The Future is Xenon!

Pathway towards reaching the neutrino floor with xenon*

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LIGHT DARK WORLD 2026

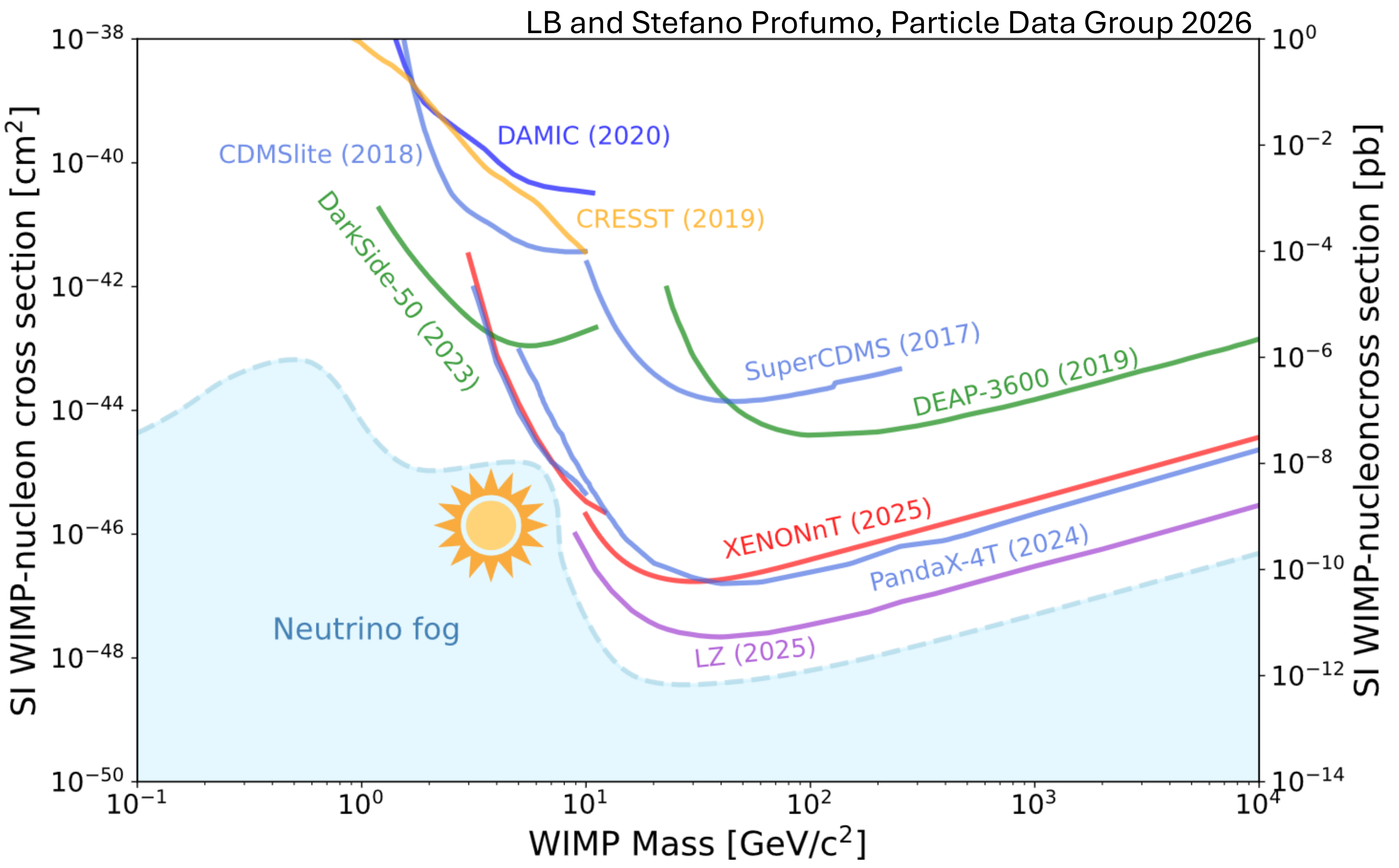
July 28th - July 31st

Carleton University

Ottawa, Canada

*Disclaimer: Canadian perspective is indicated with

Landscape of Dark Matter search

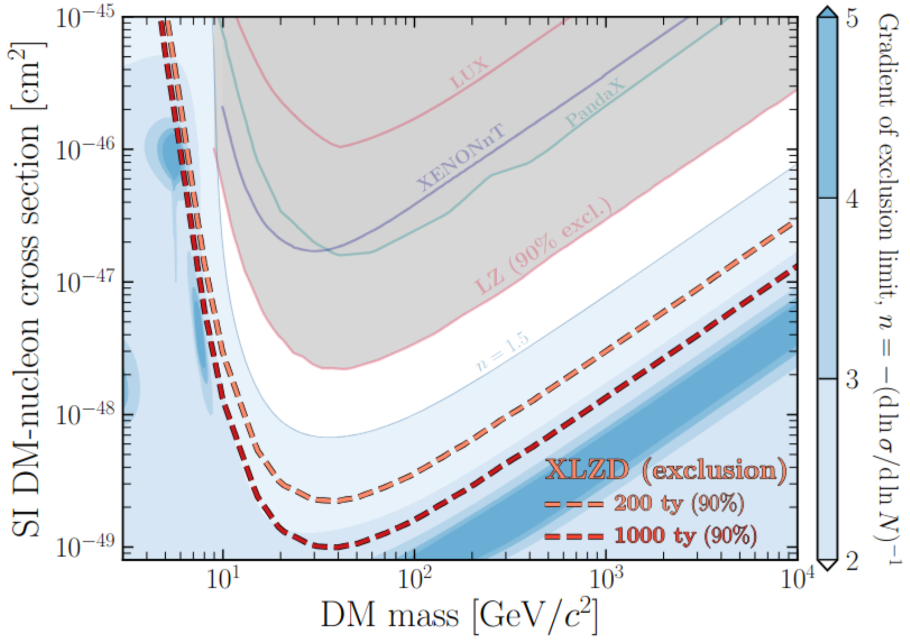


Noble Liquids

→ What does it take to teach the neutrino fog?

Sensitivity scales with detector mass

- Searching for WIMPs into the “fog”
  - Nearly indistinguishable background from astrophysical ν
  - Sensitivity rapidly falls - 20% ν flux uncertainty
  - Systematic limit (1,000 tonne-year exposure)
    = practical limit of ~100-tonne detector
  - 3-sigma discovery at 3x10^{-49} cm^2 at 40 GeV



- Next generation of DM experiments
  → Order 50-100 tonnes of Xe
  → Order 300 tonnes of Ar

Assuming technology generally demonstrated

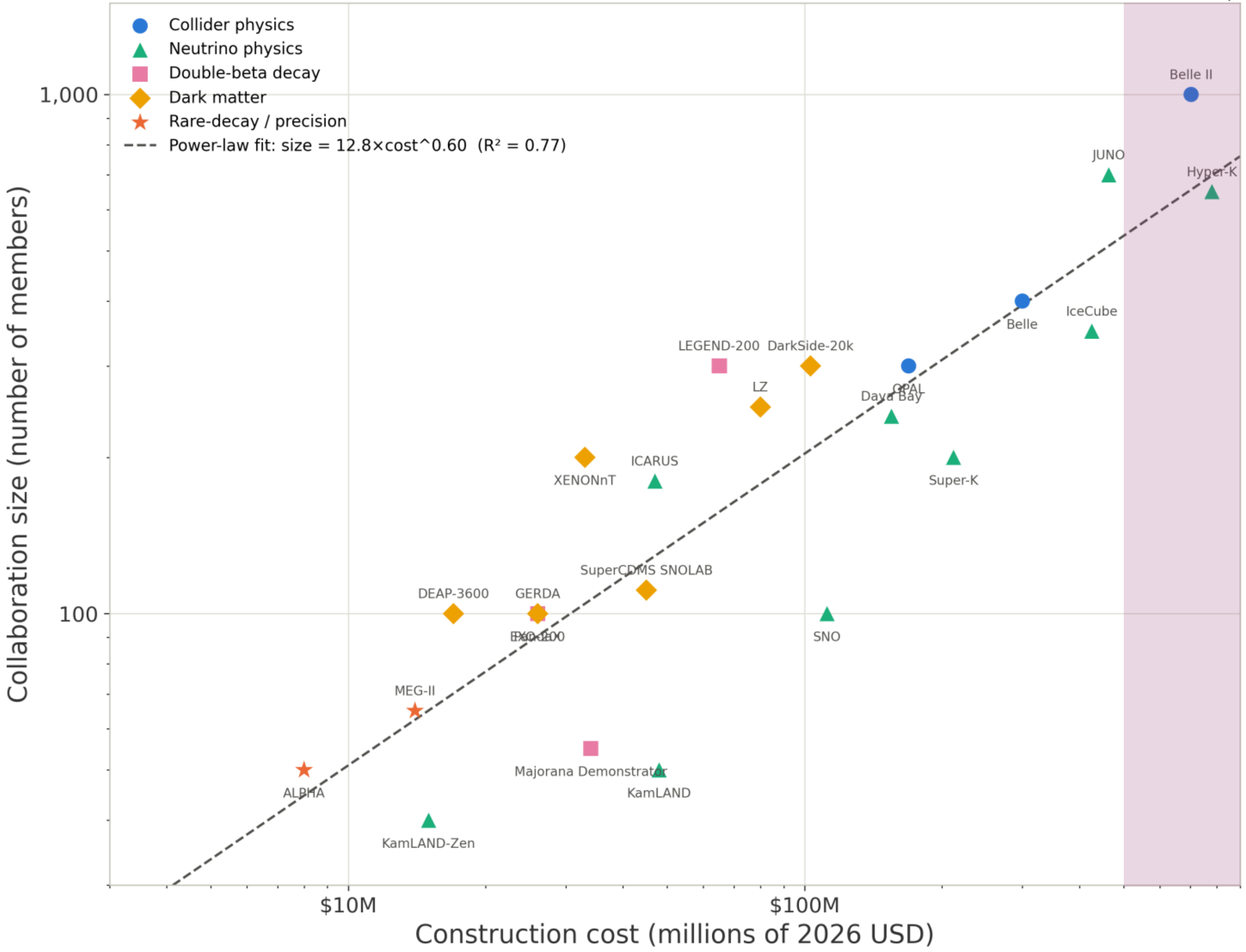
Scale of next-generation experiments determines cost of future experiments on the order of \$0.5-\$1B.

Empirical cost-collaboration size relationship

- Claude.ai generated plot of relationship between collaboration size and cost of experiment.
- Relationship:

  “$1M ≈ 1.3 members“
- Order $0.5B experiment requires ~650 scientists.

Inflation corrected to 2026 $



Global Dark Matter Community

- Claude.ai prompt: how large are current DM collaborations?
- "Distinct experimentalists working on WIMP direct detection worldwide is [...] in the **800–1,200 range**."

→ Without growing community, only 1 or maybe 2 next-generation WIMP DM experiments are plausible.

→ Realization of next-gen. experiment:

1) Consolidation of community.

2) Other physics channels?

Experiment	Collaborators
LZ	~250
DarkSide-20k	~300
XENONnT	~200
SuperCDMS SNOLAB	~111
PandaX-4T	~100–150
DEAP-3600	~100
EDELWEISS	~50
CDEX	~50
PICO	~50
CRESST	~30
NEWS-G	~30
SABRE	~30
COSINE-100	~40
DAMA/LIBRA, ANAIS	~20 each

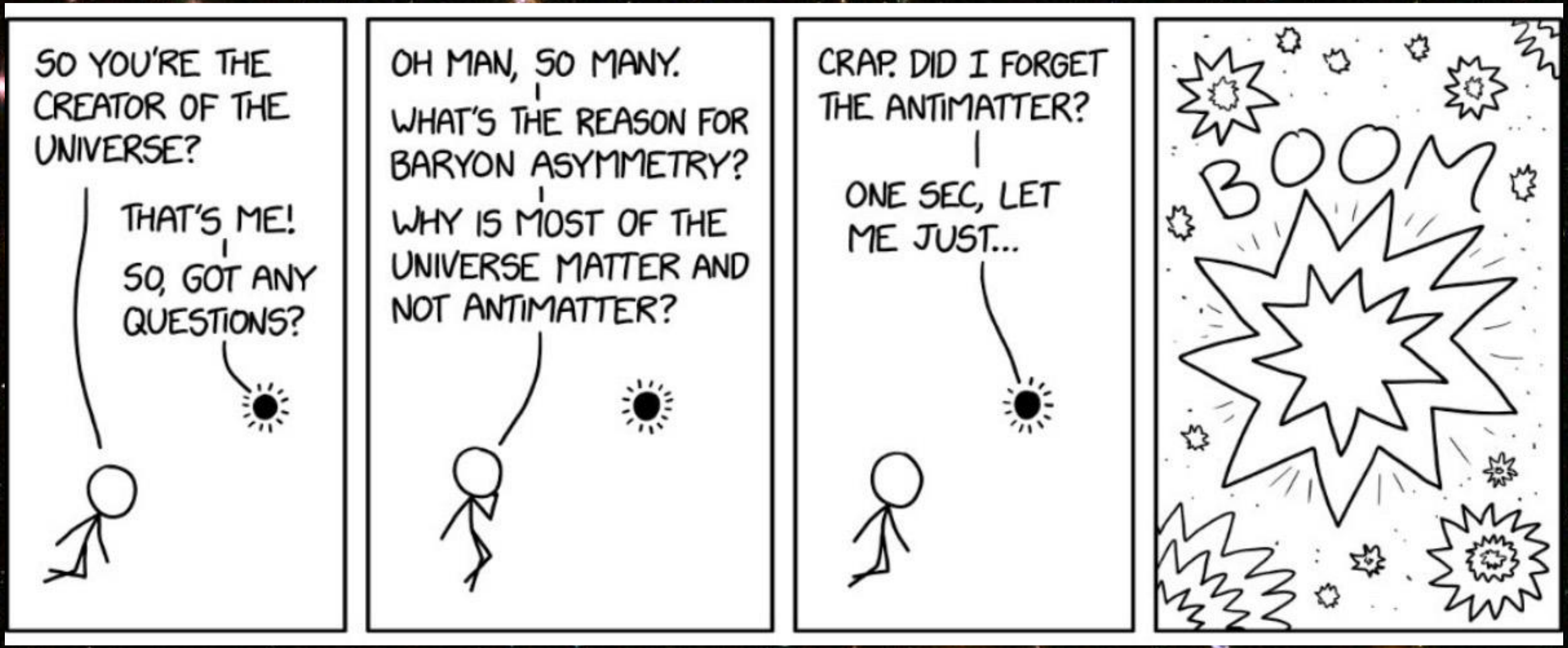
The universe is full of matter…

(and dark matter)

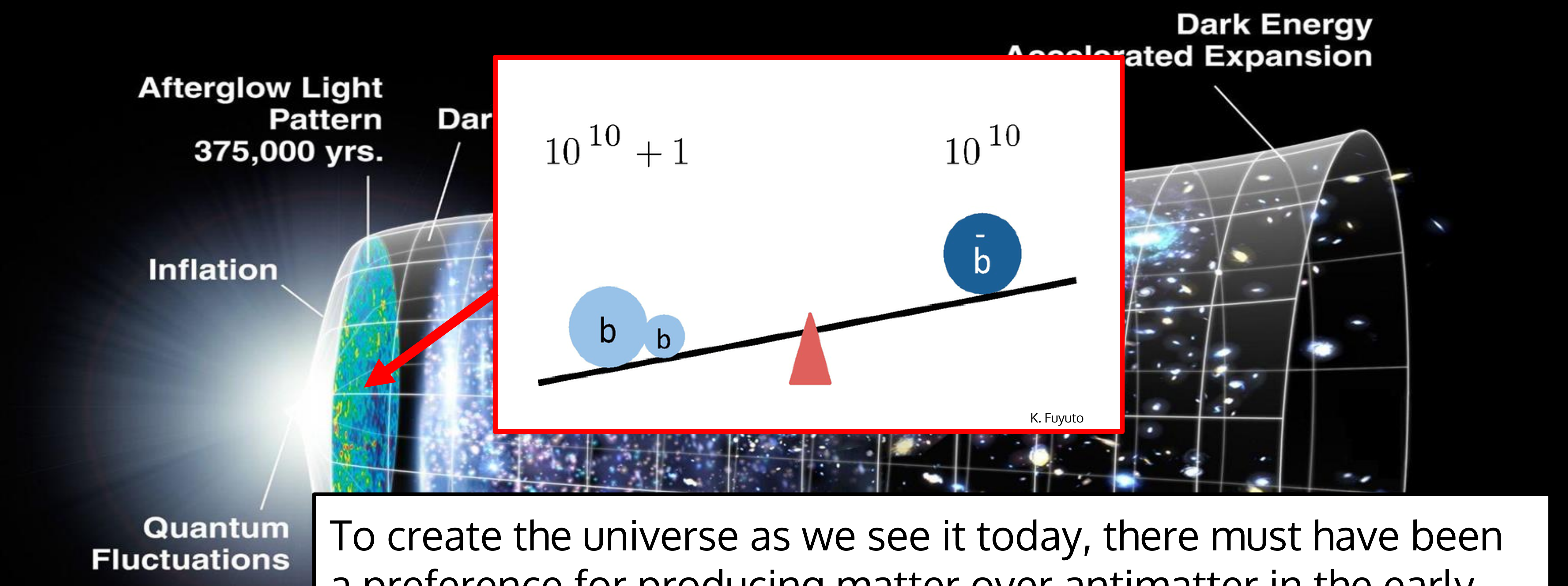
…but no antimatter?

The universe is full of matter…

(and dark matter)



…but no antimatter?



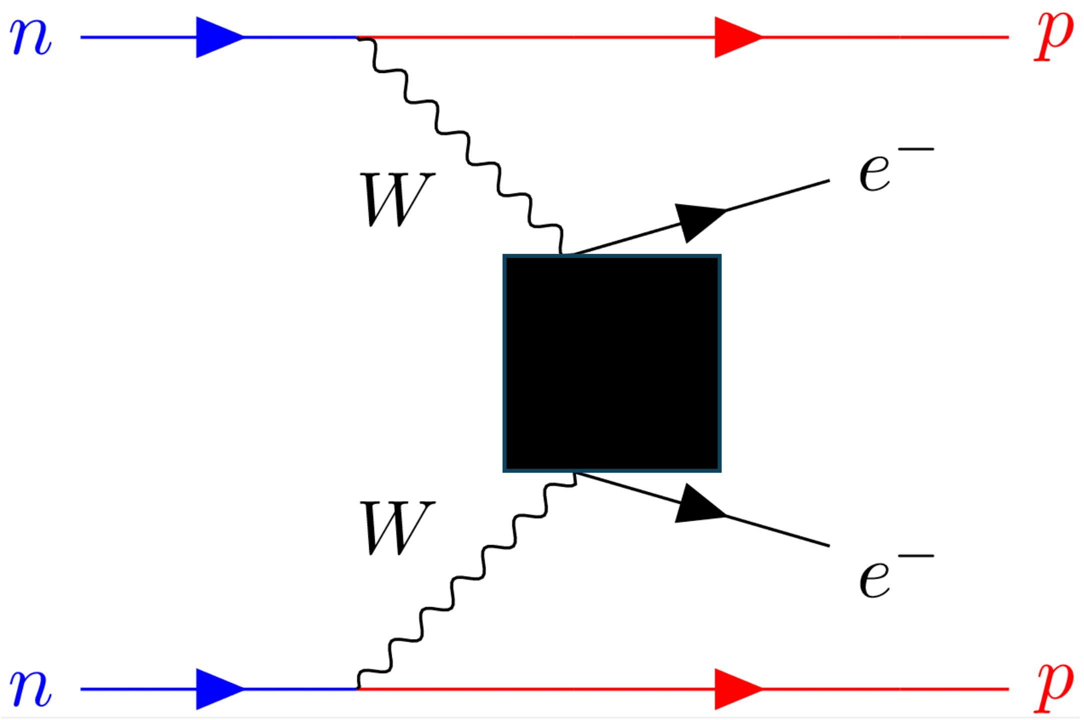
To create the universe as we see it today, there must have been a preference for producing matter over antimatter in the early universe, at the level of one part in 10^{10}.

This is the so-called “baryon asymmetry problem.”

We need something that produces more matter than anti-matter.

0νββ could help explain matter dominance

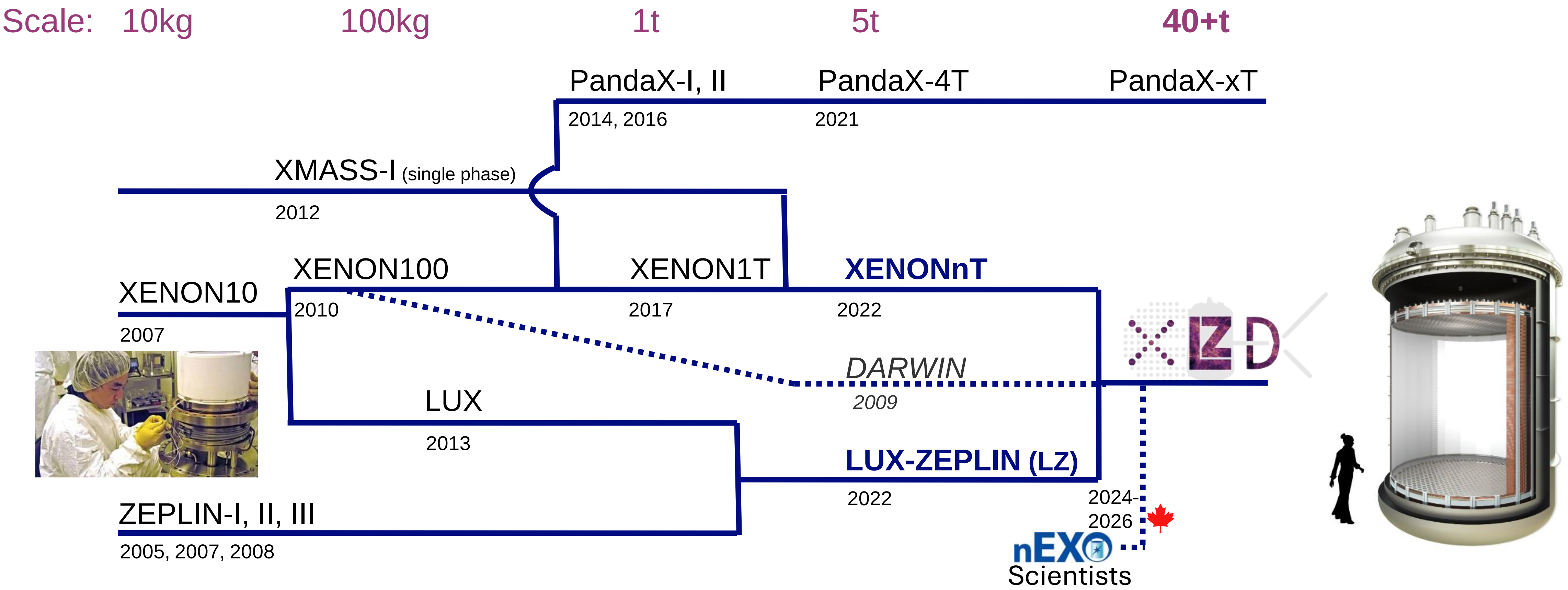
- "Black box" theorem*: Observation of 0νββ always implies **new physics**:
  - Majorana neutrinos
  - Lepton number violation
  - Help explain observed cosmic baryon asymmetry → leptogenesis



Natural xenon consists to 8.9% of ββ-decaying isotope ^{136}Xe
→ combine search for two high-priority physics channels in one experiment

*J. Schechter, and J. W. F. Valle, Phys. Rev. D25, 2951 (1982)

Consolidation: The LXe Family Tree



13 very successful LXe dark matter detectors in ~20 years!

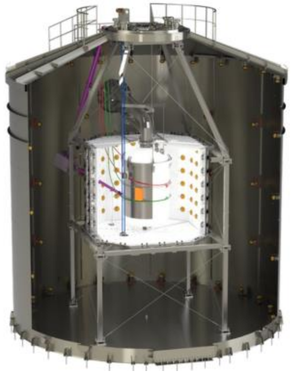
Note: timelines are only indicative,
years indicate publication of first science results

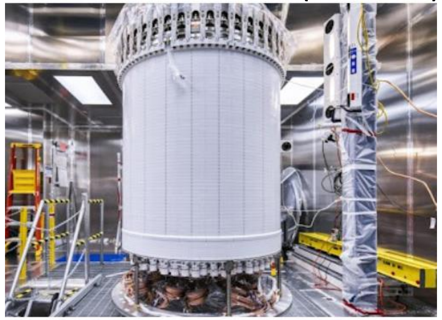
Xe as the ideal detection medium

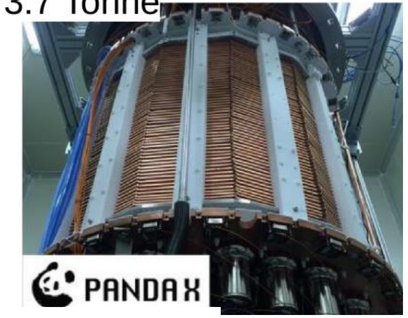
- Xe has a well established track record as WIMP DM technology.
- Some of the most competitive 0νββ limits come from Xe experiments (90% CL):
  - PandaX-4T $T_{1/2} > 2.1 \times 10^{24}$ yr (44.6 kg x yr)
  - EXO-200 $T_{1/2} > 1.6 \times 10^{25}$ yr (32.5 kg x yr)
  - EXO-200 $T_{1/2} > 3.5 \times 10^{25}$ yr (234 kg x yr)
  - *KamLAND-Zen* *$T_{1/2} > 3.8 \times 10^{26}$ yr (2.1 t x yr)*
- **Liquid noble TPC – a demonstrated technology at and beyond the tonne scale.**

0νββ results:
EXO-200: 1205.5608, 1906.02723
PandaX-4T: 2412.13979
KamLAND-Zen: 2406.11438

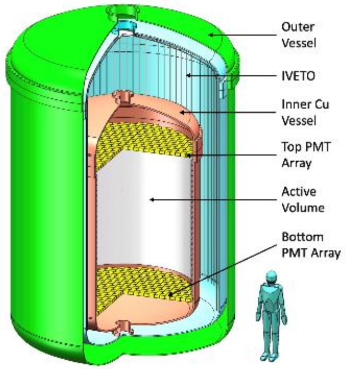
Current Generation Experiment


XENONnT
(6 Tonne)

LZ (7 Tonne)


3.7 Tonne


Next Generation Concepts



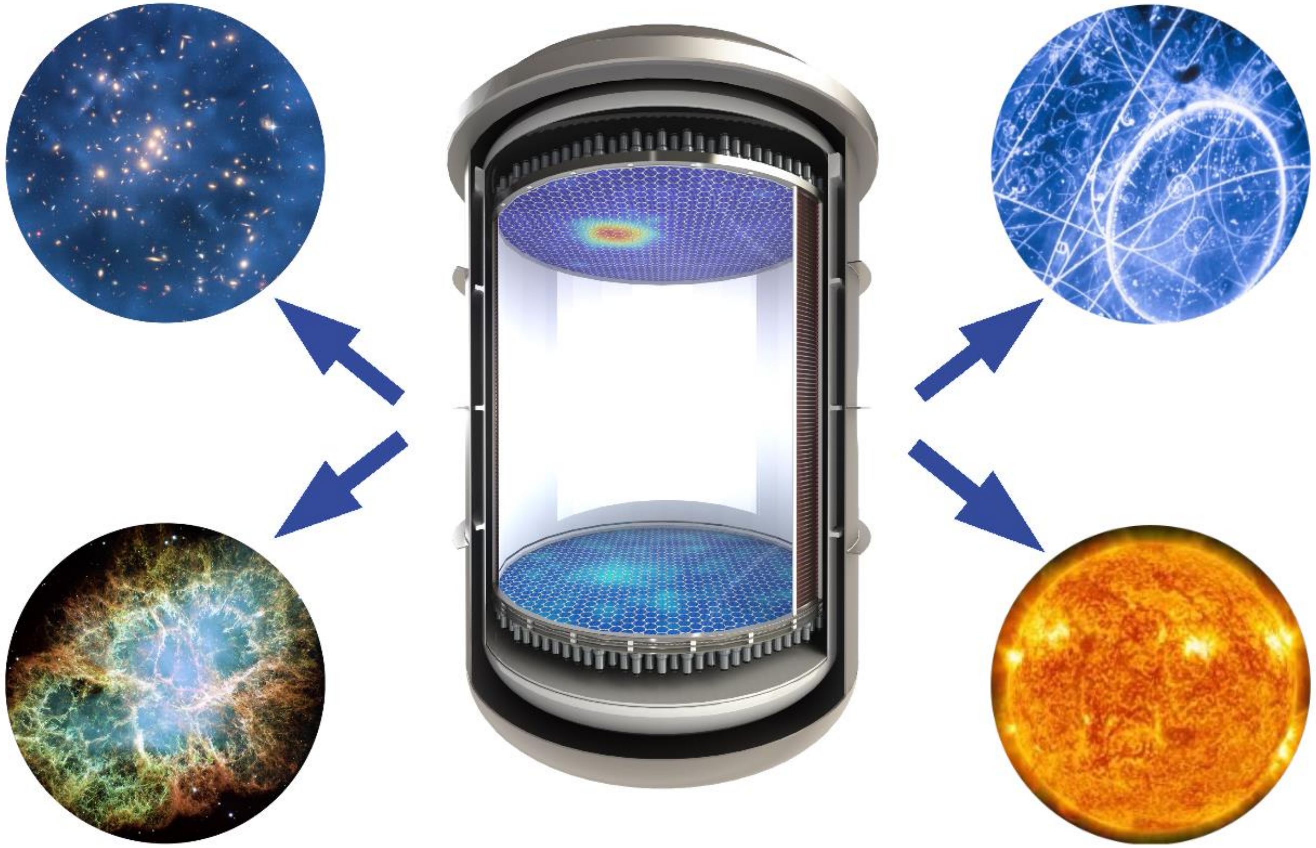
PandaX-xT
(43 Tonne)


XLZD
(60 Tonne)

XLZD Observatory

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

Supernovae
Early alert
Supernova neutrinos
Multi-messenger
astrophysics



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

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

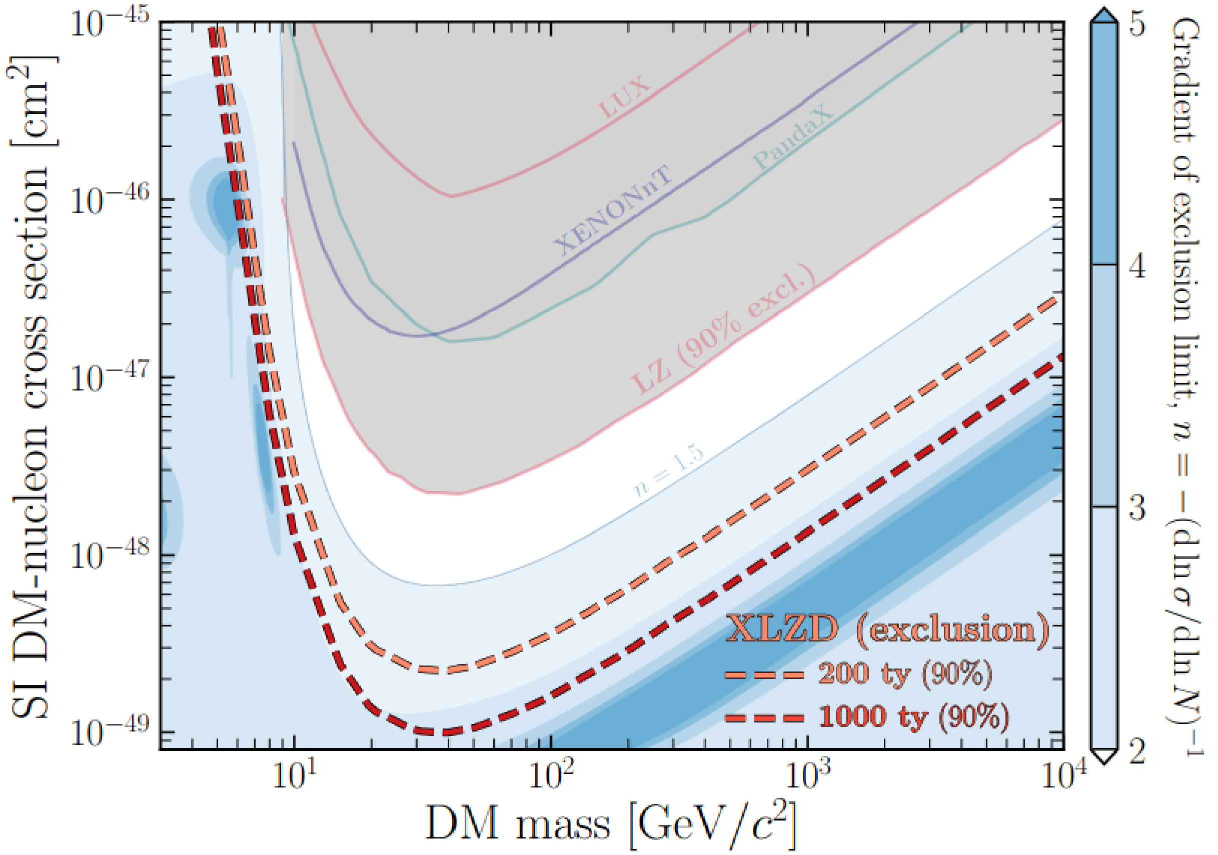
A xenon-based low-background observatory for rare events.

For detailed information see J. Phys. G 50, 013001 (2023), XLZD design book: arXiv:2410.17137

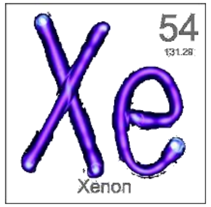
54
131.29
Xe
Xenon

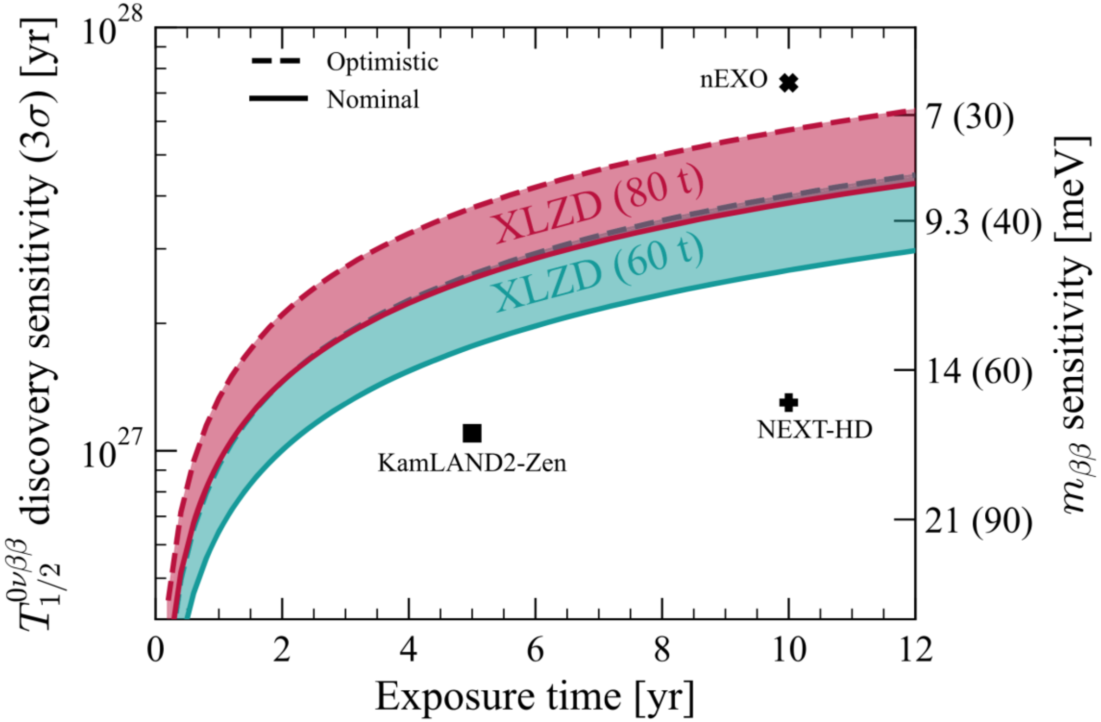
Dark Matter Reach

- Excellent sensitivity for spin-independent and spin-dependent WIMP scattering
- Explores parameter space **into the neutrino fog**
- Minimum exposure: 200 t×y, aim for ~500 t×y
- **Definite detector**: up to 1000 t×y in case hint of signal is seen earlier

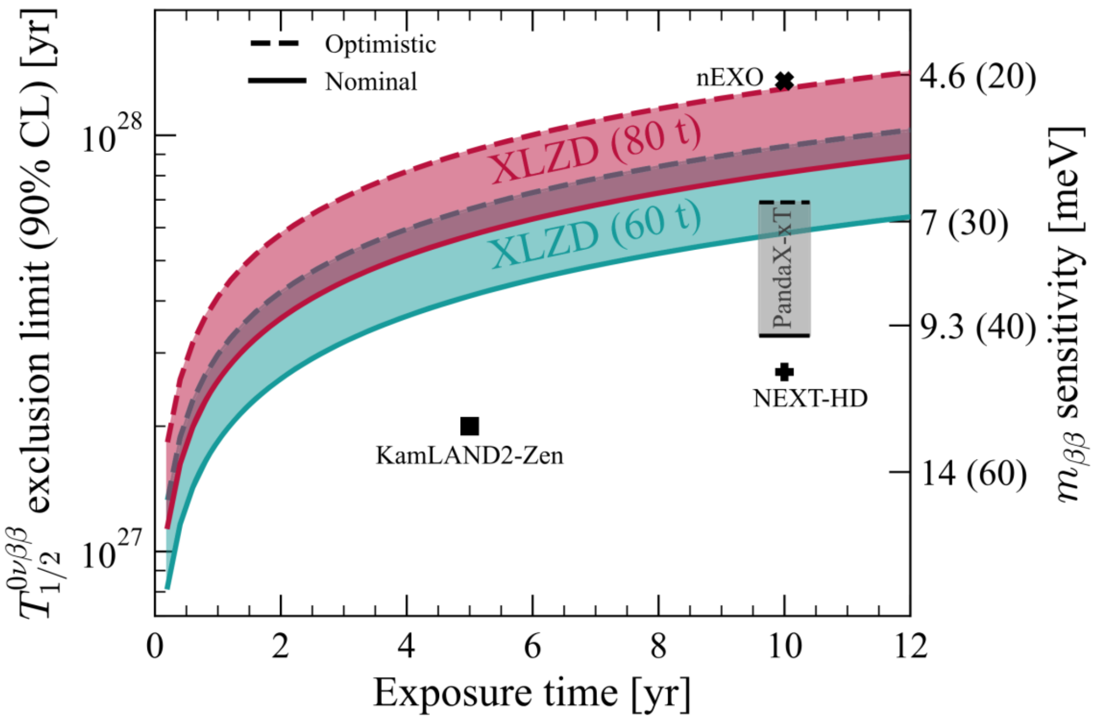


0νββ Sensitivity Projections





J. Phys. G 52, 045102 (2025)



DM/MP

Experiment	Natural Xe	Xe-136 in detector
XLZD	60 t	5.3 t
XLZD	80 t	7.1 t
PandaX-xT	43 t	3.8 t

0νββ

Experiment	Xe-136 in detector
KL2Z	0.68 t
nEXO	3.4 t (90% enr.)
NEXT-HD	0.9 t*

Quo Vadis 0νββ Search? ... it's more complicated.

Current Limit

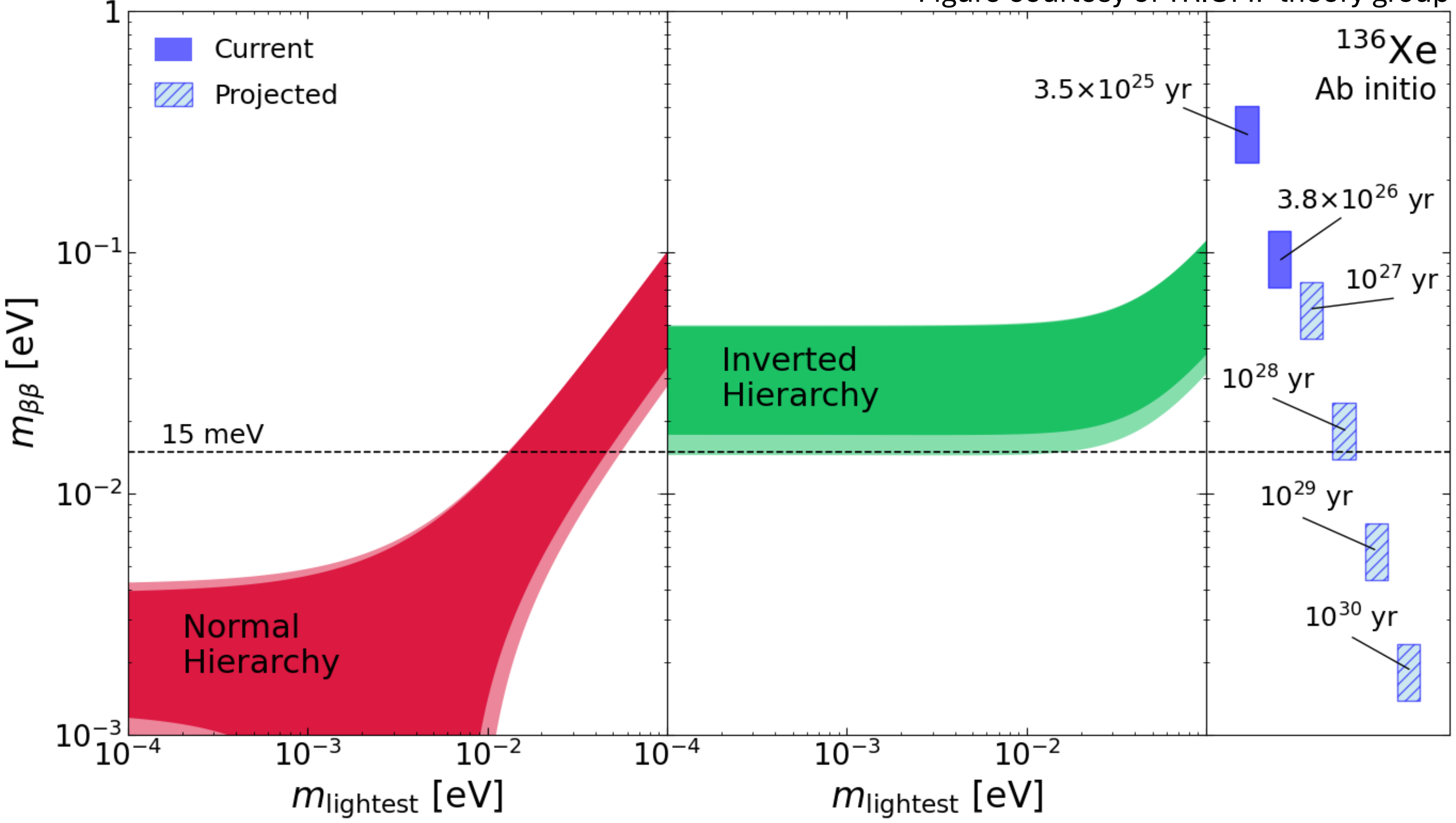
Next-Generation

We know how to do this technically, but funding unclear

Ultimate Experiment?

The ultimate goal in 0νββ of ~1 meV

Figure courtesy of TRIUMF theory group



Deeper 0νββ Physics Reach

$$\left(T^{0\nu}_{1/2}\right)^{-1} = \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} G^{0\nu} g_A^4 |M^{0\nu}|^2$$

Phase space factor

Axial coupling, $g_A = 1.27$

NME

Disclaimer: Effective Majorana mass $\langle m_{\beta\beta}\rangle$ is an effective, albeit imperfect, metric to compare physics reach between isotopes and experiments.

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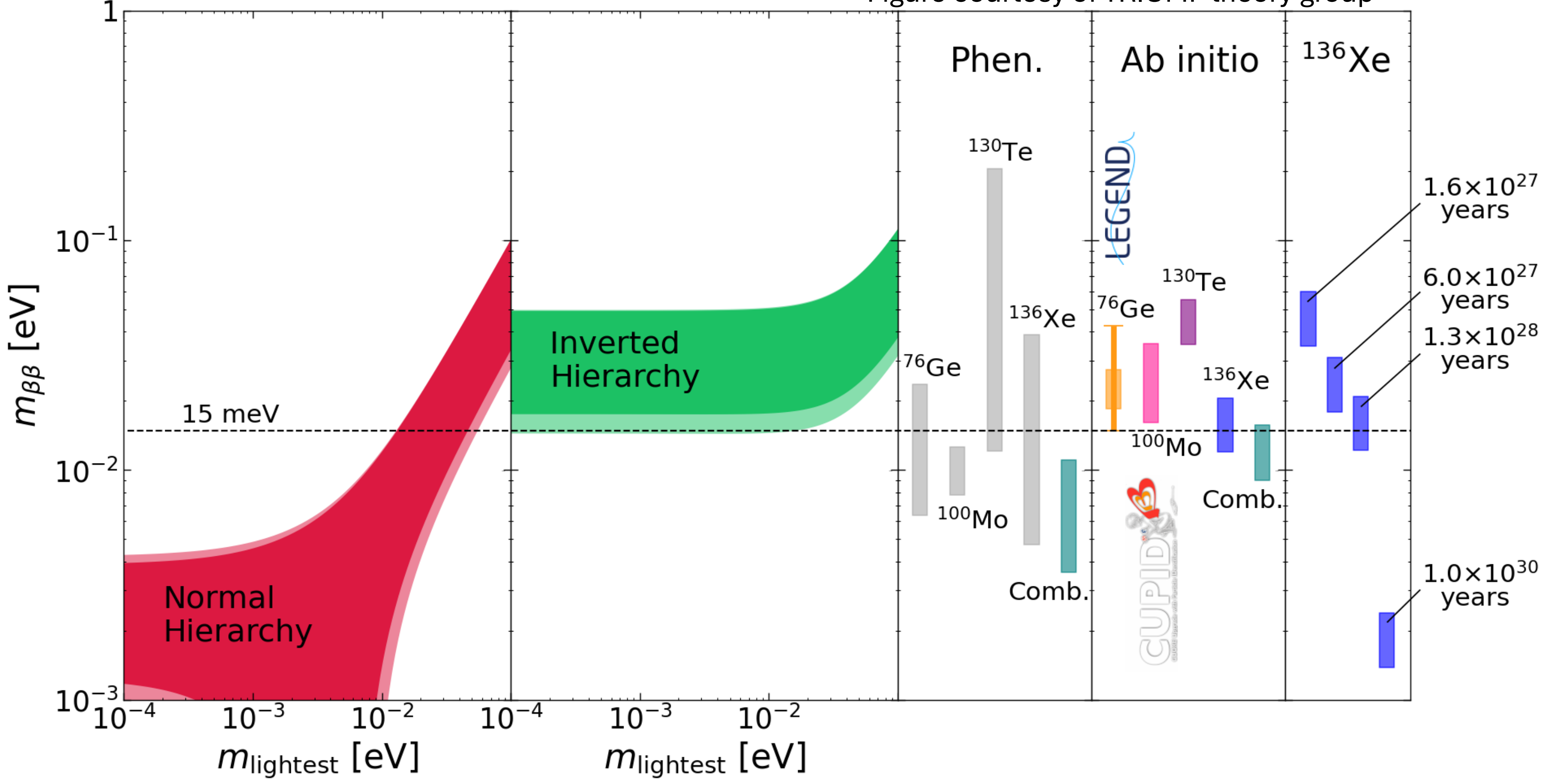

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} G^{0\nu} g_A^4 |M^{0\nu}|^2$$

NME

Phase space factor

Axial coupling, $g_A = 1.27$

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XLZD enables a step change in 0νββ sensitivity

- Sensitivity ultimately scales with exposure (number of atoms x time).
- XLZD detector scale alone enables access to 10^{28}-year regime with $^{nat.}$Xe.
- Isotope enrichment can provide an additional order-of-magnitude reach.

Deeper 0νββ Physics Reach

~10^{29} sensitivity

↑ XLZD + enriched Xe

~10^{28} sensitivity

↑ XLZD

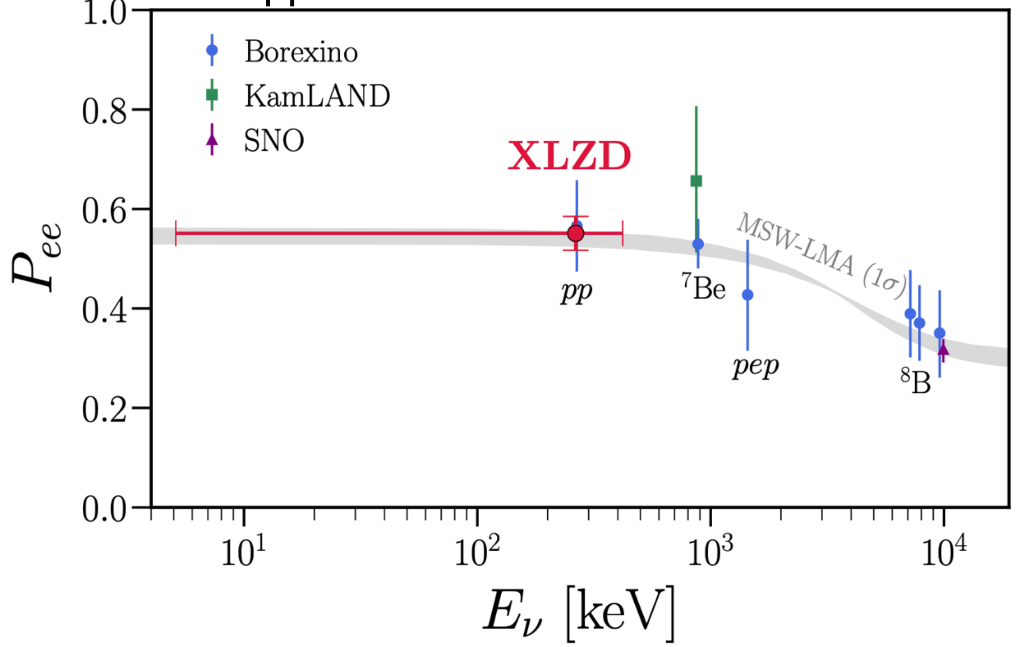
<u>^{136}Xe Rate at 10^{29} years:</u>
~0.03 decays/tonne/yr

<u>^{136}Xe Rate at 10^{28} years:</u>
~0.3 decays/tonne/yr

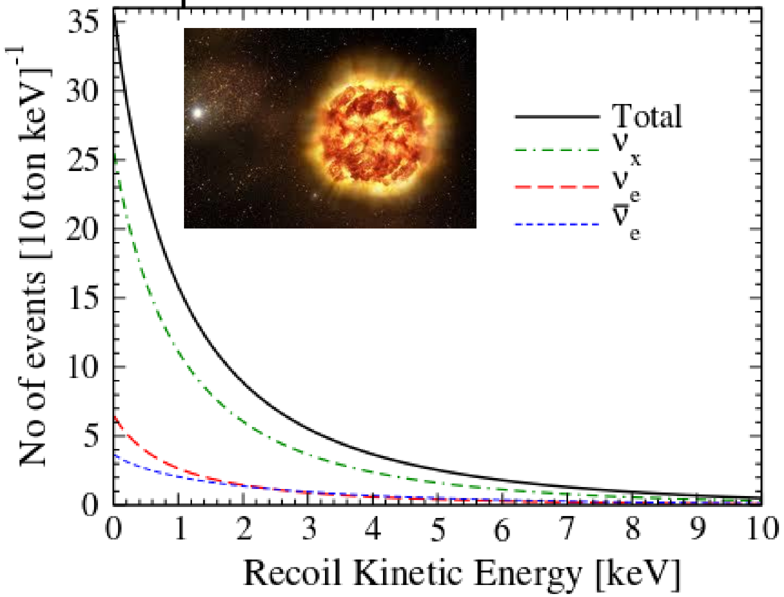
This scalability is possibly unique among 0νββ experiments.

Neutrino Science Channels

Solar pp-neutrinos

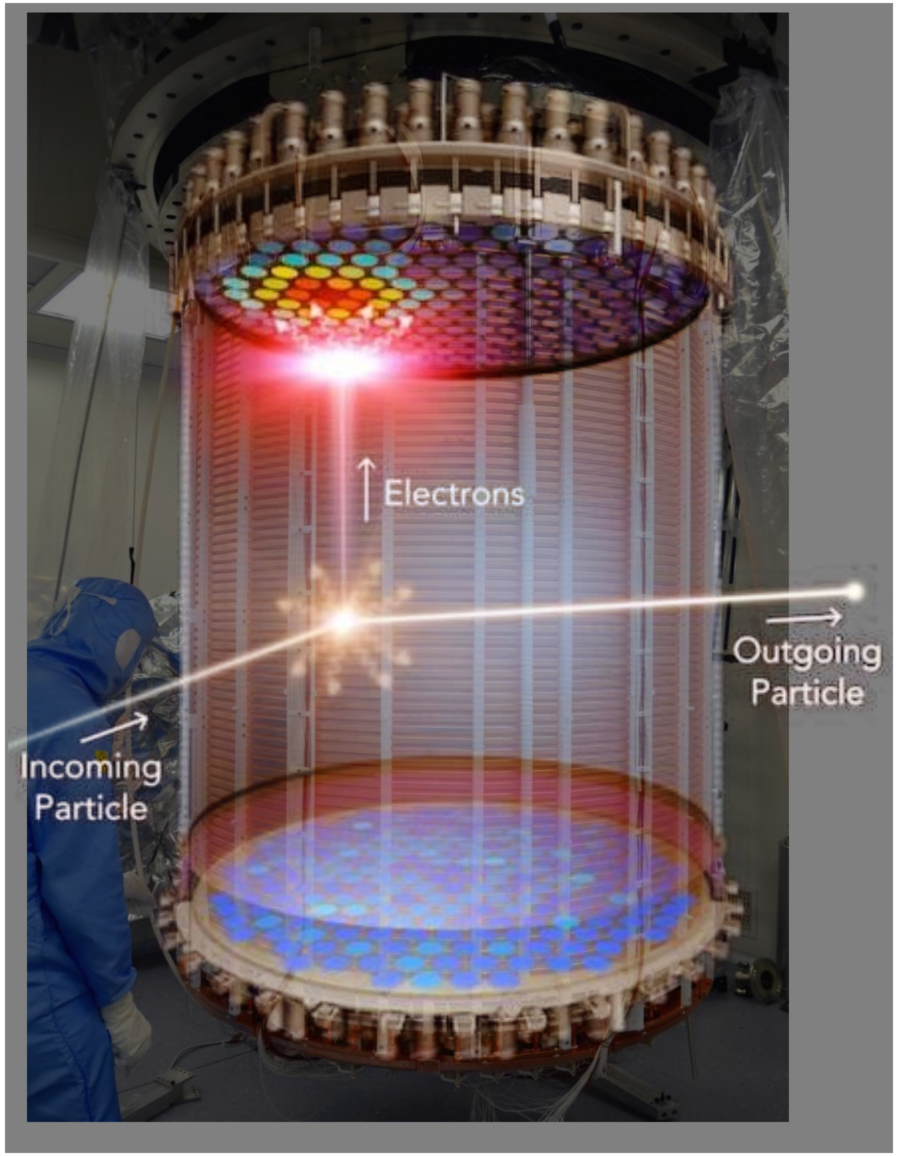


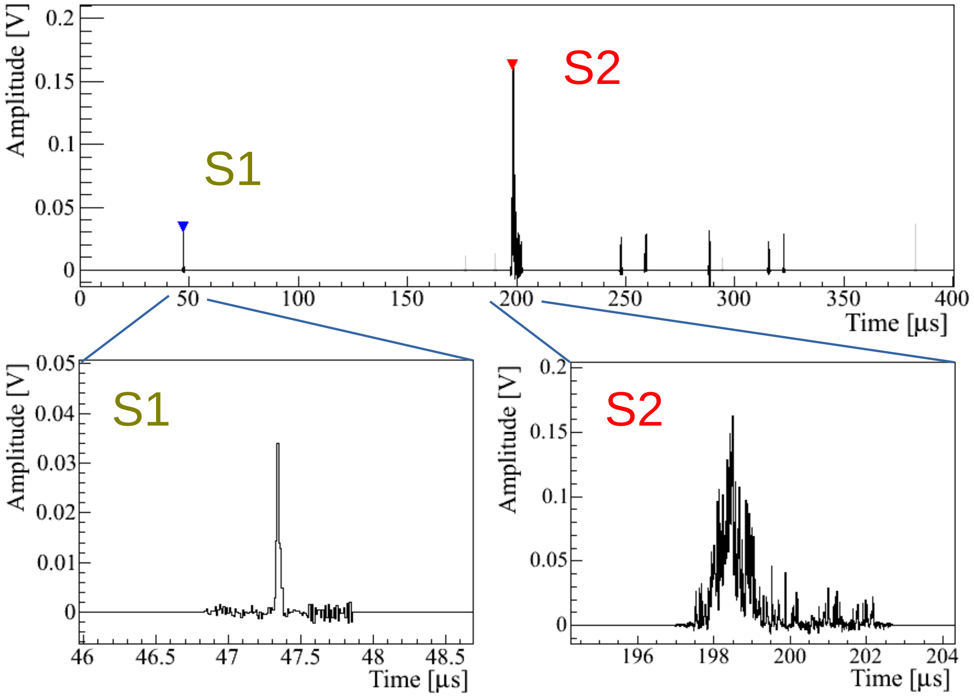
Supernova neutrinos



- XLZD low-*E* background dominated by **neutrinos**
  → precise measurements of rare processes possible
- Low-threshold: unique science possibilities
  → e.g. supernova neutrinos (XENON & LZ already part of SNEWS)

Dual-phase TPC





Detection of direct scintillation light & charge from proportional scintillation in Xe gas enables:

- 3D position reconstruction
- Energy reconstruction
- Event-mutiplicity (SS vs MS)
- Electronic vs. nuclear recoil discrimination

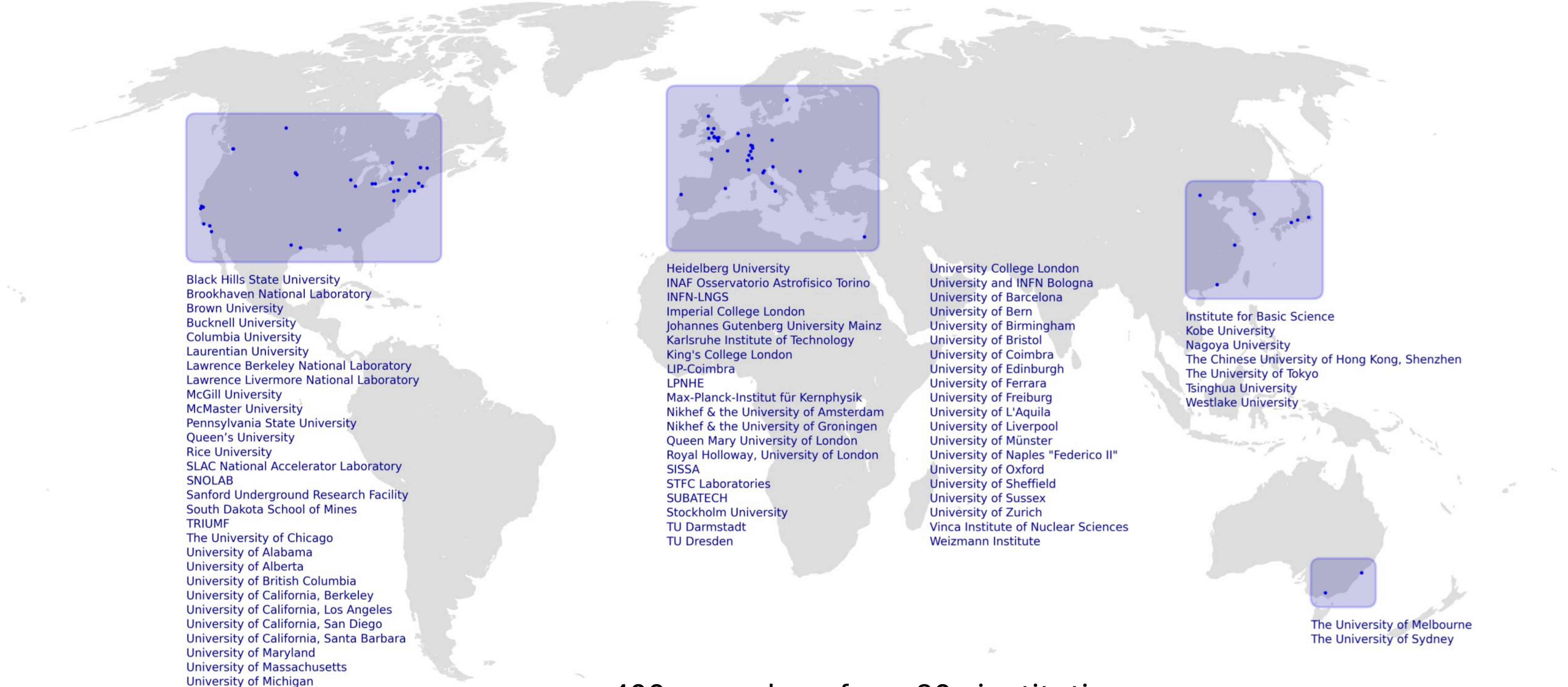
Dolgoshein, Lebedenko, Rodionov, JETP Lett. 11, 513 (1970)

XLZD Nominal Design

- **60t active natural LXe target** (78t total)
  - 80t active in case of positive funding and Xe market conditions;
    design allows straighforward implementation
- 2.97m height, 2.98m diameter
  (→ factor 2 larger than LZ and XENONnT)
- Drift field: 240-290 V/cm for optimal background rejection in WIMP dark matter ROI
- Two arrays of 3“ **low-background PMTs**
  (2362 tubes in total)
  → other sensors under study
  - optimize for large dynamic range
- Highly reflective PTFE walls
- Double-wall low-background Ti cryostat
- Various **background mitigation** methods

XLZD design book: arXiv:2410.17137

The XLZD collaboration

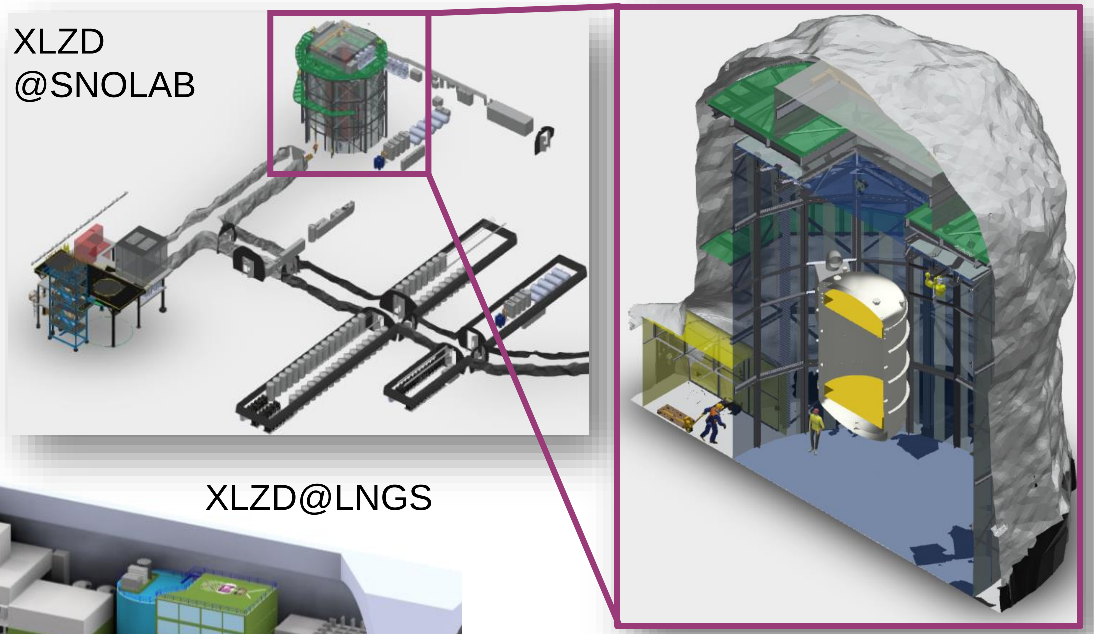


400+ members from 80+ institutions

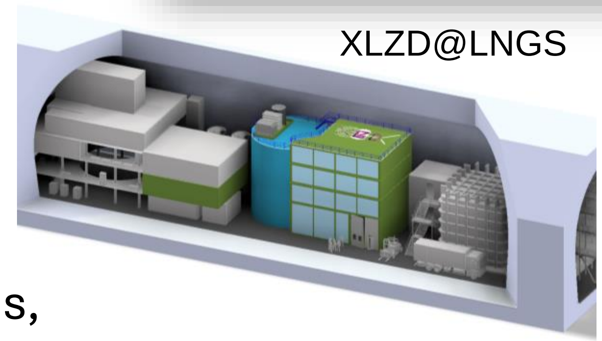
Drawing on experience from current-generation liquid xenon experiments

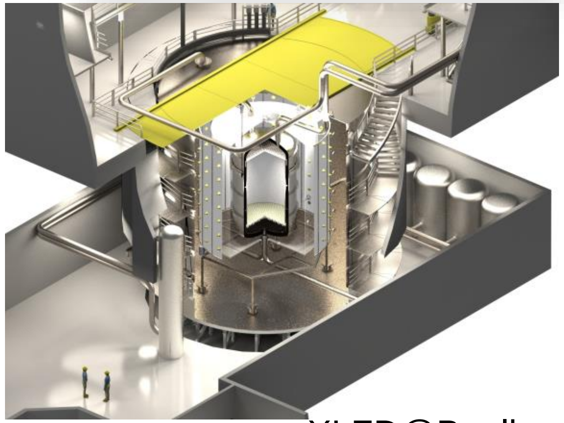
XLZD Siting Process

- Possible sites
  - Boulby, UK
  - LNGS - middle of Hall C, Italy
  - SNOLAB CryoPit/CubeHall, Canada
  - SURF - “Module of Opportunity” cavern or new excavation, USA
- Collaboration conducted siting reviews May – June 2026
- Key considerations include
  - Depth - impact on backgrounds.
  - Ability of host site and country to provide suitably outfitted space.
  - Accessibility & transport large sub-assemblies, vessels.
  - Underground fabrication capabilities.
- All sites technically capable of hosting XLZD (report forthcoming).
- Ultimately, final decision on site involves higher level stakeholders.



XLZD@LNGS





XLZD@Boulby

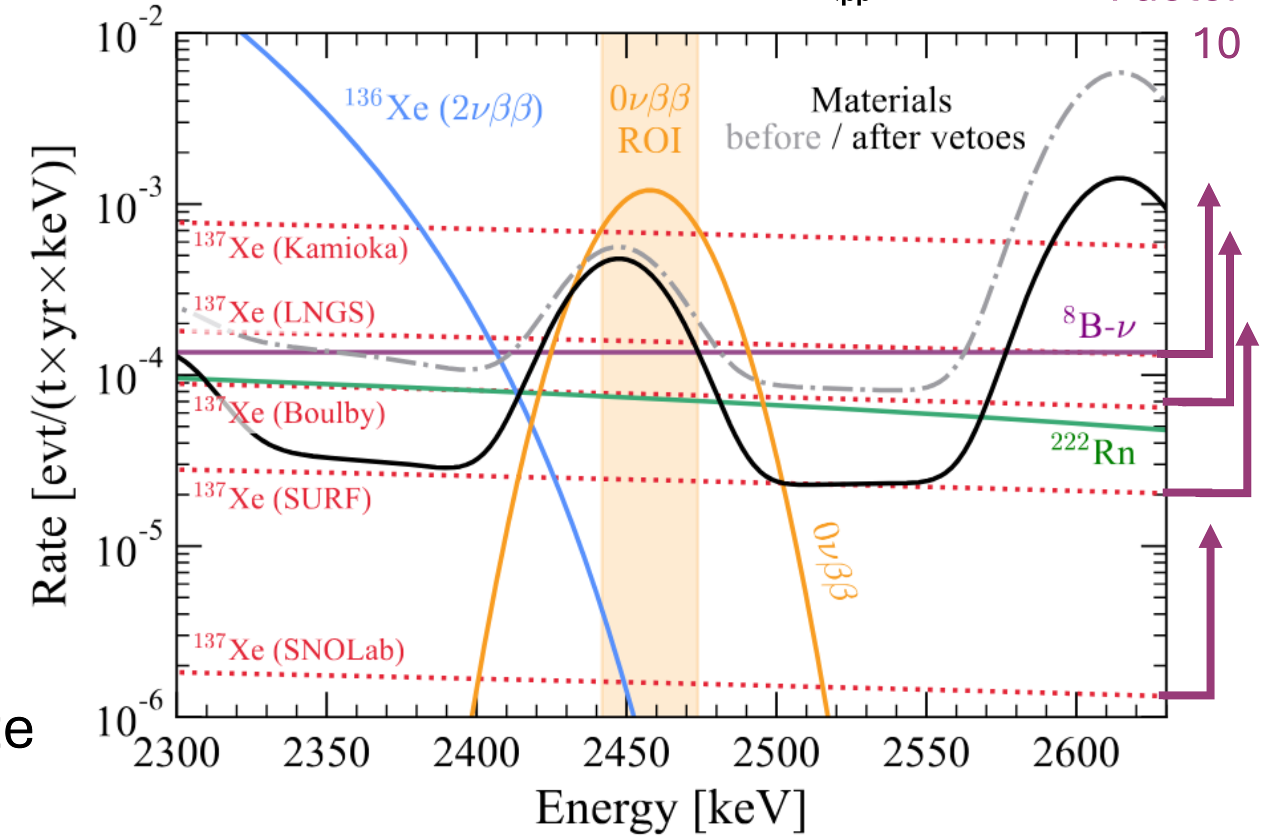
Future-Safe Location for 0νββ Search

- ^{8}B-ν background ~ total xenon mass → enrichment & site agnostic.
- ^{222}Rn background depends on detector technology → enrichment & site agnostic.
- ^{137}Xe background scales with enrichment:
  - Natural xenon: Boulby or deeper will result in subdominant ^{137}Xe bgnd.
  - For 10 times increase of ^{136}Xe, ^{137}Xe rate will be a factor ~ 10 higher at all sites.

σ/E=0.65%

±1σ around $Q_{\beta\beta}$

Factor 10



→ Even in 90% ^{136}Xe enriched XLZD-like experiment ^{137}Xe remains subdominant background compared to ^{8}B-ν only at SNOLAB!

XLZD in the Canadian LRP

Highest Priority Future Project

Broad and very strong community support
Considered by the Committee as future projects with the greatest potential scientific return on investment
Substantial involvement in those projects will confirm Canada's position as a global leader in scientific research
Resources to be allocated to reach the optimal impact of the Canadian Community

Projects

- EIC
  - Uniquely address profound questions about nucleons and probe how the nucleon-nucleon interaction arises from the QCD regime within the hadrons
  - Allow precision studies of the 3D structure of hadrons, gluon saturation, and the dynamics of quark-gluon interactions across a wide kinematic range
- FCC
  - Largest breadth of program
  - In line with European strategy and CERN council
- XLZD@SNOLAB
  - Potentially transformative opportunity to host at SNOLAB
  - Would establish Canada as the global centre for next-generation direct dark matter detection and the search for neutrinoless double beta decay

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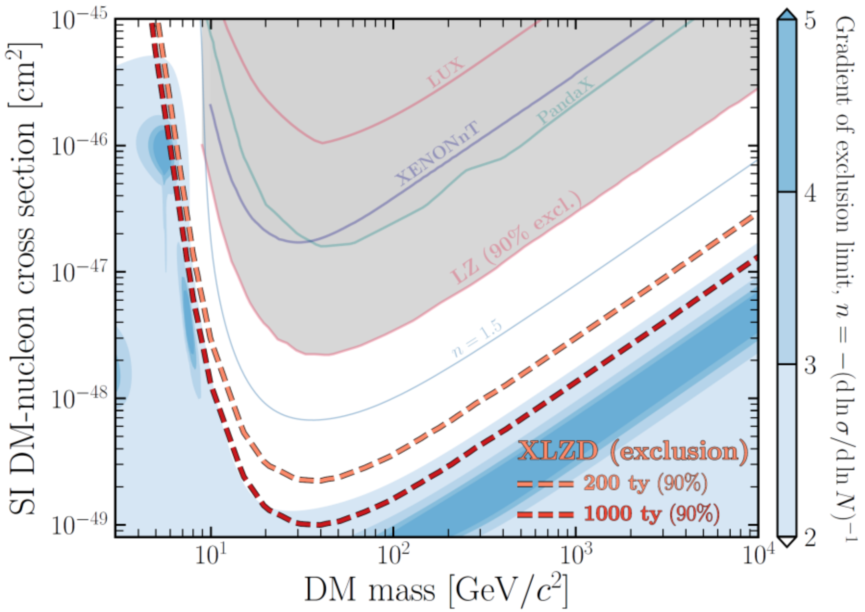
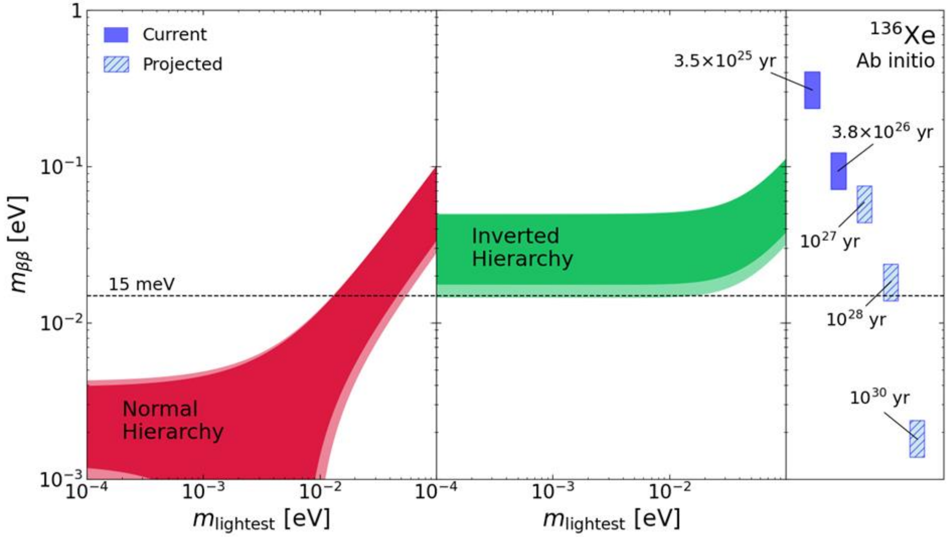
https://indico.global/event/15553/contributions/157733/attachments/72931/141380/LRPC_recommendations.pdf

Summary and Conclusion

- Next-generation noble liquid detectors strive for sensitivities where neutrinos become dominating background.
- The cost of these experiments requires consolidation of the community and sensitivities to several physics channels.
- The Xe community is consolidating in XLZD, a rare-event observatory with a rich physics program.
- XLZD aims to reach the neutrino fog and perform a competitive 0νββ search.





Thank you for your attention

2026 Collaboration Meeting, Zürich