

Universität
Münster

HERETIX

Hermetic Enriched Rare Event TPC In Xenon

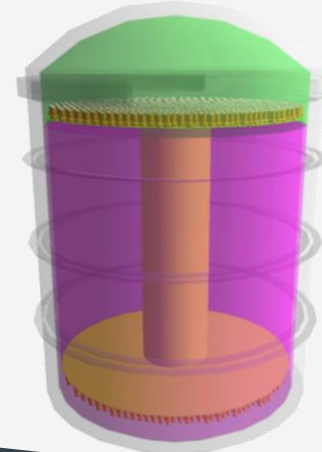
Exploiting the full potential of XLZD

Lutz Althüser - University of Münster

HERETIX project:

L. Althueser, N. Hargittai, J. Pienaar, R. Braun,
H. Landsman, C. Weinheimer, R. Budnik

Unified Rare Event
Observatory



living.knowledge



WEIZMANN
INSTITUTE
OF SCIENCE



Background and the LowRad project

My personal background with xenon TPCs

XENON1T

- Geant4 simulations: Background and optical
- Cryogenic ^{85}Kr distillation
- Rare event searches: Annual modulation, ...

XENONnT

- Geant4 model development, ...
- PTFE VUV light transmission measurements
- Distillation group leader for ^{85}Kr distillation and Radon Removal System
- Gas purification and cryogenics
- Dark matter and neutrino searches

XLZD

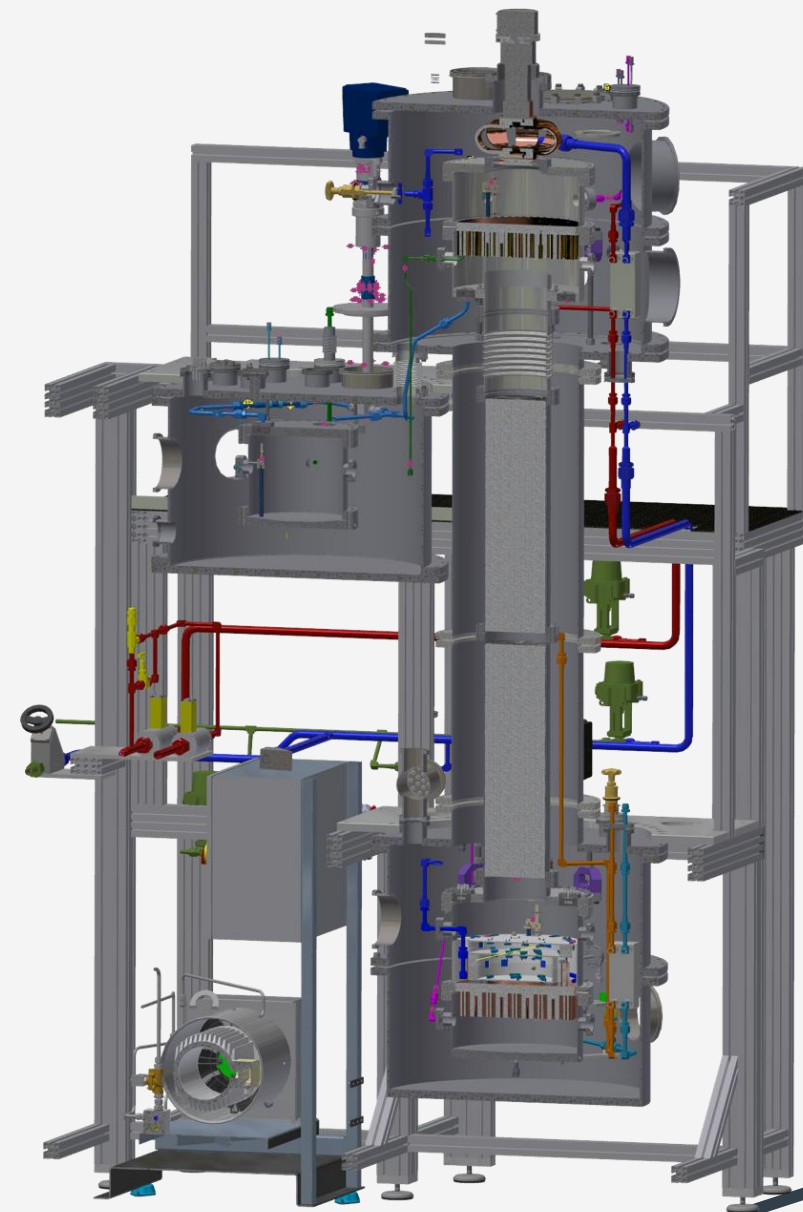
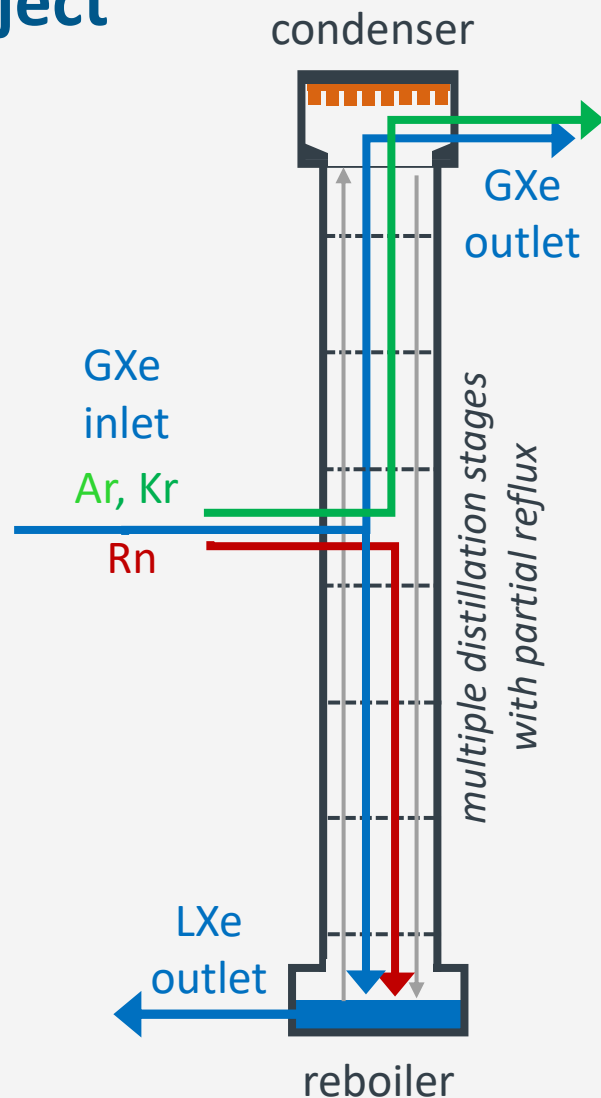
- Xenon purification, handling and cryogenics

The LowRad project

low radon and low internal radioactivity (for XLZD)

Develop technologies for:

- Continuous/online ^{85}Kr removal (30 ppq $^{\text{nat}}\text{Kr}$)
- Additional factor 10 in ^{222}Rn reduction (0.1 $\mu\text{Bq/kg}$) in combination with other Rn mitigation techniques
- R&D for novel purification methods
- Methods for physics searches/analyses



The HERETIX project

HERETIX: A Hermetic, Enriched, Rare-Event Time Projection Chamber in Xenon

L. Althueser¹ , N. Hargittai² , J. Pienaar^{2,3} , R. Braun¹ ,
H. Landsman² , C. Weinheimer¹ , R. Budnik² 

¹Institut für Kernphysik, University of Münster, 48149 Münster, Germany

²Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot 7610001, Israel

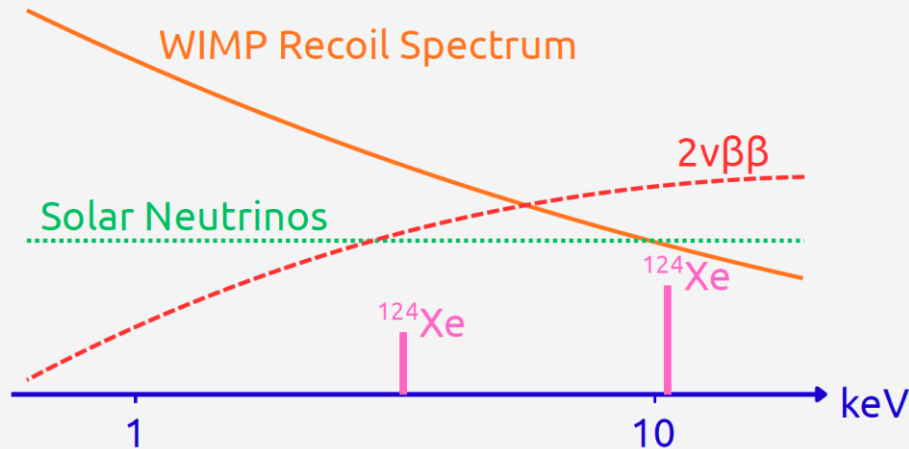
³Department of Physics Core Facilities, Weizmann Institute of Science, Rehovot 7610001, Israel

arXiv: [2606.26876]

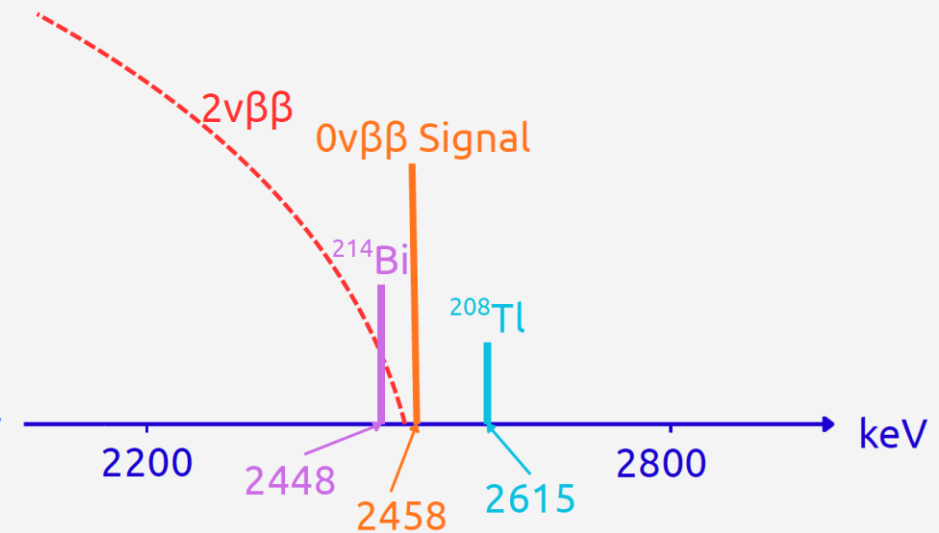


Specialized TPCs for rare event searches

	WIMPs
Signal	Nuclear recoil (NR) spectrum at O(10 keV)
Backgrounds	Low ER, NR
TPC	Dual-phase
Xenon Target	Natural liquid xenon (LXe)

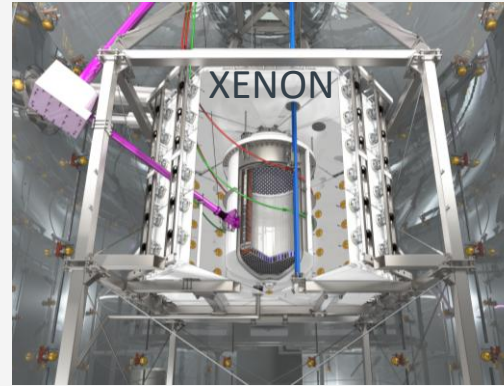


	$0\nu\beta\beta$
Signal	Electronic Recoil (ER) at $Q_{\beta\beta} = 2458$ keV
Backgrounds	High ER
TPC	Single-phase
Xenon Target	Enriched LXe in ^{136}Xe

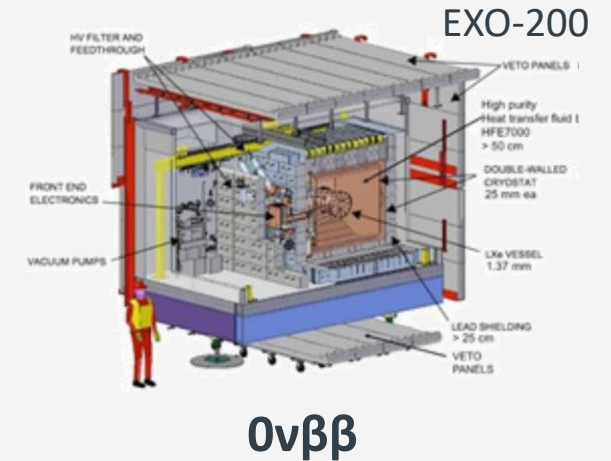


Why should $0\nu\beta\beta$ and dark matter (DM) combine?

- **Common technologies and challenges**
 - Similar purification and cryogenics
- Next-gen for both require a lot more **resources**
 - Lab space, xenon inventory, technology, funding, people, ...
- **Maximize physics, minimize overhead**
 - Reach superior sensitivity to $0\nu\beta\beta$
 - Keep WIMP search sensitivity (+ other searches)
 - Share xenon handling infrastructure, mass, shielding

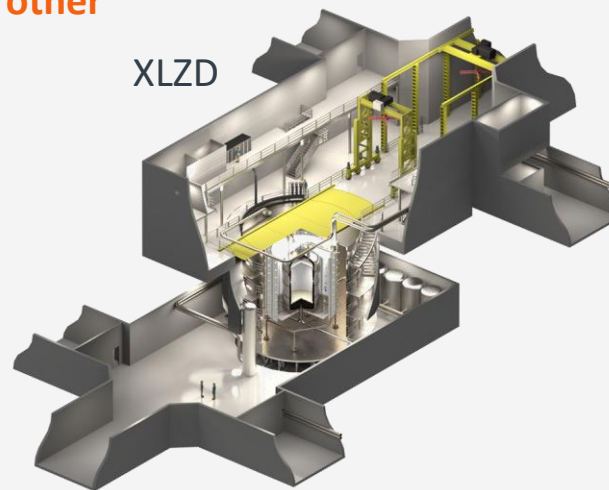
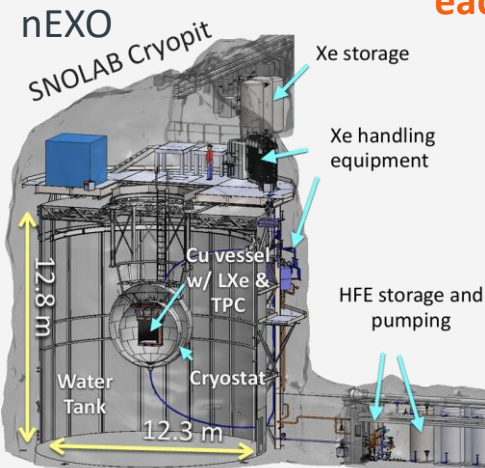


WIMPs

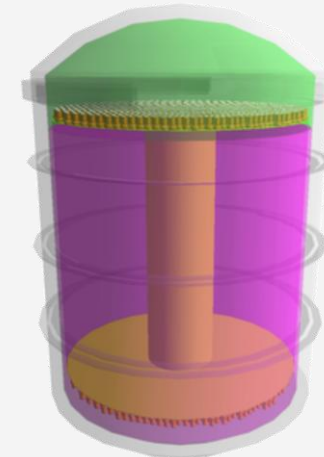


$0\nu\beta\beta$

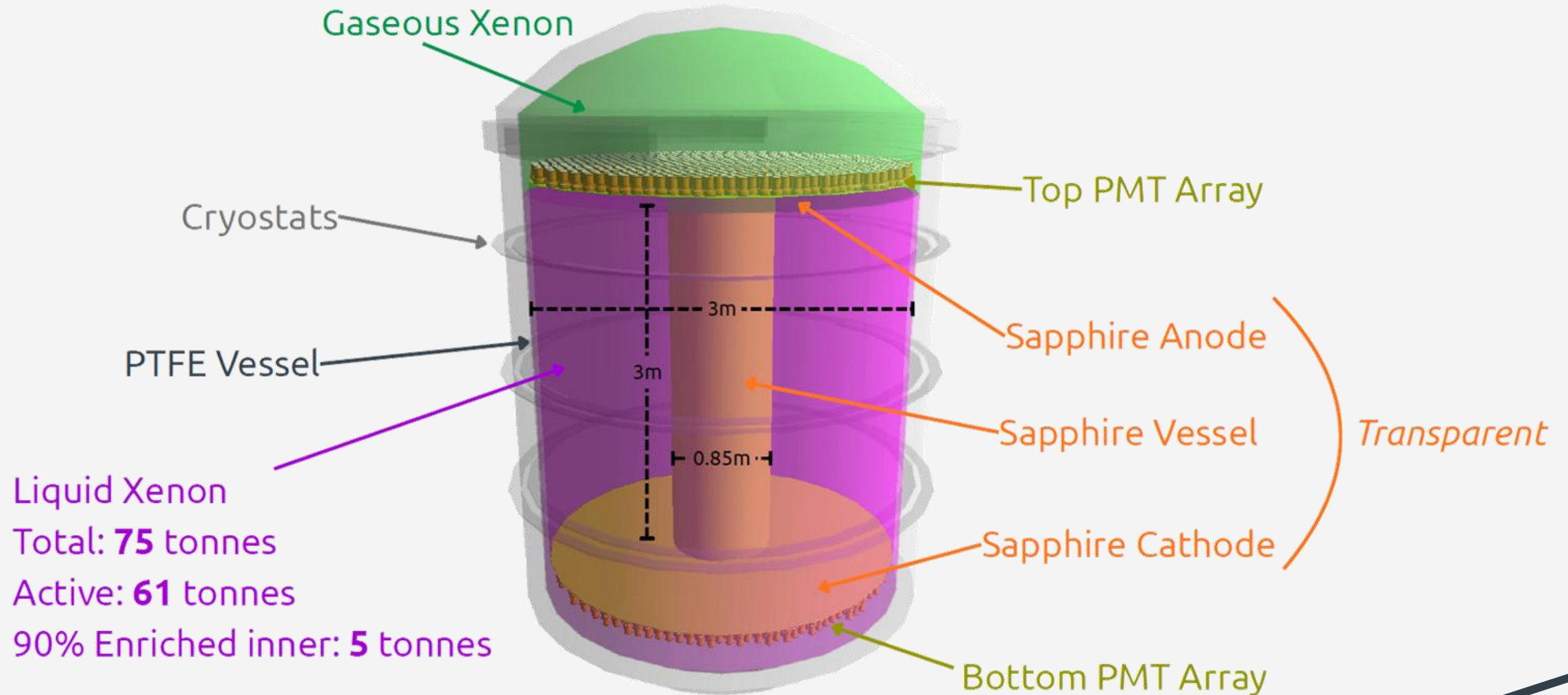
Pursued together the two efforts can work in synergy with each other



Unified Rare Event Observatory



HERETIX: Detector Design



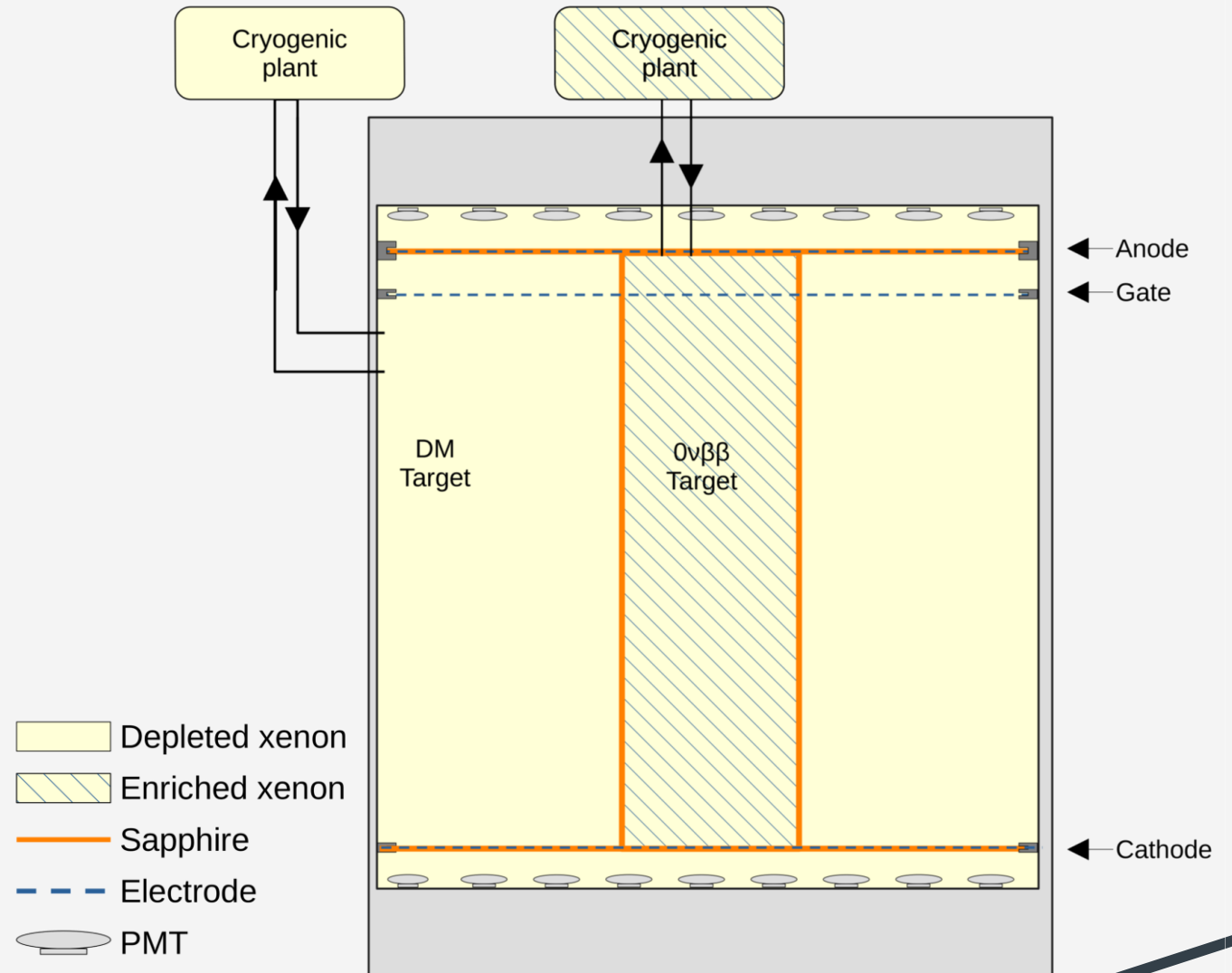
Why a Nested Design?

- Materials are the main background for $0\nu\beta\beta$
- Xenon has excellent self-shielding properties
- Enriched LXe is expensive to “waste” as shielding
 - Option to deplete the DM target in ^{136}Xe and therefore reducing the backgrounds
 - Envision ^{136}Xe enriched $0\nu\beta\beta$ target

The $0\nu\beta\beta$ volume massively benefits from shielding provided by the DM target

Key points of the current design idea

- Take the XLZD nominal detector design as baseline
- Include a hermetically sealed inner volume
 - 5 tonnes (enriched to 90% in ^{136}Xe)
 - Transparent walls of Sapphire (other materials are also in consideration)
 - Anode and Gate electrodes using Sapphire discs with coated electrodes (alternative approaches possible here)
- Two xenon infrastructures for inner and outer volume



Monte-Carlo simulations of HERETIX

XENONnT Values	Upper Limits	PandaX Values
-------------------	-----------------	------------------

GEANT4 Simulation Inputs

- **Most important detector components**
 - All components inside LXe
 - Both cryostat vessels
- **Nominal design**
 - Assumed only measured screening values or upper limits
 - 75% reduction of ^{214}Bi in PMTs
- **Optimistic design**
 - Including projected values for detector material radiopurity
 - 90% reduction of ^{214}Bi in PMTs
 - $<1 \mu\text{Bq } ^{238}\text{U}$ in Sapphire

Isotope Component	Amount	Activity Units	^{238}U	^{232}Th	^{60}Co	^{137}Cs	^{40}K
Cryostats	12900 kg	mBq/ kg	2.49	0.26	7.08	0.84	3.48
PTFE	290 kg	mBq/ kg	0.12	0.11	0.05	0.04	2.40
Sapphire	250 kg	mBq/ kg	0.03	0.01	0.99	0.11	0.21
PMTs	2368 units	mBq/ unit	2.00	0.45	0.99	0.12	14.1
Copper	500 kg	mBq/ kg	0.69	0.03	0.11	0.02	0.29

[1] E. Aprile et al. Projected WIMP sensitivity of the XENONnT dark matter experiment, JCAP 11 (2020) 31 [2007.08796];

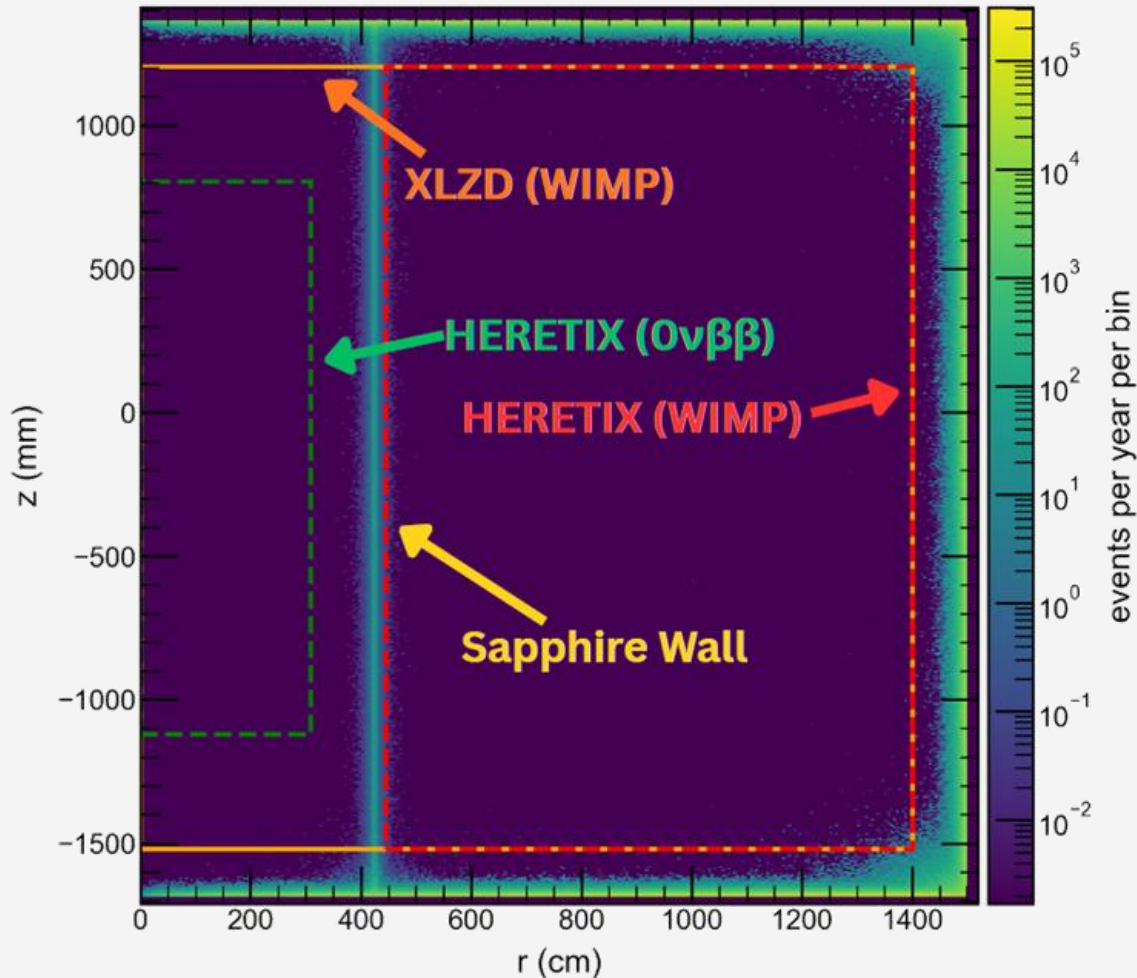
[2] XLZD collaboration, The XLZD Design Book: towards the next-generation liquid xenon observatory for dark matter and neutrino physics, Eur. Phys. J. C 85 (2025) 1192 [2410.17137];

[3] D. Chernyak et al., Enhanced sensitivity to trace U238 impurity of sapphire via coincidence neutron activation analysis, Phys. Rev. C 113 (2026) 015803 [2508.04232].

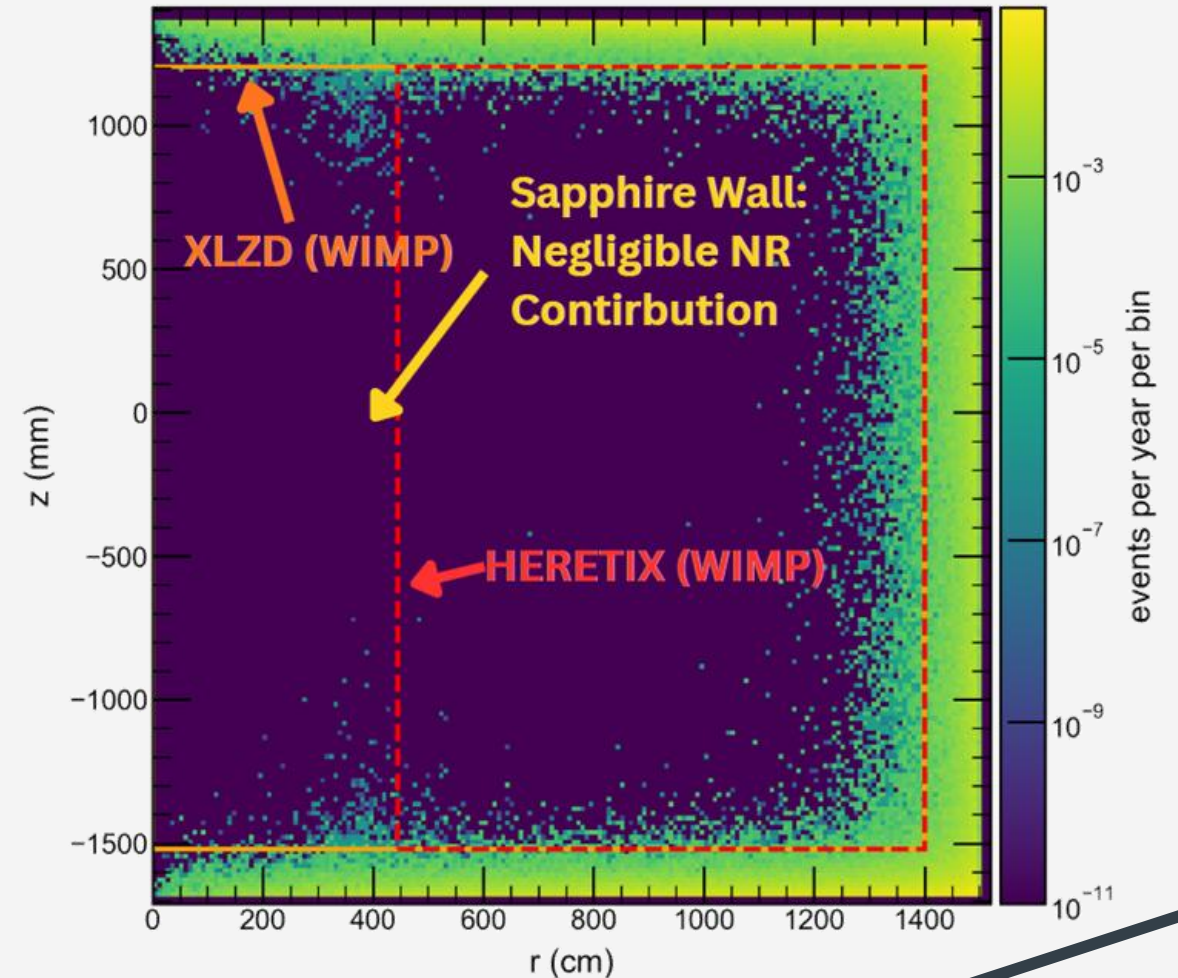
[4] G. Wang and S.a. Wang, A novel low-background photomultiplier tube r12699 in the PandaX experiment, Journal of Instrumentation 21 (2026) C03030.

Effects of Sapphire: Backgrounds

WIMP ER Backgrounds



WIMP NR Backgrounds



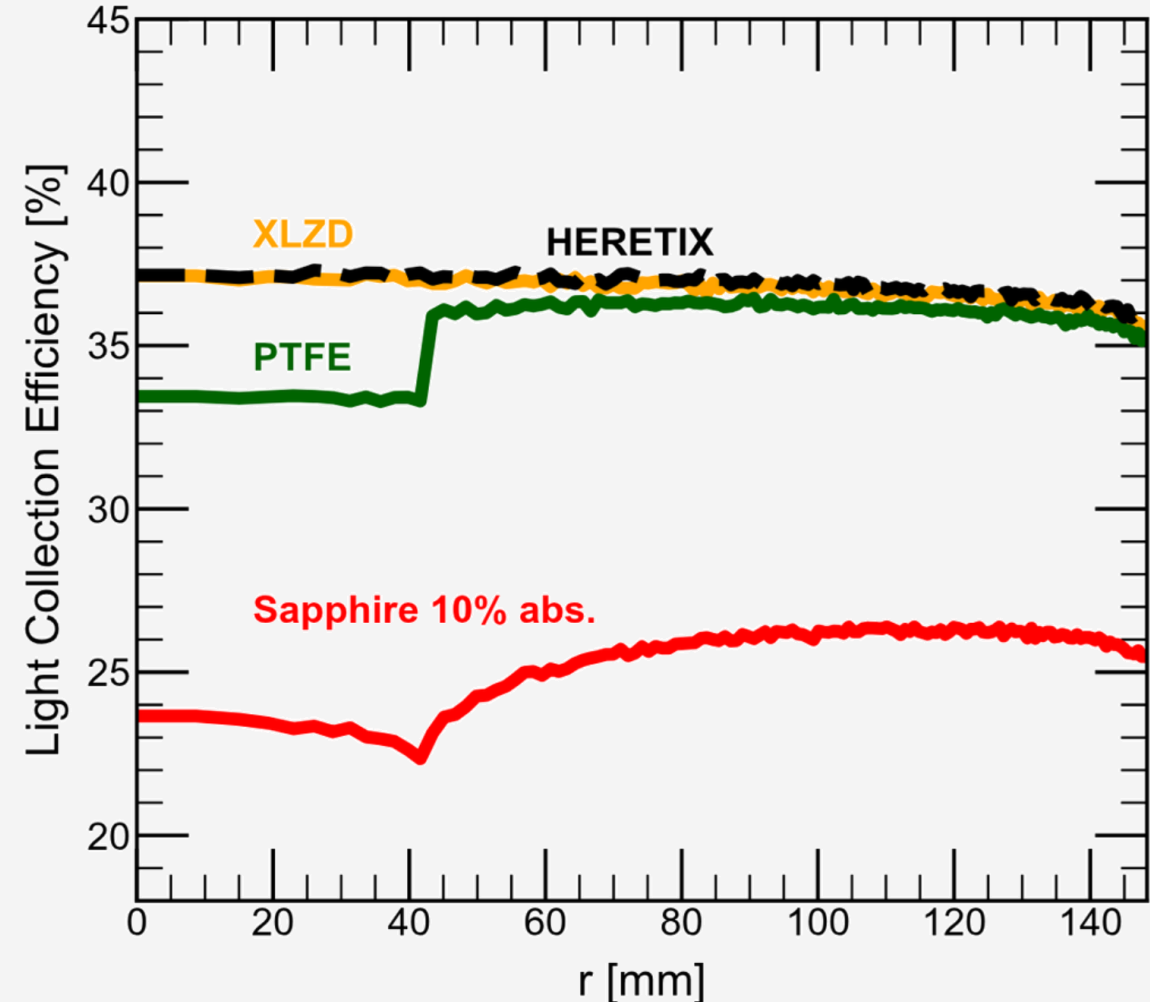
Effects of Sapphire: LCE

How is our light collection efficiency (LCE) affected?

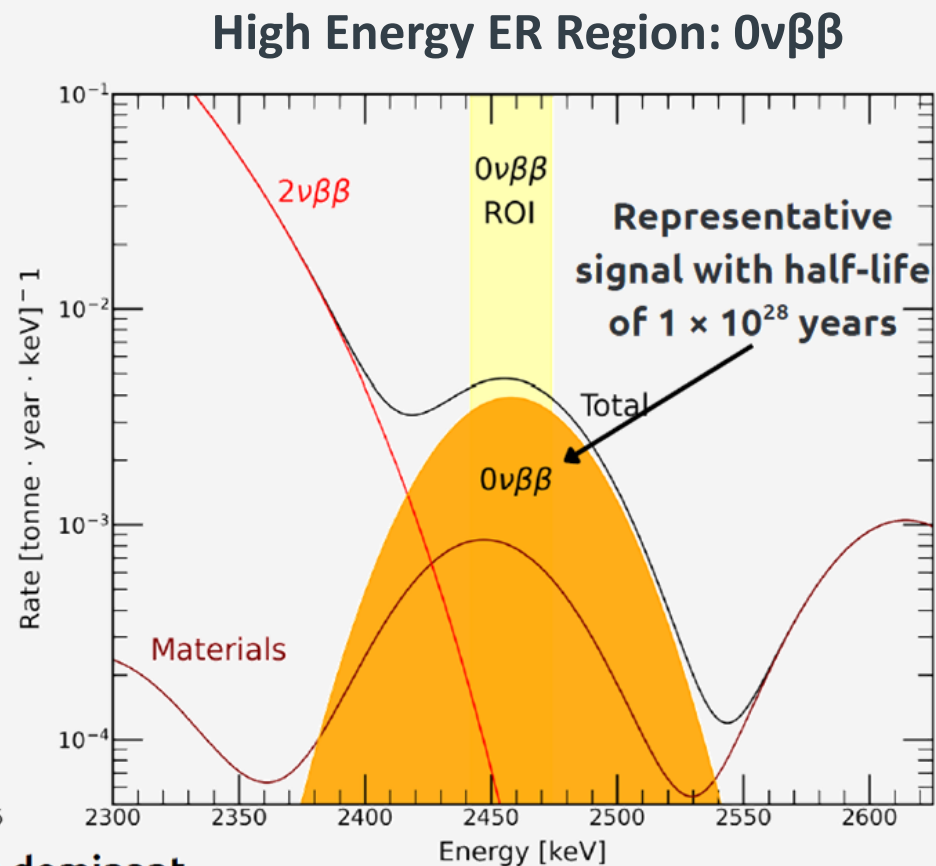
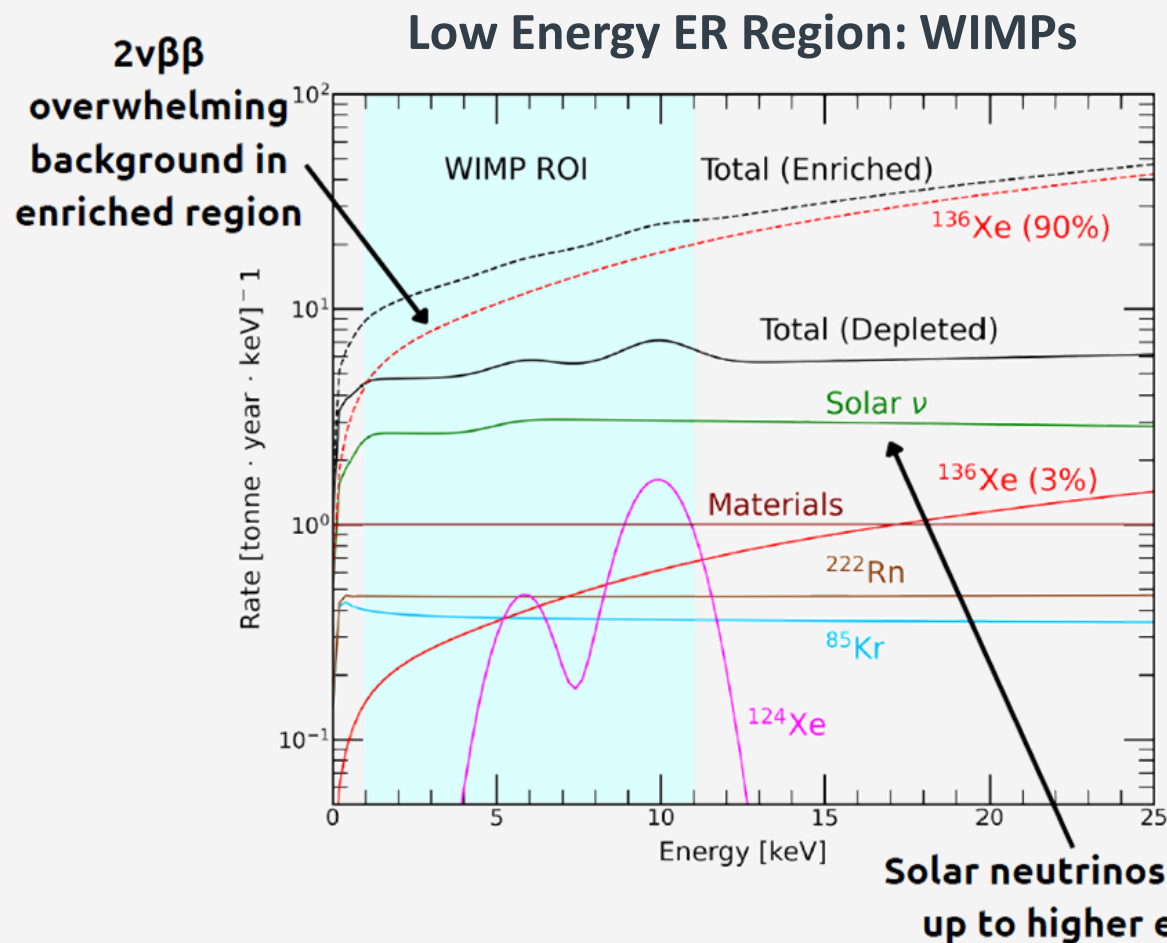
- Sapphire VUV absorption at 178nm not measured
- Nominal case assumes properties like quartz
- Absorption measurements in air indicate <10%
- Opaque but highly reflective case of PTFE also considered

Negligible effect on LCE if optical properties of sapphire at 178nm are like those of quartz

Parameter	Value
LXe refractive index	1.63
LXe absorption length	50 m
LXe scattering length	50 cm
GXe absorption length	100 m
GXe scattering length	100 m
Sapphire refractive index	1.92
Sapphire absorption length	28.5 mm - 30 m
PTFE reflectivity	99 %
Electrode transmittance	96 %
SS reflectivity	20 %

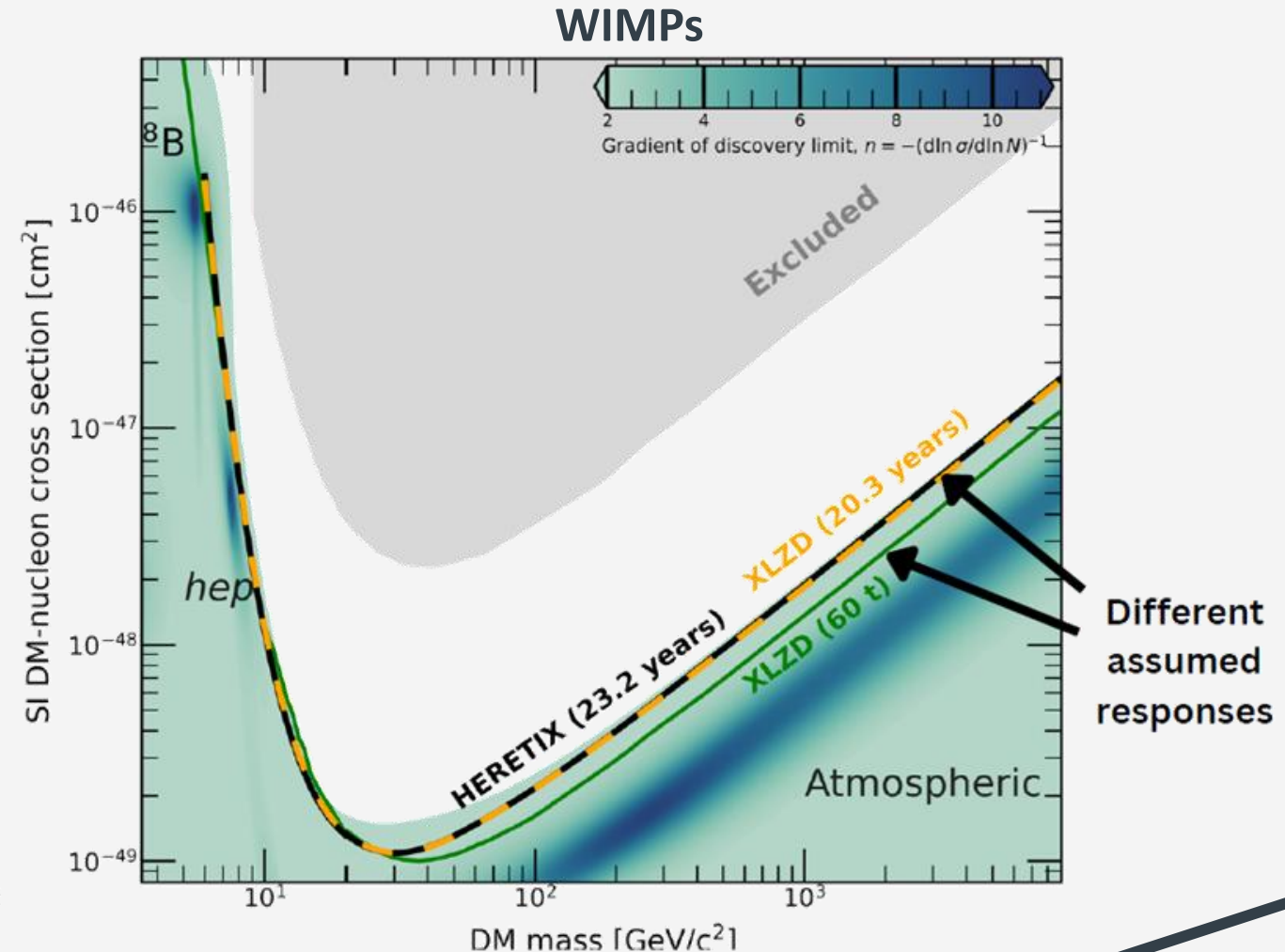
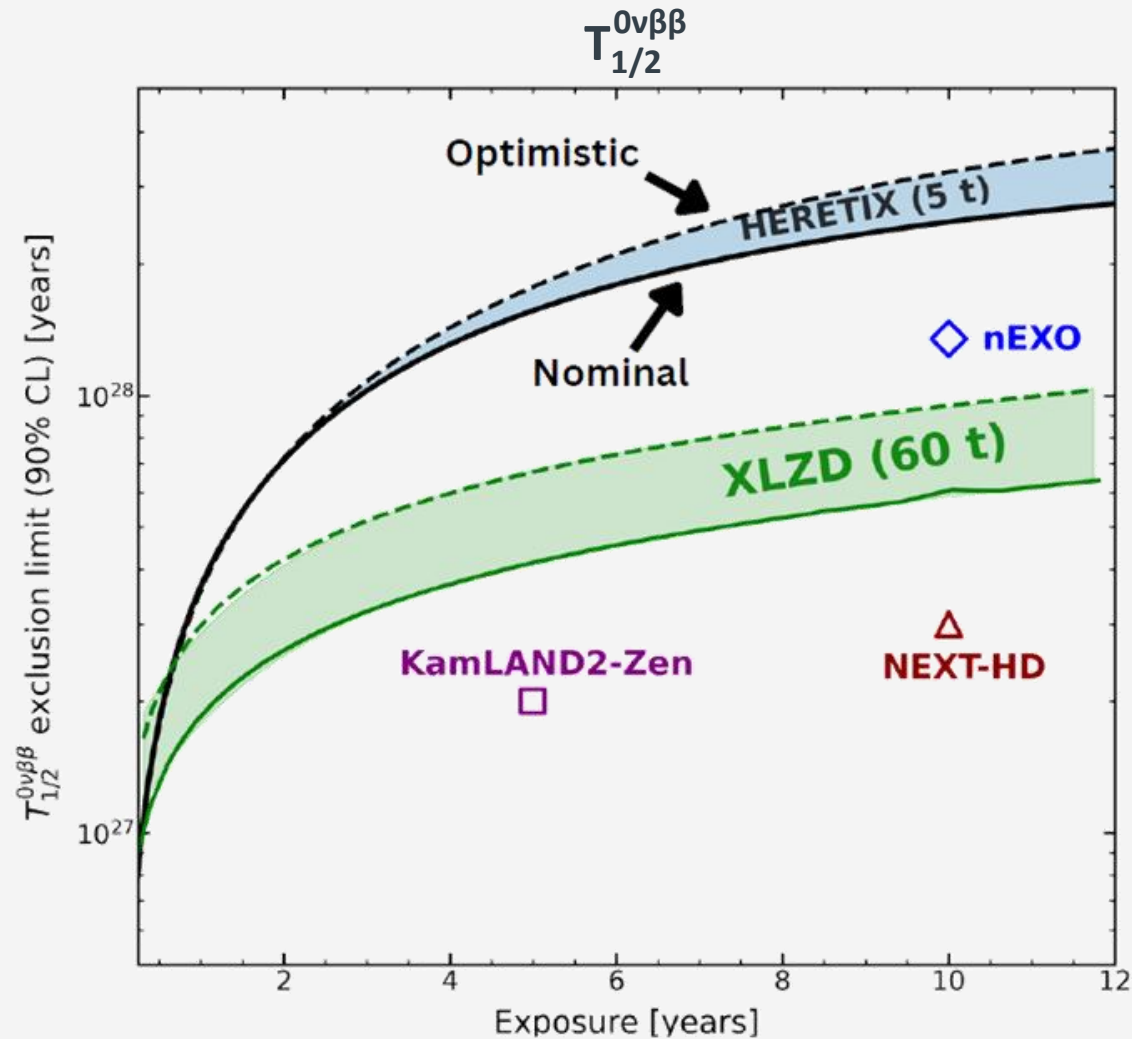


Background Templates



Sensitivity Projections

- [1] XLZD collaboration, The XLZD Design Book: towards the next-generation liquid xenon observatory for dark matter and neutrino physics, Eur. Phys. J. C 85 (2025) 1192 [2410.17137]
 [2] nEXO collaboration, nEXO: neutrinoless double beta decay search beyond 10^{28} year half-life sensitivity, J. Phys. G49 (2022) 015104 [2106.16243]
 [3] C. Grant, Results from kamland-zen and sno+, 2020.10.5281/zenodo.4142683
 [4] NEXT collaboration, Sensitivity of a tonne-scale NEXT1044 detector for neutrinoless double beta decay searches, JHEP 2021 (2021) 164 [2005.06467].

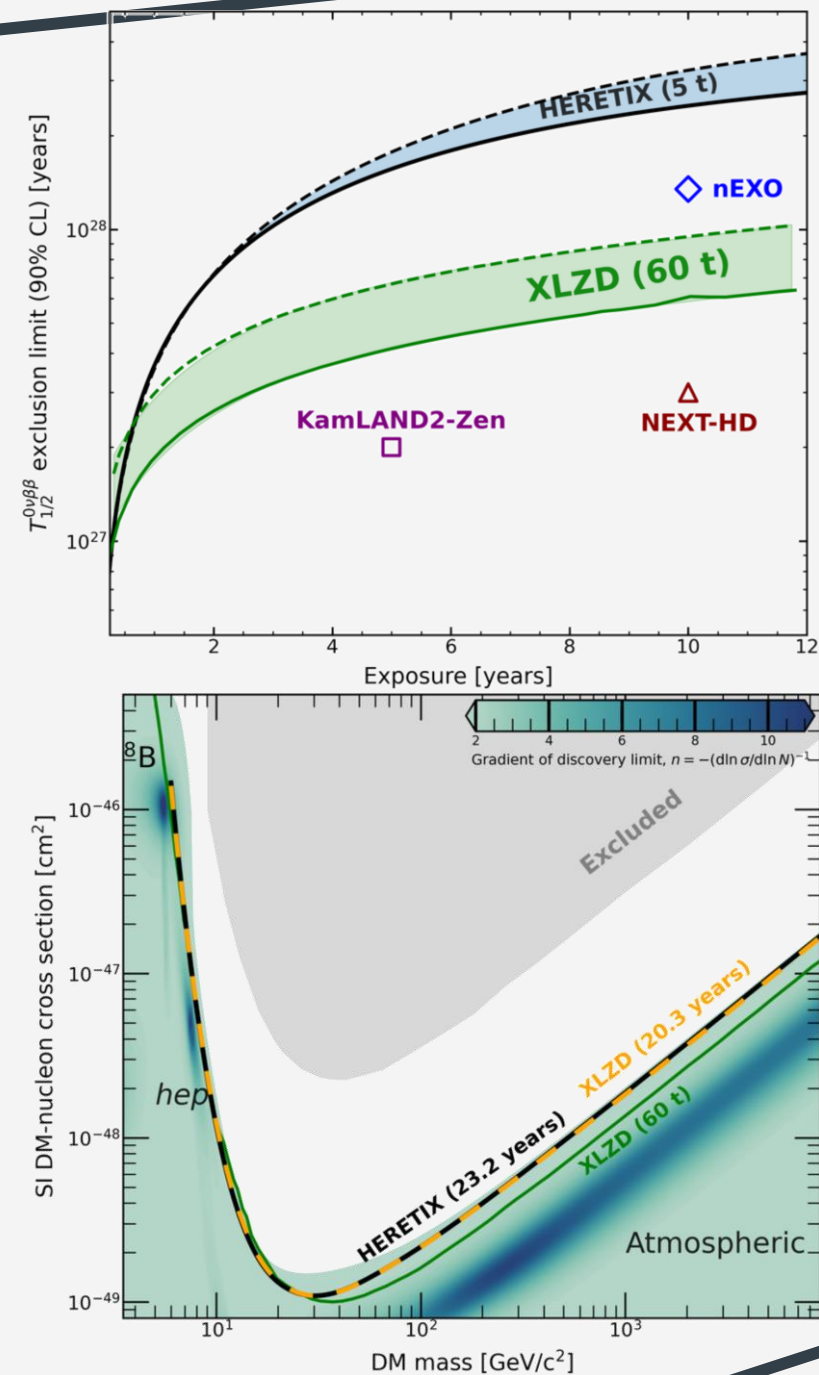


Sensitivity Projections

How much does HERETIX improve on $0\nu\beta\beta$?

- Enhanced $0\nu\beta\beta$ signal from the enriched target and very clean target in the hermetic FV pay off after 1-2 years
- Match nEXO projection with <4 years exposure time
- Small effect on WIMP search leading to longer exposure
- Nominal: $T_{1/2}^{0\nu\beta\beta}$ of 2.5×10^{28} years at a 10 years exposure
- Optimistic: $T_{1/2}^{0\nu\beta\beta}$ of 3.2×10^{28} years at a 10 years exposure

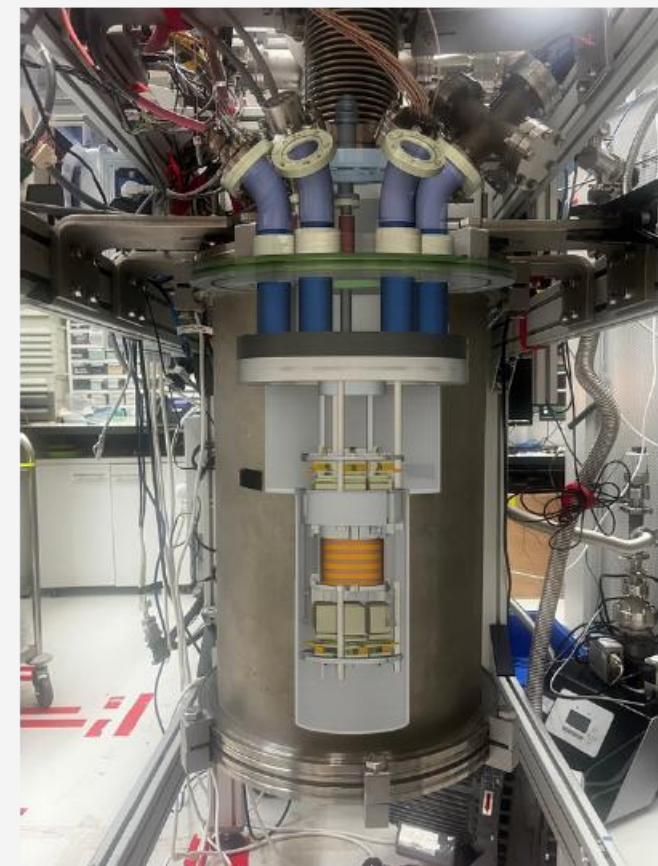
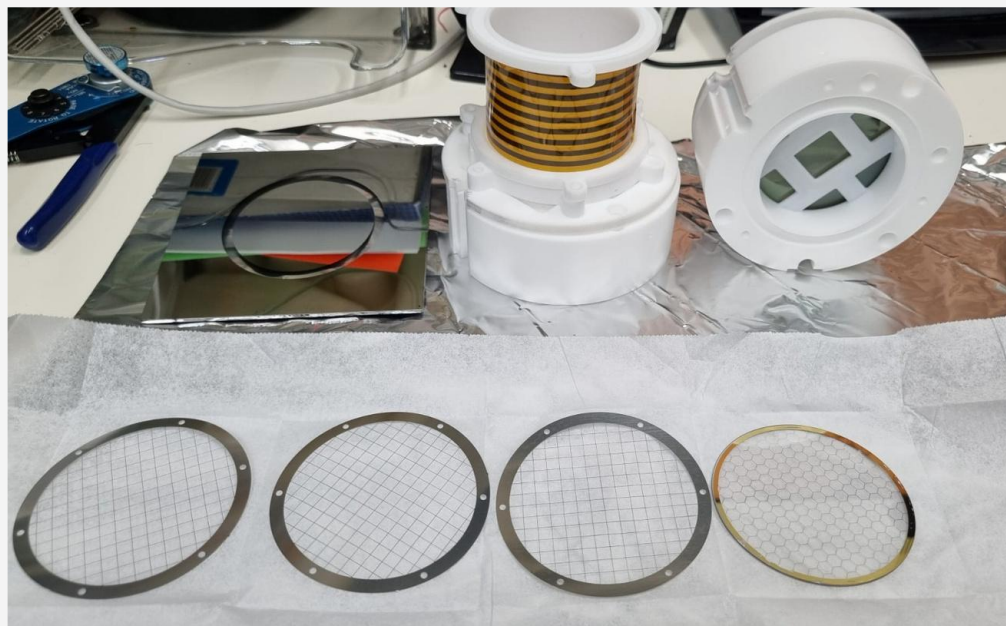
Close to background free $0\nu\beta\beta$ search using the same 5t volume as nEXO, with small cost in exposure time for WIMPs



HERETIX: Practical Challenges

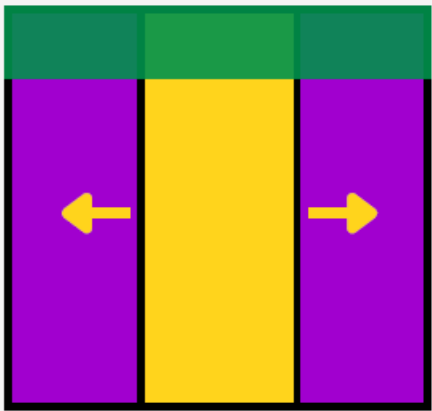
1. Integrating a second hermetic volume inside a TPC
2. **Solid and transparent anode and cathode**
3. **Fusing** the inner vessel with anode and cathode
4. Incorporating a wire-mesh gate that runs across both volumes
5. Two Xenon handling systems
6. Charge build-up on sapphire surface

Small-scale TPC @Weizmann

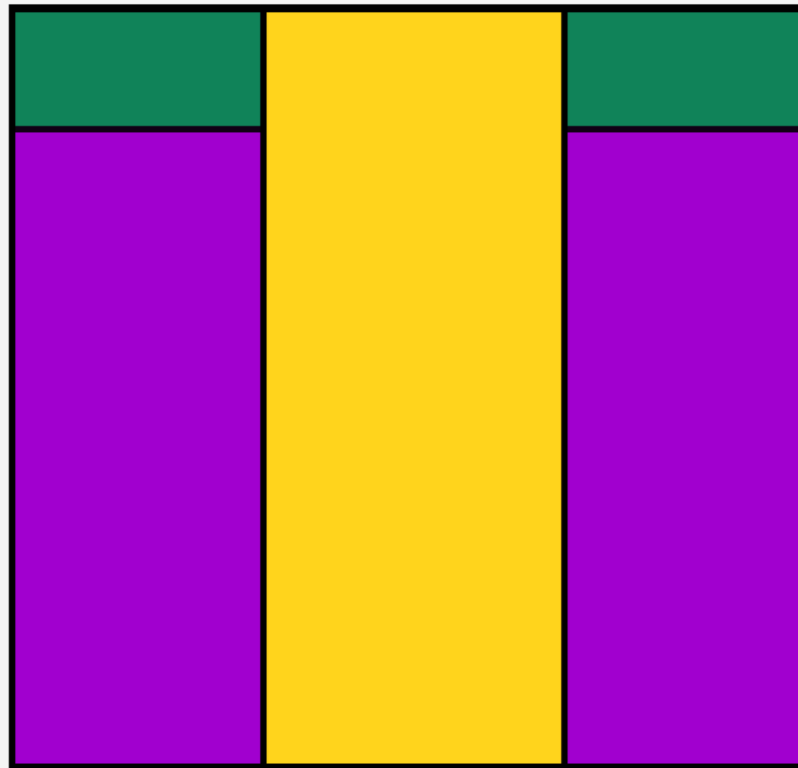


HERETIX: Scenarios

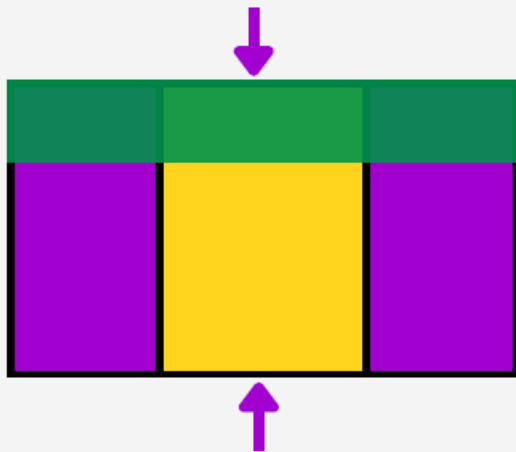
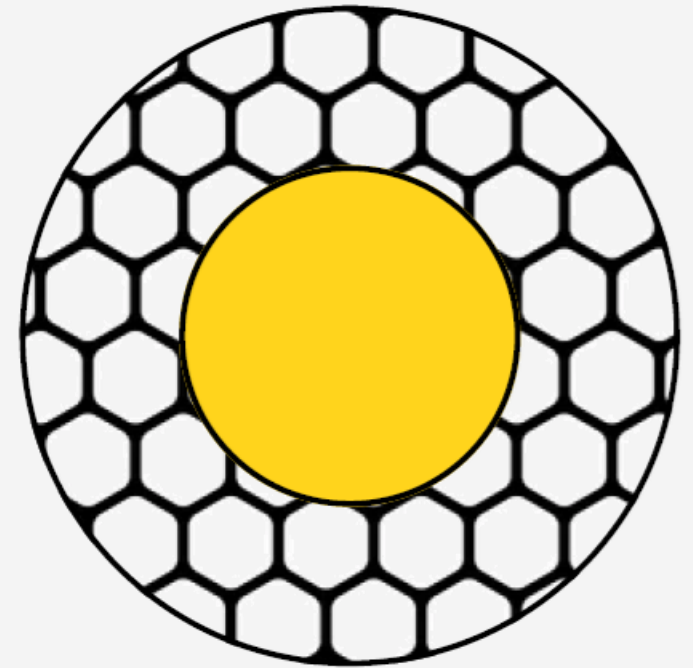
Larger inner fiducial volume



Single-phase inner TPC



Mixed wire/solid electrodes

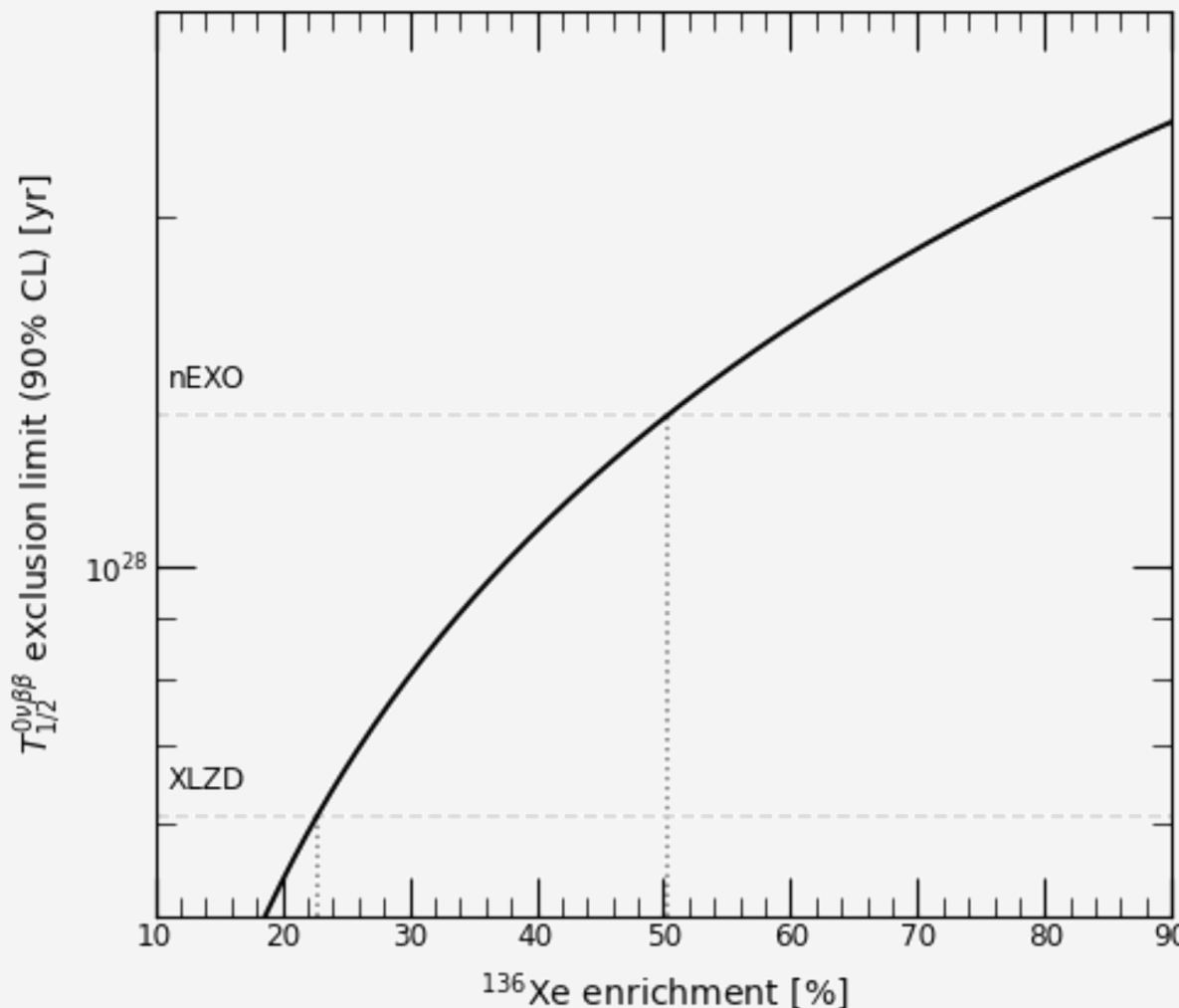
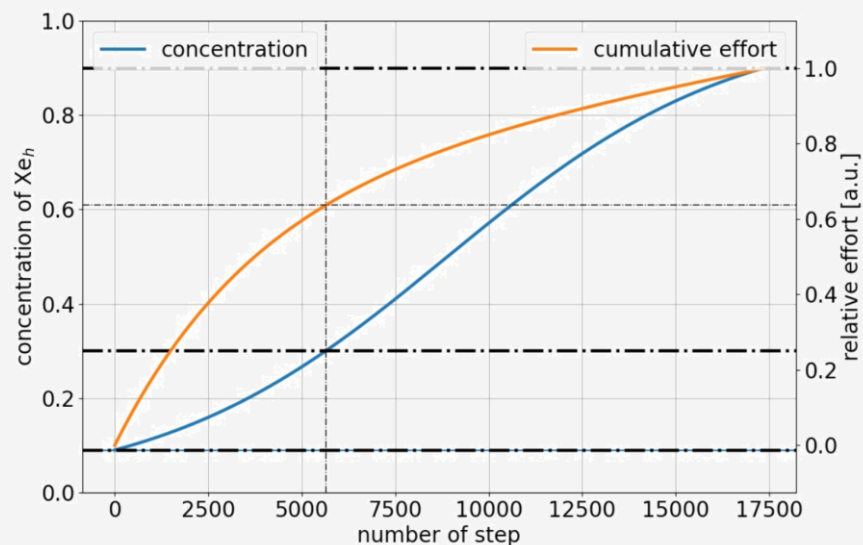


Enrichment Strategies

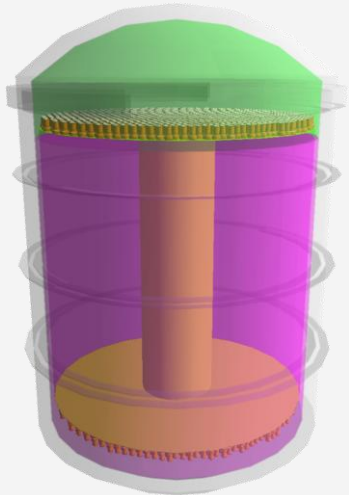
Can we be flexible with ^{136}Xe enrichment?

- Taking cryogenic multi-stage distillation as model
- Can match XLZD at 22% enrichment, and nEXO at 50%
- Staged effort can increase overall cost but provide early physics deliverables

The nested design allows HERETIX to be competitive at lower enrichment levels

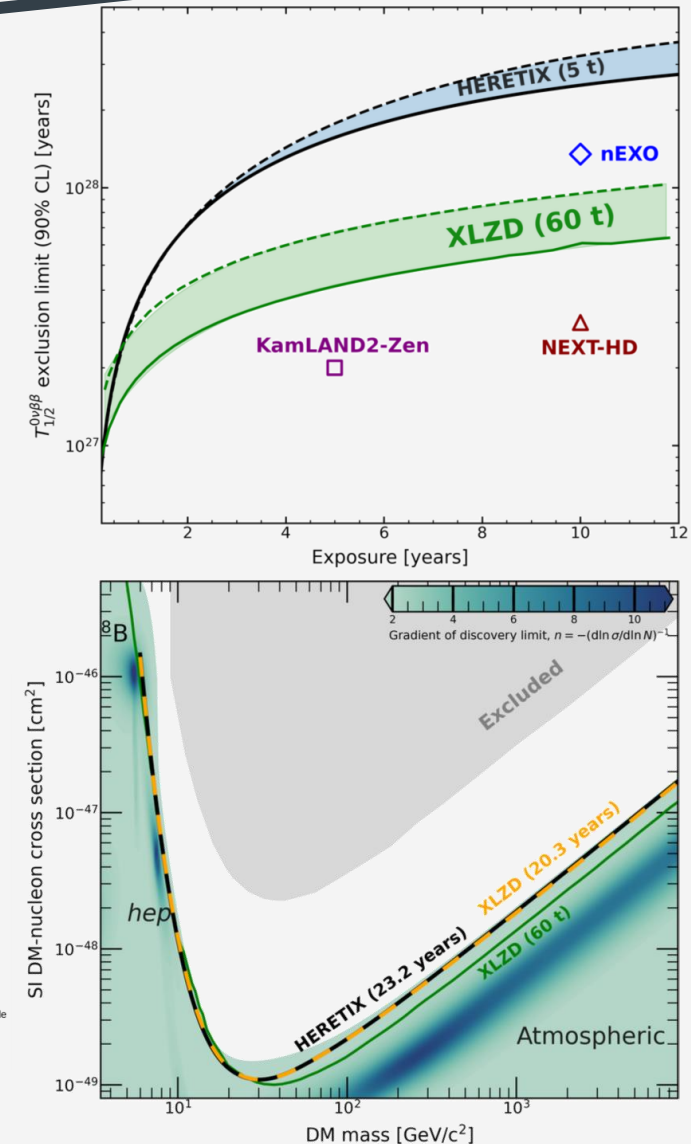
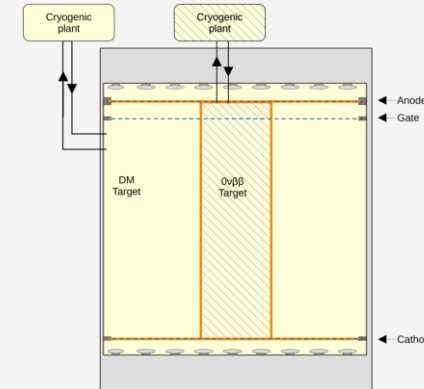
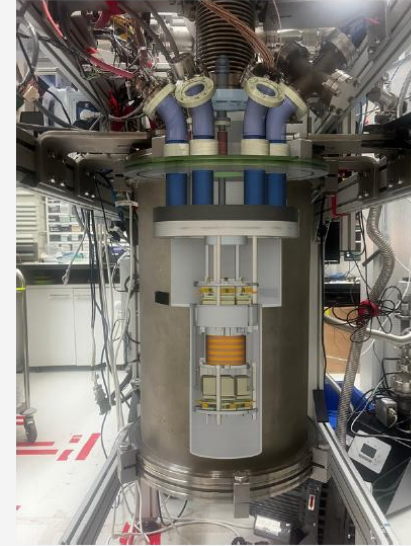


Conclusion – The HERETIX project



- Combine WIMP and $0\nu\beta\beta$ search in future detectors like XLZD
- Exploit the synergies of depleted target for reduced backgrounds in WIMP searches and enriched target for $0\nu\beta\beta$ sensitivity
- $T_{1/2}^{0\nu\beta\beta}$ of 2.5×10^{28} years at a 10 years exposure
- No loss in WIMP sensitivity when extending the exposure/experiment lifetime
- One could foresee future detector upgrade during the conceptual design
- OR include the hermetic volume and delay the enrichment to a later stage (no delay for WIMPs)

New ideas and interest in developing this concept are welcome



In collaboration with Weizmann Institute of Science

This research at University of Münster is funded by

Backup: Screening Values (nT)

Component	Mass [kg]	Activity [mBq/kg]							
		²³⁸ U	²³⁵ U	²²⁶ Ra	²³² Th	²²⁸ Th	⁶⁰ Co	⁴⁰ K	¹³⁷ Cs
Cryostat vessels	1120	3.2 (9)	0.37 (13)	0.37 (5)	0.29 (7)	0.45 (5)	2.5 (5)	2.1 (3)	< 0.41
Cryostat flanges	730	1.4 (4)	0.06 (2)	< 4	0.21 (6)	4.5 (6)	14.1 (9)	< 5.6	< 1.5
Bell and electrodes ⁽¹⁾	190	3.2 (7)	0.57 (10)	0.62 (10)	0.36 (14)	0.46 (9)	0.78 (11)	1.6 (6)	< 0.17
PTFE ⁽²⁾	128	0.12 (5)	< 0.06	0.10 (2)	0.11 (5)	< 0.06	< 0.053	2.4 (3)	< 0.038
Copper ⁽³⁾	355	< 0.69	< 0.28	0.033 (5)	< 0.027	< 0.023	0.11 (2)	< 0.29	< 0.016
PMTs and bases ⁽⁴⁾	98	53 (15)	2.2 (7)	4.6 (10)	3.5 (12)	4.2 (8)	7.1 (9)	73 (18)	0.9 (3)

Table 2. Radioactivity levels of the XENONnT detector components, with uncertainties in parenthesis. Upper limits are given at 90% confidence level. The activities are averaged by mass over all the individually simulated sub-components. Omitted components, including those outside of the cryostat, induce less than 4% of the total background rate from detector materials. ⁽¹⁾ SS diving bell and SS frames of the electrodes. ⁽²⁾ TPC pillars, blocking and sliding reflector panels, and PMT holders. ⁽³⁾ Support structure of the PMT arrays, support rings of the TPC, inner and outer field shaping rings. ⁽⁴⁾ The total mass corresponds to 494 PMTs and PMT bases.

E. Aprile et al. Projected WIMP sensitivity of the XENONnT dark matter experiment, JCAP 11 (2020) 31 [2007.08796].

Source	Rate [(t y) ⁻¹]
ER background	
Detector radioactivity	25 ± 3
²²² Rn	55 ± 6
⁸⁵ Kr	13 ± 1
¹³⁶ Xe	16 ± 2
¹²⁴ Xe	4 ± 1
Solar neutrinos	34 ± 1
Total	148 ± 7
NR background	
Neutrons	(4.1 ± 2.1) × 10 ⁻²
CEνNS (Solar ν)	(6.3 ± 0.3) × 10 ⁻³
CEνNS (Atm+DSN)	(5.4 ± 1.1) × 10 ⁻²
Total	(1.0 ± 0.2) × 10 ⁻¹

Table 3. Estimated background event rates in the 4 t fiducial volume of XENONnT, based on the energy of the recoil event. The energy ROI in which the event rates are integrated is (1, 13) keV for ERs, and (4, 50) keV for NRs. We assume an activity concentration of 1 μBq/kg of ²²²Rn and 0.1 ppt (mol/mol) ^{nat}Kr/Xe. The background contributions from Xe isotopes are determined assuming the 8.9% and 0.095% natural abundances of ¹³⁶Xe and ¹²⁴Xe, respectively.

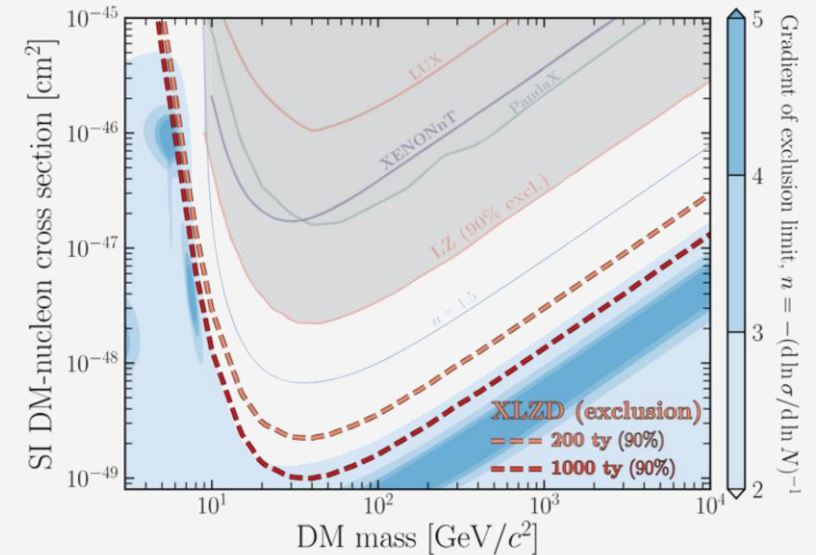
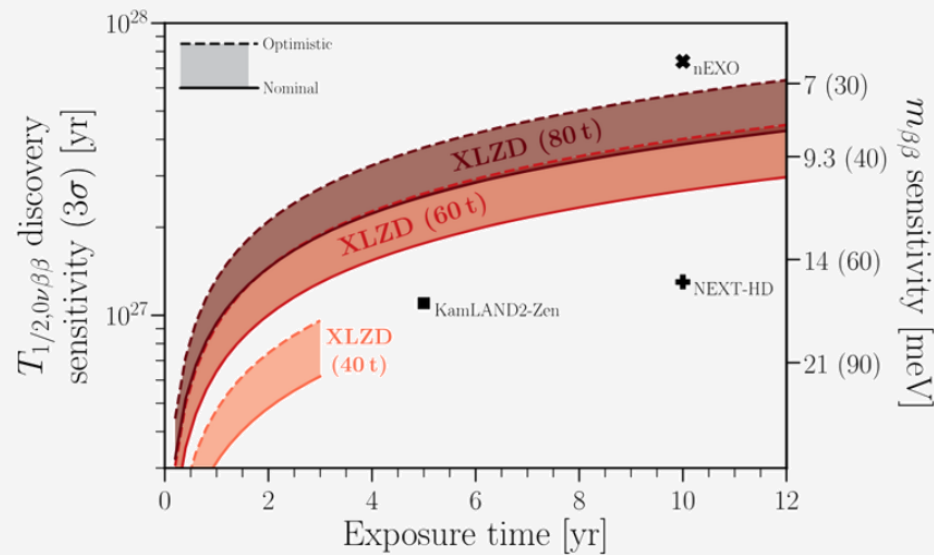
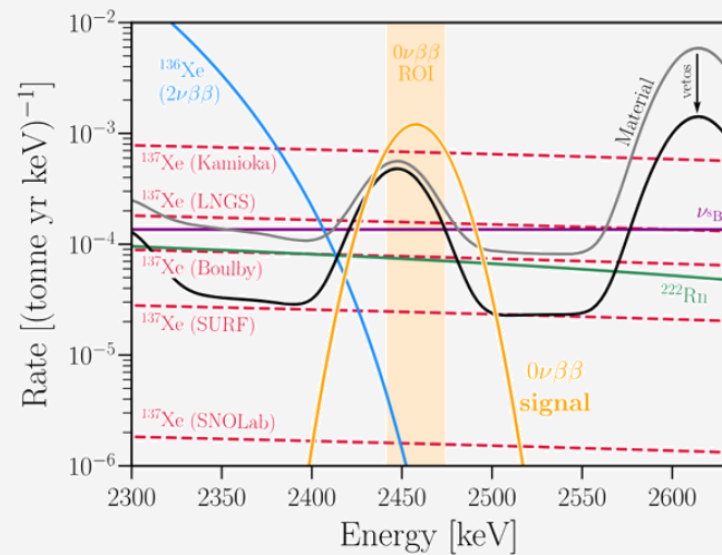
Backup: Screening Values (Sph)

TABLE II. Compilation of ^{232}Th and ^{238}U radioassay results found in the literature for sapphire and derived from our work. In some cases constraints on ^{26}Al , ^{40}K , ^{60}Co , and ^{137}Cs activities exist but are not shown. Crackle and alumina are precursors to the sapphire crystal growth. The assay method determines which part of the decay series has been probed. In the case of NAA, ^{232}Th and ^{238}U are measured. In case of Ge counting (Ge), lower chain members are counted and their activities have been converted into concentrations of the chain heads by assuming secular equilibrium. For nEXO data, limits were determined using the Feldman-Cousins approach [33]. The ^{238}U constraint marked with a * is an exception. The raw result is 2.4 standard deviations negative, resulting in an inflated sensitivity of <1.8 ppt. We decided to not interpret this result as a statistical fluctuation and state the result using the flip-flop method instead, not taking credit for the unphysicality.

Supplier	Experiment	Assay method	Th [ppt]	U [ppt]	Ref.
Single Crystal Technology (Holland)	CRESST	NAA	<33	<40	[34]
Crystal Systems (USA)	CRESST	NAA	<2.3	<20	[34]
RSA (France)	ROSEBUD	Ge	<1200	<400	[3]
RSA (France)	ROSEBUD	Ge	<500	<160	[3]
Russia	ROSEBUD	Ge	<1200	<400	[3]
Swiss Jewel Company (USA)	EXO-200	NAA	30 ± 7	<25	[35]
Marketech Intern. (Taiwan)	Majorana	NAA	<21	<300	[36]
Hamamatsu (Japan), for R11410-20	LZ	Ge	3500 ± 740	2800 ± 240	[37]
Hamamatsu (Japan), for R11410-30	XENON1T	Ge	1200 ± 310	3600 ± 200	[38]
Precision Sapphire Tech. (Lithuania)	nEXO	NAA	410 ± 41	990 ± 99	[39]
GTAT Corporation (USA), crackle	nEXO	Ge	<1100	<270	[39]
GTAT Corporation (USA)	nEXO	NAA	6.0 ± 1.1	$<8.9^*$	[39]
Saint Gobain (USA), alumina	nEXO	Ge	1800 ± 580	<270	[39]
Saint Gobain (USA), alumina	nEXO	Ge	6500 ± 1100	2600 ± 520	[39]
Saint Gobain (USA)	nEXO	NAA	<0.26	<2.3	This work

D. Chernyak et al., Enhanced sensitivity to trace U238 impurity of sapphire via coincidence neutron activation analysis, Phys. Rev. C 113 (2026) 015803 [2508.04232].

Backup: XLZD Projections



XLZD collaboration, *The XLZD Design Book: towards the next-generation liquid xenon observatory for dark matter and neutrino physics*, *Eur. Phys. J. C* 85 (2025) 1192 [2410.17137].

Optical simulations

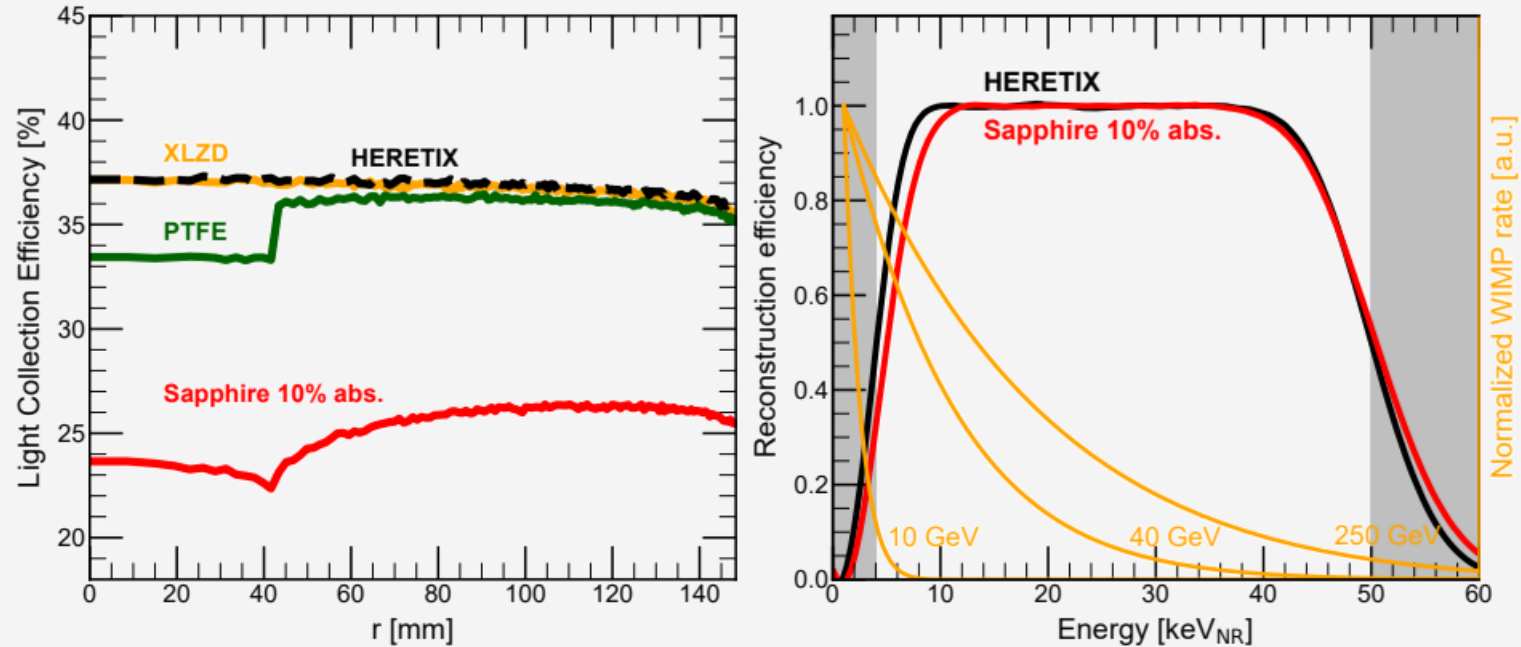


Fig. 7: Left: Average LCE along the radius of the TPC for our implementation of XLZD (orange) and for various HERETIX vessel materials: Sapphire as discussed earlier (black), Sapphire with 10 % absorption (red) and for PTFE (green). Right: Reconstruction efficiency of NR events considering the NEST parametrisation of the detector response model. The (4, 50) keV_{NR} region with at least 50% efficiency considering the HERETIX volume is highlighted and identical to our XLZD implementation. This region is reduced to (5.3, 50) keV_{NR} for Sapphire with 10 % absorption.