Measuring Optical Properties in Liquid Xenon with LIXO2

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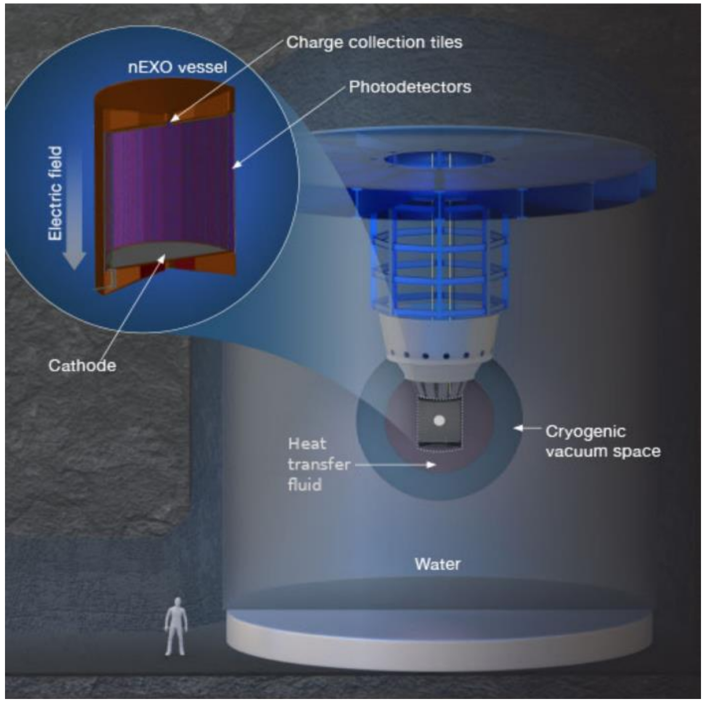
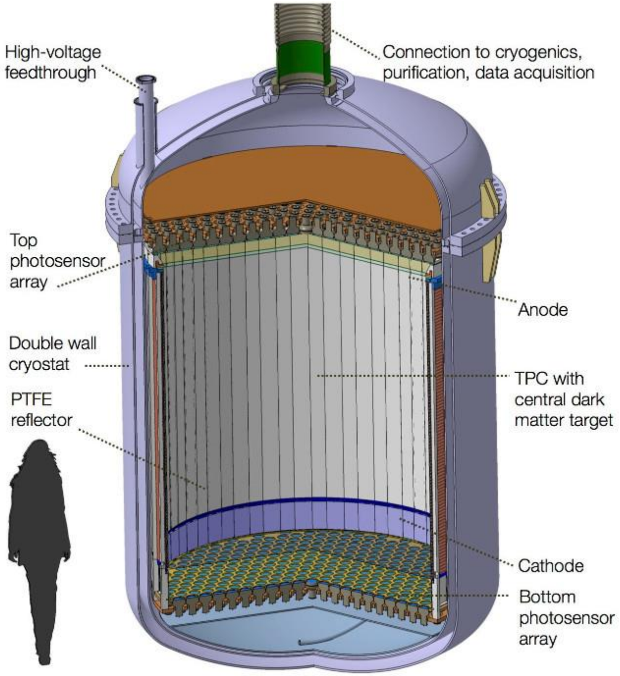
Motivation

- Next generation rare-event searches will use vast target masses to reach unprecedented sensitivity.
- nEXO experiment plans to use 5 tons of liquified xenon gas (LXe) enriched in ^{136}Xe to search for neutrinoless double-beta decay.
- DARWIN will utilize 40 tons of LXe to become the ultimate dark matter detector. It will also be sensitive to neutrinoless double-beta decay, solar neutrinos, axions.



nEXO

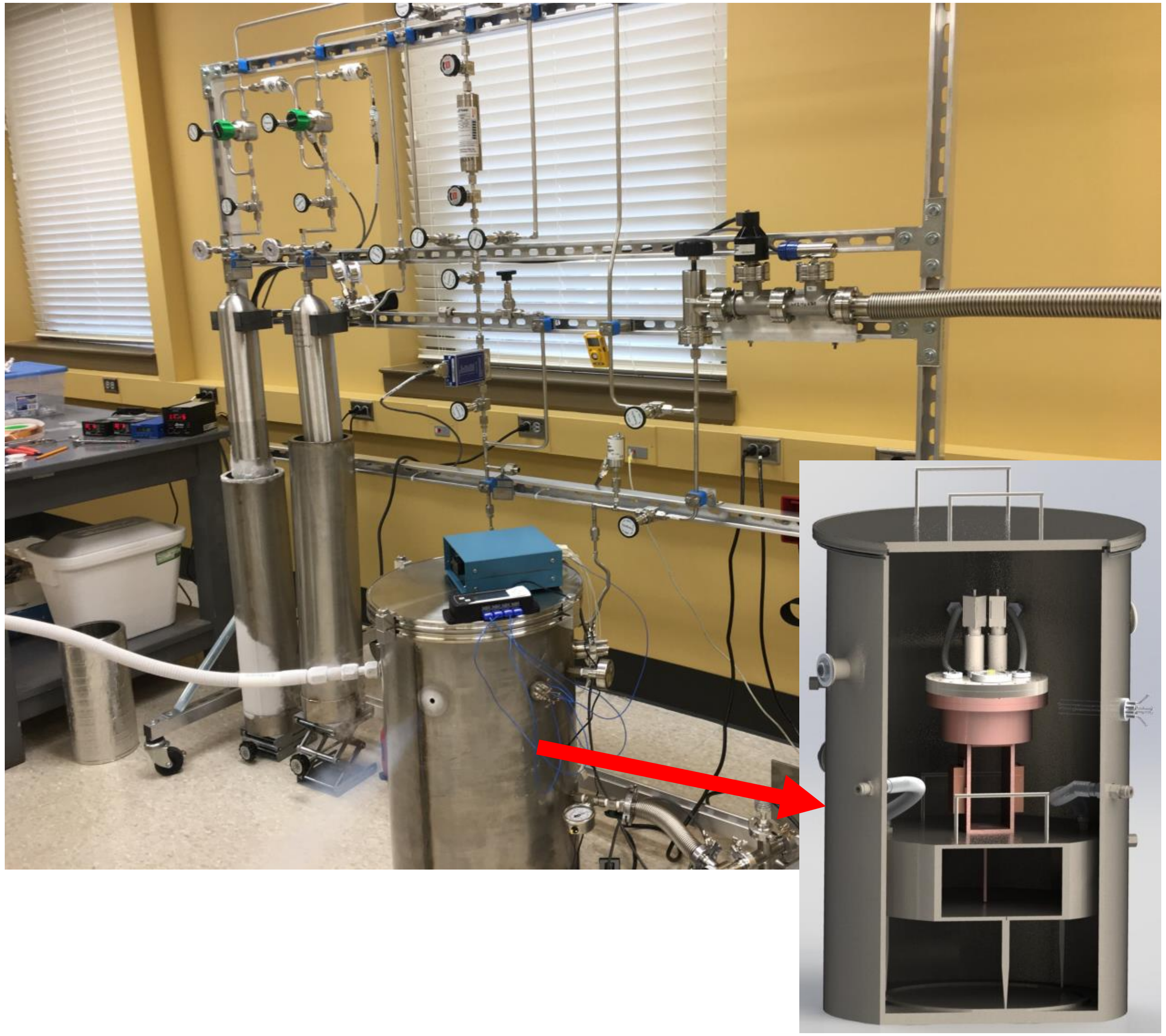


DARWIN

Motivation

- LXe scintillates in vacuum ultraviolet (VUV), and understanding light collection in such large detectors is critical to achieve their sensitivity goals
- However, little information is currently available about optical properties of many materials and photodetectors at such short wavelengths
- Our work is to study the optical properties of materials in the LXe environment. Such as the reflectivity or transmittance of the detector material, the detection efficiency of SiPM, etc.

LIXO2:Design



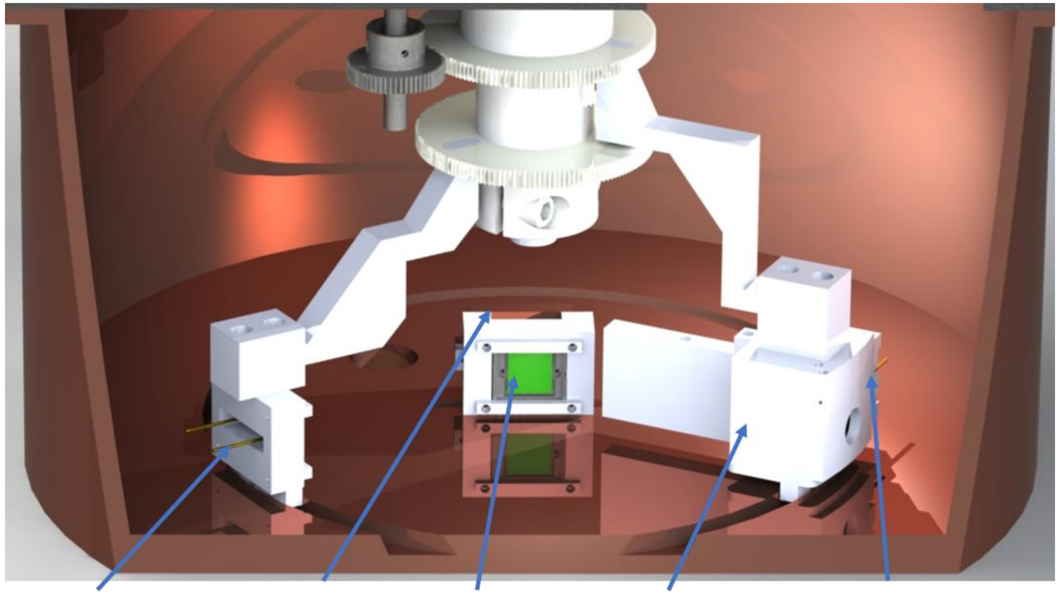
- LIXO2 **(LIquid Xenon Optical)** is a setup at the University of Alabama dedicated to research optical properties of materials in LXe

- LIXO2 system includes: Xenon circulation system, cryostat tank for liquefaction and gasification, payload for measuring the sample and rotating the light source and detector

- LIXO2 has provided, the angular dependence of PDE and reflectivity of a SiPM in LXe, Reflectivity of VUV-reflective coating
  - P. Nakarmi *et al* 2020 *JINST* **15** P01019
  - arXiv:2402.15177 [physics.ins-det]

LIXO2:Design

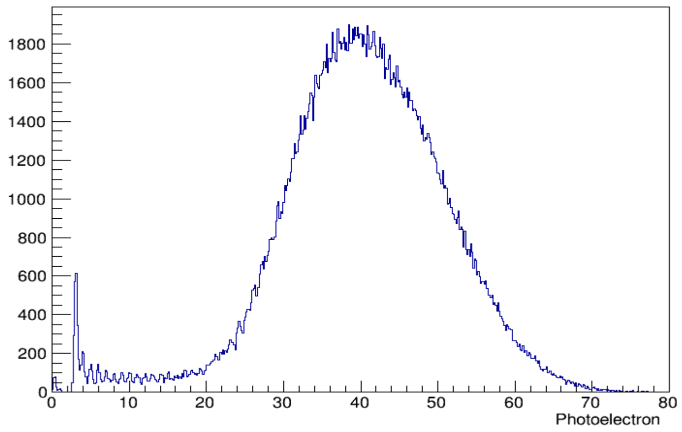
Payload



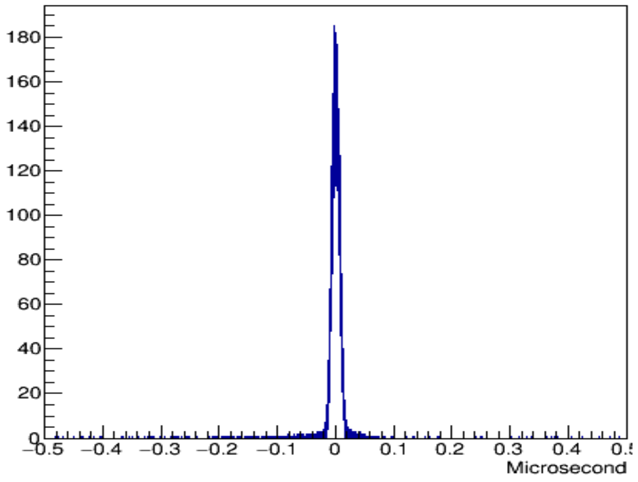
- Radioactive source inside a PEEK collimator produces scintillation light
- Collimator and detector are controlled by separate motors to achieve measurements at different angles
- A triggering SiPM is attached to the side of the collimator for triggering and light yield stability purposes
- Sample SiPM monitor the stability of the light flux at the center of the chamber
- With different sample holders, measure the reflectance or transmittance of the sample

Measuring Principle

- The triggering SiPM detects photons produced by alpha decay inside the collimator chamber
- A signal in the Detector SiPM is then searched for in the narrow time window wrt the collimator signal, suppressing random coincidences (e.g., due to dark hits in the SiPMs)
- A small correlated background, caused by natural radioactivity and cosmic muons is measured by dedicated measurements

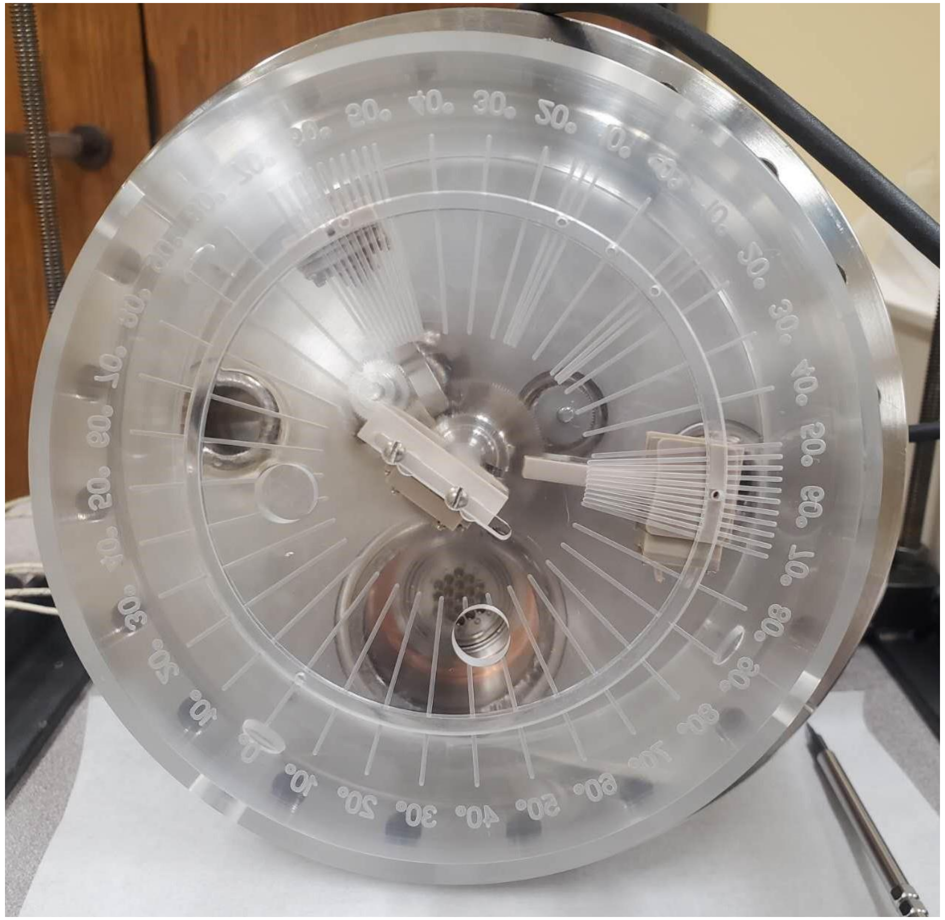


Alpha peak



T(detector)-T(alpha decay)

Position Accuracy



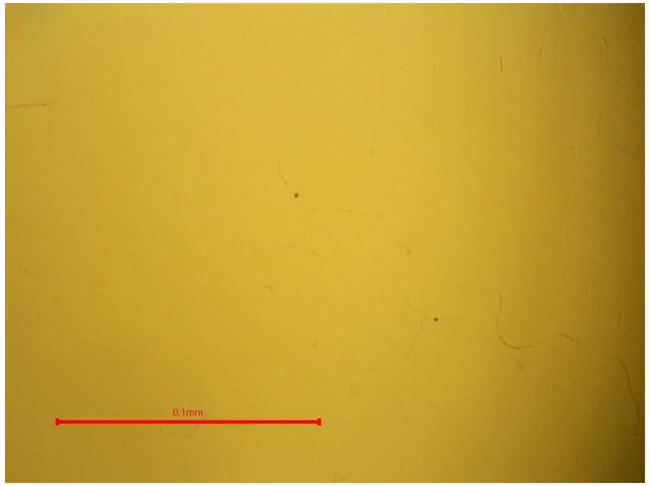
- We use an acrylic cup with a scale for rotation testing. After extensive observation, the error of rotation is less than 2 degrees.
- After doing experiments with copper cups, observe the positions of the collimator and detector. The error is also less than 2 degrees.

VUV-reflective coating

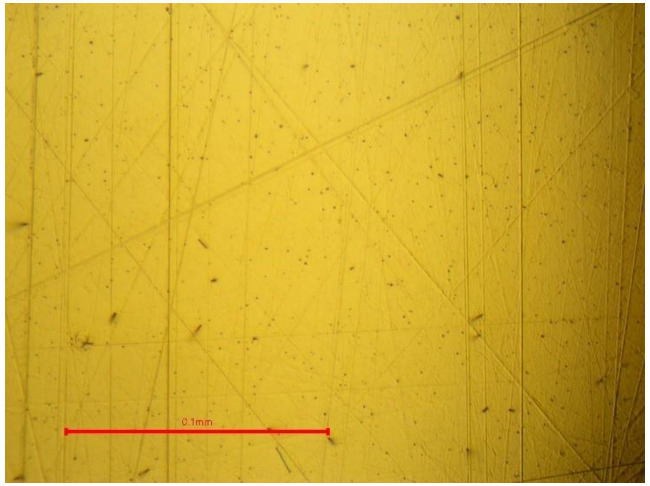
Purpose: nEXO is planning to increase the reflectivity of the copper field-shaping rings (FSRs) and cathode by coating them with VUV-reflective films. Coating the DARWIN electrodes with reflective films is expected to increase the light collection efficiency (LCE) by up to 24% rel.

MgF2-Al-MgF2 coating

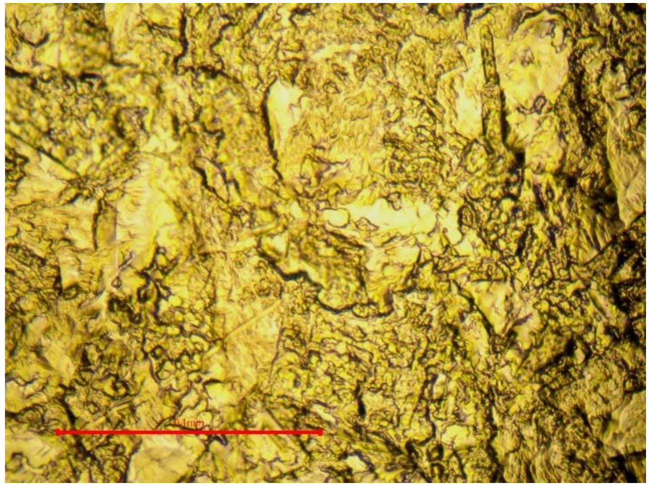
nEXO requires coating with total reflectivity greater than 80%



High polish

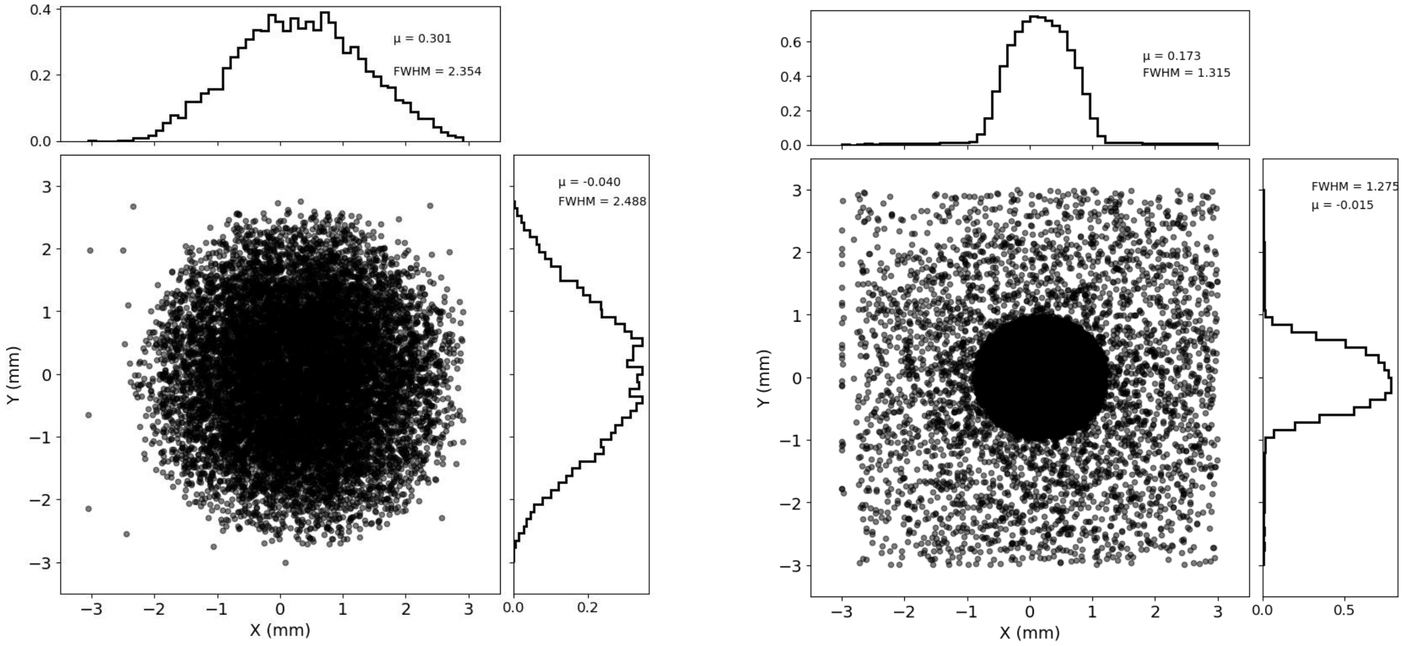


Average polish



Realistic (Unpolished)

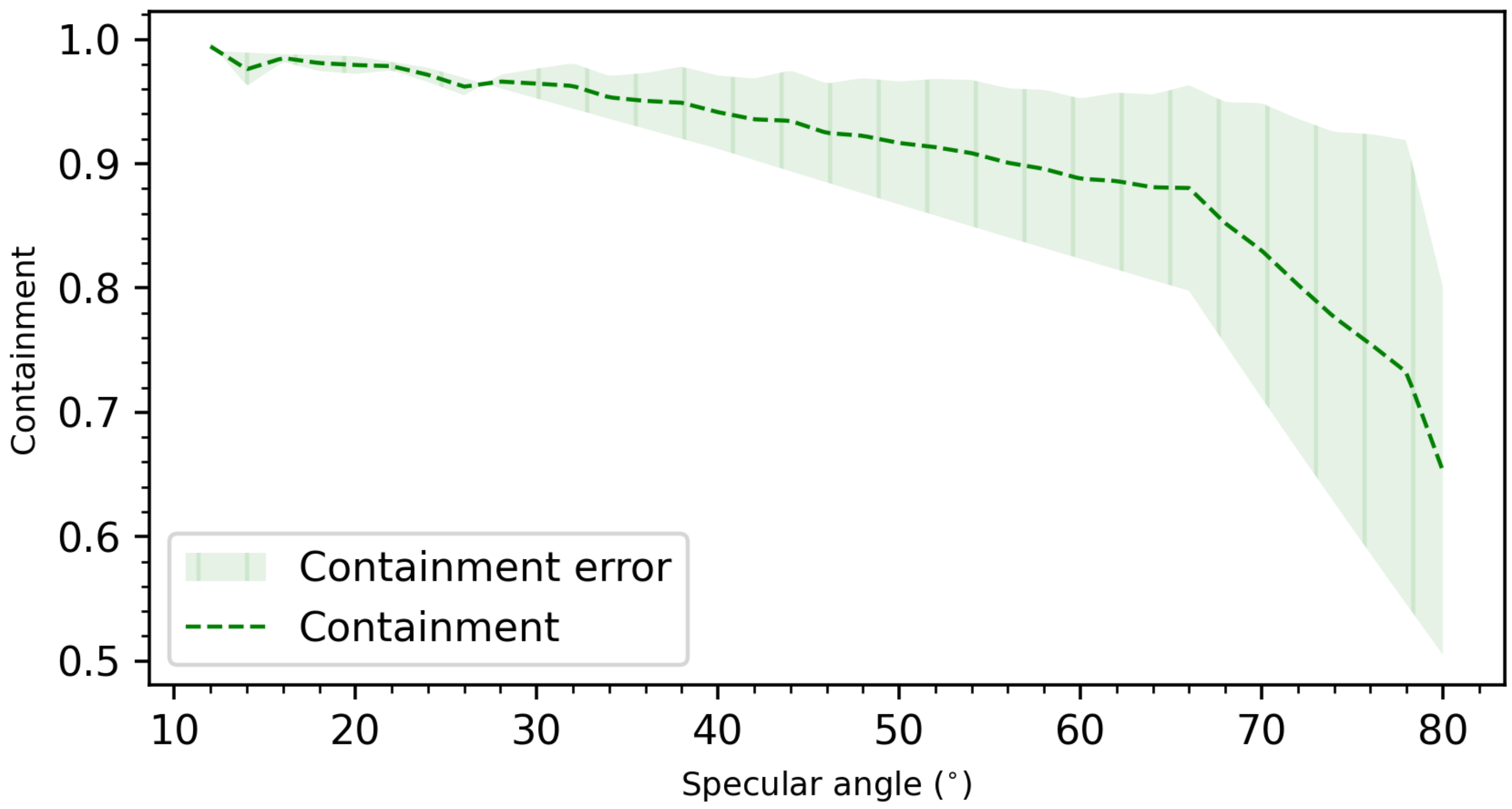
Simulation



Distribution of photon hits on the detector and sample, when the incident angle is ±20 degrees. SiPM size is 6x6 mm^2. The beam exits the collimator with a diameter of 0.99 mm.

- Light beam gets wider due to the geometric divergence and Rayleigh scattering in LXe
- The out-of-beam hits are more prominent on the sample and are mostly due to the photons reflected back from the detector SiPM
- We use simulation to determine the beam extending beyond the sample, and shadowing by the sample holder

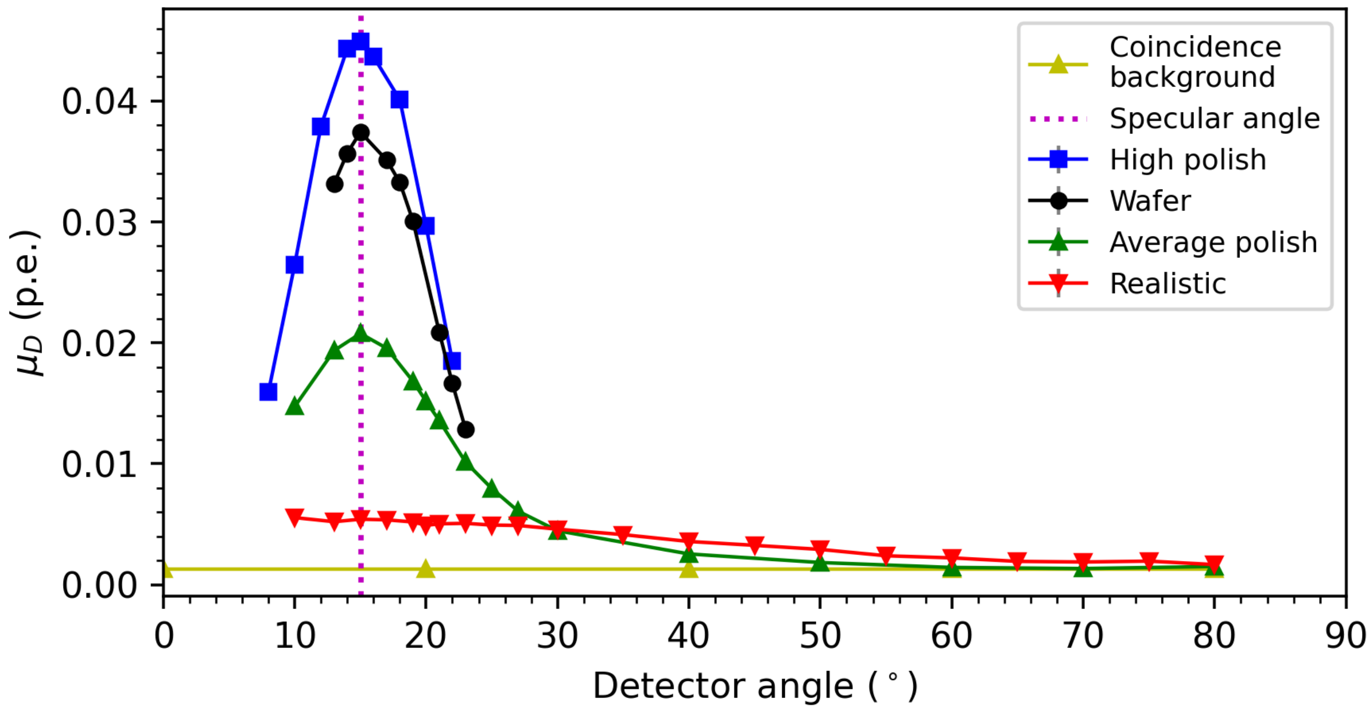
Containment



Containment of the light beam. The shaded band represents simulation uncertainty.

- Containment fraction: the fraction of these photons that would hit the active area of the detector SiPM if the sample was a perfect specular reflector
- Containment fraction decreases from 100% to 65% as incident angle increase
- We use this parameter to correct the measured results

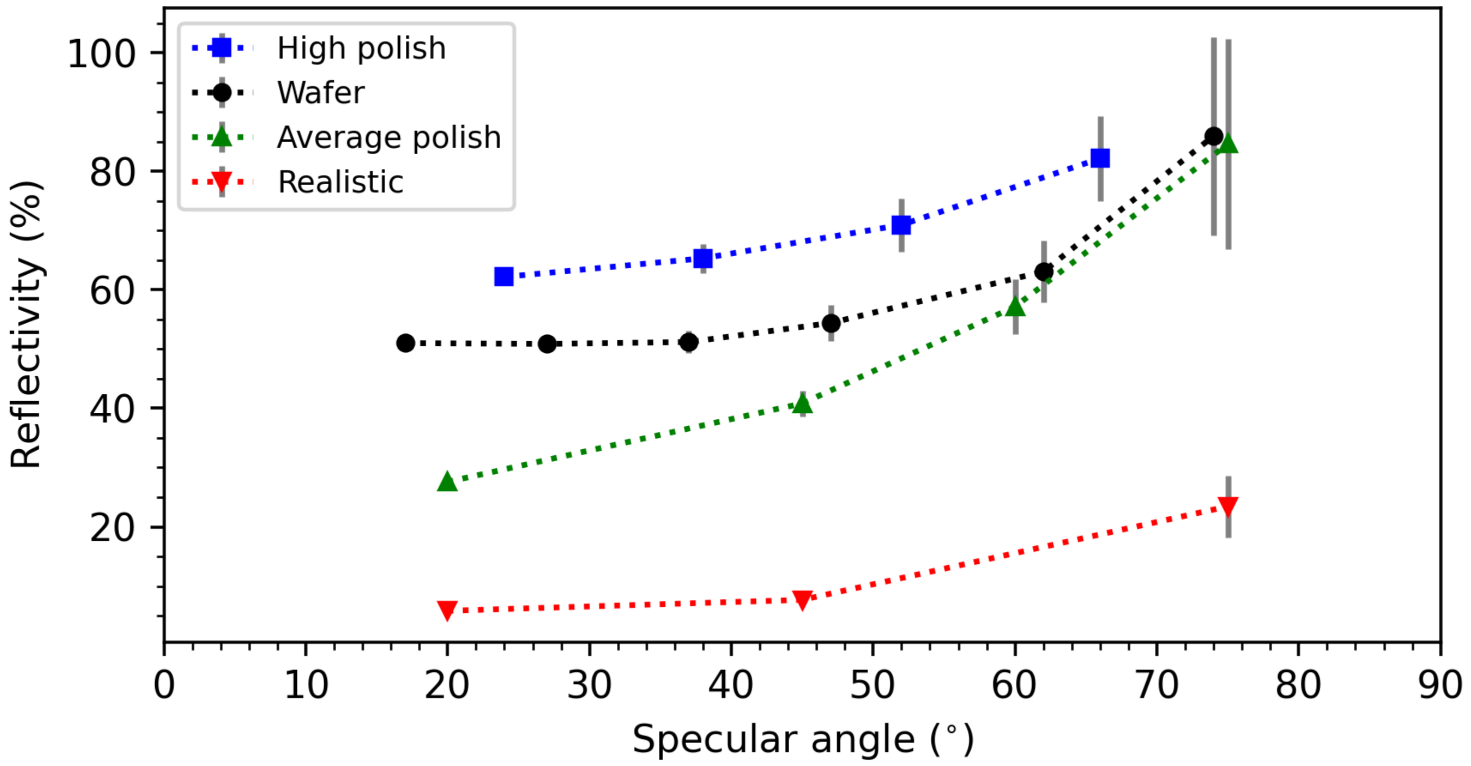
Specular reflectance in LXe



Mean number of p.e. seen by the detector SiPM as a function of the detector's angular position

- The wafer's reflectance is equal to ~51%
- Wafer measurement is used as a reference reflectance in LXe in this work
- The wide peaks for realistic and average samples are due to a large fraction of reflections is not specular
- To get the total reflectance we need diffuse/total measurements

Specular reflectance in LXe

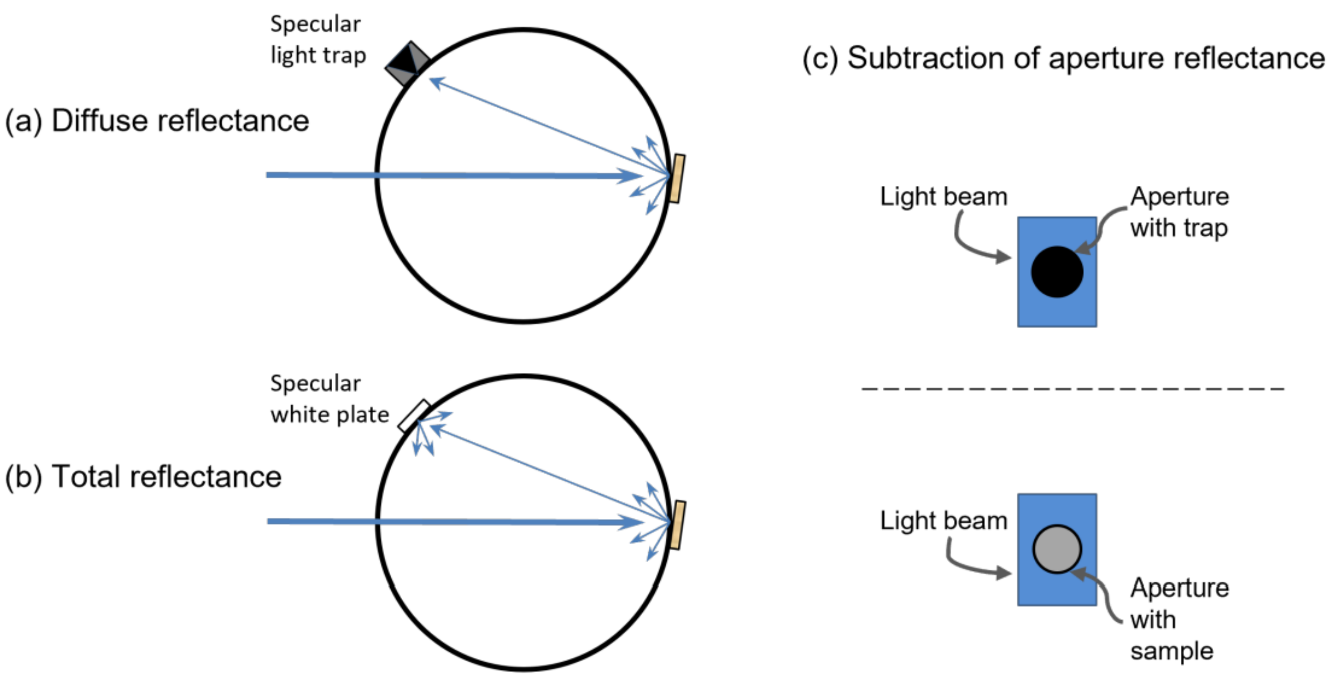


Specular reflectance in LXe of the samples as a function of the angular position of the collimated source

Sample	Angle(°)	Rspec (%)
Wafer	17 42 74	51 52.6±2.3 **85±17**
High polish	24 45 66	62.5±1.4 67.7±3.5 **80±8**
Average polish	20 40 75	27.6±0.8 40.7±2.1 **84±18**
Realistic	20 45 75	5.8±0.4 7.6±0.6 **23±5**

Rspec in LXe of different samples at low, middle and high angles

Integrating sphere measurement



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- Integrating sphere measurement setup in GN2:
- A light trap was used to remove the specular reflectance and measure the diffuse reflectance only.
- Light trap was replaced by a white plate to measure the total reflectance including both specular and diffuse components.
- Because the probing light beam area was larger than the sphere aperture for measuring the sample, a measurement without sample, with a second light trap, was subtracted from all measurements in order to remove the contribution of the light beam incident on the sphere wall around the aperture.

Reflectance values measured in GN2

- Reflectance values of the three samples as measured in GN2 (with the sphere) at 175 nm

Sample	R_{tot} (%)	R_{diff} (%)	R_{spec} at 8° (%)
High polish	**84±8**	0.0	84.1
Average polish	**85±8**	42.2	42.4
Realistic	**92±8**	90.2	1.4

Conclusion: With diffuse/total measurements, the total reflectivity of the three samples is greater than 80%, meeting the experimental requirements of nEXO.

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Summary

- LIXO2 directly measures reflectance, detection efficiency and transmittance in liquid xenon, avoiding errors caused by indirect speculation.
- Measurements also allow for a more accurate understanding of liquid xenon properties, such as the liquid xenon's refractive index. Provide similar experimental reference.
- LIXO measures optical properties of experimental materials for nEXO and DARWIN. Appropriate materials will improve the light collection efficiency, thereby improving the resolution of the detector and meeting the requirements of the experiment.
- The adhesion of the films to the substrates showed no visible signs of deteriorating after LXe measurements, during which the samples were cooled down to the LXe temperature (- 100°C) for 10–20 hours.
- The thin-film coatings studied in this work are found to posses satisfactory VUV reflectance for all three types of substrates. (See paper for details: **Validation of the VUV-reflective coating for next-generation liquid xenon detectors** arXiv:2402.15177 [physics.ins-det])