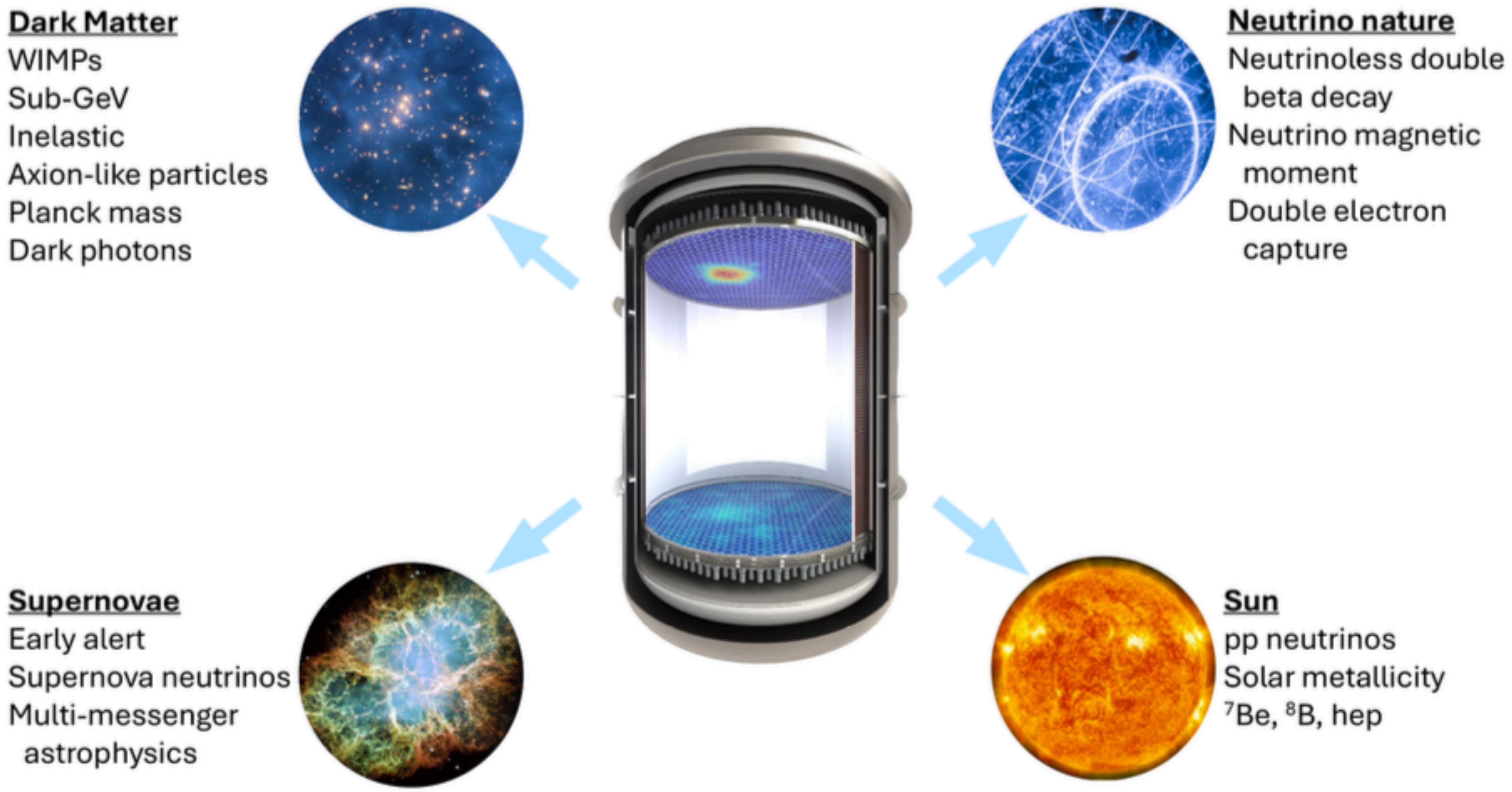
XLZD Status

Masaki Yamashita
Kavli IPMU, the University of Tokyo (WPI)

on behalf of the XLZD collaboration

2025/08/25
The XIX International Conference on Topics in Astroparticle and Underground Physics

A xenon-based low-background observatory for rare events



- WIMP detection is the primary goal
- Opportunity to be competitive in $0\nu\beta\beta$
- Other DM candidates
  (Light WIMPs, Axions, ALPs, Dark Photons, etc)
- Neutrino physics
  - Solar neutrinos (model, properties)
  - Supernovae

=> Knut's talk 'Science Prospects Of The XLZD Experiment'

The XLZD Collaboration

XENONnT + LUX-ZEPLIN + DARWIN

- **LZ** and **XENONnT** are operating and leading experiments
- **DARWIN**: planned after the XENON program.

  Initiated R&D and design studies with significant ERC support

2021 XENON, LUX-ZEPLIN, DARWIN
MOU signed:16 countries, 104 scientists
2022-2024 **Annual meetings:**
KIT 2022, UCLA 2023, RAL 2024
2024 **XLZD collaboration was formed.**
2025 **LNGS 2025 meeting**

Recent / ongoing activities

- Design and sensitivity reports posted
- Working groups: science, technical, siting
- UK Pre-construction & Boulby development

XENON + LZ + DARWIN

Highlighted papers from XLZD

- **A next-generation liquid xenon observatory for dark matter and neutrino physics** J. Phys. G: Nucl. Part. Phys. 50 013001, 2023
- **The XLZD Design Book: Towards the Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics** arXiv:2410.17137v1
- **Neutrinoless double beta decay sensitivity of the XLZD rare event observatory** J. Phys. G: Nucl. Part. Phys. 52 045102

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Recent / ongoing activities

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- **W**ork **B**reakdown **S**tructure in place to estimate costs and to distribute scope.

Work Breakdown Structure

1.01	**Project Management, Admin & Systems Engineering**	
	1.01.01	Project Management
	1.01.02	Environmental Safety and Health
	1.01.03	Quality Assurance
	1.01.04	Project Management Controls Support (PMCS)
	1.01.05	Systems Engineering Support
	1.01.06	Project Science Coordination
	1.01.07	Communications and Outreach
	1.01.08	Sustainability
1.02	**Xe Acquisition**	
	1.02.01	System Engineering & Management
	1.02.02	Xenon Procurement
	1.02.03	Long-term storage system
	1.02.04	Feed/recovery system
1.03	**Xe Purification & Handling**	
	1.03.01	System Engineering & Management
	1.03.02	Krypton Removal System
	1.03.03	Radon Removal System
	1.03.04	Liquid phase electronegative purification
	1.03.05	Gas phase electronegative purification
	1.03.06	Cryogenic Xe Storage (ReStoX)
	1.03.07	Xe Diagnostics - electronegative, Kr/Rn/Ar
1.04	**Cryogenics**	
	1.04.01	System Engineering & Management
	1.04.02	Modeling and Simulations
	1.04.03	Commercial LN Supp[illegible]
	1.04.04	Customize[illegible]
	1.04.05	Cryogen[illegible]
1.05	**Cryostat**	
	1.05.01	System En[illegible]agement
	1.05.02	Modeling an[illegible]mulations
	1.05.03	Material acquisition
	1.05.04	Outer Cryostat Vessel (OCV)
	1.05.05	Inner Cryostat Vessel (ICV)
	1.05.06	Cryostat support / suspension (CS)
	1.05.07	Ancillaries
	1.05.08	Cleaning and plating
	1.05.09	Host site integration
1.06	**Xe Detector**	
	1.06.01	System Engineering & Management
	1.06.02	Modeling and simulations
	1.06.03	Top PMT array
	1.06.04	Bottom PMT array
	1.06.05	Skin detector
	1.06.06	PMTs, cold electronics, cabling
	1.06.07	PMT calibrations
	1.06.08	Field Cage
	1.06.09	Extraction region, Gate, Anode system
	1.06.10	Cathode grid
	1.06.11	Cathode HV delivery system
	1.06.12	Instrumentation
	1.06.13	Xe fluid system
1.07	**Outer Detector System**	
	1.07.01	System Engineering & Management
	1.07.02	Water tank / outfitting and systems
	1.07.03	Optical modeling and simulations
	1.07.04	Modelling and simultaion of th[illegible]
	1.07.05	Neutron detector [illegible]
	1.07.06	Neutr[illegible]
	1.07.0[illegible]	[illegible]
	[illegible]	[illegible]
	[illegible]	[illegible] structures
	[illegible]	[illegible]alibration
	[illegible]	[illegible] photosensor system
	1.07.12	Radioscreener
1.08	**Calibrations**	
	1.08.01	System Engineering & Management
	1.08.02	Sealed source deployment system
	1.08.03	Gaseous source injection systems
	1.08.04	Tritium calibration system
	1.08.05	Nuclear recoil calibration
1.09	**Electronics, DAQ, and Online Computing**	
	1.09.01	System Engineering & Management
	1.09.02	TPC front end electronics
	1.09.03	Skin front end electronics
	1.09.04	Neutron detector front end electronics
	1.09.05	Muon detector front end electronics
	1.09.06	Digitizers
	1.09.07	DAQ+DAQ computing
	1.09.08	Event builder / trigger
	1.09.09	PMTs HV system
	1.09.10	Grids HV
	1.09.11	Run control
	1.09.12	Data quality monitor
	1.09.13	Signal, Network & Power Cables
1.10	**Controls**	
	1.10.01	System Engineering & Management
	1.10.02	Critical Systems Slow Control
	1.10.03	Non-Critical Systems Slow Control
	1.10.04	Information Serving
	1.10.05	Facility interface controls
1.11	**Computing**	
	1.11.01	System Engineering & Management
	1.11.02	Computing Infrastructure Software
	1.11.03	Onsite computing infrastructure
	1.11.04	Data Reconstruction Pipeline
	1.11.05	Data Analysis Framework
	1.11.06	Simulations Software F[illegible]ework and Pipeline
	1.11.07	Data Cente[illegible]
1.12	**Screenin[illegible]**	
	[illegible]	[illegible]ement
	[illegible]	[illegible]
	[illegible]	[illegible]eening
	[illegible]	[illegible] assays
	[illegible]	Underground outfitting and protocols
	1.12.06	Underground industrial precision cleaning
	1.12.07	Underground electrochemistry
	1.12.08	Cleaning of surfaces and treatment protocols
	1.12.08	Background tracking and evaluation
1.13	**Integration and Installation**	
	1.13.01	System Engineering & Management
	1.13.02	Surface and Underground Infrastructure
	1.13.03	Cleanroom in water tank
	1.13.04	Surface and Underground materials, supplies
	1.13.05	Integration Engineering and Design
	1.13.06	Assembly and Installation
	1.13.07	Interface to Facility
	1.13.08	Onsite safety coordination
	1.13.09	Rn removal plant
	1.13.10	Counting house
	1.13.11	UPS system
1.14	**Integrated Testing (early validation)**	
	1.14.01	System Engineering & Management
	1.14.02	Grid testing
	1.14.03	HV Feedthrough
	1.14.04	Cryogenics and purification test

The XLZD Collaboration

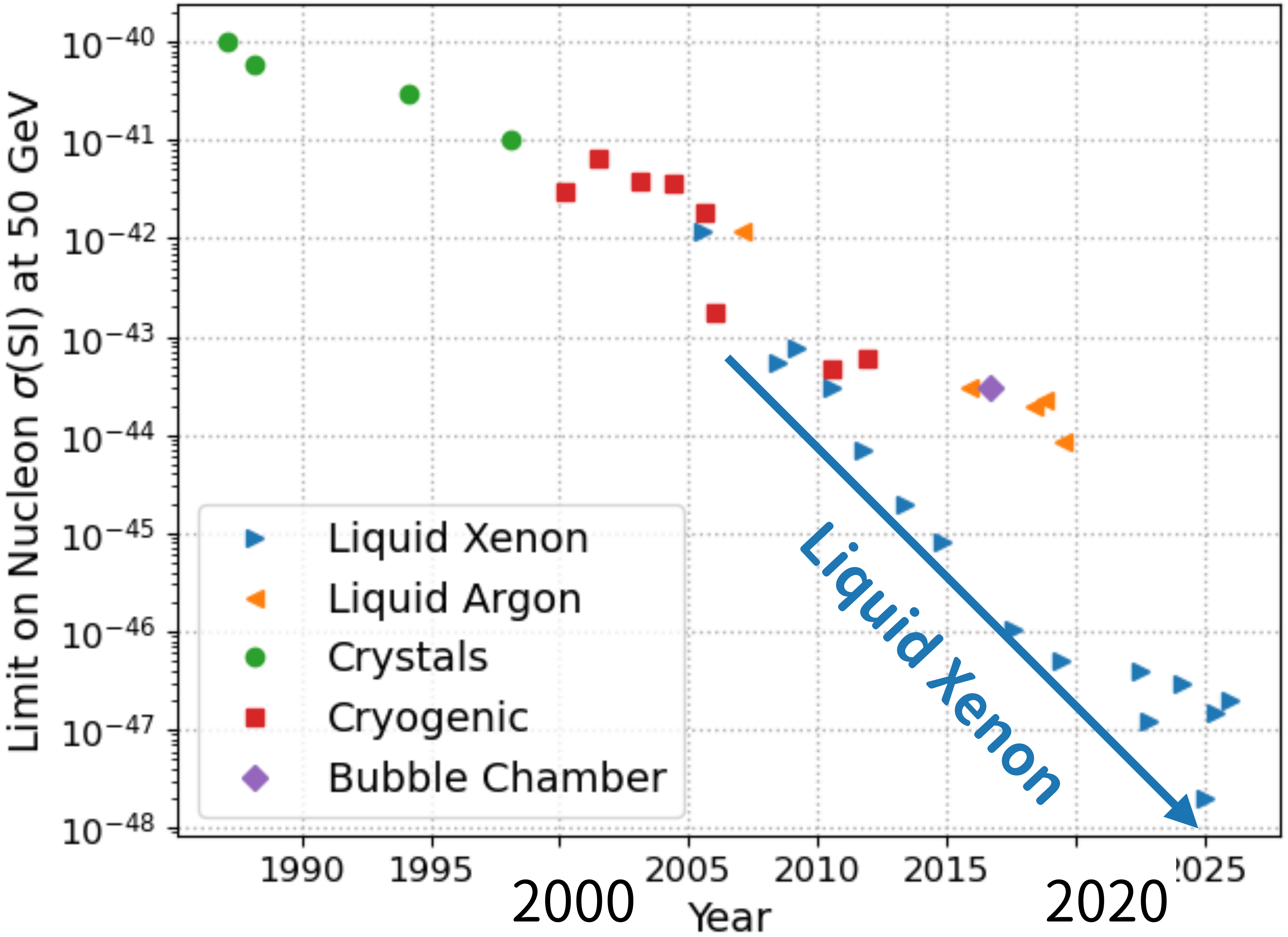
Countries: 17
Institutions: 76
Members: 440+

XLZD Meeting - LNGS, July 2025

History of Direct WIMP Dark Matter Search

Liquid-gas double phase Xe Time Projection Chamber

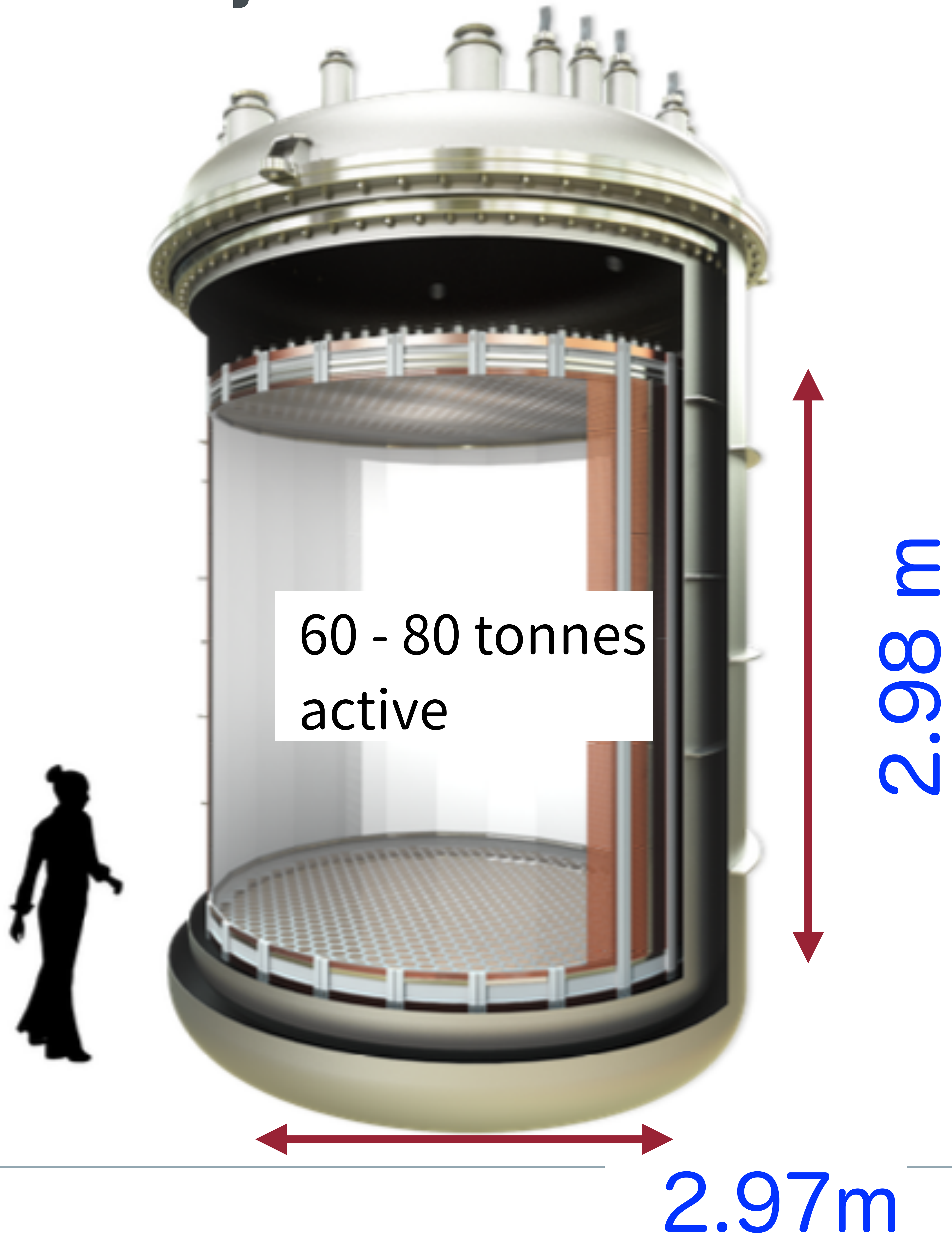
- Scalability, large mass (tonne scale)
- Self-shielding: High Z(=54) and density (~3g/cm^3)
- Easy purification in gas and liquid phase, even during science run
- Particle identification of electronic recoils and nuclear recoils
- Low energy threshold
- Liquid Xenon Detectors: World leading since 2007



D. Akerib@IDM 2025

Detector: Liquid Xenon Time Projection Chamber

- **Largest xenon observatory for rare events**
  - The design is based on the mature technology of current-generation LXe TPC and will have opportunities for further optimization of the individual detector components.



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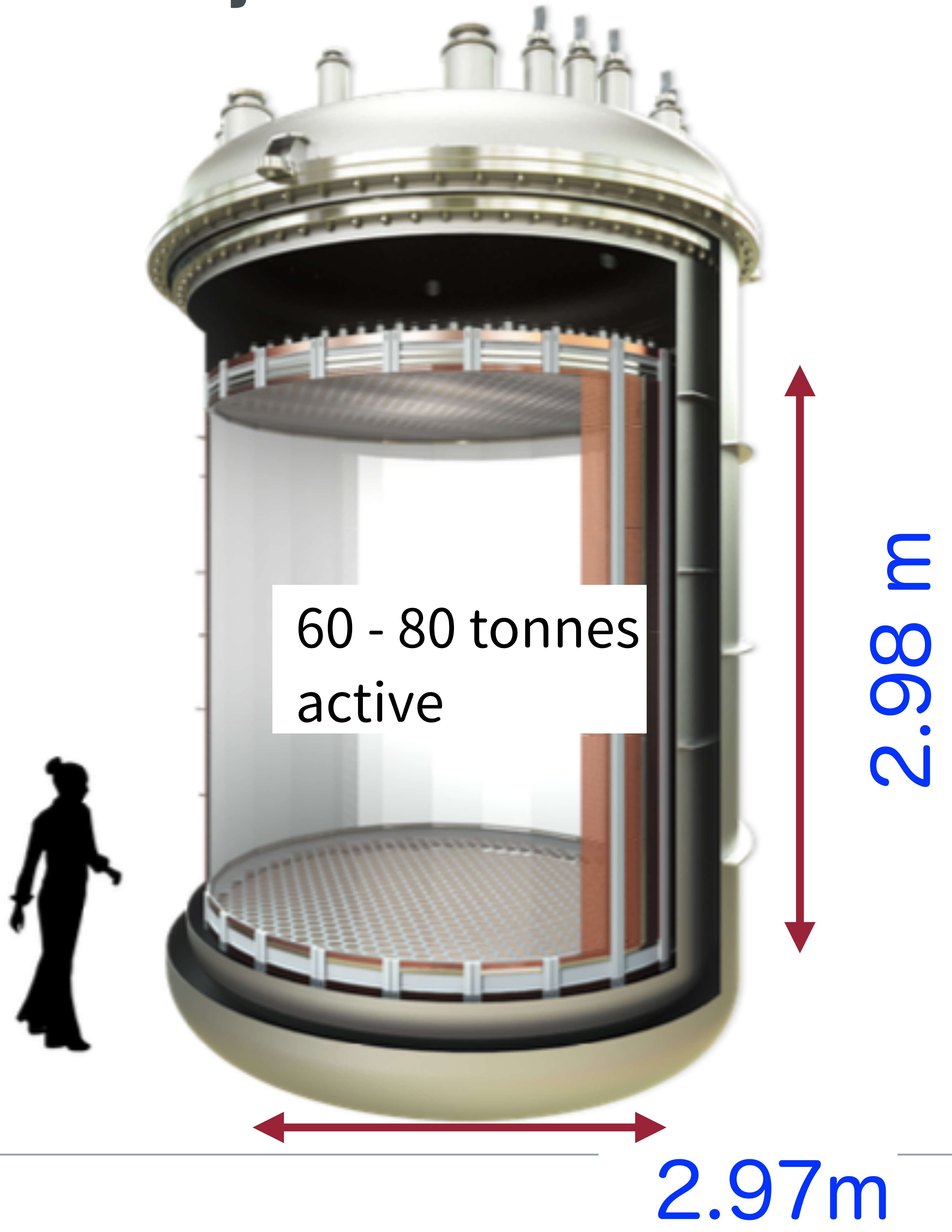

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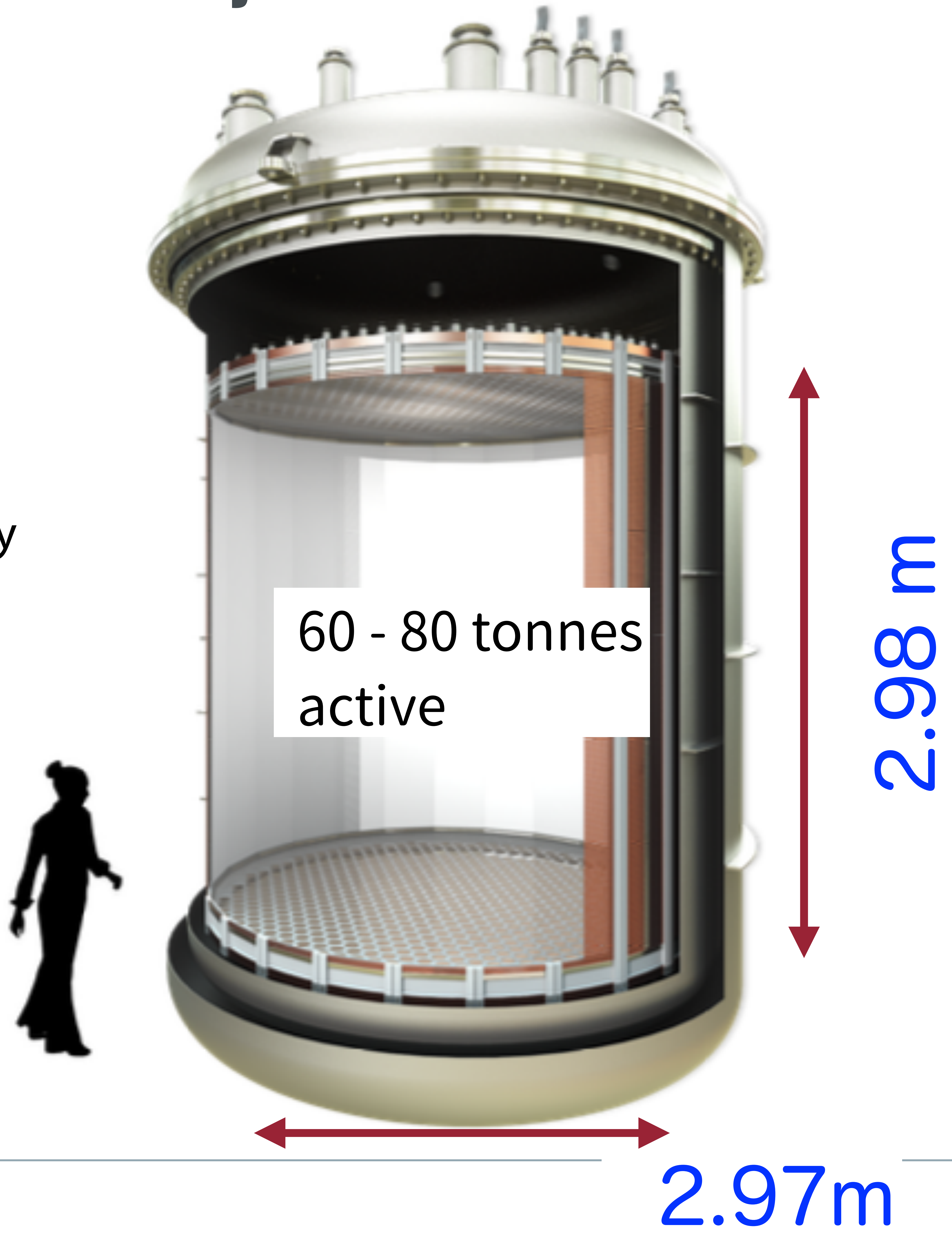
  - We will design XLZD such that its background is dominated by **irreducible neutrino events.**
  - **2.98** m diameter, and **2.97** m drift length
  - Target Mass: **60-80** tonnes LXe
    - Nominal - 60 tonnes: 1:1 aspect ratio
    - Opportunity - 80 tonnes: if the funding allows, longer drift



Xenon Isotopes

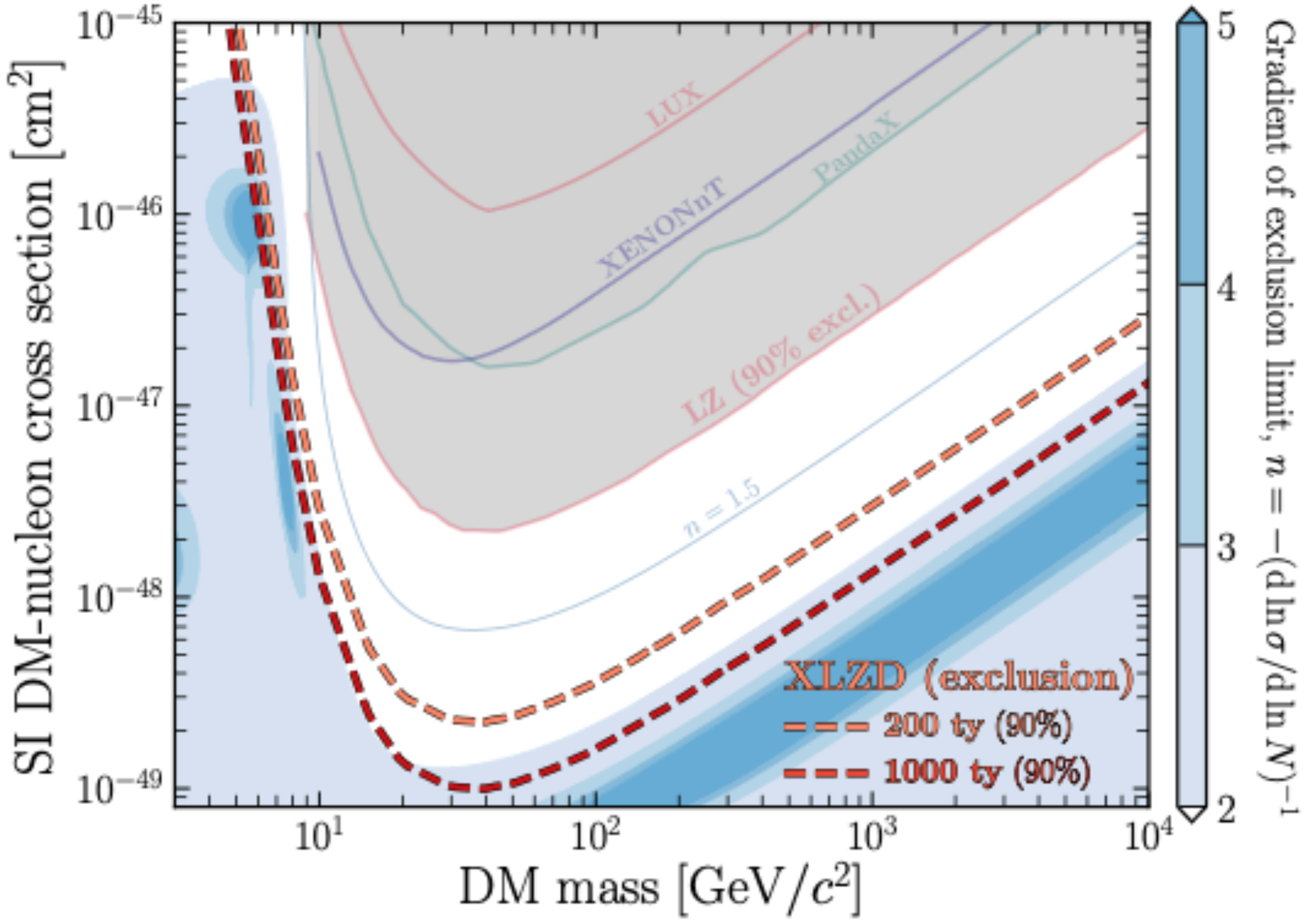
^{124}Xe	^{126}Xe	^{128}Xe	^{129}Xe	^{130}Xe	^{131}Xe	^{132}Xe	^{134}Xe	^{136}Xe
0.10%	0.09%	1.92%	26.4%	4.07%	21.2%	26.9%	10.4%	8.87%

- Both spin-independent and spin-dependent WIMP DM search (half-half)
- No long-lived isotopes except ^{124}Xe and ^{136}Xe
  - ^{124}Xe double electron capture isotope ($T_{1/2} \sim 10^{22}$ y), ^{136}Xe $2\nu\beta\beta$ decay
    - the longest half-life ever measured directly   E. Aprile et al., 532 , Nature, 568
- ^{136}Xe $0\nu\beta\beta$ decay
- In case of a discovery, varying the isotopic abundance is possible , depending on the physics targets. (spin dependence, $0\nu\beta\beta$ …)
  - e.g. Y. Suzuki arXiv:0008296

XLZD: WIMP Sensitivity

The XLZD Design Book: Towards the Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics
arXiv:2410.17137v1

Projected sensitivity and current limits



- **Searching for WIMPs down to the neutrino "fog"**
  - Indistinguishable background from astrophysical neutrinos
  - Limited sensitivity improvement (20% flux uncertainly)
  - Systematic uncertainty limit (1000 t·yr)
  - 90% C.L. exclusion 2.5×10^{-49} cm^2 (at 40 GeV, 200 t·yr)

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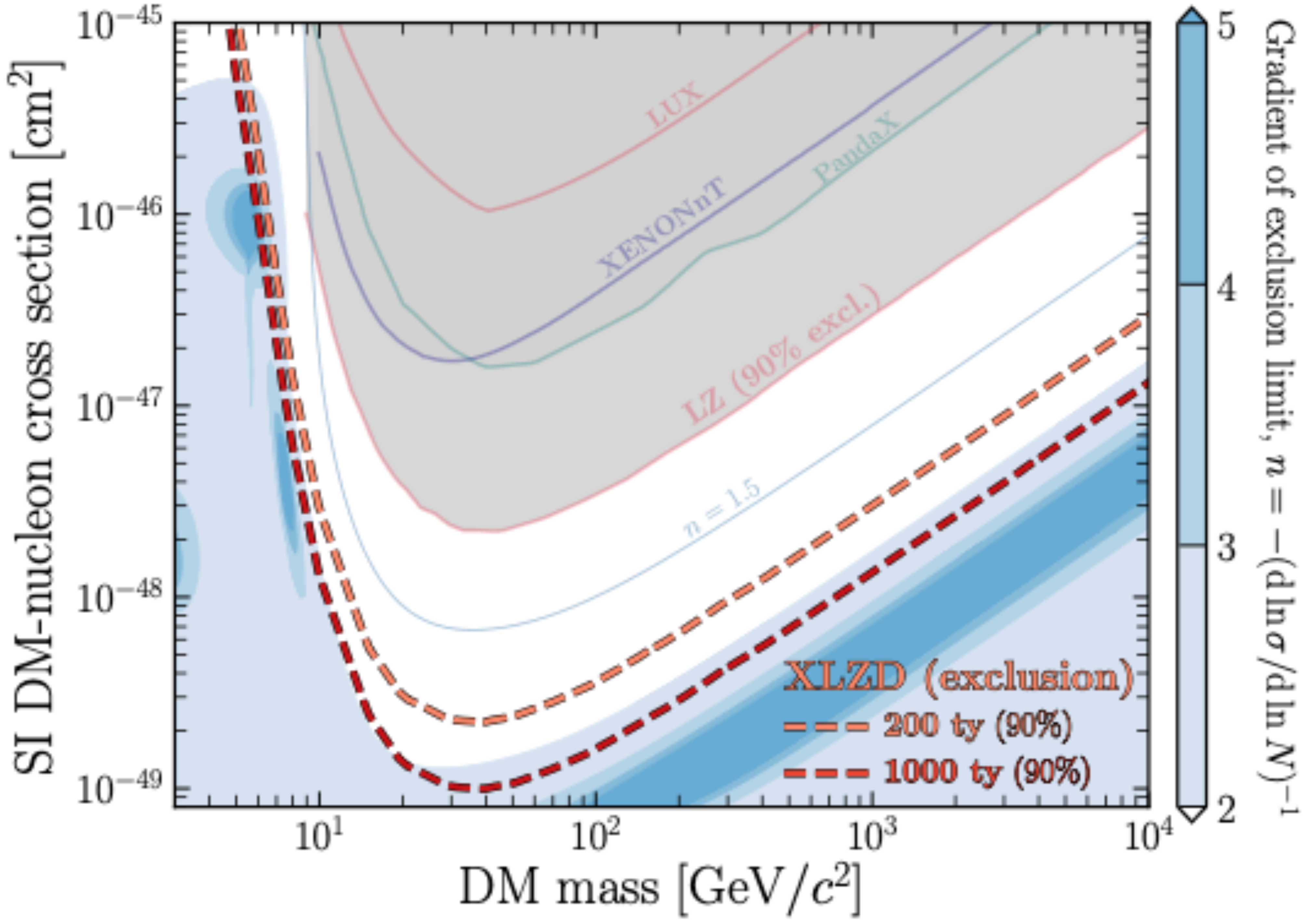
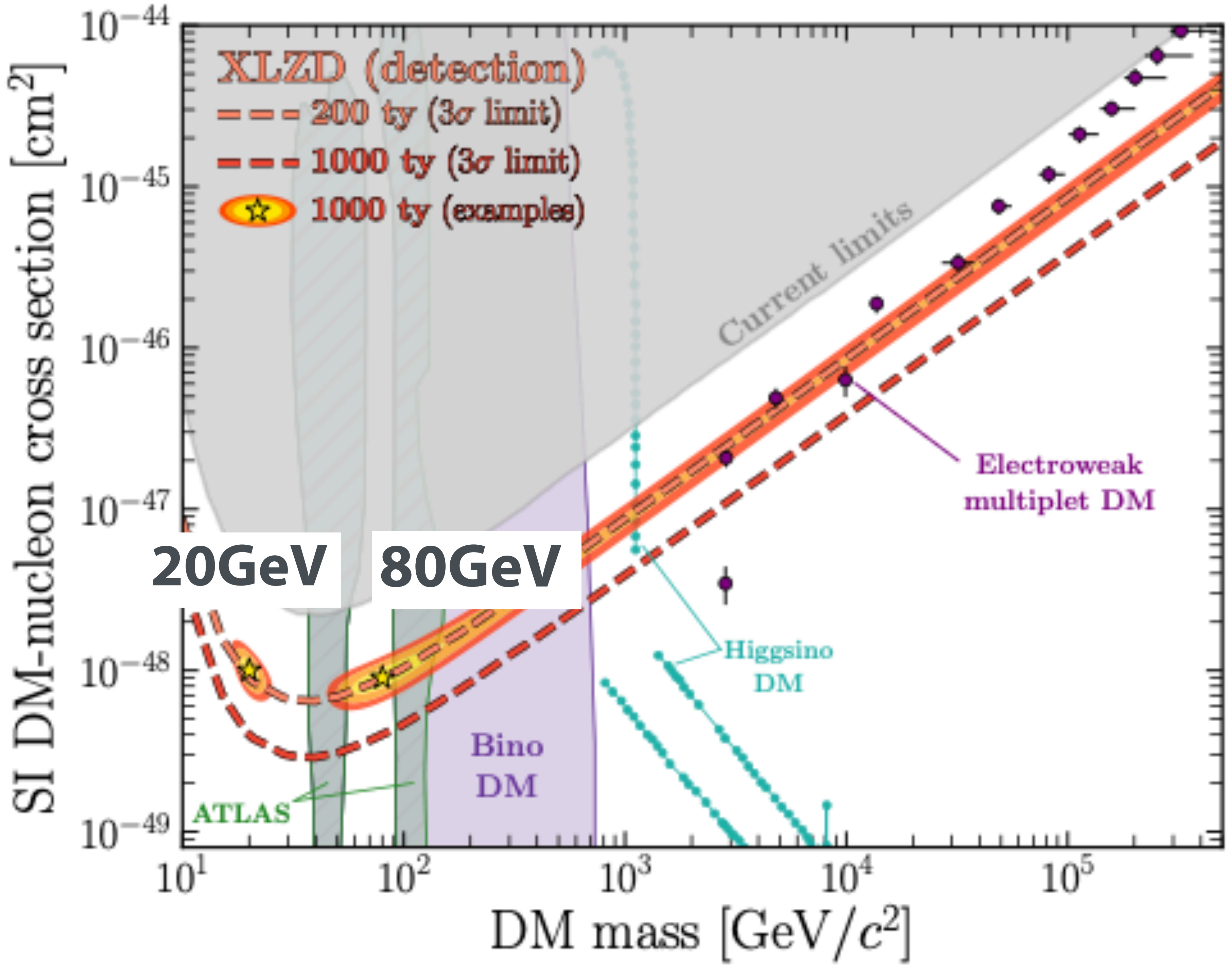


Detection capability of benchmark candidates



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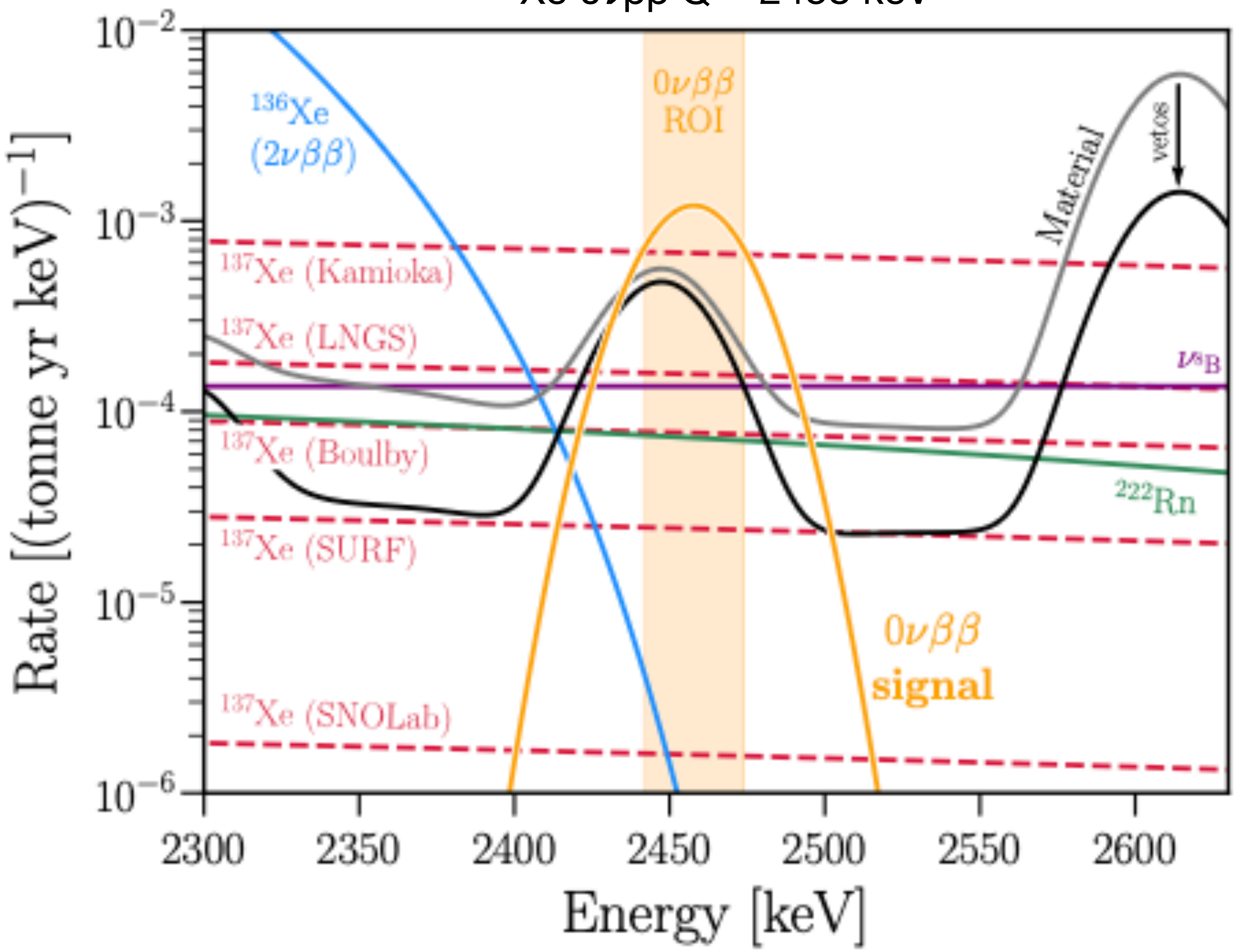
- **Constraining dark matter properties**
  - evidence contours for 20 GeV and 80 GeV WIMPs (1000 t・y)
  - covering most of the cases for Electroweak multiplet DM
  - Higgsino and Bino DM: highly complementary to that of collider

XLZD: ^{136}Xe $0\nu\beta\beta$ Search

^{136}Xe $0\nu\beta\beta$ Q = 2458 keV

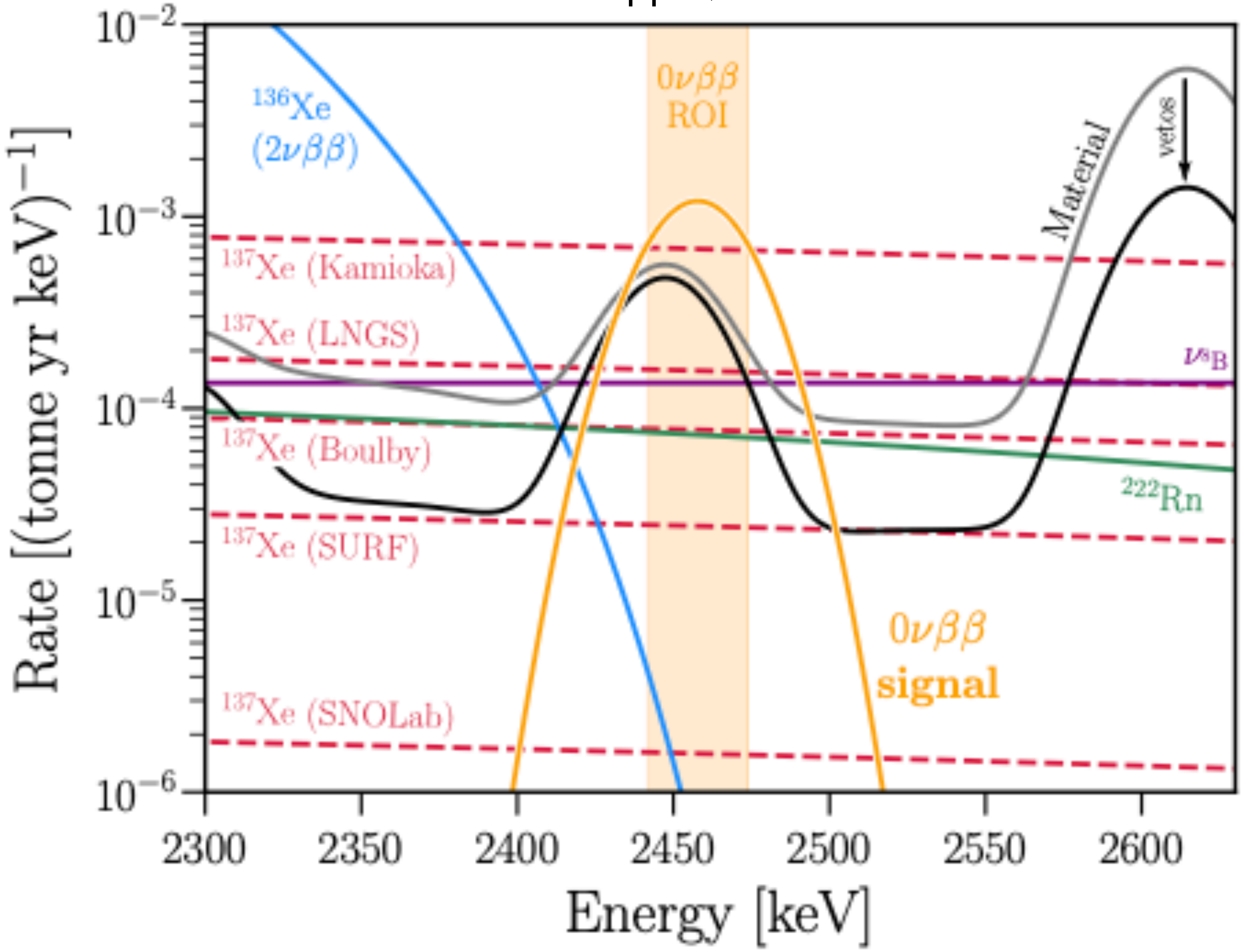


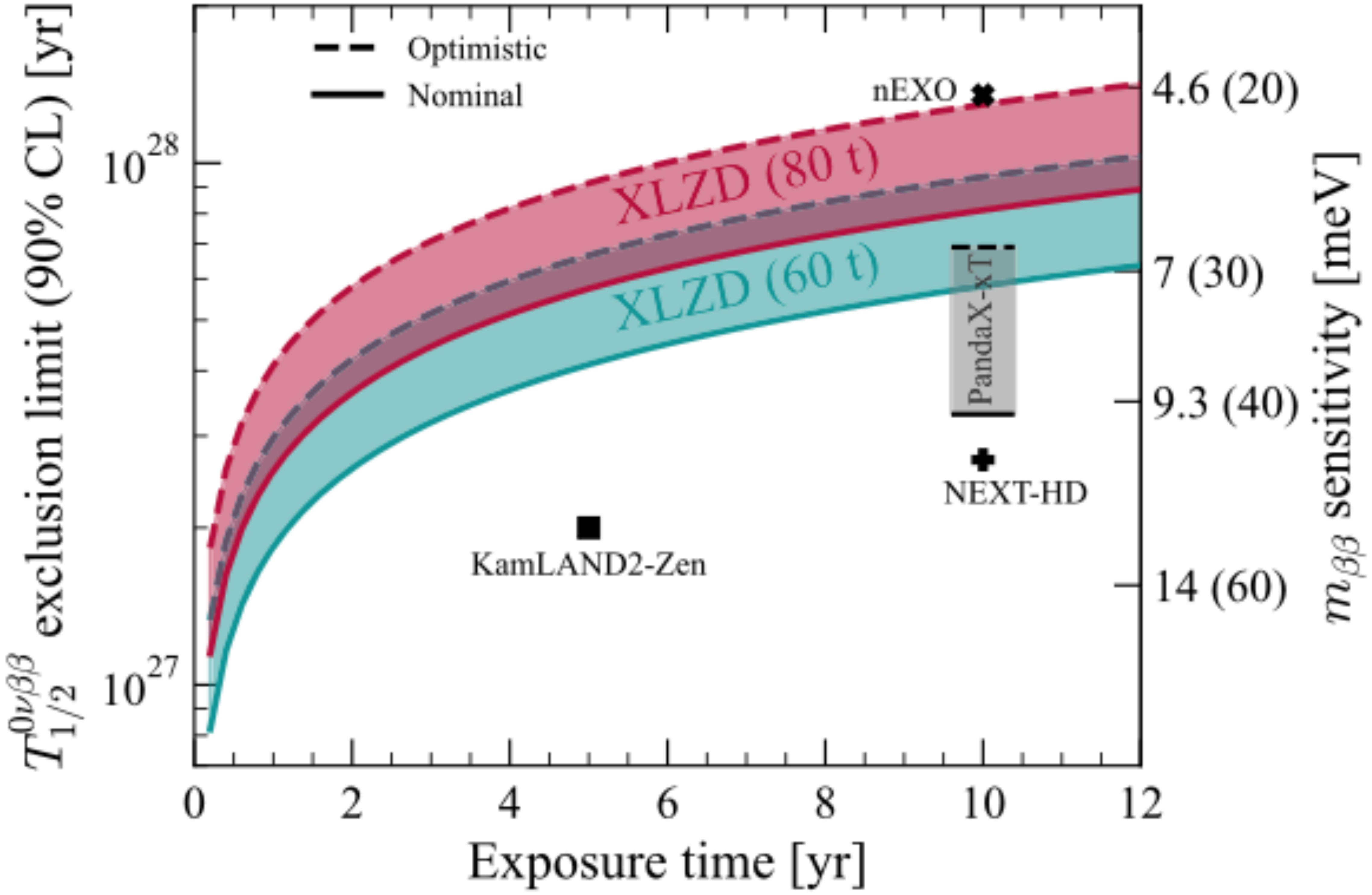
- ^{136}Xe is 8.9% of **natural xenon**
  - With 80 t target mass, XLZD will contain 7.1 t of ^{136}Xe
- Xenon TPCs have excellent resolution
  - 0.67% demonstrated in LZ, 0.8% in XENON1T

- **Internal and intrinsic backgrounds**
  - ^{214}Bi β from ^{222}Rn in the xenon (Q = 3270 keV)
    - We assume 0.1 μBq/kg ^{222}Rn rate and >99.95% BiPo tagging
  - ^{137}Xe β (Q = 4170 keV), neutron activation of ^{136}Xe
    - Mostly by muon-induced neutrons, depending on the installation site
  - Electron recoils from ν-e^- scattering (^{8}B), irreducible

XLZD: ^{136}Xe 0νββ Search

^{136}Xe 0νββ Q = 2458 keV





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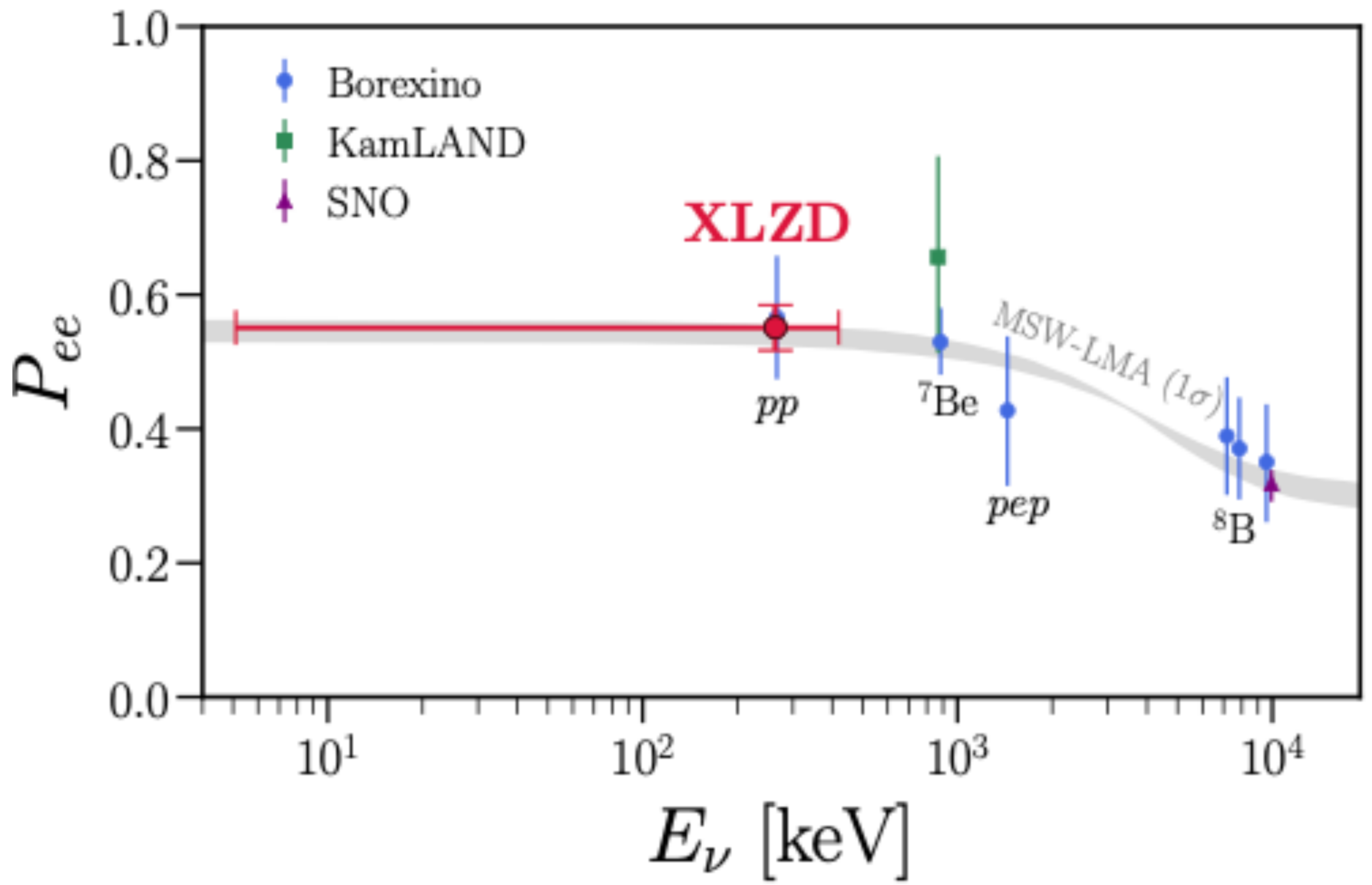
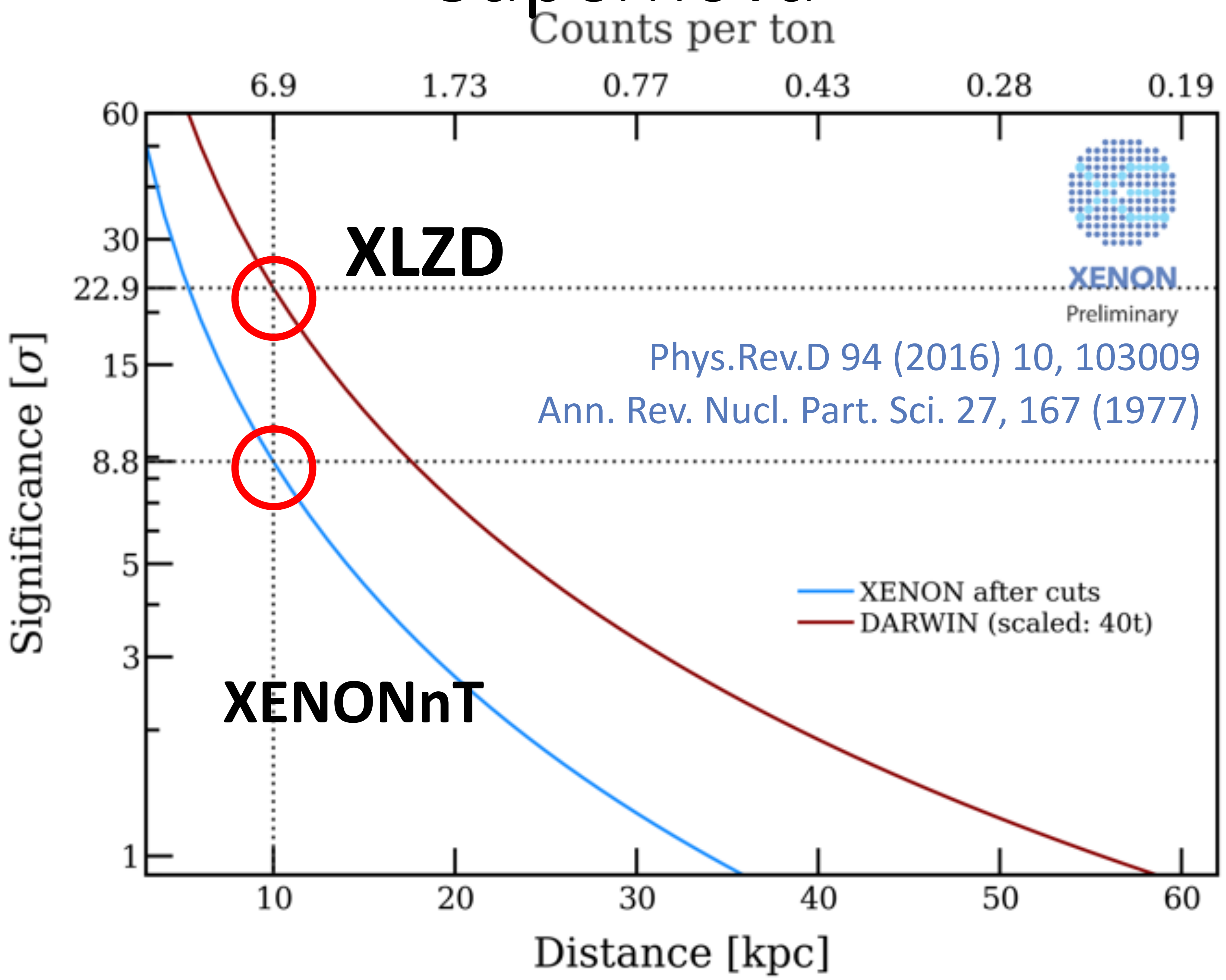
Astrophysical Neutrinos

Solar Neutrino



- Neutrinos (solar model, neutrino properties)
  - **High statistics pp neutrino measurement**
  - **Neutrino survival probability** (5.1-420 keV)
    - lowest energy threshold
    - Test the LMA-MSW solution to neutrino oscillations
  - **Neutrino magnetic moment**

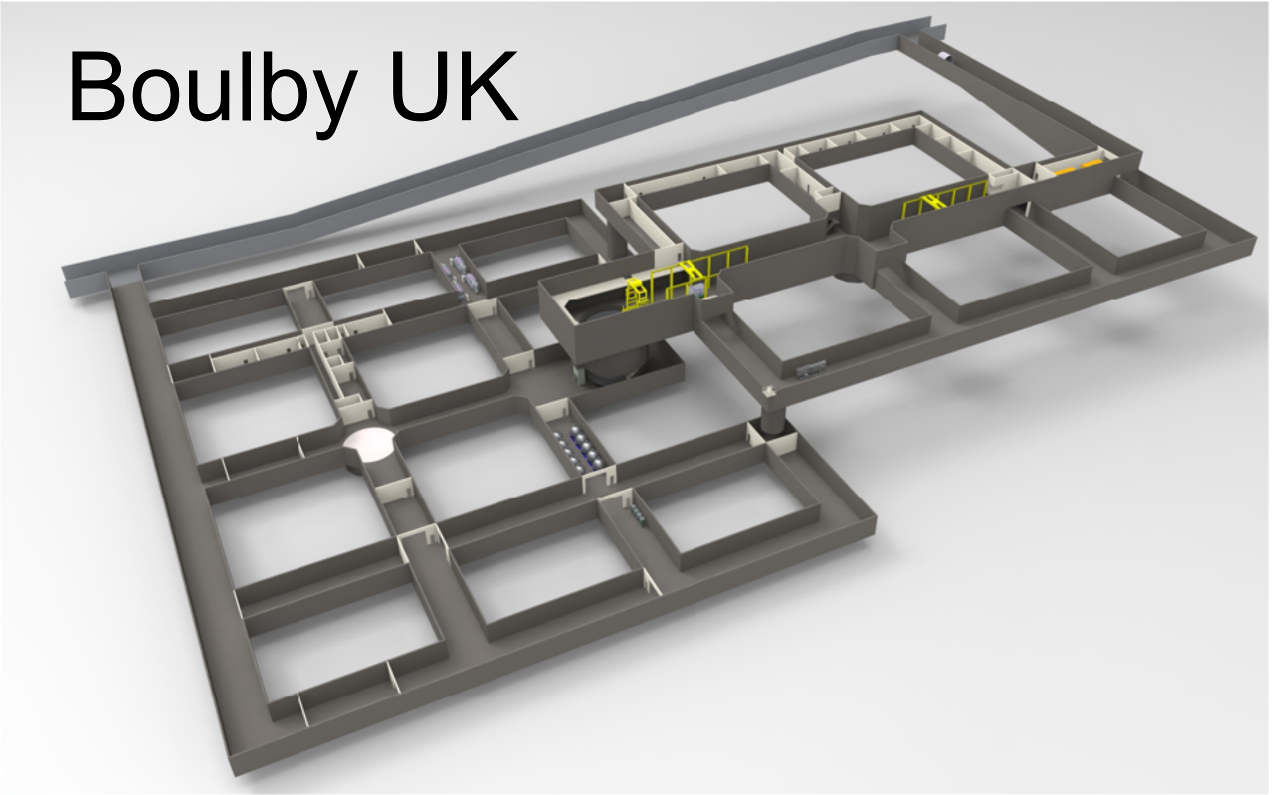
Supernova

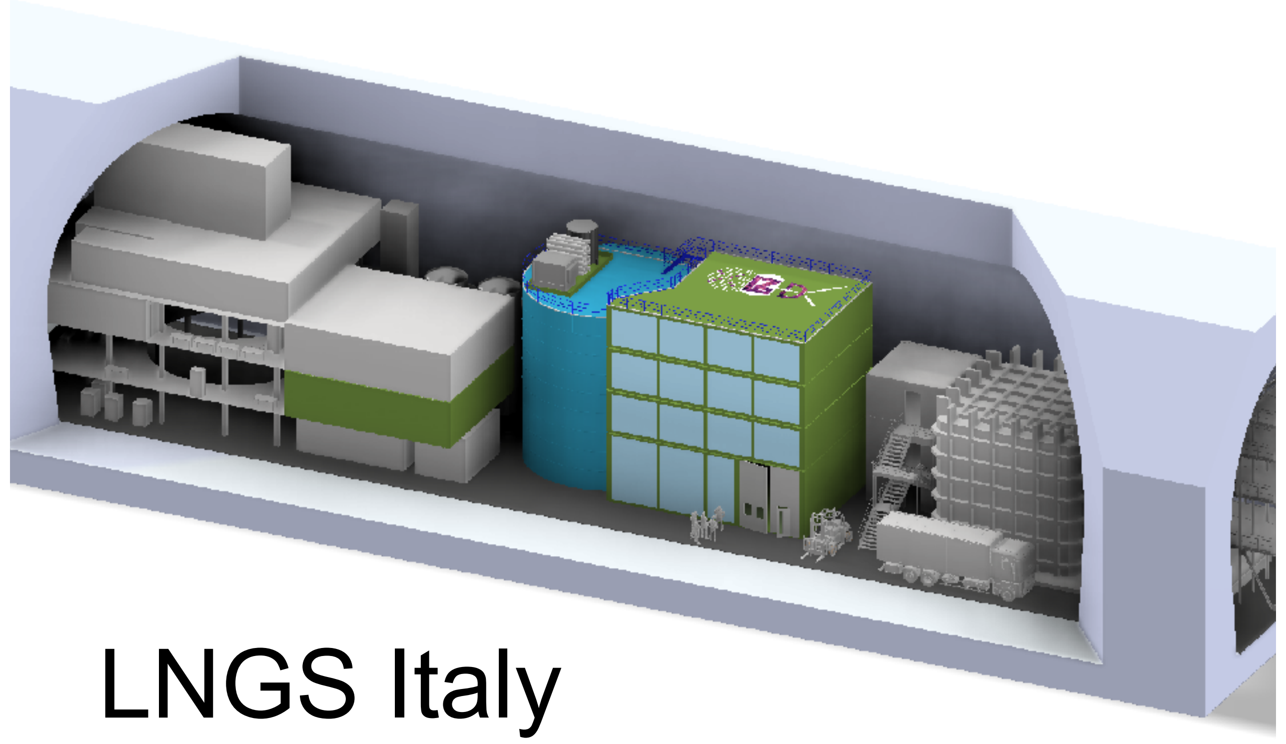


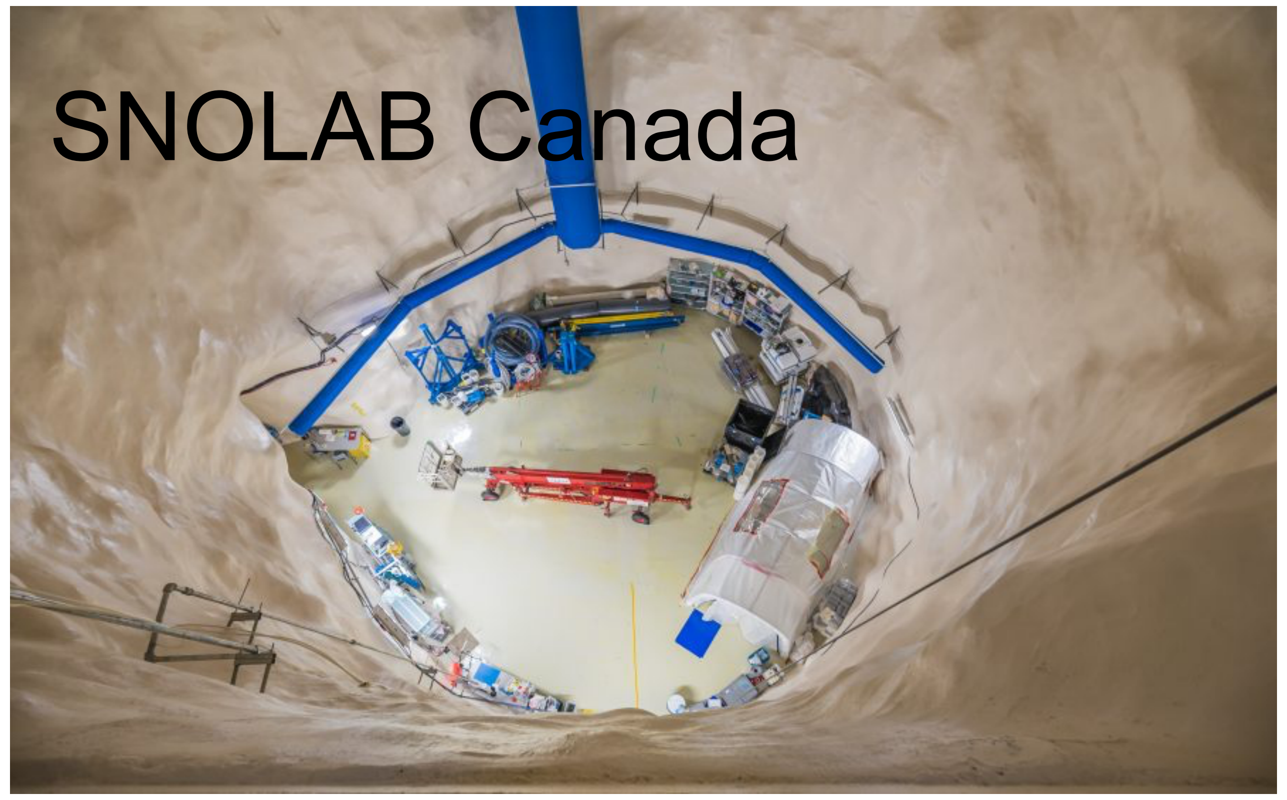
- **Flavor independent detection via CEvNS**
- A few 100s events @ 10kpc

Possible sites for XLZD

- Host laboratory to be selected in **2026**
- Key considerations include
  - Depth - impact on backgrounds, particularly for **DBD**
  - Ability of host site and country to provide suitably outfitted space compatible with project timeline and separate from project cost
  - Accessibility & transport large componts
- Key contenders
  - Boulby - new 1300 meter lab being proposed
  - LNGS - middle of Hall C
  - SNOLAB CryoPit - under evaluation
  - SURF - “Module of Opportunity” cavern or new excavation





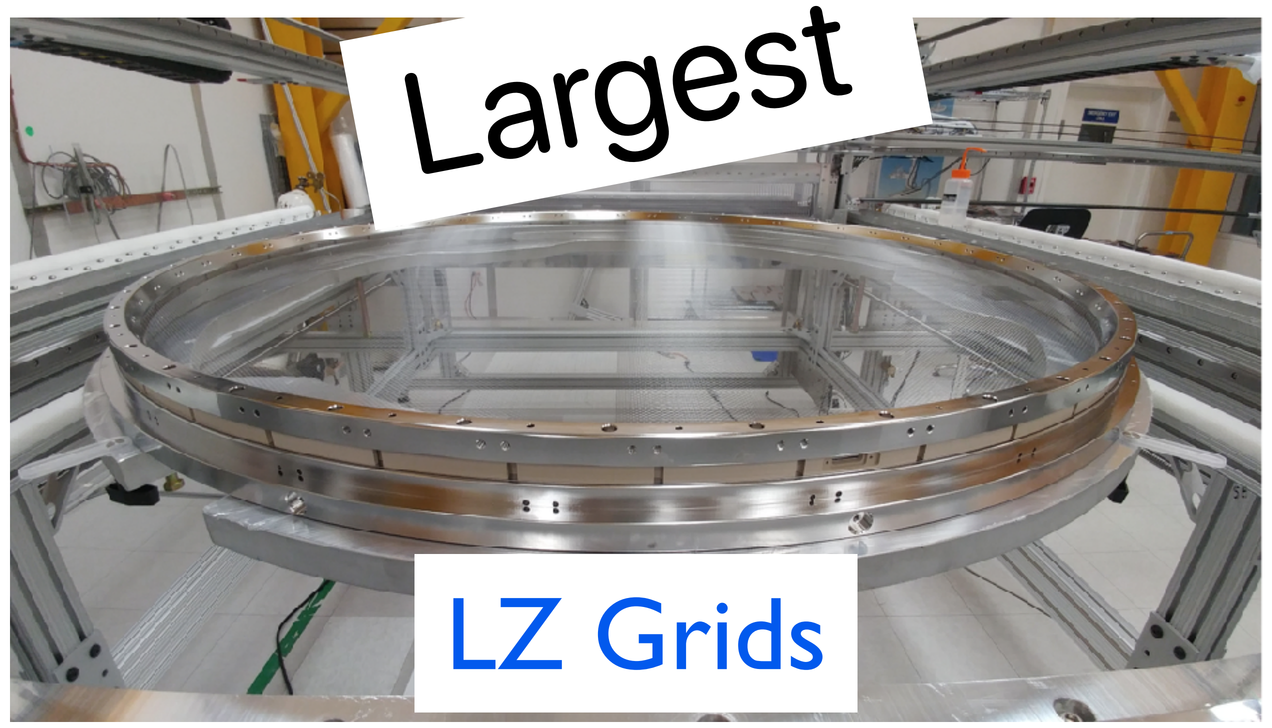


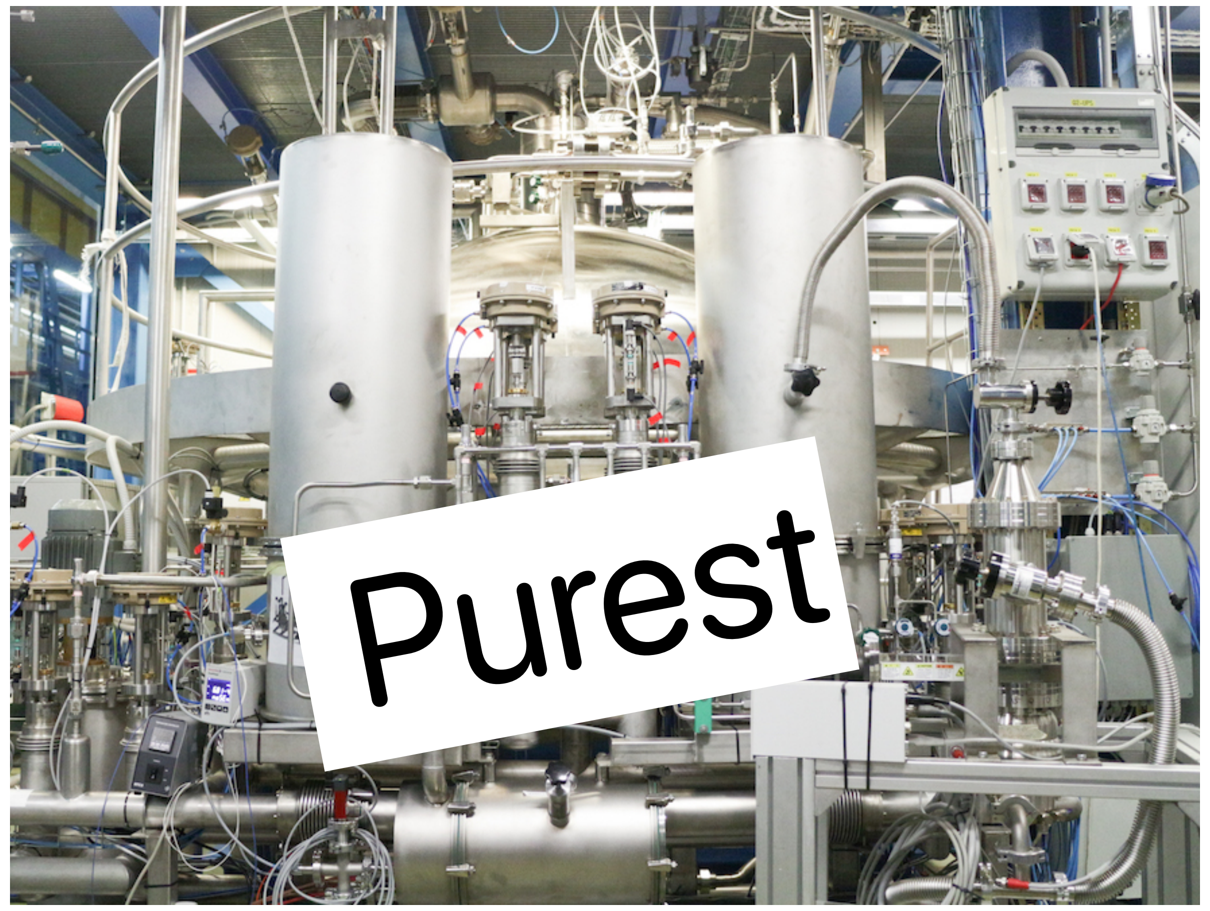
M. Kapust, SDSTA

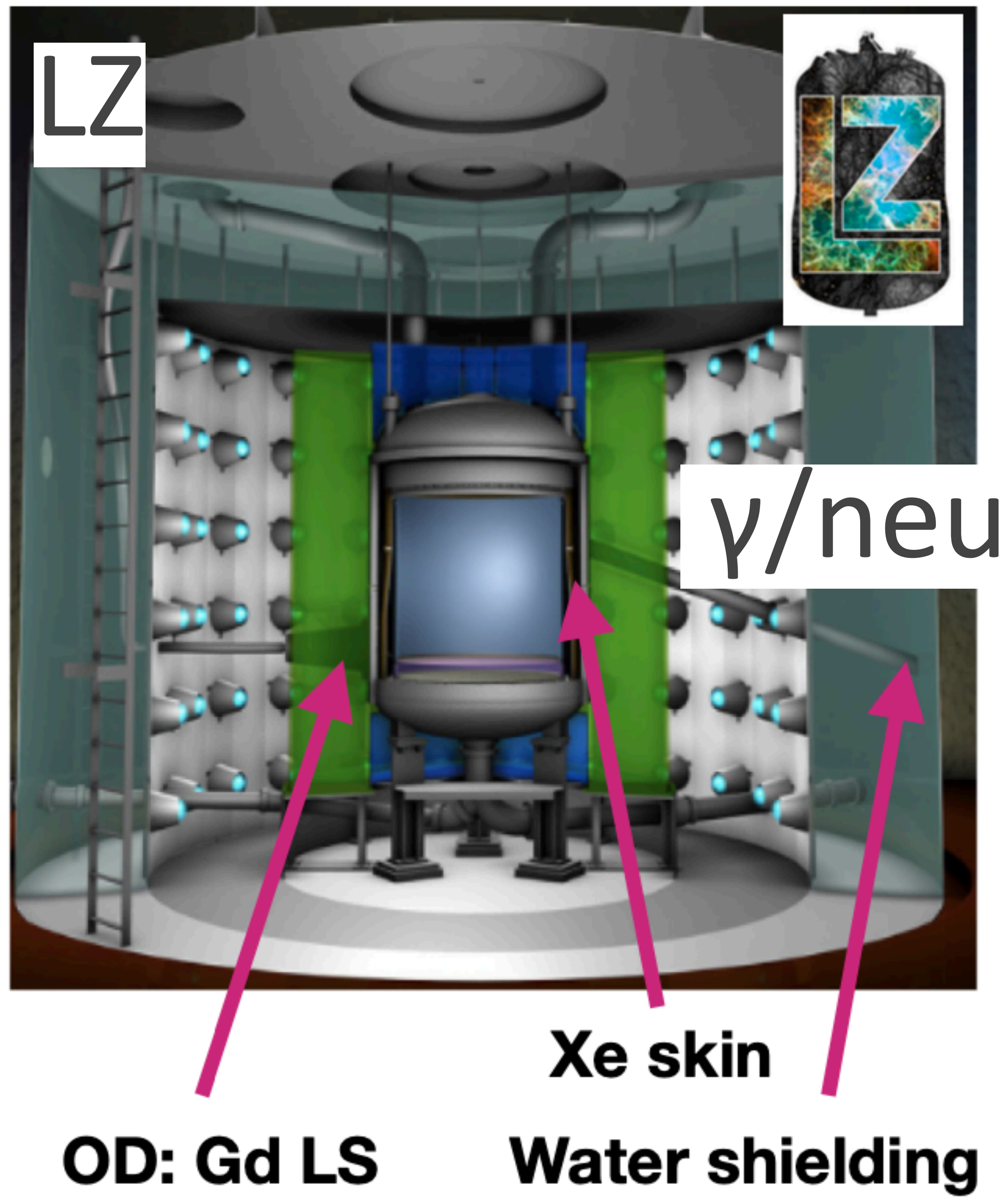
Technologies for the Ultimate detector

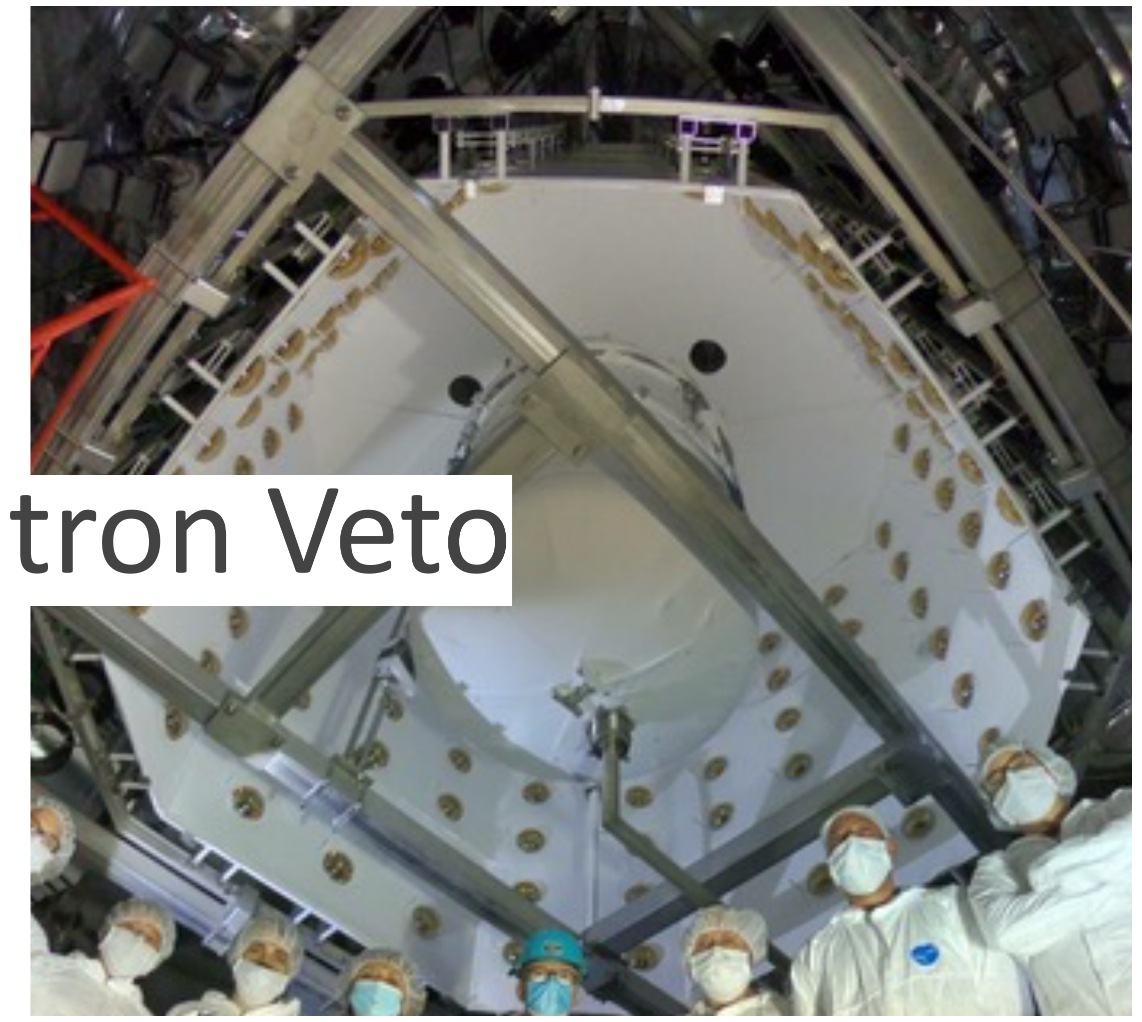
- Radon/Krypton distillation (XENONnT)
- ^{222}Rn **0.9** uBq/kg ->0.1 uBq/kg
- Kr <48 ppq - > 30 ppt

- LXePUR (XENONnT)
- Liquid phase purification
- > 15 ms electron lifetime
- => ~ 15 m drift length





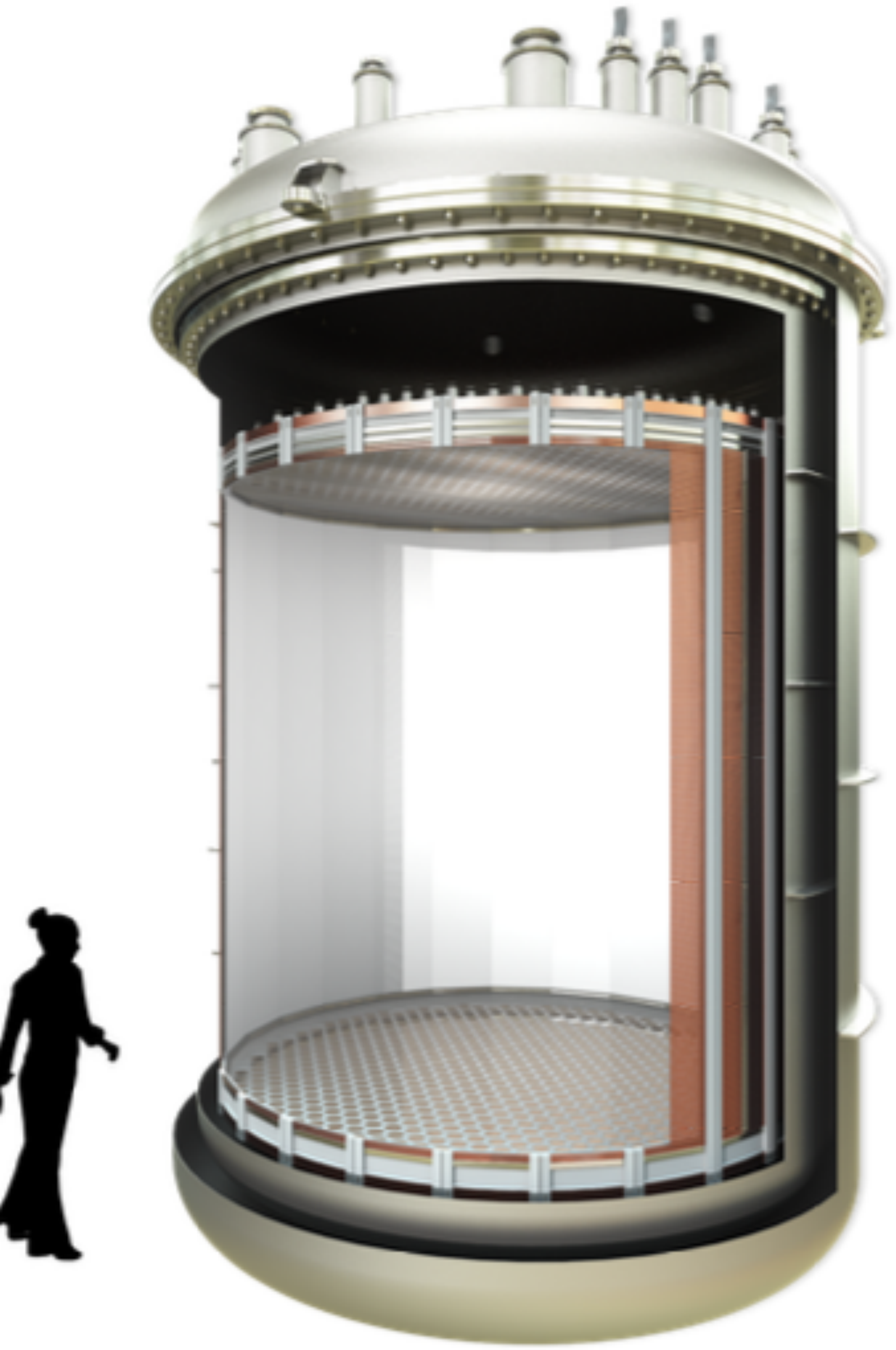




XENONnT

R&D Activities: TPC and Electrodes/HV

Full height and diameter test facilities for DARWIN/XLZD



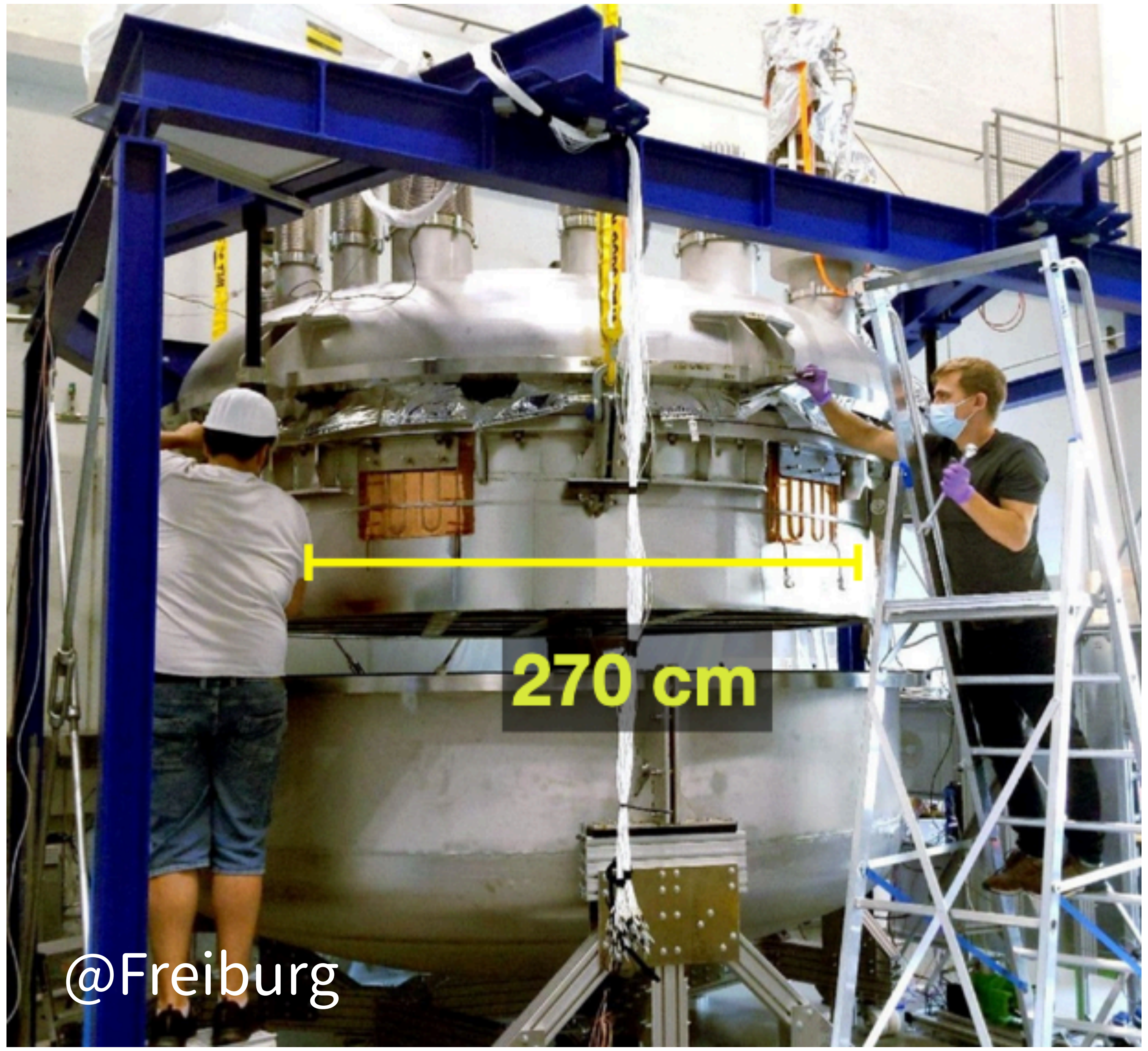
2.98 m

2.97m

2.6 m

JINST 16 P08052(2021)

High voltage, Purity …



Electrode and other detector components

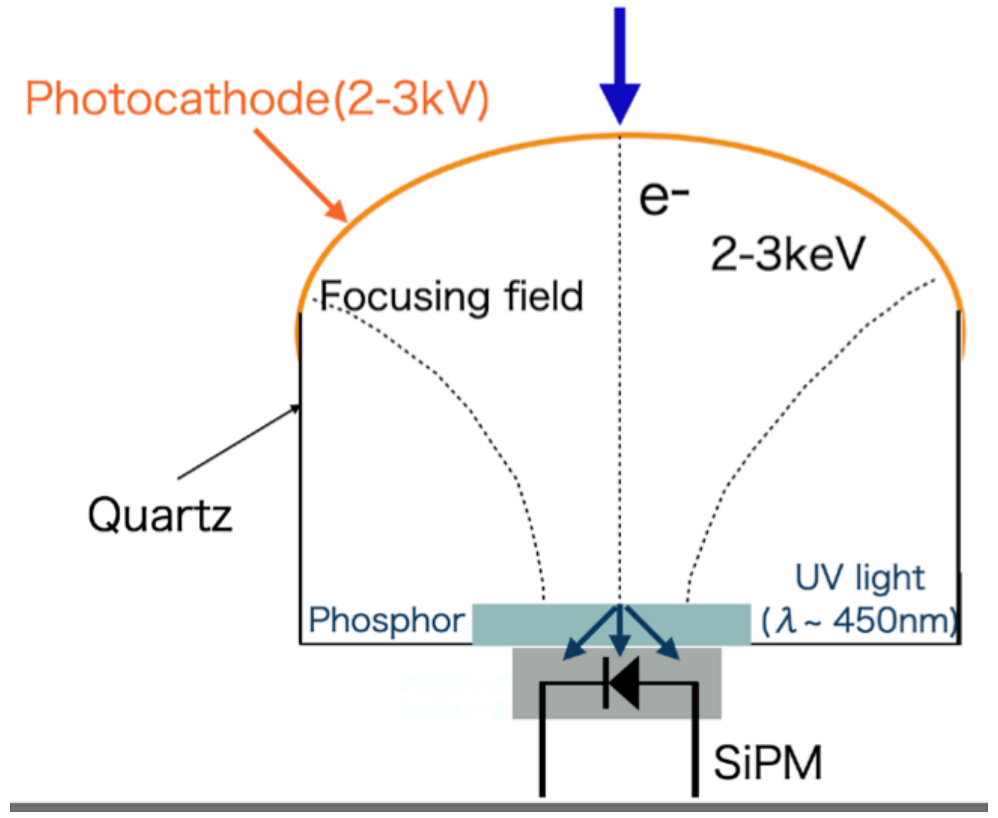
Photosensors

- Baseline design 3’’ PMTs
- Other option are being explored
- Heritage of low radioactivity technology

R11410 (LZ, XENONnT, PandaX)

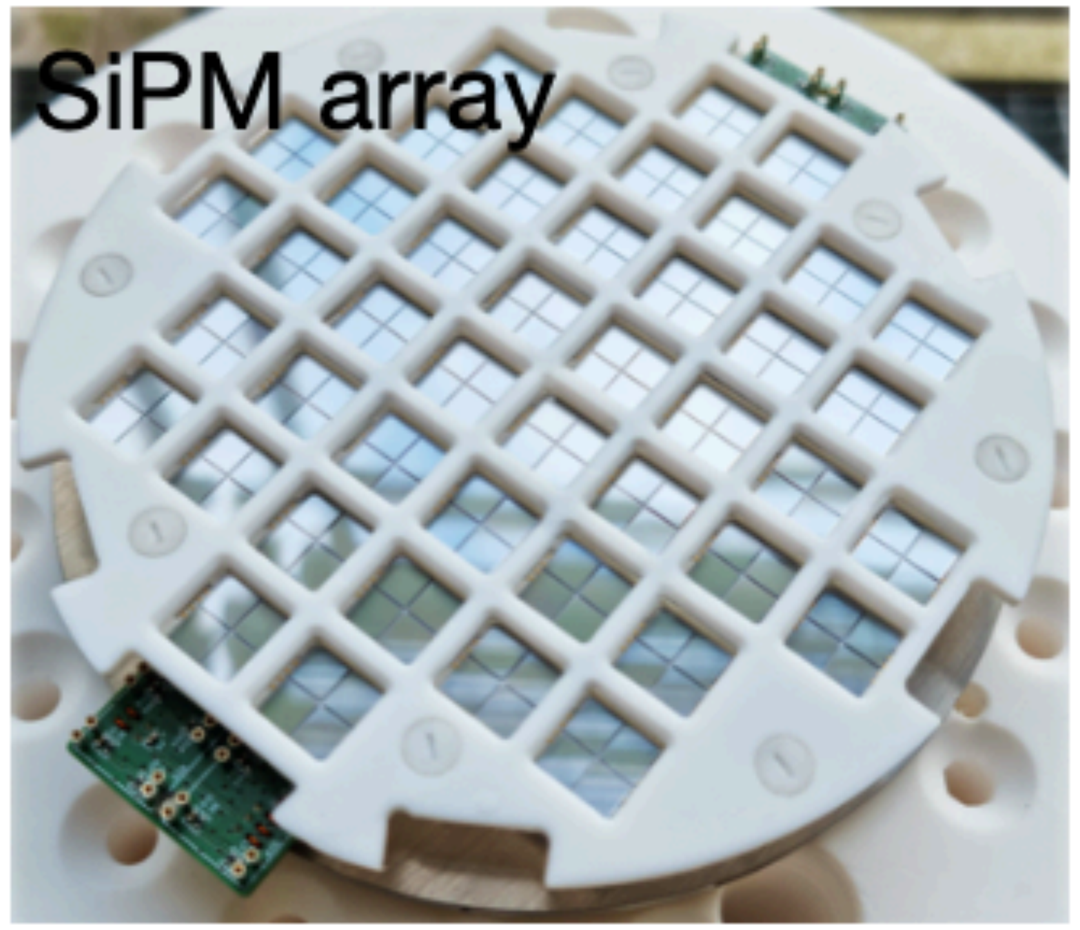
2inch square

R13111 (XMASS)
Lowest radioactivity

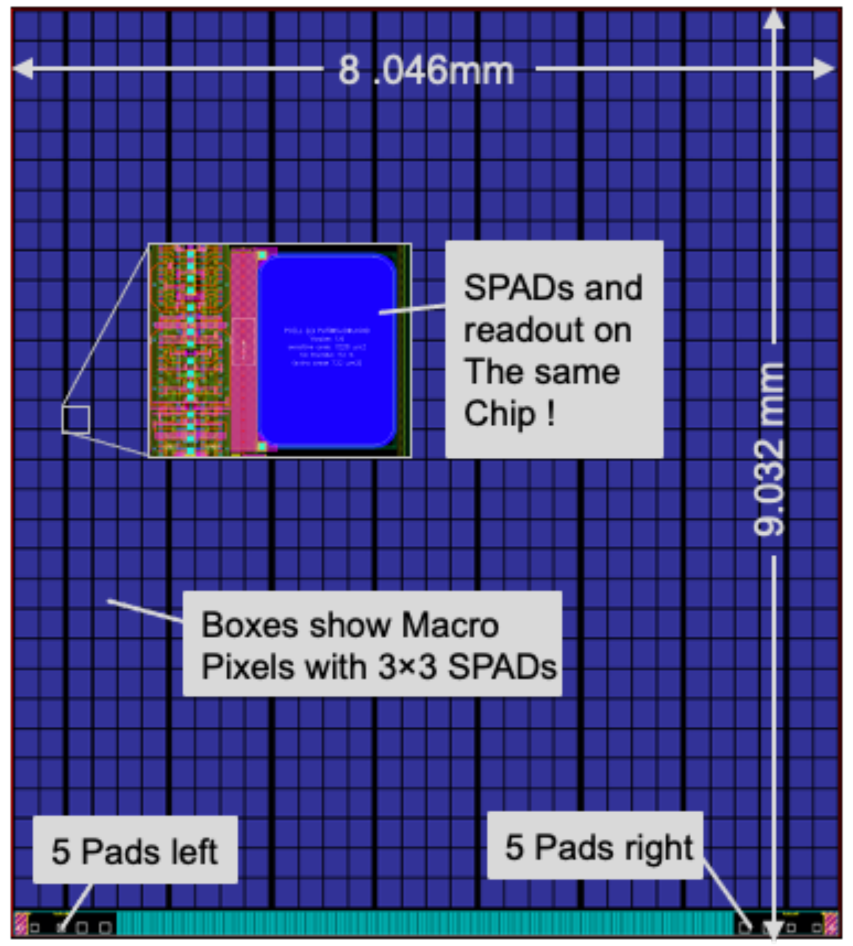


Hybrid

Low Dark Current SiPM



JINST 18 C03027 (2023)



Digital SiPM

Photosensors

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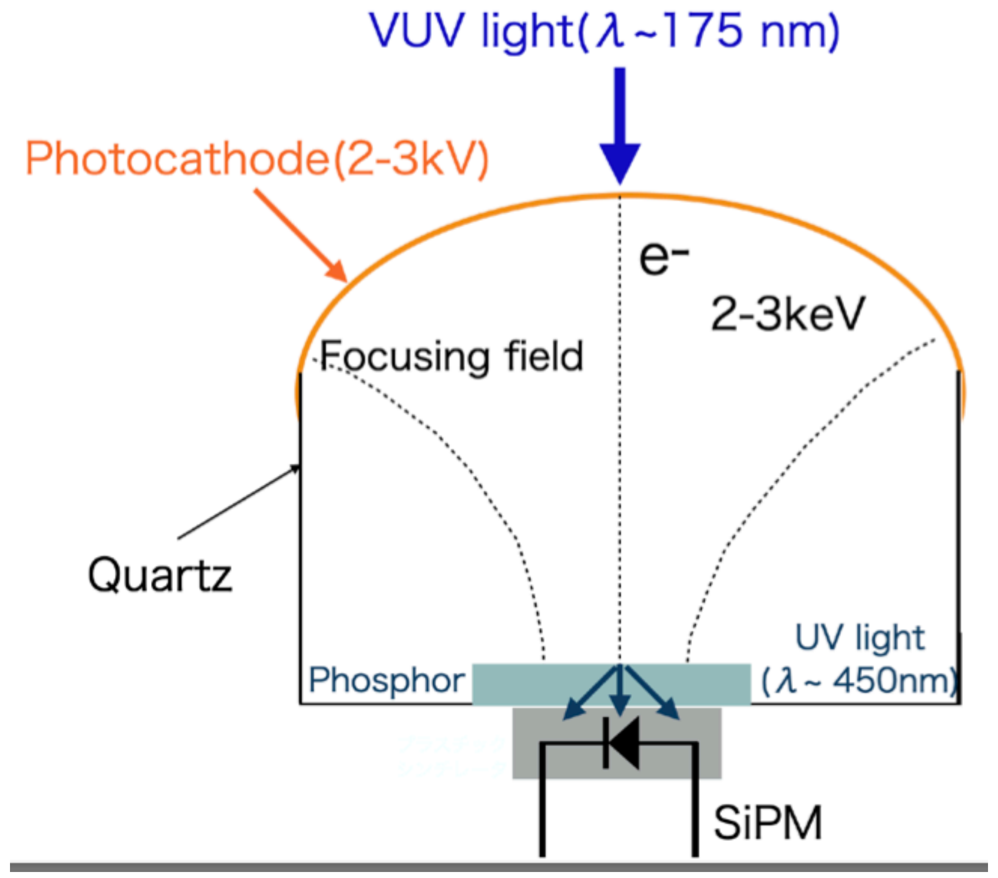
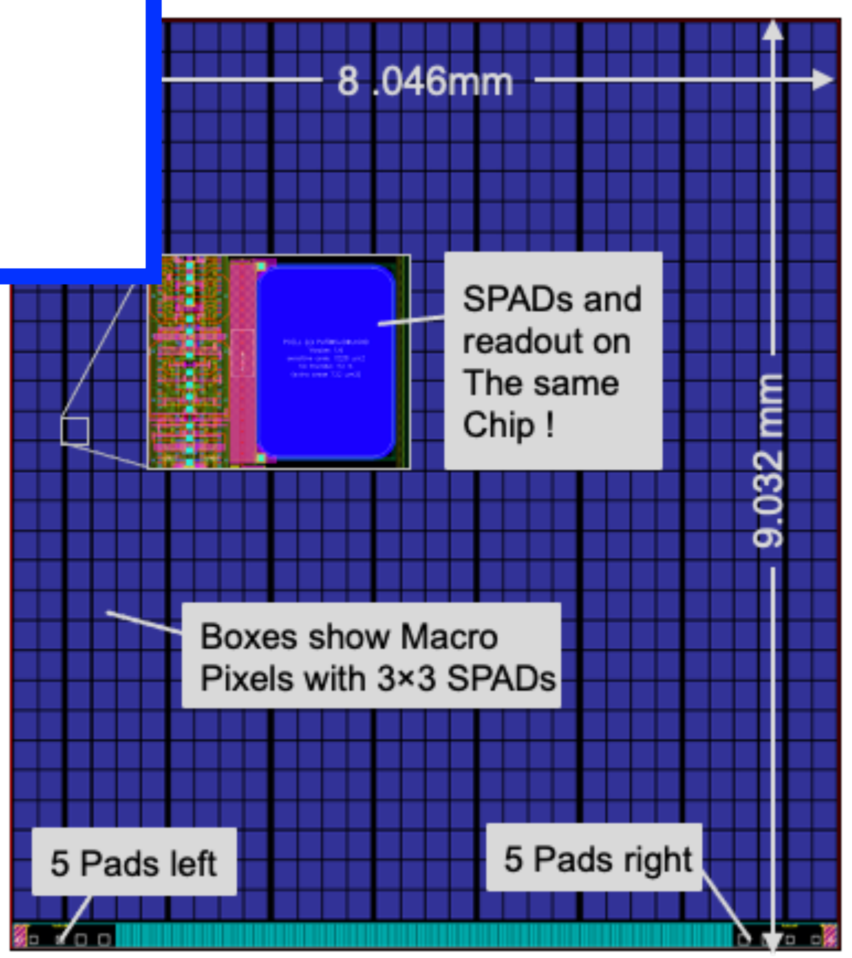


Hybrid

(1) Stem: glass material was synthesized using low-radioactive-contamination material
(2) Photocathode: produced with 39K-enriched potassium
(3) Vacuum seal: purest grade of aluminum material

μBq/PMT	^{226}Ra	^{238}U	^{228}Ra	^{40}K	^{60}Co
R13111 in 2015	$(3.8 \pm 0.7)\cdot 10^2$	$<1.6 \cdot 10^3$	$(2.9 \pm 0.6)\cdot 10^2$	$<1.4 \cdot 10^3$	$(2.2 \pm 0.5)\cdot 10^2$
R13111 in 2016	$(4.4 \pm 0.6)\cdot 10^2$	$<1.4 \cdot 10^3$	$(2.0 \pm 0.6)\cdot 10^2$	$(2.0 \pm 0.5) \cdot 10^3$	$(1.3 \pm 0.4)\cdot 10^2$
R11410-21(XENON1T) [15]	$(5.2 \pm 1.0)\cdot 10^2$	$<1.3 \cdot 10^4$	$(3.9 \pm 1.0)\cdot 10^2$	$(1.2 \pm 0.2) \cdot 10^4$	$(7.4 \pm 1.0) \cdot 10^2$
R11410-10(PandaX) [3]	$<7.2\cdot 10^2$	—	$<8.3\cdot 10^2$	$(1.5 \pm 0.8) \cdot 10^4$	$(3.4 \pm 0.4) \cdot 10^3$
R11410-10(LUX) [19]	$<4.0\cdot 10^2$	$<6.0 \cdot 10^3$	$<3.0 \cdot 10^2$	$<8.3 \cdot 10^3$	$(2.0 \pm 0.2) \cdot 10^3$



Digital SiPM

Conclusion

- The **XLZD** collaboration was formed in 2024 by
  - **XENONnT + LUX-ZEPLIN + DARWIN**
- XLZD will be a successor to the state-of-the-art liquid xenon dark matter detector.
- Ultimate detector for WIMP search (neutrino fog)
  - Solar Neutrino
  - Double Beta Decay
  - Solar neutrino, Supernova ...
- start observation in 2030'

LNGS visit during the XLZD meeting

Key endorsements & roadmaps

Illuminate the Hidden Universe

Determine the Nature of Dark Matter

P5 Recommendation

2. Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future.

a. **CMB-S4**, which looks back at the earliest moments of the universe,

b. **Re-envisioned second phase of DUNE** with an early implementation of an enhanced 2.1 MW beam and a third far detector as the definitive long-baseline neutrino oscillation experiment,

c. **Offshore Higgs factory, realized in collaboration with international partners**, in order to reveal the secrets of the Higgs boson,

d. **Ultimate Generation 3 (G3) dark matter direct detection experiment** reaching the neutrino fog,

e. **IceCube-Gen2** for the study of neutrino properties using non-beam neutrinos complementary to DUNE and for indirect detection of dark matter.

"This improvement in reach would provide coverage of important benchmark WIMP models, such as most remaining potential dark matter parameter space under the constrained minimal supersymmetric extension to the Standard Model."

- Astroparticle Physics European Consortium (APPEC) mid-term roadmap
- Helmholtz roadmap (DE)
- UKRI funds to develop XLZD
- SERI roadmap (CH)
- SCJ: Future academic advancement initiative (JP)

"APPEC strongly supports the European leadership role in Dark Matter direct detection, underpinned by the pioneering LNGS programme, to realise at least one next-generation xenon (order 50 tons) and one argon (order 300 tons) detector, respectively, of which at least one should be situated in Europe. APPEC strongly encourages detector R&D to reach down to the neutrino floor on the shortest possible me scale for WIMP searches for the widest possible mass range."

0νββ with a natural Xe target

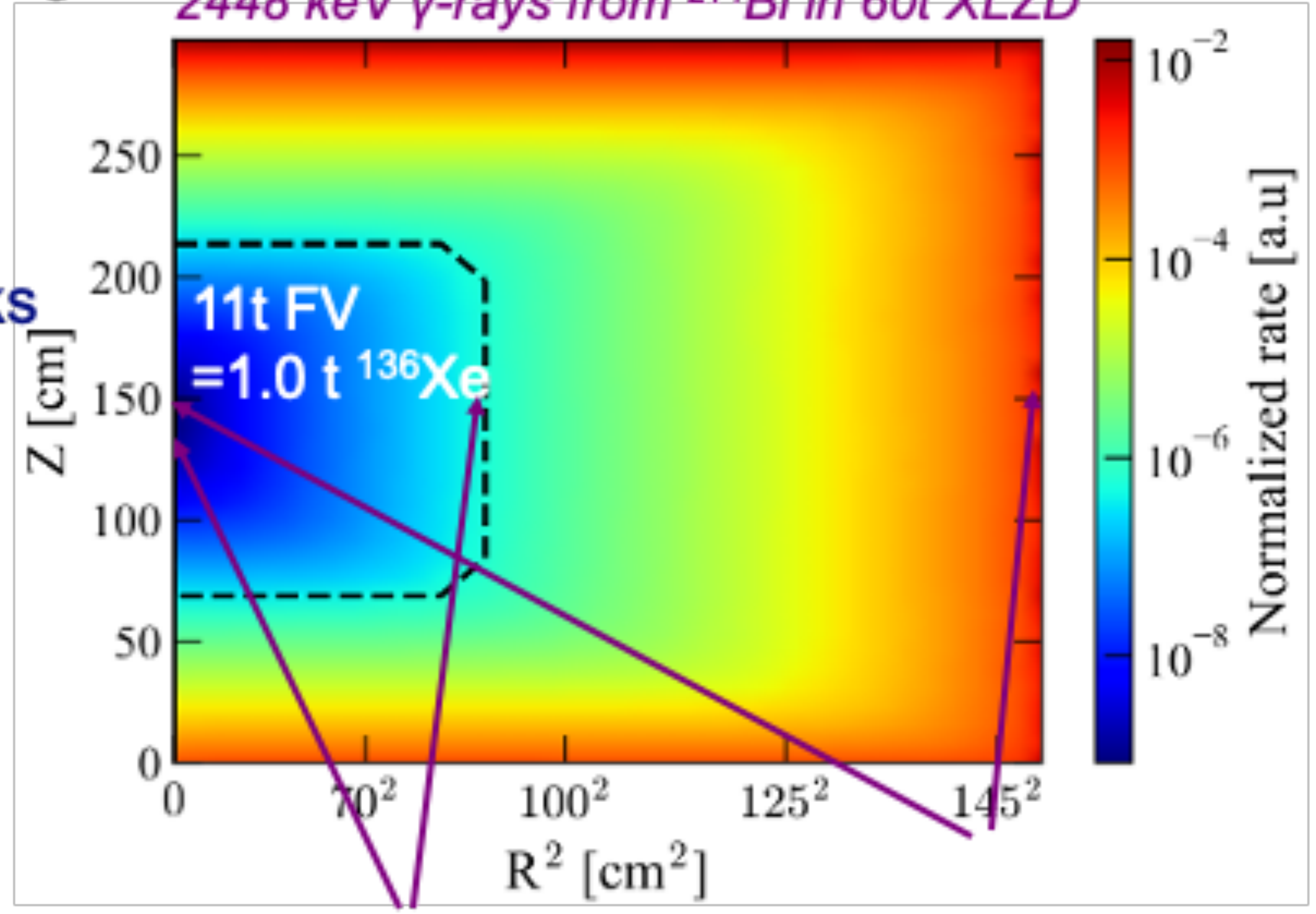
- 60t natural Xe target of XLZD contains **5.34t of ^{136}Xe**

  (7.1t in 80t)
- **XLZD does not plan for enrichment**
  would negatively affect DM and solar-ν physics
  → BUT: operation with enriched or depleted target generally possible at any stage
- **Advantages of a natural Xe target**
  - More efficient and less „expensive“ **self-shielding** thanks to large homogeneous target
    NB: from wall to center 2.5 MeV γ has to travel ~18 attenuation lengths in XLZD
  - No **costs for enrichment**; ^{nat}Xe can be sold
  - ^{136}Xe has lowest n-capture cross-section of all Xe isotopes
    → other isotopes shield ^{136}Xe and **reduce ^{137}Xe production**

J. Phys. G 52, 045102 (2025)

other studies with natural Xe:
PandaX: arXiv:2412.13979
XENON: PRC 106, 024328 (2022)
PandaX: Research 2022, 9798721 (2022)
LZ: PRC 102, 014602 (2020)
DARWIN: EPJ C 80, 808 (2020)
Baudis et al., JCAP 01, 044 (2014)

2448 keV γ-rays from ^{214}Bi in 60t XLZD



Suppression ~10^3

~10^7

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