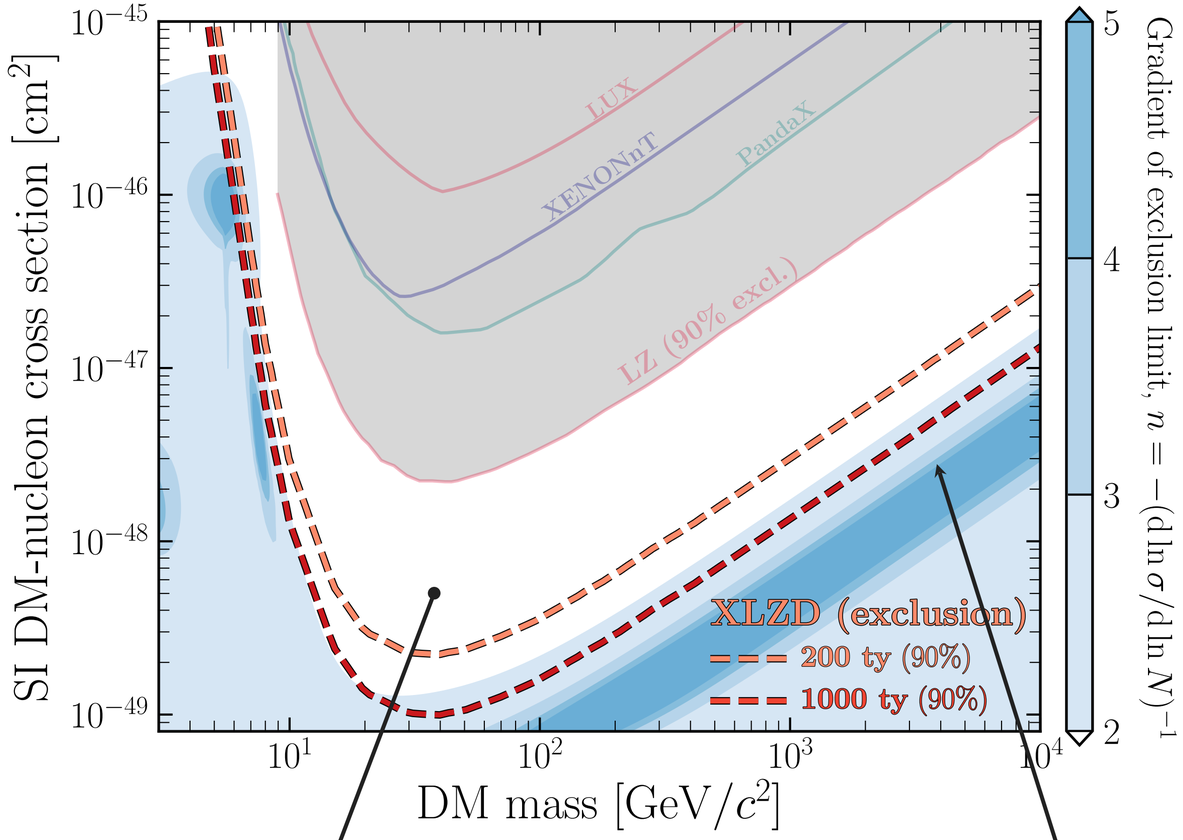
XLZD: A next generation observatory for Dark matter and rare events

Hugh Lippincott on behalf of XLZD Collaboration
UCSB

Liquid xenon detectors: the definitive search for "high-mass" WIMPs

Projected sensitivity
and current limits



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

Systematic limit imposed by coherent scattering of astrophysical neutrinos

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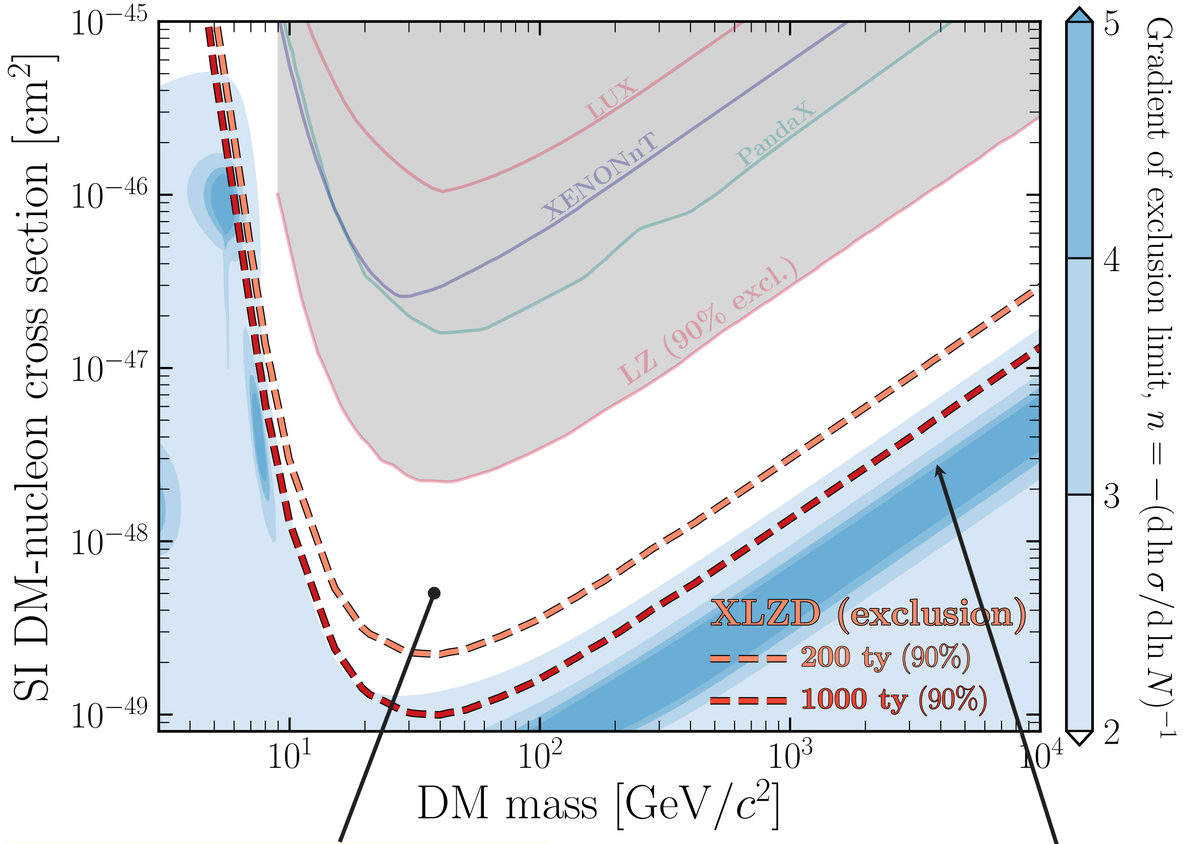

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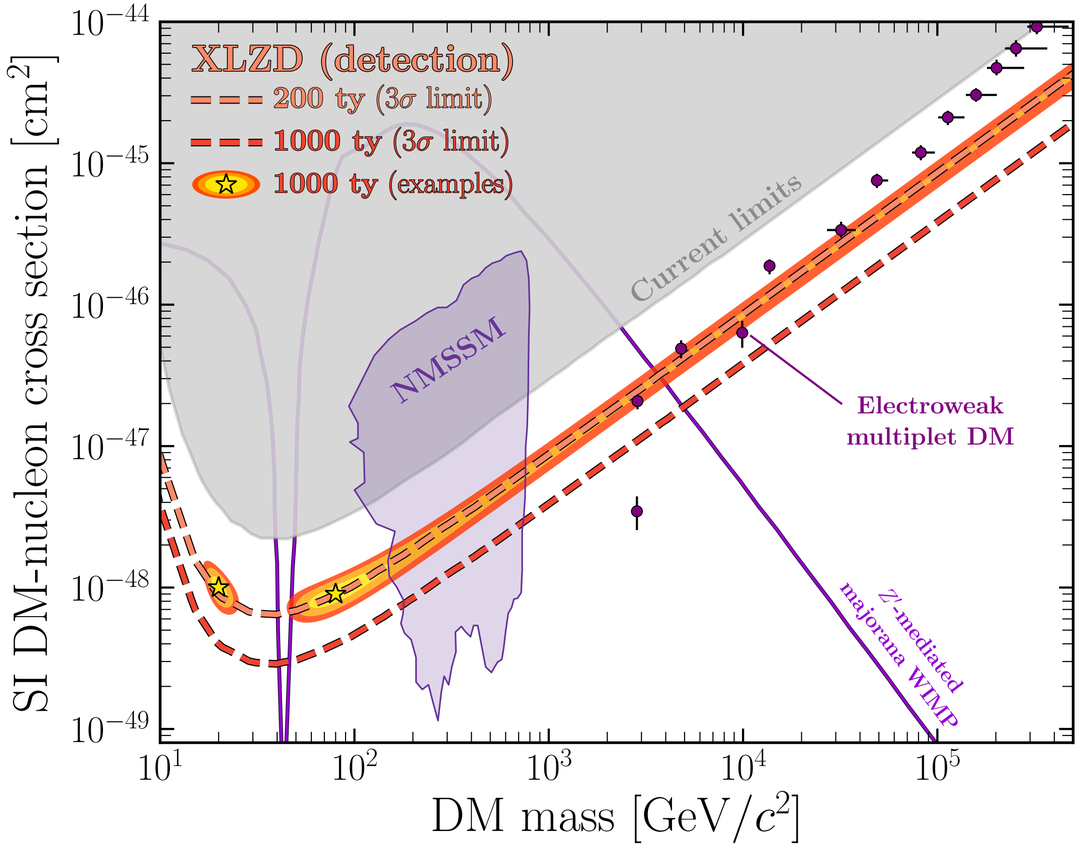

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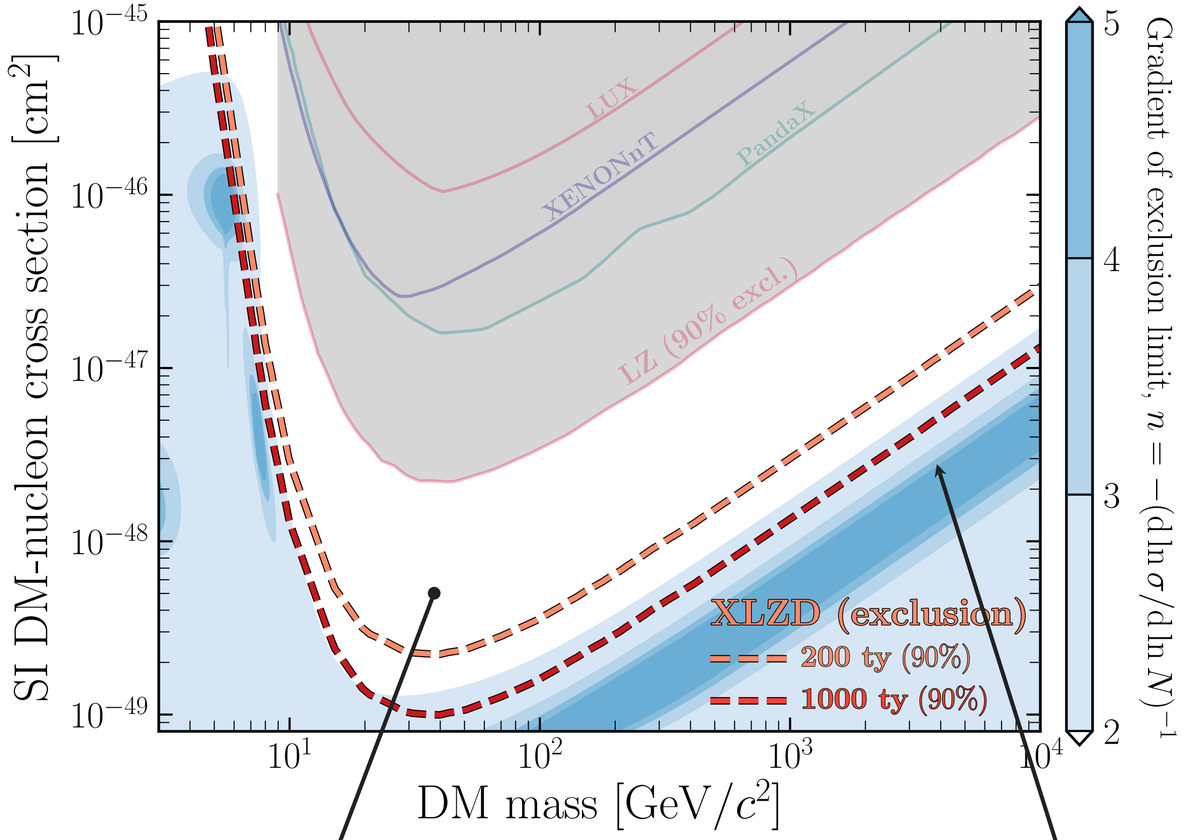

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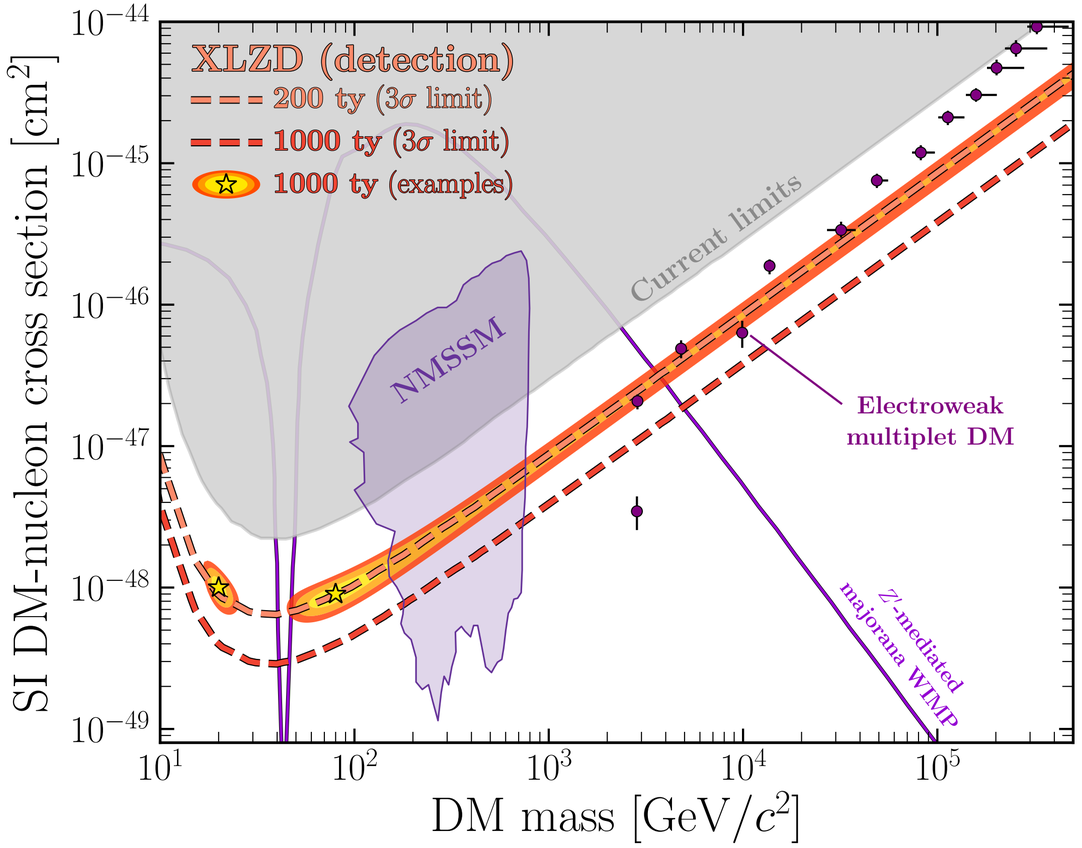
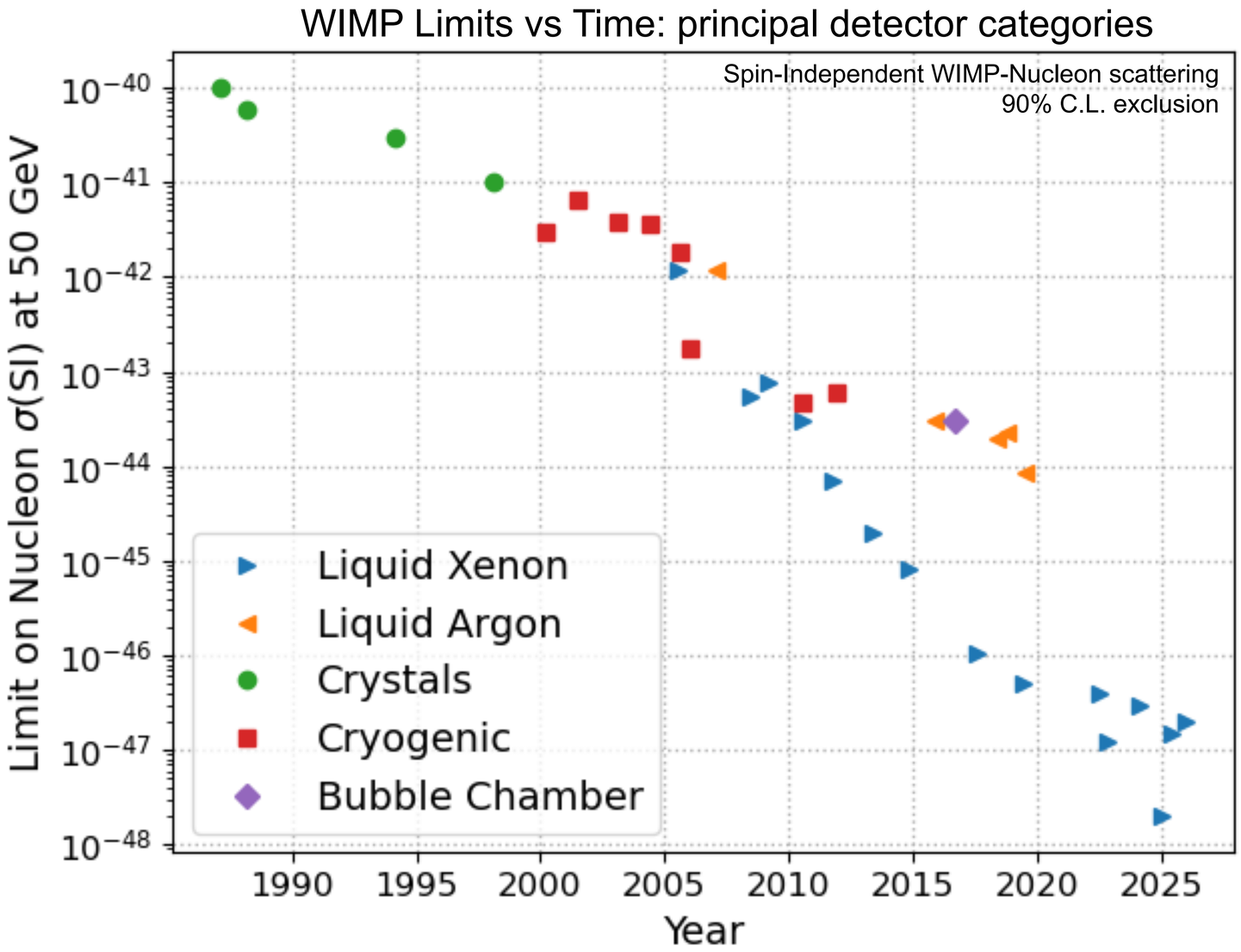


Potential for discovery and constraining DM properties

Liquid Xenon Detectors: World leading since 2007



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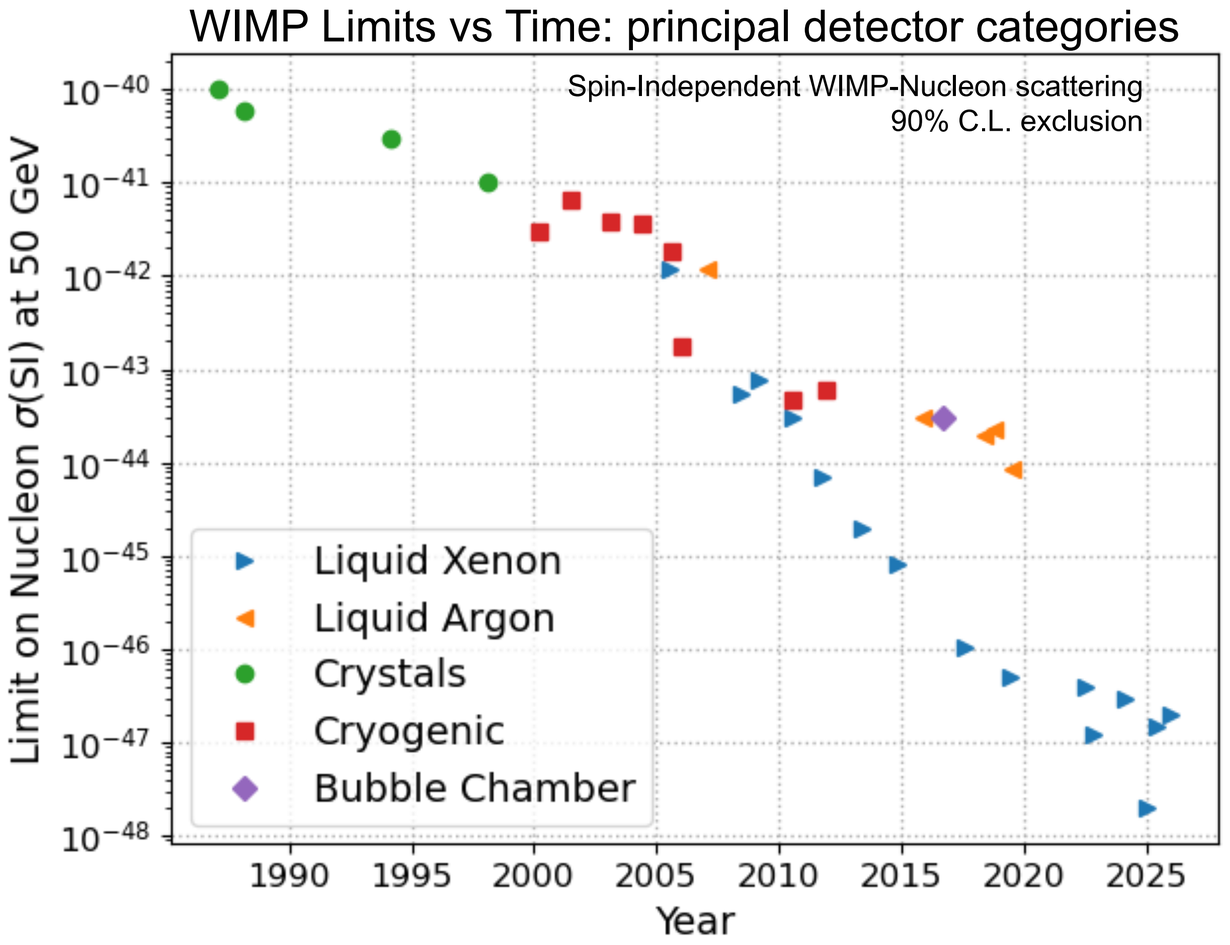

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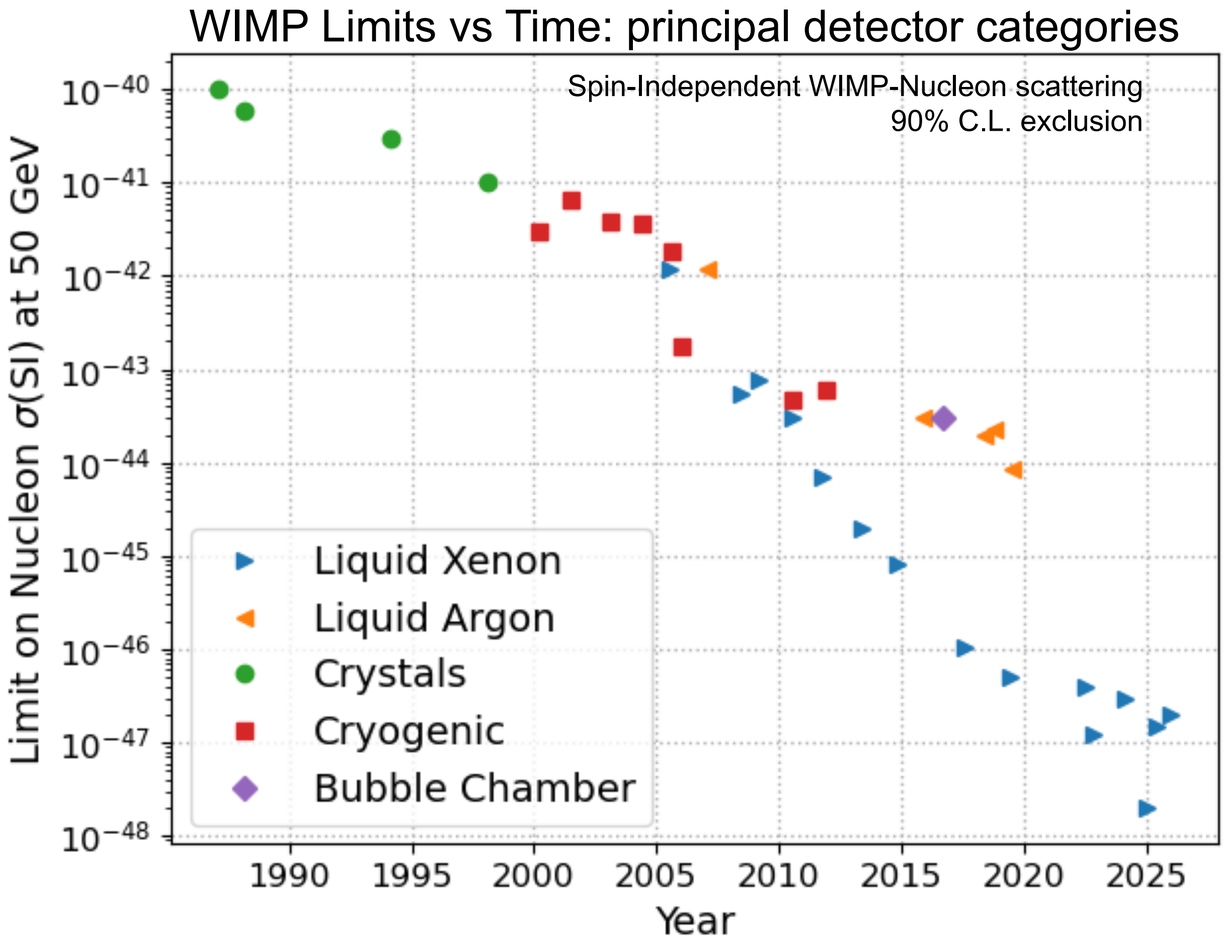
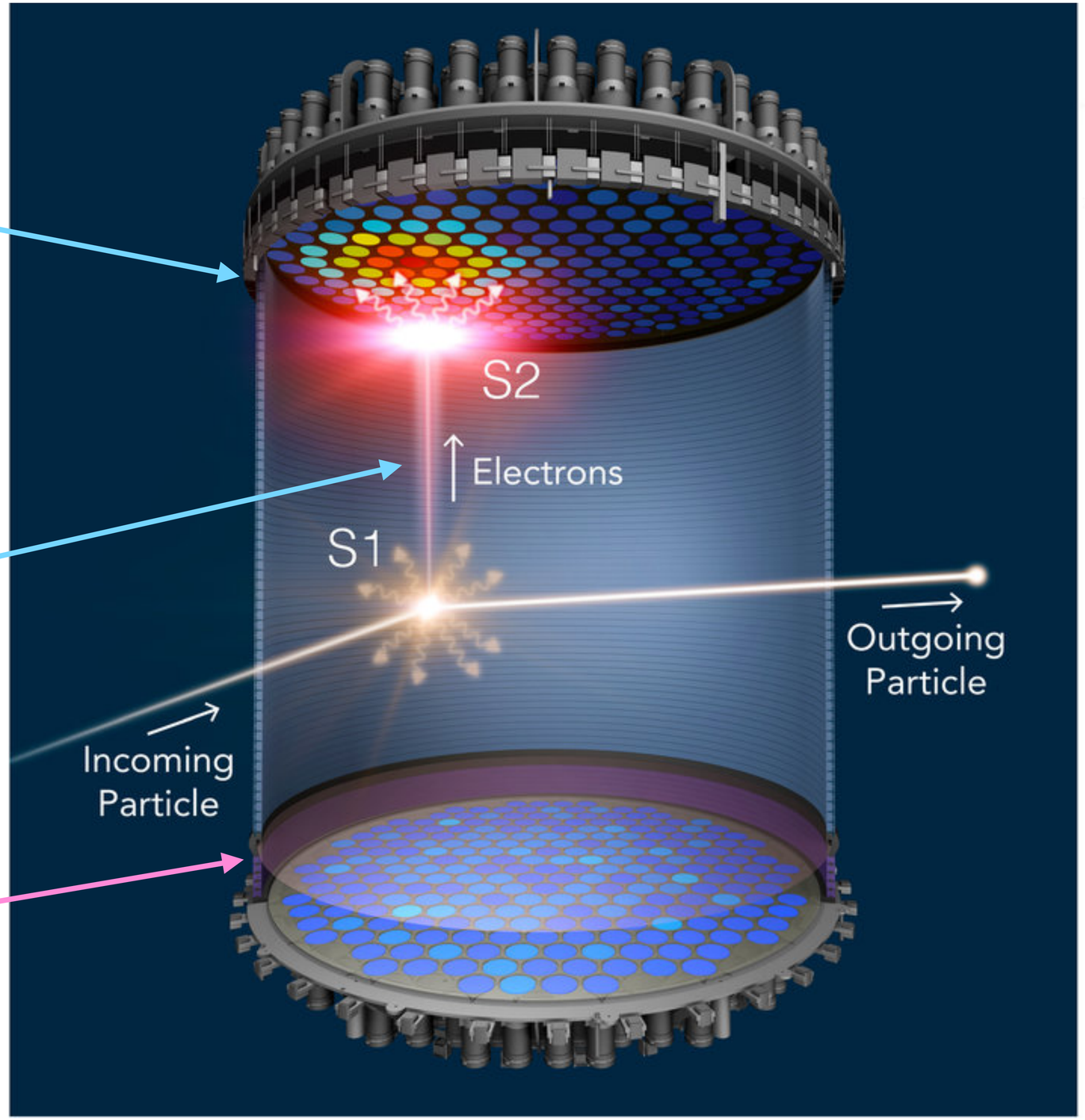
  - ER/NR discrimination
  - Low energy threshold
  - 3D position - self-shielding, singles/ multiples



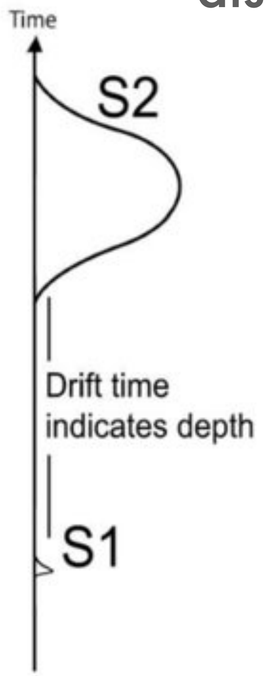
S2 light pattern gives x-y position (~few mm resolution)

Drift time gives z position (~0.5 mm resolution)

Cathode



S1-S2 relative size gives event-type discrimination



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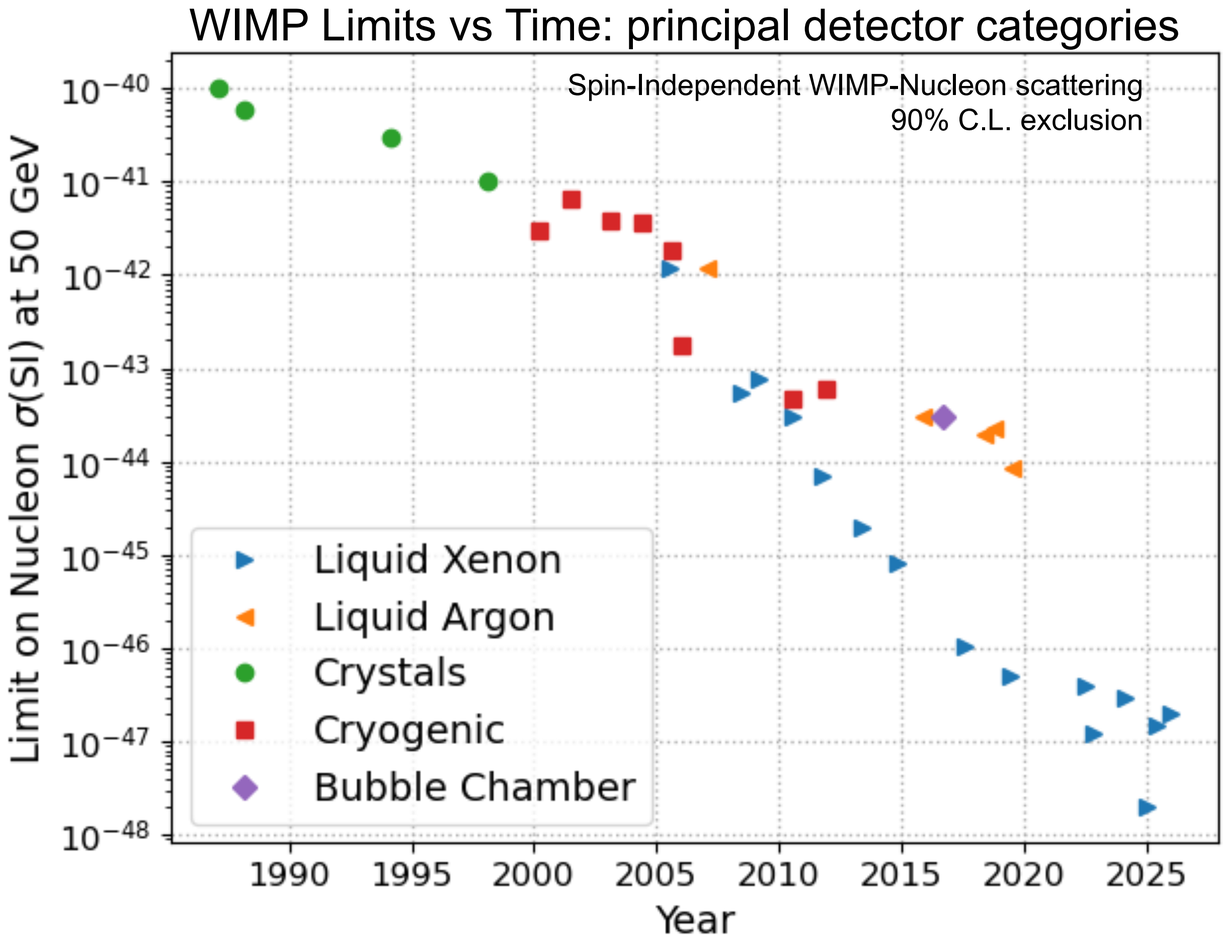
  - High density, large A^2 , many isotopes (SI, SD, NR-ETF, inelastic)



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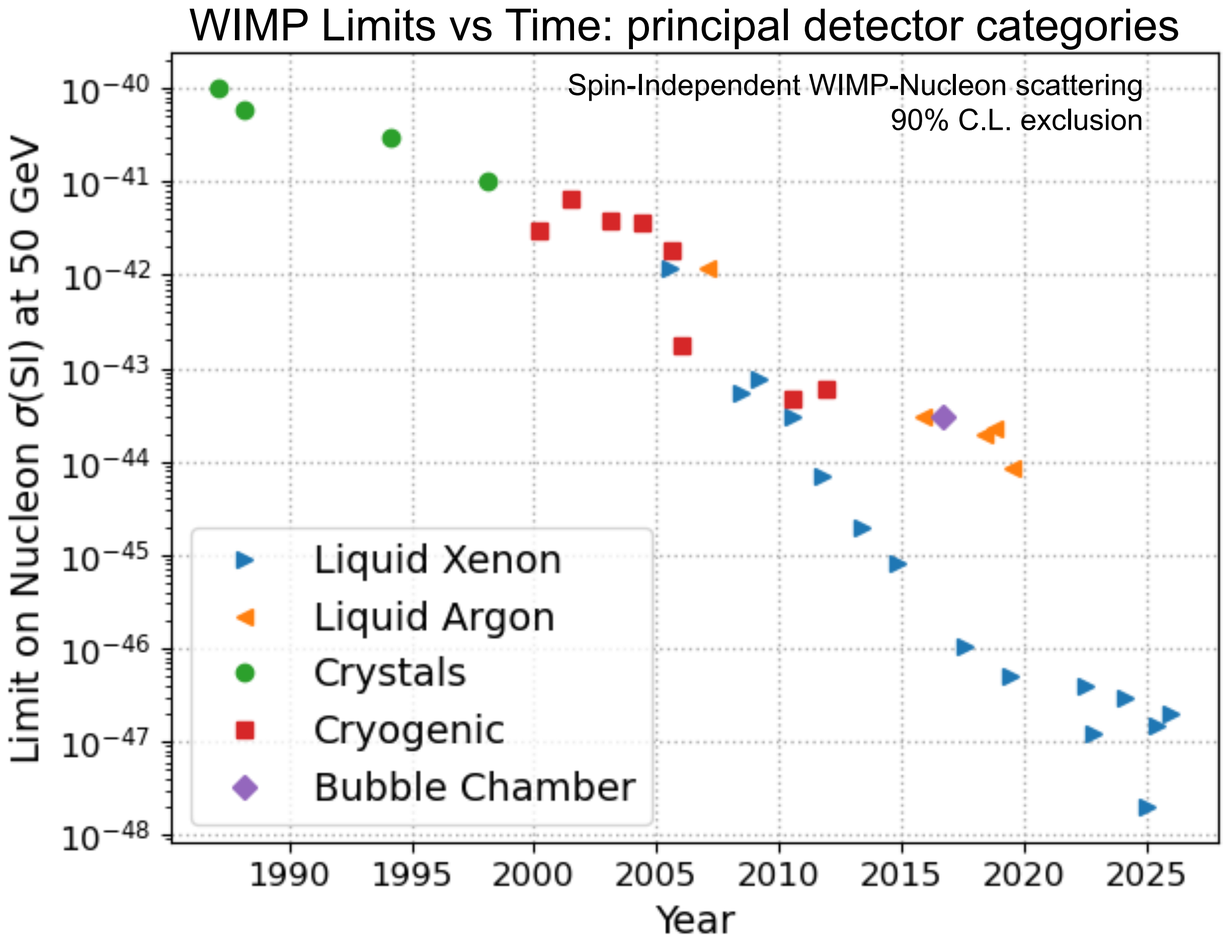
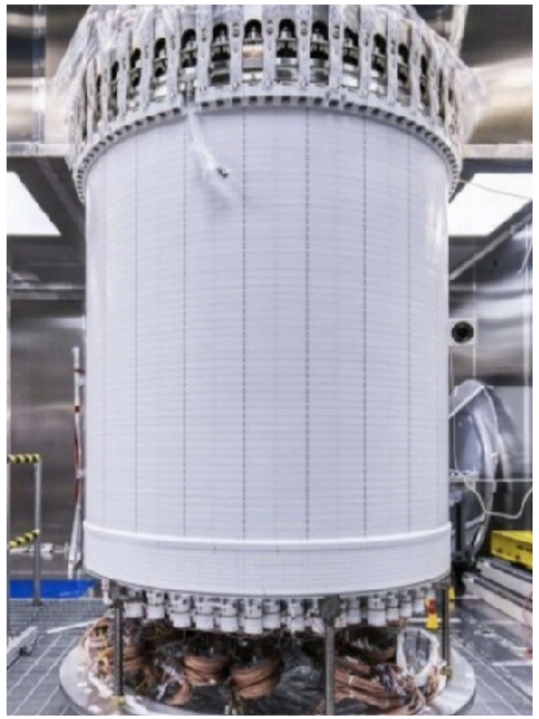


Liquid Xenon Detectors: World leading since 2007

LUX-ZEPLIN

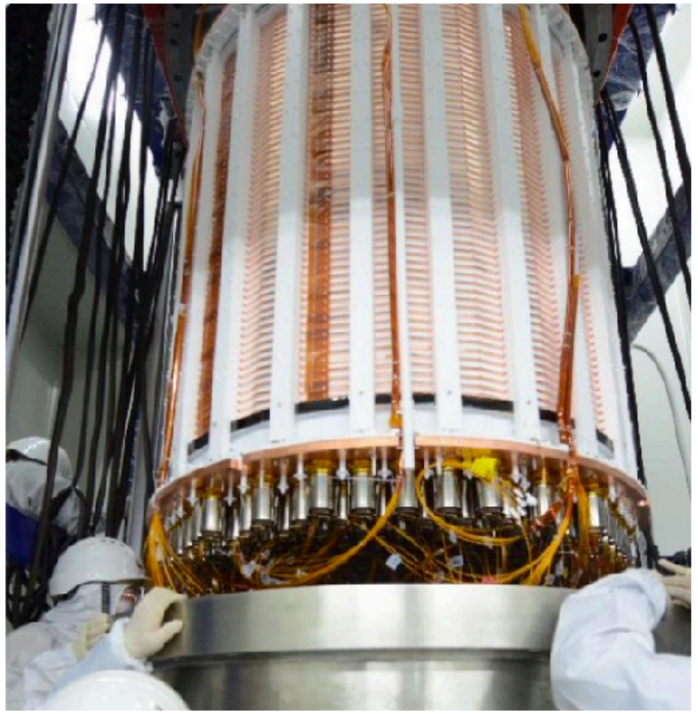


SURF, 7 t

XENONnT

LNGS, 5.9 t

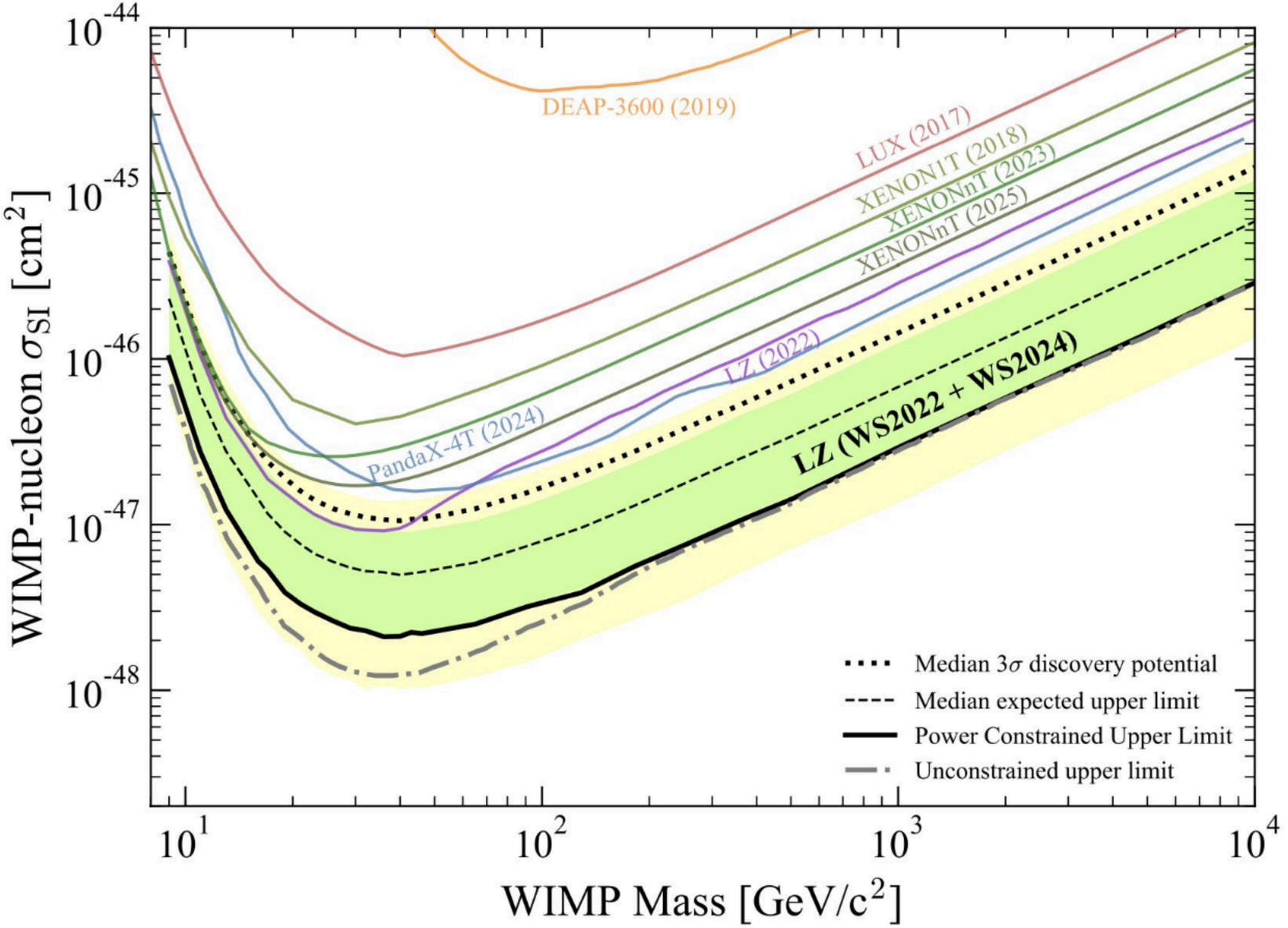
PandaX-4T



JinPing, 3.7 t

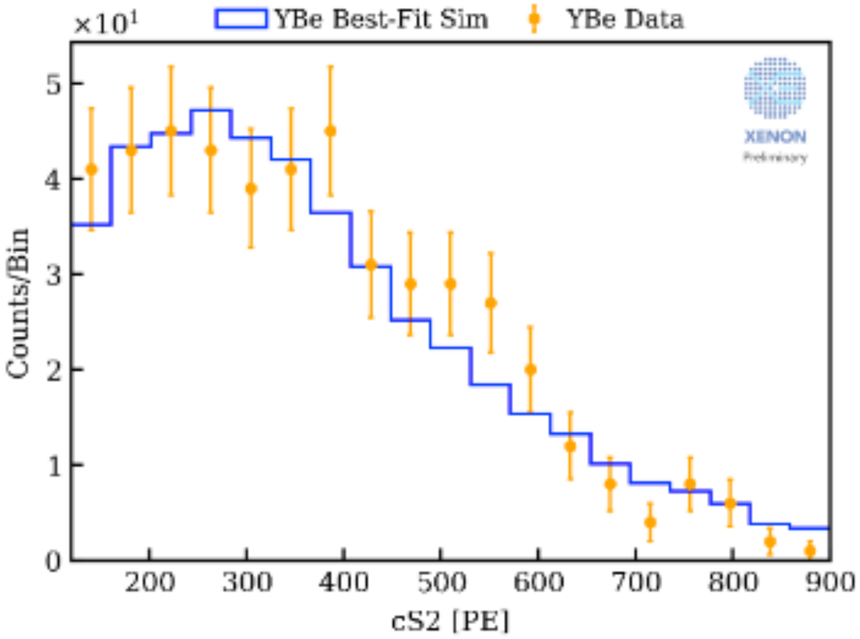
- TPCs with 2 arrays of 3-inch ø PMTs
- Kr & Rn removal techniques (to mitigate ^{85}Kr and ^{222}Rn backgrounds)
- Neutron & muon vetos, ultra-pure water shields, liquid scintillator

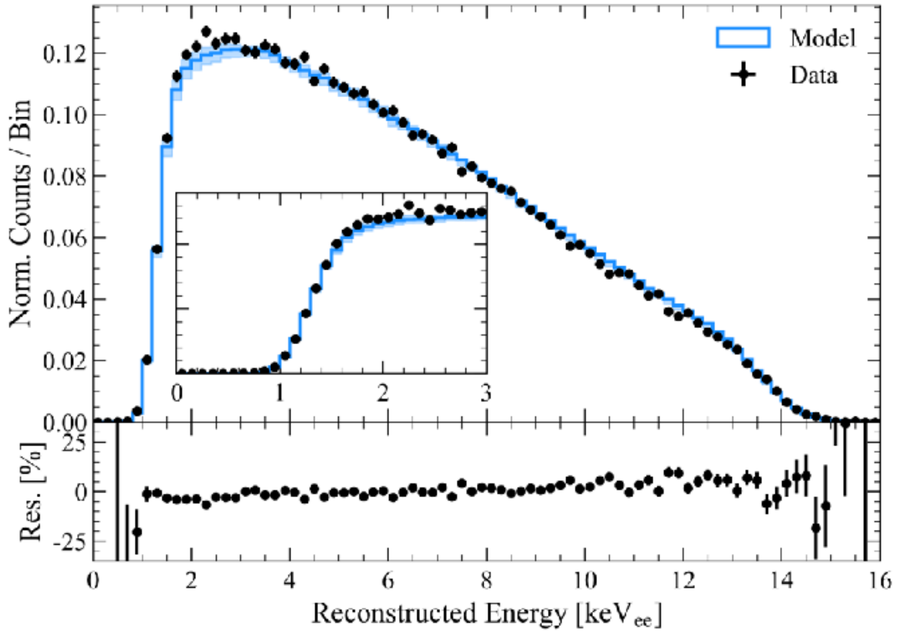
Liquid Xenon Detectors: World leading since 2007

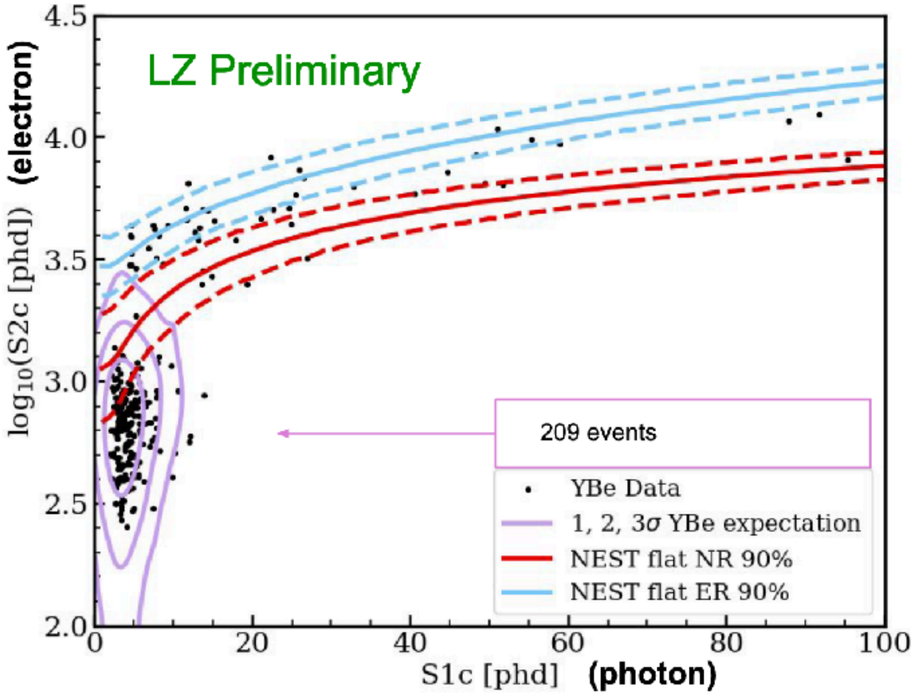


Liquid Xenon Dual Phase TPCs

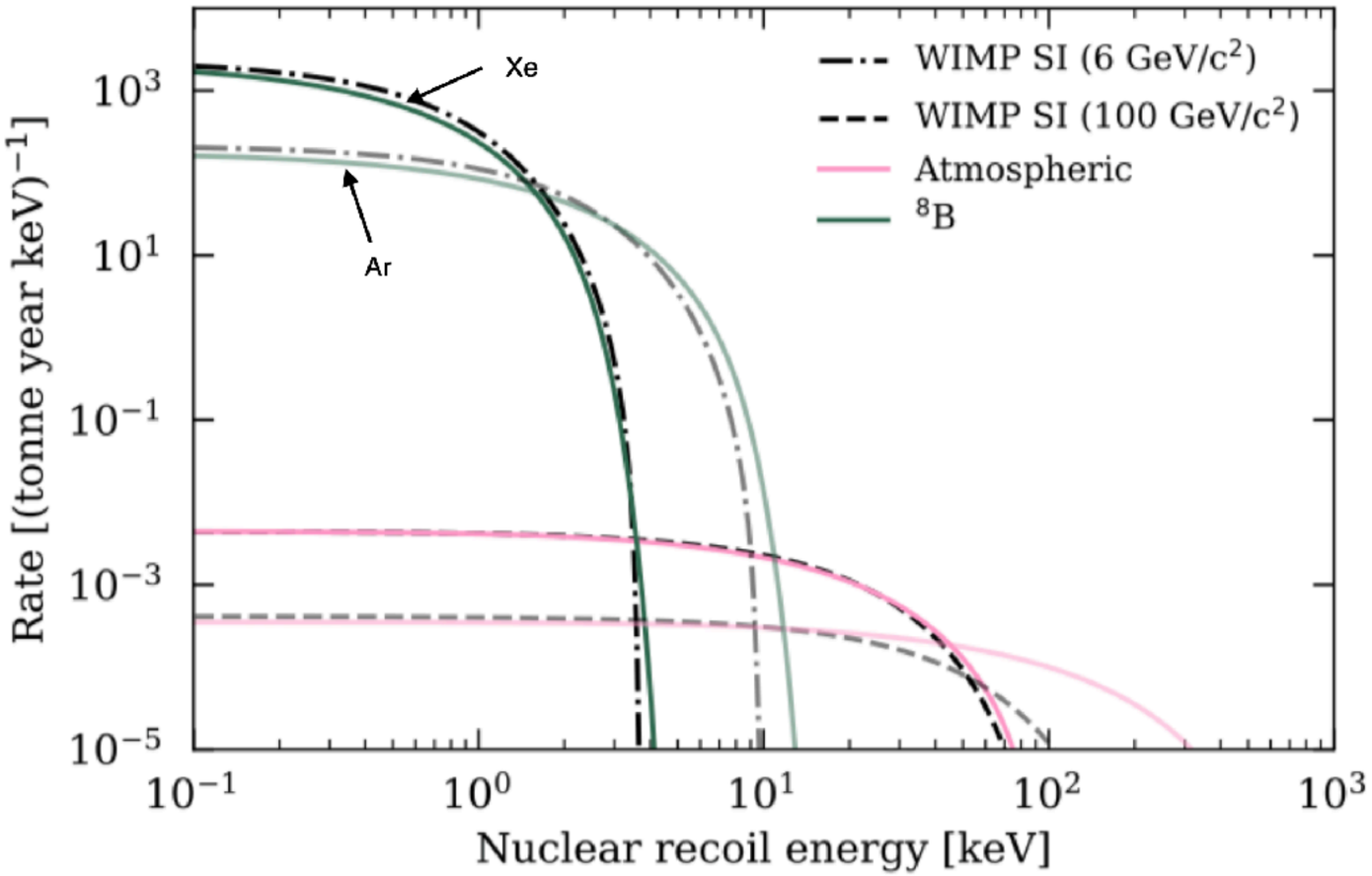
- Calibration is key - e.g.:
  - LZ - High stats of ER (background) distribution using dispersed tritium (CH_3T) - ~160k events!
  - LZ and XENON have now used YBe to calibrate low energy NR
- Allows for precise modeling in final analysis, enables discovery







The Neutrino Fog

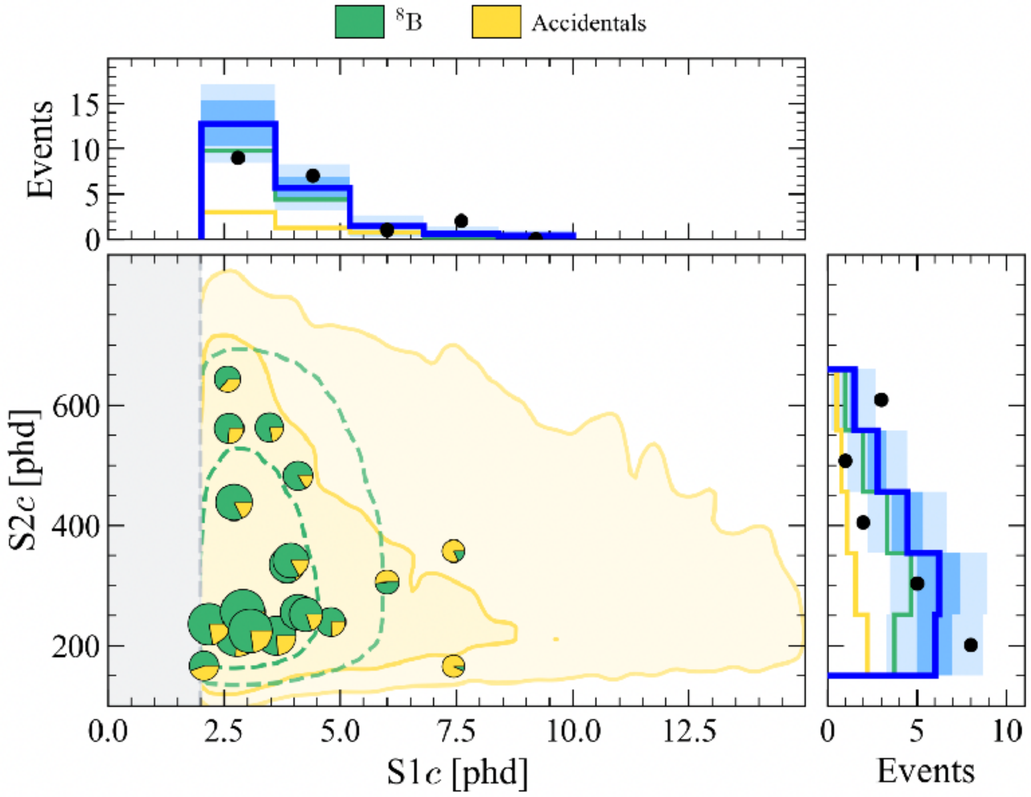


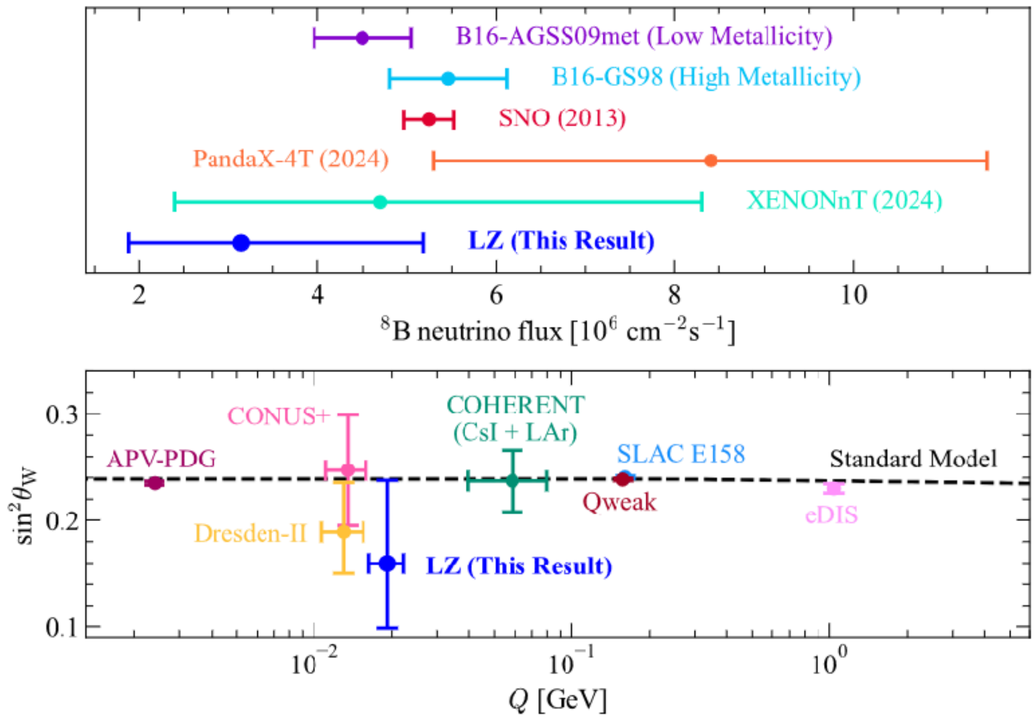
- ^{8}B solar neutrinos have a measured flux (SNO, SuperK, etc)
- Interact coherently with nuclei like DM - coherent neutrino nucleus scattering
  - First observed in 2017 by COHERENT collaboration at Spallation Neutron Source at Oak Ridge
- Atmospheric neutrinos look like >100 GeV WIMPs, 8B like ~5.5 GeV WIMPs

We're into the fog!

- The three xenon experiments are seeing clear evidence for solar ^{8}B neutrinos
- PandaX (2407.10892) and XENONnT (2408.02877) reported in 2024 with ~2.7 sigma
- LZ reported in December with 4.5 sigma (2512.08065)

Components	Expectation	Background-Only Fit
Spin-Independent DM	-	-
^{8}B CEνNS	$20.6^{+8.9}_{-6.8}$	$15.0^{+2.9}_{-2.5}$
Accidental coincidences	6.6 ± 0.3	6.5 ± 0.3
Detector neutrons	$0.04^{+0.25}_{-0.04}$	$0.1^{+0.2}_{-0.1}$
Total	$27.2^{+9.2}_{-6.7}$	$21.6^{+4.7}_{-3.8}$





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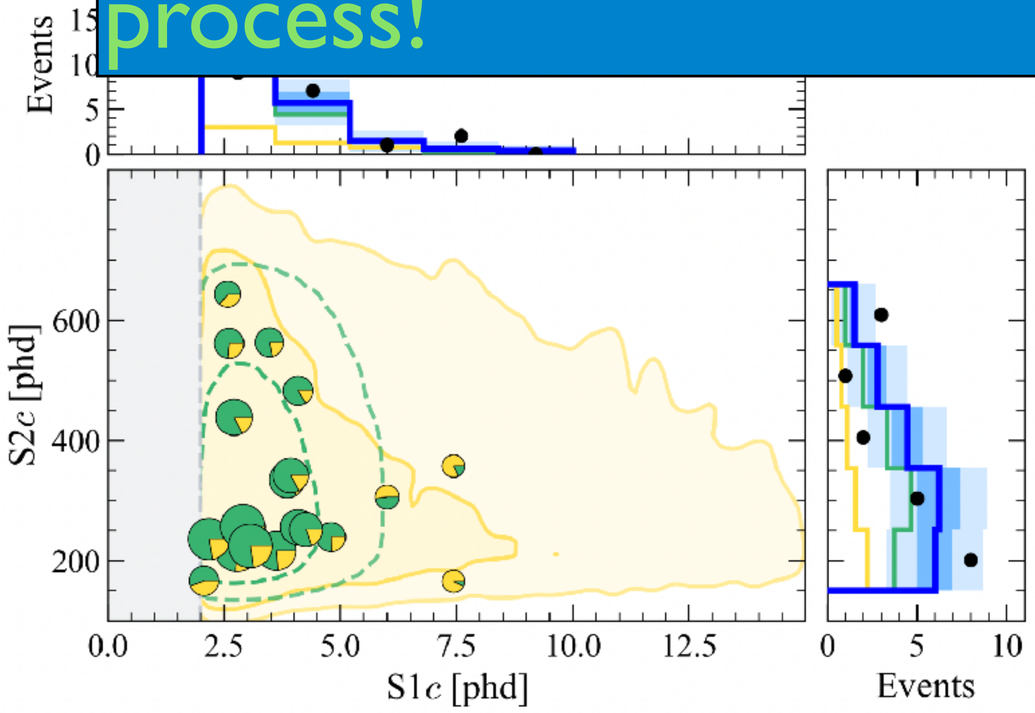
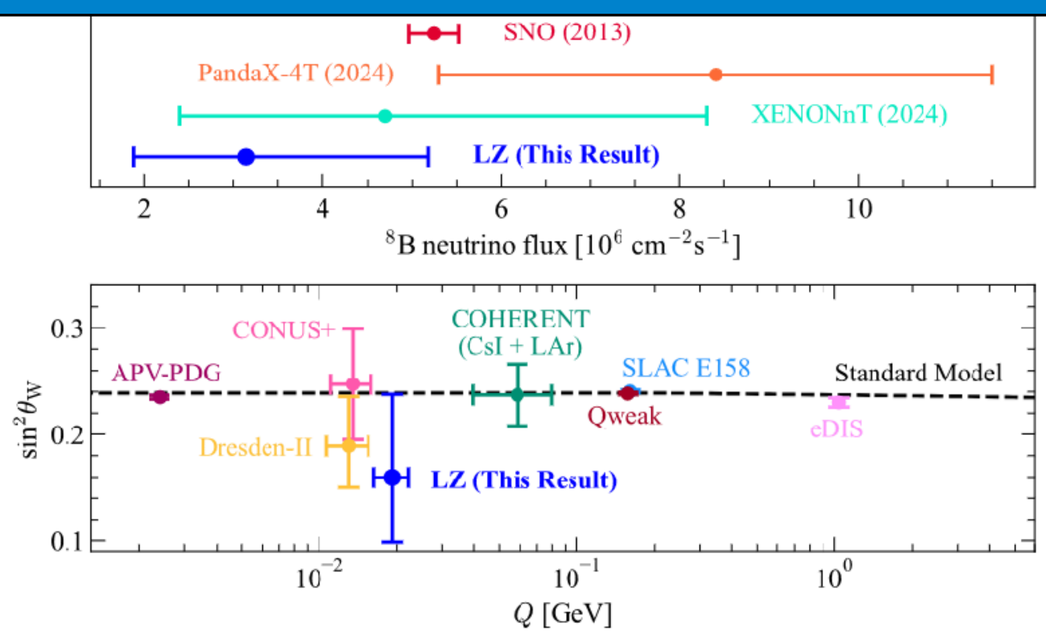
Clear observation of astrophysical sources of low energy nuclear recoils via a coherent scattering process!

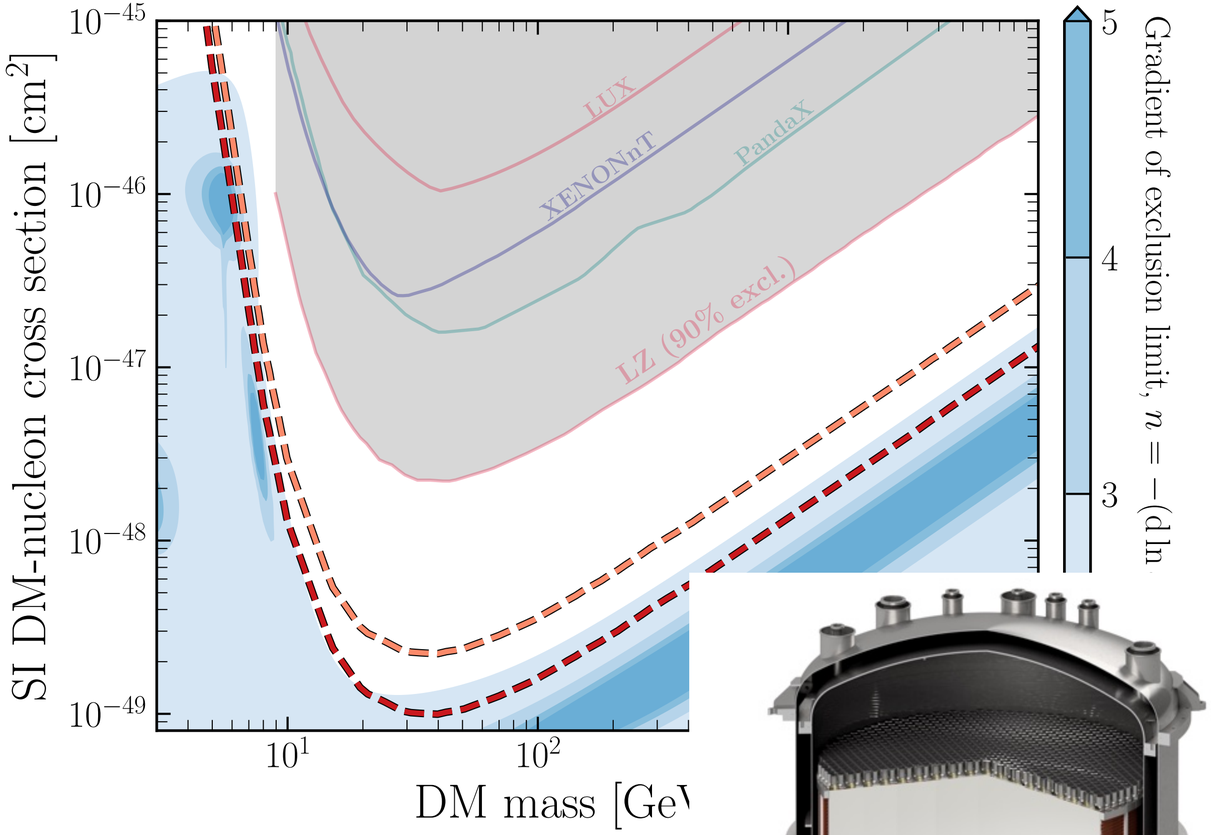


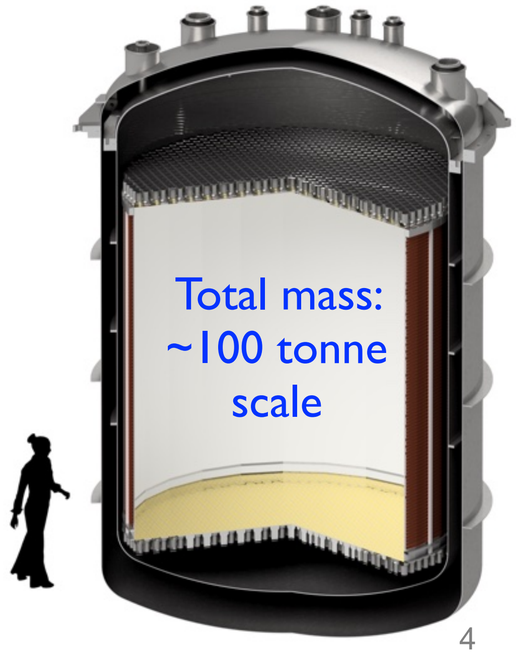


XLZD: definitive search for high mass WIMPs

- 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

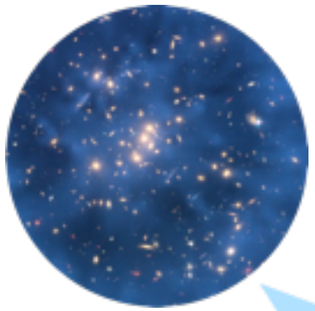
- Combine best of LZ and XENONnT
  - 10x mass: 60 tonnes (80 if funding permits) of active LXe
  - Double TPC linear dimensions
  - Compact geometry: readout, underground transport & fit

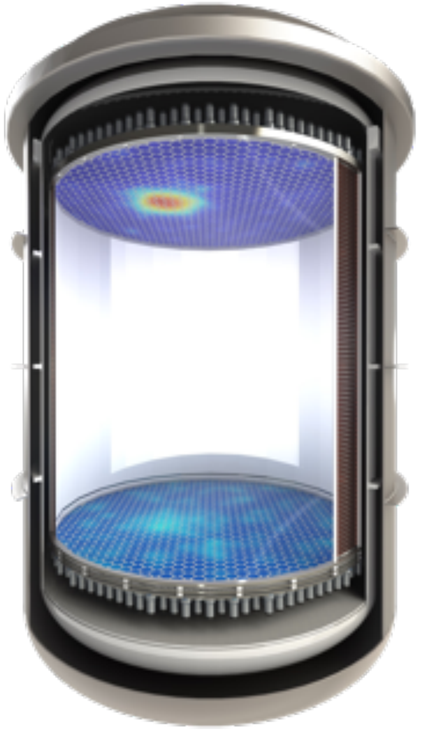




A Liquid Xenon Observatory with a broad science program

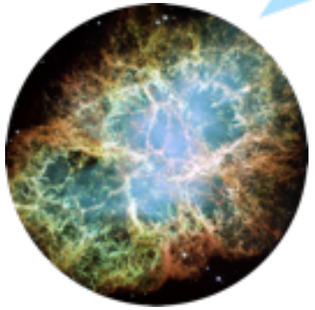
Dark Matter
WIMPs
Sub-GeV
Inelastic
Axion-like particles
Planck mass
Dark photons





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

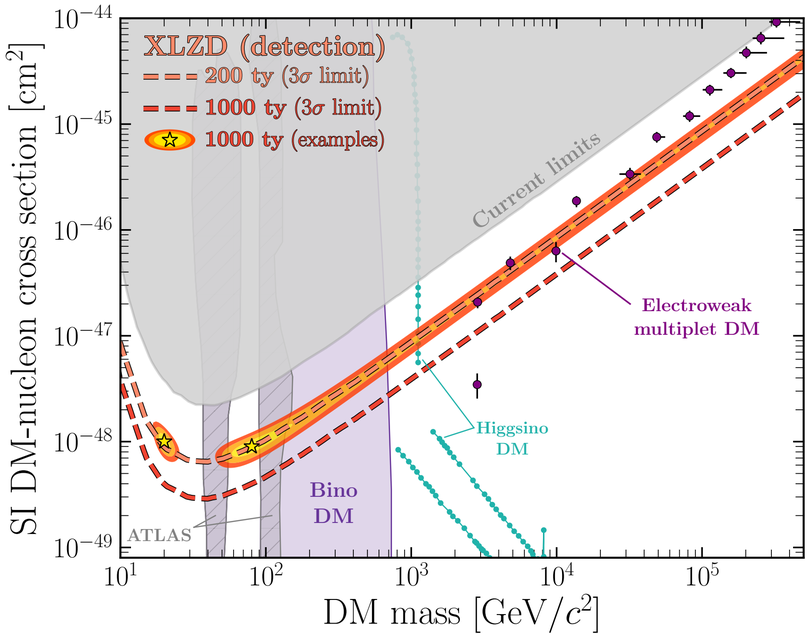
Supernovae
Early alert
Supernova neutrinos
Multi-messenger astrophysics

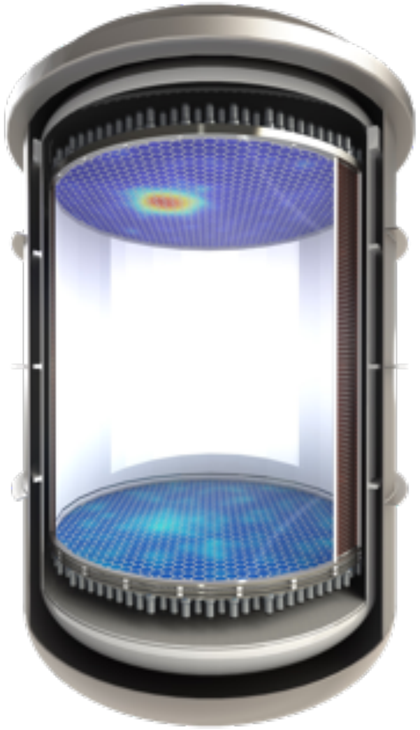


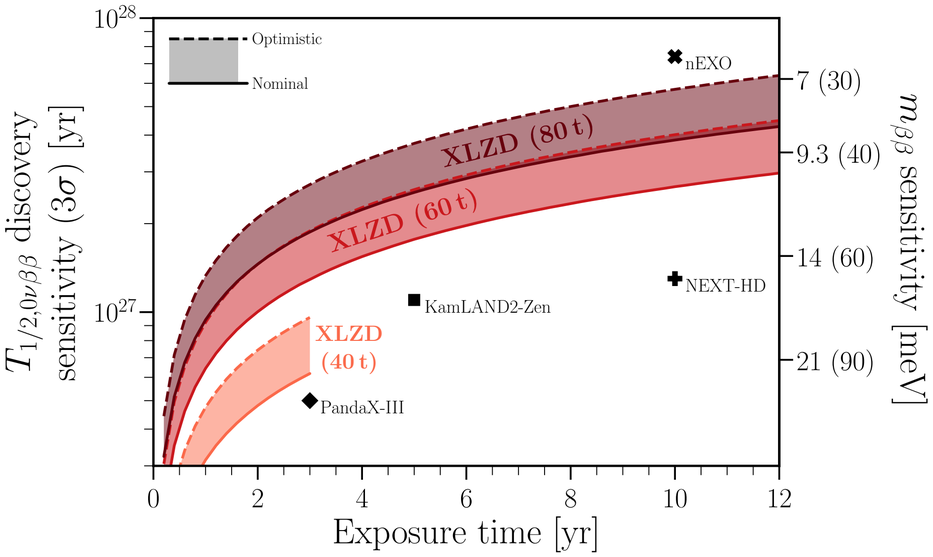
Sun
pp neutrinos
Solar metallicity
^{7}Be, ^{8}B, hep

arXiv:2410.17137, 2203.02309

A Liquid Xenon Observatory with a broad science program







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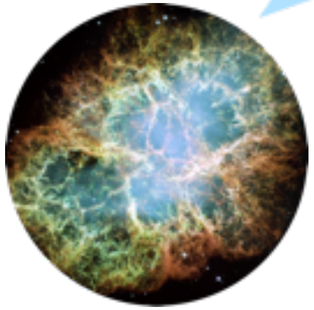

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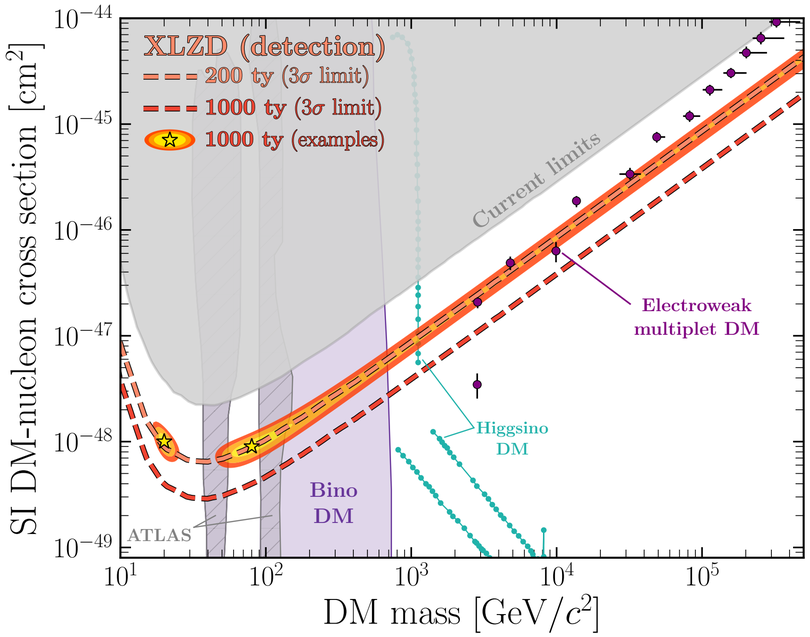

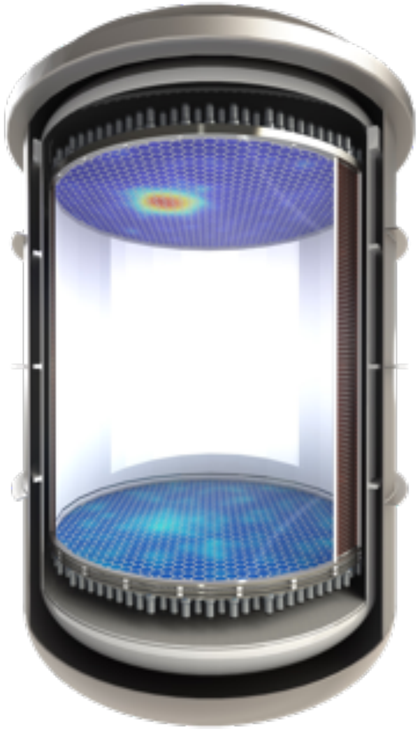

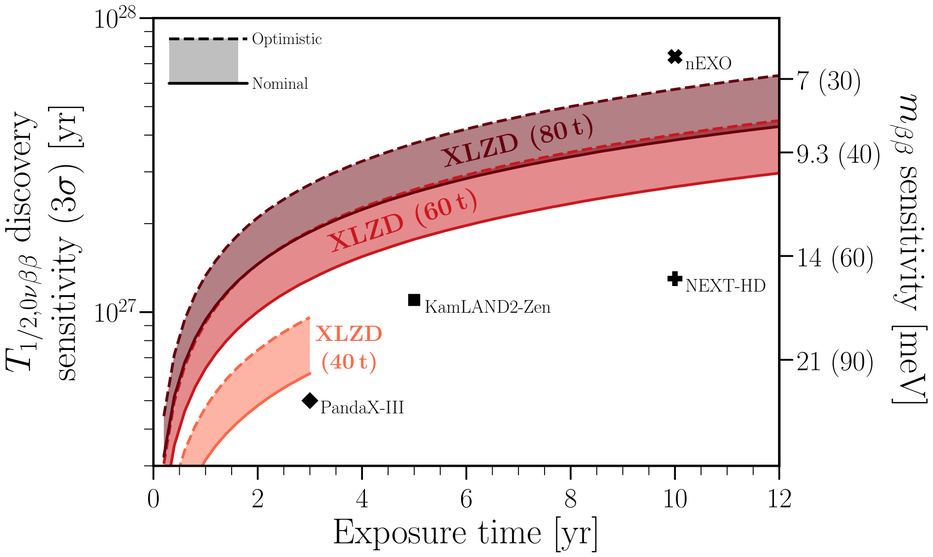

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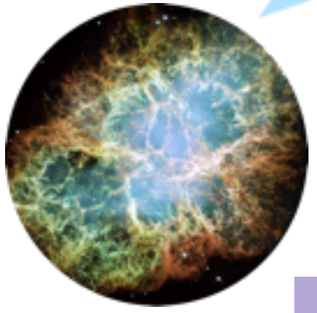

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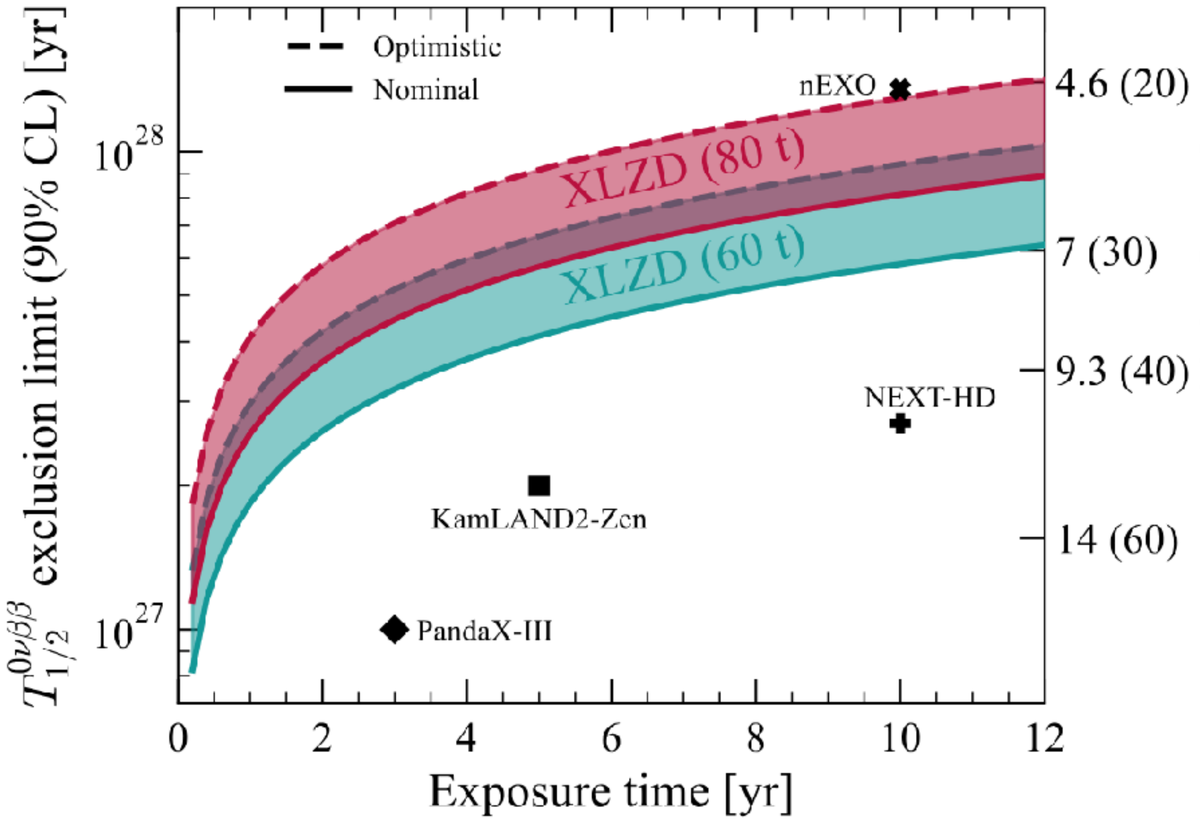
^{7}Be, ^{8}B, hep

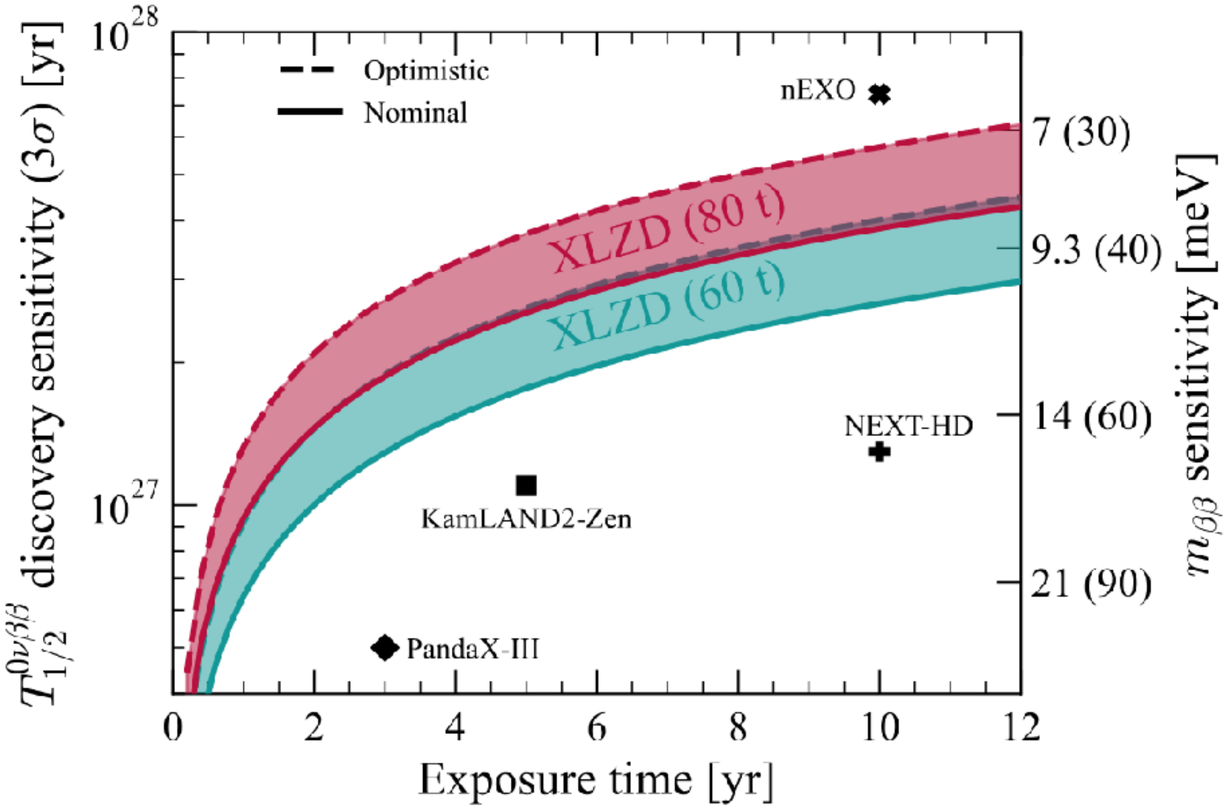
Unprecedented reach for low-energy rare processes

arXiv:2410.17137, 2203.02309

A Liquid Xenon Observatory with a broad science program

Parameter	Scenario Nominal	Optimistic
^{222}Rn concentration [μBq/kg]	0.1	
BiPo tagging efficiency [%]	99.95	99.99
External γ-ray [% LZ]	25	10
Installation site	LNGS	SURF
Energy resolution [%]	0.65	0.60
SS/MS vert. separation [mm]	3	2





- XLZD uses figure of merit estimator, not a full analysis

https://arxiv.org/pdf/2410.19016

XLZD: A Unified Community to build the definitive experiment

- Consortium MOU signed in July 2021 by **X**ENONnT, **L**UX-**Z**EPLIN, **D**ARWIN
- Collaboration agreement signed in Sept 2024
- XENONnT and LZ: ongoing science programs, technology progenitors
- DARWIN: initiated R&D and design studies with significant ERC support

First annual XLZD meeting ay KIT in Karlsruhe, Germany (June 2022)

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- Recent / ongoing activities
  - Design and sensitivity reports posted
  - Working groups: science, technical, siting
  - UK Pre-construction & Boulby development
  - Annual gatherings: KIT 2022, UCLA 2023, RAL 2024, LNGS 2025
  - xlzd.org

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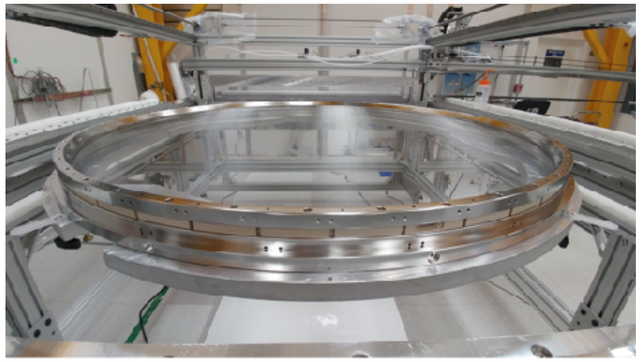
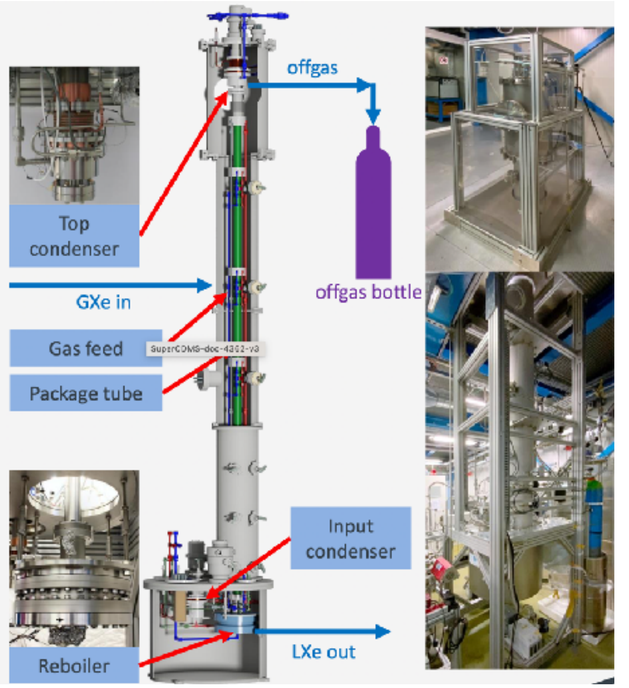
Design Heritage: technical foundation from LZ and XnT

- Rich heritage from two successful programs
- Deep bench of expertise in key areas, including:
  - Radioactivity, including extensive Rn screening programs
  - High voltage electrodes and delivery
  - Low-background PMTs w/Hamamatsu
  - Purification and cryogenics



LZ Grids



XnT Kr distillation

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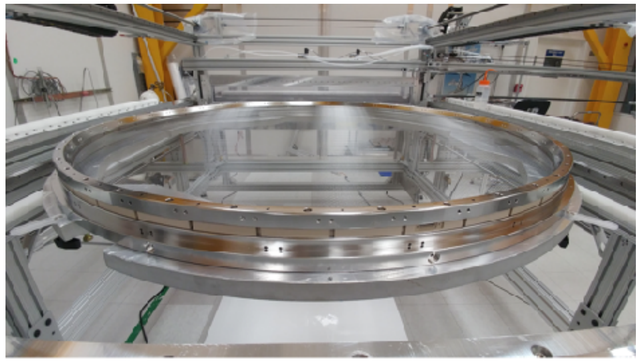
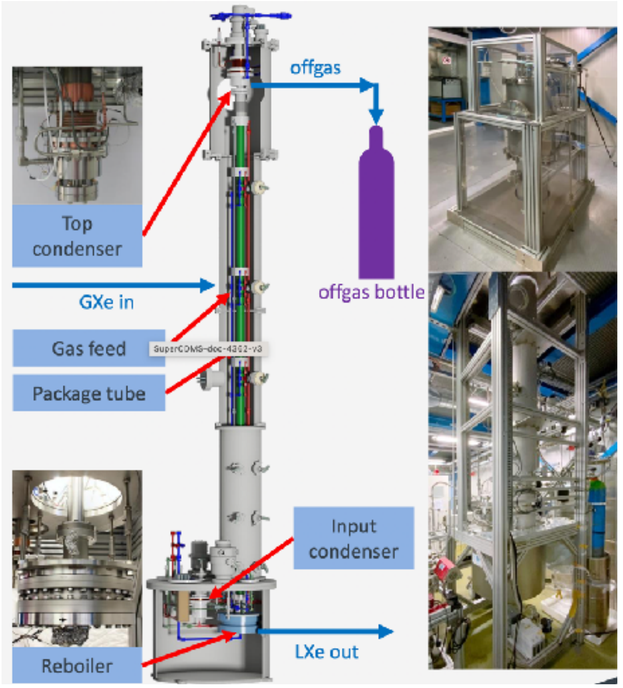
  - Purification and cryogenics

- Multiple design approaches to draw from:

LZ	XnT
Woven grids and HV delivery system	*Strung wire grids*
All poly HV cable, and side entrance geometry	*Top entrance HV cable*
Compressor driven gas phase purification and storage	*Liquid phase purification and storage*
Chromatographic Kr and Rn removal	*In-line distillation Rn and Kr removal*
Distillation based impurity sampling	*Chromatography based impurity sampling*
Gd-LS outer veto + Xe skin	*Gd-water outer veto and shield*
Low radioactivity Ti vessel	*SS vessel*
Multiple weir liquid level control	*Bell jar liquid level control*



LZ Grids



XnT Kr distillation

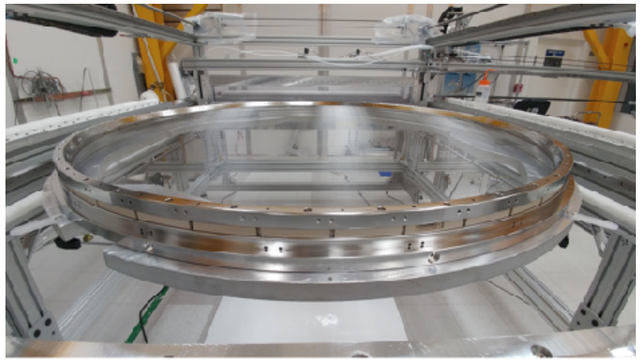
Design Heritage: technical foundation from LZ and XnT

- Rich heritage from two successful programs
- Deep bench of expertise in key areas, including:
  - Radioactivity, including extensive Rn screening programs
  - High voltage electrodes and delivery
  - Low-background PMTs w/Hamamatsu
  - Purification and cryogenics

- Multiple design approaches to draw from:

LZ	XnT
Woven grids and HV delivery system	*Strung wire grids*
All poly HV	
Compressor	
Chromatogr	
Distillation	
Gd-LS outer veto + Xe skin	*Gd-water outer veto and shield*
Low radioactivity Ti vessel	*SS vessel*
Multiple weir liquid level control	*Bell jar liquid level control*

More details in XLZD Design Book, 2410.17137



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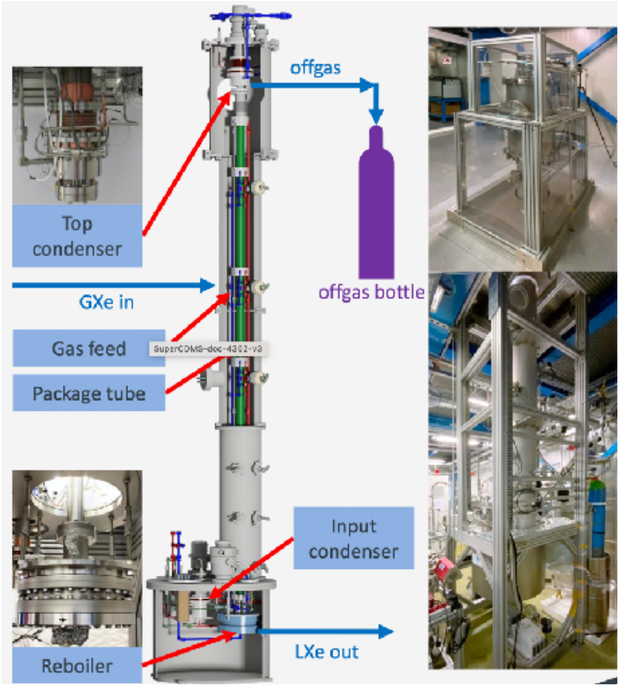

XnT Kr distillation

R&D to mitigate top technical risks

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)
R&D and mitigations: • Alternative grid mechanics • HV component testing	**Potential R&D and mitigations:** • High-throughput in-line radon removal • Radon barrier around TPC active region

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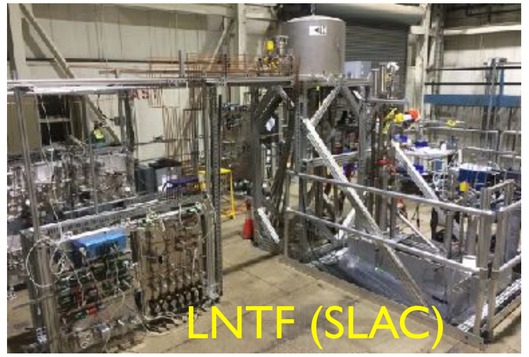
- Studies of accidentals, detector effects in LZ/XnT data
- Investments across XLZD groups in medium and large scale test platforms
- Possible definitive performance testing using existing shielded underground infrastructure


LNTF (SLAC)


"Pancake" (Freiburg)


LZ Loom & "LSST" clean room (SLAC)


Xenoscope (Zurich)

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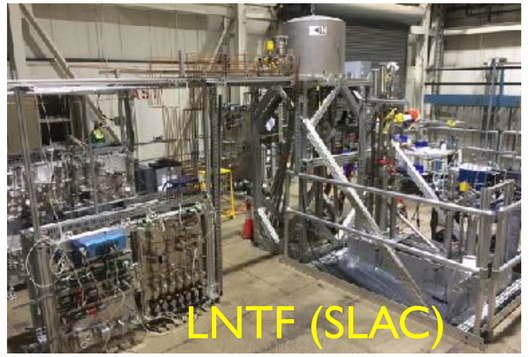
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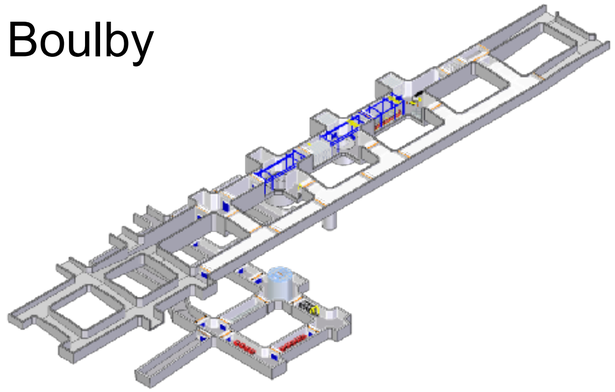
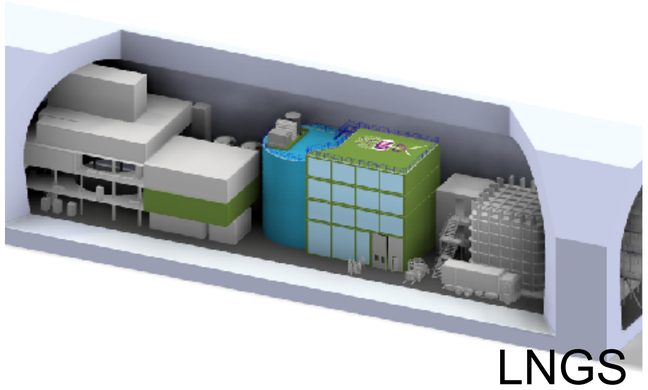
Combined team's track record establishes technical foundation and capabilities for making the necessary advances

Possible sites for XLZD

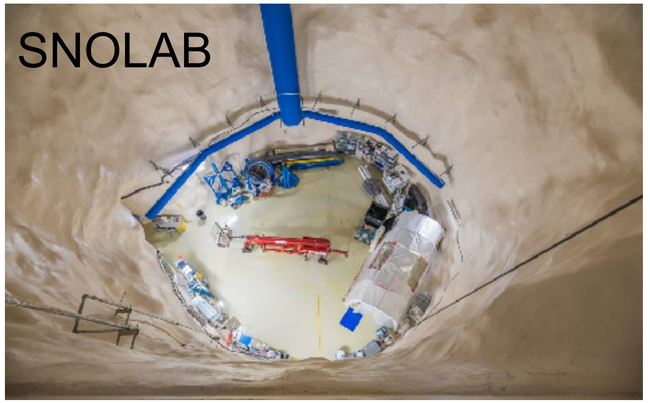
- Completing a study of siting options
- Key considerations include
  - Depth - impact on backgrounds, particularly for DBD
  - Ability of host site and country to provide suitably outfitted space compatible with project timeline and separate from project cost
  - Accessibility & transport large sub-assemblies, vessels
  - Underground fabrication and staging where required
- Key contenders - shortlist
  - Boulby - proposed in 1100/1300 m deep configurations
  - LNGS - middle of Hall C
  - SNOLAB CryoPit/CubeHall - under evaluation
  - SURF - "Module of Opportunity" cavern or new excavation

Boulby





LNGS



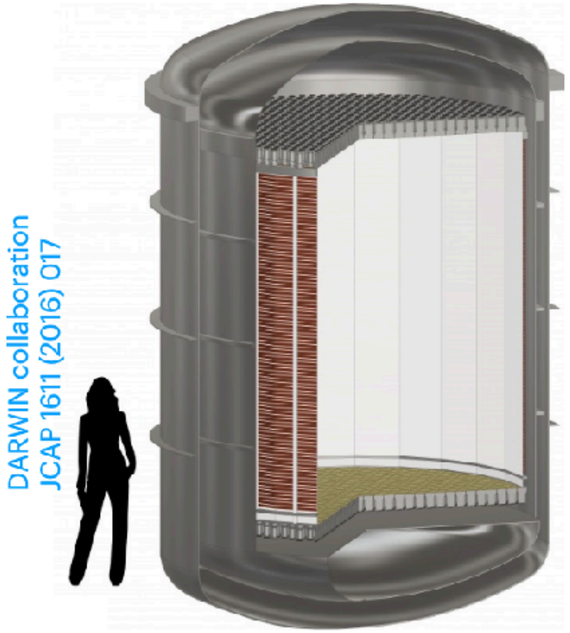
M. Kapust, SDSTA

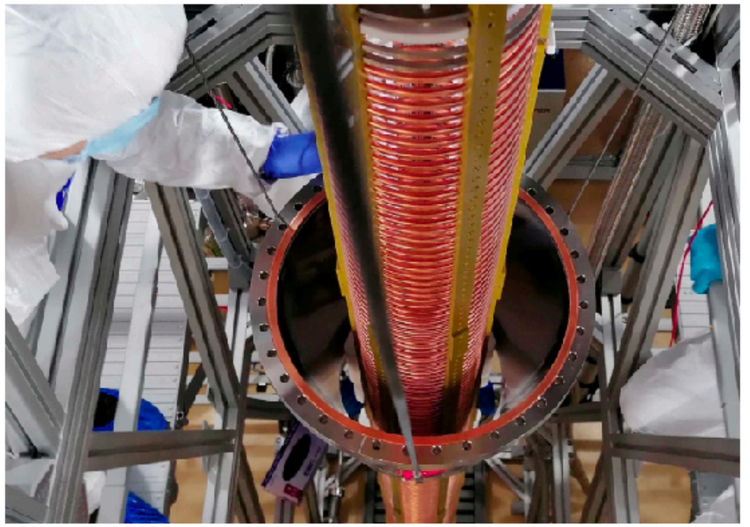
Major site considerations

- How do we build this detector underground?
  - 4+ meter diameter cryostats
  - 3+ meter diameter TPC components
    - Fabricated in clean, low radon environment
  - Xenon handling
    - Online krypton/radon distillation columns (significant scale up from XnT)
    - Neutron shielding for xenon that leaves water tank (mitigate activation)
  - Xenon recovery (capacity for 100t of xenon)
  - Liquid scintillator plant for outer detector
  - XLZD Site Review Process ongoing now
    - Establish technical feasibility of all sites under consideration

DARWIN R&D

- R&D for next-generation liquid xenon detector
- Several large-scale demonstrators in operation (3 ERCs)
- Photosensors, TPC design, large-scale purification, Rn removal, Gd-loaded water, etc.





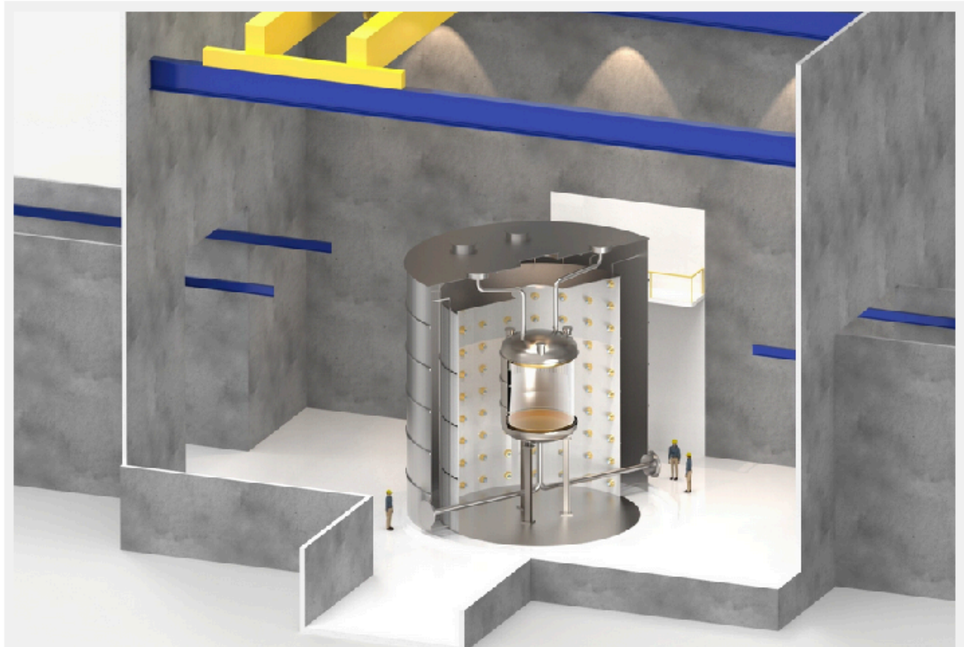
Xenoscope at UZH
L. Baudis et al., JINST 16, 2021, EPJ-C 83, 2023

Pancake in Freiburg
A. Brown at al., JINST 19, 2024

Supporting XLZD project to host world-leading dark matter experiment

The Technology Department will provide vital engineering expertise to the XLZD project to demonstrate that STFC can host the world's most advanced dark matter detector at Boulby Underground Laboratory.

The XLZD Consortium combines three world-leading collaborations, Xenon, Lux-Zeplin and Darwin, to design and build a single dark matter experiment.



Several locations internationally are being considered to host this experiment, with the UK developing plans to potentially house the detector at STFC's Boulby Underground Laboratory.

The UK consortium, led by Imperial College

Related Sections

▶ Projects and Mechanical Engineering (RAL)

Related Content

▶ HP Highlights

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,

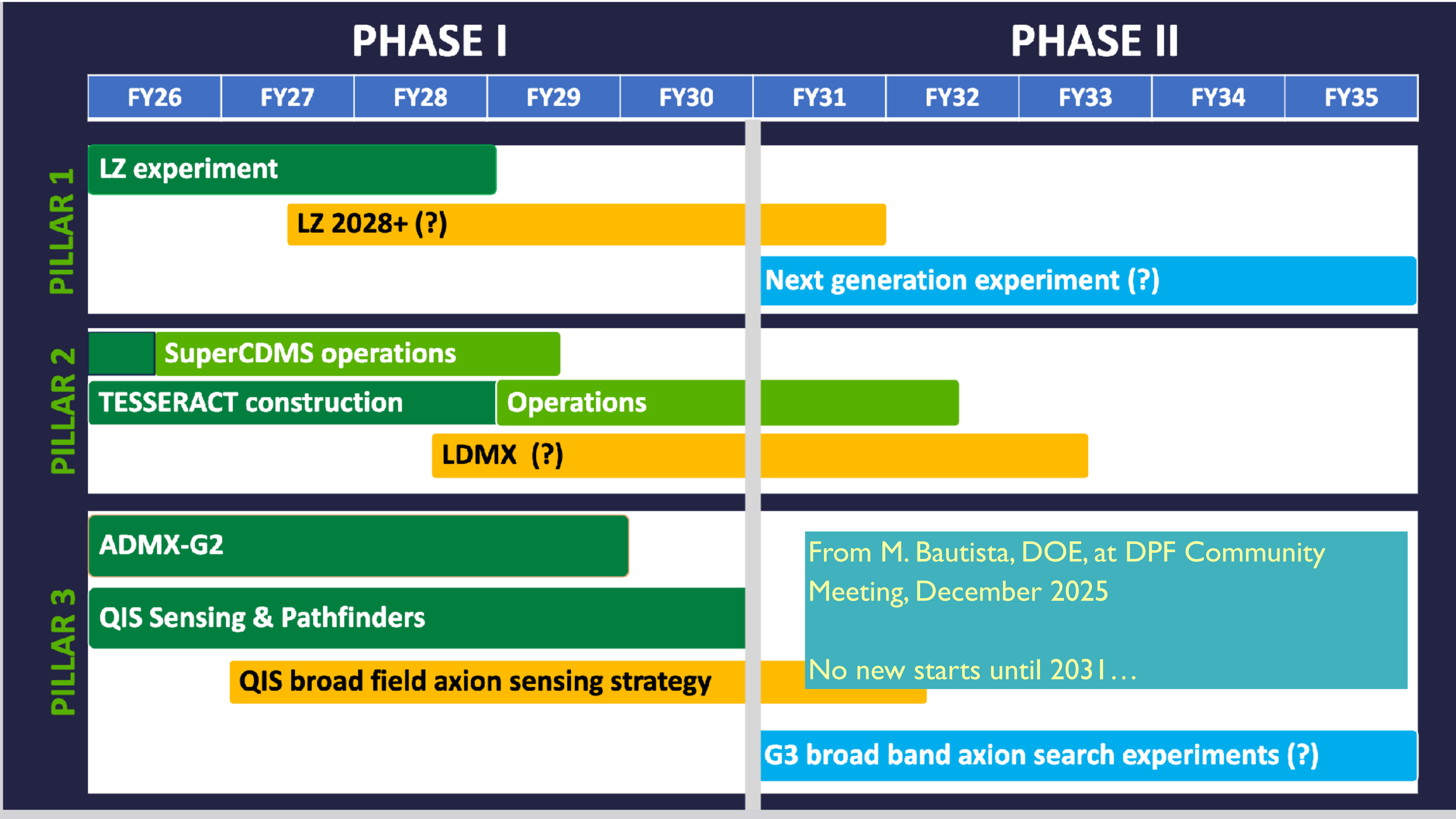
d. **Ultimate Generation 3 (G3) dark matter direct detection experiment** reaching the neutrino fog,

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)

"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."

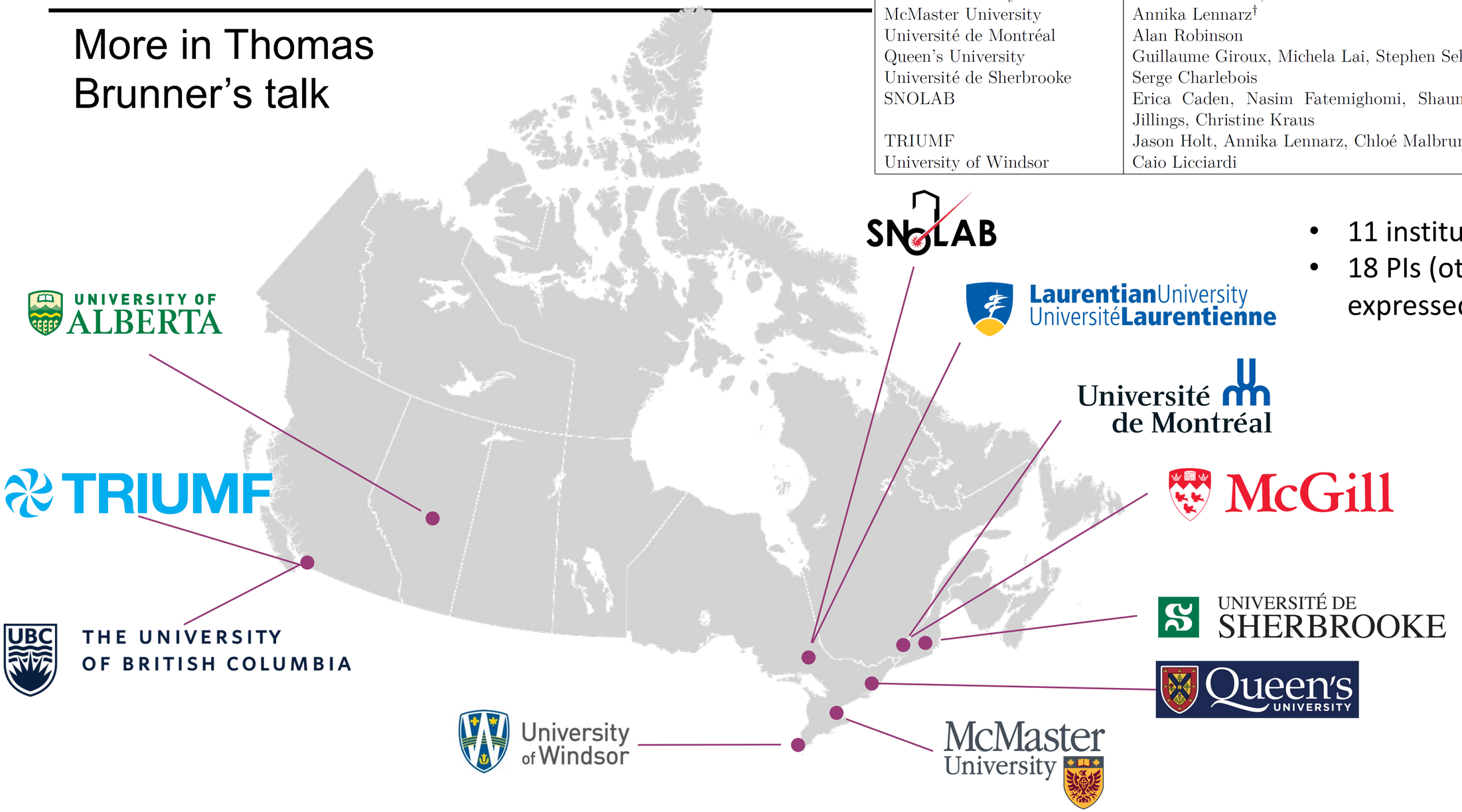

PHASE I
PHASE II
FY26
FY27
FY28
FY29
FY30
FY31
FY32
FY33
FY34
FY35
PILLAR 1
LZ experiment
LZ 2028+ (?)
Next generation experiment (?)
PILLAR 2
SuperCDMS operations
TESSERACT construction
Operations
LDMX (?)
PILLAR 3
ADMX-G2
QIS Sensing & Pathfinders
QIS broad field axion sensing strategy
From M. Bautista, DOE, at DPF Community Meeting, December 2025
No new starts until 2031…
G3 broad band axion search experiments (?)

Canadian Team

New Members!

More in Thomas Brunner's talk

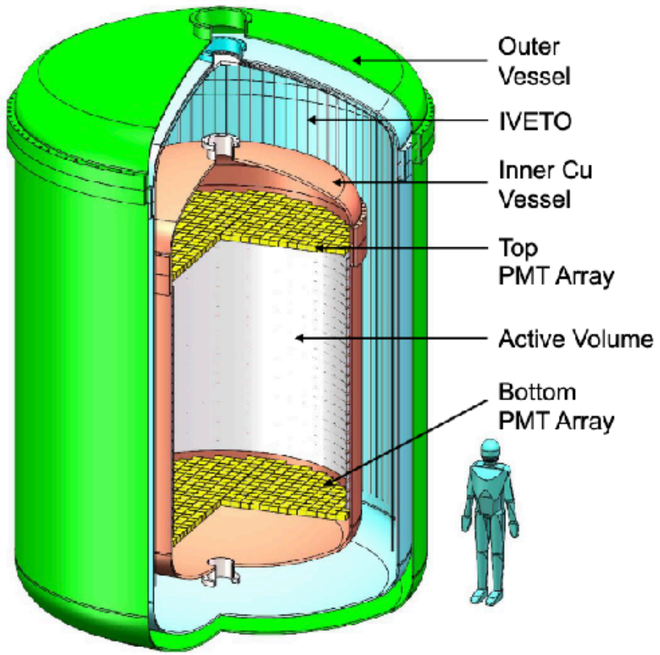
Institution	PIs
University of Alberta	Carsten Krauss
University of British Columbia	Chloé Malbrunot†
Laurentian University	Christopher Jillings◇
McGill University	Thomas Brunner, Katelin Schutz
McMaster University	Annika Lennarz†
Université de Montréal	Alan Robinson
Queen's University	Guillaume Giroux, Michela Lai, Stephen Sekula
Université de Sherbrooke	Serge Charlebois
SNOLAB	Erica Caden, Nasim Fatemighomi, Shaun Hall, Christopher Jillings, Christine Kraus
TRIUMF	Jason Holt, Annika Lennarz, Chloé Malbrunot, Fabrice Retière
University of Windsor	Caio Licciardi

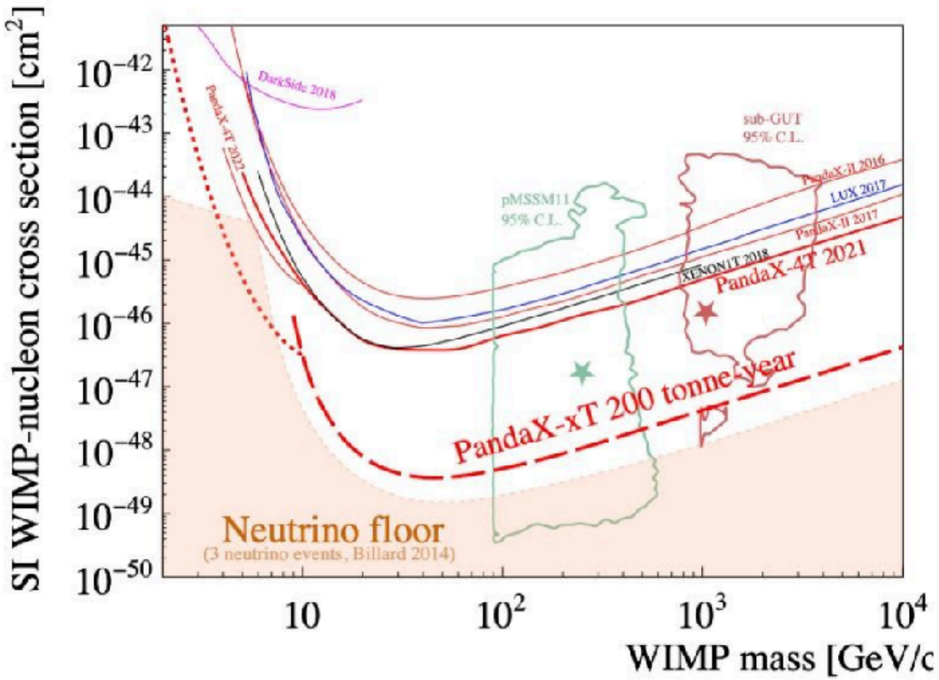


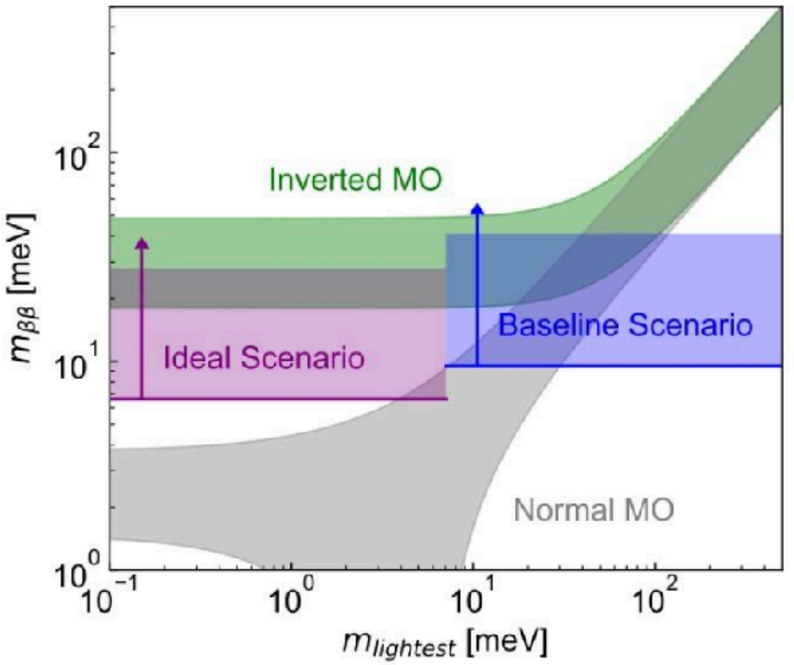
- 11 institutions
- 18 PIs (others expressed interest)

PandaX - the competition

- Planned 40t LXe detector - similar science goals as XLZD
- 20 tonne intermediate scale
  - Infrastructure planned to complete in second half of 2026
  - Commissioning in 2027
  - First physics data starting in 2028!

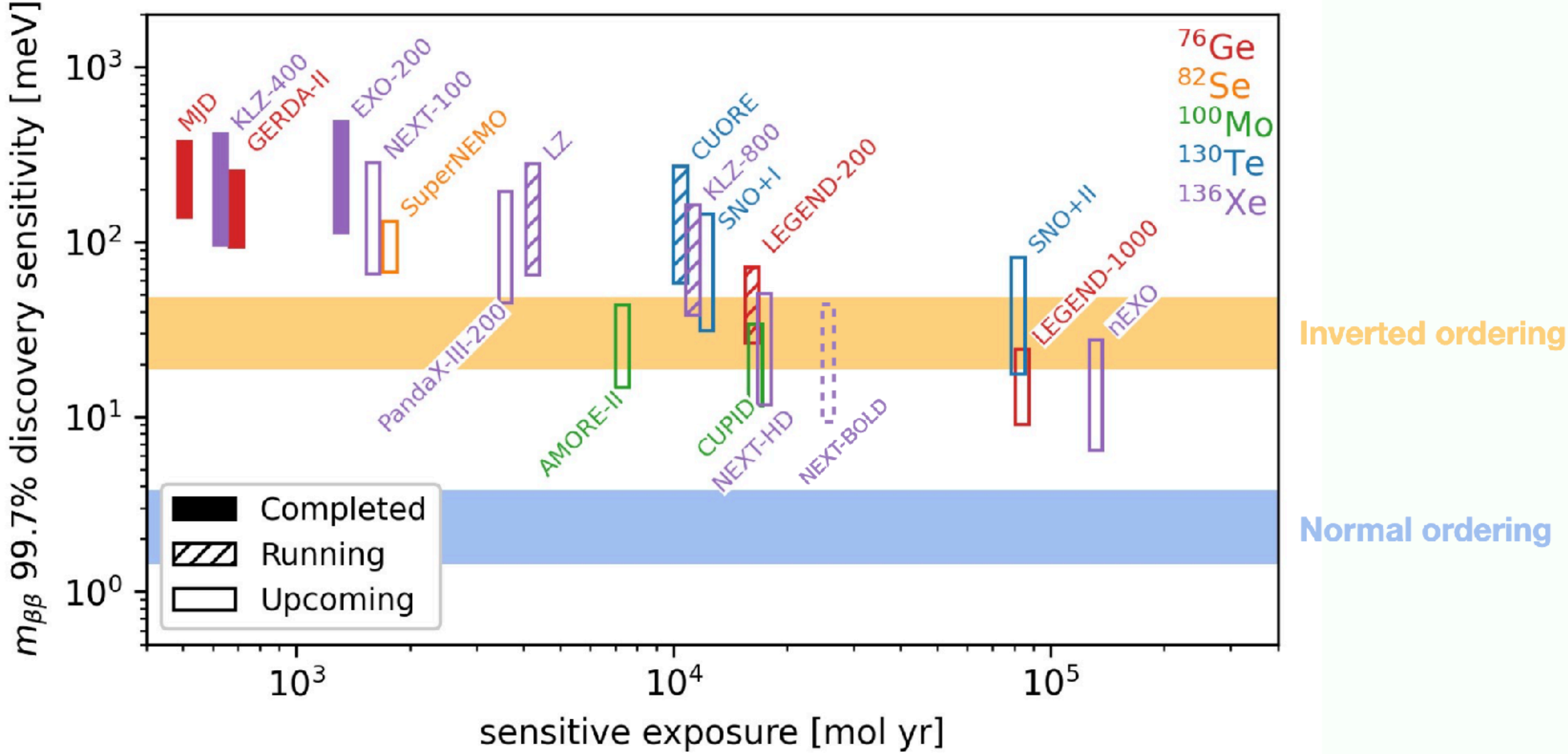






arXiv:2402.03596, **SCPMA** 68, 221011 (2025)

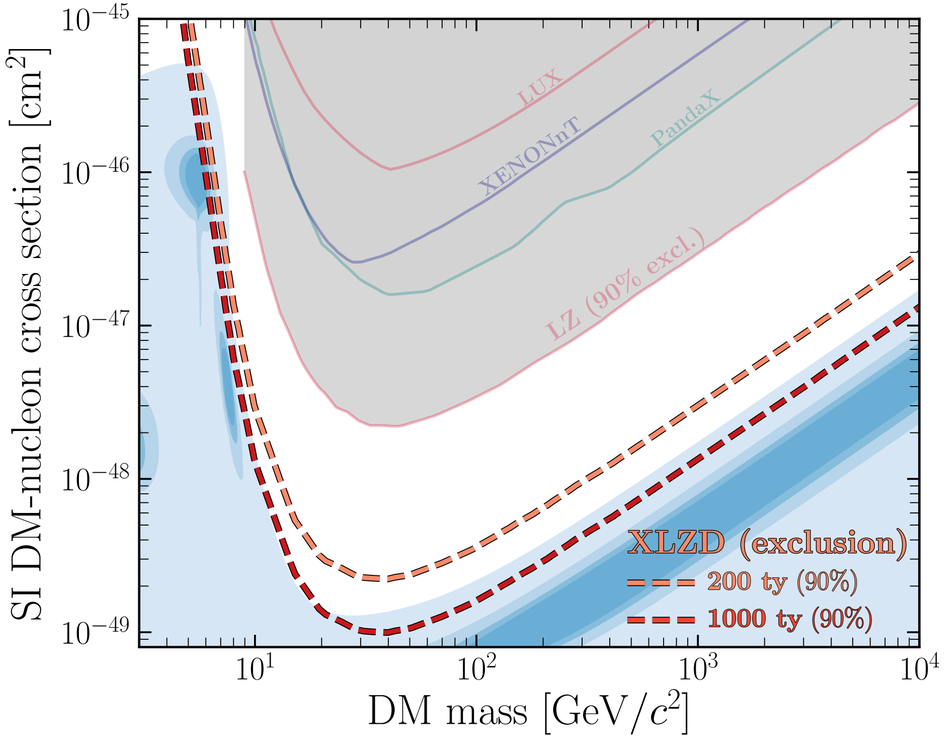
0vbb - the competition

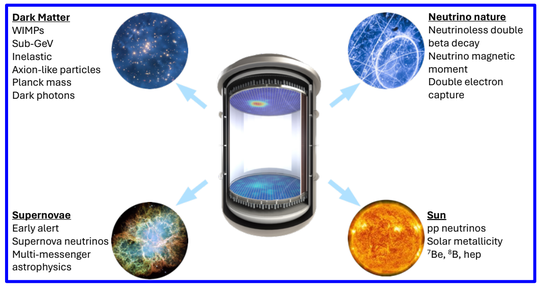


Adapted from arxiv:2304.03451 (Whitepaper for the 2023 NSAC Long Range Plan)

Definitive WIMP search is attainable, timely and competitive

- WIMP science - potential for major discovery





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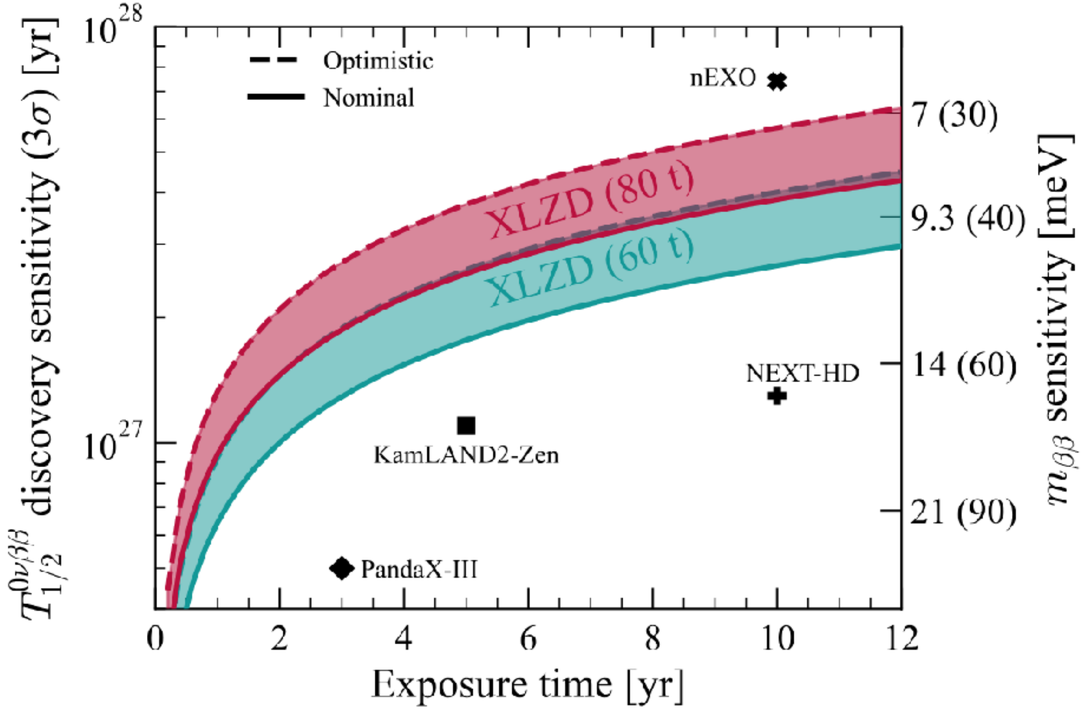
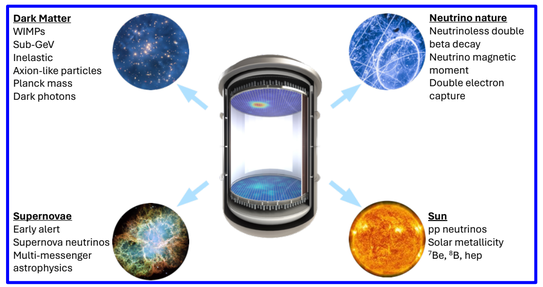
- WIMP science - potential for major discovery
- 0vBB is equally important goal, see 2410.19016
  - Many other exciting science channels





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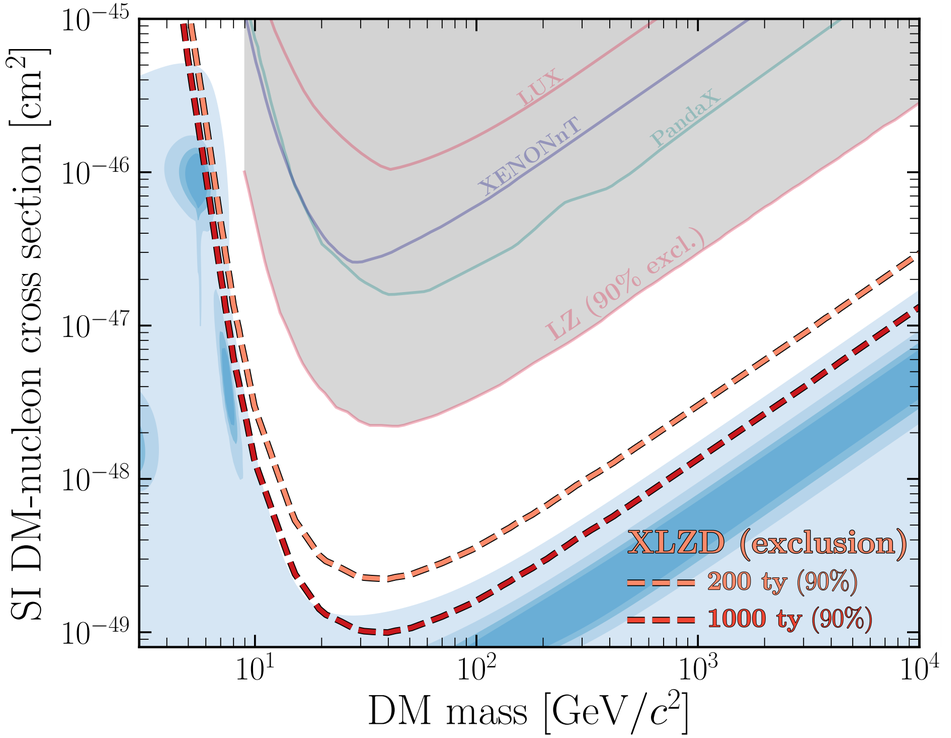

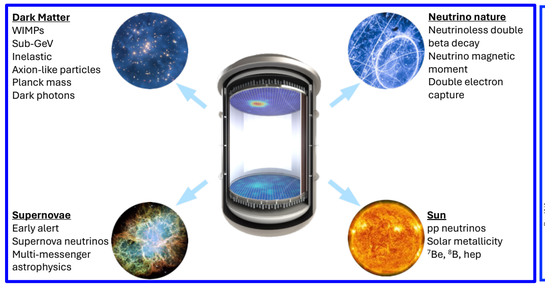

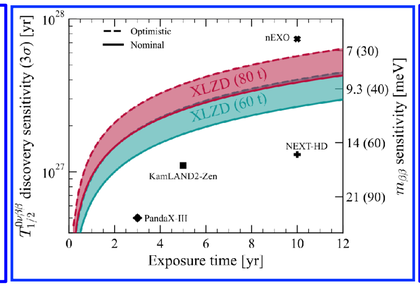

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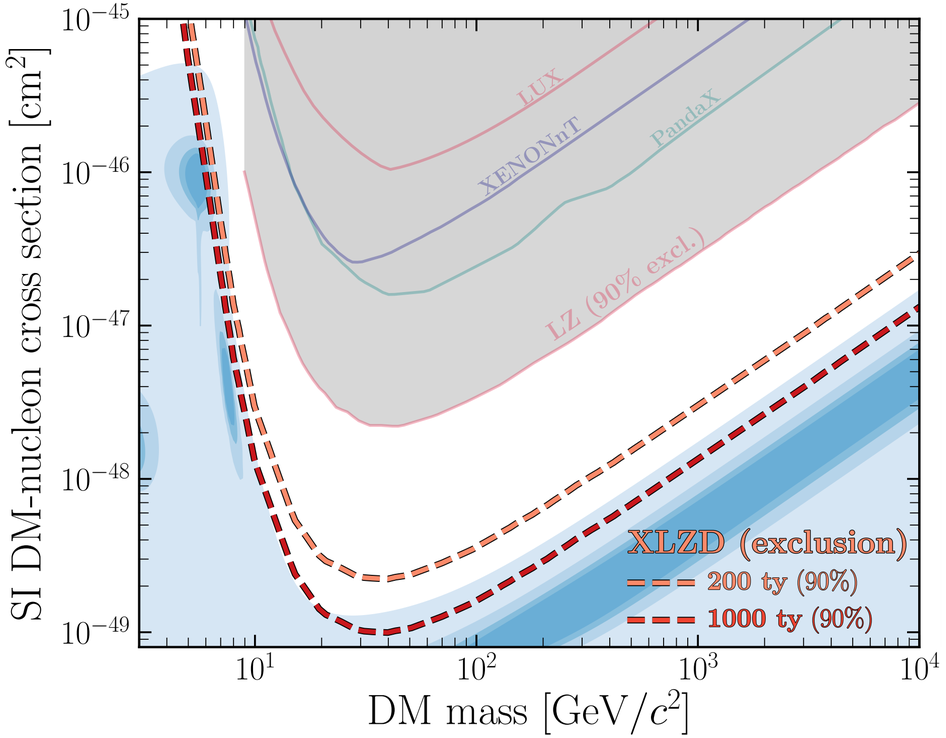

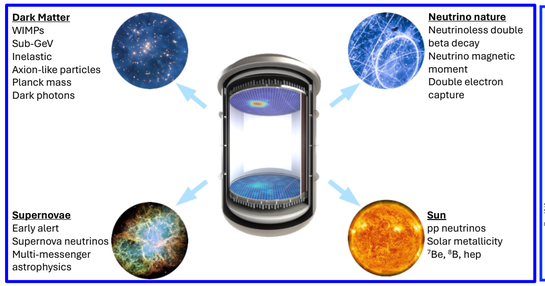

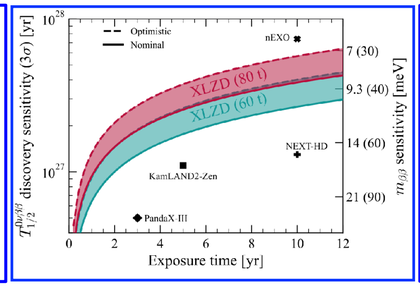

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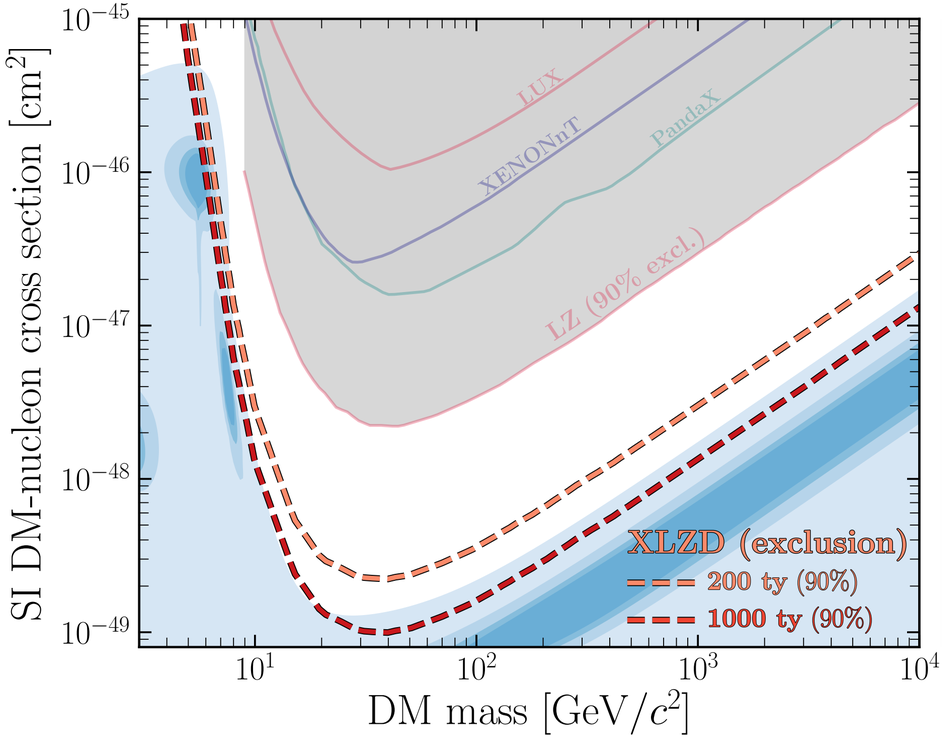

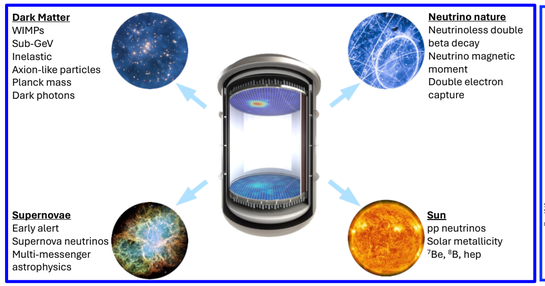

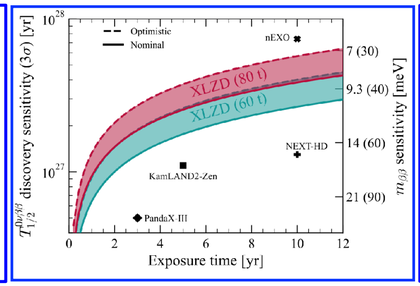

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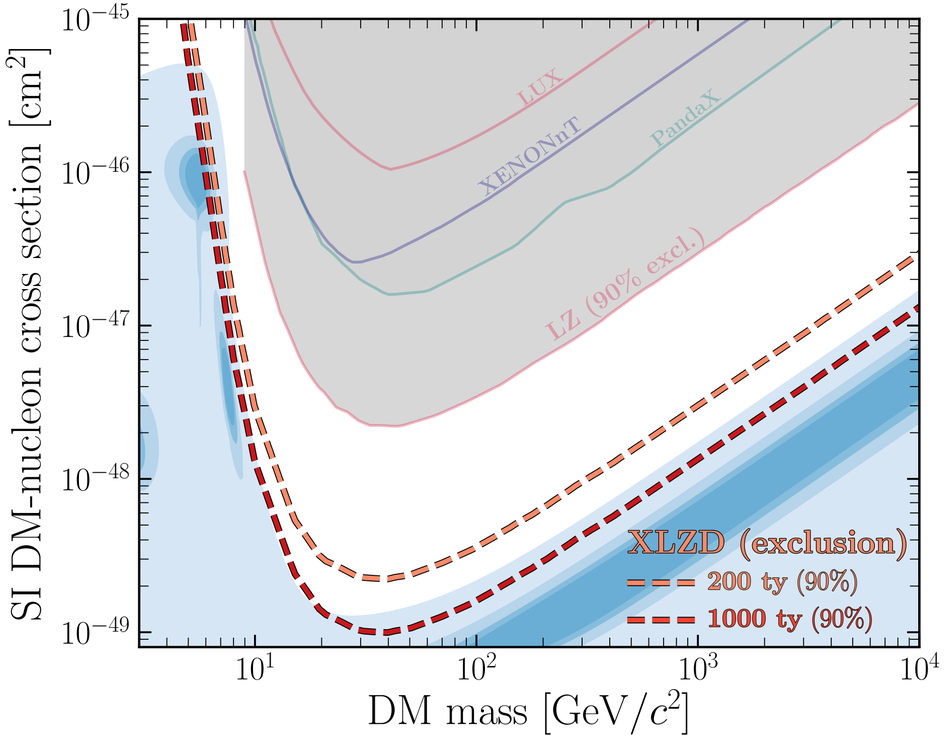
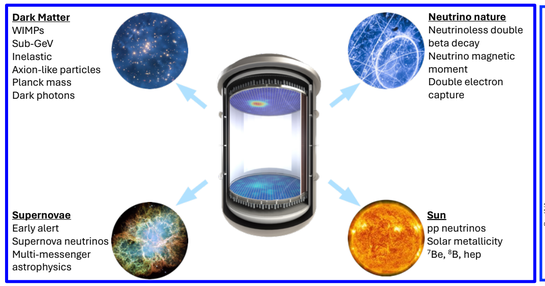
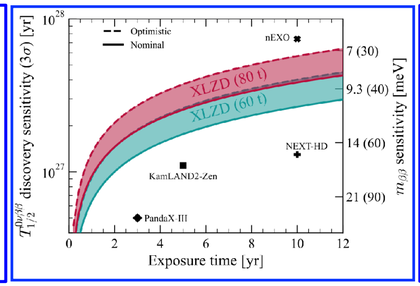
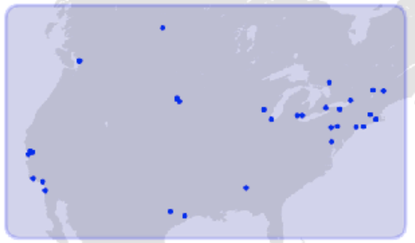






If WIMPs exist above the systematic limit of astrophysical neutrinos, XLZD will observe them.



Black Hills State University
Brookhaven National Laboratory
Brown University
Bucknell University
Columbia University
Laurentian University
Lawrence Berkeley National Laboratory
Lawrence Livermore National Laboratory
McGill University
McMaster University
Pennsylvania State University
Queen's University
Rice University
SLAC National Accelerator Laboratory
SNOLAB
Sanford Underground Research Facility
South Dakota School of Mines
TRIUMF
The University of Chicago
University of Alabama
University of Alberta
University of British Columbia
University of California, Berkeley
University of California, Los Angeles
University of California, San Diego
University of California, Santa Barbara
University of Maryland
University of Massachusetts
University of Michigan
University of Rochester
University of Texas, Austin
University of Windsor
University of Wisconsin
Université de Montreal
Université de Sherbrooke

Heidelberg University
INAF Osservatorio Astrofisico Torino
INFN-LNGS
Imperial College London
Johannes Gutenberg University Mainz
Karlsruhe Institute of Technology
King's College London
LIP-Coimbra
LPNHE
Max-Planck-Institut für Kernphysik
Nikhef & the University of Amsterdam
Nikhef & the University of Groningen
Queen Mary University of London
Royal Holloway, University of London
SISSA
STFC Laboratories
SUBATECH
Stockholm University
TU Darmstadt
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University and INFN Bologna
University of Barcelona
University of Bern
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University of L'Aquila
University of Liverpool
University of Münster
University of Naples "Federico II"
University of Oxford
University of Sheffield
University of Sussex
University of Zurich
Vinca Institute of Nuclear Sciences
Weizmann Institute

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

The University of Melbourne
The University of Sydney