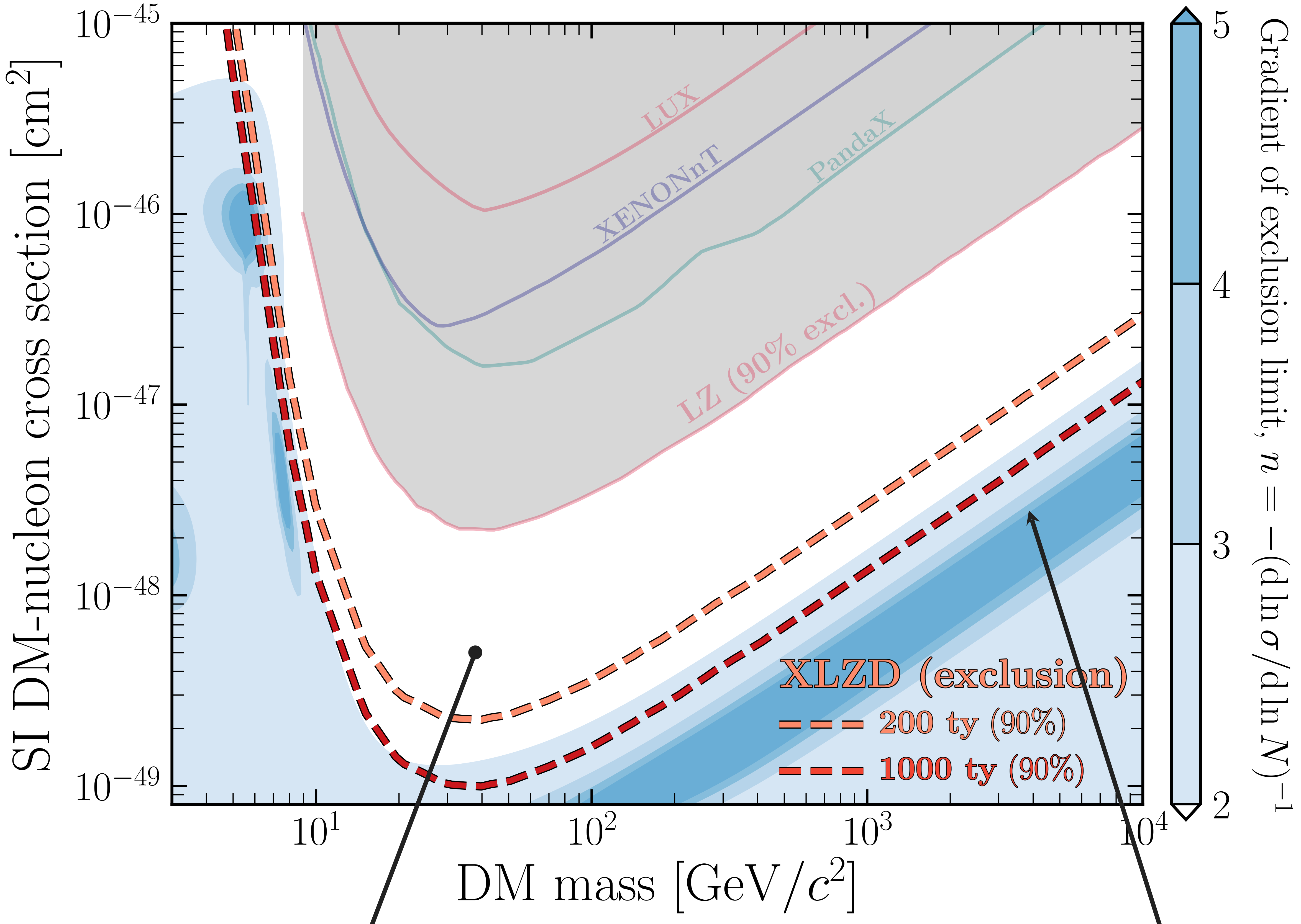
XLZD: A next generation observatory for Dark matter and rare events

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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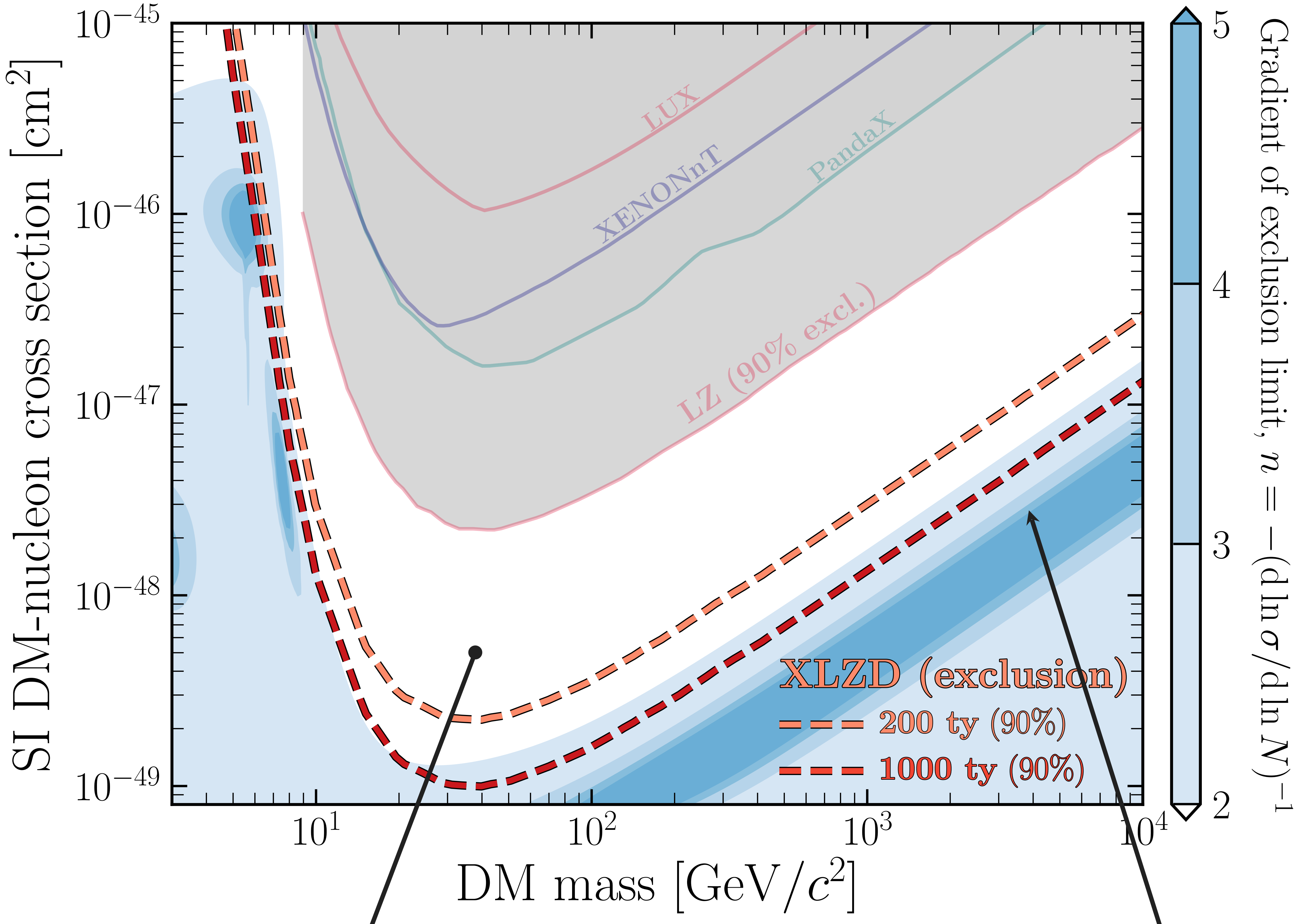

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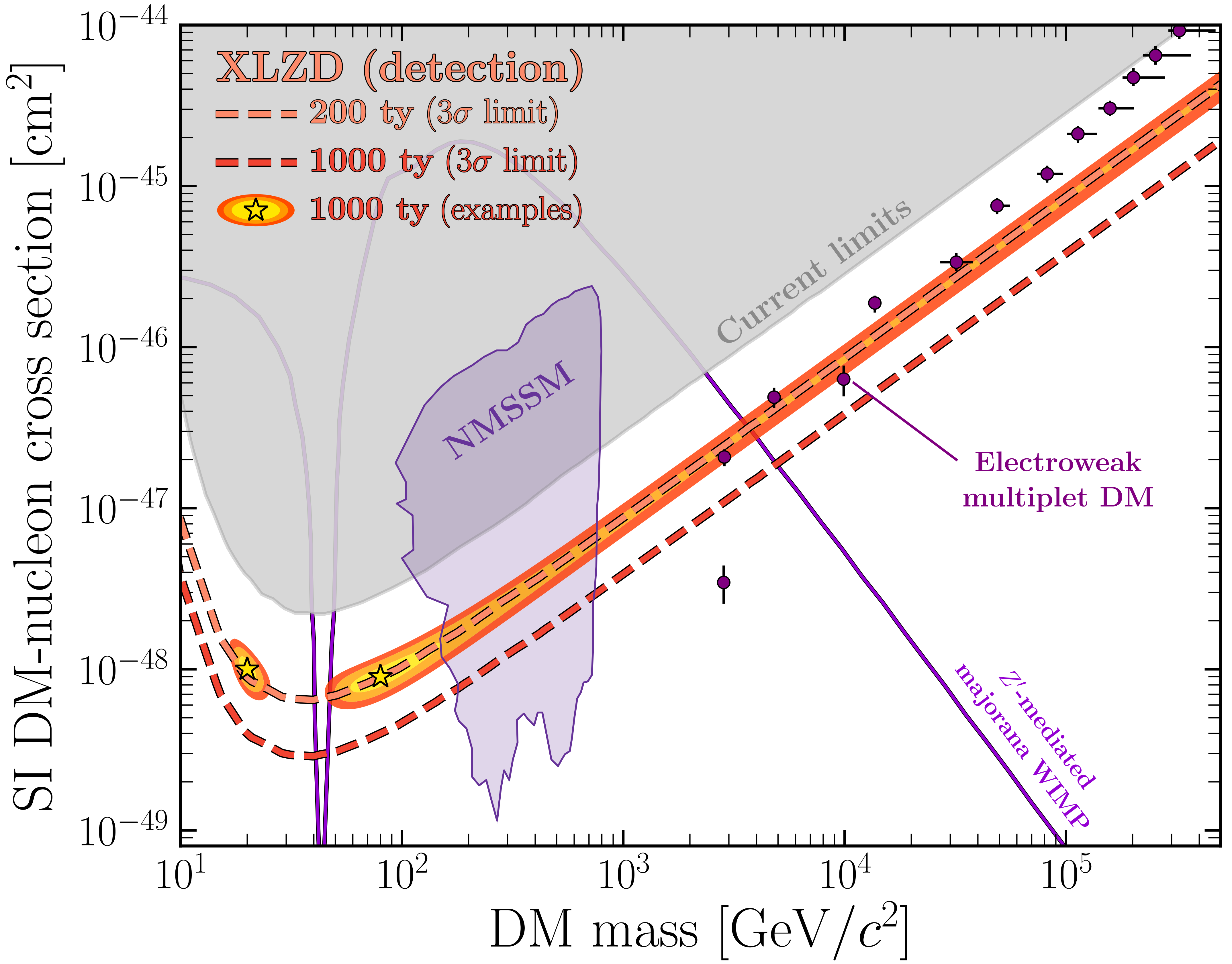

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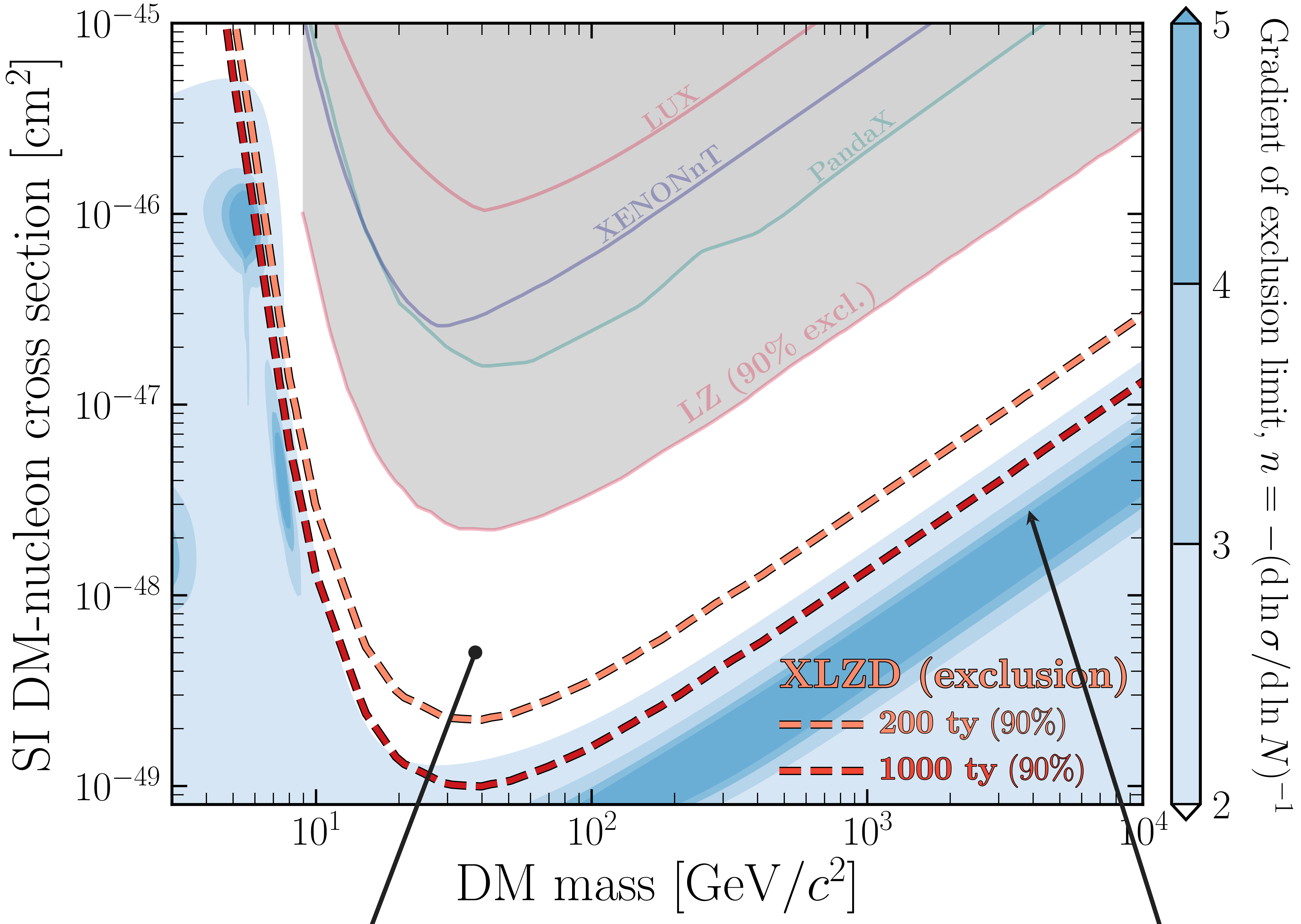

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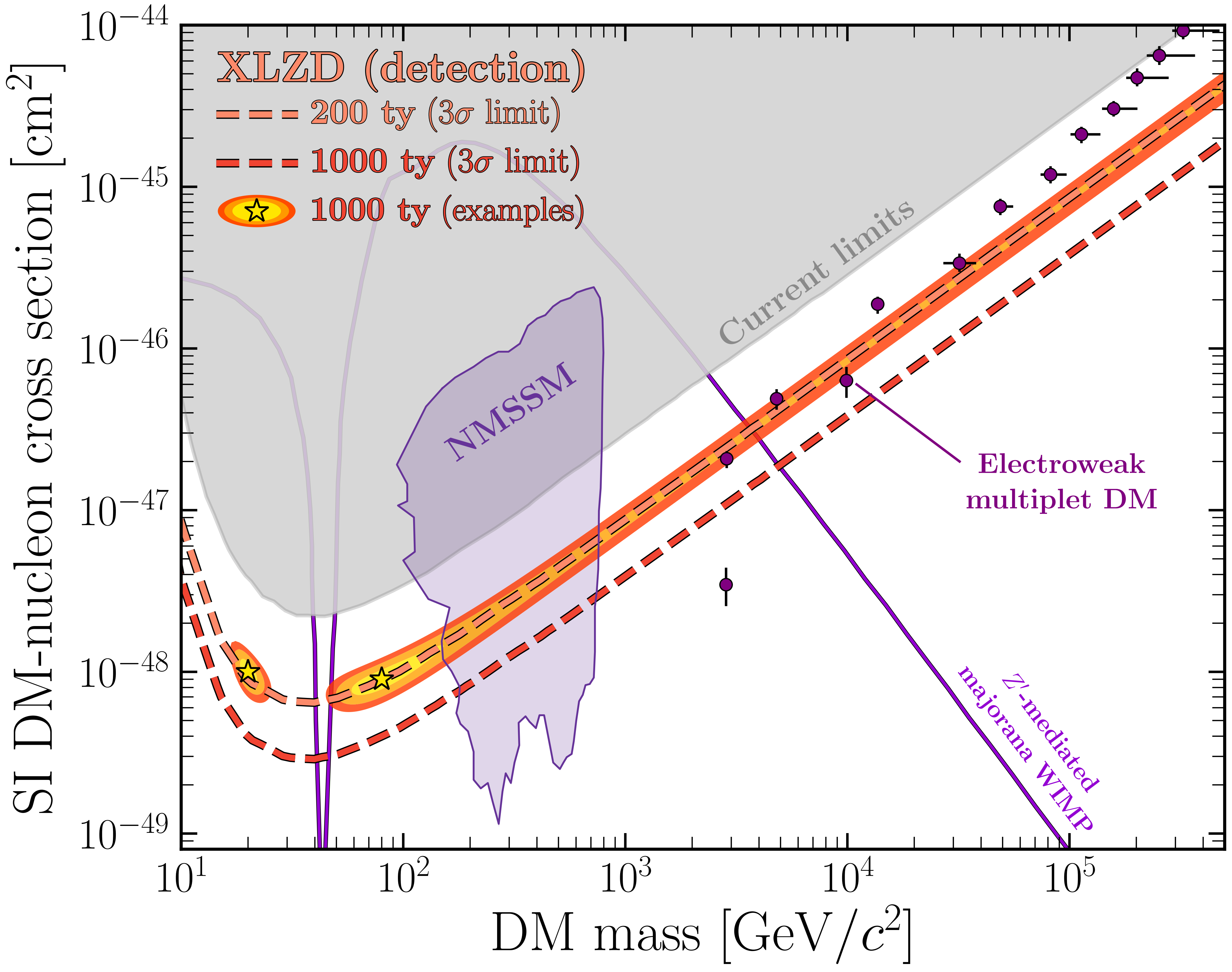
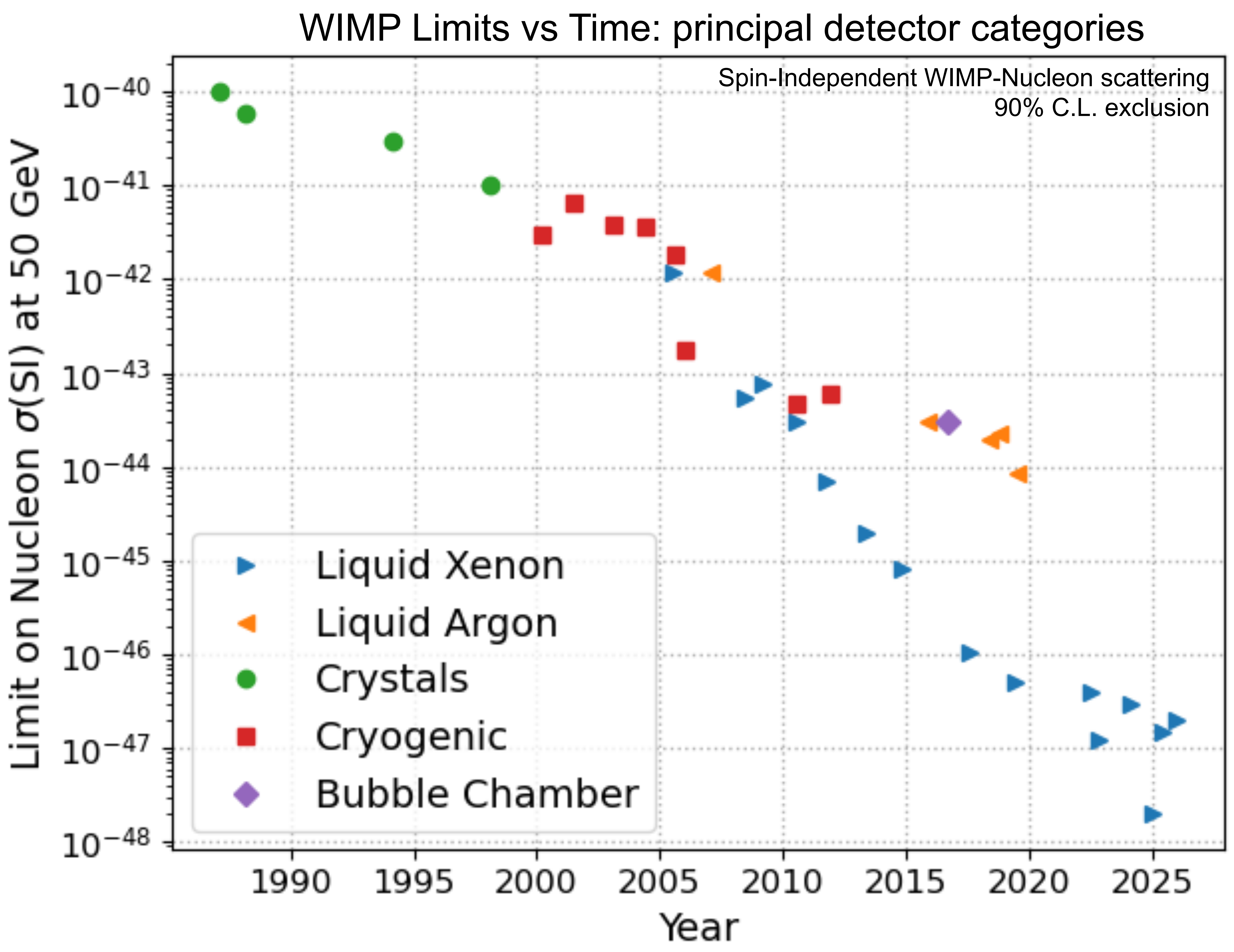


Potential for discovery and constraining DM properties

Liquid Xenon Detectors: World leading since 2007



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- Tool of choice for massive detectors
  - Liquid targets can scale "easily" (⬆ mass)
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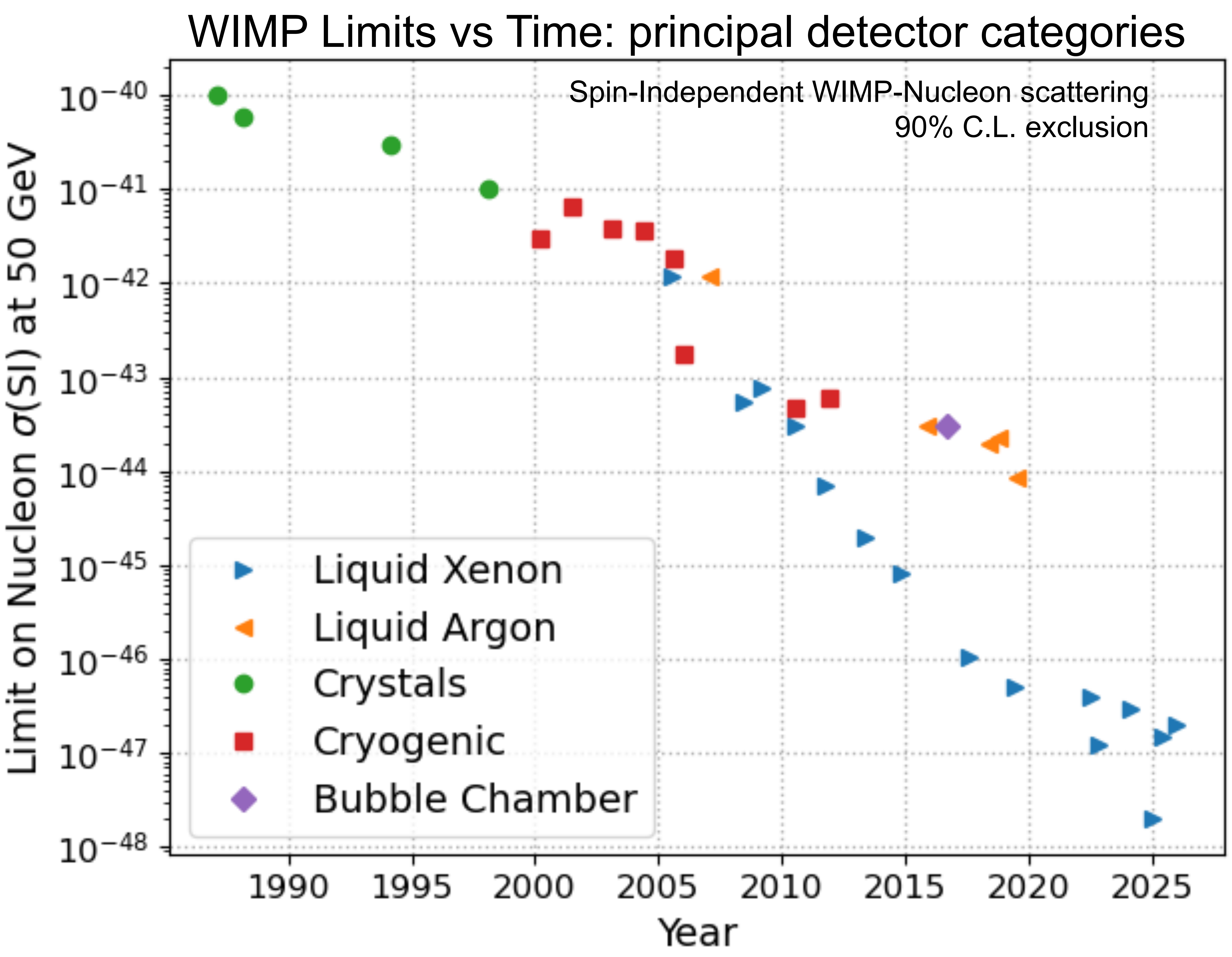

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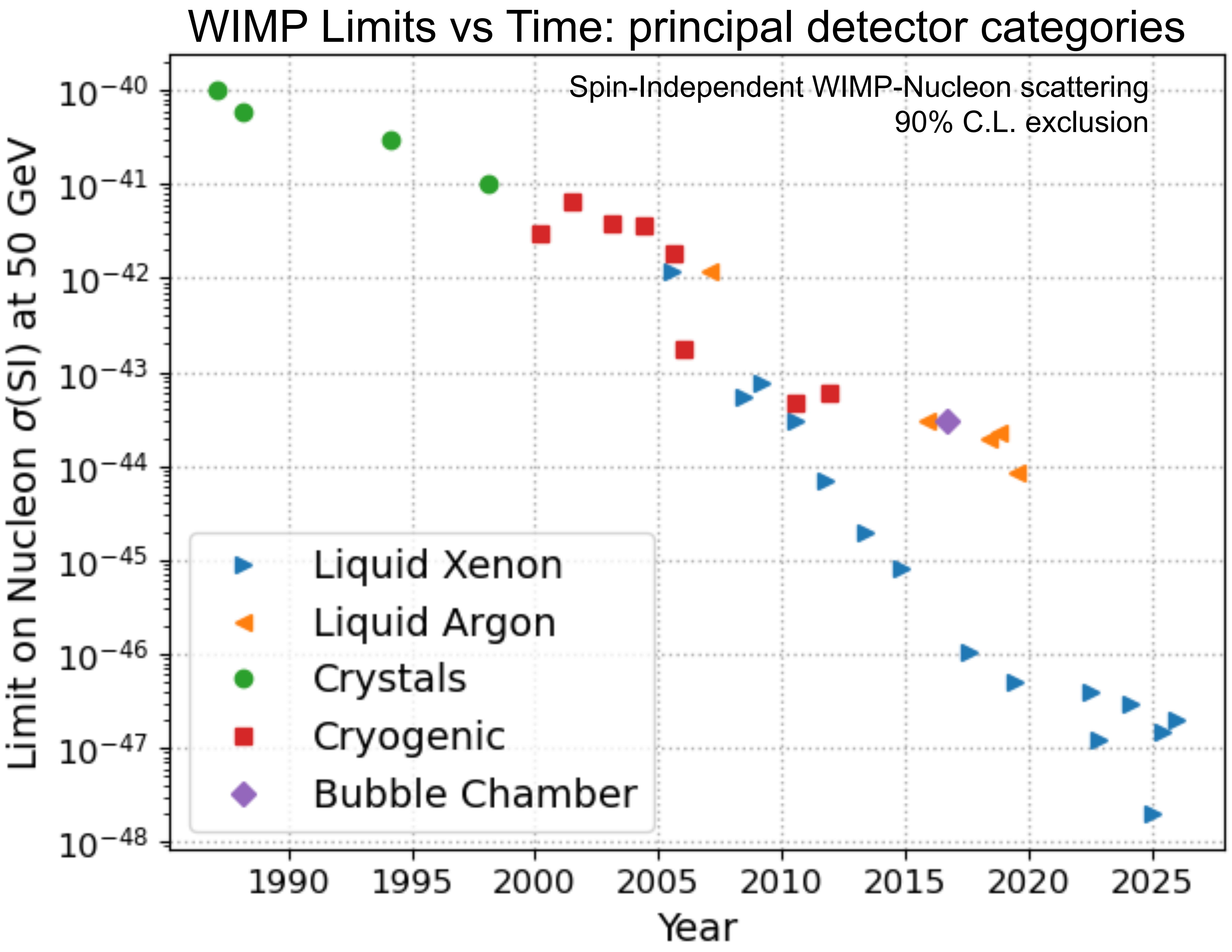
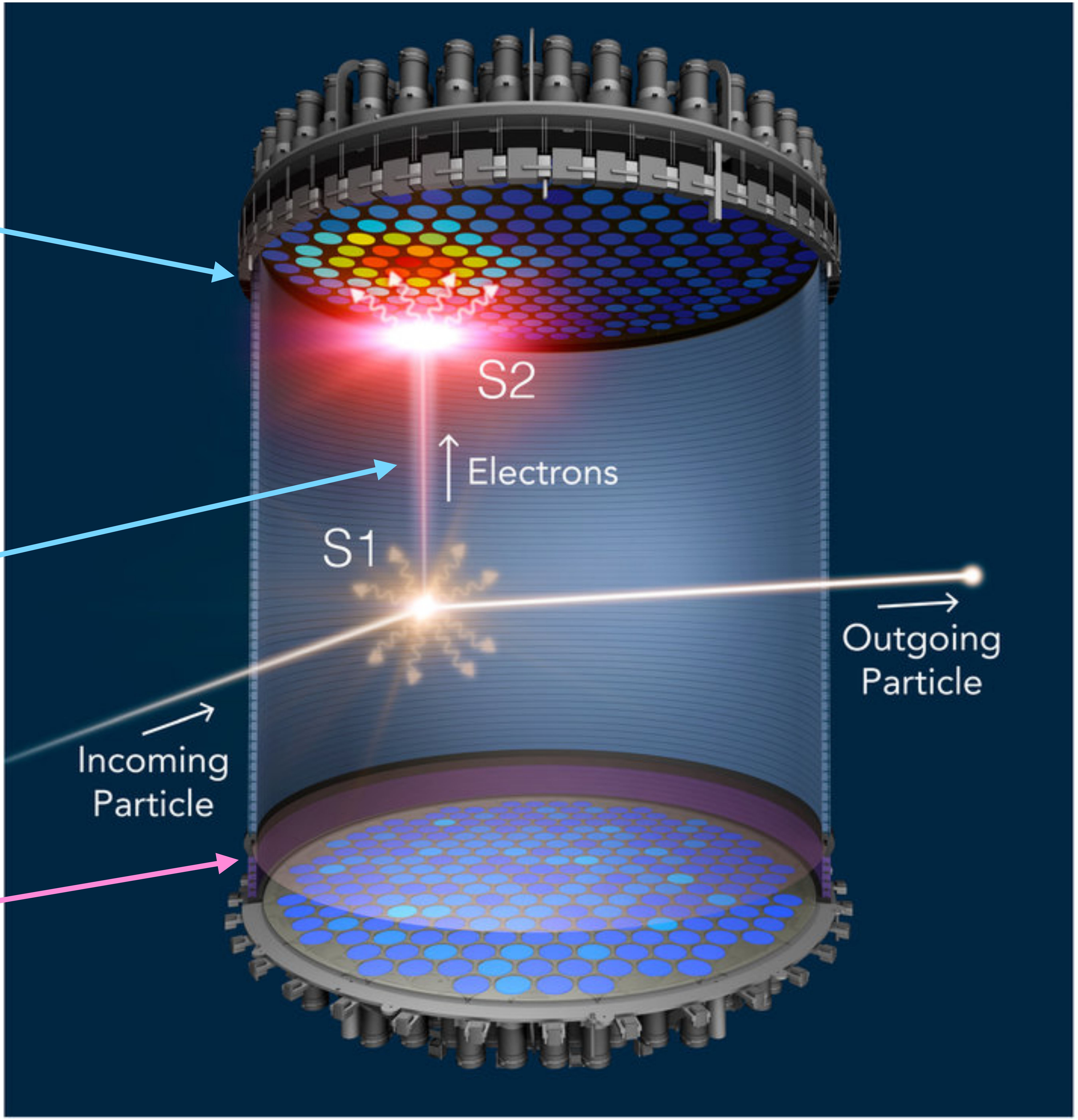
  - ER/NR discrimination
  - Low energy threshold
  - 3D position - self-shielding, singles/ multiples



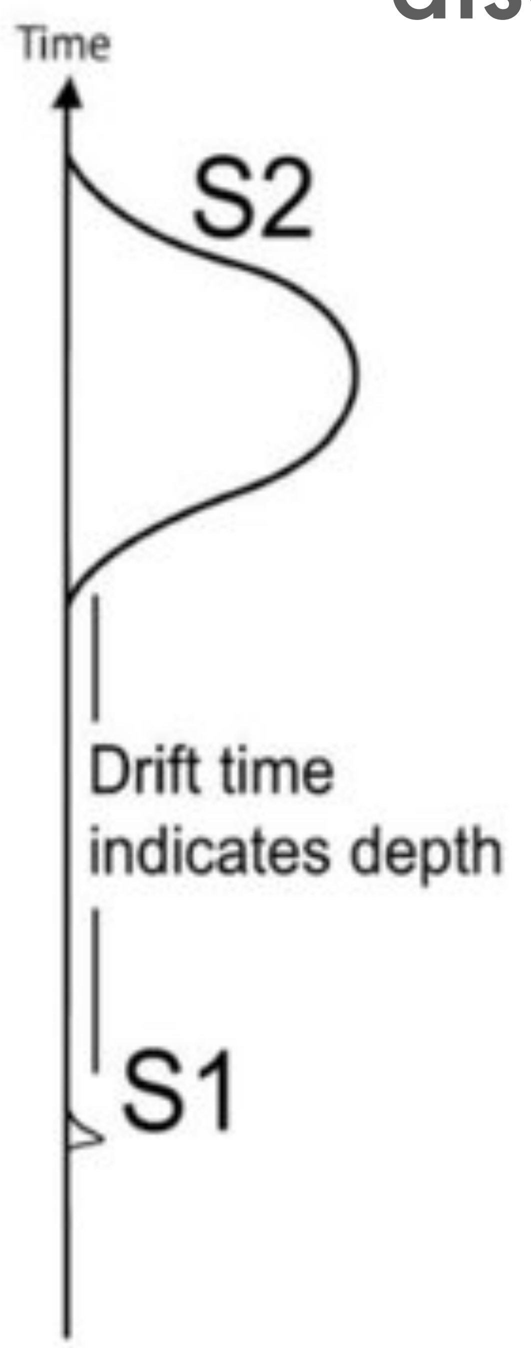
S2 light pattern gives x-y position (~few mm resolution)

Drift time gives z position (~0.5 mm resolution)

Cathode



S1-S2 relative size gives event-type discrimination



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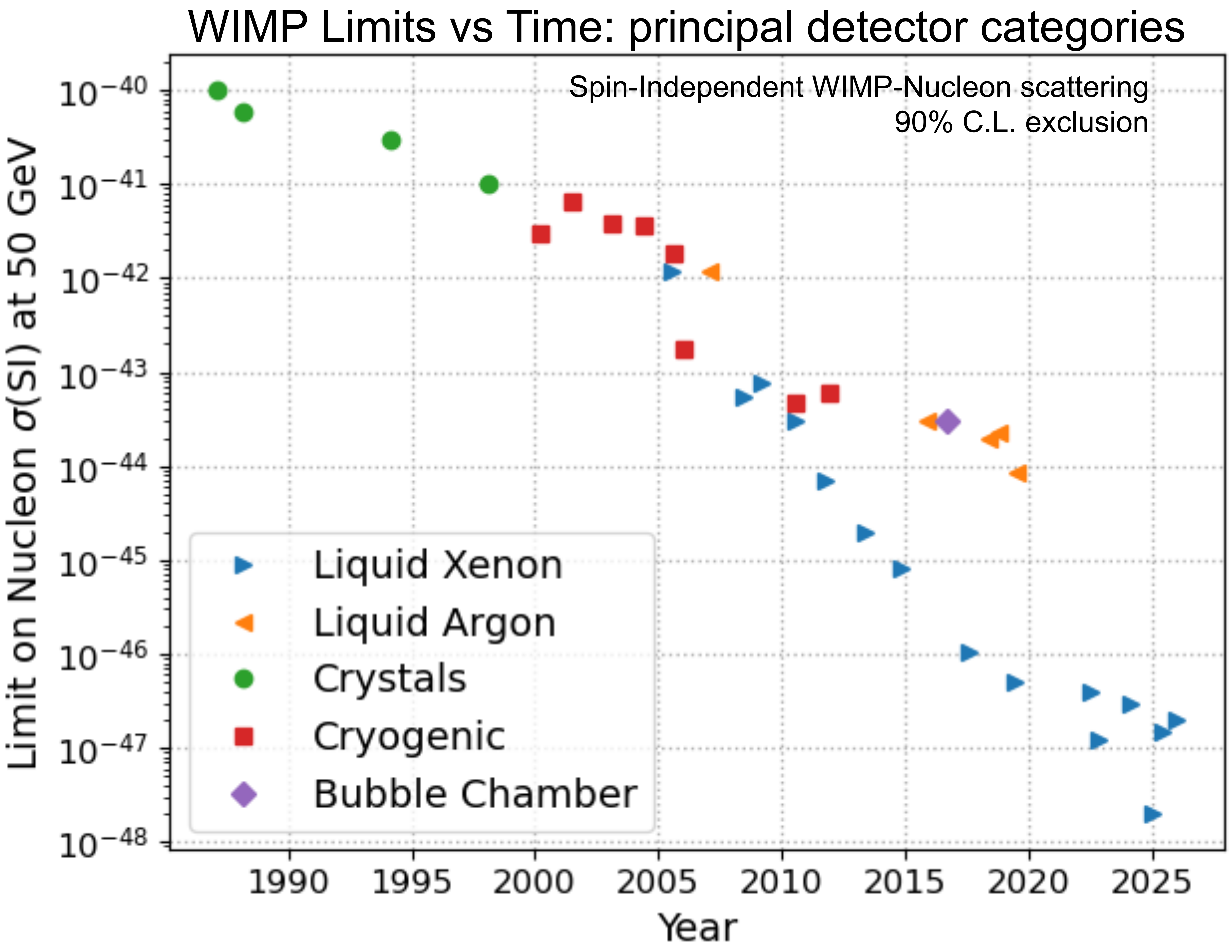
  - High density, large A^2, many isotopes (SI, SD, NR-ETF, inelastic)



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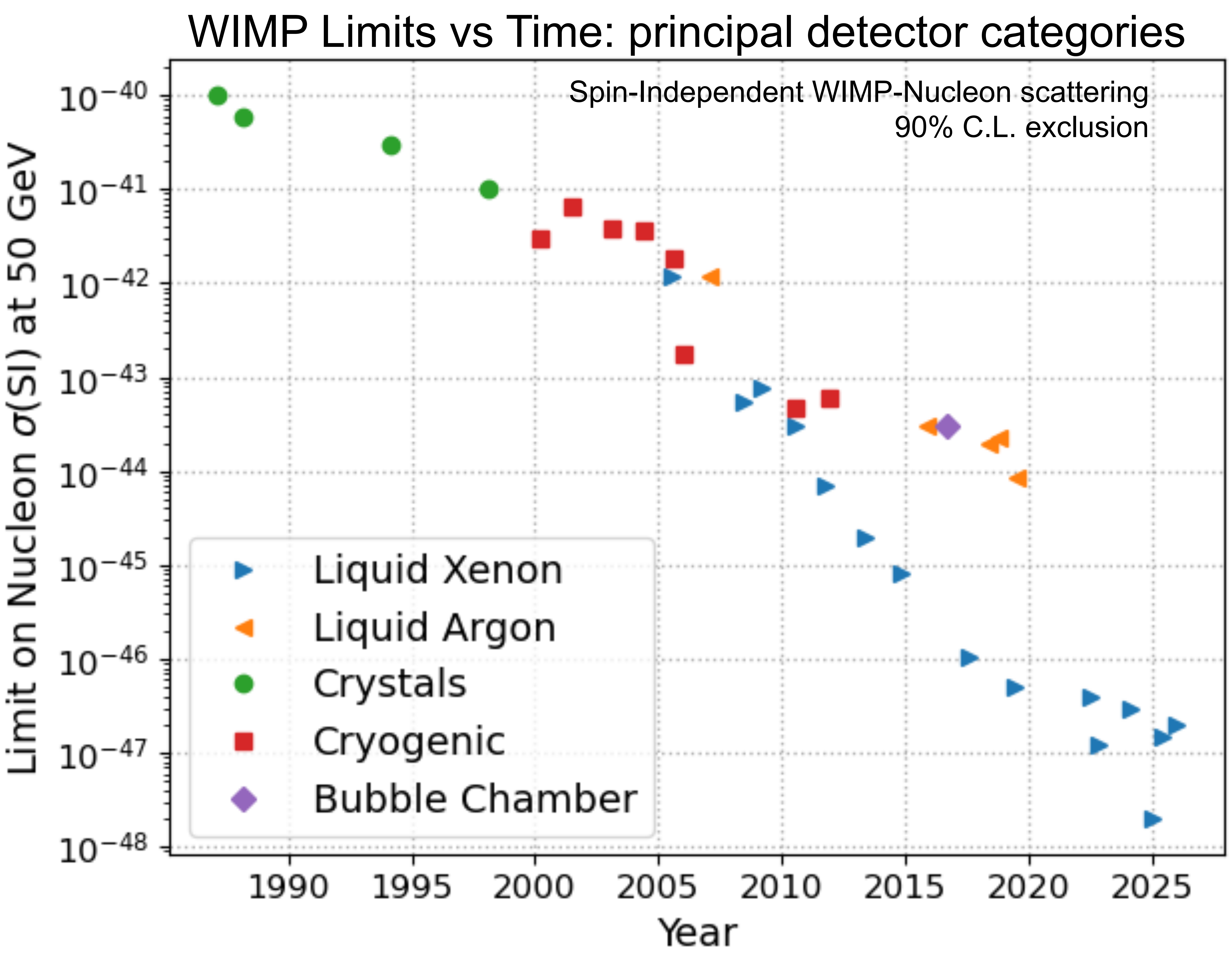
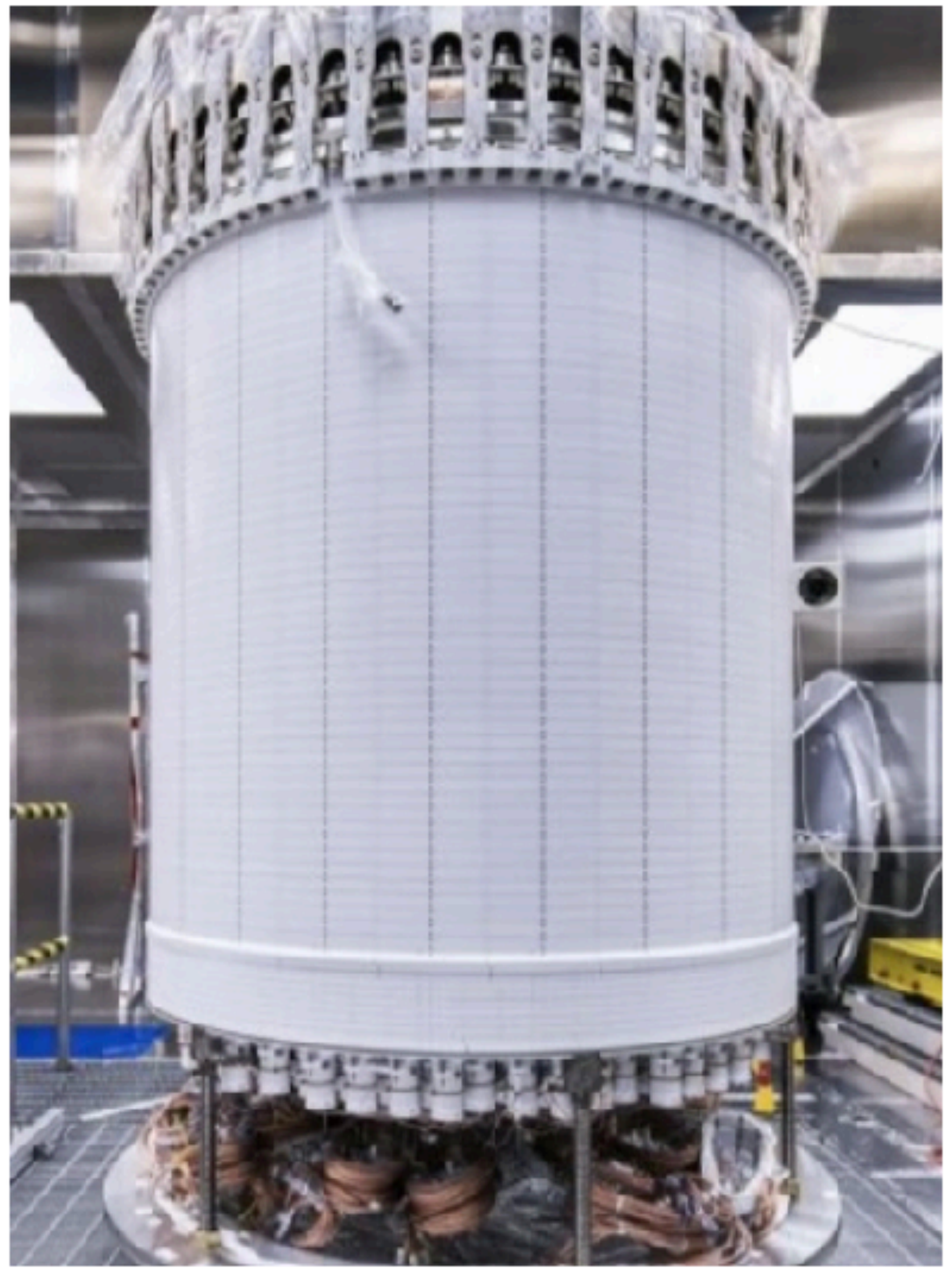


Liquid Xenon Detectors: World leading since 2007

LUX-ZEPLIN

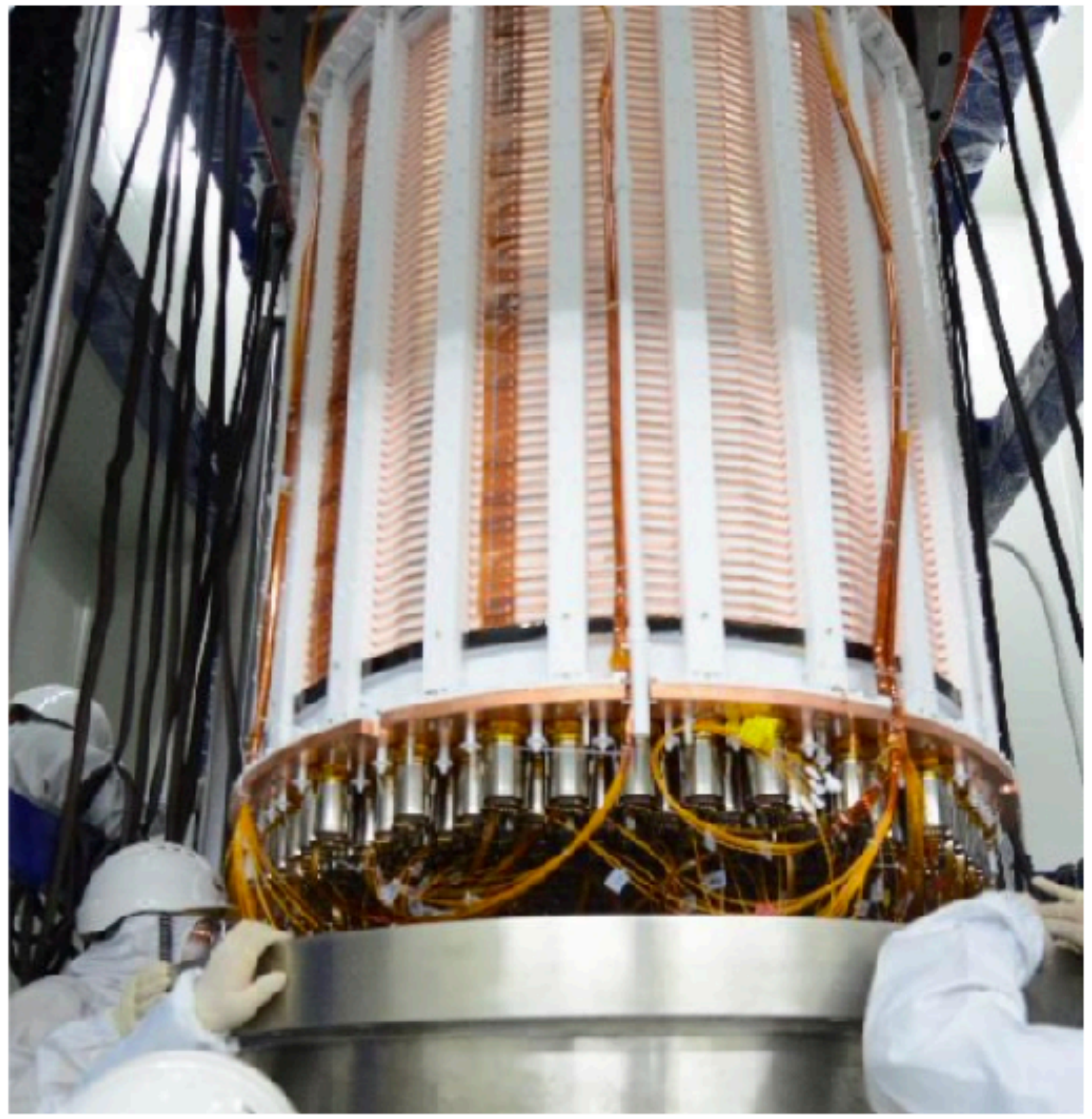


SURF, 7 t

XENONnT

LNGS, 5.9 t

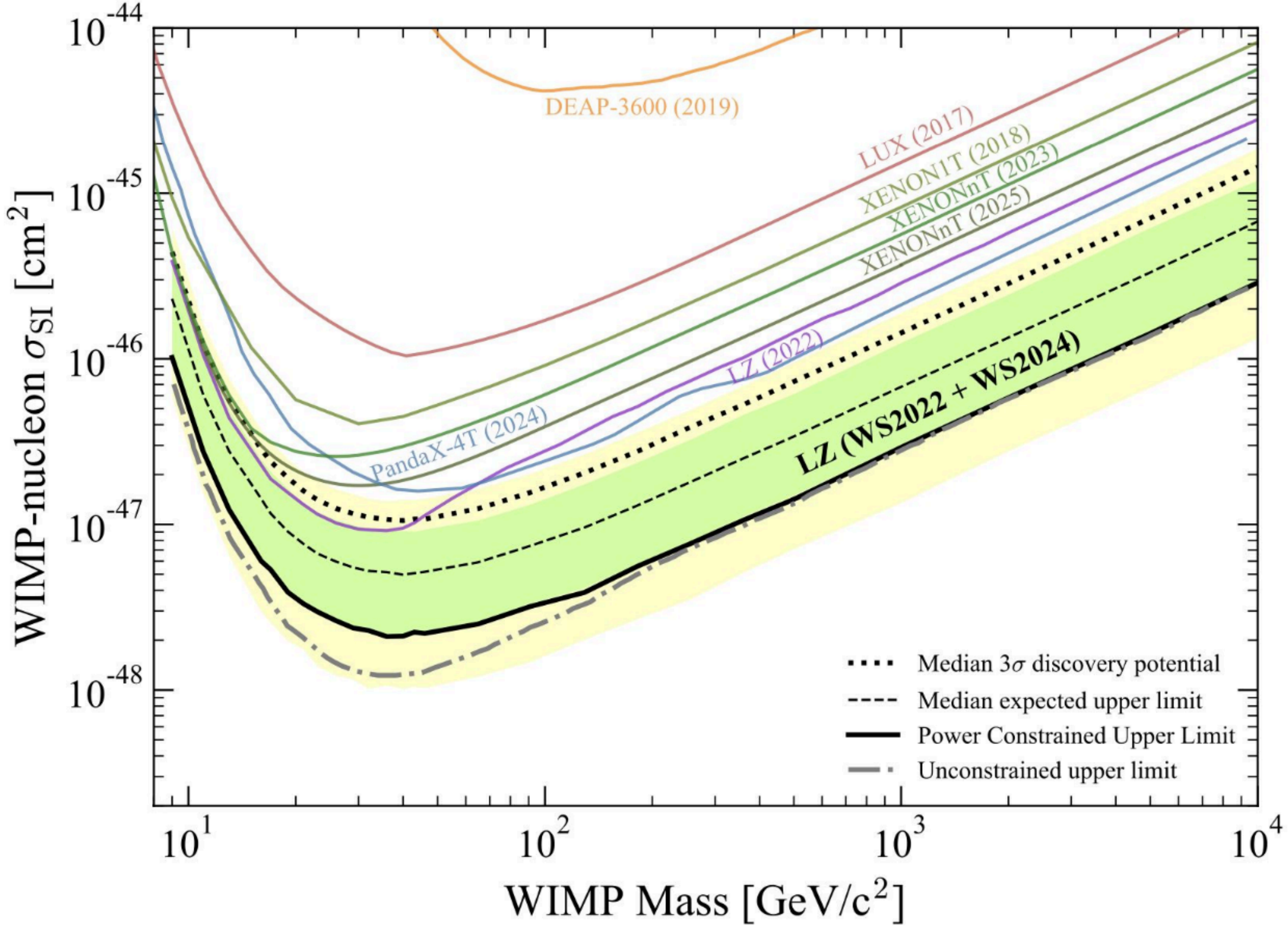
PandaX-4T



JinPing, 3.7 t

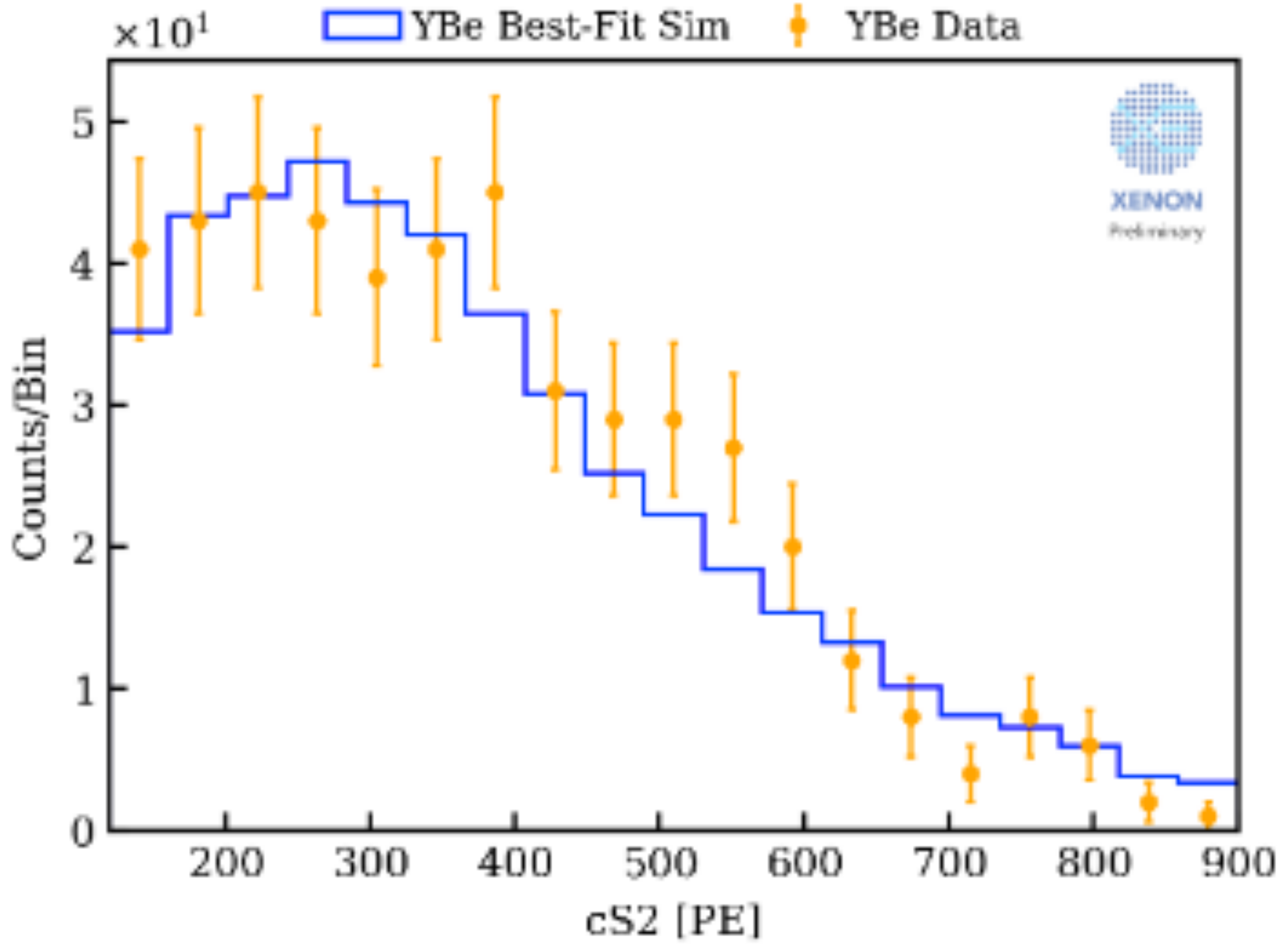
- TPCs with 2 arrays of 3-inch ø PMTs
- Kr & Rn removal techniques (to mitigate ^{85}Kr and ^{222}Rn backgrounds)
- Neutron & muon vetos, ultra-pure water shields, liquid scintillator

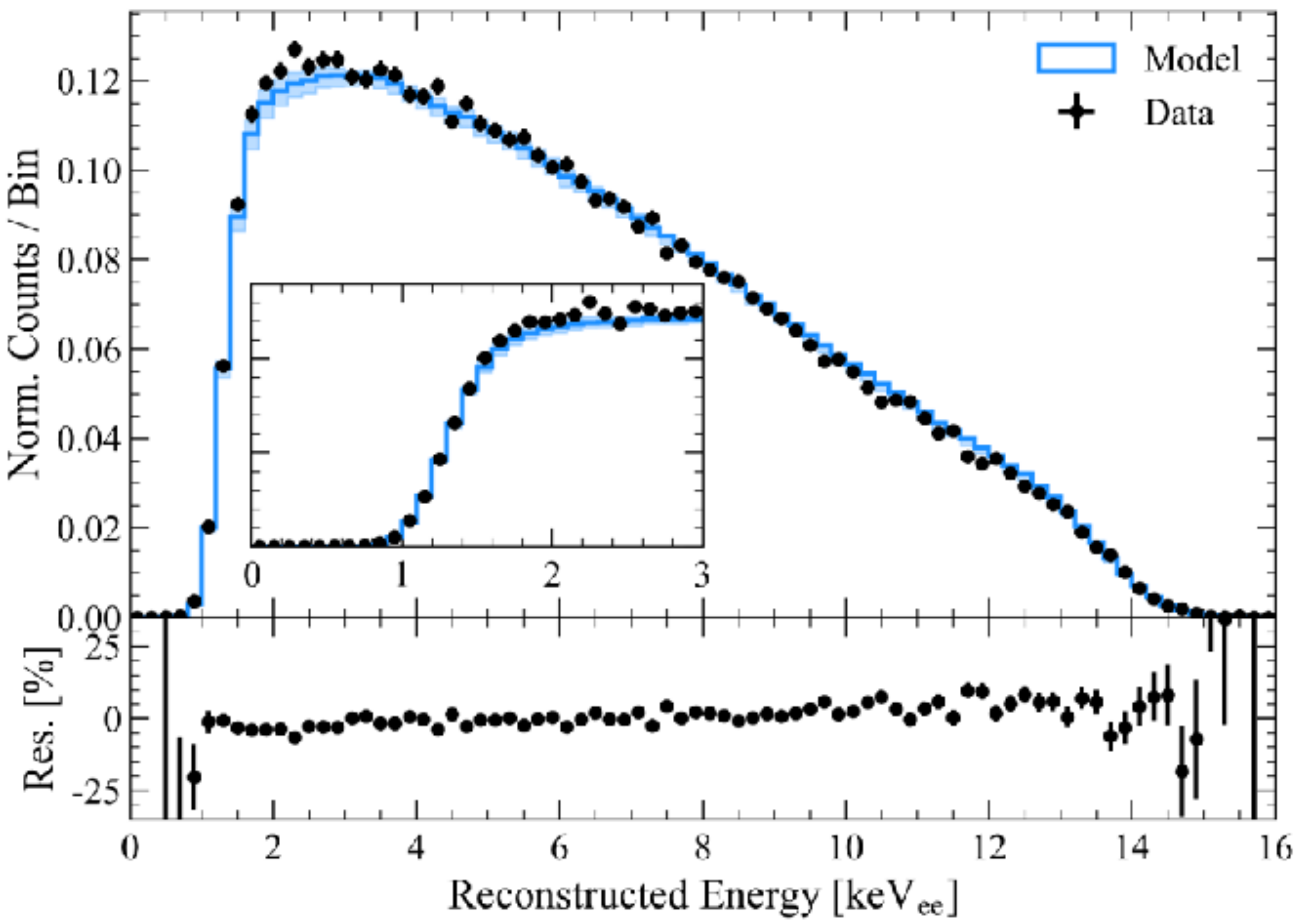
Liquid Xenon Detectors: World leading since 2007

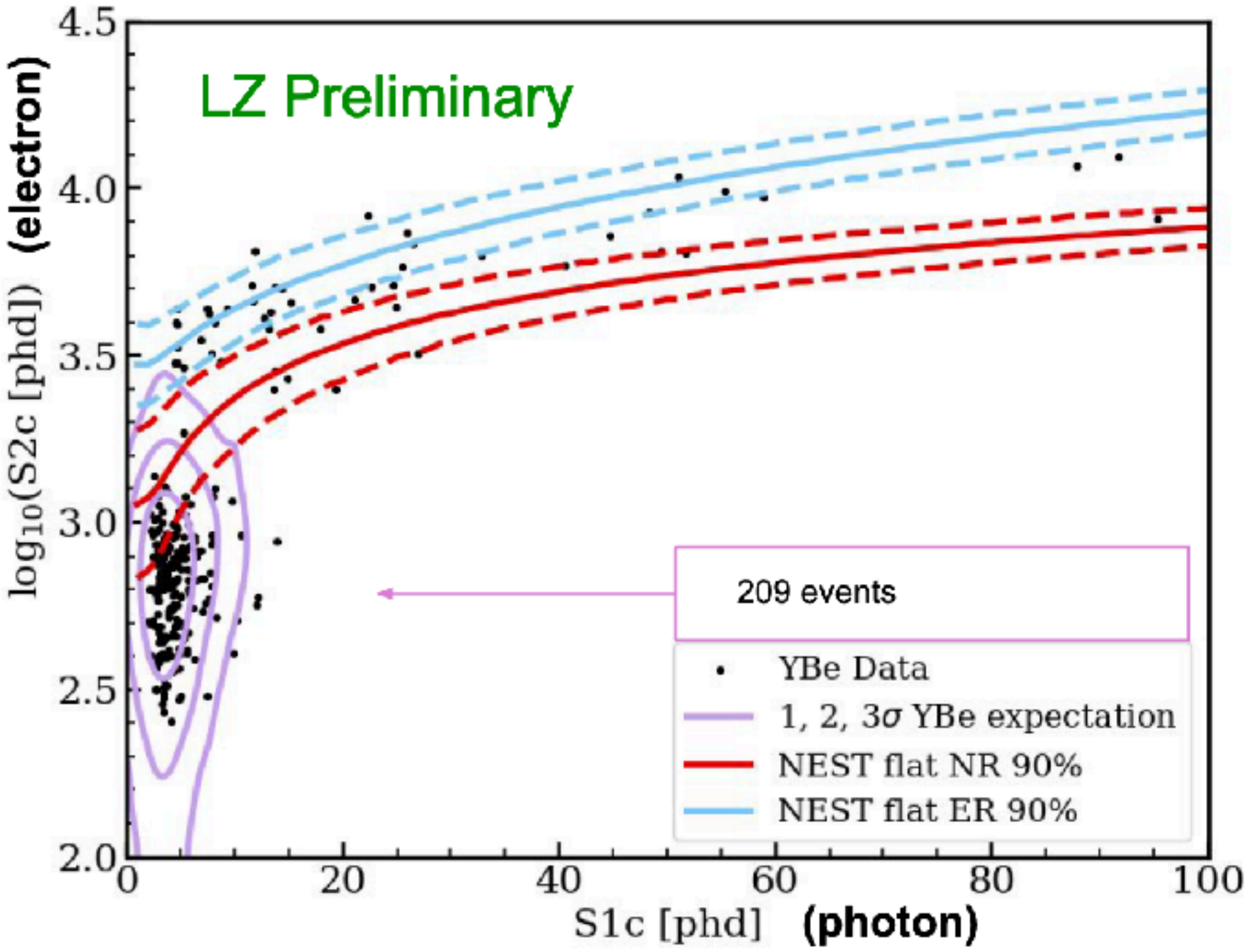


Liquid Xenon Dual Phase TPCs

- 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







- Searching for WIMPs into the "fog"
  - Nearly indistinguishable background from astrophysical neutrinos
  - Sensitivity rapidly falls - 20% flux uncertainty
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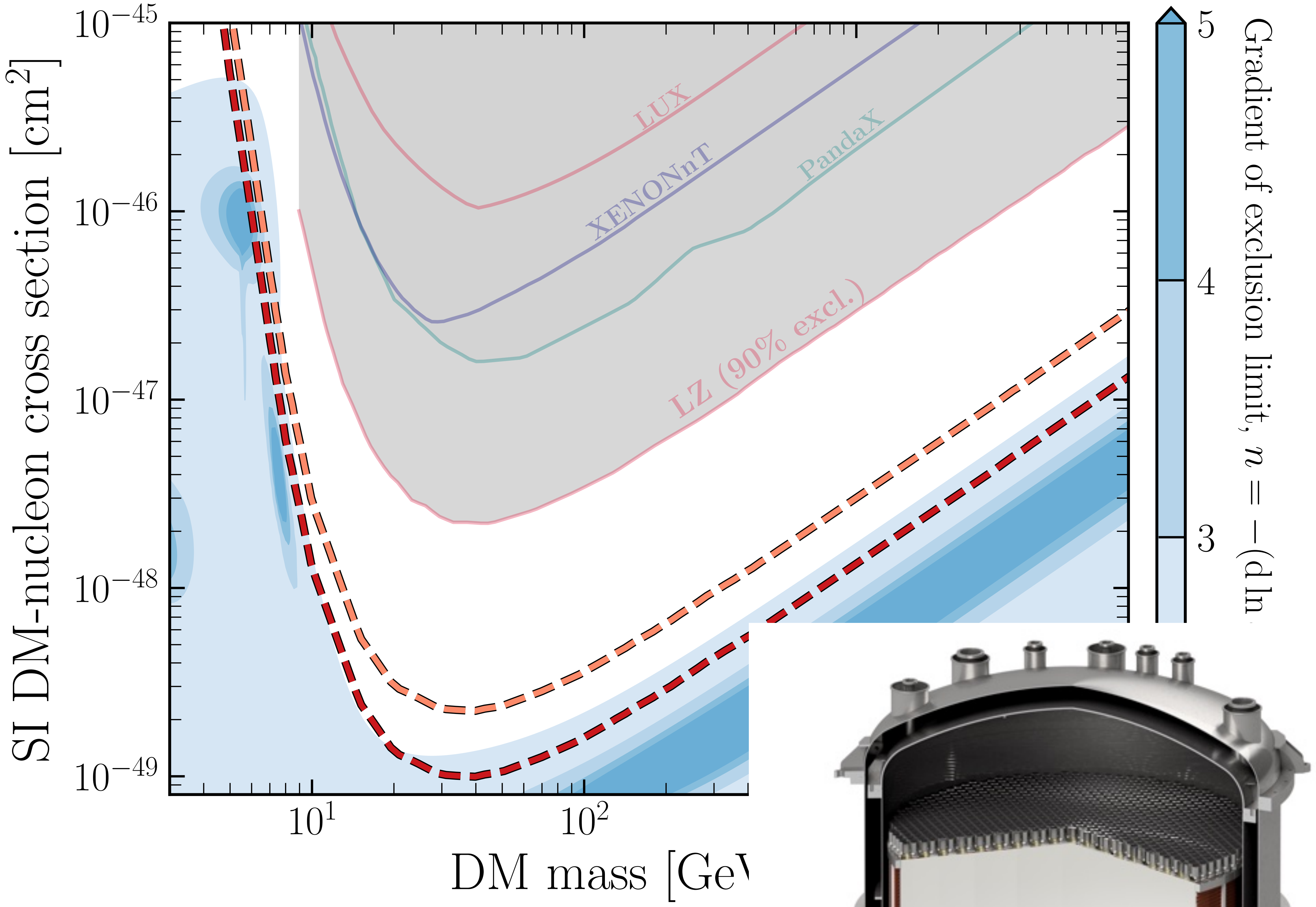
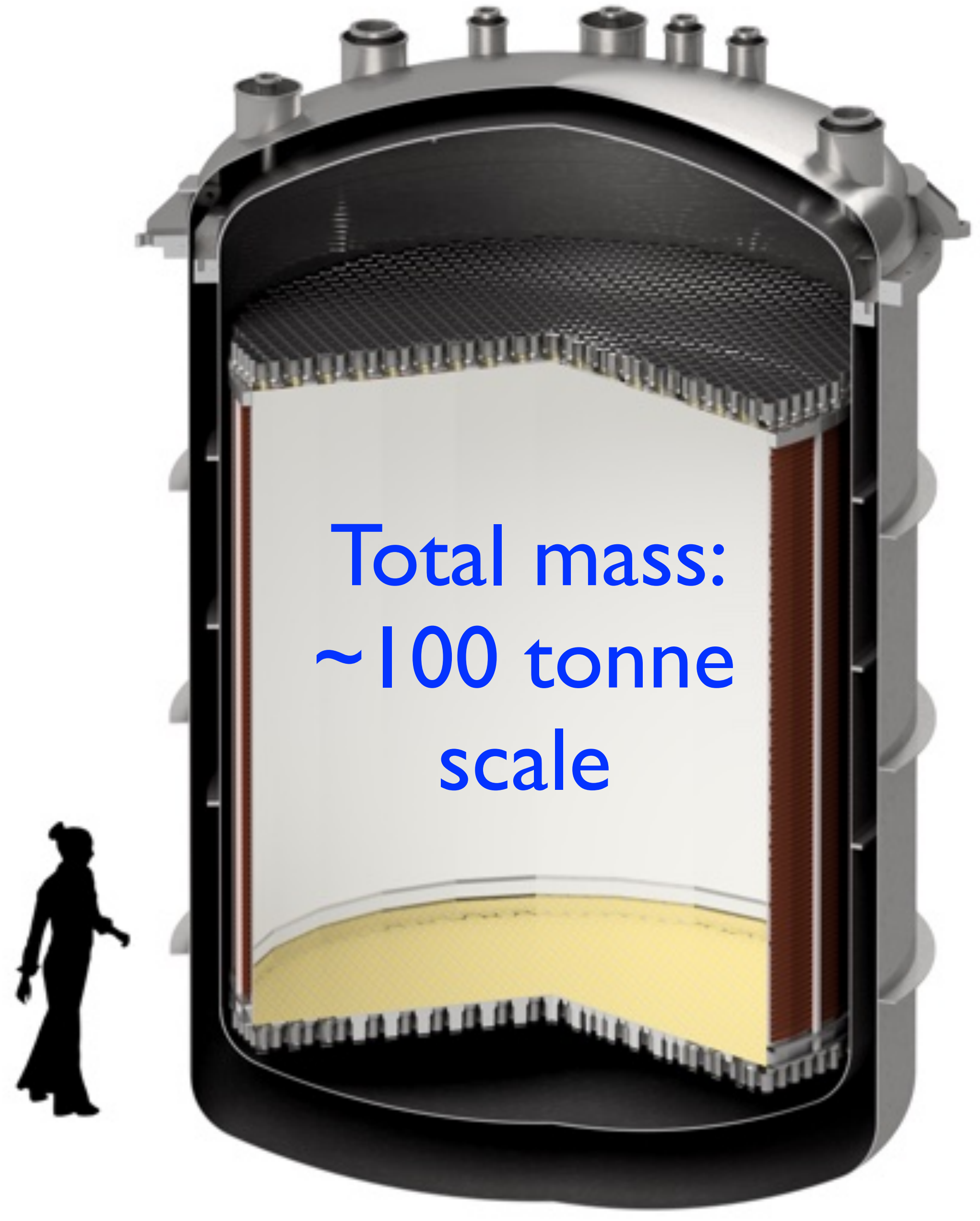
  - 3-sigma discovery at 3×10^{-49} at 40 GeV





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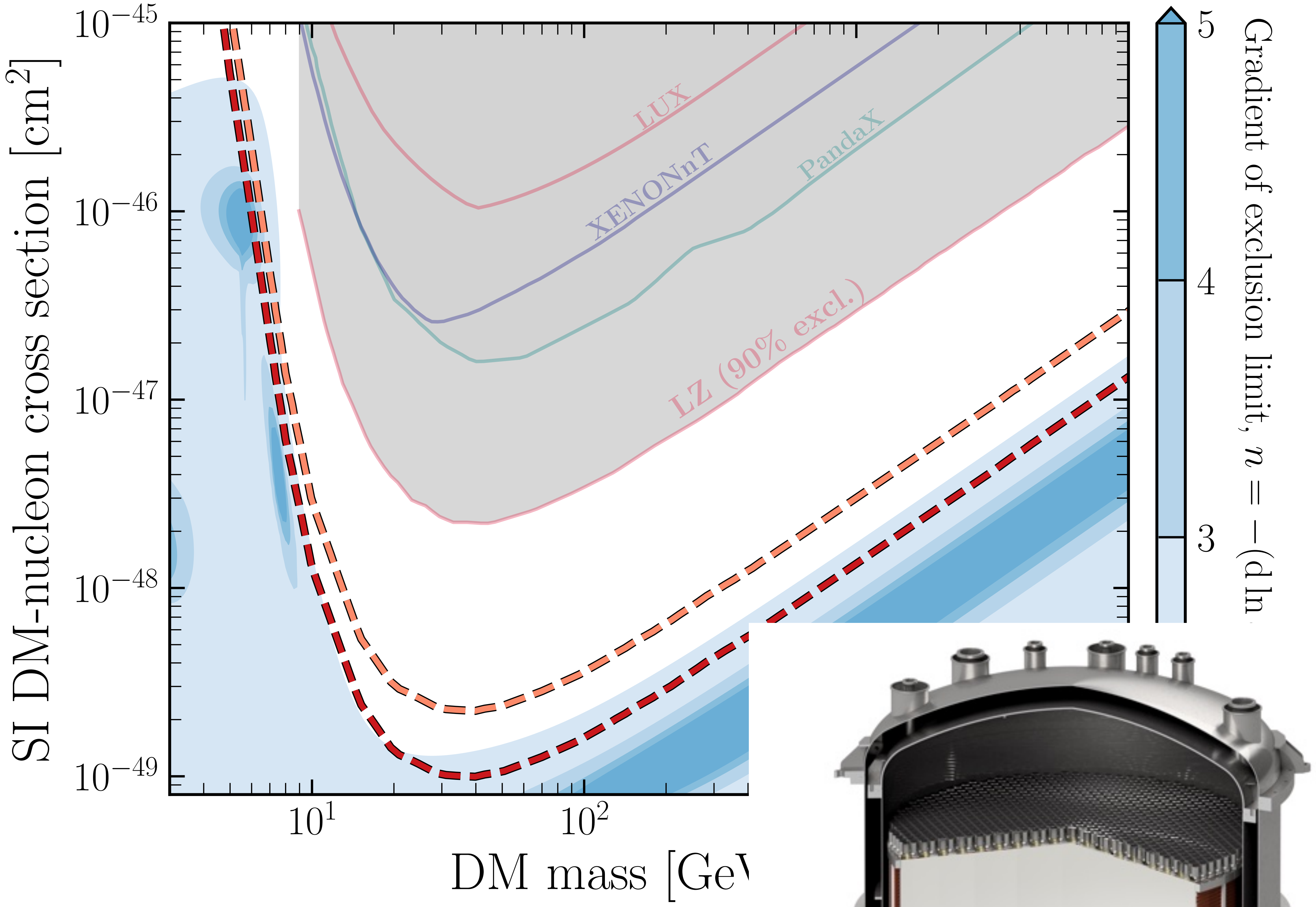
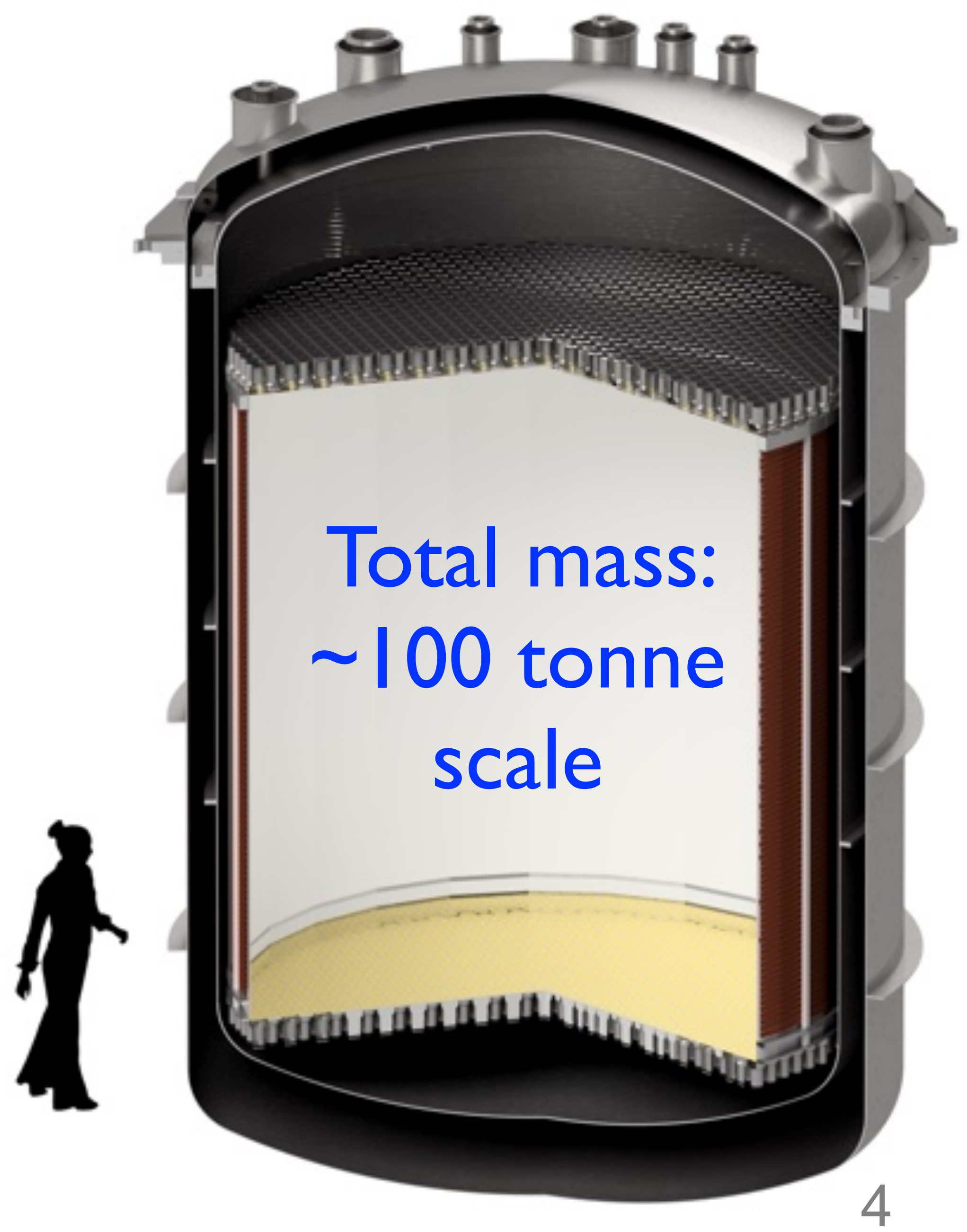
  - Double TPC linear dimensions
  - Compact geometry: readout, underground transport & fit





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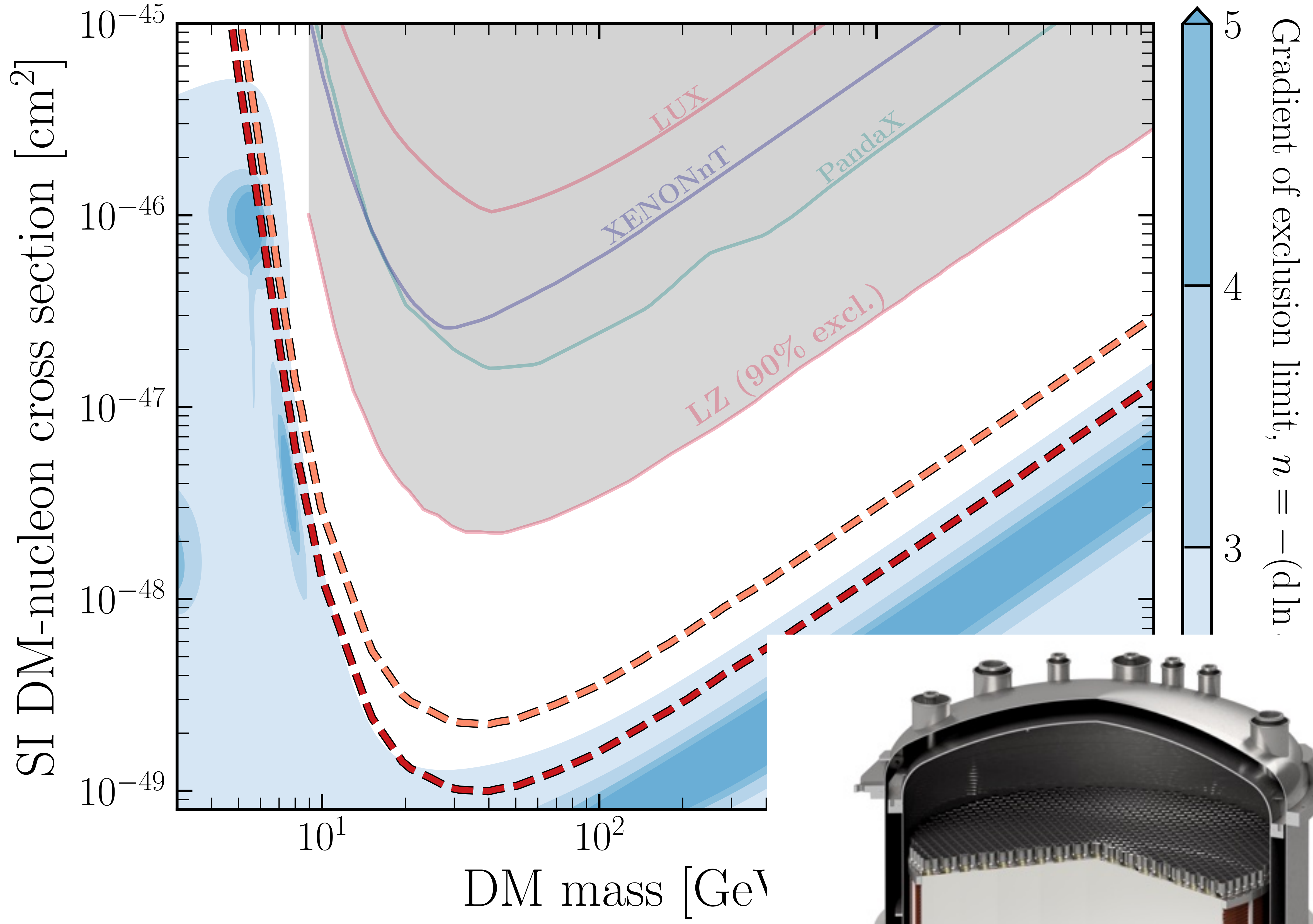
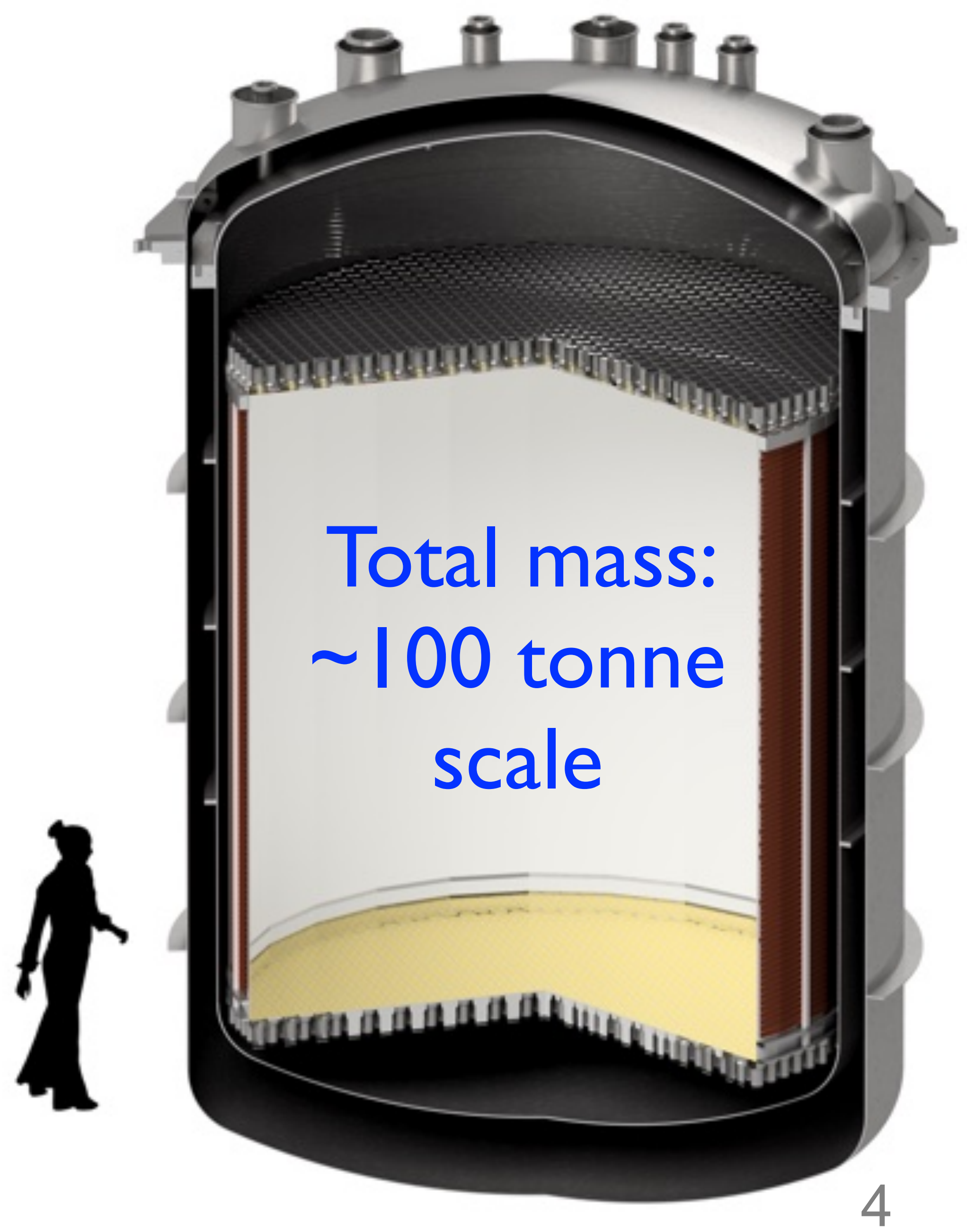
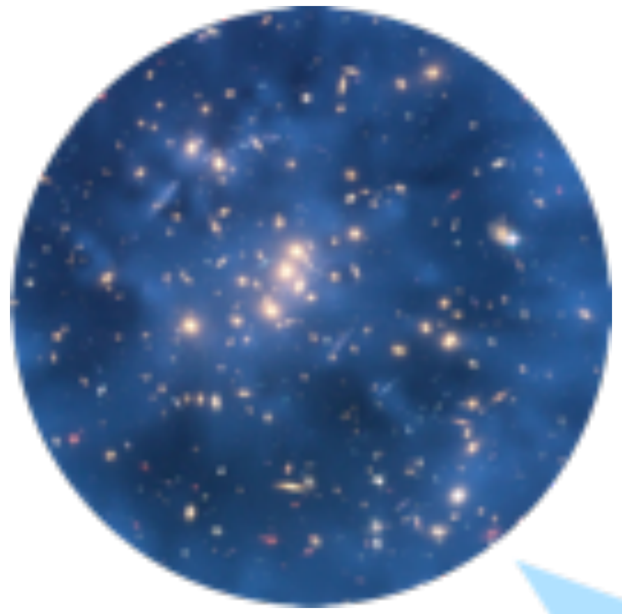


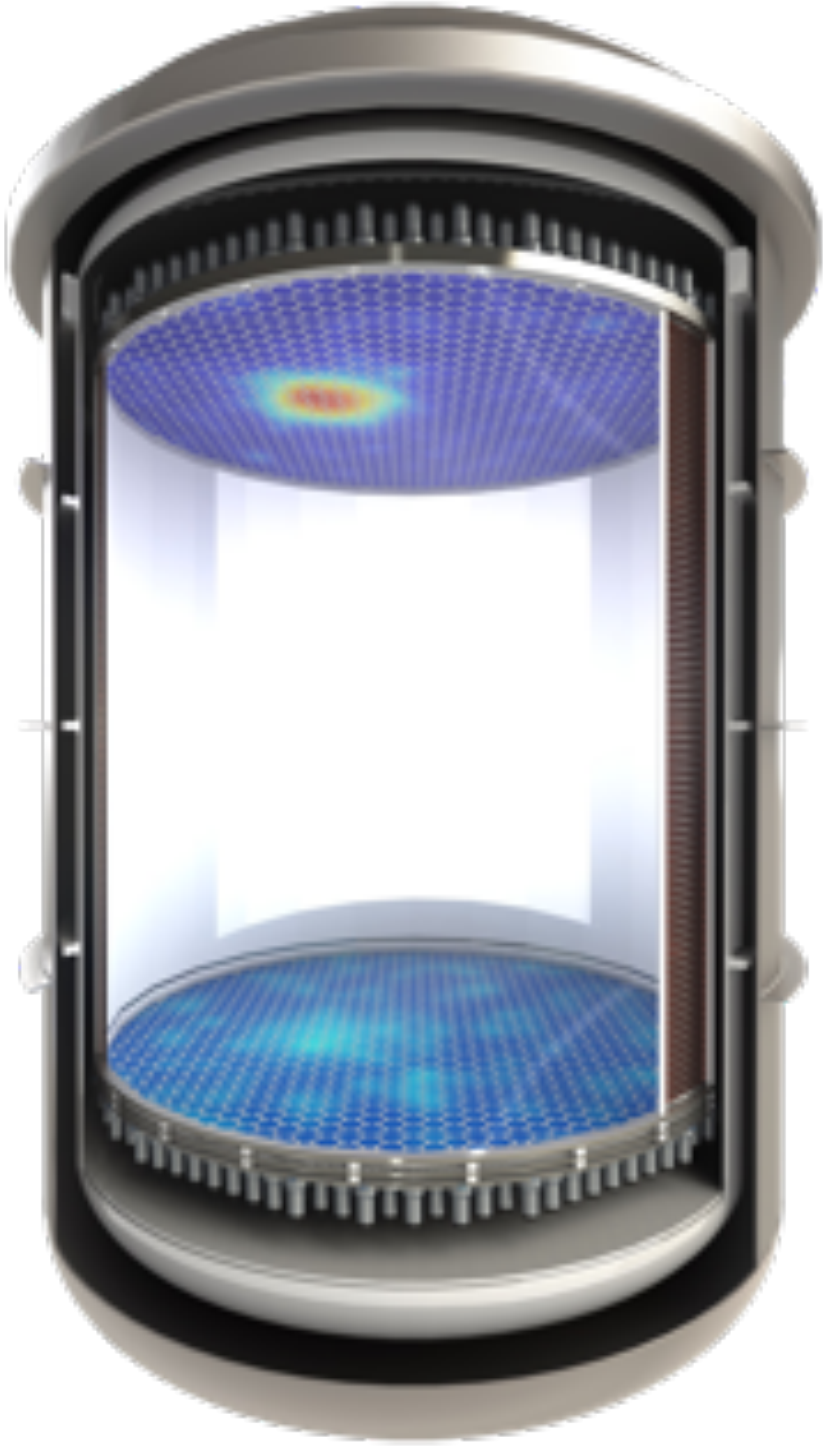


A Liquid Xenon Observatory with a broad science program

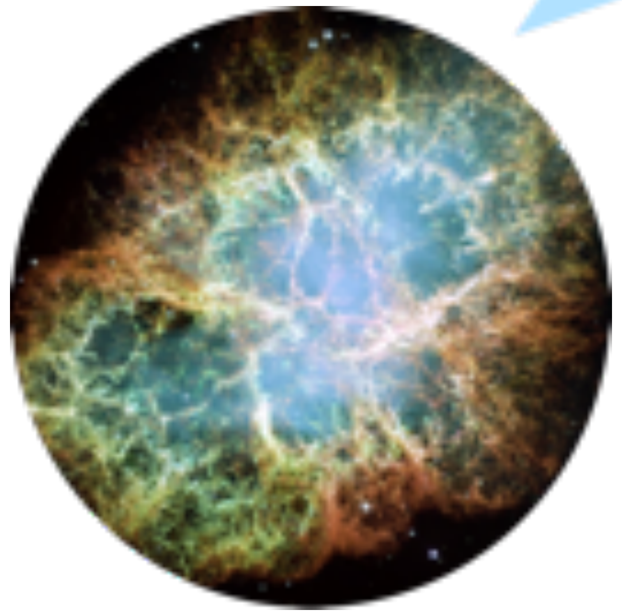
Dark Matter
WIMPs
Sub-GeV
Inelastic
Axion-like particles
Planck mass
Dark photons



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

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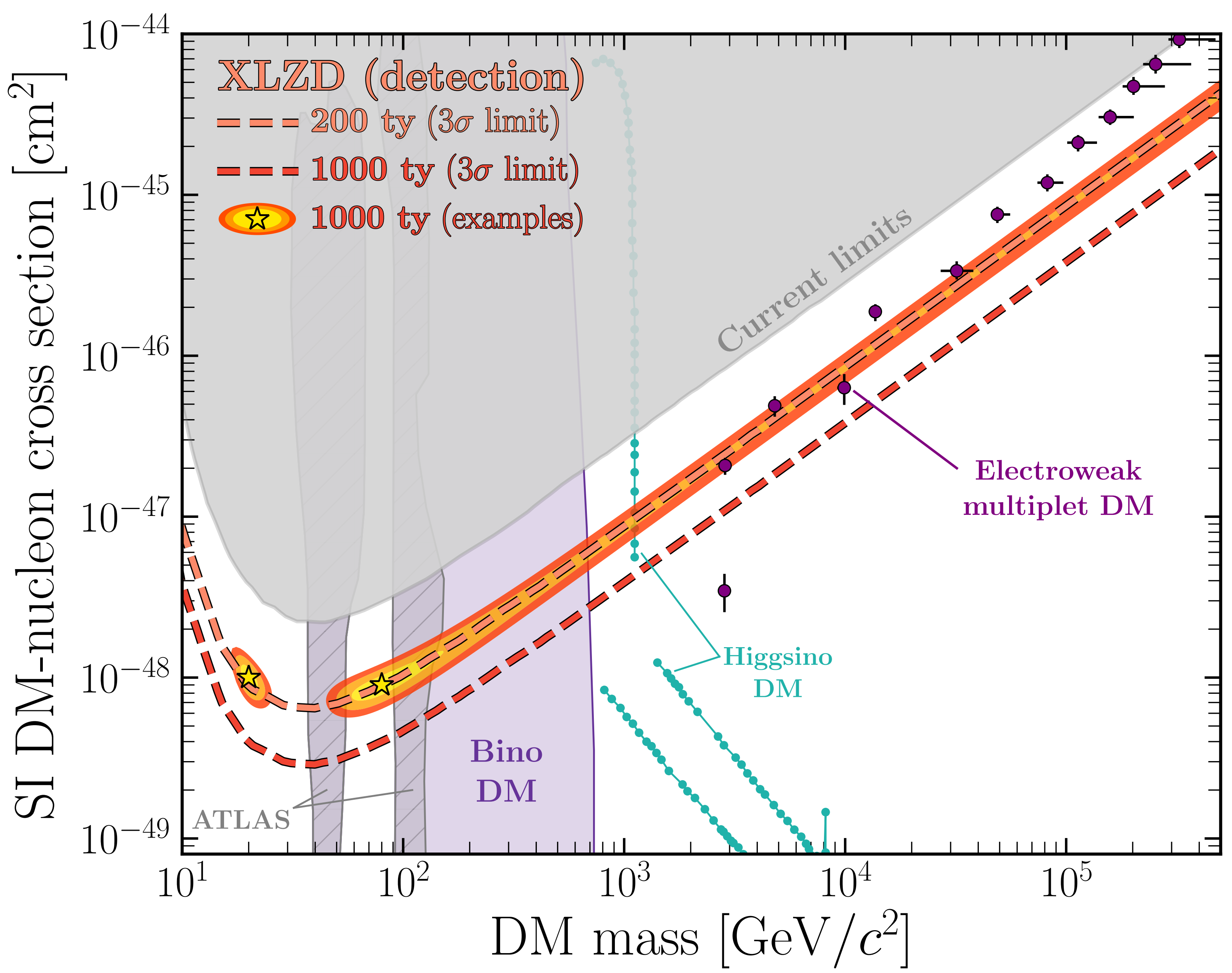

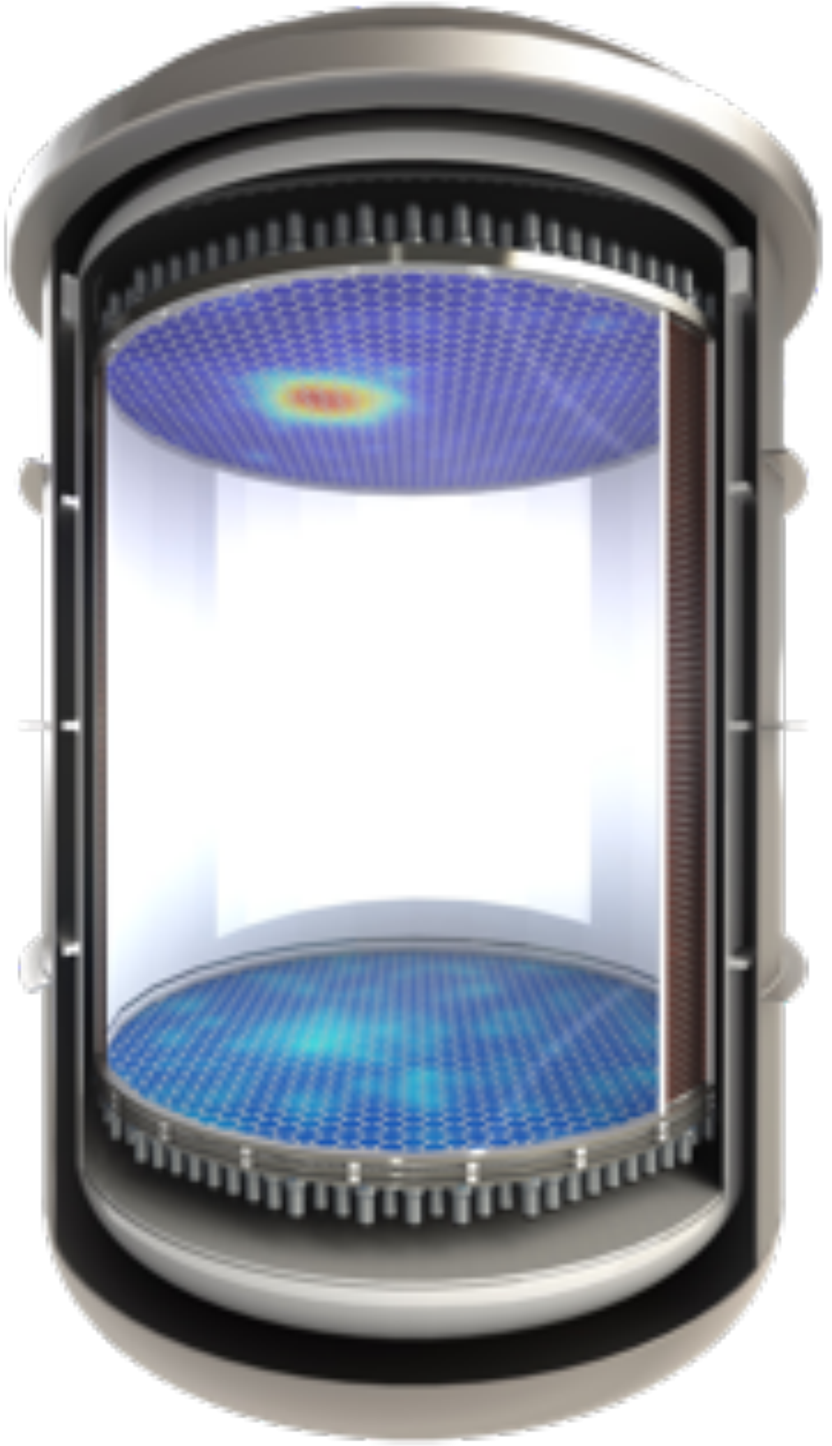

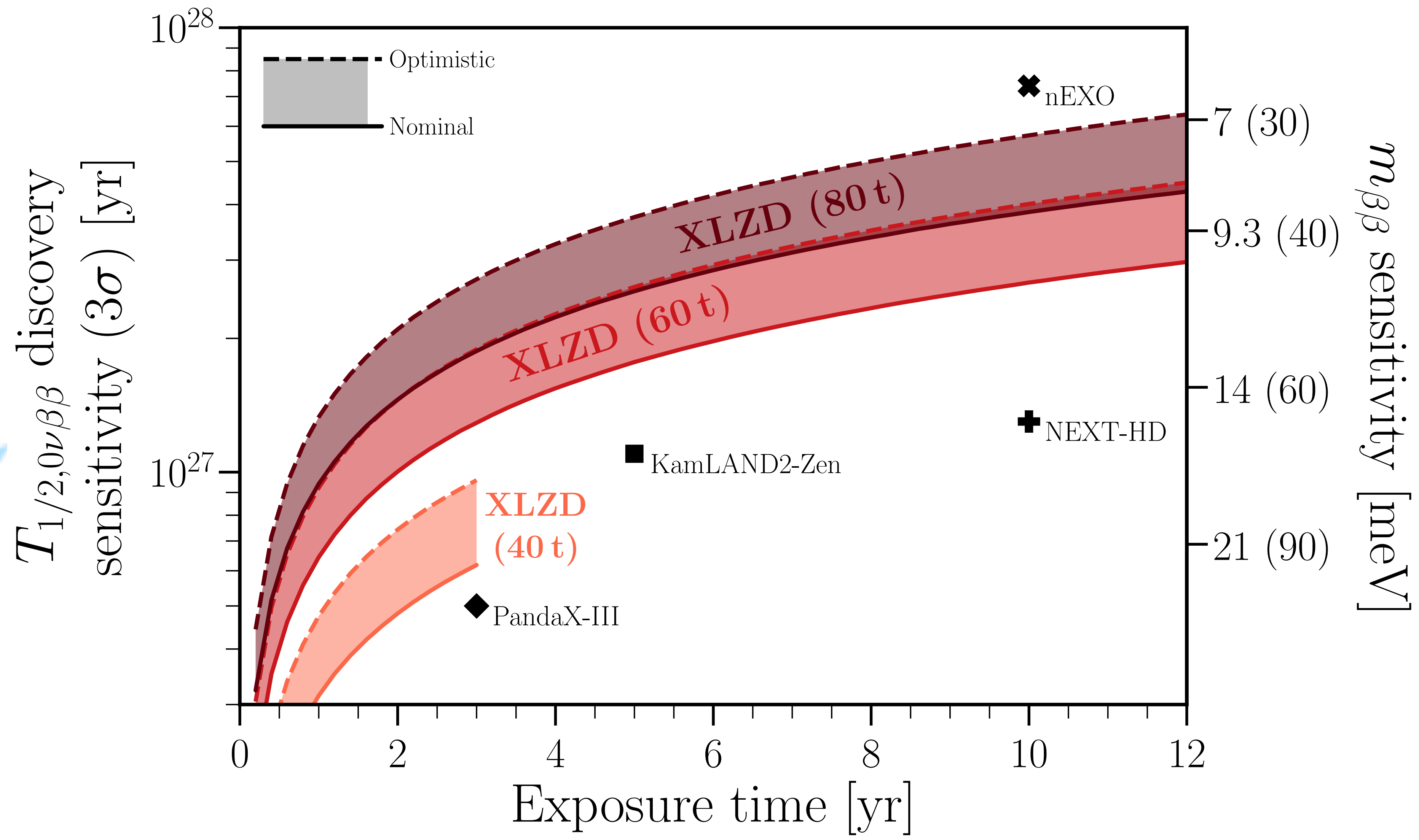

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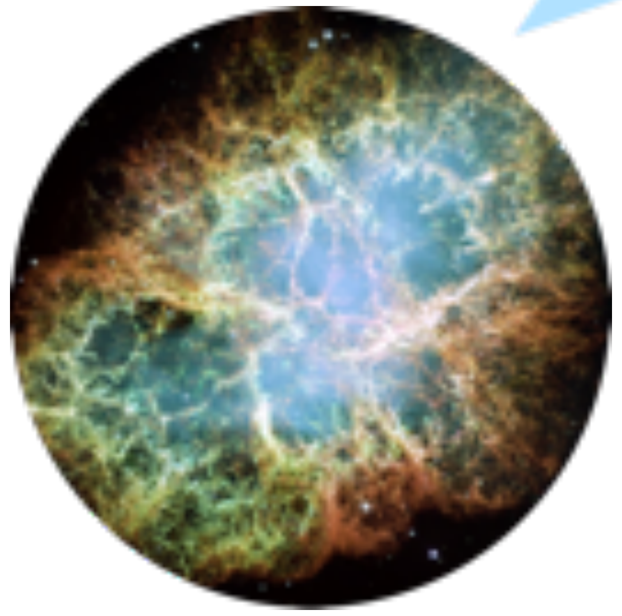

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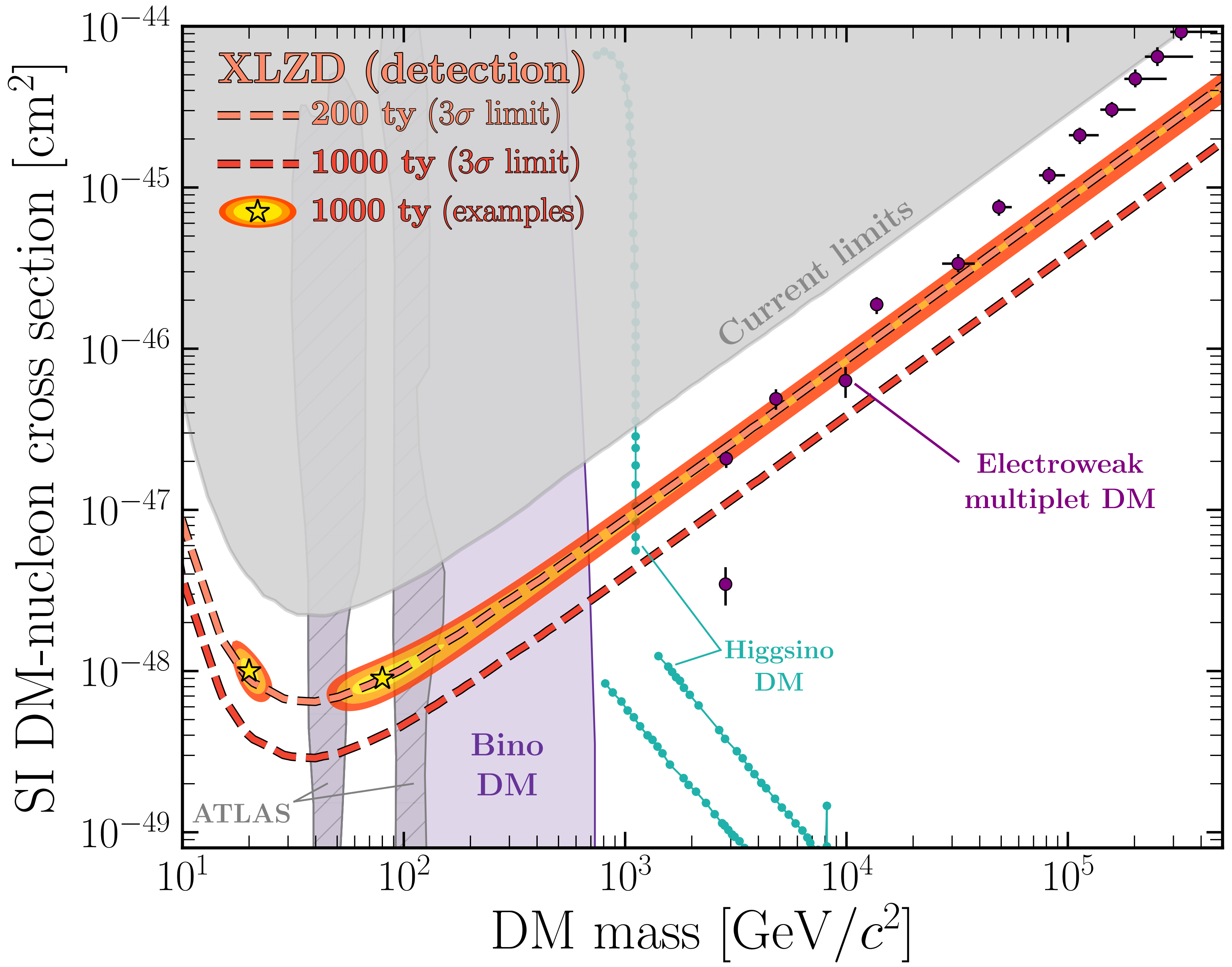

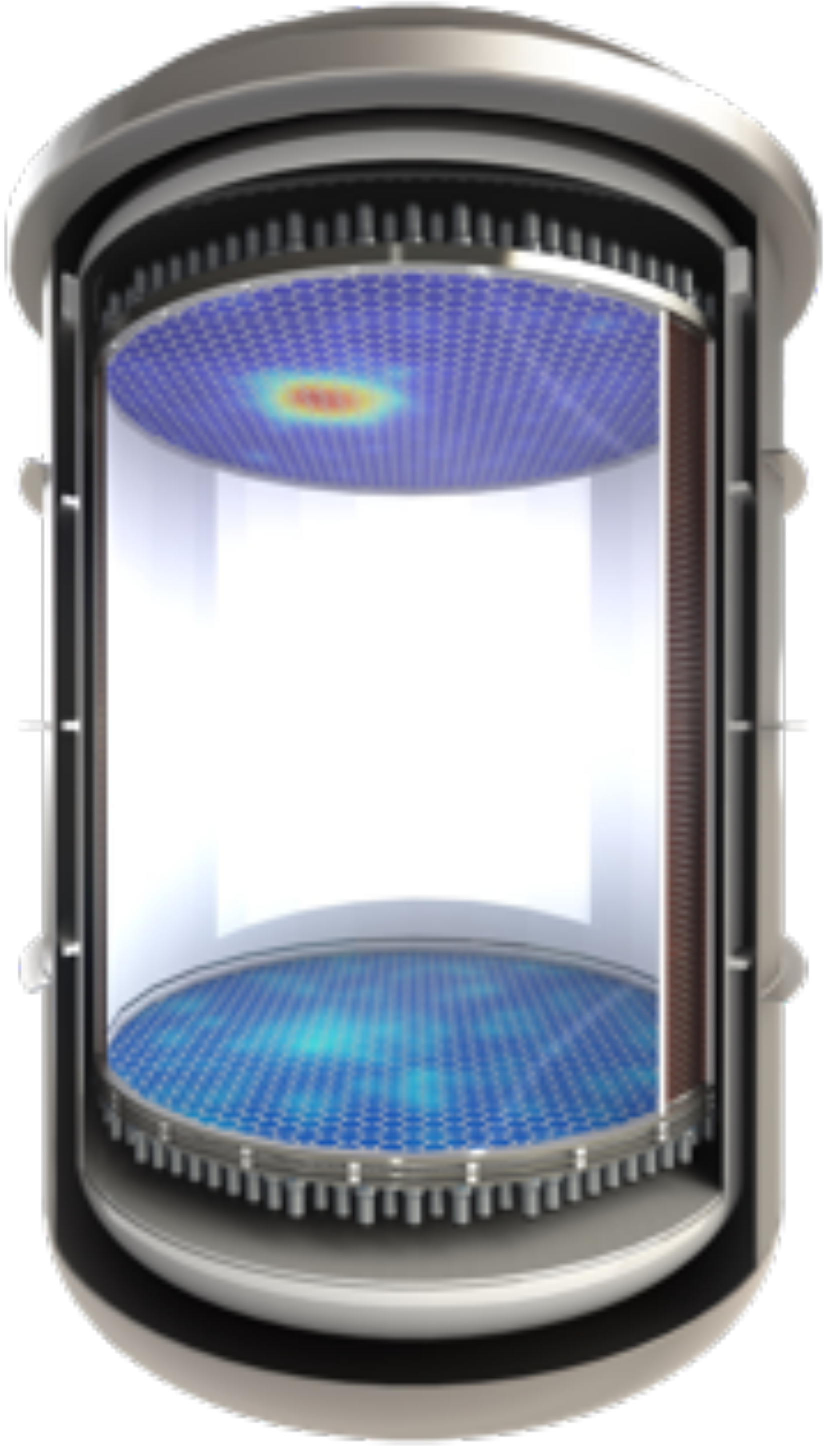

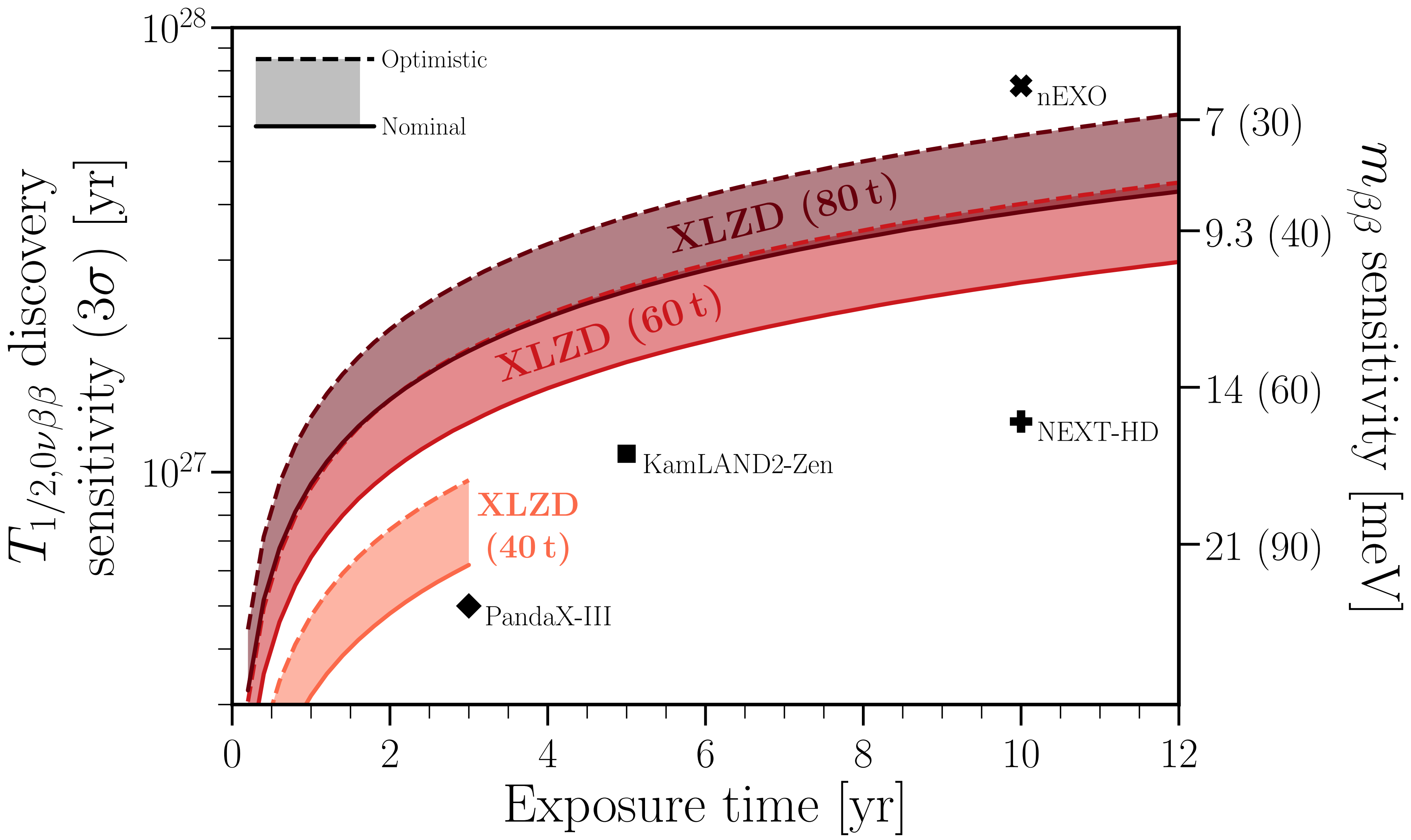

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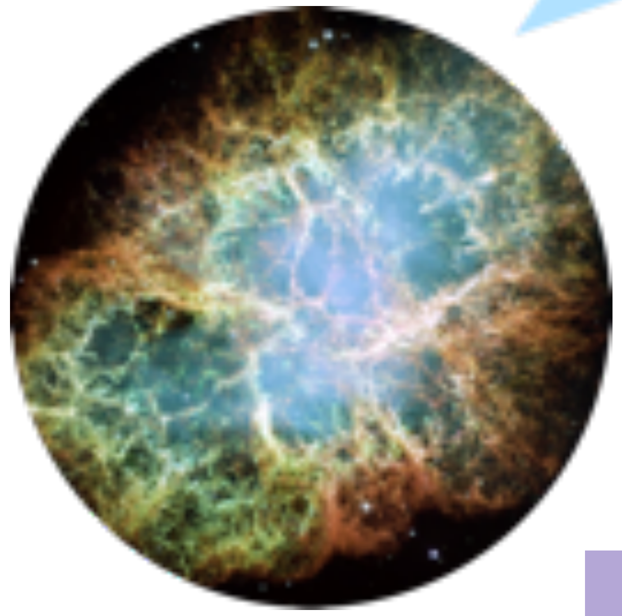


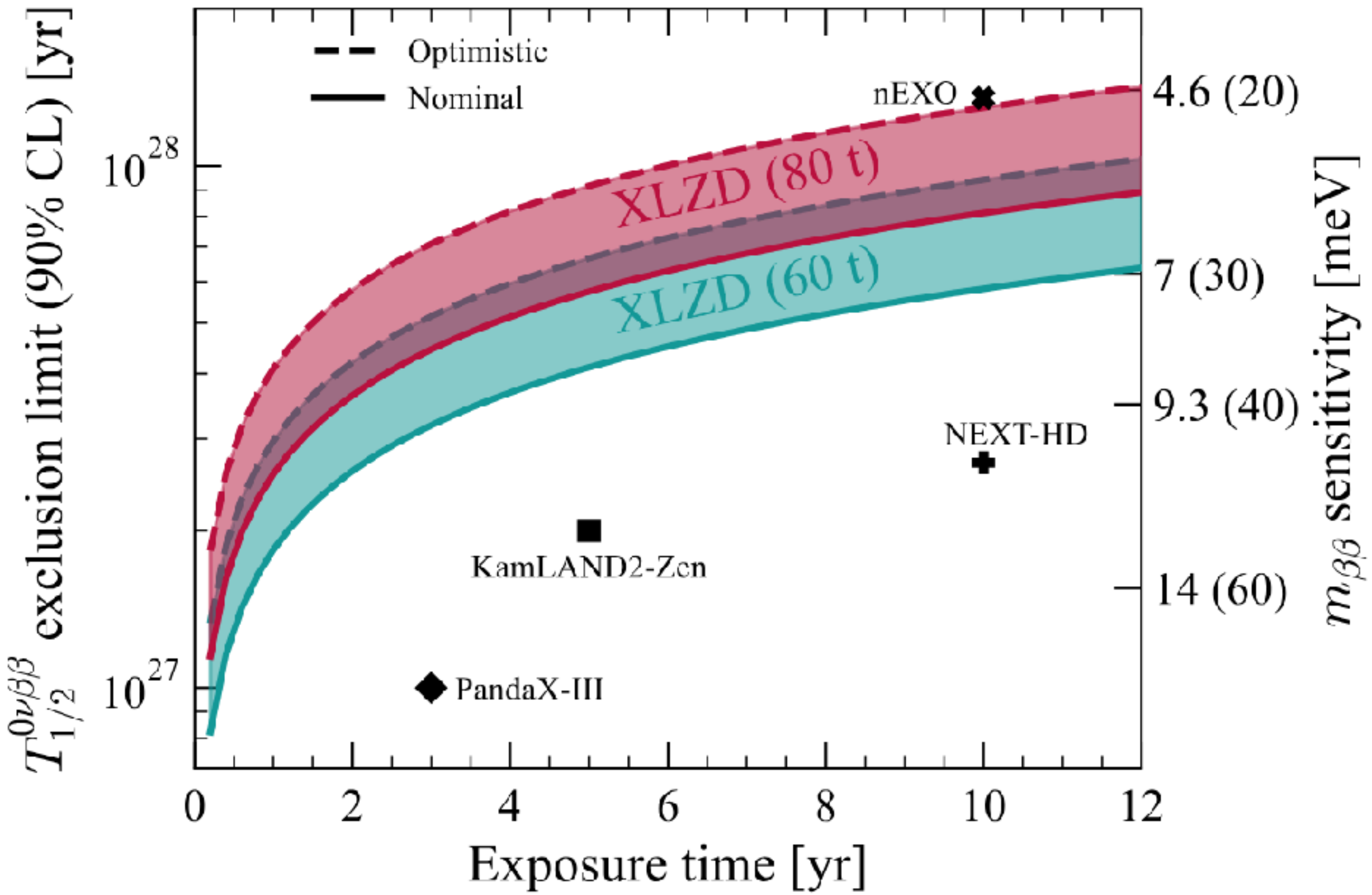
<u>Sun</u>
pp neutrinos
Solar metallicity
^{7}Be, ^{8}B, hep

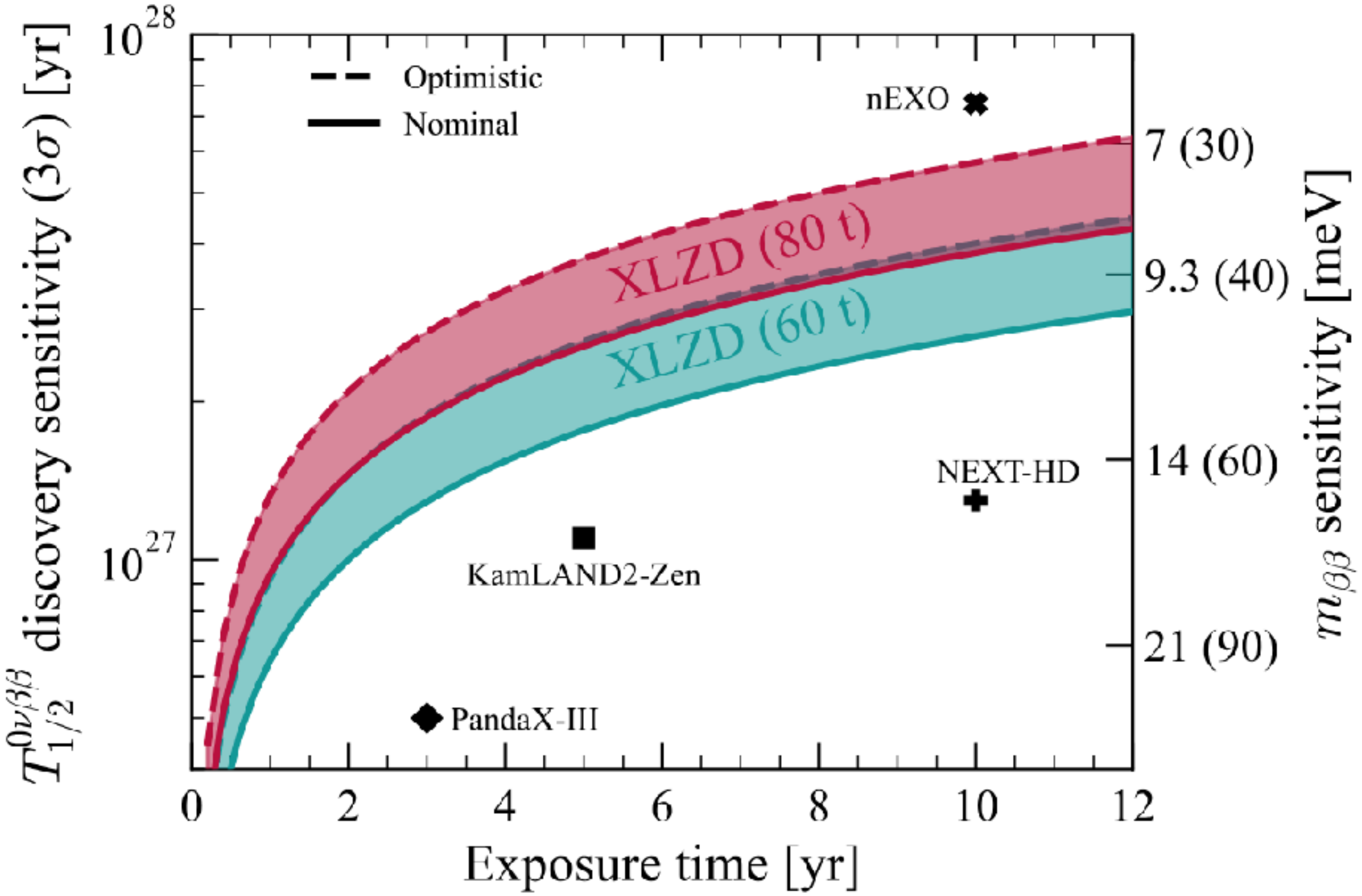
Unprecedented reach for low-energy rare processes

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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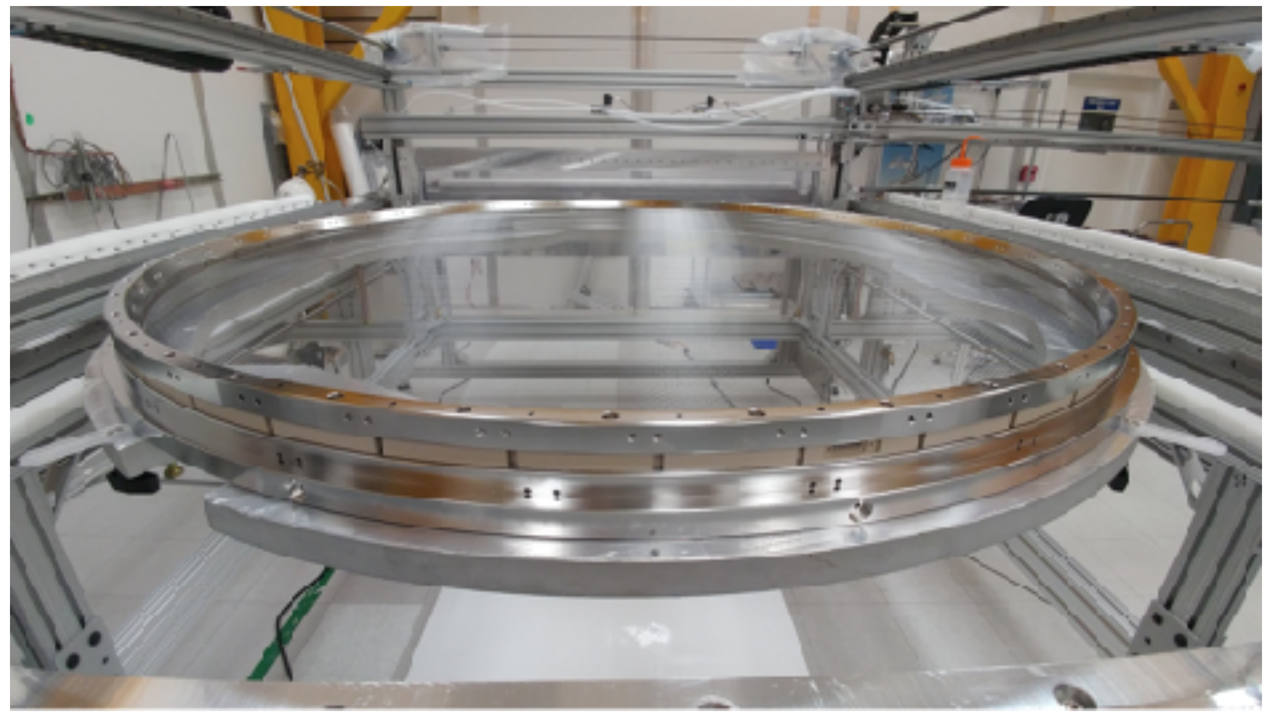
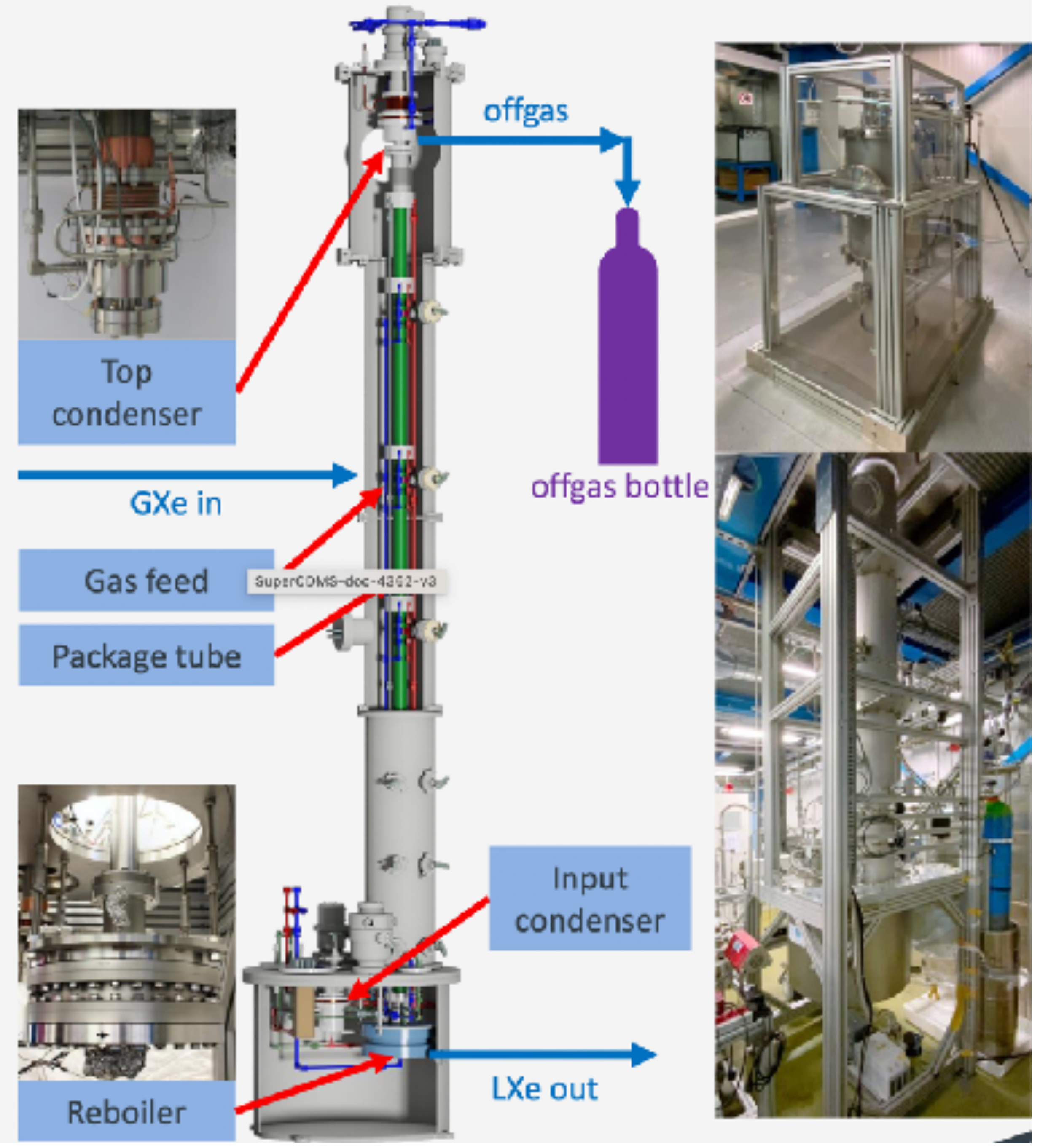
Design Heritage: technical foundation from LZ and XnT

- 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



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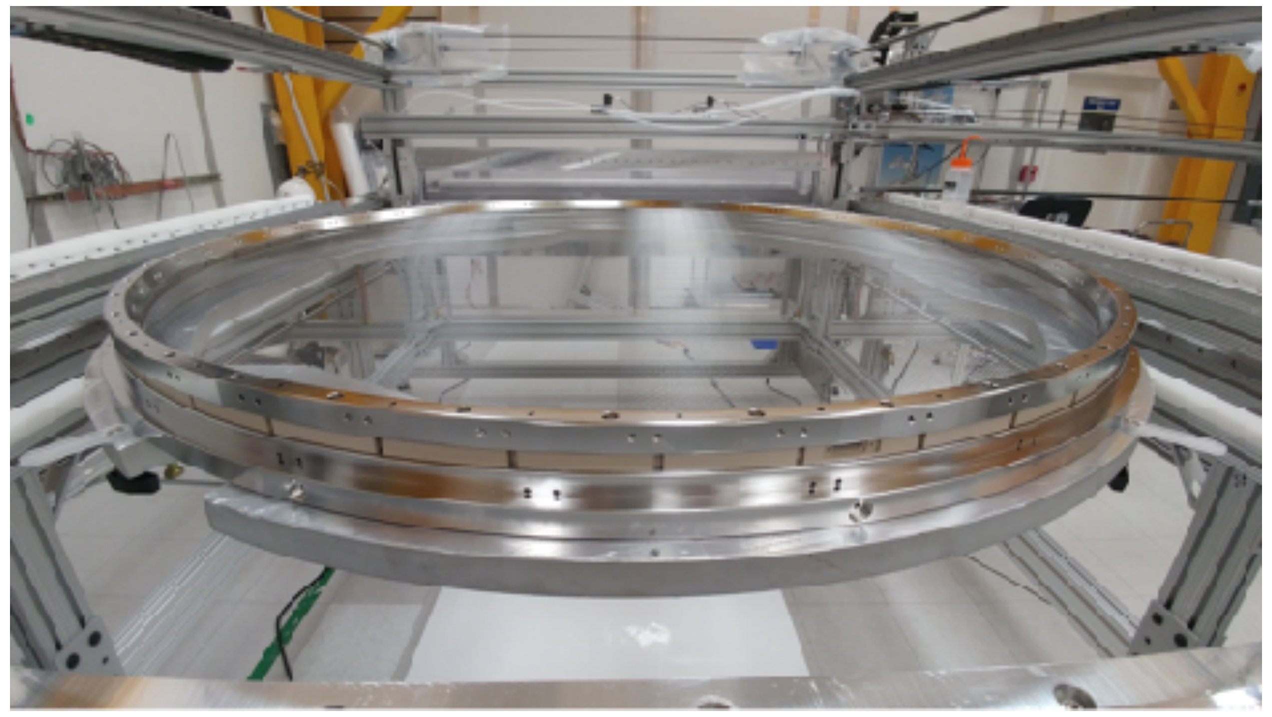
- Multiple design approaches to draw from:

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*



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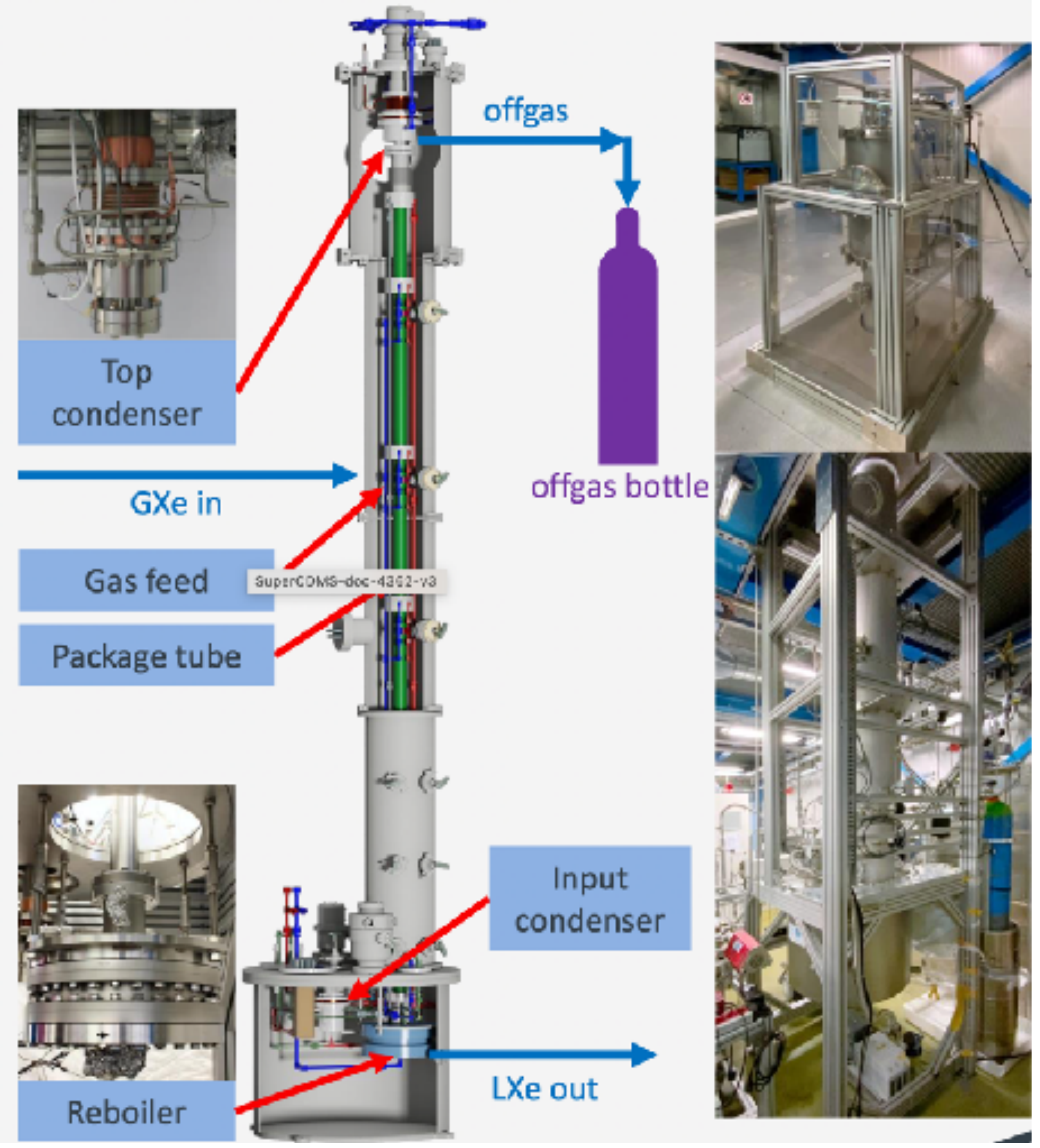

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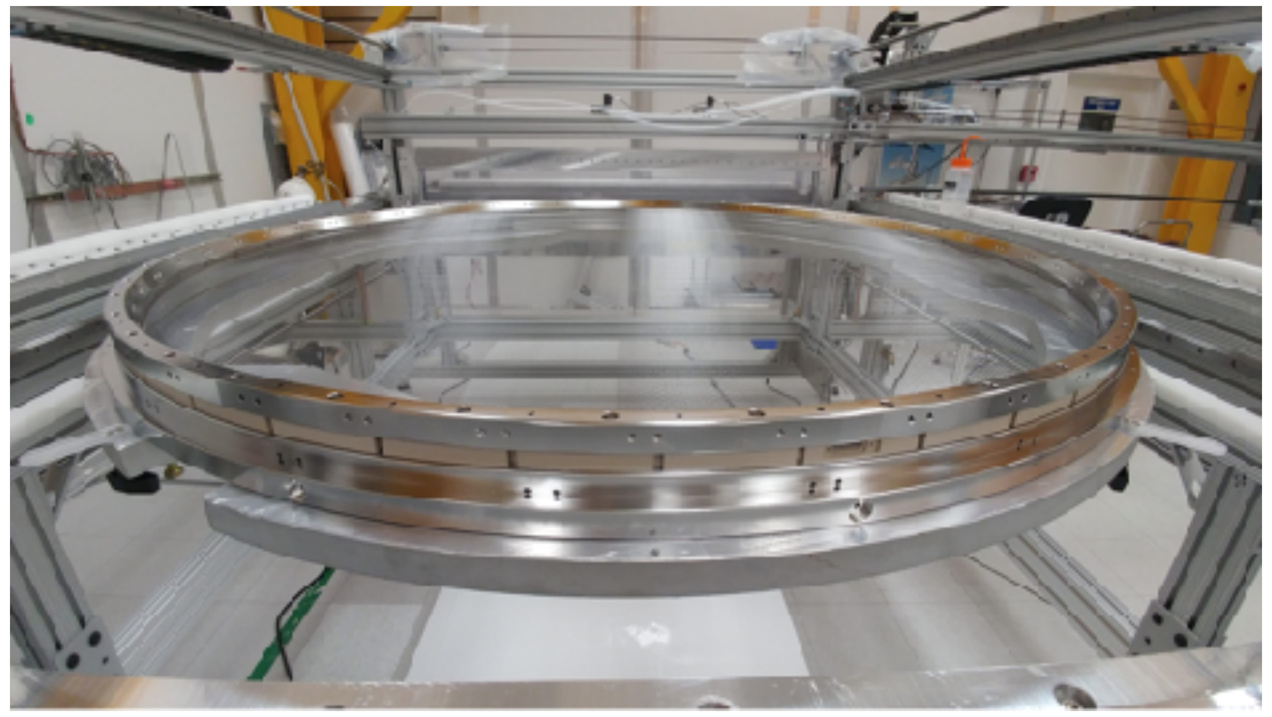
More details in XLZD Design Book, 2410.17137



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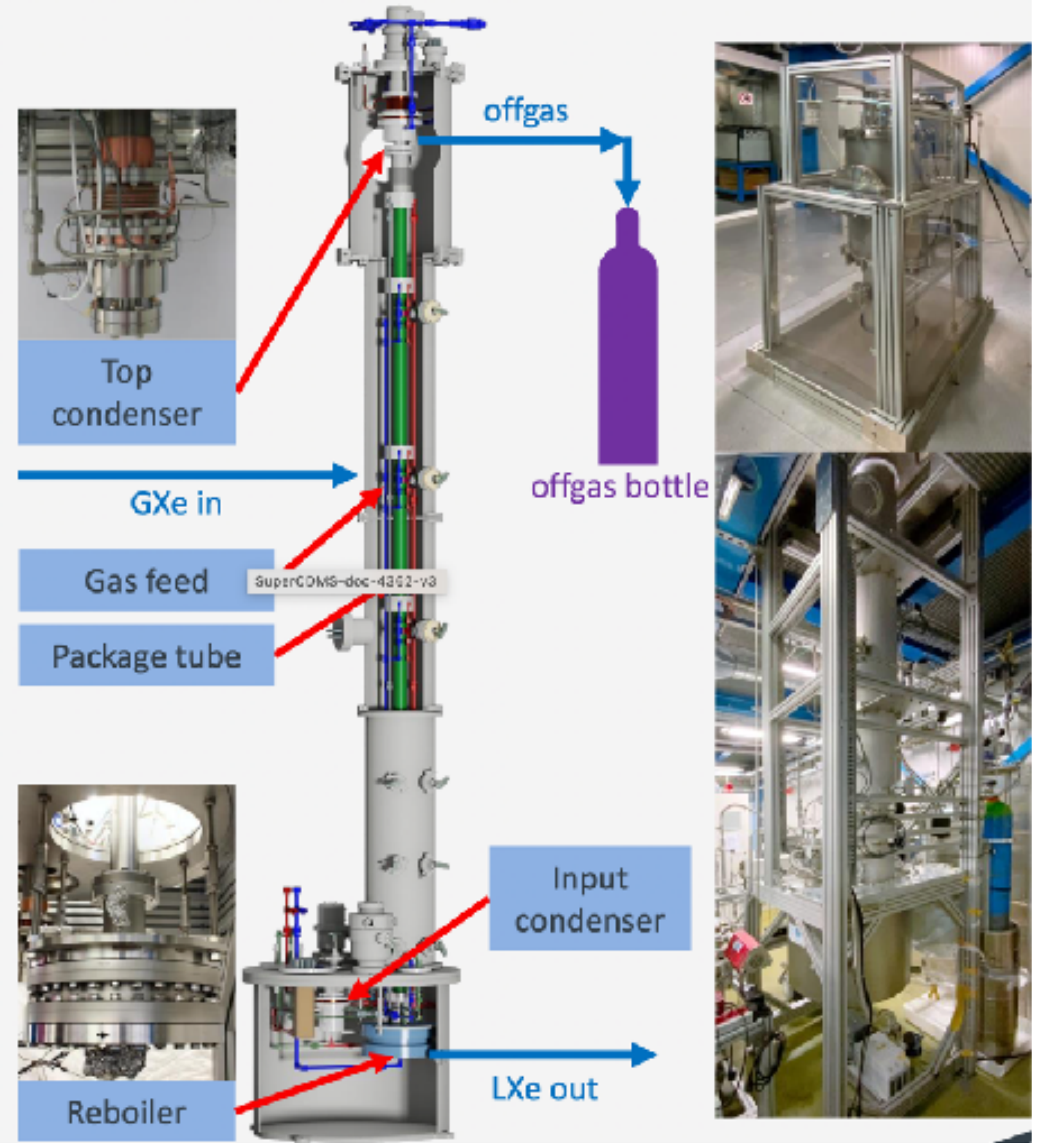

XnT Kr distillation

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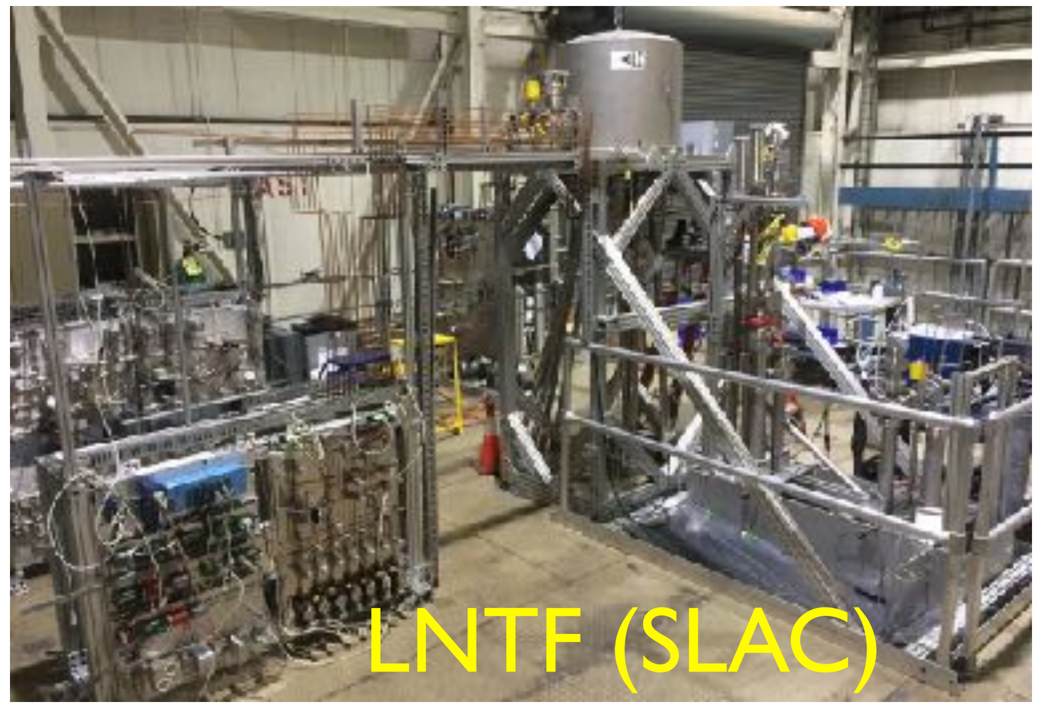
- Studies of accidentals, detector effects in LZ/XnT data
- Investments across XLZD groups in medium and large scale test platforms
- Possible definitive performance testing using existing shielded underground infrastructure



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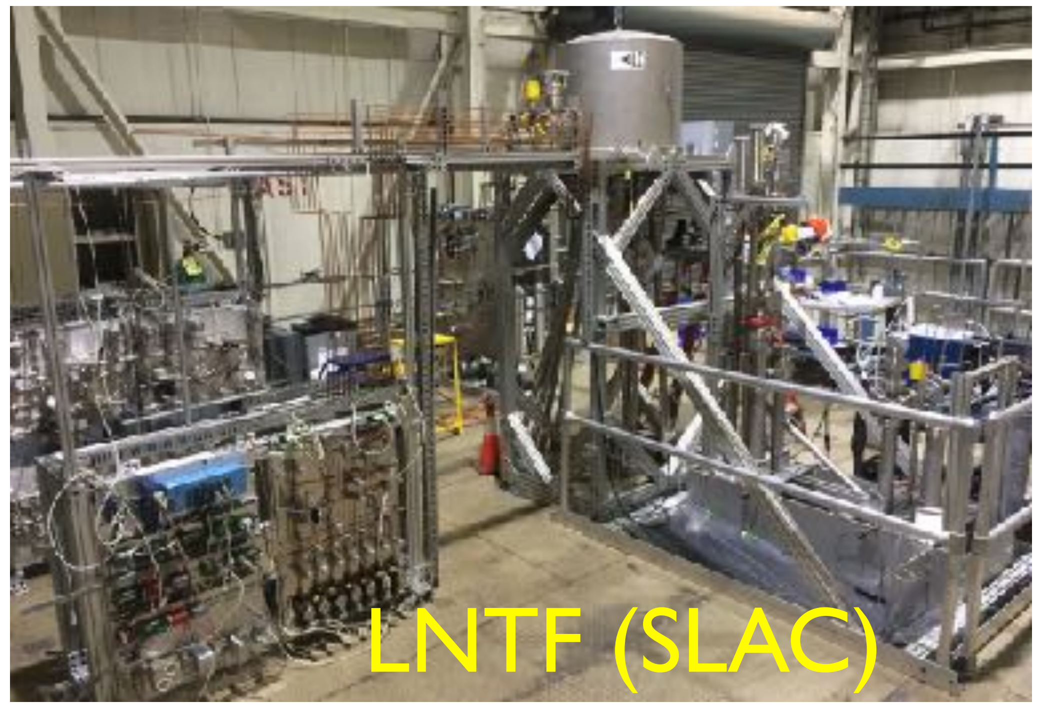
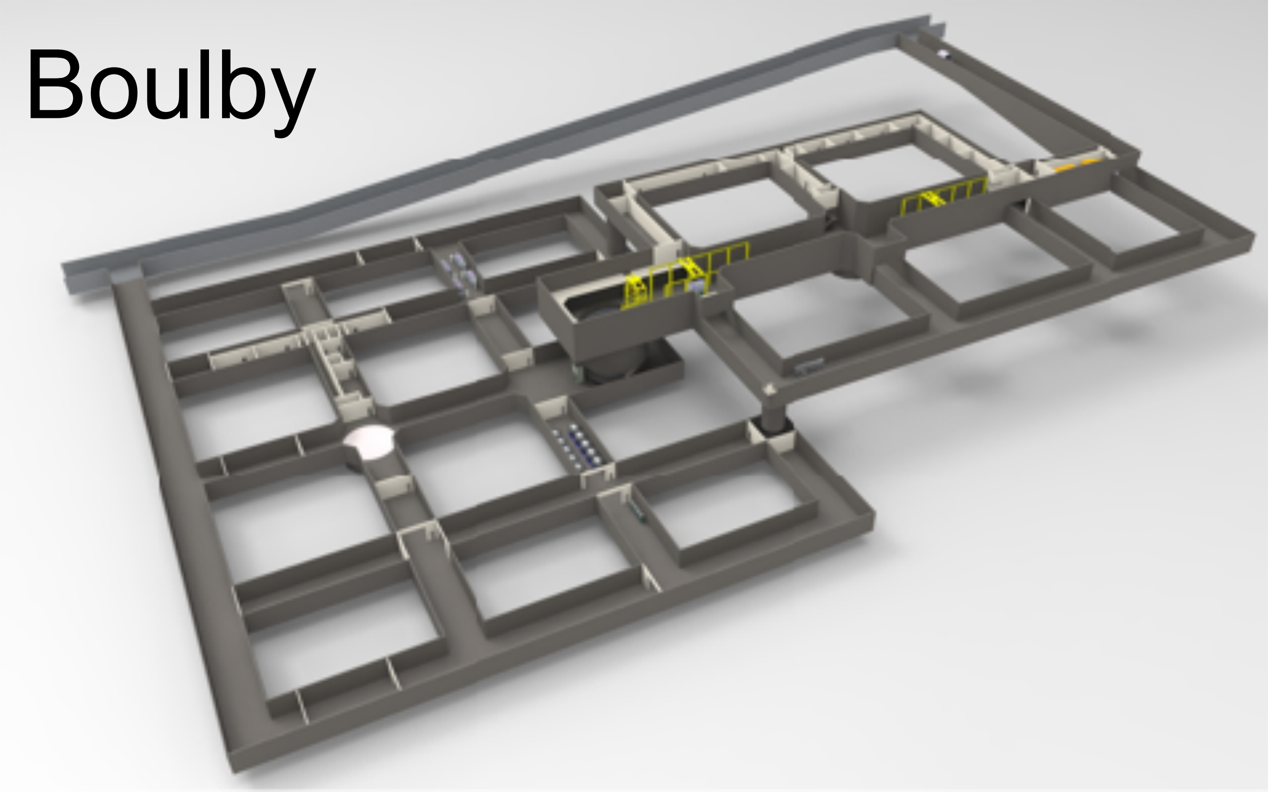
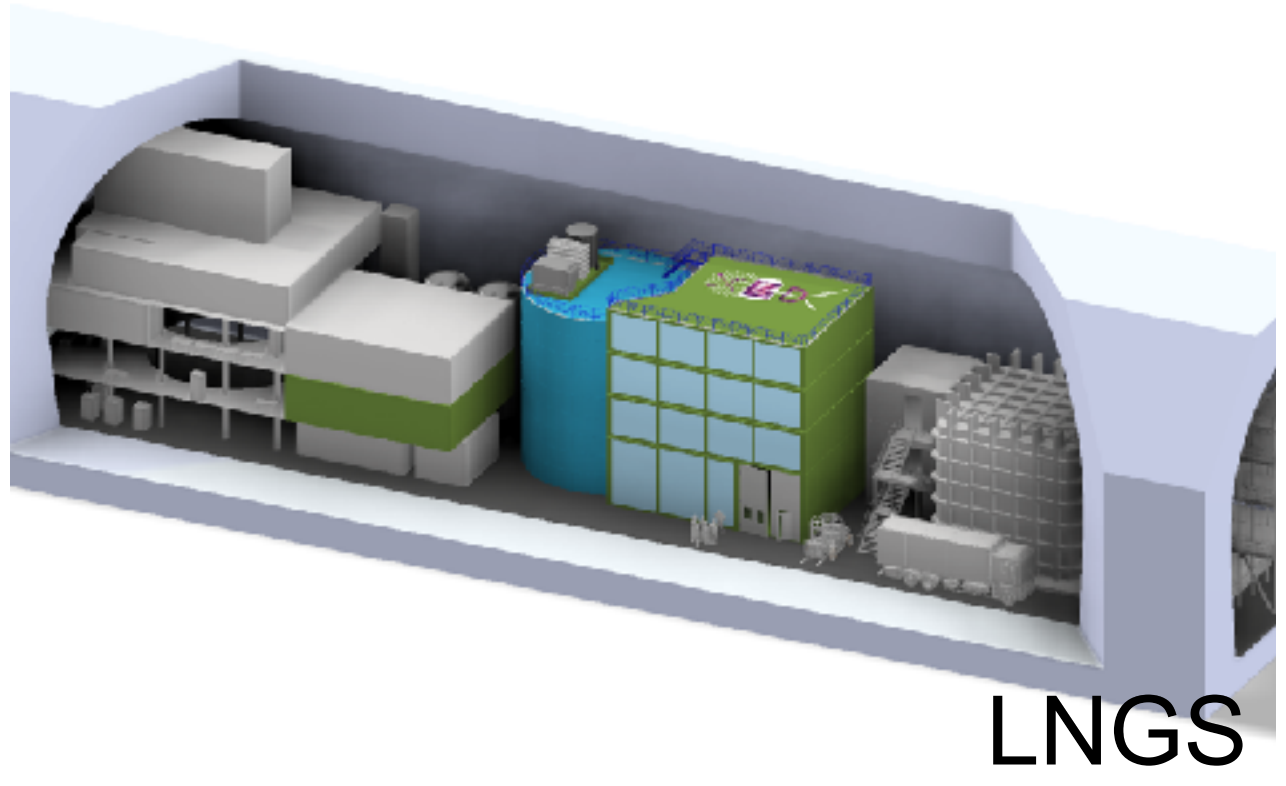


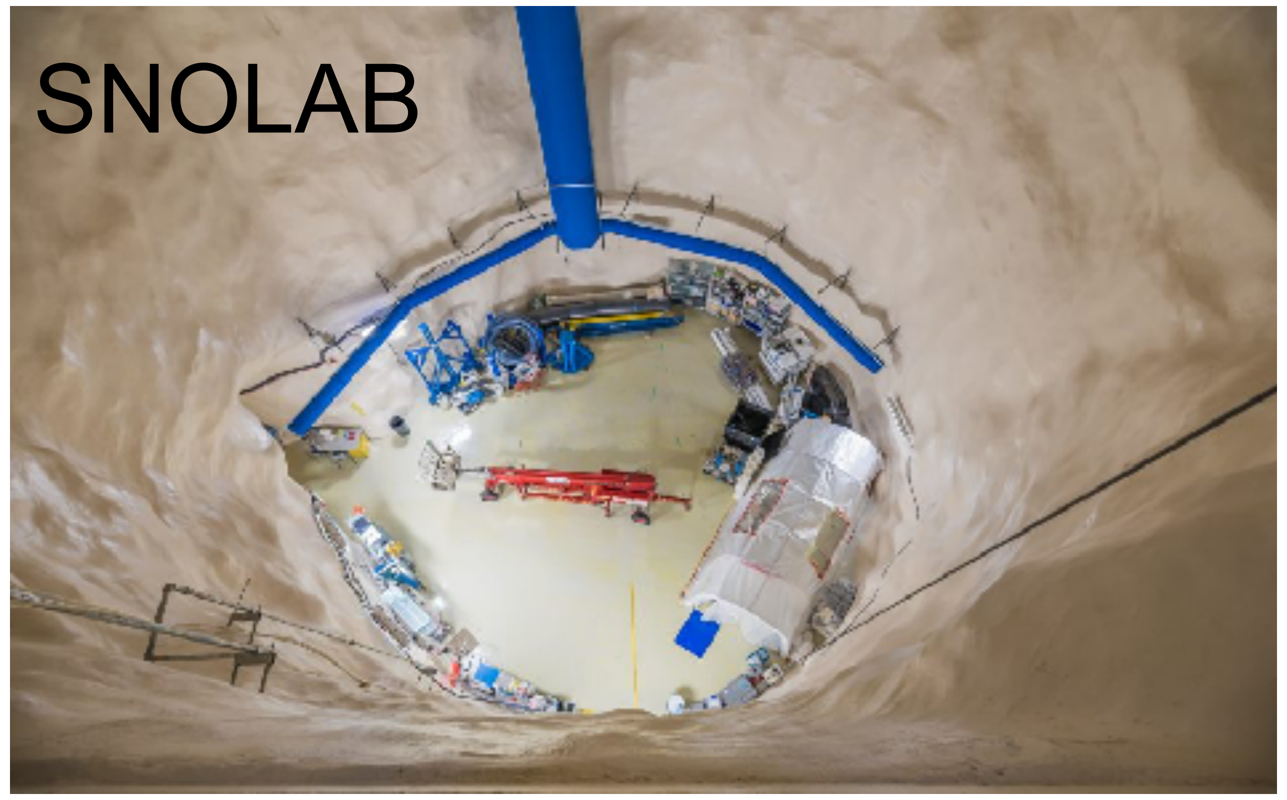
Combined team's track record establishes technical foundation and capabilities for making the necessary advances

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 - new 1300 meter lab being proposed
  - LNGS - middle of Hall C
  - SNOLAB CryoPit/CubeHall - under evaluation
  - SURF - "Module of Opportunity" cavern or new excavation







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 60-80t of xenon)
  - Liquid scintillator plant for outer detector

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)

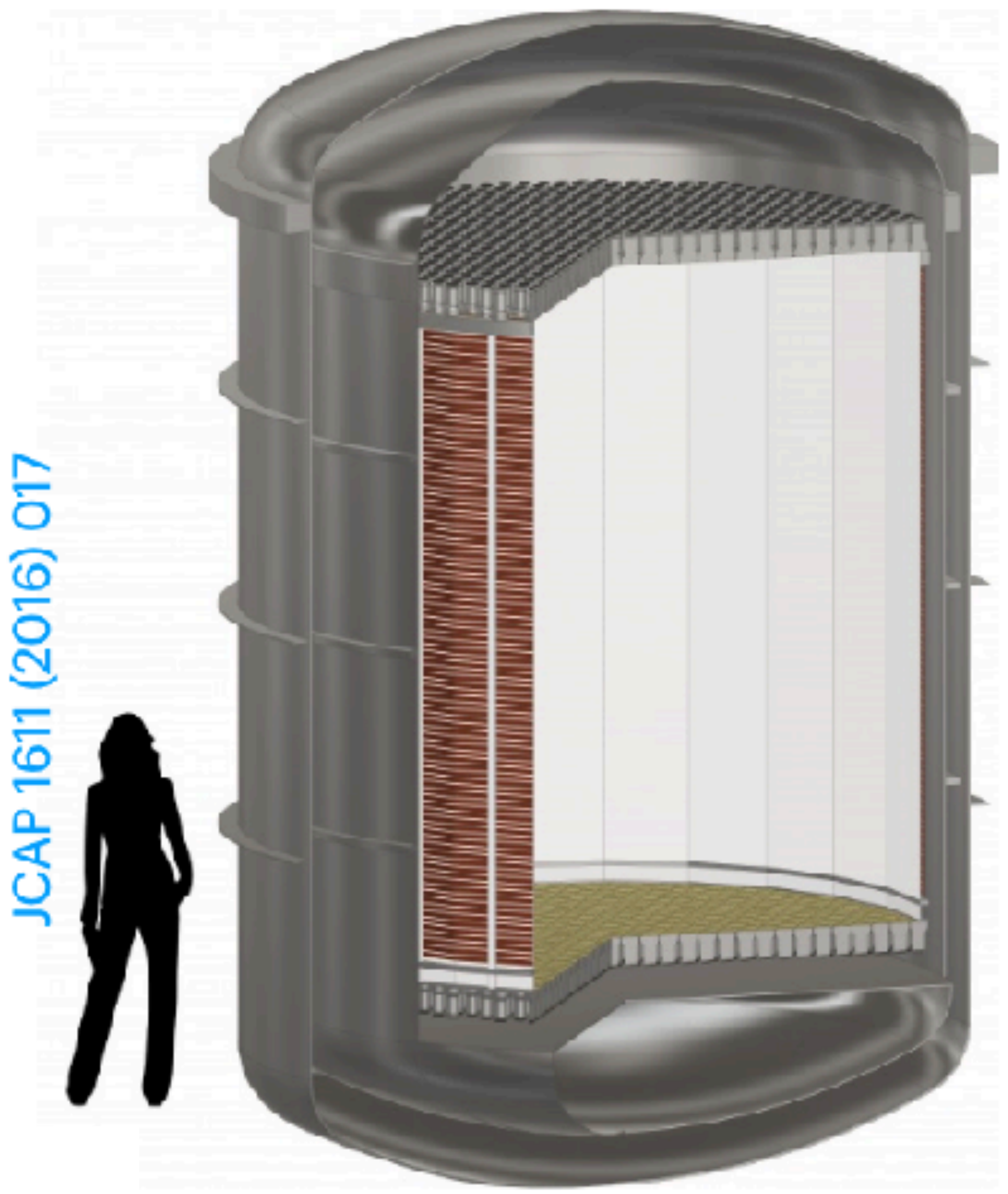
"APPEC strongly supports the European leadership role in Dark Matter direct detection, underpinned by the pioneering LNGS programme, to realise at least one next-generation xenon (order 50 tons) and one argon (order 300 tons) detector, respectively, of which at least one should be situated in Europe. 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."

G3 Dark Matter

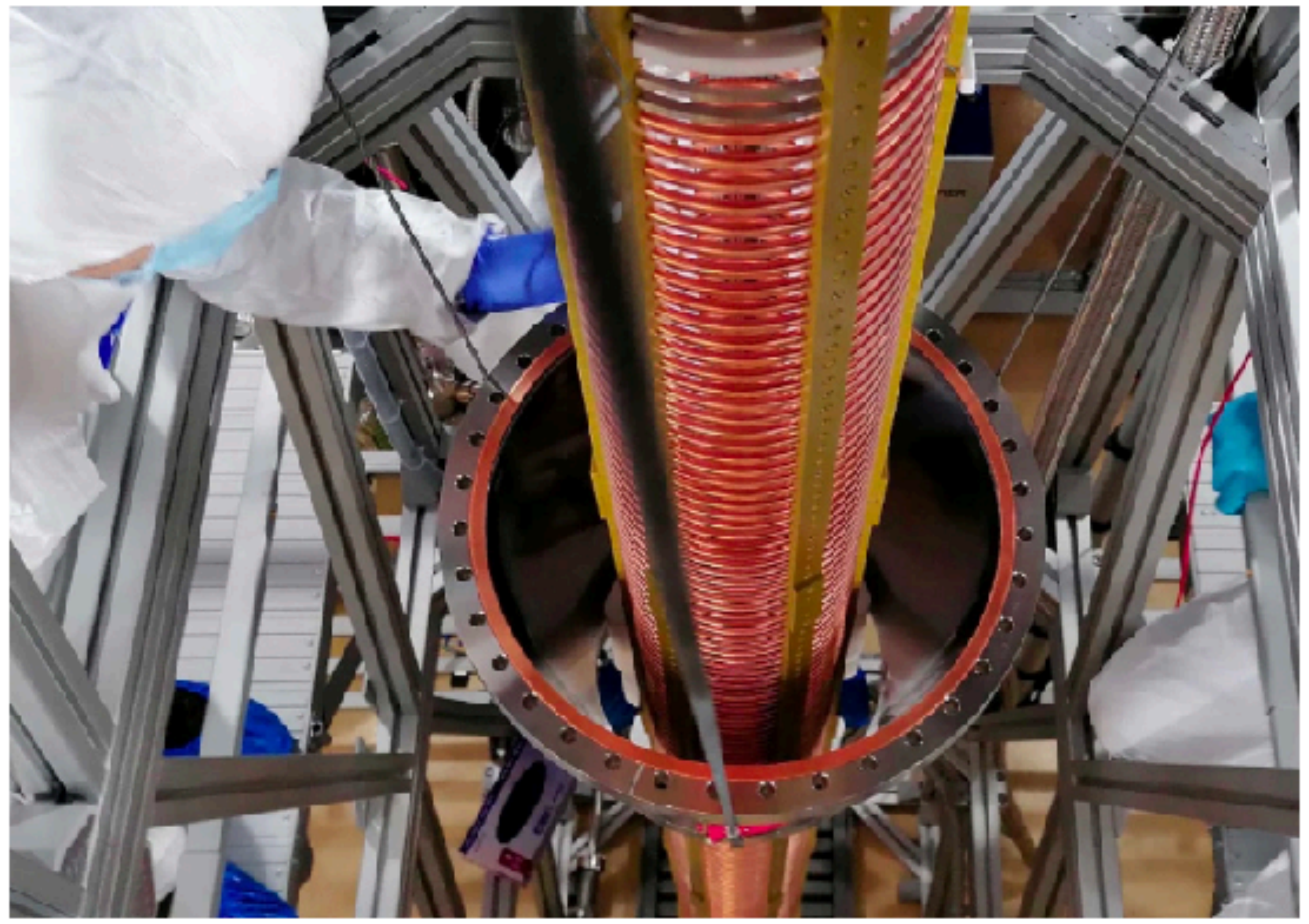
- From P5 Recommendation 2, Priority 4 out of 5 :
  - An **ultimate Generation 3 (G3) dark matter** direct detection experiment reaching the neutrino fog, in coordination with international partners and **preferably sited in the US**.
- DOE response and actions:
  - At the present time, based on the Snowmass Community Summer Study, there have been two proposals for G3 Dark Matter detectors : XLZD and ARGO
  - P5 recommended a **domestic site for the experiment in the higher funding scenario** and an international site in the lower funding scenario.
  - Start with site independent R&D as we understand the funding that will be available.
    - Engage with partners who are interested in hosting.
  - DOE will entertain proposals by U.S. groups for pre-project R&D.

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.



DARWIN collaboration
JCAP 1611 (2016) 017



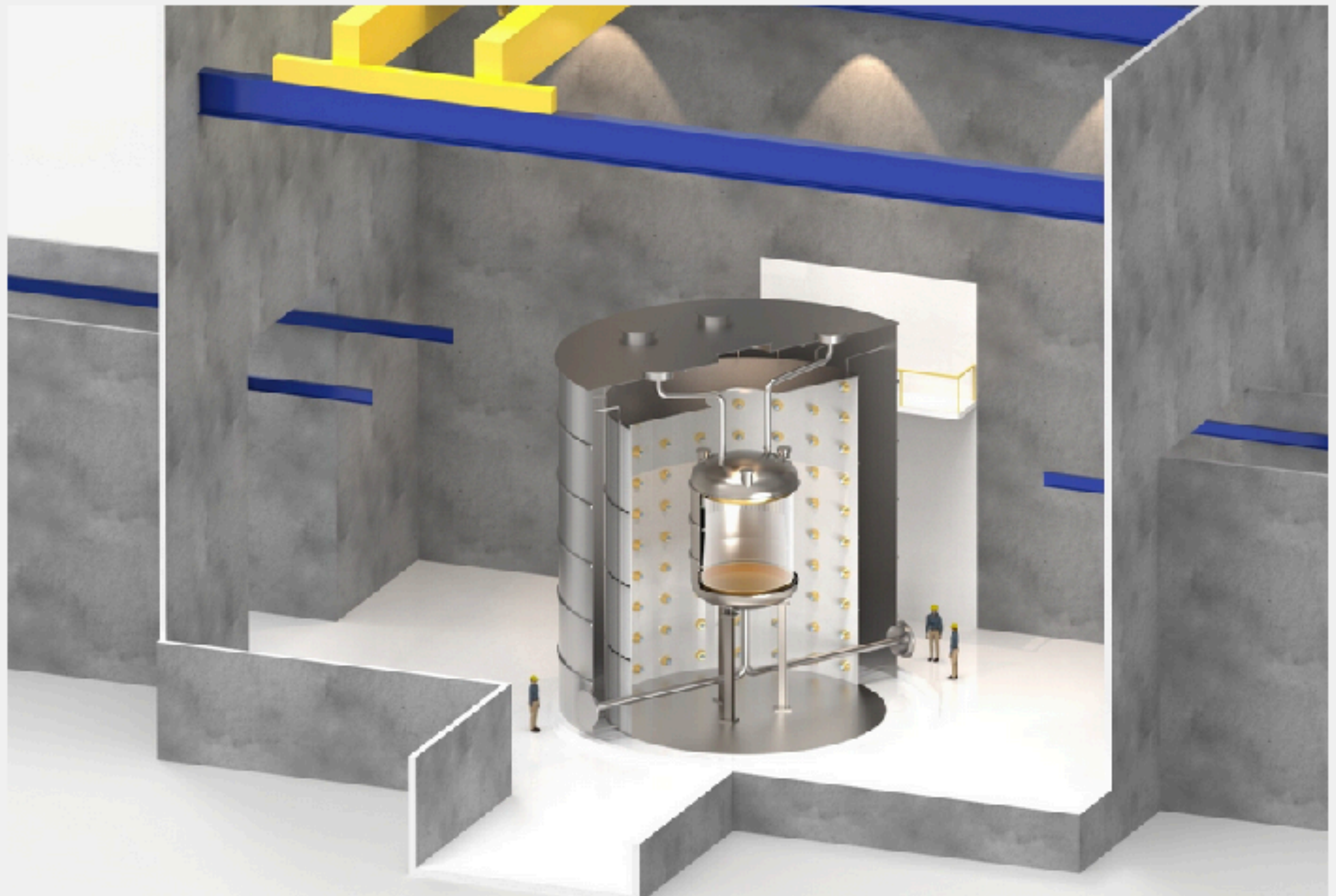
Xenoscope at UZH
L. Baudis et al., JINST 16, 2021, EPJ-C 83, 2023

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.



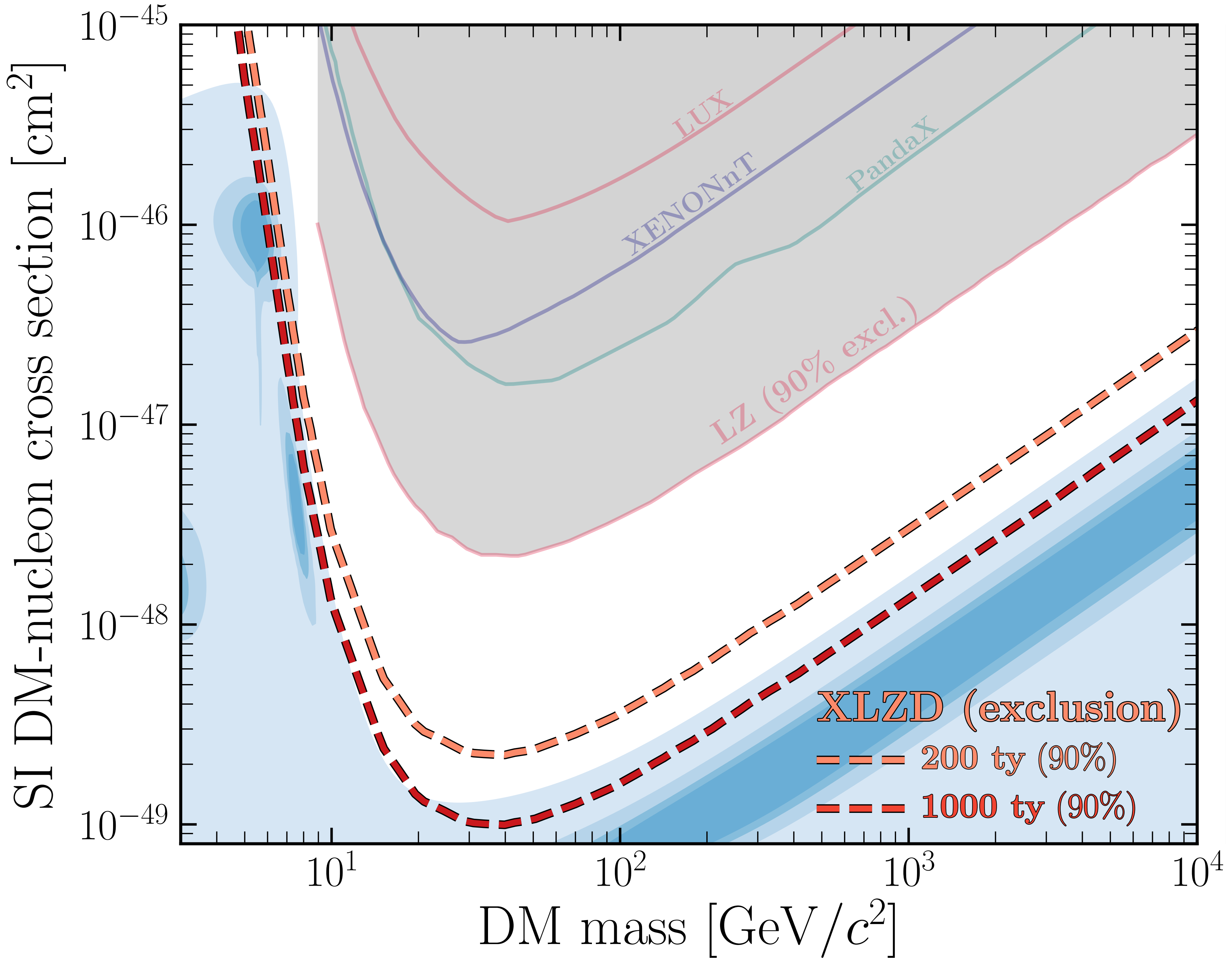
Several locations internationally are being considered to host this experiment, with the UK developing plans to potentially house the detector at STFC's Boulby Underground Laboratory.

The UK consortium, led by Imperial College

Related Sections
Projects and Mechanical Engineering (RAL)

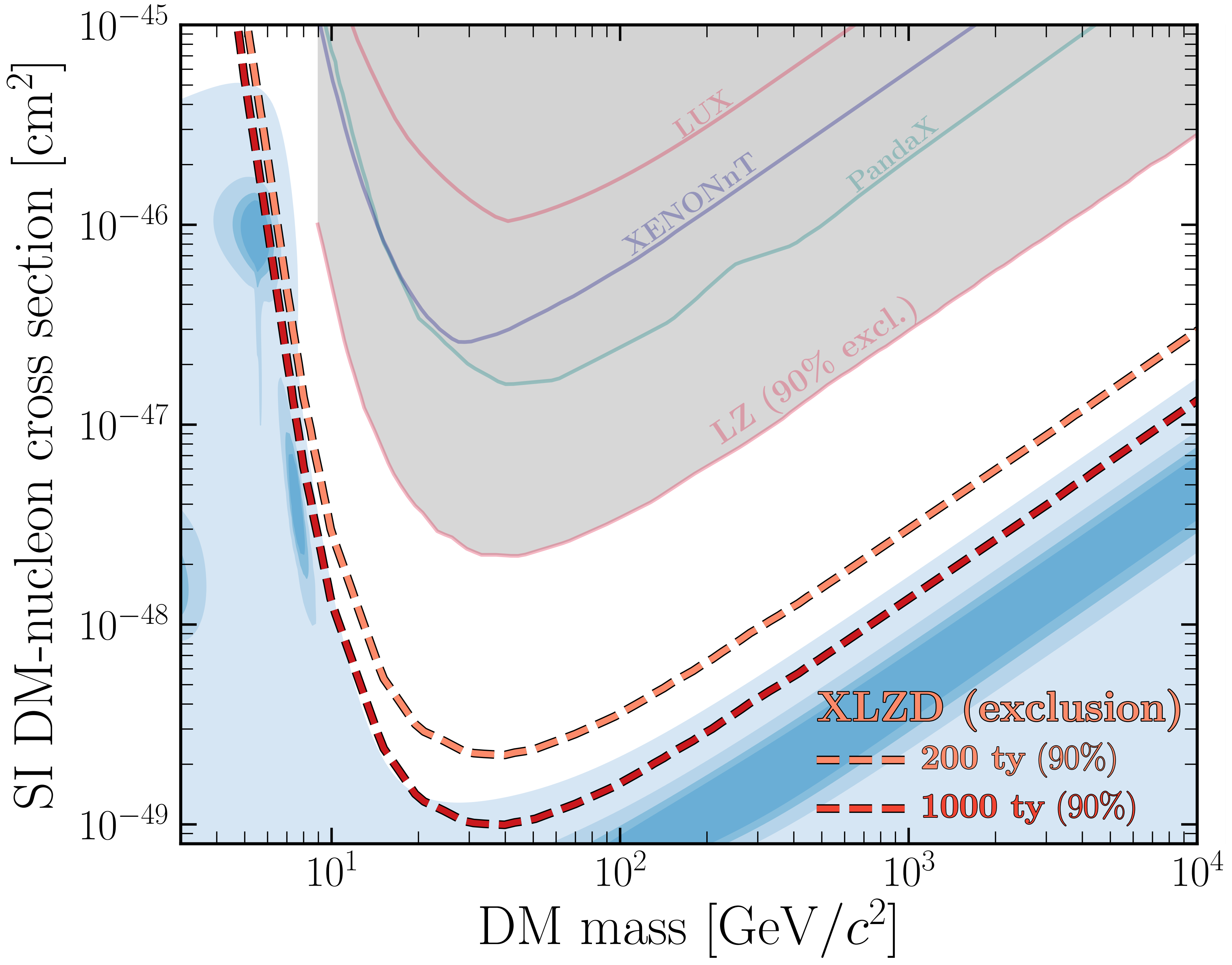
Related Content
HP Highlights

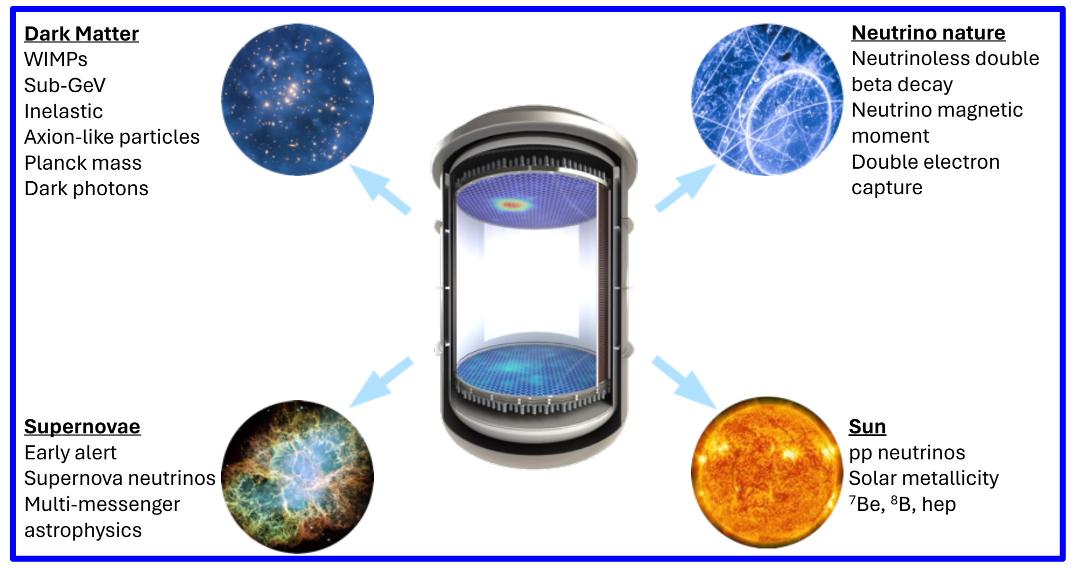
Definitive WIMP search is attainable, timely and competitive



Definitive WIMP search is attainable, timely and competitive

- WIMP science - potential for major discovery
- Scientific breadth - exciting additional goals
  - 0vBB is major goal, see 2410.19016





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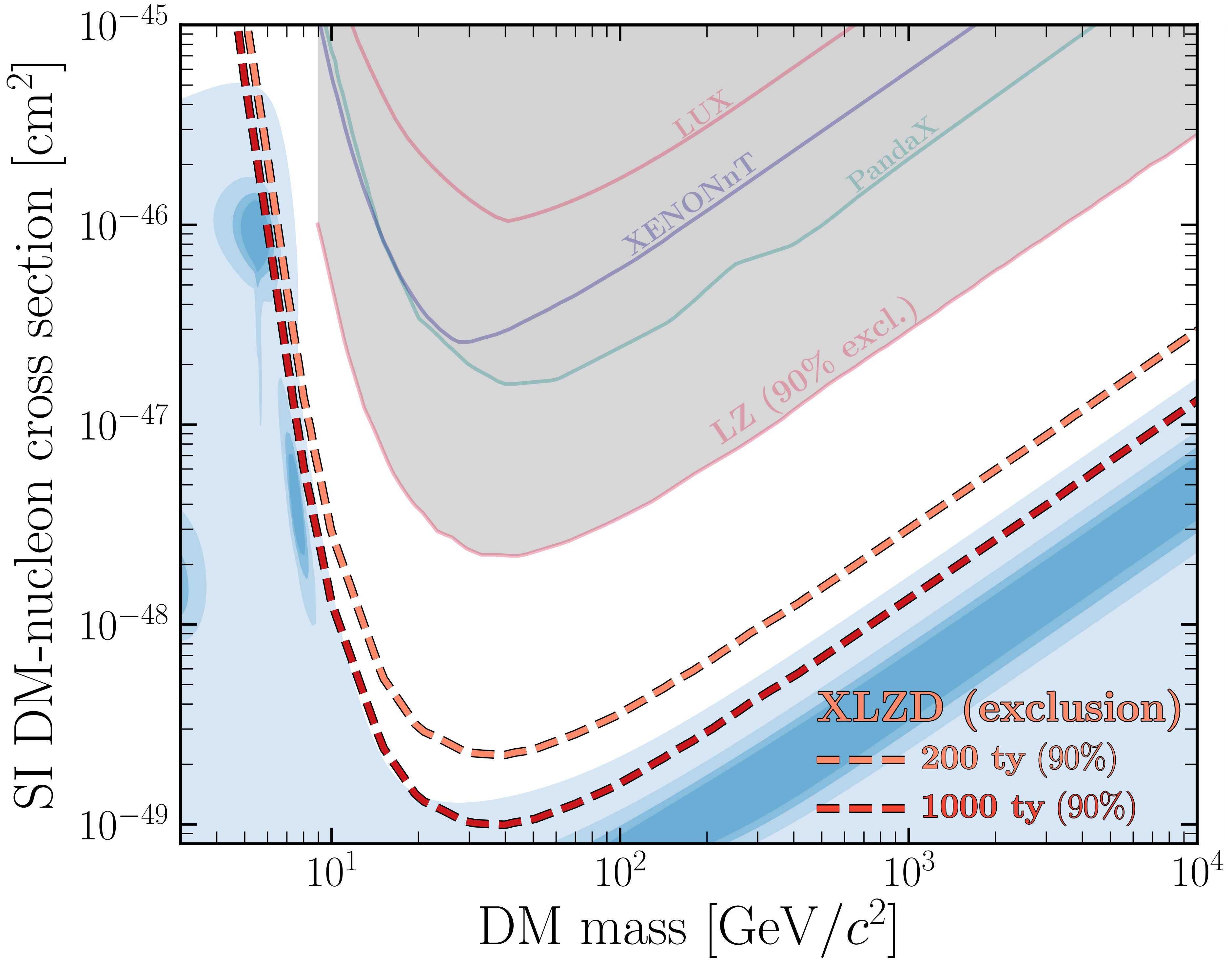

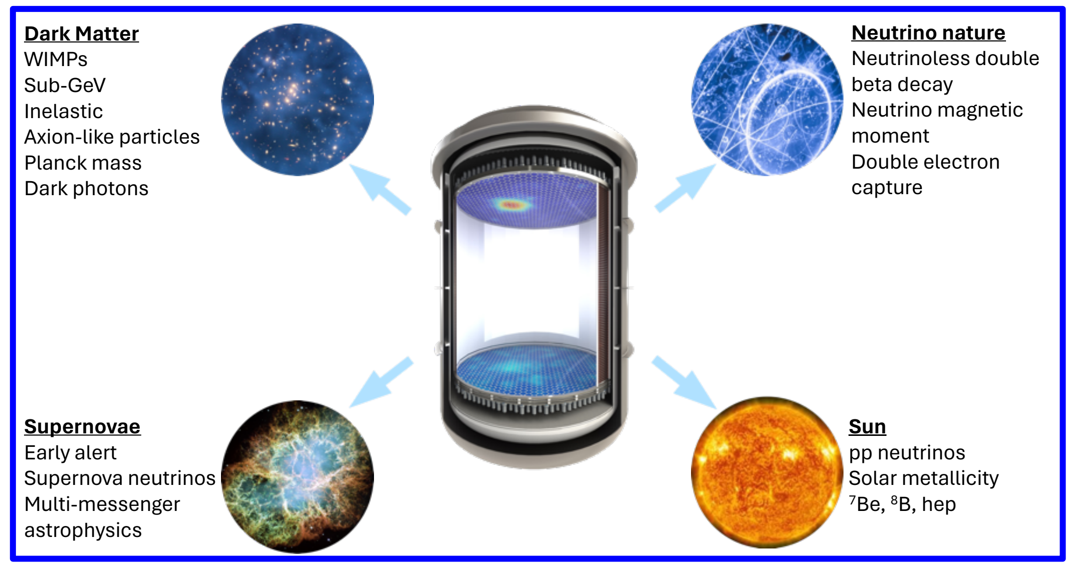

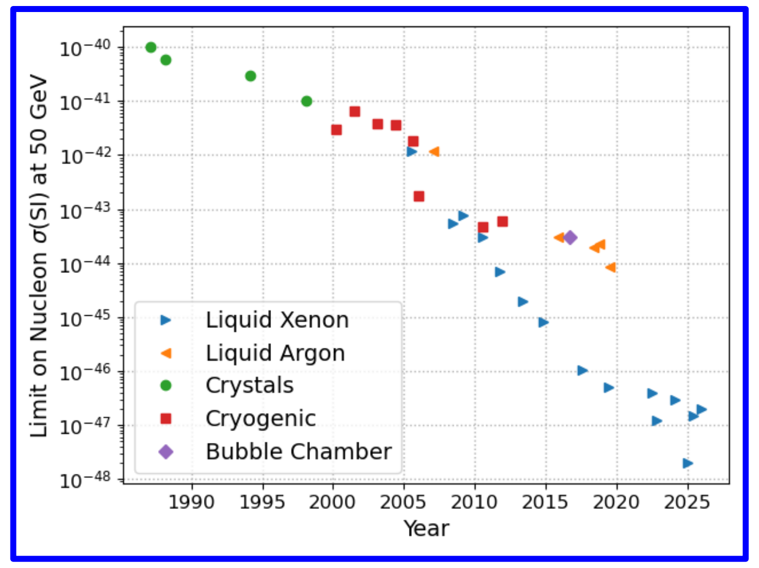

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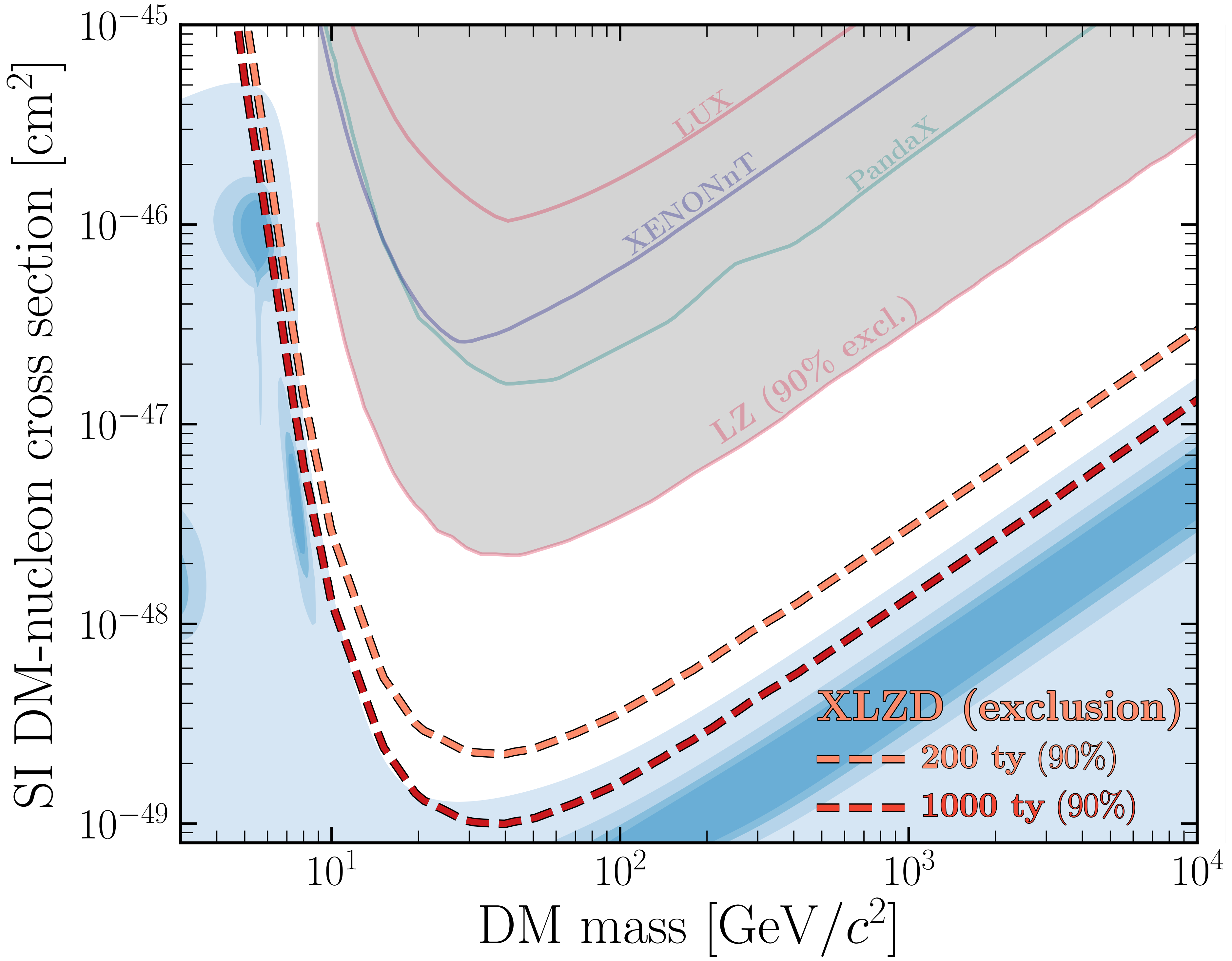

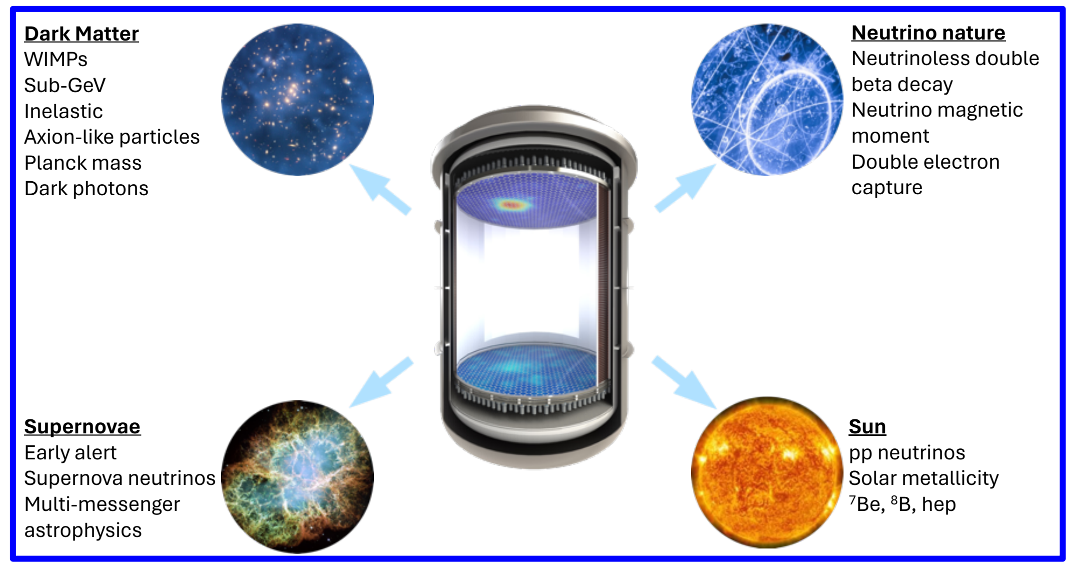

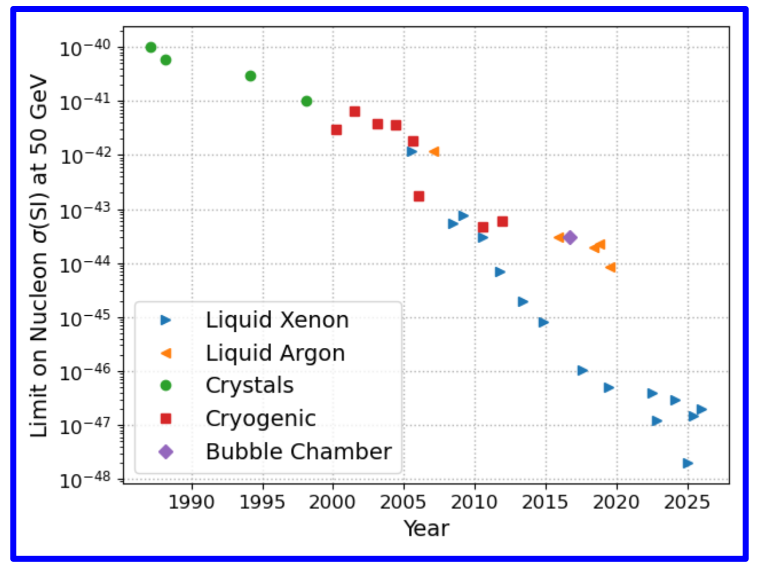

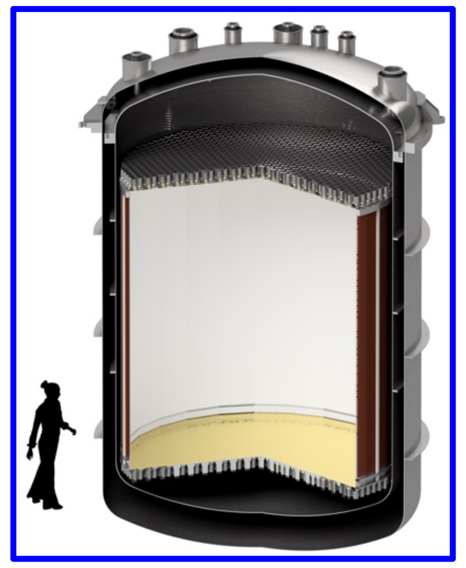

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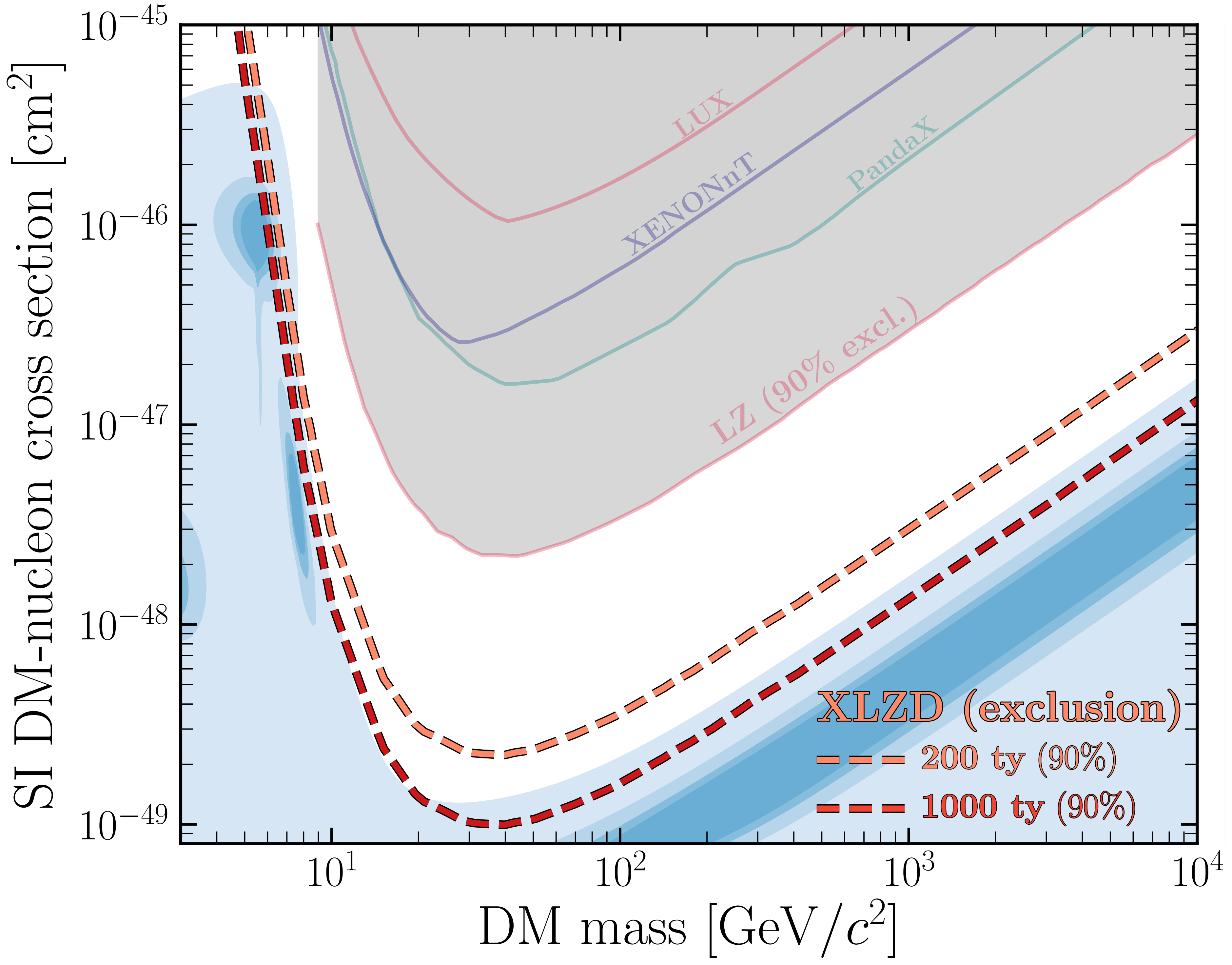

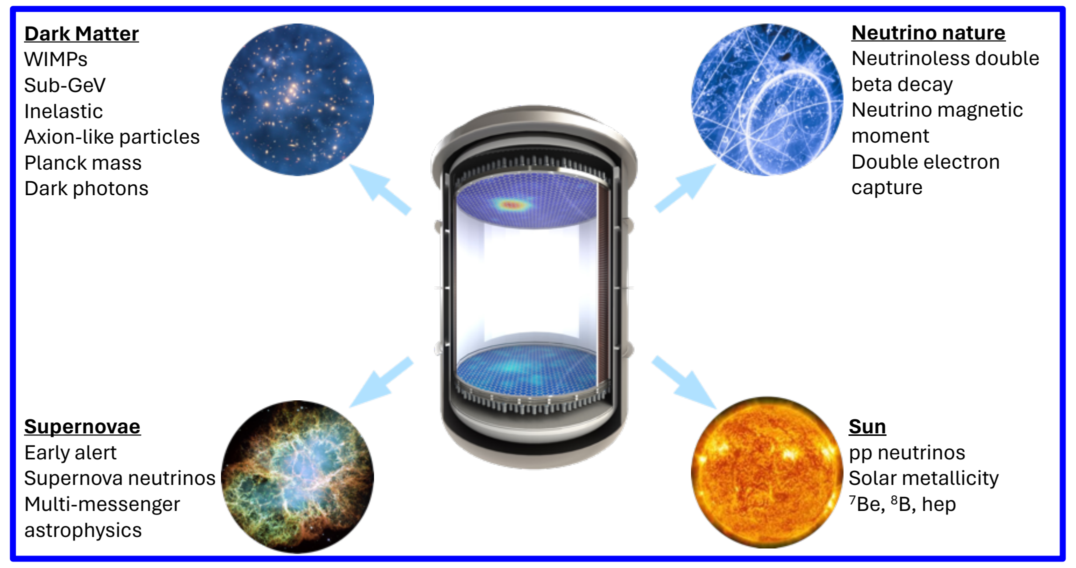

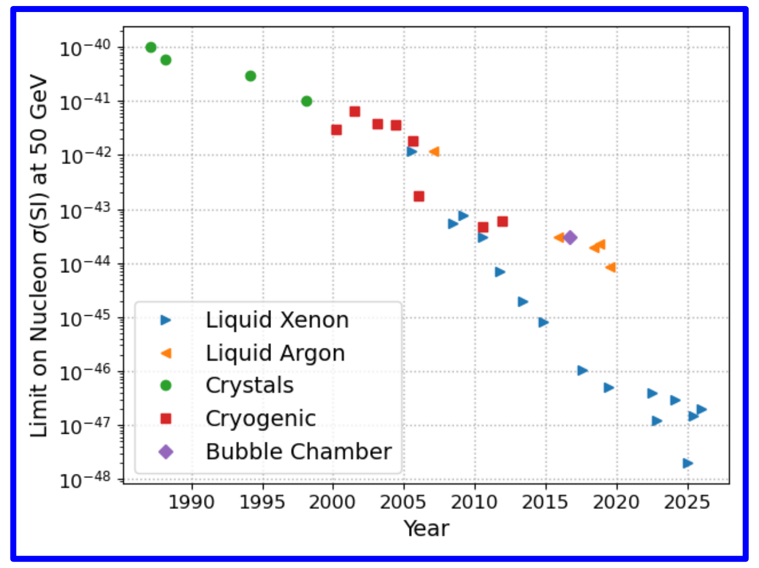

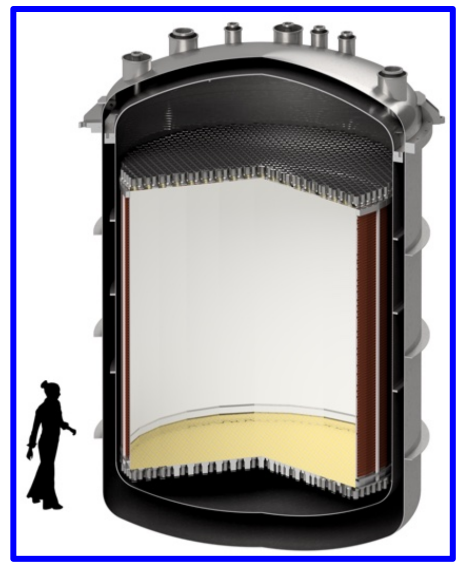

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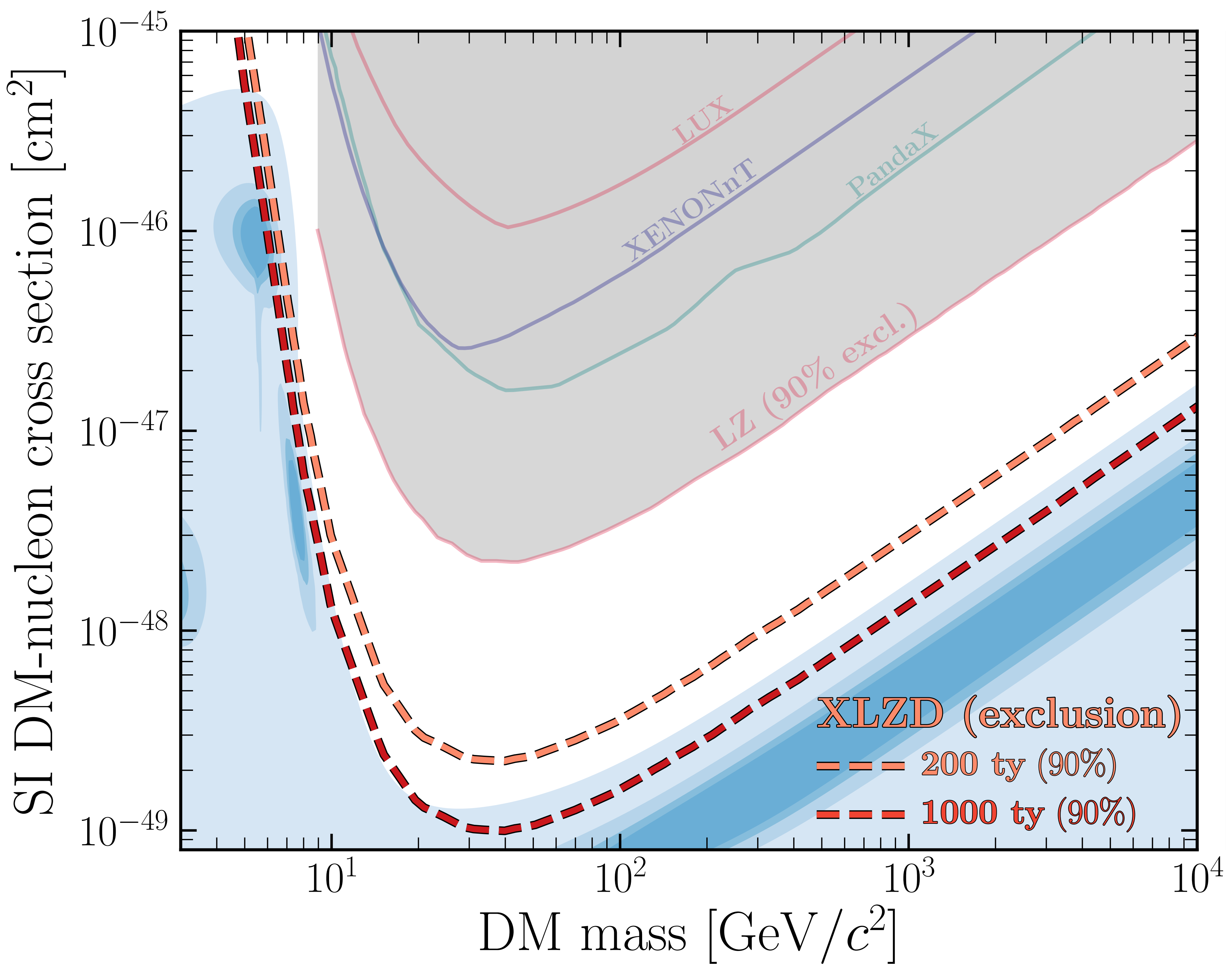

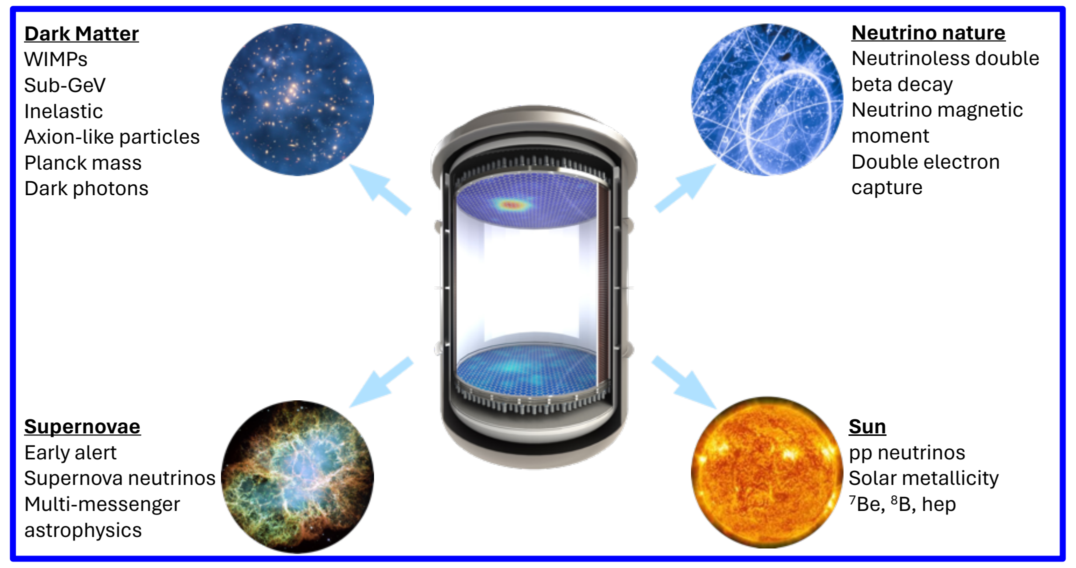

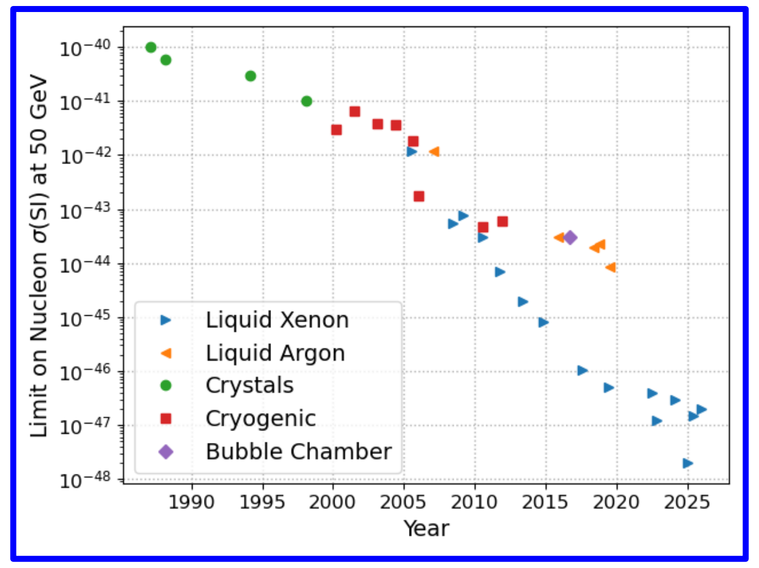

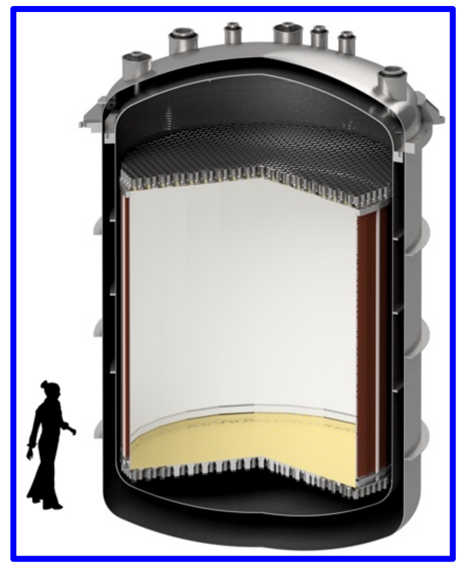

If WIMPs exist above the systematic limit of astrophysical neutrinos, XLZD will observe them.

The XLZD Collaboration

Countries: 17
Institutions: 76
Members: 440+

xlzd.org

2nd XLZD Meeting - UCLA, April 2023