Dual Phase Xenon TPC

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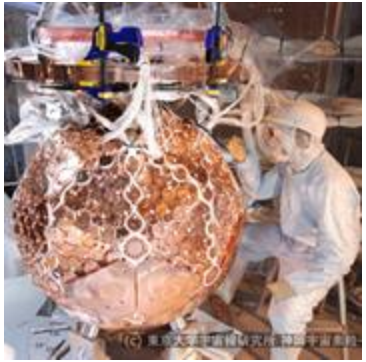
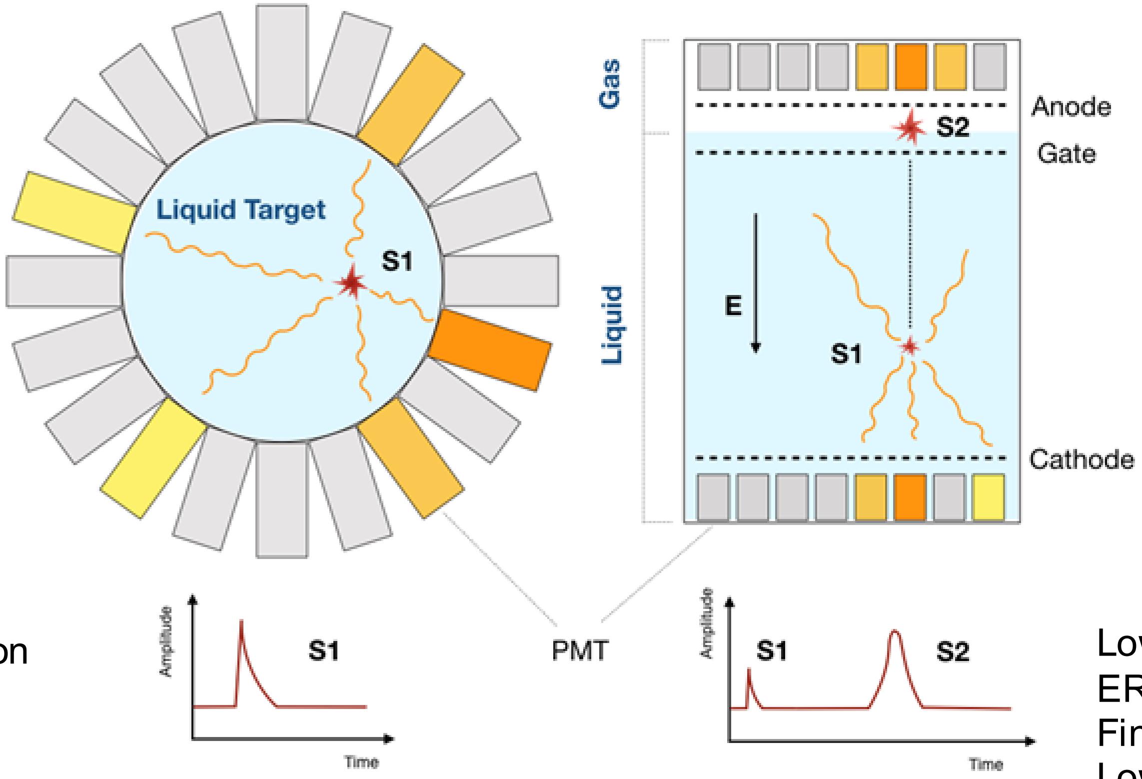
Next generation 0vbb searches with liquid xenon workshop
Montreal Nov. 12-14, 2025

“single phase” and “dual phase” in DM searches

Single phase | Dual phase





XMASS

High S1 light collection
No HV/electrodes

XENON1T

Low energy threshold
ER/NR discrimination
Fine 3D position
Lower background

The evolution of dark matter detectors with LXe

PandaX-4T

XENONnT (6T)

LZ (7T)

Concept of using LXe for DM Detection

DAMA/LXe, ZEPLIN, XMASS, XENON

G1 Experiments (100-1000 kg)

XENON100, LUX, PandaX-I/II, XMASS

G2 Experiments (2-10 T, dual-phase)

~2000 — **2007** — **2010** — **2017** — **2020** — **2030**

First Results from Two-Phase Xe detectors

XENON10, ZEPLIN-II/III

First results from the ton-scale detector

XENON1T

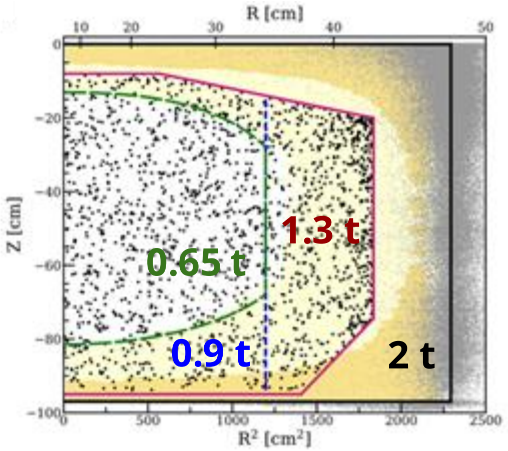
G3 Experiments (40~80 T, dual-phase)

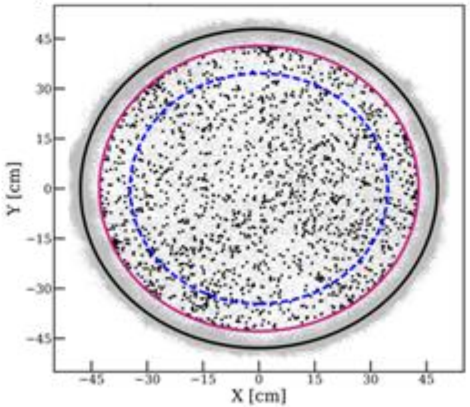
PandaX-xT, XLZD

Dual-phase XeTPCs offer superior performance because they achieve lower energy thresholds, provide robust ER/NR discrimination, and operate with overall lower background rates.

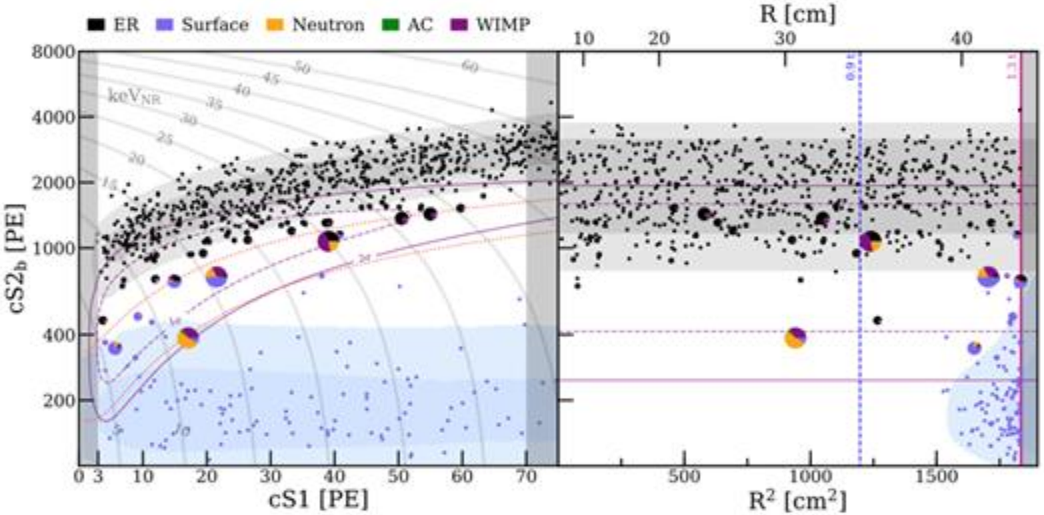
Using the S1 & S2 signals: positions and fiducialization

XENON1T as an example





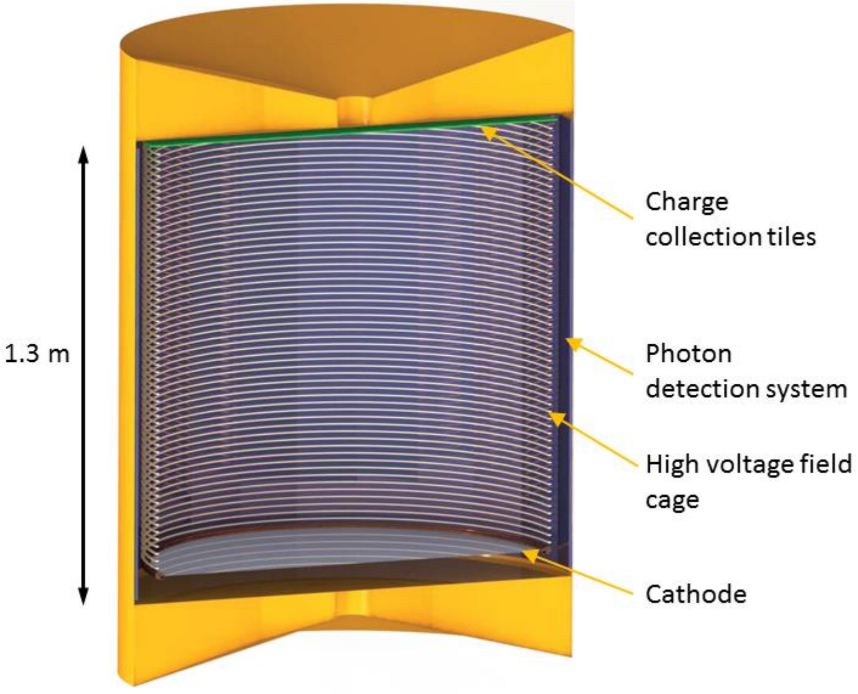
Combining ER/NR discrimination and fiducilization makes two-phase LXeTPC experiments very powerful in background rejection



XENON1T arXiv:1805.12562, PRL

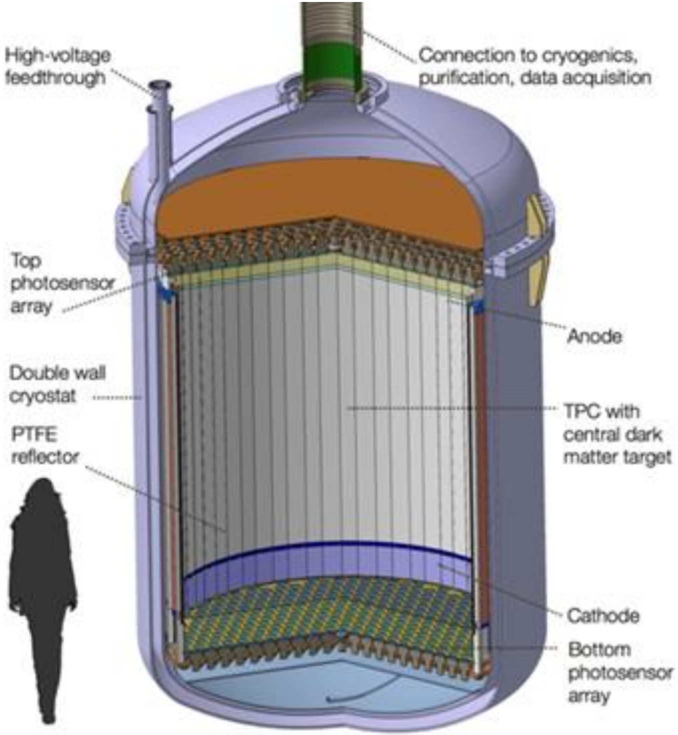
“single phase” and “dual phase” in 0vbb searches

Single phase



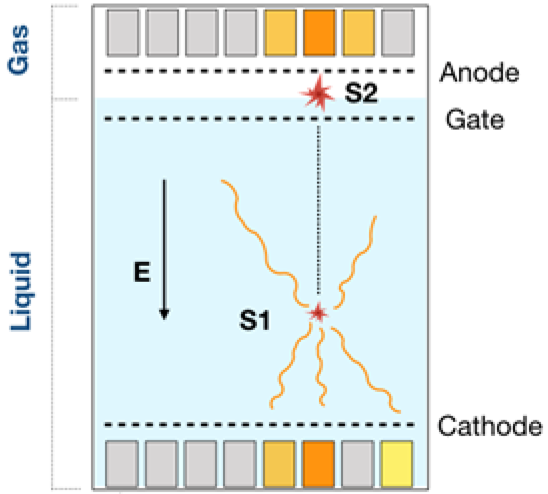
nEXO Concept

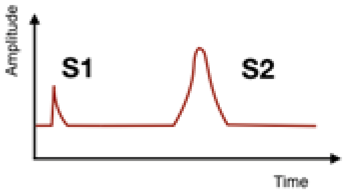
Dual phase

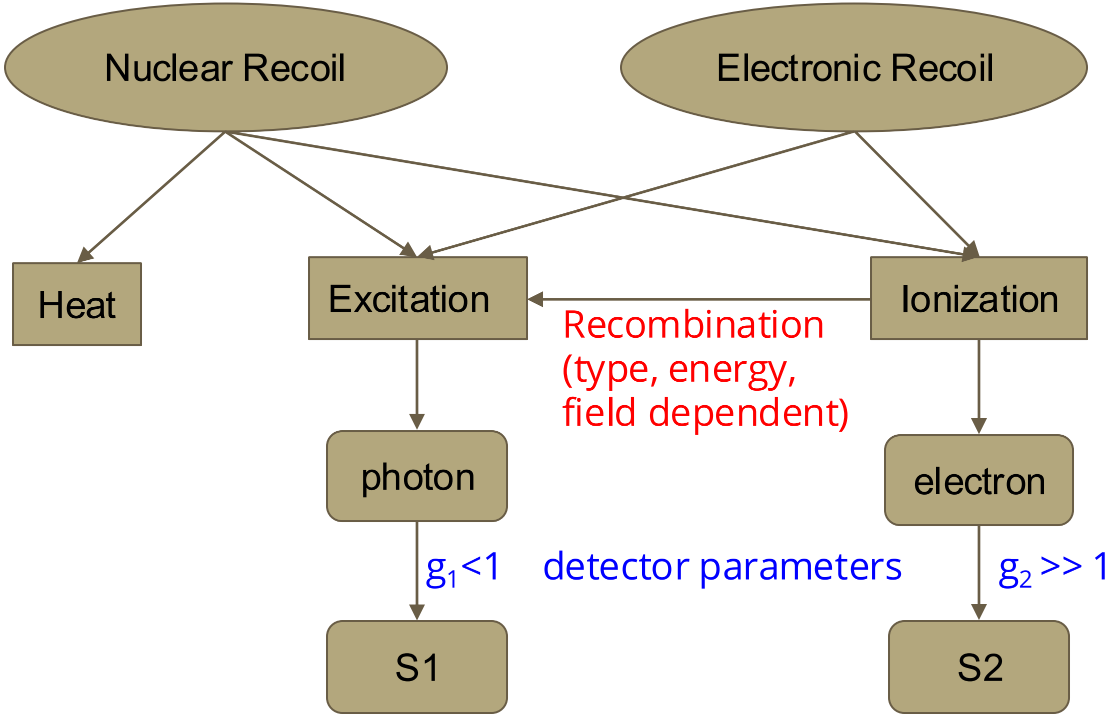


DARWIN/XZLD Concept

Use S1 & S2 for both DM and 0vbb searches

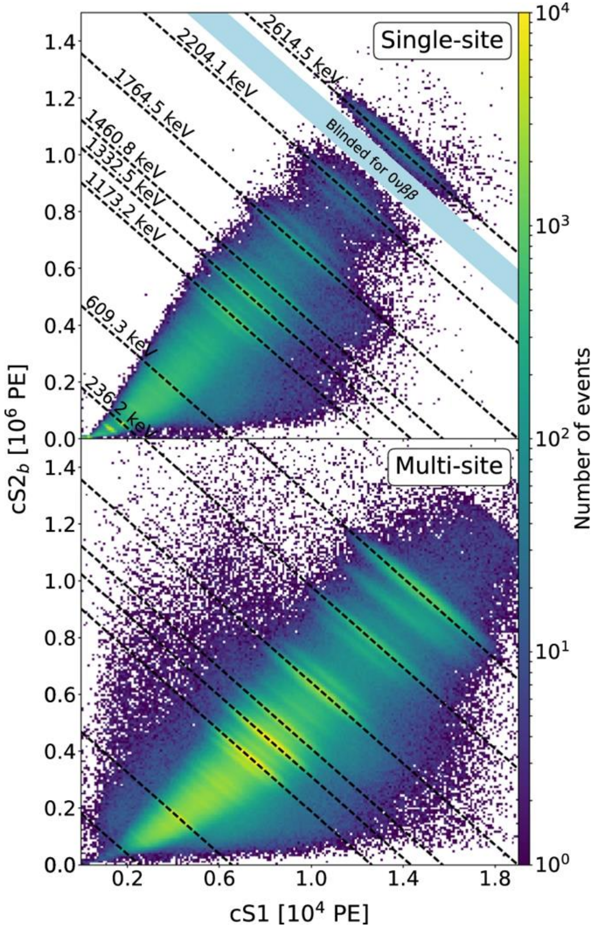




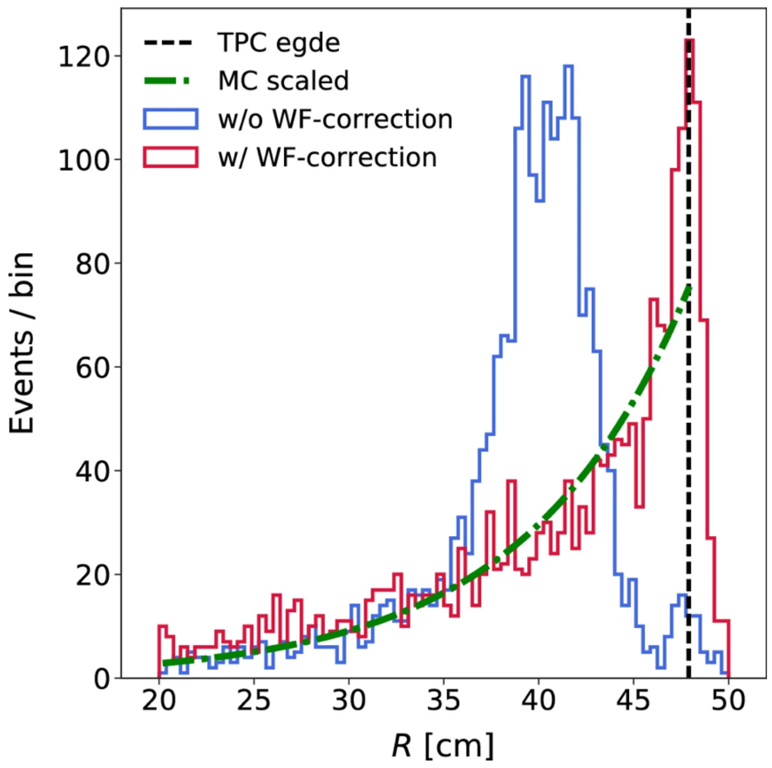


$$E_{obs} = (n_{ph} + n_e) \cdot W = (\frac{S1}{g_1} + \frac{S2}{g_2}) \cdot W$$

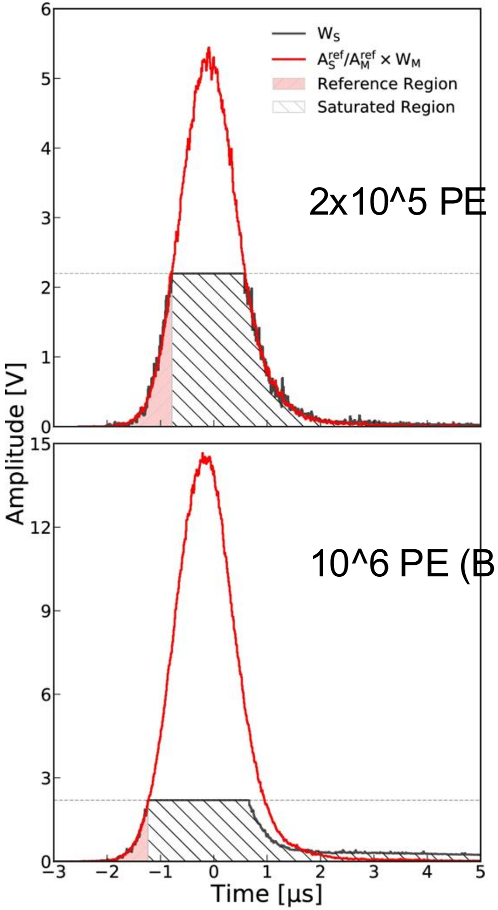
Position reconstruction and SS/MS identification with corrected S2



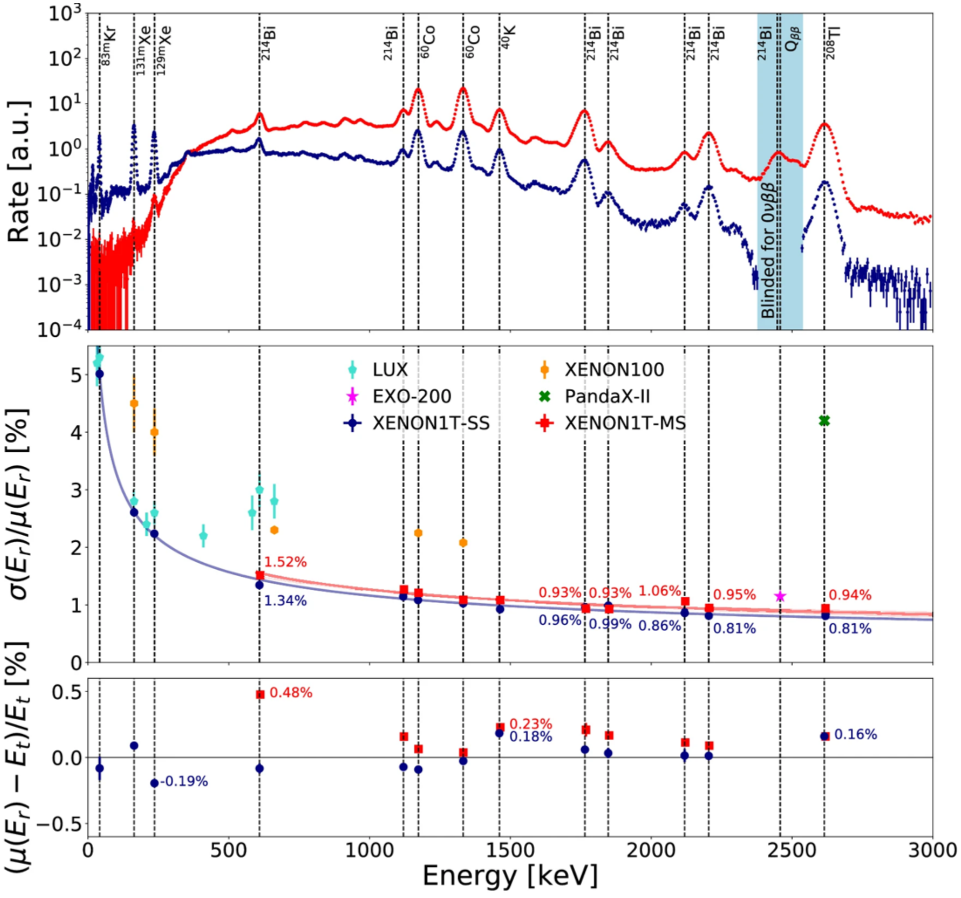
Energy resolution and linearity of XENON1T in the MeV energy range, EPJ C (2020)



S2 pulses usually saturated for high energy events but can be corrected based on pulse shape template

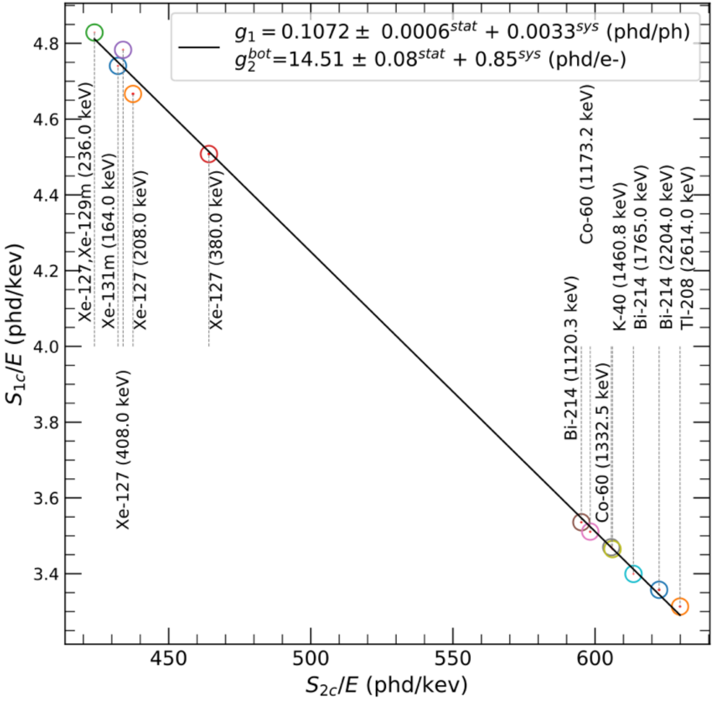


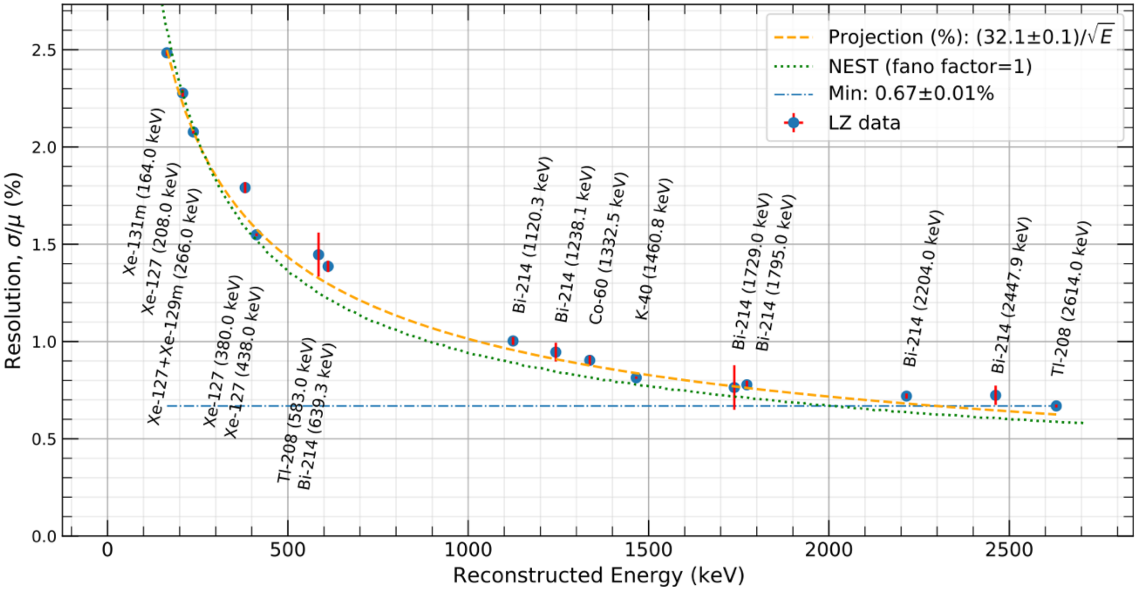
Energy resolution and linearity of XENON1T in the MeV energy range, EPJ C (2020)



LZ achieved even higher energy resolution

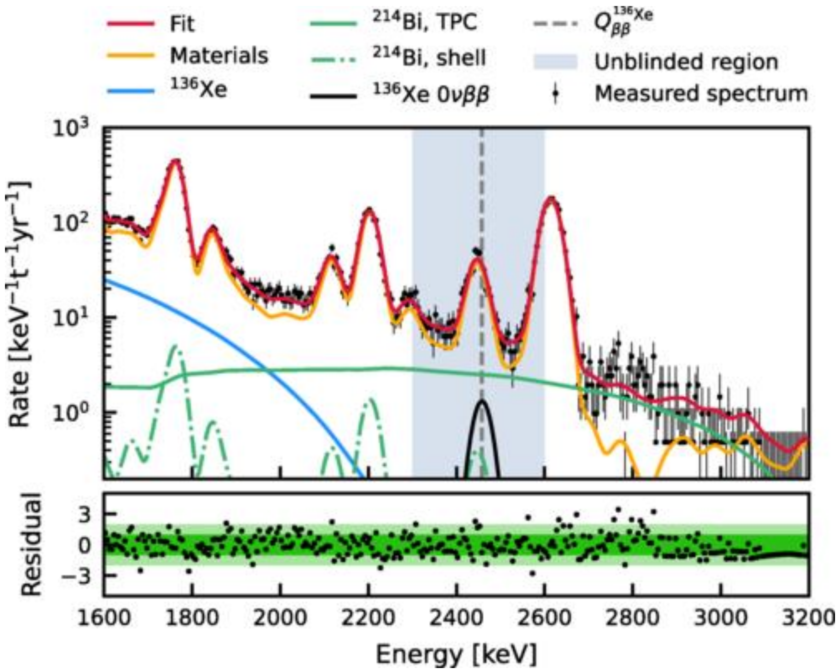
Energy resolution of the LZ detector for high-energy electronic recoils, JINST (2023)

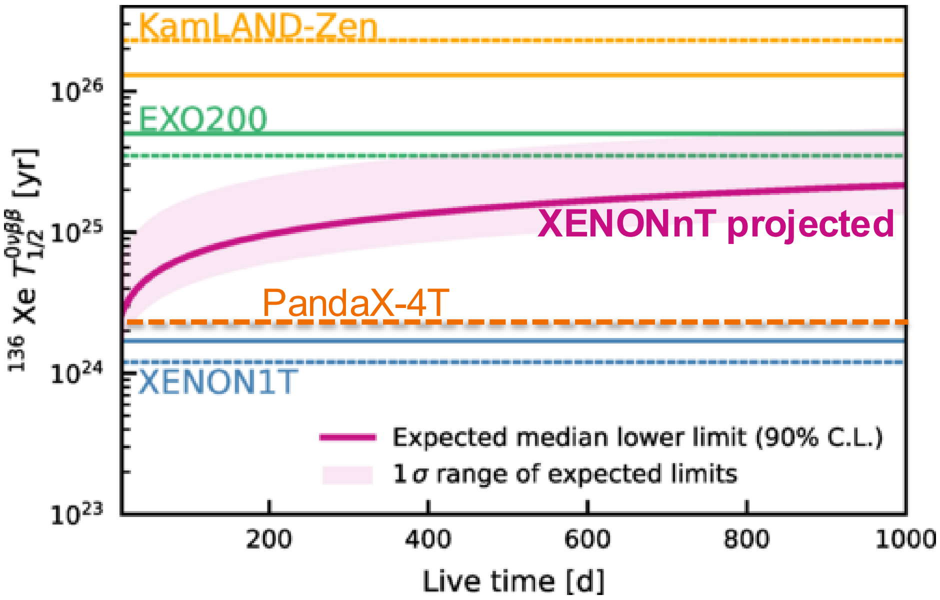




0vbb search results and projections from dual-phase XeTPCs

Double-weak decays of 124Xe and 136Xe in the XENON1T and XENONnT experiments, PRC (2022)



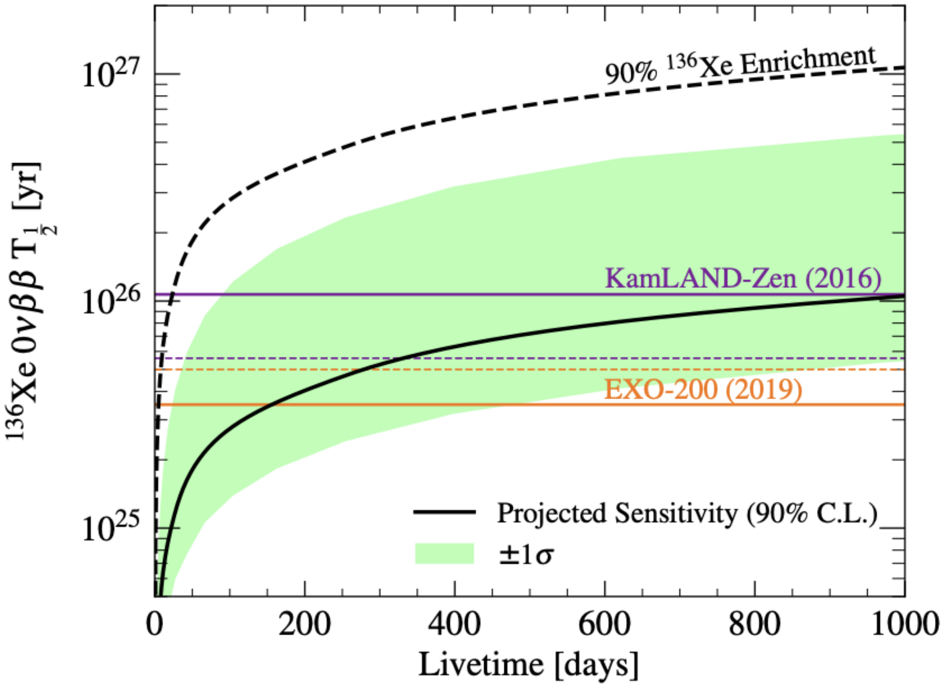


0vbb search results and projections from dual-phase XeTPCs

TABLE I. Summary table of the masses, activities and estimated background counts in the $\pm 1\sigma$ ROI and inner 967 kg mass, for a 1000 day run, considering 1.0% energy resolution at Q-value and 0.3 cm multiple scatter rejection along z (see text for details).

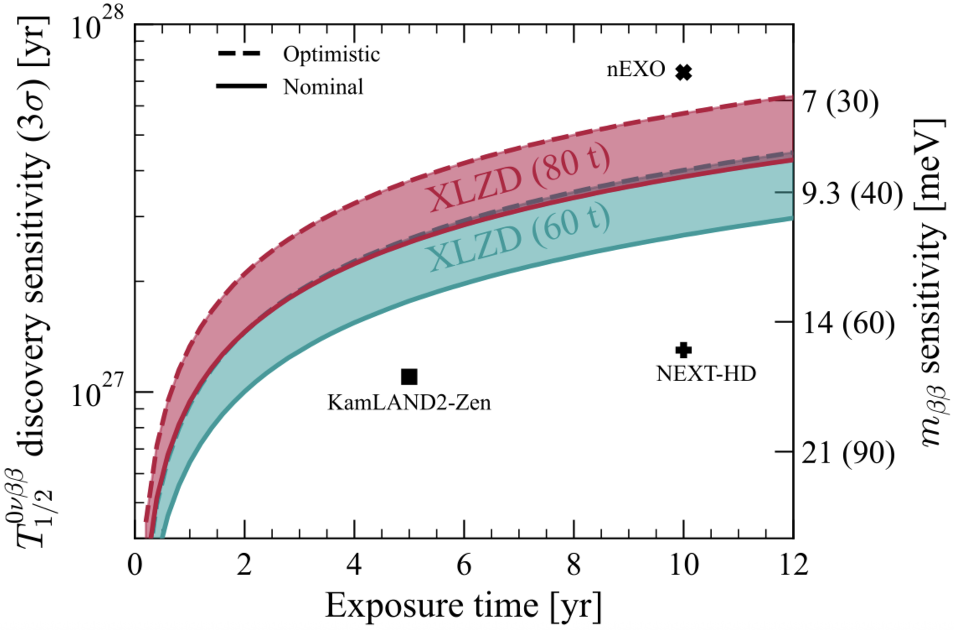
Item	Mass (kg)	^{238}U-late (mBq/kg)	Counts from ^{238}U	^{232}Th-late (mBq/kg)	Counts from ^{232}Th	Total Counts
TPC PMTs	91.9	3.22	2.95	1.61	0.10	3.05
TPC PMT bases	2.80	75.9	1.52	33.1	0.03	1.55
TPC PMT structures	166	1.60	2.65	1.06	0.12	2.77
TPC PMT cables	88.7	4.31	1.44	0.82	0.19	1.63
Skin PMTs and bases	8.59	46.0	0.75	14.9	0.02	0.78
PTFE walls	184	0.04	0.39	0.01	0.00	0.39
TPC sensors	5.02	5.82	1.19	1.88	0.00	1.19
Field grids and holders	89.1	2.63	0.62	1.46	0.11	0.73
Field-cage resistors	0.06	1350	2.63	2010	0.03	2.65
Field-cage rings	93.0	$0.35^{\dagger}$	0.82	$0.24^{\dagger}$	0.00	0.82
Ti cryostat vessel	2590	$0.08^{\dagger}$	1.30	$0.22^{\dagger}$	0.20	1.49
Cryostat insulation	13.8	$11.1^{\dagger}$	0.90	$7.79^{\dagger}$	0.04	0.94
Outer detector system	22900	$4.71^{\dagger}$	1.70	$3.73^{\dagger}$	1.08	2.79
Other components	438	1.83	2.10	1.65	0.31	2.41
Det. components subtotal	-	-	21.0	-	2.32	23.3
Cavern walls	-	29000.00	3.21	12500.00	8.41	11.6
Neutron-induced ^{137}Xe	-	-	-	-	-	0.28^{*}
Internal ^{222}Rn	-	-	-	-	-	0.45^{*}
^{136}Xe $2\nu\beta\beta$	-	-	-	-	-	$0.01^{\dagger}$
^{8}B solar neutrinos	-	-	-	-	-	0.03
Total	-	-	24.2	-	10.7	35.6

LZ Projected, 1912.04248



Projected 0vbb sensitivity from future dual-phase XeTPCs

Neutrinoless double beta decay sensitivity of the XLZD rare event observatory, **arXiv:** 2410.19016



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

Projected 0vbb sensitivity from future dual-phase XeTPCs

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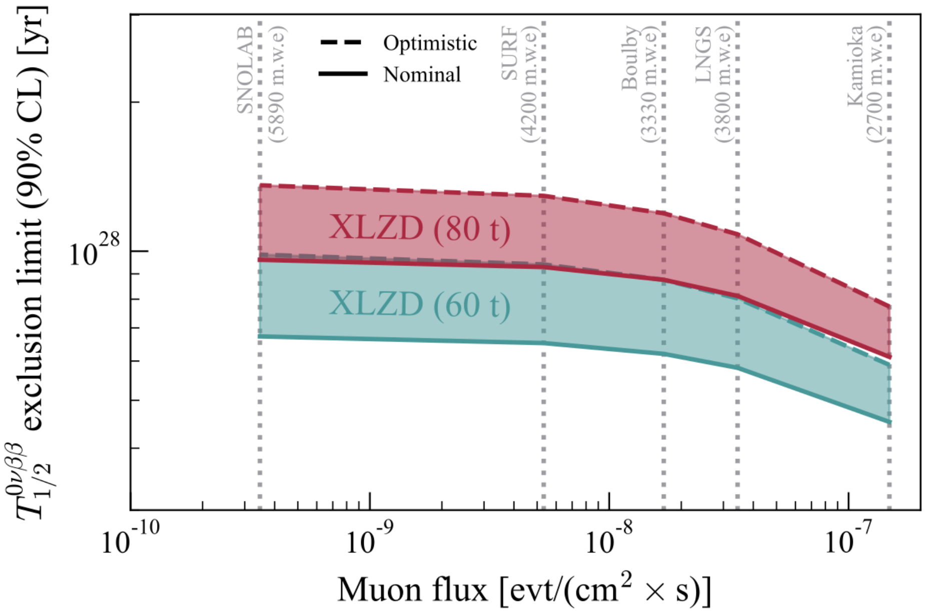
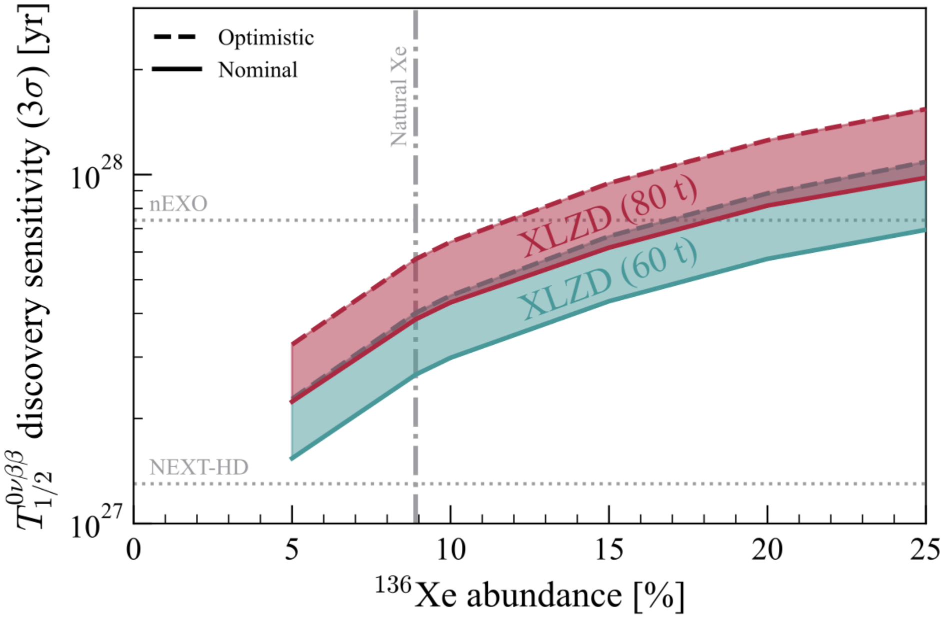


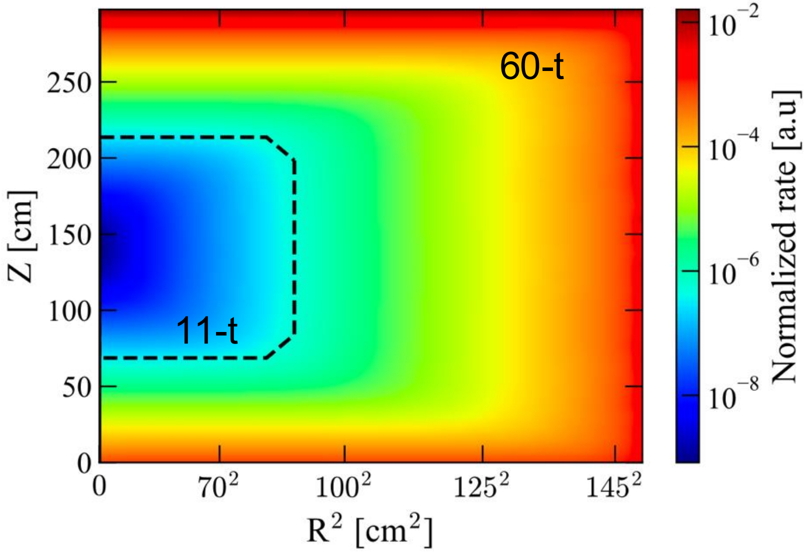


What are the advantages of dual-phase XeTPC?

- **High energy resolution (<1% at 0vbb energy)**
  - High reflectivity PTFE enhances Light Collection Efficiency
  - High Quantum Efficiency PMTs improves Photon Detection Efficiency
  - "noise free" readout of ionization through Electroluminescence (S2)
- **Low energy threshold**
  - ~keV with both S1 & S2
  - sub-keV with S2-only
- **Low background**
  - LXe self-shielding and fiducial volume selection
  - Electronic and nuclear recoils discrimination (good for WIMP DM)
  - Single site/multi-site event discrimination
- **Cost effective**
  - Single (simpler) readout with PMTs for both scintillation and ionization (through S2)
  - Typically, with natural xenon target
- **Broad energy range for competitive multi-purpose science: DM, 0vbb, astrophysical neutrinos)**

What are the challenges of dual-phase XeTPC for 0vbb searches?

- Radioactive (Bi-214) background
  - Material background for 0vbb is stricter than for the low energy region for DM
  - Need lower radioactive PMTs/components/vessels to further reduce this background
  - Choice of low radioactive photosensors should not sacrifice light detection (QE, dark counts etc.)



XLZD, 2410.19016

	^{214}Bi events		
	LZ (967 kg × 1000 d)		XLZD (8.2 t × 10 yr)
Component	Nominal	Reduced	Projected
TPC PMTs	2.95	0.98	0.61
PMT structures	2.75	0.54	0.33
Field-cage resistors	2.46	0	0
Internal sensors	1.81	0.22	0.14
PMT bases	1.52	0.39	0.24
Cryostat	1.26	0.82	0.51
PMT cables	1.01	0.16	0.10
Field-cage rings	0.97	0.40	0.25
OD tank supports	0.73	0	0
OD foam	0.71	0	0
Skin PMTs	0.69	0.06	0.04
Other skin parts	0.68	0.05	0.03
Other components	3.56	1.42	0.88
Total	21.10	5.05	3.15

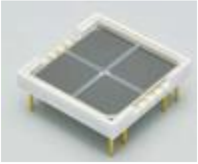
What are the challenges of dual-phase XeTPC for 0vbb searches?

- XY resolution (to improve SS/MS discrimination –> Brian Lenardo's talk)
    - 2~3-mm in Z
    - XY resolution scales with **Top PMT size** and is ultimately limited by the anode/gate **wire pitches** (6 mm is reachable but 3 mm is challenging: need smaller PMTs and finer wire pitches)
- Optimize the size of **top photosensors** (and their radioactivity) can benefit both the XY resolution and background budget

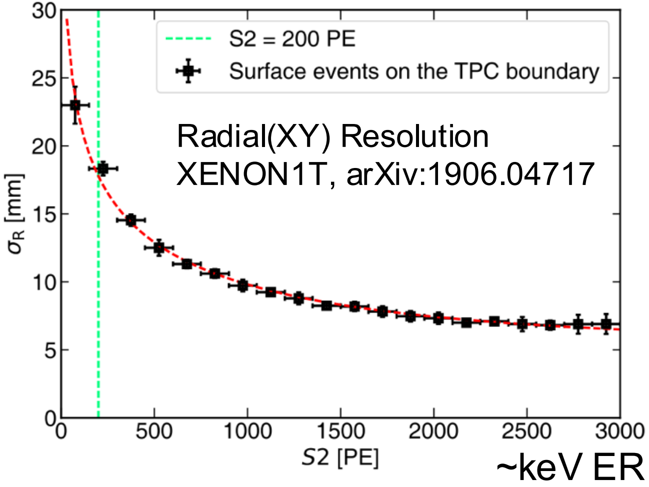
3-inch PMT, R11410-21

PMT (R13111) 3-inch

2-inch (4x1inch^2) R12699

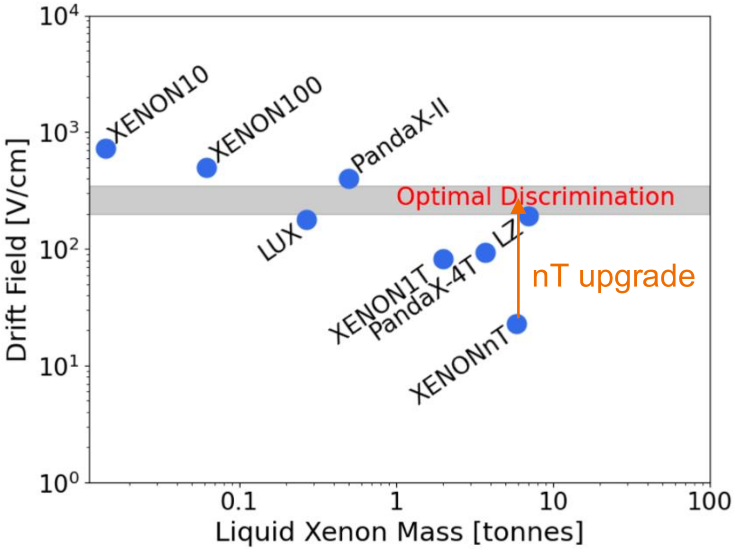


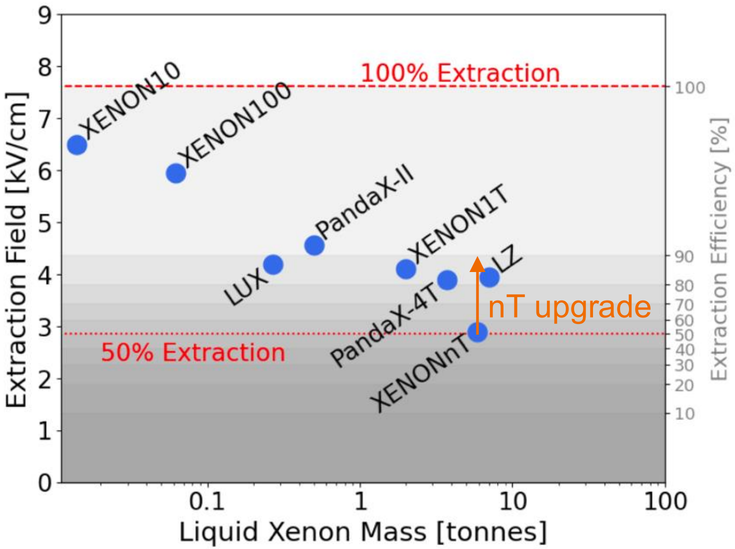
15mm VUV MPPC



What are the challenges of dual-phase XeTPC for 0vbb searches?

- Electrodes
  - Need high transparency for light collection
  - Require high voltage on the cathode that is close to the bottom PMTs (inactive LXe: 3~5% target in the reversed field region -> cost & lone S1s)
  - Require uniform and high extraction field at the top

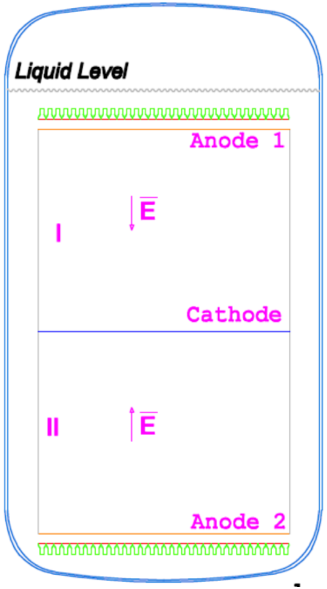




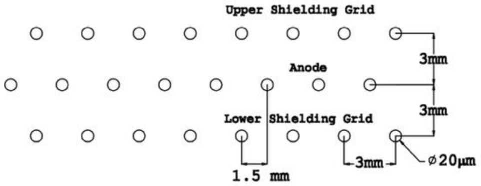
A. Kopec, Design challenges for a future liquid xenon observatory, arXiv:2310.00722

A hybrid design that unites the advantages of single- and dual-phase TPCs

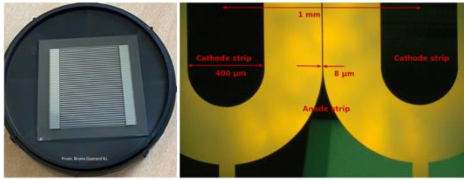
- Single-phase LXeTPC that reads out electroluminescence in liquid xenon directly
- No gas gap: 100% electron "extraction"
- No inactive LXe region below cathode
- S2 is ~1/10 smaller (less saturation, less bkg)!
- Recent progress shows good ER/NR discrimination for low energy physics
- Thin wire is too delicate for large TPCs -> micro-pattern on fused silica offers more robust solution & better XY resolution (only one large area cathode is needed)

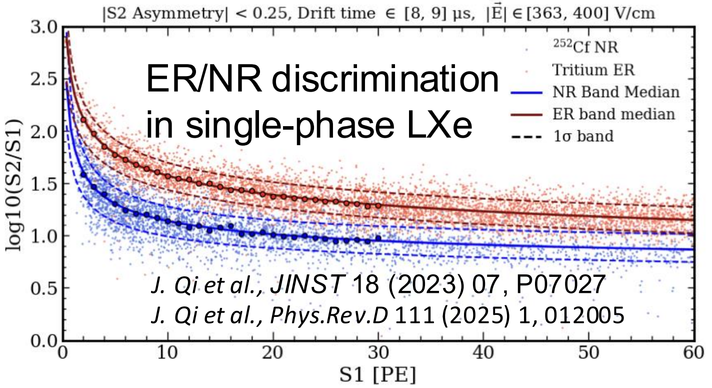


K. Giboni et al., arXiv:2107.07798

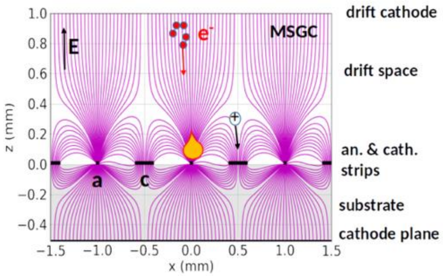


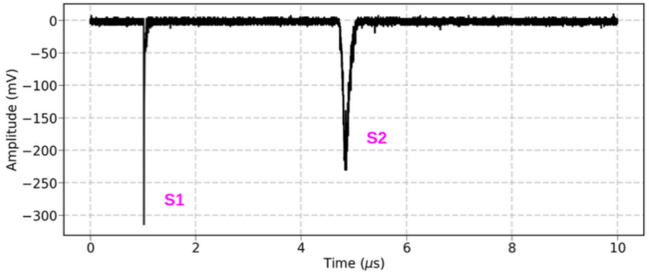
G. Martinez-Lema et al. *JINST* 19 (2024) 02, P02037, see also: 2505.24611





J. Qi et al., JINST 18 (2023) 07, P07027
J. Qi et al., Phys.Rev.D 111 (2025) 1, 012005





Summary

•**Dual-phase XeTPCs deliver ultra low-energy sensitivity, strong ER/NR discrimination, and excellent energy resolution at MeV-scale**, enabling competitive searches for both dark matter and 0νββ.

•**Key challenges for 0νββ optimization** include achieving ultra-low radioactivity, improving XY/SS-MS discrimination, and developing transparent electrodes with optimized high voltage performance.

•Combine the strengths of both single/dual-phase designs—**using liquid electroluminescence and micro-pattern structures**—offer a promising (backup) solution.