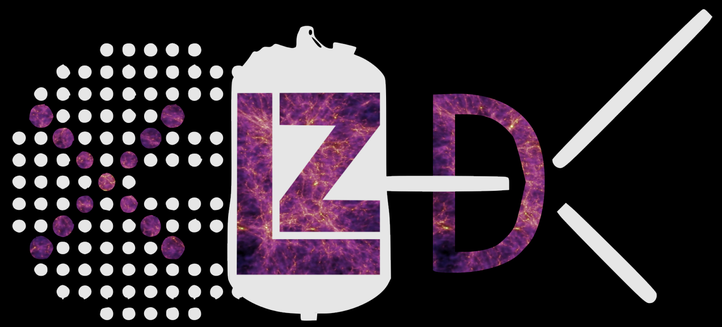
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

XLZD Overview: Physics Potential, and research and development

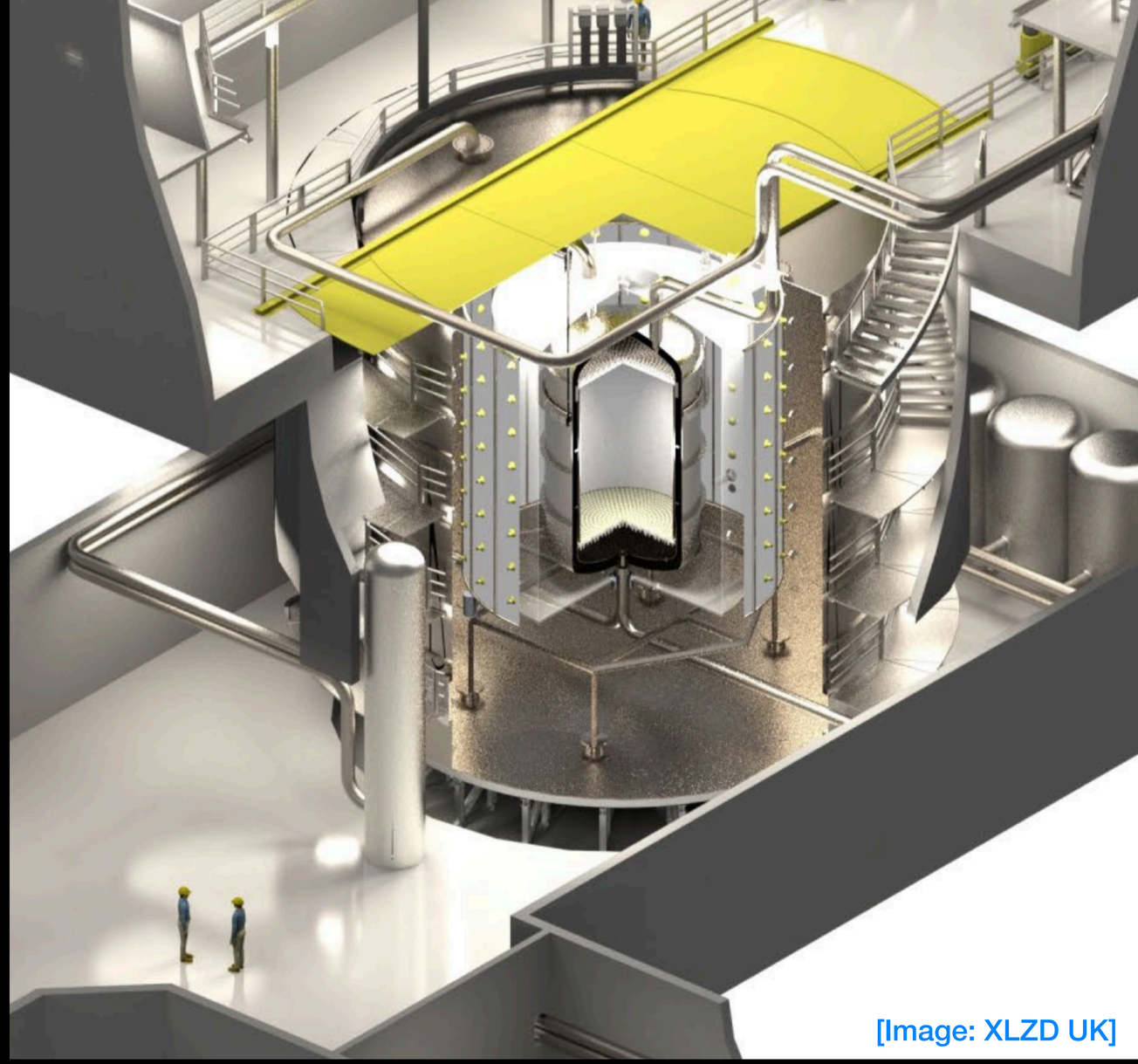
Alexander Deisting (JGU Mainz)

Elementary Particle Physics Seminars
- Warwick, 8th of October 2026



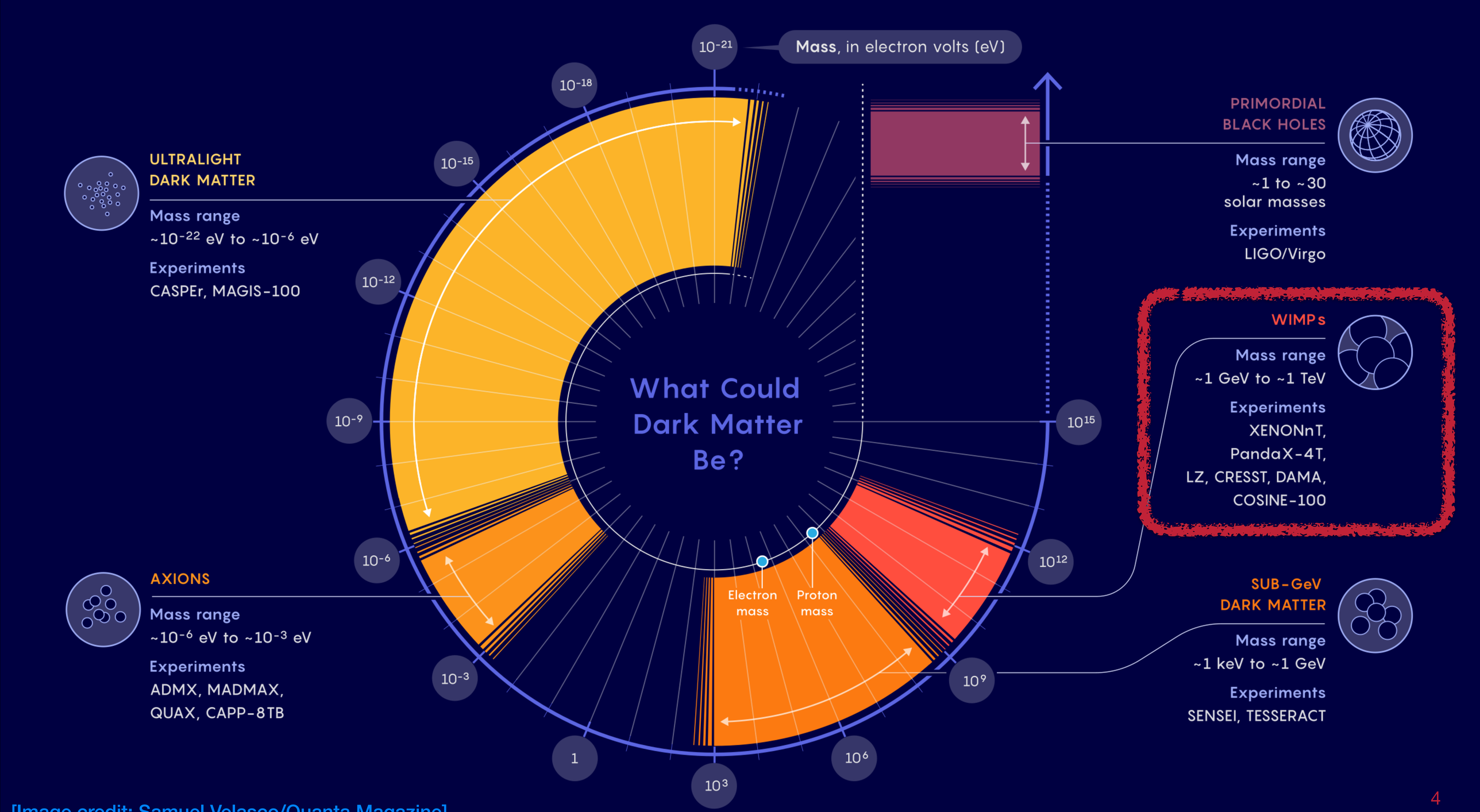
Outline

- Introduction: Direct searches for dark matter (DM) and …
  - … dual-phase xenon time projection chambers (TPC)
- XLZD collaboration & Introduction to the experiment
- Research and Development (R&D) topics towards the realisation of the experiment
- Status & Summary



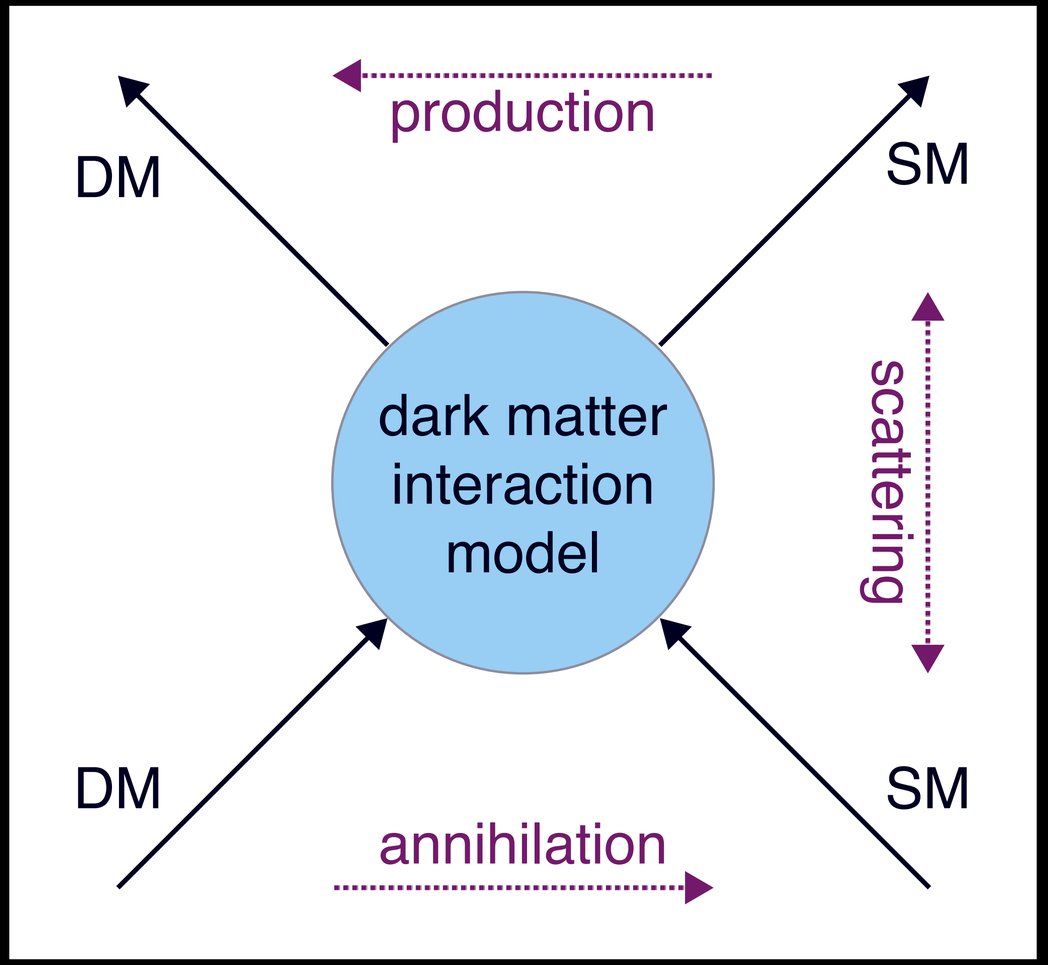
[Image: XLZD UK]

You have to believe me it is worth to look for dark matter…



[Image credit: Samuel Velasco/Quanta Magazine]

e.g. collider searches



direct detection
experiments

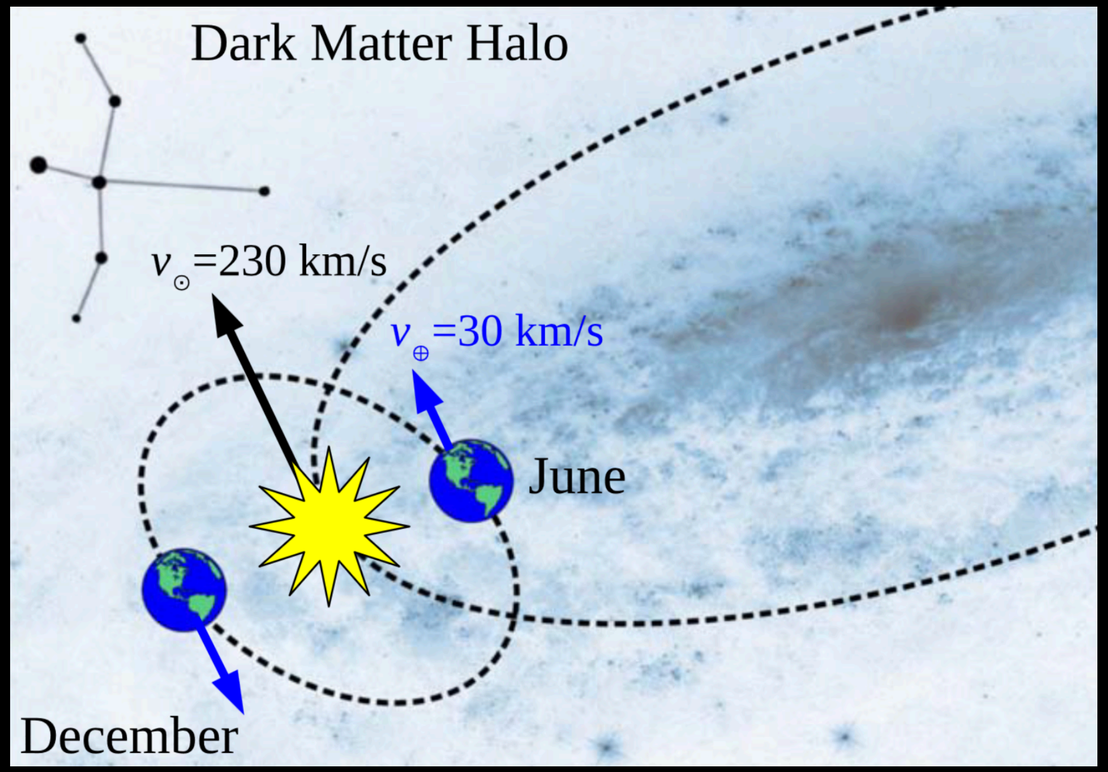
e.g. standard model particle flux from regions
with potentially high dark matter density

Direct detection

- Local dark matter density

$$\rho_0 = 0.3\ \text{GeV}\, c^{-2}\, \text{cm}^{-3}$$

- Detector moves around the galactic centre and through the dark matter halo
- Build an as background-free as possible detector, place it in an underground lab and wait …
- … for en event in your dual-phase time projection chamber (TPC)

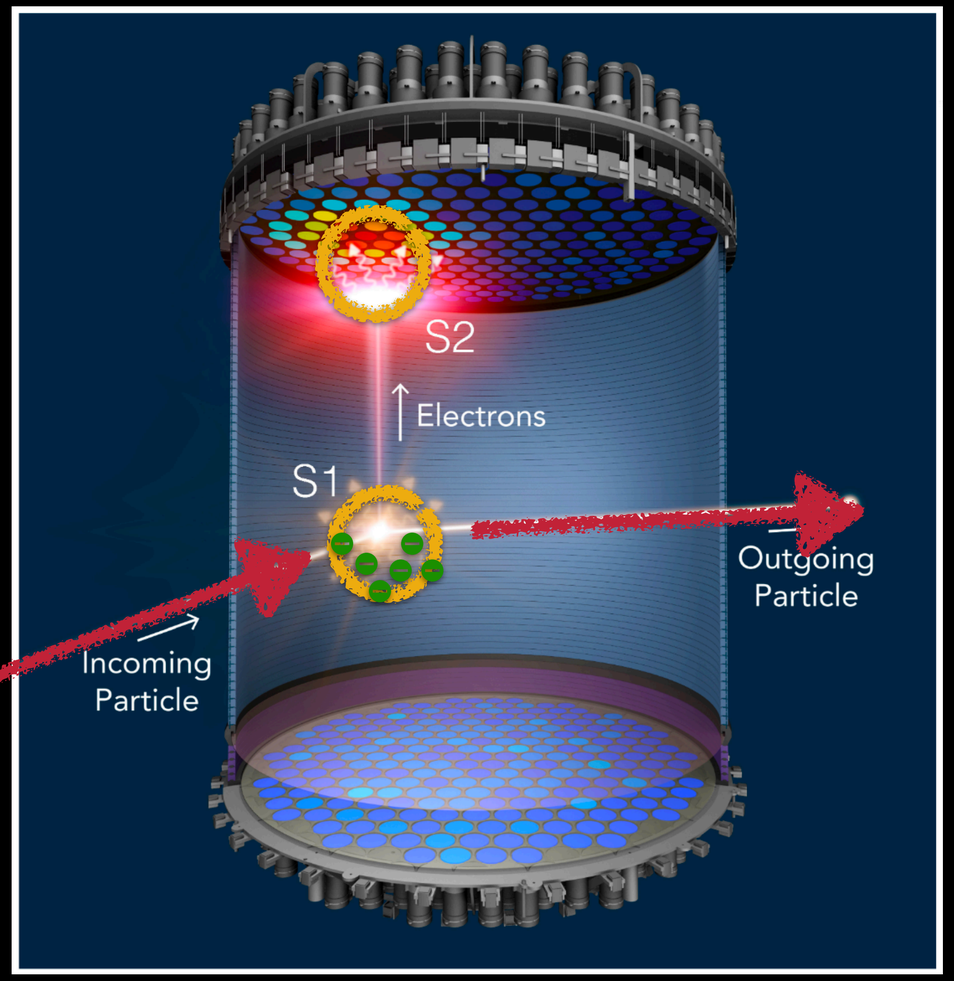


[Marc Schumann 2019 J. Phys. G: Nucl. Part. Phys. 46 103003]

Dual-Phase TPC*: Working Principle

[arXiv:1703.09144]

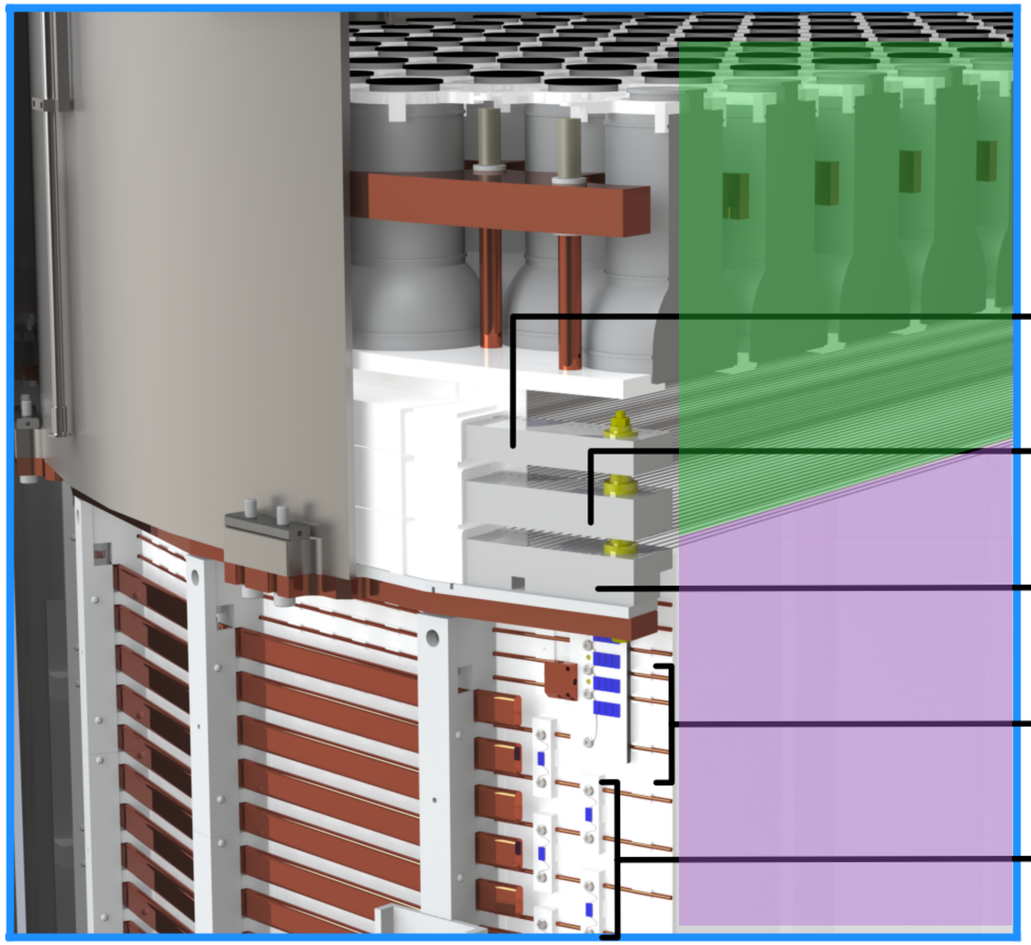
*As currently employed by LZ, Panda-x, and XENONnT



- Liquid xenon volume with xenon vapour on top enclosed between electrodes
- Particle interaction in the detector produces primary scintillation light (S1) as well as free electrons
- Electrons drift to the top of the detector and are extracted from the liquid, accelerated and produce electroluminesence light in the gas (S2)

Dual-Phase TPC: Working Principle

[Image: XENON collaboration]



Top Screening Grid

Anode Grid

Gate Grid

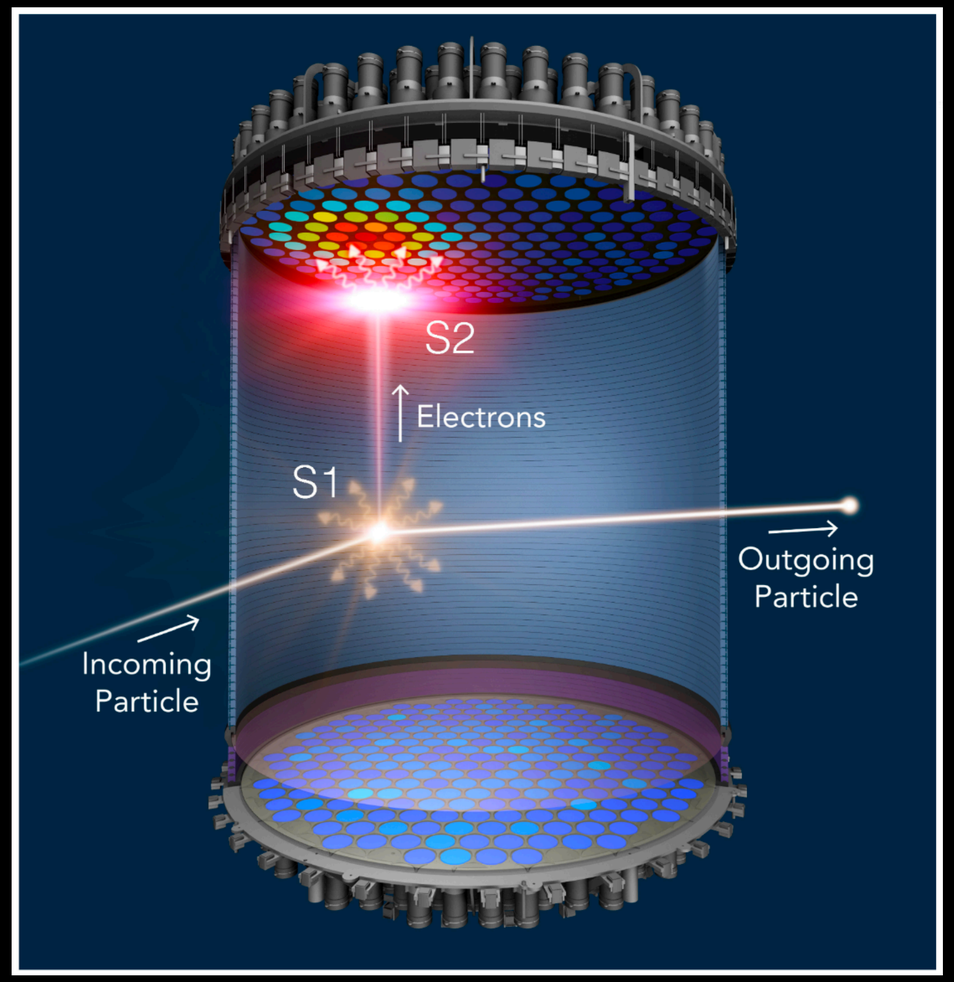
- Liquid-gas interface
- ~1 cm distance
- 6 kV ΔV

Field Shaping Wires

Resistor Chain

Dual-Phase TPC: Working Principle

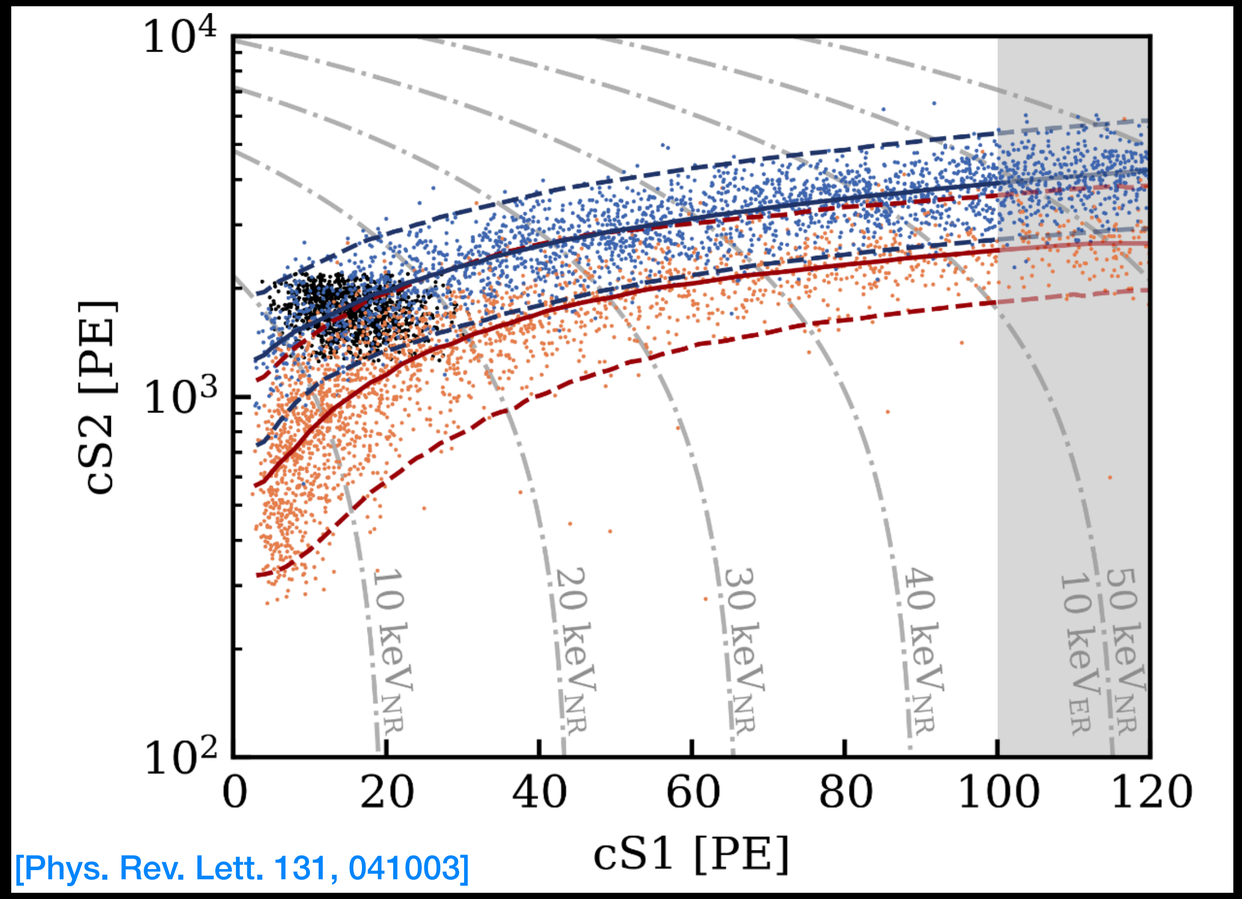
[arXiv:1703.09144]



- XY position reconstructed from S2 pattern
- Z reconstruction from the time difference between S1 and S2 and the known electron drift time
- Ratio of S2/S1 light different for different classes of events → background discrimination, i.e. between
  - electron recoil and
  - nuclear recoil

Electron recoil vs nuclear recoil

- Electron recoil: Scattering events with the shell of the (xenon) atom - α, β, γ, axions, neutrinos
- Nuclear recoil: Scattering events with the atomic nucleus - neutrons, WIMPs, neutrinos
- Higher ionisation density for NRs vs ERs and causes larger recombination, reducing the electron / S2 signal.



[Phys. Rev. Lett. 131, 041003]

Liquid Xe TPCs: State of the Art

- LXe filled dual-phase TPCs: World leaders in the search for WIMP dark matter
- Underground experiments, TPCs shielded by water tanks and active vetos
- XLZD collaboration working on the next chapter of this success story

LZ	XENONnT	PandaX-4T	XLZD
			
7 t LXe, SURF	5.9 t LXe, LNGS	3.7 t LXe, JinPing	60 - 80 t LXe

[Images: LZ, XENON, PandaX, XLZD collaborations]

Recent LZ Result

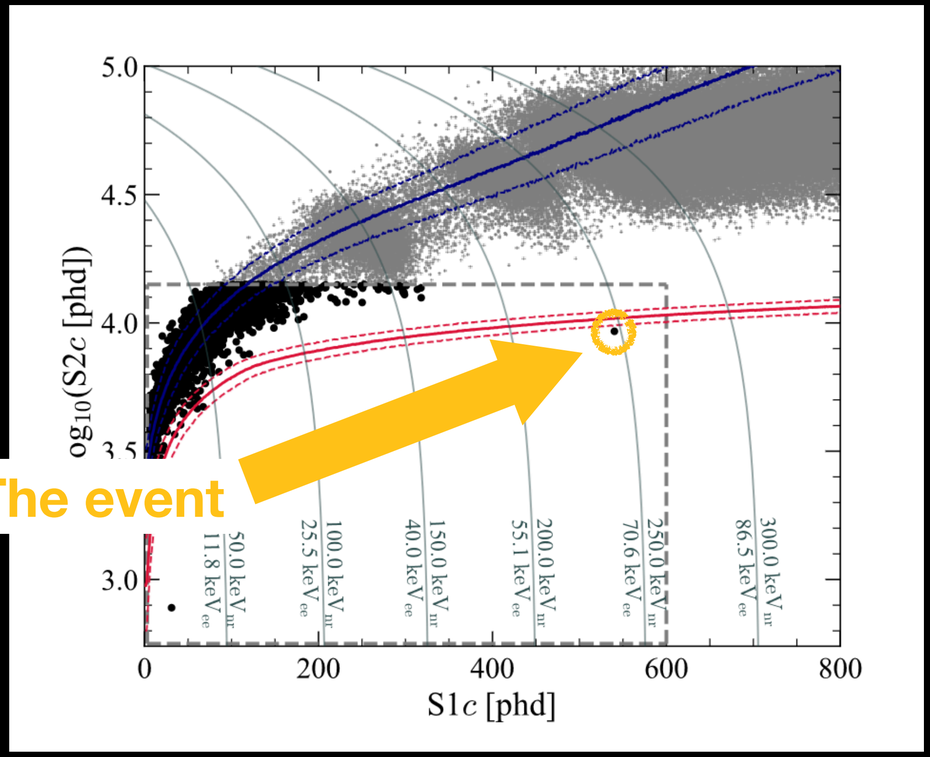
- Possible WIMP detection by the LZ experiment?
- Confirmation/exclusion by XLZD, and/or with XENONnT and more LZ data in the nearer future

[arXiv:2609.02823]

Search for dark matter particle interactions in an extended nuclear recoil energy window with the LUX-ZEPLIN (LZ) experiment

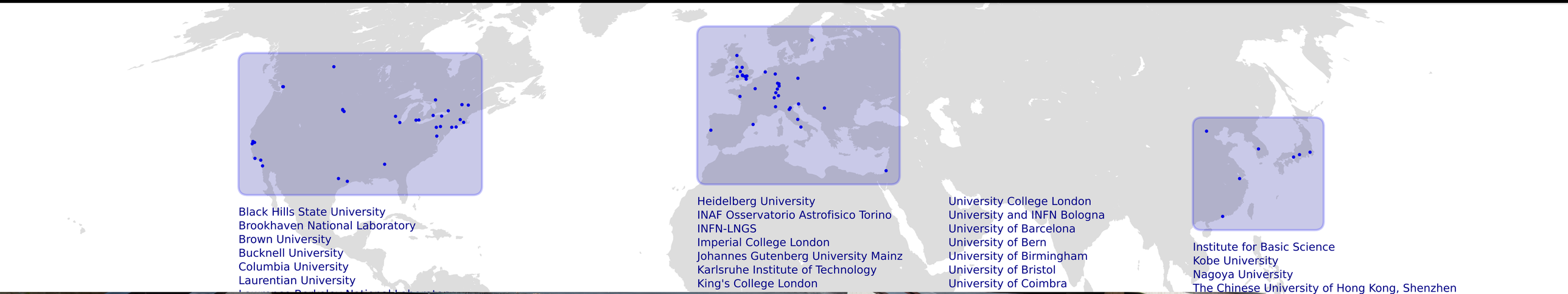
D.S. Akerib,[1,2] A.K. Al Musalhi,[3] B.J. Almquist,[4] C.S. Amarasinghe,[5] A. Ames,[1,2] T. Anderson,[6] N. Angelides,[7] H.M. Araújo,[8,9] J.E. Armstrong,[10] M. Arthurs,[1,2] A. Baker,[11] S. Balashov,[9] J. Bang,[4] J.W. Bargemann,[5] E.E. Barillier,[7] D. Bauer,[8] K. Beattie,[6] A. Beauchene,[12] T.L. Benson,[13] A. Bhatti,[10] T.P. Biesiadzinski,[1,2] H.J. Birch,[7] E. Bishop,[14] G.M. Blockinger,[15] B. Boxer,[16] C.A.J. Brew,[9] P. Brás,[17] S. Burdin,[18] M.C. Carmona-Benitez,[19] M. Carter,[18] A. Chawla,[20] J.J. Cherwinka,[13] Y.T. Chin,[19] S. Contreras,[21] M.V. Converse,[22] R. Coronel,[1,2] A. Cottle,[3] C. Coulson,[23] G. Cox,[24] C.E. Dahl,[23,25] I. Darlington,[3] S. Dave,[3] J. Delgaudio,[24] S. Desai,[21] S. Dey,[12] L. de Viveiros,[19] L. Di Felice,[8] C. Ding,[4] J.E.Y. Dobson,[11] E. Druszkiewicz,[22] S. Dubey,[4] C.L. Dunbar,[24] S.R. Eriksen,[26,*] S. Fayer,[8] N. Fieldhouse,[12] S. Fiorucci,[6] H. Flaecher,[26] E.D. Fraser,[18] T.M.A. Fruth,[27] P.W. Gaemers,[1,2] R.J. Gaitskell,[4] A. Geffre,[24] J. Genovesi,[19] C. Ghag,[3] J. Ghamsari,[11] A. Ghosh,[15] S. Ghosh,[1,2] R. Gibbons,[6,28] S. Gokhale,[29] J. Green,[3] M.G.D.van der Grinten,[9] J.J. Haiston,[30] C.R. Hall,[10] T. Hall,[18] R.N. Hampp,[7] S.J. Haselschwardt,[31] M.A. Hernandez,[7] S.A. Hertel,[32] G.J. Homenides,[33] M. Horn,[24]

The event can be described by signal spectra predicted by several NREFT Lagrangians or inelastic DM models, resulting in a global significance of 2.6 σ and a maximum local significance of 3.4 σ, typically for WIMP masses above 200 GeV c^{-2}. Several rare background processes and detector effects were studied in detail but none could be identified as a likely explanation for the event of interest.



XLZD Collaboration & Science Goals

XLZD Collaboration



Black Hills State University
Brookhaven National Laboratory
Brown University
Bucknell University
Columbia University
Laurentian University

Heidelberg University
INAF Osservatorio Astrofisico Torino
INFN-LNGS
Imperial College London
Johannes Gutenberg University Mainz
Karlsruhe Institute of Technology
King's College London
University College London
University and INFN Bologna
University of Barcelona
University of Bern
University of Birmingham
University of Bristol
University of Coimbra

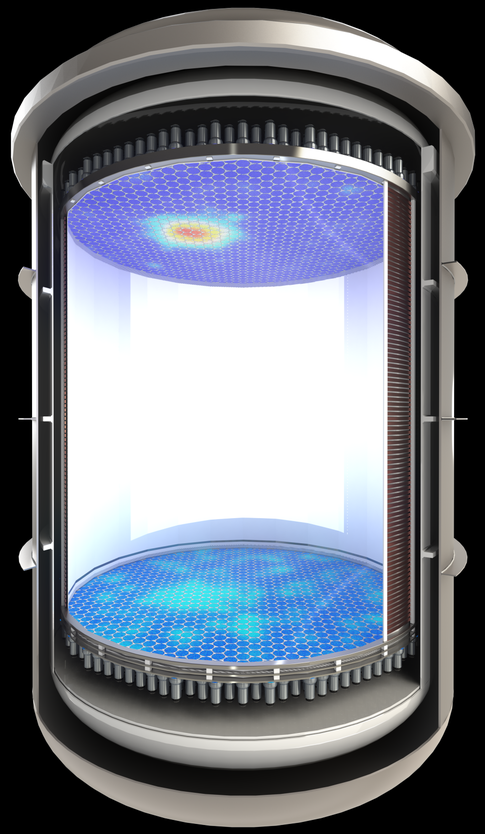
Institute for Basic Science
Kobe University
Nagoya University
The Chinese University of Hong Kong, Shenzhen
of Tokyo
versity
versity

The University of Melbourne
The University of Sydney



[Images: XLZD collaboration]

XLZD Science Programme

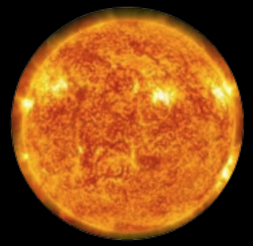


[Eur. Phys. J. C 85, 1192 (2025)]



Dark Matter (DM)

- Weakly interacting massive particles (WIMPs)
- Sub-GeV
- Axion-like particles
- Inelastic
- Dark photons



Sun

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



Neutrino nature

- $0\nu\beta\beta$ decay of ^{136}Xe
- Neutrino magnetic moment
- Double electron capture

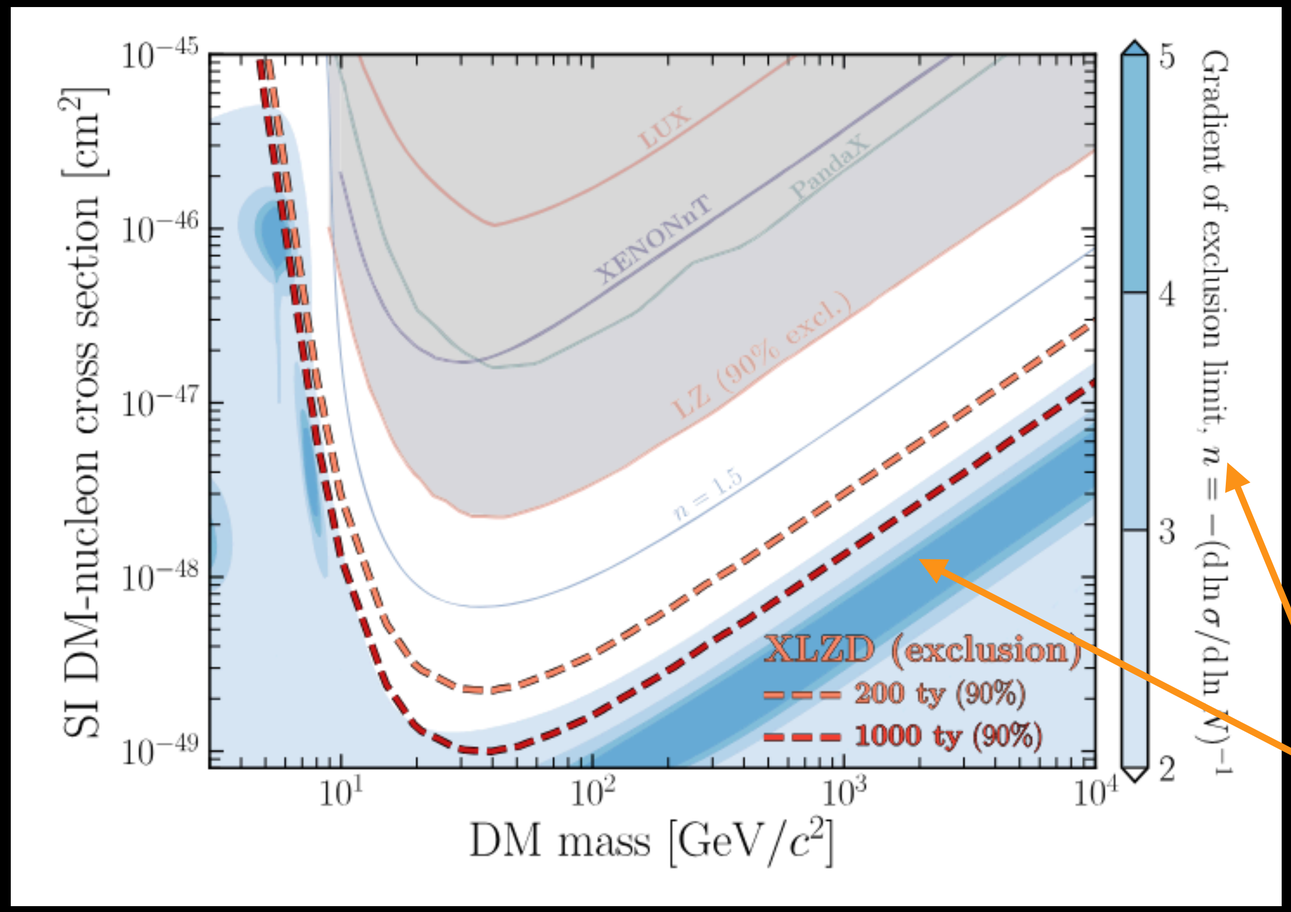


Supernovae

- Early alert
- Supernova neutrinos
- Multi-messenger astrophysics



DM Searches into the Neutrino Fog



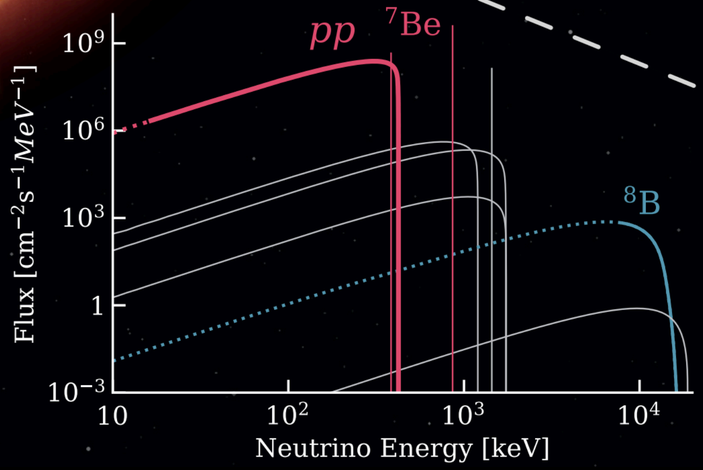
[Phys. Rev. Lett. 127, 251802]

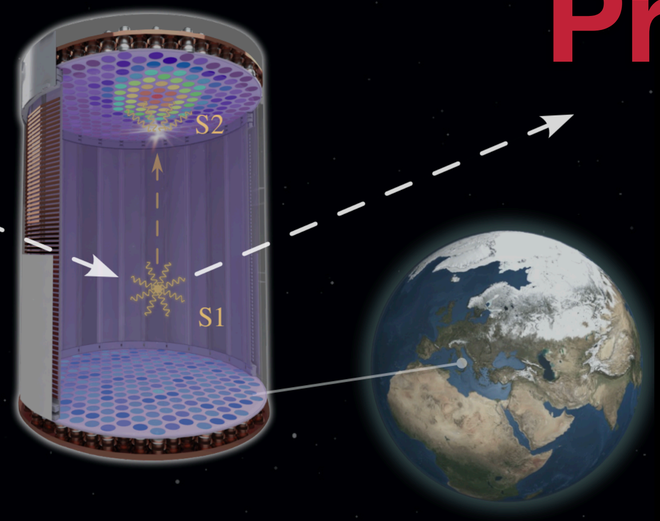
- Sensitivity only systematically limited by the neutrino fog, not other backgrounds
  - Neutrino interactions are an irreducible background inside the detector
- Large xenon mass required to reach 1000 t yr in reasonable time

For each n: lowering the cross section by $\times 10$ requires an increase in exposure by 10^n

Probing Solar Neutrinos

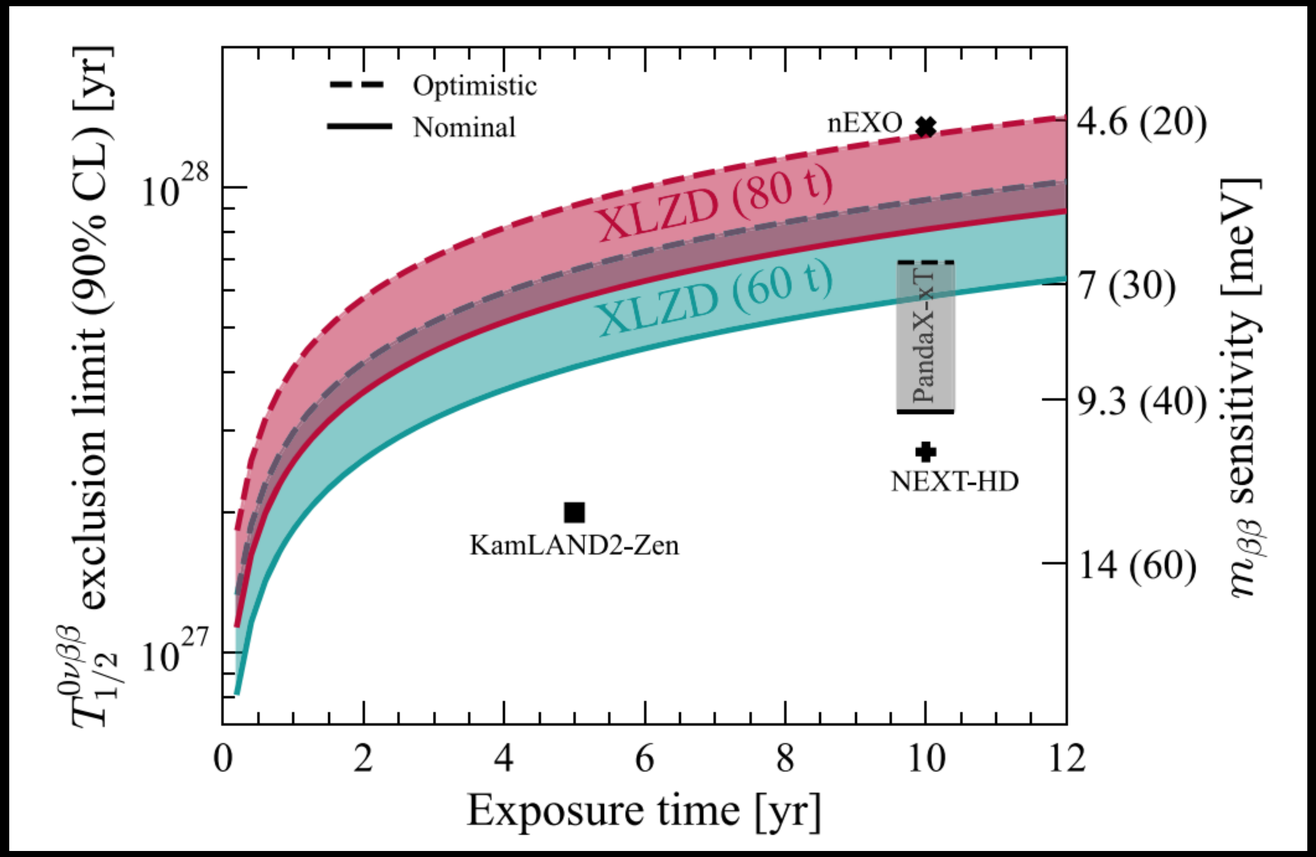
$$p + p \rightarrow d + e^+ + \nu_e$$
$$^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$$





- Today's LXe filled TPCs have seen now already indications for:
  - Coherent elastic neutrino nucleus scattering of solar ^{8}B … [Phys. Rev. Lett. 133, 191001 (2024)] [Phys. Rev. Lett. 133, 191002 (2024)] [Phys. Rev. Lett. 137, 091806 (2026)]
  - … and solar pp neutrinos [Chinese Phys. C 48 091001 (2024)] [arXiv:2608.29450 (2026)]
- XLZD will be capable of a precision measurement

$0\nu\beta\beta$ Sensitivity

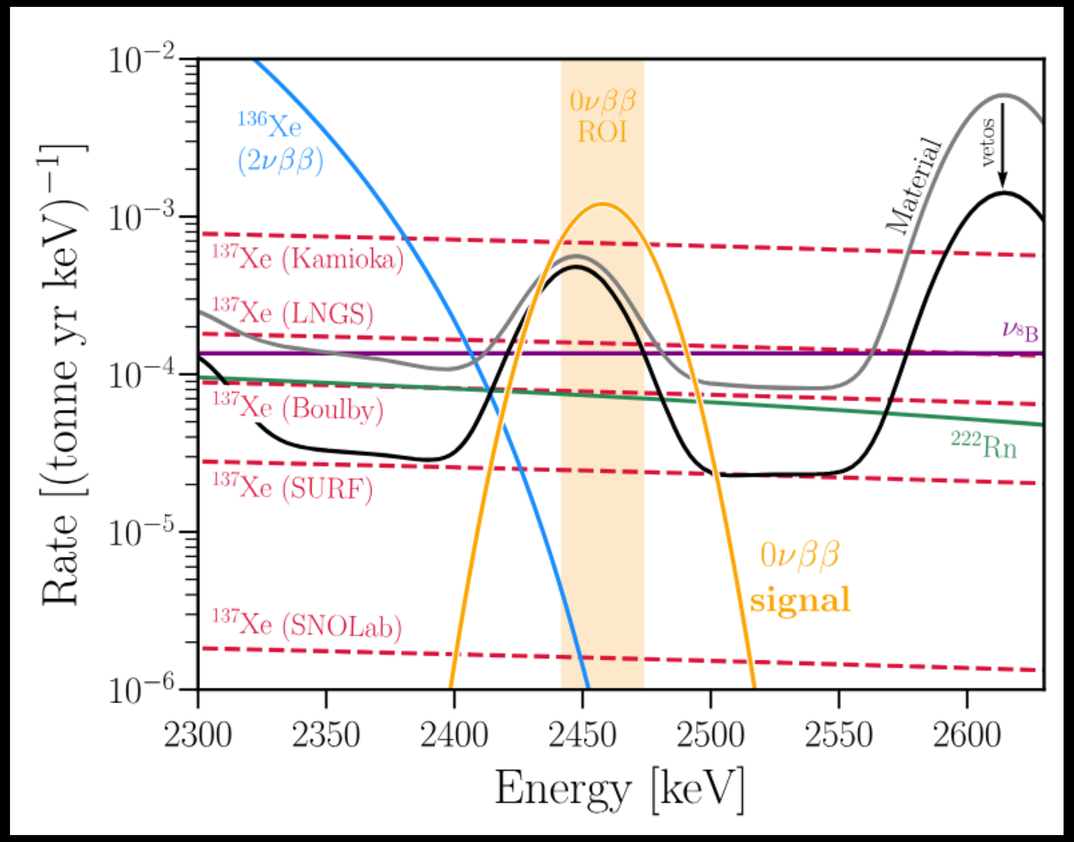


[J. Phys. G: Nucl. Part. Phys. 52 (2025) 045102]

- XLZD has the capability to measure neutrino less double beta decay of ^{136}Xe ($8.9\,\%$ abundance)
- A $80\,$t ($60\,$t) detector is thus a ton scale $0\nu\beta\beta$ experiment in its own right

  ➡ Multi-t target mass
- In case of a signal: Option to enrich the xenon further to boost signal rate

$0\nu\beta\beta$ Decay: Backgrounds



[Eur. Phys. J. C 85, 1192 (2025)]

- Assume a hypothetical ^{136}Xe $0\nu\beta\beta$ decay signal of $5 \cdot 10^{27}$ yr
- Main backgrounds:
  - β decay of ^{137}Xe, activated by cosmic muons
  - ^{8}B neutrinos
  - ^{222}Rn and ^{214}Bi, ^{208}Tl
- Further background mitigation required
- Choice of site has significant impact

Candidate Sites



Boulby Underground Laboratory, UK



INFN Gran Sasso National Laboratory (LNGS), IT



Sanford Underground Research Facility, US

- Technical site reviews have been completed

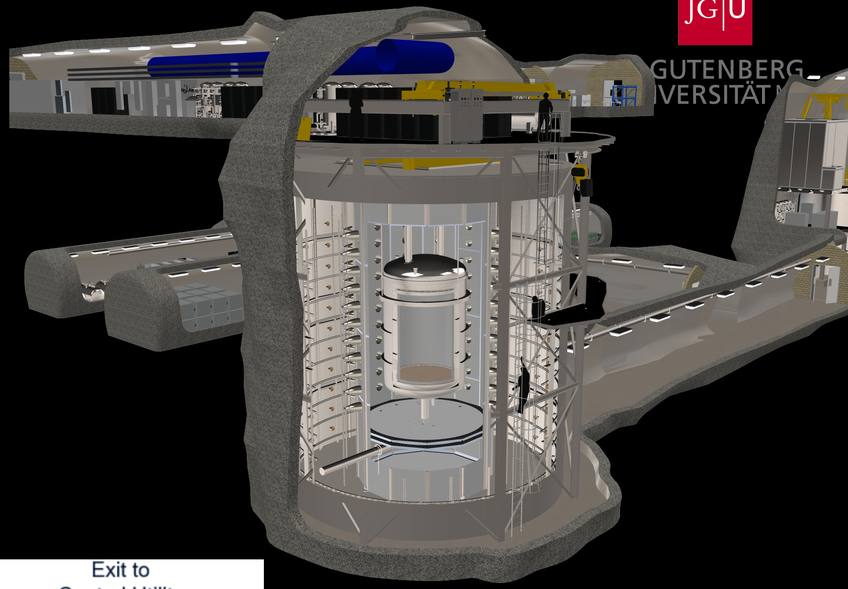


SNOLAB, CA

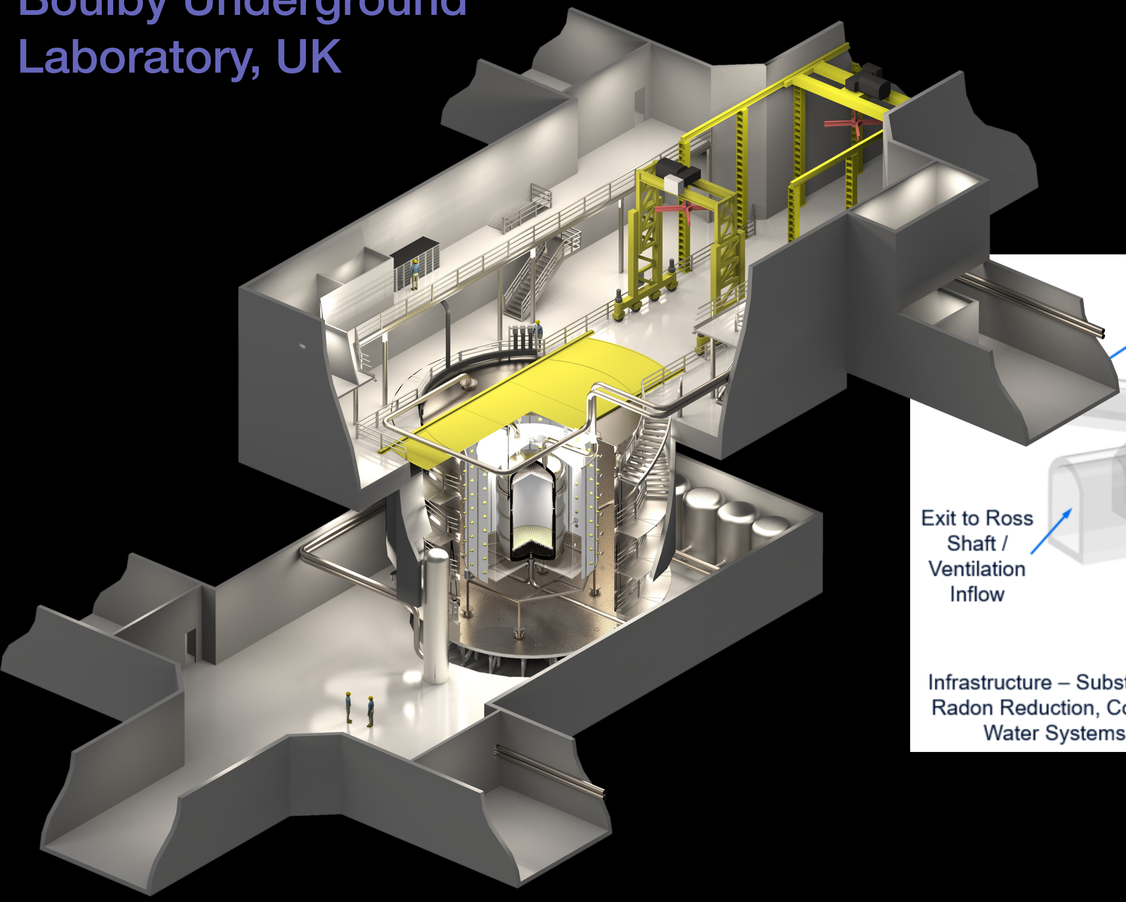
[Images: XLZD UK, XLZD collaboration, Frédéric Girard, SURF & SDSTA]

Candidate Sites

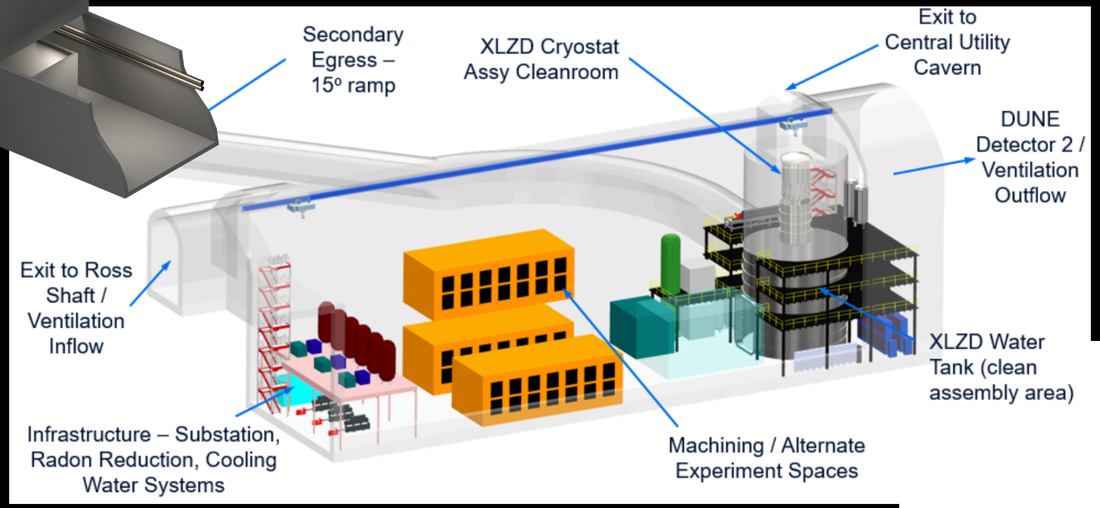
SNOLAB, CA



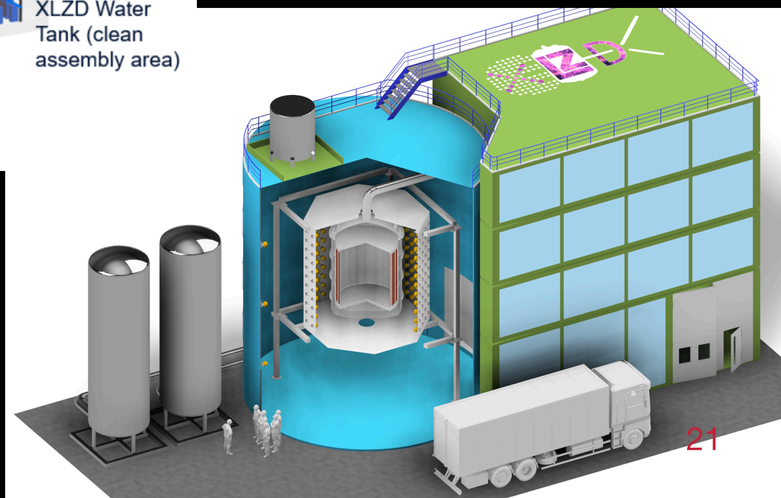
Boulby Underground Laboratory, UK



Sanford Underground Research Facility, US



INFN Gran Sasso National Laboratory (LNGS), IT



Disclaimer

- This is a — my — biased selection
- Some obvious topics missing: Calibration, radio-pure manufacturing, cryostat construction & engineering ….

Detector design

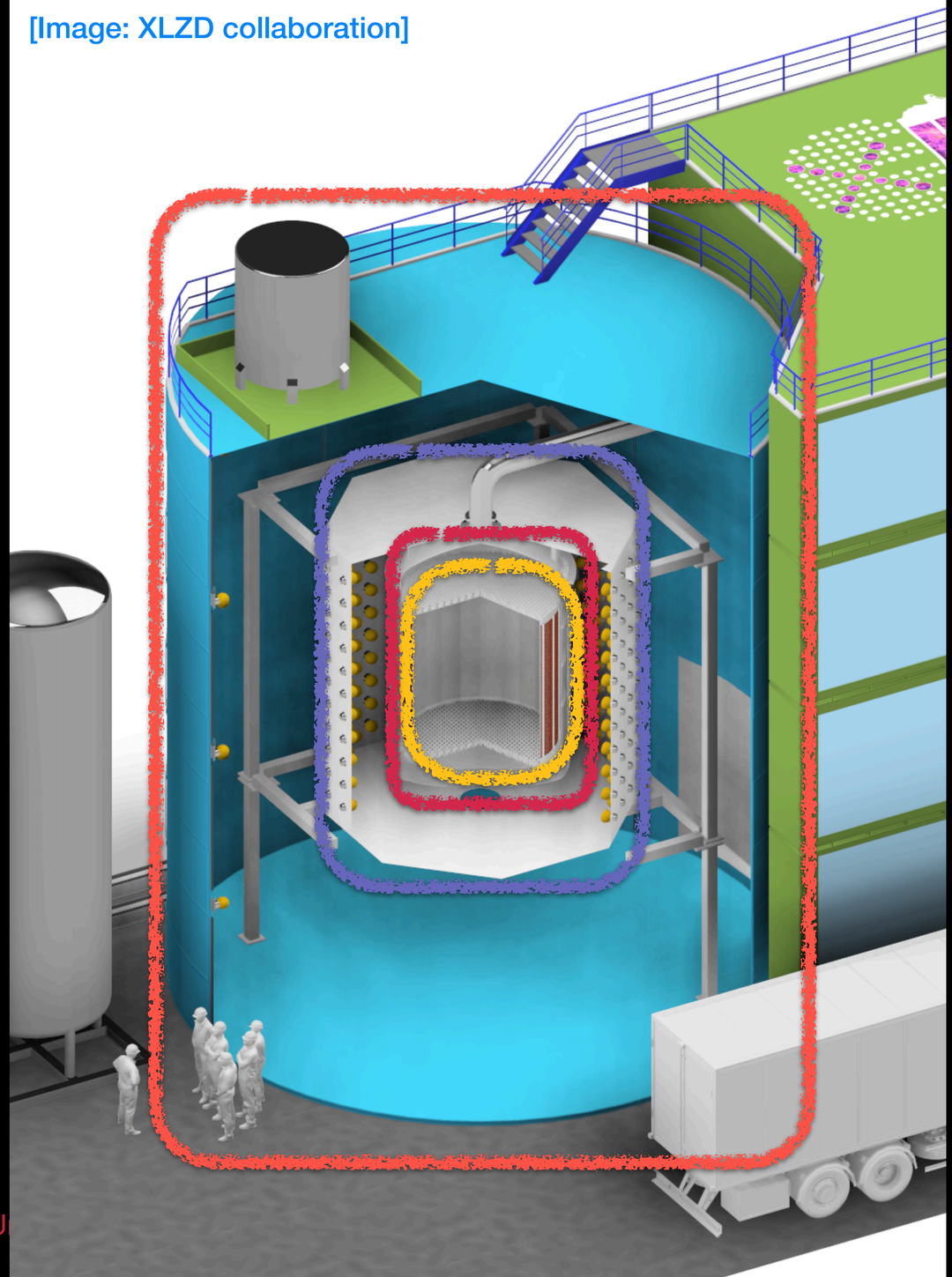
But:

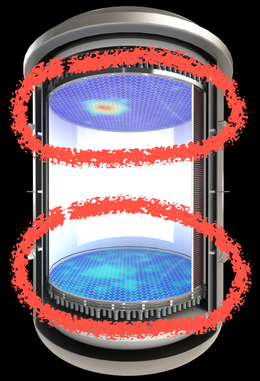
There is the Conceptual Design Report soon; read for a comprehensive overview

Design Overview

- TPC with 60 t LXe (includes 5.1 t of ^{136}Xe):
  - 3 m diameter, 3 m drift length
  - Outer diameter cryostat: ~ 4 m
  - Funding allowing, 80 t LXe and longer drift
- Anti-coincidence vetos:
  - LXe skin detector
  - Neutron veto
  - Active water-shield / muon veto

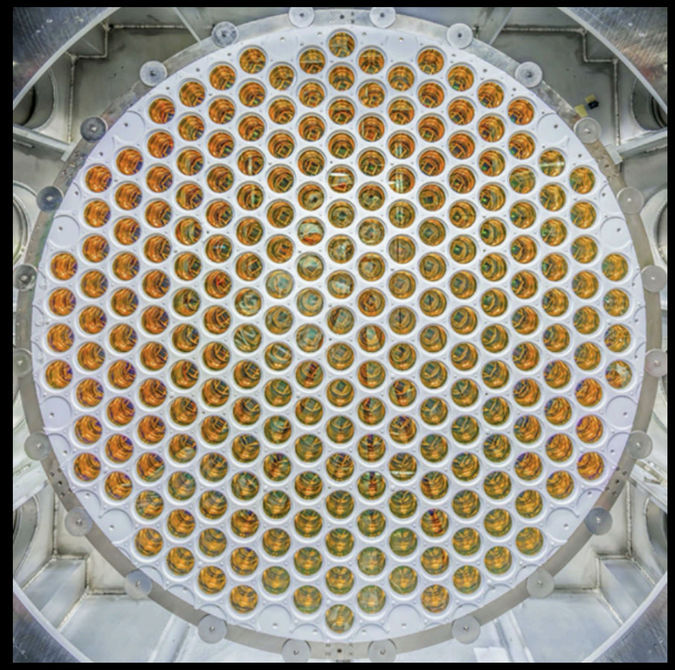
[Image: XLZD collaboration]





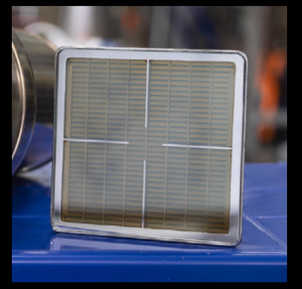
Photosensor Arrays

- Baseline design: 1182 low radioactivity, 3 inch photomultiplier tubes (PMTs) in top and bottom array each
- Extensive experience from operating similar PMTs in LZ, XENONnT
- Dark count rate (DCR) $\sim 0.2\,\mathrm{Hz\,mm^{-2}}$, quantum efficiency (QE) $\gtrsim 40\,\%$ at $175\,\mathrm{nm}$
- R&D: Improved radio-purity, ensuring long term stability

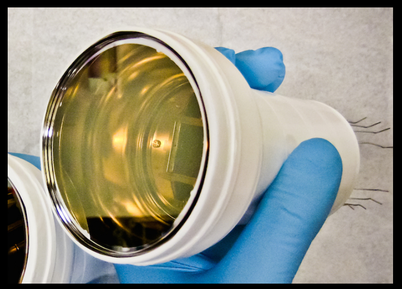


LZ bottom PMT array

2” by 2” Hamamatsu R12699 (PandaX-4T)

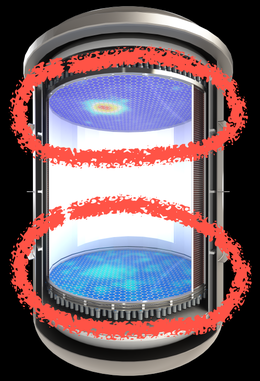


[NIM A 1073 170290]
[2025 JINST 20 P12021]



[Image: LZ]

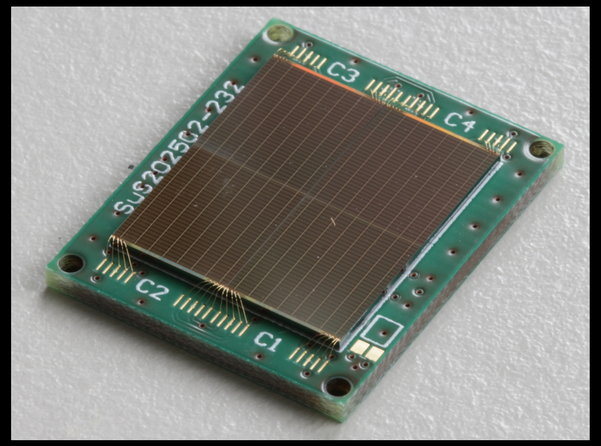
3” Hamamatsu R11410 (LZ & XENONnT)



Alternative Photosensors

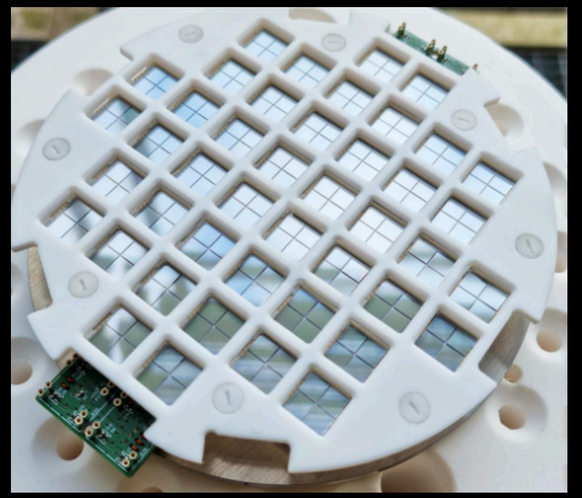
- Silicon photomultipliers (SiPMs): Lower radioactivity per area, require only 10s of V, instead of $\mathcal{O}(1000\,\mathrm{V})$
  - But: Lower QE at LXe light and DCR per area still to high by a factor of 10-100
  - Digital SiPMs: Noisy SPADs can be disabled → low DCR
    e.g. [2025 JINST 20 C06008]
- Hybrid devices: E.g. Photocathode combined with an APD or SiPM

Digital SiPMs



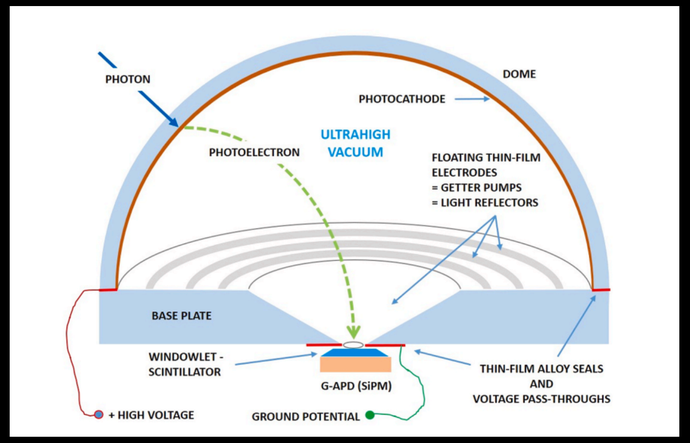
[Image: Peter Fischer]

SiPM arrays

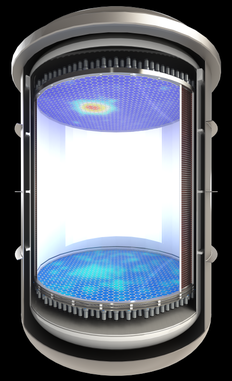


[2023 JINST 18 C03027]

Hybrid concepts



[2022 JINST 17 C01038]

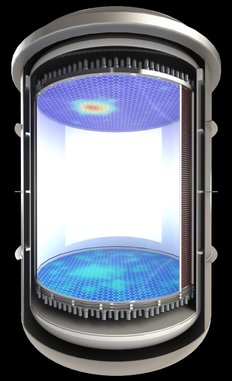


Background in LXe: ^{85}Kr and ^{222}Rn

- ^{85}Kr, present in trace amounts in commercial xenon
  - May enter the detector through tiny air leaks or by outgassing of plastics
  - Required: < 0.03 ppt
- ^{222}Rn, daughter of ^{226}Ra, present in the detector materials
  - Continuous outgassing
  - Required: $< 0.1 \times 10^{-6}$ Bq kg^{-1}

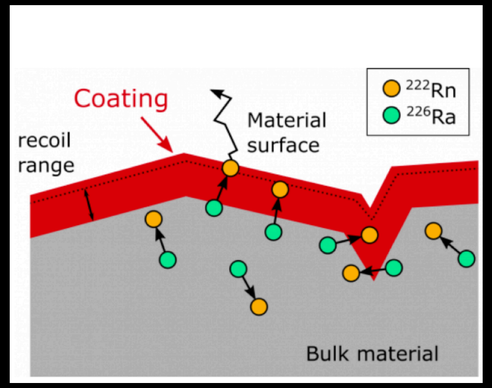
[nndc.bnl.gov/nudat3/]

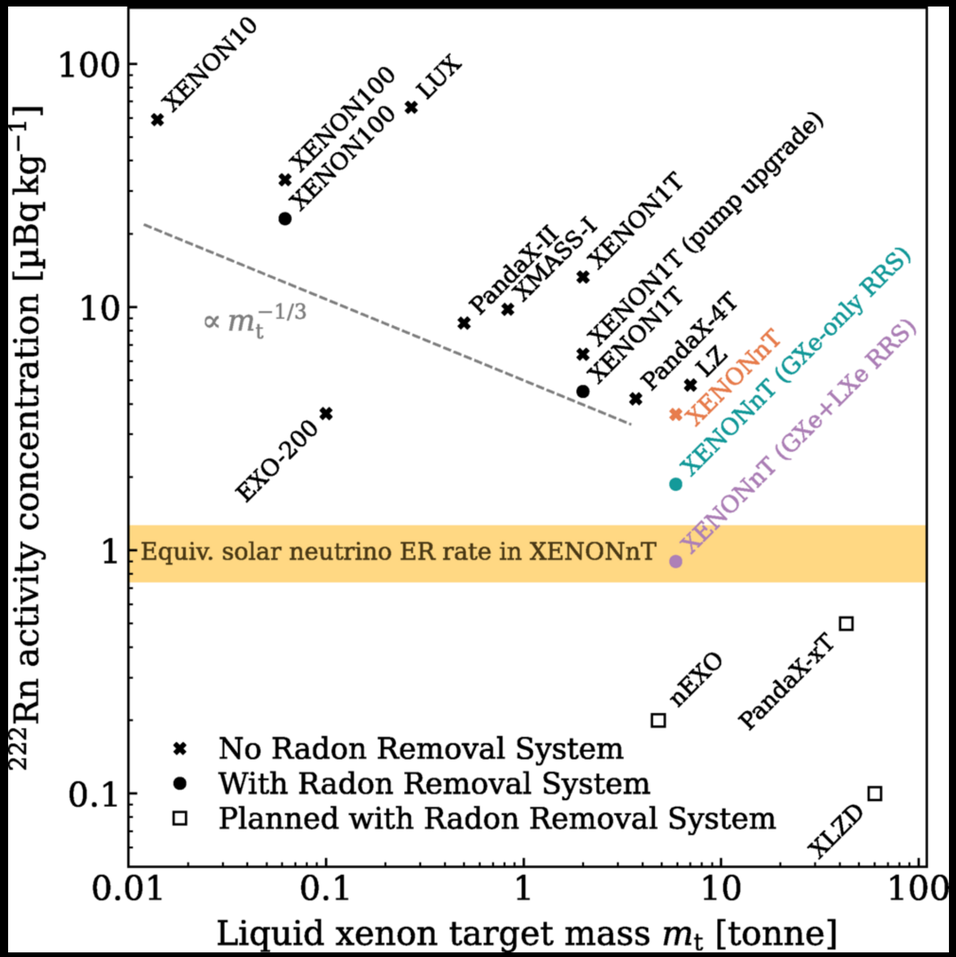


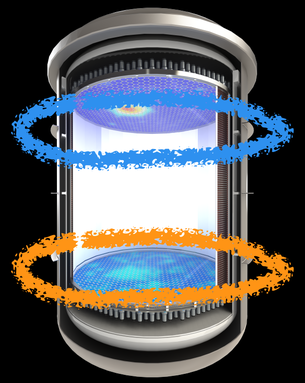


R&D on ^{222}Rn and ^{85}Kr Reduction

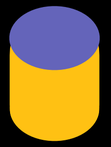
- Radio pure materials without radioisotope emanation
- ^{222}Rn & ^{85}Kr removal by distillation
  - Success in XENON1T & nT [Eur. Phys. J. C 77, 275 (2017)] [Phys. Rev. X 15, 031079]
  - On XLZD scales: $\mathcal{O}(10\,\mathrm{t\,day^{-1}})$ distillation required
- Coating of bulk materials to reduce ^{222}Rn outgassing

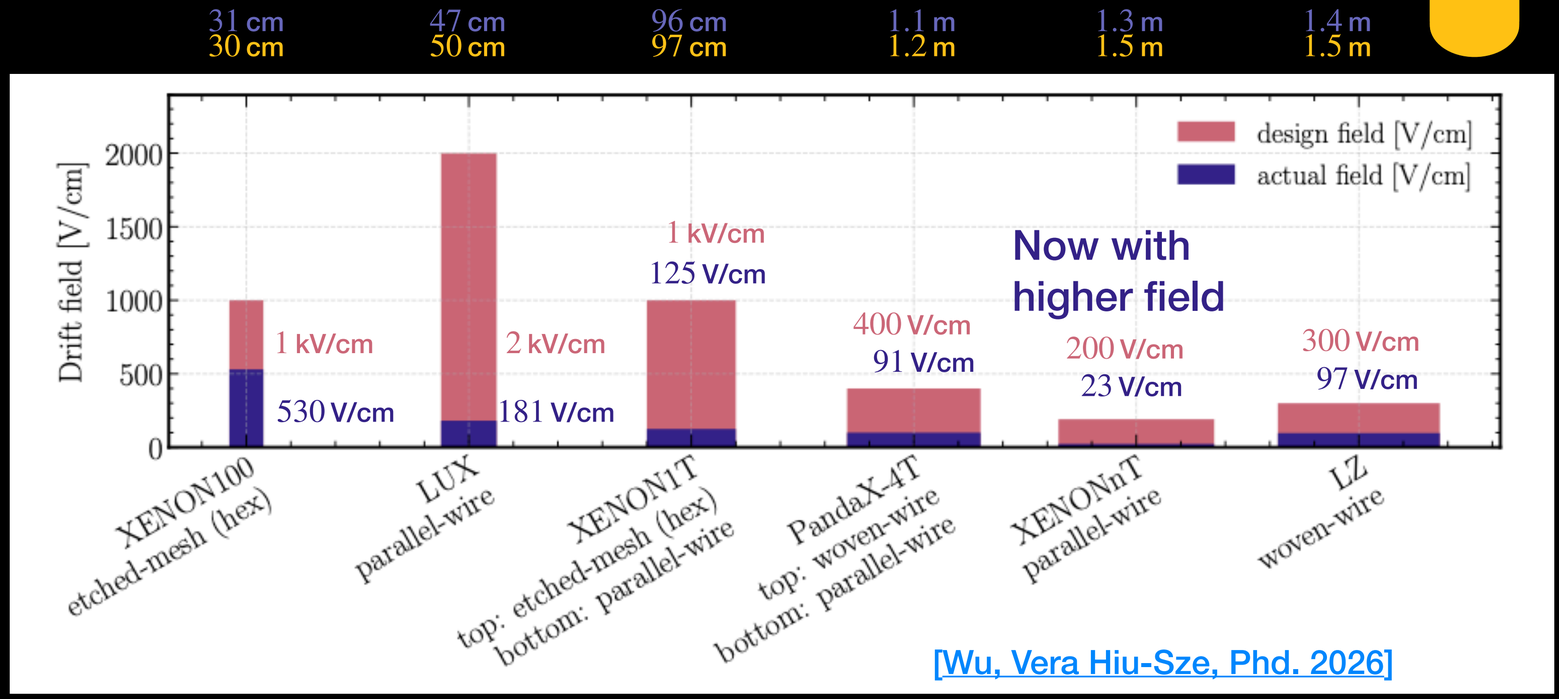






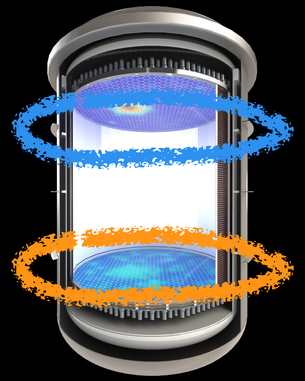
High Voltage Stability





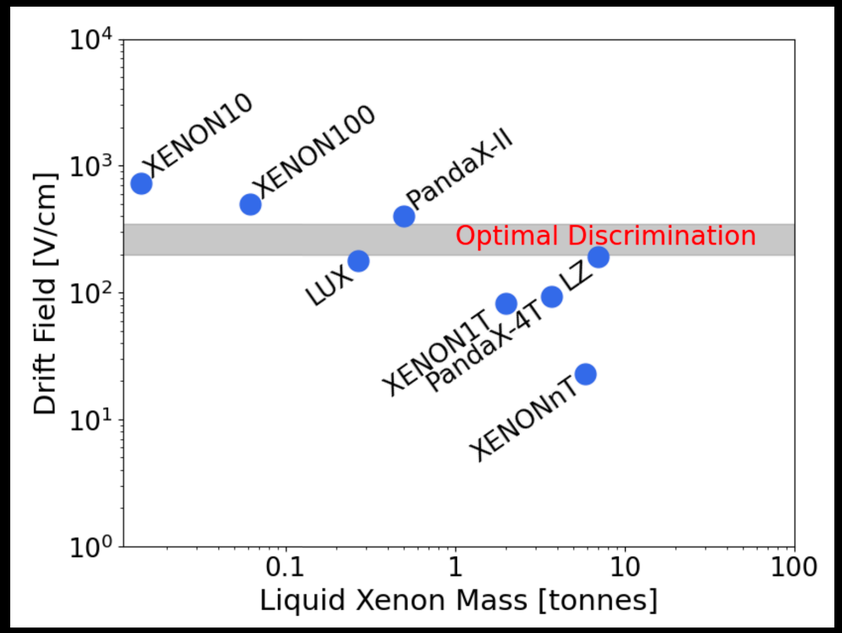
[Wu, Vera Hiu-Sze, Phd. 2026]

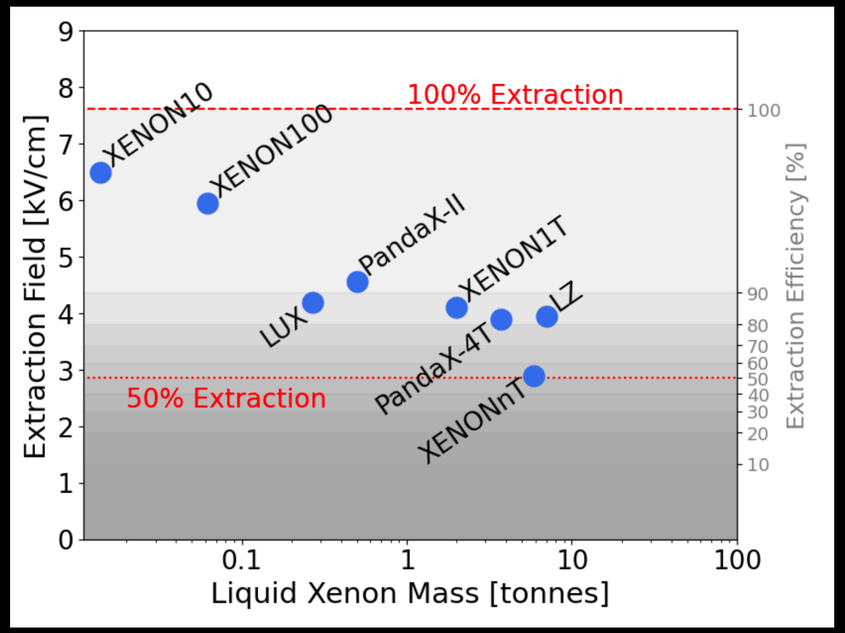
- Stable fields are required inside of the TPC
- Drift field of $\sim 150\,\mathrm{V\,cm^{-1}}$ requires ~ 45 kV (60 t) or ~ 60 kV (80 t) on the cathode
- R&D on new electrodes and how their performance can be assured (before employing them inside a TPC)



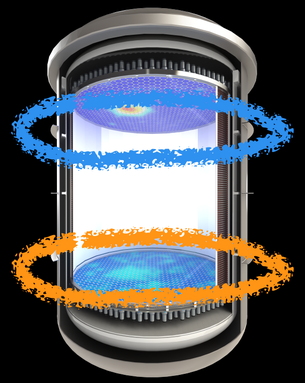
Target Fields

- Best separation between nuclear and electronic recoils:
  - $E_{\mathrm{d}} \sim 170\,\mathrm{V\,cm^{-1}}$
- Extraction $\gg 90\,\%$ at $6\,\mathrm{kV\,cm^{-1}}$ in the liquid:
  - 6 kV voltage difference between anode and gate (1 cm gap, liquid level centred)



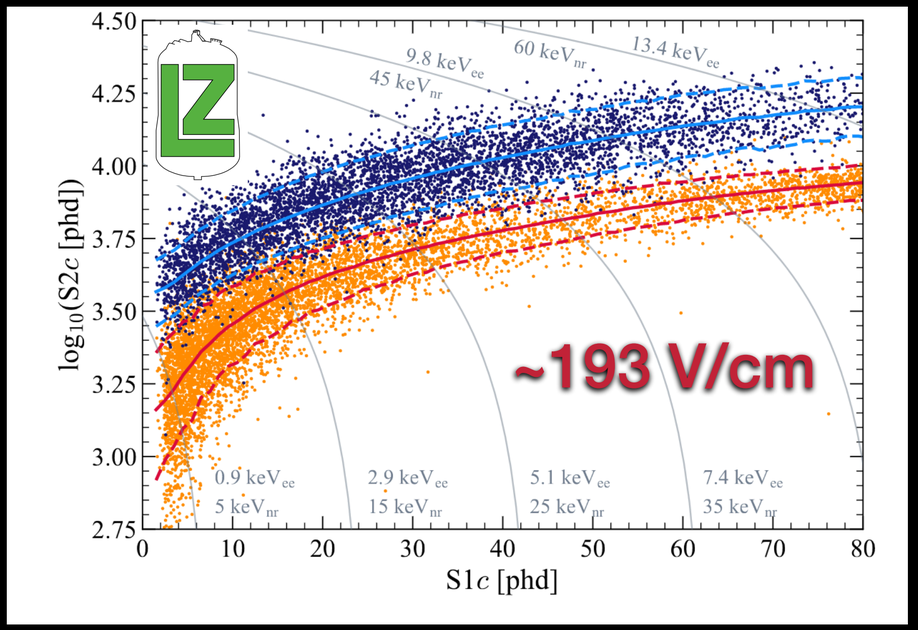


[A. Kopec, JAIS, vol. 2024, no. 1, Feb. 2024]

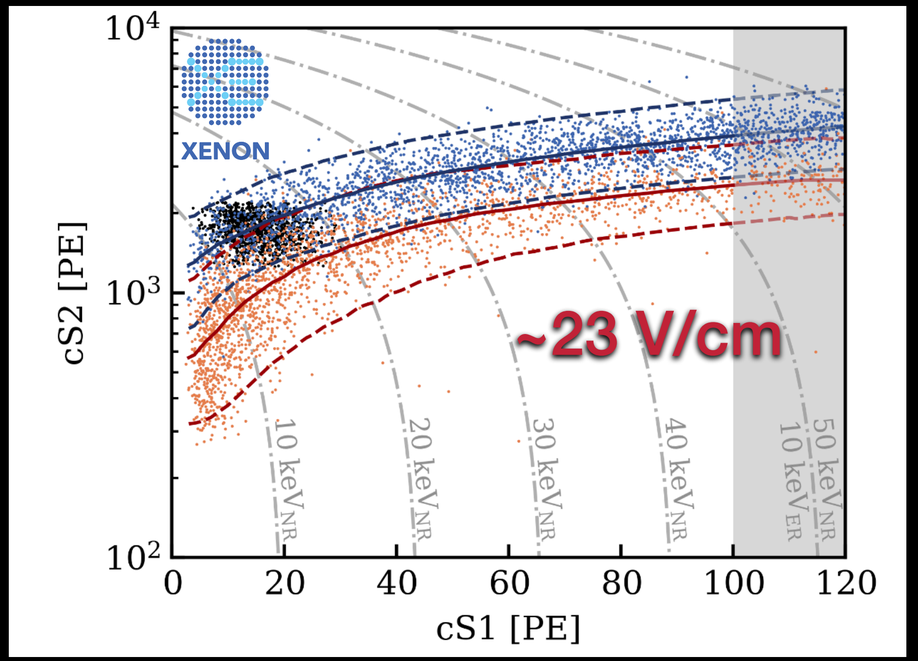


Drift field and NR/ER separation

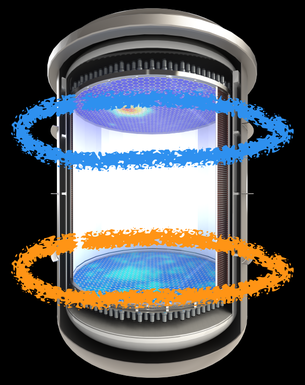
- Drift field affects greatly the NR/ER separation
- nT plot: $\pm 2\sigma$ - LZ plot 10 % and 90 % quantile
- Significantly larger overlap of the NR and ER band in the XENONnT case
- Crucial to ensure electrodes work at their design voltages (e.g. ~ 20 kV for the cathode)
- One reason for the XENONnT electrode upgrade in 2025



[Phys. Rev. Lett. 131, 041002]

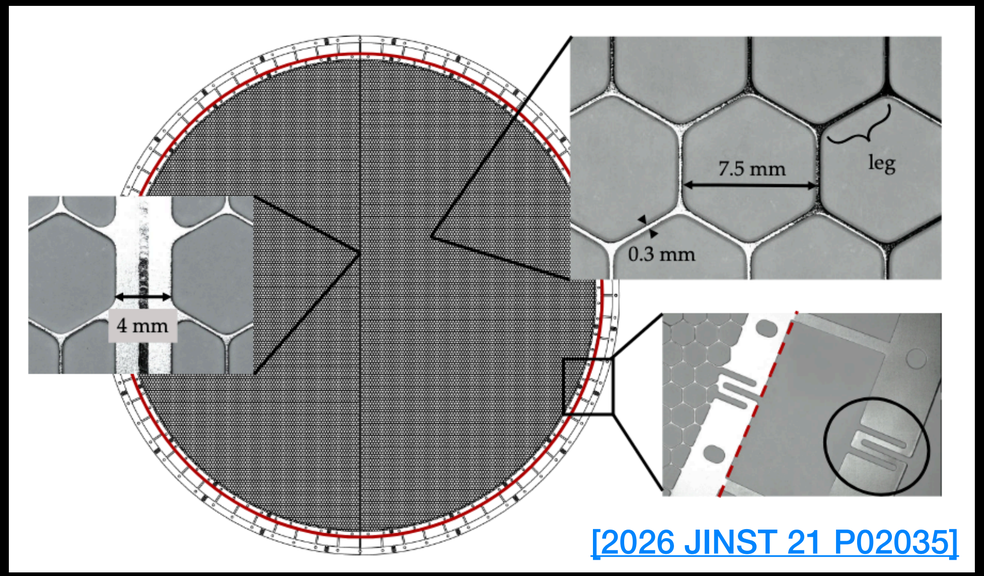


[Phys. Rev. Lett. 131, 041003]



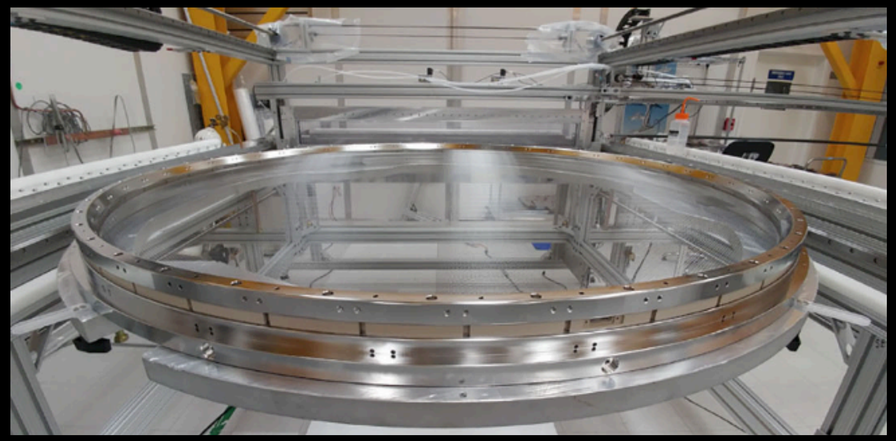
Electrodes for XLZD

XENONnT: Photomechanically etched cathode mesh — two half-grid laser-welded into one

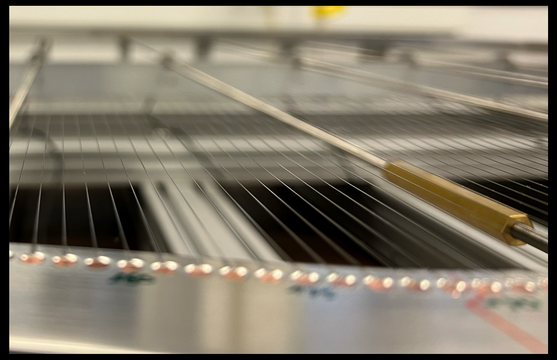


[2026 JINST 21 P02035]

[NIM A 953, 163047 (2020)]



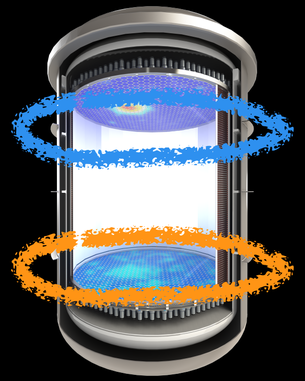
LZ: Woven meshes with custom built loom



[Image: A. Deisting]

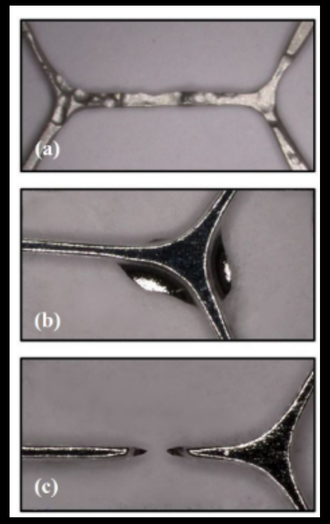
Test wiring of a parallel wire electrode

- Parallel wire grids: Very challenging to reach required tension for 3 m electrodes
- Meshes (woven/etched): Promising with regard to tension and optical transparency
  - Still needs to be demonstrated on XLZD scale

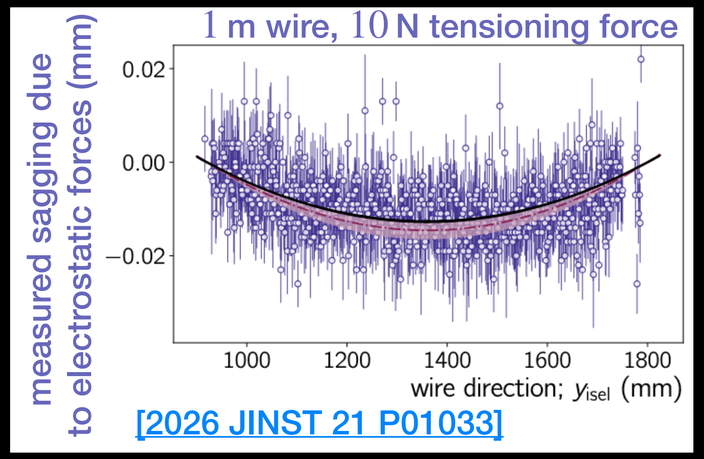


Electrode Quality Assurance

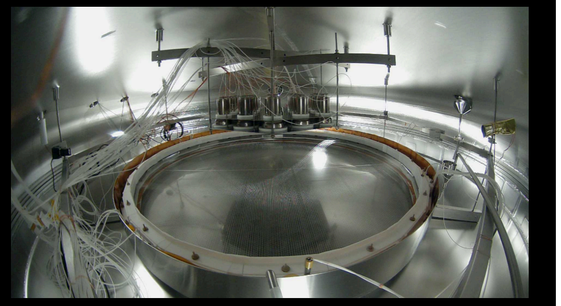
- Wire tension determination by measuring induced oscillations (wire grids) or by measuring the absolute sagging (e.g. meshes)
- Optical inspection, combined with machine learning methods for defect detection
- Correlation of defects with dark discharge currents
- Electrode tests in air, other, cheaper gases than xenon, and in LXe (e.g. PANCAKE)



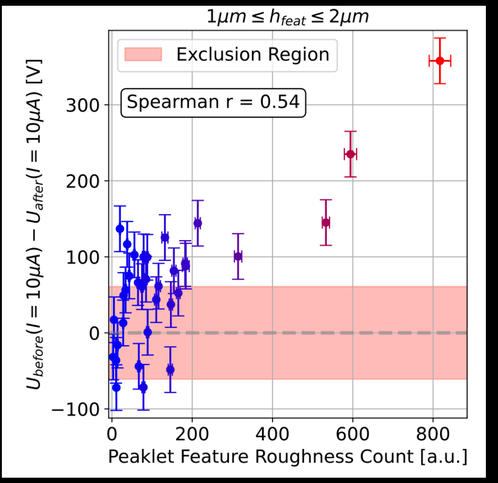
[2026 JINST 21 P02035]



[2026 JINST 21 P01033]



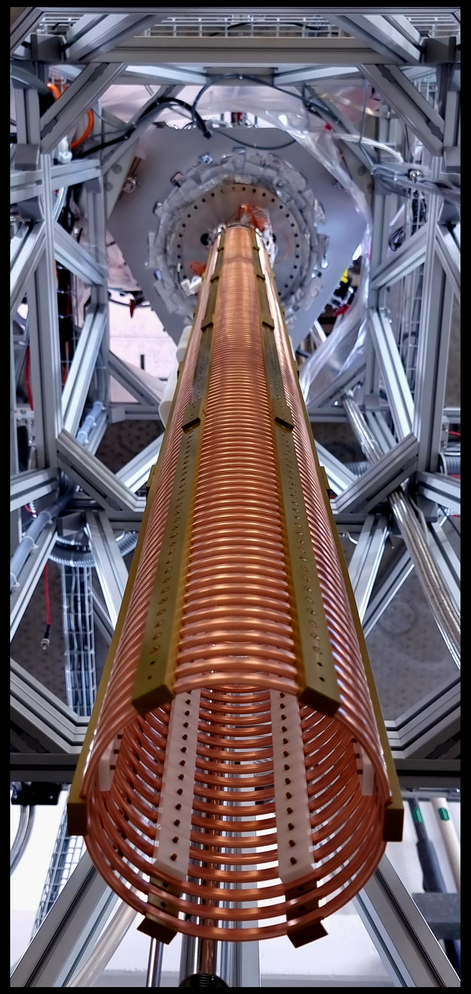
[arXiv:2601.15938]



[2026 JINST 21 P01034]

[Image: F. Giard]
[2021 JINST 16 P08052]

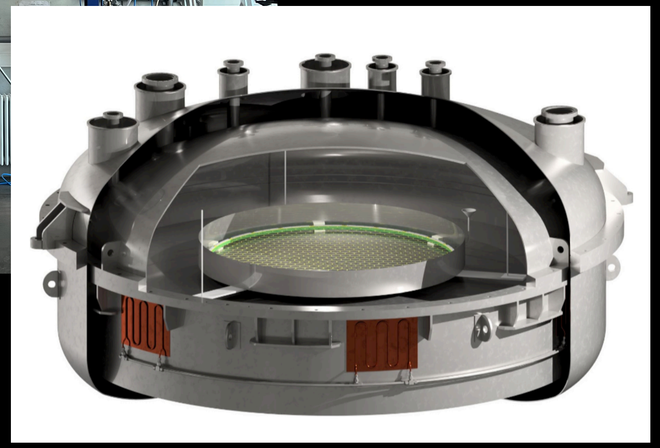
Large Scale Testing Facilities



Xenoscope



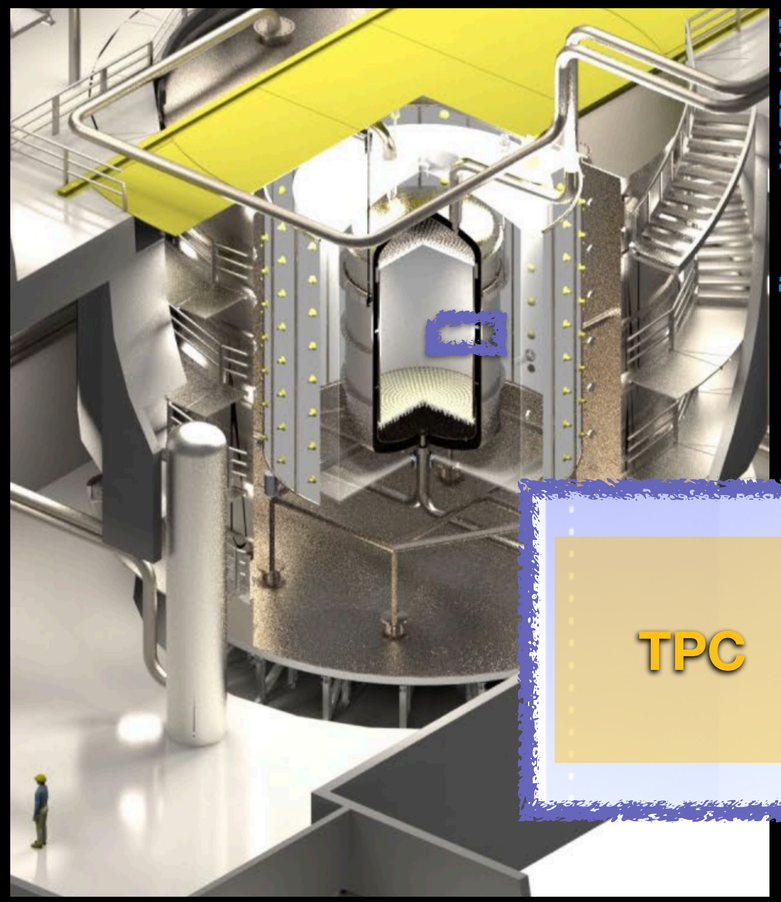
PANCAKE

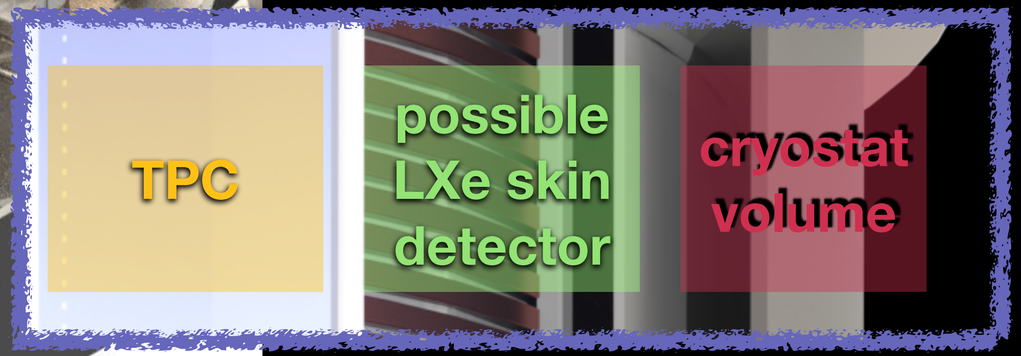


[2024 JINST 19 P05018]
[arXiv:2601.15938]

- **Xenoscope**: Demonstrator with 15 cm inner diameter and drift length up to 2.6 m
- **PANCAKE**: Cryostat with 2.6 m inner diameter for electrode tests
  - Employed to test XENONnT sized electrodes with an inner vessel (“bathtub“)

LXe Skin Detector

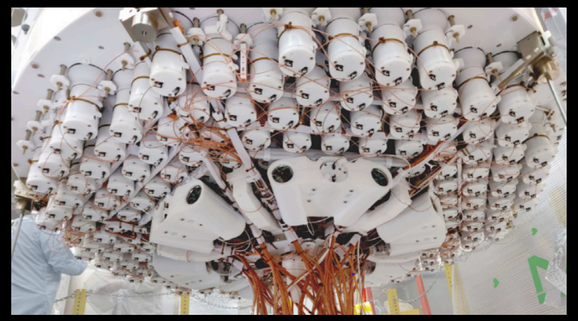

[Image: XLZD UK]



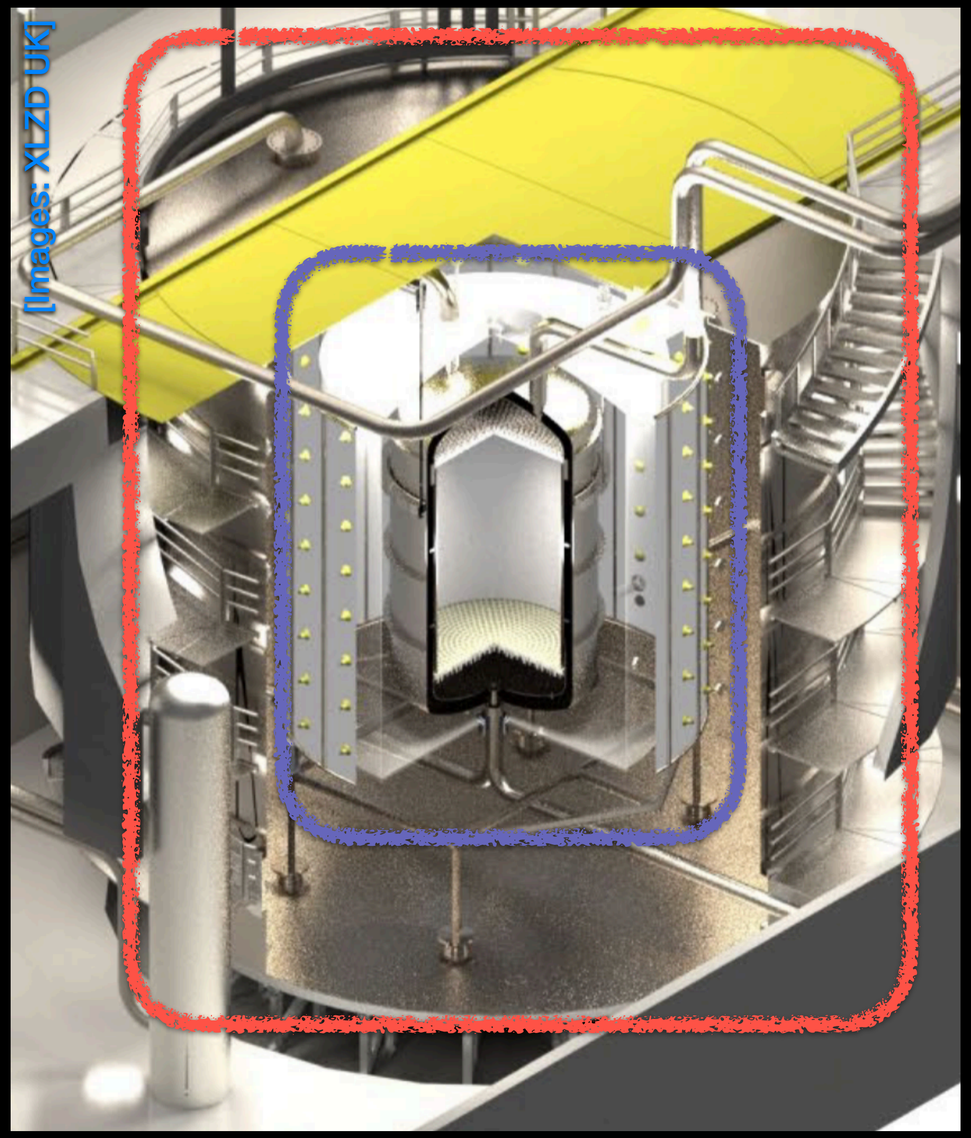
- "LXe Skin" located in the ~ 5 cm volume between TPC and inner cryostat
- As well as below and above the TPC

- Veto against γ and neutron interactions inside the TPC
- Together with outer detectors: high efficiency in rejecting single scatter neutron events

LZ LXe skin PMTs



[NIM A 953, 163047 (2020)]



Outer Detectors

- Provide shielding against external radiation (e.g. γs from the cavern wall, neutrons) as well as anti-coincidence tagging
- Neutron veto:
  - Gadolinium doped liquid scintillator (LZ) or Gd doped ultra-pure water (XENONnT) considered for XLZD
  - Gd decreases capture time for neutrons and increases the energy released in γs (2.2 MeV $\rightarrow$ ~ 8 MeV captures on Gd vs H)
- Active water-shield (muon veto)

Summary

- XLZD will be the ultimate LXe observatory for WIMP DM, sensitivity to $0\nu\beta\beta$ being worked on
- The new observatory doubles the size of the largest currently running experiments
- Despite not being a fully funded collaboration yet, R&D is ongoing
- More topics than shown here are being worked on. (Apologies to colleagues working e.g. on the cryostat design, Xe handling, procurement, ….)
- Conceptual design report being written right now

Exciting times ahead!*

*Even before the LZ event ;)

