XLZD Beyond WIMPS: Neutrinoless Double Beta Decay and More!

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2 LZ postdoc positions soon open

Symmetry Magazine, Sandbox Studio, Chicago with Ana Kova

XLZD Consortium

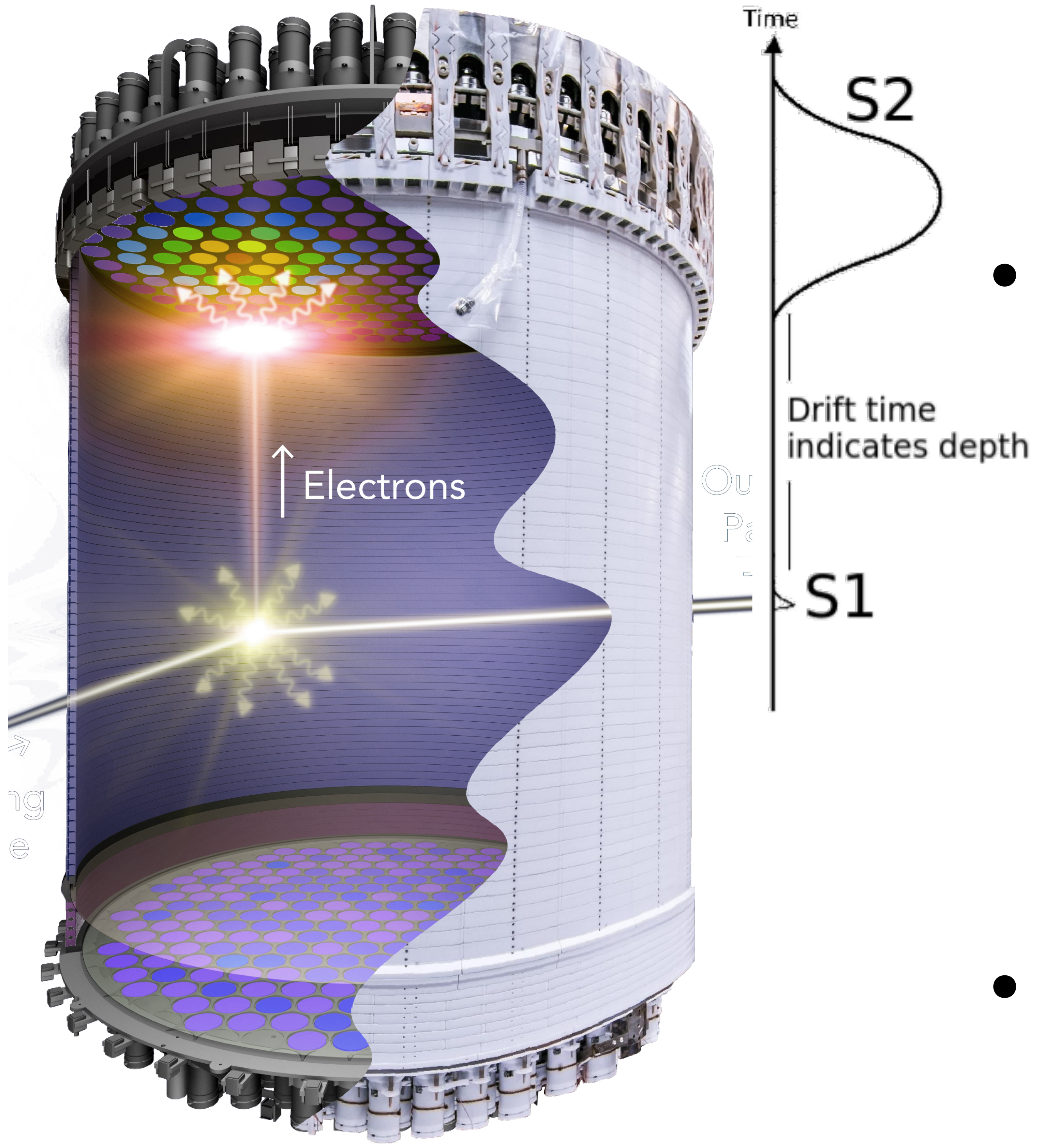
- Consortium MOU signed in July 2021 by **X**ENONnT, **L**UX-**Z**EPLIN, **D**ARWIN
- XENONnT and LZ: ongoing science programs, technology progenitors
- DARWIN: initiated R&D and design studies
- Led by Steering Committee
- Working groups: science, technical, siting
- In-person meetings - KIT in June 2022, UCLA in March 2023
- xlzd.org

XLZD Meeting at KIT in Karlsruhe, Germany (June 2022)

R. Munroe, XKCD

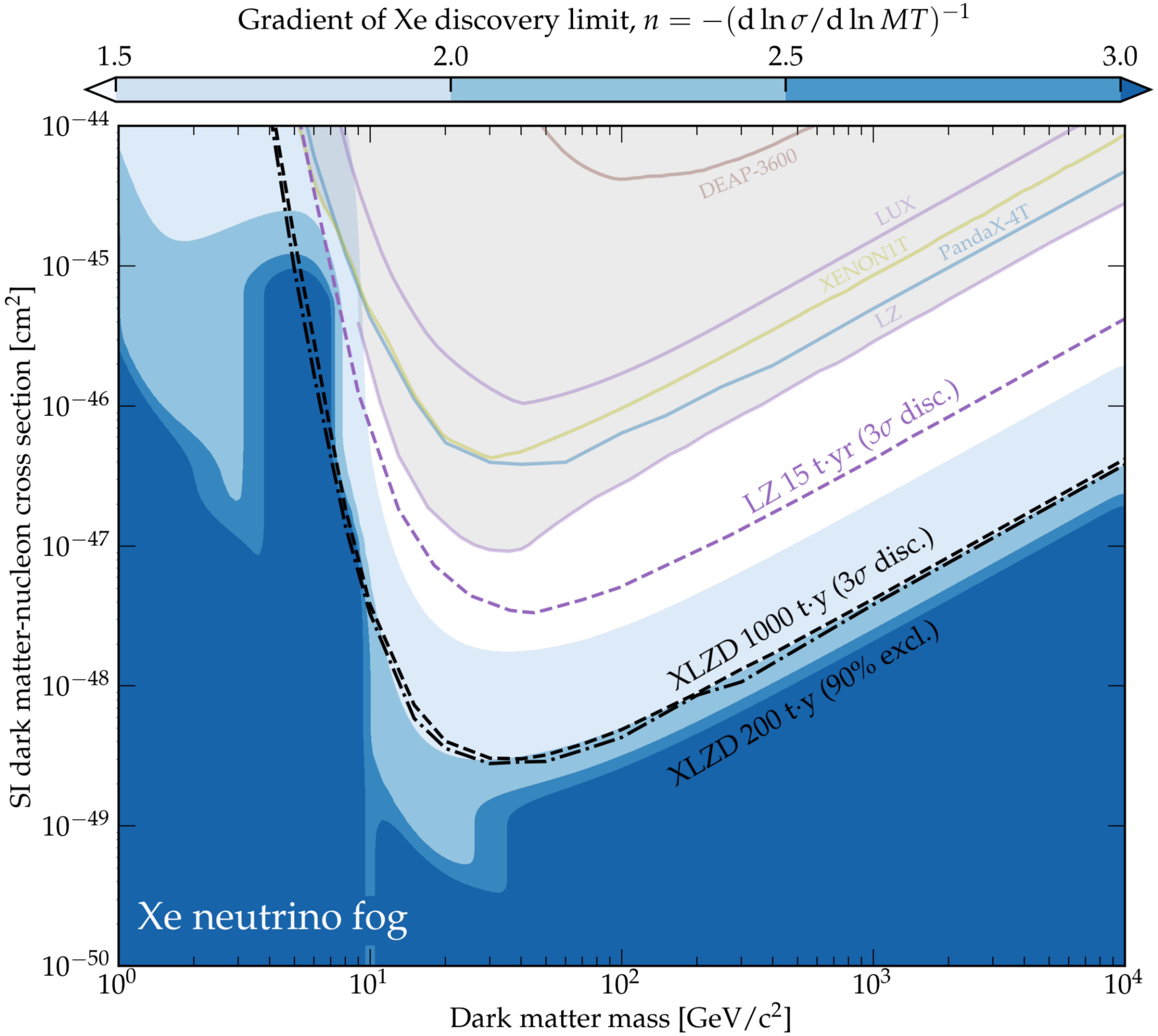
See Tina Pollmann's talk today 16:00 in DM session in BIG-Hörsaal

XLZD Detector



- Design for Discovery into the neutrino fog
  - a detector that drives the full consortium to come together
- 60t active 1:1 aspect ratio at (300cm)
  - Xe acquisition may drive stages or final scale
  - also considering 40 t and 80 t options
- Engineer for access
  - risk mitigation and opportunity for growth

XLZD DM Sensitivity



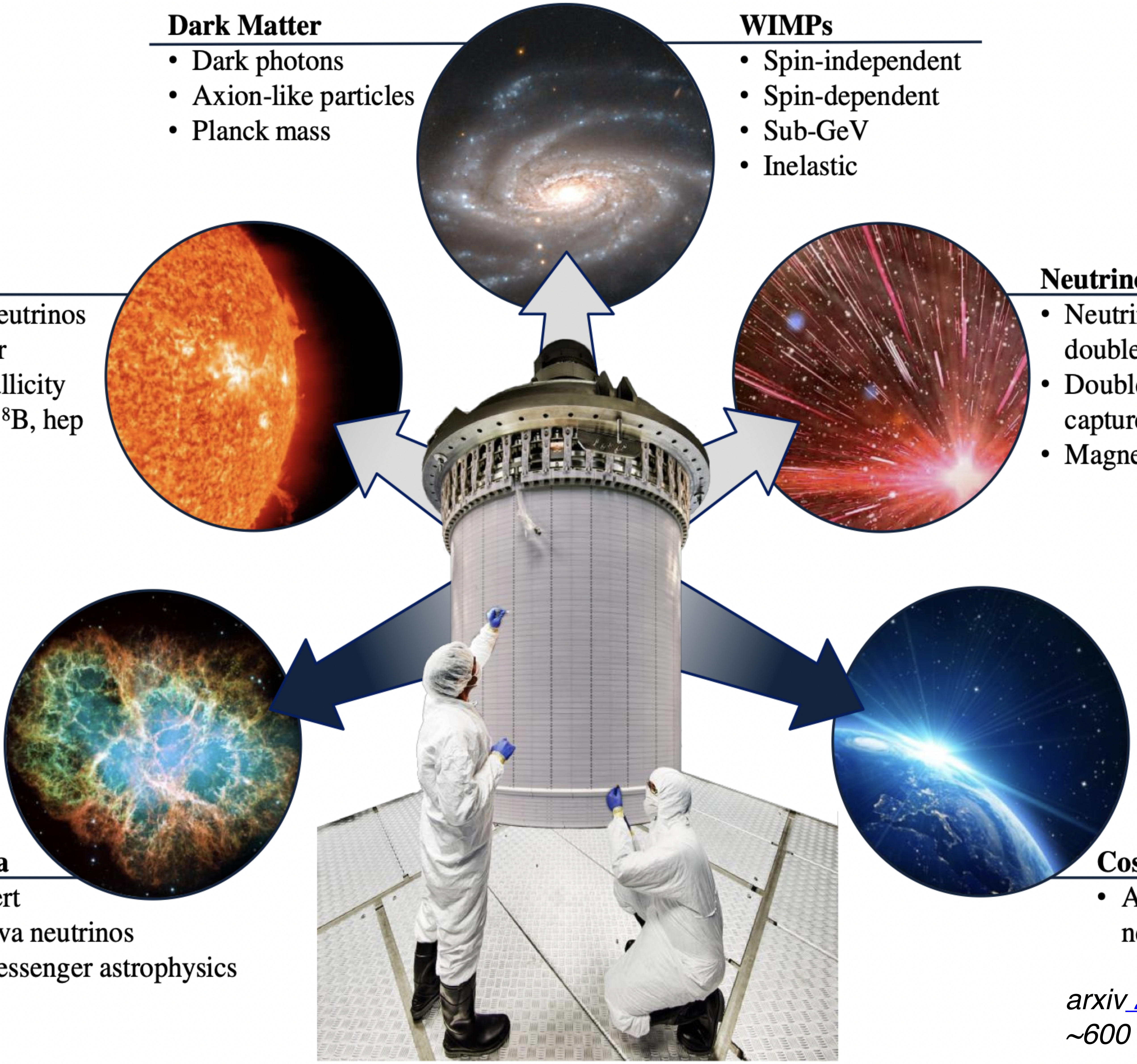
XLZD Science

Dark Matter
- Dark photons
- Axion-like particles
- Planck mass

WIMPs
- Spin-independent
- Spin-dependent
- Sub-GeV
- Inelastic

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

Neutrino Nature
- Neutrinoless double beta decay
- Double electron capture
- Magnetic Moment

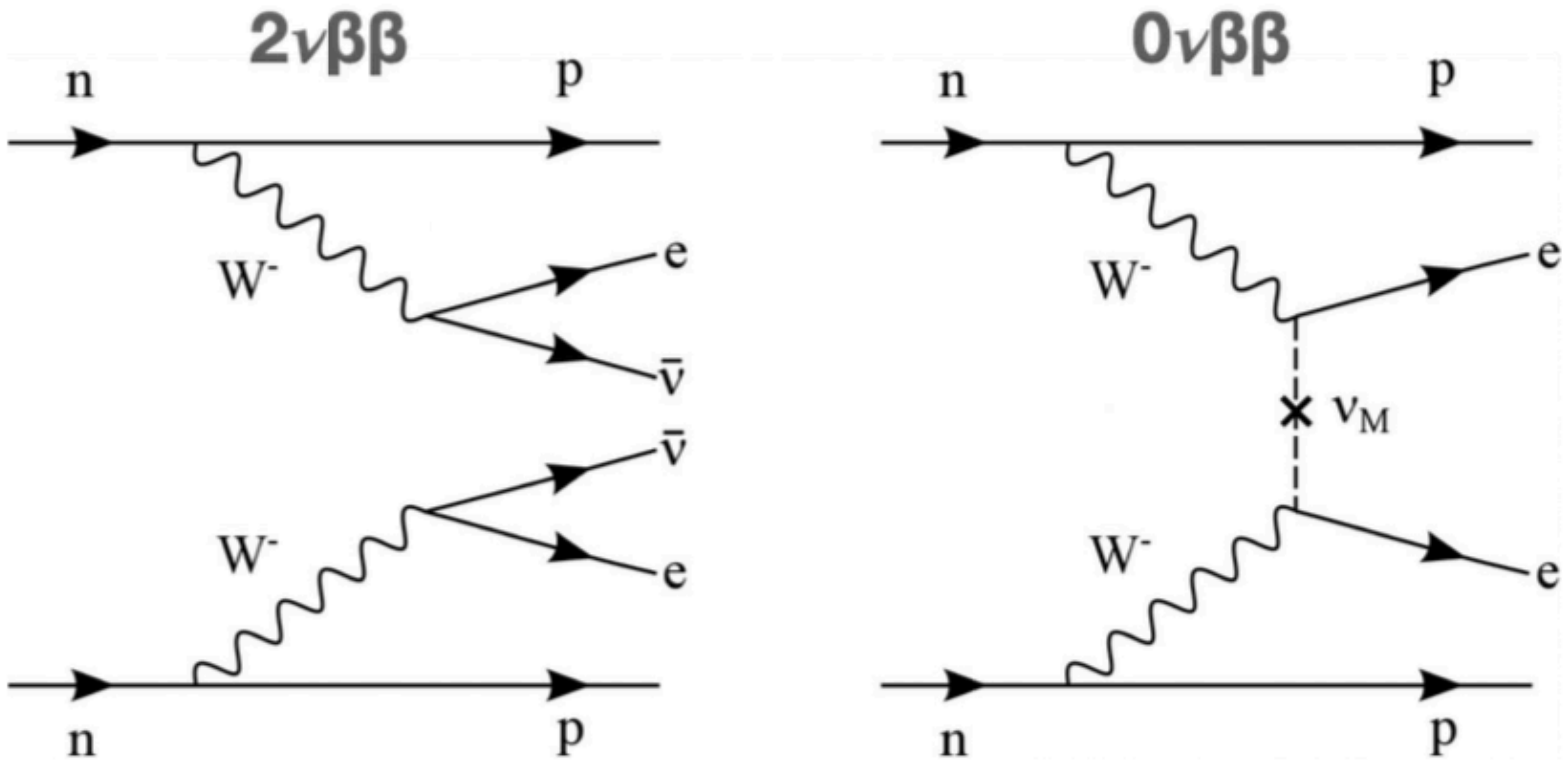


Supernova
- Early alert
- Supernova neutrinos
- Multi-messenger astrophysics

Cosmic Rays
- Atmospheric neutrinos

arxiv 2203.02309 / J. Phys. G: Nucl. Part. Phys.
~600 author whitepaper on the science reach

Neutrinoless Double Beta Decay

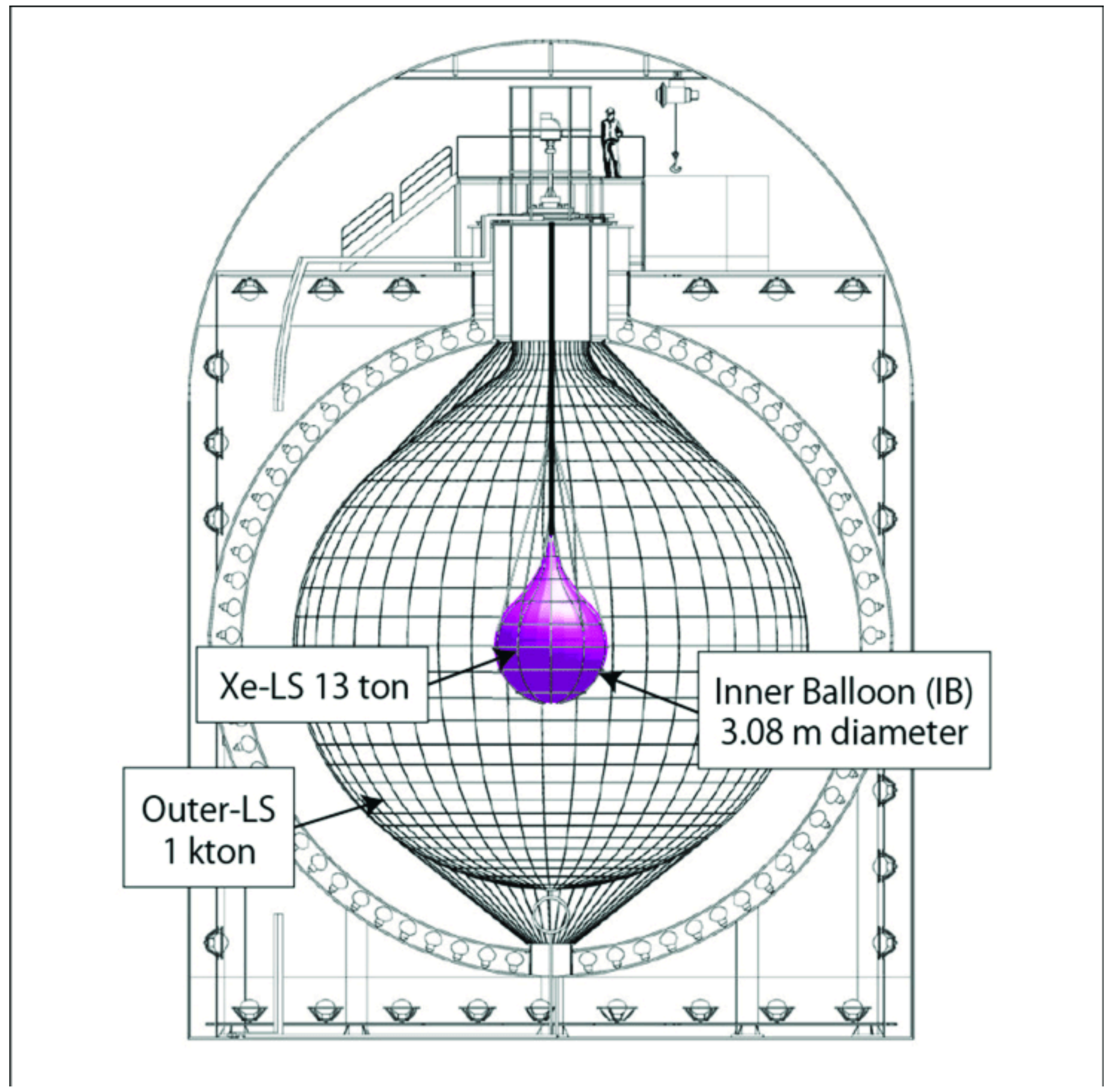


D. Moore's Morning Plenary

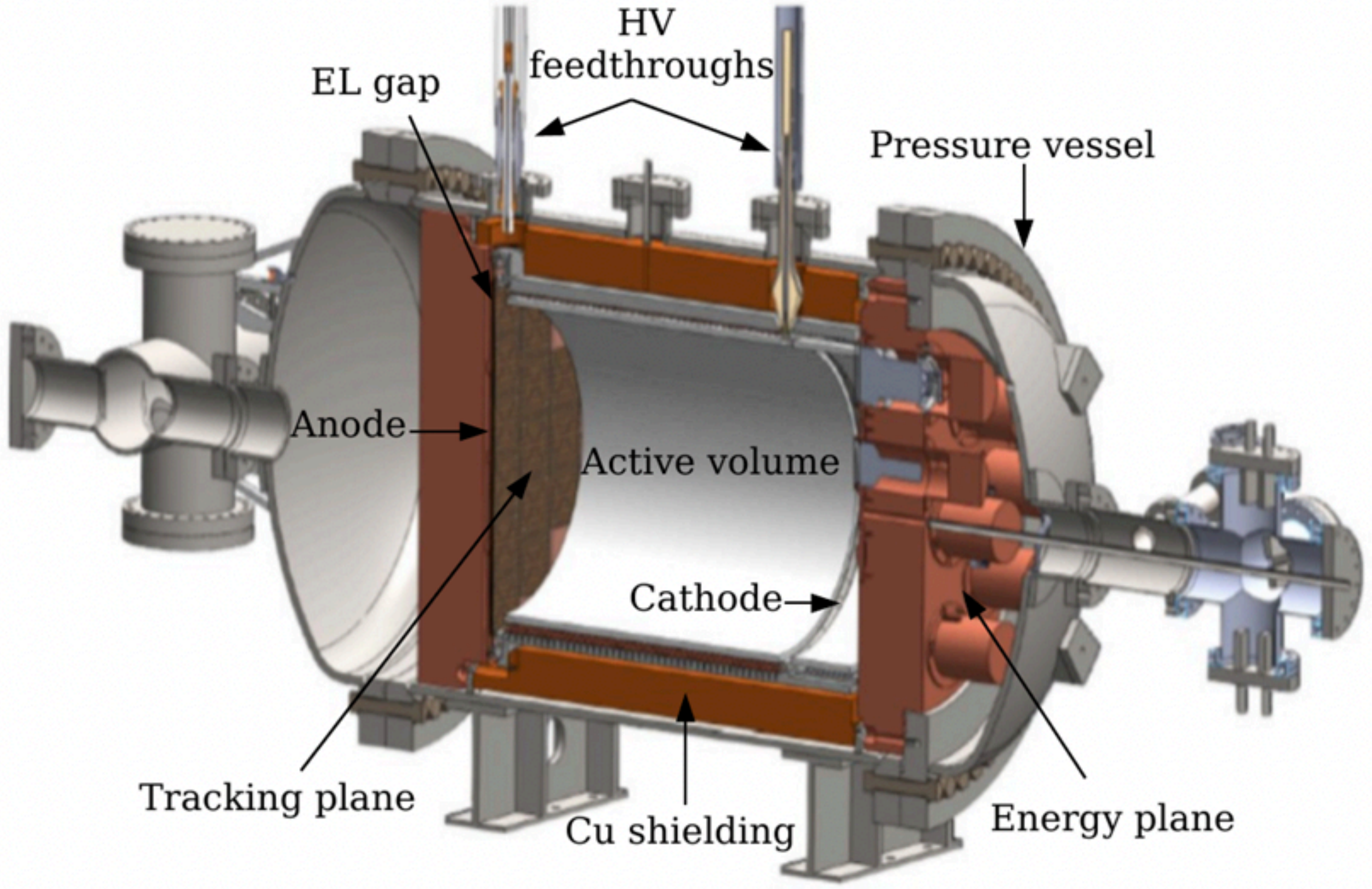
- Standard Double beta decay occurs when single beta decay is forbidden or suppressed
    - Confirmed in 14 isotopes
- Neutrinoless double beta decay can occur if neutrinos are Majorana particles
    - Beyond the standard model process, yet unobserved, linked to matter/antimatter asymmetry

^{136}Xe 0νbb

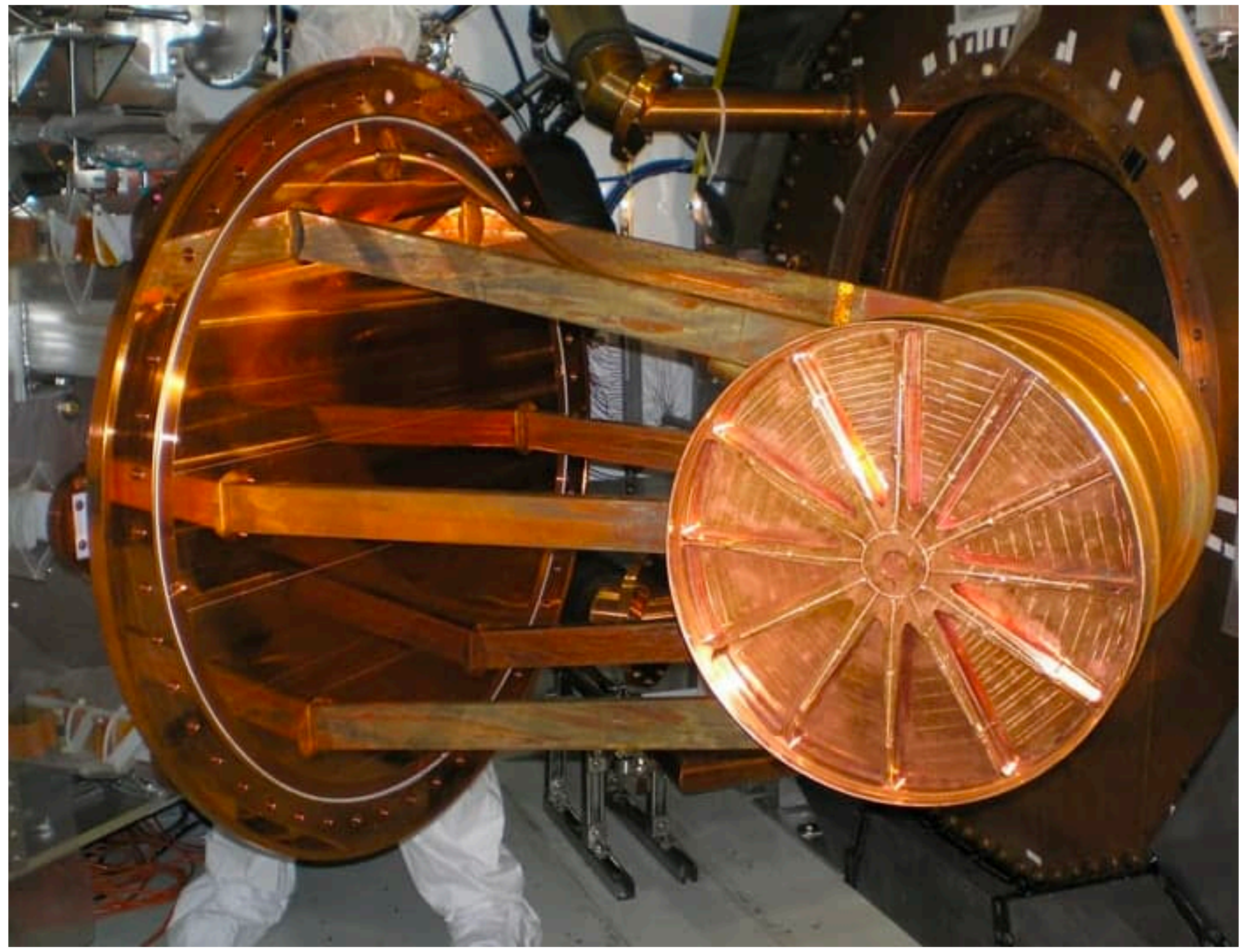
- ^{136}Xe is a 0νbb candidate with a natural abundance of 8.9%
- Past and future experiments, many dedicated to 0νbb
  - Future detectors could tag the Barium daughter
  - World leading limit from KamLAND-Zen $T_{1/2} > 2.3 \times 10^{26}$ yr



KamLAND-ZEN



NEXT-White



EXO-200

0νbb in XLZD

- My personal wording of our approach
  - If we are careful and pay attention to details from siting, detector design, materials choices etc, how sensitive can XLZD be to ^{136}Xe 0νbb?
  - The primary physics driver for XLZD is the WIMP search and discovery capability to the neutrino fog, but with modest investment, can we also improve our sensitivity 0νbb?
- Format of this discussion:
  - Energy resolution
  - Backgrounds (detector materials, intrinsic, activation)
  - Current sensitivity projections and decision impacts

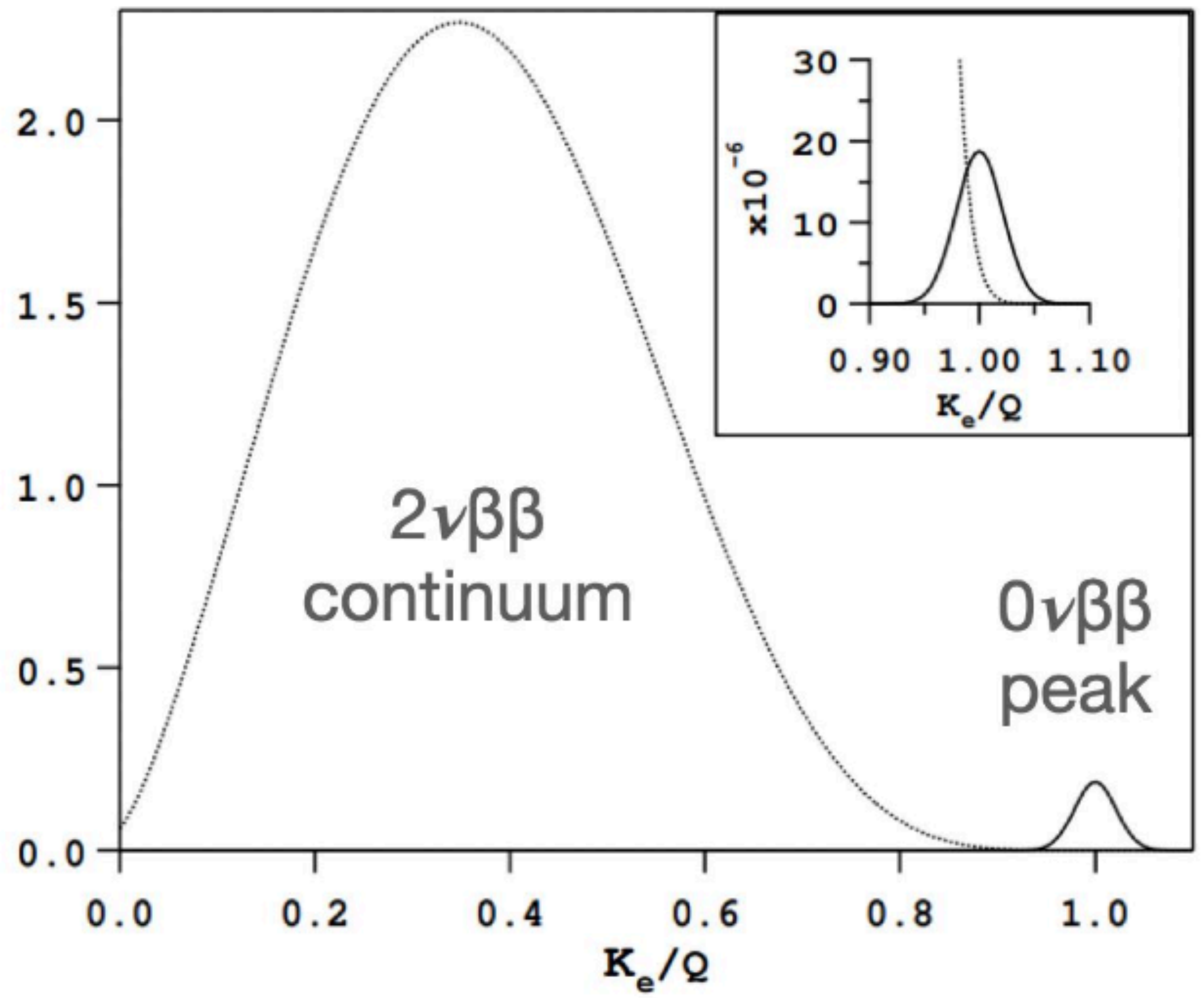
Studies presented here from:

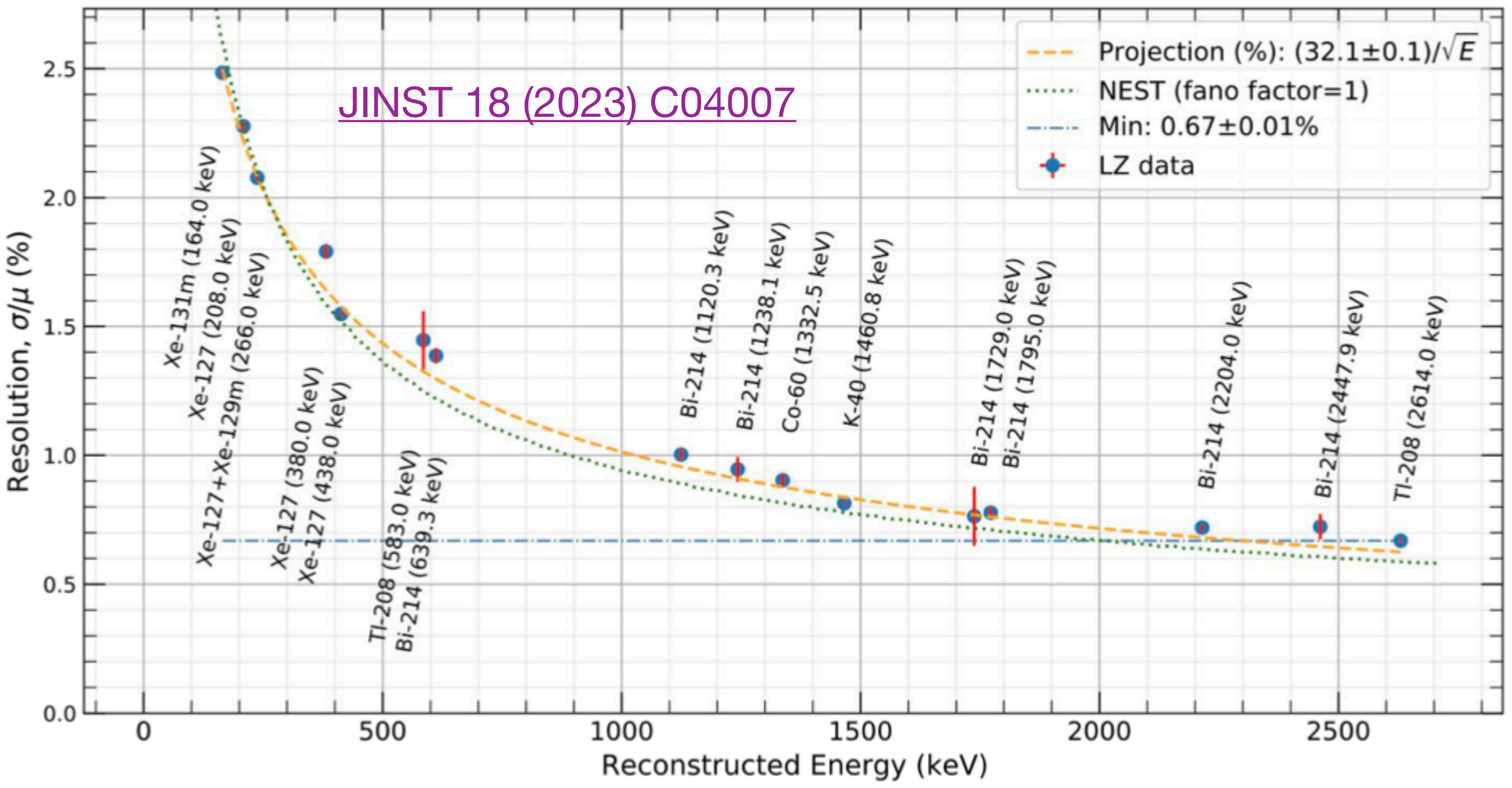
Alex Lindote
LIP Coimbra

Fabian Kuger
formerly Freiburg

Collaboration, advice, and engagement with 0νbb experts is wonderful!

Energy Resolution

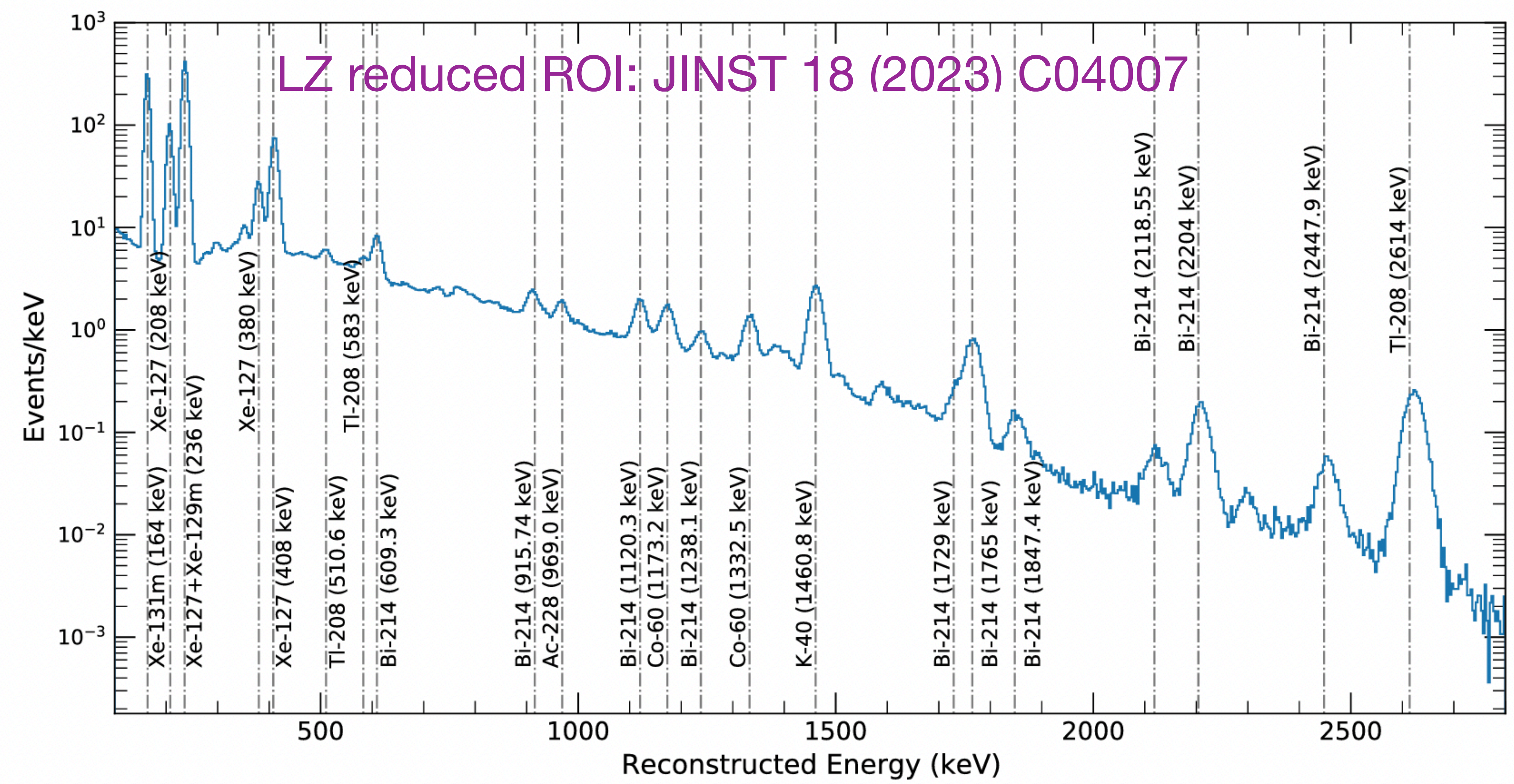


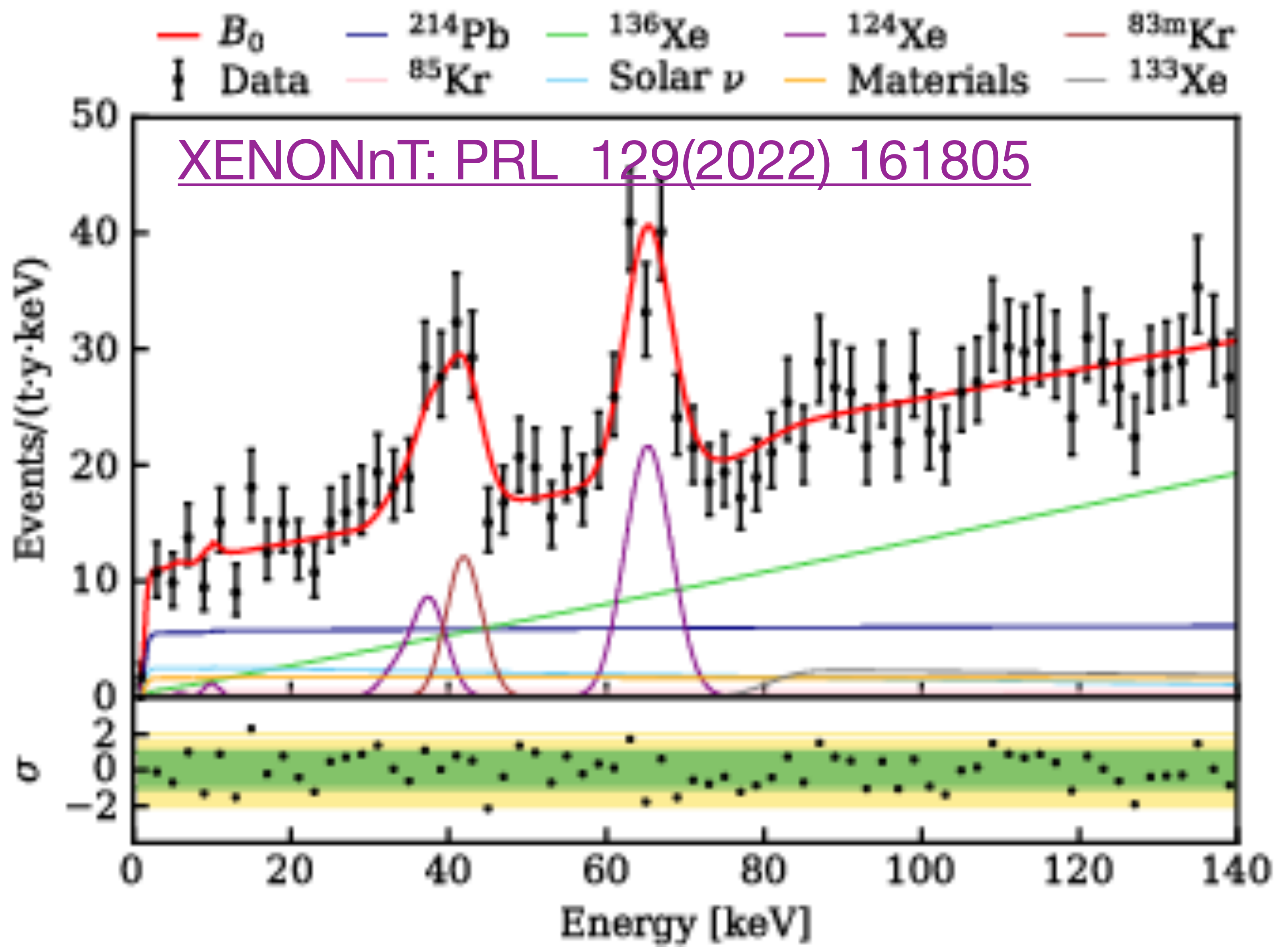


- At Q= 2458 keV
  - Assume 0.65%, LZ has demonstrated .67% energy resolution
    - requires 3D position-based corrections to scintillation and ionization signals
  - $\pm 1\sigma$ defined ROI around Q value: 33 keV wide

Detector Backgrounds

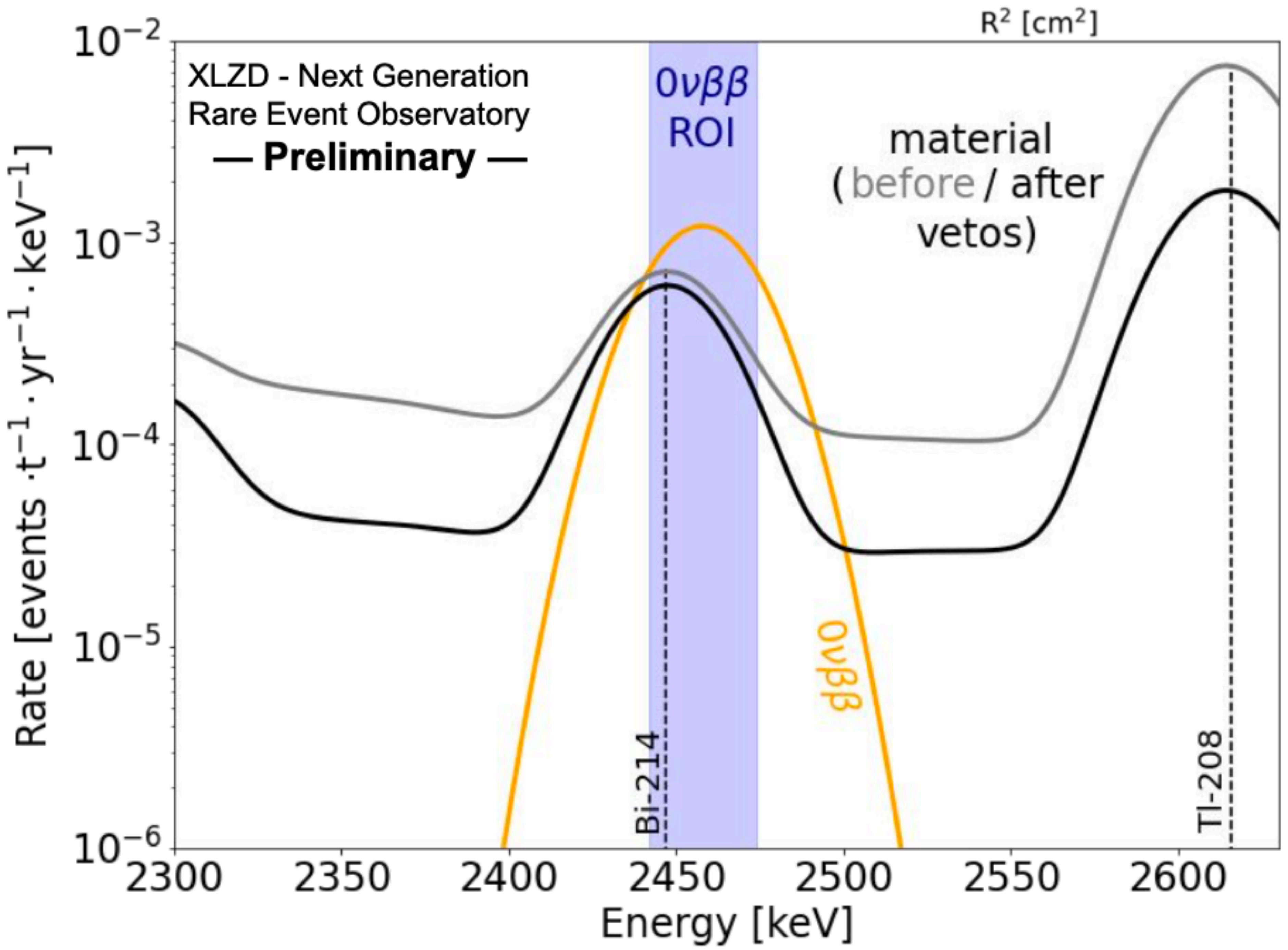
- Build upon successes of current detectors
- High energy Gammas
  - LZ radioactivity control
    PRD 108(2023) 012010
- Radon removal
  - XENONnT Rn down to 0.8 μBq/kg
  - total events 15.8 $\pm$ 1.3 ev/(t y keV)
- Analysis of ^{136}Xe 2νbb spectrum shape not yet explored





Veto Detectors

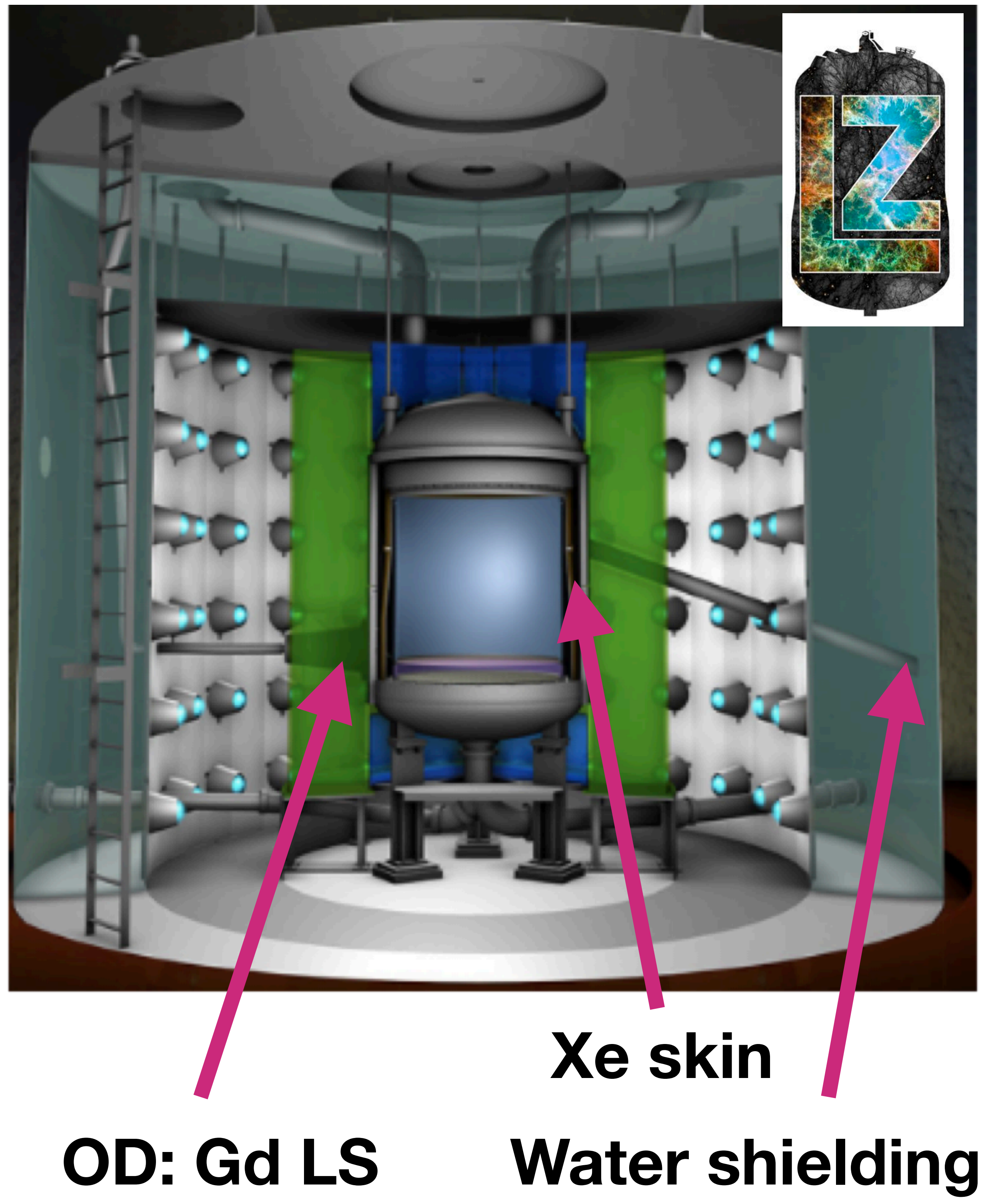
- Nested veto detectors provide shielding and background tagging
- 12 m diameter tank to shield against cavern gammas
- Gammas from detector materials near the TPC
  - ^{214}Bi γ from ^{238}U chain (2447 keV)
  - ^{208}Tl γ from ^{232}Th chain (2615 keV)
- Xe self-shielding is also key, optimized 0νbb FV used, not WIMP FV, benefit from larger detectors



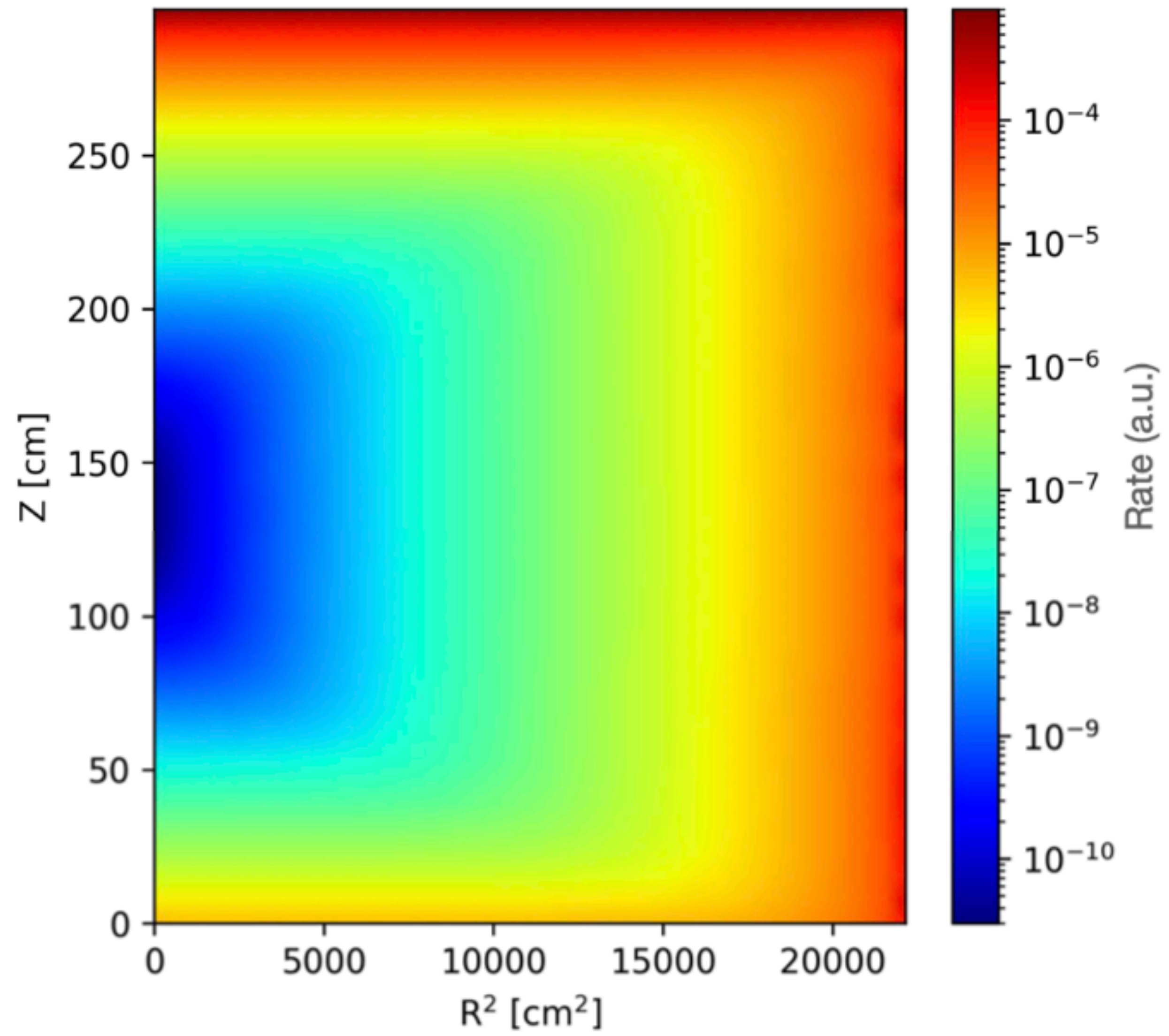
External BG spectrum in the XLZD (60 t) fiducial volume

$0\nu\beta\beta$ signal with $T_{1/2}$ = 5x10^{27} yr

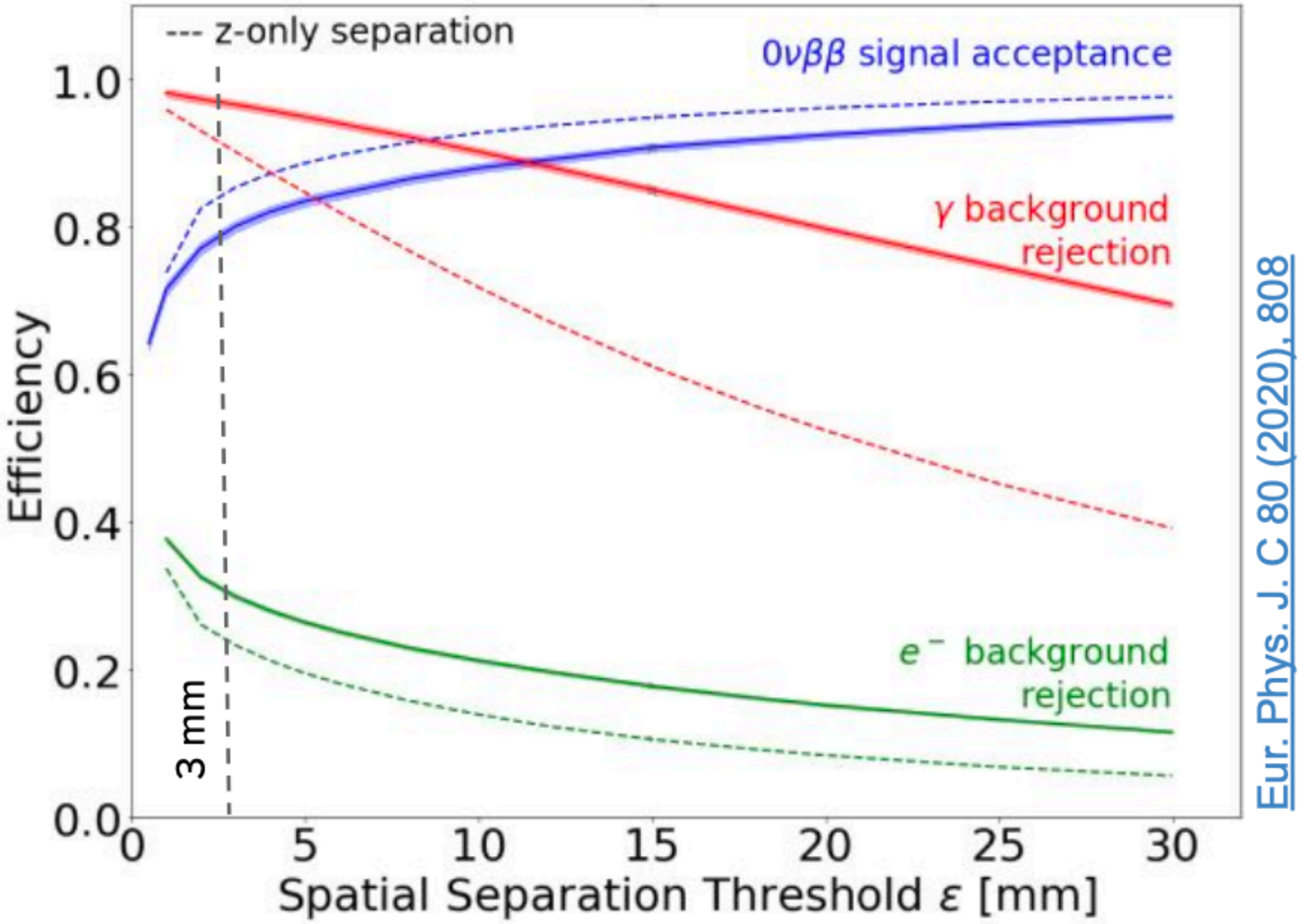
- Instrumented Xe skin + OD allows for tagging of the coincident gammas or Compton scatters from ^{208}Tl 2615 keV, reducing the bkgds by >80% (70% reduction skin alone)

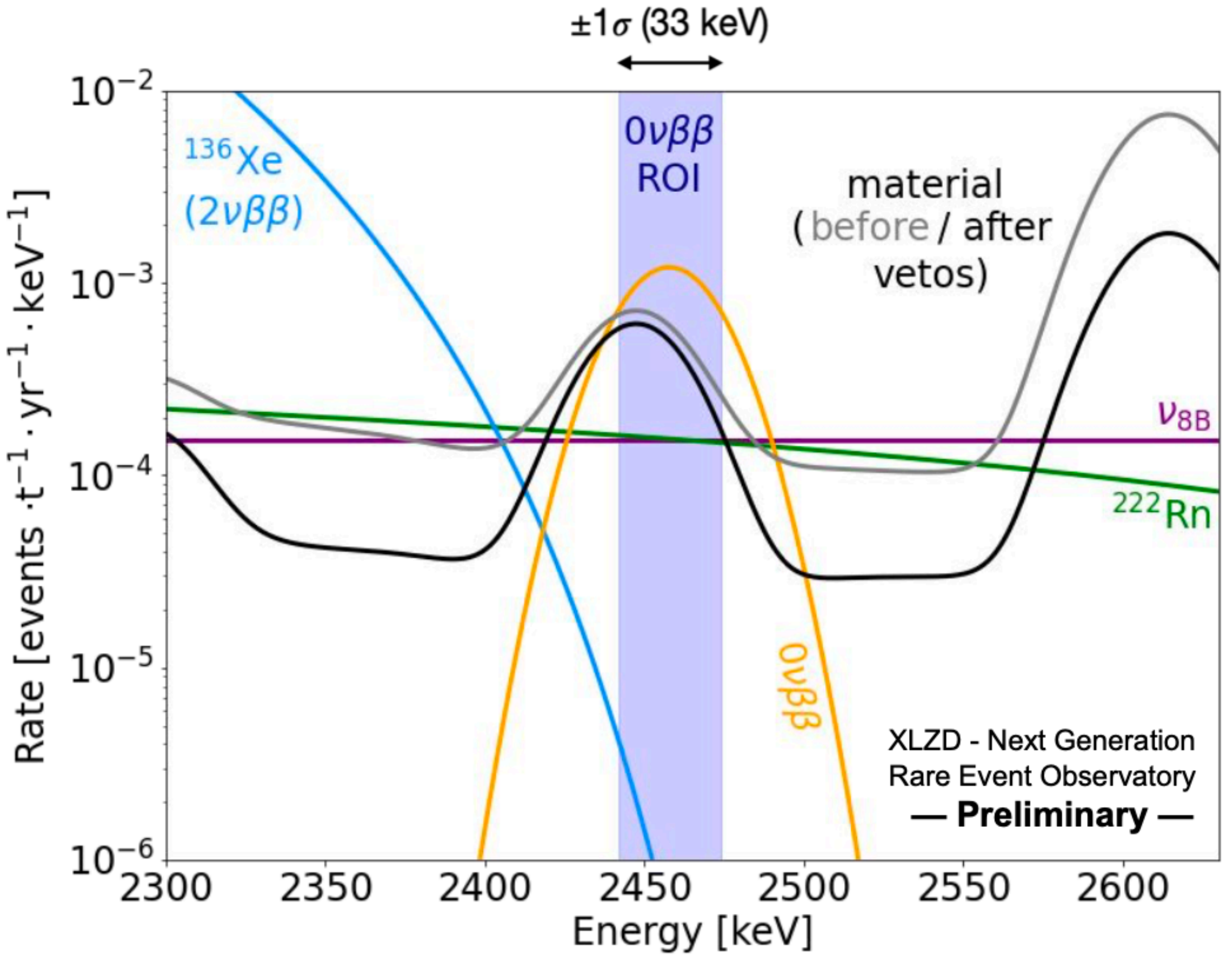


Example γ SS BG ROI rate in a 60 t TPC



Multiple Scatters and Intrinsic Backgrounds

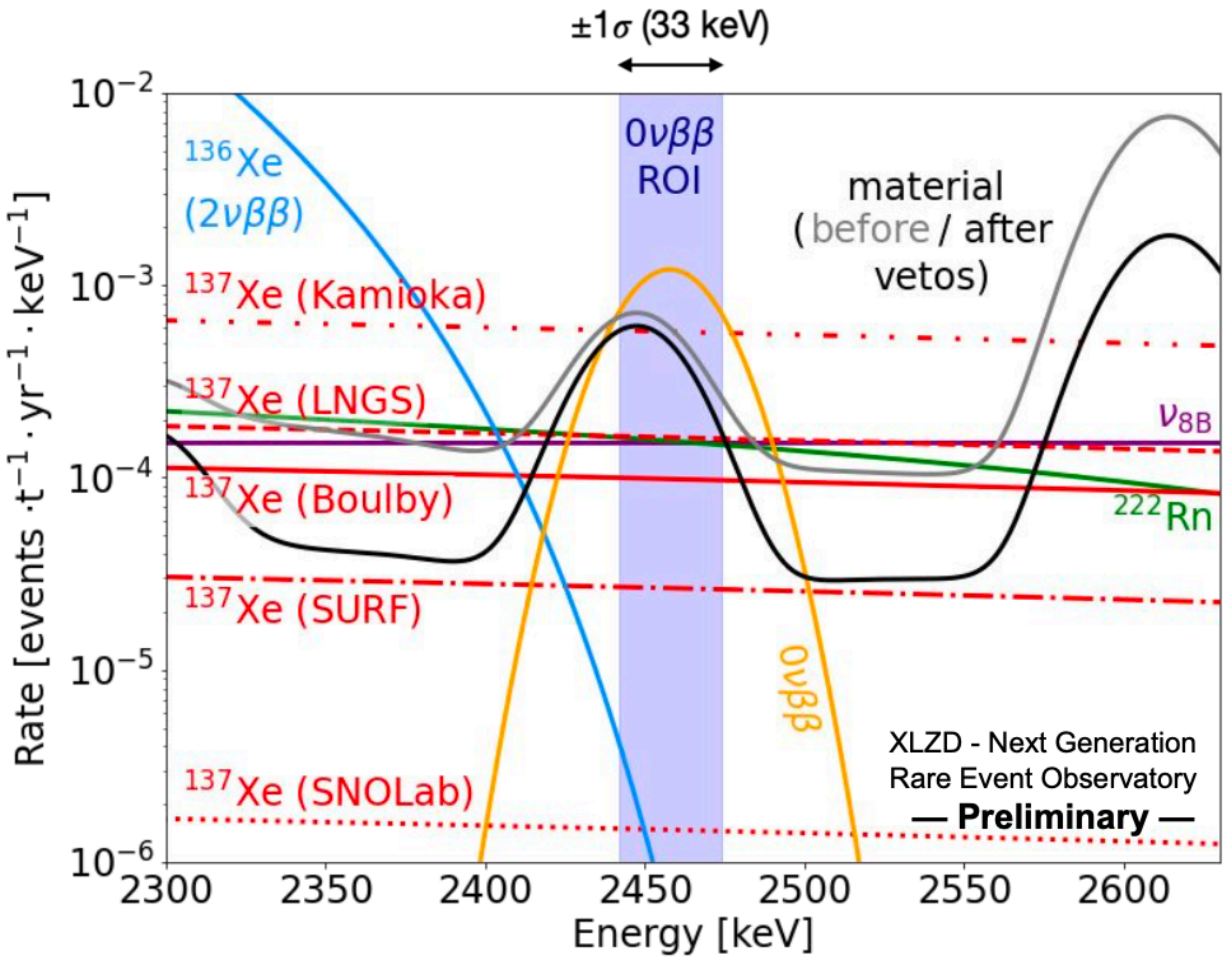




- Multiple scatters reduce the gamma and single electron (bremsstrahlung) backgrounds
  - 0νbb will appear as single scatter
- 3 mm vertical separation threshold used

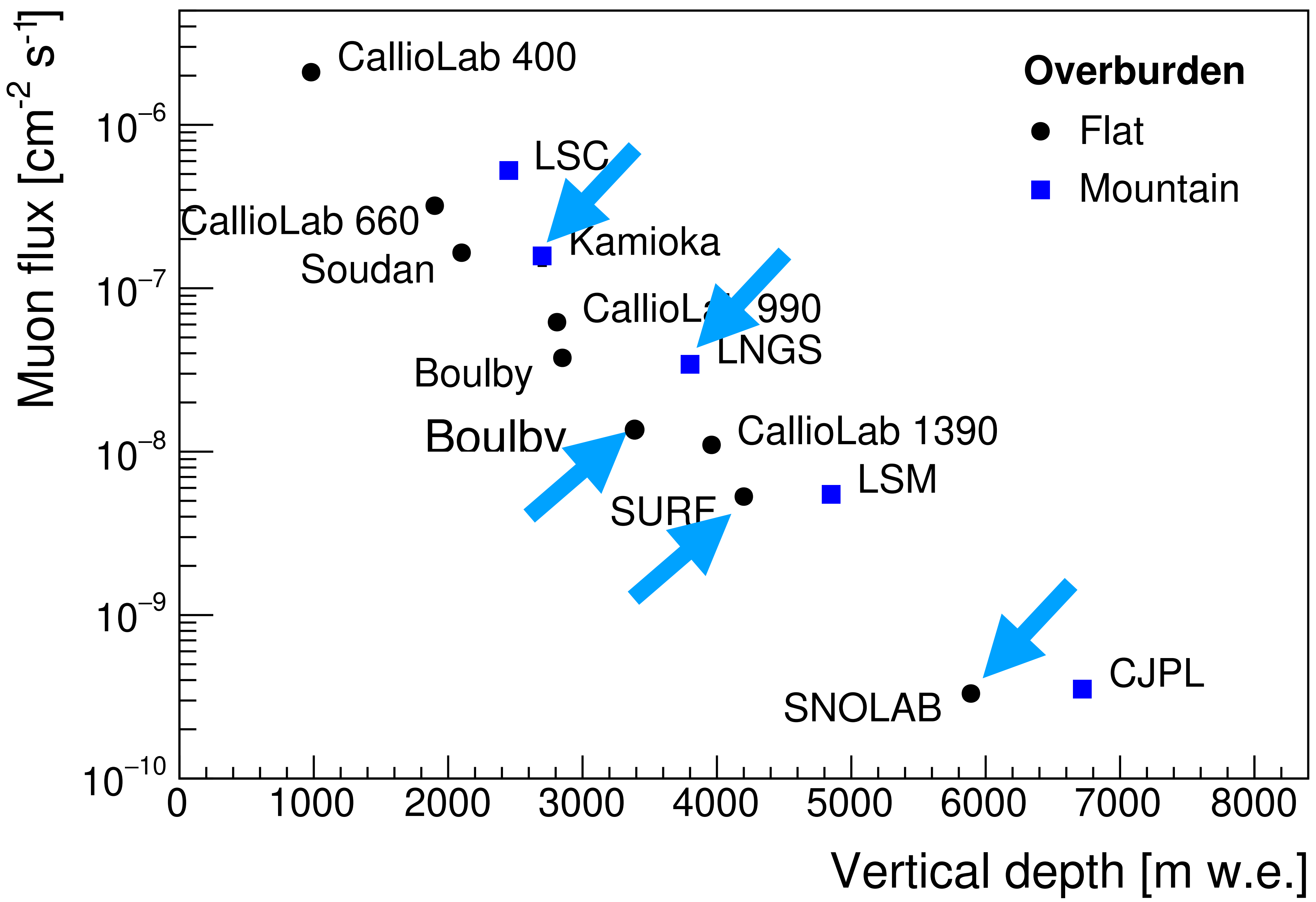
- Uniform across volume, mostly flat spectra
- ^{222}Rn at 0.1 μBq/kg (~10% of current)
- BiPo tagging of α >99.95%
- Small contribution from ^{136}Xe 2νbb

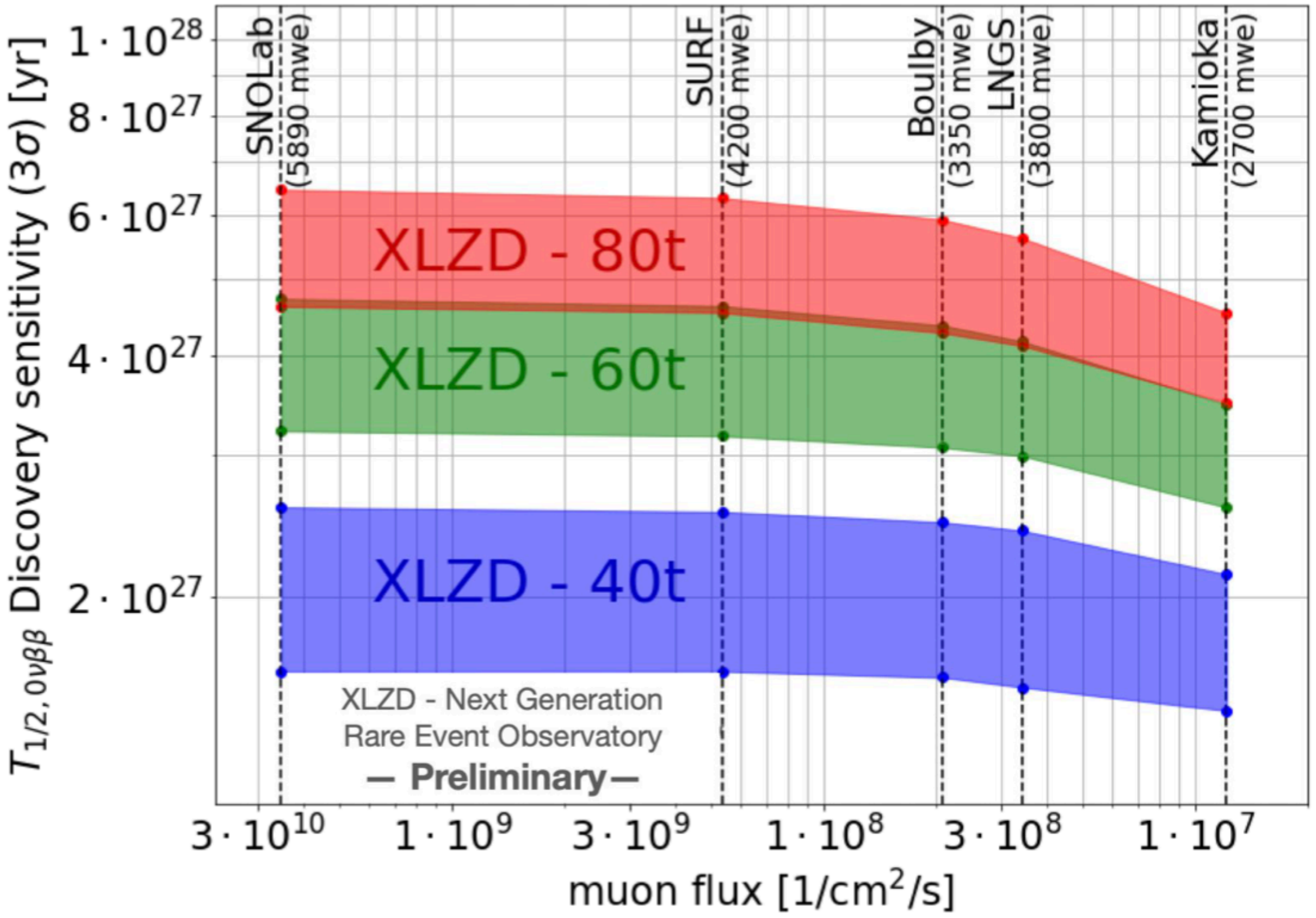
Cosmogenic Activation



- Primarily concerned with ^{137}Xe (beta decay with Q=4162 keV)
  - Muon-induced neutrons capture on ^{136}Xe
- Lab depth dependent
  - Estimates from the DARWIN muon studies arXiv:2306.1634
- Xenon in purification/circulation system should also have neutron shielding, or shielded delayed re-feed

Laboratory Location





- XLZD is evaluating 5 UG laboratories, XLZD science-driven Siting Report due this autumn
- Siting decision expected in ~2025, likely made above the pay grade of researchers

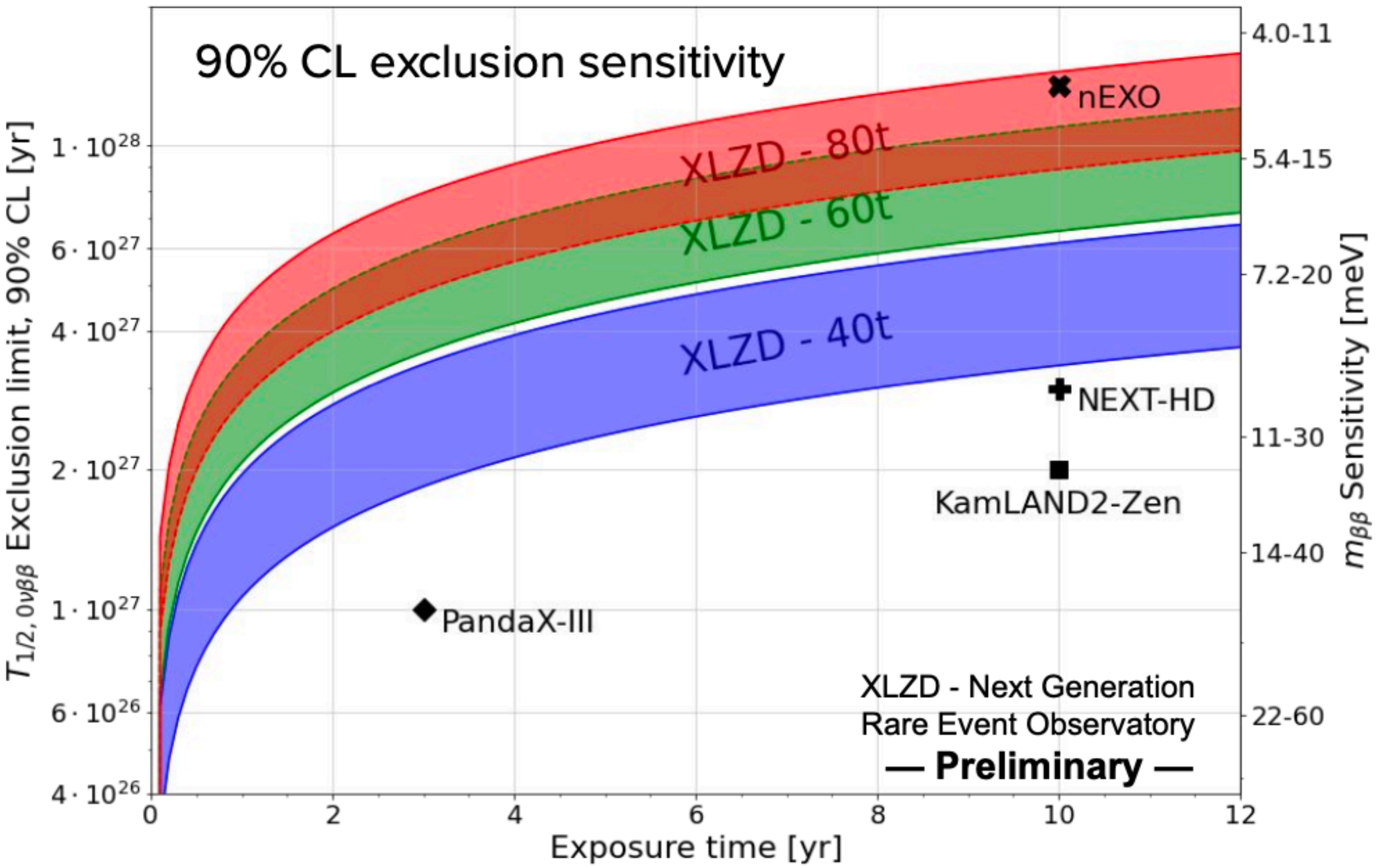
Studying XLZD $0\nu bb$ Sensitivity

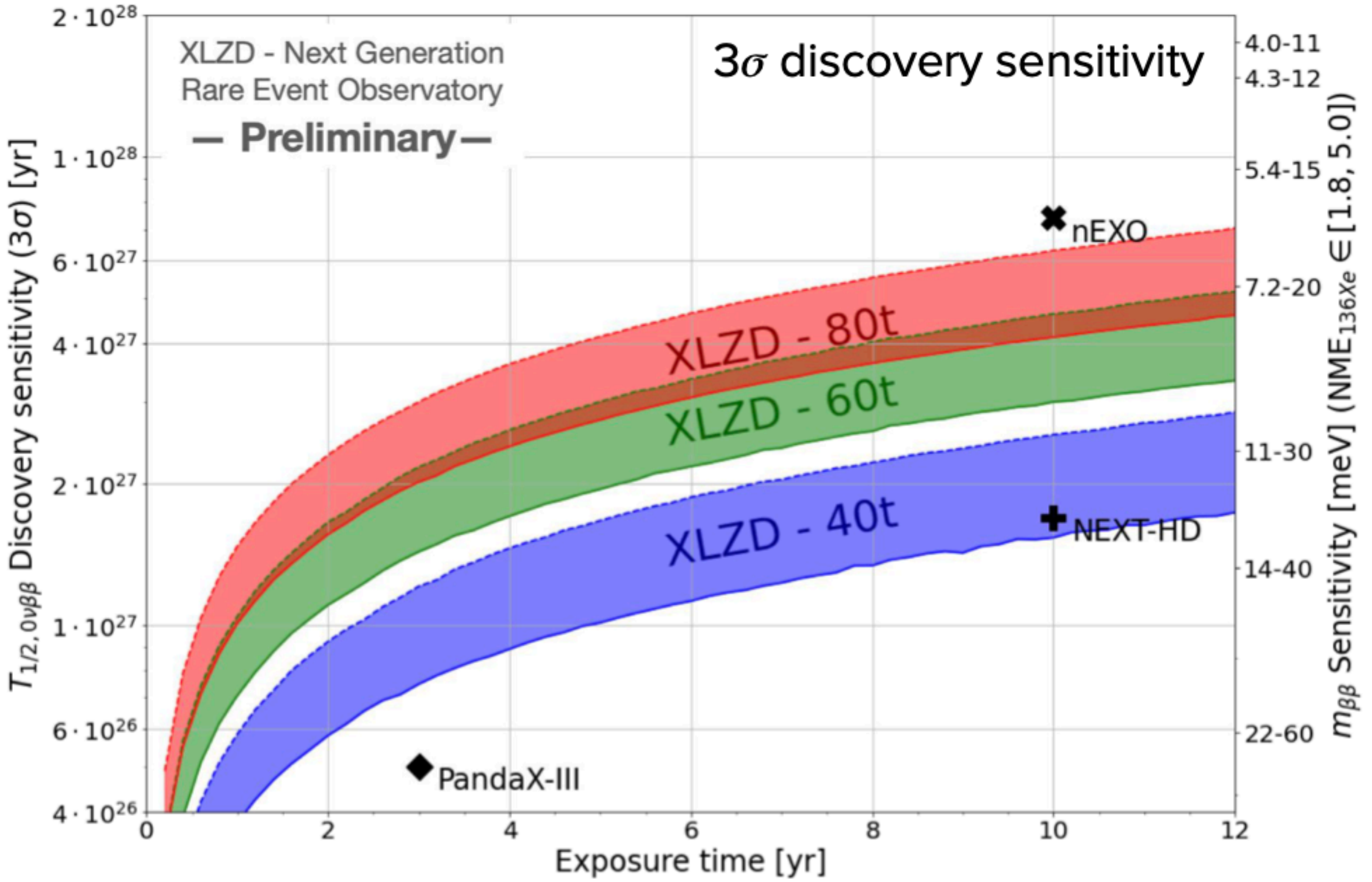
- Study all 3 detector geometries, and provide baseline and progressive input parameter curves for each
- Materials gamma backgrounds use the LZ detector materials background budget, but mitigate non-PMT sources
- Gamma attenuation is studied with a semi-analytical toy model (verified against LZ and DARWIN simulations) to quantify backgrounds surviving vetos and Multiple Scattering cuts
- Rn reduction and BiPo tagging
- Site muon rates range from 2.58×10^{-8} muons/cm^2/s (LNGS) to 6.16×10^{-9} muons/cm^2/s (SURF)

Parameter	Baseline	Progressive
External gamma flux (% of LZ)	30	10
Energy resolution (%)	0.65	0.6
Vertical SS/MS discrimination (mm)	3	2
BiPo tagging efficiency @ 0.1 µBq/kg ^{222}Rn (%)	99.95	99.99
Installation site	LNGS	SURF

- Studied in multiple optimized FV shells (not yet PLR)
- FV of baseline (progressive) models for each active mass, assume natural abundance of ^{136}Xe (8.9%)
  - 6 (7) t FV for 40 t (progressive 0.6 t ^{136}Xe)
  - 9 (12) t FV for 60 t (progressive 1.1 t ^{136}Xe)
  - 15 (18) t FV for 80 t (progressive 1.6 t ^{136}Xe)
- 90% C.L. and 3σ discovery following method of PRD 96 (2017) 053001

Projected XLZD 0νbb Sensitivity

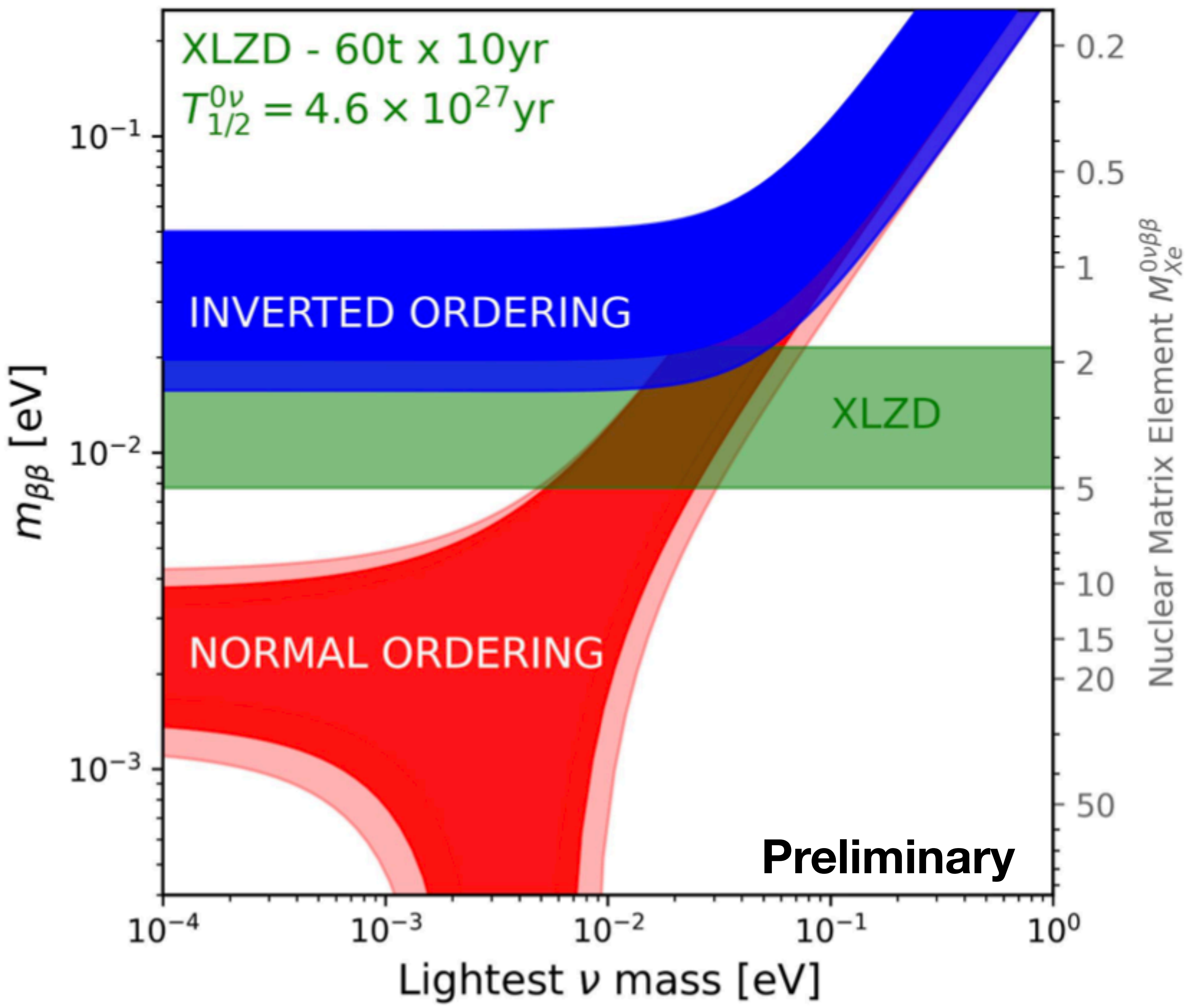


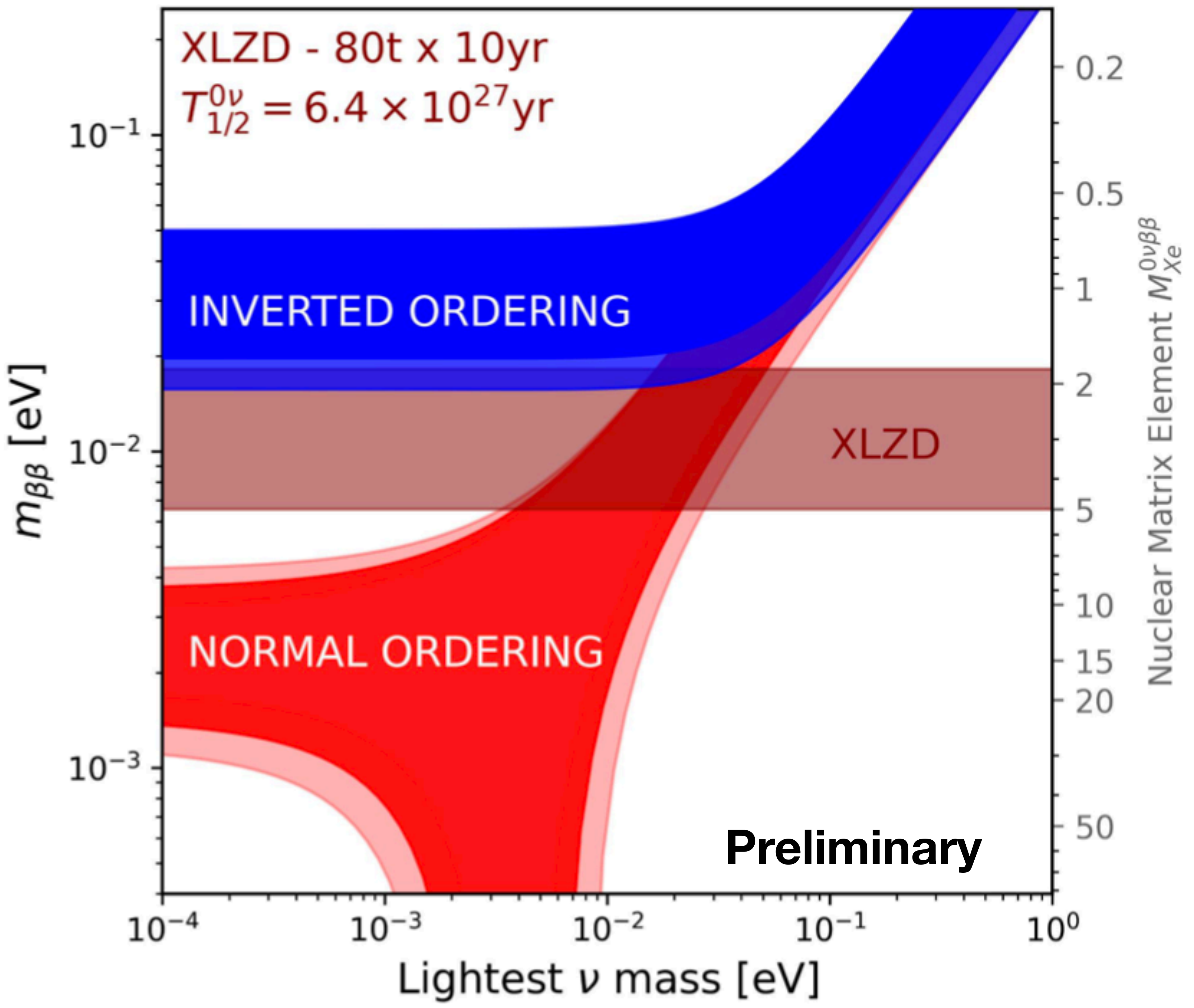


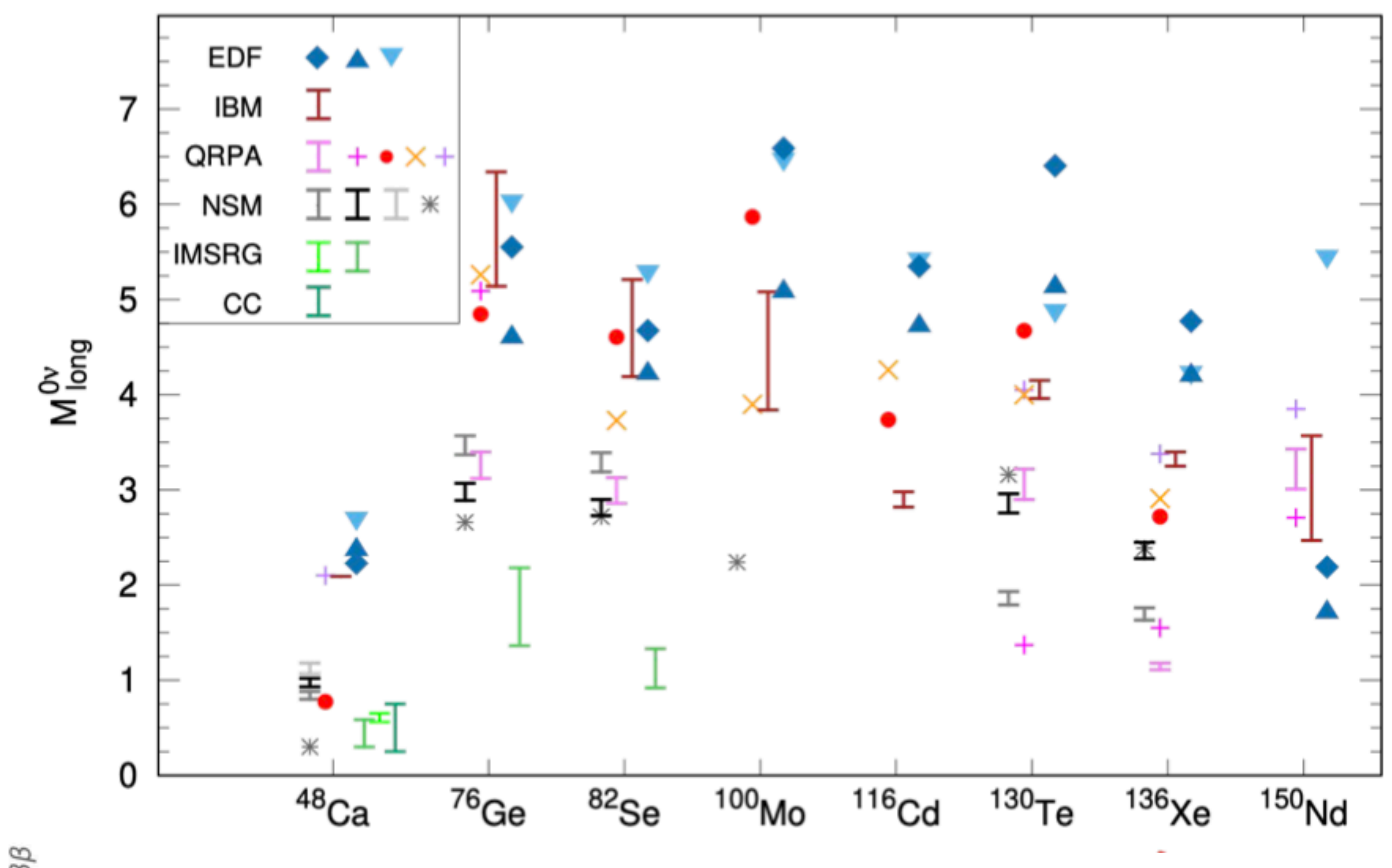
Rev Mod Phys 95 (2023) 025002 nEXO: JPhys G 49 (2022) 015104 NEXT-HD: JHEP 08 (2021) 164

XLZD Majorana Mass Reach

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

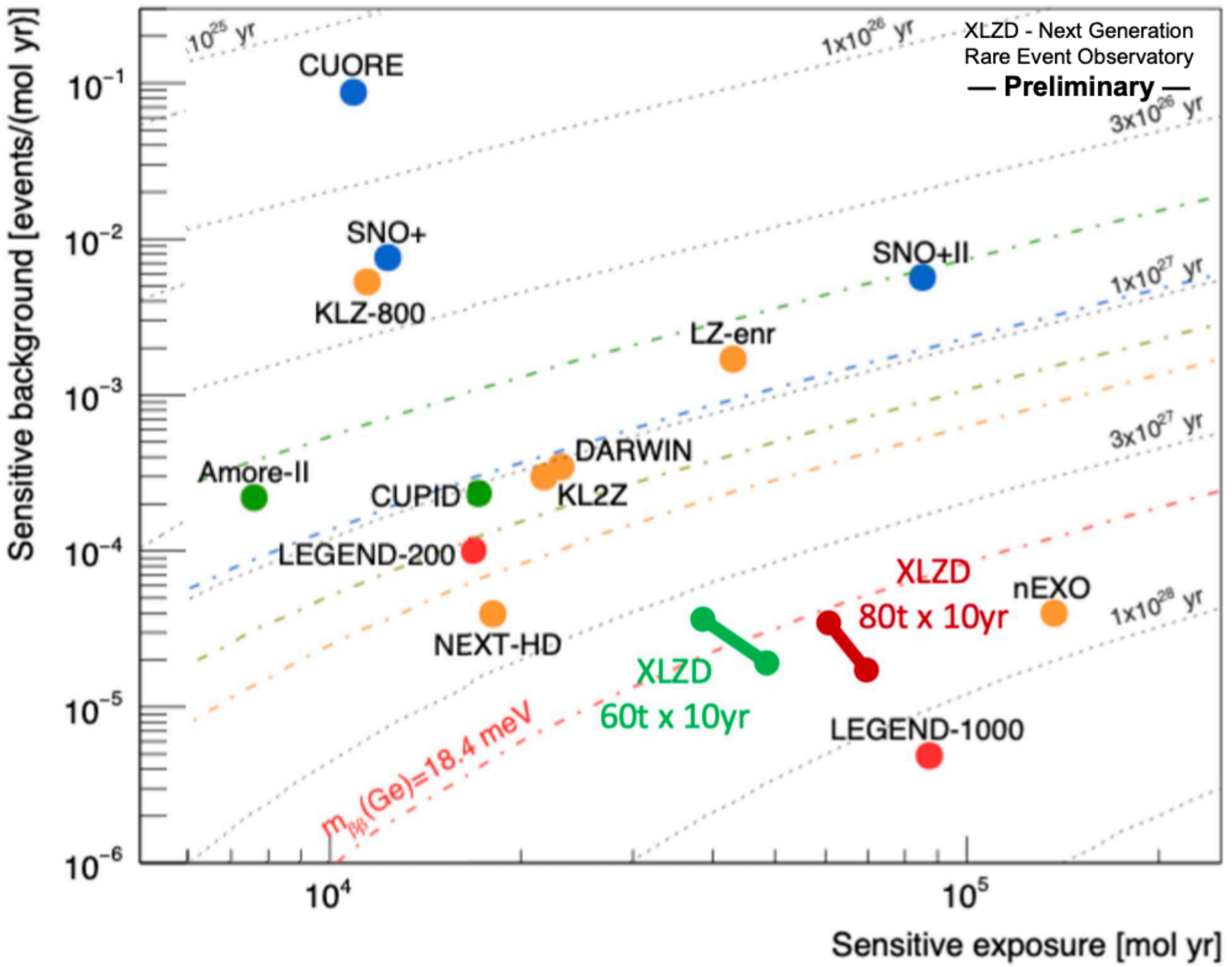






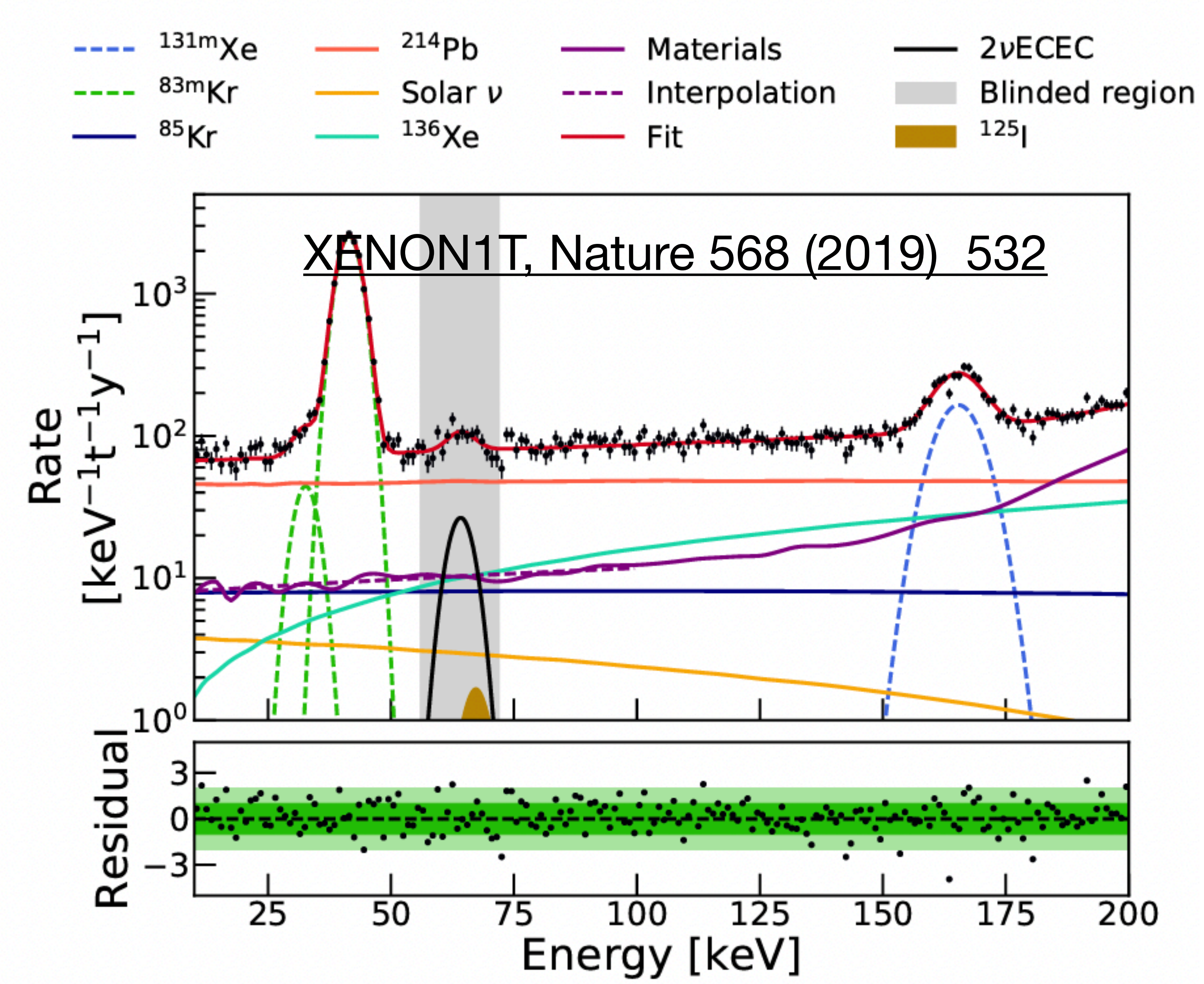
The Majorana mass is highly dependent on the nuclear matrix model

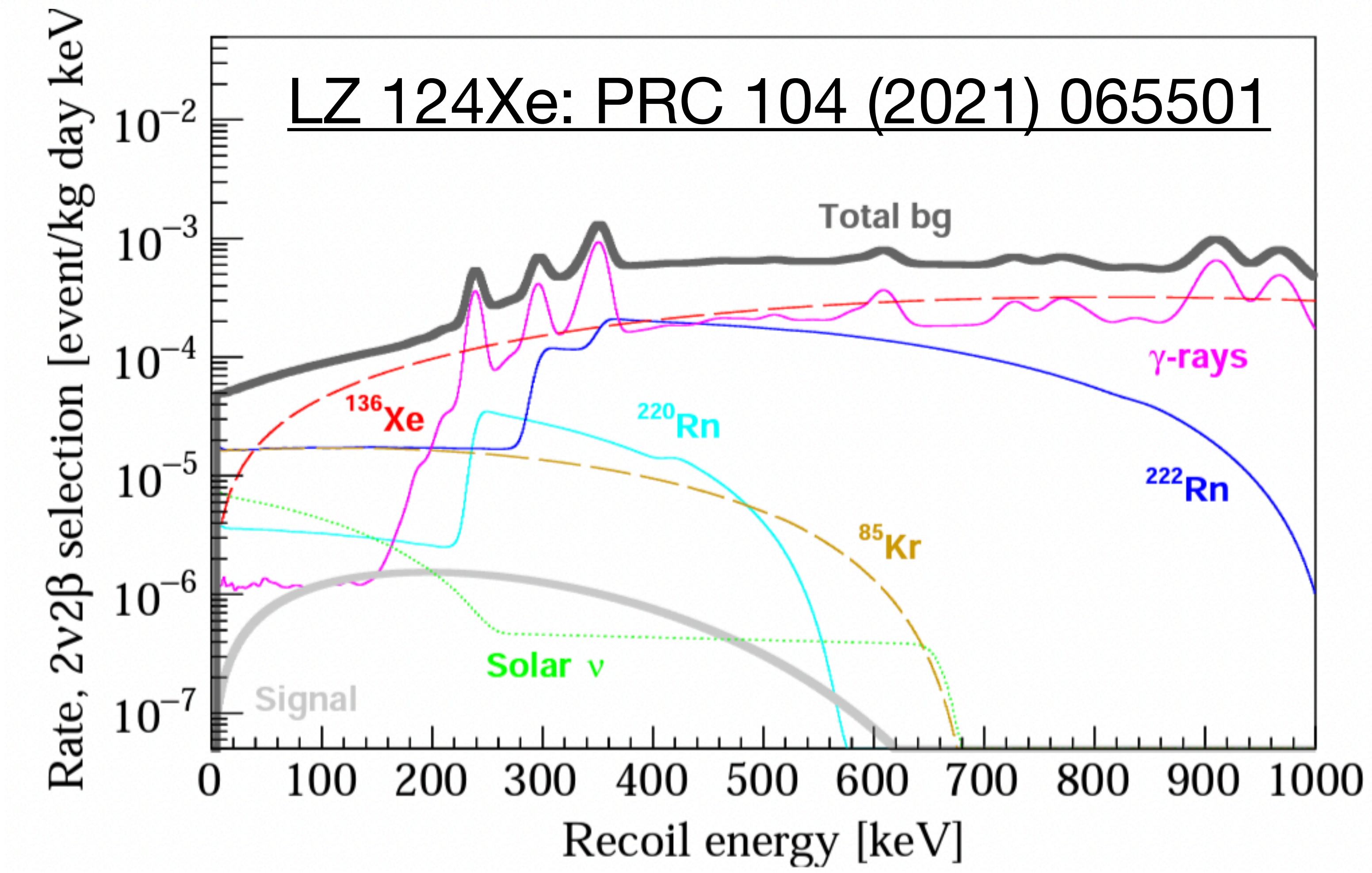
Sensitive Exposure



Adding XLZD to the overview plot from Rev Mod Phys 95 (2023) 025002

Double-electron capture



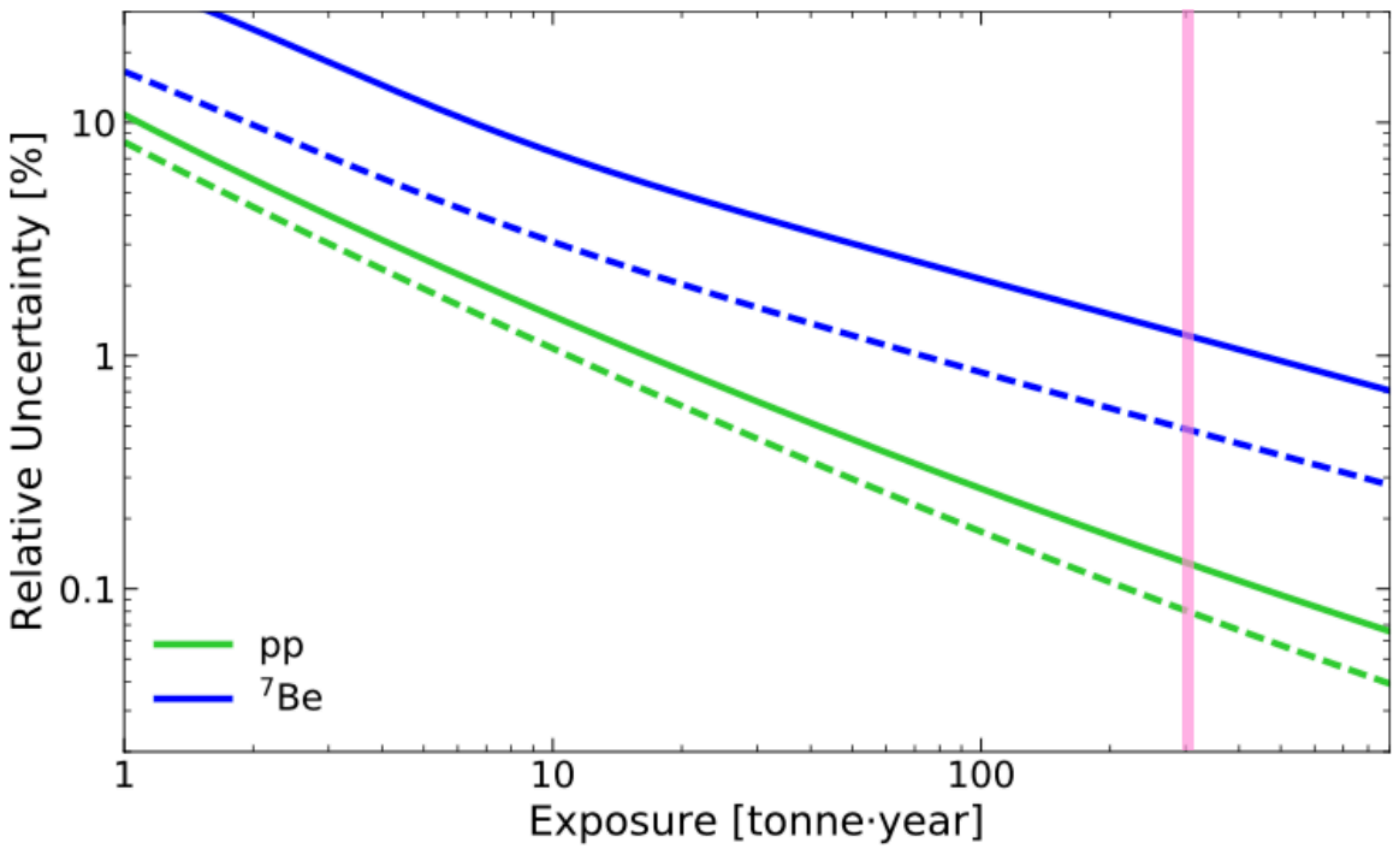


- 2ν DEC observed by XENON1T for ^{124}Xe (64.3 keV)
  - $T_{1/2}^{2\nu KK} = (1.8 \pm 0.5 \text{ stat} \pm 0.1 \text{ sys}) \times 10^{22}$ years
  - 0νDEC can be searched for too
- ^{134}Xe is also predicted to double beta decay, 2νbb not yet detected
  - Q=825.8 keV , 10.4% abundance
  - Low Rn and depleted ^{136}Xe necessary

More Neutrino Physics

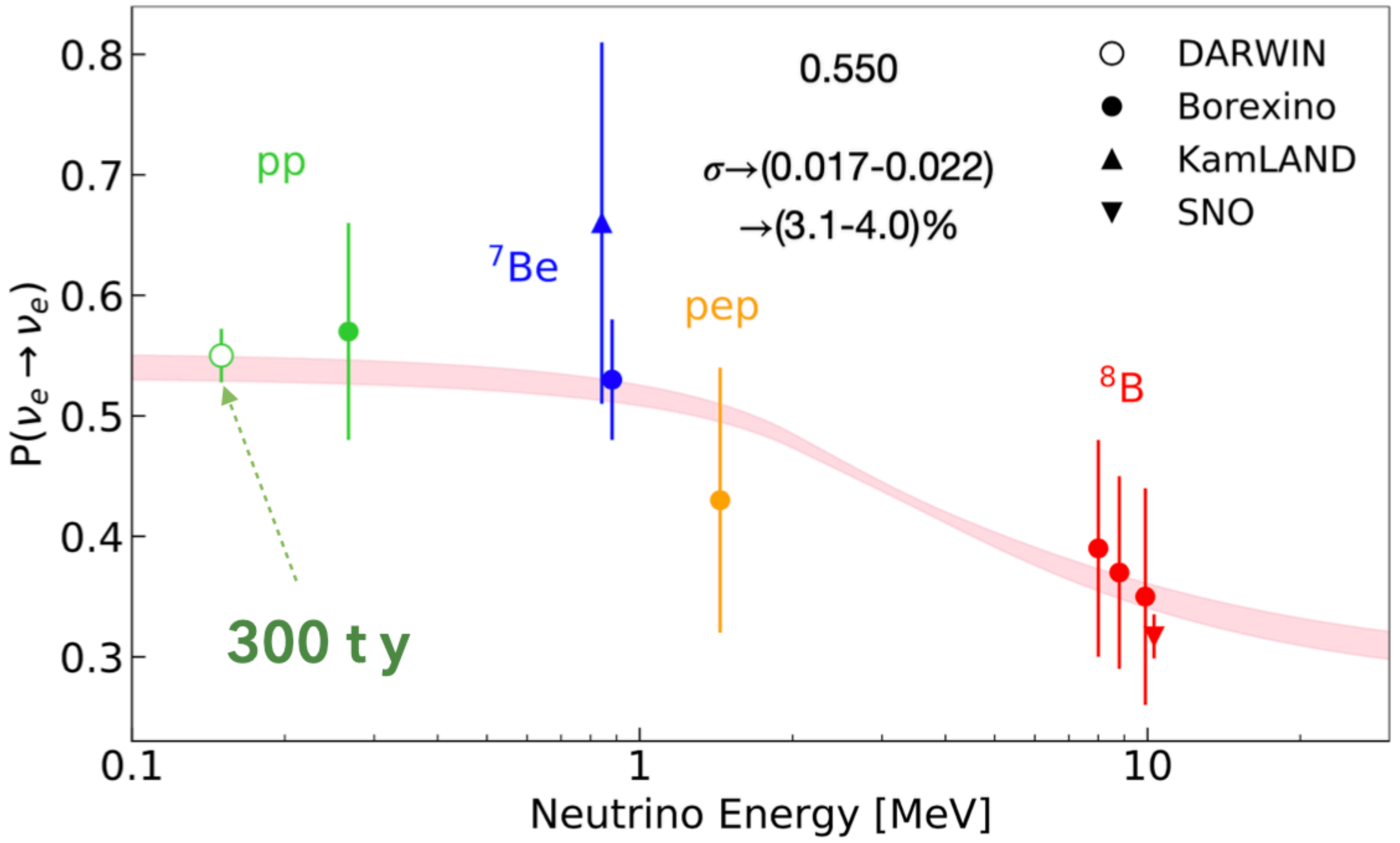
Solar neutrinos

0.15 % precision on pp flux with 300 ty

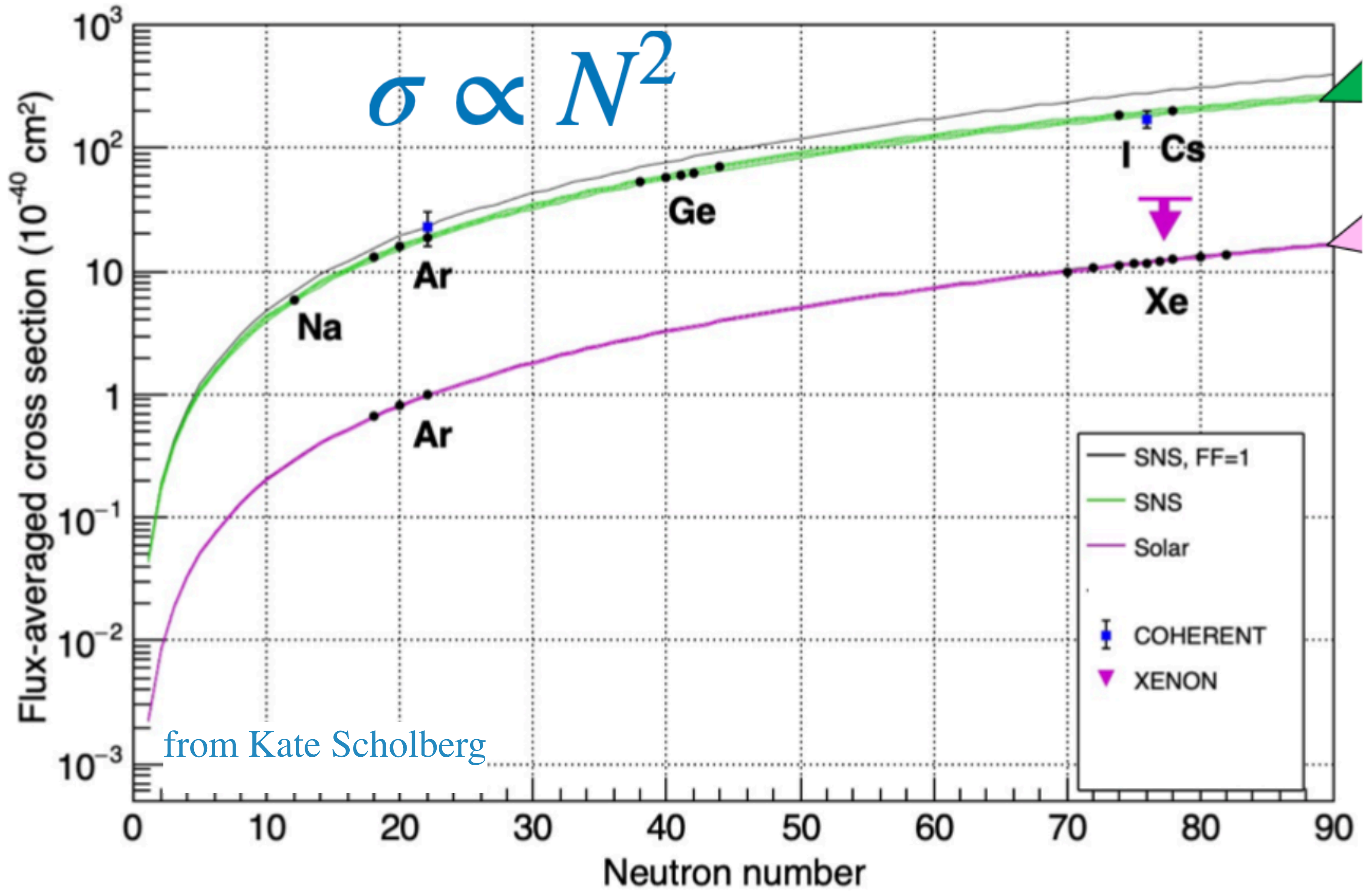


DARWIN collaboration, EPJ-C 80 12 (2020)

300 t y

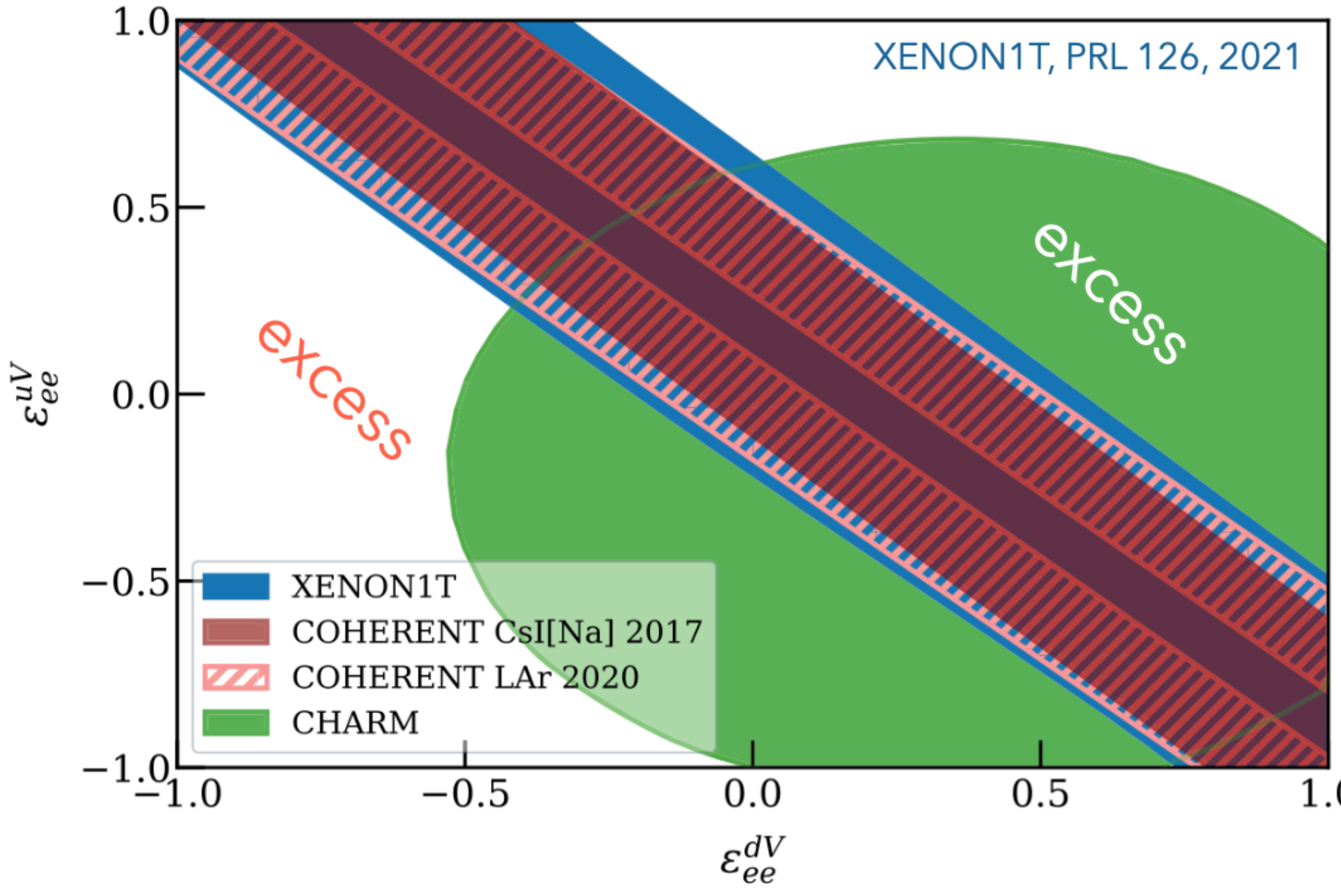


CEνNs and Non-Standard Interactions



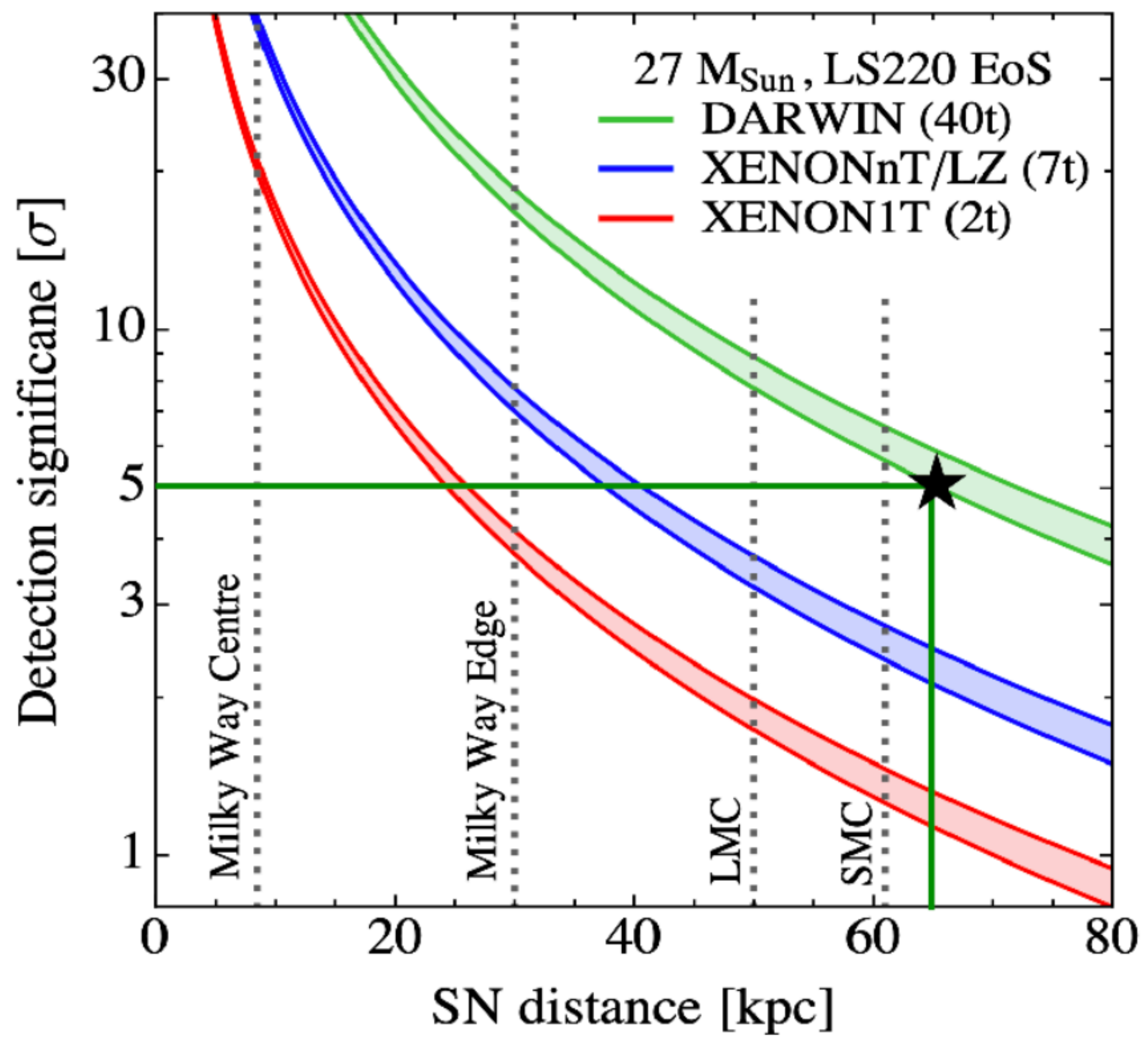
Ratio wrt SM

New ν_e-u quark interaction



New ν_e-d quark interaction

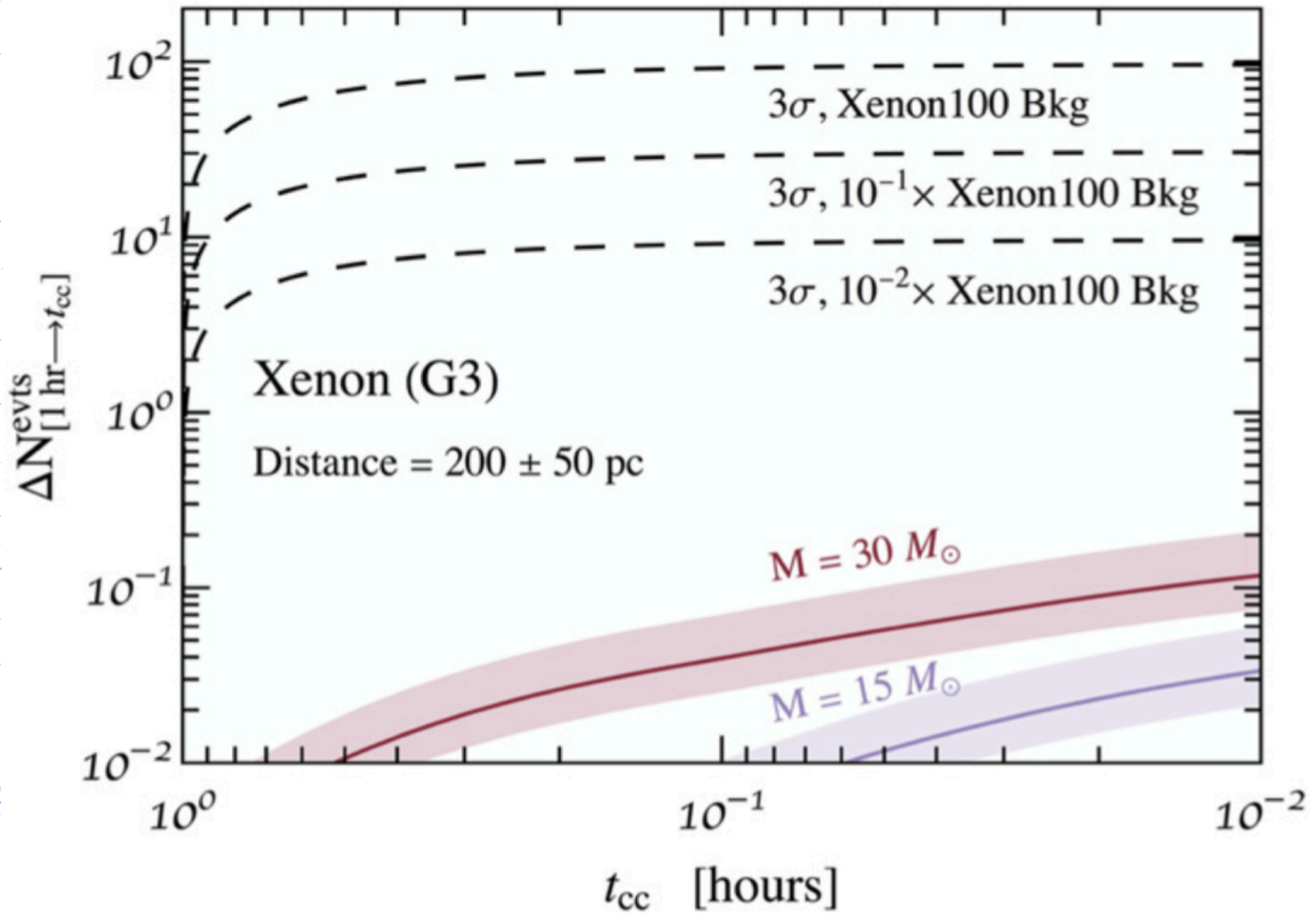
Core collapse SN



R. Lang et al., PRD 94, 103009

50 t LXe

J. Phys. G 50, 2023, 013001

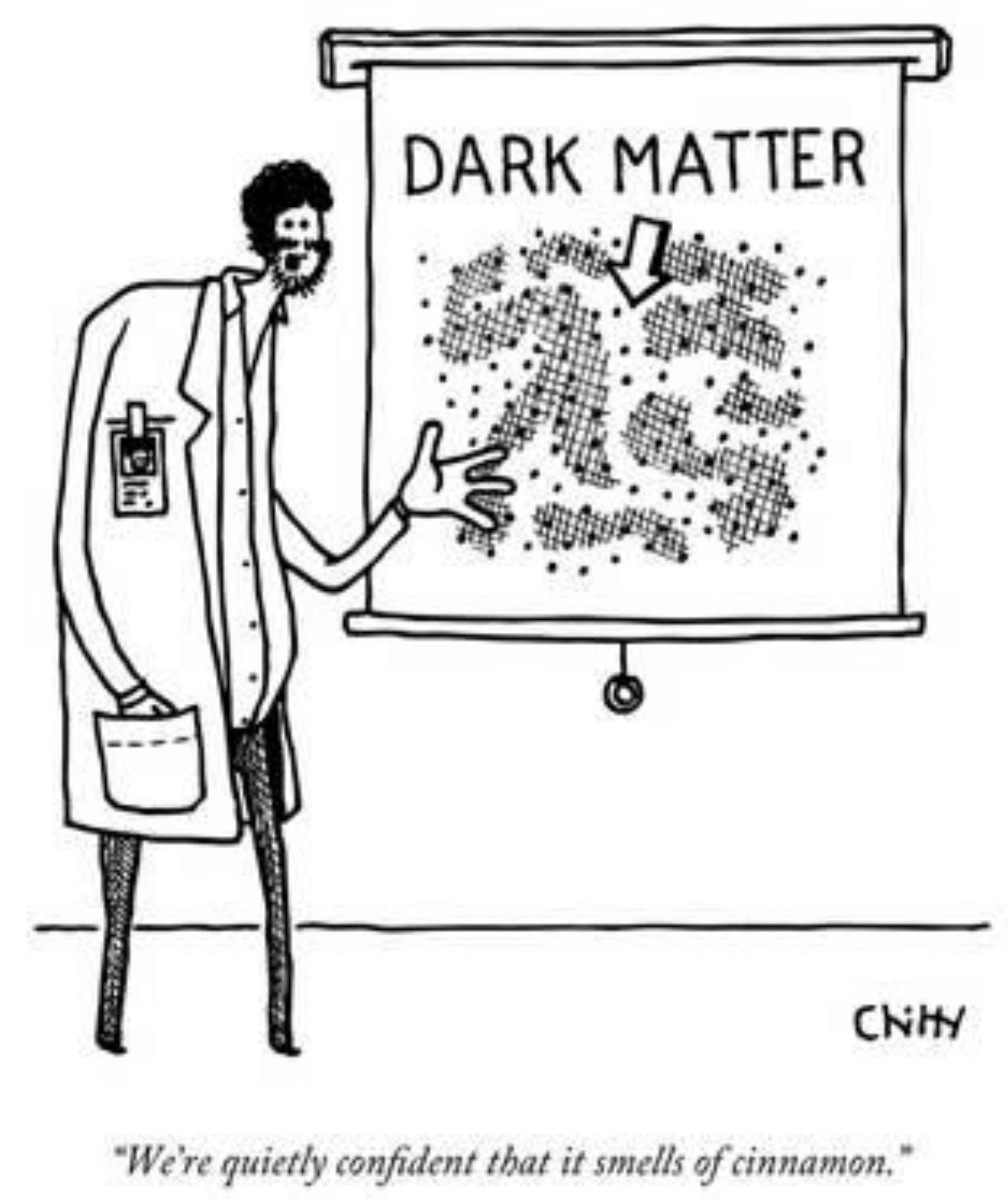


XLZD is more than WIMPs

XLZDers at the Getty Center in LA
-Florian Jorg

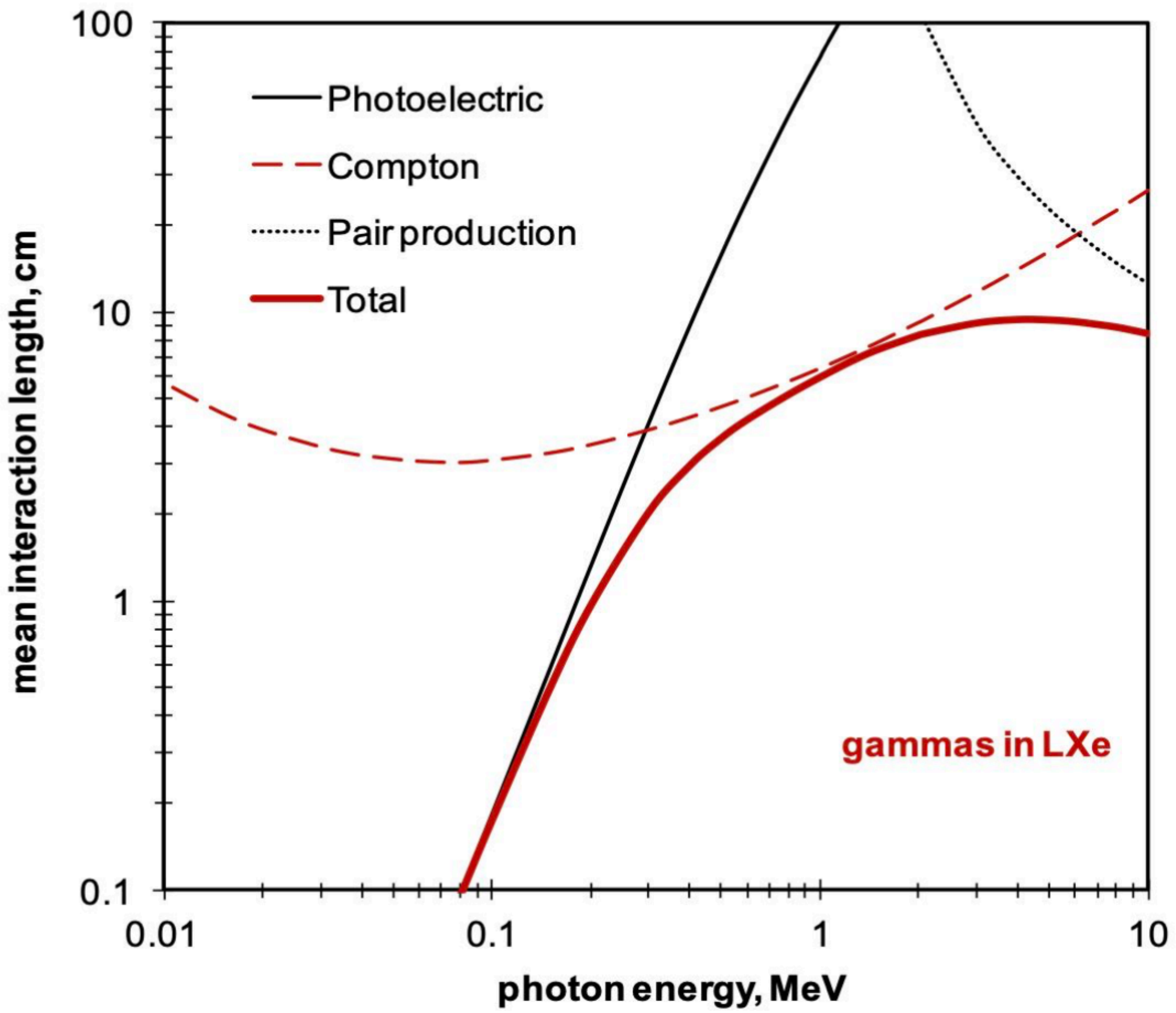
- XLZD can do competitive searches for 0νbb
  - Energy resolution and multiple-scatter rejection shown in current detectors
- Final sensitivity will depend on detector size, site, and detector backgrounds
- A rare event observatory, with low backgrounds and broad energy ROI can search for a variety of new physics signals!

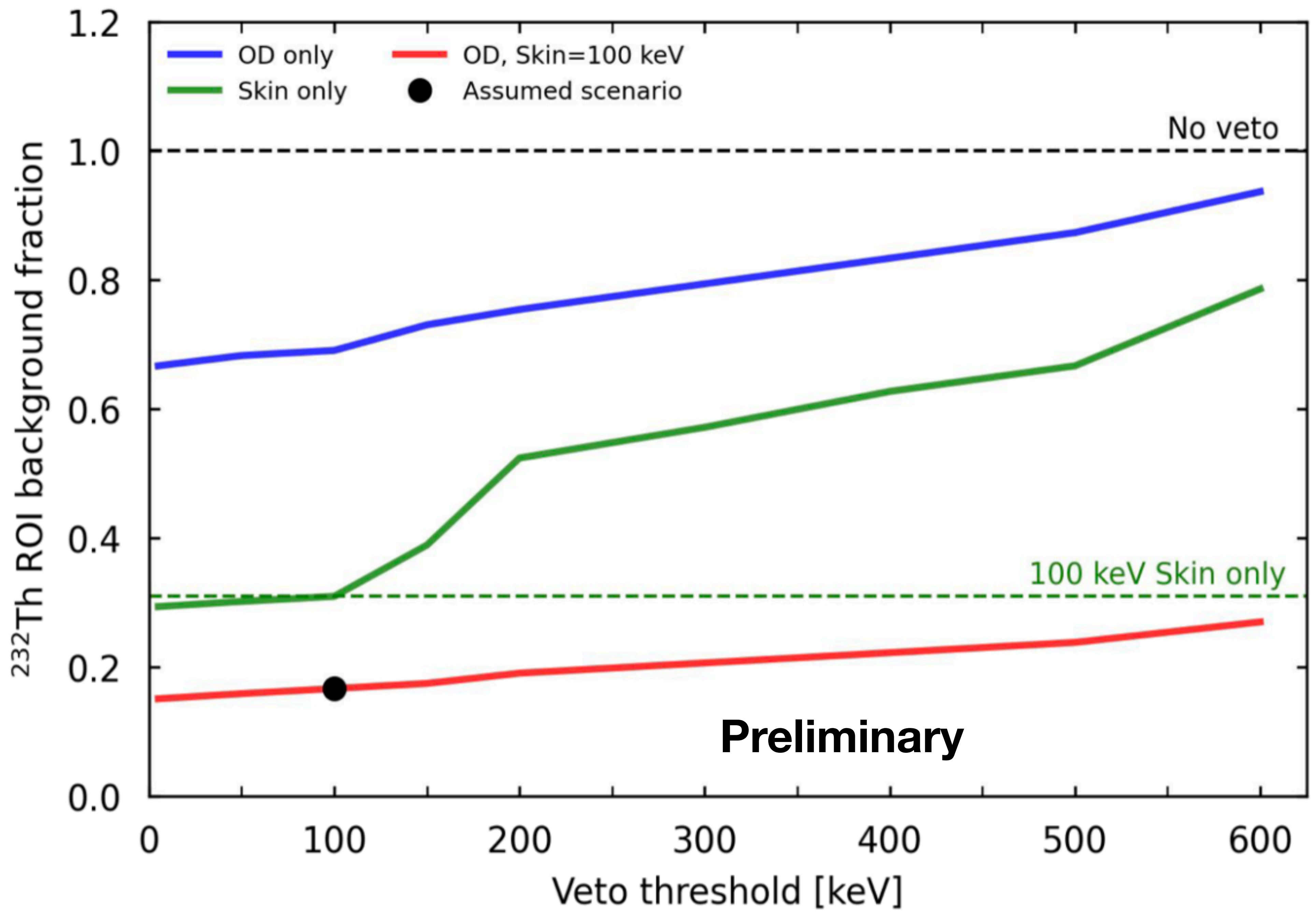
Backup Slides



Tom Chitty 2016, New Yorker

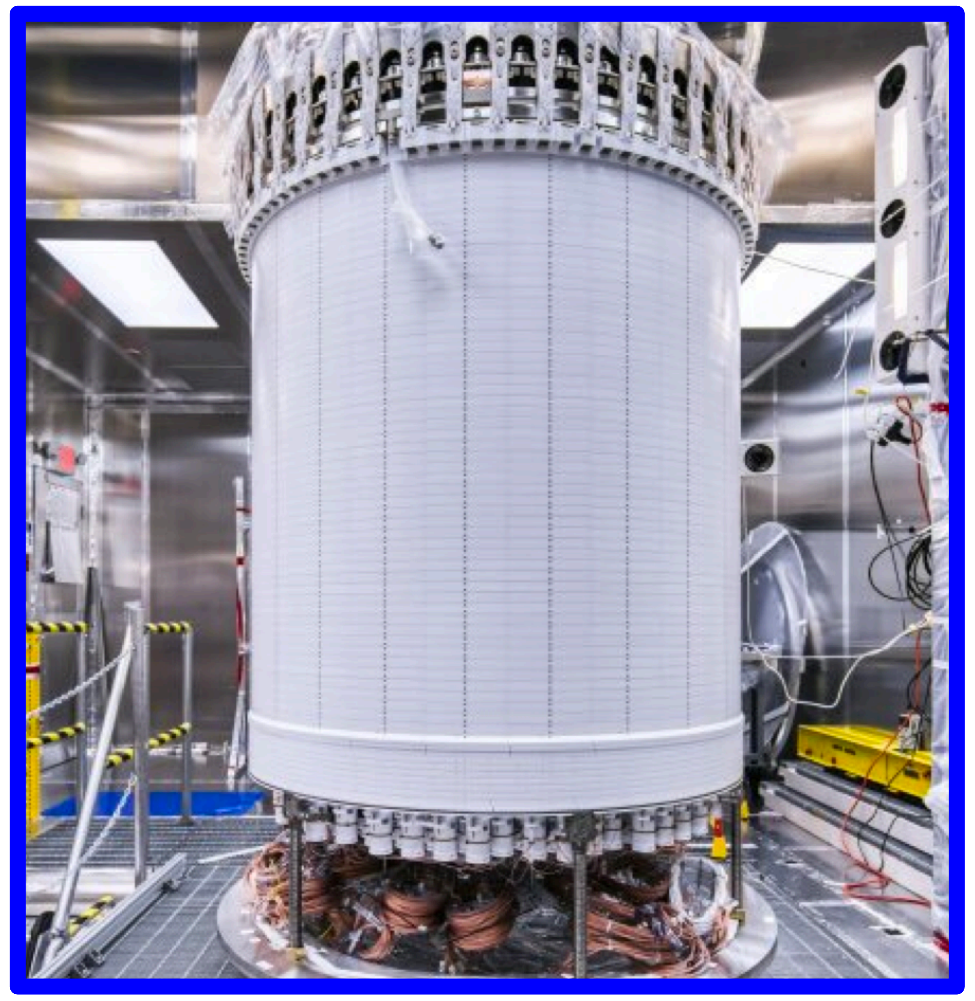
Mean Free Paths and Multiple Scatters



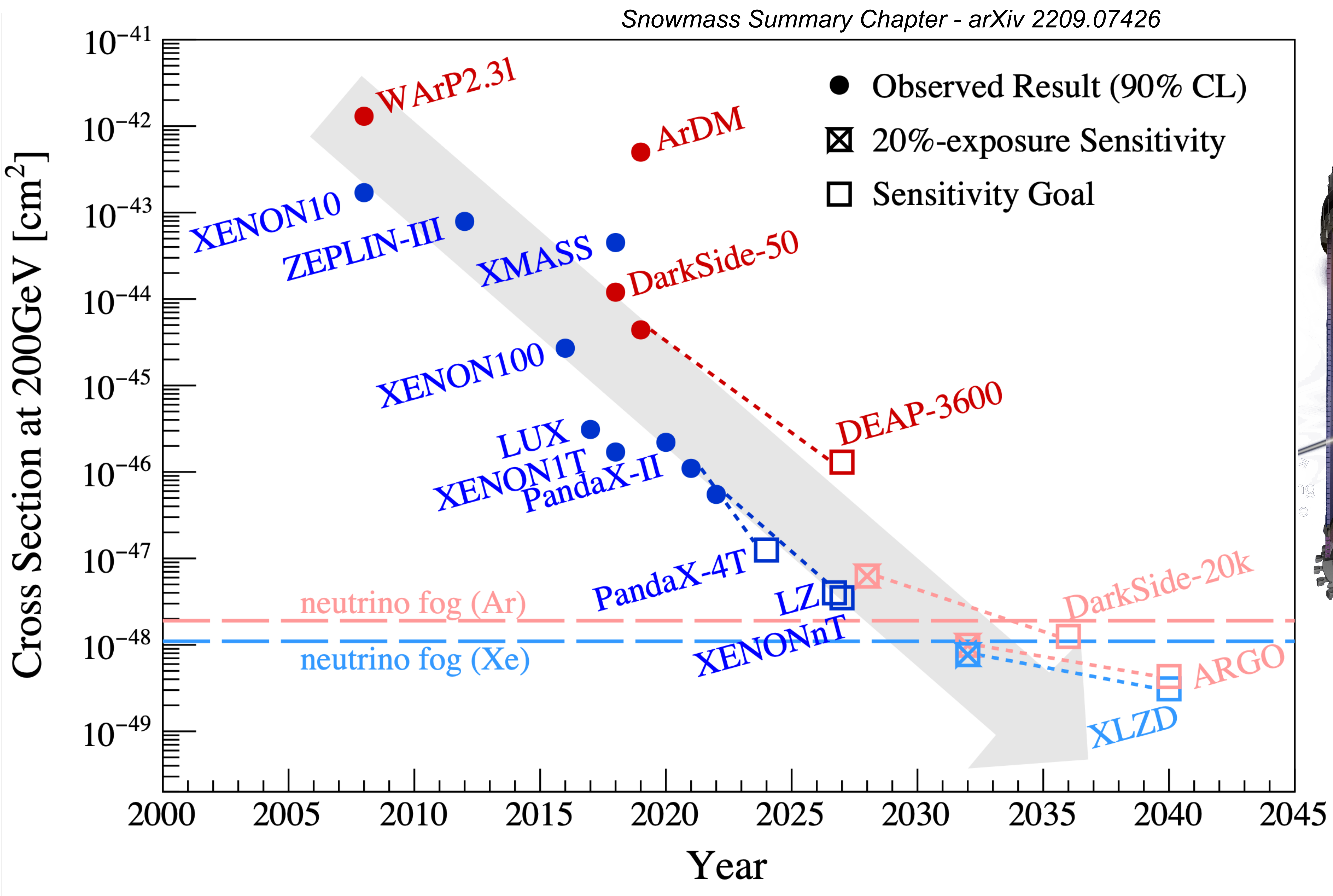


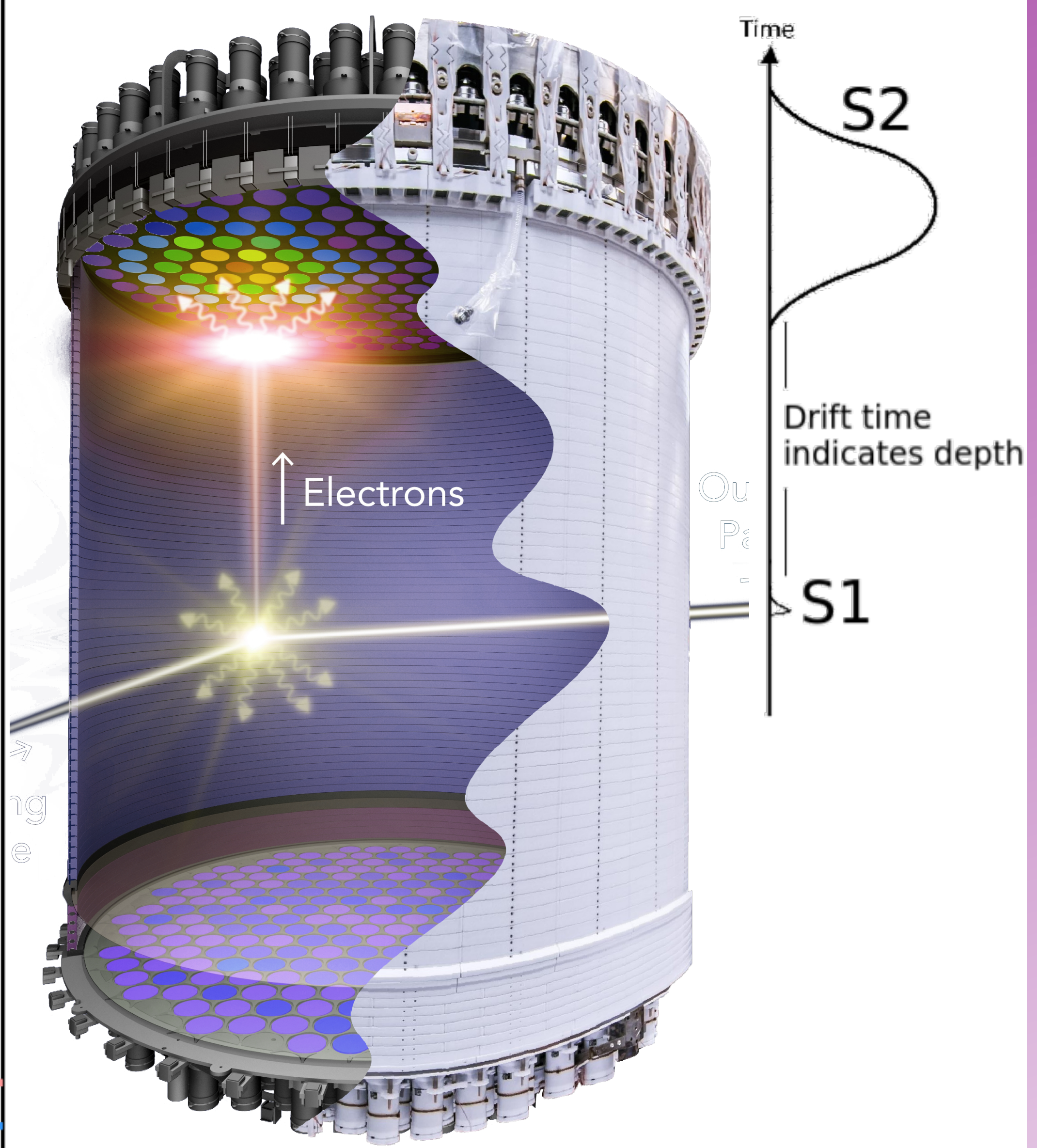
- Gammas near Q value likely to have multiple Compton scatters (10 cm MFP) before photoelectric effect (2 m)

Liquid Noble Detectors



LUX-ZEPLIN

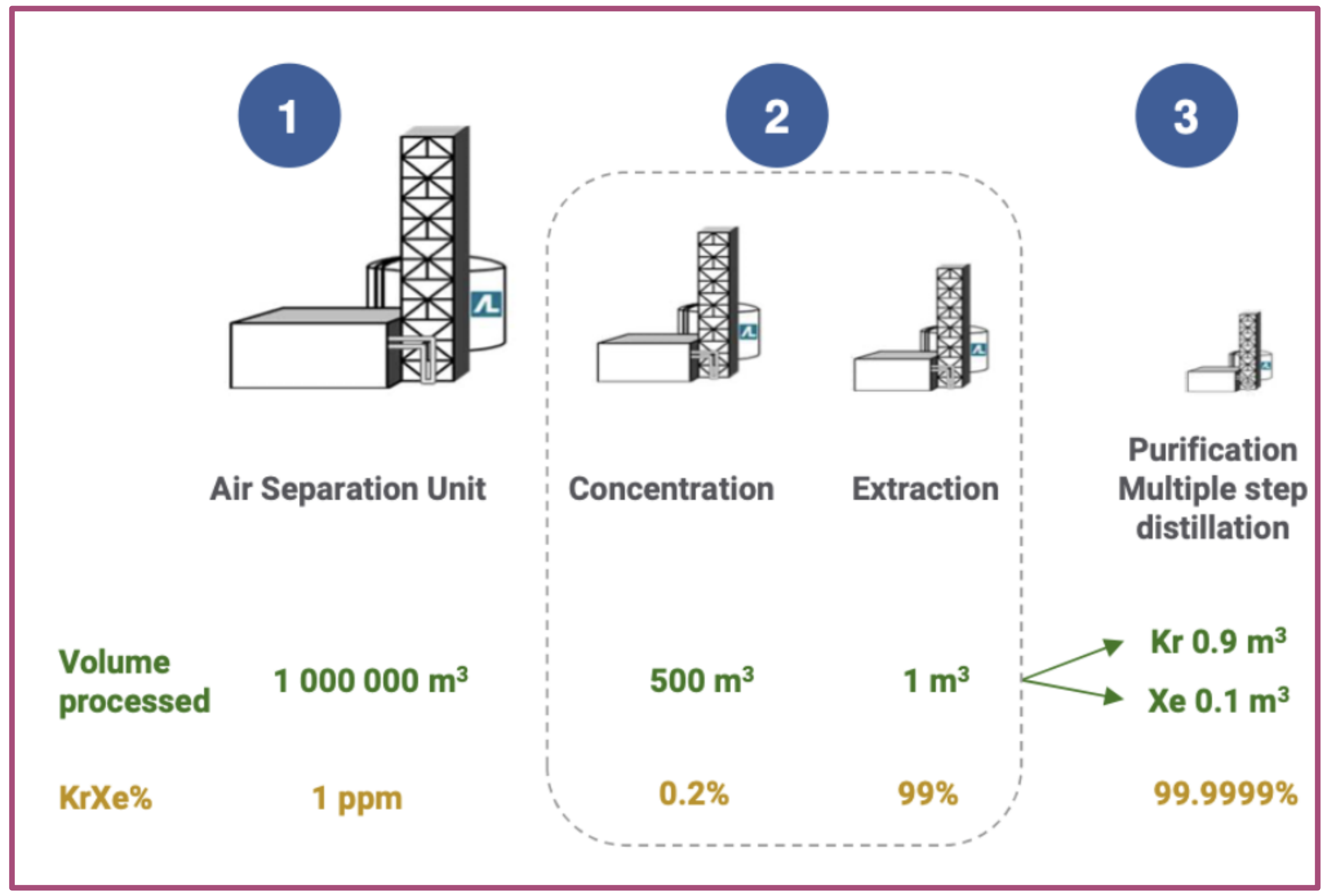


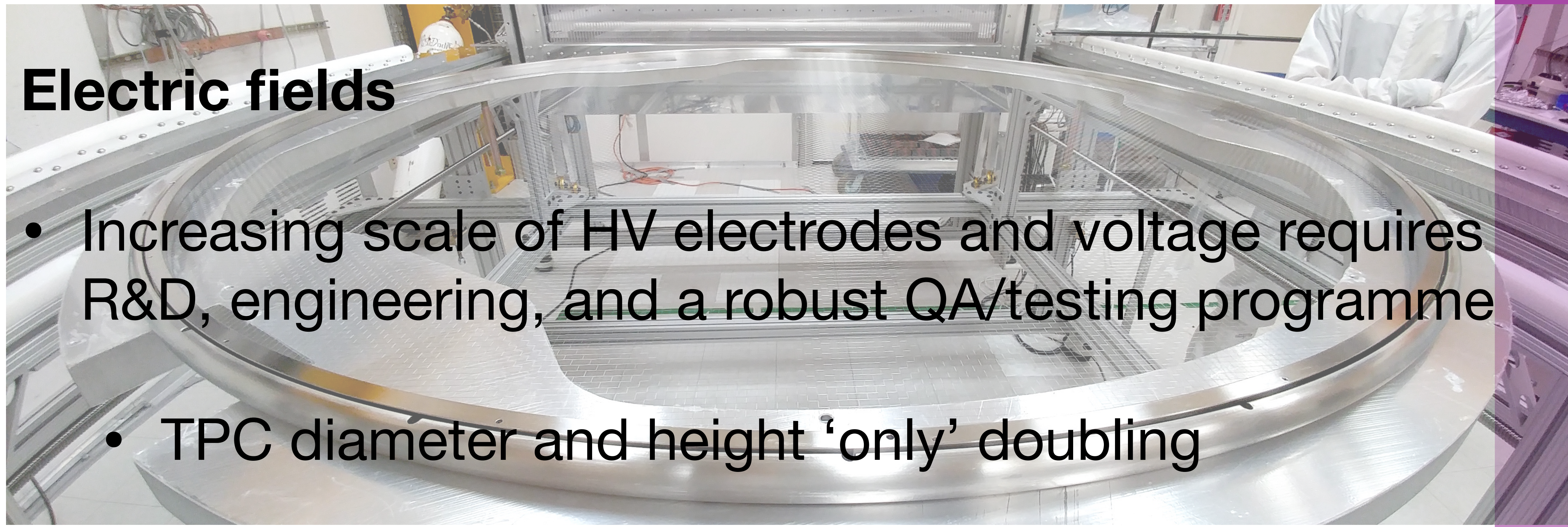


Known Risks and R&D Areas

Xenon Supply

- Commodity produced at ~60t/yr and increasing - XLZD needs to acquire ~1 year of world production
- Coordinated acquisition through long-term contracts over a decade and multiple suppliers
- Continued discussion with suppliers necessary



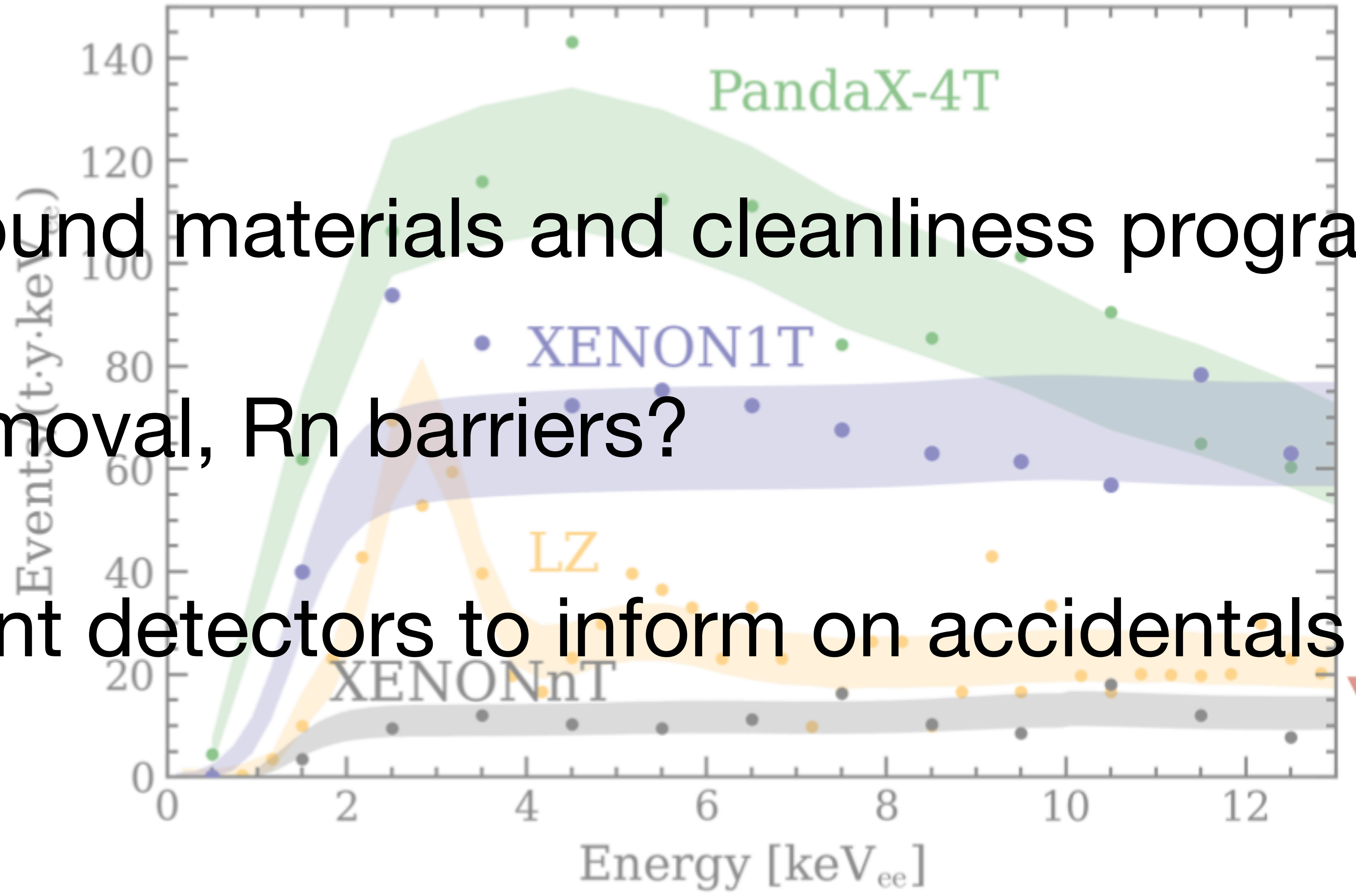


Electric fields

- Increasing scale of HV electrodes and voltage requires R&D, engineering, and a robust QA/testing programme
  - TPC diameter and height 'only' doubling

Backgrounds

- Low background materials and cleanliness programme
- In-line Rn removal, Rn barriers?
- Exploit current detectors to inform on accidentals and other effects



Track record of the combined teams in scaling from 10 kg to 10 tonnes provides the technical foundation and capabilities for making the necessary advances