Universität Zürich UZH

KNUT DUNDAS MORÅ

SCIENCE PROSPECTS OF THE XLZD EXPERIMENT

NOMINAL XLZD DESIGN GOAL

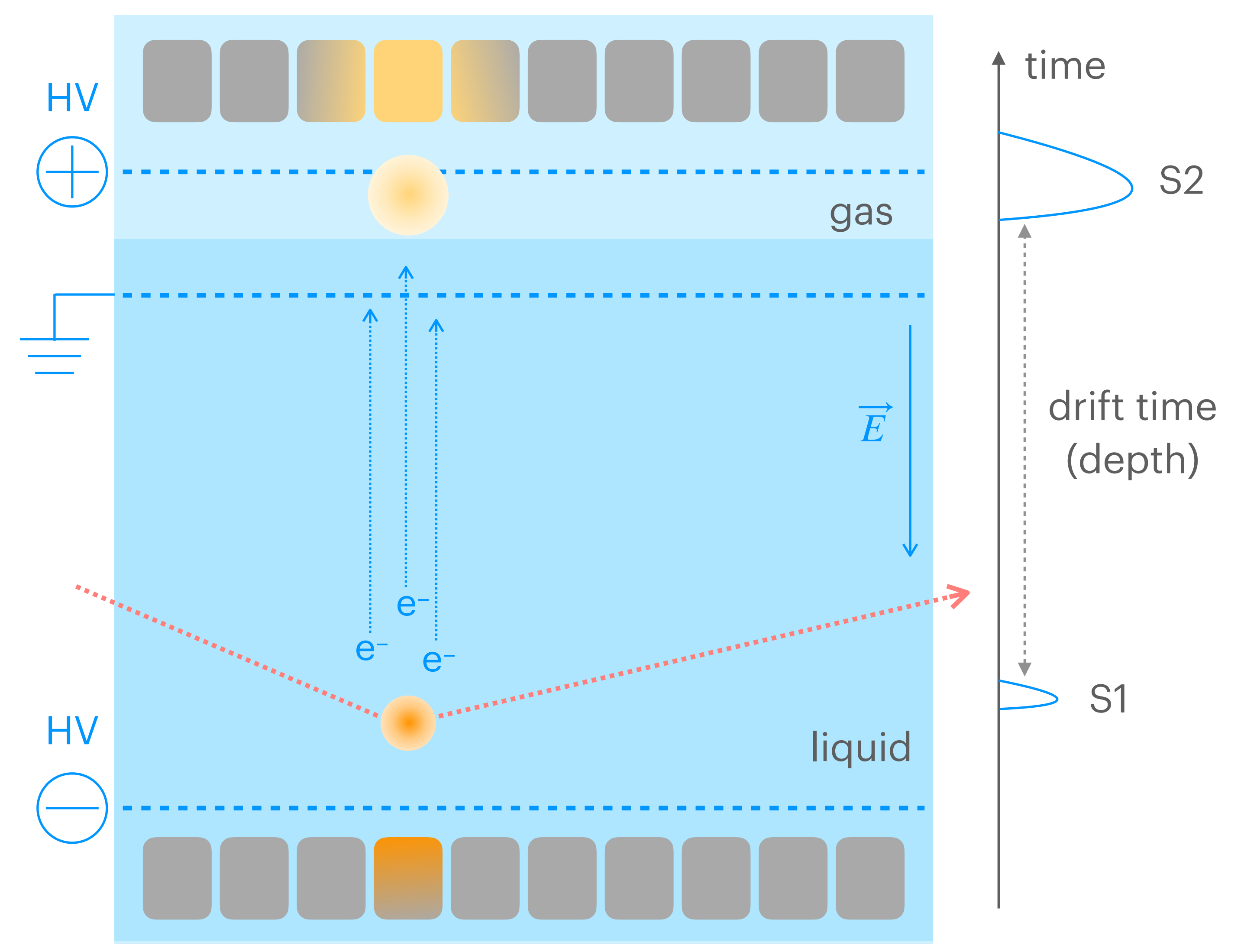
FOR MORE DETAILS ON XLZD DESIGN AND R&D SEE MASAKI YAMASHITAS PRESENTATION!

- TPC: 60-80 t LXe is possible
- Two arrays of 3-inch PMTs, 1182/array
- 3 m e- drift, 3 m diameter
- Drift field: 240-290 V/cm
- Extraction field: 6-8 kV/cm
- Double-walled Ti cryostat, ~ 5 cm LXe "skin" detector around the TPC

LXE TPC OBSERVABLES

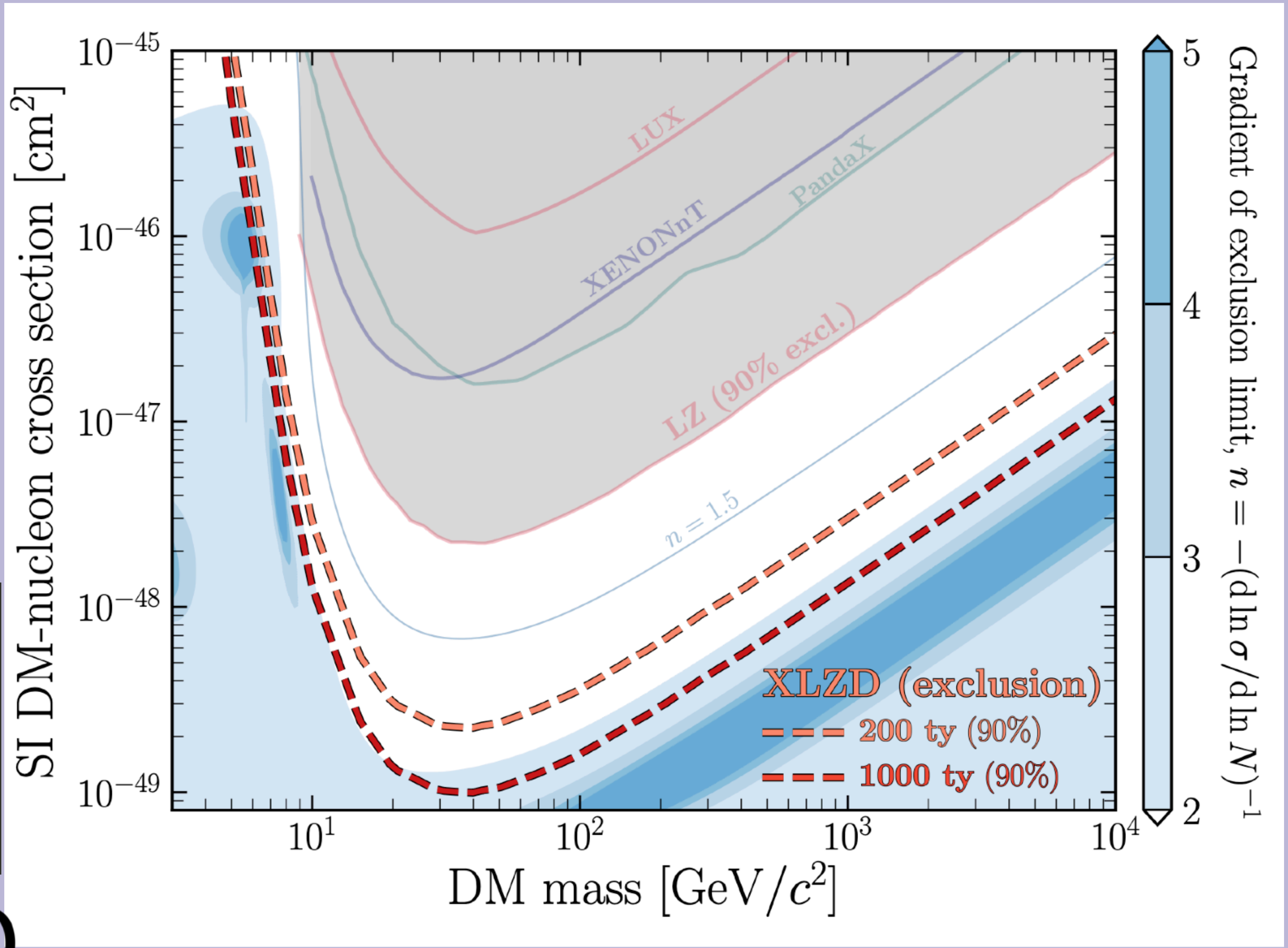
DETAILS ON LXE OPERATION PRINCIPLES AND OBSERVABLES IN THE TALKS FROM MAXIME, AMY AND MINZHEN

- **LXe TPCs reconstruct three-dimensional position (X, Y, Z, or R, Z, θ)**
- **scintillation light**
- **and ionisation light**
- **The latter two can be combined to reconstruct the total deposited energy**



THIS TALK WILL FOCUS ON TWO OF THE PRIMARY SCIENCE GOALS OF XLZD

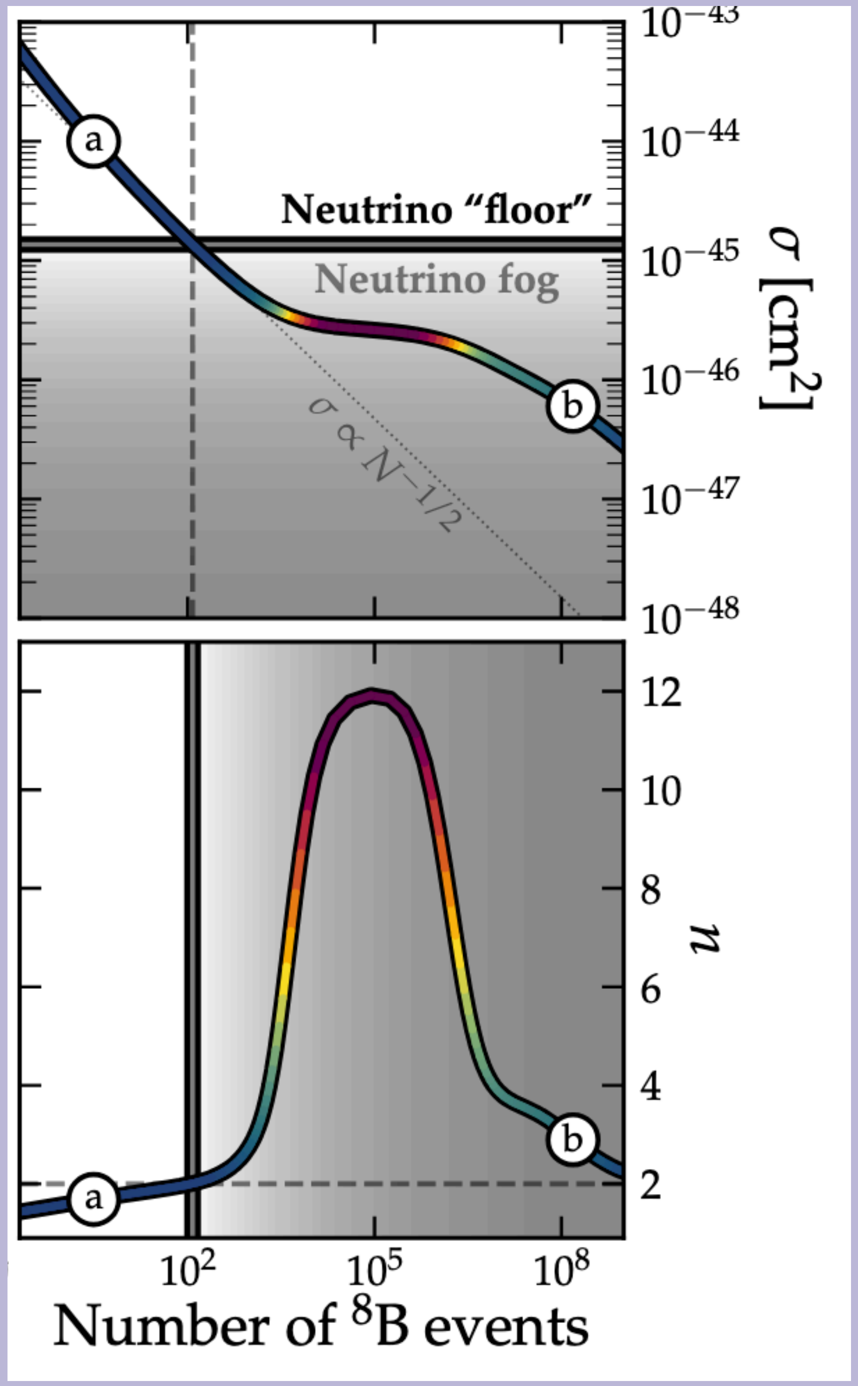
XLZD WILL DISCOVER OR CONSTRAIN WIMPS ALL THE WAY TO THE "NEUTRINO FLOOR"



The XLZD Design Book: Towards the Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics, XLZD Collaboration e-Print: 2410.17137 [hep-ex]

WIMP SEARCHES

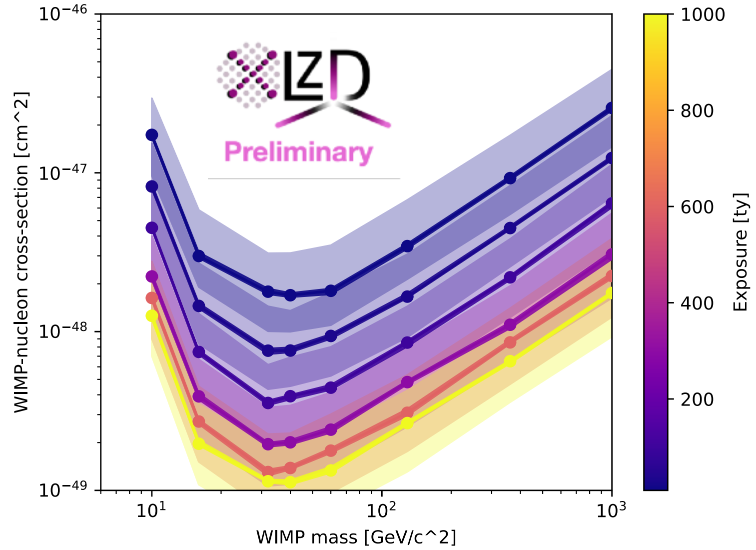
- **Searching for and discovering dark matter is the primary motivation of XLZD**
- **As seen in the preceding talks, LXe TPCs are excellent machines for constraining WIMP-nucleon interactions**
- **XLZD aims to discover or constrain WIMP-nucleon interactions to the point where astrophysical neutrinos become the dominant background**
- **This sensitivity to WIMP signals is the main driver of the requirements for XLZD**
- **In this presentation I will go over some of the design choices and assumptions that went into WIMP sensitivity curves, these are all preliminary!**



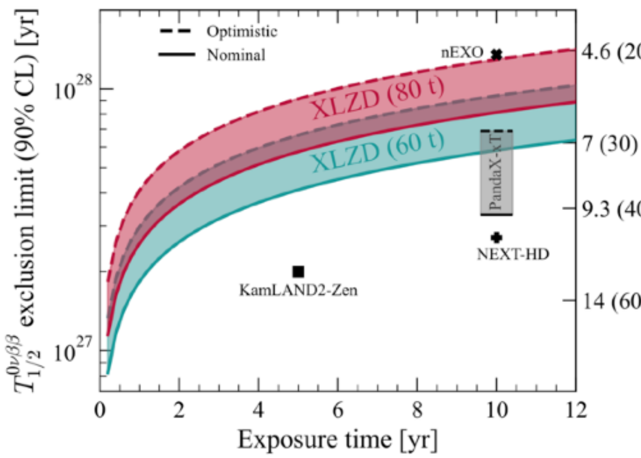
New Definition of the Neutrino Floor for Direct Dark Matter Searches, Ciaran A.J. O'Hare, Phys.Rev.Lett. 127 (2021) 25, 251802

WHERE ARE "REQUIREMENTS"?

- At its current stage, XLZD is defining high-level performance requirements:
  - Exposure (lifetime times fiducial mass)
  - analysis threshold
  - ER backgrounds
  - neutron backgrounds
- More detailed second-level analysis will use these as targets to see if each upstream requirement reaches its targets



WIMP SENSITIVITY



$0\nu\beta\beta$ SENSITIVITY

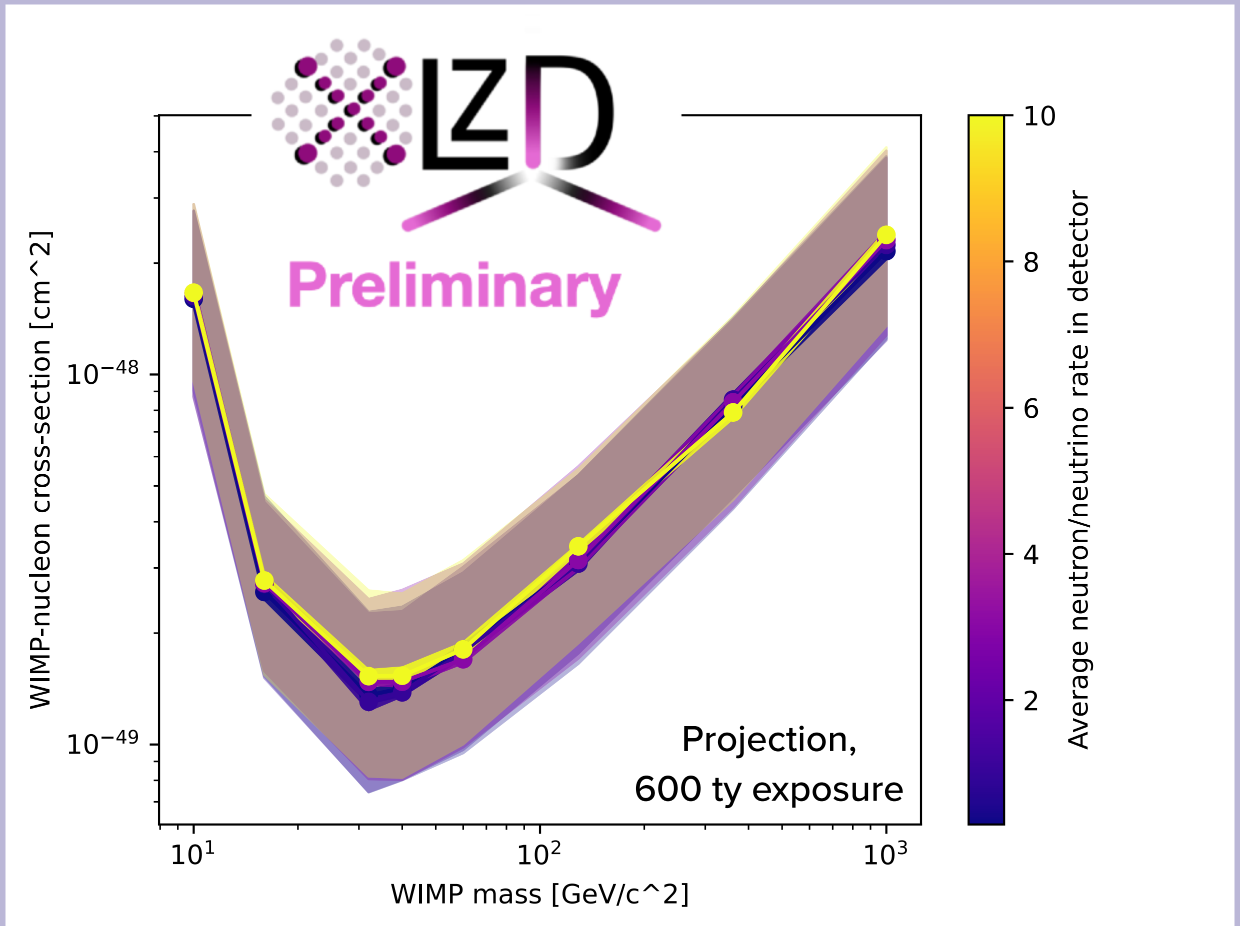
Energy threshold | Intrinsic Backgrounds | Neutron Rate | Fiducial Volume | Energy Resolution

PMT performance | Detector Size | Veto Performance

Drift Field | Veto Performance | Electron Livetime

DETECTOR PERFORMANCE AND NEUTRON DISCRIMINATION

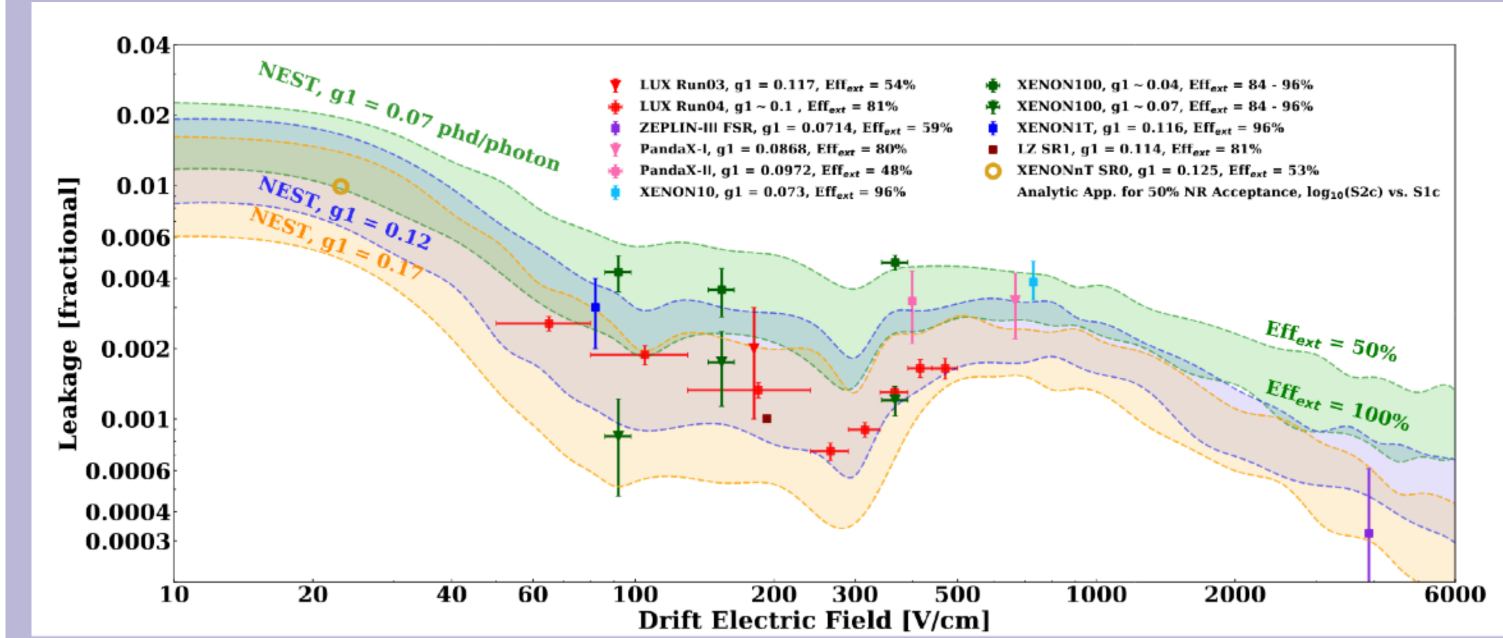
- **The detector sensitivity to light, in particular fainter S1s determine the energy threshold and has a significant impact on performance for lower-mass WIMPs— a 20% change in combined LCE and PMT QE changes limits at $10\ \mathrm{GeV}/c^2$ by 15%**
- **Neutrons from detector materials and surrounding rock cause WIMP-like NR events, but will be rejected and constrained both by a surrounding neutron veto and multiple-scatter events in the large TPC**
  - **Including r^2 as an analysis dimension strongly reduced the impact of changing neutron rates**
  - **For XLZD performance, an average neutron flux comparable to the neutrino fog allows us to reach the science goals**

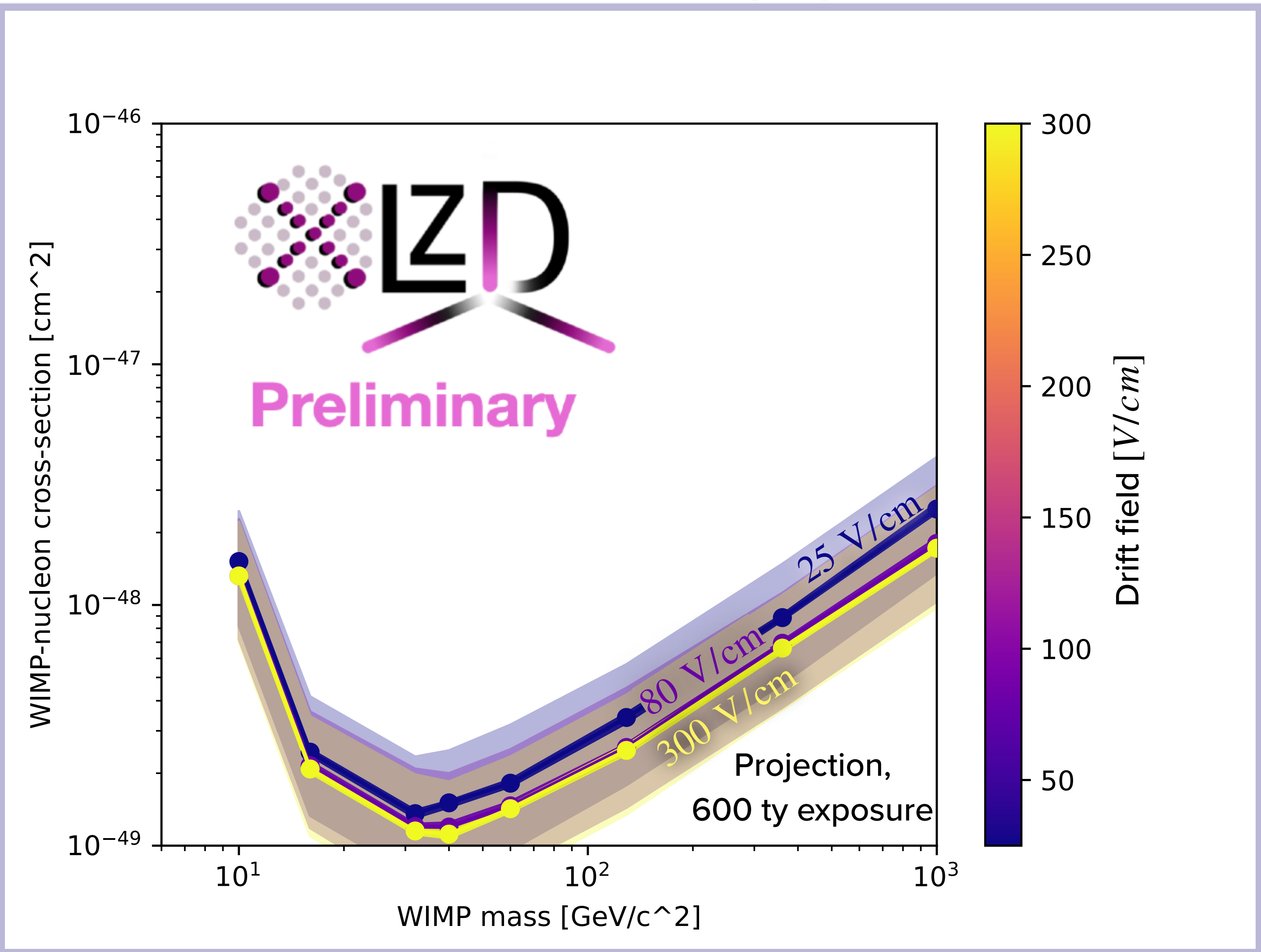


ER BACKGROUNDS AND DRIFT FIELD

- **Following DARWIN nominal values of $0.1\mu\mathrm{Bq}/kg\ \ {}^{222}\mathrm{Rn}$ and $0.1ppt\ {}^{nat}\mathrm{Kr}$ gives acceptable ER rate**
- **The separation between electronic recoils and nuclear recoil signals depend on the applied drift field, with a relatively broad optimum around $250\mathrm{V/cm}$ — however even $80\ \mathrm{V/cm}$ shows only slight reduction**
- **A higher drift field increases the drift speed and reduces the drift time with additional benefits which are not included in these studies:**
  - **Reduced time for S2 signals to diffuse, improving reconstruction**
  - **Reduced time for an event to overlap with noise, reducing mispairing**
  - **Reduced overlap with other events during higher-intensity calibrations**

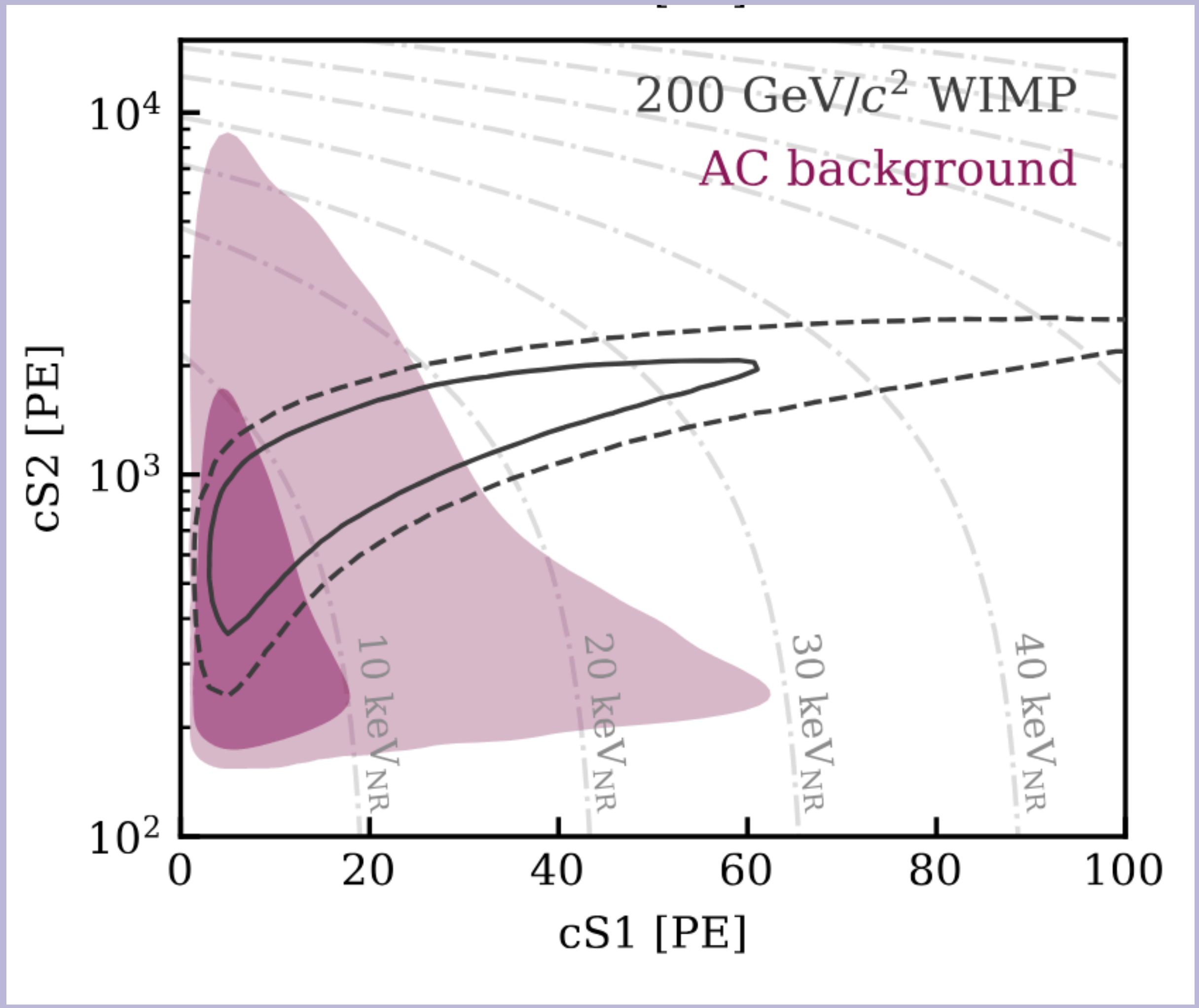
A review of NEST models for liquid xenon and an exhaustive comparison with other approaches M. Szydagis et al. DOI: 10.3389/fdest.2024.1480975 Front.Detect.Sci.Tech. 2 (2024)





LOW-ENERGY BACKGROUND MODELS?

- "Accidental" backgrounds—mispaired lone S1 and S2s are an important background in current-generation detectors at low energy, but there is no general model to predict these events
- Efforts are underway to bring the expertise together to best compare the running detectors' data-driven models
- Current WIMP projections, focusing on determining performance towards the neutrino floor do not include an AC component, but set conservative energy thresholds
  - XENONnT example: $\sim 7/\mathrm{ty}$ AC events in ^8B search, 3.1 in WIMP search
- XLZD will start to dive into solar neutrino background at low WIMP masses-> slower gains in sensitivity there



XENON: XENONnT WIMP search: Signal and background modeling and statistical inference, Phys. Rev. D **111**, 103040 (2025) , DOI: https://doi.org/10.1103/PhysRevD.111.103040

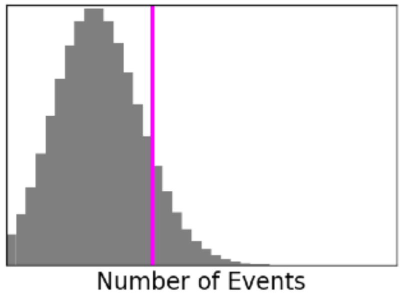
TOOLS AND APPROACH

- XLZD uses the extensive models and software developed by current-generation experiments:
  - NEST for fast detector simulations
  - inference frameworks:
    - alea (XENON inference suite)
    - FlameFit (abbreviated version of LZ inference suite)
- And the statistical models used for XLZD studies!
- The statistical model follows the results reporting recommendation and common practice in the field: unbinned extended likelihood with templates in cS1, cS2 and R

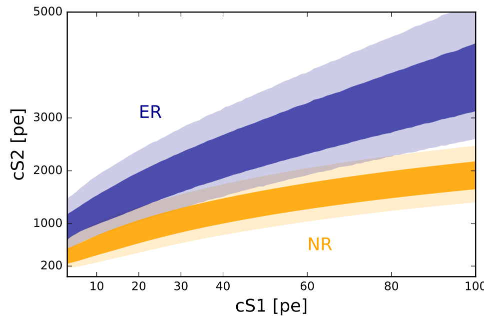
$$\mathcal{L}_{\mathrm{SR}}(\sigma,\theta \neq \sigma, M) = \mathcal{L}_{\mathrm{sci\ SR}} \cdot \mathcal{L}_{\mathrm{cal\ SR}} \cdot \mathcal{L}_{\mathrm{meas\ CNNS}} \mathcal{L}_{\mathrm{meas\ eff}} \cdot \mathcal{L}_{\mathrm{meas\ AC}} \cdot \mathcal{L}_{\mathrm{meas\ AC\ cal}}$$

Extended Likelihoods

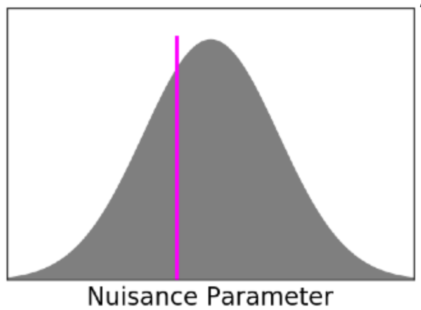
Measurements



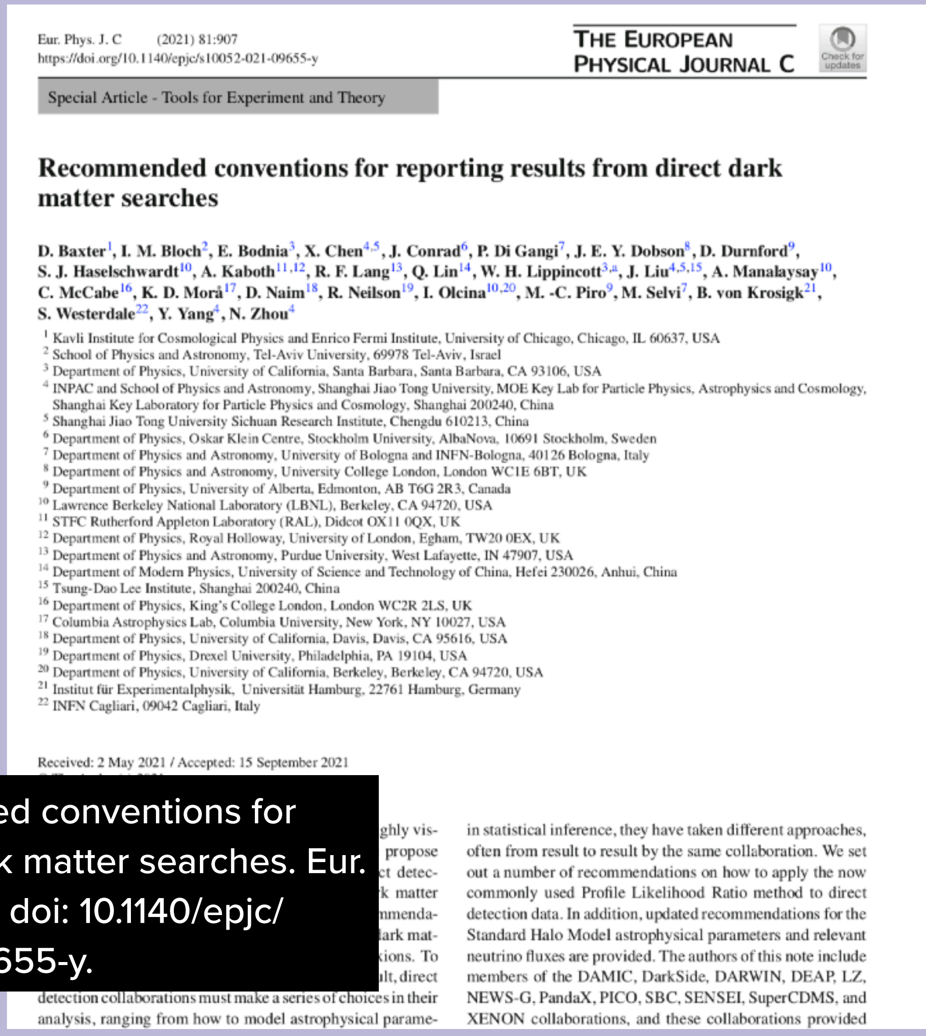
Poisson Term



cs1/cs2/r shape



Nuisance Constraint



Eur. Phys. J. C (2021) 81:907
https://doi.org/10.1140/epjc/s10052-021-09655-y

THE EUROPEAN PHYSICAL JOURNAL C

Special Article - Tools for Experiment and Theory

Recommended conventions for reporting results from direct dark matter searches

D. Baxter[1], I. M. Bloch[2], E. Bodnia[3], X. Chen[4,5], J. Conrad[6], P. Di Gangi[7], J. E. Y. Dobson[8], D. Durnford[9], S. J. Haselschwardt[10], A. Kaboth[11,12], R. F. Lang[13], Q. Lin[14], W. H. Lippincott[3,a], J. Liu[4,5,15], A. Manalaysay[10], C. McCabe[16], K. D. Morå[17], D. Naim[18], R. Neilson[19], I. Olcina[10,20], M. -C. Piro[9], M. Selvi[7], B. von Krosigk[21], S. Westerdale[22], Y. Yang[4], N. Zhou[4]

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Received: 2 May 2021 / Accepted: 15 September 2021

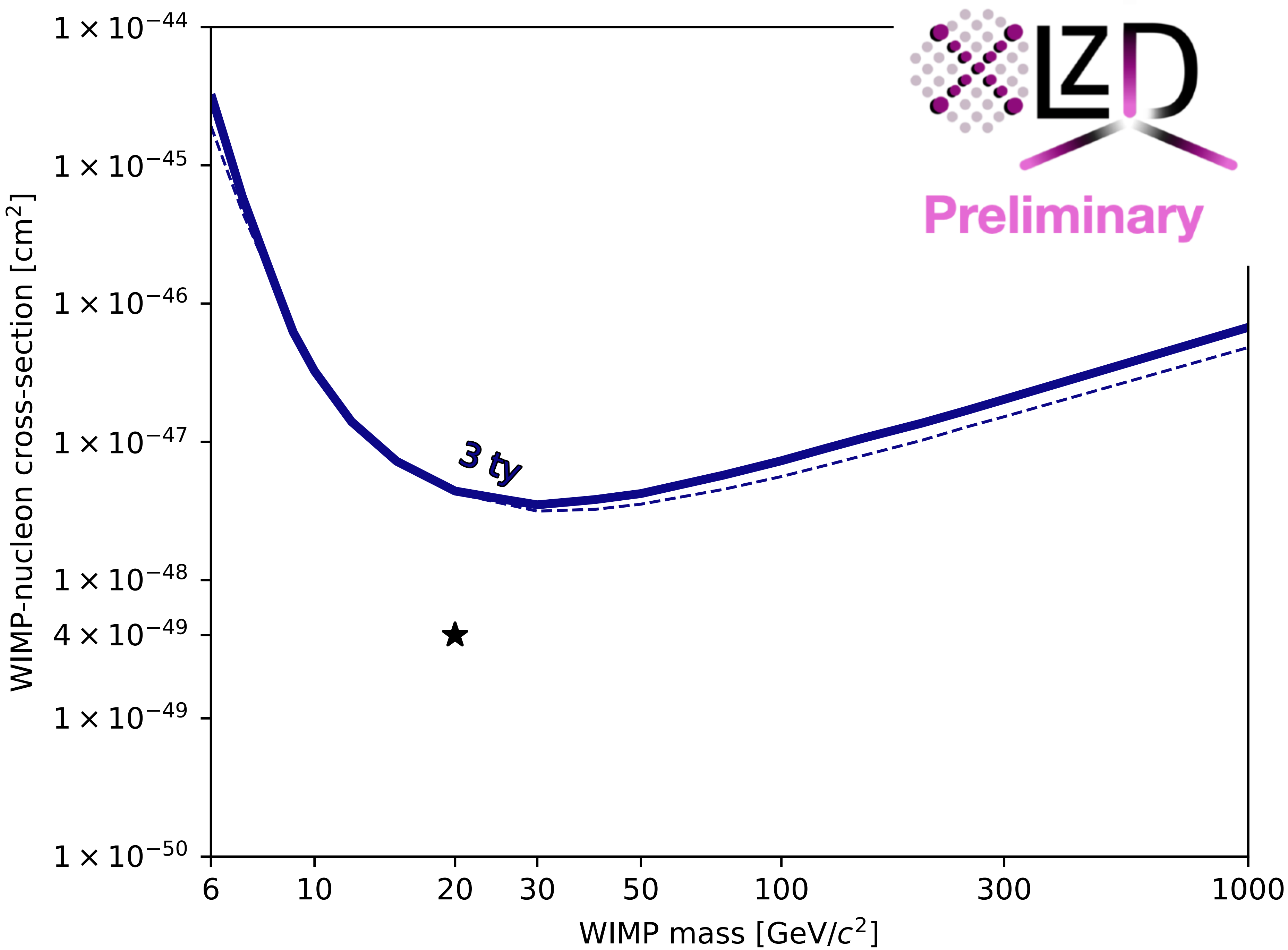
...ghly vis- ... propose ...ct detec- ...k matter ...mmenda- ...dark mat- ...ions. To ...lt, direct detection collaborations must make a series of choices in their analysis, ranging from how to model astrophysical parame-

in statistical inference, they have taken different approaches, often from result to result by the same collaboration. We set out a number of recommendations on how to apply the now commonly used Profile Likelihood Ratio method to direct detection data. In addition, updated recommendations for the Standard Halo Model astrophysical parameters and relevant neutrino fluxes are provided. The authors of this note include members of the DAMIC, DarkSide, DARWIN, DEAP, LZ, NEWS-G, PandaX, PICO, SBC, SENSEI, SuperCDMS, and XENON collaborations, and these collaborations provided

D. Baxter et al Recommended conventions for reporting results from direct dark matter searches. Eur. Phys. J. C, 81(10):907, 2021. doi: 10.1140/epjc/s10052-021-09655-y.

PUTTING ALL THE INGREDIENTS TOGETHER: IMAGINED DISCOVERY!

- A true WIMP signal (marked with a star) first shows up by worse upper limits
- As more data is collected, and the significance exceeds 3σ, the collaboration would draw two-sided limits and a closed interval
- Above $\sim 100\mathrm{GeV}/c^2$, WIMP recoil spectra are almost degenerate, so the mass may not be tightly constrained



Code to run XLZD requirements projections is available on github!

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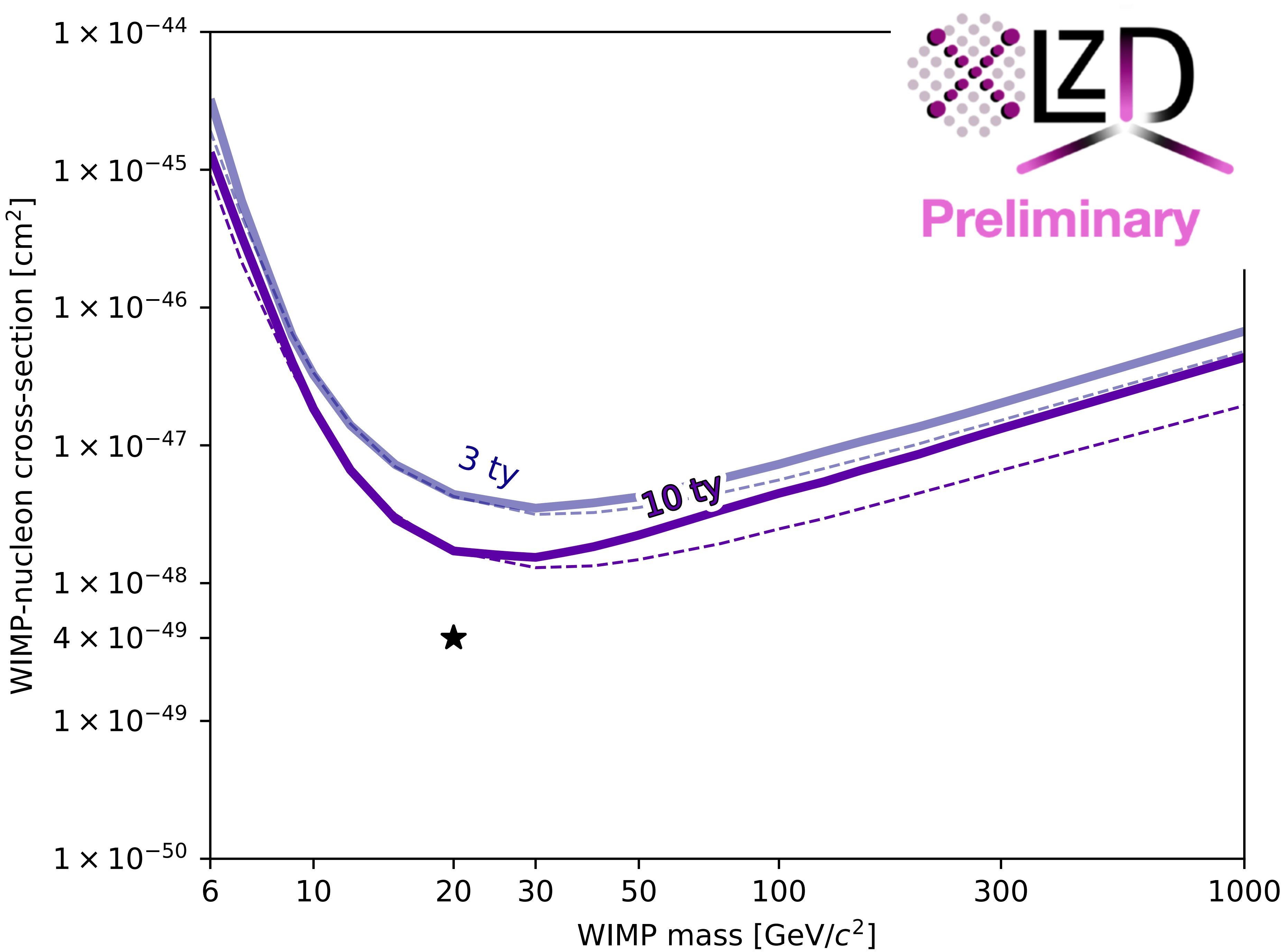

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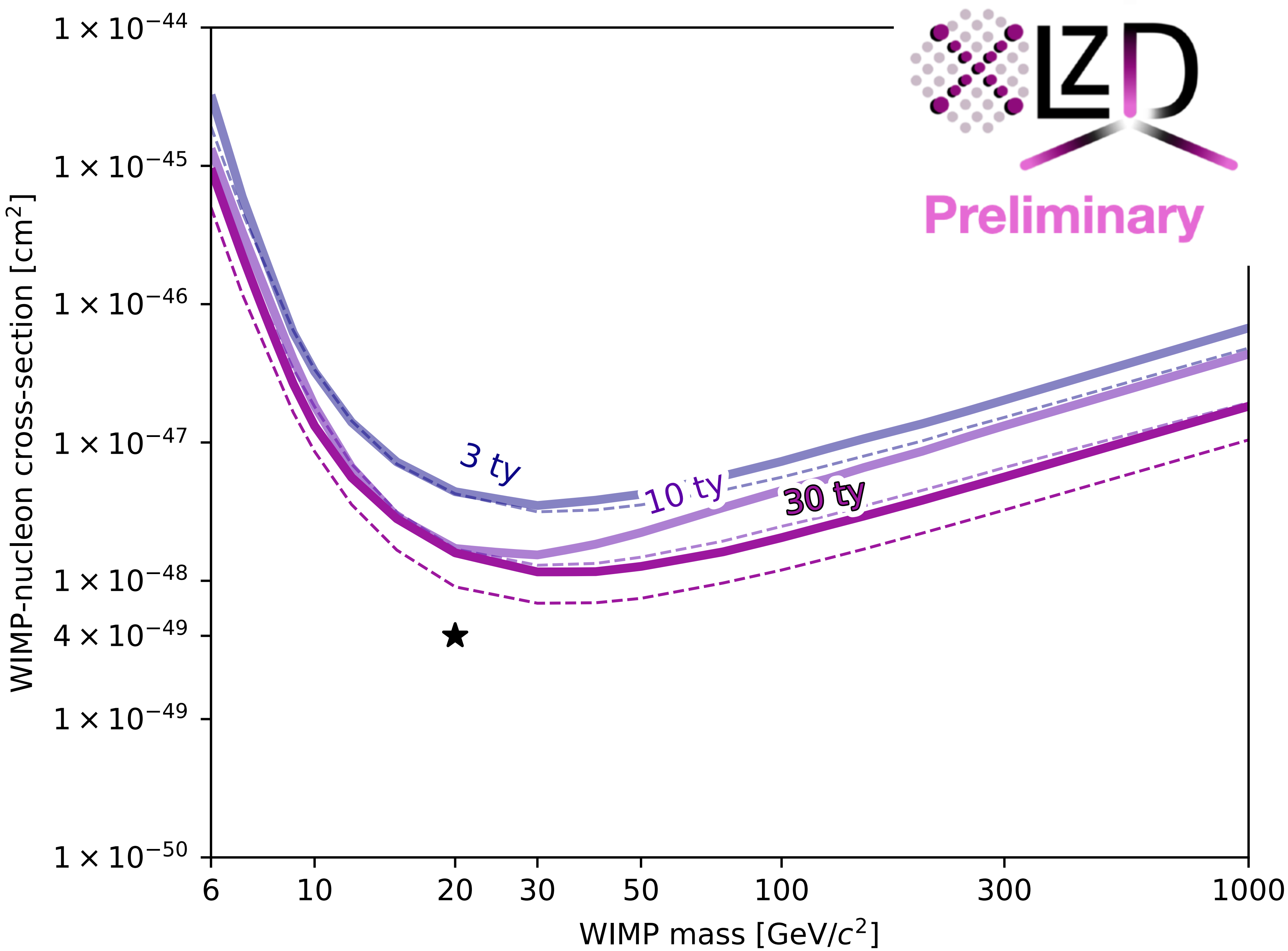

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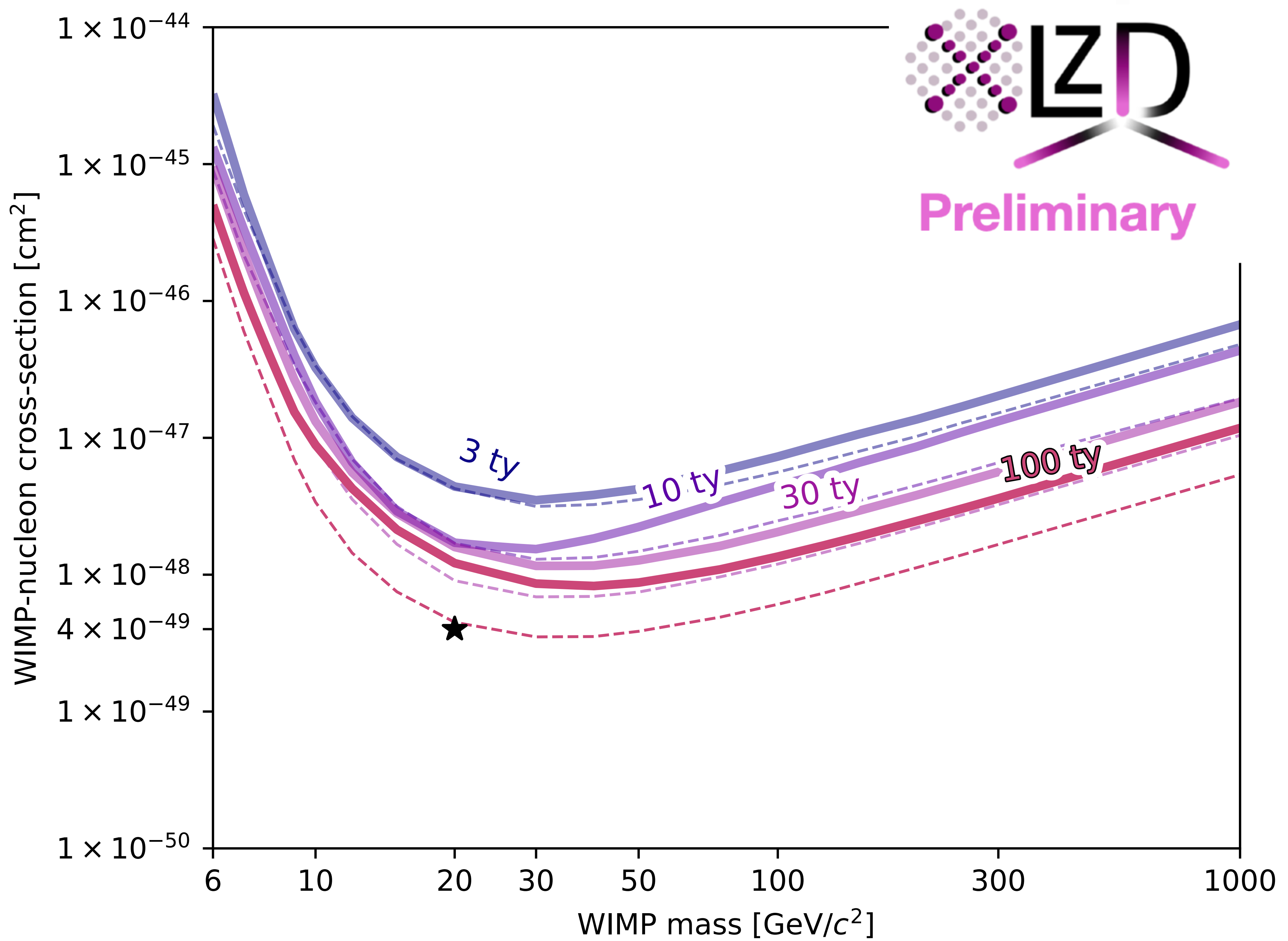

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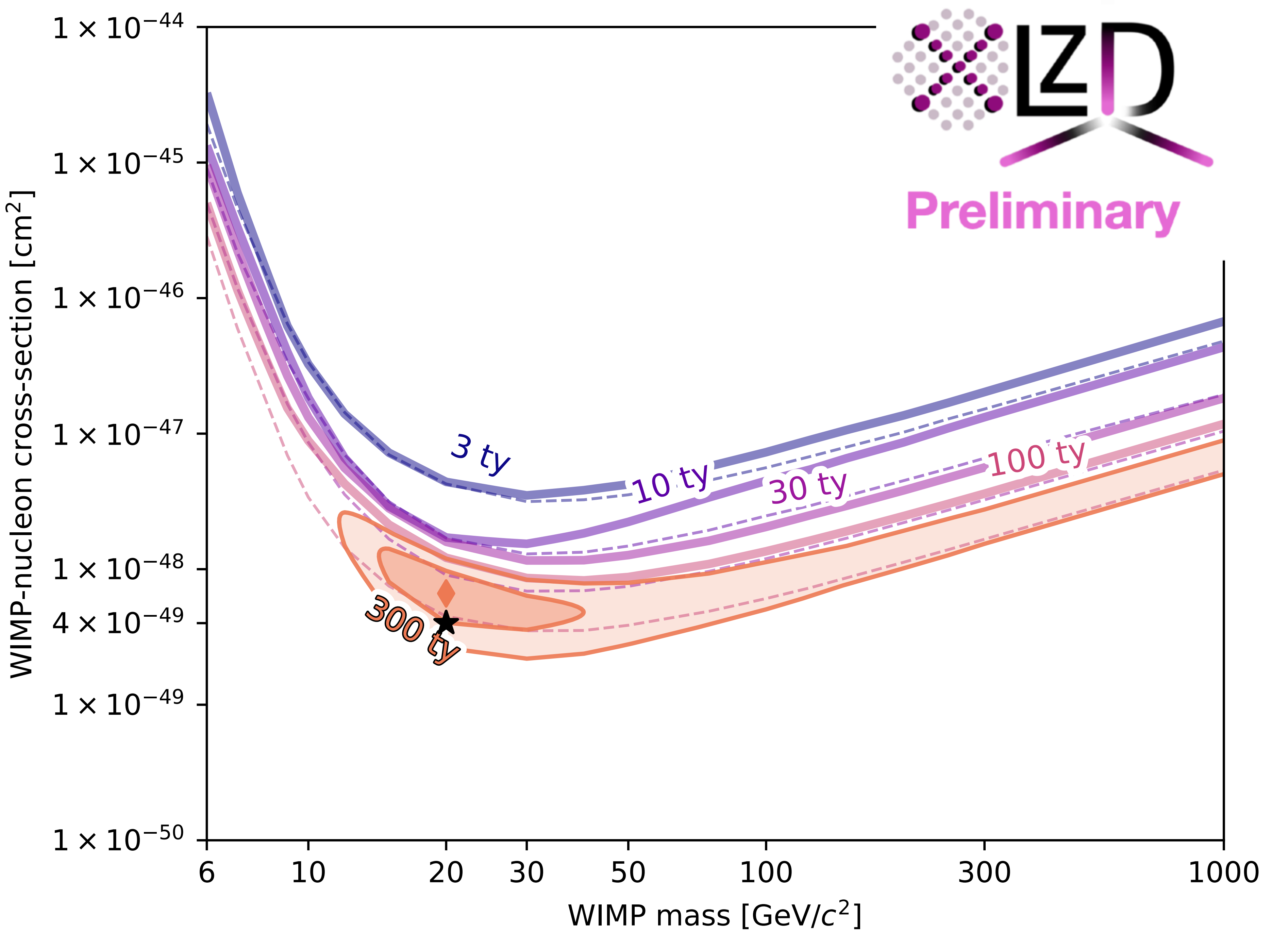

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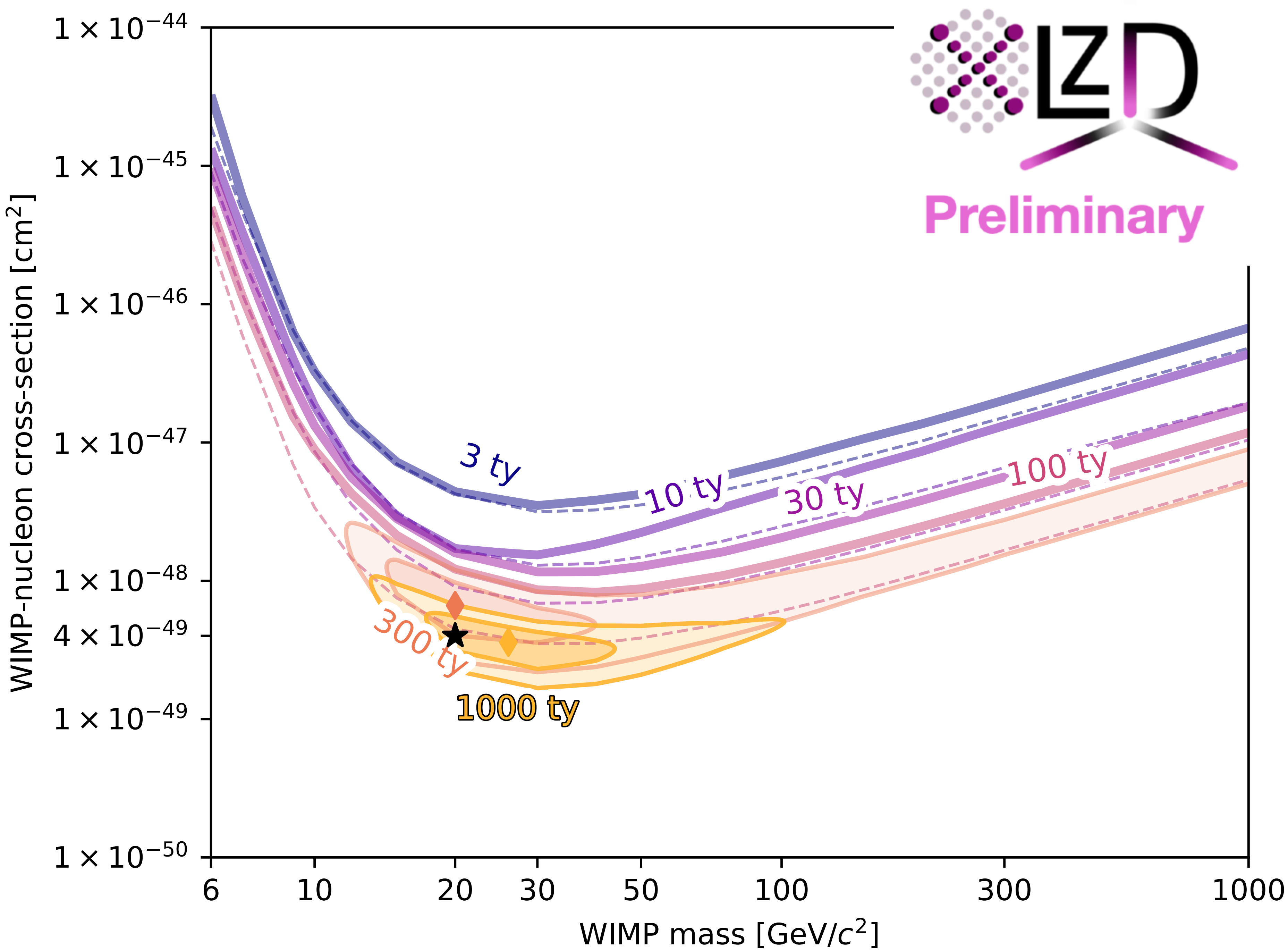

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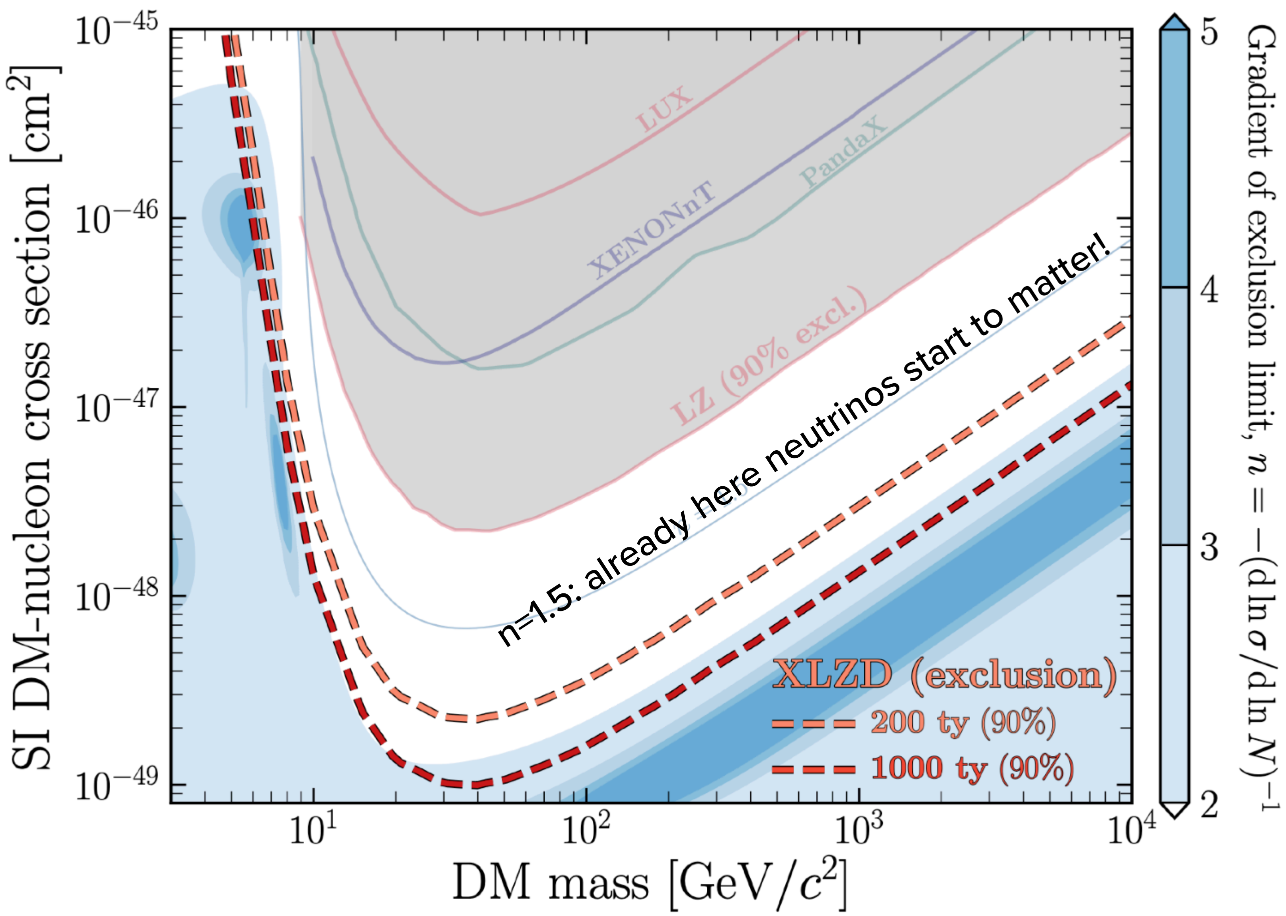
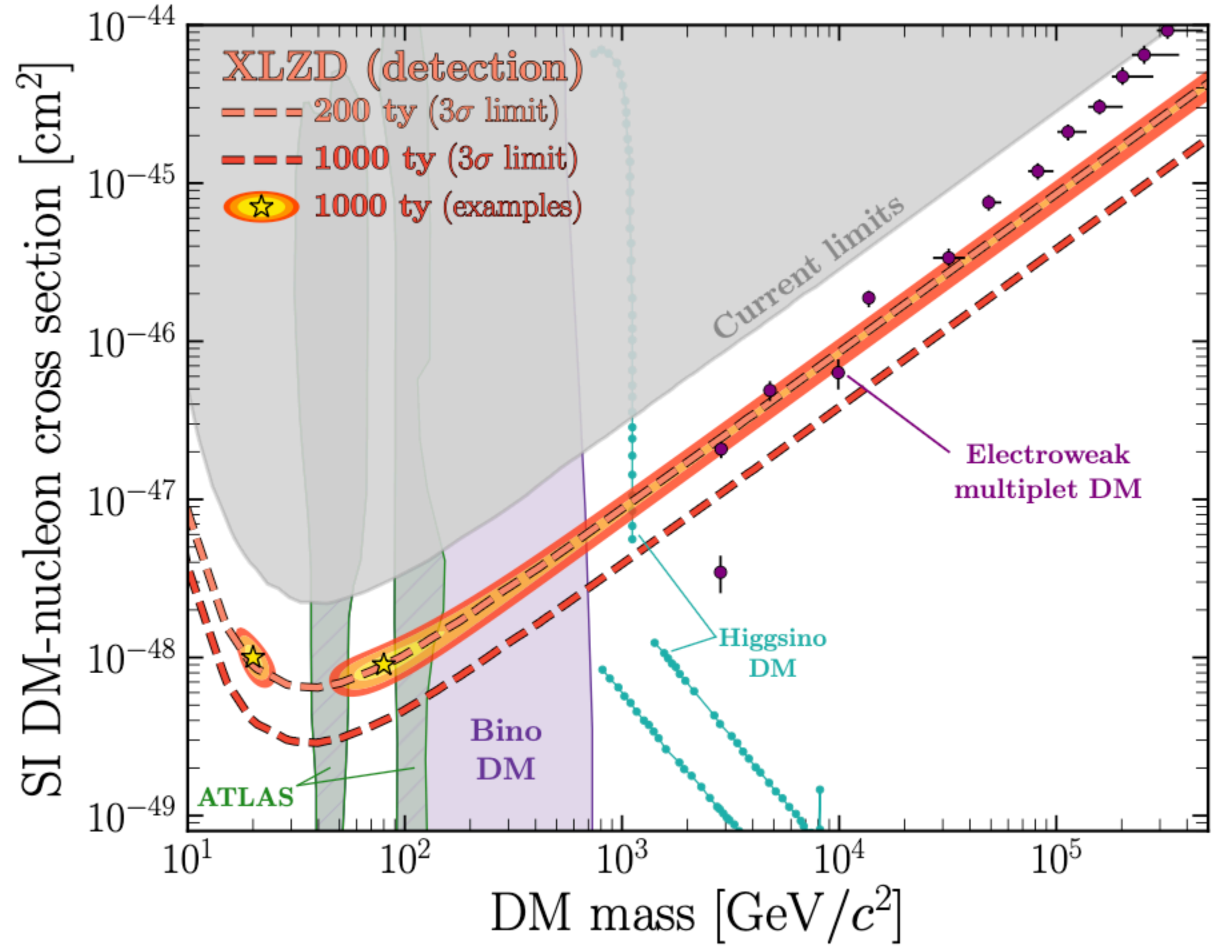
XLZD SENSITIVITY REACHES THE NEUTRINO FLOOR

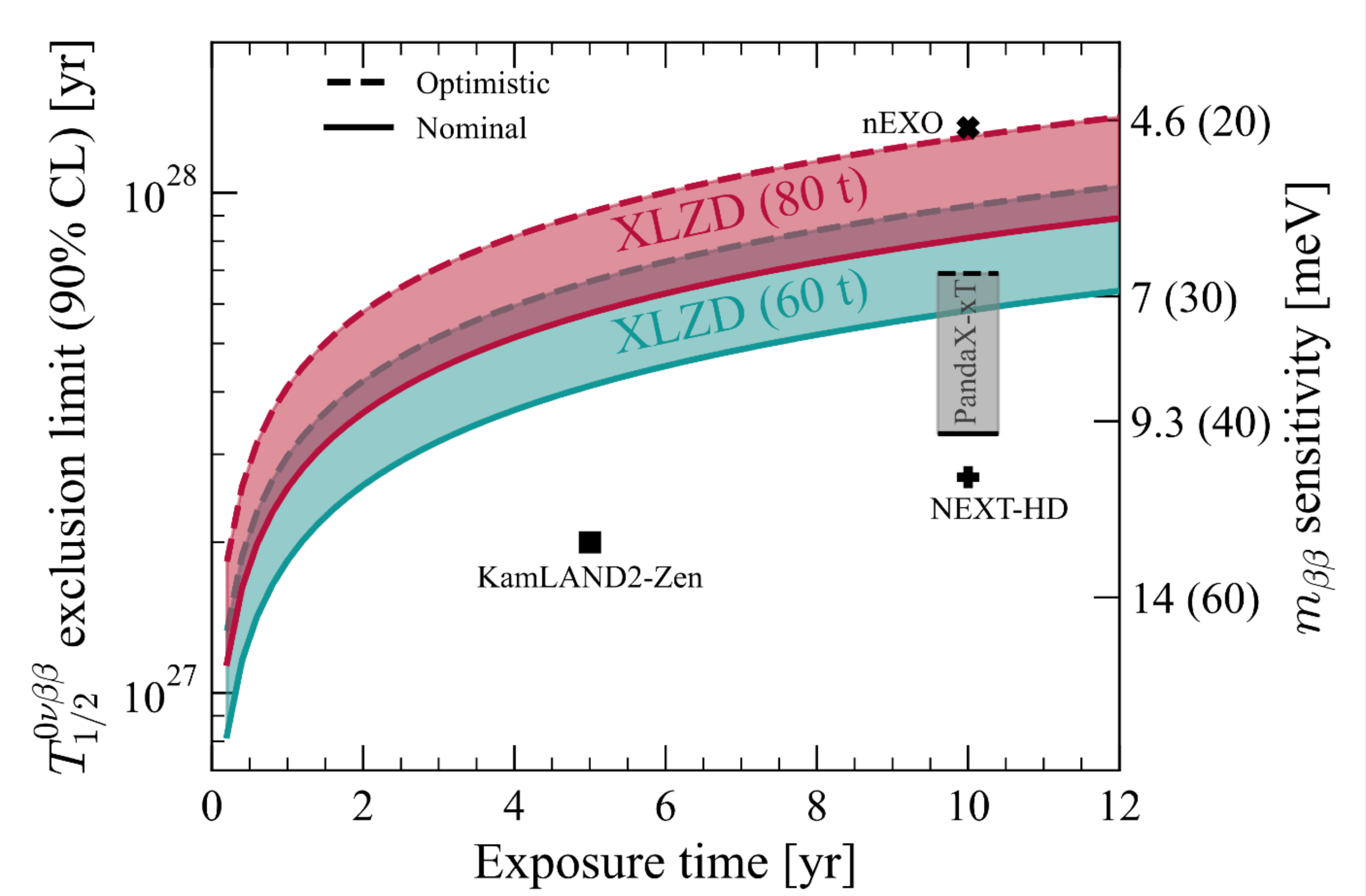




- **XLZD expects to see more than 10 (200ty) compatible with high-mass WIMPs while constraining WIMP cross-sections within the neutrino fog**
- **Within the unconstrained parameter space, several BSM models include possible discoveries!**

The XLZD Design Book: Towards the Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics, XLZD Collaboration e-Print: 2410.17137 [hep-ex]

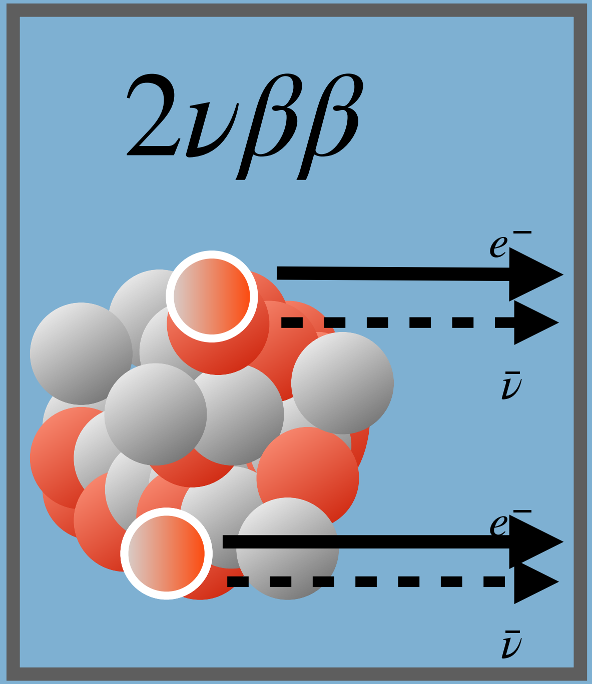
XLZD WILL BE COMPETITIVE IN THE SEARCH FOR LEPTON-NUMBER-VIOLATING NEUTRINOLESS DOUBLE-BETA DECAYS

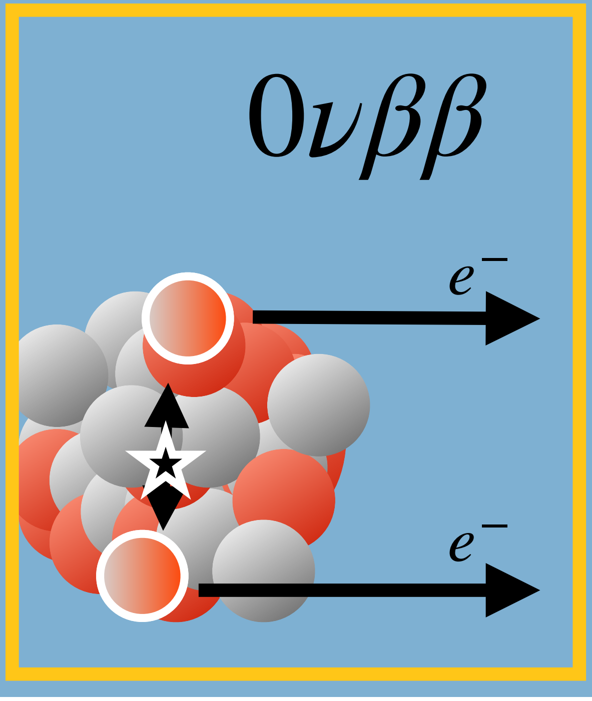


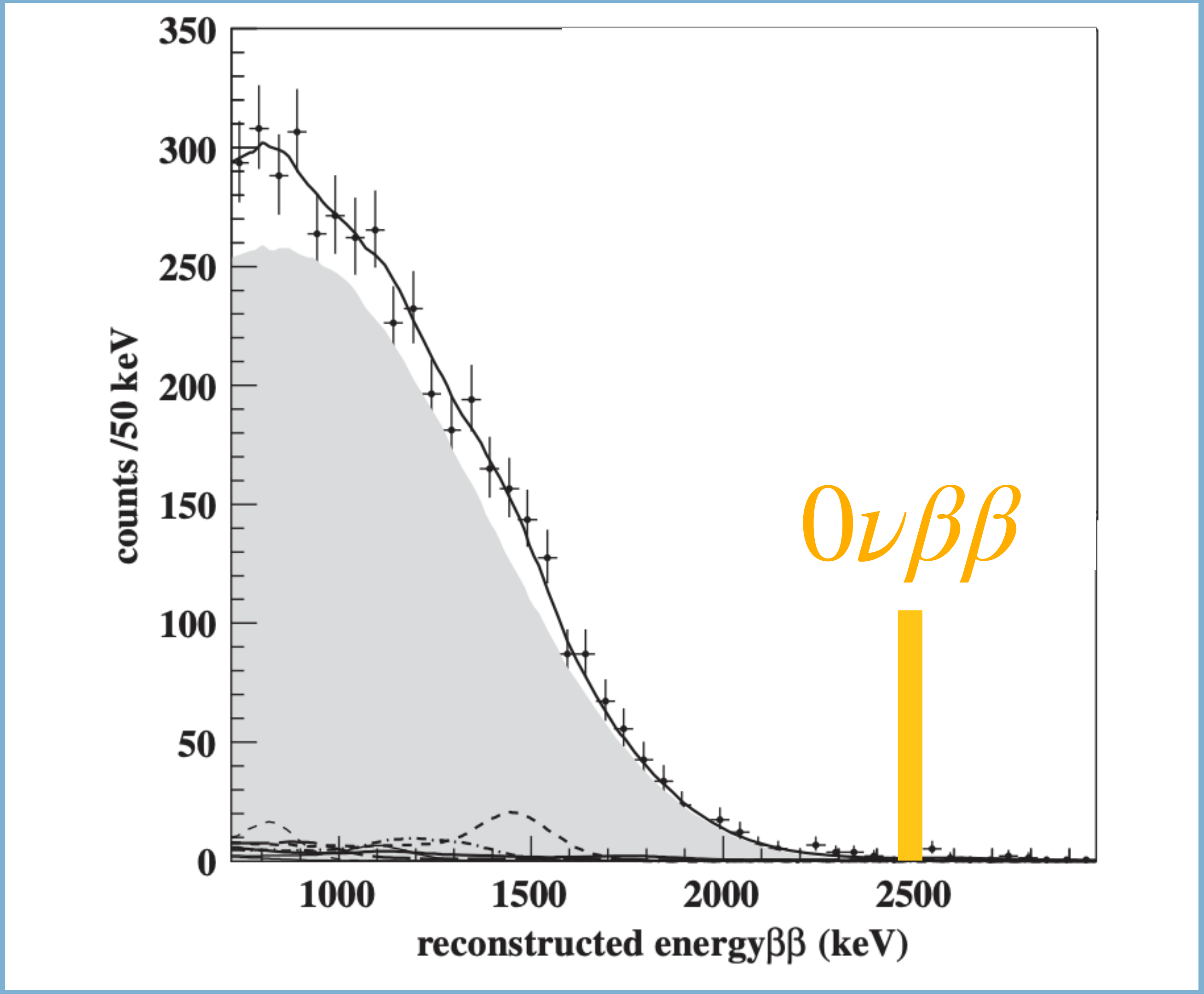
Neutrinoless double beta decay sensitivity of the XLZD rare event observatory, XLZD Collaboration, J.Phys.G 52 (2025) 4, 045102 DOI: 10.1088/1361-6471/adb900

NEUTRINOLESS DOUBLE-BETA DECAY

- Neutrinoless double-beta ($0\nu\beta\beta$) decays would indicate that lepton number is not a conserved quantity
- Using natural xenon the XLZD TPC will contain over 5 (7) tonnes of $^{136}\mathrm{Xe}$ (abundance of $8.9\,\%$) which undergoes double-beta decay, avoiding costly isotope separation.
- The $^{136}\mathrm{Xe} \rightarrow ^{136}Ba\ 0\nu\beta\beta$ signal would be a peak at the Q-value of $2.46\ \mathrm{MeV}$
- If the lepton number violation is mediated by a Majorana neutrino, the half-life is proportional to $1/\sqrt{m_\nu}$



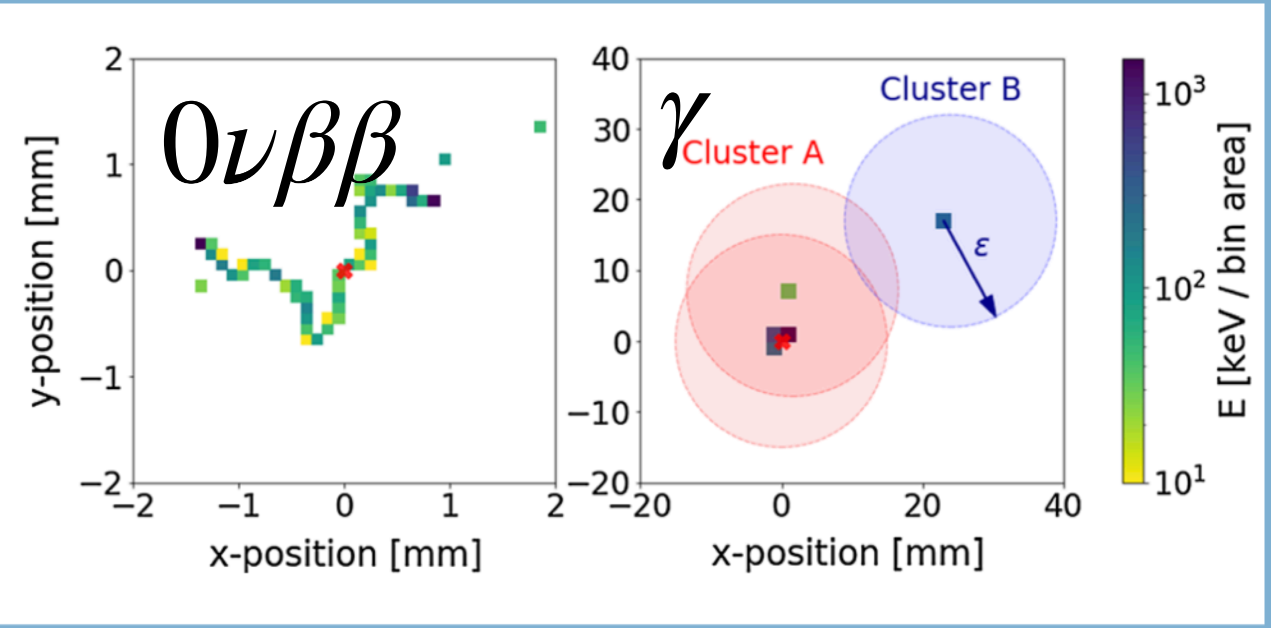


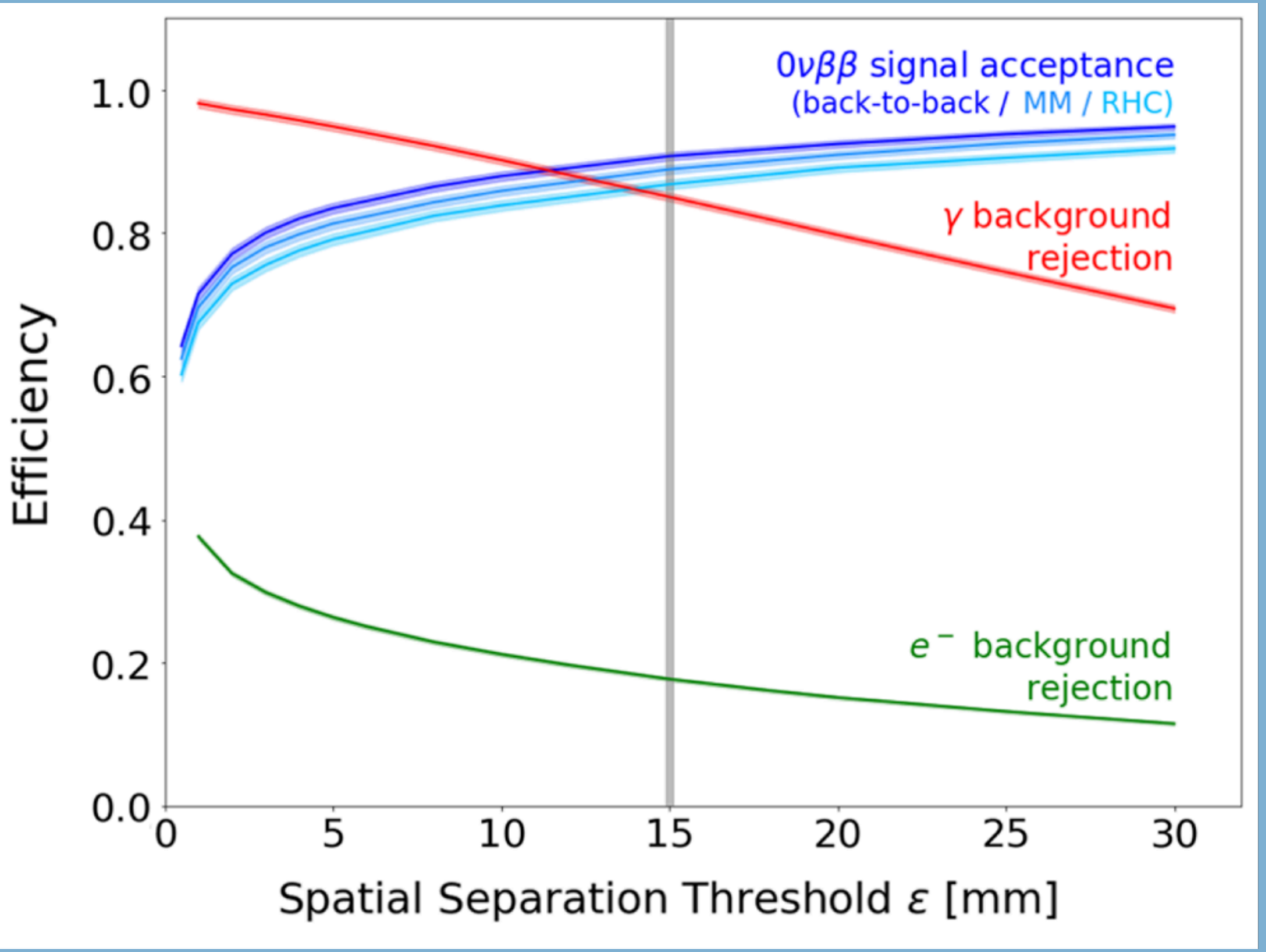


EXO-200: Observation of Two-Neutrino Double-Beta Decay in 136Xe with the EXO-200 Detector, Phys. Rev. Lett. **107**, 212501

PRECISION RECONSTRUCTION

- Projections assume a 1σ resolution of $0.65\,\%$ at the peak—a slight improvement over the $0.8\,\%$,$0.67\,\%$ resolutions currently achieved by XENON and LZ
    - Requires detailed spatiotemporal corrections based on calibration campaigns
- γs may Compton scatter leading to extended/multiple-site interactions unlike most β -depositions. We assume a $3\,$ mm resolution in the drift direction only
    - Current experiments achieve $2\,$ mm
    - DARWIN studies show that this resolution can give a $90\,\%$ background rejection for a $15\,\%$ signal loss

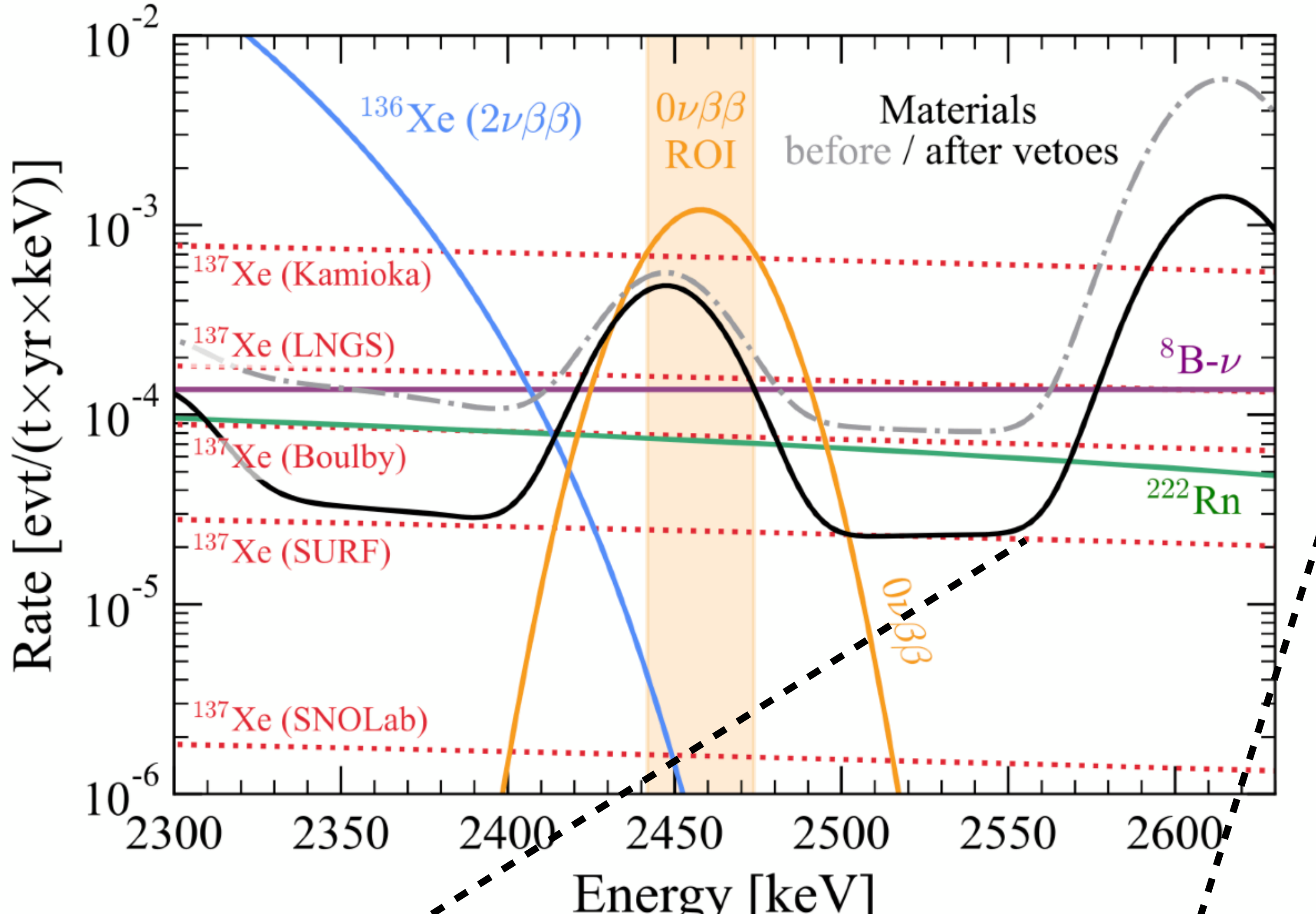


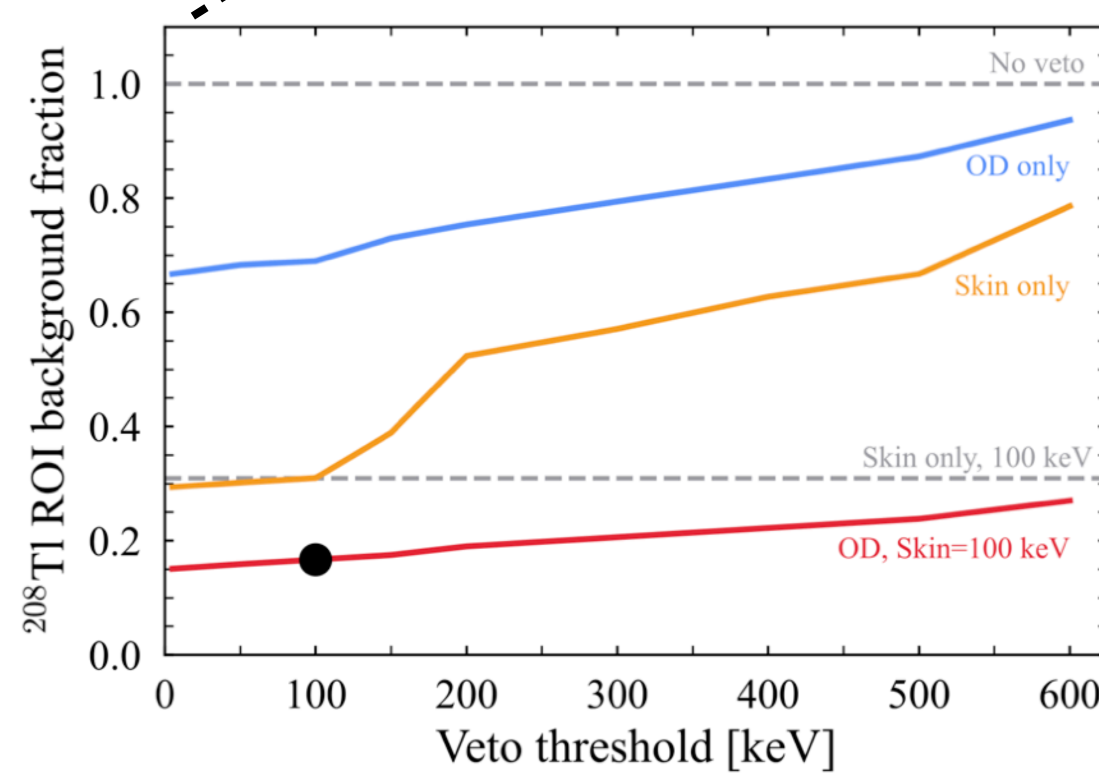


Sensitivity of the DARWIN observatory to the neutrinoless double beta decay of 136Xe, DARWIN Collaboration Eur.Phys.J.C 80 (2020) 9, 808

MATERIALS AND SHIELDING AGAINST BACKGROUNDS

- **In addition to the $2\nu\beta\beta$ background from ^{136}Xe, detector material gamma-rays are the most important background for the search:**
  - ^{214}Bi **gives a γ-peak at** $2.448\ \mathrm{MeV}$
  - ^{208}Tl **gives a γ-peak at** $2.615\ \mathrm{MeV}$
- ^{208}Tl **can be strongly rejected with veto systems, either with coincident γ rays or by the** $2.615\ \mathrm{MeV}$ **γ compton-scattering in the outer detector**
  - **The best rejection is achieved with the instrumented "skin" of LXe surrounding the TPC**

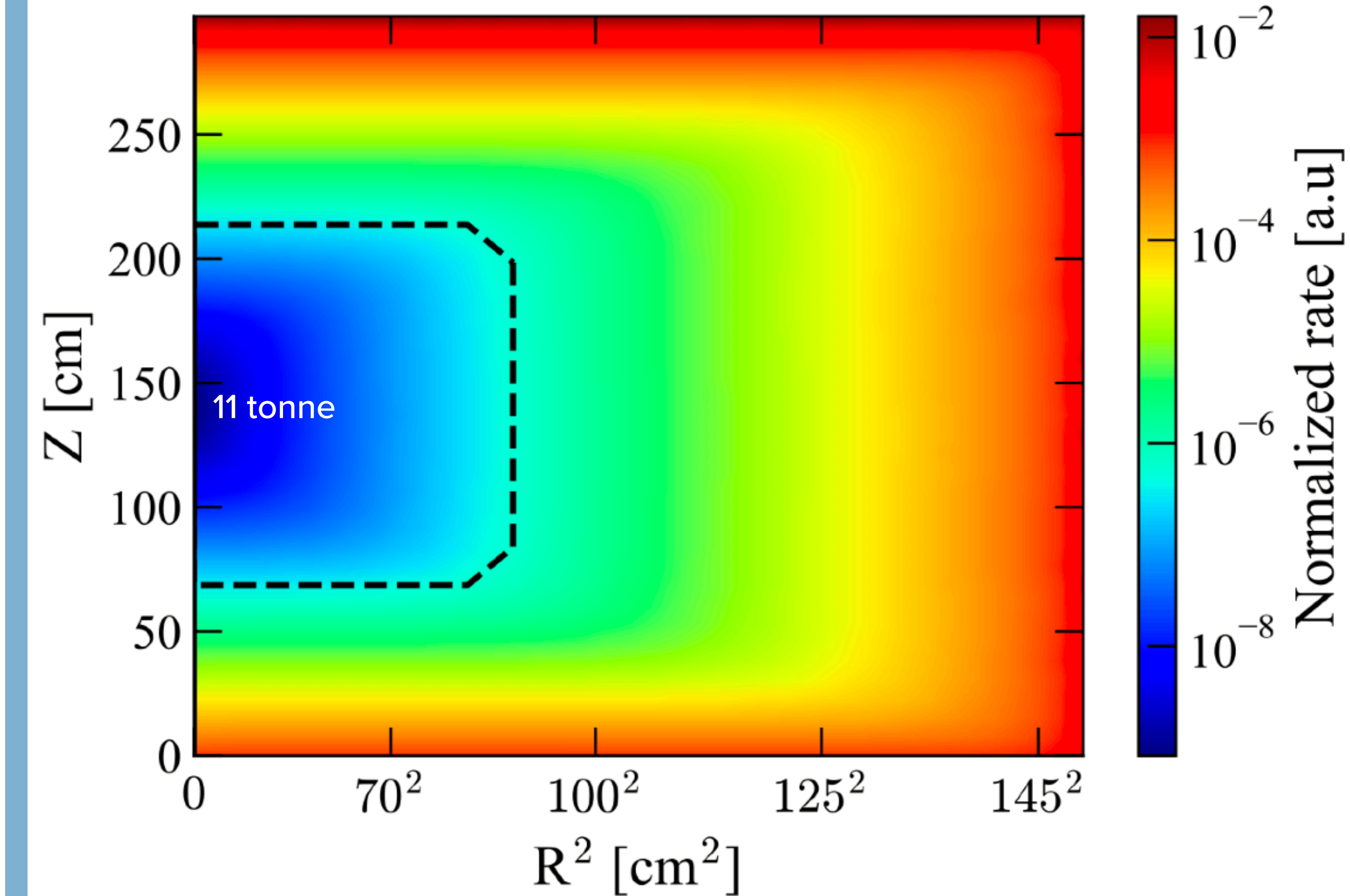




Neutrinoless double beta decay sensitivity of the XLZD rare event observatory, XLZD Collaboration, J.Phys.G 52 (2025) 4, 045102 DOI: 10.1088/1361-6471/adb900

FIDUCIAL VOLUME AGAINST BACKGROUNDS

- **At the $0\nu\beta\beta$ energy, the mean Compton interaction length is ~ 10 cm, while for photoelectric absorption it is ~ 4 m**
- **Detecting these Compton scatters allows ^{214}Bi events to be rejected with high efficiency towards the centre of the detector.**
- **The attenuation profile of the events are matched to LZ and DARWIN simulations and assumes the construction materials will be similar in composition to those used by LZ, but assuming a 75% reduction in rate based on available assays**



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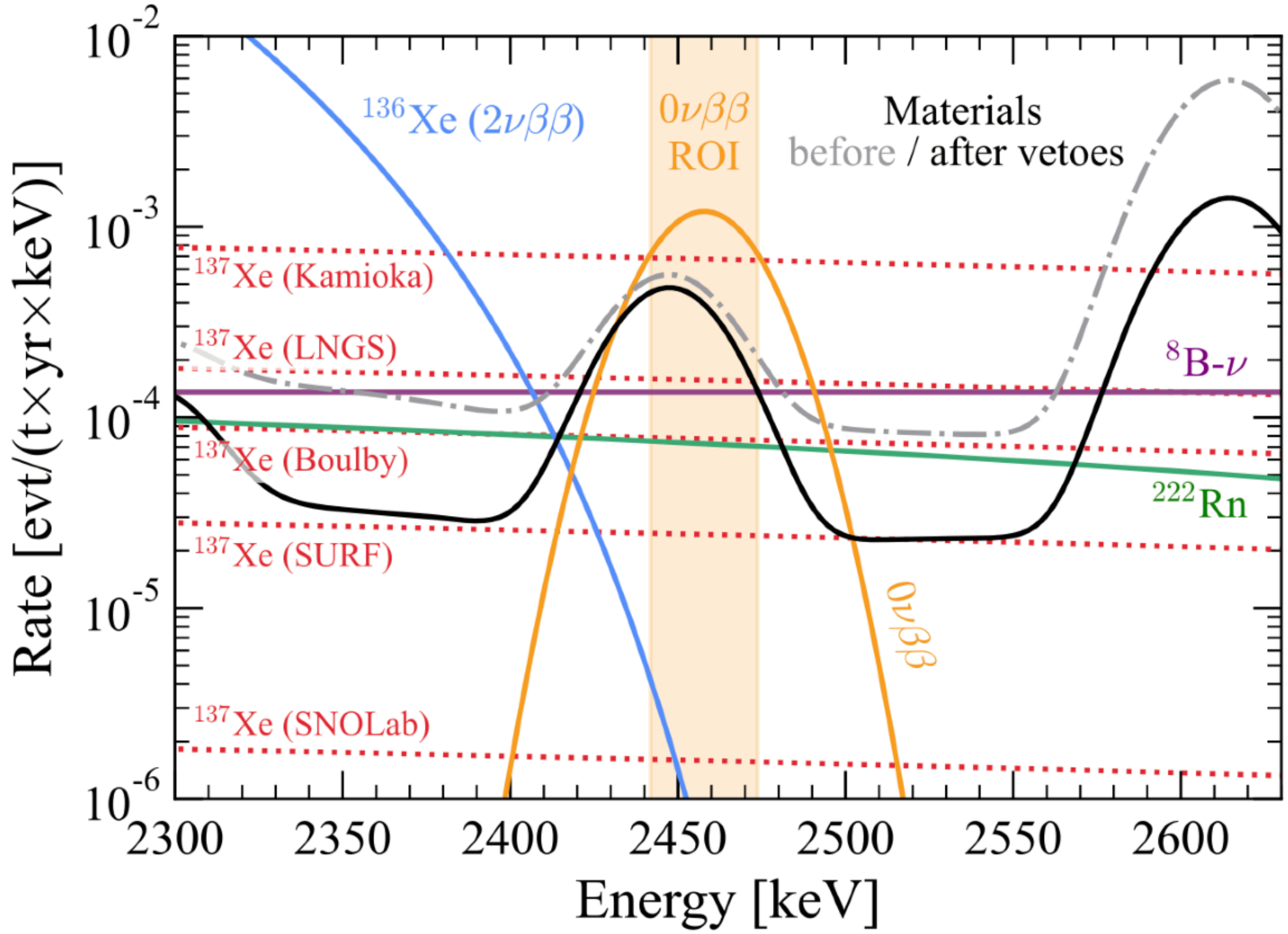
OTHER BACKGROUNDS

- **Solar neutrinos from ^{8}B decays give a nearly flat spectrum up to 16 MeV**
- **The standard double-beta decay of ^{136}Xe only contributes at lower energy.**
- **The ^{222}Rn decay product ^{214}Bi β-decaying directly to the ground state ^{214}Po also give a relatively flat energy spectrum**
  - **XLZD aims to reduce the ^{222}Rn activity to $0.1\ \mu$Bq/kg**
  - **^{214}Po $\alpha-$decays with $\tau_{1/2} = 162\mu$s, allowing the vast majority of these events to be tagged — assumed 99.95%**
  - **^{222}Rn can also attach to detector surfaces partially hiding the β and the ^{214}Po $\alpha-$decay, this is under further investigation**



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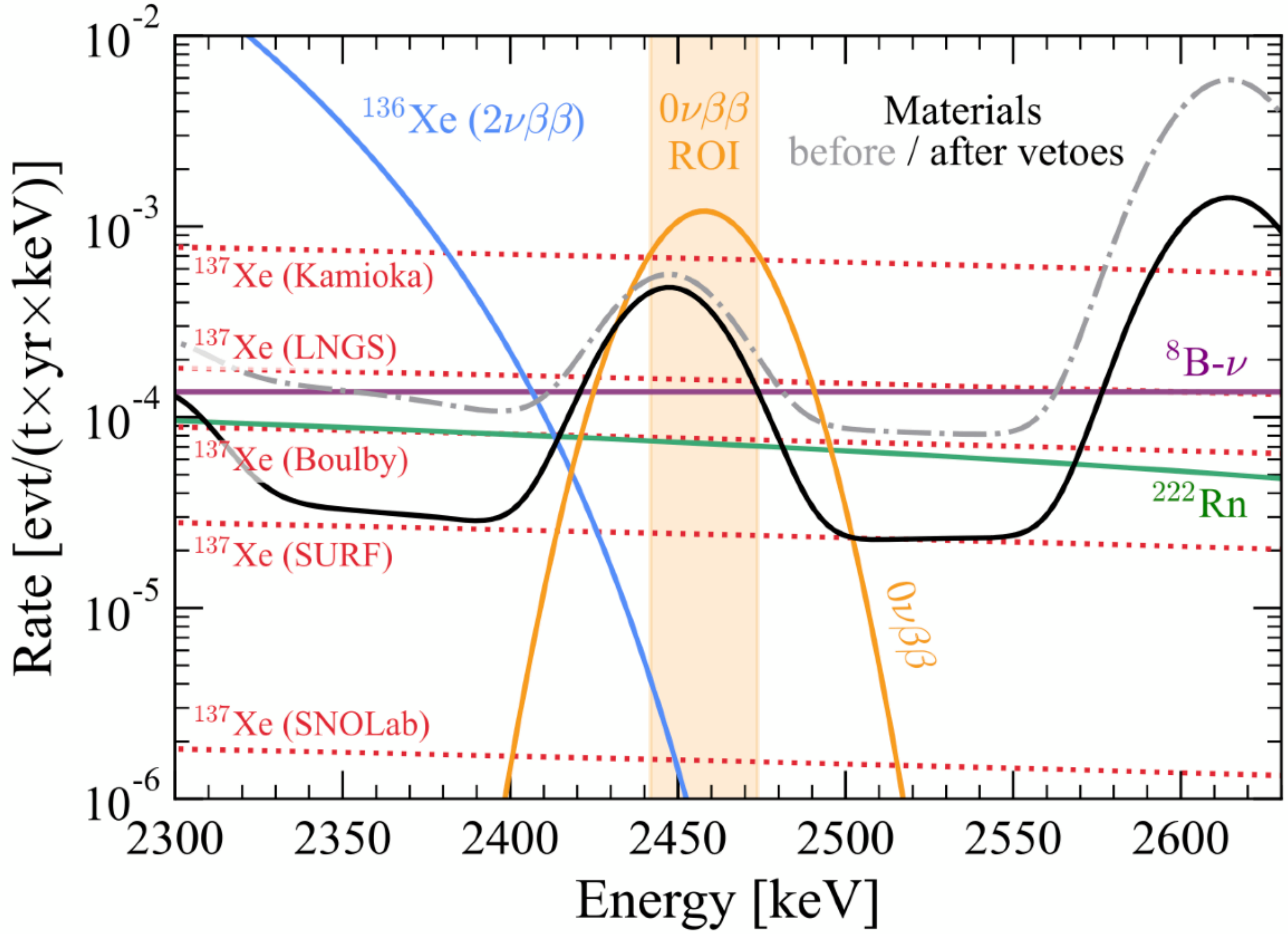
COSMOGENIC

^{137}Xe

- **The cosmic muon ray flux generate neutrons that then produce ^{137}Xe, which decays via β-decay.**
- **Due to the additional neutron shielding, this production will mostly happen outside the inner TPC as the liquid is cooled and purified.**
- **This study uses DARWIN projections of the activation**
- **Further studies may apply some veto immediately after a muon transiting the TPC—these results do not apply one**



Neutrinoless double beta decay sensitivity of the XLZD rare event observatory, XLZD Collaboration, J.Phys.G 52 (2025) 4, 045102 DOI: 10.1088/1361-6471/adb900

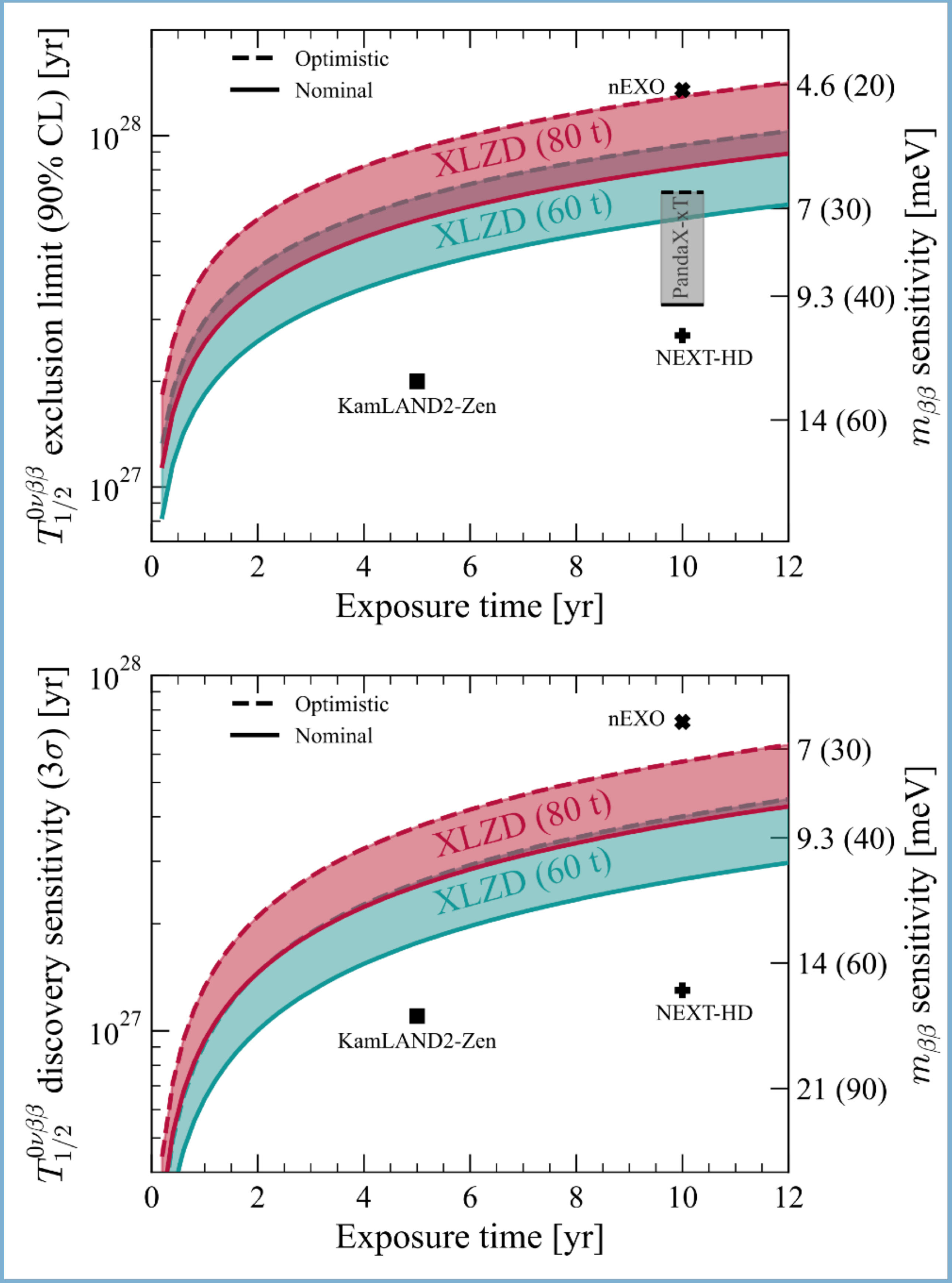
Site	Depth [m]	Depth [m w.e.]	μ flux [/(m^2·d)]	^{137}Xe rate [/(t·yr)]	SS ROI rate [evt/(t·yr·keV)]
SNOLAB	2070	5890	<0.3	0.007	1.29×10^{-6}
SURF	1490	4300	4.6	0.142	2.72×10^{-5}
Boulby	1300	3330	14.6	0.404	7.73×10^{-5}
LNGS	1400	3800	29.7	0.822	1.57×10^{-4}
Kamioka	1000	2700	128	3.54	6.78×10^{-4}

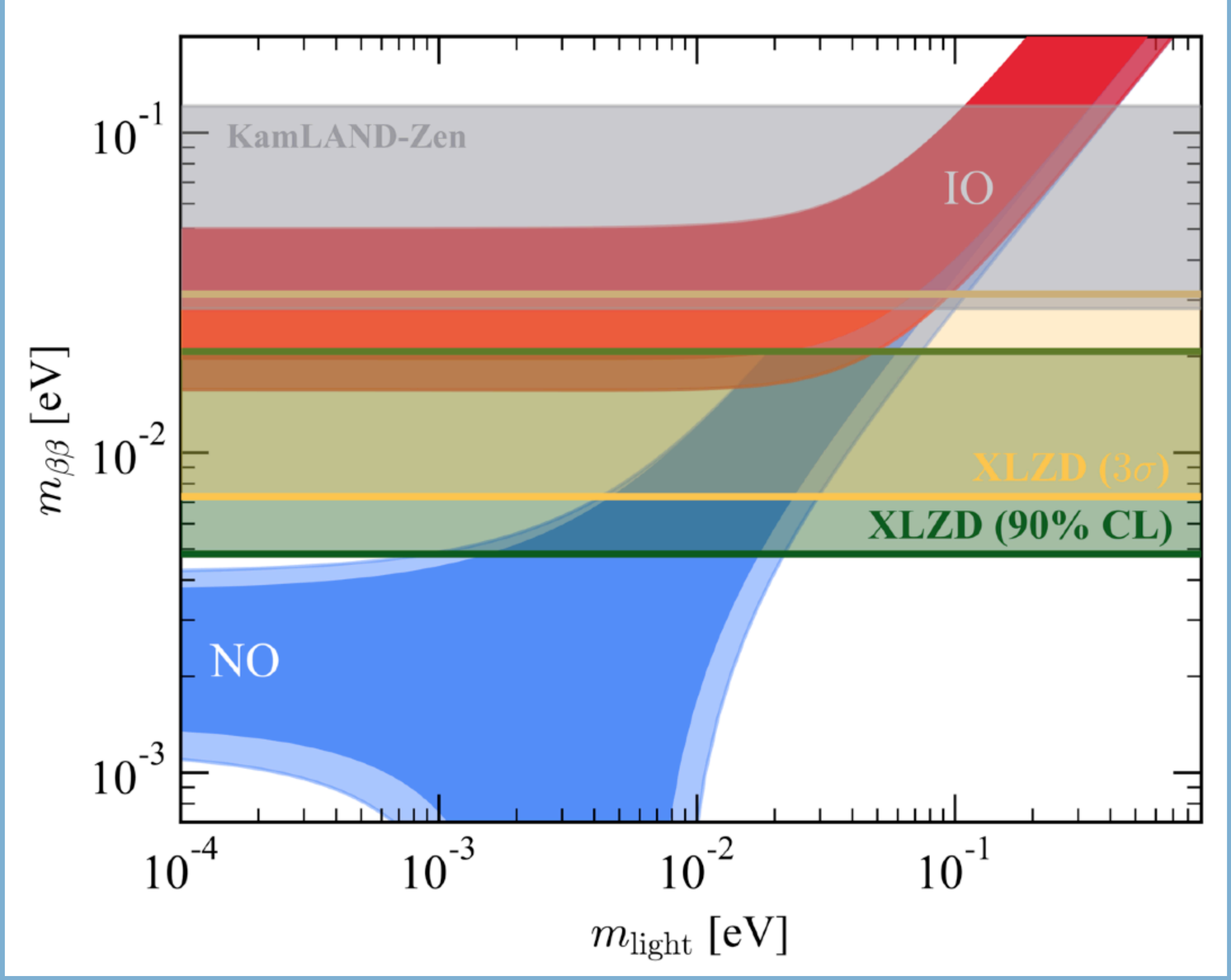
SENSITIVITY

- **Assuming either the nominal performance described before or a more optimistic performance for parameters**
- **The fiducial volume and energy region are both optimised for a counting significance**
  - **For the nominal performance, a 8.2(11)t FV is favoured for the 60 and 80t XLZD configuration.**
- **Future studies will implement the full statistical model using profile likelihood tests**
  - **This will allow a wider mass and energy region to be used**
  - **LZ found 40% improvements in sensitivity using a full statistical model**

Parameter	Scenario Nominal	Scenario 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

FOR THE OPTIMISTIC SCENARIO, XLZD WILL PROBE THE ENTIRE INVERTED ORDERING SCENARIO





DARK MATTER

NEUTRINOS

XLZD WILL PROBE THE WIMP PARAMETER SPACE DOWN TO THE NEUTRINO FOG

AND BE AMONG THE MOST SENSITIVE PROBES FOR NEUTRINOLESS DOUBLE-BETA DECAYS

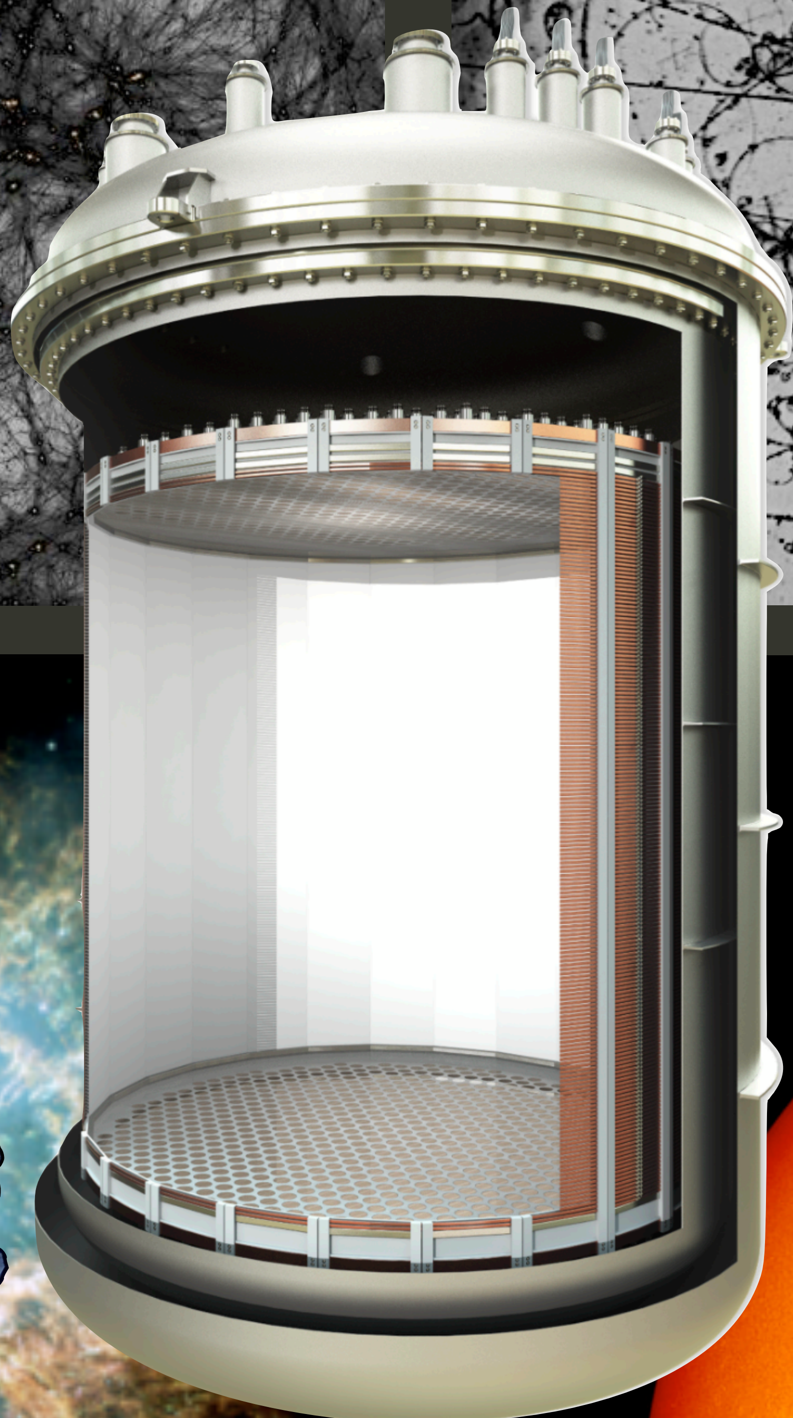
The XLZD Design Book: Towards the Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics, XLZD Collaboration e-Print: 2410.17137 [hep-ex]

DARK MATTER

- WIMPs
- Light DM (sub-GeV/c^2)
- Axion-like particles
- Dark Photons

NEUTRINOS

- $0\nu\beta\beta$
- Double electron capture
- Neutrino magnetic moment



SUPERNOVÆ

- Early alert
- SN neutrinos with low energy-threshold

SUN

- $^{8}\mathrm{B}, ^{7}\mathrm{B}$, **hep**
- pp neutrinos

The XLZD Design Book: Towards the Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics, XLZD Collaboration e-Print: 2410.17137 [hep-ex]

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XLZD COLLABORATION MEETING JULY 2025 AT LNGS

EXPOSURE–TO-DISCOVERY

- **(backup)**