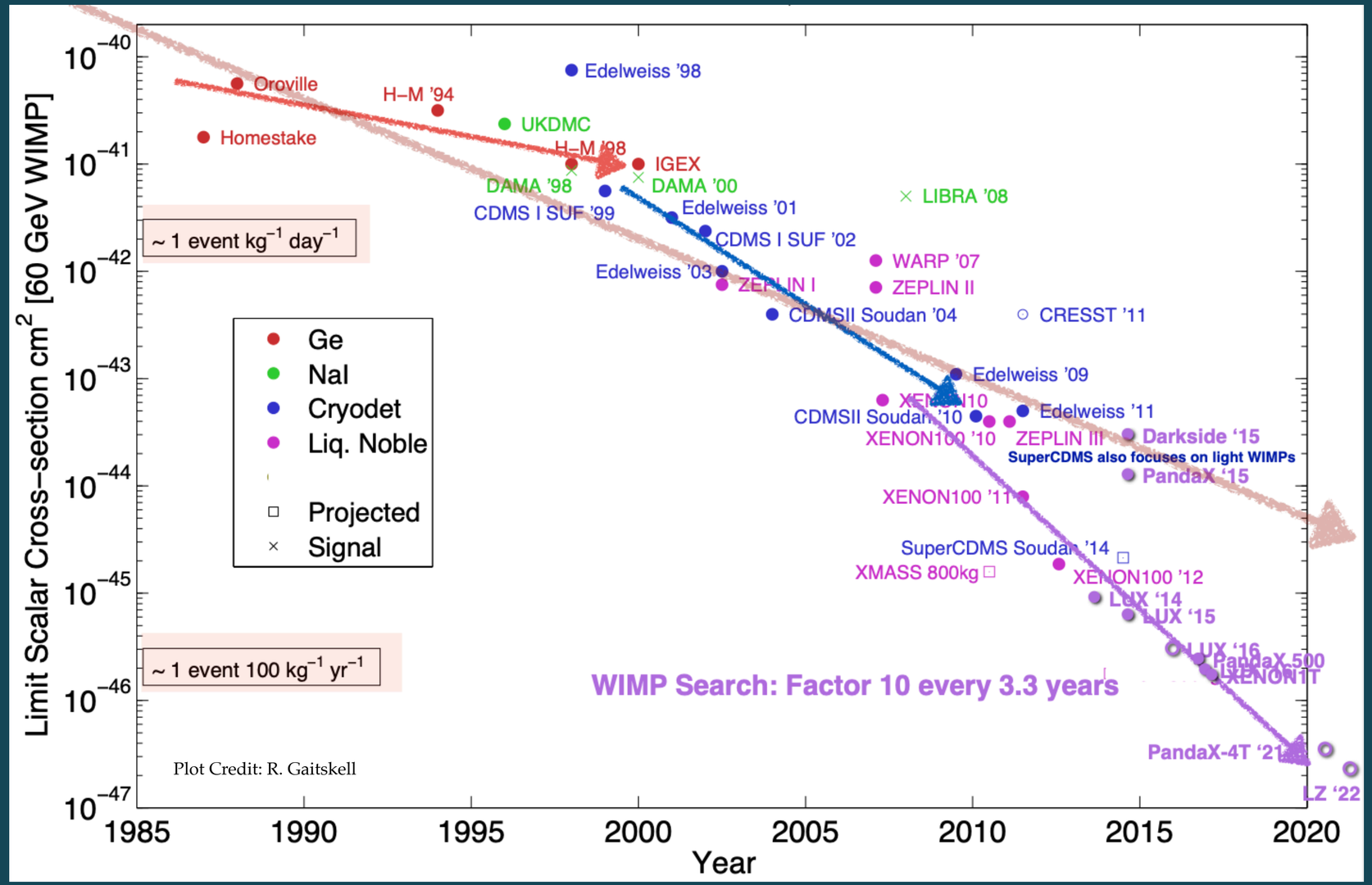
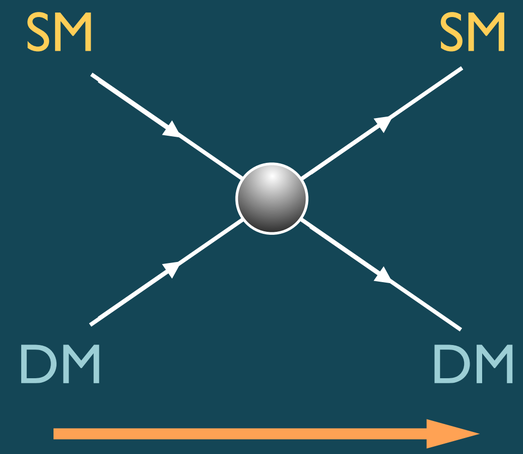
The LUX-ZEPLIN Experiment - New WIMP Search Results & Status

Amy Cottle, UCL

DM SEARCHES WITH XENON DETECTORS

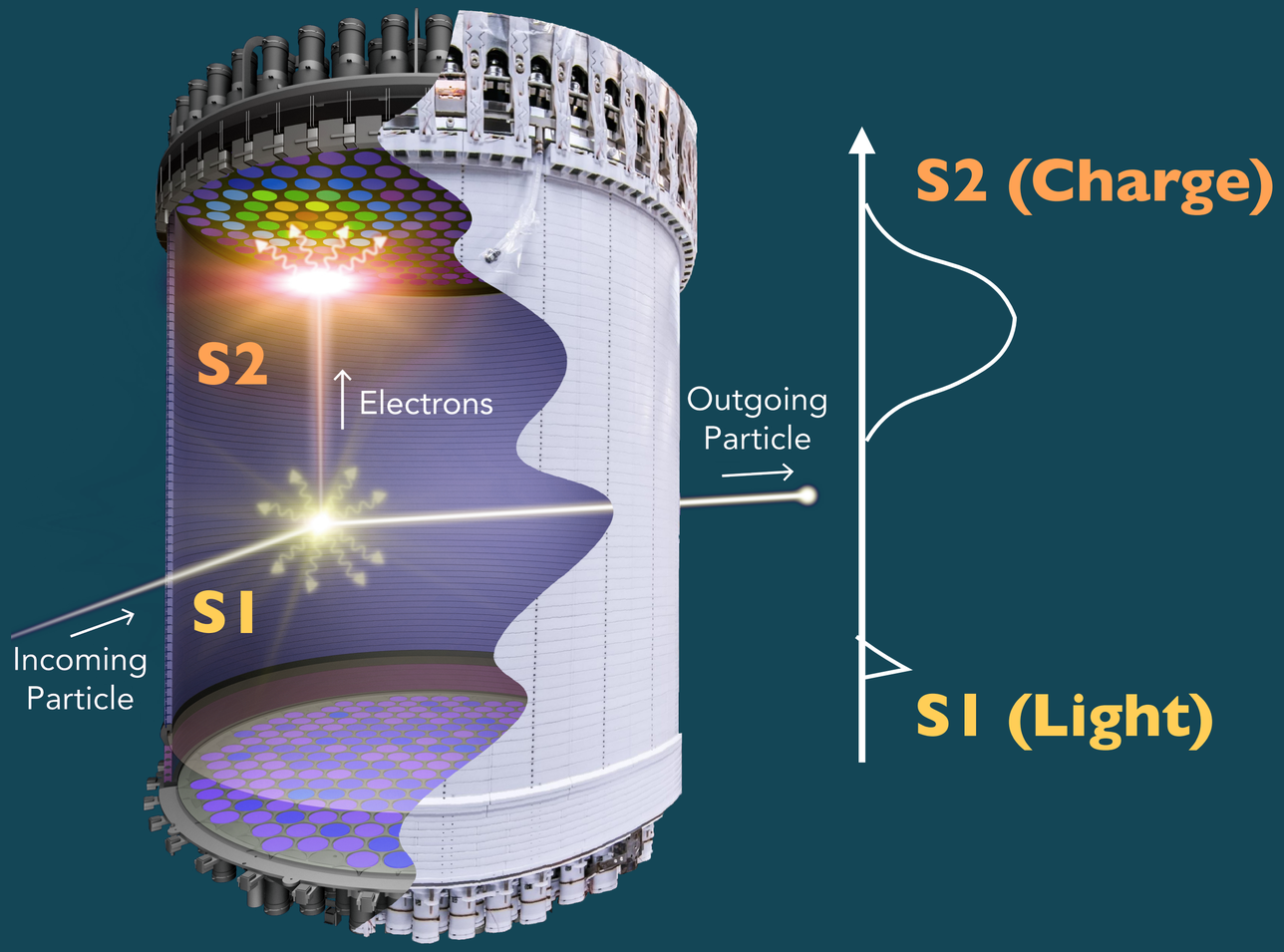


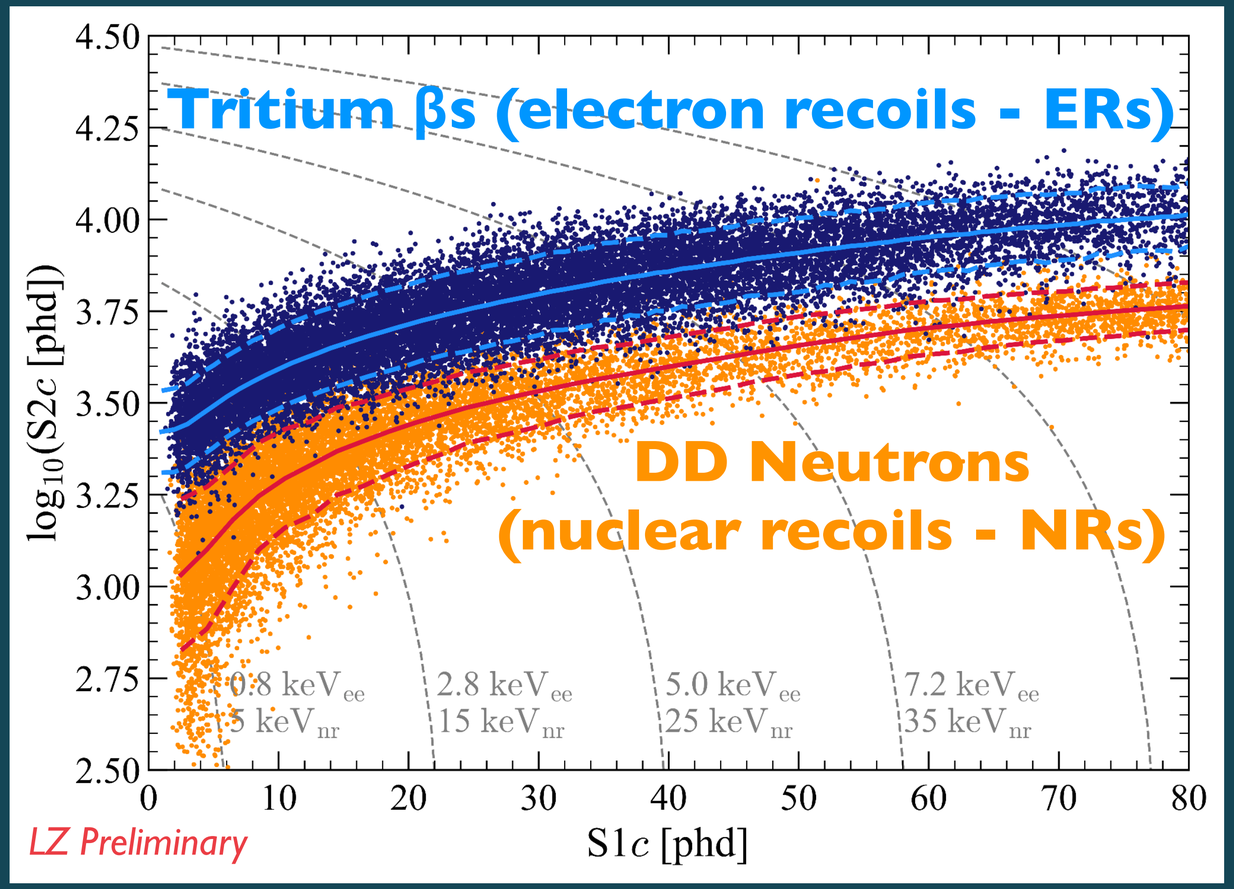
- Weakly Interacting Massive Particles (WIMPs)
  → key galactic DM candidate



- Direct detection via scatters with target nuclei
- Xe experiments driving sensitivity to WIMPs in last 15 years

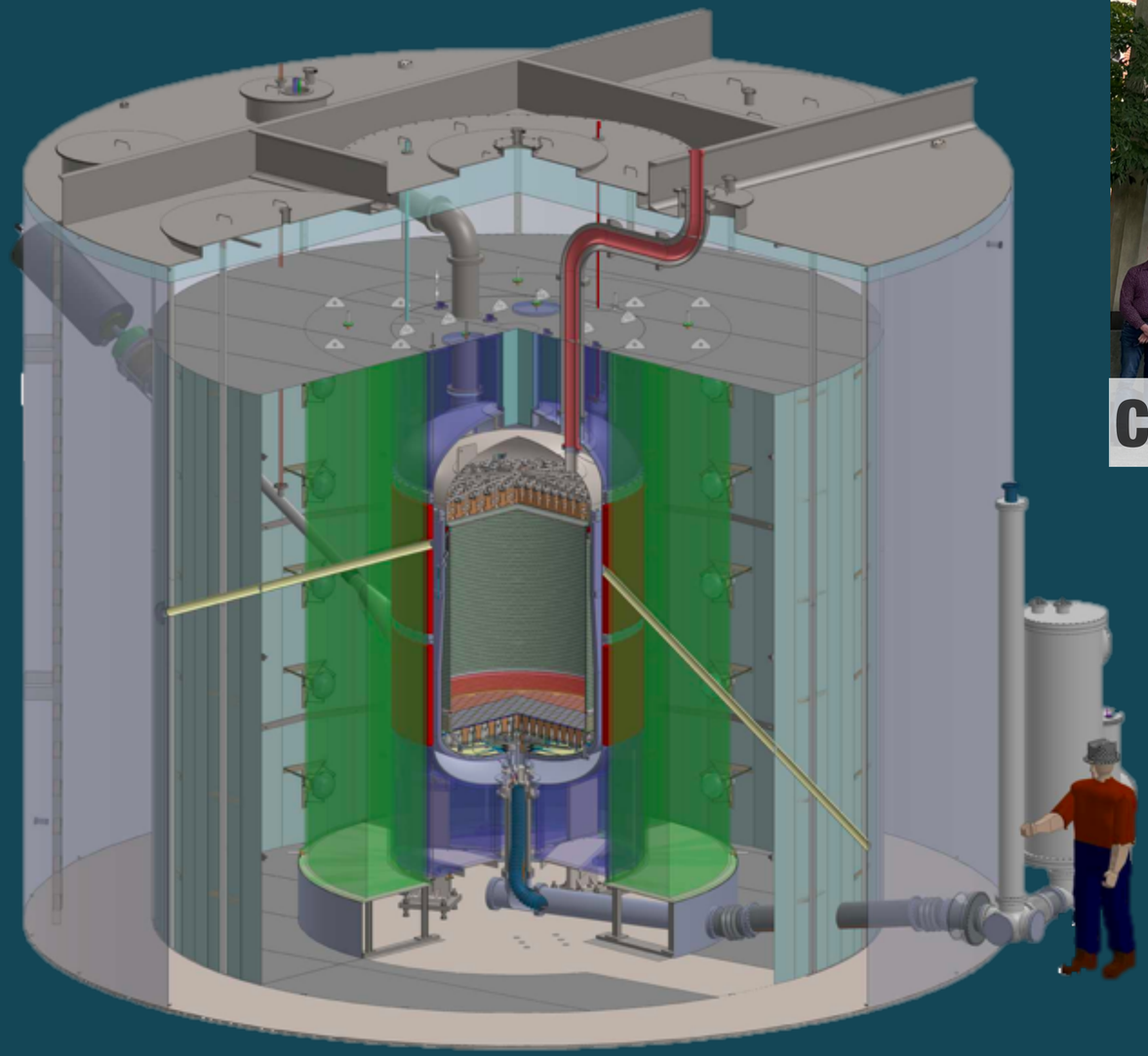
DUAL-PHASE TIME PROJECTION CHAMBER (TPC)





- Self-shielding xenon + excellent 3D position reconstruction (~mm) → BG-light fiducial volume
- S2:S1 ratio → discrimination between WIMP (NR) & β-particle or γ-ray (ER) events

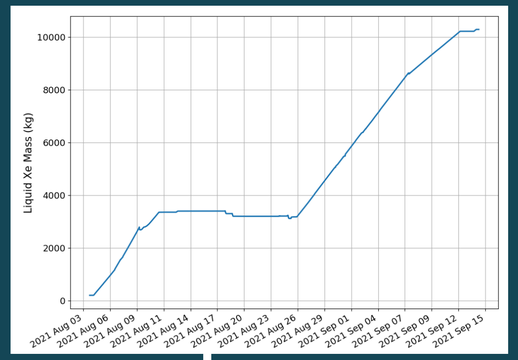
INTRO TO LZ



- Operating the world’s largest dual-phase xenon TPC (7 tonne active) + two active veto detectors
- Based in the Davis Cavern at the Sanford Underground Research Facility (SURF) in Lead, SD
- International collaboration with 38 institutes (10 UK) & ~250 collaborators (~50 UK)

LZ TIMELINE

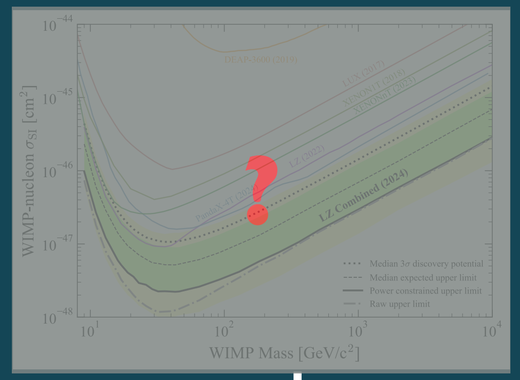
TPC Underground



Commissioning Begins

WS2024 Starts

New WIMP Search Results (WS2024+WS2022)



2020

2021

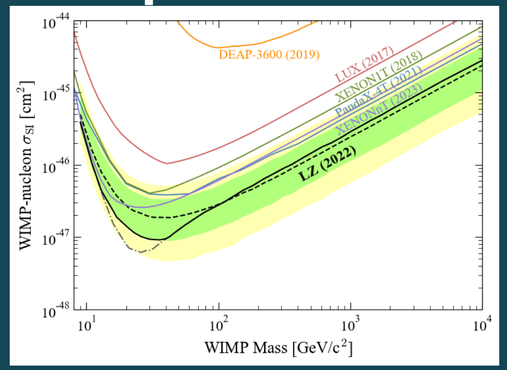
2022

2023

2024

Installation Complete

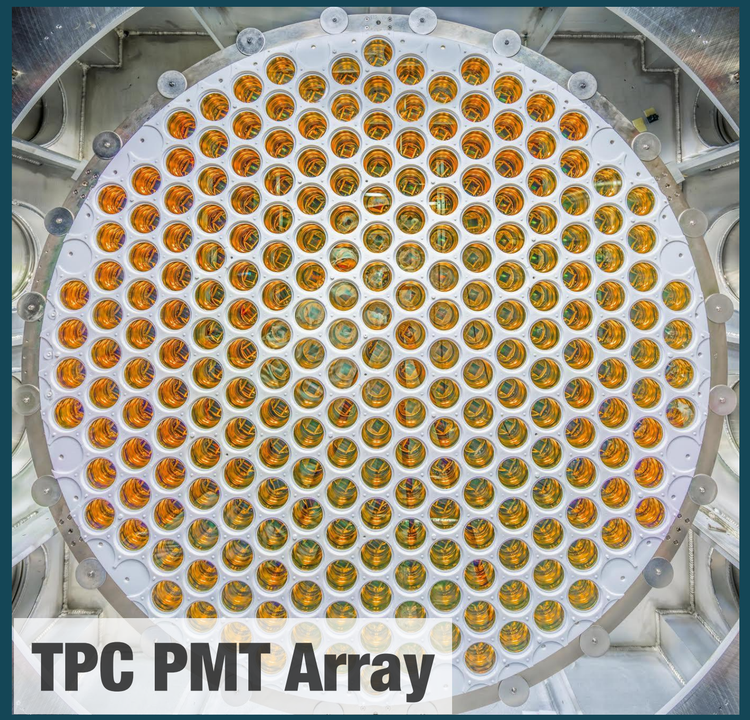
WS2022 Starts



First WIMP Search Results (WS2022)

UK EFFORT IN LZ CONSTRUCTION & OPERATIONS

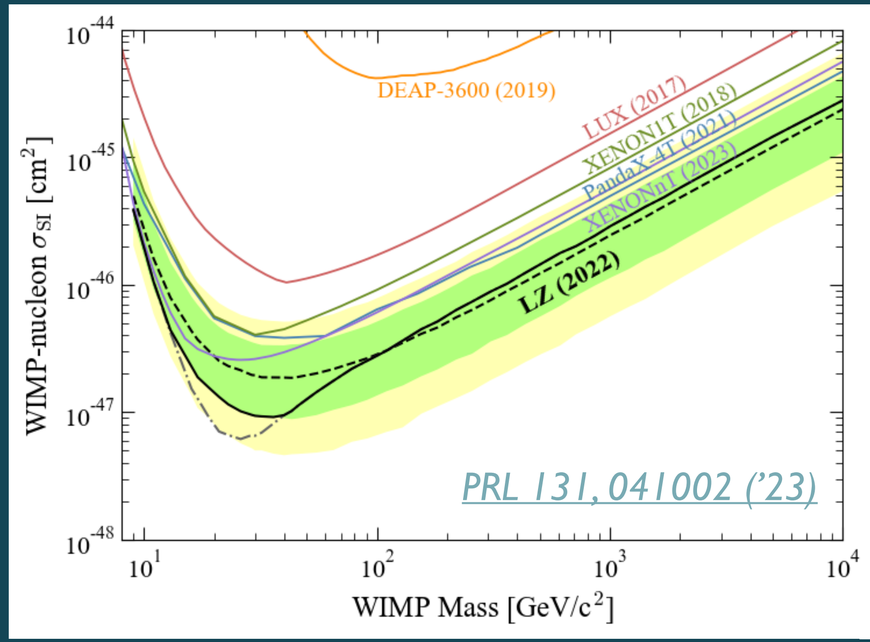

Cryostat Insertion

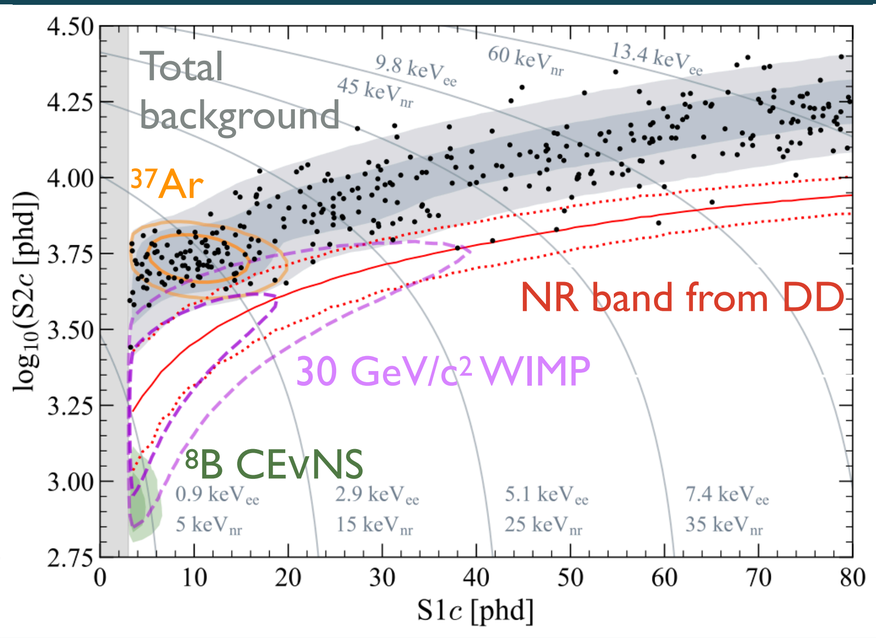

TPC PMT Array

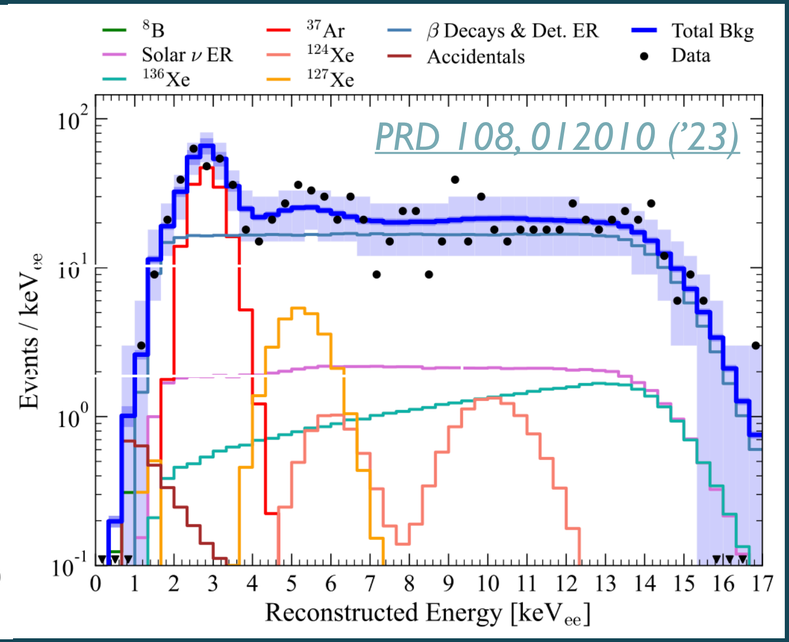

Cleanliness Inspection

- UK work package leaderships for cryostat, xenon detector, cleanliness/screening; key responsibilities for PMTs & sensors
- Significant support of remote/on-site operations (and now physics exploitation) via HEP CG mechanism, including student LTAs

RECAP OF LZ'S FIRST WIMP SEARCH



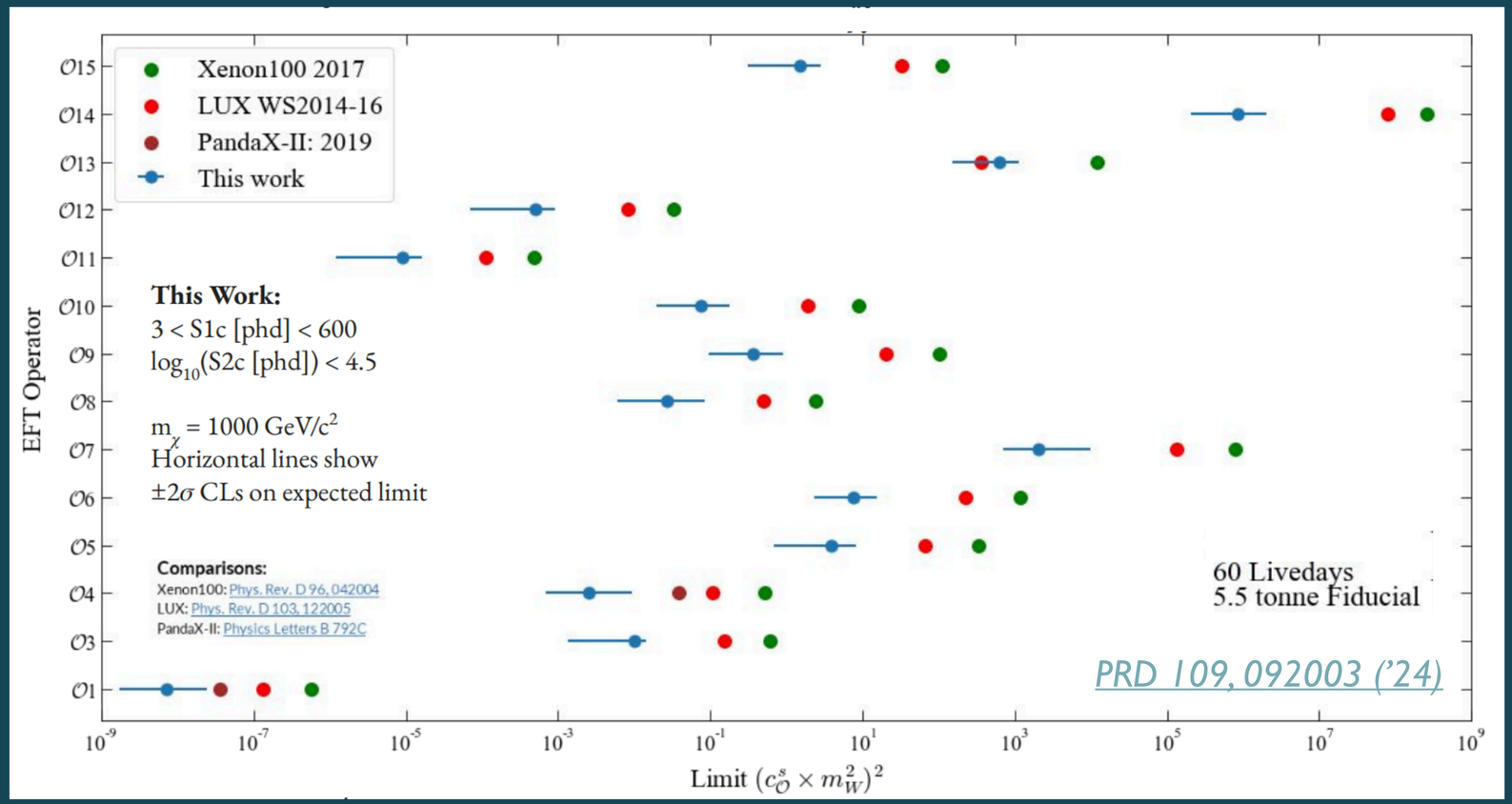




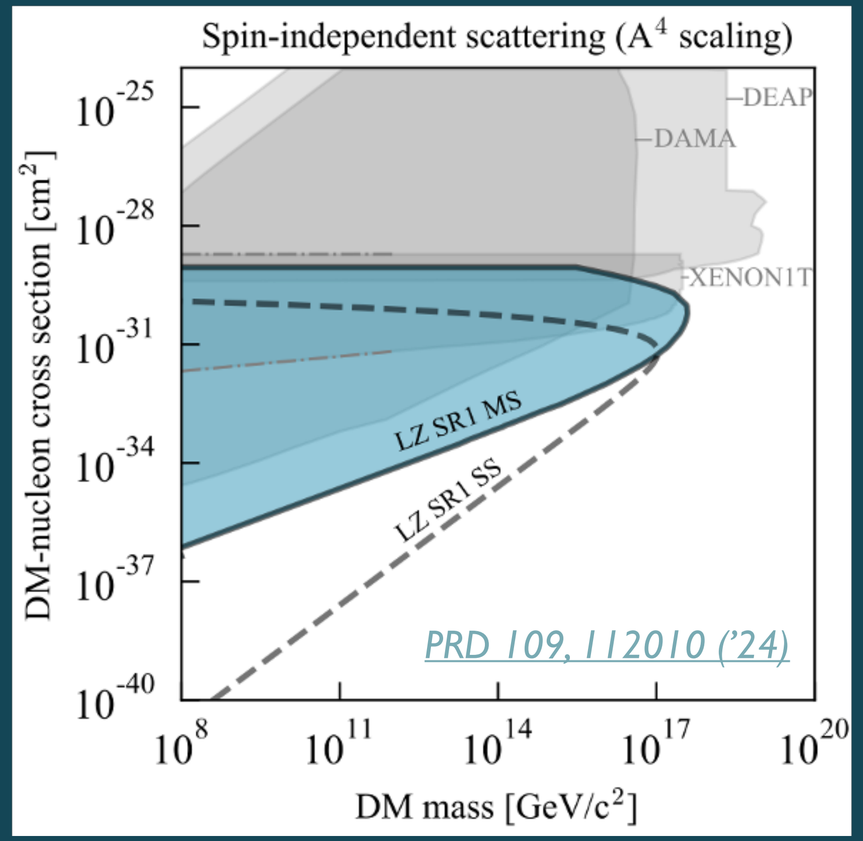
- World-leading limits with demonstration run (WS2022) of just 60 live days (0.9 tonne years) (Minimum cross-section of $\sigma_{SI} = 9.2 \times 10^{-48}$ cm^2 for WIMP mass of 36 GeV/c^2
- Backgrounds model delivered with UK leadership, extending beyond the WIMP ROI
  → enabling further BSM physics searches

MORE DARK MATTER RESULTS

Effective Field Theory Couplings



Ultra-heavy Dark Matter

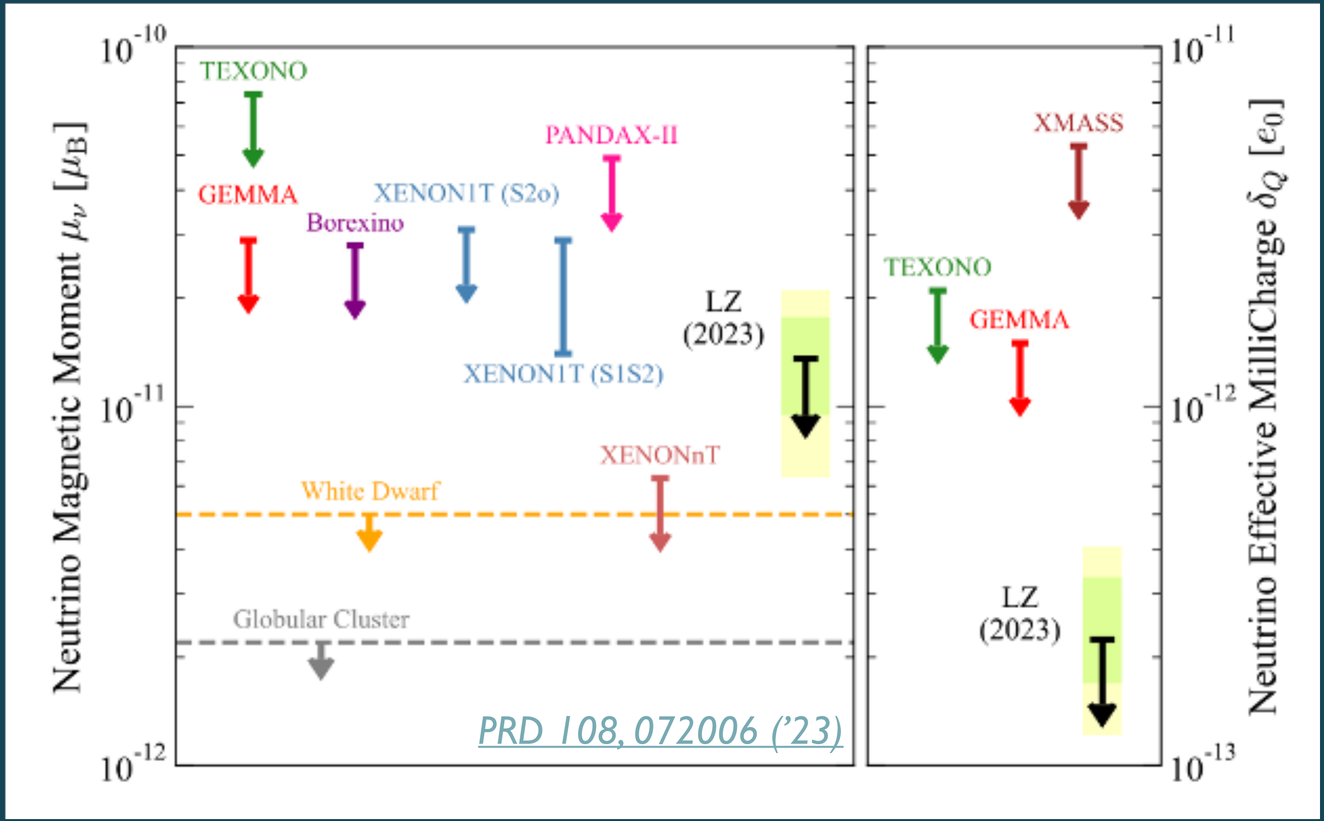


New world-leading constraints on several EFT operators; high-energy MIMP interactions

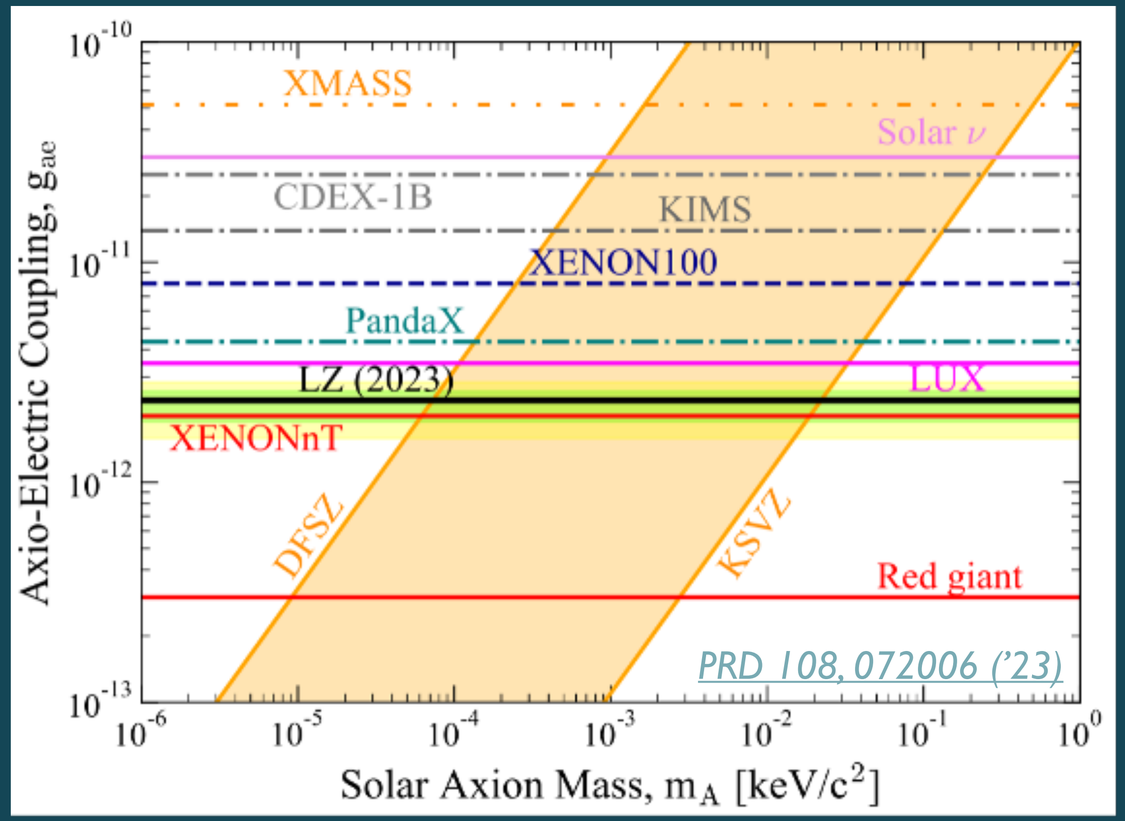
→ broadband detectors, capable of searches across a wide range of candidate masses

PHYSICS VIA ELECTRON RECOIL CHANNEL

Neutrino Magnetic Moment & Effective Millicharge



Solar Axion Interactions



Neutrino interactions & properties; axions and ALPs; rare decays of xenon isotopes

SUMMARY OF PHYSICS RESULTS TO DATE

- First dark matter results from the LZ Experiment - *PRL 131, 041002 ('23)*
- Search for new physics in low-energy electron recoils from the first LZ exposure - *PRD 108, 072006 ('23)*
- First Constraints on WIMP-Nucleon Effective Field Theory Couplings in an Extended Energy Region From LZ - *PRD 109, 092003 ('24)*
- New constraints on ultraheavy dark matter from the LZ experiment - *PRD 109, 112010 ('24)*
- Constraints On Covariant WIMP-Nucleon Effective Field Theory Interactions from the First Science Run of the LUX-ZEPLIN experiment - *arXiv:2404.17666*
- Probing the Scalar WIMP-Pion Coupling with the First LUX-ZEPLIN Data - *arXiv:2406.02441*
- Two-Neutrino Double Electron Capture of Xe-124 in the First LUX-ZEPLIN Exposure - *arXiv:2408.17391*

→ All publications have at least one corresponding author based in the UK

NEW WIMP SEARCH RESULTS!

UCL

UCL Home » UCL News » LZ experiment sets new record in search for dark matter

LZ experiment sets new record in search for dark matter

27 August 2024

New results from the LUX-ZEPLIN (LZ) collaboration involving UCL researchers have put the best-ever limits on weakly interacting massive particles (WIMPs), a leading candidate for what makes up our universe's invisible mass.

symmetry topics

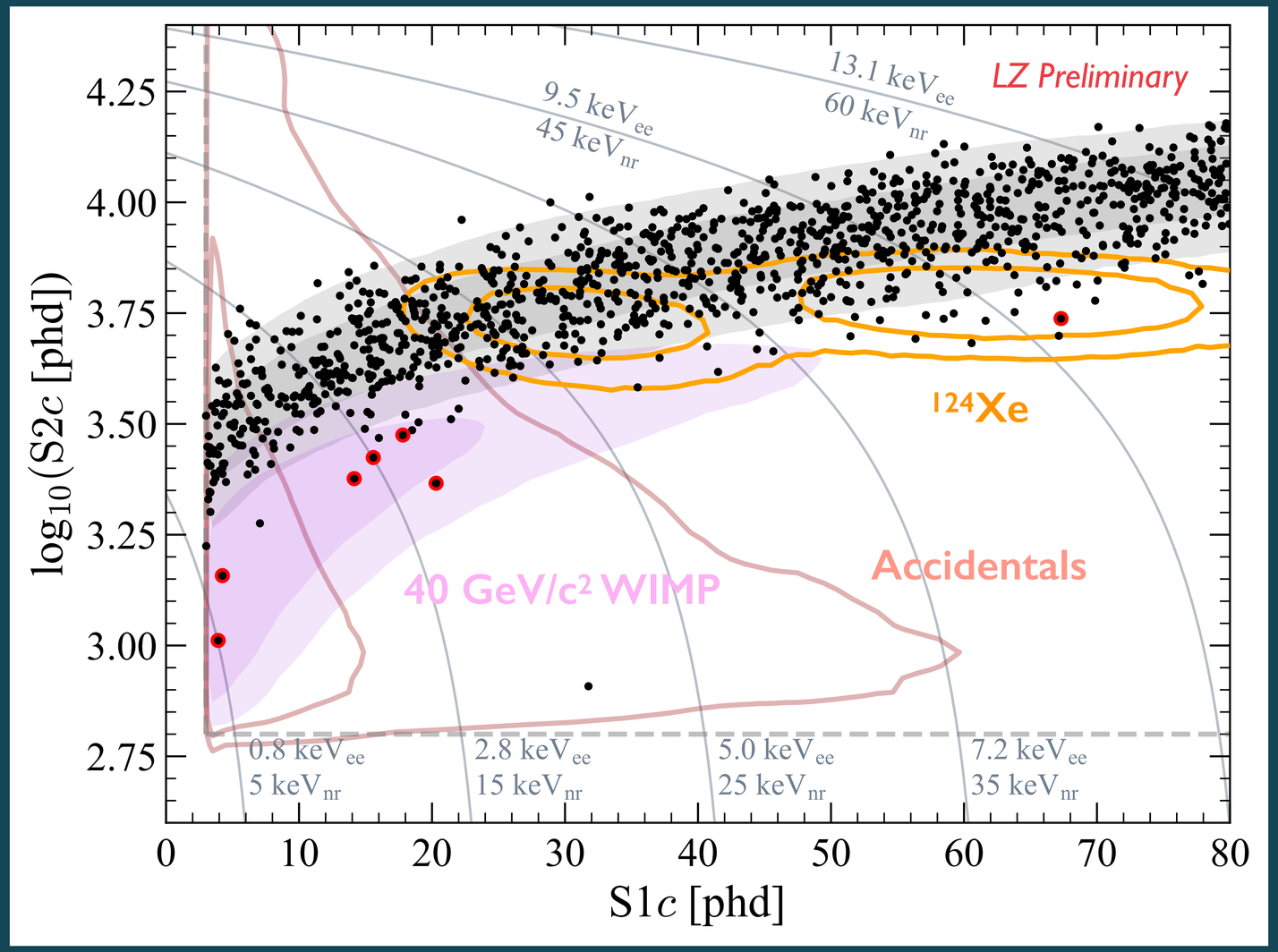
LZ experiment sets new record in search for dark matter

physicsworld

LUX-ZEPLIN 'digs deeper' for dark-matter WIMPs

New results announced on August 26th, with simultaneous talks at LIDINE & TeVPA

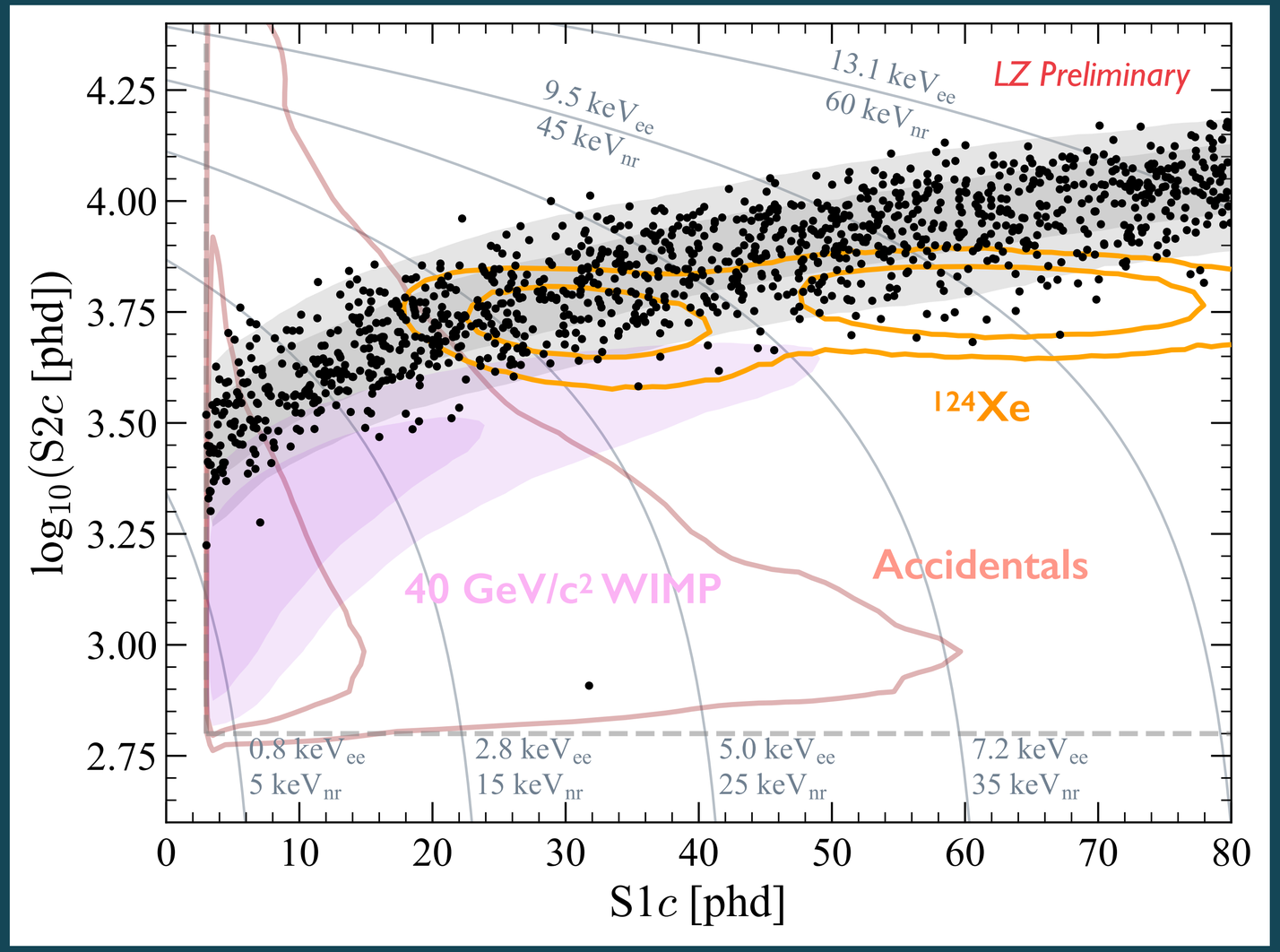
LATEST WIMP SEARCH



- New WS2024 exposure taken between Mar ’23 & Mar ‘24
  → 220 live days * 5.5 tonnes
  = **3.3 tonne years**

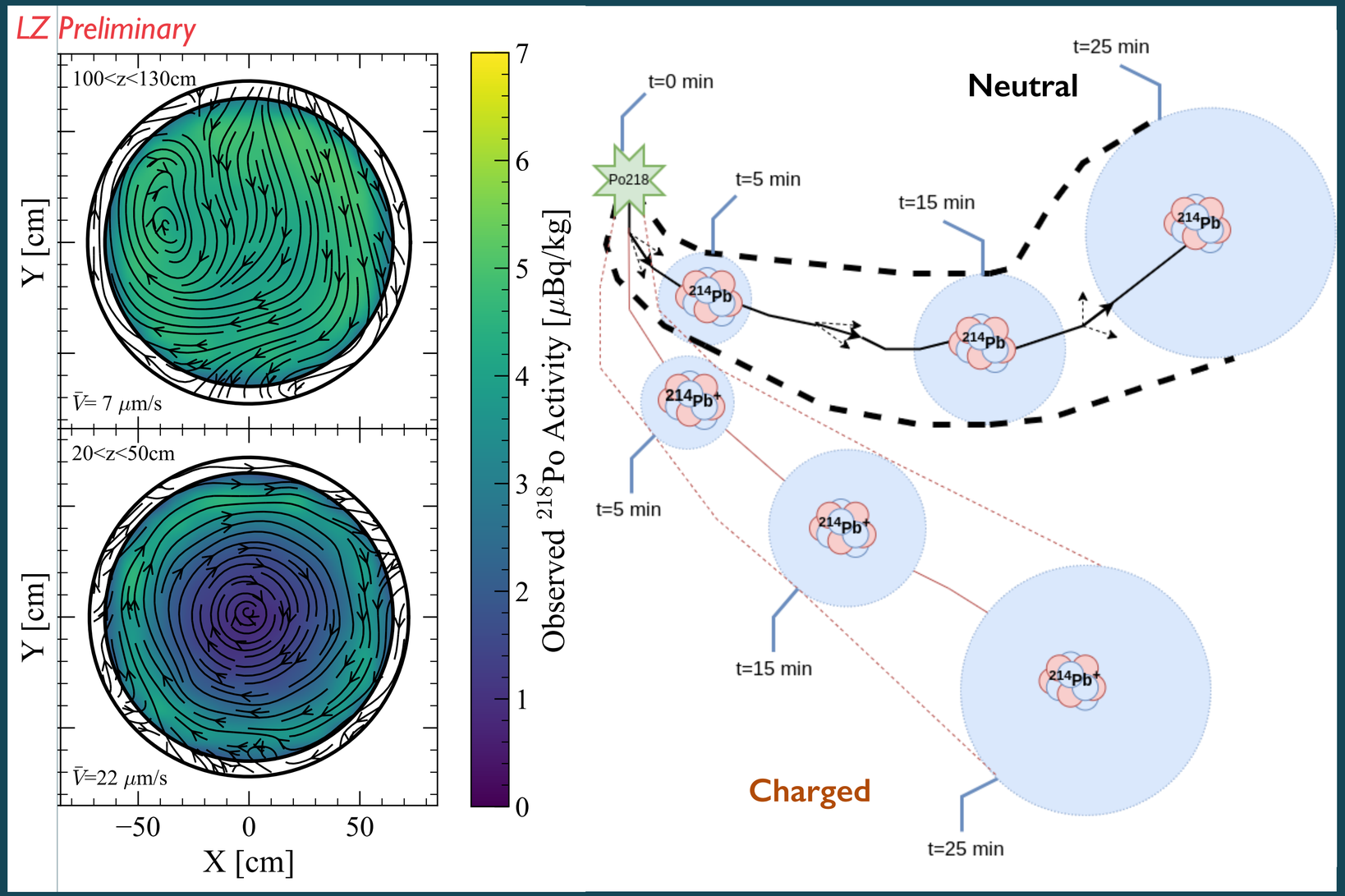
- WS2024 **salted** for bias mitigation

LATEST WIMP SEARCH



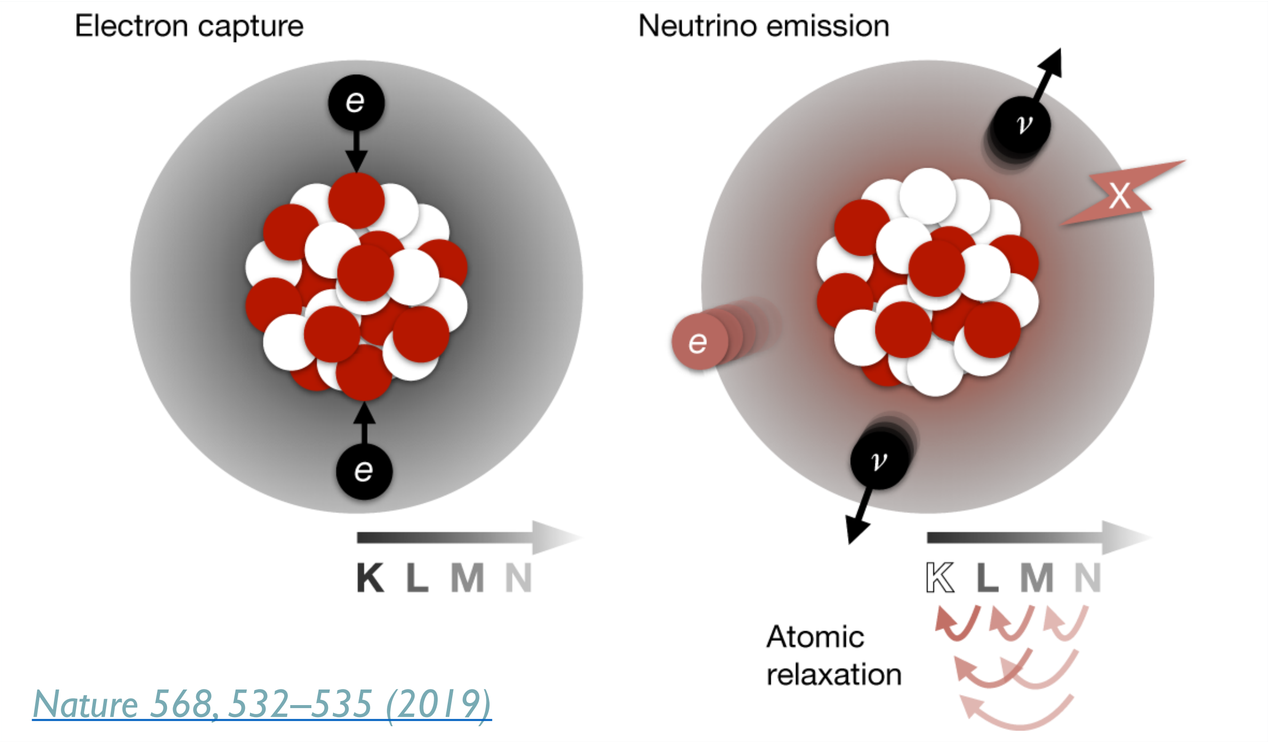
- New WS2024 exposure taken between Mar '23 & Mar '24
  → 220 live days * 5.5 tonnes
  = **3.3 tonne years**
- WS2024 **salted** for bias mitigation
  → no post-unsalting changes to models & assumptions
- Combined analysis performed with WS2022+WS2024 (**4.2 tonne years**)
- Driven by a **UK-led team** (spokesperson, WIMP search lead, physics coordinator)

HIGHLIGHTS - RADON TAG

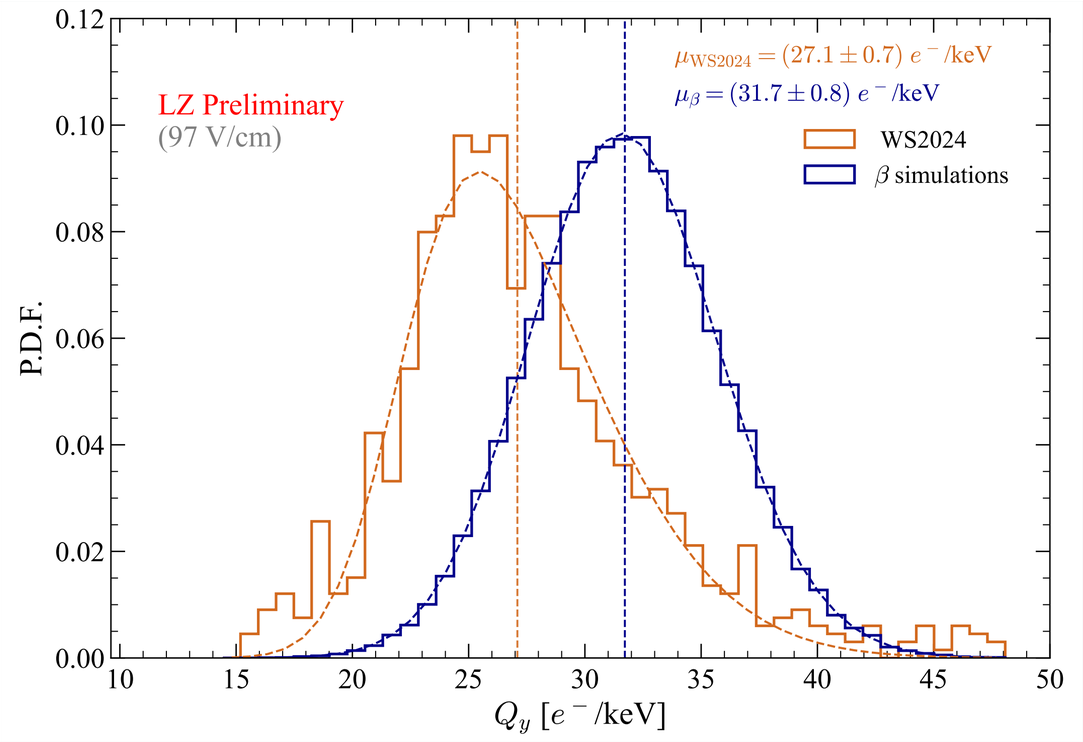


- Biggest background from ^{214}Pb β decays (^{222}Rn chain)
- ^{222}Rn emanates from materials
- ^{222}Rn-^{218}Po α decay pairs ($T_{1/2}$ = 3.1 min)
  → use to map flow vectors
- Radon tag developed with flow map & ion drift simulations
  → tag 60% ^{214}Pb in just 15% of the analysis volume

HIGHLIGHTS - ELECTRON CAPTURE (EC)



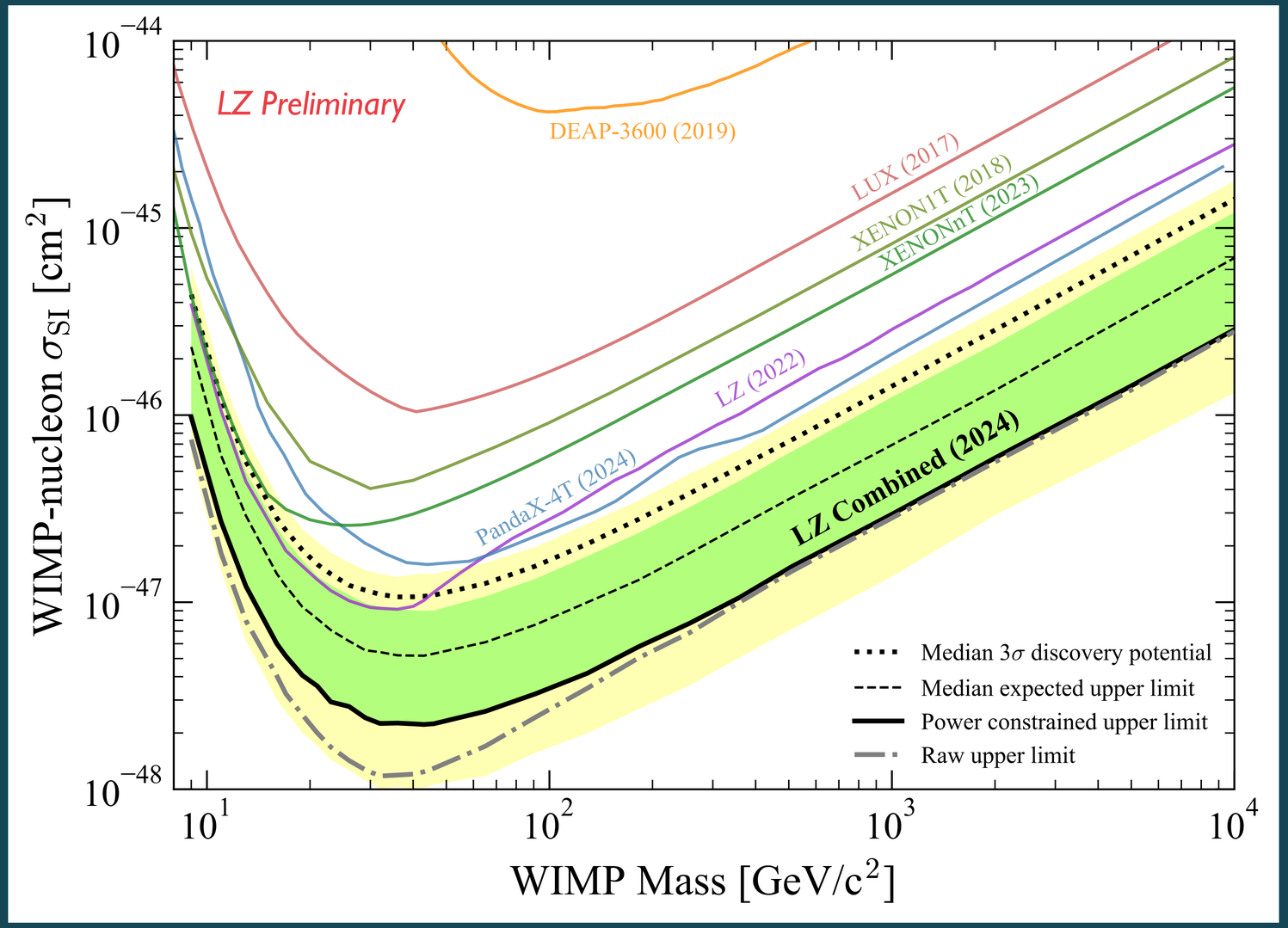
Nature 568, 532–535 (2019)



- ^{124}Xe 2ν double EC - **"World's rarest decay"** - $T_{1/2} = (1.09 \pm 0.14_{stat} \pm 0.05_{sys}) \times 10^{22}$ yr (LZ)

- Enhanced recombination of Xe L-shell EC compared to β decay of same energy (more NR-like)
  → preliminary *in-situ* measurement of effect with ^{127}Xe & ^{125}Xe decays - paper in preparation
  → Effect for LL-shell expected to be greater - noted for the first time in this analysis

SPIN-INDEPENDENT WIMP SEARCH RESULTS

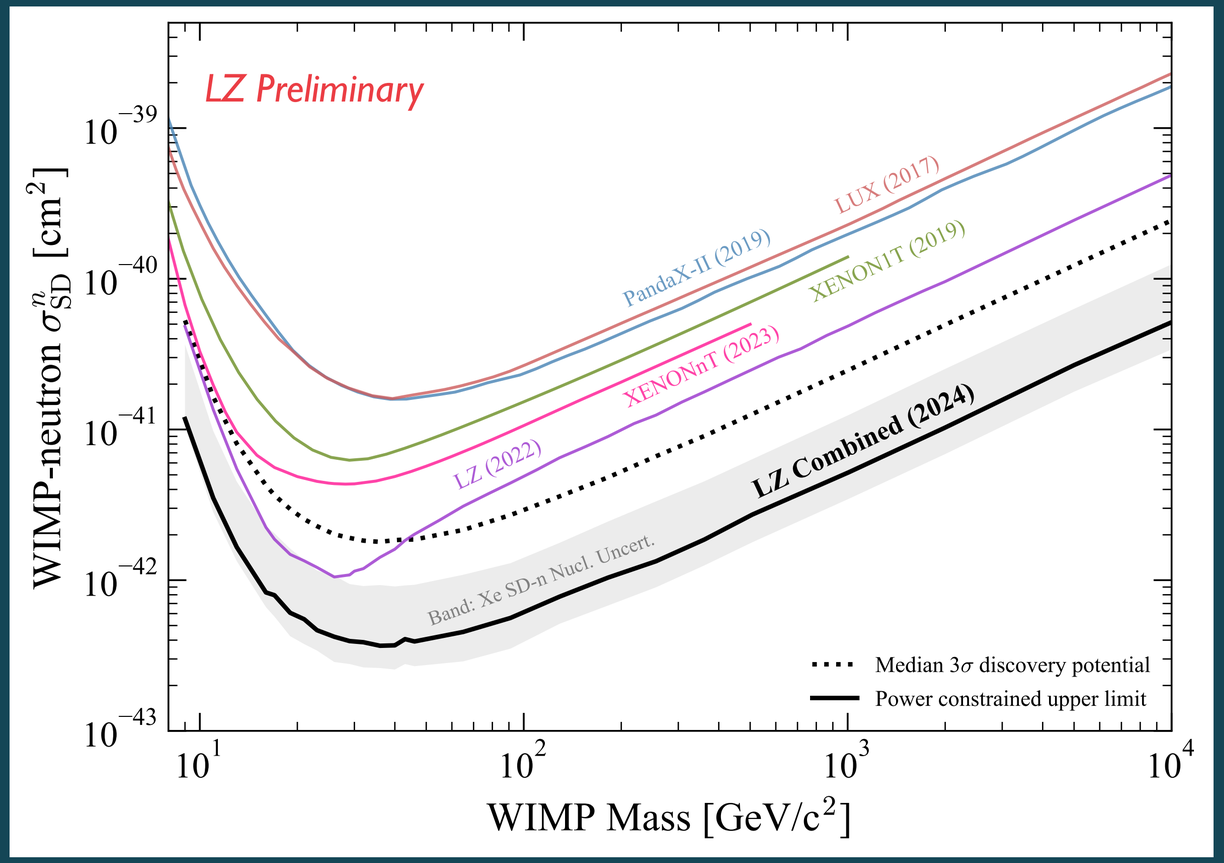


- Best fit of zero WIMPs at all masses tested (9 GeV/c^2 - 100 TeV/c^2)
- World-leading limits: strongest from combined analysis of $\sigma_{SI} = 2.2 \times 10^{-48}$ cm^2 for 43 GeV/c^2
- Power constrained at -1σ as per recommended community conventions *EPJC 81, 907 ('21)*

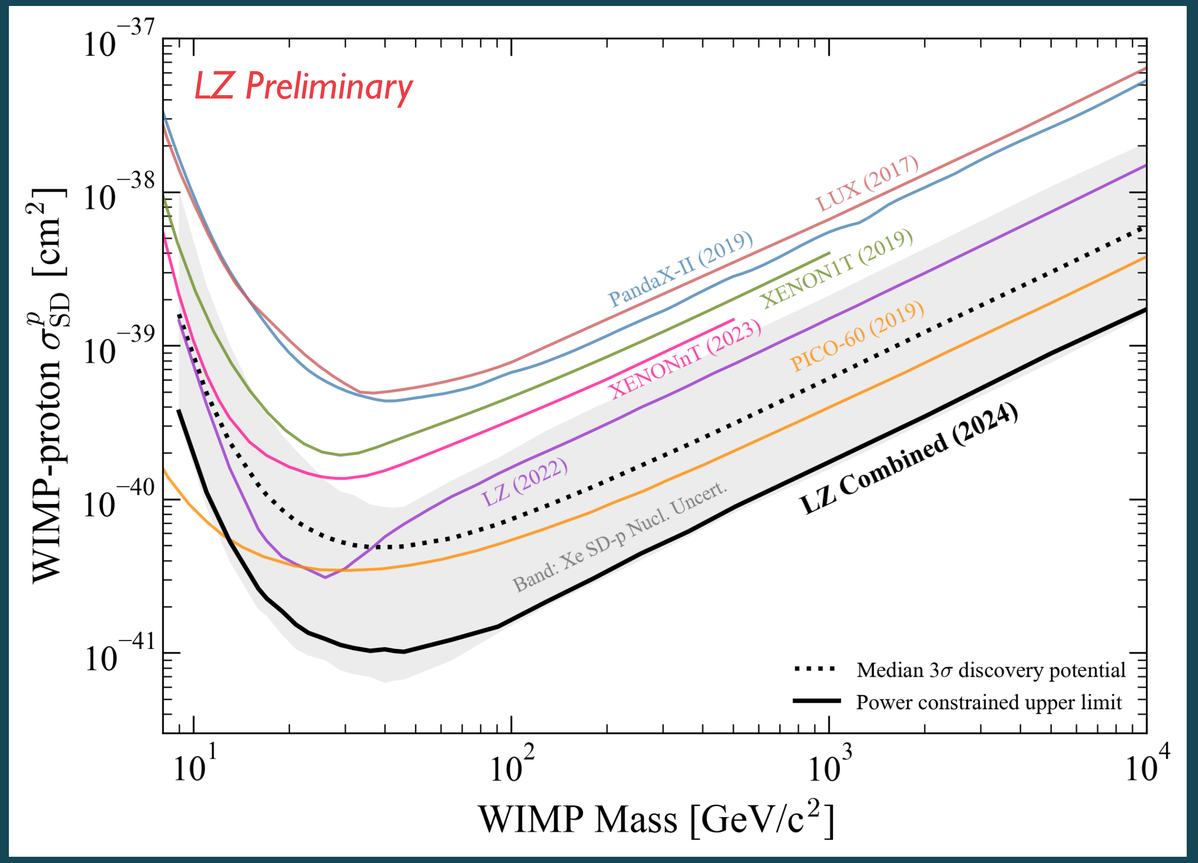
LZ firmly in discovery mode, probing uncharted electroweak parameter space

SPIN-DEPENDENT WIMP SEARCH RESULTS

WIMP-Neutron Scattering



WIMP-Proton Scattering



World-leading constraints; sensitivity provided by ^{129}Xe (26%) & ^{131}Xe (21%)

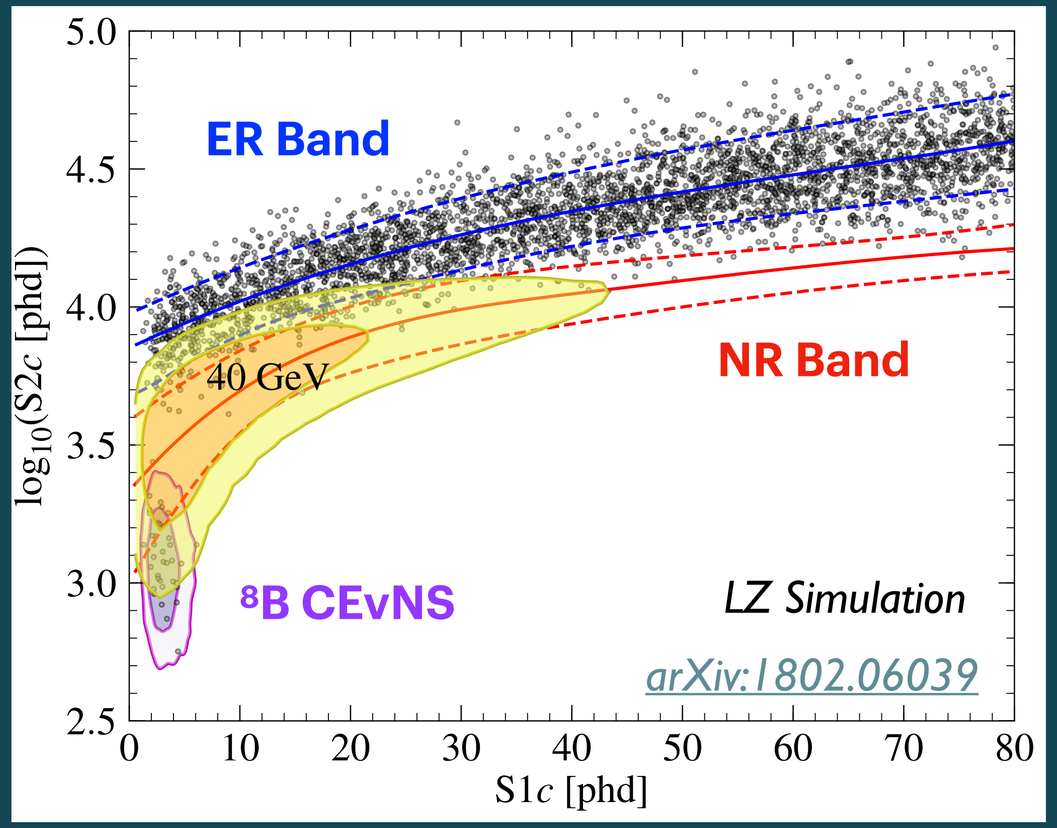
P5 ENDORSEMENT & LONG-TERM RUNNING

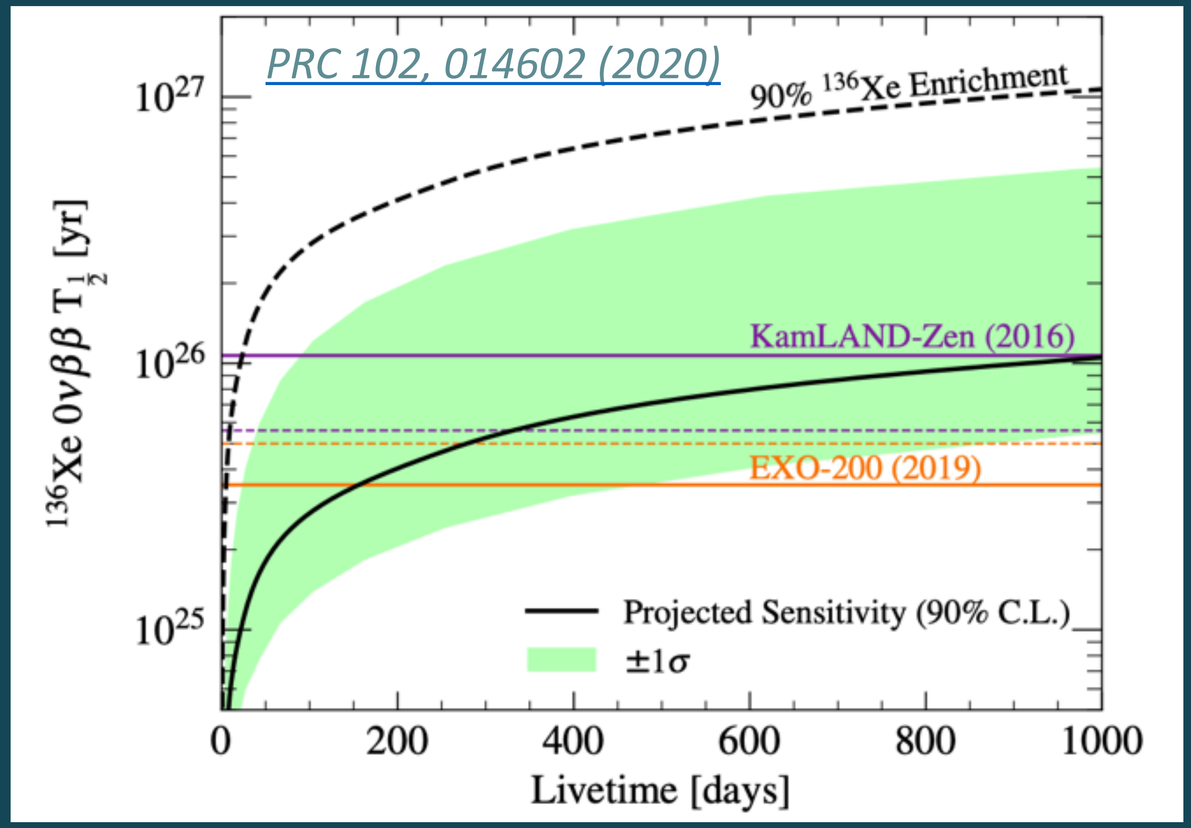
"..dark matter experiments currently taking data are venturing into unexplored territories and hold the potential for groundbreaking discoveries..."

Recommendation 1:
As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science

- LZ operation extension recently approved after DOE review following strong P5 endorsement
  → Extension for running through FY 2027-8 - target 1000 live days
- Consistent with UK planning with recent CG submission

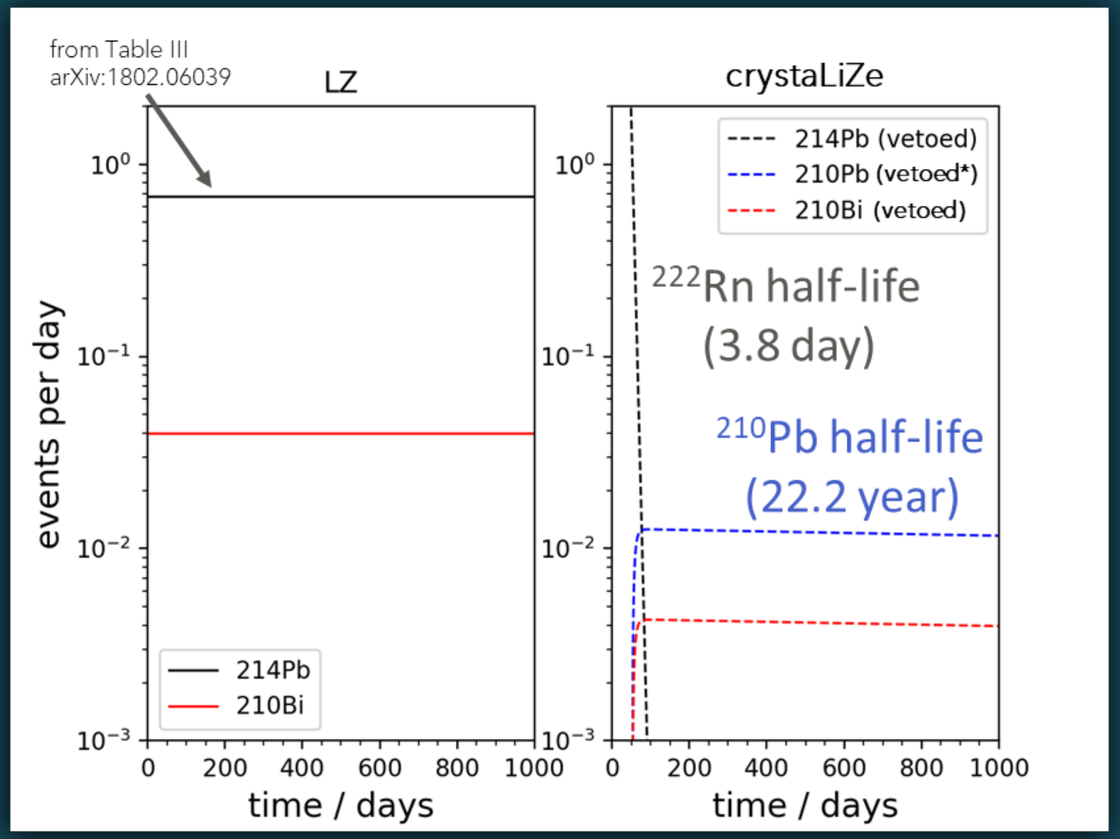
WHAT'S NEXT FOR LZ?

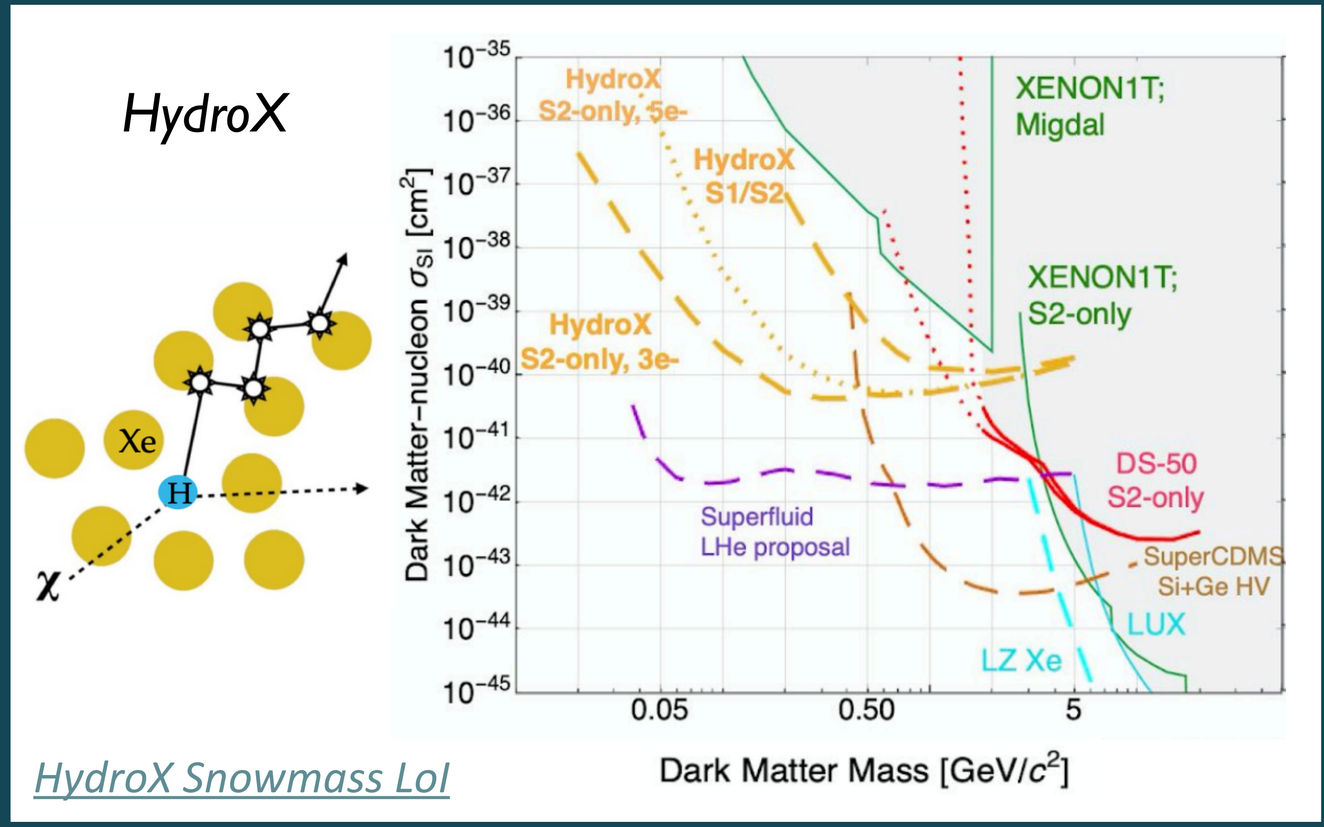




- LZ will continue flagship WIMP searches, but also show it is a multi-physics machine
- Observation of boron-8 solar neutrino CEvNS - first for natural neutrinos
- ^{136}Xe 0νββ decay search - demonstrate competitiveness of a next-generation detector (XLZD)

FURTHER INTO THE FUTURE





HydroX Snowmass LoI

- Potential upgrade paths: crystaLiZe (solid xenon); HydroX (hydrogen doping)
- Science & R&D with LZ will inform direction & strategy of XLZD (see Adam's talk tomorrow)

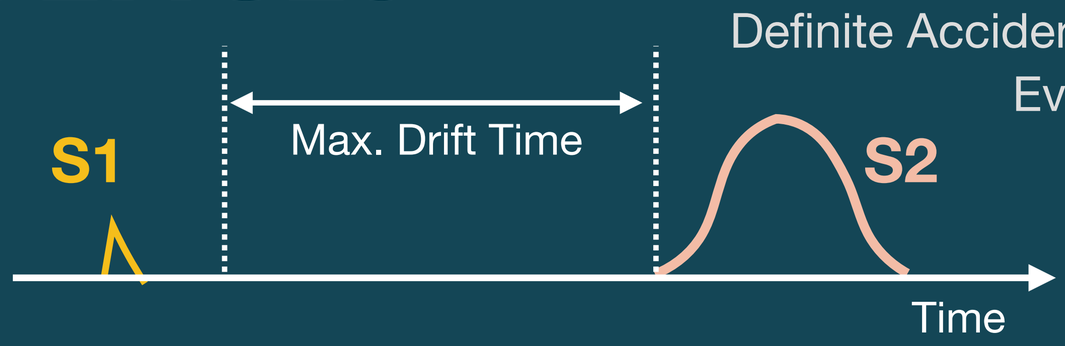
CONCLUSIONS

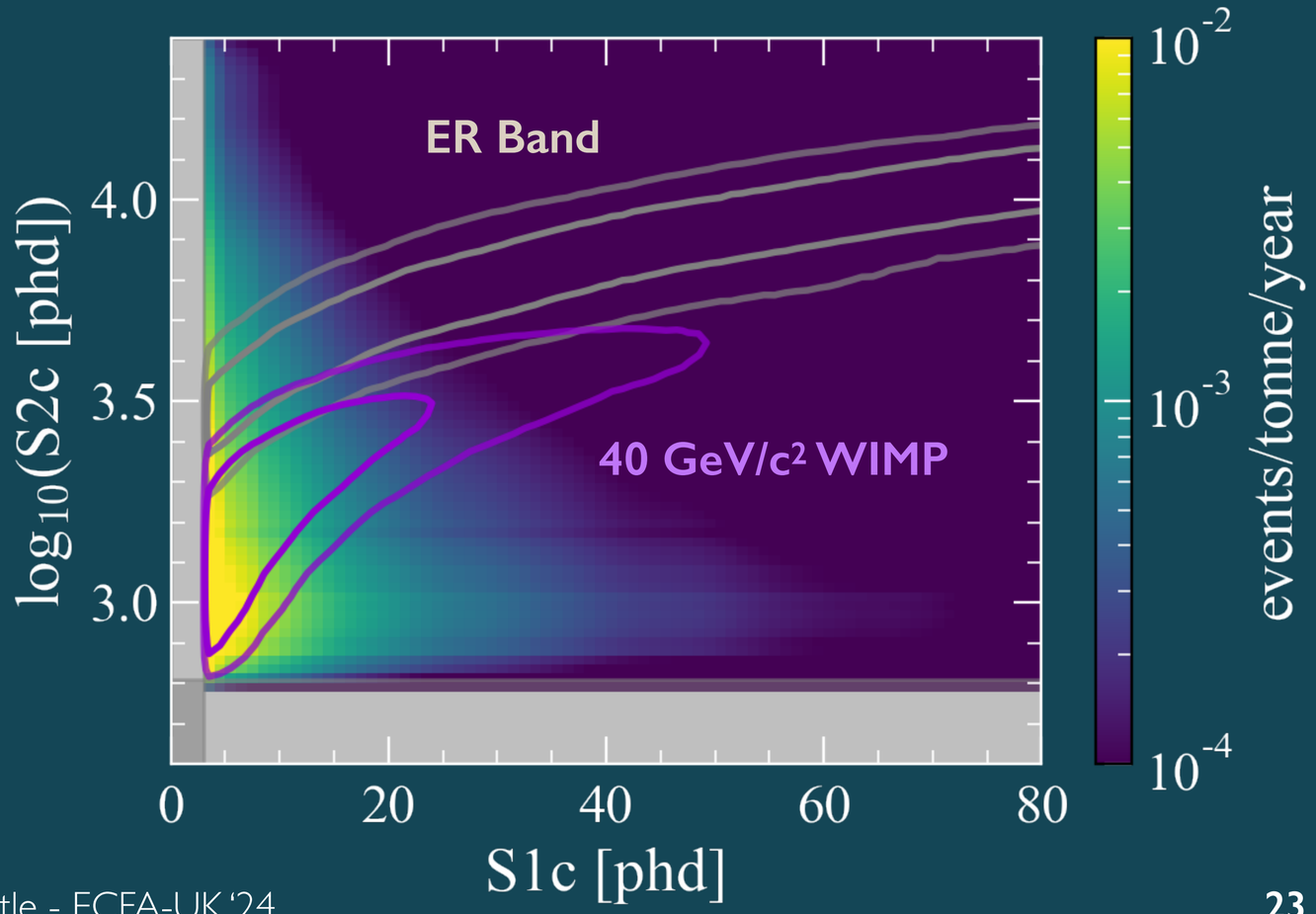
- New world-leading WIMP results with 4.2 tonne year exposure exceed previous best constraints by >4 times
  - Radon tag developed and used for the first time: 60% reduction in main ER background
  - First observation of charge-suppressed ^{124}Xe DEC
- LZ will take data until 2028, towards 1000 live days
  - Multiple physics channels e.g. ^{8}B CEvNS, 0νββ decay
  - **LZ is discovery-ready for WIMPs**
- XLZD is the logical next step to confirm/discover/exclude WIMPs, covering well-motivated space to the neutrino fog

Back Up Slides

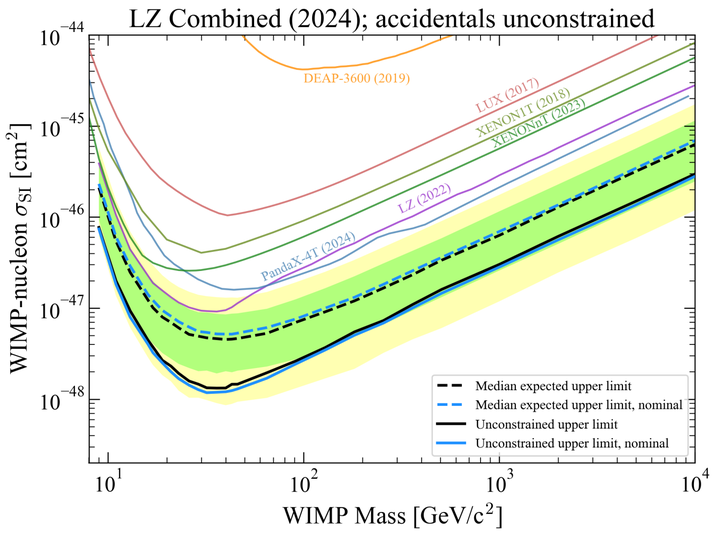
ACCIDENTAL COINCIDENCES

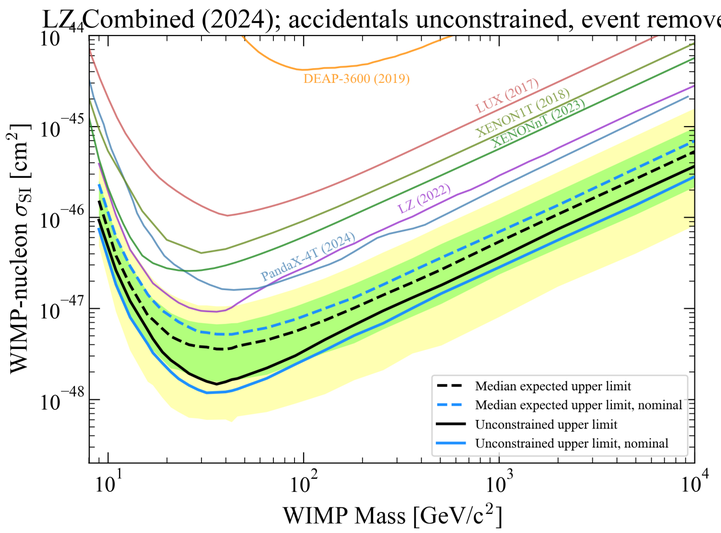
- Unrelated S1s & S2s can accidentally combine to produce single scatter events → could mimic a WIMP signal
- Rate: population of definite accidental events with unphysical drift time >1 ms
- Distribution: fake events constructed from lone S1 & S2 pulse waveforms
- Analysis cuts developed to combat observed pulse/event pathologies
  - >99.5% rejection efficiency
  - WS2024 counts: 2.8 ± 0.6

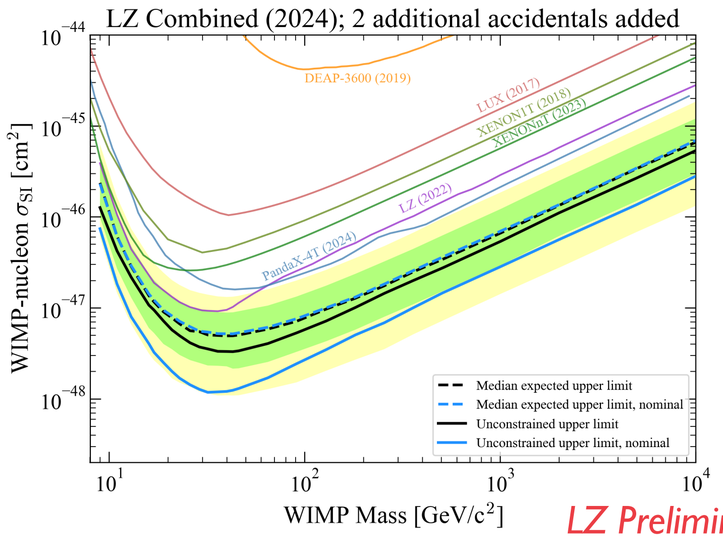




CHECKS OF ACCIDENTALS IMPACT ON LIMIT







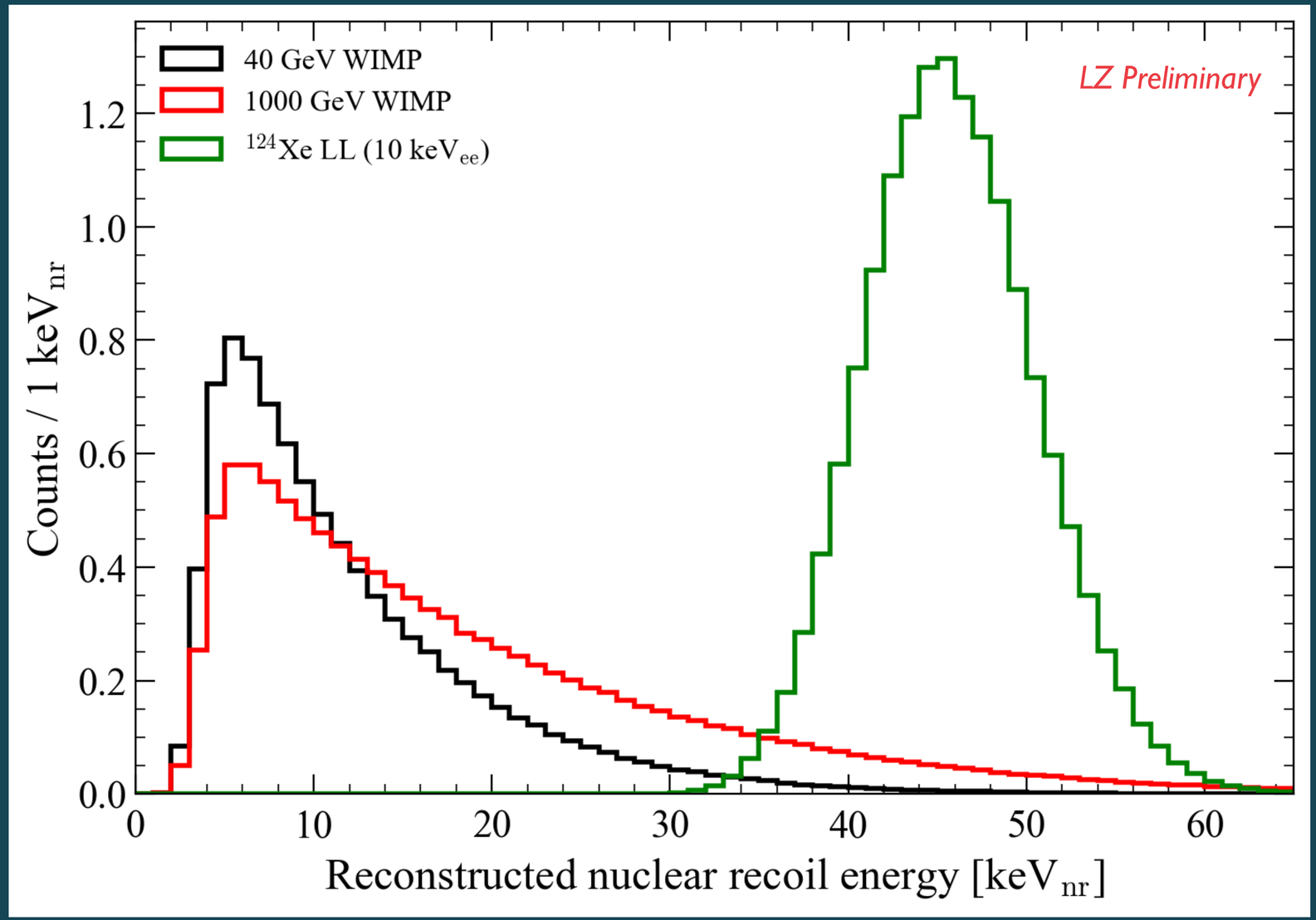
1. Remove accidental rate constraint: best fit drops 2.6 → 1.4
2. Remove constraint & outlier event: best fit drops 1.4 → 0
   - Outlier event holds model up, over subtracting in the WIMP region
3. Adding fake events - props limit back up

→ under-fluctuation of accidental events in the WIMP region

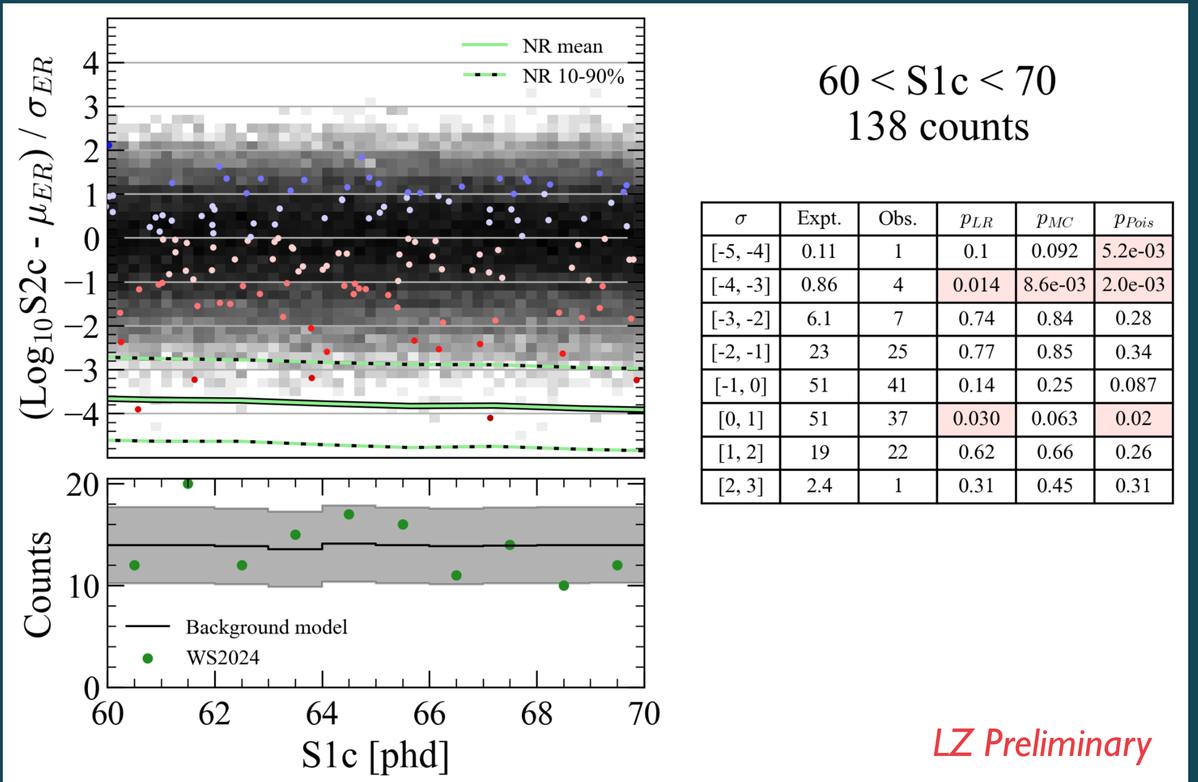
^{124}XE LL-SHELL COMPARED TO DARK MATTER SPECTRA

WIMP spectra normalised to LZ's 4.2 tonne year median 3σ discovery potential:

- 9 events @ 40 GeV
- 11 events @ 1000 GeV



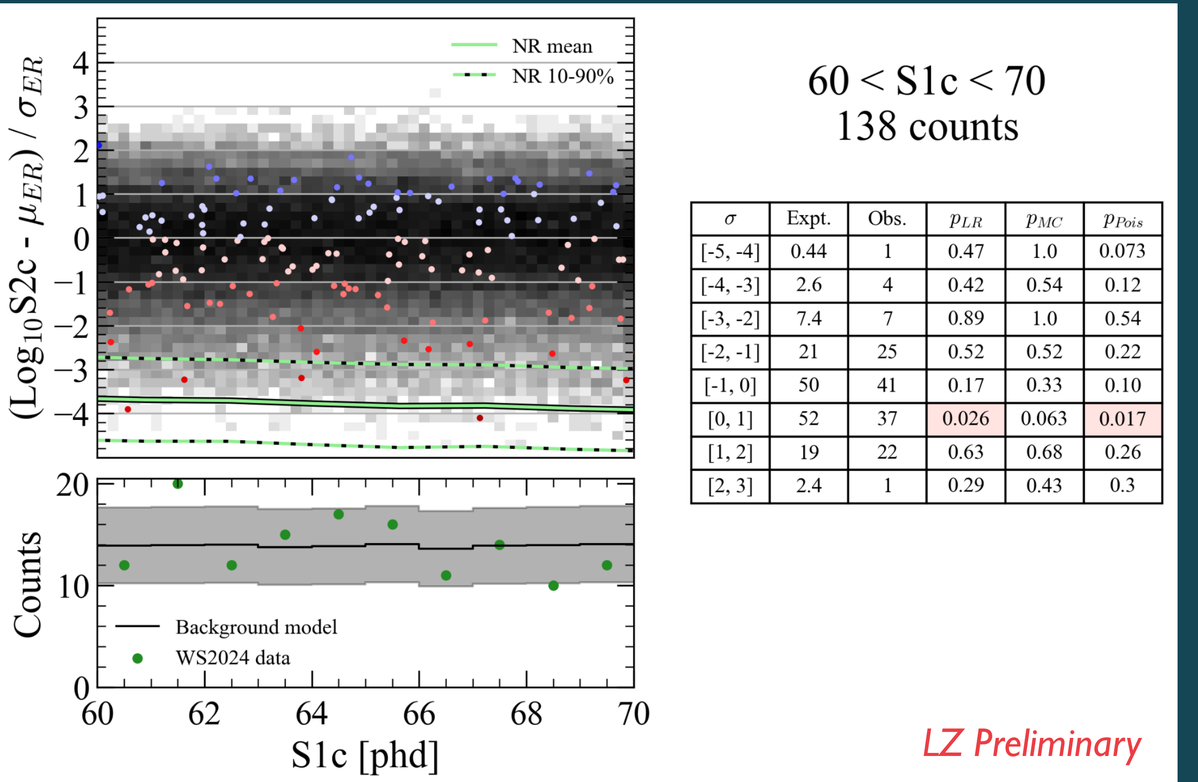
GOODNESS OF FITS IN KEY ^{124}XE REGION



60 < S1c < 70
138 counts

σ	Expt.	Obs.	p_{LR}	p_{MC}	p_{Pois}
[-5, -4]	0.11	1	0.1	0.092	5.2e-03
[-4, -3]	0.86	4	0.014	8.6e-03	2.0e-03
[-3, -2]	6.1	7	0.74	0.84	0.28
[-2, -1]	23	25	0.77	0.85	0.34
[-1, 0]	51	41	0.14	0.25	0.087
[0, 1]	51	37	0.030	0.063	0.02
[1, 2]	19	22	0.62	0.66	0.26
[2, 3]	2.4	1	0.31	0.45	0.31

LZ Preliminary



60 < S1c < 70
138 counts

σ	Expt.	Obs.	p_{LR}	p_{MC}	p_{Pois}
[-5, -4]	0.44	1	0.47	1.0	0.073
[-4, -3]	2.6	4	0.42	0.54	0.12
[-3, -2]	7.4	7	0.89	1.0	0.54
[-2, -1]	21	25	0.52	0.52	0.22
[-1, 0]	50	41	0.17	0.33	0.10
[0, 1]	52	37	0.026	0.063	0.017
[1, 2]	19	22	0.63	0.68	0.26
[2, 3]	2.4	1	0.29	0.43	0.3

LZ Preliminary

Q_{LL}/Q_{β} = 0.87

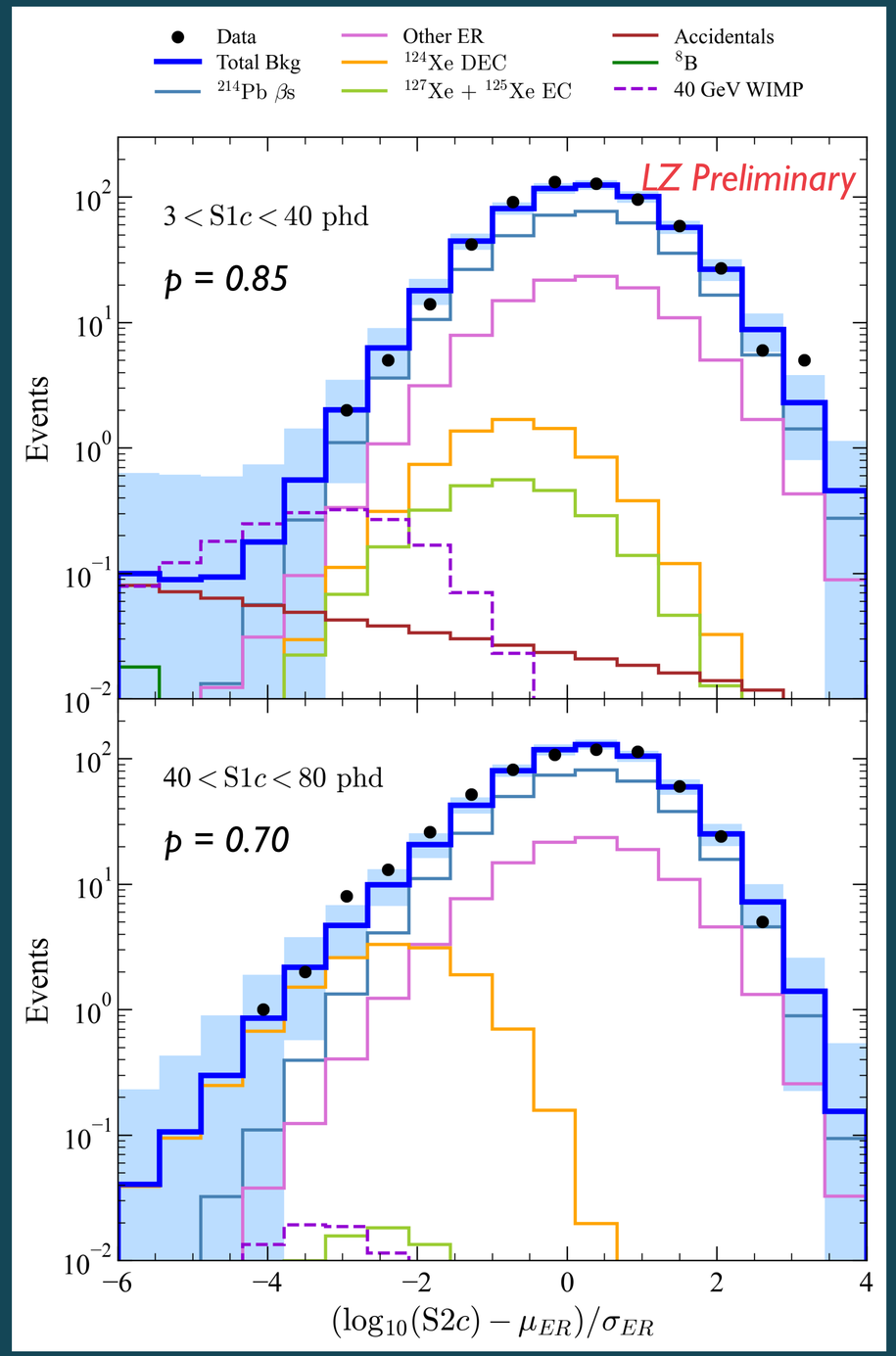
(i.e. L-shell suppression)

Q_{LL}/Q_{β} = 0.65

(i.e. double L-shell ionisation density)

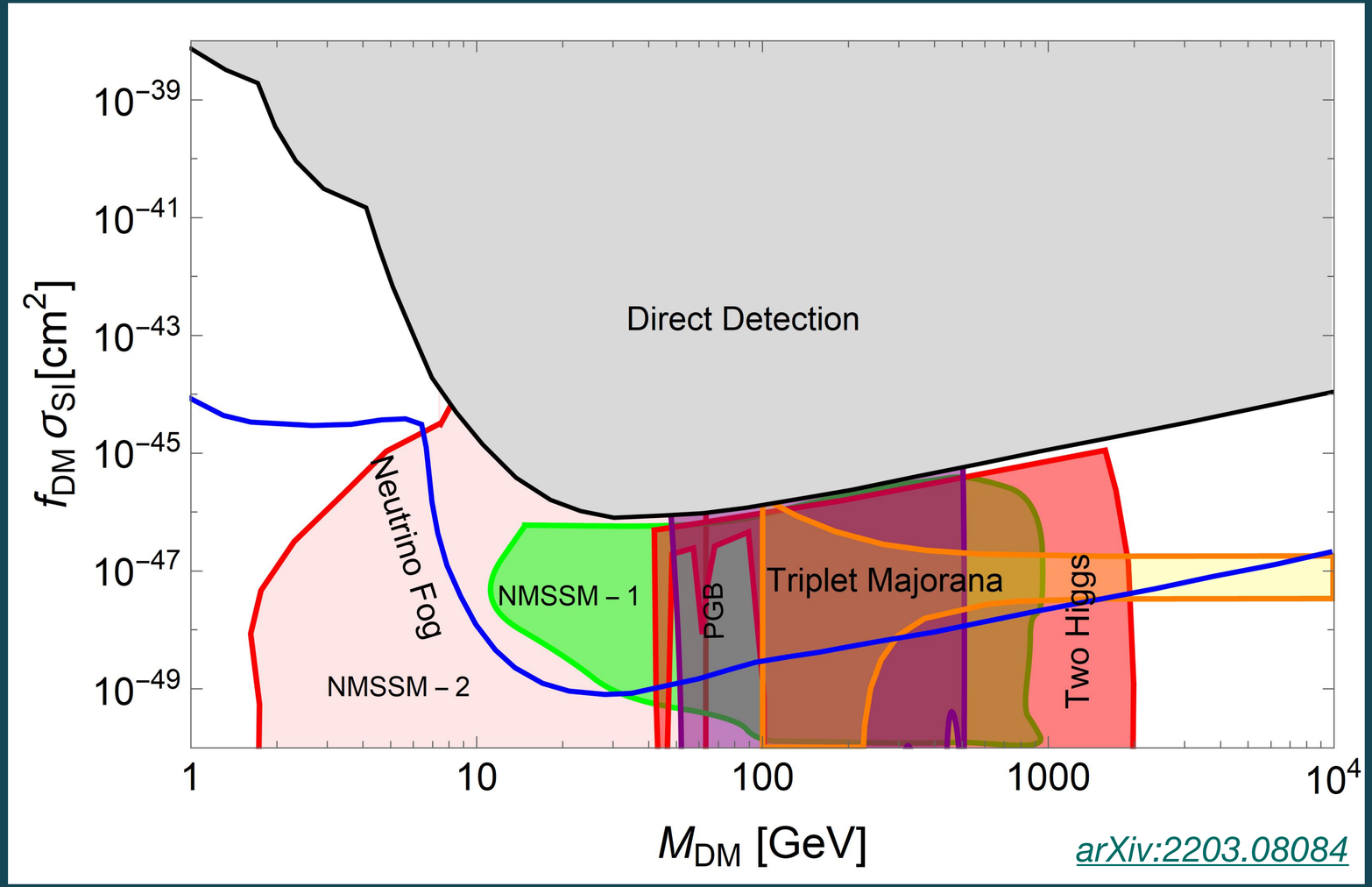
WS2024 FIT RESULTS

Component	Expected Events	Best Fit Events
^{214}Pb β decays	743 ± 88	733 ± 34
^{85}Kr + ^{39}Ar +detector γs	162 ± 22	161 ± 21
Solar ν ERs	102 ± 6	102 ± 6
^{212}Pb + ^{218}Po β decays	62.7 ± 7.5	63.7 ± 7.4
^{3}H + ^{14}C β decays	58.3 ± 3.3	59.7 ± 3.3
^{136}Xe 2νββ decay	55.6 ± 8.3	55.8 ± 8.3
^{124}Xe DEC	19.4 ± 3.9	21.4 ± 3.6
^{127}Xe + ^{125}Xe EC	3.2 ± 0.6	2.7 ± 0.6
Atm. ν CEvNS	0.12 ± 0.02	0.12 ± 0.02
^{8}B + *hep* ν CEvNS	0.06 ± 0.01	0.06 ± 0.01
Det. Neutrons	-	$0.0^{+0.2}$
Accidentals	2.8 ± 0.6	2.6 ± 0.6
Total	1210 ± 91	1203 ± 41



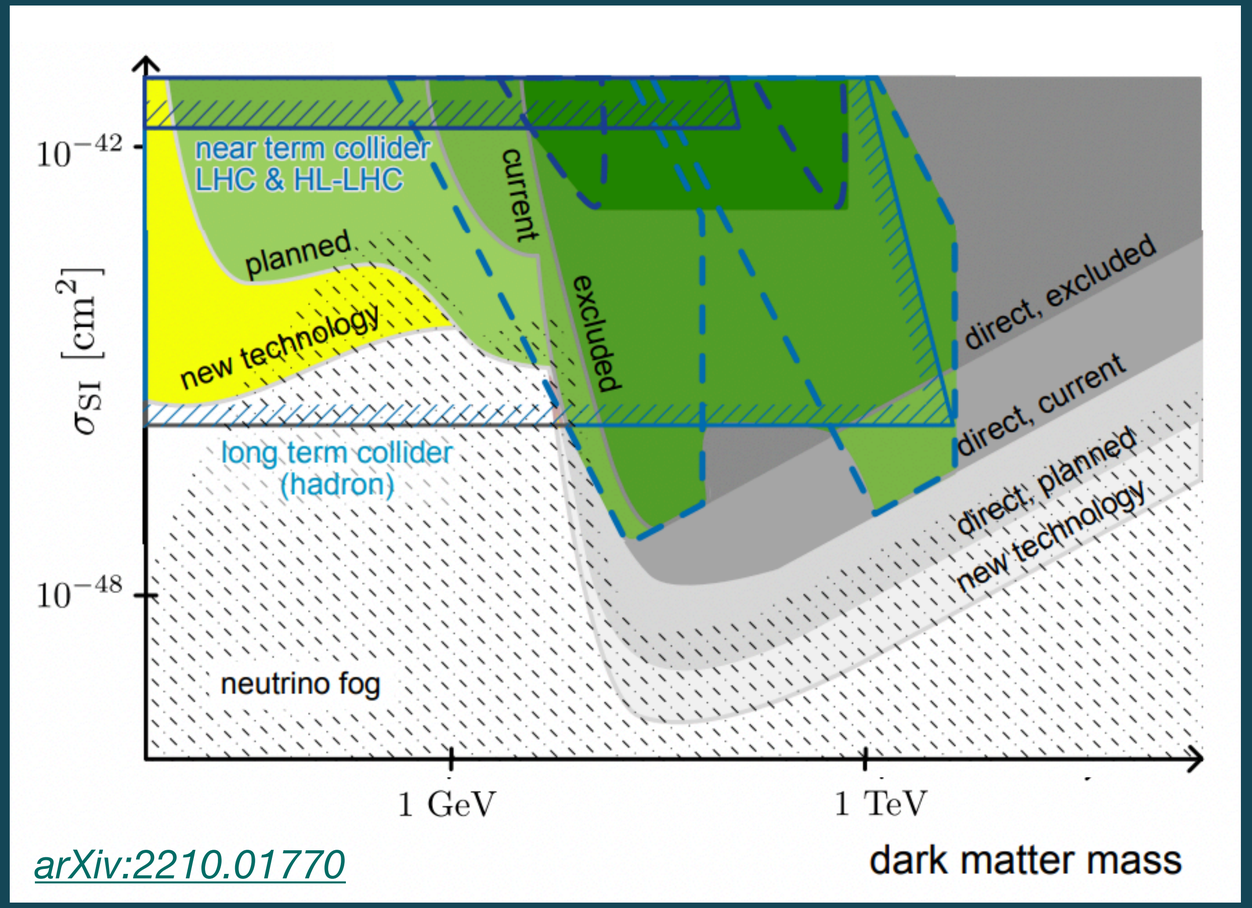
WHAT ARE WE LOOKING FOR?

- Simplest theories with Z or Higgs mediated WIMPs ruled out
- Types of models remaining include:
  - NMSSM & pMSSM
  - Higgs scalar portal
  - Asymmetric dark matter



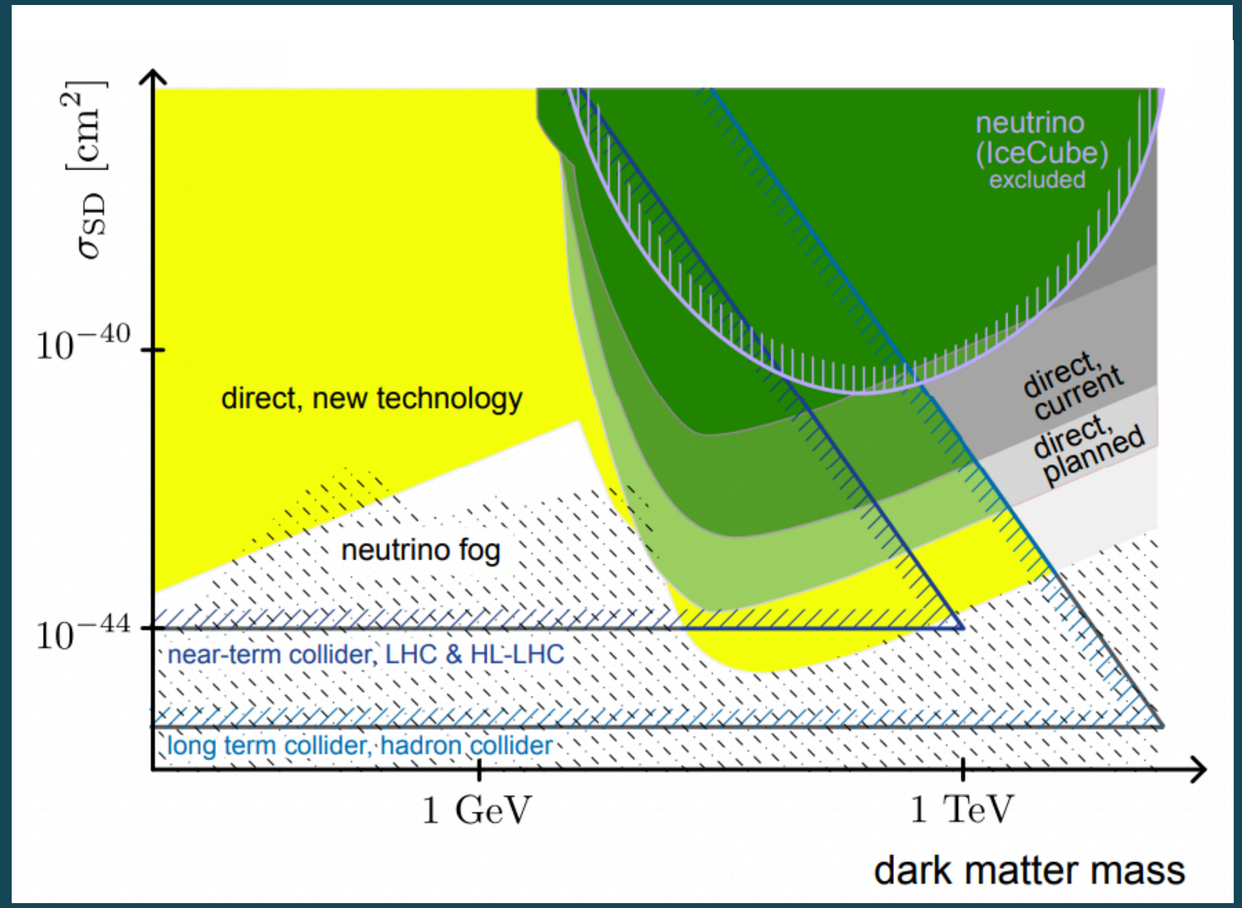
DARK MATTER SEARCH COMPLEMENTARITY

Spin-Independent



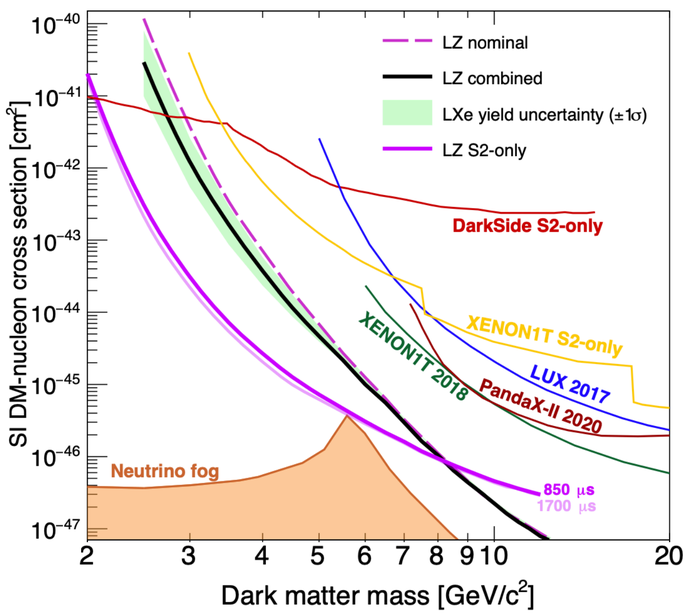
arXiv:2210.01770

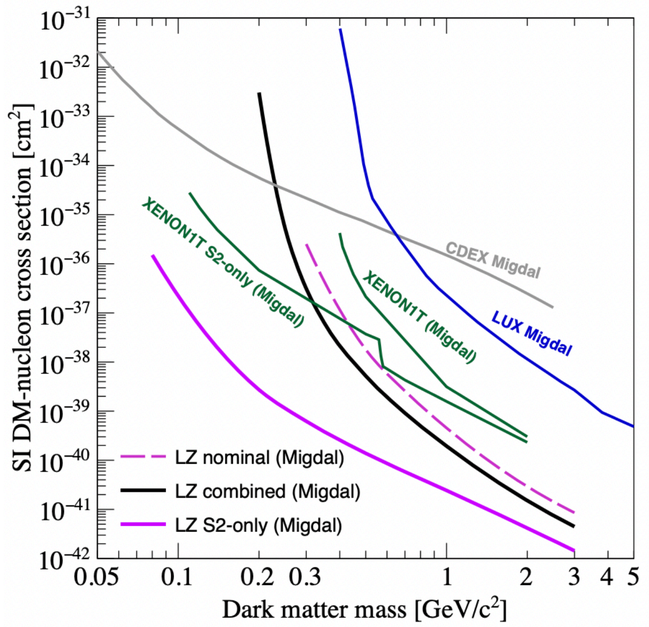
Spin-Dependent



EXTENDING TO LOWER MASS CANDIDATES

- Lowering the energy threshold
  - Exploit 2-phe effect to reduce S1 coincidence requirement from 3 to 2 → ~4x sensitivity gain at 2.5 GeV/c^2
  - Conduct an S2-only search
    - Discriminate backgrounds based on S2 pulse shape/width
- Sub-GeV masses accessible when considering Migdal electron emission





arXiv: 2101.08753

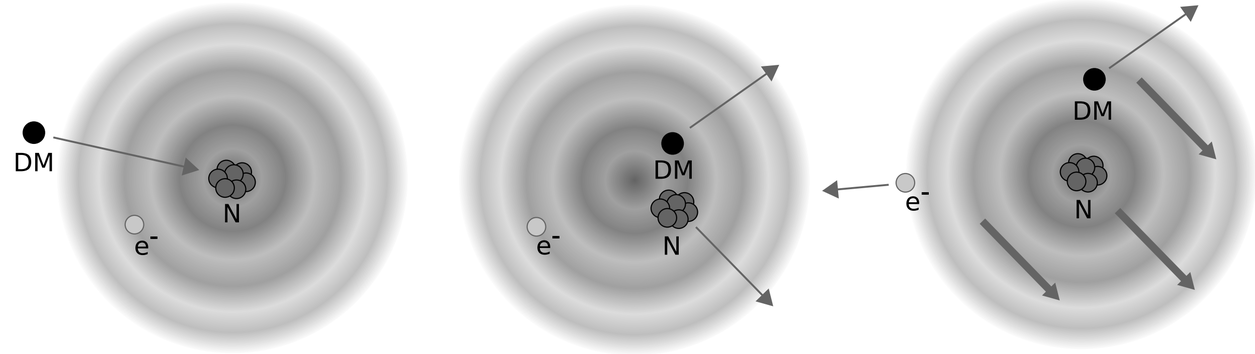


Image credit: PRL 121, 101801