Noble Gas Based Direct Detection & G3 (XLZD Proposal)

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XLZD Consortium

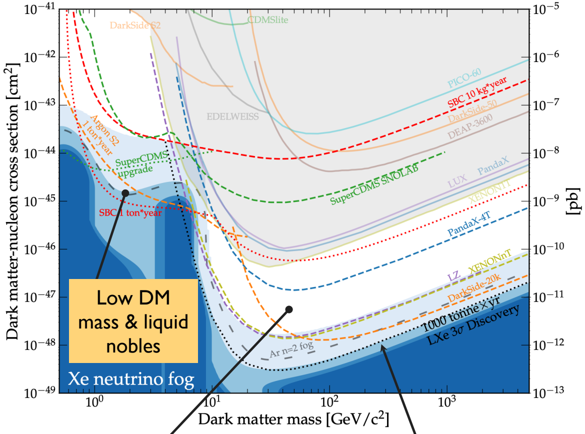
P5 Cosmic Frontier Town Hall, LBNL
22 February 2023

SLAC NATIONAL ACCELERATOR LABORATORY
KIPAC

Liquid nobles and the Discovery Potential for “high-mass” WIMPs

Snowmass White Paper on particle dark matter - arXiv 2203.08084

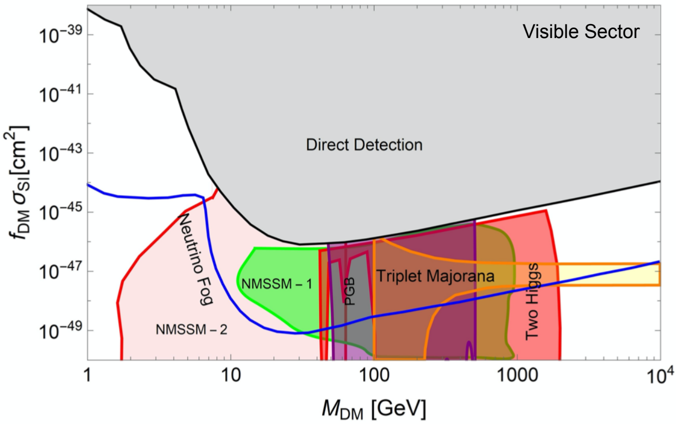
Experimental sensitivity and irreducible backgrounds



Low cross section and high mass (>10 GeV) → large liquid noble detectors

Systematic limit imposed by coherent scattering of astrophysical neutrinos

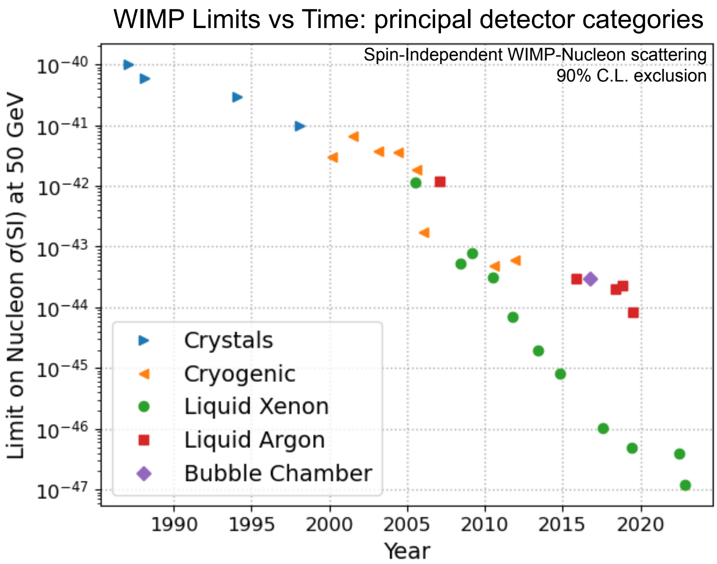
Rich parameter space of well-motivated BSM particle dark matter candidates



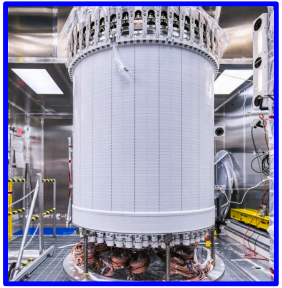
GOAL: complete the search in this parameter space in the 2030s

Liquid Noble Technology: World leading since 2007

- Tool of choice for massive detectors
  - Liquid targets can scale "easily" (⬆ mass)
  - Readily purified (⬇ backgrounds)
- Architectures explored → 2-Phase TPCs
  - ER/NR discrimination
  - Low energy threshold
  - 3D position - self-shielding, singles/multiples
- LXe world leading, 10-tonne scale
  - High density, large A2 , many isotopes (SI, SD, NR-ETF, inelastic)
- LAr only viable alternative
  - Confirmation in case of DM discovery
  - DM couplings/properties



Liquid Nobles: current status, future plans

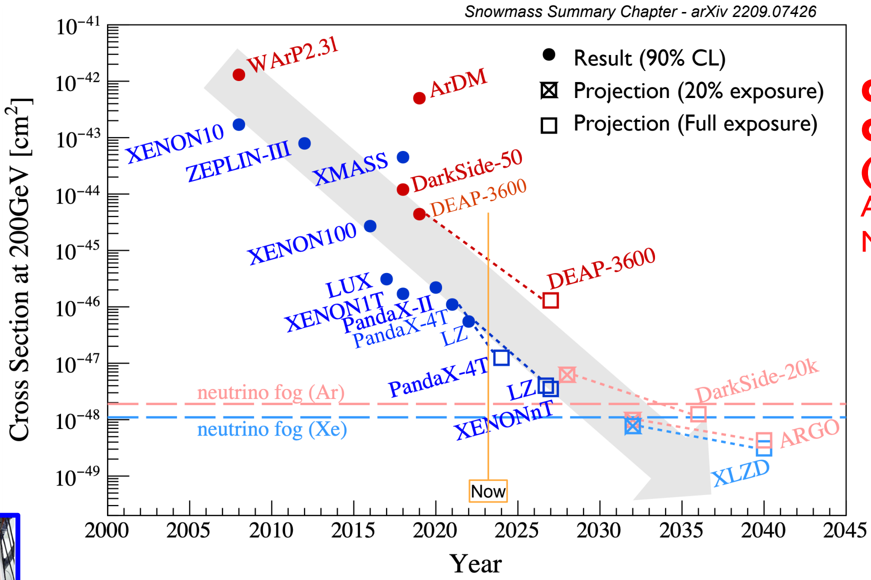


LUX-ZEPLIN

XLZD

XENONnT (inc. XMASS)
LUX-ZEPLIN
DARWIN

PandaX



Global Argon DM Collaboration (GADMC)

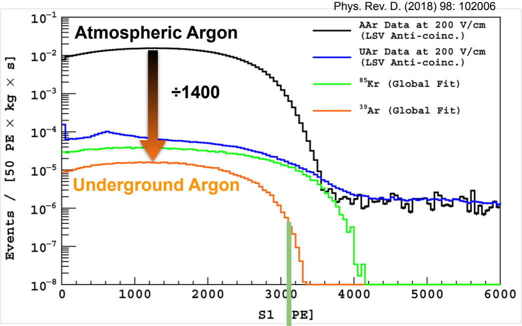
ArDM, DarkSide, DEAP, MiniCLEAN

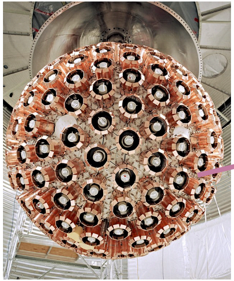
DarkSide-50

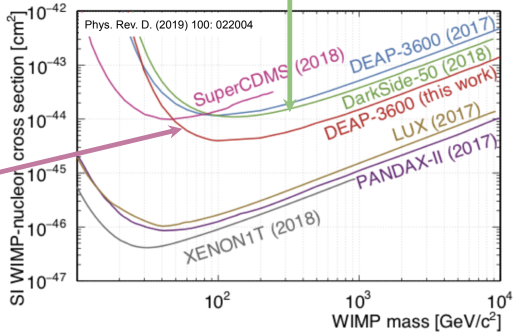
Liquid Argon, DarkSide-50 and DEAP-3600

- Liquid argon detectors
  - Atmospheric argon: ^{39}Ar beta background
  - Pulse shape discrimination
- DarkSide-50 Dual Phase LAr
  - 50 kg active mass, 31 kg fiducial
  - Underground Ar: reduce ^{39}Ar
- DEAP-3600 Single Phase LAr
  - 3.3 tonne active, 1 tonne fiducial
  - Low-background acrylic vessel
  - Best WIMP sensitivity on Ar
  - 4x more data in analysis phase


DarkSide-50

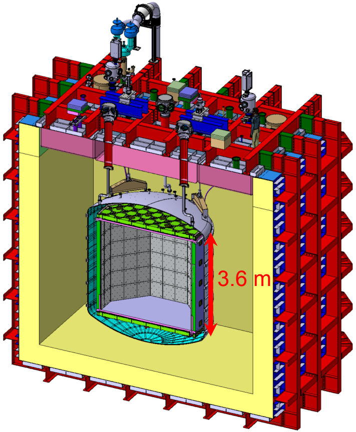



DEAP-3600

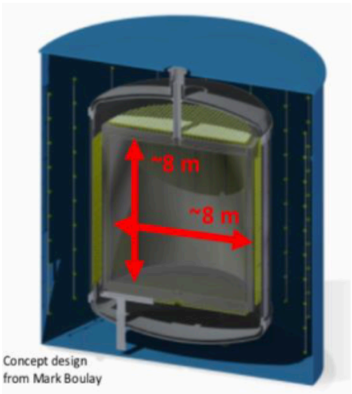


GADMC: Future LAr TPCs → DS20k → ARGO

- DarkSide-20k: 20 tonne fiducial in construction
  - UAr extraction/purification ~ 100 tonne/y
  - Radiopure acrylic technology
  - SiPMs ~ 26 m^2 at Nuova Officina Assergi
  - Operations in 2026 at LNGS
  - 200 tonne-years → 1.3 x 10^{-48} at 100 GeV
- ARGO: 300 tonne fiducial
  - Planning phase for follow up instrument
  - Continue use of NOA → 250 m^2 SiPM
  - 100 tonne/y UAr extraction 2026-2029
    + LEGEND, DUNE, COHERENT
  - 3000 tonne-years → 3 x 10^{-49} at 100 GeV



DarkSide-20k @ LNGS
400x mass of DS50



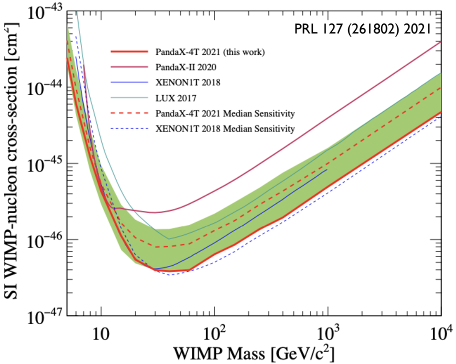
ARGO @ SNOLAB
Construction 2030-2035
Operations 2035-2051

Seek P5 endorsement: US support for UAr & SiPMs with partners in Canada, Italy, UK

PandaX - status and plans

- PandaX program LXe TPC program in Jinping Underground lab, China
- PandaX-4t operating
  - 3.7-tonne active mass, 2.7-tonne fiducial
  - World-leading first result - 2021 commissioning run
  - 6 tonne-years: 4 x 10^{-48} at 40 GeV WIMP mass in 2024
- PandaX-30t planned
  - Incremental upgrades to 30-tonne fiducial
  - 200 tonne-years → 3 x 10^{-49} at 40 GeV
  - Technology development underway

PandaX-4t



30 tonne liquid xenon management system

arXiv:2301.06044

XLZD: A Unified Community to build the definitive experiment

- Consortium MOU signed in July 2021 by **X**ENONnT, **L**UX-**Z**EPLIN, **D**ARWIN
- XENONnT and LZ: ongoing science programs, technology progenitors
- DARWIN: initiated R&D and design studies
- Ongoing activities
  - Co-authored key Snowmass papers
  - Working groups: science, technical, siting
  - In-person meetings - Germany in June 2022, UCLA April 2023
  - xlzd.org

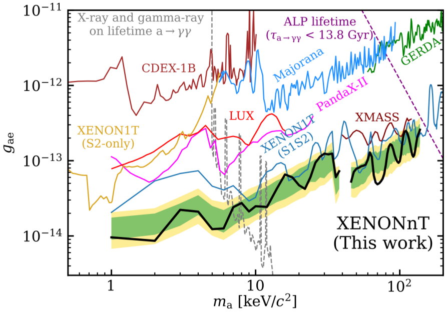
XLZD Meeting ay KIT in Karlsruhe, Germany (June 2022)

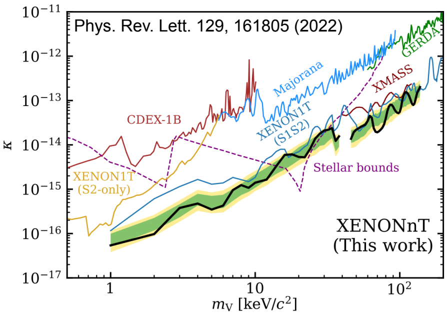
Consortium goal: establish international project and collaboration

XENONnT at Gran Sasso: First science results

- US (NSF), Europe, Japan - XENON and XMASS
- 6-tonne active, 4-tonne fiducial
- Early science from 97 day run
  - Example - best constraints on bosonic dark matter

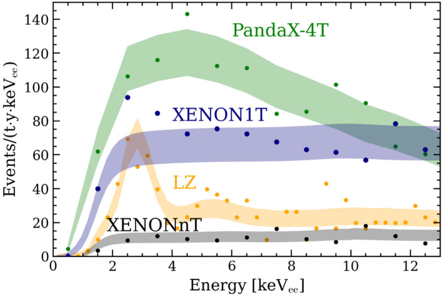
Galactic ALPs and dark photons





LXe TPC, Outer detector, Water shield at LNGS

Electron recoil backgrounds in LXe TPCs

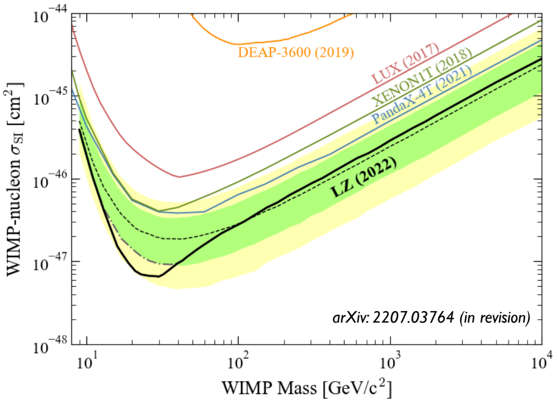


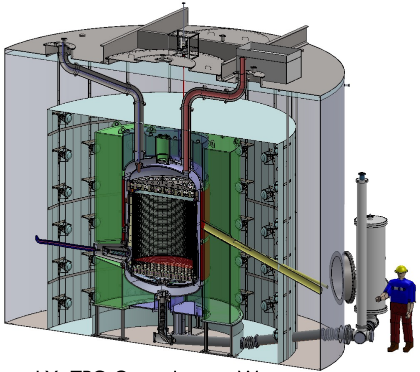
Technology accomplishments

- Liquid phase purification and storage, including in-line Rn and Kr removal
- Gd-loaded water shield
- Lowest ER background rate in DM detector

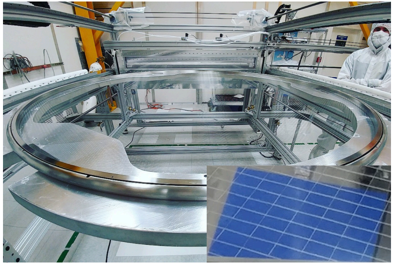
LZ at SURF: First WIMP search results

- US (DOE), UK, Portugal - LUX & ZEPLIN-III
- LXe TPC: 7-tonne active, 5.6-tonne fiducial
- 6% of expected LZ data: World Leading WIMP sensitivity





LXe TPC, Outer detector, Water shield at SURF 4850 level



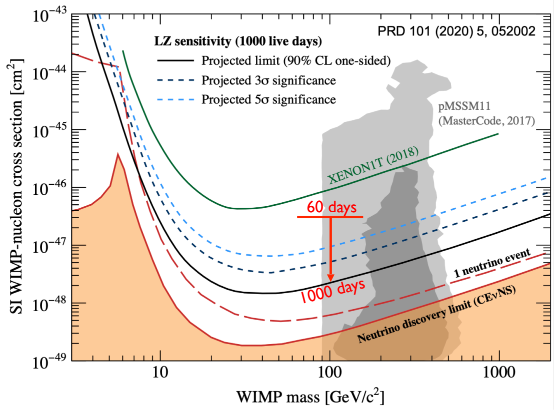
Custom HV grids

Technology accomplishments

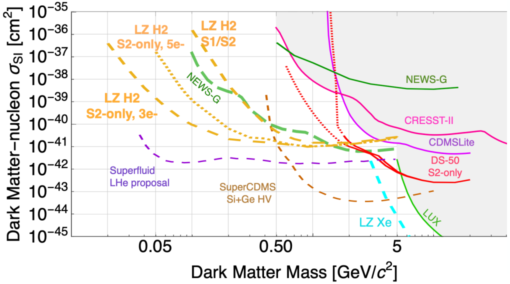
- Grid and HV delivery system
- Outer detector system (GdLS, Xe skin)
- Low radioactivity Ti vessel
- CH_3T and Kr-83m *in situ* calibration
- PB/year: data-intensive science, DOE Supercomputing

LZ: science operations and potential extensions

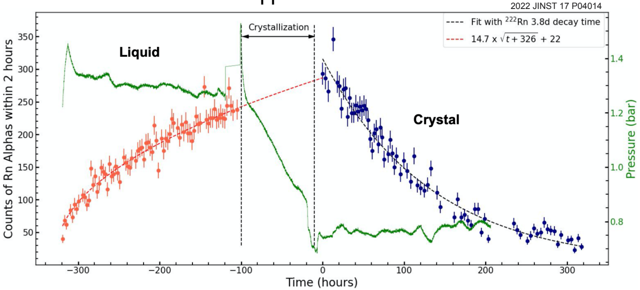
- Full LZ science program
  - Science Run 2 WIMP search in progress
  - Coherent nuclear scatters from ^{8}B solar ν
  - Full sensitivity for 1000 live days
    15 tonne-years ~ 2027
- R&D for possible LZ upgrades -- only external modifications to detector required



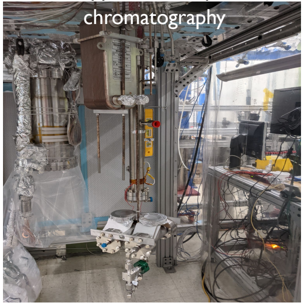
HydroX: low-mass reach - dissolved H_2, CH_4



Rn suppression: Solid Xe

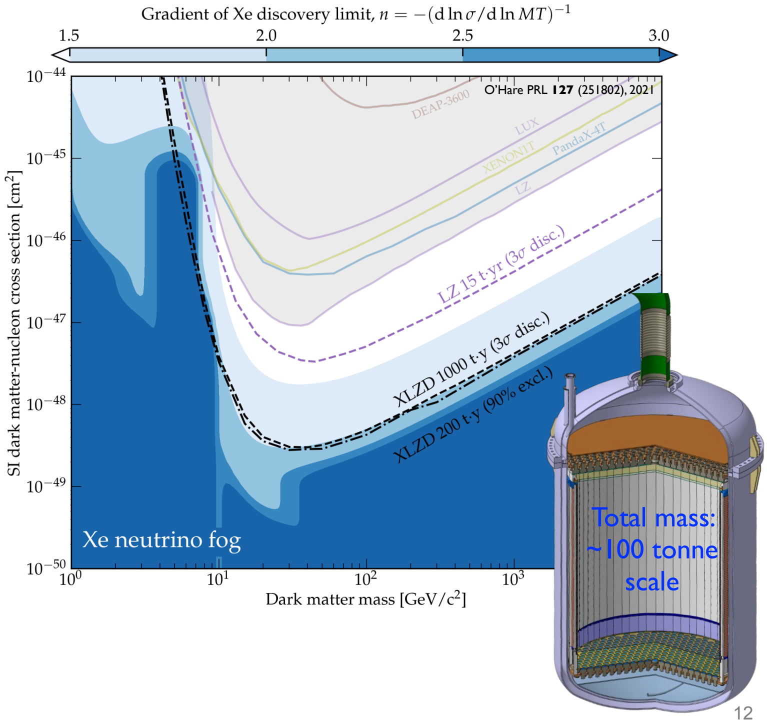


Rn suppression: Liquid Xe



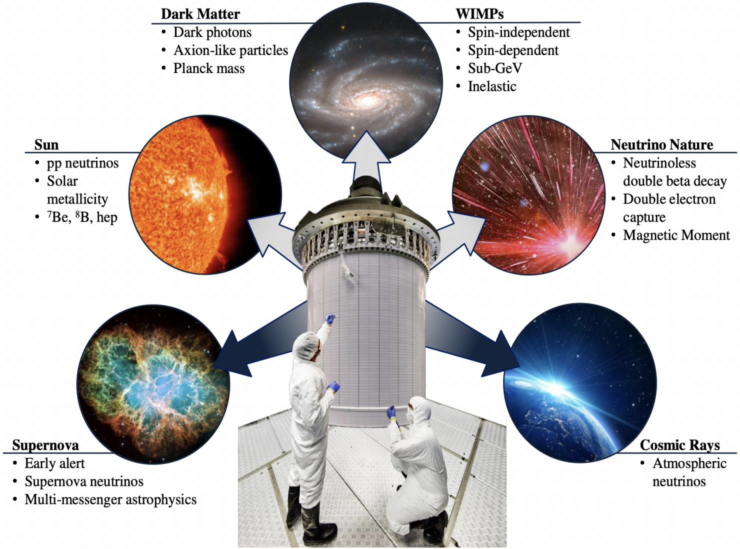
XLZD: definitive search for high mass WIMPs

- Searching for WIMPs into the "fog"
  - Nearly indistinguishable background from astrophysical neutrinos
  - Sensitivity rapidly falls - 20% flux uncertainty
  - Systematic limit (1000 tonne-year exposure) = practical limit of ~100-tonne detector
  - 3-sigma discovery at 3×10^{-49} at 40 GeV
- Combine best of LZ and XENONnT
  - 10x mass: 63-tonne fiducial of 70 active
  - Double TPC linear dimensions
  - Compact geometry: readout, underground transport & fit



XLZD: A Xenon Observatory with a broad science program

- Primary WIMP measurement drives design
- Neutrinoless DBD - major opportunity
  - Comparable to nEXO sensitivity
  - Possible pathfinder for beyond nEXO
- Highlights from "Next Gen. Observatory"
  - Solar neutrinos - solar model, neutrino properties
  - Diffuse Supernova Neutrino Background
  - Supernovae
    - 10 kpc → 100 events
    - 1 kpc → Si burning hours before core collapse
  - Solar axions - non-DM - axioelectric effect

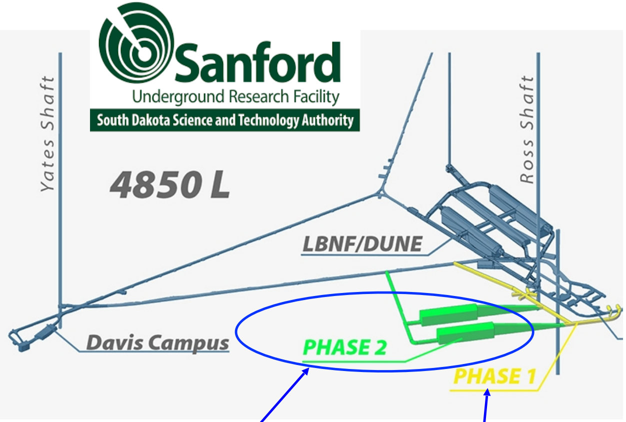


"A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics" —600 authors

arxiv 2203.02309 / J. Phys. G: Nucl. Part. Phys.

XLZD and SURF: US Siting Option

- XLZD partners each pitching to host, with 5 sites under technical study
  - SURF, LNGS, Boulby, SNOLAB, Kamioka
- SURF: Excellent support during LZ construction and ongoing operations
  - Surface lab with radon-reduced clean room
  - Davis cavern at 4850L - supports LZ science
- Proposed SURF expansion to meet US needs
  - Phase I - connecting tunnels - current mobilization
  - Phase II - start excavation for new lab modules in 2027
  - Snowmass Summary: "*Excavate and outfit one or more new underground caverns at SURF at the depth of 4850' to house at least one large next-generation experiment and some mid-size and small experiments.*"



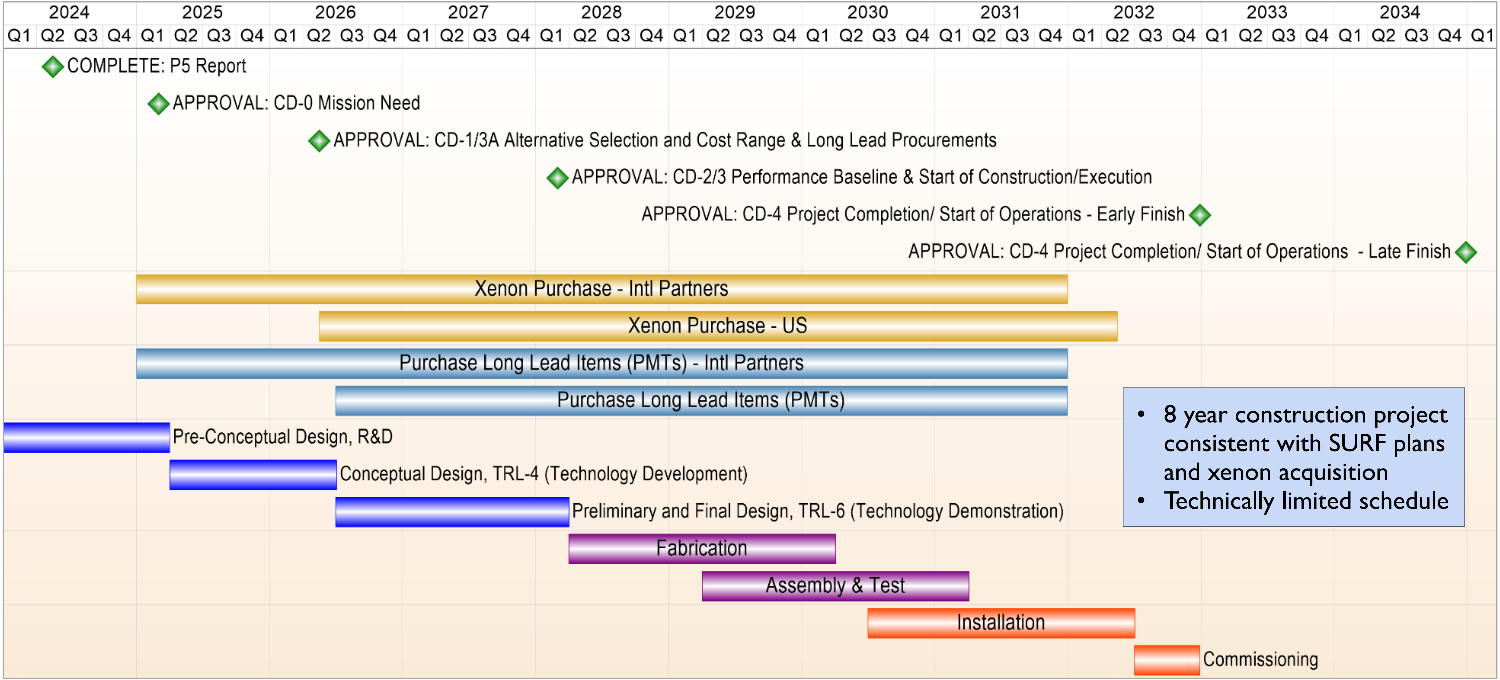
arXiv:2203.08293

Could complete by ~2030, meeting XLZD requirements (2: 100m x 20m x 24 m H)

Phase I connecting tunnels: future 4850 excavations compatible with LBNF/DUNE

SURF Expansion at 4850L would allow US to host XLZD.
Compatible with timeline, depth and environmental requirements.

Summary schedule with science starting in 2032



- 8 year construction project consistent with SURF plans and xenon acquisition
- Technically limited schedule

XLZD Project Costing

US Cost estimate: ~$350M including 50% contingency

- Scaled from actual cost of LZ MIE Project per DOE Order 413.3B

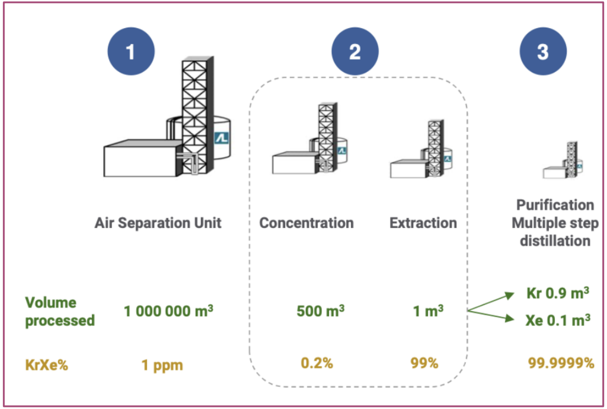
- Assumptions:
  - Escalated from 2017 to 2023 dollars
  - Xenon - average price of $15/liter
  - US costing method - materials, management, technical labor

- Xenon is a long-term asset

Description	Cost Estimate $M in 2023 dollars
Instrument (Management, Cryostat, Cryogenics, Purification, Detector, Calibration, Electronics, DAQ, Controls, Computing, Integration/ Installation, Offline Computing)	$251
Xenon Acquisition	$218
Sub-Total	**$470**
50% Contingency	$235
Project Total	**$705**
US Contributes 50% of Project Total	**$352**

Xenon Acquisition is Top XLZD Project Risk

- Xenon market
  - Industrial commodity ~ 60 tonnes/year and increasing
  - Short term price volatility with average price $12 -- $20/liter
  - New capacity ~ 2-3 years after price reaches $20/liter
- Market experts: 15$/liter is reasonable for large users
  - DOE Labs - track record with producers
  - XLZD would be among top 3 users
- Vendors: Air Liquide "Main players plan and secure their volumes in advance (~5 years)"



XLZD needs to drive supply - establish purchase plan several years in advance of full acquisition rate. Funding commitments must be in place. Engage multiple vendors.

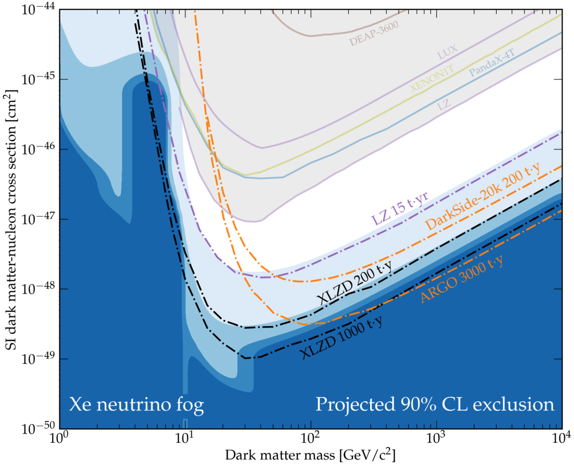
XLZD Detector: Roadmap to Technical Readiness

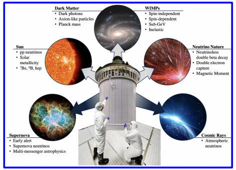
Highest risks that require early R&D	
Establish Electric Fields	Control Detector Backgrounds
Key requirements: • ⬆ grid size • ⬆ cathode HV	**Key requirements:** • ⬇ intrinsic background from radon • ⬇ accidentals (⬆ surface & PMT count)
Potential R&D and mitigations: • Alternative grid mechanics • HV component testing	**Potential R&D and mitigations**: • High-throughput in-line radon distillation • Radon barrier around TPC active region • Study accidentals in LZ/XENONnT → inform bench tests

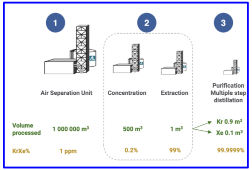
Track record of the combined teams in scaling from 10 kg to 10 tonnes provides the technical foundation and capabilities for making the necessary advances

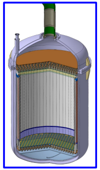
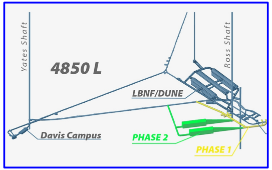
Definitive WIMP search is attainable, timely and competitive

- WIMP science - potential for major discovery
- Scientific breadth - exciting additional goals
- XLZD is timely - merger of expert teams
  - International planning underway
- Technical readiness - risks defined and tractable
- P5 endorsement will sustain US leadership





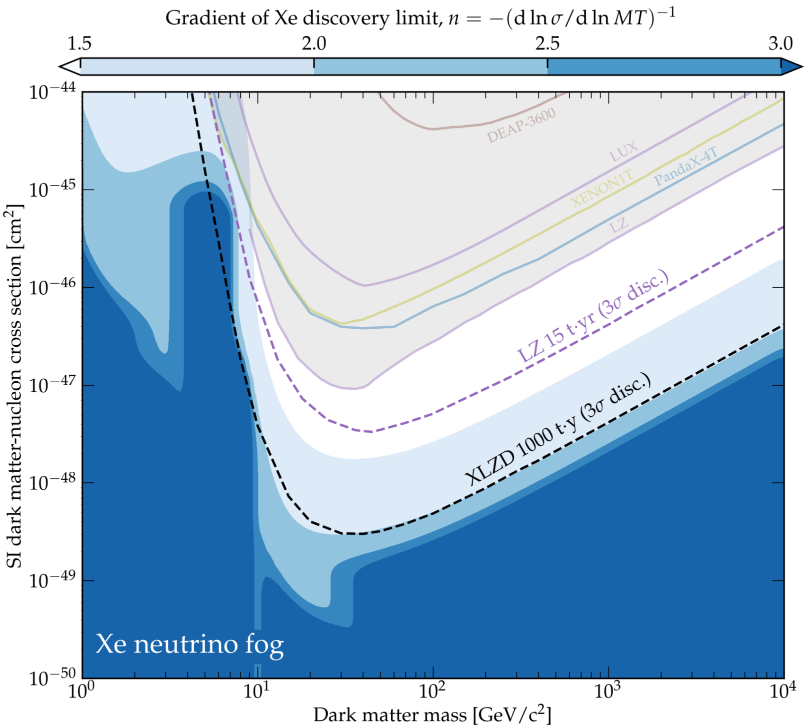



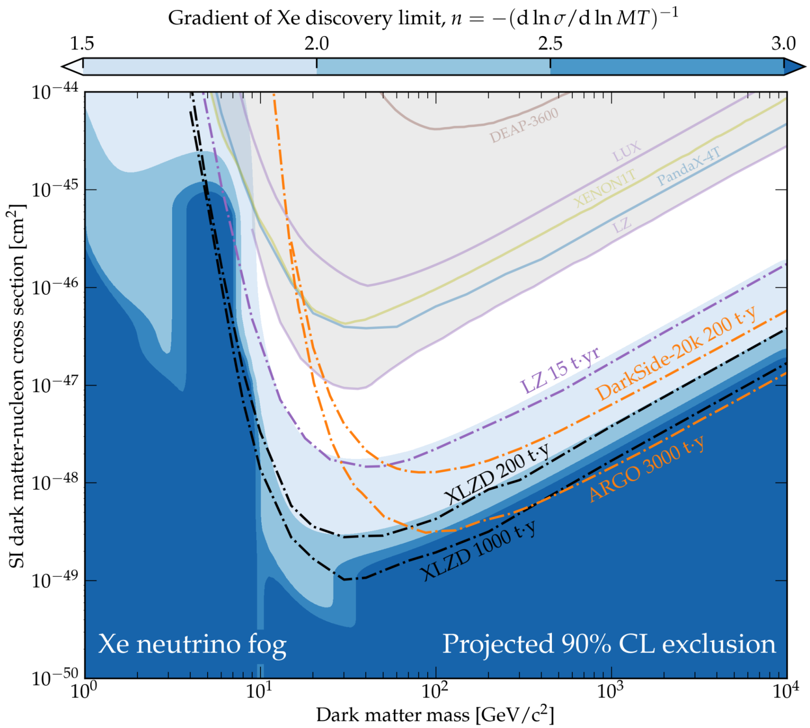
If WIMPs exist above the systematic limit of astrophysical neutrinos, XLZD will observe them.

Backup slides

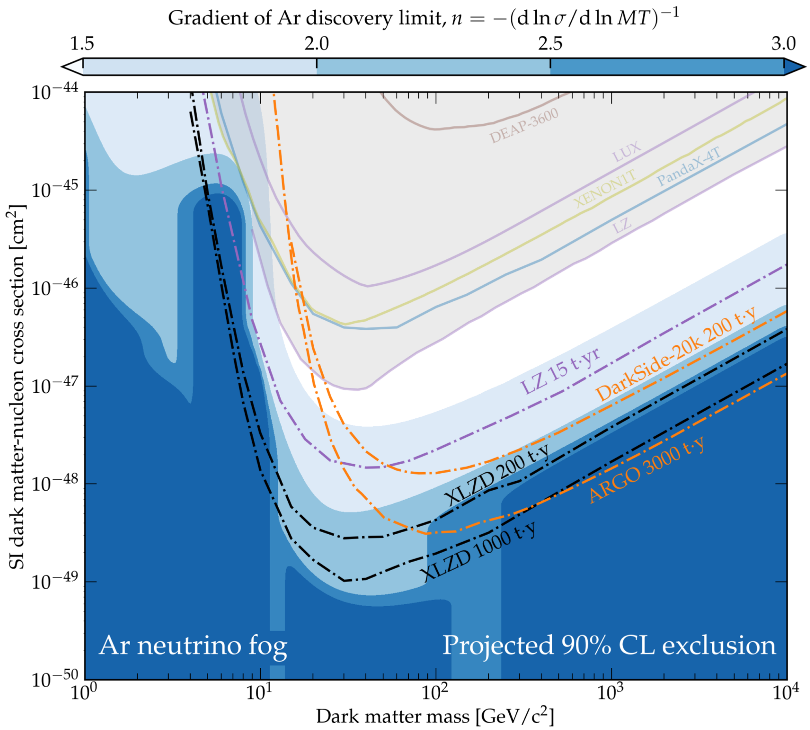
Xe fog / discovery reach



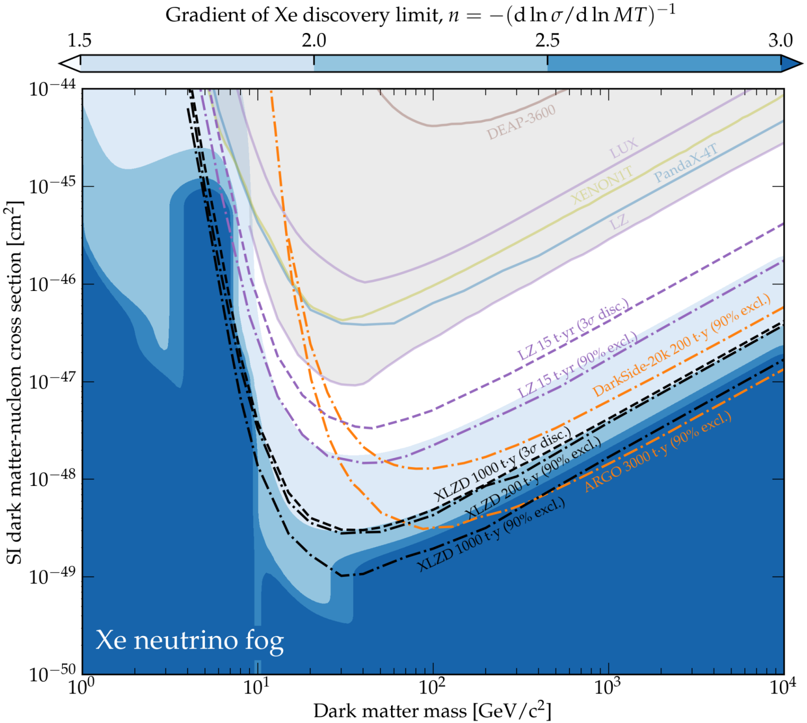
Xe fog / exclusion reach



Ar fog / exclusion reach



Everything, Everywhere, All at Once (Xe fog)



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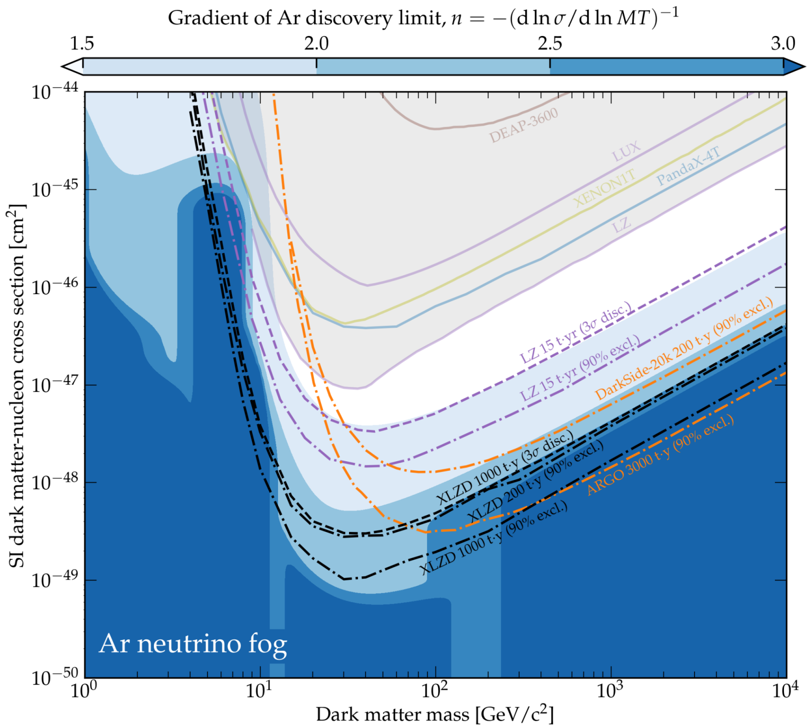
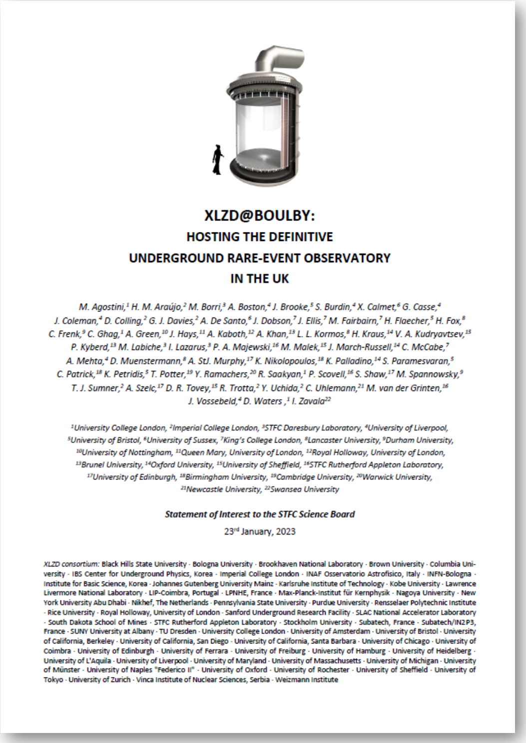


Henrique Araujo, PI, Imperial College London

XLZD@BOULBY

- Statement of Interest submitted to STFC (Jan 2023)
- Signed by 58 lead researchers from 22 institutes
- Substantial support from UK community
  - 0NBB, AIT/NEO, Theory/Pheno, …
  - Forging partnerships with industry (engineering)
- UK to contribute 1/3 of total project cost if host
  - Delivery of major systems naturally suited for host
  - One-third contribution to xenon stock
  - Centres for engineering, clean manufacture, and computing



XLZD@BOULBY:
HOSTING THE DEFINITIVE
UNDERGROUND RARE-EVENT OBSERVATORY
IN THE UK

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Statement of Interest to the STFC Science Board

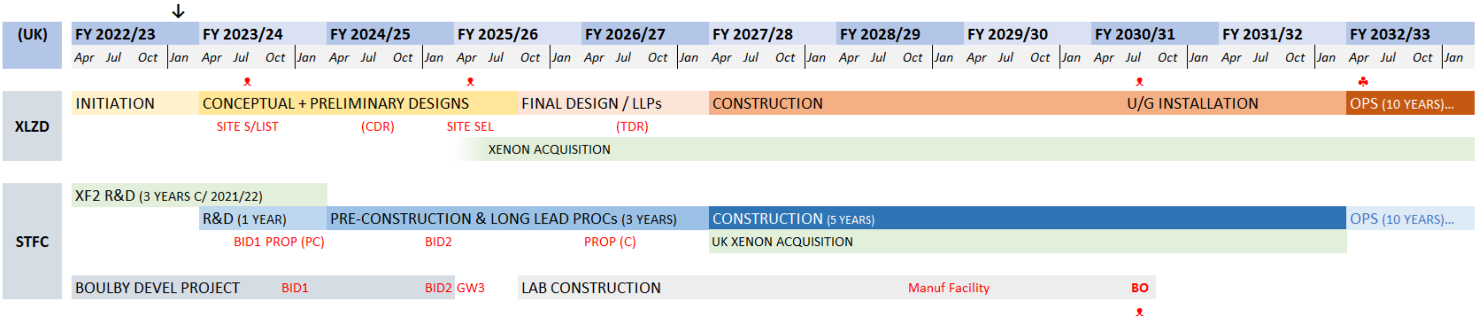
23rd January, 2023

XLZD consortium: Black Hills State University · Bologna University · Brookhaven National Laboratory · Brown University · Columbia University · IBS Center for Underground Physics, Korea · Imperial College London · INAF Osservatorio Astrofisico, Italy · INFN-Bologna · Institute for Basic Science, Korea · Johannes Gutenberg University Mainz · Karlsruhe Institute of Technology · Kobe University · Lawrence Livermore National Laboratory · LIP-Coimbra, Portugal · LPNHE, France · Max-Planck-Institut für Kernphysik · Nagoya University · New York University Abu Dhabi · Nikhef, The Netherlands · Pennsylvania State University · Purdue University · Rensselaer Polytechnic Institute · Rice University · Royal Holloway, University of London · Sanford Underground Research Facility · SLAC National Accelerator Laboratory · South Dakota School of Mines · STFC Rutherford Appleton Laboratory · Stockholm University · Subatech, France · Subatech/IN2P3, France · SUNY University at Albany · TU Dresden · University College London · University of Amsterdam · University of Bristol · University of California, Berkeley · University of California, San Diego · University of California, Santa Barbara · University of Chicago · University of Coimbra · University of Edinburgh · University of Ferrara · University of Freiburg · University of Hamburg · University of Heidelberg · University of L'Aquila · University of Liverpool · University of Maryland · University of Massachusetts · University of Michigan · University of Münster · University of Naples "Federico II" · University of Oxford · University of Rochester · University of Sheffield · University of Tokyo · University of Zurich · Vinca Institute of Nuclear Sciences, Serbia · Weizmann Institute

Henrique Araujo, PI, Imperial College London

XLZD@BOULBY

- Top-up R&D funds + 3-year Pre-Construction (£6M) + 5-year Construction (~£170M) + Ops (10 years)
- Timeline below, aligns with STFC-led Boulby Development Project; investment decision circa 2025
- Beneficial occupancy in 2030/31; clean manufacture facility from 2028/29
- Depth: likely 1,300 m (existing lab 1,100 m)

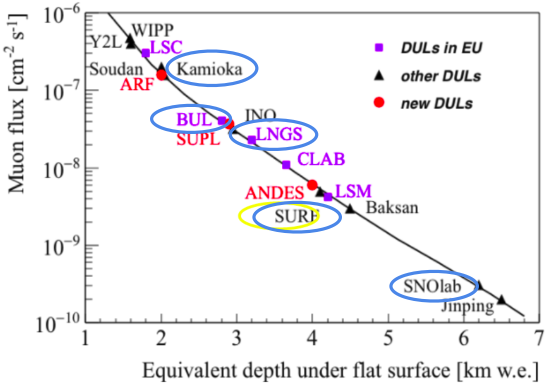


DARWIN & Helmholtz scope

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

- Helmholtz Association (Germany): program-based research
  - Long-term funding of R&D (since 2020: includes xenon-based DM search)
  - Construction & operation of large research infrastructures (DARWIN on preliminary roadmap since 2021)
- DARWIN project outline (Helmholtz roadmap)
  - Project cost: 175 M€ (capital, no labor)
  - Project category: international projects with German share < 50 M€
  - Technical scope: 50-ton Xe mass with 40-ton active, 200 t-yr exposure
- Preliminary roadmap entries need approval through review process:
  - Pre-proposal for DARWIN handed in by Karlsruhe Institute of Technology (KIT; Helmholtz Center) in July 2022; scientific review reports received.
  - Next step: presentation to Roadmap Committee in March 2023.Successful review of pre-proposal needed for submission of project proposal to federal ministry.
- If XLZD internationally supported: Helmholtz process towards XLZD

XLZD: Siting



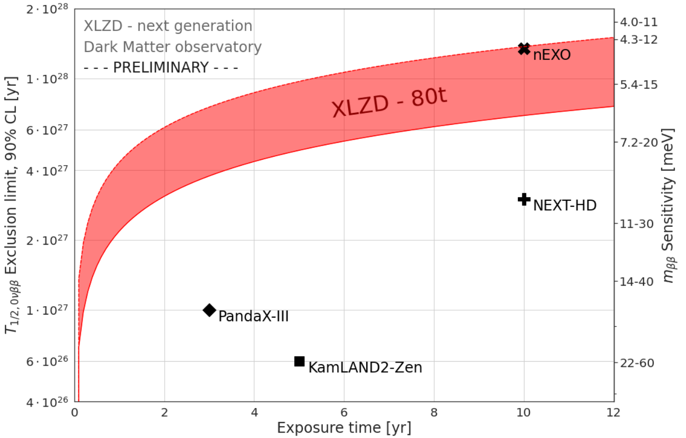
- 5 sites are being evaluated for XLZD: SURF, Kamioka, Boulby, SNOLab, LNGS
  - Established sites that have demonstrated good support capabilities to carry out the science goals of state-of-the-art rare event search experiments
- A next generation G3 detector like XLZD (~3 meter-scale TPC) will require capabilities:
  - Staging space and underground fabrication capabilities (e.g., larger and lower Radon Reduced Clean Room)
  - Required cavity ~20 to 25 meters in diameter: Gran Sasso (exists), Boulby (new construction), SURF (new construction)
- Alternatives analysis of site options will be a key technical aspect of site selection and must be incorporated into the earliest stages of the Project, taking into account timeline and full life cycle

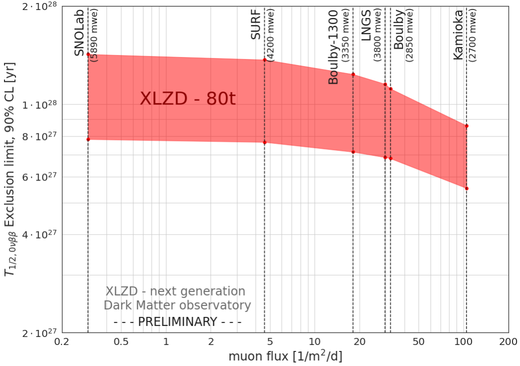
XLZD 0vββ science

TPC with large xenon target, calorimetry, position reconstruction and low background

⇒ High sensitivity to 0vββ-decay

Studied a conservative baseline scenario (bottom bounds) with little improvement over state-of-the-art DM TPCs vs. progressive assumptions (top bounds) on backgrounds.





Main 0vββ half-life sensitivity drivers
(within the tested parameter space)

1. instrumented target mass
2. external background and 222-Rn contamination
3. laboratory depth → muon flux
4. energy resolution and SS/MS discrimination

stronger impact ↓ smaller impact

Sensitivity to eff. Majorana mass $m_{\beta\beta}$ is dominated by NME.

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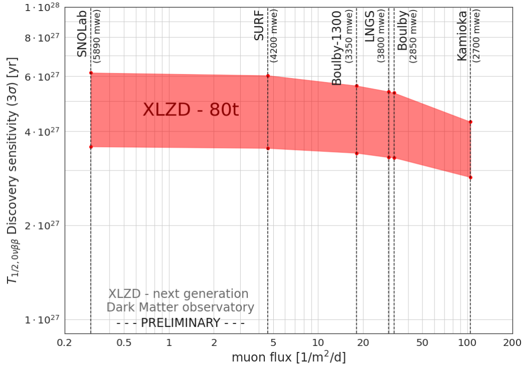

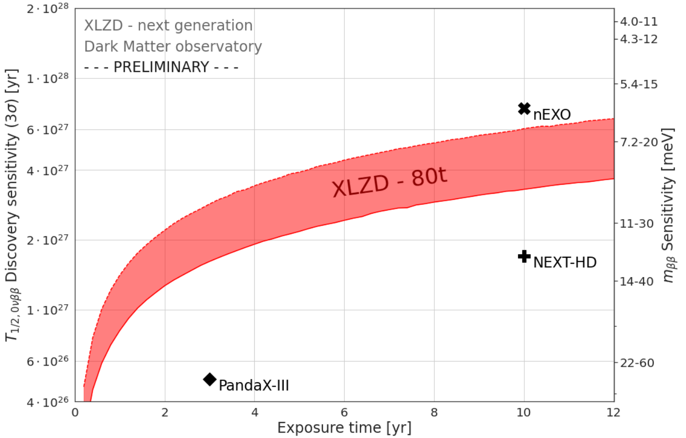

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P5 2014 Report Highlights

- p. 14 - The U.S. should host at least one of the third-generation experiments in this complementary global suite.
- p. 14 - Recommendation 20: Support one or more third-generation (G3) direct detection experiments, guided by the results of the preceding searches. Seek a globally complementary program and increased international partnership in G3 experiments.
- p36 - Following either a G2 discovery or further constraints, there should be at least one U.S.-led, internationally attractive Generation 3 (G3) direct detection experiment with maximal discovery potential. In addition, the U.S. should participate in other global advanced direct detection experiments at the G3 scale. If no G3 discovery is made, DM searches will become limited by solar, atmospheric, and diffuse supernova neutrino coherent scattering backgrounds, so *the goal of G3 experiments will be to explore DM parameter space comprehensively down to the limits set by neutrino backgrounds*. This provides a well-defined target for this field over the next 20 years.

Snowmass summary chapter highlights (arXiv:2301.06581)

- p9: In the Cosmic Frontier, a coordinated multi-scale dark matter program would combine direct, indirect, and cosmic probe experiments to explore the large dark-matter landscape (and, in total, rise to the "large" project category). Note that an expansion of underground facilities at SURF may be required as a component of this program. In the observational Cosmic program, projects may leverage funding from sources outside of HEP itself, as denoted by the asterisks in the table. Both CMB-S4 and Gen-3 WIMP searches (previously DM-G3) were endorsed as promising future directions by the previous Snowmass/P5 process.
  - Table 1.1 "Multi-Scale Dark Matter Program (incl. Gen-3 WIMP searches)"
- p18: The next generation of these direct-detection searches will aim at $O(10^2)$ tons of target material. These are multi-purpose experiments that are also sensitive to neutrinos from the Sun, the atmosphere, and supernova explosions.
- p54, UF Conclusion 1: Leverage the Long-Baseline Neutrino Facility excavation enterprise to increase underground space at SURF in a timely and cost-effective way to permit siting of next-generation underground high energy physics research experiments.
  - Excavate and outfit one or more new underground caverns at SURF at the depth of 4850' to house at least one large next-generation experiment and some mid-size and small experiments.

Snowmass summary chapter highlights (arXiv:2301.06581)

- p55, UF Conclusion 4: Following the 2014 P5 Recommendation 20, R&D and decision making for a third- generation direct detection dark matter program should commence immediately to enable a construction start in the late 2020s.
- p61 - complementarity
- pp65-66 - Neutrinoless double beta (0νββ) decay remains an important topic for both HEP and NP. The next- generation ("ton-scale") experiments will be stewarded by the Office of Nuclear Physics, as recommended by the 2015 LRP. It is also well recognized by the community and the funding agencies that the quest for, or perhaps precision measurements of, 0νββ decay must continue beyond these experiments, independently of whether the discovery is made at the ton scale. The Snowmass process has showcased a plethora of novel ideas and experimental techniques aimed at developing experiments with sensitivity beyond the parameter space defined by the inverted ordering of light neutrino masses. *At this scale, it would be especially important to develop multi-purpose detectors and maximize the scientific return on investment. Synergies in technologies between 0νββ and dark matter experiments, 0νββ and CEνNS experiments, as well as 0νββ and the long- baseline neutrino program, were discussed at Snowmass. Deployment of such multi-purpose detectors may require cooperation between multiple communities and funding agencies.*

Liquid Noble Bubble Chambers

Objective:

Quasi-background-free detection of sub-keV Nuclear Recoils

Signal:

Single bubble with little or no coincident scintillation

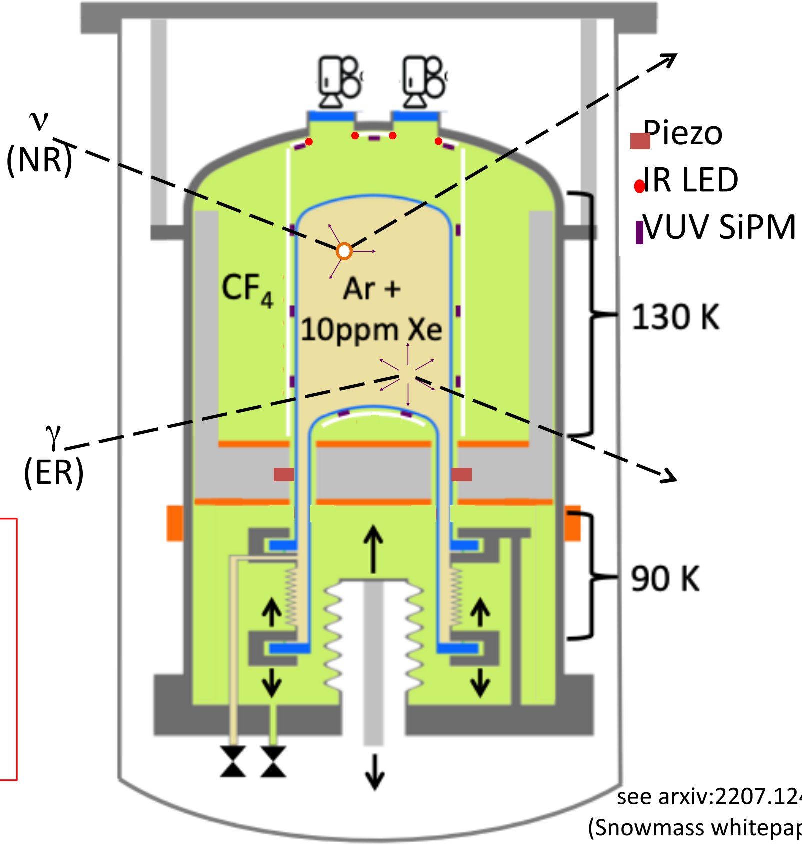
Backgrounds:

ER's (beta, gamma):
No bubbles

Depends on NR threshold and target fluid:

- *Freon-based chambers*
  ER-blind @ ~3 keV
- *Liquid-noble chambers*
  ER-blind @ < 500 eV,
  (target 100 eV)

NR's (fast neutron):
Multiple bubbles
Strong coincident scintillation

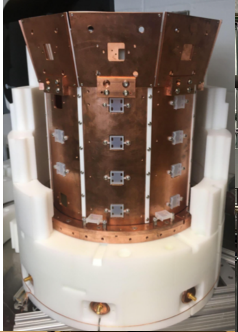


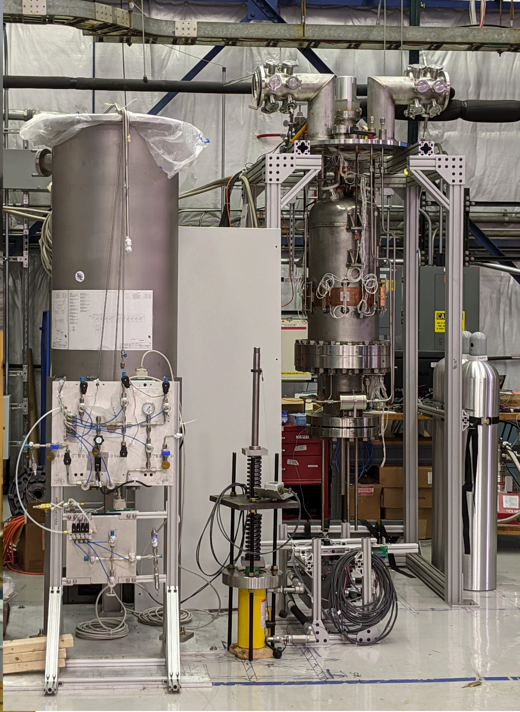
see arxiv:2207.12400
(Snowmass whitepaper)

Liquid Noble Bubble Chambers

SBC-LAr10 – Now commissioning

(Fermilab LDRD 2018-003)





Objectives:

- Demonstrate operation of physics scale (10-kg) LAr bubble chamber
- Calibrate low-threshold (~100 eV) discrimination and nuclear recoil sensitivity

see arxiv:2207.12400
(Snowmass whitepaper)

END