– XLZD@BOULBY –
HOSTING A RARE EVENT OBSERVATORY FOR DARK MATTER AND NEUTRINO PHYSICS?

(and all else that goes "ping" in the night...)

Henrique Araújo

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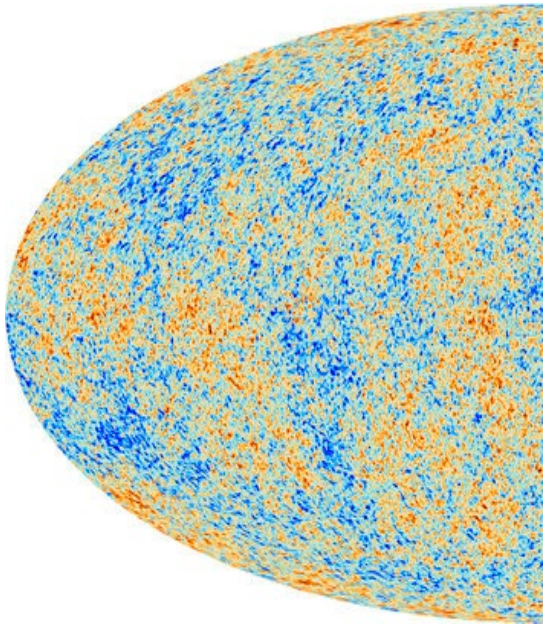
Strongly interacting dinosaur wandering in the dark at NSL-2025

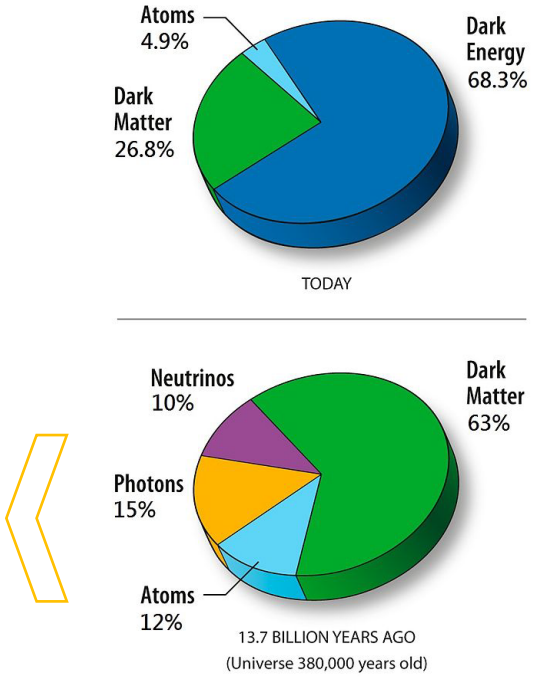
WANDERING IN THE DARK – UK HEP FORUM 2025 – 20-22 OCTOBER 2025 – COSENER'S HOUSE

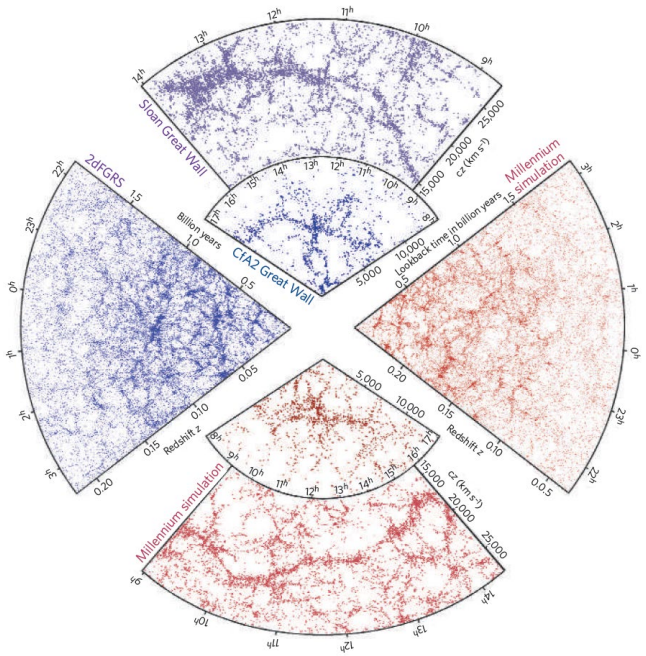
DARK MATTER AT THE LARGEST SCALES

The Standard Model of Cosmology (Λ-CDM) is remarkably successful (still…)

- Initial conditions photographed at the surface of last scatters (the cosmic microwave background)
  - Left to evolve for 13.7 Gyr under two dark 'fluids' – dark energy (Λ) and cold dark matter (CDM)
    - To produce the "structure" we see today – ordinary matter (almost) does not matter…



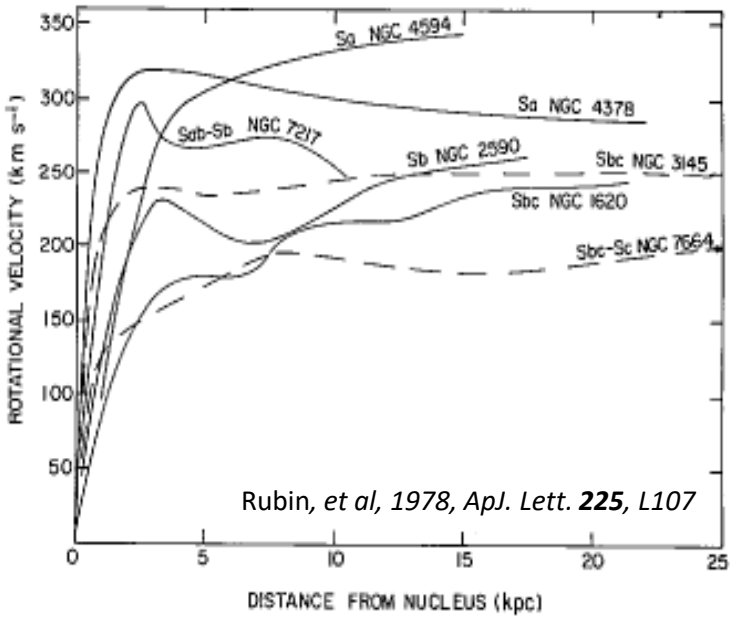




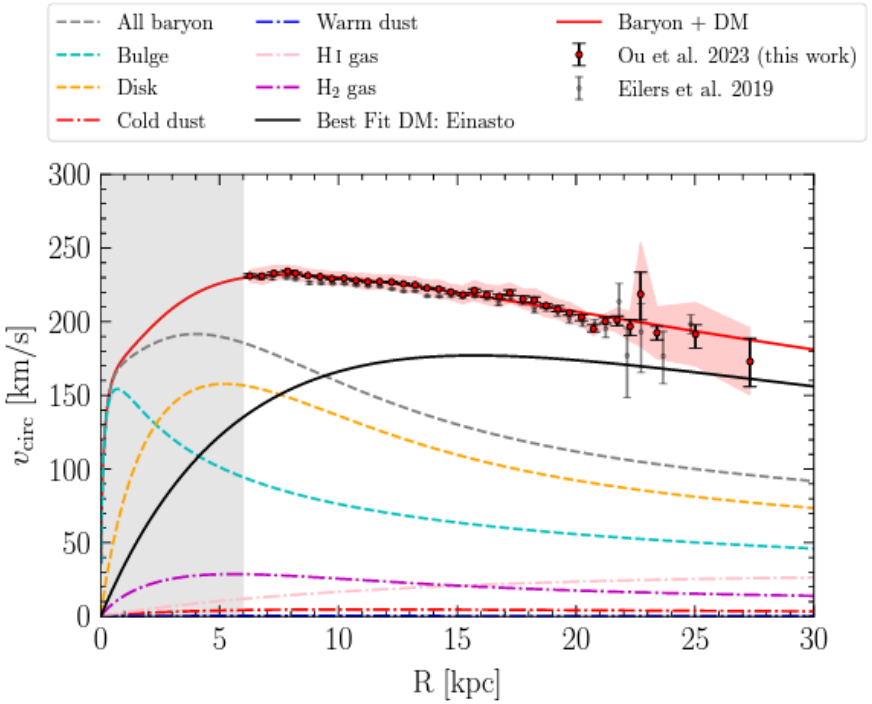
DARK MATTER AT THE SMALLEST SCALES

DM manifests itself also within individual galaxies (e.g. rotation curves of spiral galaxies)

- Our Milky Way is not exceptional – it, too, spins too quickly for the luminous matter it contains: we seem to be immersed in a large dark matter ‘halo’

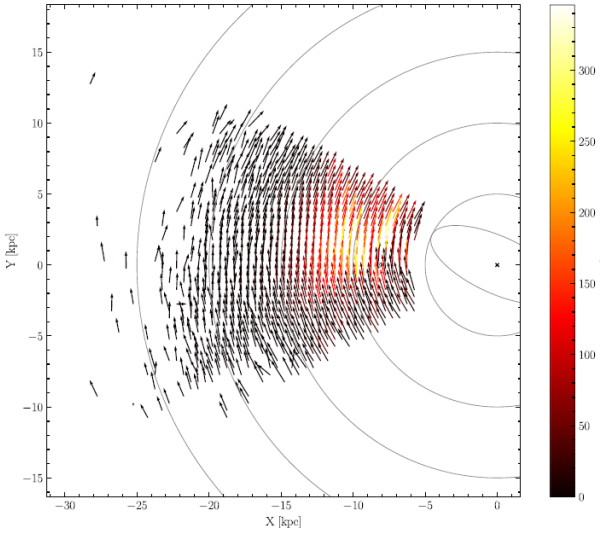


Rubin, *et al, 1978, ApJ. Lett.* ***225****, L107*

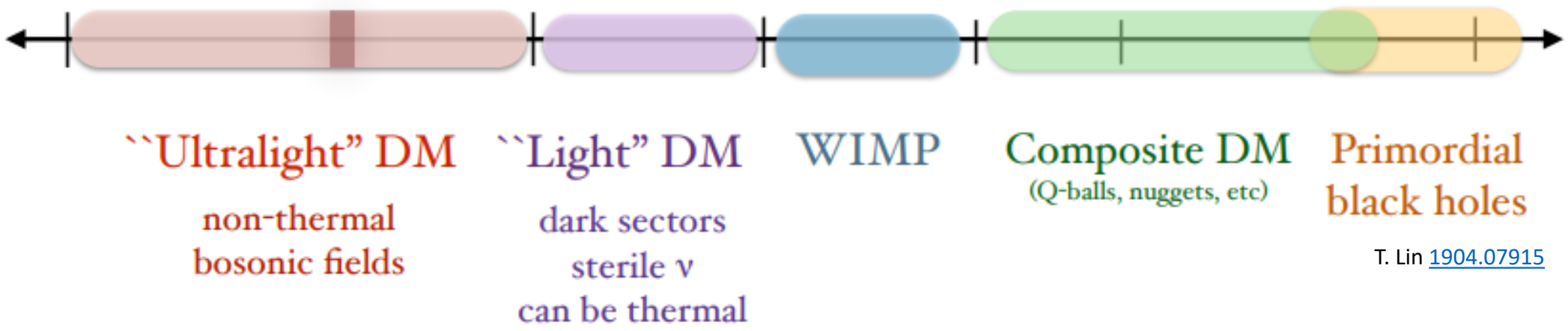


$\rho_0 = 0.447 \pm 0.004$ GeV/cm^3

Ou et al, 2024 MNRAS ***528****, 693*



ALL CREATURES GREAT AND SMALL COULD BE IT…



T. Lin [1904.07915](1904.07915)

← wave-like (bosons) | particle-like (fermions & bosons) →

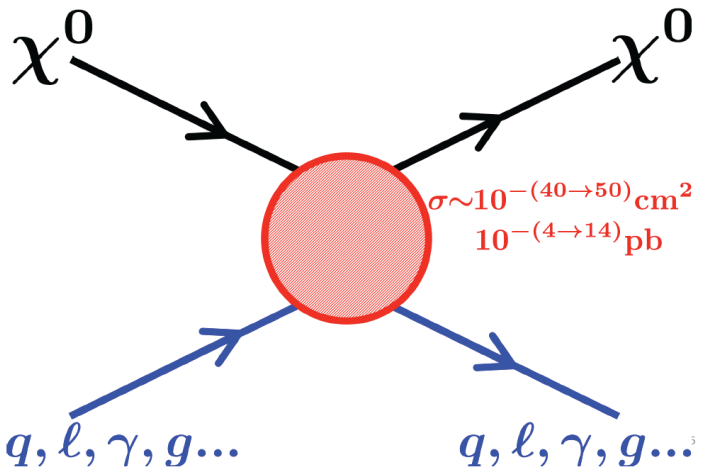
Weakly Interacting Massive Particles are the most studied dark matter candidate for two key reasons:

- New physics is needed at the electroweak scale to alleviate the 'hierarchy problem' ("why is the Higgs so light"?)
- Any new particles with weak-scale masses & couplings are 'naturally' produced with the right relic abundance

MINING FOR WIMPS WITH SCATTERING EXPERIMENTS

Electroweak particles with mass between ~1 GeV and 100 TeV solve the dark matter problem in all its dimensions: astrophysical, cosmological, particle physics

They must be stable, neutral, cold, interact via gravity – and, by construction, the weak force



WIMP-quark interaction

↓

WIMP-nucleon interaction

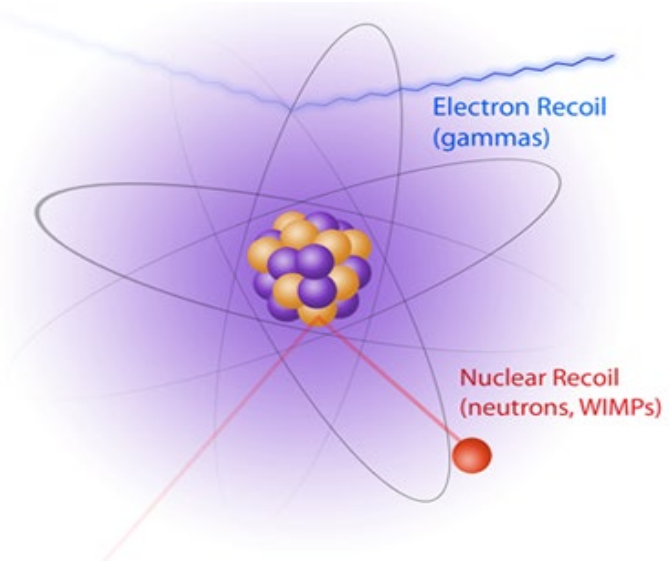
↓

WIMP-nucleus interaction

↓

Scattering rate:

$R = \phi\, \sigma_A\, N$



We seek to detect galactic DM particles using very sensitive detectors deep underground: "direct detection" – a very low-energy technique (keV), quite insensitive to the EW-scale physics (≫GeV) – broadband!

OUR QUIET POND IS THE NOBLE LIQUID XENON

Liquid xenon is an excellent medium for particle detection

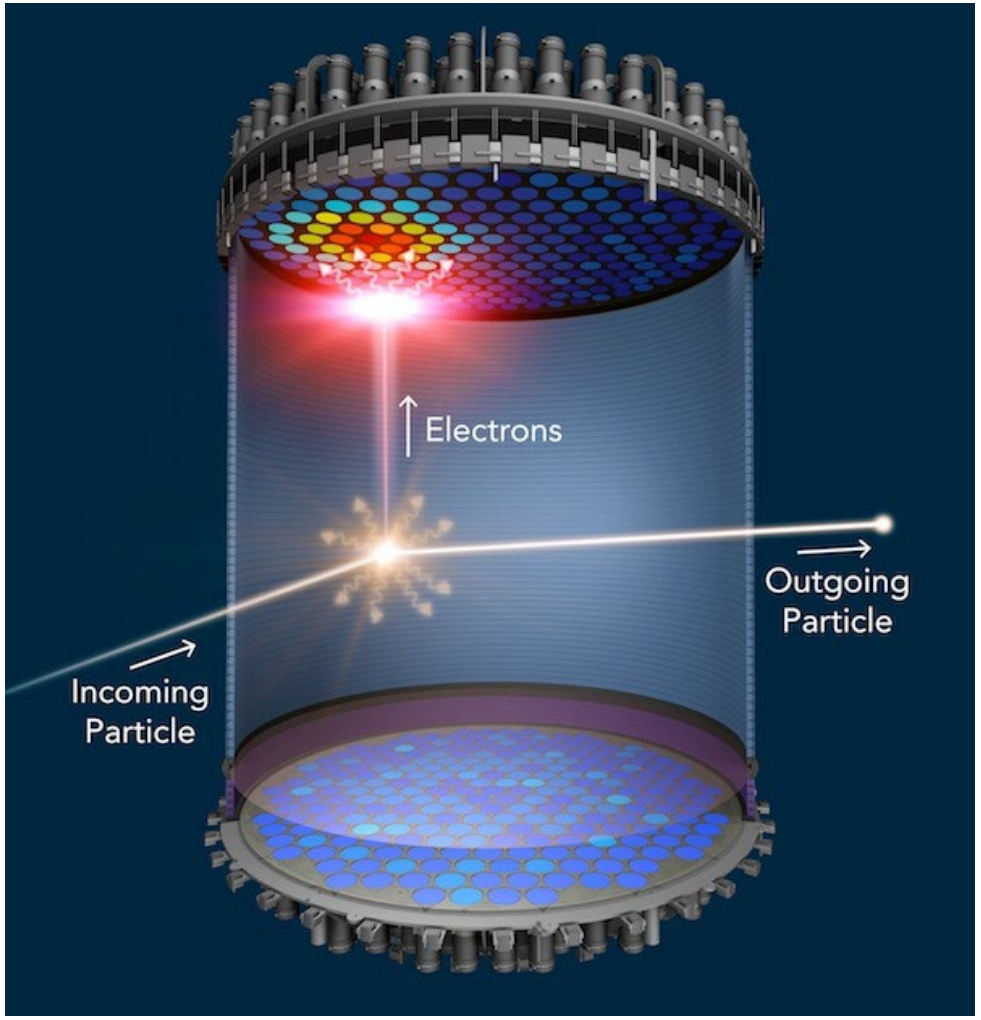
- High scintillation and ionisation yields: low detection threshold
- Heavy and dense material: effective self-shielding of external backgrounds
- A very quiet medium: very low internal backgrounds

Rich portfolio of isotopes: same chemistry, diverse nuclear physics

- Spin-independent interaction rate gains A^2 factor from scattering coherence
- Coherent elastic neutrino-nucleus scattering (CEvNS) with N^2 dependence
- Spin-dependent sensitivity via odd-neutron isotopes
- Several double-beta decay isotopes

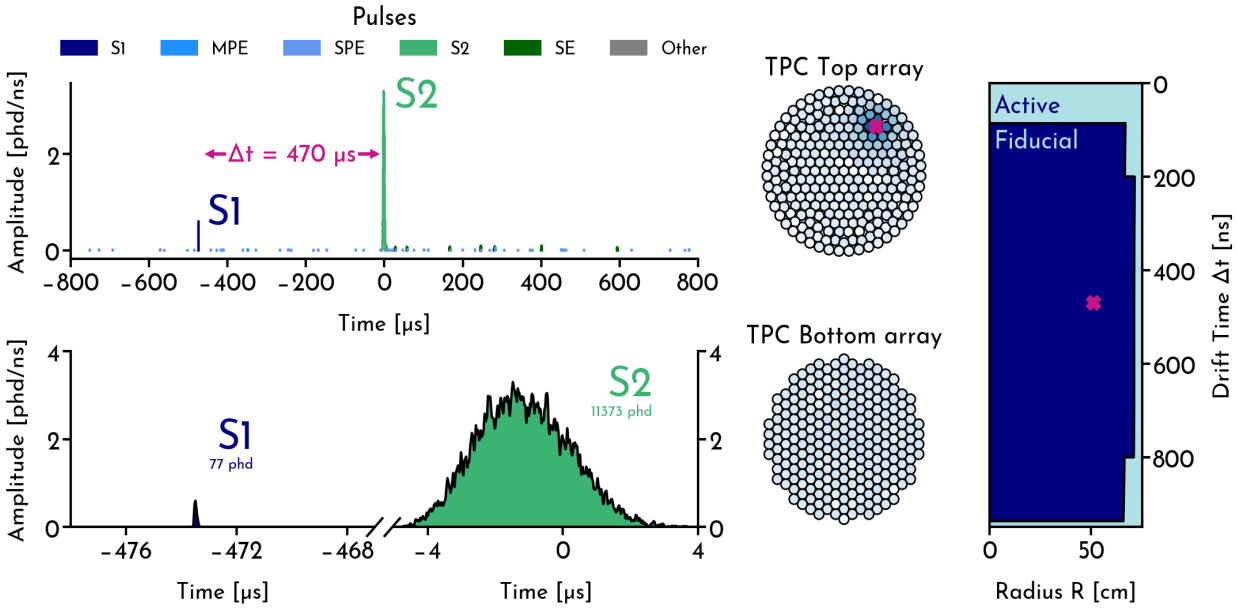
^{124}Xe	^{126}Xe	^{128}Xe	^{129}Xe	^{131}Xe	^{130}Xe	^{132}Xe	^{134}Xe	^{136}Xe
123.90589	125.90426	127.90353	128.9047	130.905083	129.90350	131.90415	133.90539	135.90722
0.10%	0.09%	1.91%	26.4%	21.2%	4.1%	26.9%	10.4%	8.90%
Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable

THE (DUAL-PHASE) XENON TIME PROJECTION CHAMBER



S1: Primary scintillation (VUV) in the liquid
S2: Secondary scintillation (electroluminescence) in the gas

Sensitive to single quanta of scintillation (S1) and ionisation (S2)



UK pioneered this technology through ZEPLIN programme at Boulby!

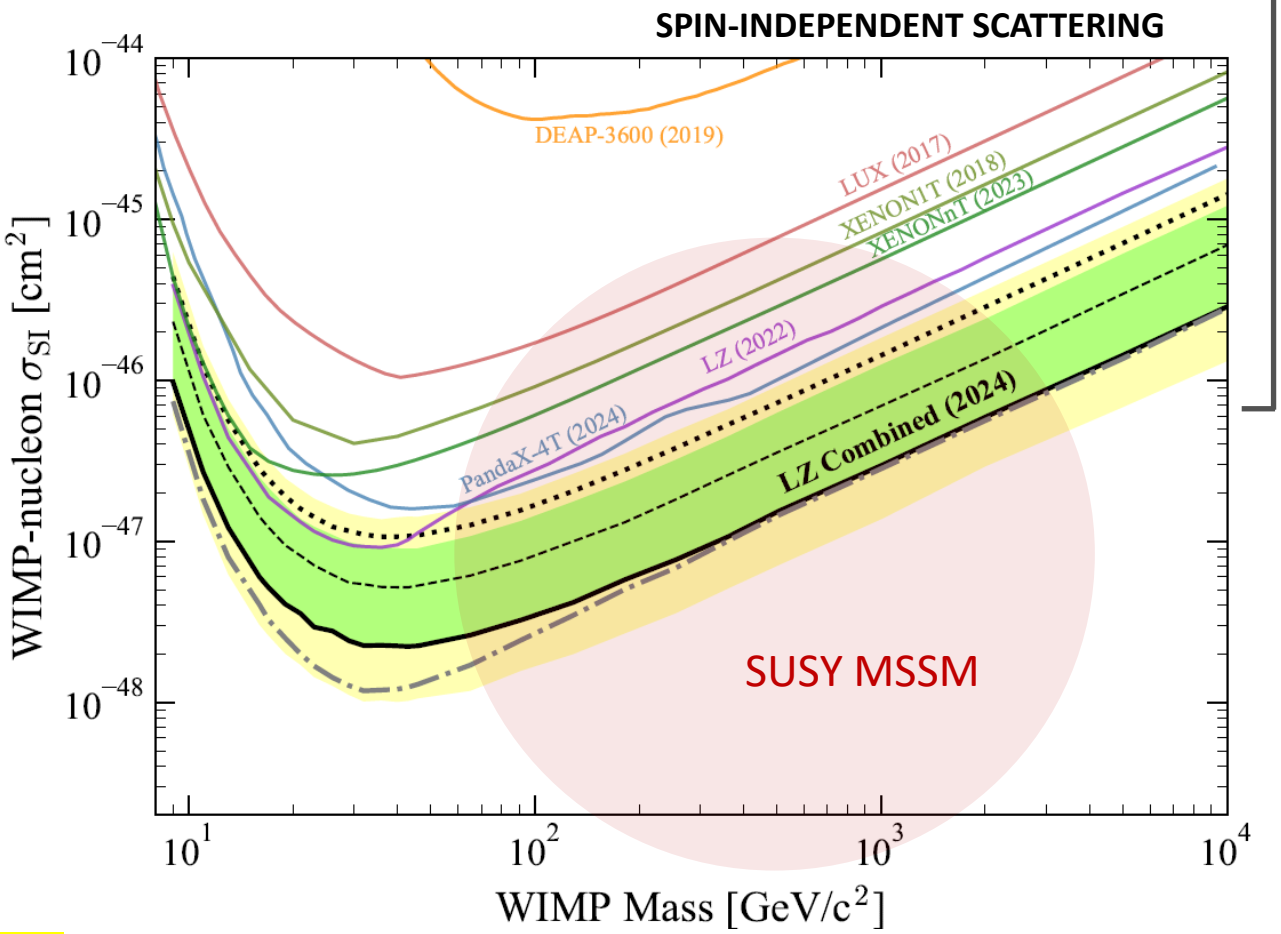
WIMP SEARCH STATUS

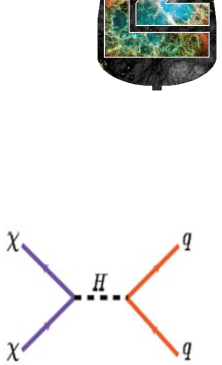
LZ continues to lead above a few GeV
Exposure so far: 4.2 tonne-years
(~1/3 of planned)

Peak sensitivity:
2×10^{-48} cm^2 @ 36 GeV

Four-fold improvement into new parameter space: continuing to squeeze minimal SUSY, and to directly constrain the coupling strength of dark matter to the Higgs

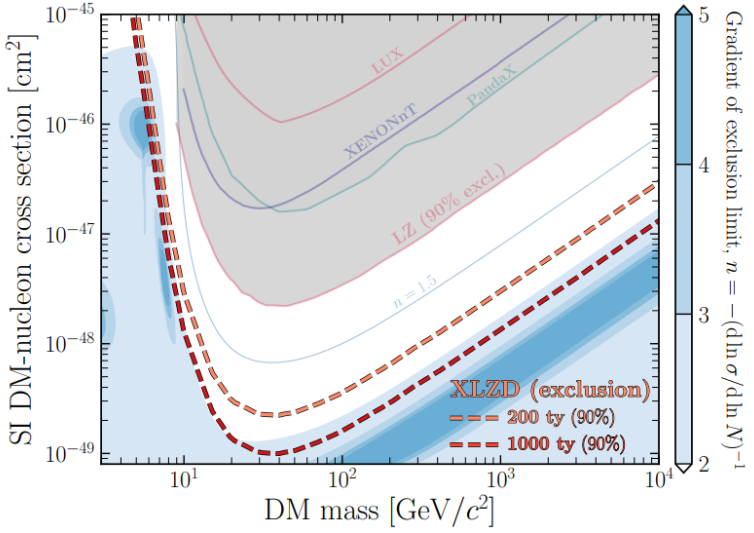
But we need hundreds of tonne-years to fully probe the accessible WIMP paradigm…

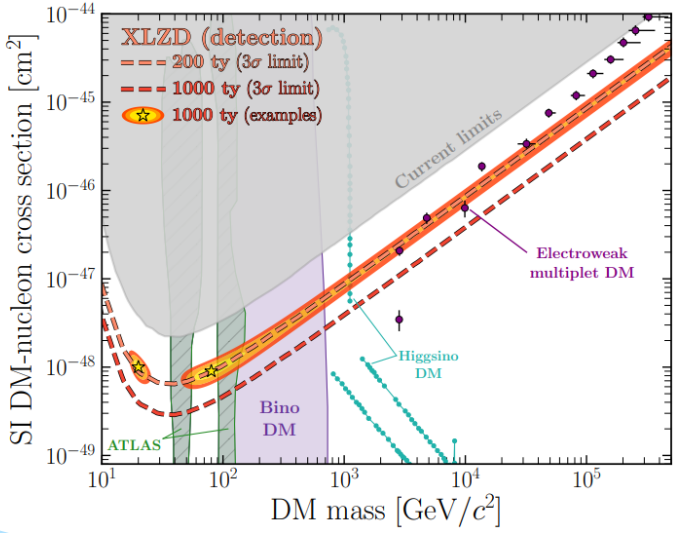




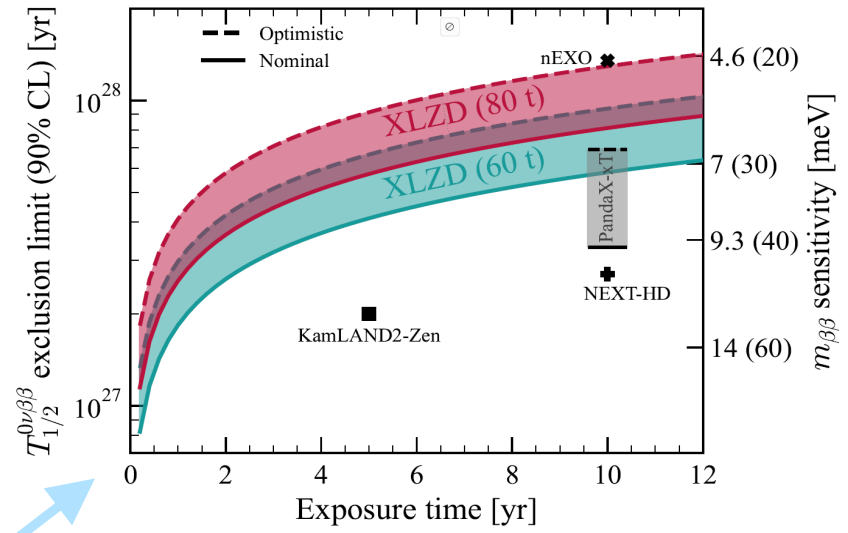
PRL 135 (2025)

A RARE EVENT OBSERVATORY BASED ON THE NOBLE LIQUID XENON





[XLZD Design Book](#) (2025)



[XLZD 0νββ sensitivity](#) (2025)

LXe-TPC
Active mass: 60-80 tonnes, 10x LZ
Diameter: 3.0 m, 2x LZ

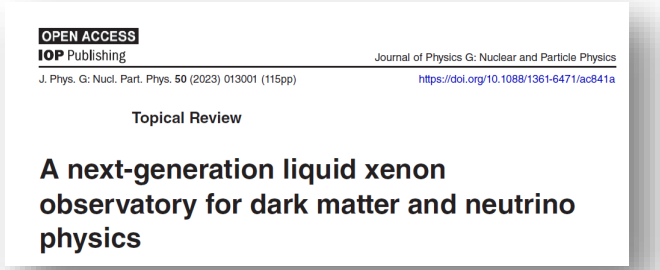
Dark Matter
WIMPs
Sub-GeV
Inelastic
Axion-like particles
Planck mass
Dark photons

Neutrino nature
Neutrinoless double beta decay
Neutrino magnetic moment
Double electron capture

Supernovae
Early alert
Supernova neutrinos
Multi-messenger astrophysics

Sun
pp neutrinos
Solar metallicity
^{7}Be, ^{8}B, hep

[Science White Paper](#) (2023)

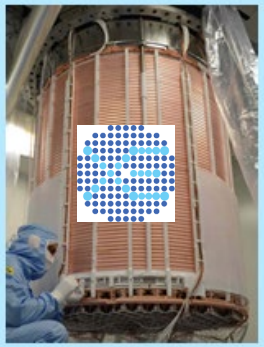

OPEN ACCESS
IOP Publishing
Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. 50 (2023) 013001 (115pp)
https://doi.org/10.1088/1361-6471/ac841a

Topical Review

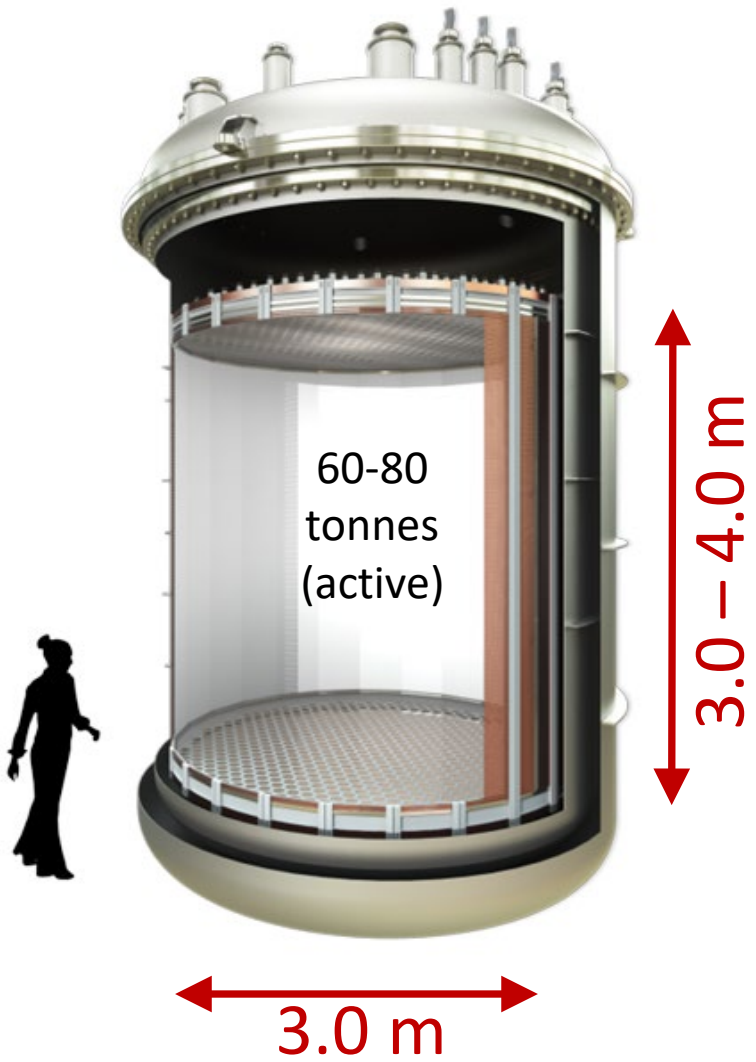
A next-generation liquid xenon observatory for dark matter and neutrino physics

XENON-LUX-ZEPLIN-DARWIN

- XLZD Consortium MoU between competing collaborations signed in 2021
- Collaboration Agreement signed in 2024 by 163 senior members from 70+ institutions in 17 countries
- Our team(s) are still operating competitively the largest LXe-TPCs: LZ and XENON-nT
  - Two leading experiments operating underground
  - Experience & track record of two major collaborations
- Ongoing activities
  - Pre-Conceptual Design and sensitivity reports posted
  - Working Groups on science, technical, siting, …
  - “Global WBS” in place to develop and cost project
  - Evaluating design options and key materials

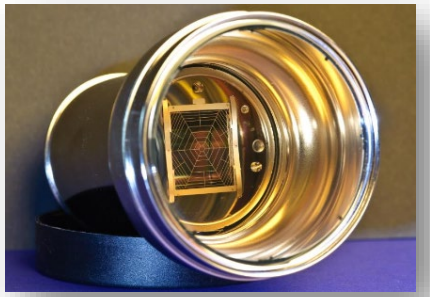


XLZD



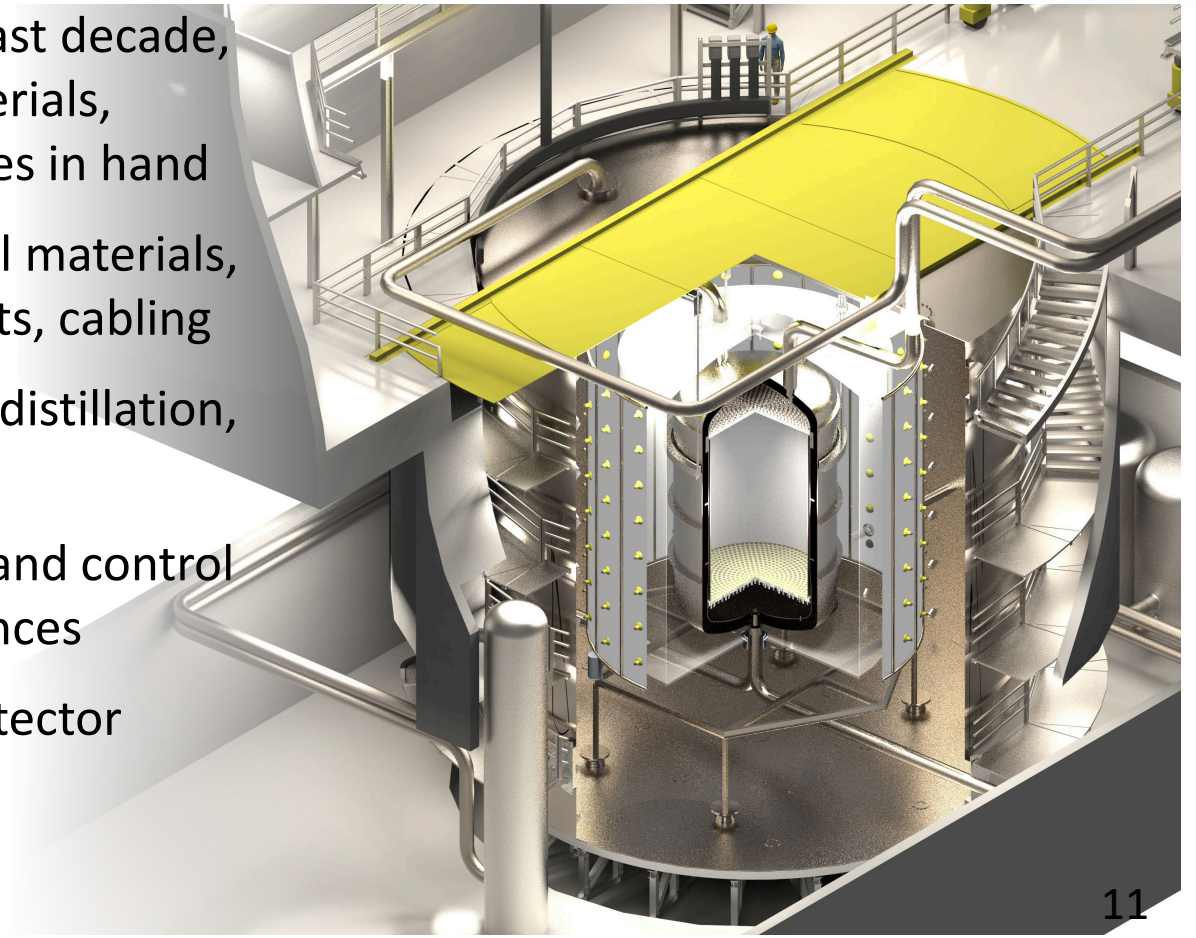
Designed for large exposures, up to 1000 tonne-years (systematic uncertainty limit at the neutrino 'floor')

Further reduction in backgrounds needed: longer operation plus $0\nu\beta\beta$-decay sensitivity (Bi-214)



LZ & XnT built over the last decade, further advances in materials, components & techniques in hand

- Better PMTs, structural materials, electronics components, cabling
- Radon barriers, radon distillation, radon tagging
- Better understanding and control of accidental coincidences
- Better vetoes: Skin Detector and Outer Detector



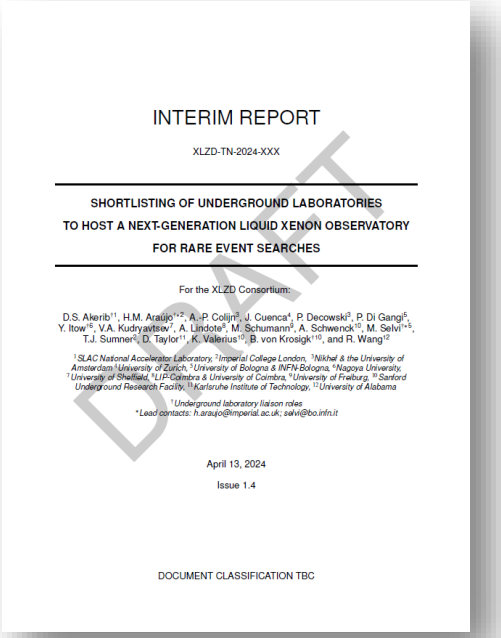
HOST LABORATORY

Five laboratories expressed interest, four were shortlisted based on ability to meet XLZD technical requirements: **Boulby, LNGS, SNOLAB, SURF**

Site selection involves both technical and political factors

- Depth: backgrounds for DM and $0\nu\beta\beta$-decay science
- Access: vertical (shaft) or horizontal (tunnel)
- Space: required footprint is substantial (1000-2000 m^2)
- Timeline: competitive “first dark”
- Investment in XLZD by host nation

The combination of quality space, early interest from STFC, UKRI & DSIT, and the possibility of major UK investment in XLZD means the UK plan is very compelling


INTERIM REPORT

XLZD-TN-2024-XXX

SHORTLISTING OF UNDERGROUND LABORATORIES TO HOST A NEXT-GENERATION LIQUID XENON OBSERVATORY FOR RARE EVENT SEARCHES

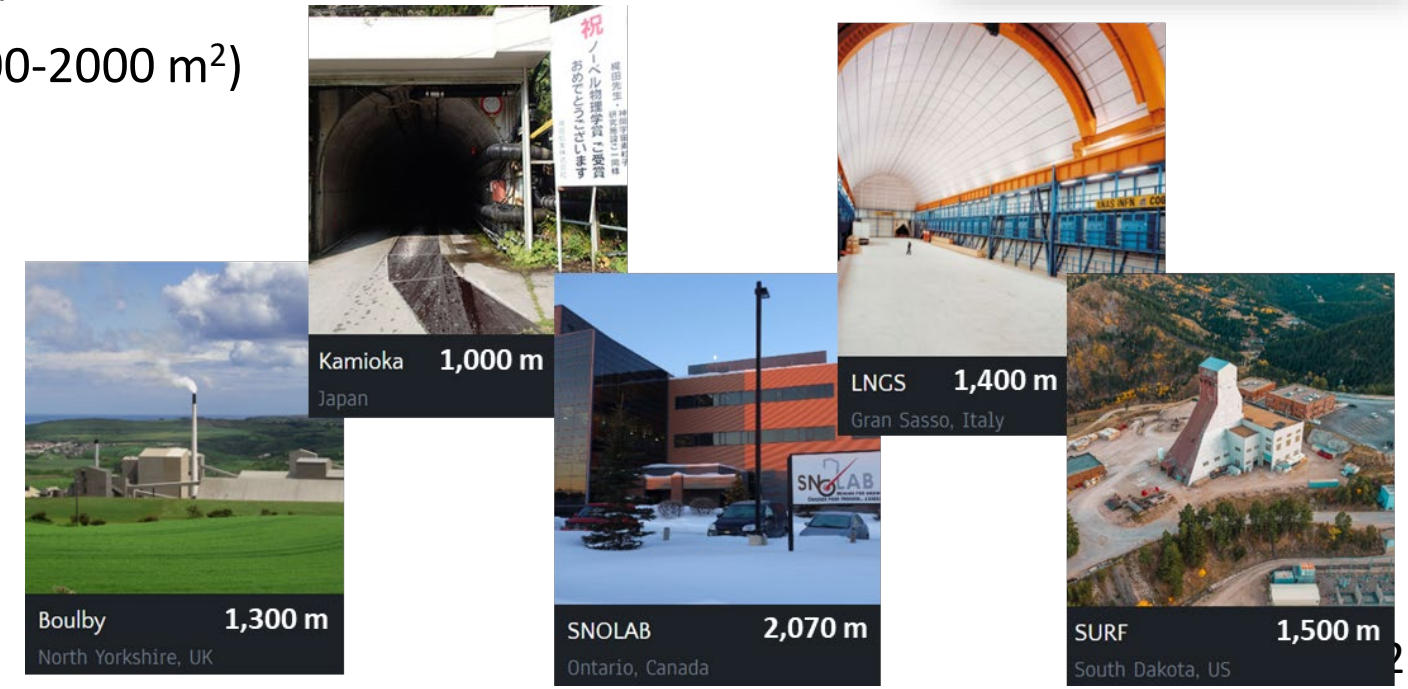
For the XLZD Consortium:

DRAFT

April 13, 2024

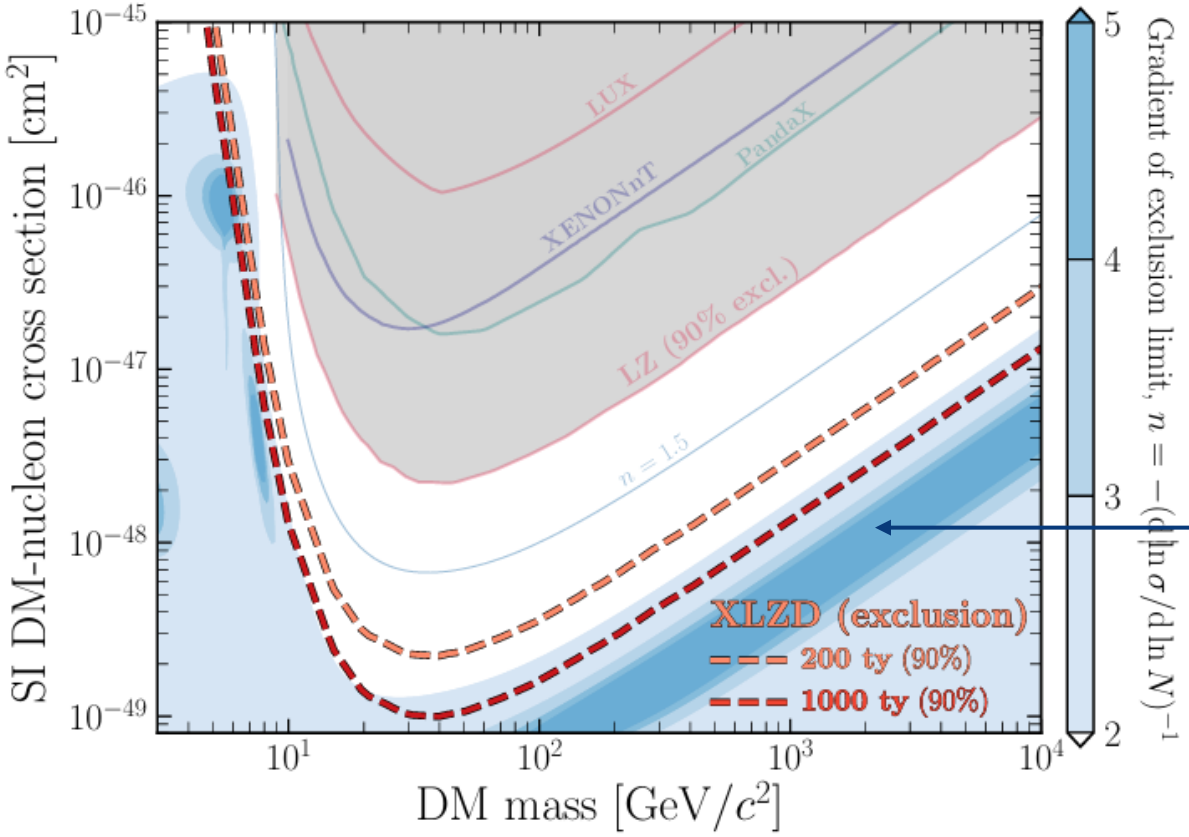
Issue 1.4

DOCUMENT CLASSIFICATION TBC



DARK MATTER SENSITIVITY

Mission statement: probe the entire range of accessible parameter space for thermal WIMPs (2 GeV – 100 TeV) with discovery sensitivity down to the neutrino fog



Explore fully a "natural coupling" of dark matter to the Higgs boson with 3σ discovery sensitivity

Probe spin-independent, spin-dependent and other interactions described by the NR-EFT operators, reaching further beyond the Standard Model

"neutrino fog" where astrophysical neutrino interactions (CEvNS) will obscure a WIMP signal

2410.17137

DARK MATTER SENSITIVITY

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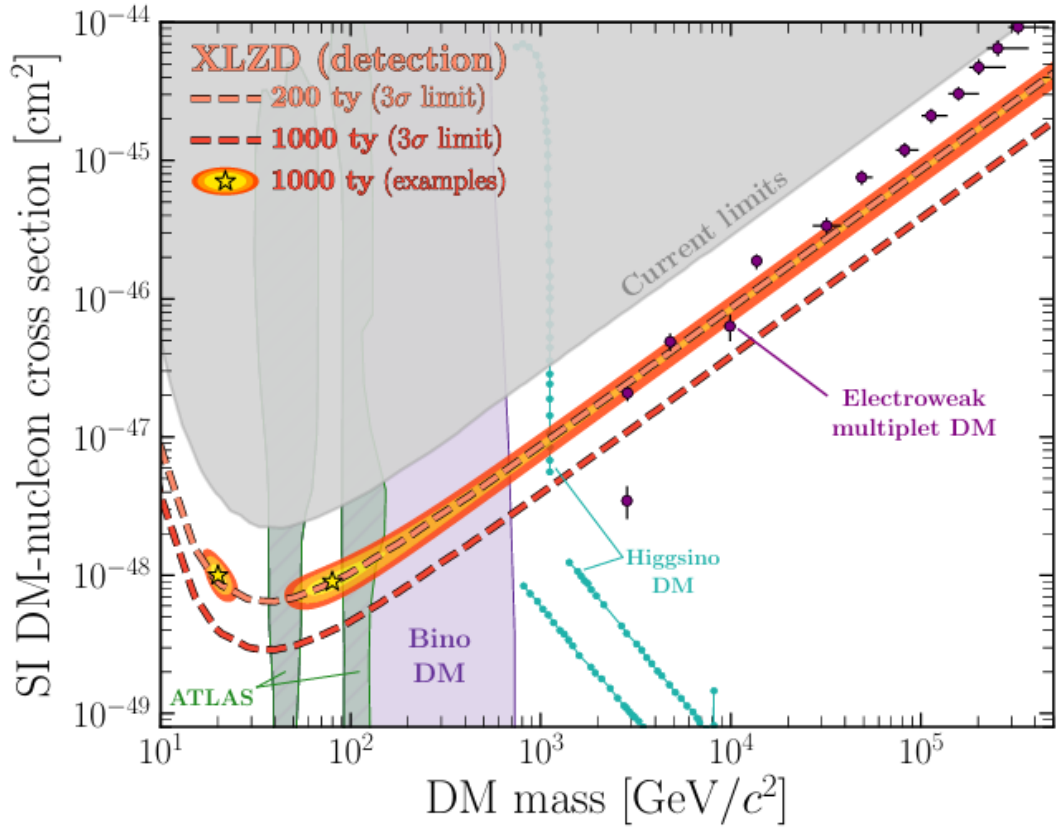

Probe compelling Bino & Higgsino models

Probe (at last!) the "minimal dark matter" model – this canonical WIMP is a member of an electroweak multiplet with interactions mediated by the SM gauge bosons and the Higgs – no new mediators

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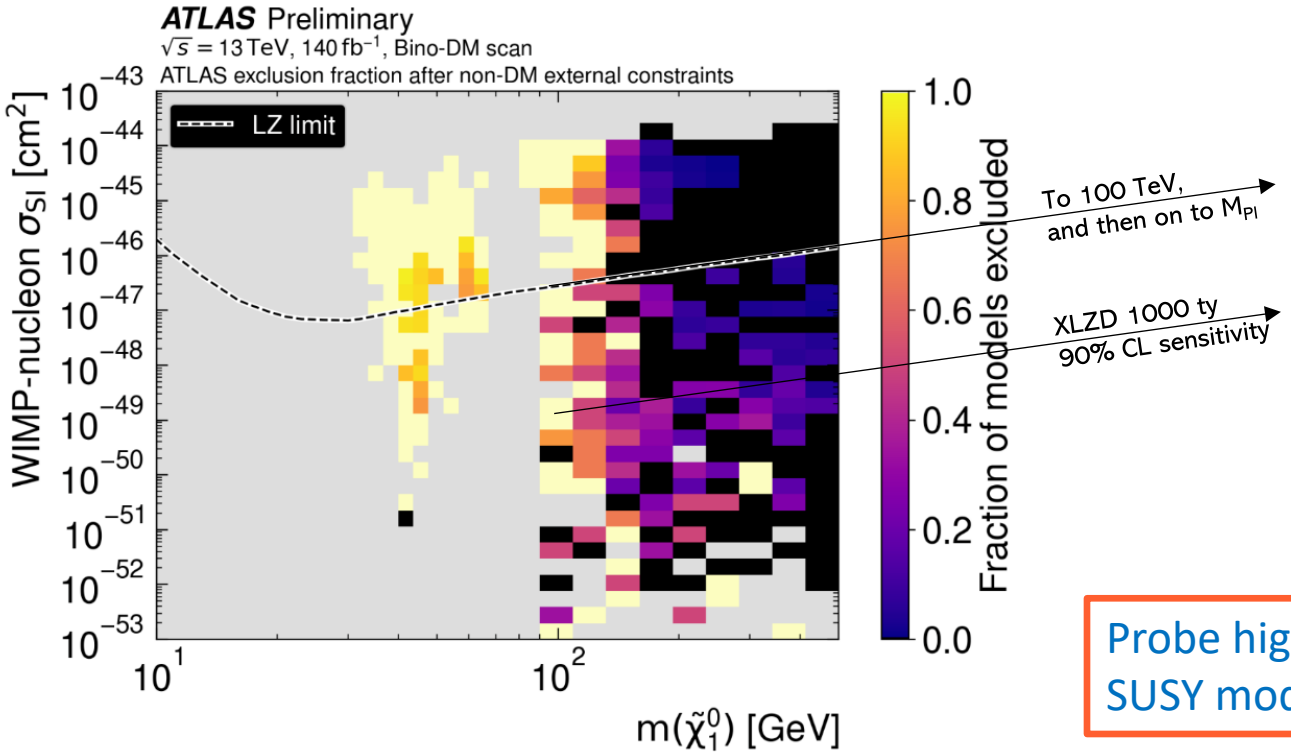
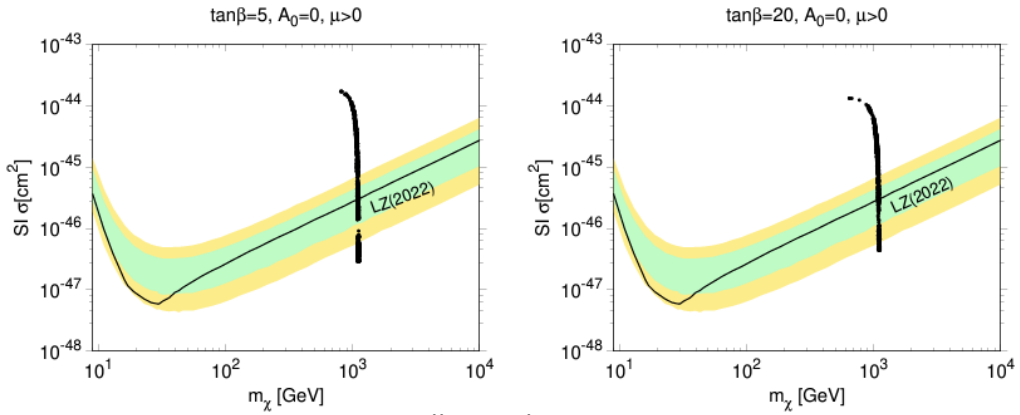
DARK MATTER SENSITIVITY

Mission statement: probe the entire range of accessible parameter space for thermal WIMPs (2 GeV – 100 TeV) with discovery sensitivity down to the neutrino fog





Ellis *et al.*, 2210.16337

Probe higher-energy (less natural, i.e. more fine-tuned) SUSY models in complementarity to the LHC

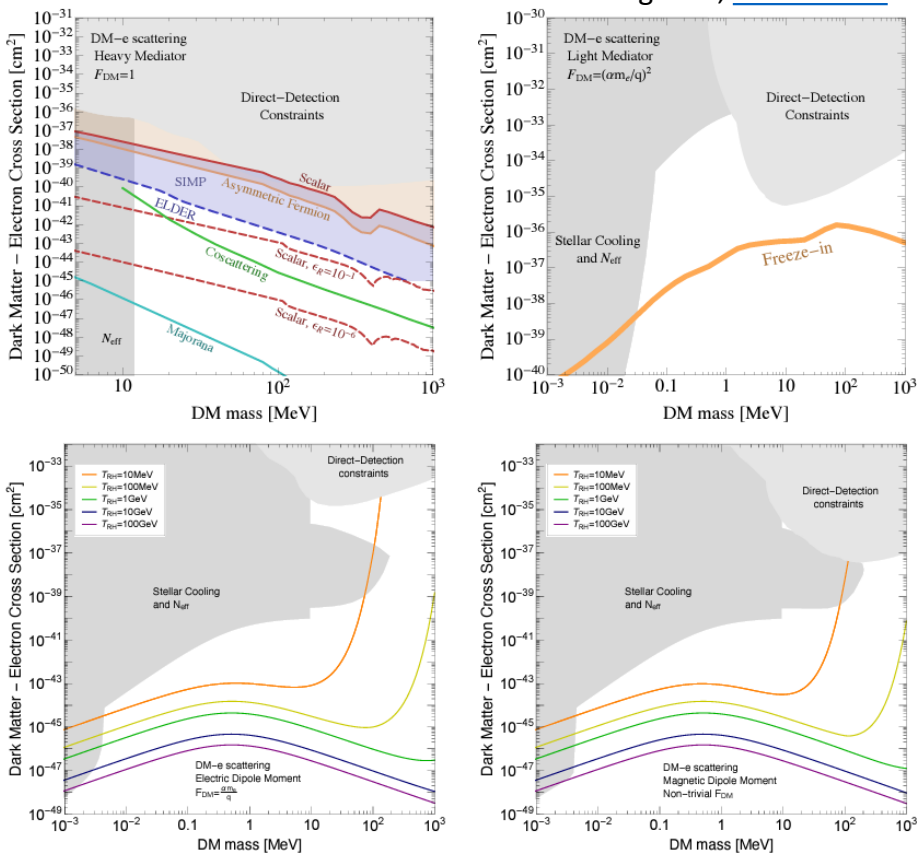
https://atlas.cern/Updates/Physics-Briefing/SUSY-Dark-Matter

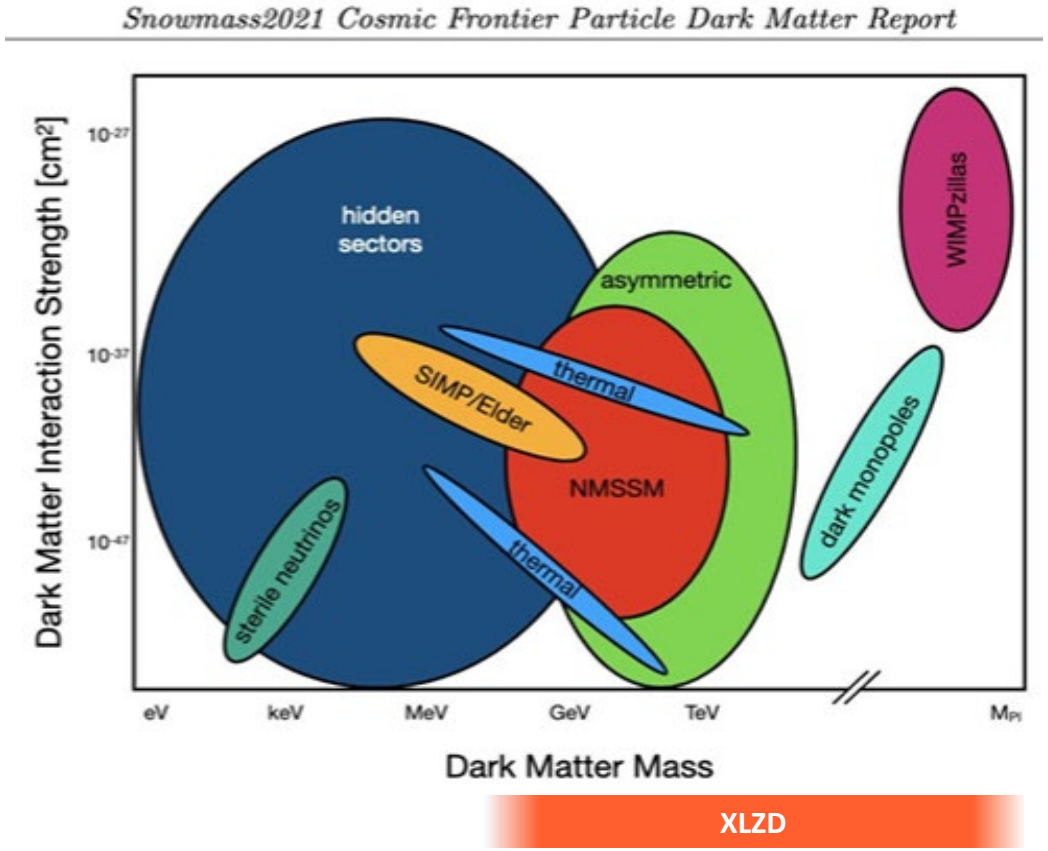
2410.17137

DARK MATTER SENSITIVITY – ALL CREATURES…

Mission statement: keep an open mind!

Essig et al, 2203.08297



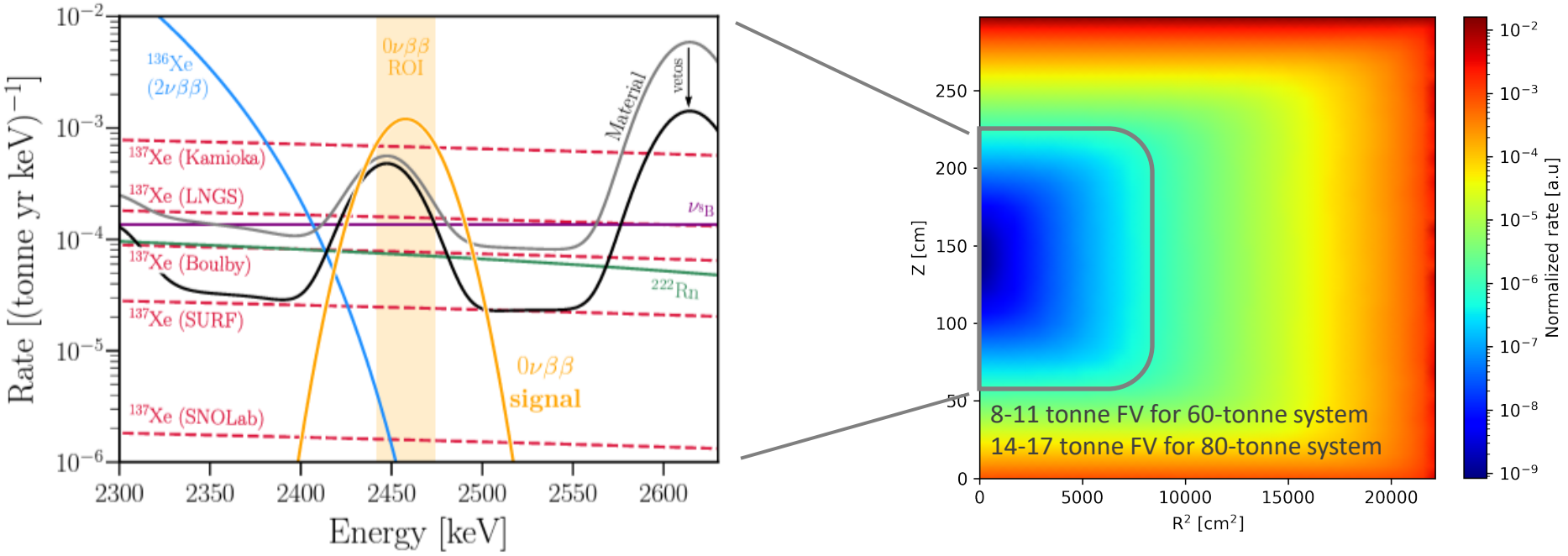


Probe interactions for non-thermal sub-GeV DM, and all the way up to the Planck mass, scattering off nuclei or electrons

0νββ-DECAY SENSITIVITY

Mission statement:
probe fully the inverted mass hierarchy

A change in paradigm: trade-off component radioactivity for self-shielding in a natural abundance target

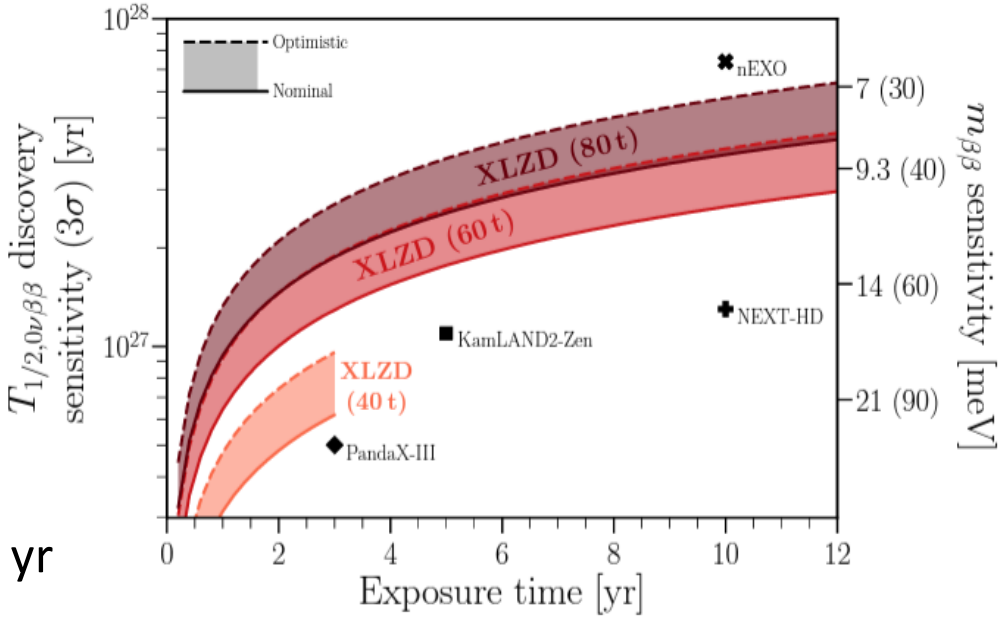


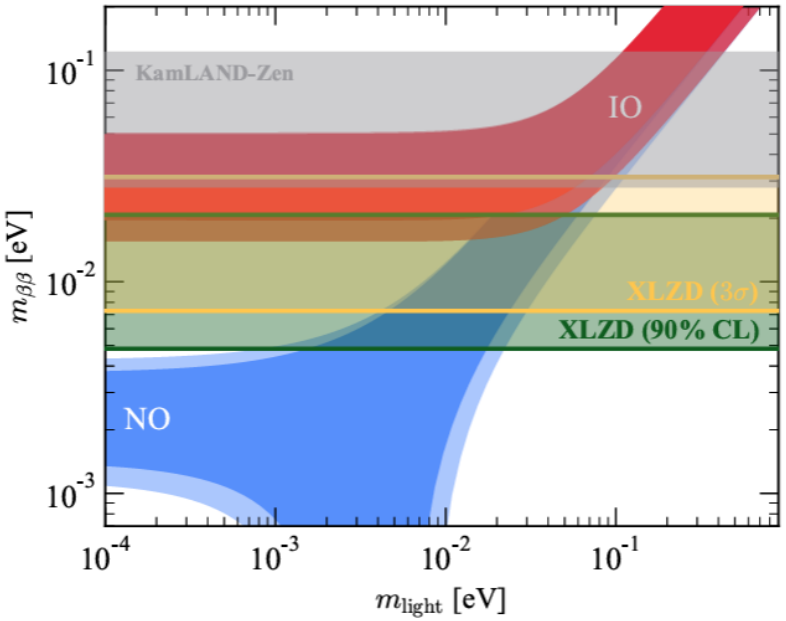
"Neutrinoless Double Beta Decay Sensitivity of the XLZD Rare Event Observatory": 2410.19016

0νββ-DECAY SENSITIVITY

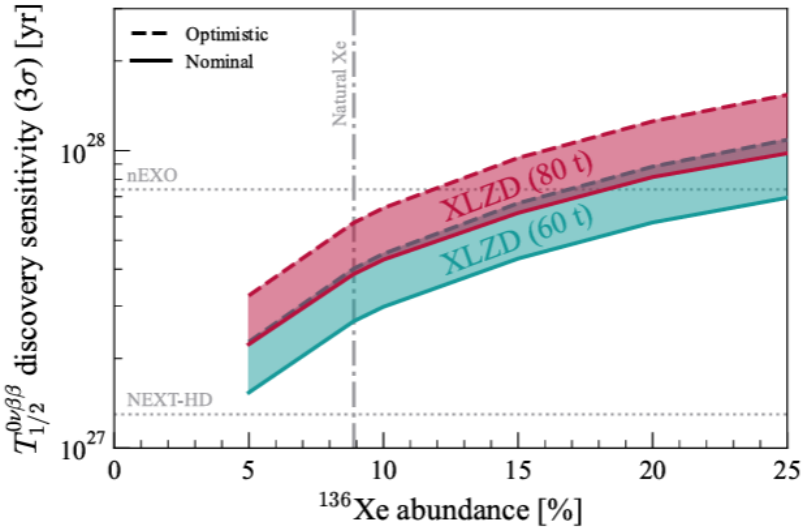
Mission statement:
probe fully the inverted mass hierarchy

- Competing with the best dedicated ^{136}Xe-based experiments: effective Majorana mass $m_{\beta\beta} \sim$ 7-30 meV, $T_{1/2} \sim$ 0.3-0.6x10^{28} yr





One last dial available:
partial enrichment,
pushing towards
$T_{1/2} \sim$ 1 x 10^{28} years



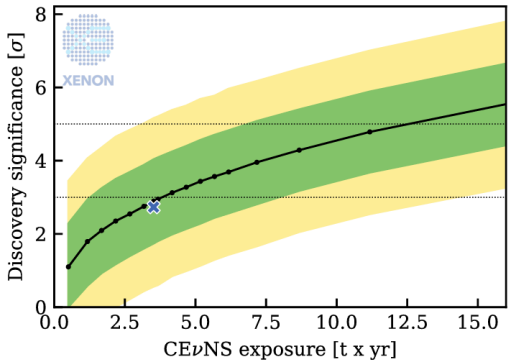
2410.19016

ASTROPHYSICAL NEUTRINOS

A unique observatory for MeV-scale astrophysical neutrinos through keV-scale nuclear- and electron-recoil signatures

SOLAR NEUTRINOS (^{8}B)

~90 events per tonne-year above 1 keVnr, to provide an independent measurement of the total flux



Current-generation experiments seeing "hints"

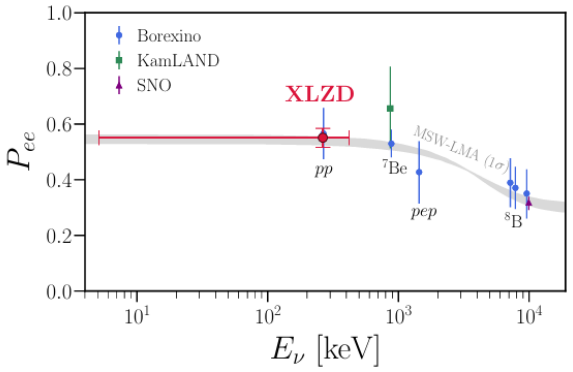
→ *Also a great calibration for a supernova detection*

GALACTIC SUPERNOVA

O(100) events from a Type II core-collapse supernova at 10 kpc within a 10-s window

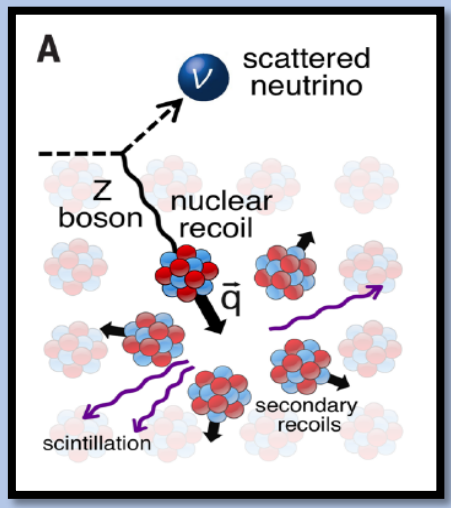
SOLAR NEUTRINOS (pp)

pp flux via ν-e elastic scattering to 0.15% with 300 tonne-years, constraining solar luminosity and ν_e survival probability at low energy



COHERENT n-N SCATTERING

Flavour-blind interaction, allows reconstruction of the total neutrino flux



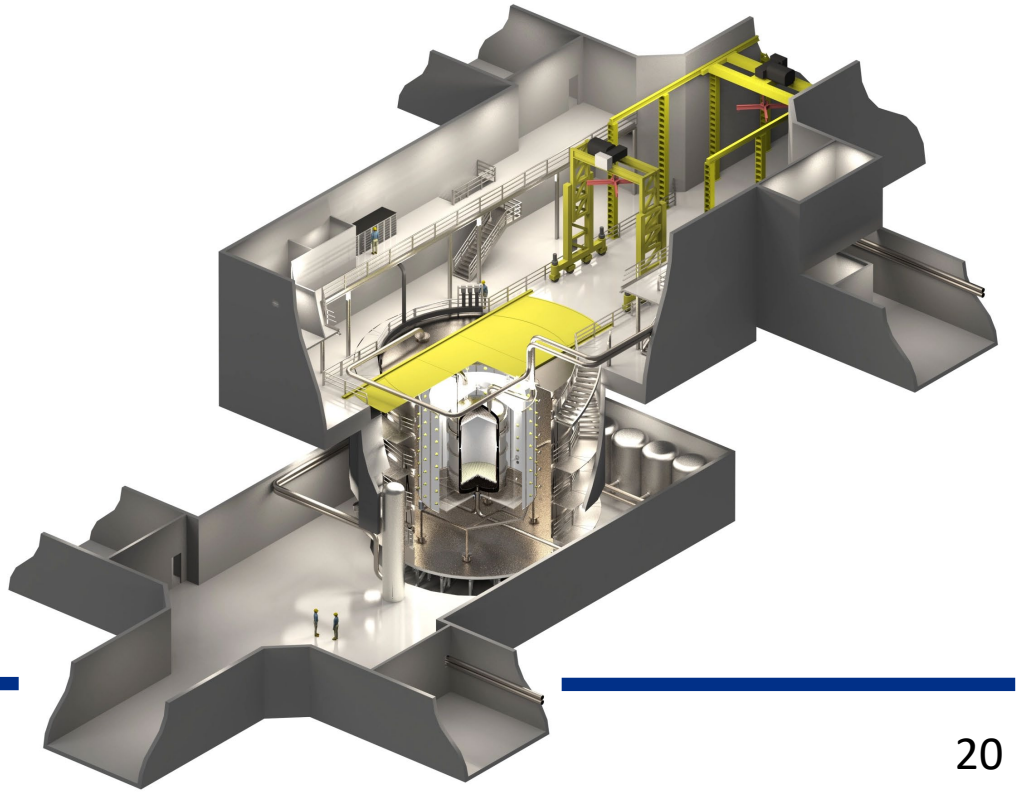
First CEvNS detection by COHERENT collaboration using man-made neutrinos

ATMOSPHERIC NEUTRINOS

First measurement at low energies (≲100 MeV): our neutrino floor!

XLZD@BOULBY

COULD WE HOST IN THE UK?



ELEVATOR PITCH (A LONG ELEVATOR…)

The science mission

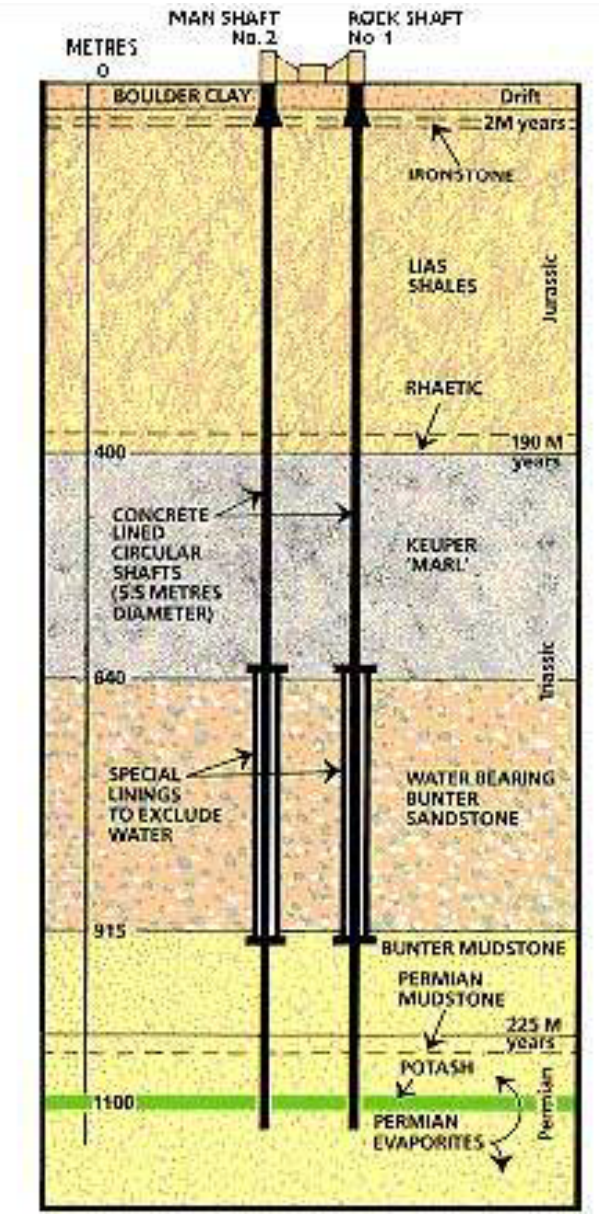
XLZD is an **underground observatory for rare particle interactions and nuclear decays,** aiming to make paradigm-shifting discoveries related to the composition of the universe:

- Revealing the nature of particle **dark matter,** and so explain the long-standing mystery of the missing mass of the cosmos;
- Probing the existence of the **neutrinoless double-beta decay** process which could explain why the known mass of the universe is made of matter rather than antimatter;
- Studying **astrophysical neutrinos** from the sun and galactic supernova explosions.

The societal mission

Hosting XLZD at a major new facility at Boulby represents an excellent opportunity to

- **Invest in North East England** – bringing economic returns to the region;
- **Enthuse and upskill its young people** in an area with limited science opportunities and infrastructure – and contributing to address a fast-growing skills gap;
- Enhance the **UK's global profile, reputation and leadership** in scientific research.



XLZD@BOULBY: THE EARLY YEARS

0. Xenon Futures R&D project (2019-25)

- Technical R&D around LXe-TPC technologies

1. Boulby Feasibility Study (2019-21)

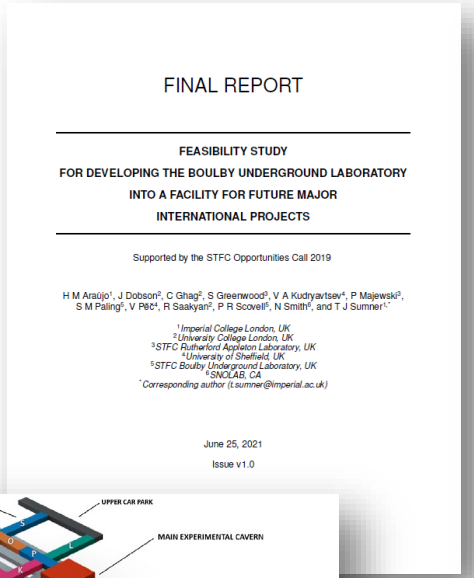
- Resonated with the STFC Strategic Delivery Plan 2020-25
- And with the (then) Government strategy (“Levelling up”, …)

2. Boulby Development Project (2022-25+) (£2.8M+)

- Funded through UKRI Infrastructure Fund (Preliminary Activity)
- Developing facility design
- Additional funds awarded for Stage 1 excavations (~£6.5M)

3. XLZD@Boulby Pre-Construction Project (2024-27) (£8.7M)

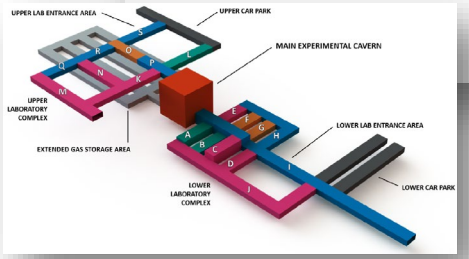
- Funded through UKRI Infrastructure Fund (Preliminary Activity)
- **Broad objectives:**
  - Technical design of UK hardware systems and their interfaces to facility and partner contributions
  - Planning and capacity-building in key areas (e.g. clean manufacture, skills pipeline, sustainability)
  - Working with international partners to build the XLZD collaboration and international project
  - To position the UK to host the experiment at Boulby


FINAL REPORT

FEASIBILITY STUDY
FOR DEVELOPING THE BOULBY UNDERGROUND LABORATORY
INTO A FACILITY FOR FUTURE MAJOR
INTERNATIONAL PROJECTS

Supported by the STFC Opportunities Call 2019

June 25, 2021
Issue v1.0



XLZD@BOULBY DEVELOPMENT

XLZD-UK "Pre-Construction" project funded by the UKRI Infrastructure Fund

XLZD-UK PRE-CONSTRUCTION PROJECT

A TEAM OF AROUND 80 PHYSICISTS & ENGINEERS IN 13 UK INSTITUTES

XLZD@BOULBY PROPONENTS

58 SENIOR RESEARCHERS IN 21 INSTITUTES

H. M. Araújo*[1], D. Bauer[1], C. Boehm[2], A. Boston[3], S. Burdin[3], X. Calmet[4], G. Casse[3], J. Coleman[3], D. Colling[1], D. Costanzo[5], A. Cottle[6], G. J. Davies[1], A. De Santo[4], J. Dobson[7], J. Ellis[7], M. Fairbairn[7], H. Flaecher[8], H. Fox[9], C. Frenk[10], C. Ghag[6], E. Hardy[3], J. Hays[11], S. Jones[5,12], A. Kaboth[13], A. Khan[14], L. L. Kormos[9], H. Kraus[15], V. A. Kudryavtsev[5], P. Kyberd[14], M. Labiche[16], I. Lazarus[16], P. A. Majewski[17], J. March-Russell[15], C. McCabe[7], A. Mehta[3], D. Muenstermann[9], A. StJ. Murphy[2], K. Nikolopoulos[18], K. Palladino[15], S. Paramesvaran[8], C. Patrick[2], K. Petridis[8], T. Potter[19], R. Saakyan[6], P. Scovell[17], S. Shaw[2], J. Smirnov[3], M. Spannowsky[10], T. J. Sumner[1], A. Szelc[2], D. R. Tovey[5], Y. Uchida[1], C. Uhlemann[20], M. van der Grinten[17], J. Vossebeld[3], D. Waters[6], S. West[13], and I. Zavala[21]

[1]*Imperial College London,* [2]*University of Edinburgh,* [3]*University of Liverpool,* [4]*University of Sussex,* [5]*University of Sheffield,* [6]*University College London,* [7]*King's College London,* [8]*University of Bristol,* [9]*Lancaster University,* [10]*Durham University,* [11]*Queen Mary, University of London,* [12]*Nuclear Advanced Manufacturing Research Centre, University of Sheffield,* [13]*Royal Holloway, University of London,* [14]*Brunel University,* [15]*Oxford University,* [16]*STFC Daresbury Laboratory,* [17]*STFC Rutherford Appleton Laboratory,* [18]*Birmingham University,* [19]*Cambridge University,* [20]*Newcastle University,* [21]*Swansea University*

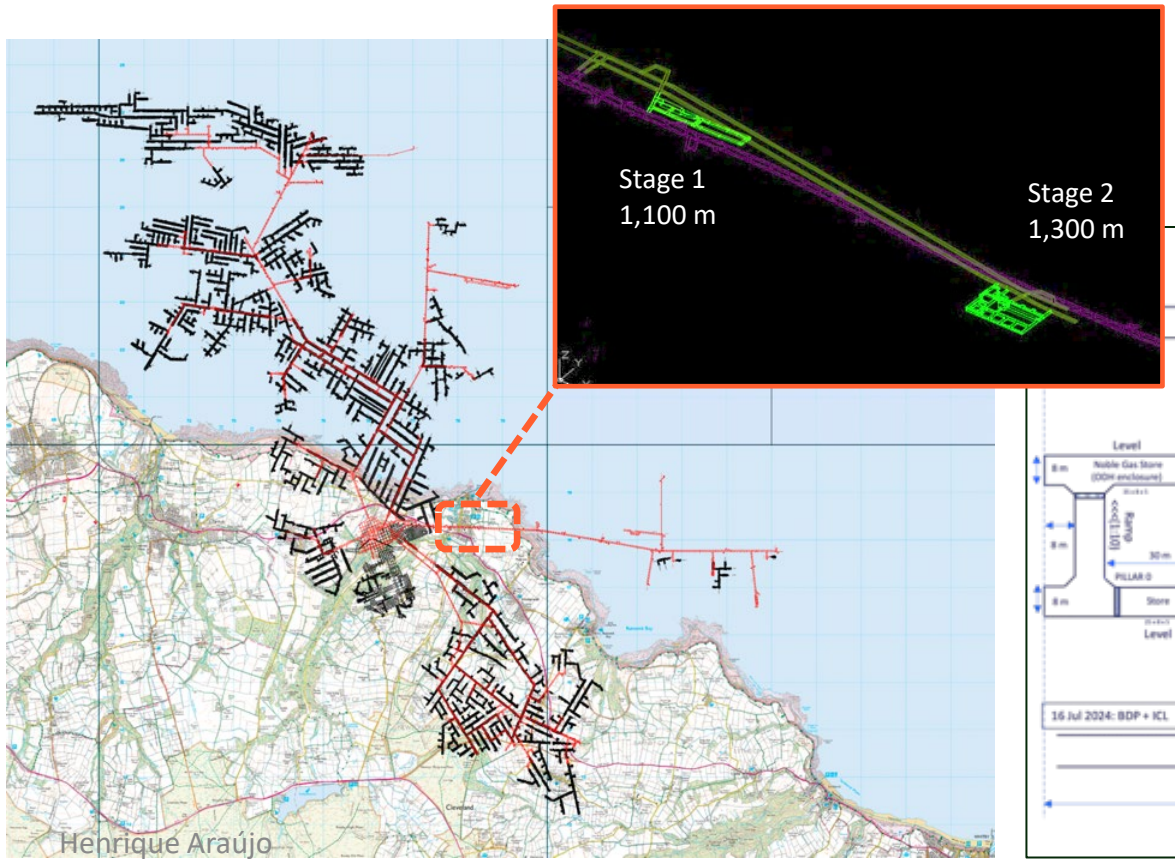
KEY UK PARTNERS

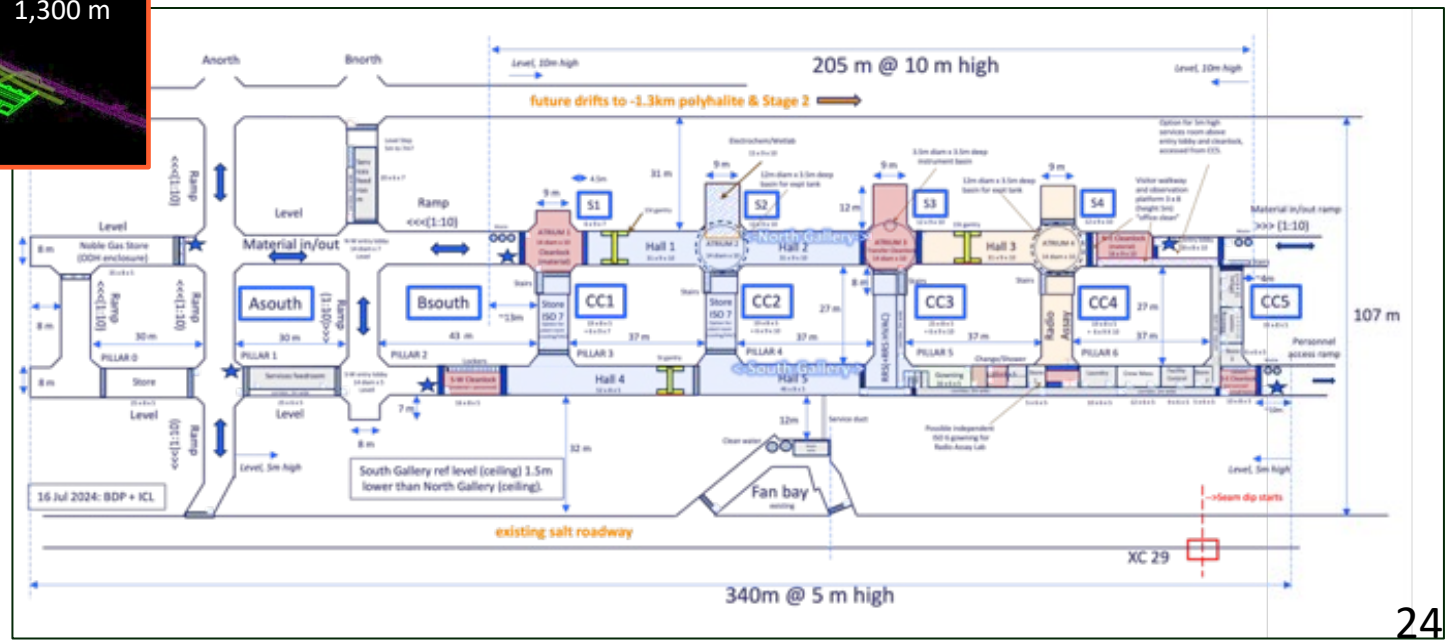
- STFC Boulby Underground Laboratory
- STFC Technology Department
- RAL-PPD Project Management Office
- Advanced Manufacturing Research Centre (AMRC)
- ICL-Boulby
- BUTTON, DarkSPHERE, …

BOULBY STAGE 1: MANUFACTURING FACILITY

Stage 1 in salt (1,100 m): Clean Manufacturing Facility, beneficial occupancy 2028+ (XLZD + others)

- Manufacture past-the-bottleneck: radon-reduced cleanrooms, electrochemistry, radioassay, ...
- A major new facility in its own right, for science beyond XLZD





BOULBY STAGE 1: MANUFACTURING

Stage 1 in salt (1,100 m): Clean Manufacturing Facility, beneficial c

- Manufacture past-the-bottleneck: radon-reduced cleanrooms, el
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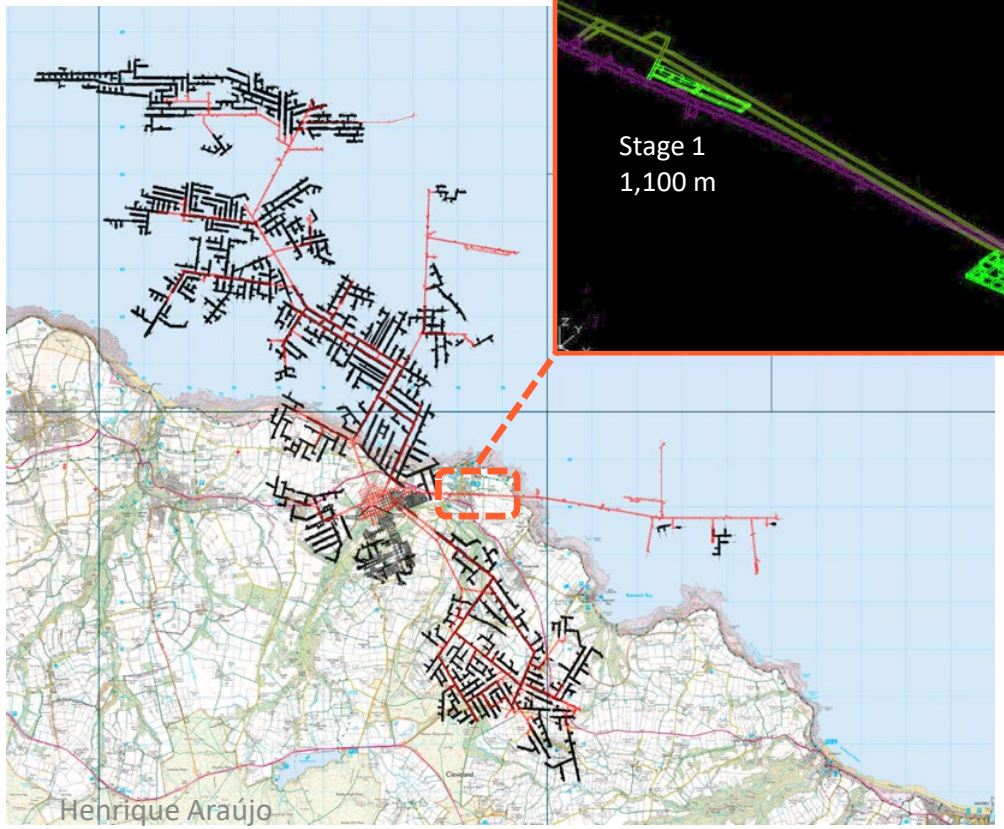
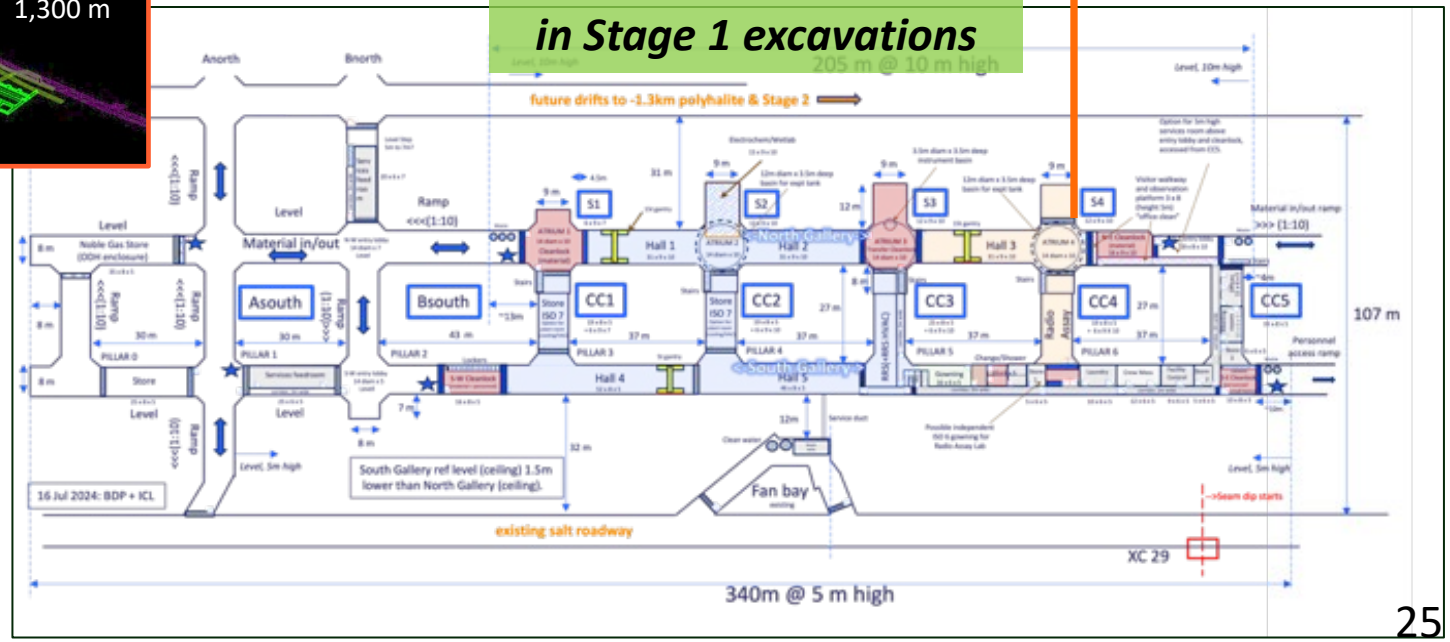


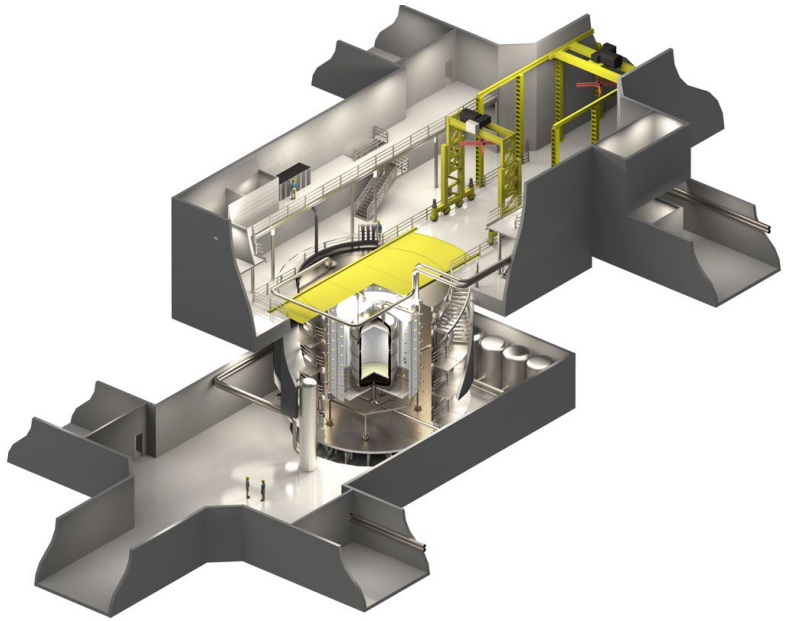
STFC has invested £6.5M in Stage 1 excavations

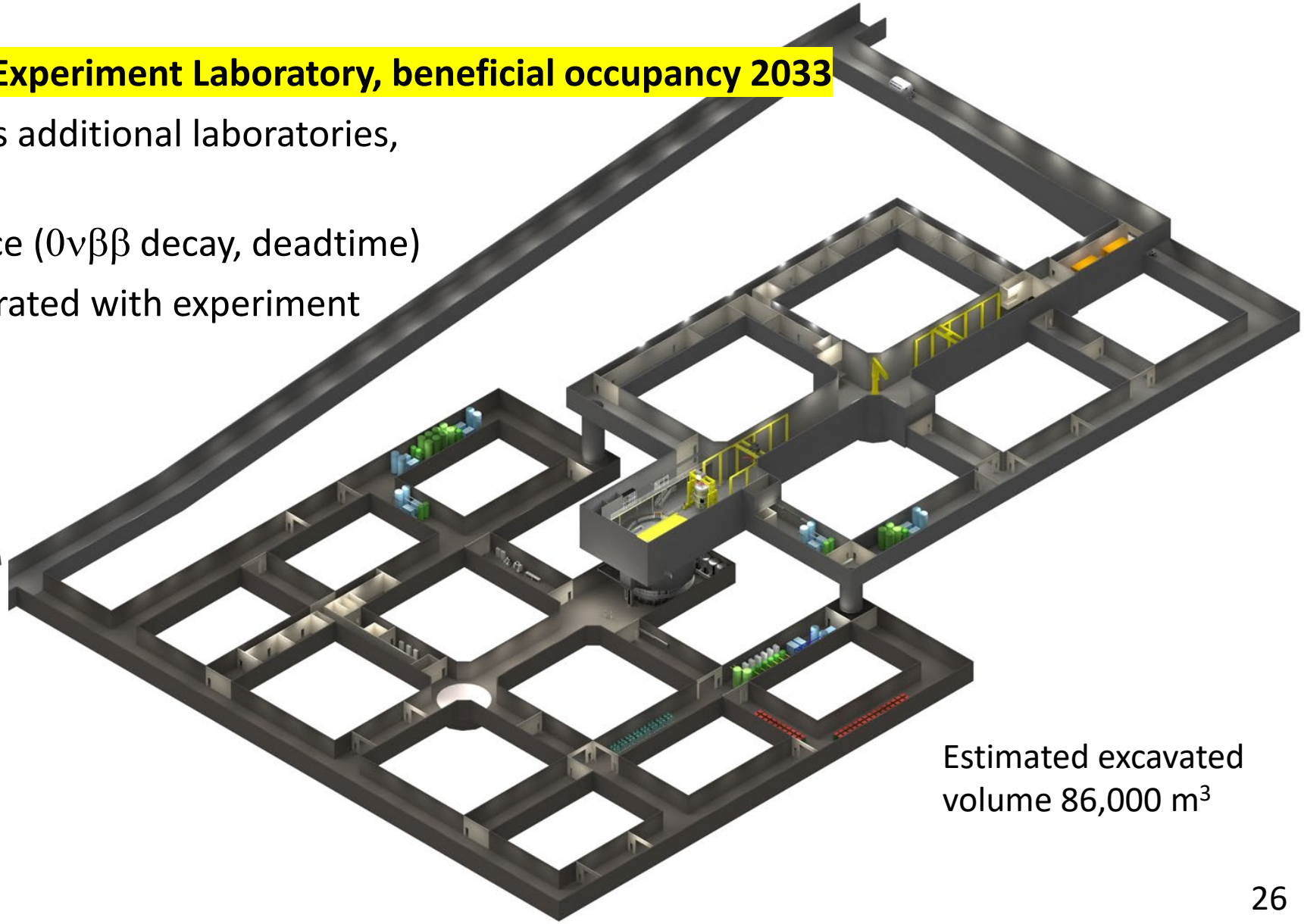


BOULBY STAGE 2: EXPERIMENT LABORATORY

Stage 2 in polyhalite (1,300 m): Experiment Laboratory, beneficial occupancy 2033

- Large experimental cavern plus additional laboratories, made to measure for XLZD
- Deeper lab desirable for science ($0\nu\beta\beta$ decay, deadtime)
- Preliminary design being integrated with experiment





Estimated excavated volume 86,000 m^3

XLZD@BOULBY

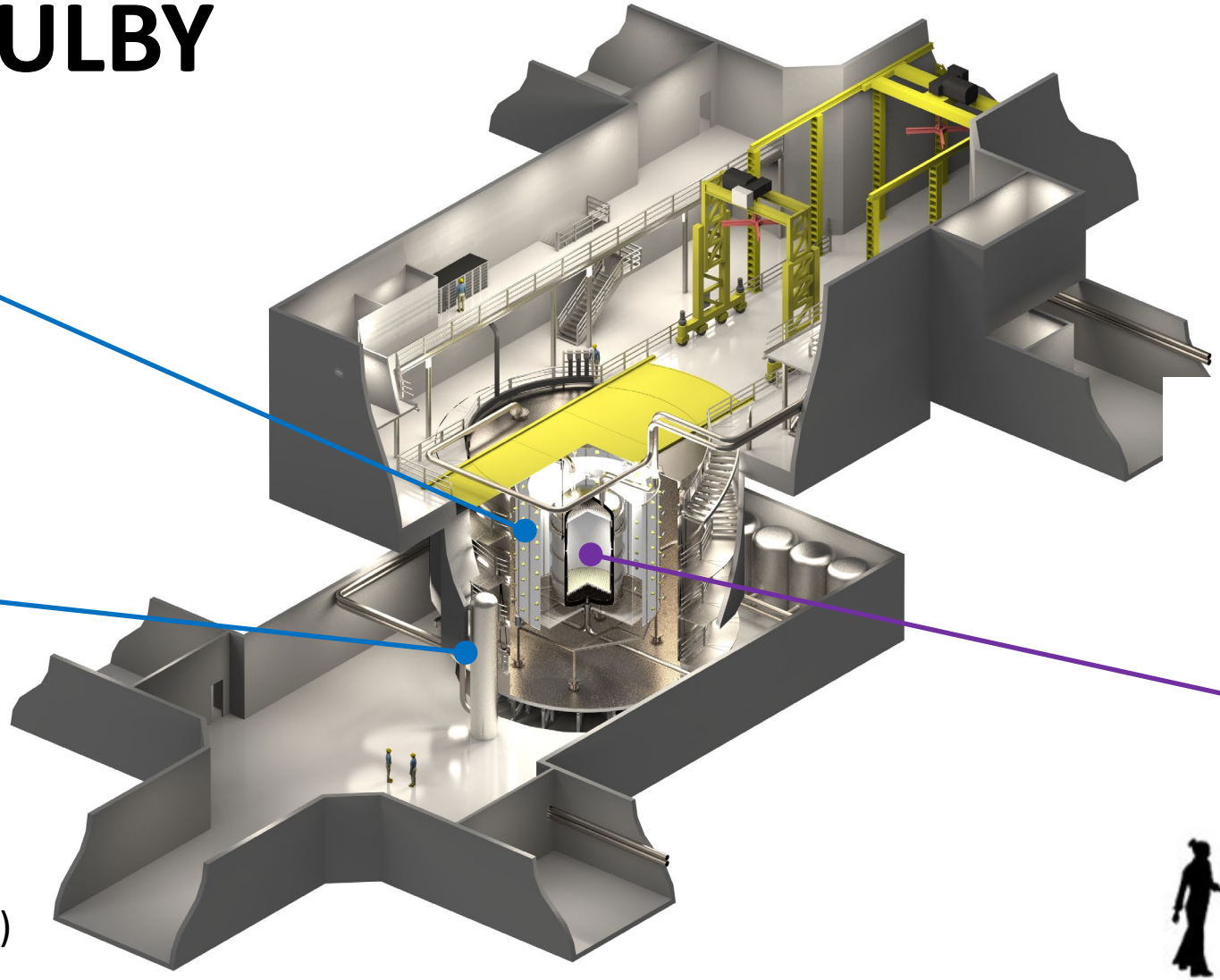
LXe-TPC with
60-80 tonnes
(active) LXe mass,
~2500 photosensors

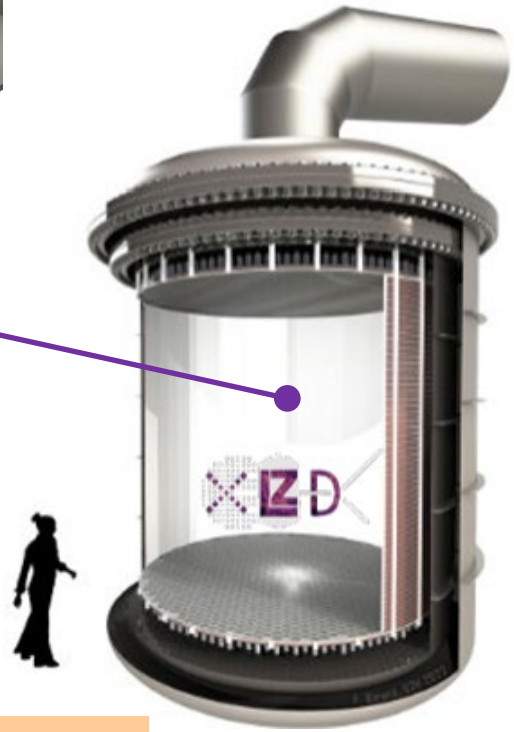
Contained in ultra-low
radioactivity **cryostat**

Scintillator-based
Outer Detector
contained in 12-m
diameter tank

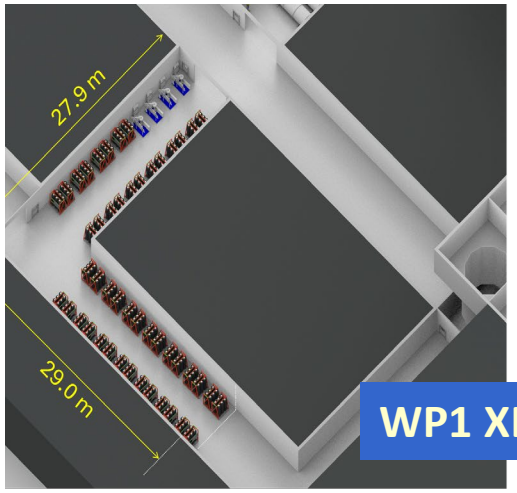
Xenon purification
and emergency
recovery systems

Many ancillary systems
not shown (controls,
electronics, cryogenics,
scintillator purification, …)



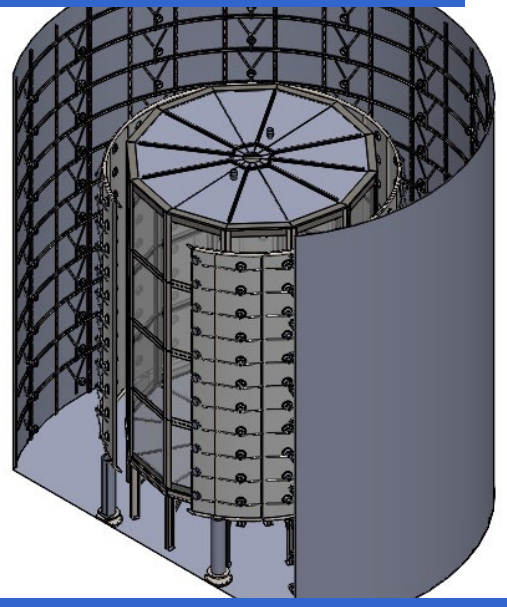


Challenge: manufacturing and assembling these systems underground, under extremely demanding quality assurance – esp. cleanliness and radioactivity controls – well beyond industrial standards

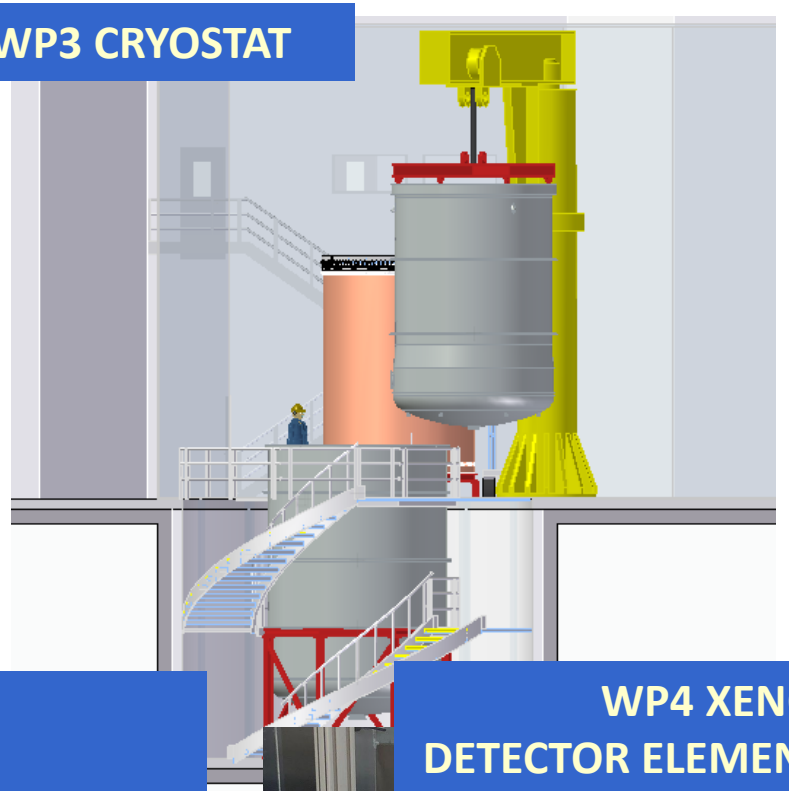


WP1 XENON GAS & SYSTEMS

WP2 OUTER DETECTOR



WP3 CRYOSTAT

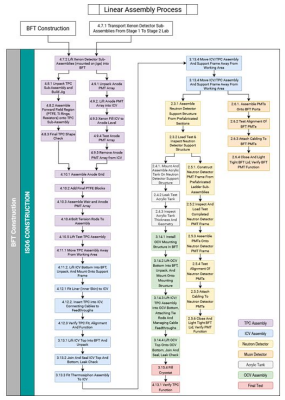


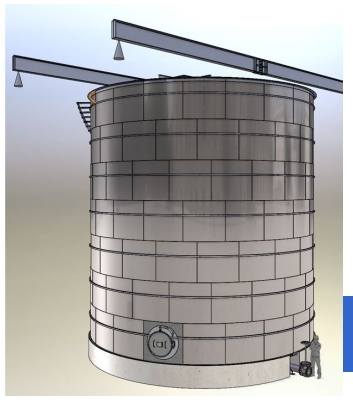
WP8 SUSTAINABILITY

XLZD-UK SCOPE

WP4 XENON DETECTOR ELEMENTS

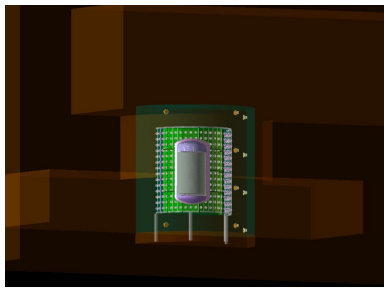
WP7 ENGINEERING & SKILLS

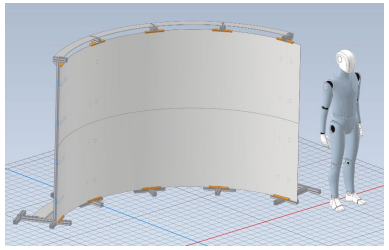


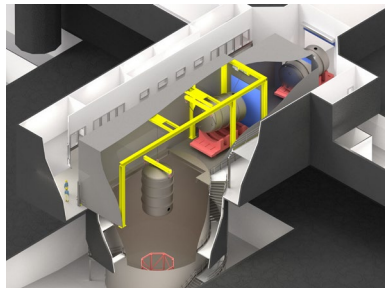


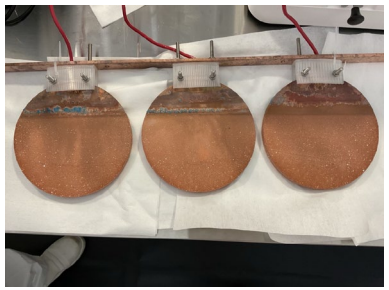
WP6 CLEAN MANUFACTURE

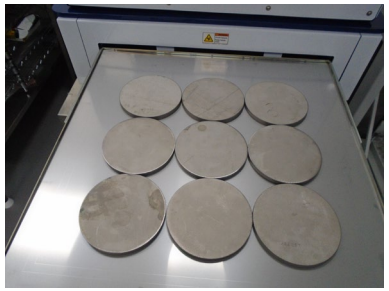
WP5 UK DATA CENTRE & ONSITE COMPUTING









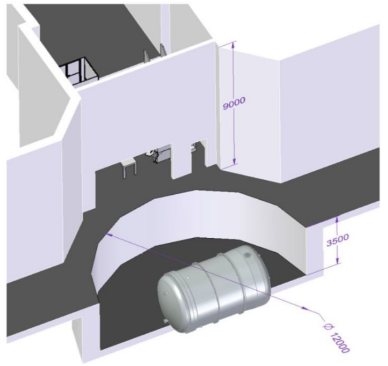


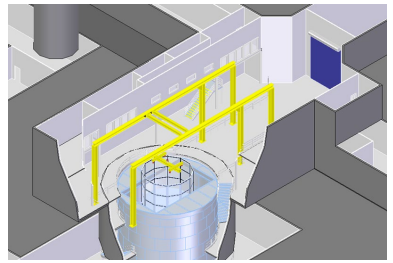
XLZD-UK PRE-CONSTRUCTION STATUS

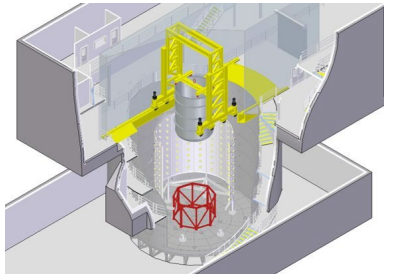
- >1 year after kick off, project is on track (dashboard is green)
- Design activities progressing at pace, CDR in the coming months
- Very good technical progress, challenges are mostly external…
- UK team is driving XLZD development along

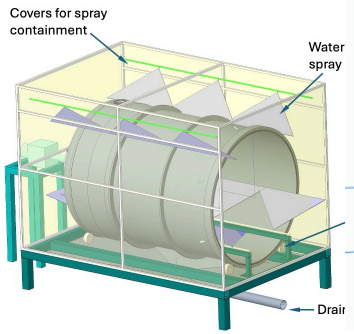
What are we doing now?

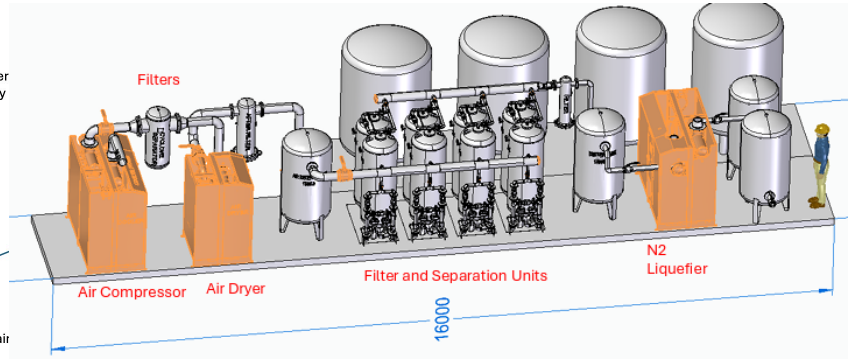
- Options analysis for Outer Detector, Cryostat, TPC Fieldcage & Skin, …
- Monte Carlo simulations, requirements flow-down (esp. radioactivity)
- R&D on materials and coatings, radioactivity and cleanliness controls
- Planning for Computing and Sustainability
- Integration engineering: story-boarding, lab integration, …

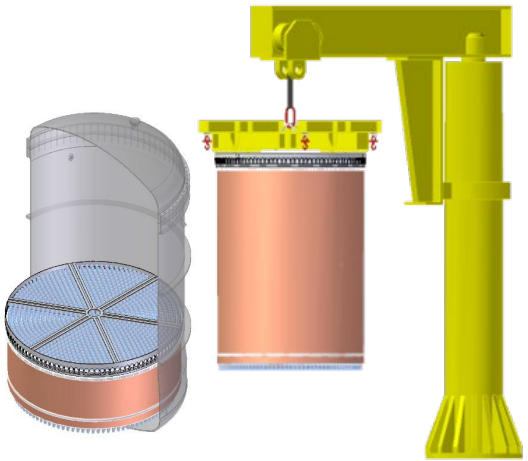


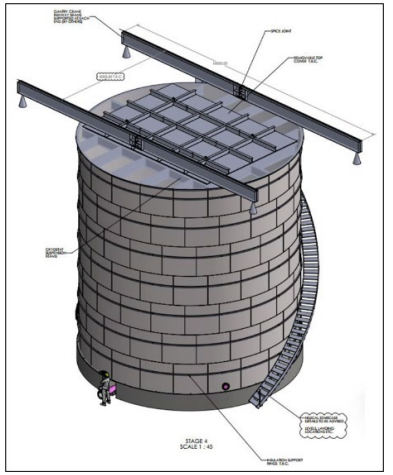












XLZD IMPACT: OUR AMBITIOUS PLAN

STRATEGY: ECONOMIC IMPACT ◊ SKILLS DEVELOPMENT ◊ OUTREACH

- Driving economic impact through wide-ranging industrial engagement
- Developing the skills pipeline to support the project and the facility (and beyond) through an apprenticeship programme in the region
- Skills pipeline driven by a strategic outreach programme
- Visible presence in the region is essential for all of these aspects
- XLZD@Boulby is attractive to regional stakeholders and could act as a catalyst for surrounding industrial projects

CONCLUSION

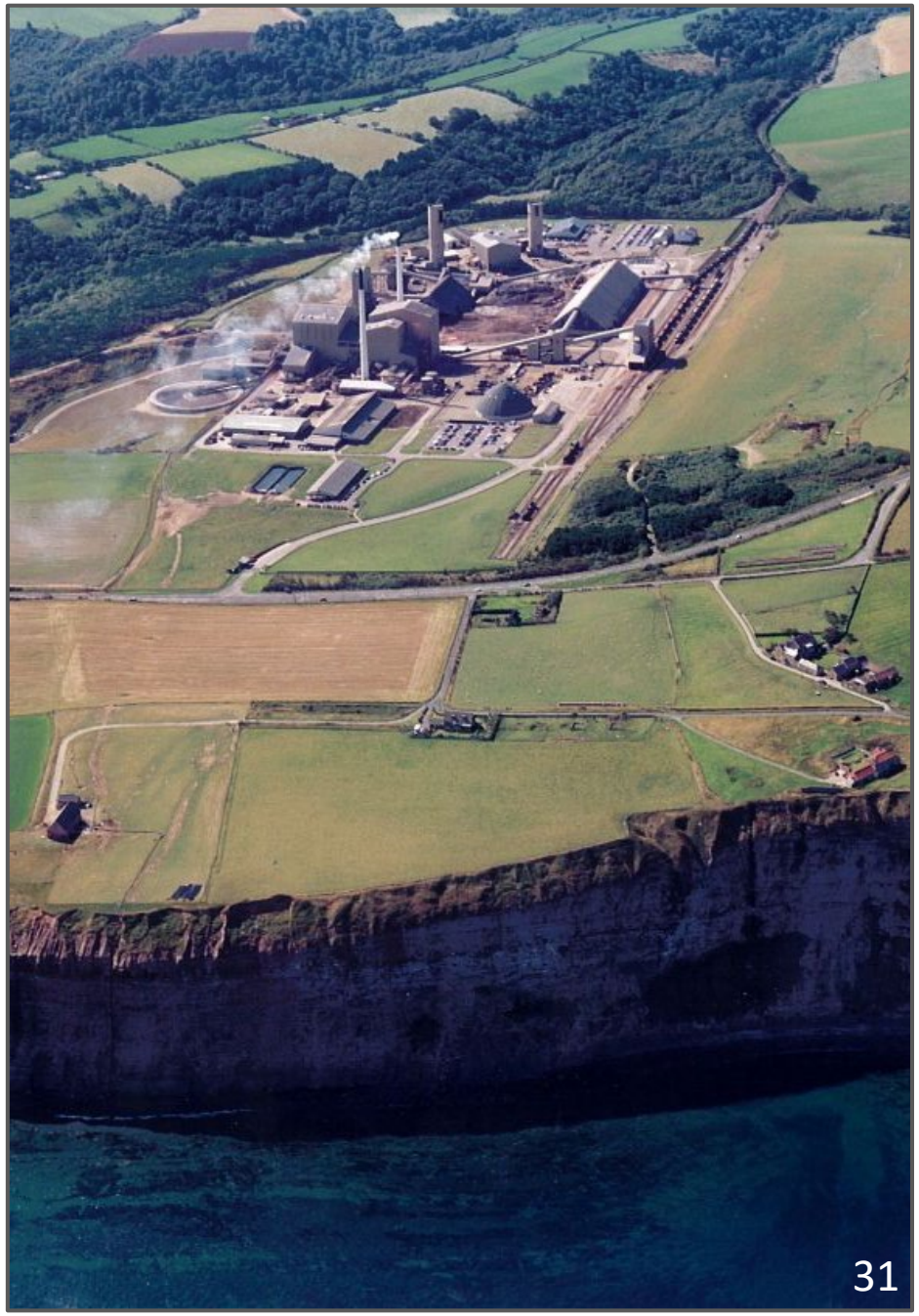
The **XLZD Rare Event Observatory** has started development, aiming for a 10-fold upscale from current experiments

It will seek answers for some of the key questions in science:

- Is the elusive **dark matter** related to new electroweak physics?
  - ✓ XLZD can provide the definitive test of the natural WIMP paradigm
- What is the nature of neutrino mass and the **missing antimatter**?
  - ✓ XLZD offers a competitive search for $0\nu\beta\beta$ decay and other rare decays
- Can astrophysical neutrinos help reveal new physics?
  - ✓ Bringing CEvNS to Multi-Messenger Astronomy

XLZD builds on two major experiments operating now in real-world conditions: LZ and XENON-nT – major risk mitigation

XLZD@Boulby – a unique opportunity to host world-leading, fundamental science in the UK with substantial impact!



The XLZD Collaboration

Imperial College London
King's College London
Royal Holloway, University of London
STFC Daresbury Laboratory
STFC Rutherford Appleton Laboratory
University College London
University of Bristol
University of Edinburgh
University of Liverpool
University of Oxford
University of Sheffield
University of Sussex
LPNHE
Subatech/IN2P3
LIP-Coimbra
University of Coimbra
University of Barcelona
Stockholm University
Nikhef
Johannes Gutenberg University Mainz
Karlsruhe Institute of Technology
Max-Planck-Institut für Kernphysik
TU Darmstadt
TU Dresden
University of Freiburg
University of Heidelberg
University of Münster
University of Bern
University of Zurich
Vinca Institute of Nuclear Sciences
INAF Osservatorio Astrofisico Torino
INFN-LNGS
SISSA
University and INFN Bologna
University of Ferrara
University of L'Aquila
University of Naples "Federico II"
Weizmann Institute
Black Hills State University
SURF
South Dakota School of Mines
Lawrence Berkeley National Laboratory
Lawrence Livermore National Laboratory
SLAC National Accelerator Laboratory
University of California, Berkeley
University of California, Davis
University of California, Los Angeles
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University of California, Santa Barbara
Rice University
University of Chicago
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XLZD Meeting - LNGS, July 2025