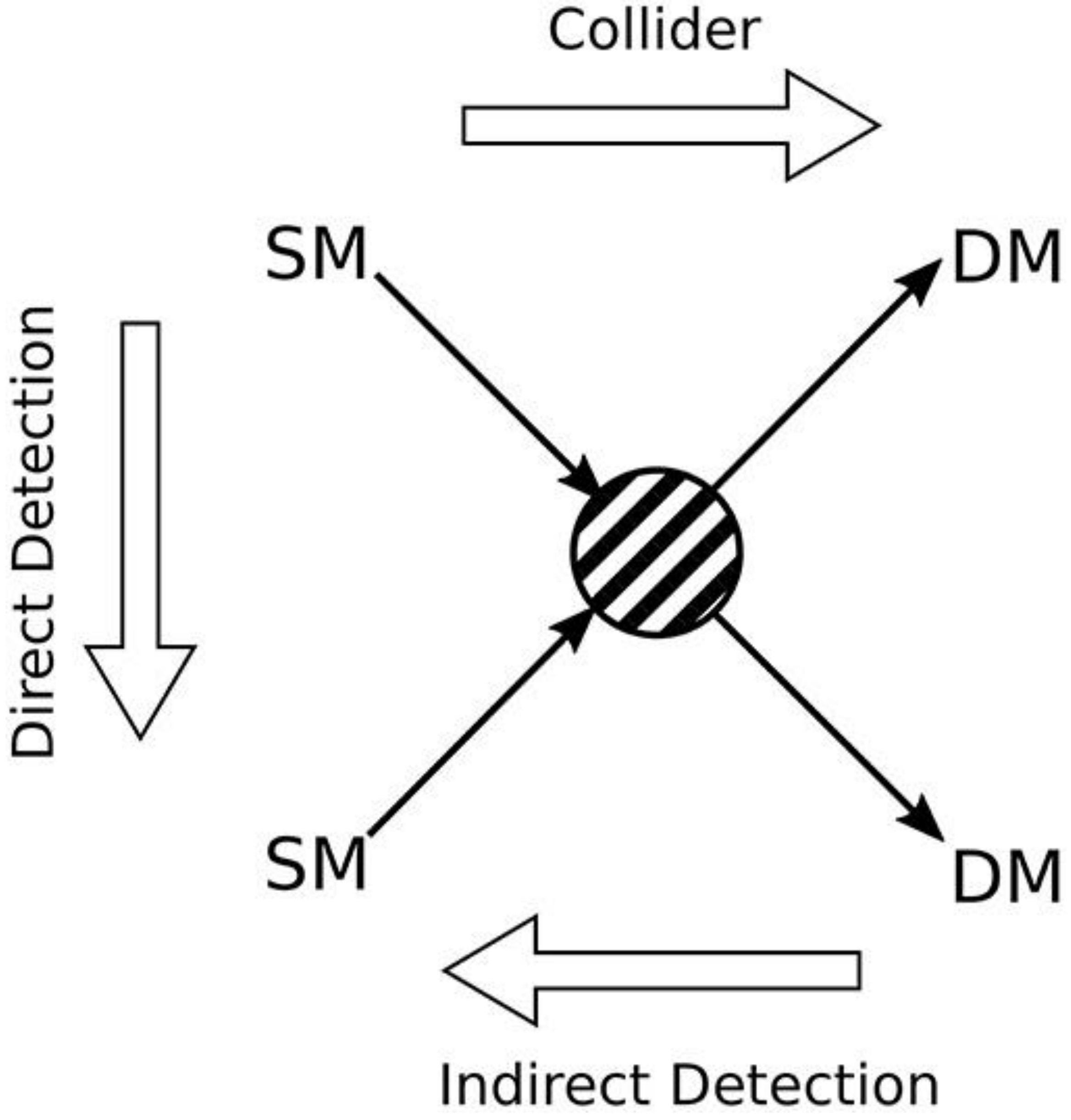
Dark Matter Searches

Dan Tovey
University of Sheffield

Dark Matter Searches

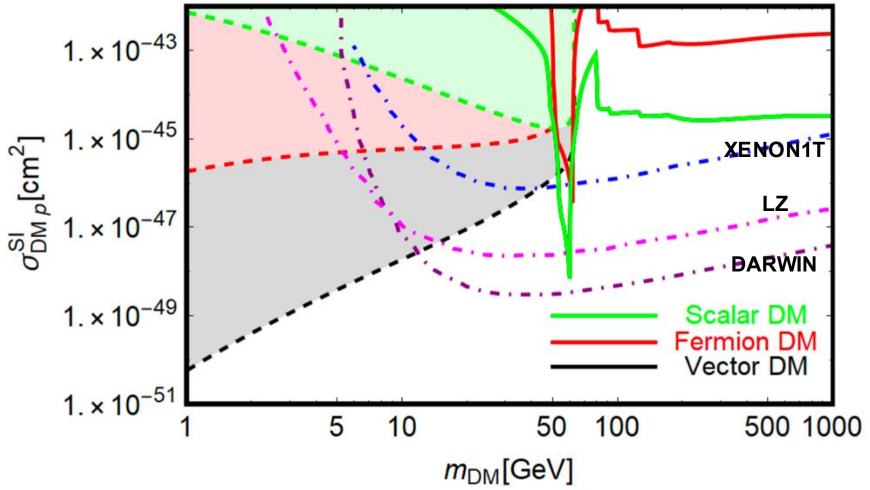
- 85% of the matter in the universe
- No SM candidates – must be BSM
- Models predicting DM also solve other problems, e.g.
  - Gauge hierarchy problem (SUSY)
  - Strong CP problem (Axions)
- Three possible approaches:
  - Collider (make it from SM particles)
  - Indirect (annihilation signatures)
  - Direct (scattering signatures)
- Here focus on searches for electroweak scale WIMPs (Weakly Interacting Massive Particles), e.g. from SUSY
- Will not discuss collider searches, or light DM searches (see QTFP talk later)

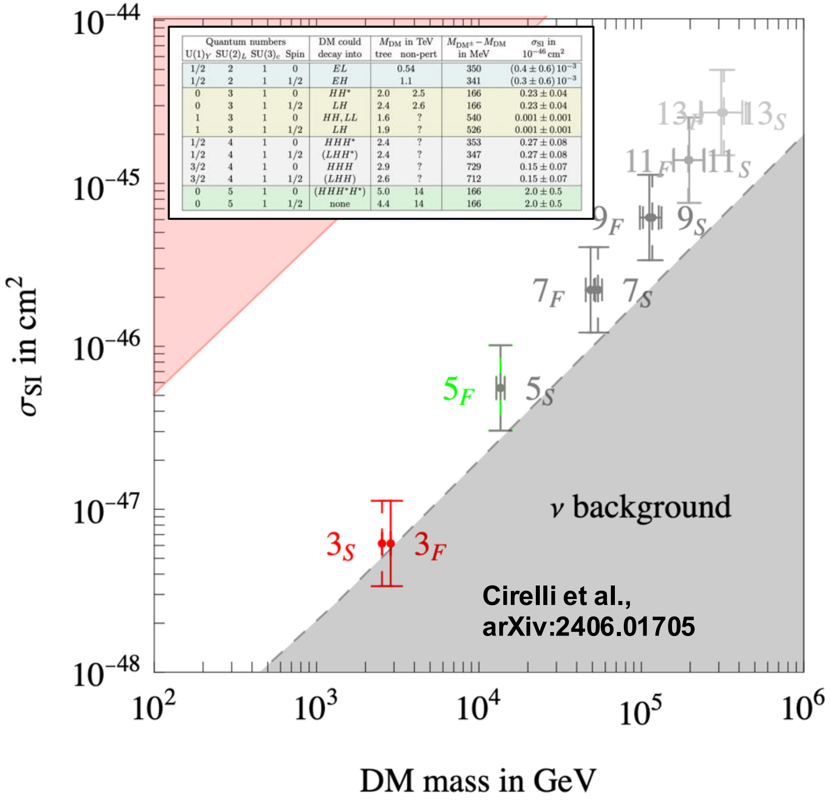


Simple Dark Matter Models

- Models vary in complexity, depending on additional BSM states beyond DM.
- Higgs Portal:
  - DM interacts through SM Higgs
  - Relic density (PLANCK) fixes coupling for given mass
  - *Almost* already excluded by direct DM search and LHC constraints

Arcadi et al. arXiv:1903.03616



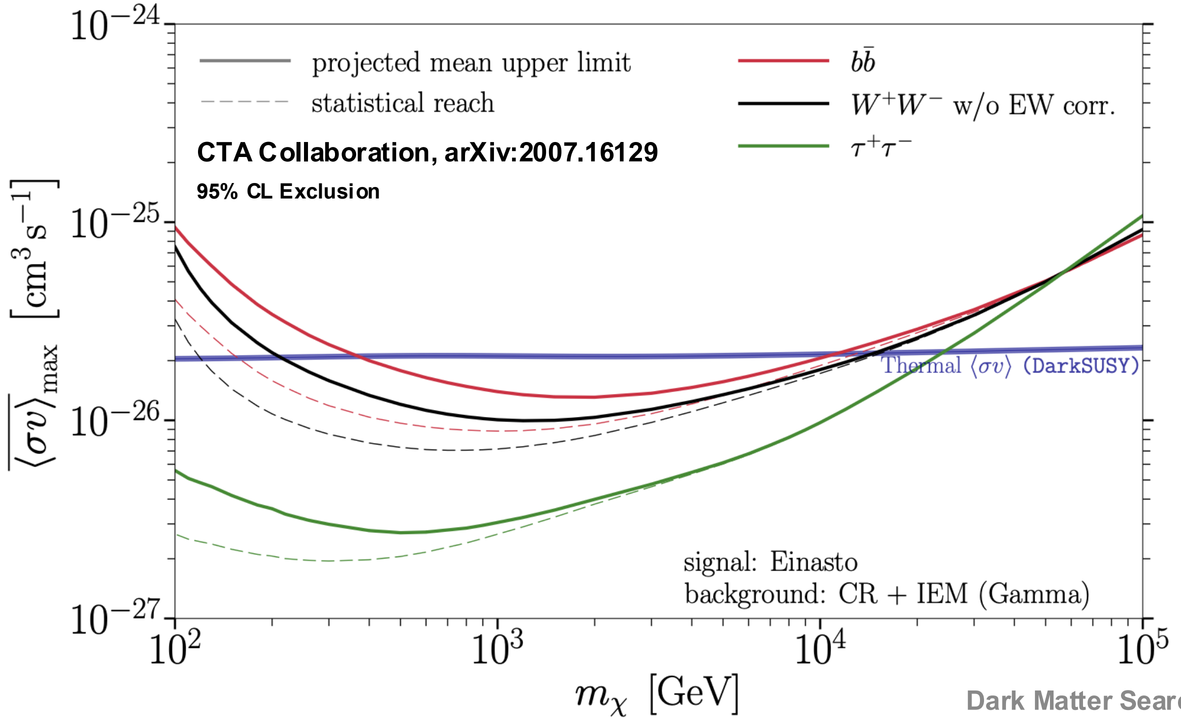


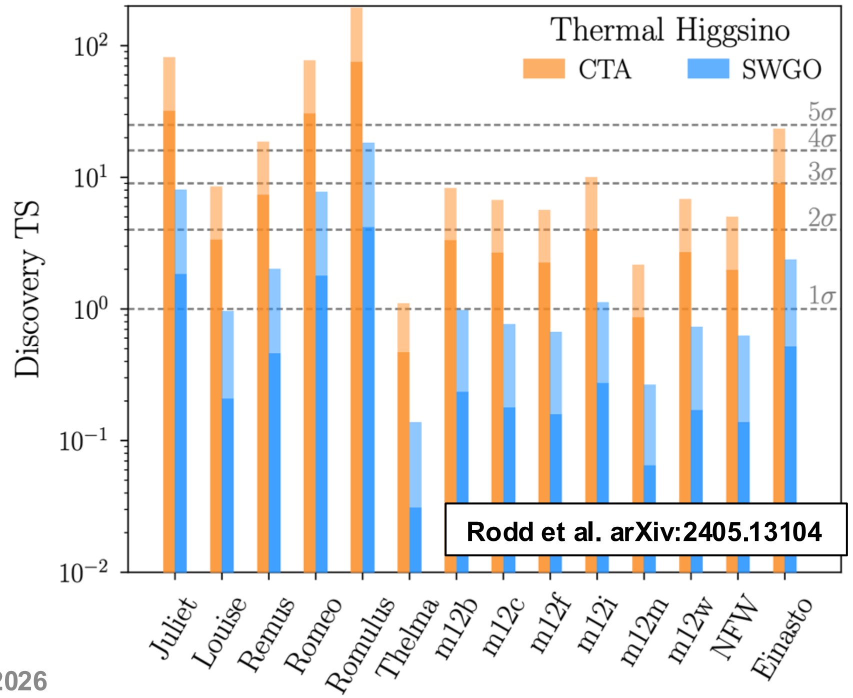
Quantum numbers U(1)$_Y$	SU(2)$_L$	SU(3)$_c$	Spin	DM could decay into	M_{DM} in TeV tree	non-pert	$M_{DM^\pm} - M_{DM}$ in MeV	σ_{SI} in 10^{-46} cm^2
1/2	2	1	0	EL	0.54		350	$(0.4 \pm 0.6)\,10^{-3}$
1/2	2	1	1/2	EH	1.1		341	$(0.3 \pm 0.6)\,10^{-3}$
0	3	1	0	HH^*	2.0	2.5	166	0.23 ± 0.04
0	3	1	1/2	LH	2.4	2.6	166	0.23 ± 0.04
1	3	1	0	HH, LL	1.6	?	540	0.001 ± 0.001
1	3	1	1/2	LH	1.9	?	526	0.001 ± 0.001
1/2	4	1	0	HHH^*	2.4	?	353	0.27 ± 0.08
1/2	4	1	1/2	(LHH^*)	2.4	?	347	0.27 ± 0.08
3/2	4	1	0	HHH	2.9	?	729	0.15 ± 0.07
3/2	4	1	1/2	(LHH)	2.6	?	712	0.15 ± 0.07
0	5	1	0	(HHH^*H^*)	5.0	14	166	2.0 ± 0.5
0	5	1	1/2	none	4.4	14	166	2.0 ± 0.5

- Minimal Electroweak Dark Matter:
  - New state charged under SM gauge group
  - Relic density (PLANCK) fixes mass for given SM coupling
  - Very predictive!
  - Includes simplest SUSY WIMPs, e.g. pure wino (**3_F** with Y=0) and pure higgsino (**2_F** with Y=1/2)
  - Within reach of next generation of direct and indirect searches

Indirect Searches with Gamma Rays

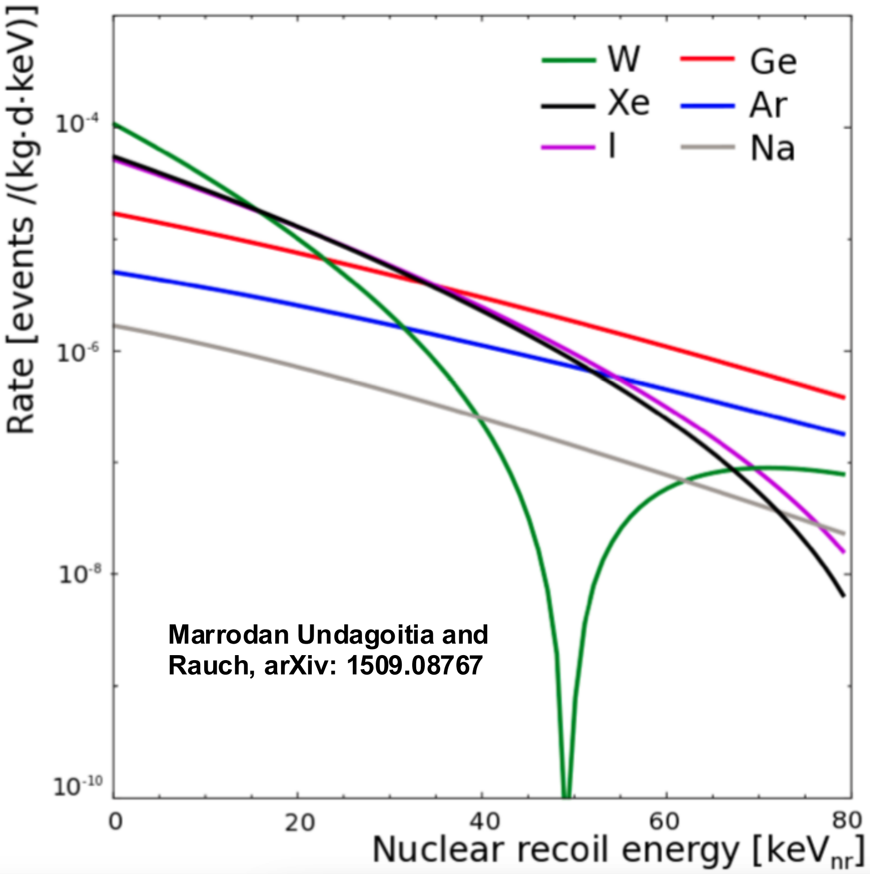
- Indirect searches with gamma rays already powerful probes of well motivated models
- CTA will transform indirect search landscape
- Searches for DM annihilating to pairs of SM states (e.g. W^+W^-, bb, $\tau^+\tau^-$), generating gamma rays in final state
- Best sensitivity from galactic centre, but sensitivity is DM halo model dependent

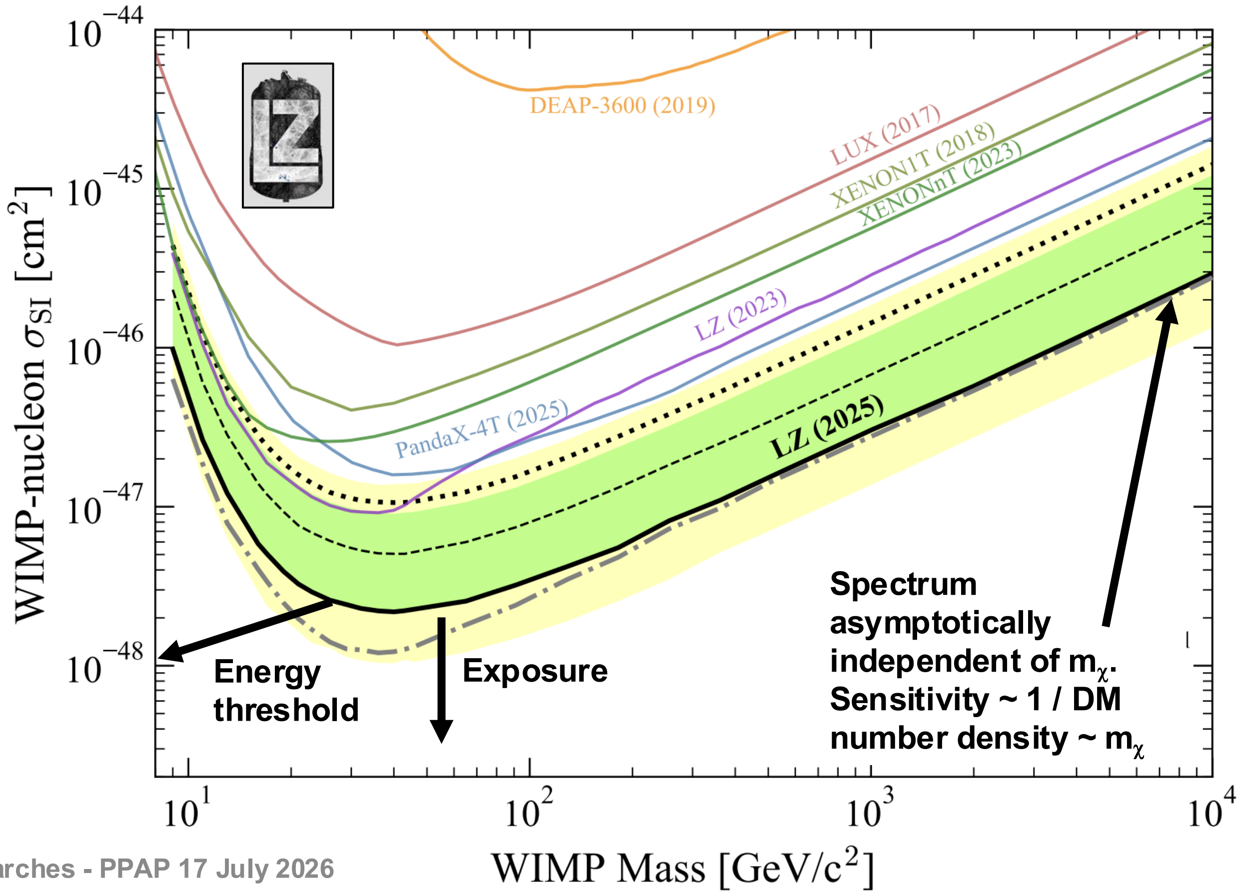




Direct Dark Matter Searches

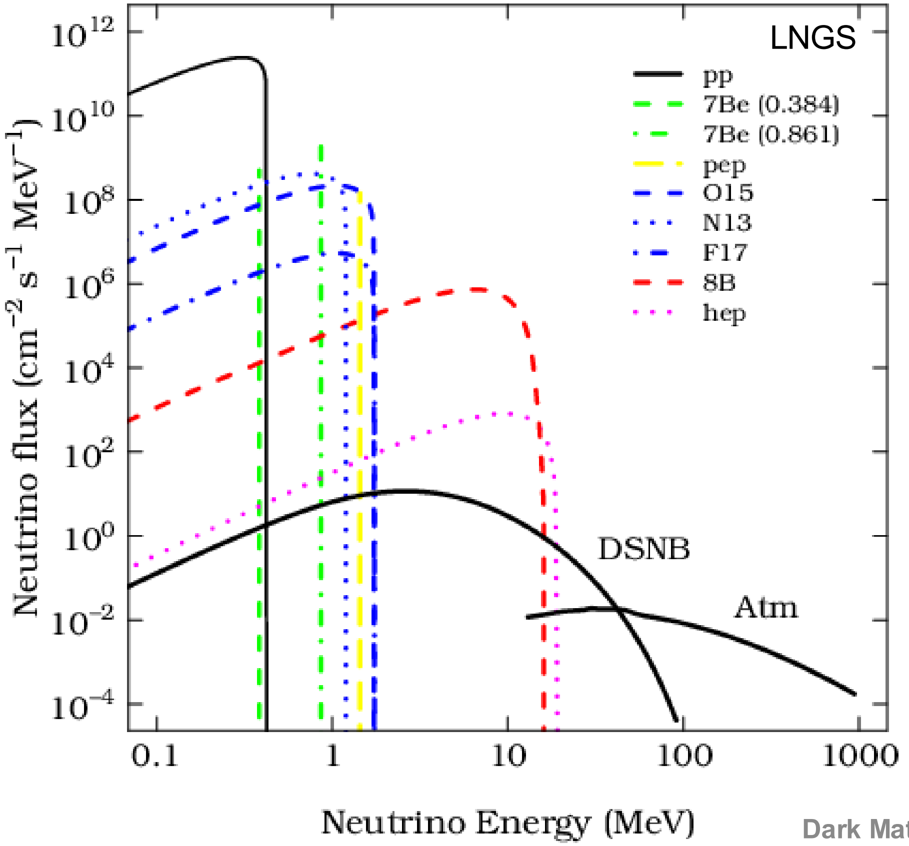
- Elastic scattering of DM from atomic nuclei (or electrons)
  - Maxwellian DM halo → exponentially falling recoil energy spectrum → low energy threshold crucial
  - Wide variety of possible couplings – simplest is spin-independent scalar
  - Coherent scattering across all nucleons scales cross-section by A^2
  - Loss of coherence at high momentum transfer leads to form-factor suppression

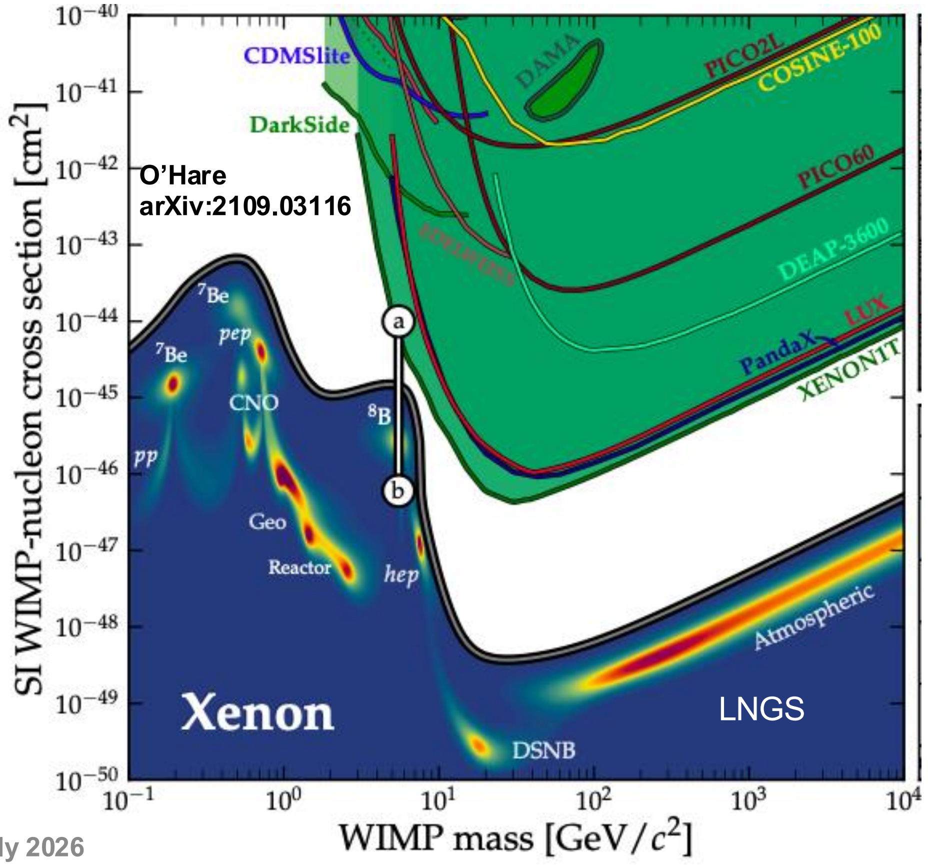




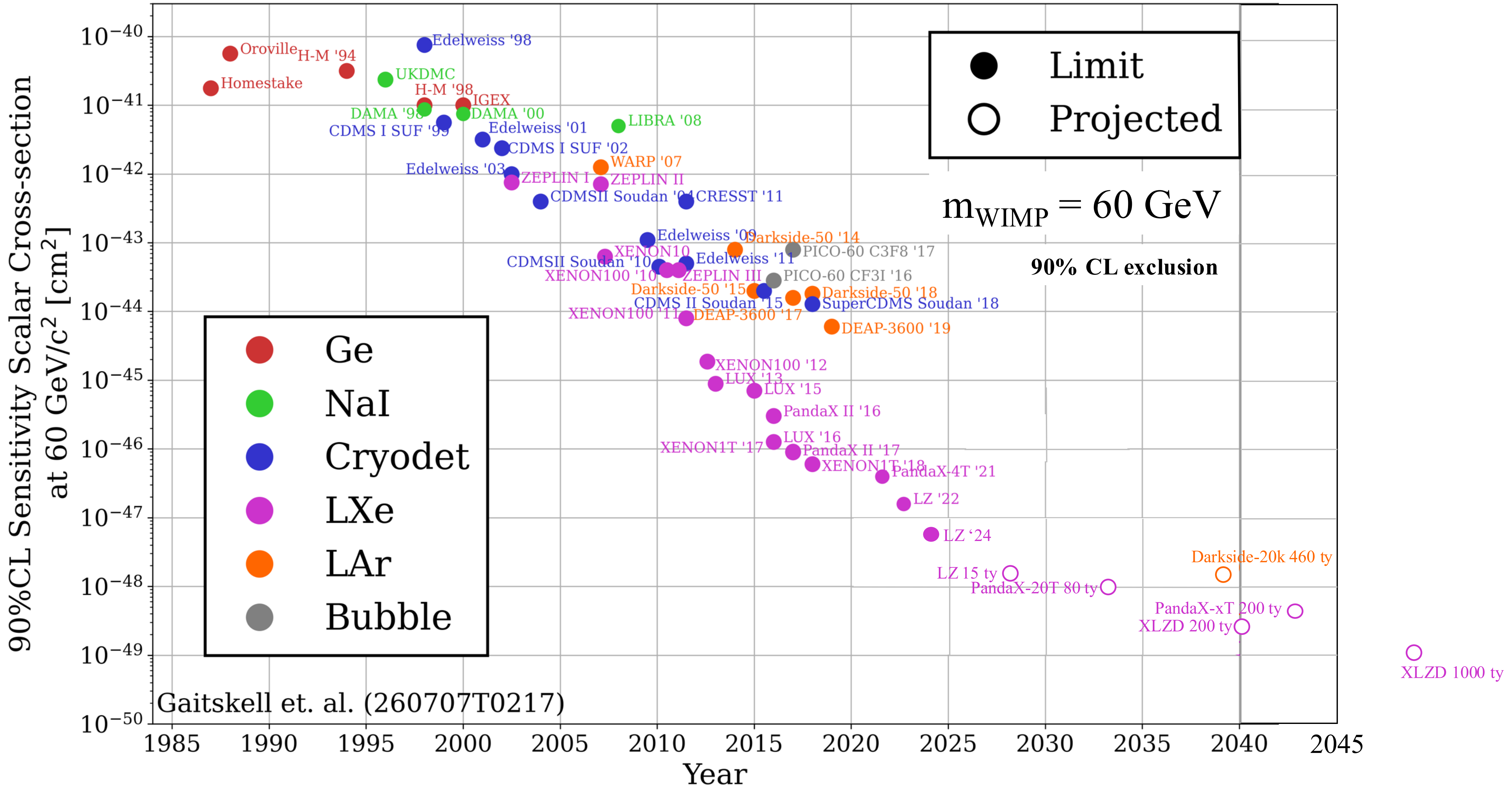
Neutrino "Fog"

- Coherent Elastic neutrino Nucleus Scattering (CEvNS) generates irreducible background to direct DM searches; recoil spectra very similar to DM
  - Solar neutrinos (mainly ^{8}B) at low energy
  - Atmospheric and DSNB neutrinos at high energy
- Fluxes well understood, so <u>not a limiting factor for current or next generation experiments</u>
  - Atmospheric CEvNS observable after 100-200 tonne-years (Xe), systematics limited after >1000 tonne-years



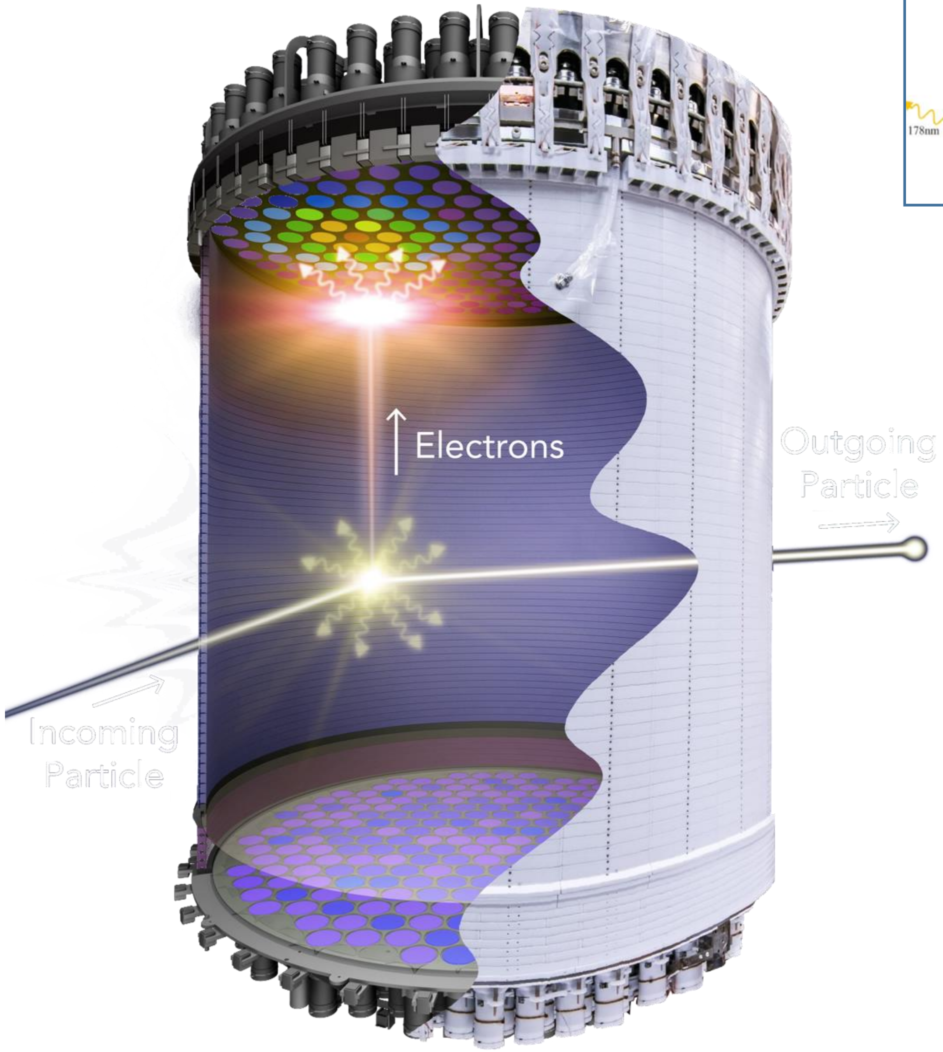


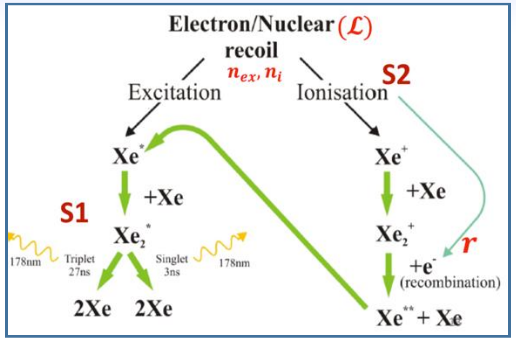
Sensitivity Progression

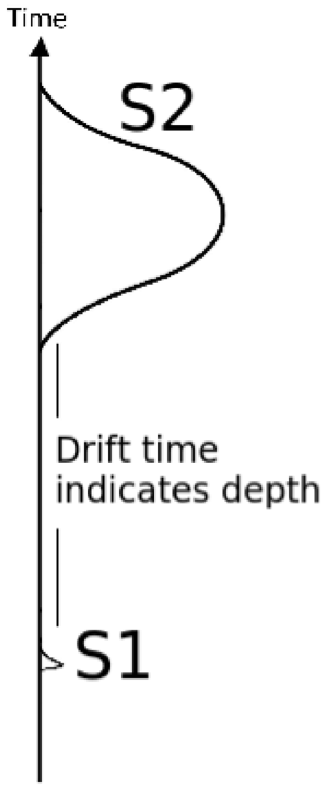


Liquid Xenon Detectors

- Liquid Xenon TPC
  - Recoil generates excitation and ionisation
  - PMT S1 light (VUV 175 nm) read-out
  - Gas-phase charge read-out with electro-luminescence (S2)
- S2 light measures x-y, drift time S1-S2 z
  - Allows fiducialisation / self-shielding
  - Veto multi-scatter γ/n background
- Features:
  - A~131, spin-dependent isotopes
  - Very radiopure
  - ~99.7% e/n-recoil discrimination (50% efficiency)
  - Mature, well understood technology







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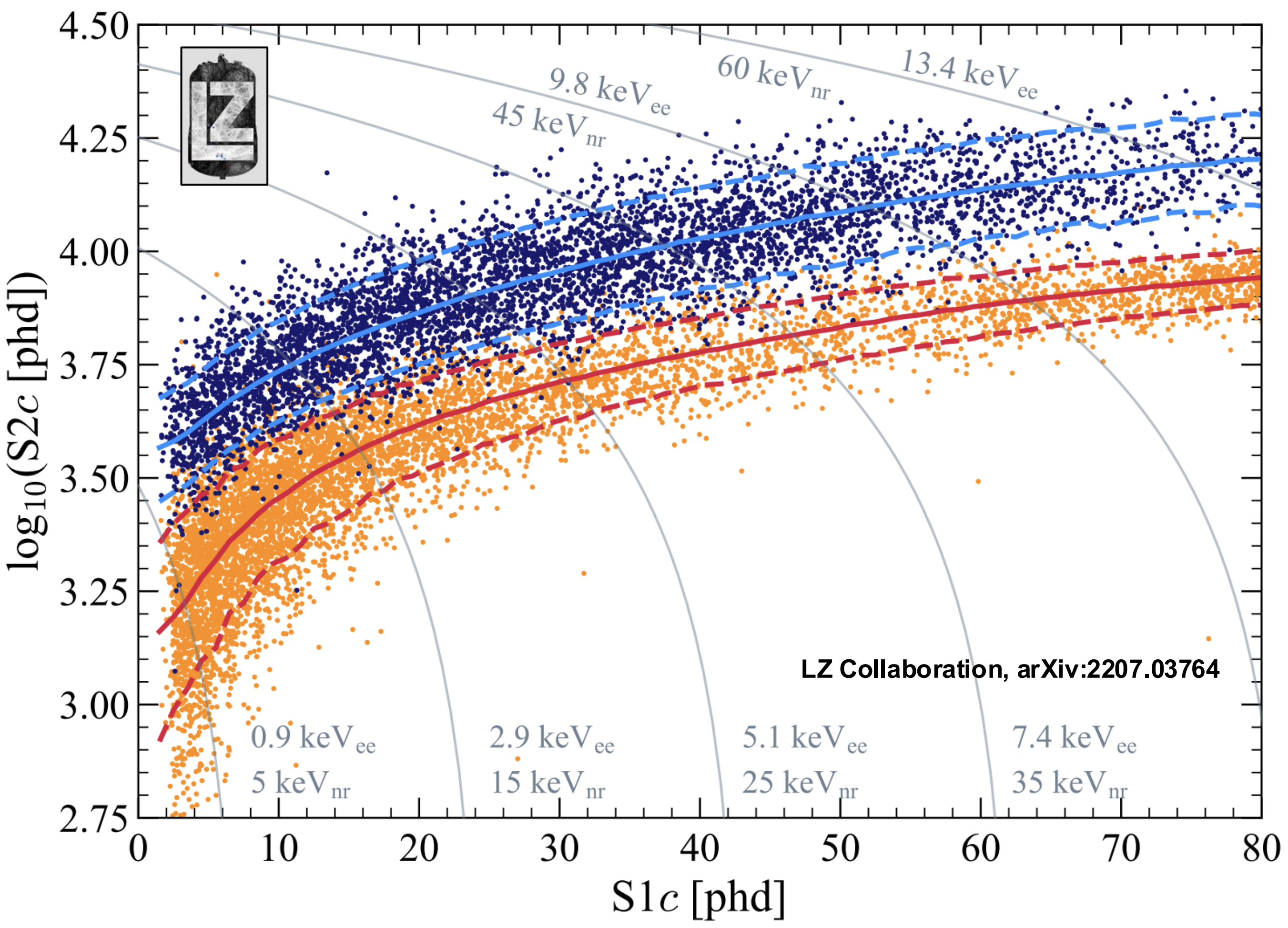
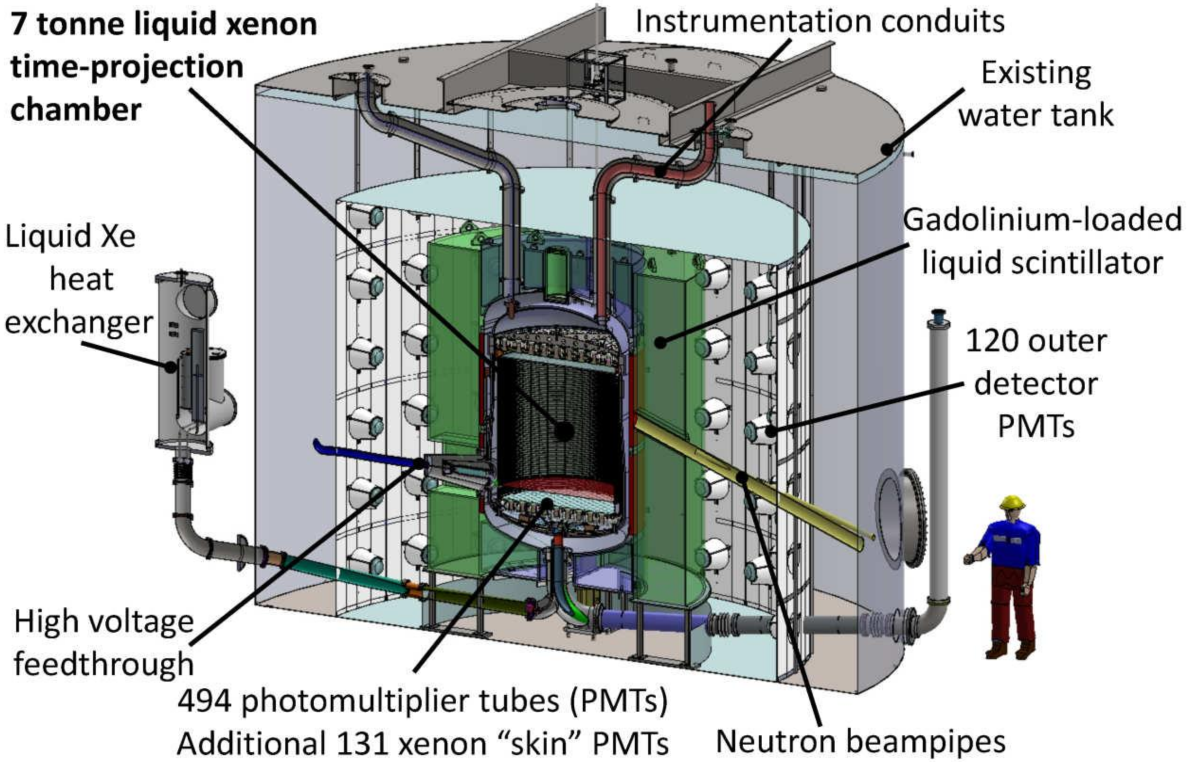


LZ Experiment

- Collaboration of US, UK (10 institutes), Portugal and Korea
- Stable operation of 5.6 tonne (fiducial) at SURF at Homestake Mine in South Dakota since 2021
- Major UK contributions to Xenon detector, Outer Detector (neutron veto), calibration systems, cryostat, clean manufacture, computing, and background simulations. UK physicist previous spokesperson.

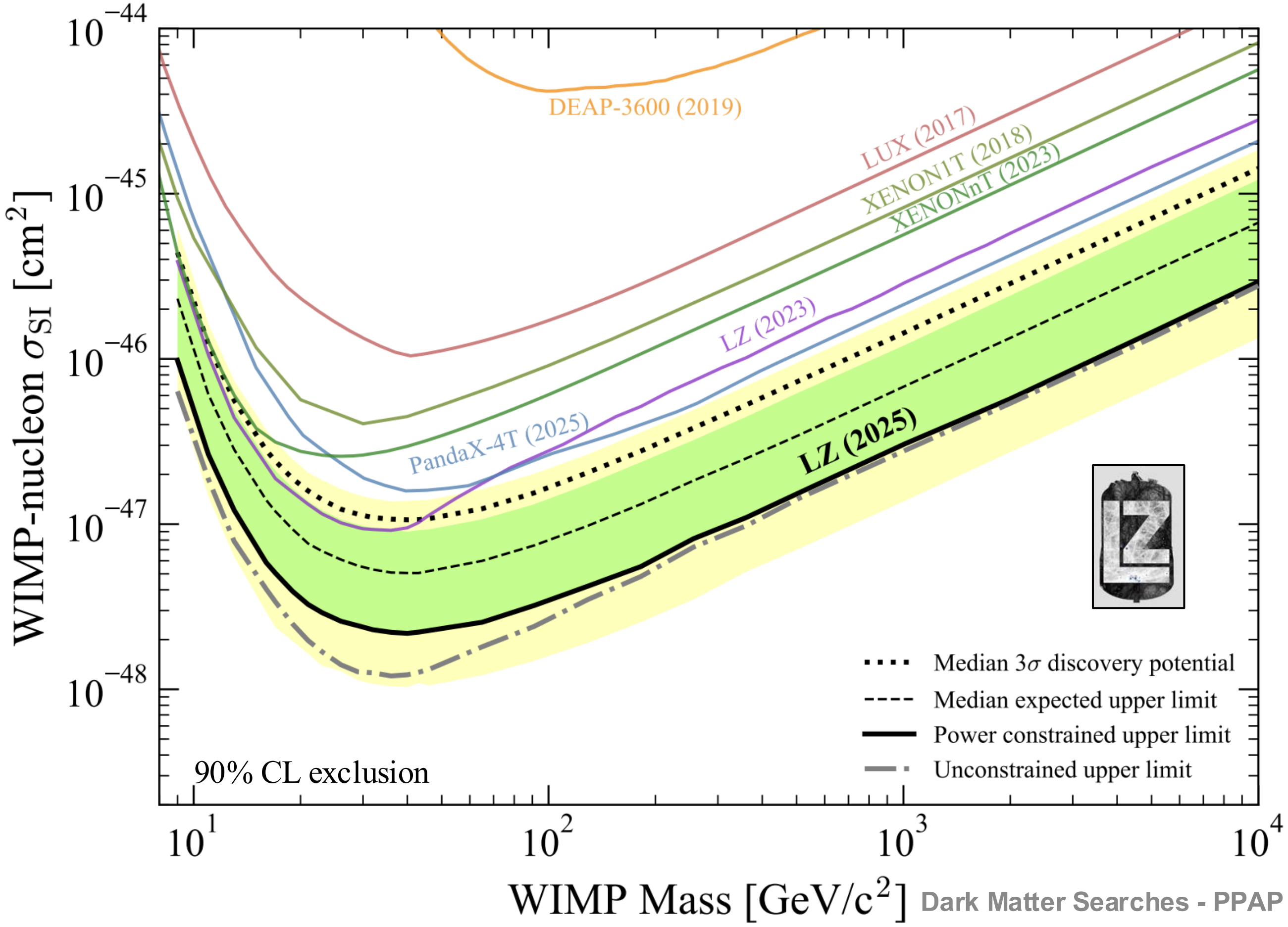


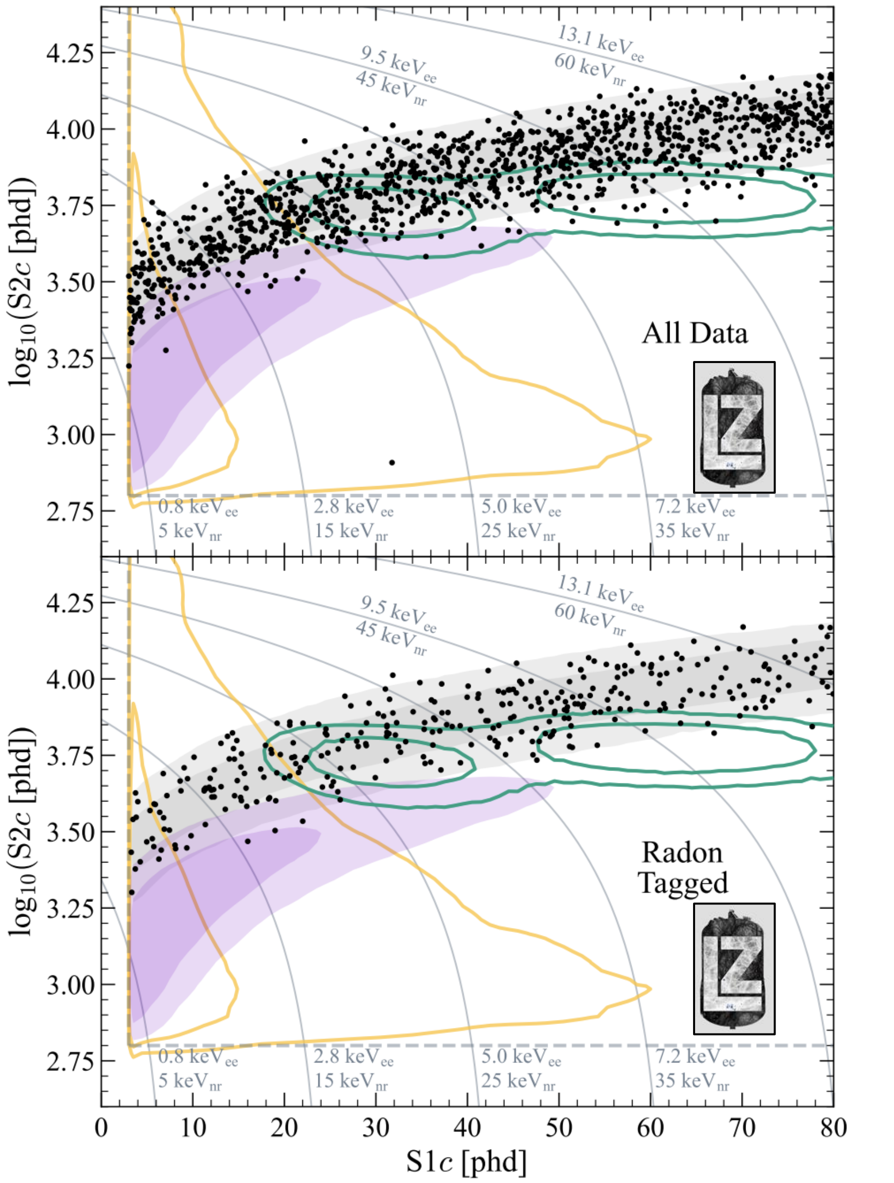
LZ Collaboration Meeting, Bristol, June 2026

LZ: WIMP DM Search

LZ Collaboration, Phys. Rev. Lett. 135, 011802 (2025), arXiv:2410.17036

- Results with 4.2 tonne-year dataset released in 2024
- No evidence of excess above backgrounds
- World's best limits on WIMP dark matter for m_{WIMP}>10 GeV, by some way

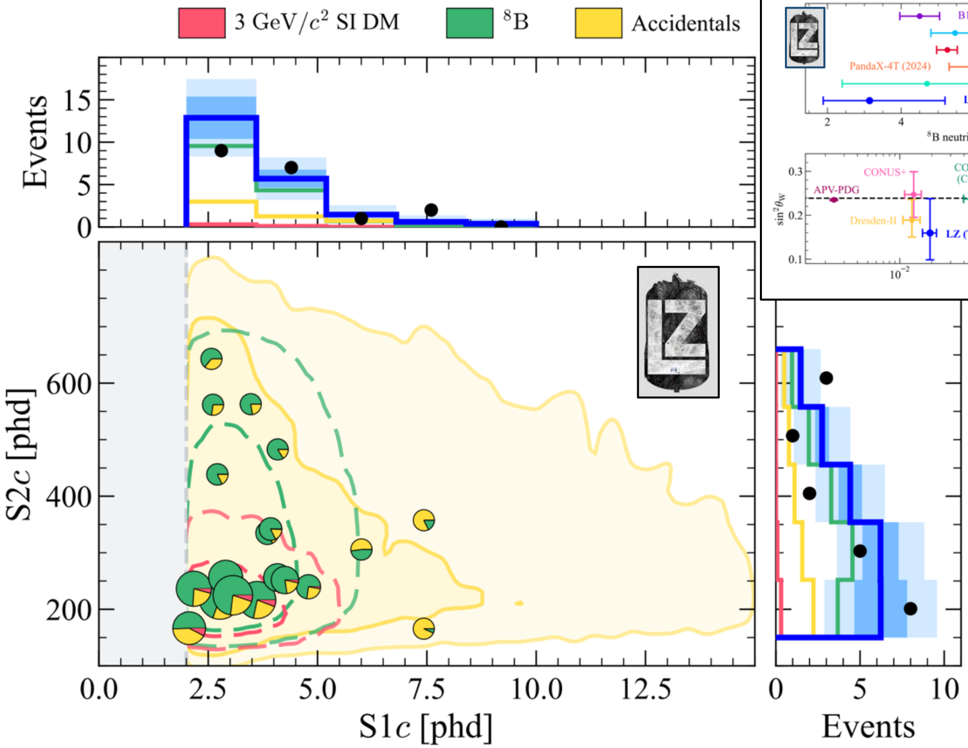


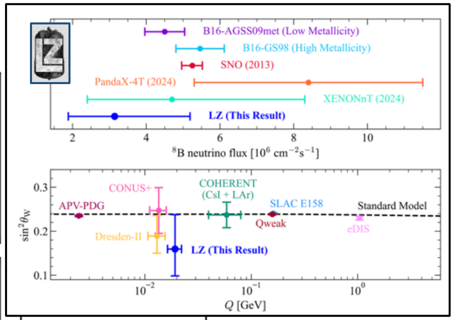


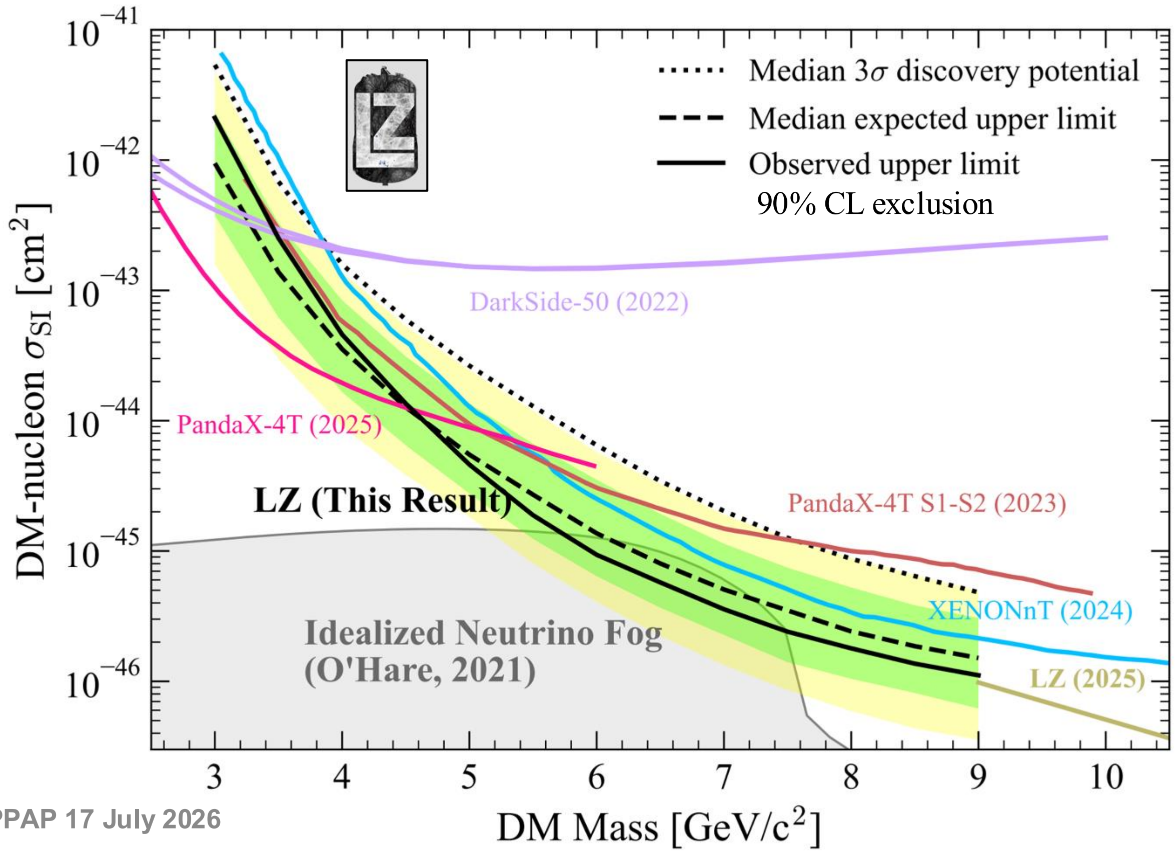
LZ: Low Mass WIMPs / ^{8}B CEvNS

LZ Collaboration, arXiv:2512.08065

- Latest results (2025) focus on low mass WIMPs with 5.7 tonne-year dataset
- Requires exquisite understanding of backgrounds close to threshold – esp. accidental coincidences
- First evidence (4.5σ) for ^{8}B solar neutrino CEvNS process – key milestone for the field – into the fog!
  - Also measures $\sin^2\theta_w$ at momentum transfer Q ~ 19 MeV
- Known ^{8}B flux enables world's best WIMP limits in mass range 4.5 – 9 GeV/c^2

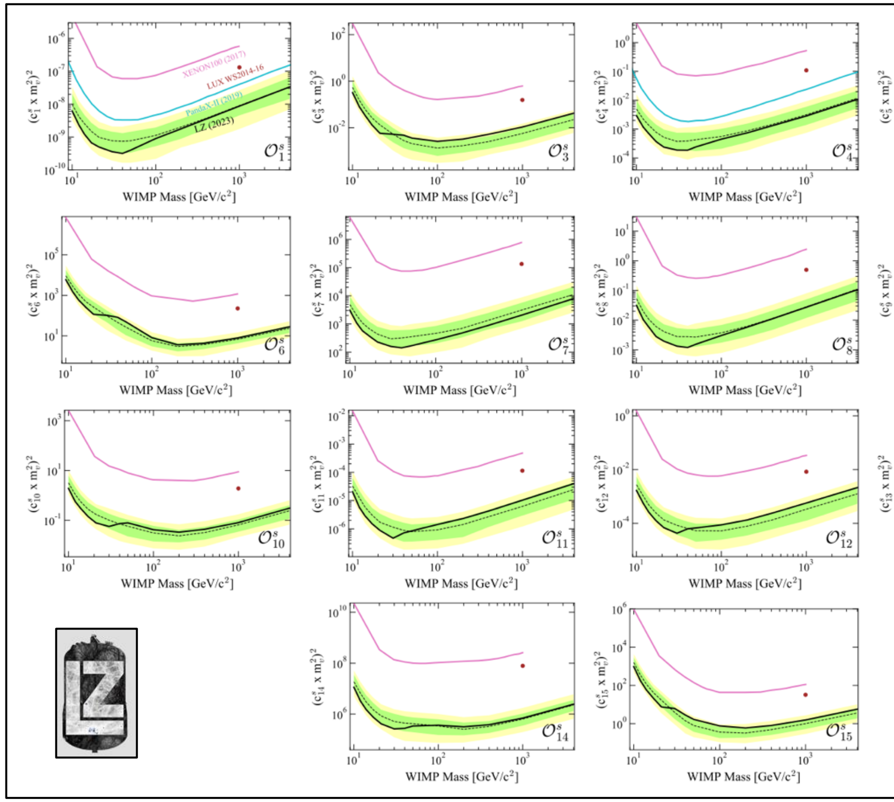






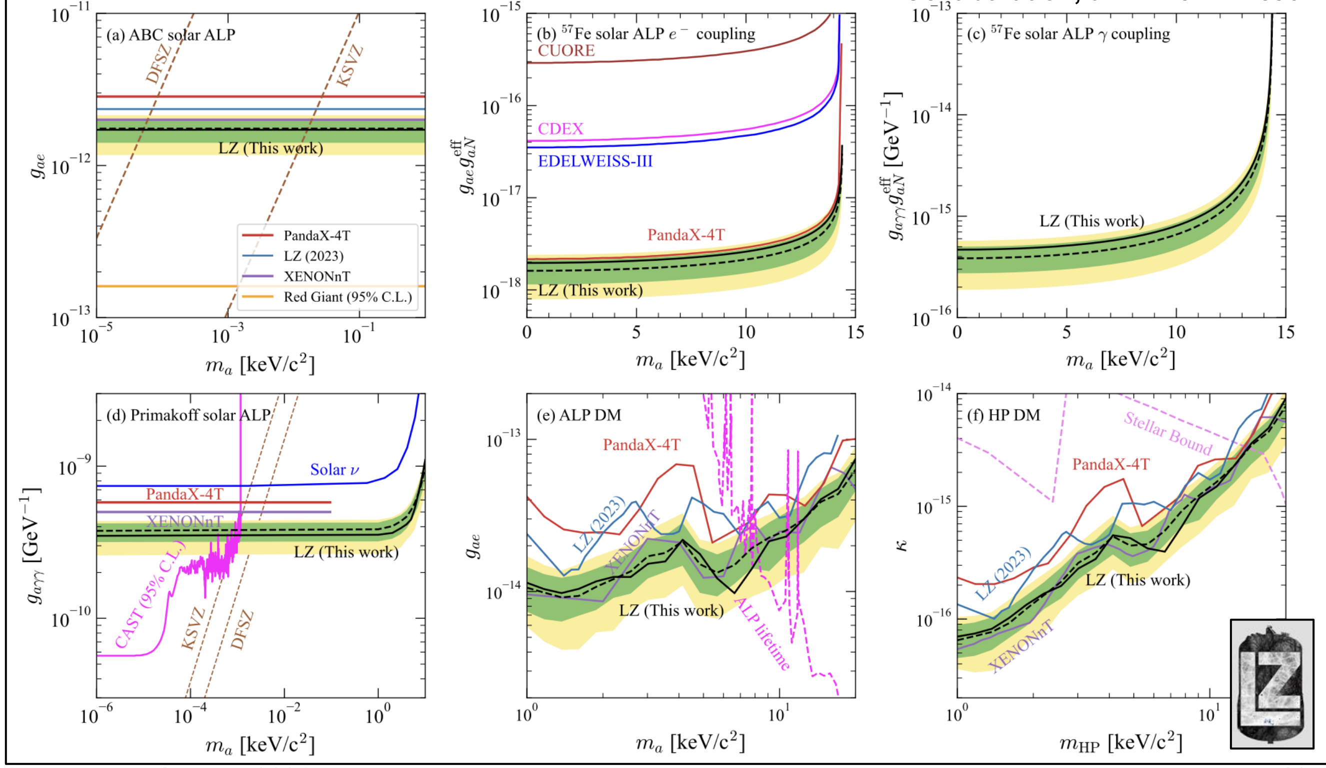
LZ: More Results

- Rich harvest of additional physics results obtained with LZ data, e.g.
  - High energy nuclear recoils → non-standard EFT DM-nucleus couplings [Phys. Rev. D109, 092003 (2024)]
  - Low energy electron recoils → solar ALPs, Mirror DM [arXiv:2511.17350]
  - Rare nuclear decays → measurement of ^{124}Xe 2ν double electron capture [J. Phys. G 52 015103 (2025)]
- Much more to come! See https://lz.lbl.gov/publications/ for latest results



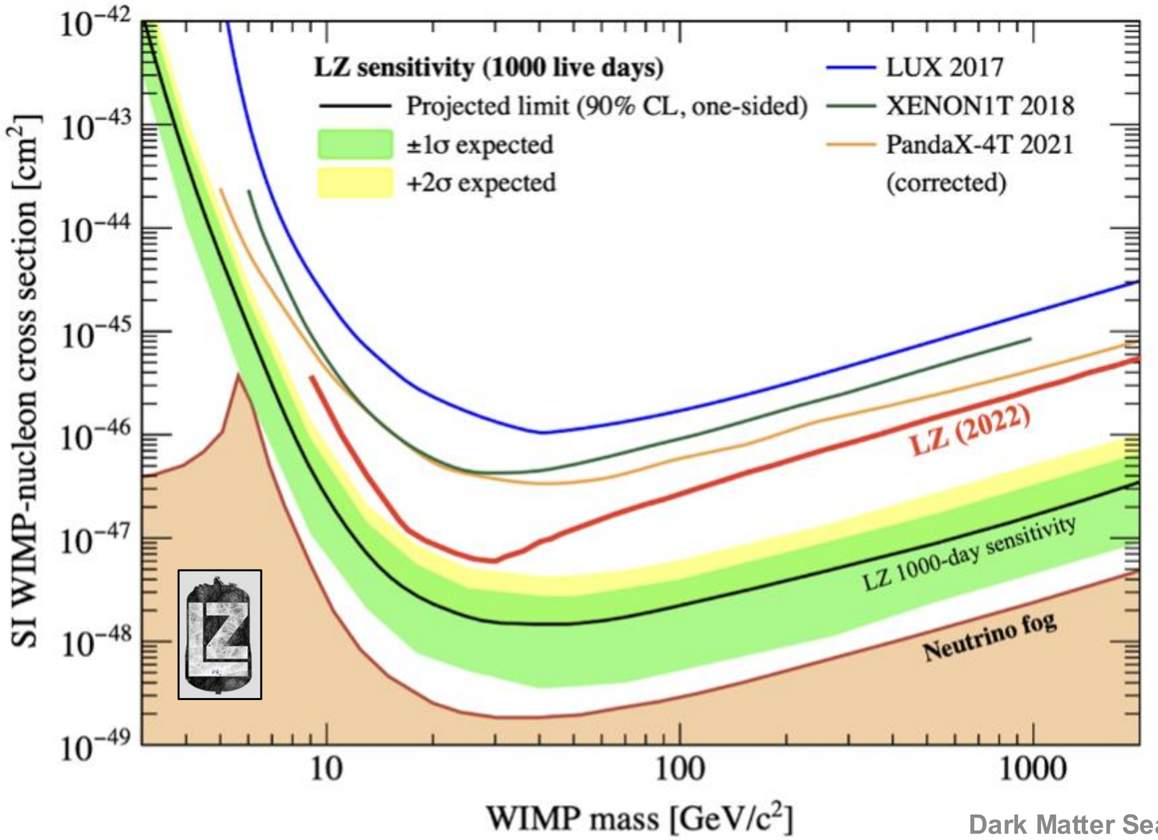
LZ Collaboration, PRD109, 092003 (2024), arXiv:2312.02030

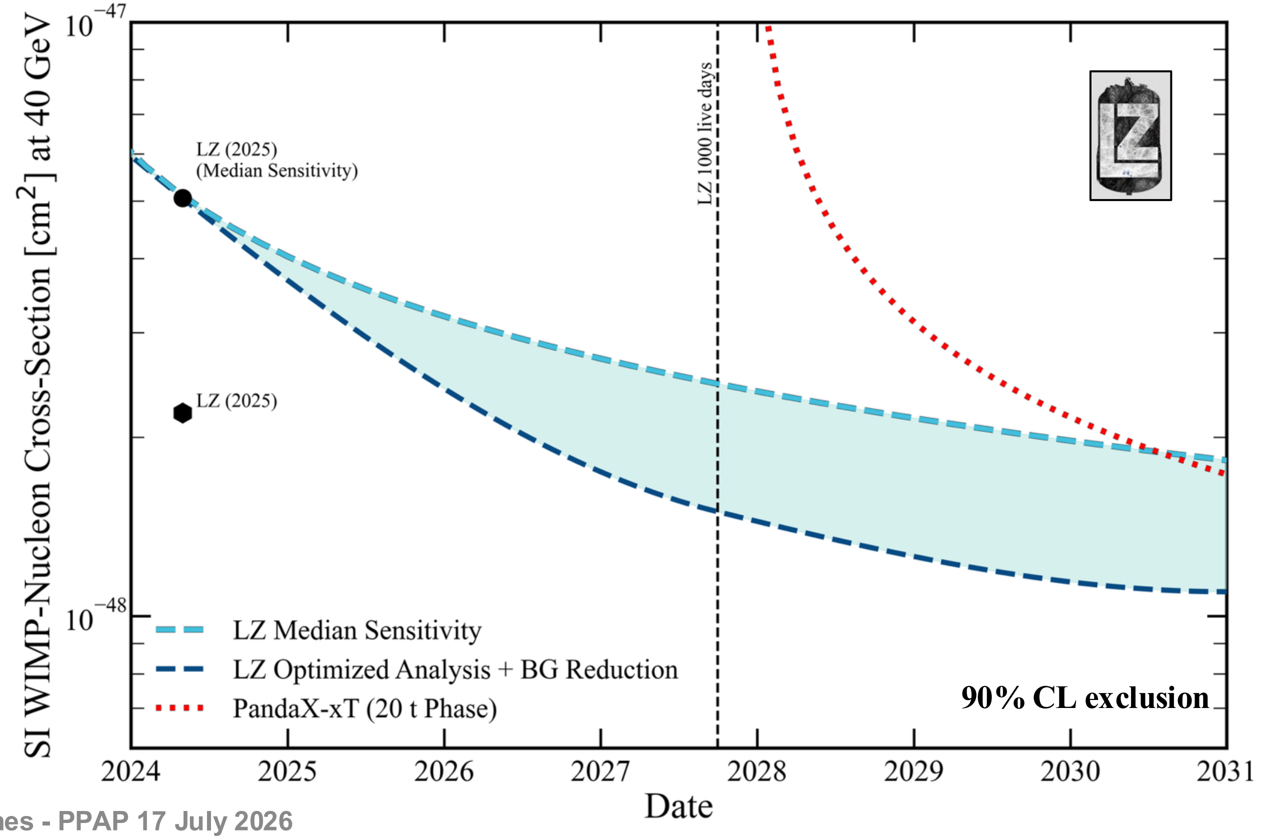
LZ Collaboration, arXiv:2511.17350



LZ Future Plans

- LZ is currently foreseen to run until late 2027, accumulating 1000 live days of data
- Recent guidance from US DOE encourages LZ to study feasibility of continued operation into early 2030's. PANDAX-xT (CJPL China) competitive from ~2031 onwards.
- Studies also being undertaken into possible upgrades of experiment targeting e.g. improved sensitivity to lower mass WIMP DM

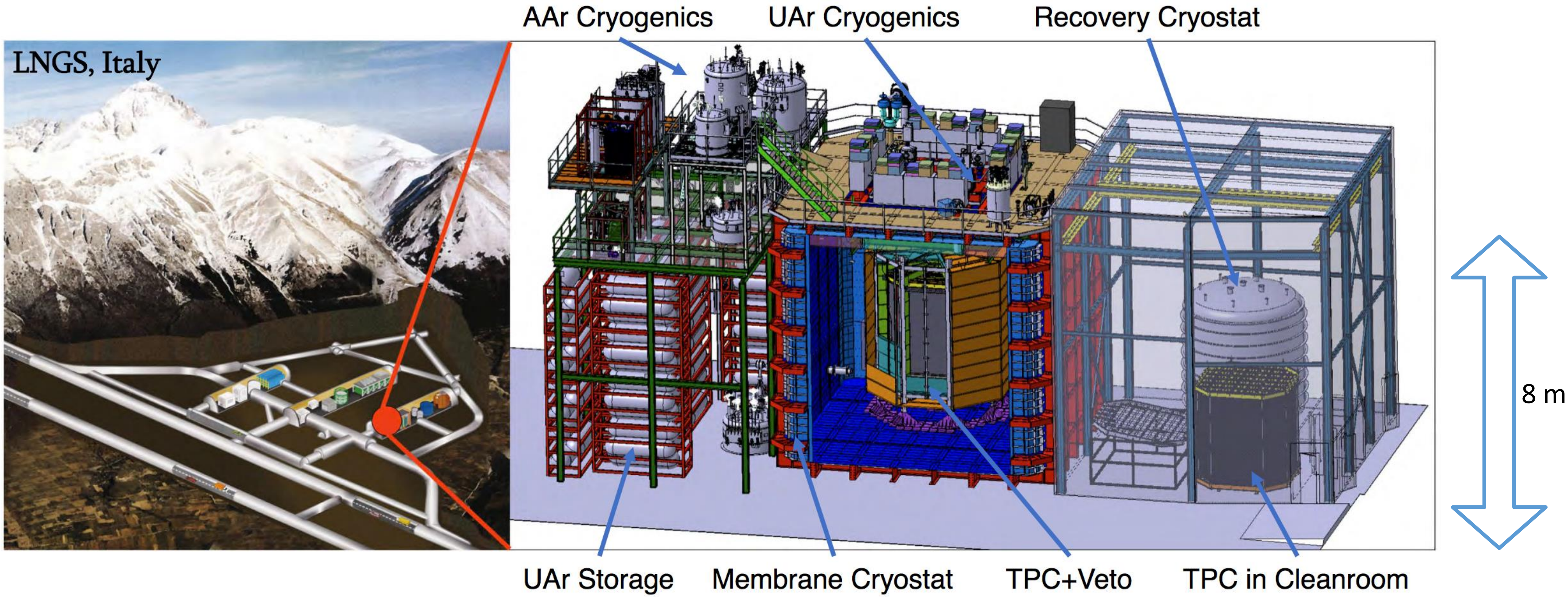




DarkSide-20k

Global Argon Dark Matter Collaboration of >400 scientists in 14 countries (UK~10%) building the DarkSide-20 experiment.

DarkSide-20k is a dual-phase TPC filled with 50 t underground argon target (UAr), surrounded by 35 t UAr inner veto, inside 700 t LAr outer veto in a protoDUNE-like cryostat, under construction in LNGS underground laboratory.



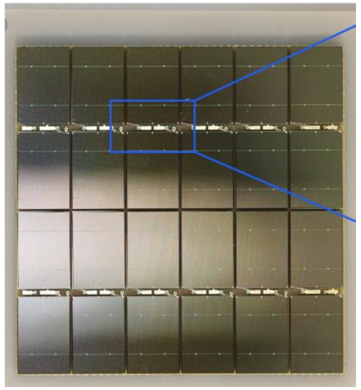
A low-background observatory for dark matter and neutrino physics,
DarkSide-20k is designed to operate for a decade with <1 instrumental background event.

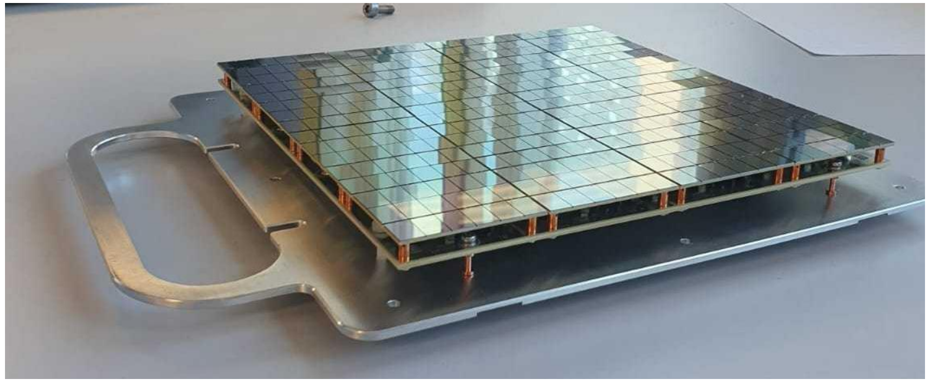
DarkSide-20k

- Construction at Gran Sasso Laboratory (LNGS) is advanced, with major infrastructures completed. Ar fill scheduled in 2028.

- DarkSide-UK STFC project delivering SiPM array detectors, with 10x lower noise, >10x lower radioactivity and >3x higher photon detection efficiency than predecessor PMTs, to instrument the veto detectors.
  - Production/qualification of hardware started in 2021 in Birmingham, Edinburgh, Lancaster, Liverpool, Manchester, Oxford, RAL PPD, RHUL, STFC Interconnect, Warwick + assay at Boulby
  - UK delivery 7 m^2 of SiPM arrays (>50,000 sensors) **completed in 2026**!
  - UK installation activities at LNGS underway: 100% of detectors acceptance tested at LNGS as of June 2026, achieving 94% yield.

arXiv:2604.02551; Eur.Phys.J.C 85 (2025) 11, 1334; Eur.Phys.J.C 85 (2025) 5, 534





UK ambassador to Italy visits DarkSide-20k, LNGS Hall C

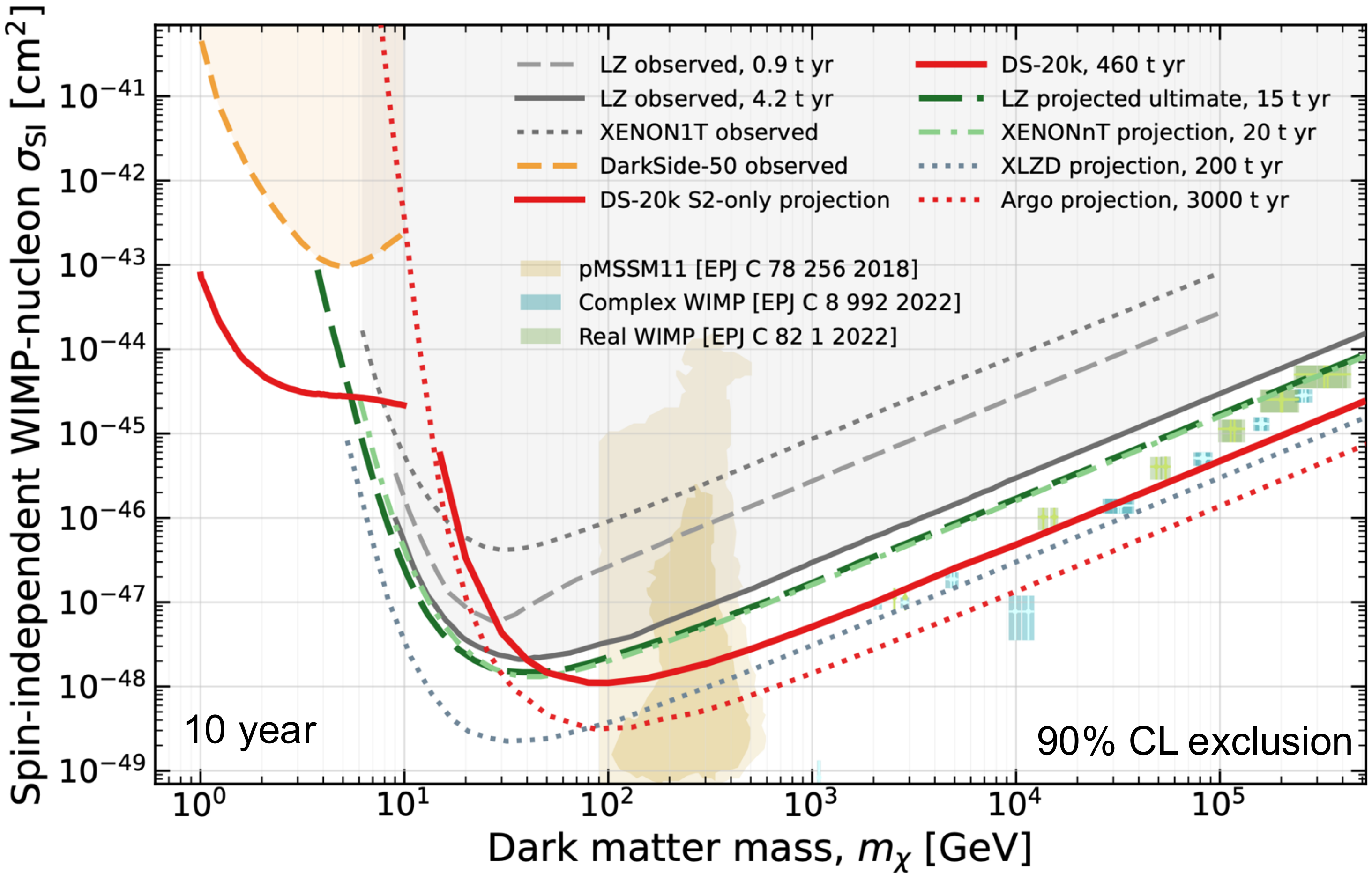
The STFC-supported UK groups play key roles in detector development and delivery and hold leadership roles in collaboration, construction WBS, and planning for a decade of science exploitation.

DarkSide-20k

UK exploitation activities focus:

1) Neutron tagging for the flagship WIMP dark matter (DM) search.
   - Neutron single scatters can produce the same final state as a DM interaction!
   - Tagging neutrons in the UK-instrumented veto is fundamental to achieving background goal.

2) Searches for DM beyond WIMPs with low-mass emphasis [*Commun.Phys. 7 (2024) 1, 422]*, sensitive to
   - asymmetric DM models,
   - hidden sector portals (i.e. dark photons, ALPs),
   - self-interacting DM,
   - warm sterile neutrino DM,
   - even spin-dependent DM! *(Ritchie-Yates, IOP'26)*



Science beyond WIMPs with LAr DM experiments

- *First evidence of neutrino absorption on argon: arXiv: 2605.12769*
- *First search for nuclear dark matter (SiDM): arXiv:2602.09421*
- *First direct detection search for primordial black hole dark matter: Phys.Rev.D 112 (2025) 123058*
- *First search for warm sterile neutrino dark matter: Phys.Rev.Lett. 130 (2023) 10, 1*
- *First direct detection constraints on Planck-scale dark matter: Phys.Rev.Lett. 128 (2022) 1, 011801*
- *Sensitivity to 100s of neutral current neutrino scattering events from galactic supernovae (all flavours!): JCAP 03 (2021) 043*

DarkSide-20k will explore new parameter space for a broad range of dark matter candidates, within and beyond WIMPs

Spherical Proportional Counters (SPC) at Boulby

DarkSPHERE

Phys. Rev. D 108, 112006

P. Knights, I. Manthos, L. Milligan, L. Millins, K. Nikolopoulos, G. Rogers, D. Spathara, P. Walters
University of Birmingham, University of Hamburg and international NEWS-G Collaboration

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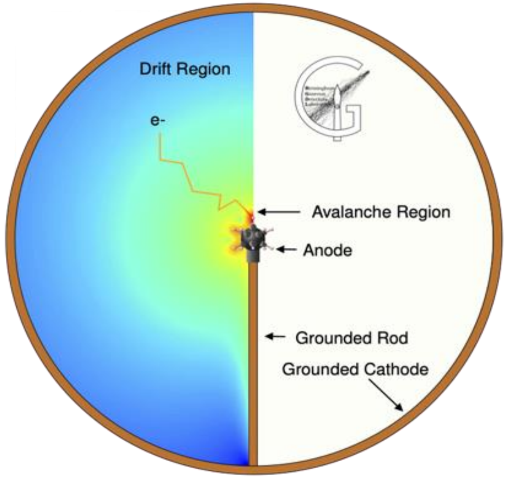
NEWS-G Collab Meeting Boulby 2023

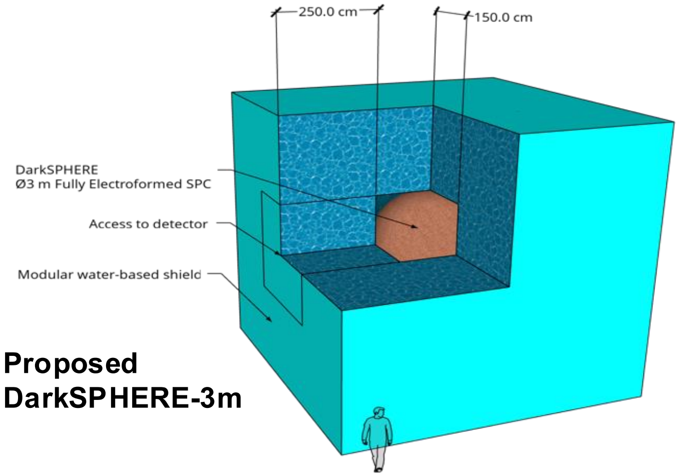
Activities at Boulby

- Instrumentation developments
  - Multi-anode sensor
  - Gas filtration
  - Rate effect studies
- Neutron spectroscopy (with N_2 gas)
  - Neutron background surveys
  - Industrial applications
- High-purity copper electroformation
- **Towards scaled-up, electroformed, detector at Boulby, 3m diam. 5 bar He:CH_4H_{10}** ***DarkSPHERE***



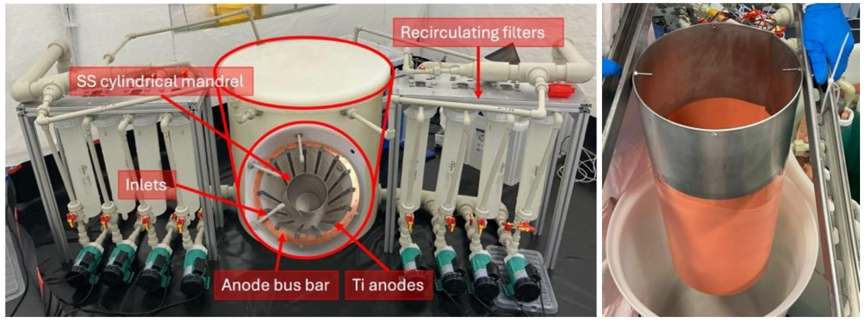
SPC concept: Variable target
Low E_{th}, Low mass sensitivity

11-anode sensor



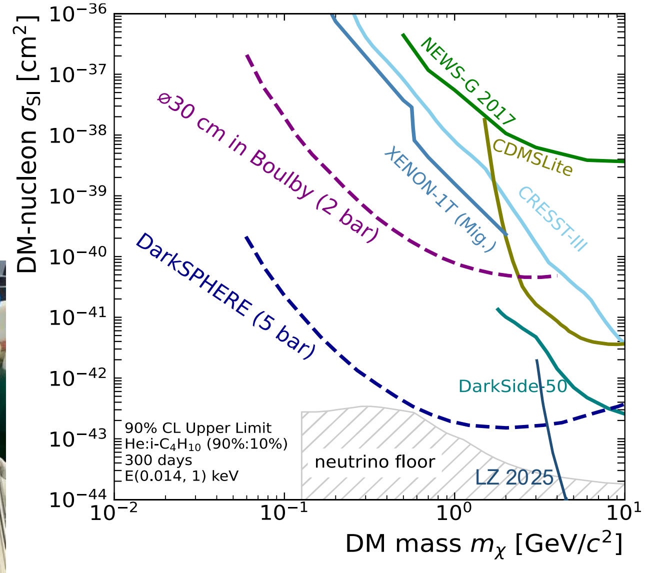
Proposed DarkSPHERE-3m

Al-S30 R&D Detector



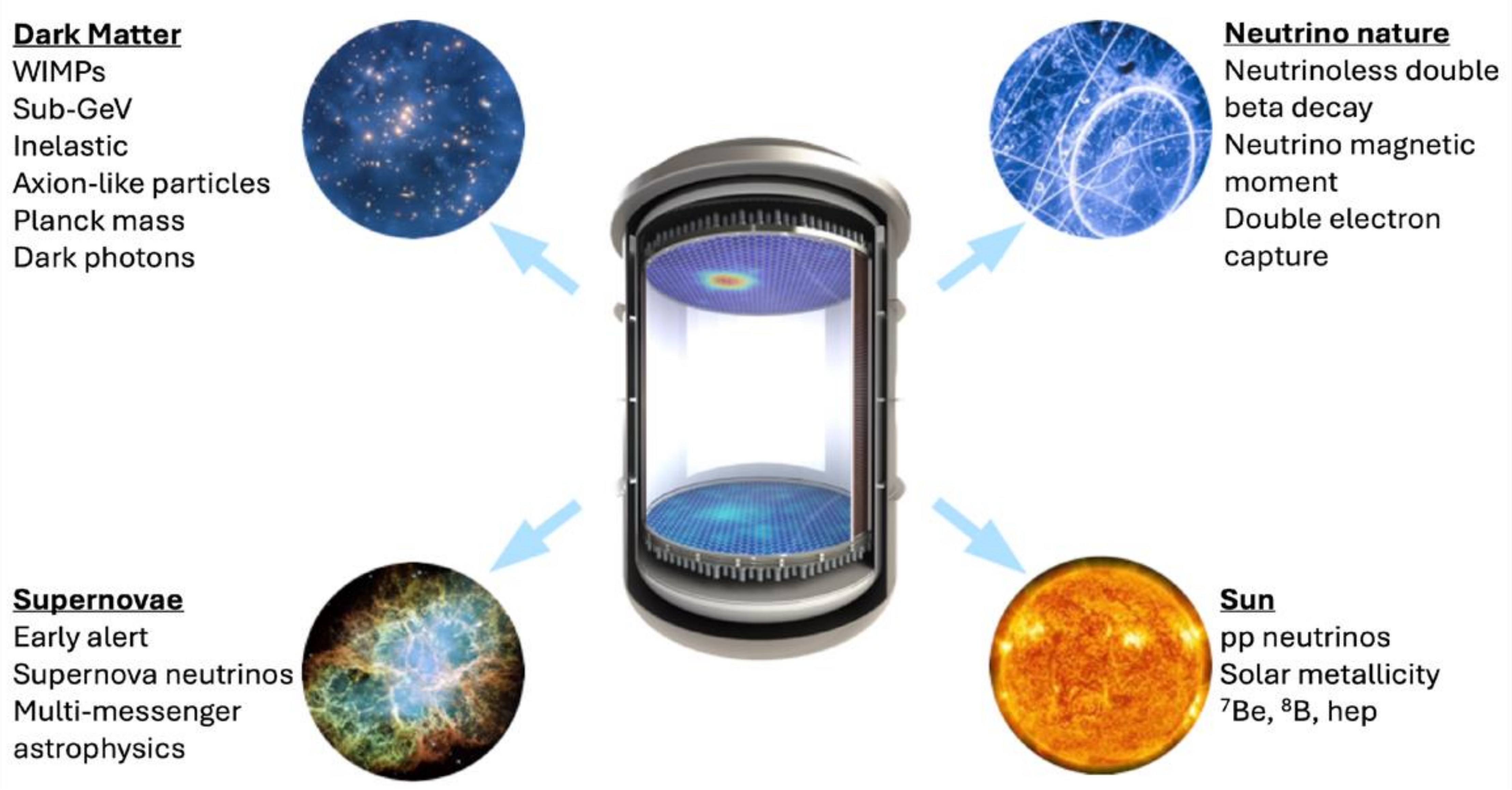
Copper electroforming at Boulby

SPC Sensitivities



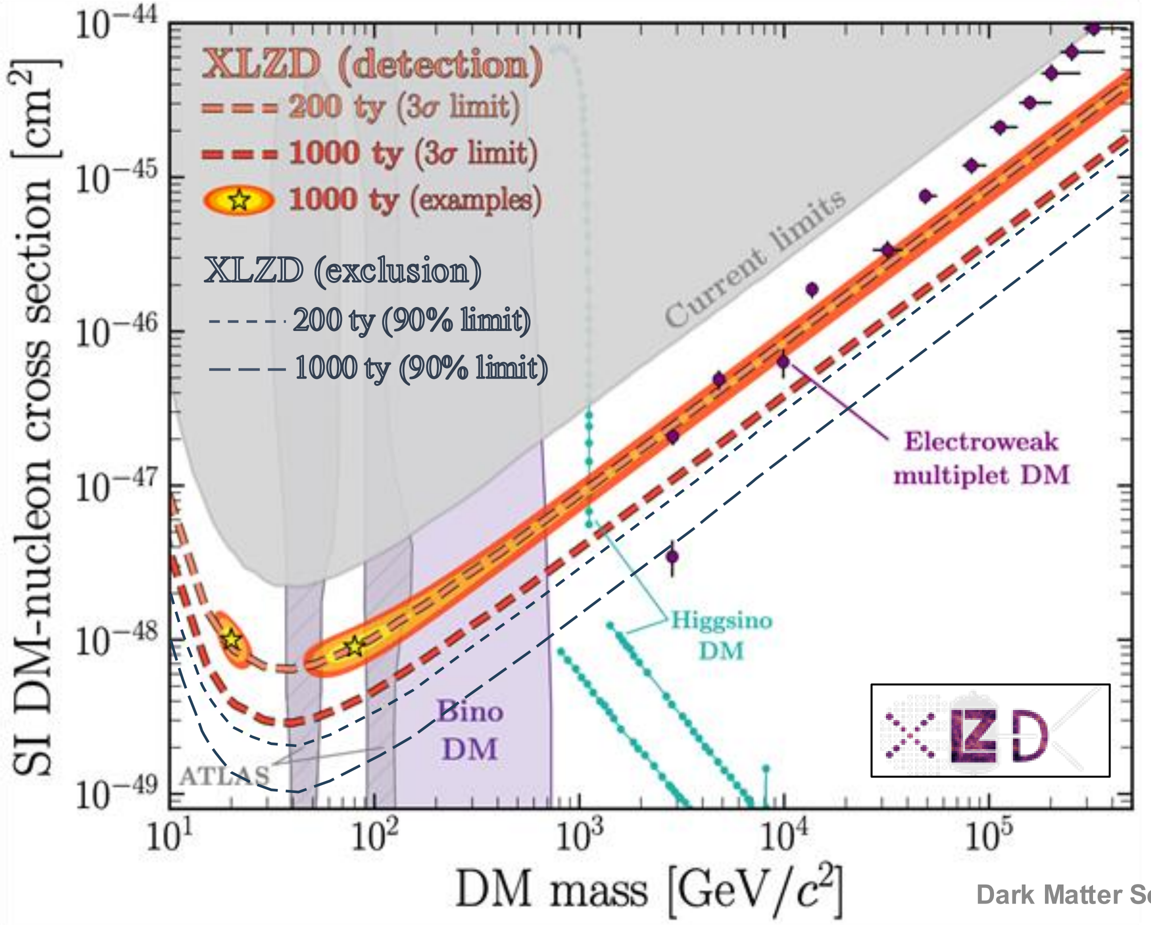
UKRI Science and Technology Facilities Council
Boulby Underground Laboratory

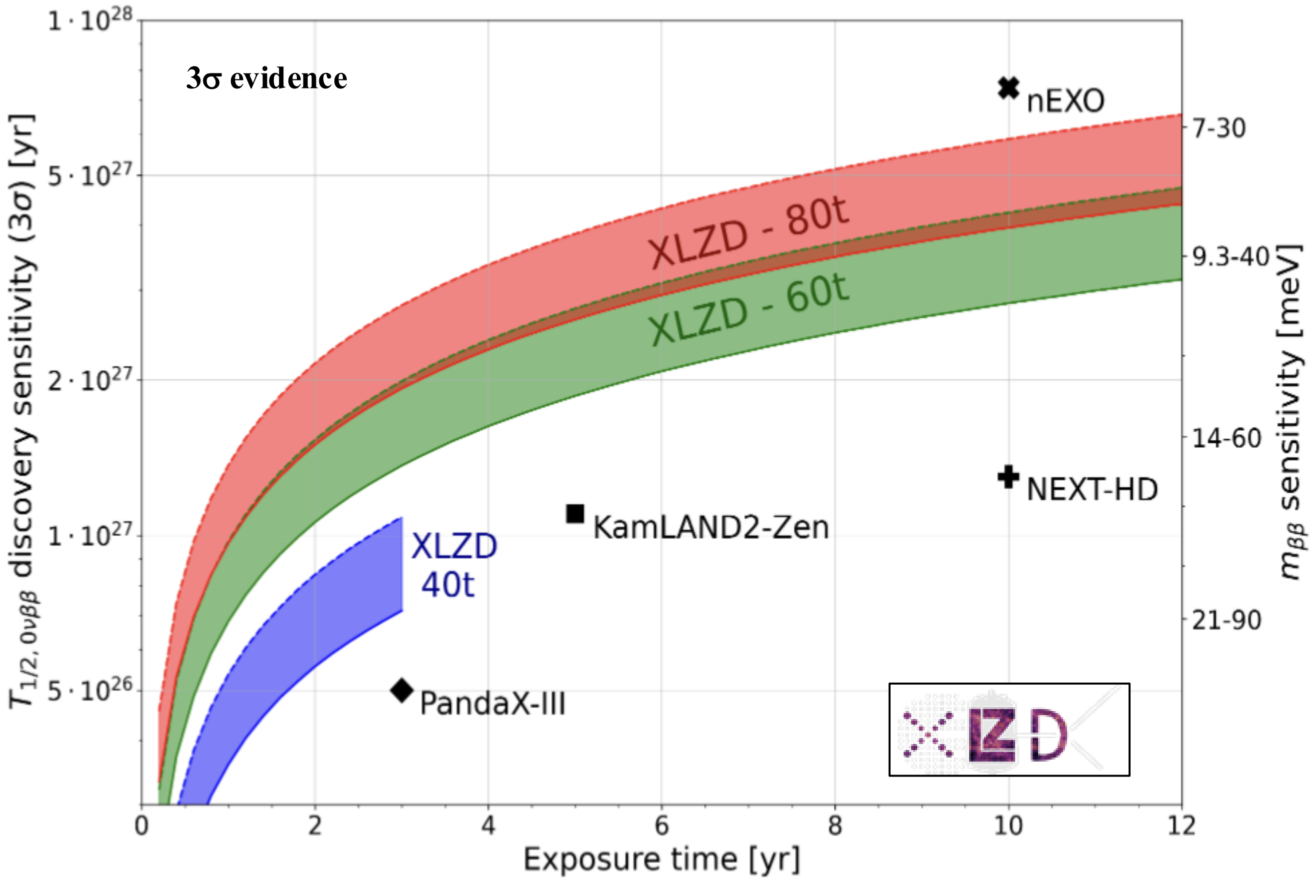
XLZD Rare Event Observatory



XLZD Rare Event Observatory

- Next generation experiment using proven LXe technology
  - Baseline 60 tonnes active mass, with capability for expansion to 80 tonnes
- Will be the definitive WIMP search experiment, capable of discovering wide range of DM signals, delivering world's best sensitivity to $0\nu\beta\beta$ in ^{136}Xe and much more!



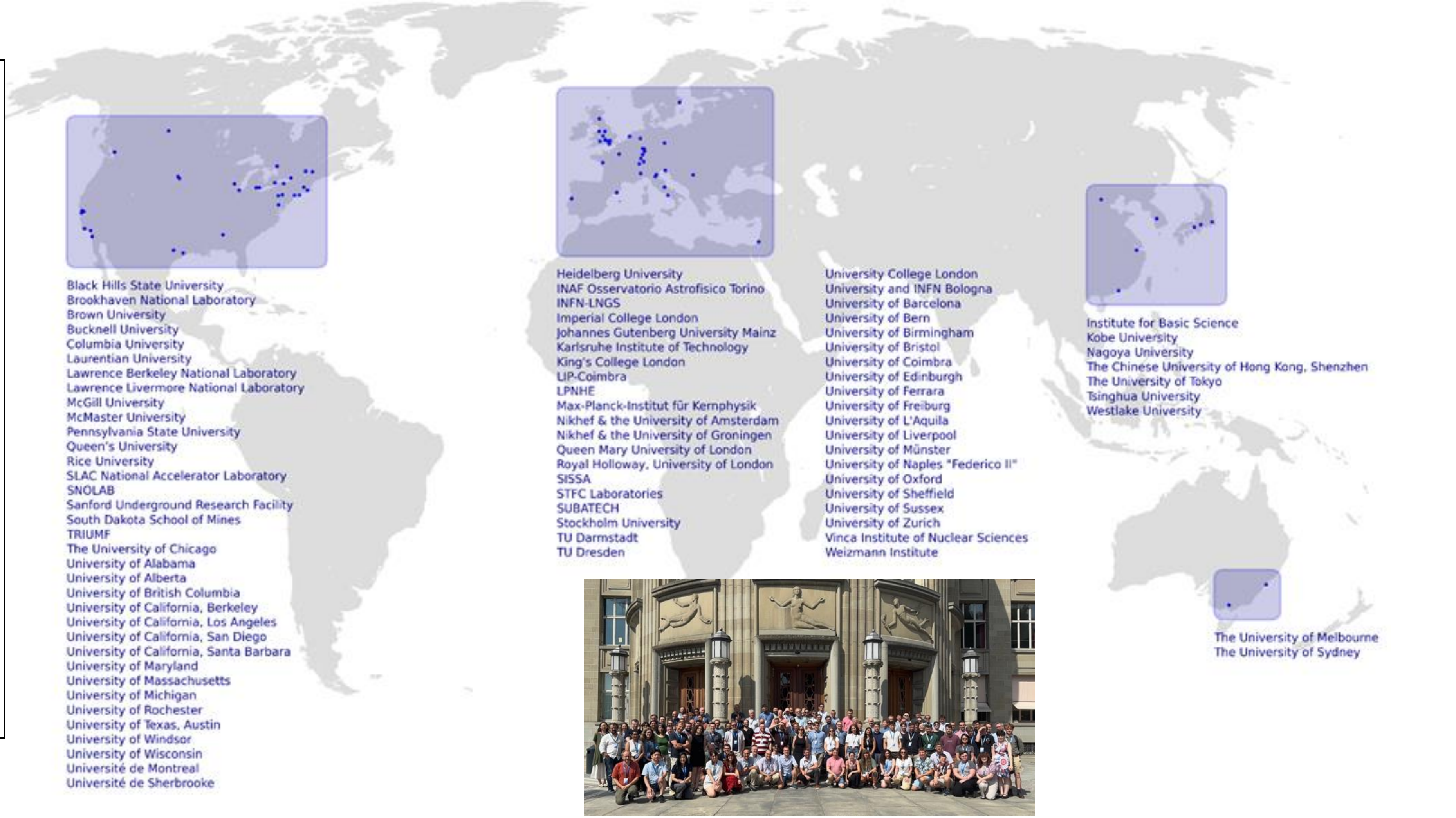


XLZD Collaboration

- International collaboration of >500 members from 84 institutes in 18 countries. Merger of experienced XENON-nT, LZ, DARWIN and (new!) Canadian + ex-nEXO teams. UK physicist is now co-spokesperson.

13 UK institutes (2nd largest national team)

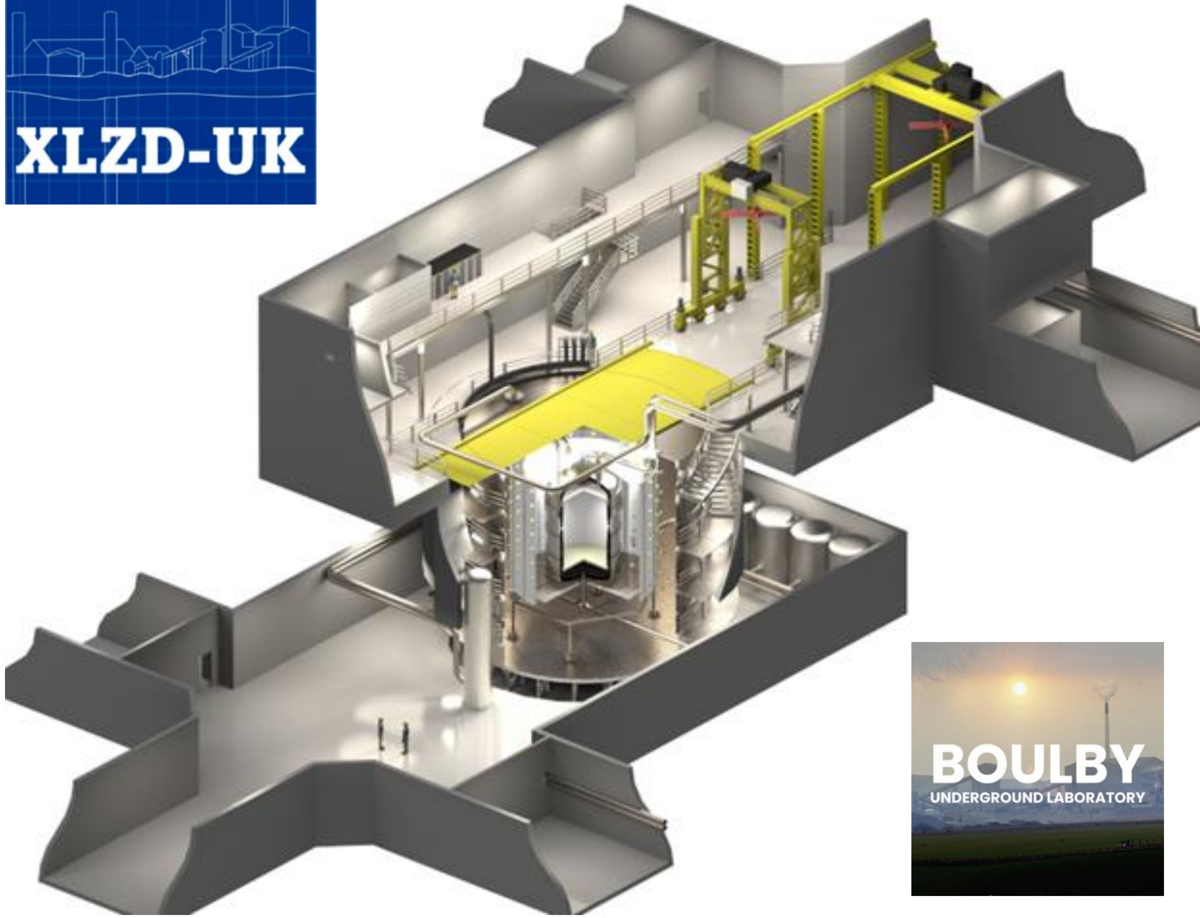
- Imperial College London
- King's College London
- Queen Mary University of London
- Royal Holloway University of London
- STFC Laboratories
- University College London
- University of Birmingham
- University of Bristol
- University of Edinburgh
- University of Liverpool
- University of Oxford
- University of Sheffield
- University of Sussex



XLZD@Boulby

- Boulby is currently the front-runner to host
- Relies on the STFC-funded Boulby Development Project to provide a bespoke laboratory space for construction (Stage 1), and to host the experiment (Stage 2)
- Strong support from STFC and UKRI
  - Pre-construction project funded under Wave 4 of the UKRI IF (July 24 – Dec 27)
  - Eight work-packages including outer detector, cryostat and xenon detector, as well as xenon supply, computing, cleanliness & backgrounds, engineering & skills, sustainability (XLZD will be net-zero in operation)
  - Aiming for full project under UKRI IF Wave 5, or direct funding from HMT/DSIT
  - Construction (6 years) could start in 2028, operations in 2035, 200 tonne-years by 2040.
  - Up to 2 years bridging required – announced last week by STFC, but level unknown
- Once-in-a-generation opportunity to host a world-leading fundamental physics experiment in the UK

XLZD-UK



BOULBY UNDERGROUND LABORATORY

"…the UK will continue to review the possibility to host a new international research facility as part of the global effort to drive innovation through international collaboration in science and technology." Lord Vallance, G7 Ministerial, Bologna, July 2024

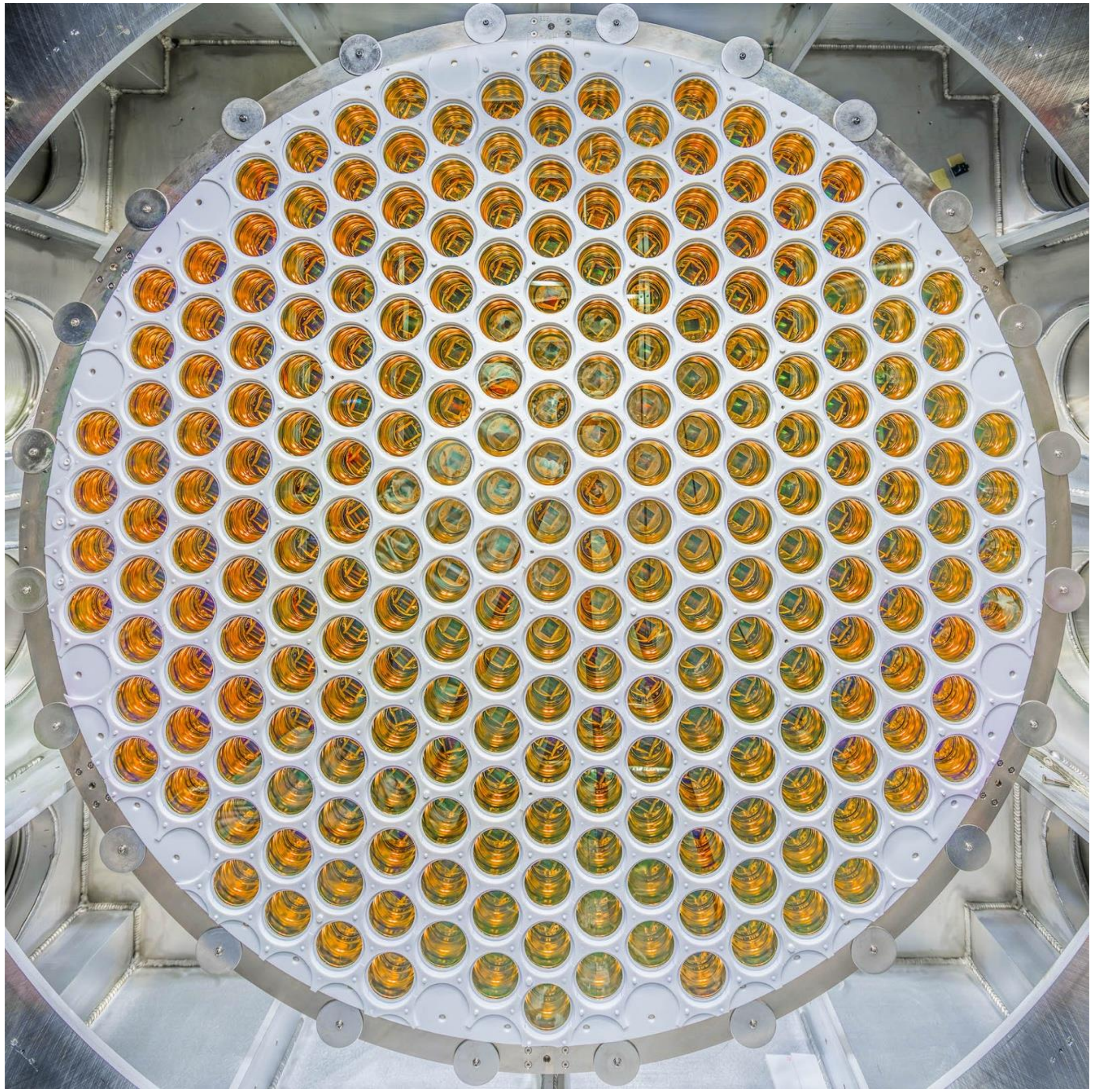
XLZD Socio-Economic Case

- XLZD@Boulby is one of very few PPAN projects that can deliver on priorities set out in recent UKRI and UK government strategy documents:
  - **Growth Agenda:** partnership with regional industry to deliver economic impact, high value manufacturing innovation and high quality STEM sector jobs in Advanced Manufacturing, Clean Energy, Digital and other IS8 sectors
  - **Skills Agenda:** partnership with local schools, colleges and universities to recruit and train apprentices equipped with cutting edge technical skills that will support and grow businesses across the region
    - *"The UK has a lack of technical skills – such as in electrical, mechanical and welding trades, key to the advanced manufacturing and clean energy industries …"* [The UK's Modern Industrial Strategy]
  - **Place Agenda:** investment in high value manufacturing and skills in a UK region currently under-supported by UKRI
    - *"The UK has world-leading clusters across the country, including:… advanced manufacturing in … the North East… The industrial strategy will … overcome place-based barriers in key clusters and enhance their attractiveness as destinations for private investment."* [The UK's Modern Industrial Strategy]
- These considerations are not optional extras for XLZD, or indeed for any other future large project. Without them, projects will be increasingly hard to justify.
- The UK particle physics community must not lose this rare opportunity for attracting inward investment from new government sources and overseas FA's

UKRI Mission Statement:
Advance knowledge, improve lives, drive growth

Final Words

- The UK was a pioneer of direct dark matter searches in the early 1990’s at Boulby Underground Laboratory
- These experiments have already excluded many well motivated BSM models, and could soon make (several!) revolutionary discoveries
- The UK is a world-leader in this field, and has the opportunity to host a definitive experiment in North Yorkshire and the North-East
- XLZD exploits a unique alignment of arguments based on scientific, economic, and social impact
- This project will only happen if we can demonstrate strong and widespread community support. This is an opportunity to bring new money into the field - this is not a zero-sum game.

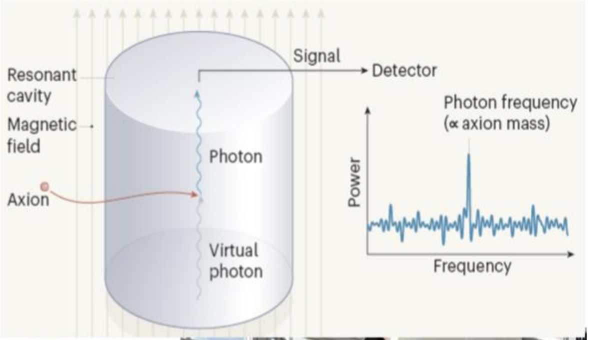


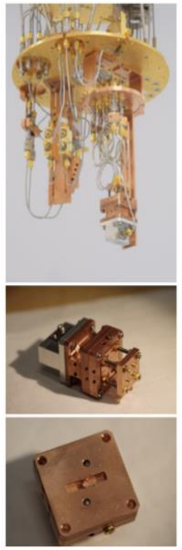
Backup

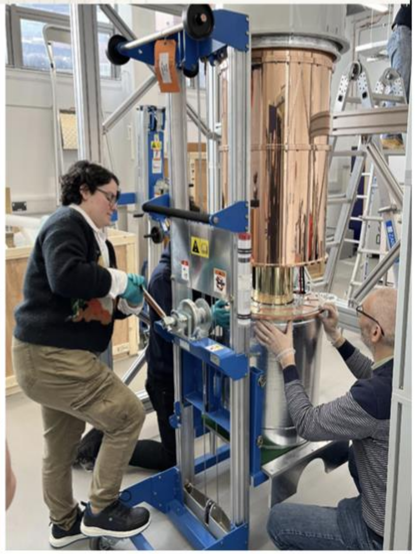
QTFP

- **QSHS** is working on quantum enhanced scanning of the QCD axion parameter space, MOU with ADMX
- **AION** has access to scalar dark matter, and gravitational waves in its larger incarnations, MOU with MAGIS
- Many other projects are also exploring the dark sector

Quantum Sensors for the Hidden Sector

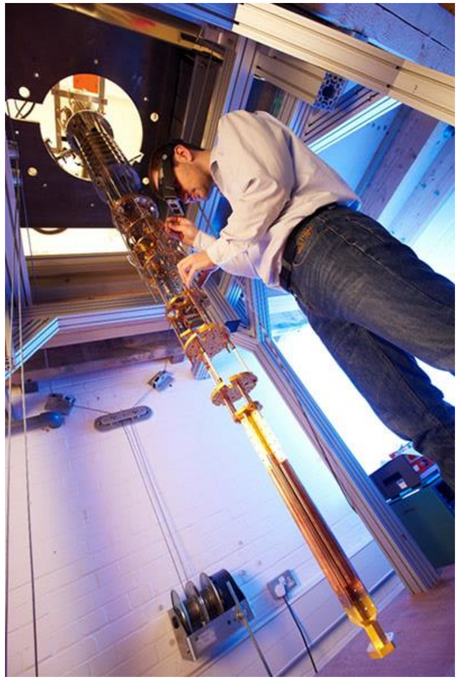


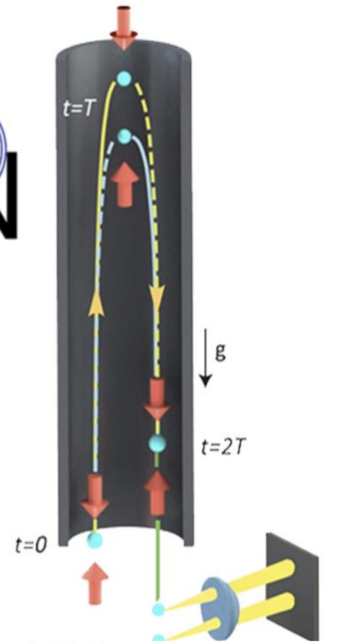


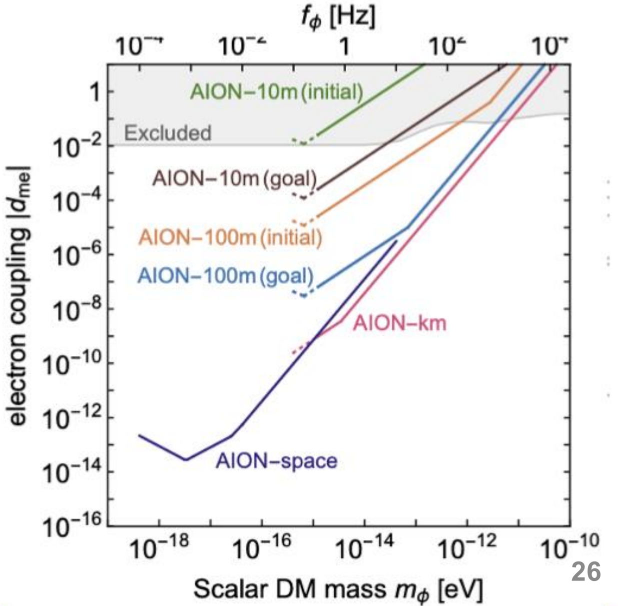


A quantum jump sensor for dark matter detection
Institution: Imperial College London
Principal investigator: J. Devlin

- Development of levitated quantum optomechanical sensors for dark matter detection
Institution: UCL
Principal investigator: P. Barker

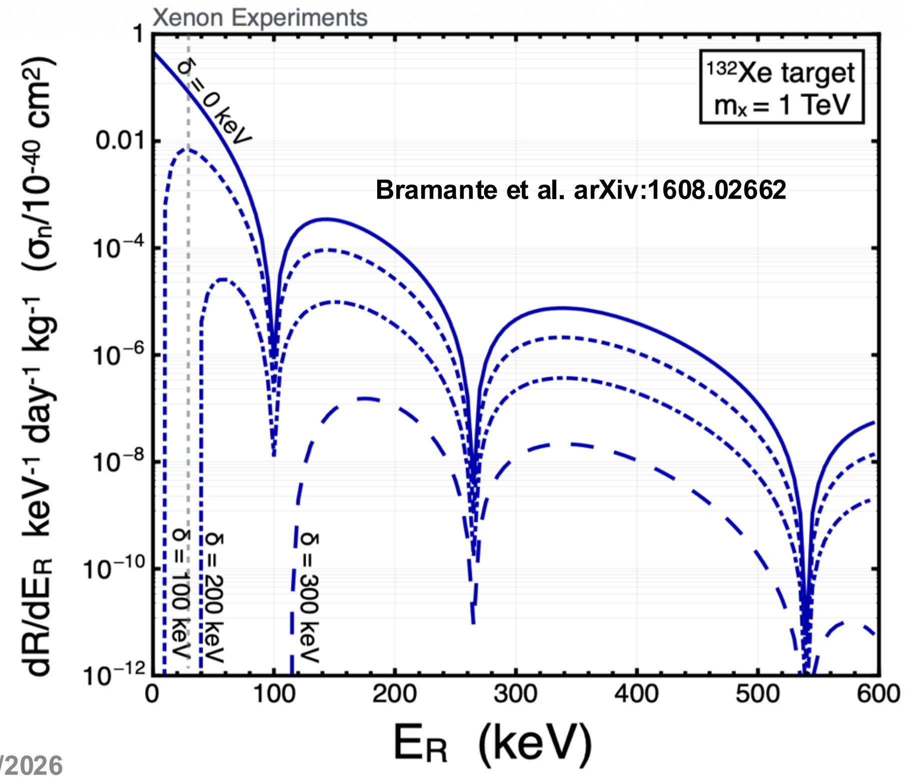


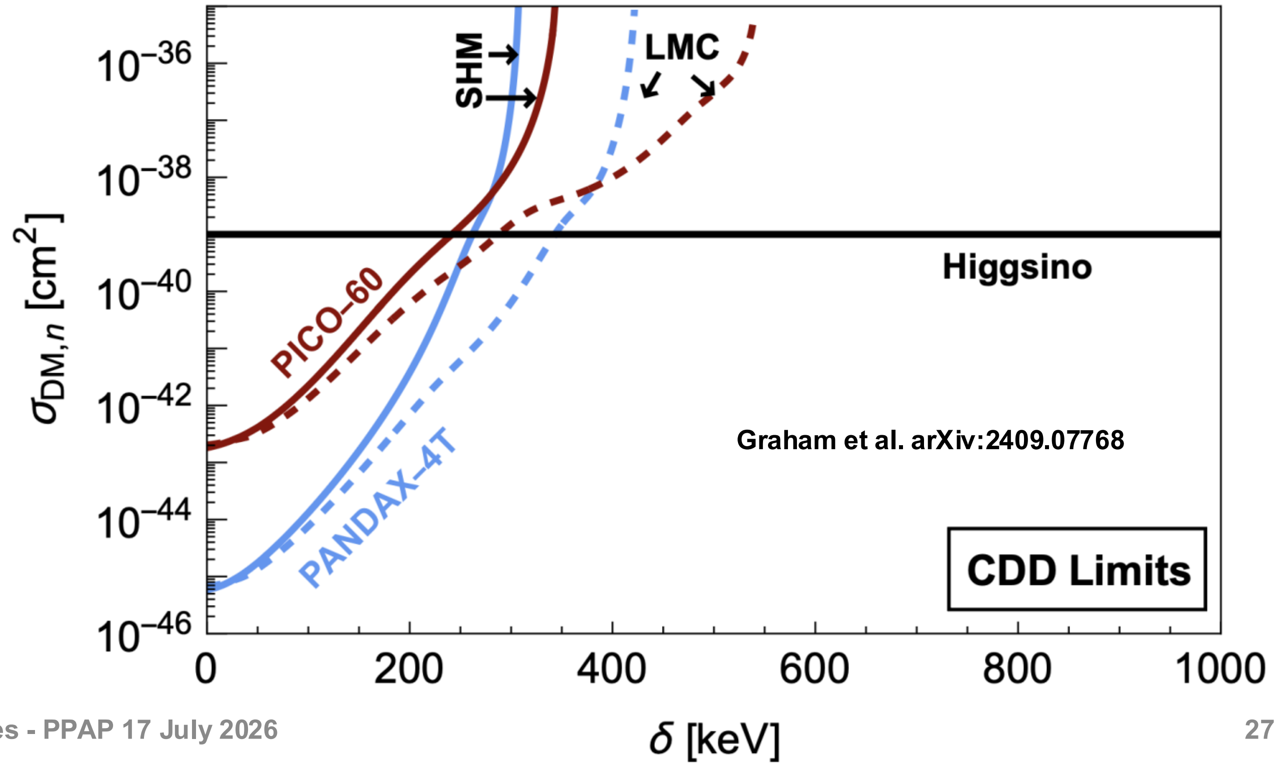




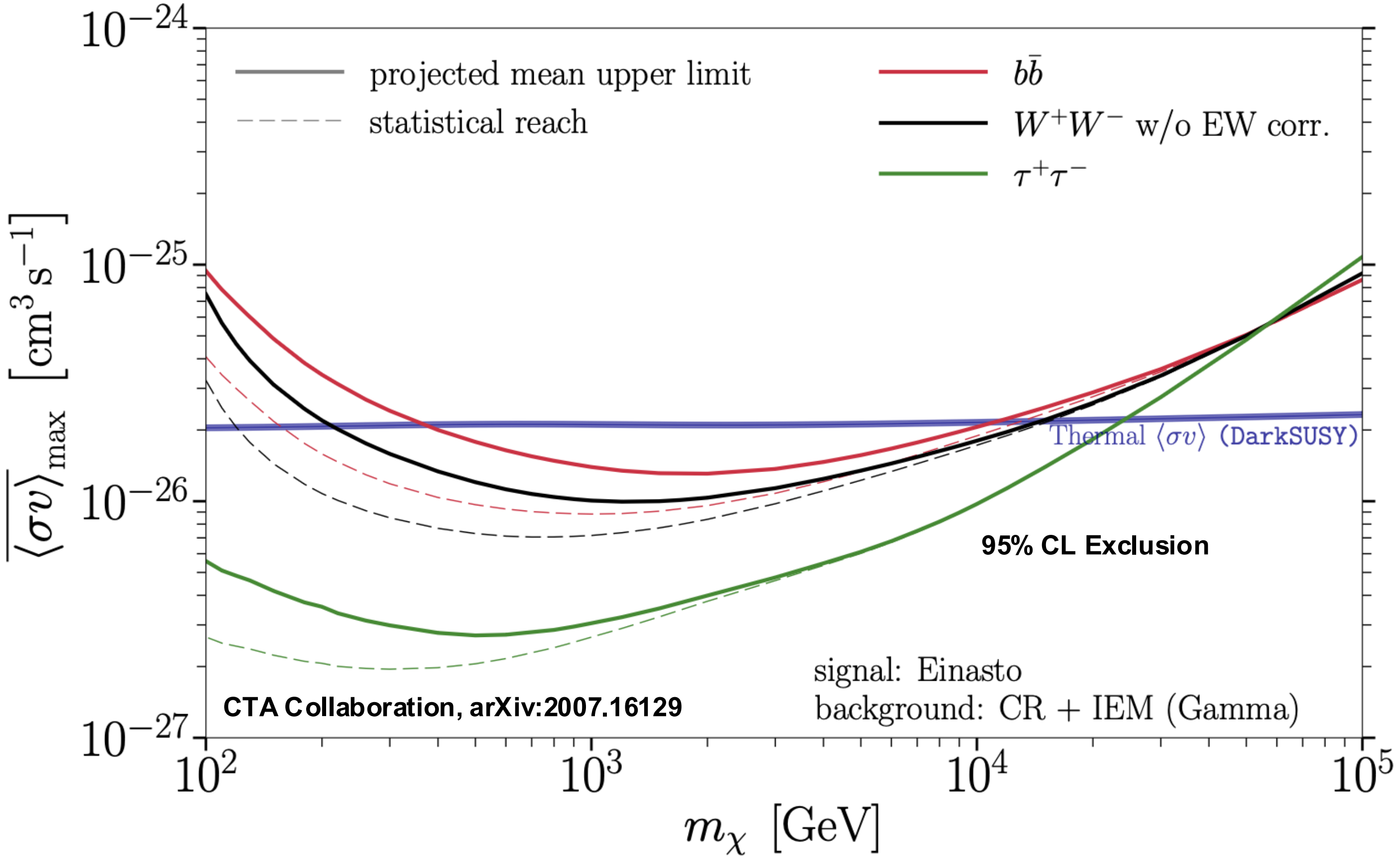
Inelastic Signatures

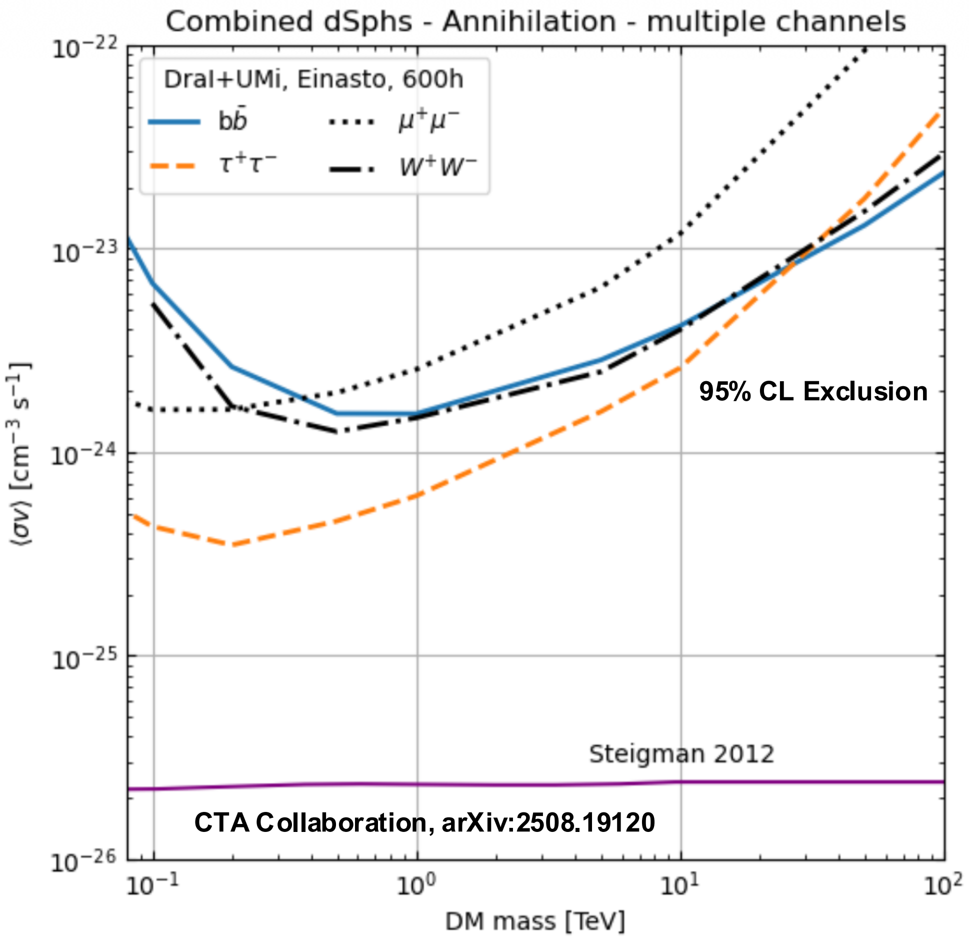
- More exotic signatures sensitive to particular models
- If additional close-by BSM states, kinetic energy of nuclear scattering could up-convert into higher mass state → Inelastic scattering
  - Imposes minimum energy threshold → high energy events
  - Requires large cross-section to be visible
- Gives sensitivity to pure higgsino models through spin-independent Z^0 exchange





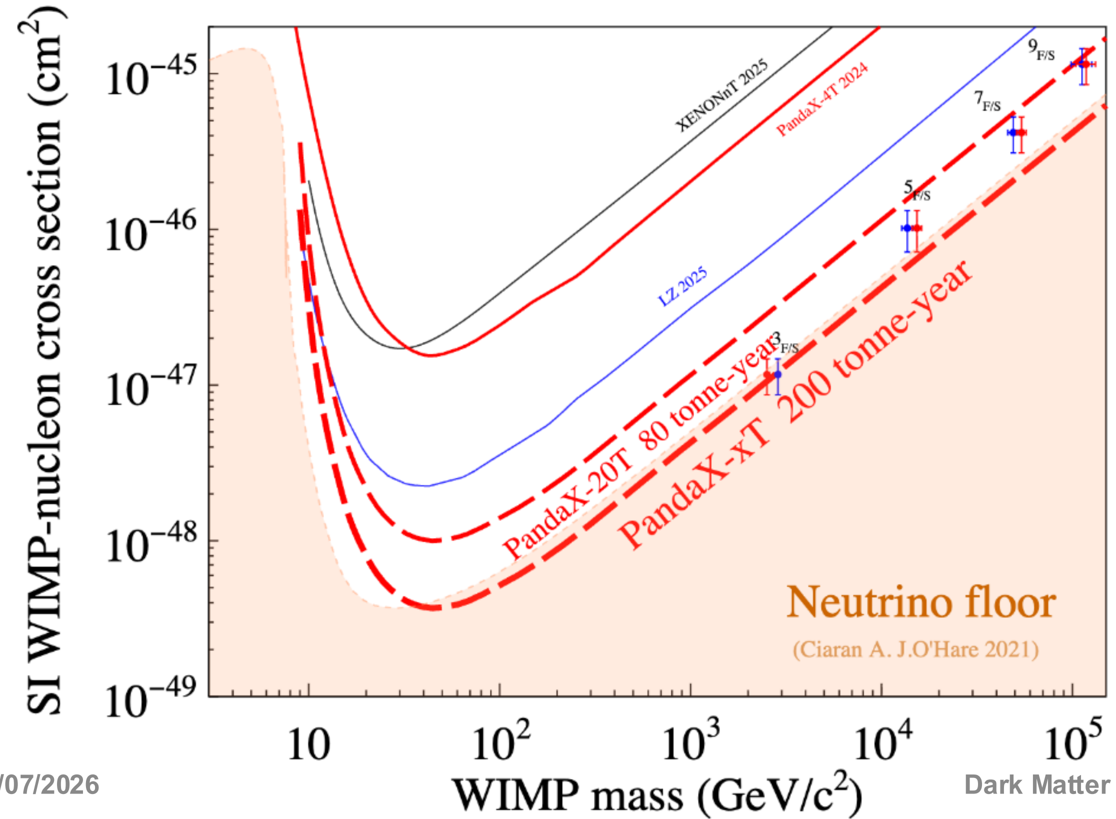
Indirect Searches with Gamma Rays

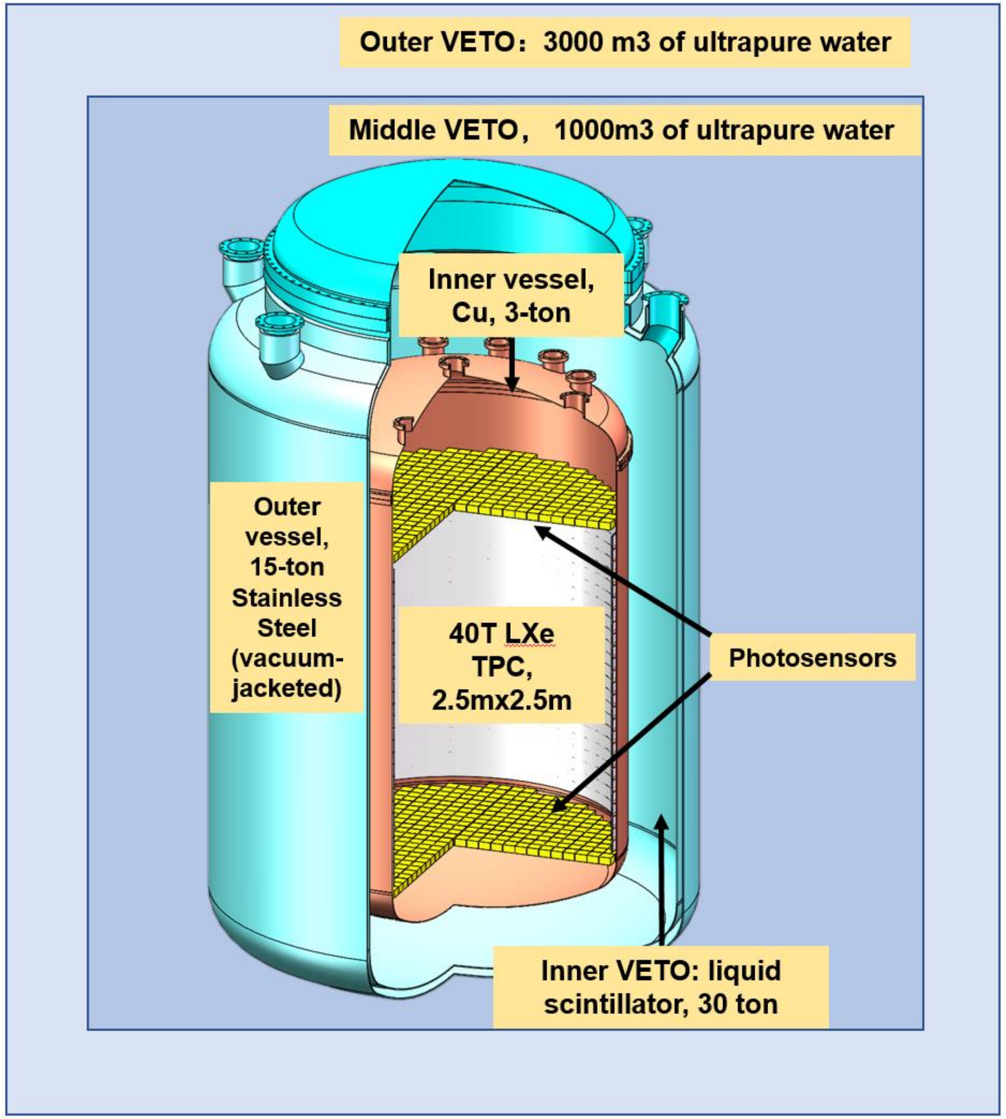




PandaX

- 2026.4-6 PandaX-4T decommissioning
- 2026.6-12 PandaX-20T infrastructure construction
- 2027.1-2027.6 PandaX-20T installation
- 2027.7-2027.12 PandaX-20T commissioning
- 2028.1- Physics operation

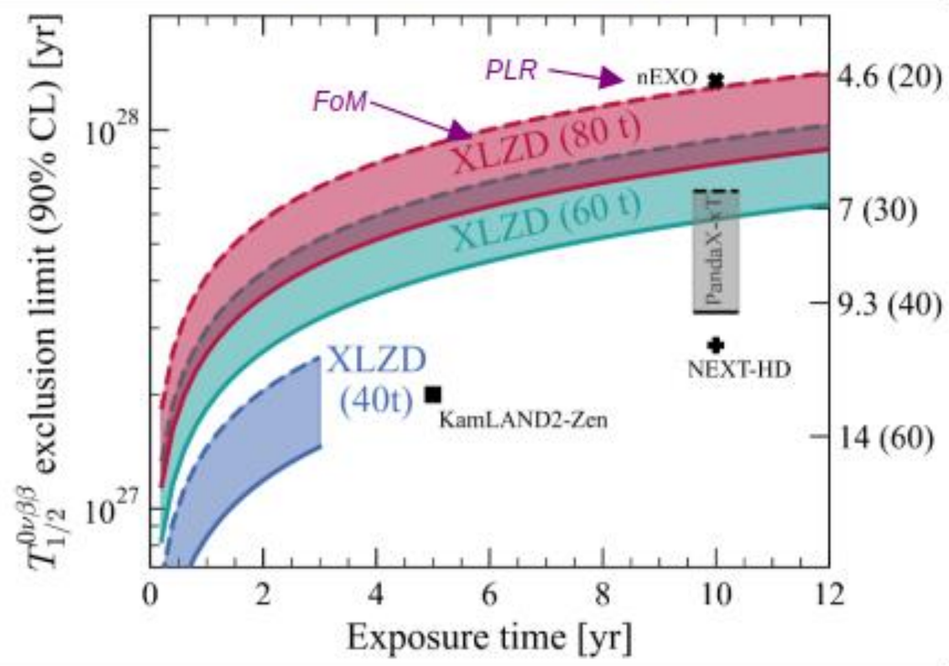




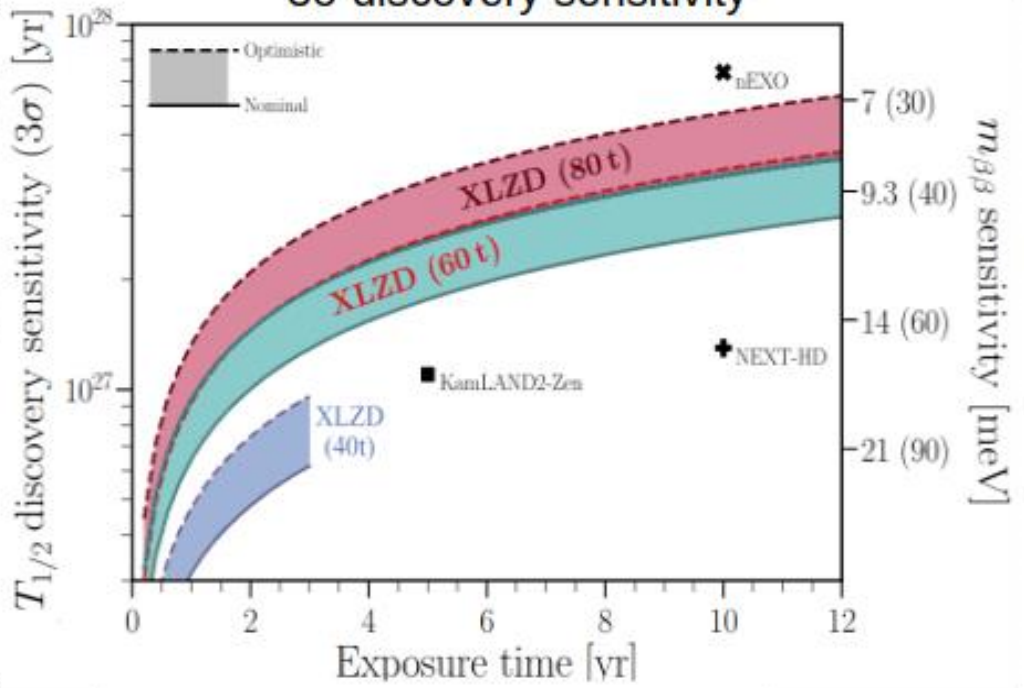
XLZD Double Beta Decay

J. Phys. G 52, 045102 (2025)

Exclusion sensitivity



3σ discovery sensitivity



- Sensitivity via **Figure-of-Merit estimator**
  Agostini et al., PRD 96, 053001 (2017)
- **3 target masses, 2 background scenarios**
  → optimized fiducial targets
- Expect improved sensitivity with PLR study
  → 40% improvement in LZ study
  PRC 102, 014602 (2020)

Parameter	Scenario: Nominal	Scenario: Optimistic
^{222}Rn concentration [μBq/kg]	0.1	
BiPo tagging efficiency [%]	99.95	99.99
External γ-ray [% LZ]	25	10
Installation site	LNGS	SURF
Energy resolution [%]	0.65	0.60
SS/MS vert. separation [mm]	3	2