

Optical Imaging of High-Energy Interactions in Dual-Phase Xenon Time Projection Chambers

CPAD 2026 Meeting
October 20th, 2026

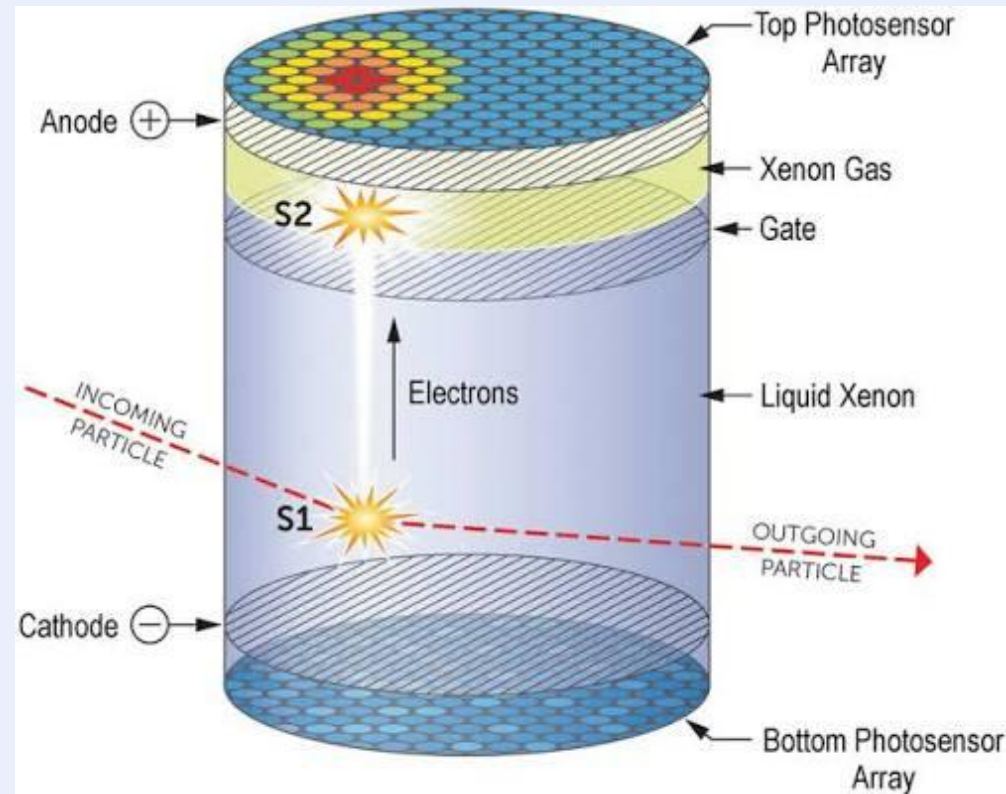
<https://arxiv.org/abs/2610.26739v1>



Adam Tidball, Jingke Xu
UC Davis, LLNL

Dual-Phase Xe TPCs for Dark Matter Searches

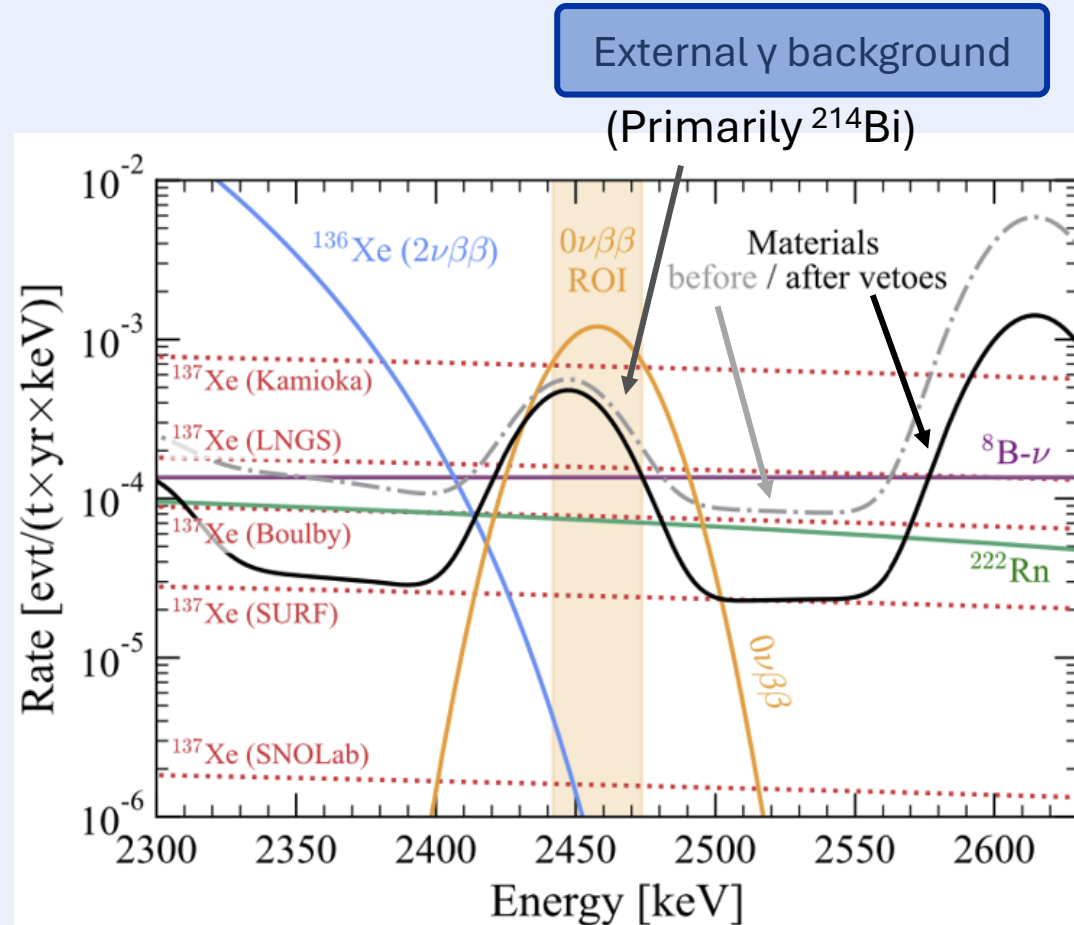
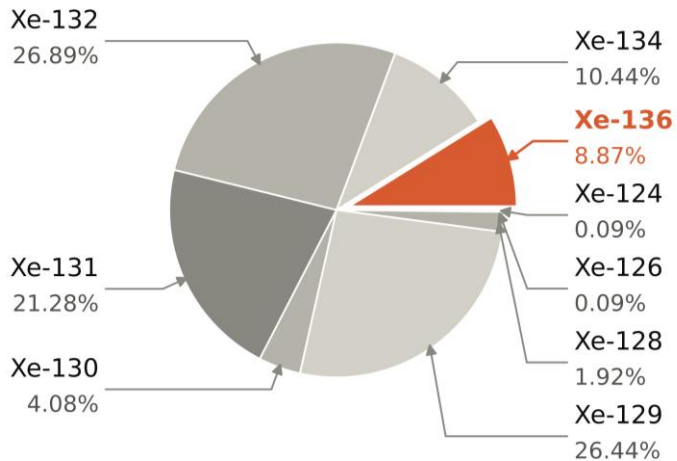
- Leading technology for WIMP dark matter searches ([LZ](#), [XENONnT](#), [PandaX-4T](#))
- 3D position: z from drift time, x-y from the S2 light pattern on top PMT array
- Large mass, low background, single-electron sensitivity (~ 500 EL photons produced per extracted e^-)



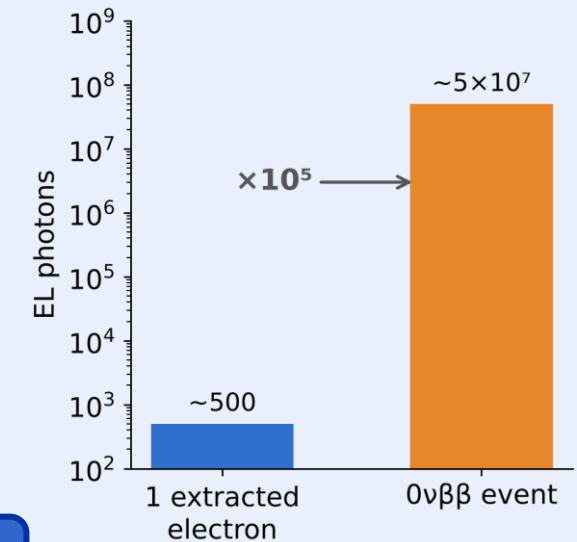
Two signals per event: prompt scintillation (S1) + electroluminescence from drifted electrons (S2)

Can it be optimized for detecting $0\nu\beta\beta$?

Natural xenon contains
~8.9% ^{136}Xe , a
neutrinoless double
beta decay ($0\nu\beta\beta$)
candidate



$0\nu\beta\beta$ of ^{136}Xe
produces O(MeV)
signals- current light
collection strategies
designed for O(keV)
signals but can also
detect O(MeV)
events



Position reconstruction for events near $0\nu\beta\beta$ energy
would benefit from further optimization

Further background reduction with 3D position resolution

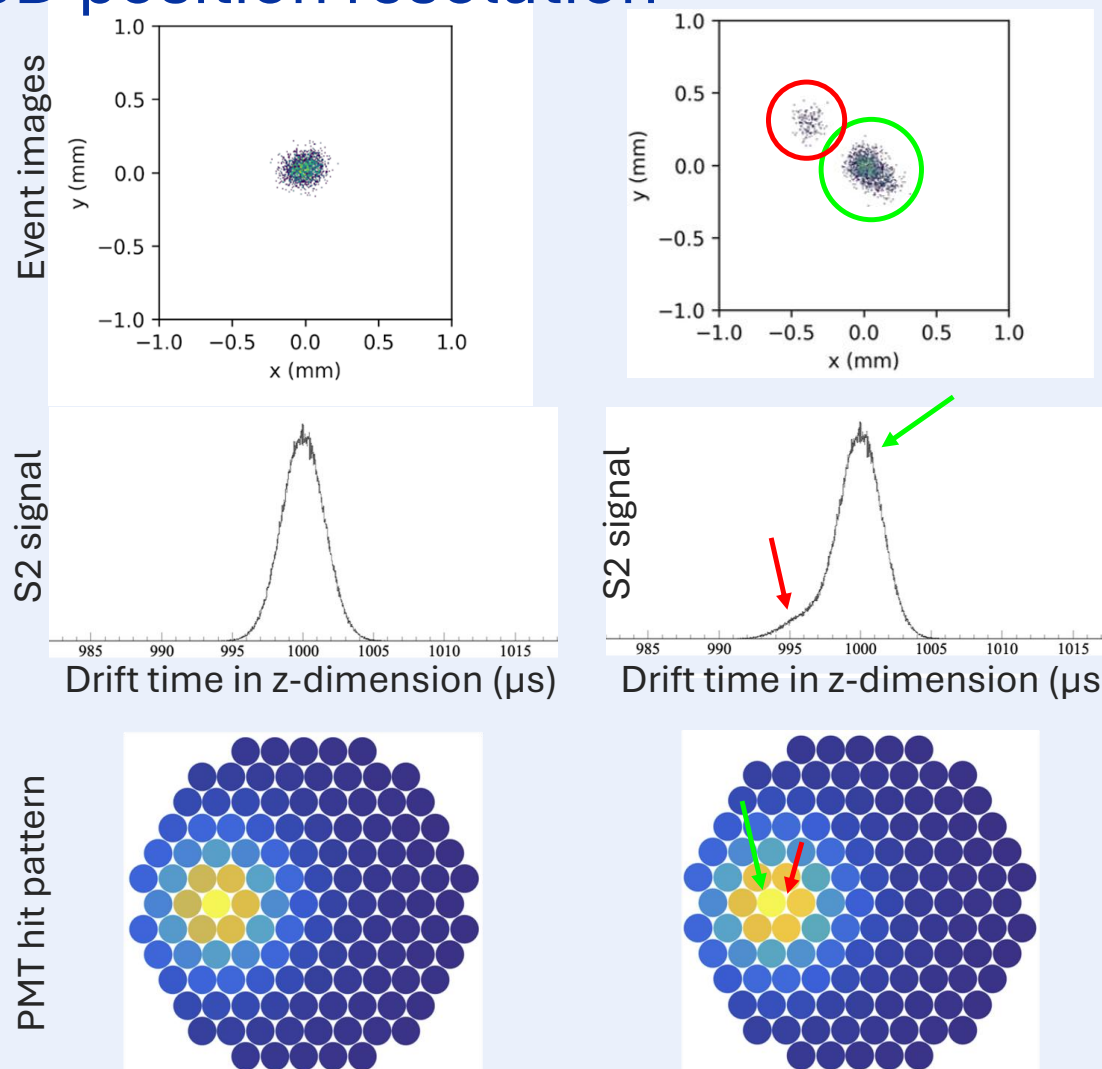
Background: MeV gamma rays

- Main background: gammas from ^{214}Bi (2.447 MeV) and ^{208}Tl (2.615 MeV)
- Signal: ~85% of $0\nu\beta\beta$ events are single-site (energy deposition within a few mm)
- Background: gammas mostly Compton scatter into multiple sites; < 3% are single-site
- SS/MS discrimination efficiently rejects gamma backgrounds

3D position resolution of Xe TPCs

- z: O(mm) accuracy from drift timing
- x-y: weakly encoded in EL light pattern on photosensors
- mm precision possible for SS, but overlapping sensor patterns blur MS events

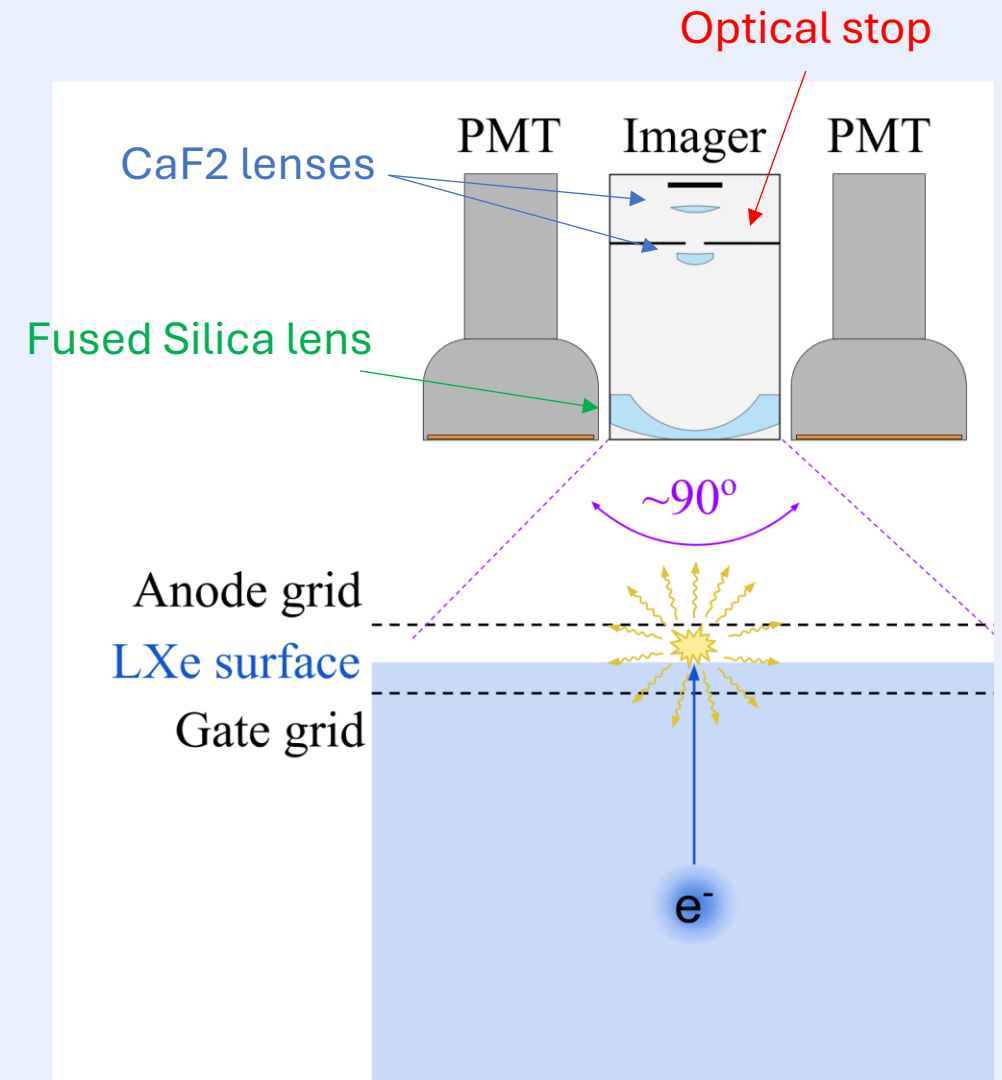
J Xu et al, *DPF 2026 Meeting (July 2026)*



An optical camera for high energy event reconstruction

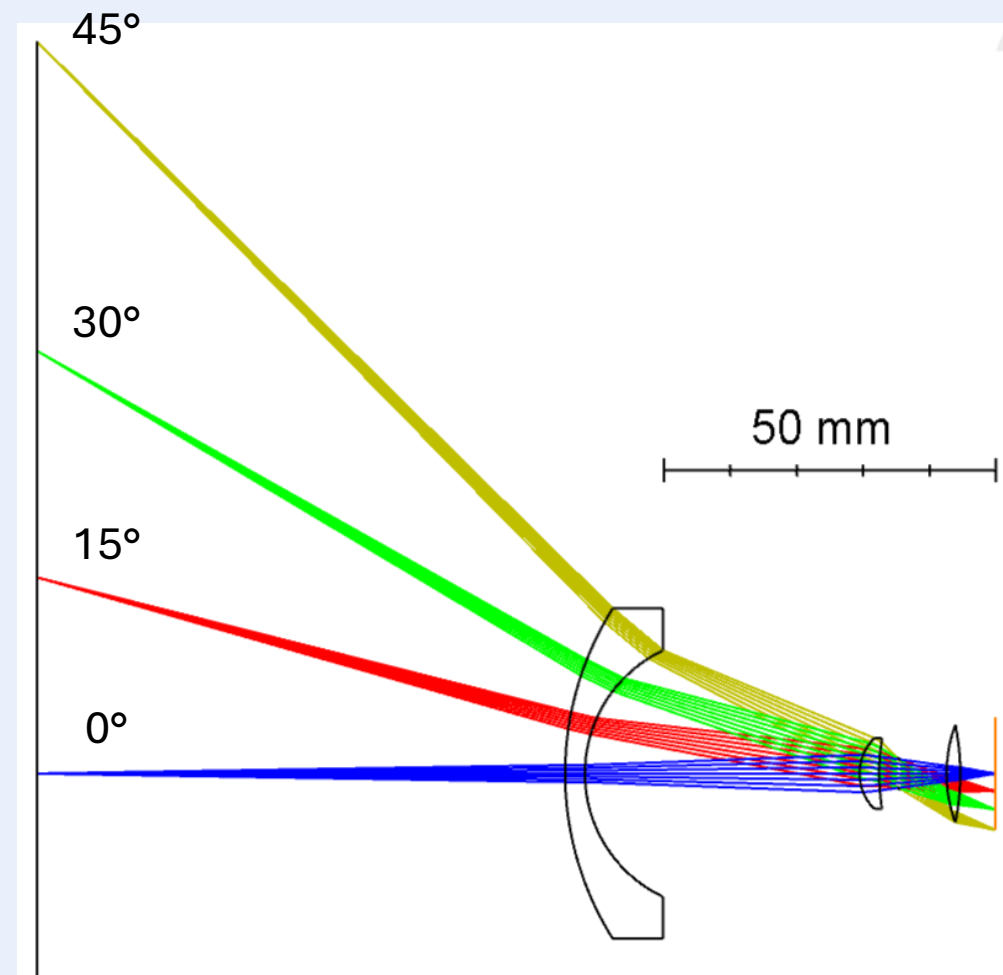
- A $0\nu\beta\beta$ event (~ 2.46 MeV) produces $\sim 10^5\times$ more EL light than a single extracted electron
- Photon flux from the thin EL region at liquid surface large enough to directly image event in x-y
- Relatively lax position resolution requirements, O(1 mm) in object plane

Optimizes TPC for $0\nu\beta\beta$ detection without compromising sensitivity to DM

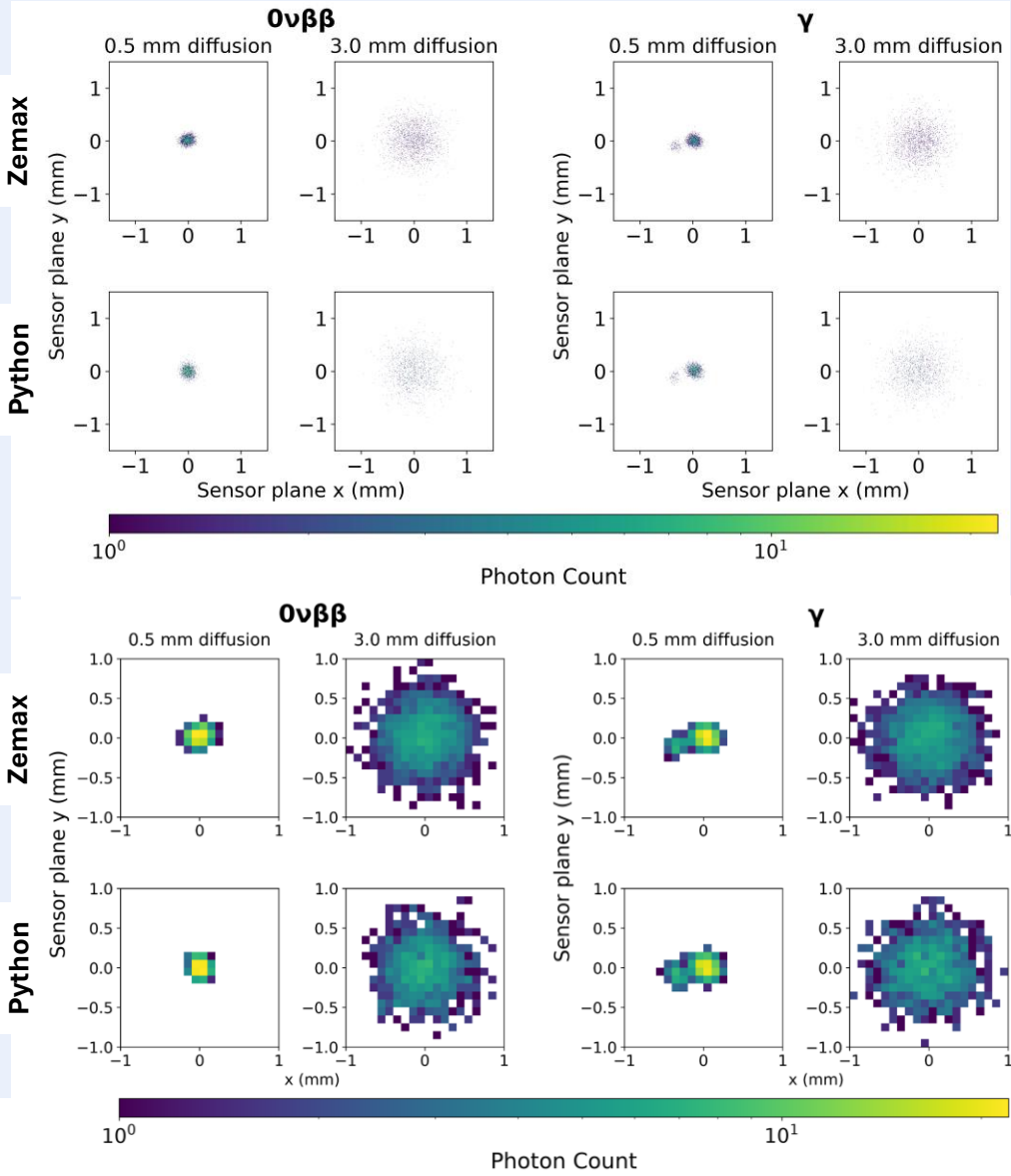
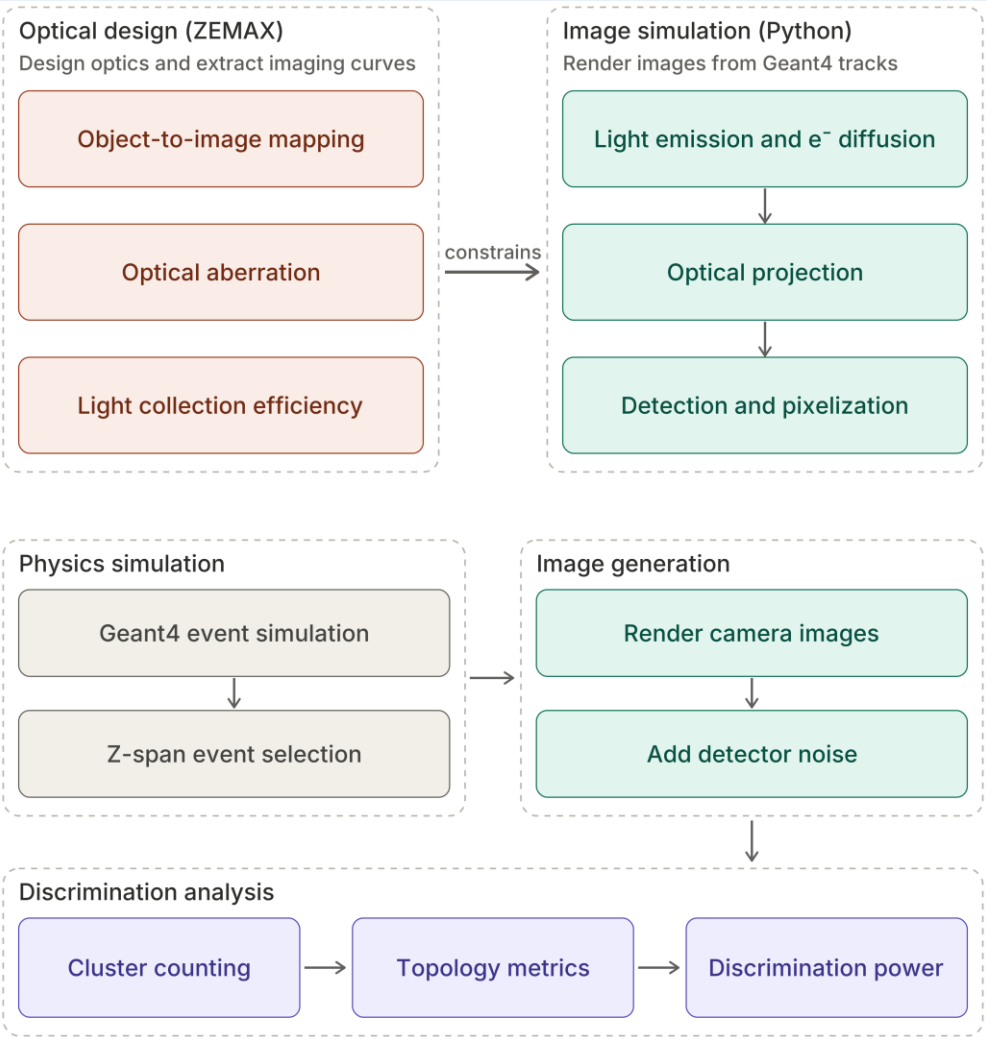


Optical camera design

- Wide-angle “fisheye” camera design with large FOV and short focal length
- Images 90° area at short distance O(10 cm)
- Designed for VUV sensitivity: xenon EL light is emitted at ~ 175 nm
- Small number of lenses with carefully selected materials (CaF_2 , VUV-grade fused silica)
 - Mitigate losses due to Fresnel reflections, bulk absorption
 - Limit radioactive background contribution of components
- Roughly shape and size of PMT
 - Replacing O(10%) PMTs allows full coverage of LXe surface with minimal impact to light collection efficiency at lower energies



Evaluating science impact- performance in $0\nu\beta\beta$ detection



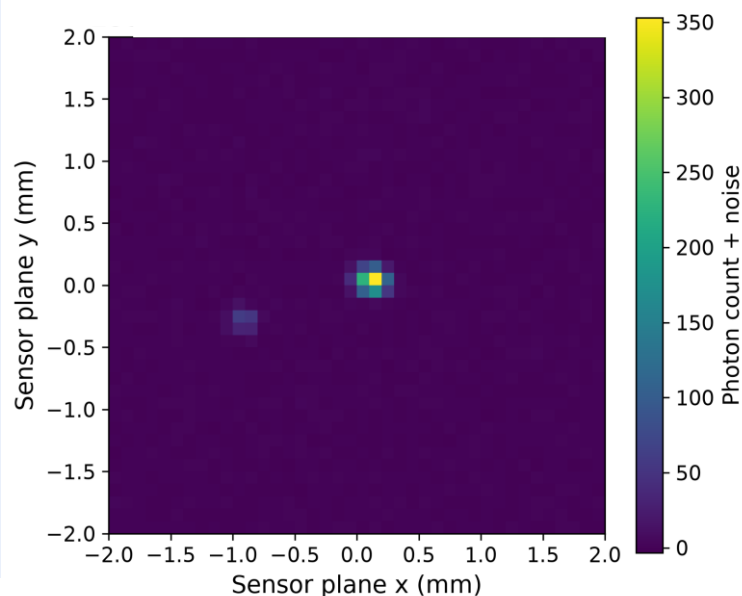
Transverse diffusion: Drifting electrons spread laterally in the x-y plane on their way to the liquid surface, blurring the image. The spread grows with drift distance (0.5 mm and 3 mm shown, representing ideal and realistic smearing cases).

Pixel size: Larger pixels give a stronger signal per pixel at the cost of extra smearing. With 100 μm pixels, such as those shown on the right, smearing is still dominated by electron diffusion.

Two sensor models

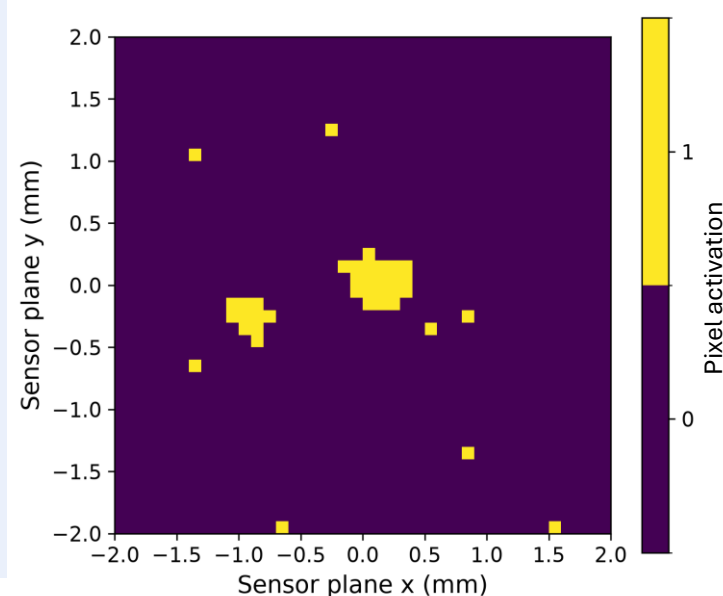
Linear sensor model (sCMOS sensor)

- Each pixel sensitive to photon count
- Assume 50% quantum efficiency
- Gaussian noise model with 1.0 electron read noise



Binary sensor model (SPAD array)

- Pixels insensitive to photon count, binary valued
- Assume 20% quantum efficiency
- Dark count noise model with 0.19 Hz/mm² assumed rate



(Note: DCR exaggerated $\times 1000$ for visualization)

Discriminating between $0\nu\beta\beta$ and gamma

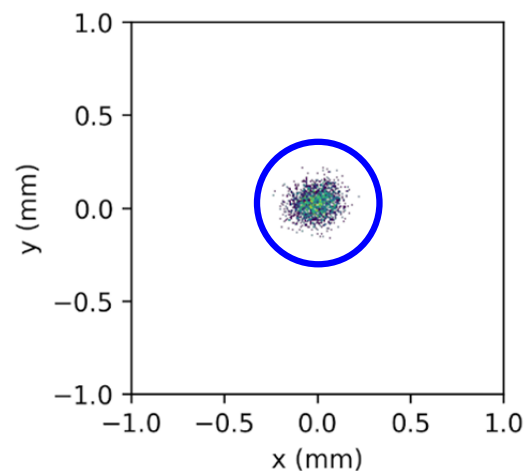
Step 1: cluster count

DBSCAN finds interaction vertices. Events with more than one cluster rejected as gamma.

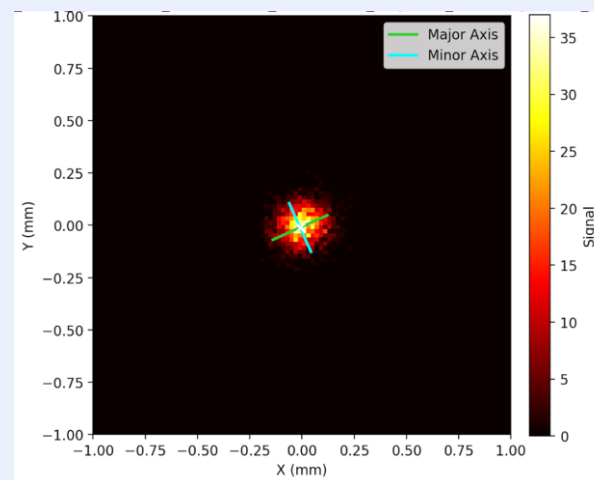
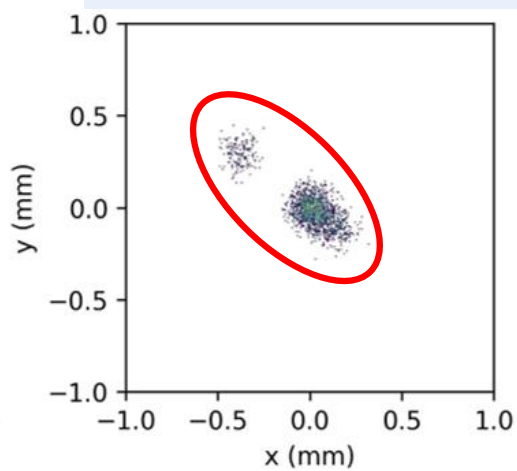
Step 2: cluster shape

For single-cluster events, skewness along principal axis. Merged gamma multi-scatters less symmetric than $0\nu\beta\beta$.

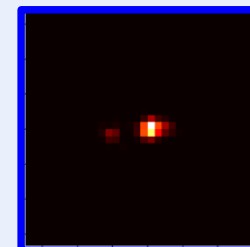
Single cluster: proceed to step 2



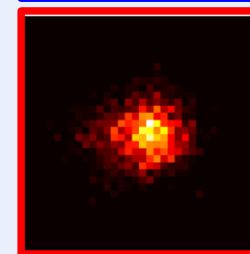
Multi-cluster: Reject



$$\sigma_{xy} = 0.5$$



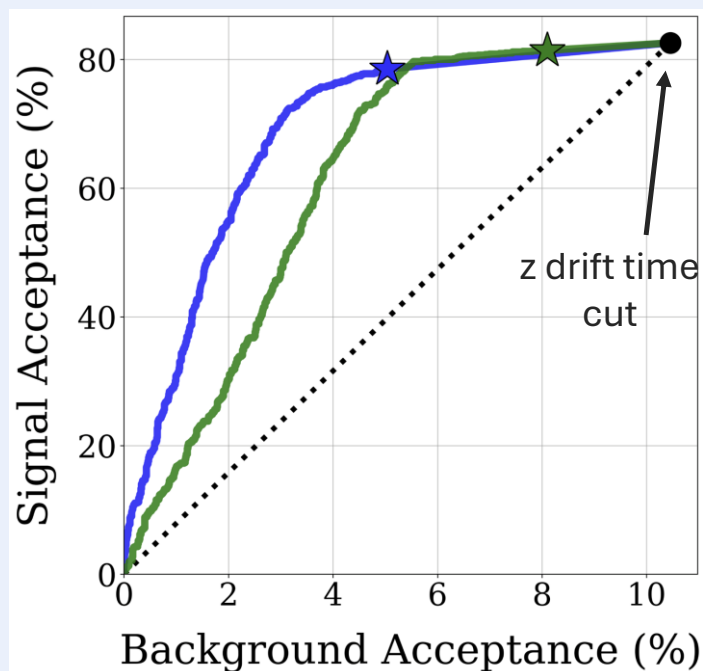
$$\sigma_{xy} = 3.0$$



Worst-case gamma: max-energy Compton scatter followed by photo-absorption within a few mm away at same z, particularly with electron diffusion. Drift time/cm-scale PMTs insensitive- **skewness good classifier.**

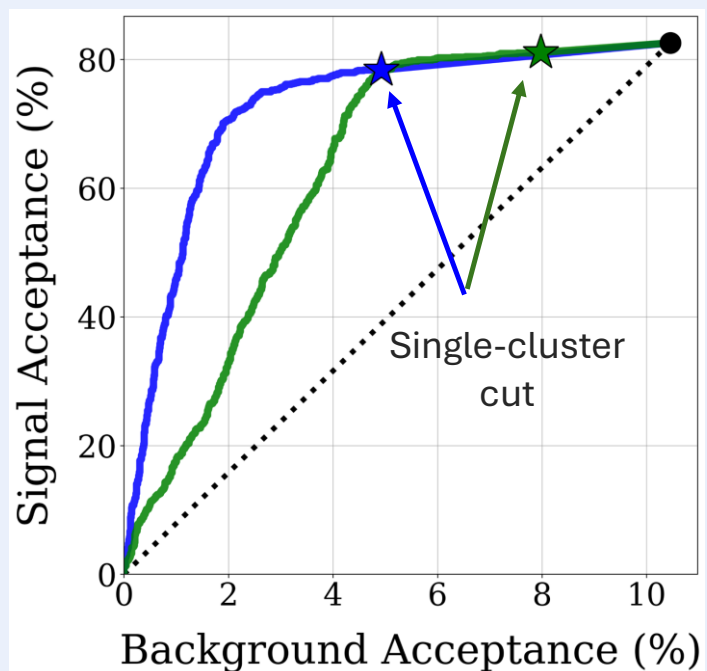
How well can we tell $0\nu\beta\beta$ from gamma?

Binary SPAD array with 0.19 Hz/mm² DCR ($t = 3$ ms)



- 0.5 mm diffusion

Linear sCMOS sensor with single-electron read noise



- 3.0 mm diffusion

~2/3 gamma background rejected with ~5% loss of signal events

~1/2 gamma background rejected with ~5% loss of signal events

2-3× gamma background suppression with < 10% of top PMTs replaced

A. D. Tidball, J. Xu, B. G. Lenardo, and N. Antipa, *arXiv:2610.26739* (2026)

Summary

- Dual-phase Xe TPCs lead dark matter searches, and can be simultaneously optimized for $0\nu\beta\beta$ with mm-scale position resolution at high energies
- A compact wide-angle imager in the top PMT array can image MeV events with $\sim$ mm resolution, separating multi-site gamma events from single-site $0\nu\beta\beta$
- The imager is designed with low-radioactivity components so that it introduces minimal additional background
- A fast, ZEMAX-constrained pipeline produces simulated images of $0\nu\beta\beta$ and gamma events, including realistic noise models for sCMOS and SPAD sensors
- Simple cluster and skewness cuts reject $\sim 1/2 - 2/3$ of residual gammas with $\sim 5\%$ signal loss
- Replacing $O(10\%)$ of top PMTs allows a single TPC to be leveraged for both dark matter and $0\nu\beta\beta$ searches simultaneously

Future studies will explore...

- More realistic image model with PSF from Zemax
- Higher order optical effects (reflections, etc.)
- Grid focusing effects
- 3D position reconstruction
- More sophisticated clustering analysis
- More sophisticated discrimination metrics

See our most recent paper, just uploaded to arXiv

Optical imaging in dual-phase xenon time projection chambers for neutrinoless double beta decay searches

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Dual-phase xenon time projection chambers (TPCs) are the leading technology for WIMP dark matter searches and have also demonstrated competitive sensitivities to neutrinoless double beta decays ($0\nu\beta\beta$) of ^{136}Xe . However, the large energy disparity between these two signals requires different detector optimizations. In particular, $0\nu\beta\beta$ searches in liquid xenon desire efficient rejection of closely located multiscatters of background gamma rays near the $0\nu\beta\beta$ energy, a capability achieved only in the vertical dimension in existing dual-phase xenon TPCs. We propose a highly customized, wide-angle optical system that can be conveniently integrated into large xenon TPCs and provide mm-scale transverse position resolution for MeV signals by imaging gas electroluminescence light. This approach preserves a TPC's low-energy sensitivity and optimizes a single experiment for both dark matter and $0\nu\beta\beta$ searches. This paper discusses the design, simulated performance, and implications of the imaging system for future liquid xenon-based $0\nu\beta\beta$ searches.

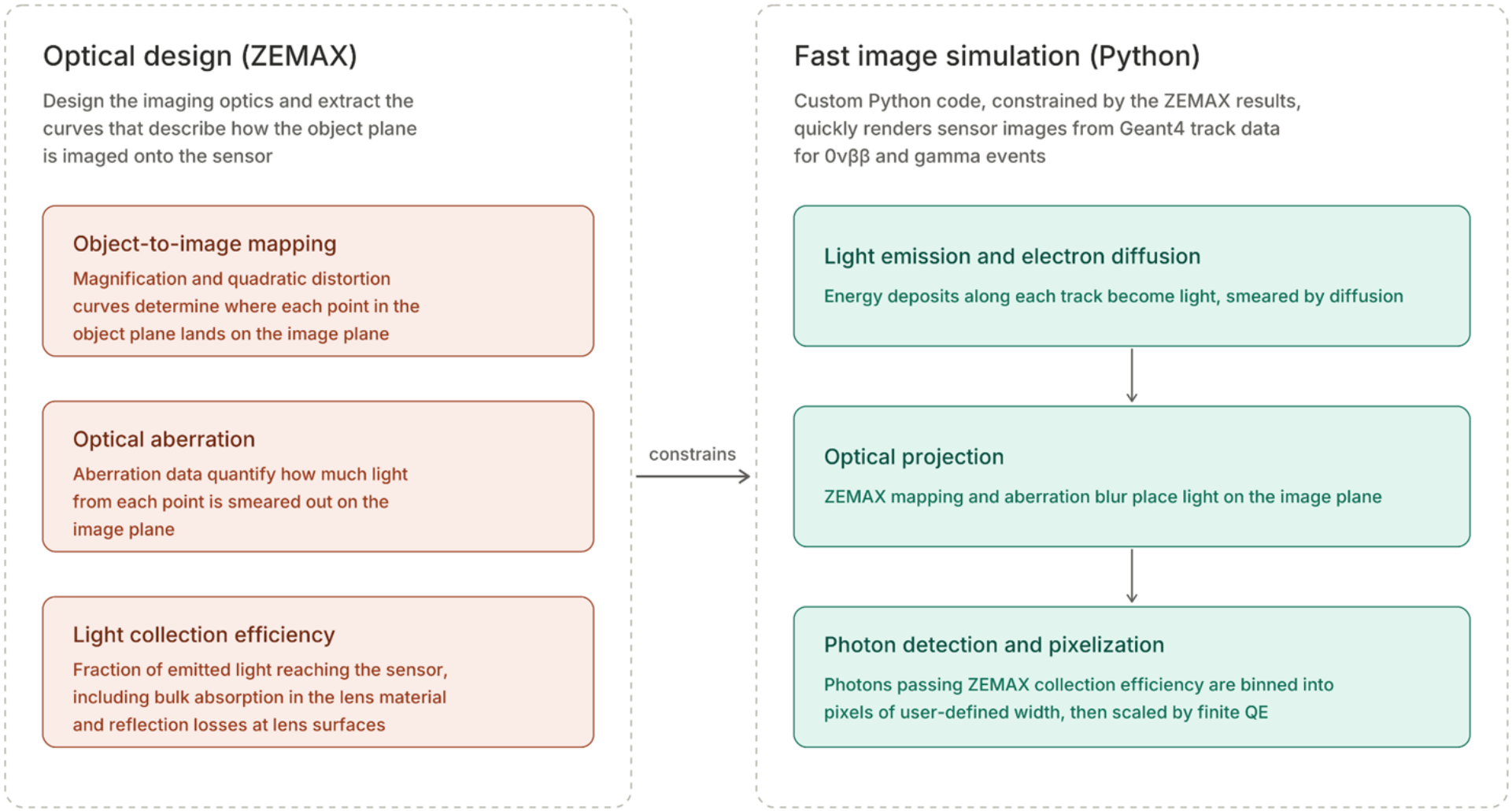


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BACKUP SLIDES

A pipeline for fast image generation



Evaluating science impact- performance in $0\nu\beta\beta$ detection

