R&D TOWARD NEXT-GENERATION LXE EXPERIMENTS WITH

XEBRA & IBEX

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Lawrence Berkeley National Lab / UC Berkeley

Patras Workshop
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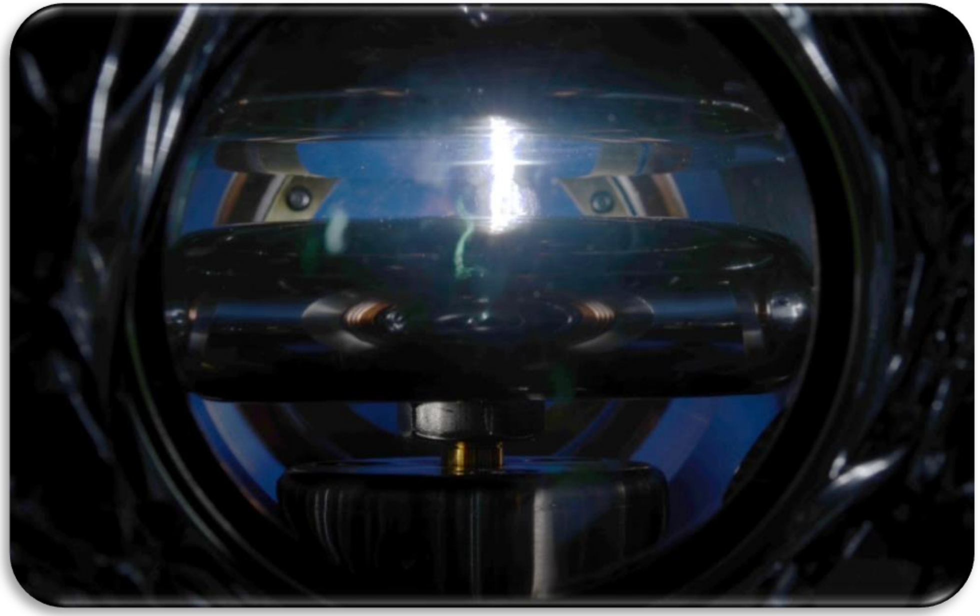
Outline

XEBRA

- Study of high voltage breakdown in LAr and LXe
- Dependence on electrode area, pressure
- Checks for spark precursors



IBEX

- Study of angle-resolved PTFE reflectivity in LXe
- Dependence on material, surface preparation, LXe pressure, wavelength

*Supported through the LBNL LDRD program

Motivation for XEBRA

Problem

- Lack of data characterizing high voltage (HV) behavior in noble liquids needed for dark matter detector design
  - Larger detectors need higher voltage, larger electrodes – is there a threshold that will impede the scale up?

Solution

XEBRA **Xenon Breakdown Apparatus**

- Used to acquire data characterizing HV in liquid argon (LAr) and liquid xenon (LXe)

Upcoming experiments

Current  measurements

VS

HV breakdown in LXe is not well understood

LAr & LHe data suggest breakdown depends on:

- Electrode stressed area
- Dielectric stressed volume
- Surface finish
- Liquid purity
- Polarity
- Pressure & temperature
- And more …

But there is very little data in LXe!

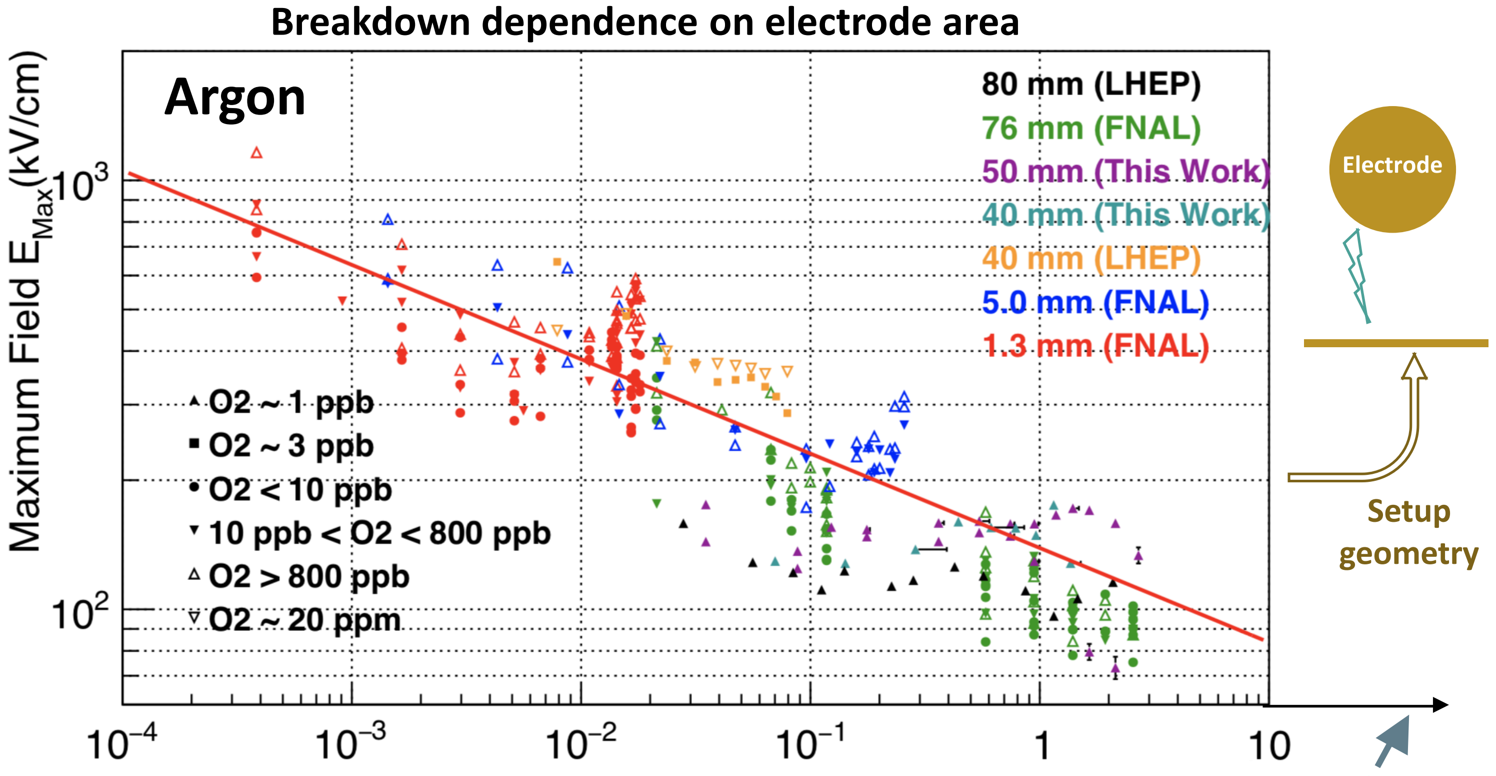


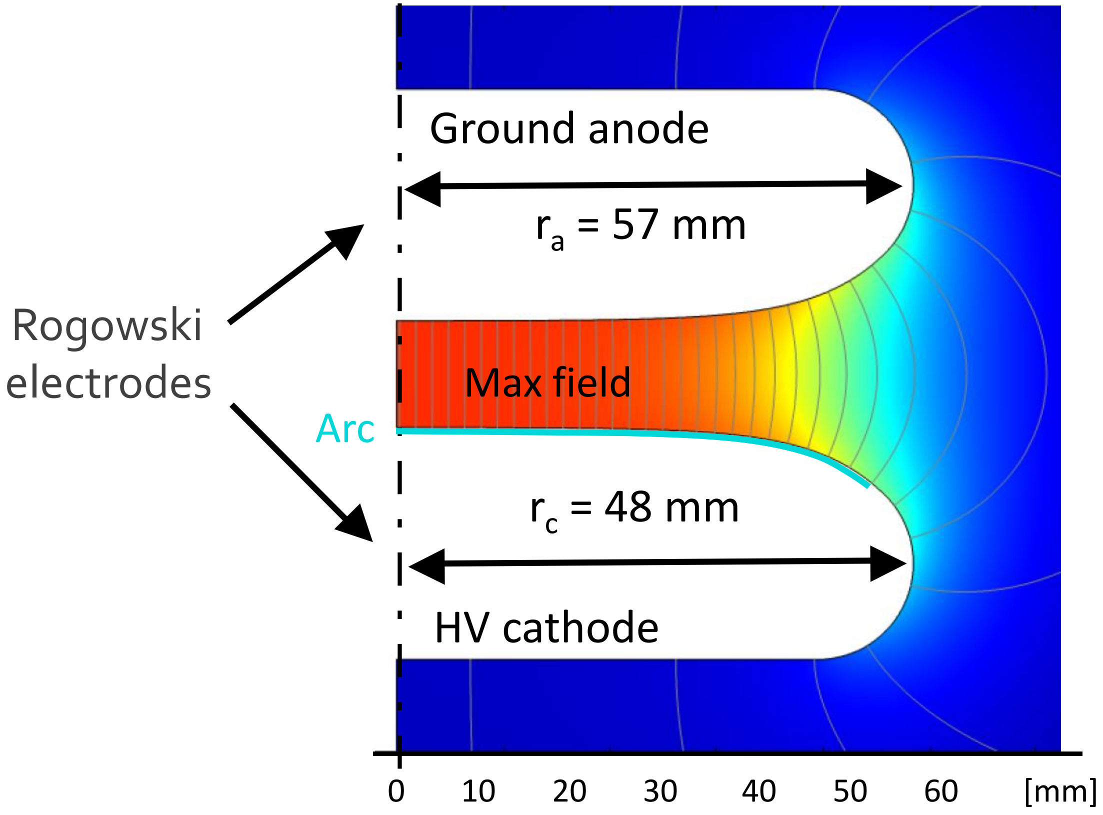
Figure from JINST 11 P03017 (2016)

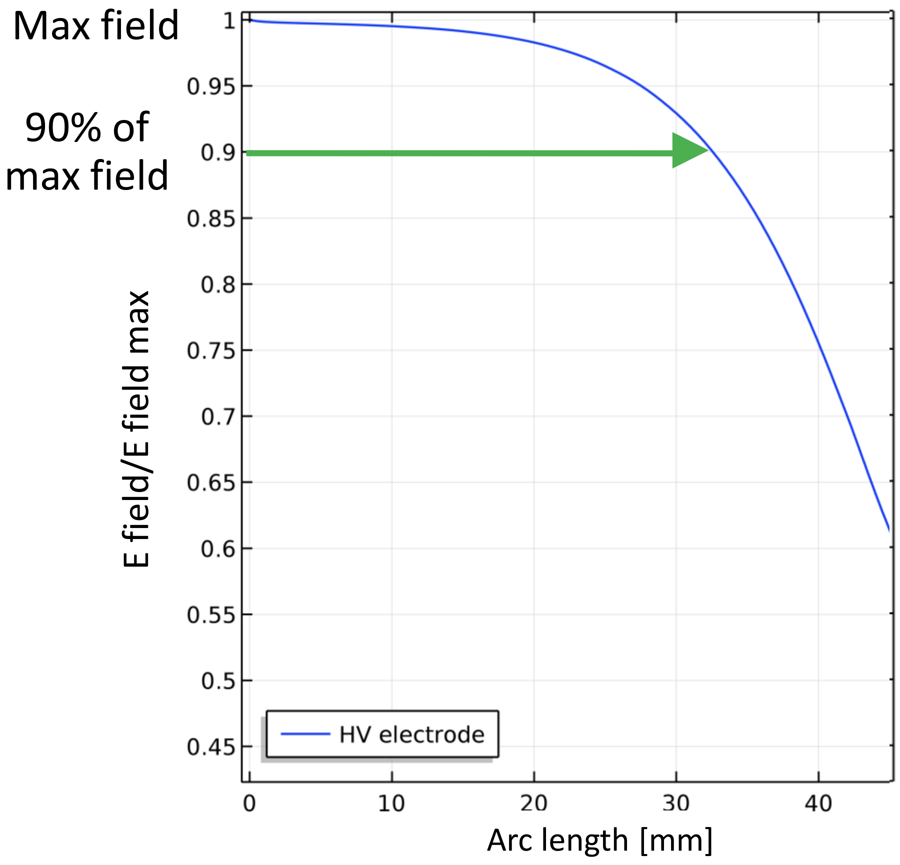
Design for the LZ cathode stressed area (500 cm^2)

Only consider area within 90% of max E-field

"Stressed area"

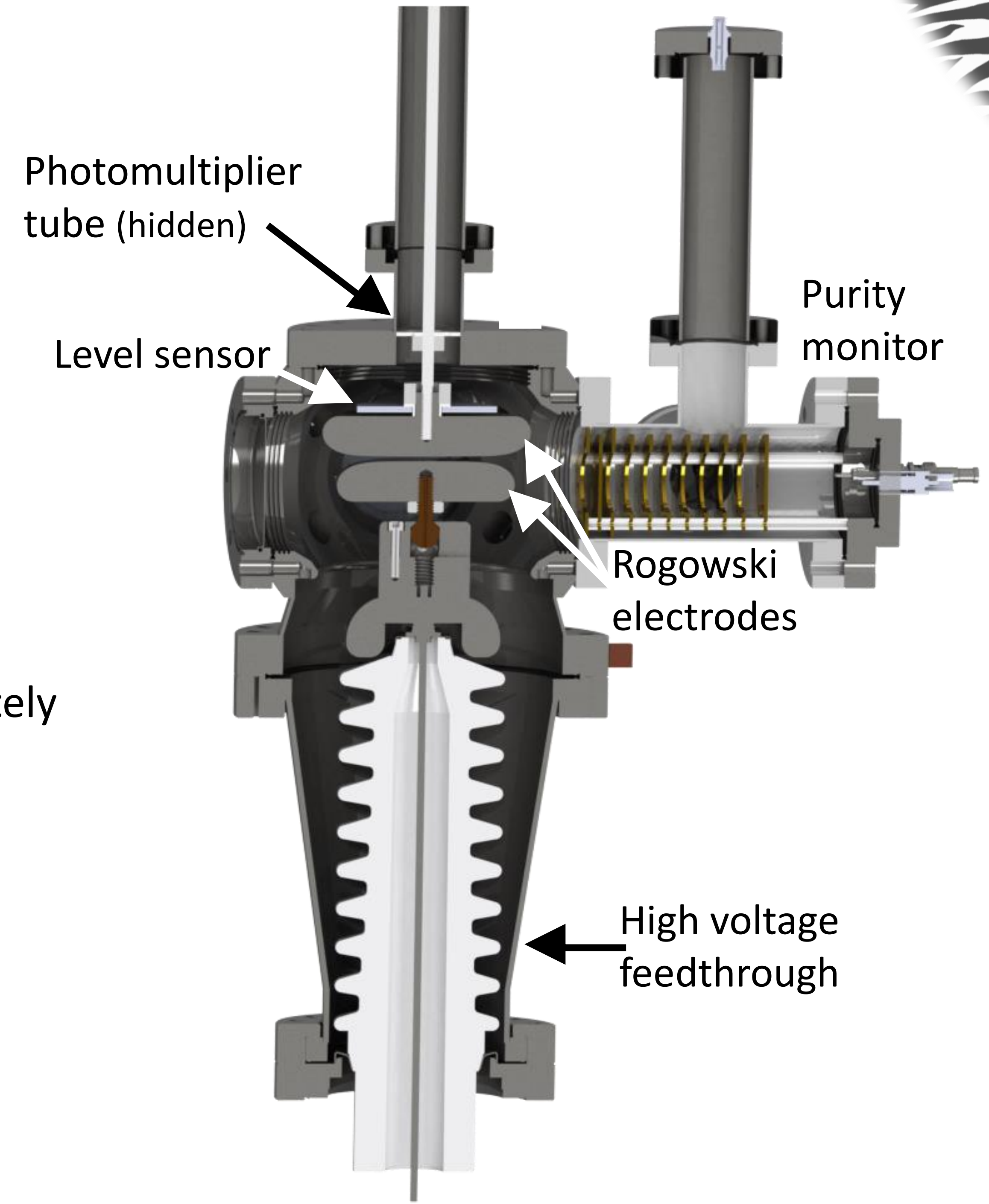
i.e. where the sparks are most likely to happen





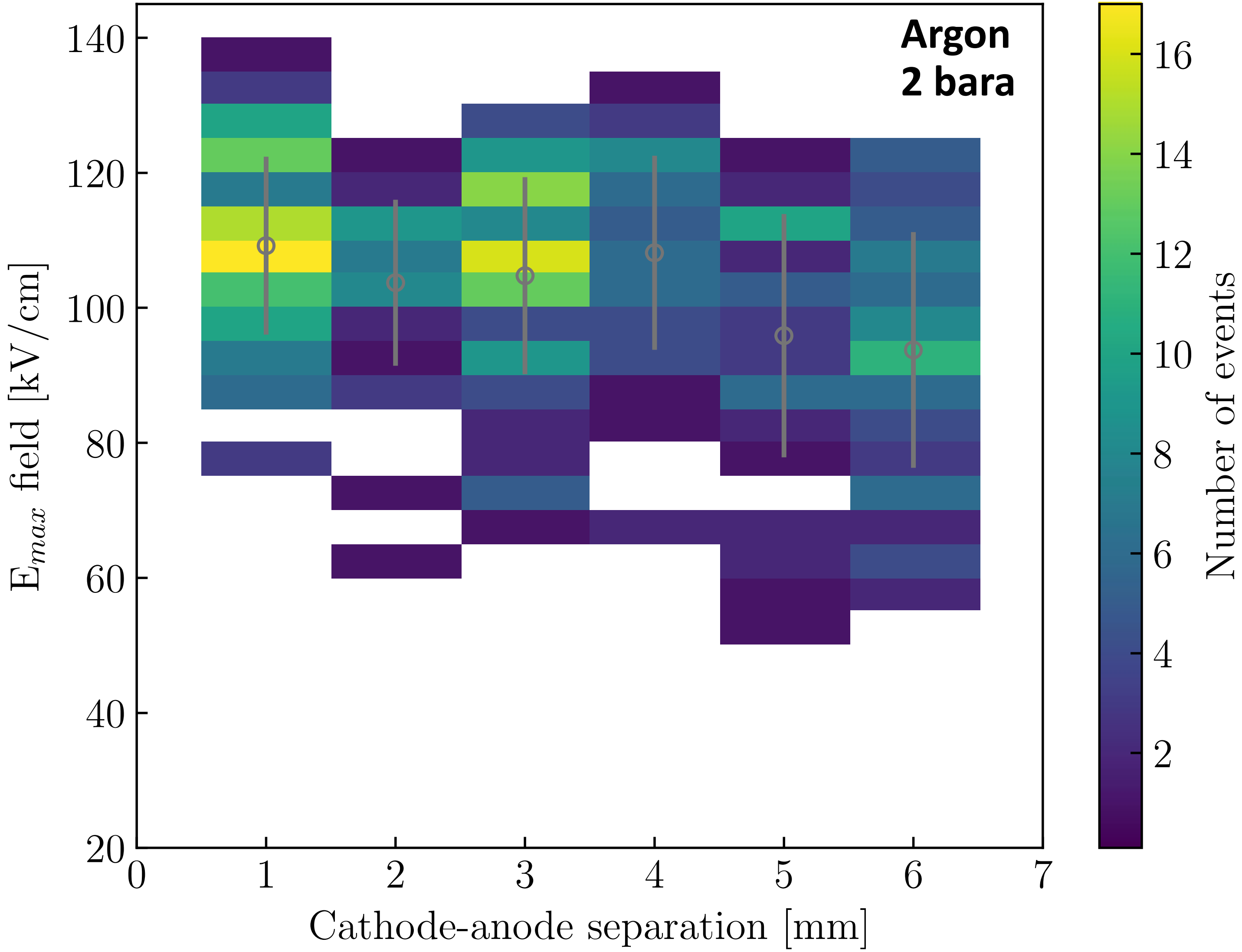
Apparatus details

- Can be filled with either LXe or LAr with total experimental volume = 5.6 L
- Designed for HV up to -75 kV
- Max stressed electrode area = 58 cm^2
- Max electrode separation = 10 mm
- Ability to vary electrode separation remotely
- Continuous purification
- Monitoring of liquid purity
- Detection of glow onset & breakdown
  - Current sensing, PMT & camera



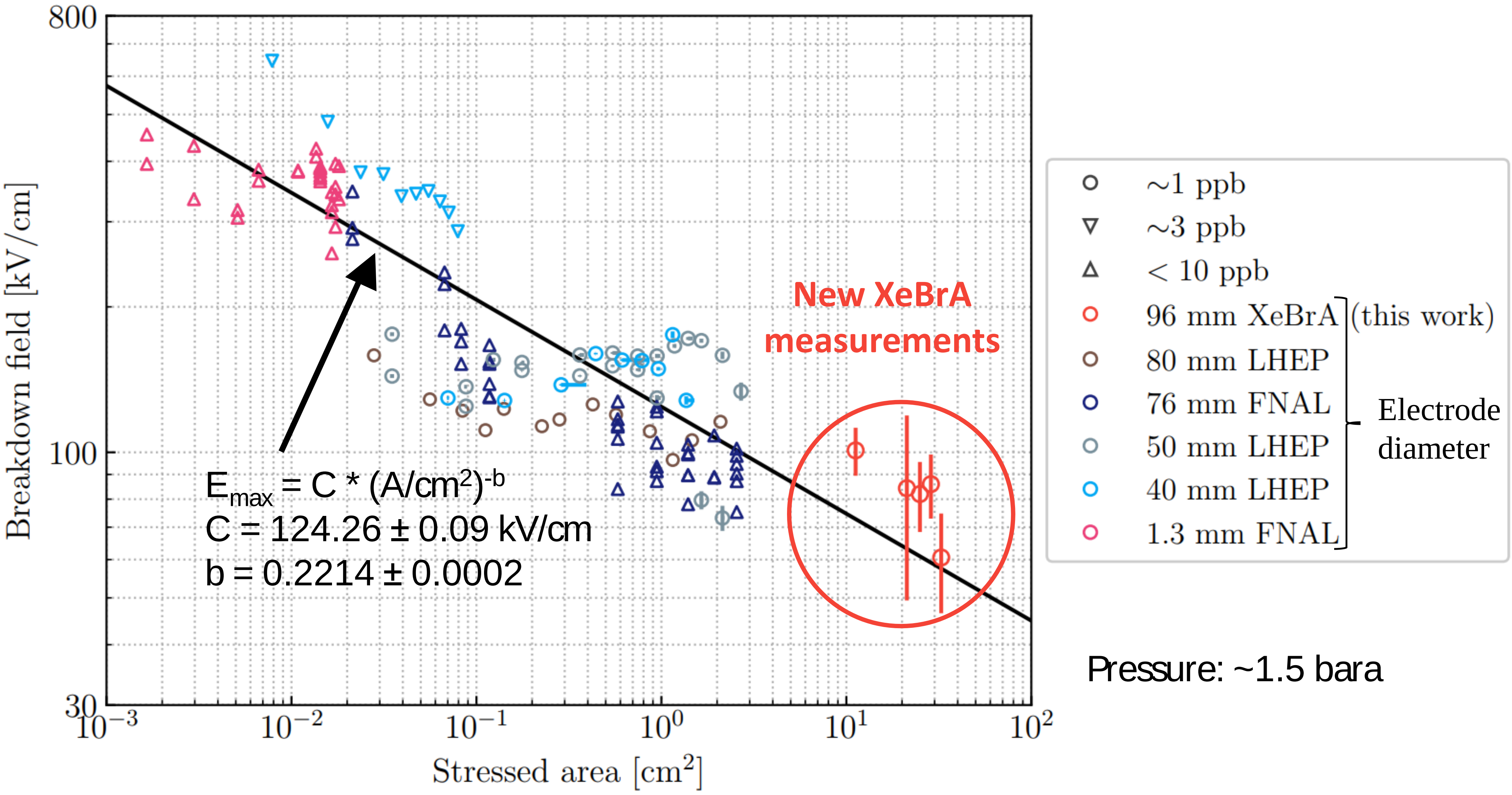
Data: Breakdown field vs. separation in LAr

- Pressure: 1.5 & 2 bara
- >1 ppb (~300 µs) as measured by the purity monitor



Note: circles represent the mean breakdown field and "error bars" the standard deviation

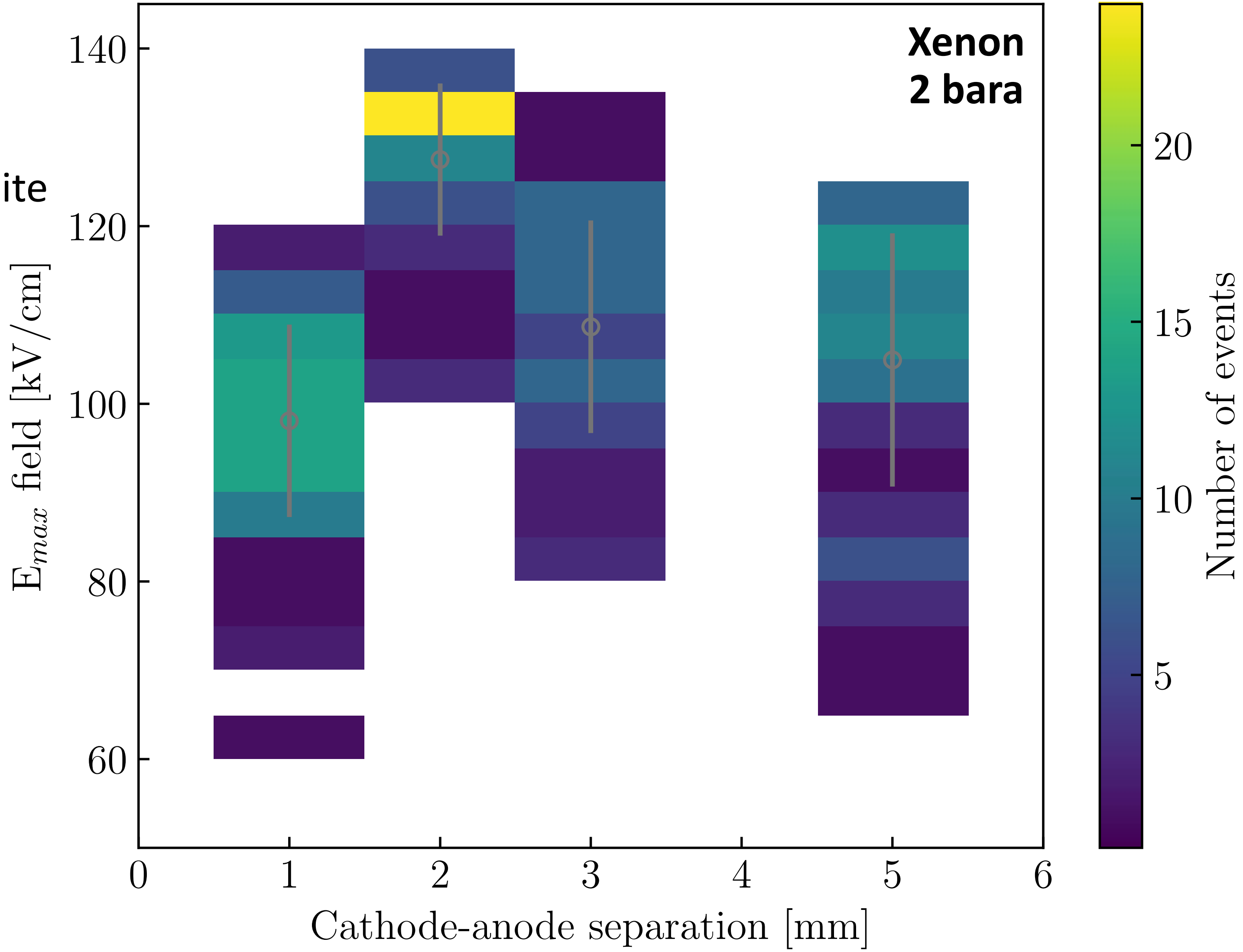
Breakdown field vs. stressed area in LAr



Pressure: ~1.5 bara

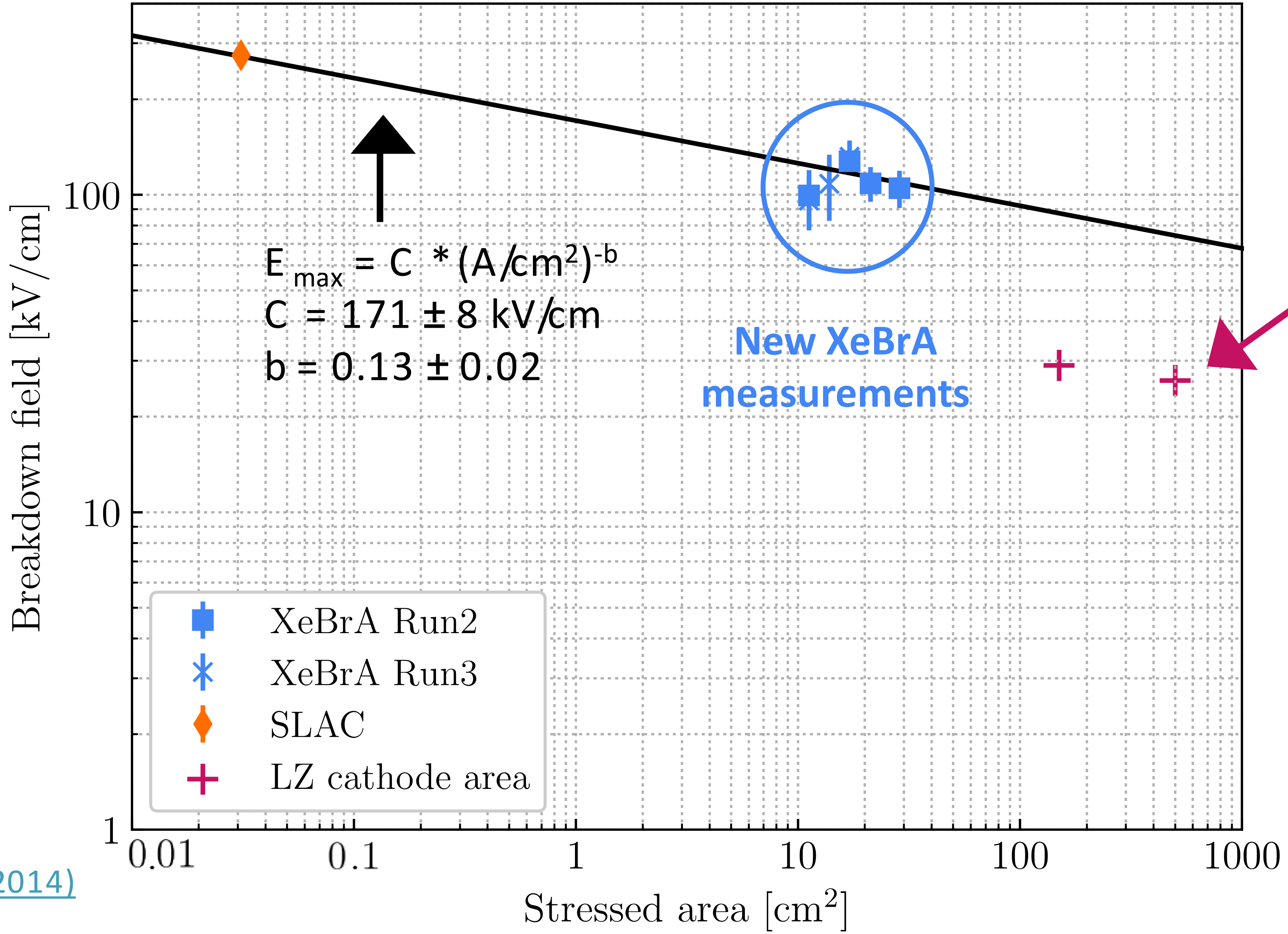
Breakdown field vs. electrode separation in LXe

- Pressure: 2 bara
- 2 xenon datasets:
  1. Purity unknown, but likely quite poor (>ppm?)
  2. Purity ~200 ppb (~2 μs)



Note: circles represent the mean breakdown field and "error bars" the standard deviation

Breakdown field vs. stressed area in LXe

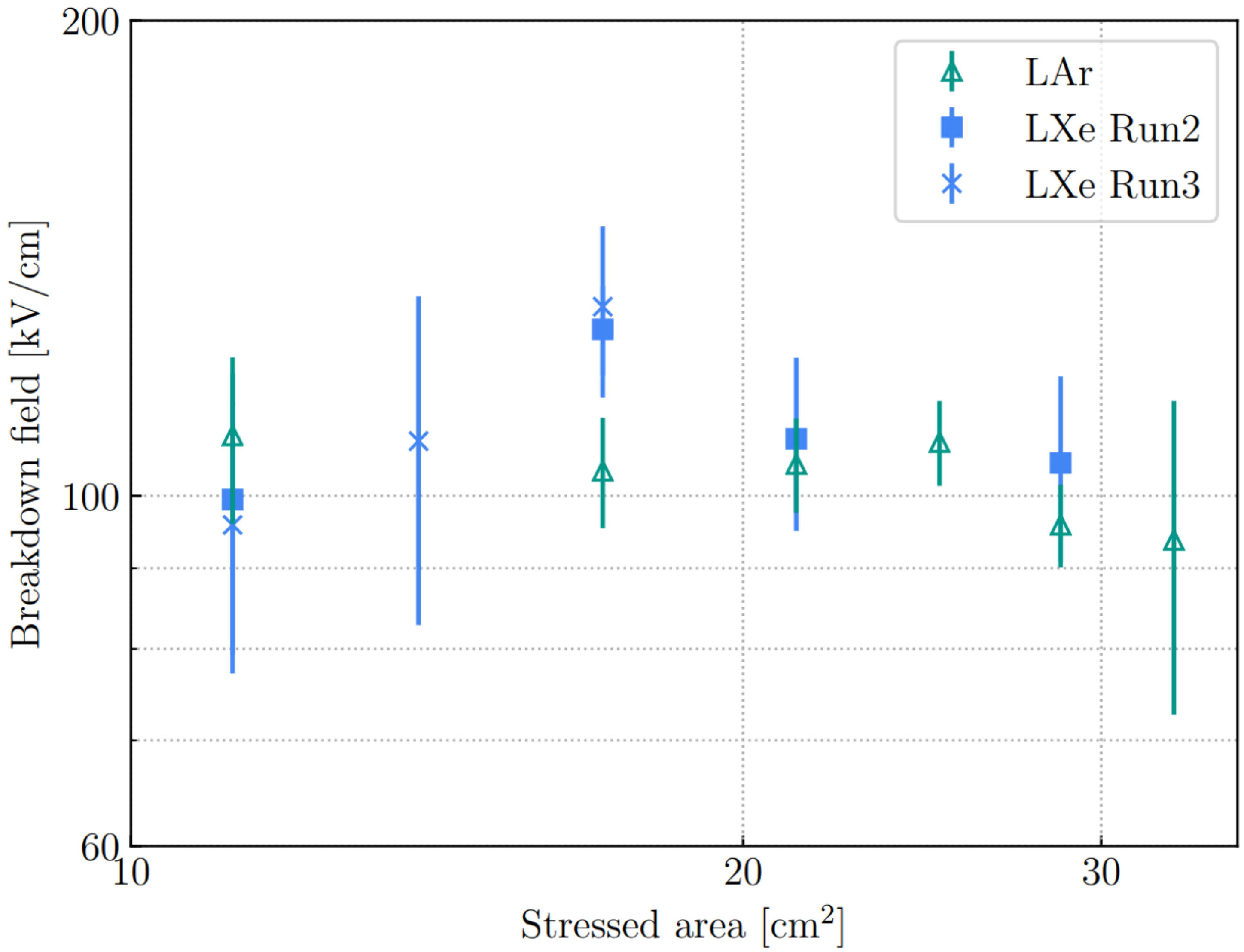


LZ cathode ring surface field at 100 kV in LXe (not a measurement)

Pressure: 2.0 bara

SLAC data from [JINST 9 T08004 (2014)]

Comparison of LAr and LXe data from XeBrA

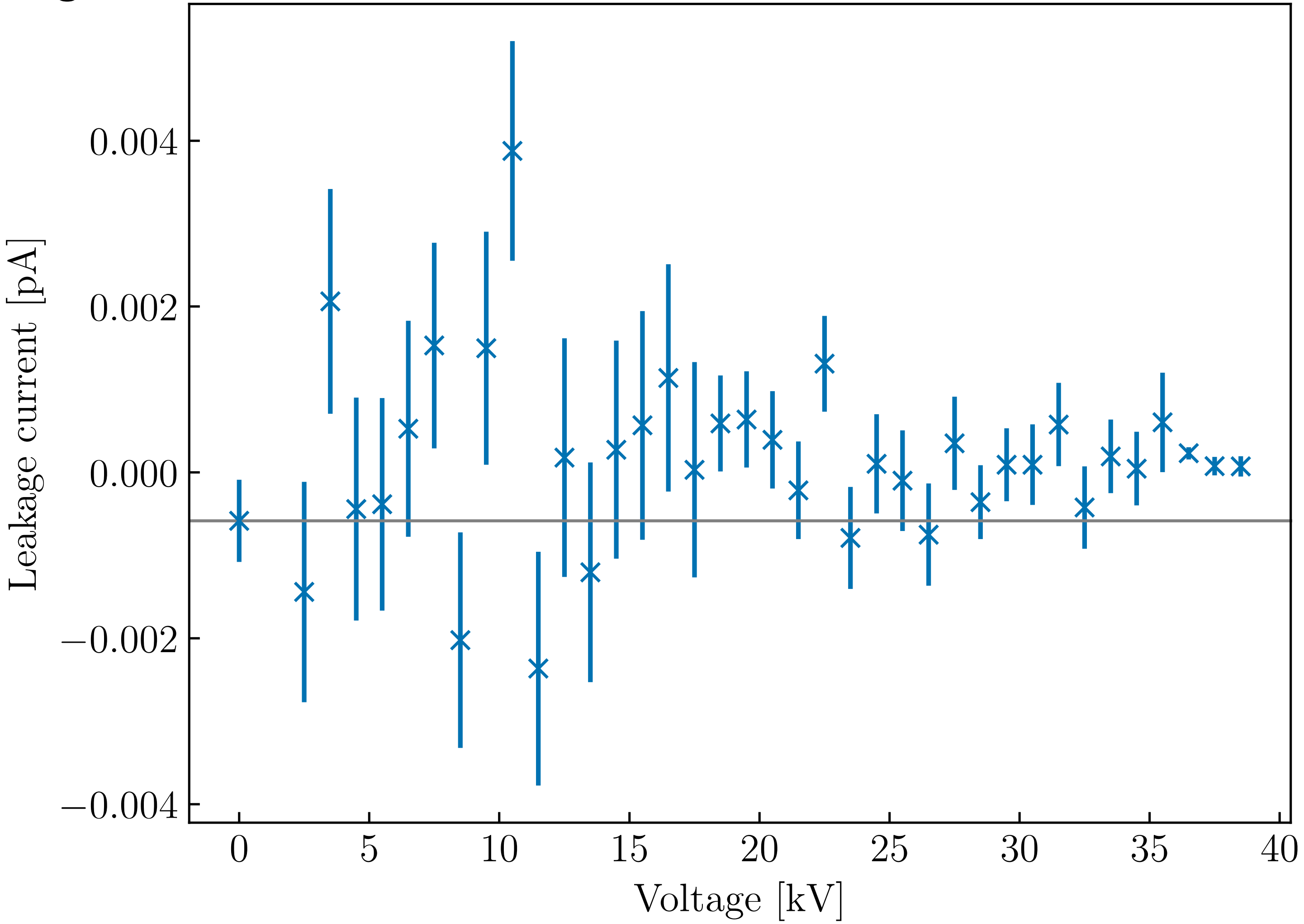


Pressure: 2.0 bara

Leakage current

- No obvious dependence of leakage current on voltage
- LXe: leakage current < 5 fA
- LAr: leakage current < 50 fA
- Suggests spark precursors are less concerning for direct detection experiments

Leakage current in LXe
3 mm electrode separation

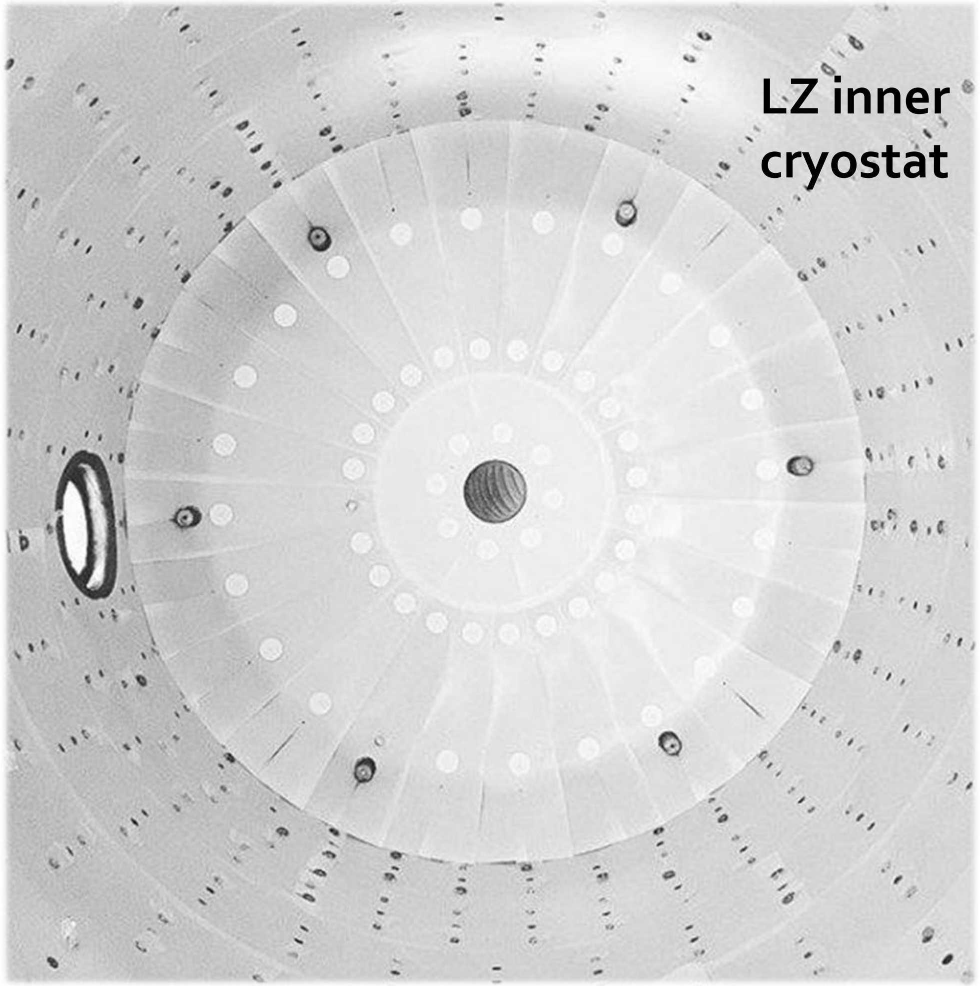


Conclusion & outlook

- Measured HV breakdown over larger electrode areas than previously studied
- XeBrA enables direct comparison of dielectric breakdown measurements in LAr and LXe
- Further data collection forthcoming
- Many parameters of breakdown behavior to study in the future:
  - Electrode material + varying finishes & coatings
  - Liquid purity & effect of different impurities
- Publication in preparation

IBEX Background

- PTFE used in LXe time projection chambers (e.g. LUX, LZ, XENON, PandaX, EXO) to enhance light collection
- Prior work finds PTFE reflects xenon scintillation light (178 nm) very well in LXe: >97% [1] (mostly diffuse model)
- Other studies: dependence on thickness[2], angular distribution reflection in vacuum[3]
- Projected reflectance in LXe based on angle-resolved measurements in vacuum is more modest (~85%) than observed[4]

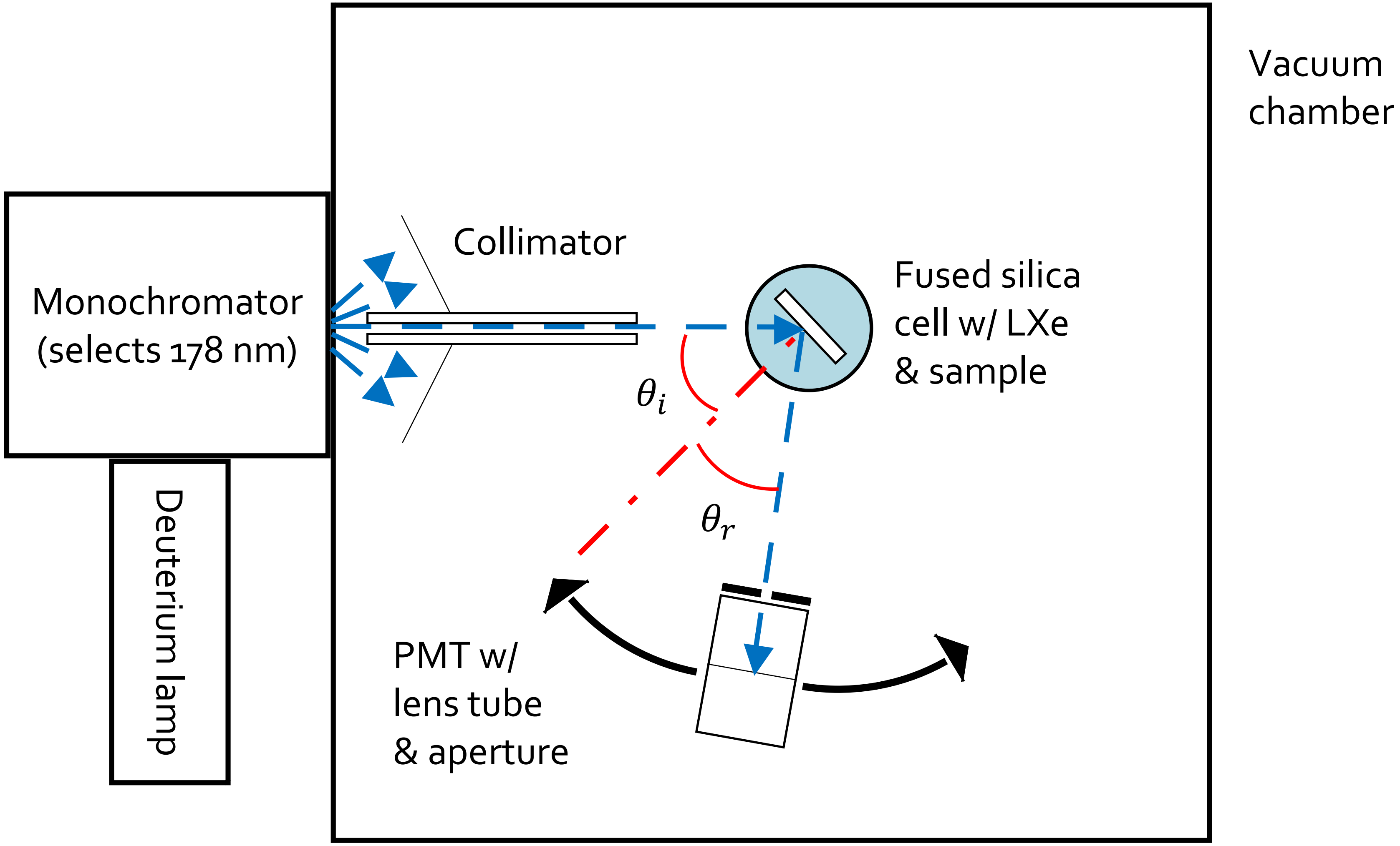


[1]arXiv:1612.07965 [2]arXiv:1608.01717
[3]arXiv:0910.1056 [4]Silva thesis, 2010

IBEX Goals

- **I**mmersed **B**RIDF **E**xperiment in **X**enon
- BRIDF: bi-directional reflectance intensity distribution function
- Measure **angular distribution** of light reflected off PTFE in vacuum and in liquid xenon
- Want a physical model capable of fully describing reflectance phenomena
  - Determine how reflectance is affected by **PTFE type, surface treatment**
  - Determine **ideal operating conditions** for detector, e.g. LXe temp
  - Improve **optical modeling** in MC simulations
- Complementary to other experiments focused on total reflectivity

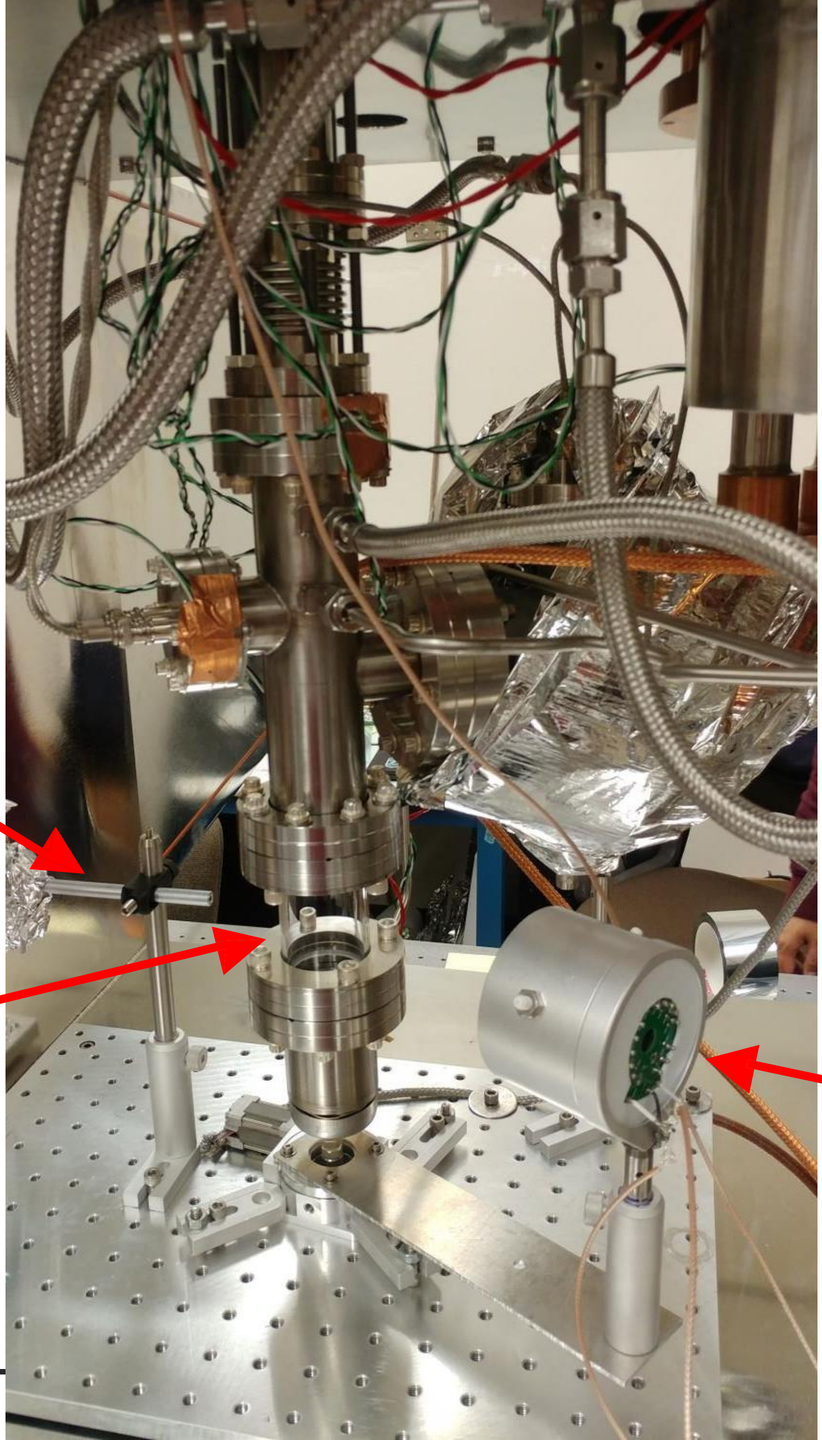
Optics Schematic



Apparatus

Collimator

Cell

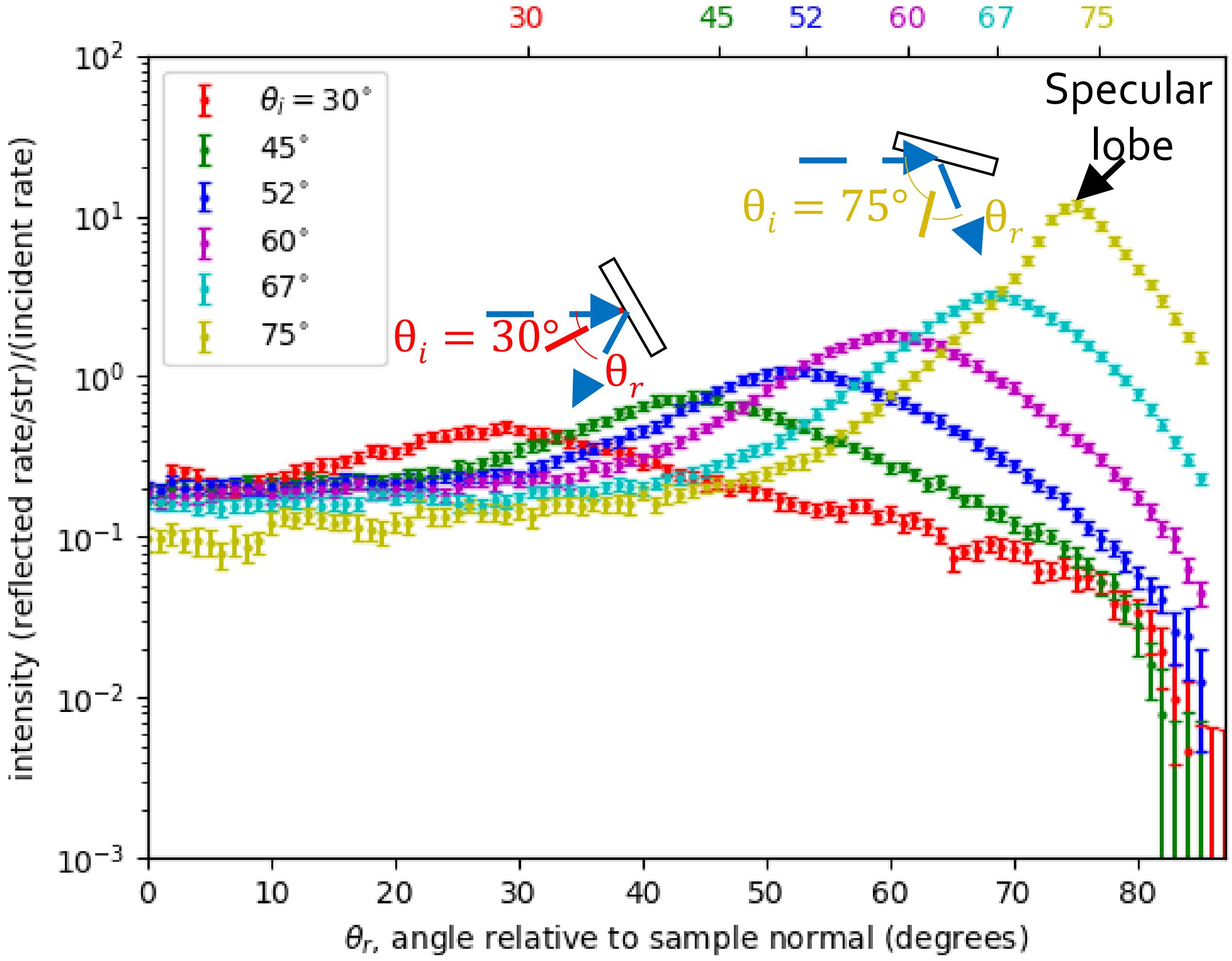


PMT

PTFE
Sample

Example data

Material used to coat inside of LZ cryostat, measured in vacuum at 178 nm



Model

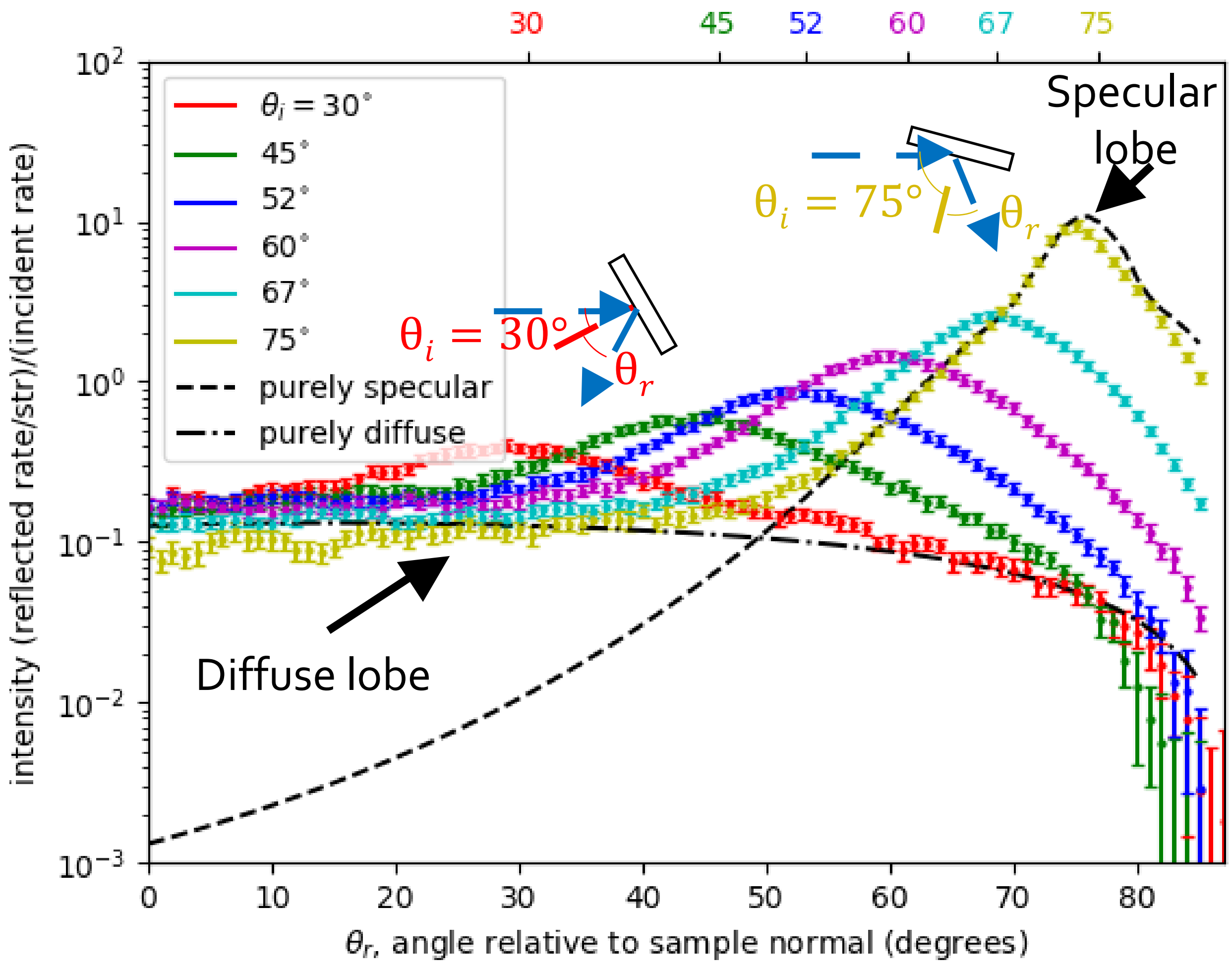
Qualitative features

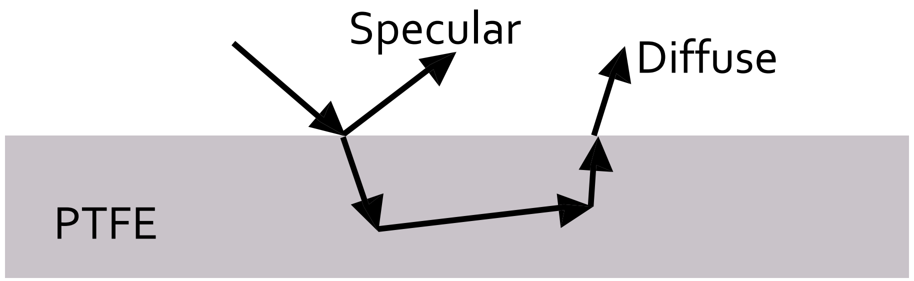
- Specular lobe: **mirror-like** reflection at PTFE surface off of **distribution of microfacets**
- Diffuse lobe: light **transmitting** into PTFE bulk, **scattering within** that bulk, transmitting back out

Model parameters

- $\mathbf{n_{PTFE}}$: index of refraction of PTFE
- **ρ**: albedo of PTFE, related to probability that light in the bulk scatters back to the surface
- **γ**: surface roughness of PTFE
- $\mathbf{n_{LXe}}$: index of refraction of LXe, fixed to literature value of 1.69[1]

[1]arXiv:physics/0307044



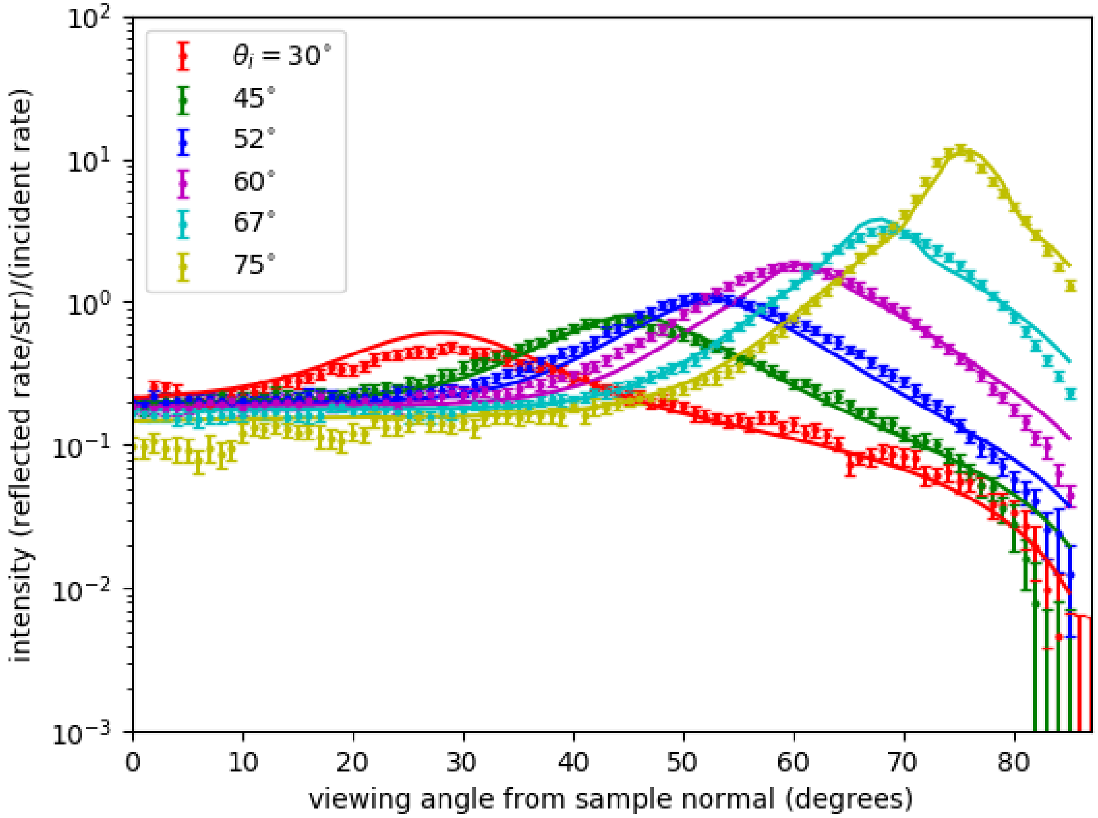


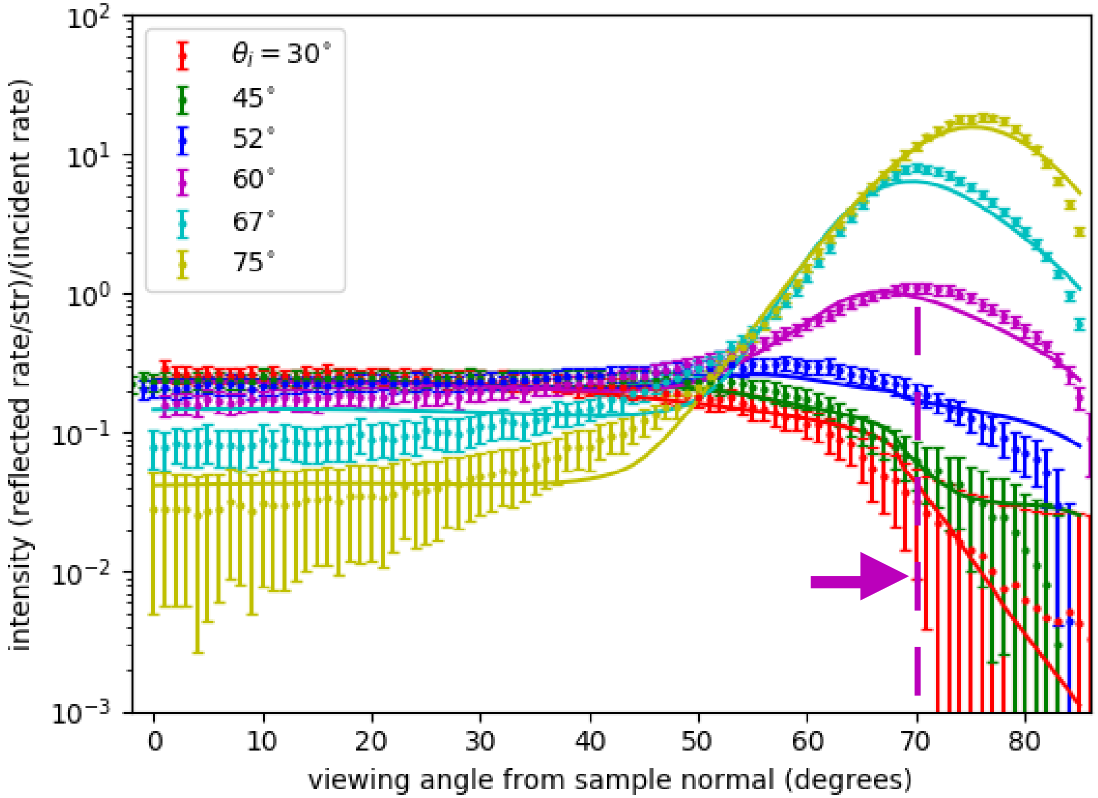
Vacuum vs. LXe

In liquid xenon, PTFE reflectance is not entirely diffuse

Specular peaks are shifted towards high viewing angles due to total internal reflection

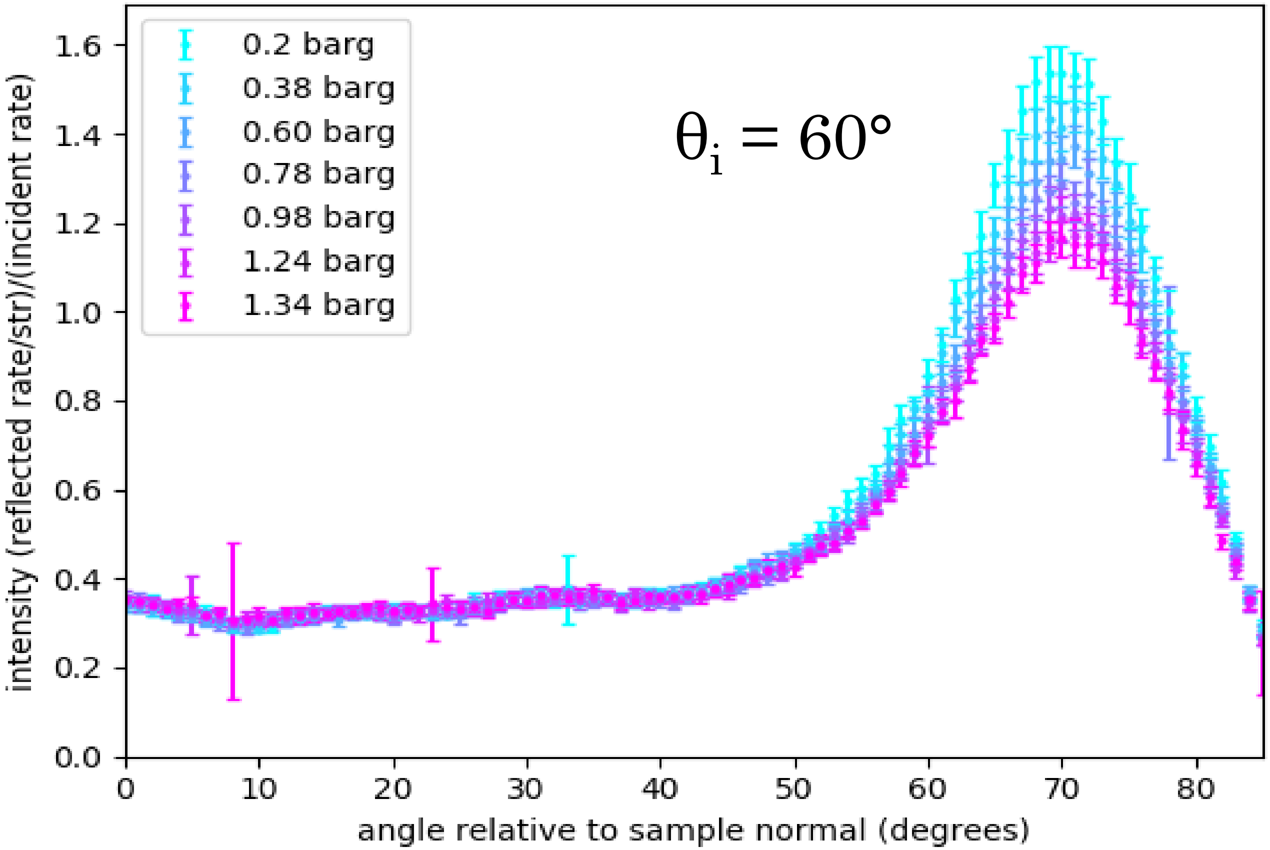
LXe model requires a smooth distribution of n_{PTFE} to match rising edge of specular peak from TIR





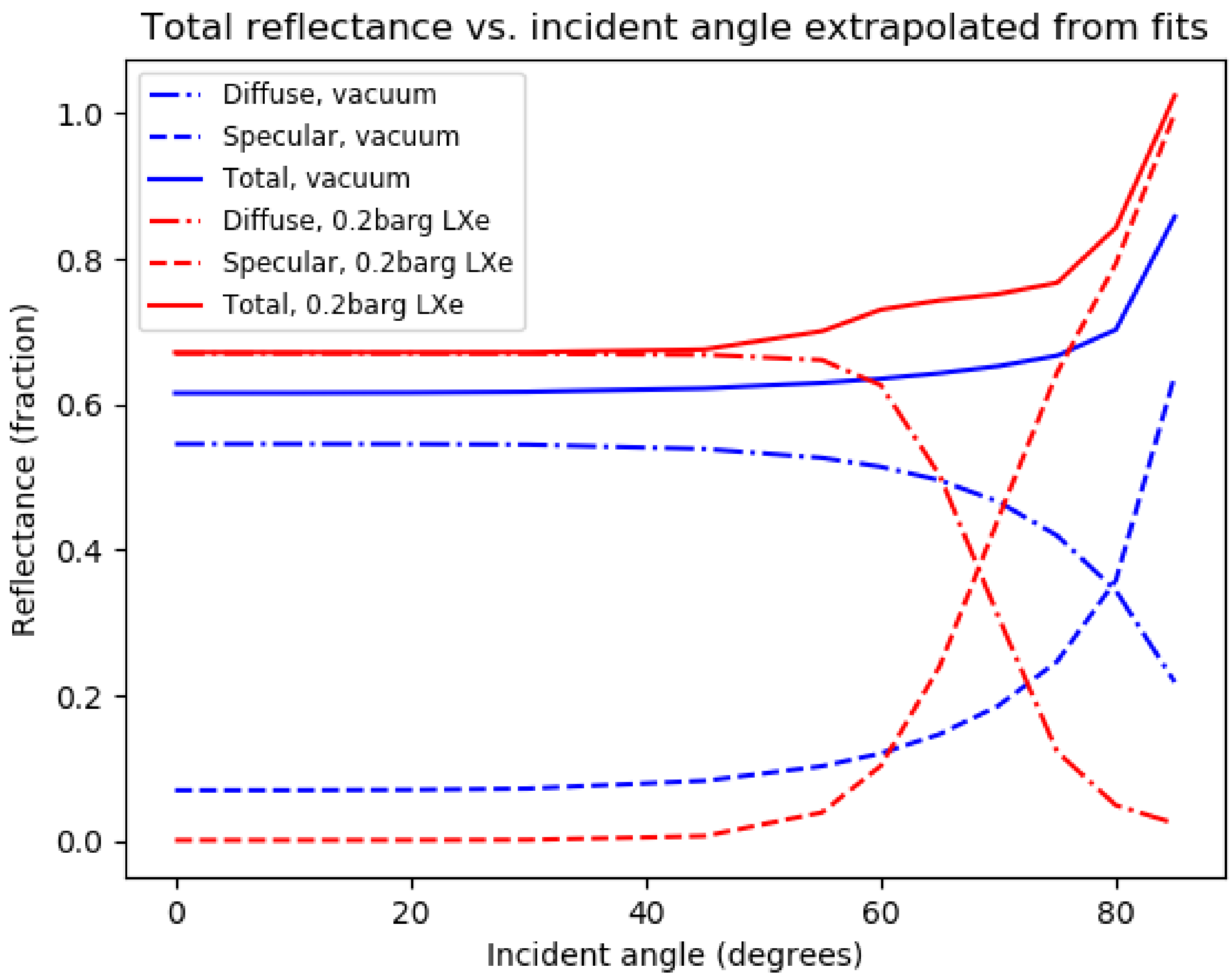
Pressure effect

Increased pressure/temperature suppresses specular peak for incident angles near the critical angle: very sensitive to LXe index of refraction



Total reflectance

- Measurements are w/in plane of incidence; total reflectance is extrapolated from model
- Reflectance is fairly flat over small incident angles, but increases sharply above critical angle
- Lower reflectance seen than from dedicated total reflectance studies:
  - Different experiment geometry
  - Sample prep (R > 80% seen for polished sample in IBEX)
  - Incorrect model in either case

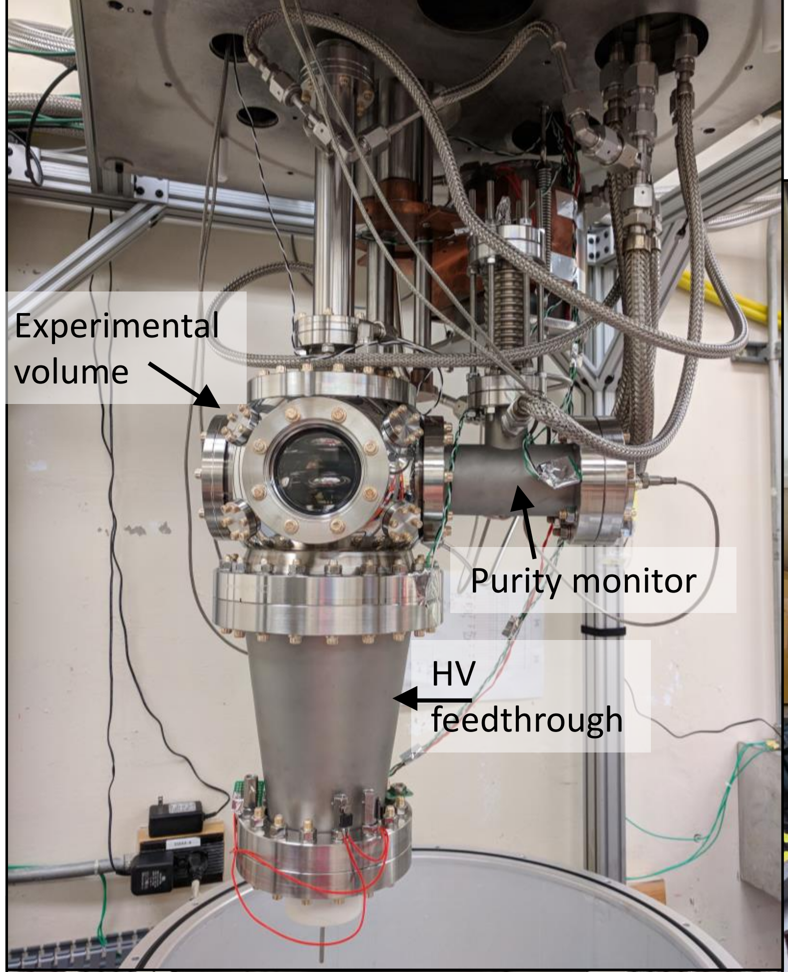


Conclusions

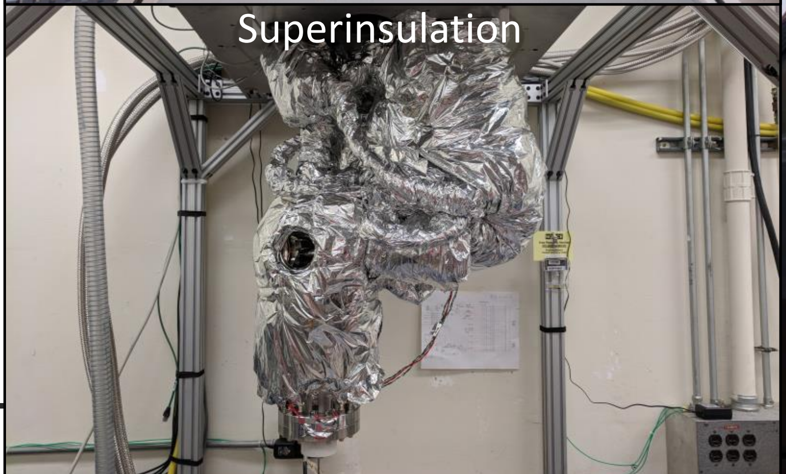
- IBEX data informs a more realistic, physically-motivated model for optical simulations of LXe TPCs
- PTFE reflectivity is dominated by diffuse component below critical angle ~65°, specular component above
- Distribution of reflectance can vary somewhat with detector pressure
- Publication in preparation

Backup Slides

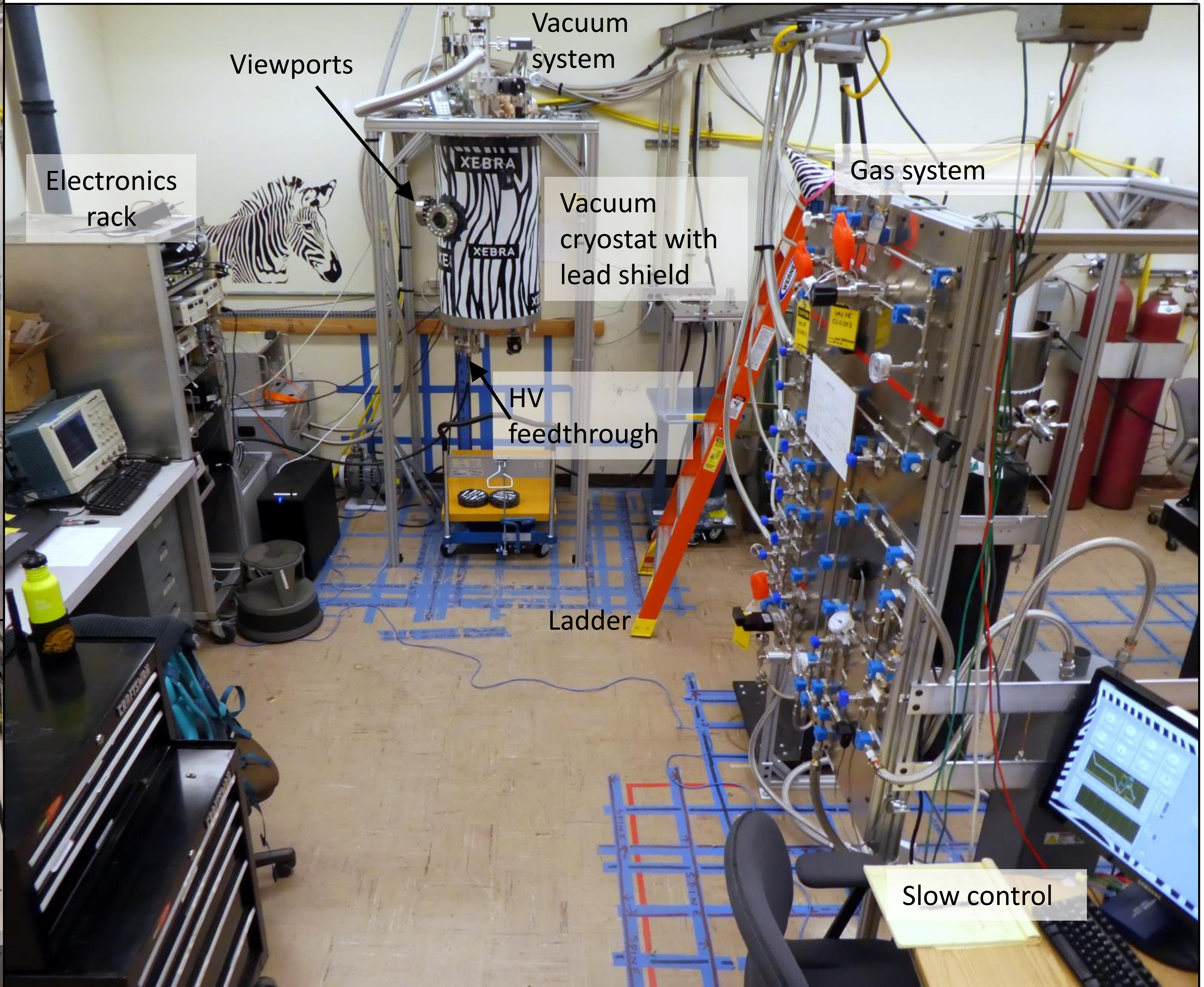
XEBRA set up



Experimental volume
Purity monitor
HV feedthrough



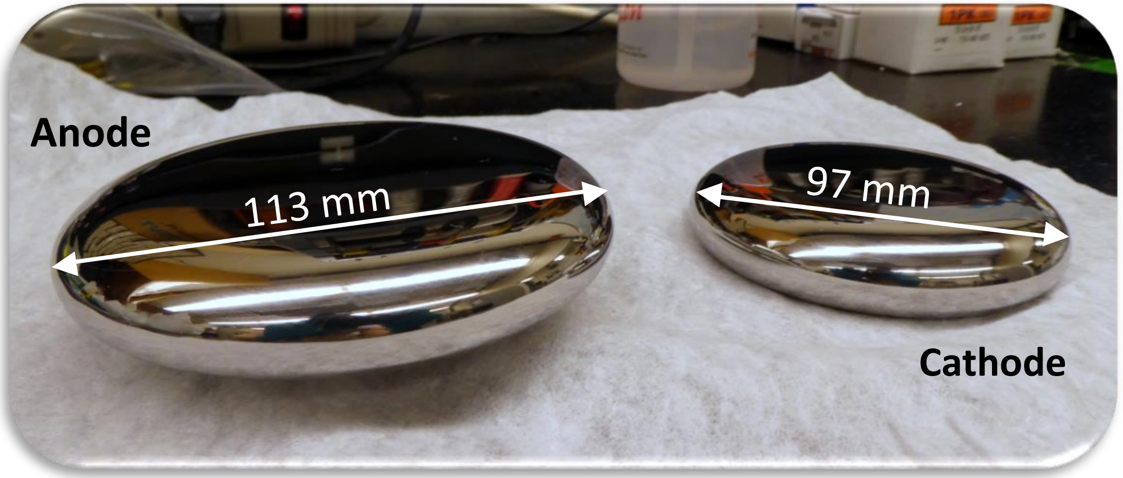
Superinsulation

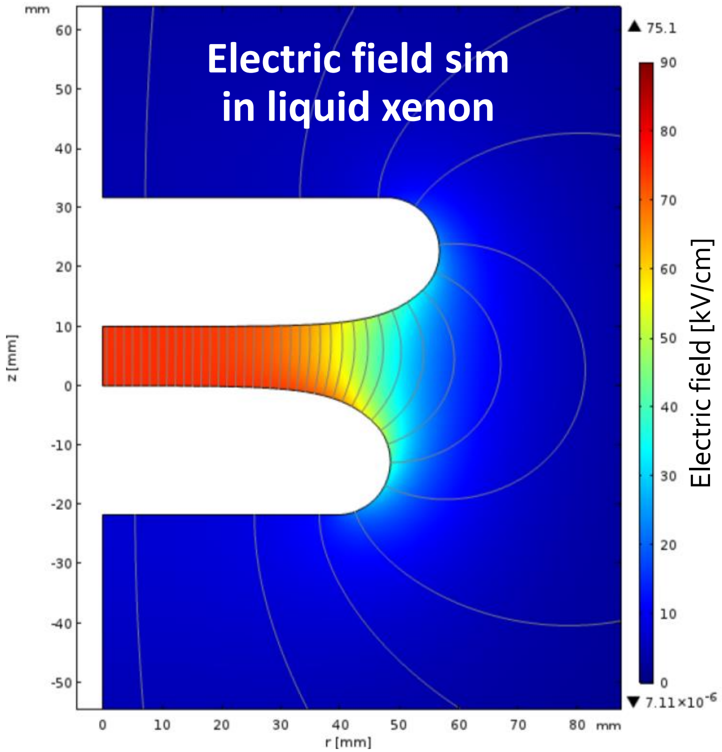


Vacuum system
Viewports
Electronics rack
XEBRA
Vacuum cryostat with lead shield
Gas system
HV feedthrough
Ladder
Slow control

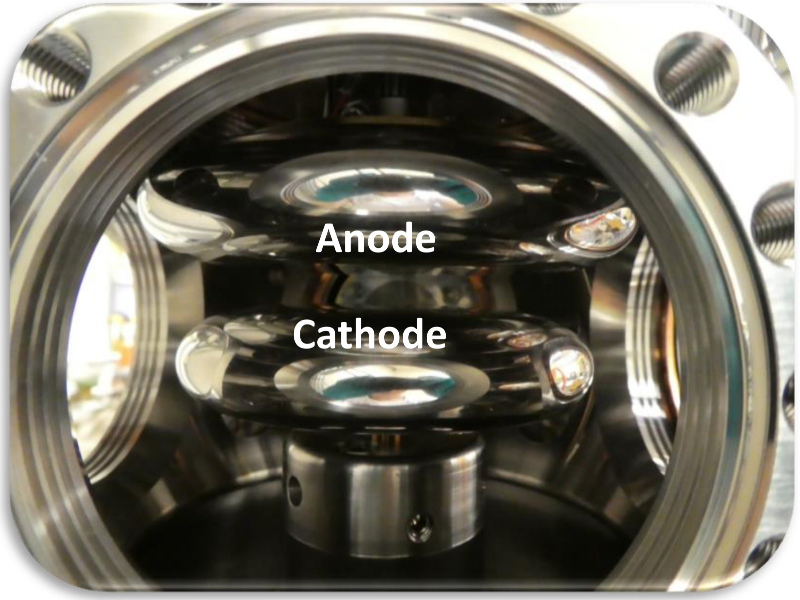
Rogowski electrodes

- Electrodes designed to have highest field near the center and maintain a nearly uniform field over a large area





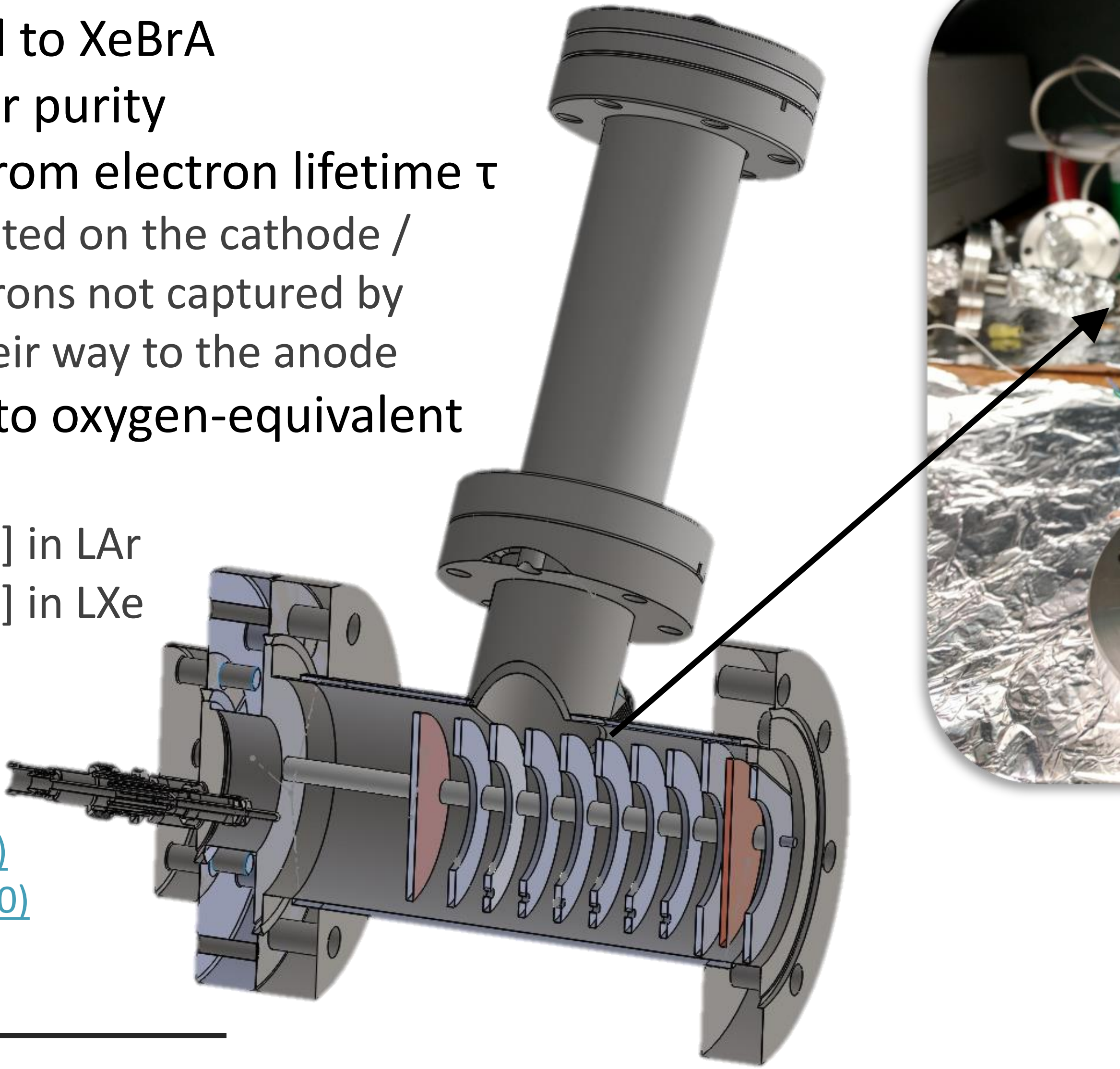
Location of electrodes in the apparatus

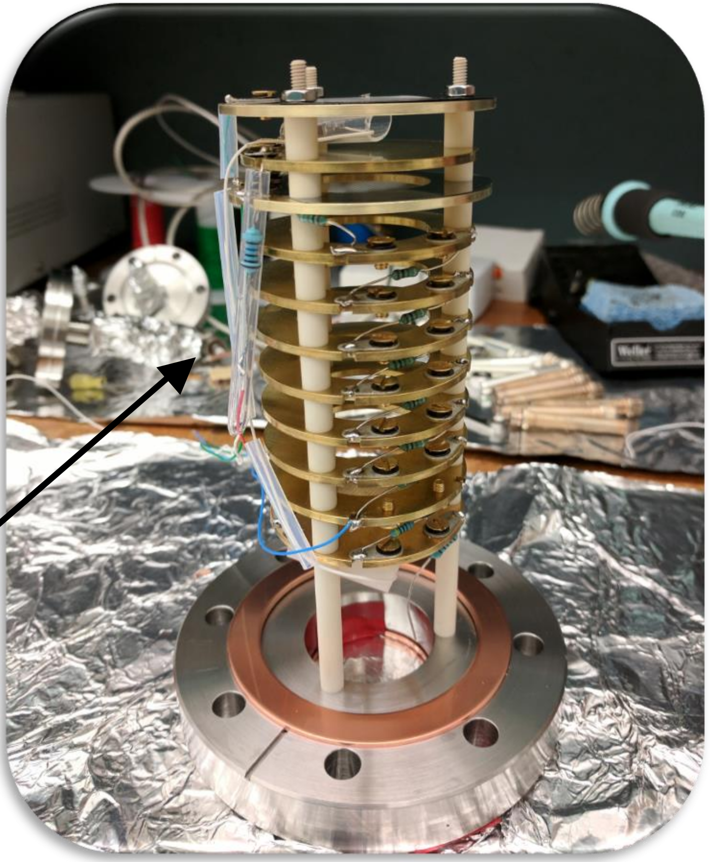


Cathode + HV feedthrough

XeBrA contains a purity monitor

- Directly connected to XeBrA
- Monitors LXe & LAr purity
- Purity calculated from electron lifetime τ
  - Electrons generated on the cathode / number of electrons not captured by impurities on their way to the anode
- Can be converted to oxygen-equivalent concentration
  - ρ[ppb]~408/τ[μs] in LAr
  - ρ[ppb]~455/τ[μs] in LXe





See, for example:

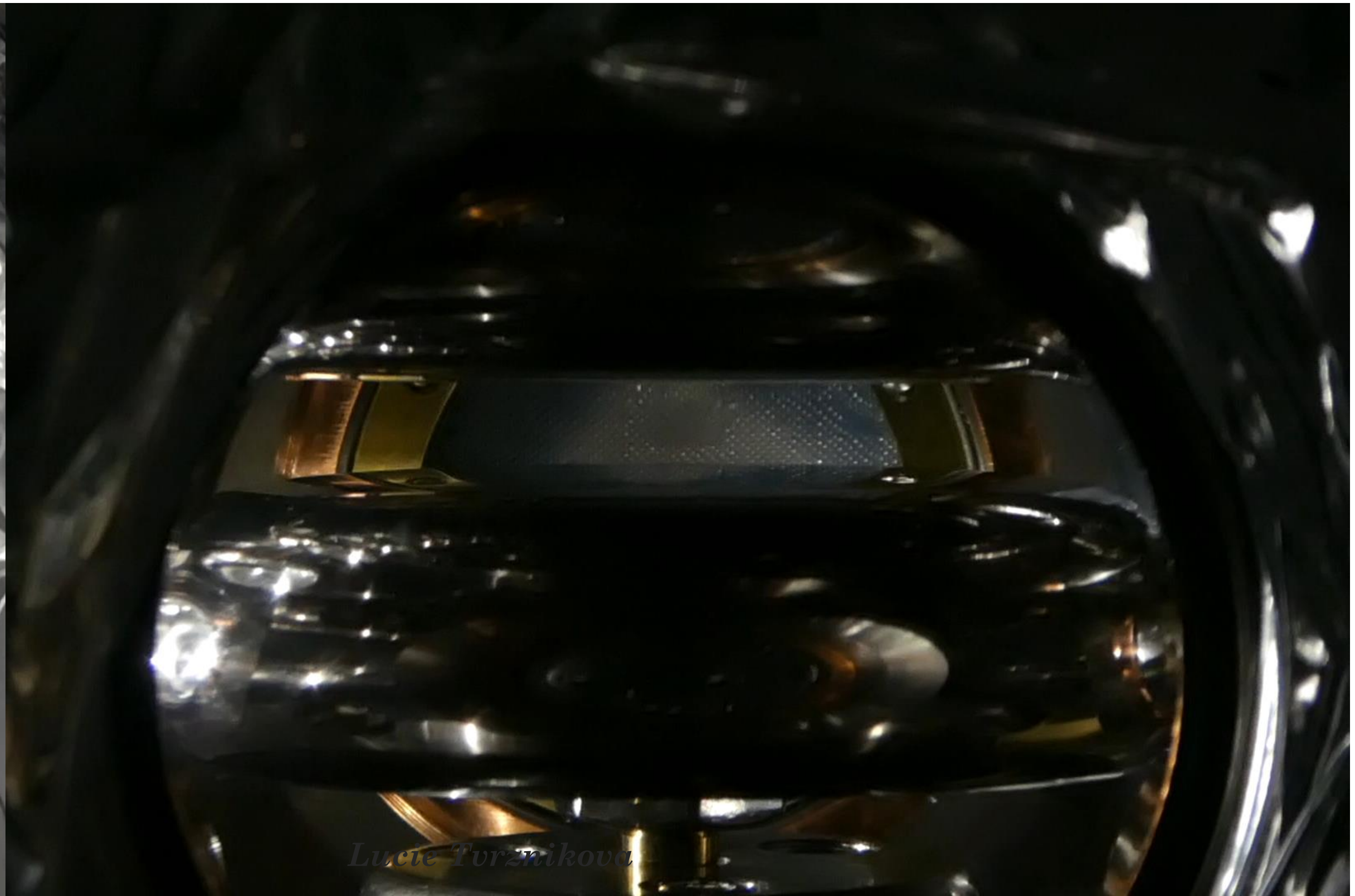
A. Bettini, et al. NIM A 305.1 (1991)
G. Carugno, et al. NIMA 292.3 (1990)
Y. Li, et al. JINST 11 T06001 (2016)

Sparks & bubbles in LAr and LXe

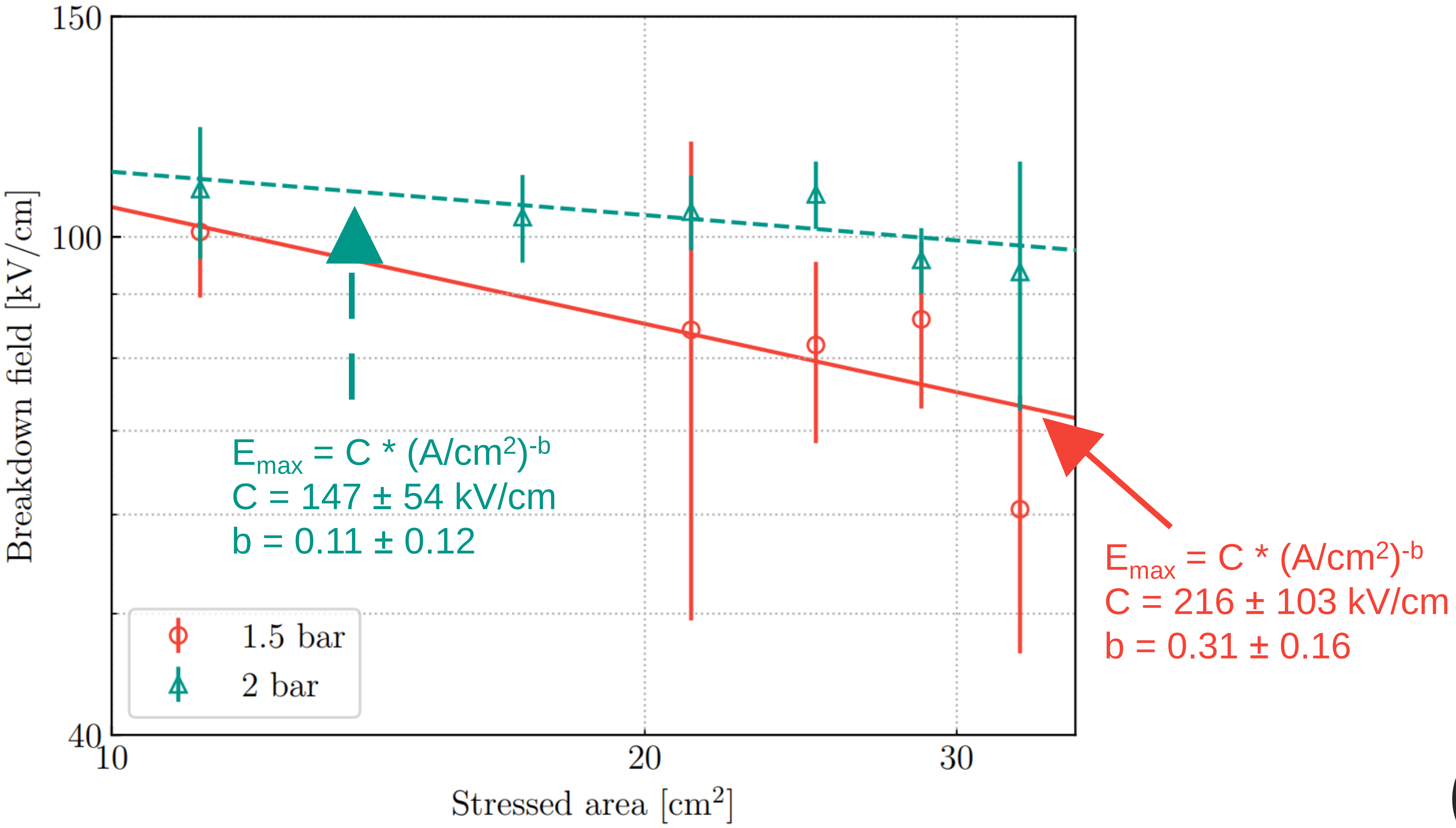
- [Bubbles in LXe (3 hours of it): goo.gl/xaKvQN]
- [Selection of sparks in LXe]
- [Selection of sparks in LAr]

Spark at 5mm in LXe

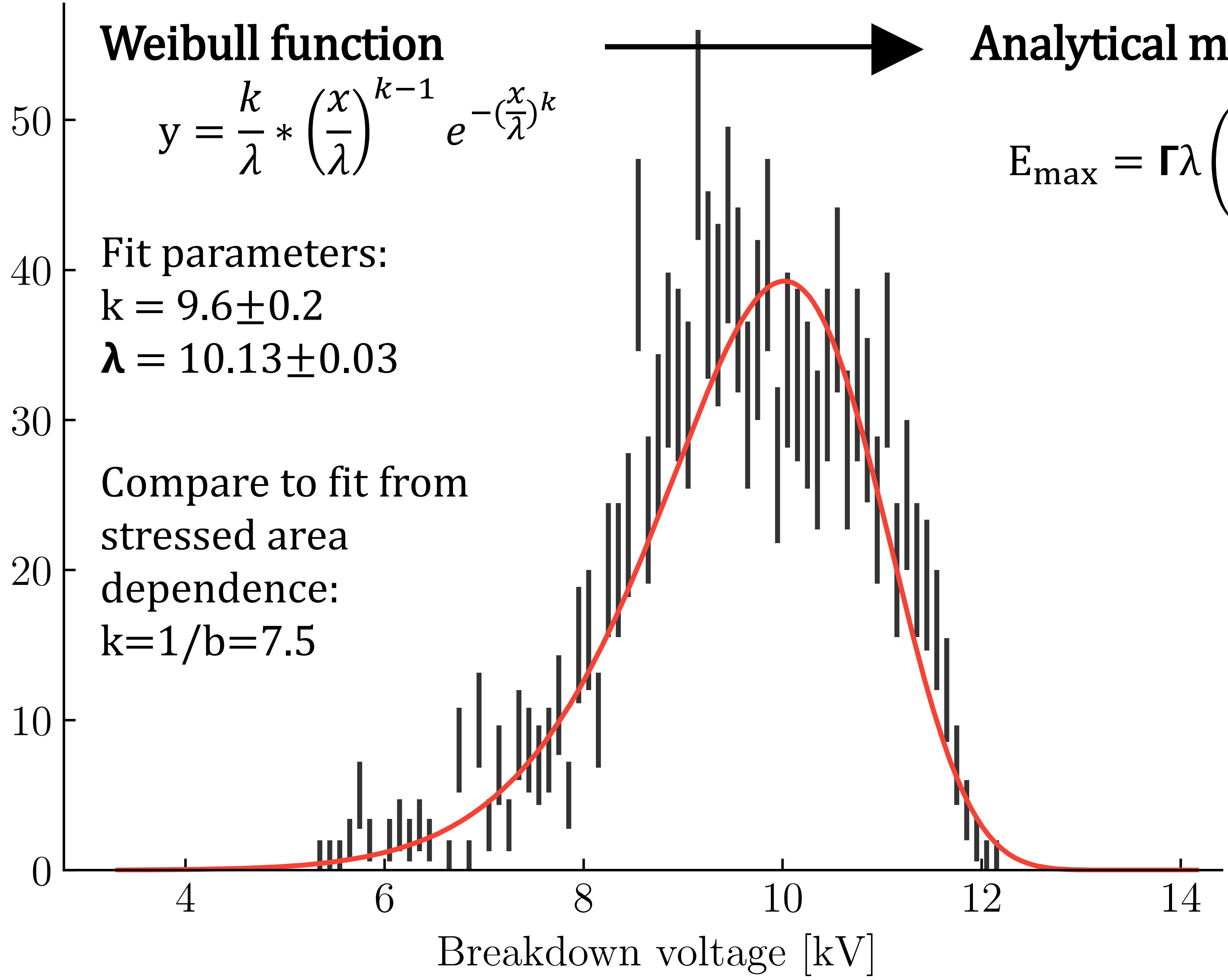
Spark at 7mm separation in LAr



Breakdown field vs. stressed area & pressure in LAr



Breakdown distribution in LXe: Weibull function



Weibull function

$$y = \frac{k}{\lambda} * \left(\frac{x}{\lambda}\right)^{k-1} e^{-\left(\frac{x}{\lambda}\right)^{k}}$$

Analytical mean

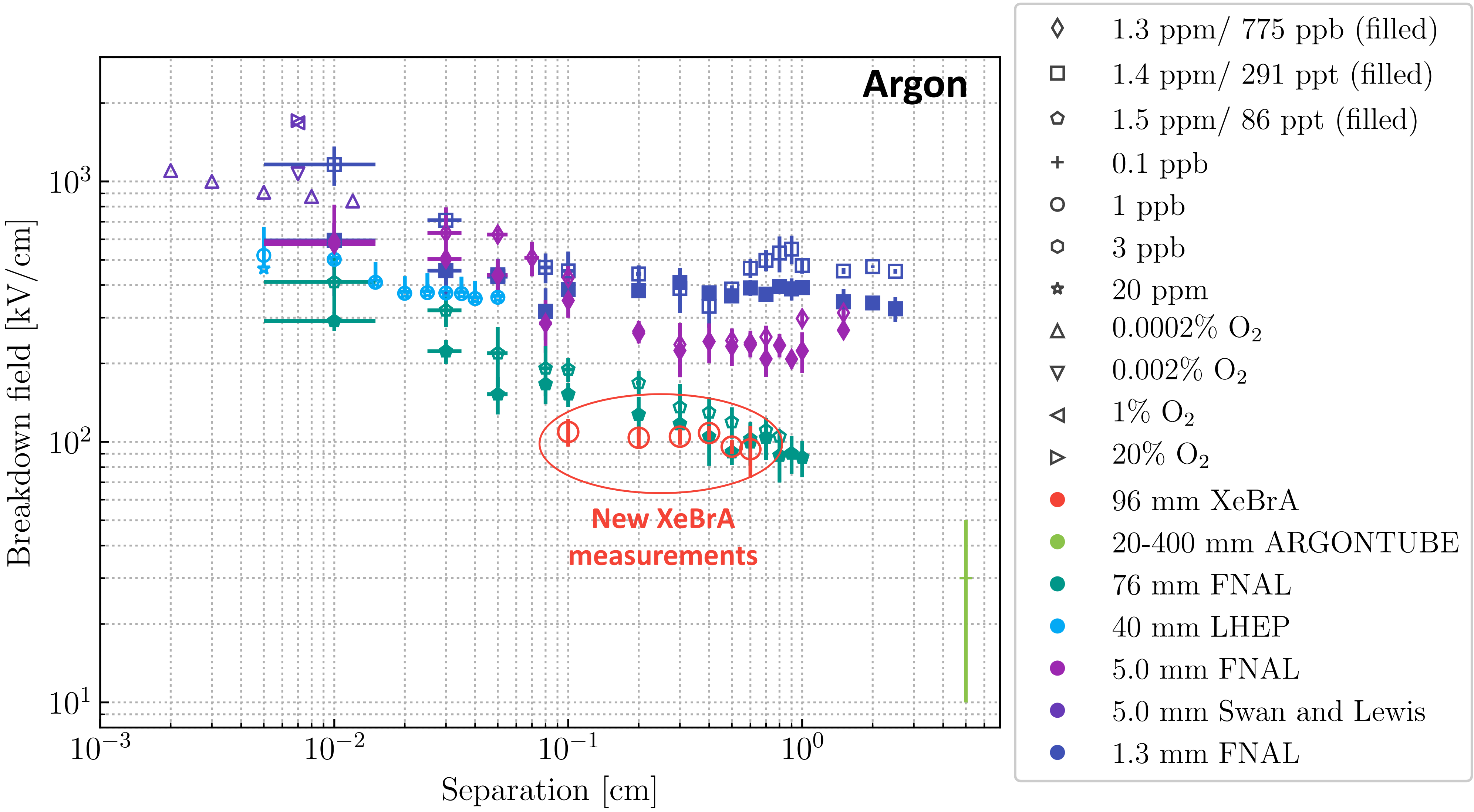
$$E_{max} = \Gamma\lambda\left(1 + \frac{1}{k}\right)\left(\frac{A}{A_0}\right)^{-\frac{1}{k}}$$

Fit parameters:
k = 9.6±0.2
λ = 10.13±0.03

Compare to fit from stressed area dependence:
k=1/b=7.5

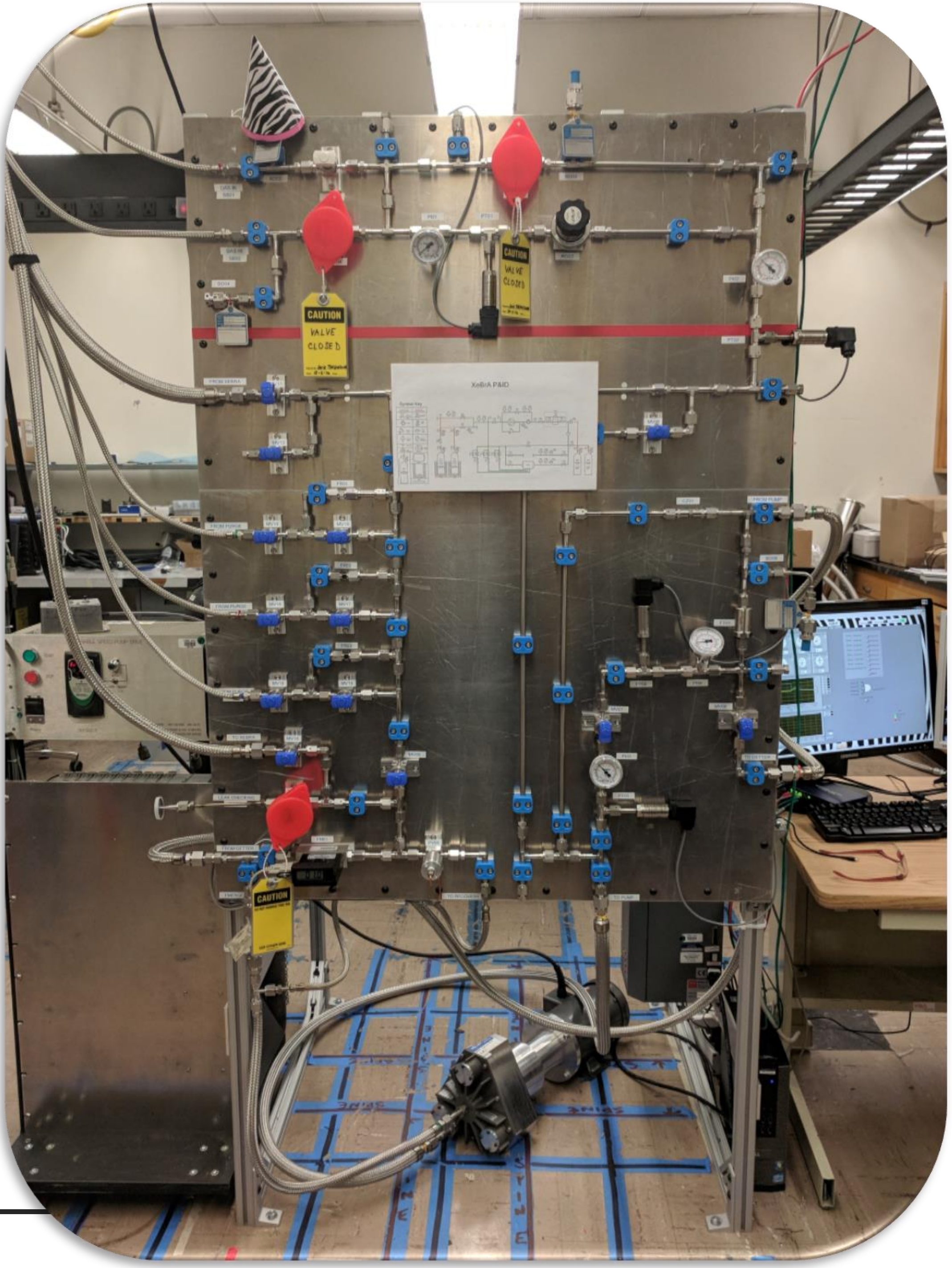
30

Breakdown field vs. separation in LAr

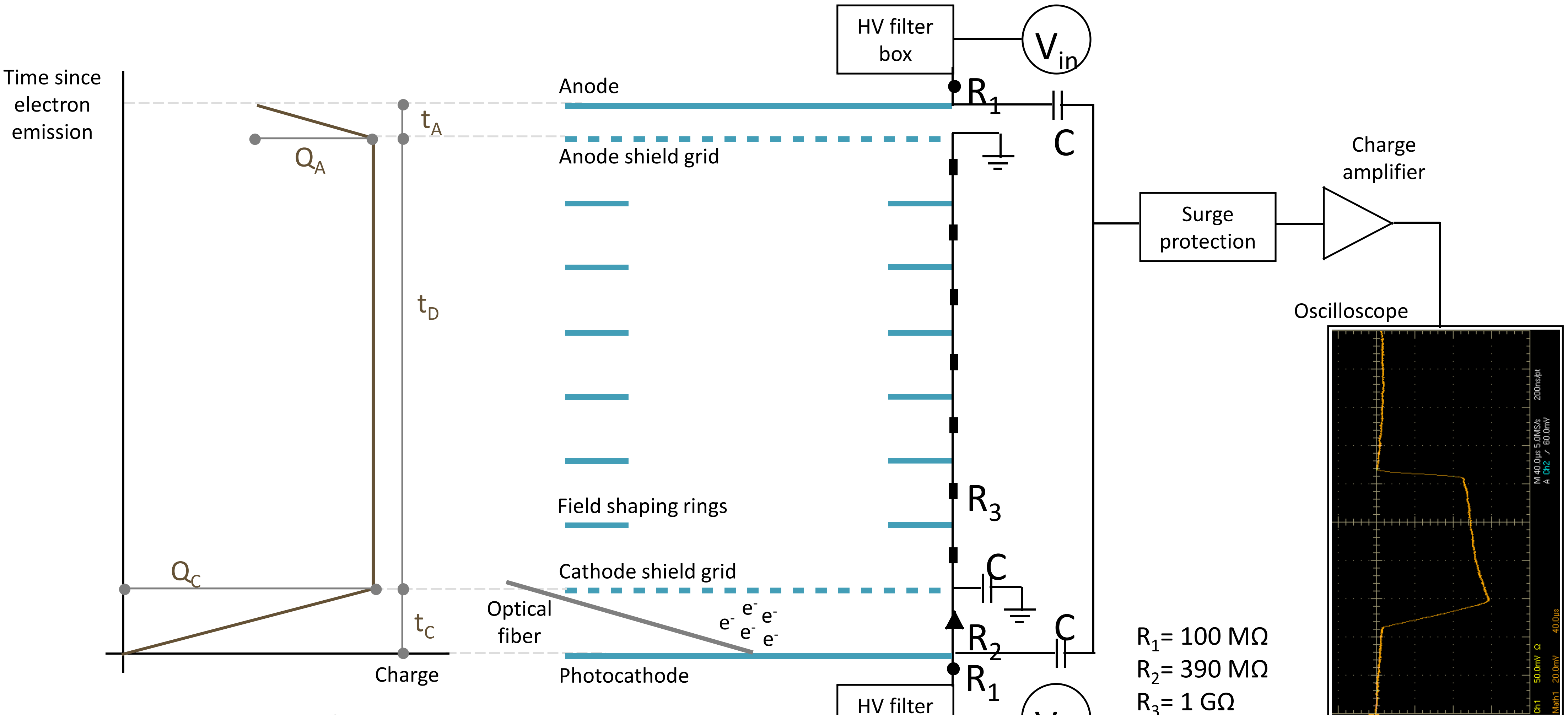


Gas system

- Built to serve multiple apparatuses



Purity monitor schematics



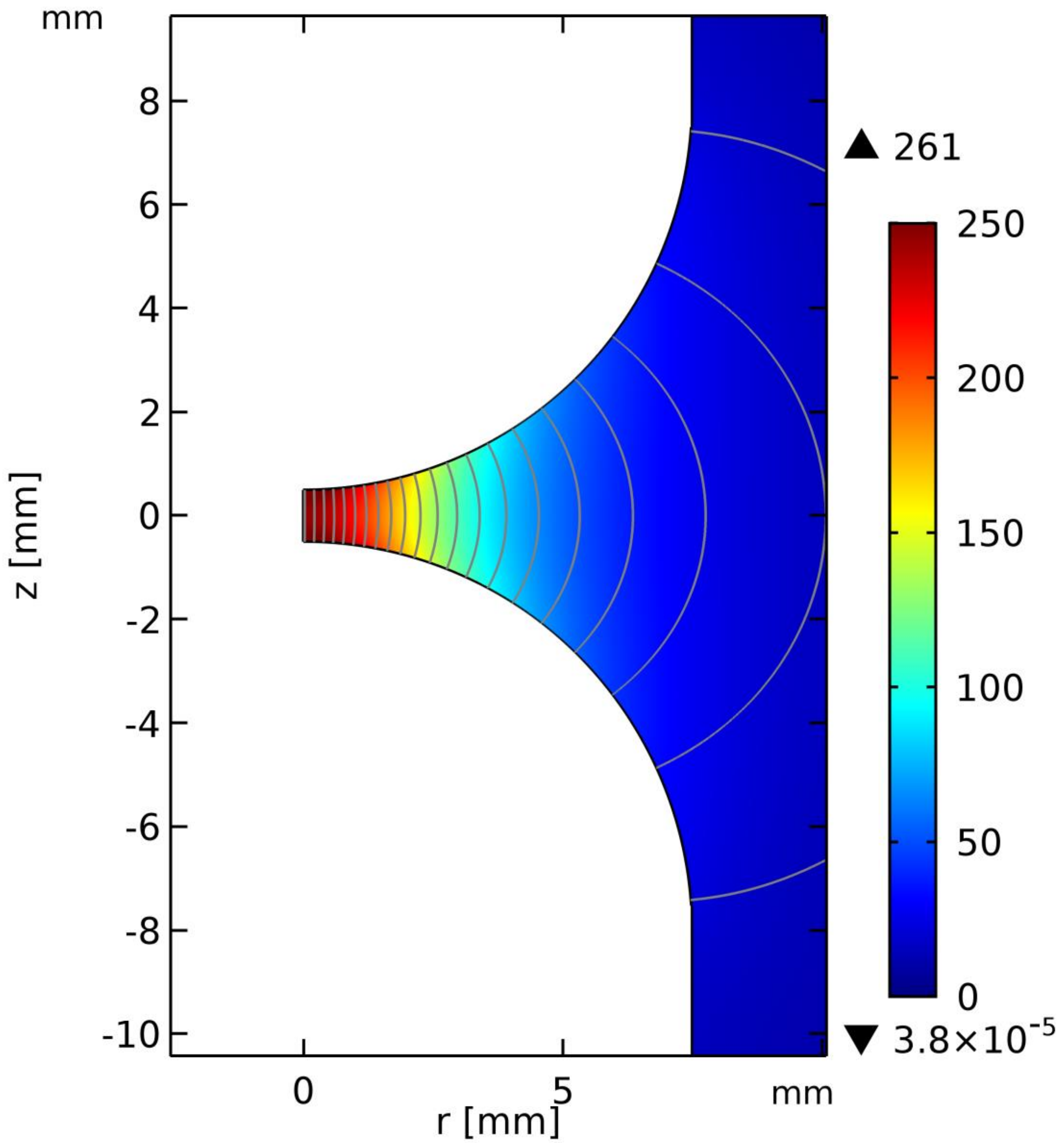
$$Q_A/Q_C = e^{-t/\tau}$$

Xenon data point from SLAC

Peter Rowson published breakdown field from his setup with two 1.5 cm diameter spheres separated by 1mm

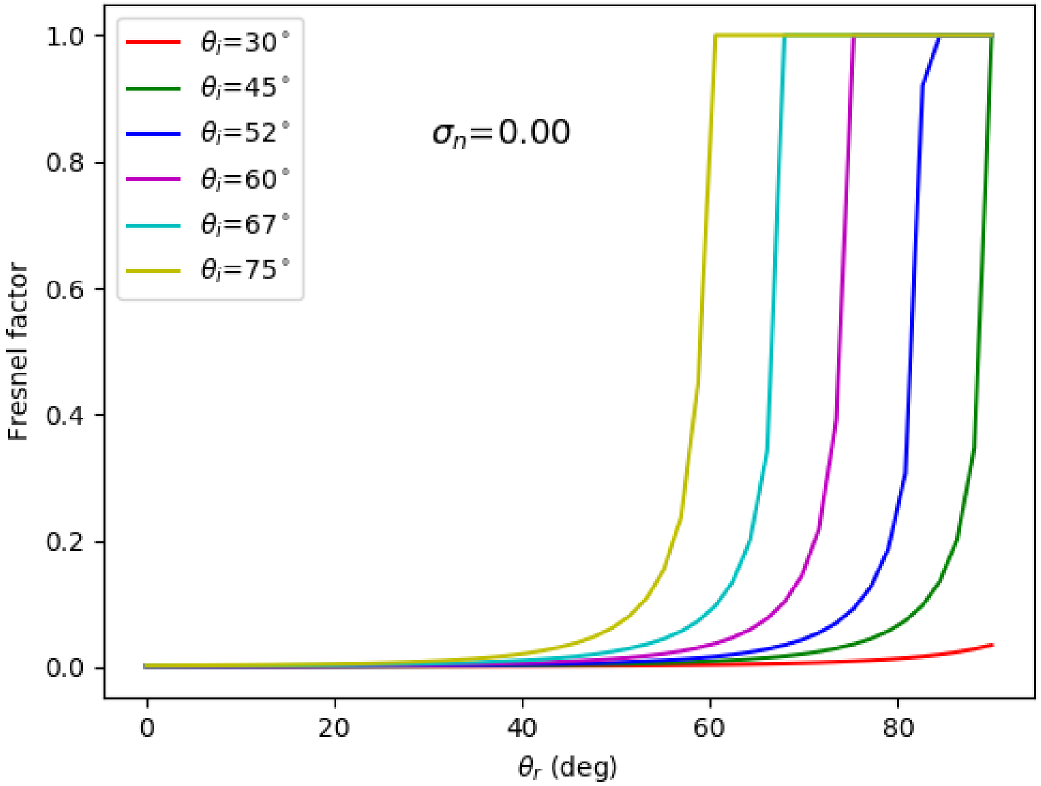
My simple COMSOL sim shows that SLAC setup has area of ~3.1 mm^2

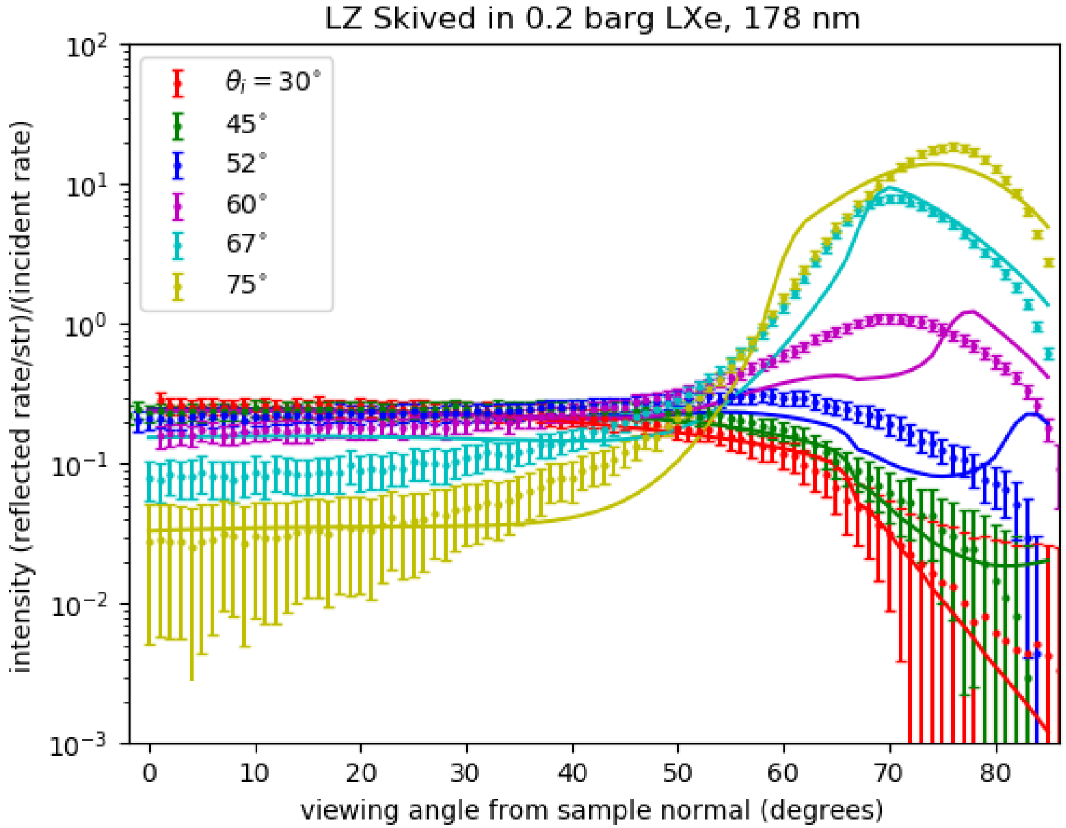
For detail see p. 31: http://iopscience.iop.org/article/10.1088/1748-0221/9/08/T08004/pdf



Modifications to model in LXe

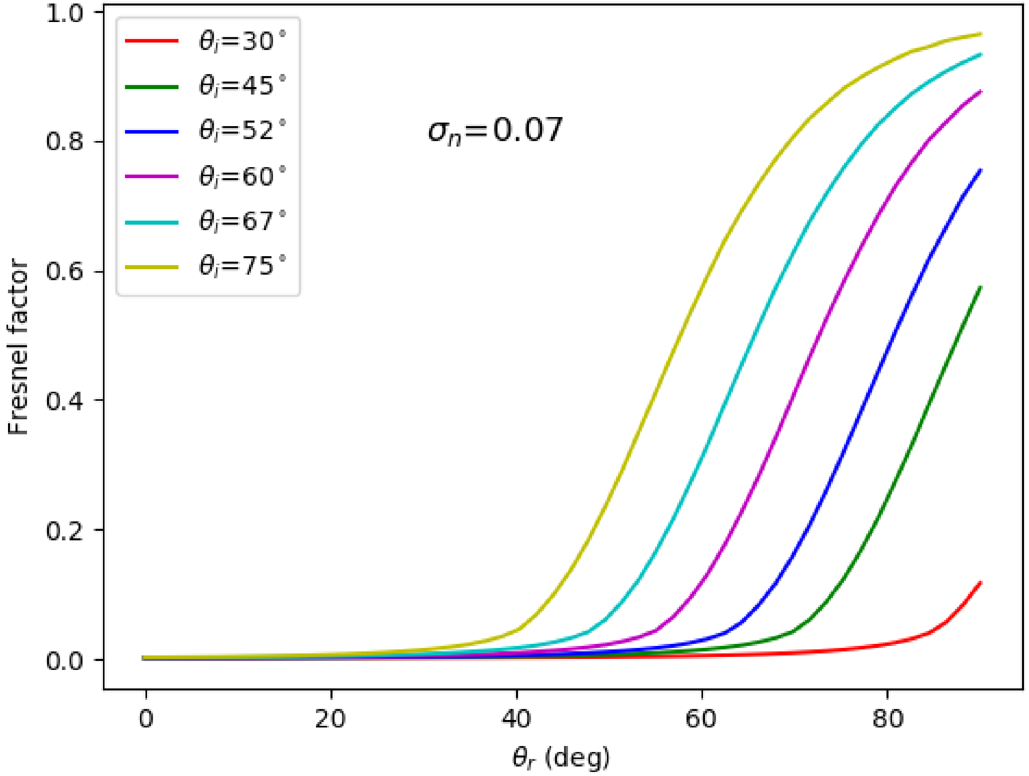
Sharp rise in Fresnel factor results in sharper features in model than are observed in data

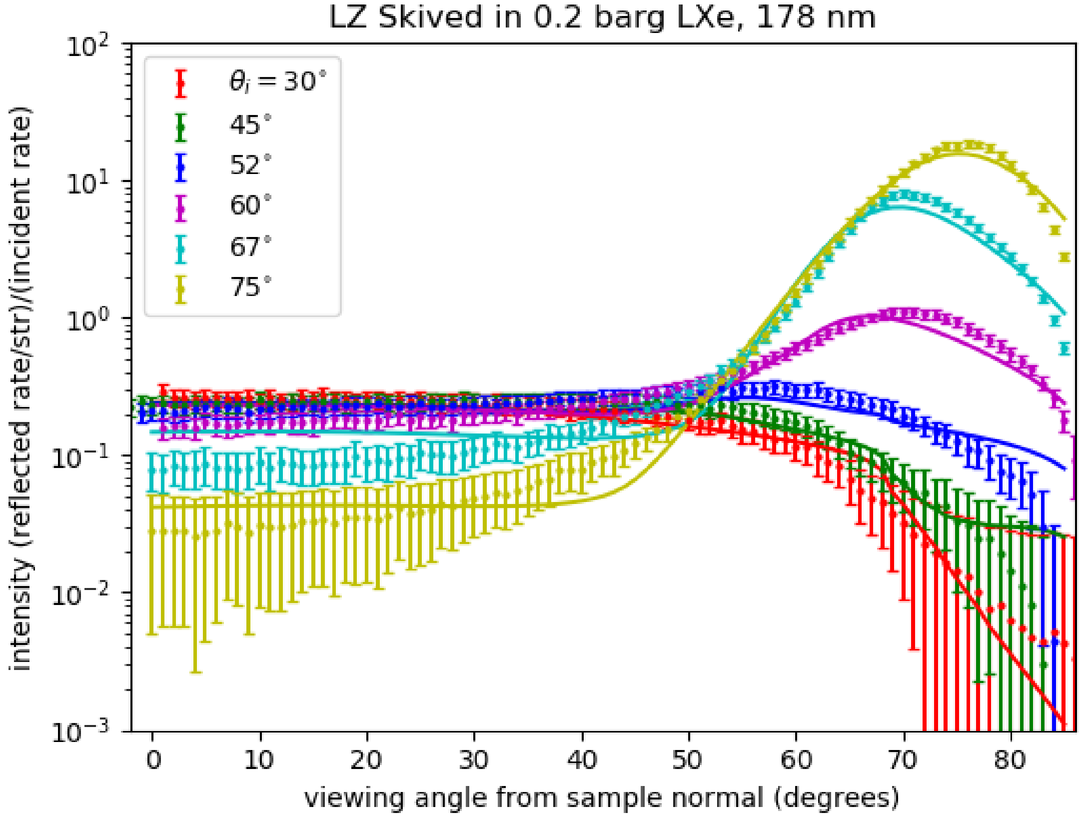




Modifications to model in LXe

LXe fit improved markedly by using Gaussian distribution of index ratio n_{PTFE}/ n_{LXe}





Comparison to calibrated total reflectance

Three samples (including one shown above) sent to Labsphere for total reflectance measurements at several wavelengths

Same trend with wavelength observed, IBEX measures lower reflectance by average of ~8%

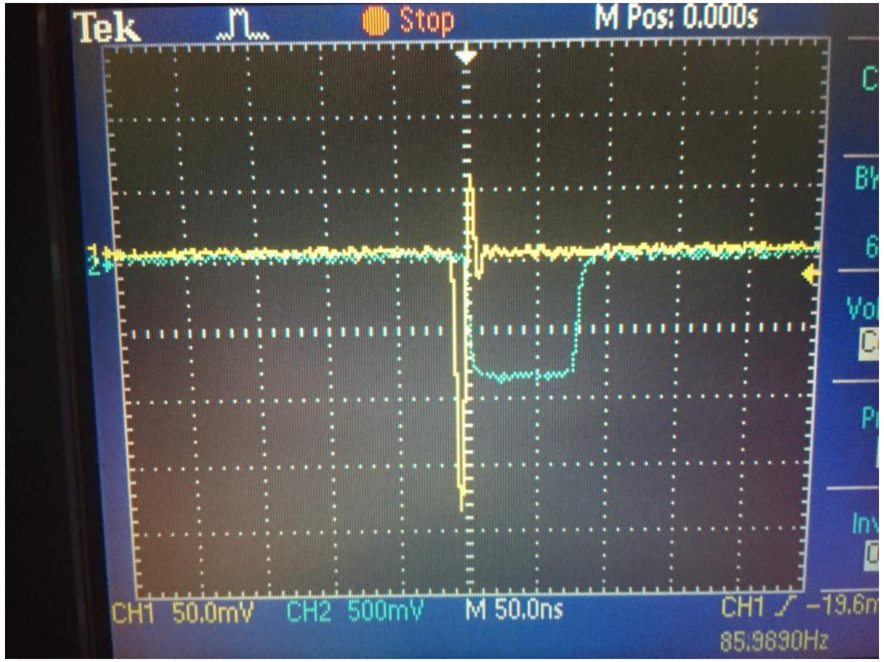
Wavelength	IBEX reflectance	Labsphere reflectance
255nm	0.87	0.91
310nm	0.90	1.06
400nm	0.78	0.74
500nm	0.64	0.68

Readout

NIM modules

PMT → Amplifier → Discriminator → Amplifier → Ratemeter → Digitizer (Lock-in) → Computer

Kept running for temperature stability



- Pulse counting
- Validated and optimized by cross-check with digitized waveforms
- Discriminator threshold set for minimal effect of changing PMT gain
- Incident rate always measured before/after datasets to ensure normalization of reflectivity data is accurate

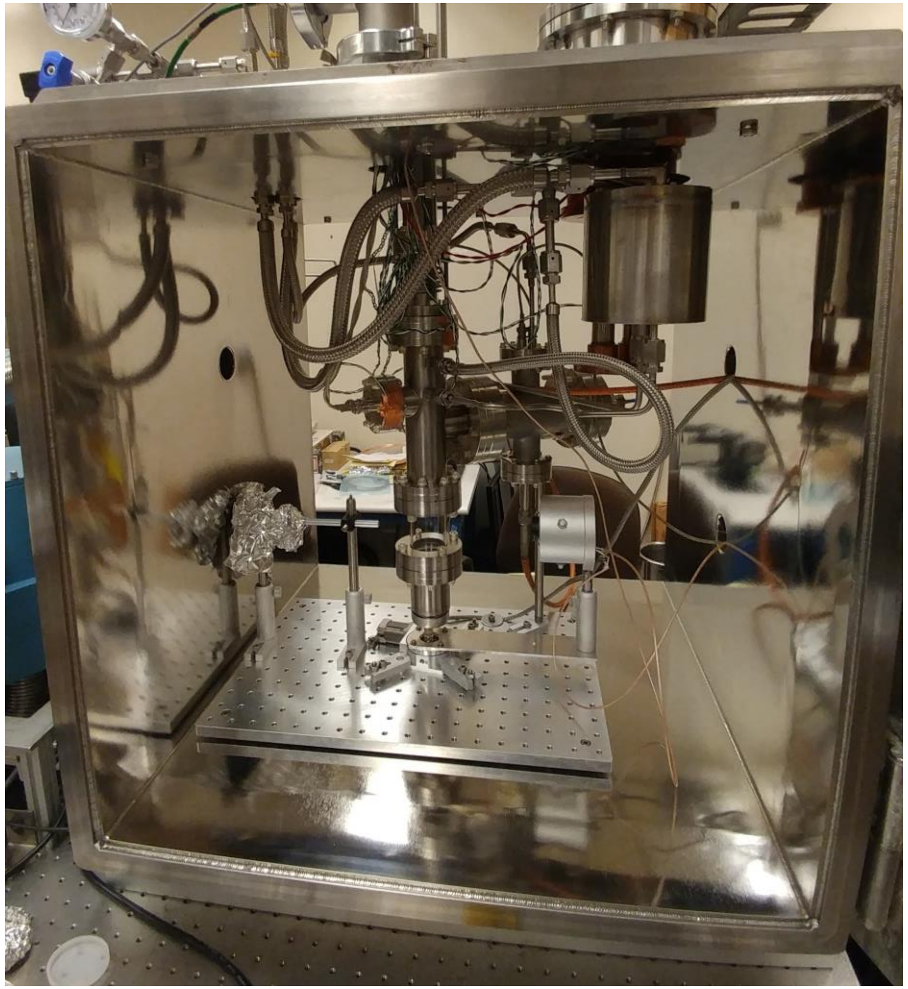
LXe Handling

Heat exchanger attached to pulse tube refrigerator provides cooling

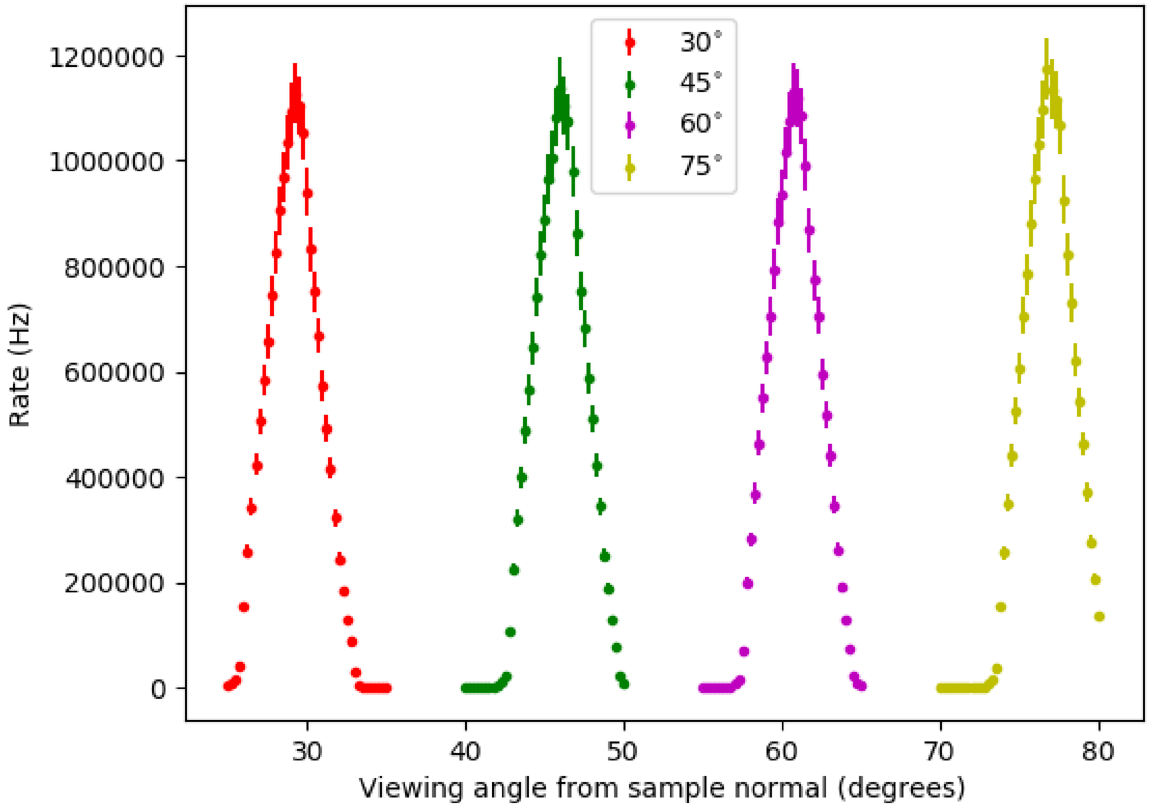
Capability to continuously circulate LXe, purify w/ getter

Liquid purity monitor instrumented

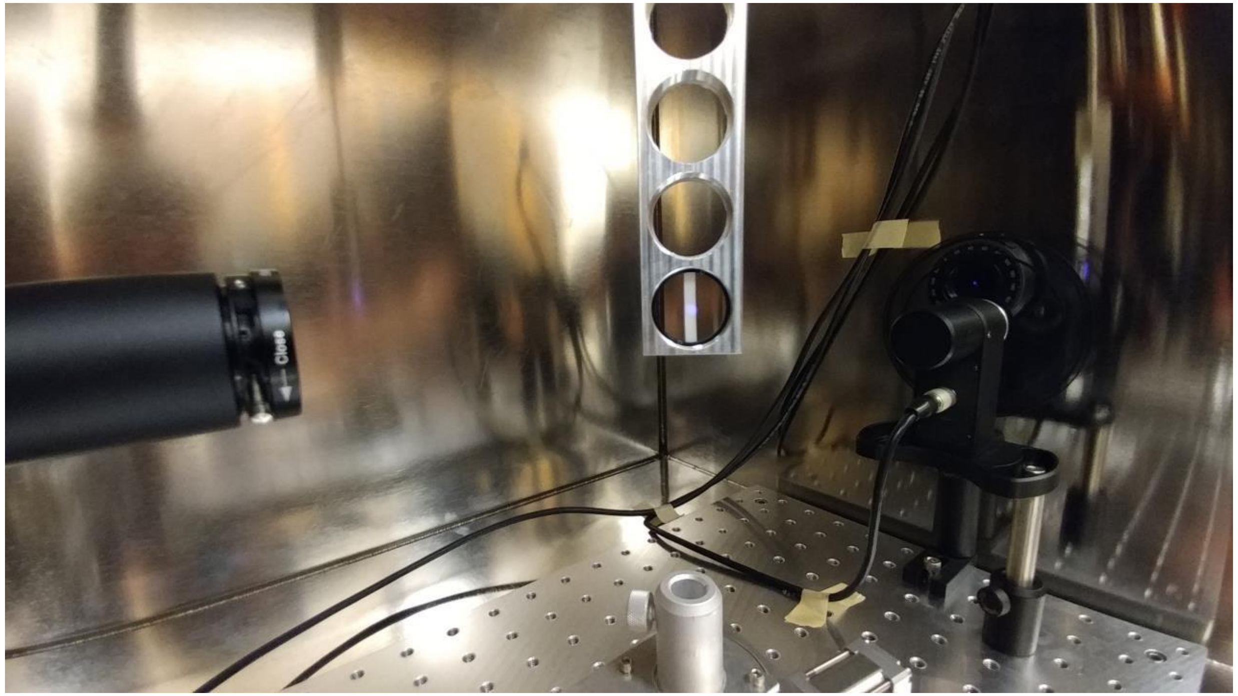
Issues w/ getter
- Didn't seem to purify LXe
- Purity too poor to measure w/ monitor



Alignment and calibration



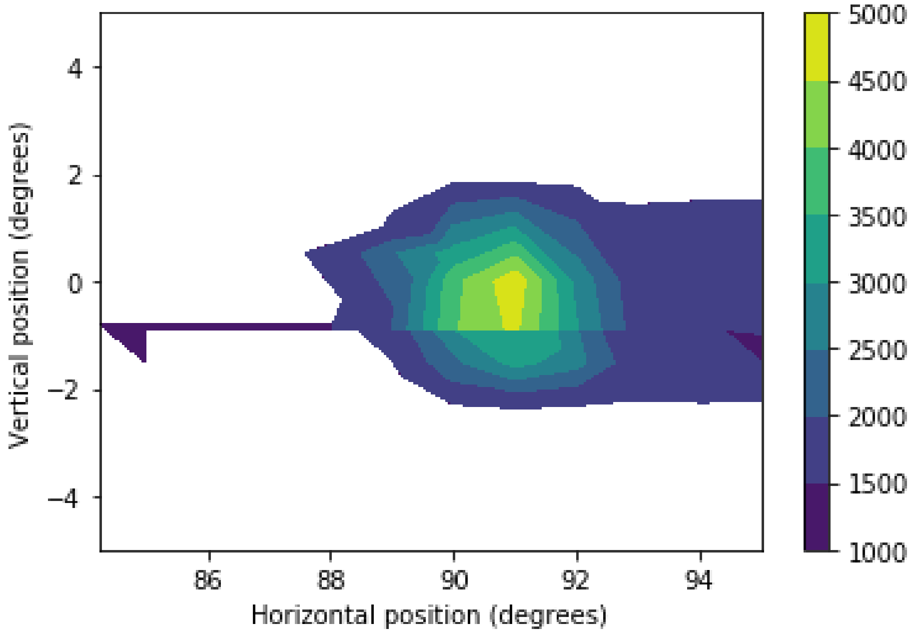
Mirror measurements allow us to check alignment of rotation axes, calibrate incident angles



Aligning beam to center of sample

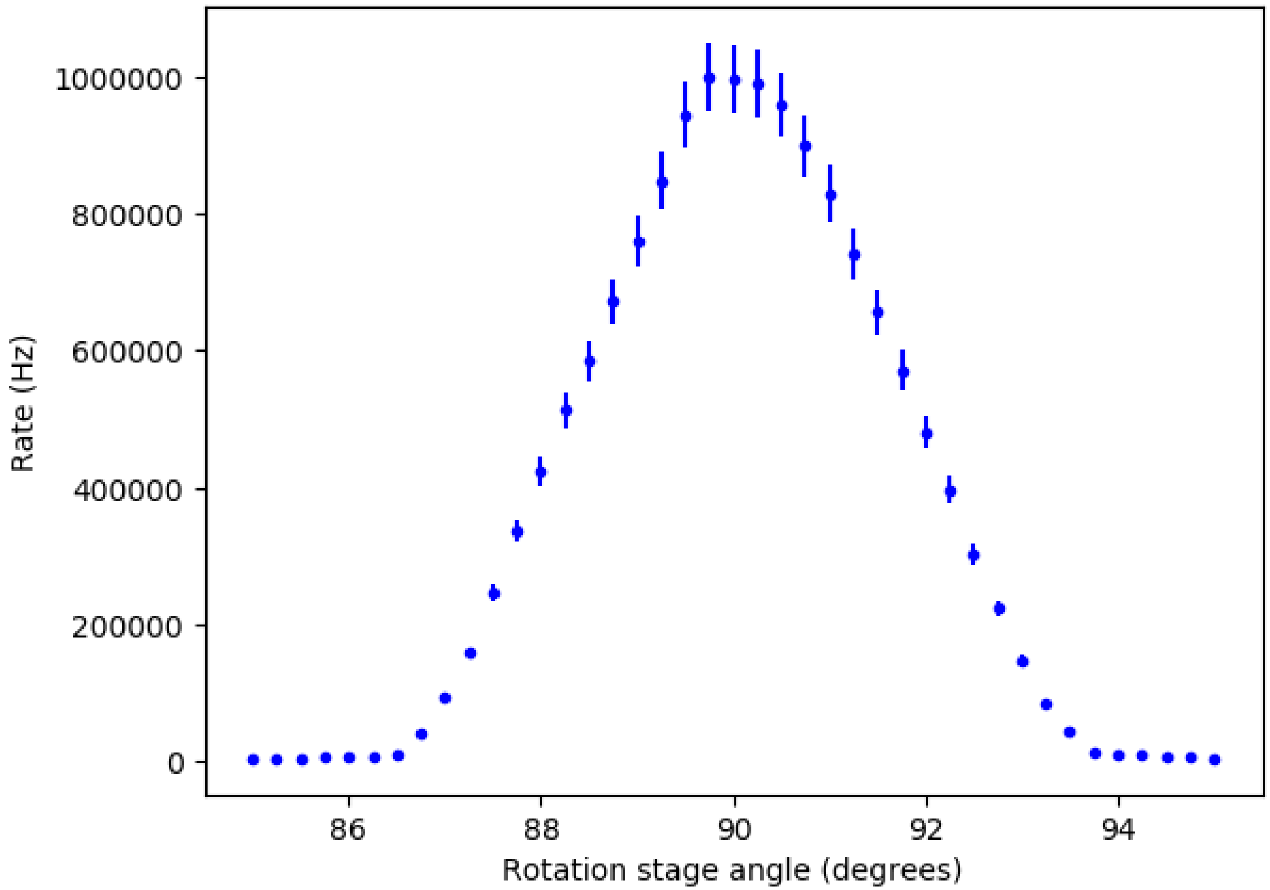
Alignment and calibration

Measurements of 2d profile of unobstructed beam are used to set height of PMT, zero of rotation stage



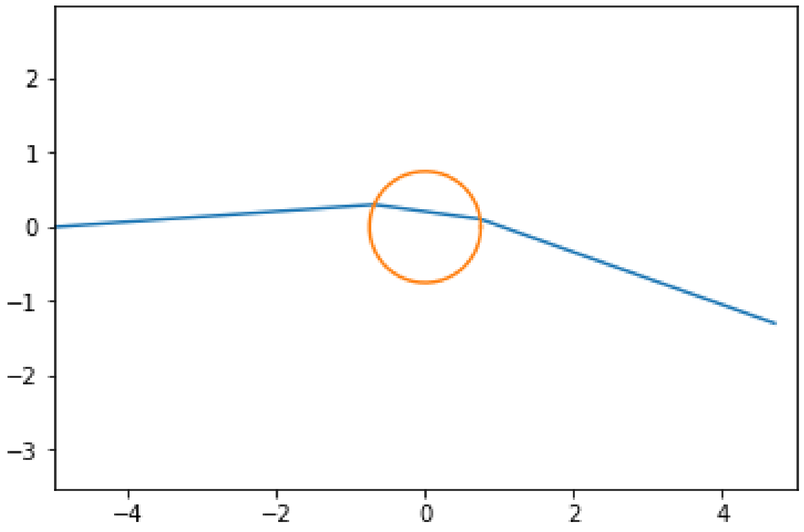
Power measurement

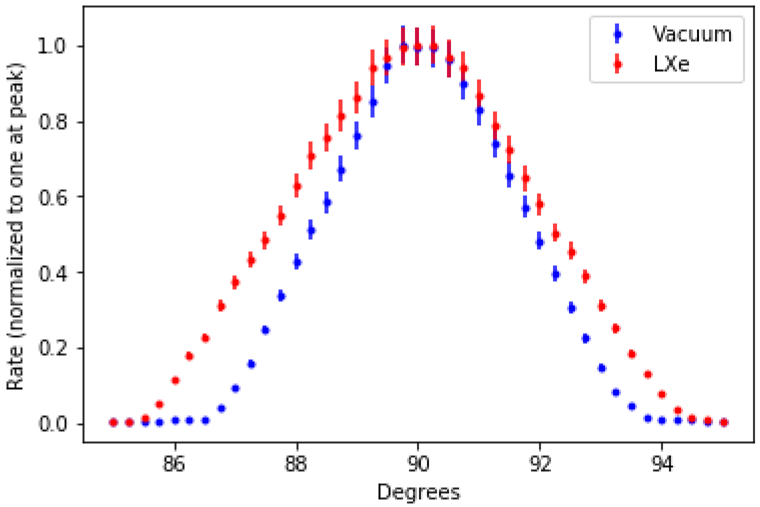
Sweep PMT across beam when sample rack is out of its path, record peak rate

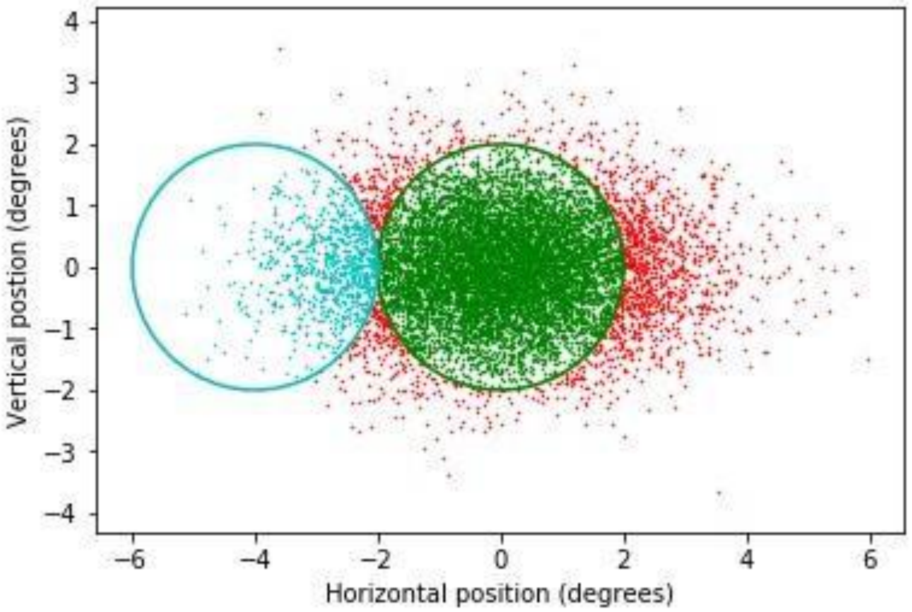


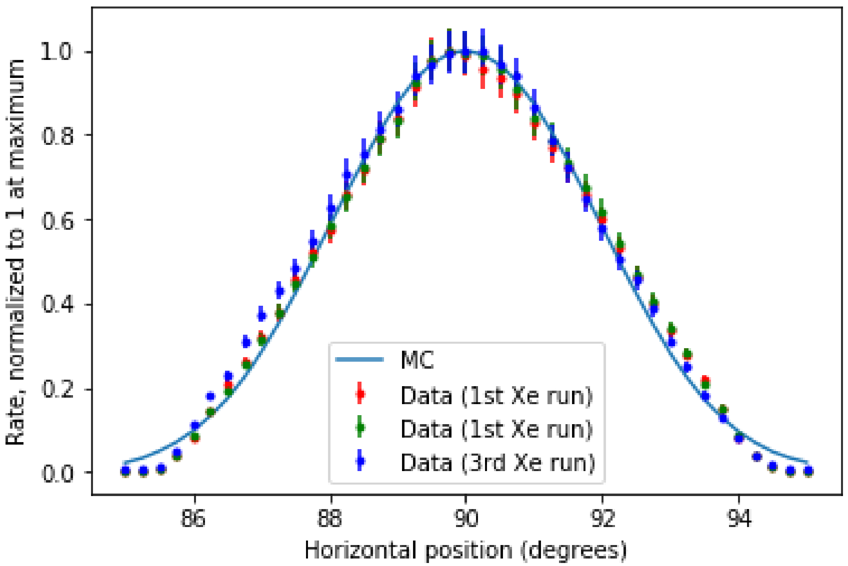
Beam lensing

When running in LXe, beam at PMT distance is spread out by lensing at cell





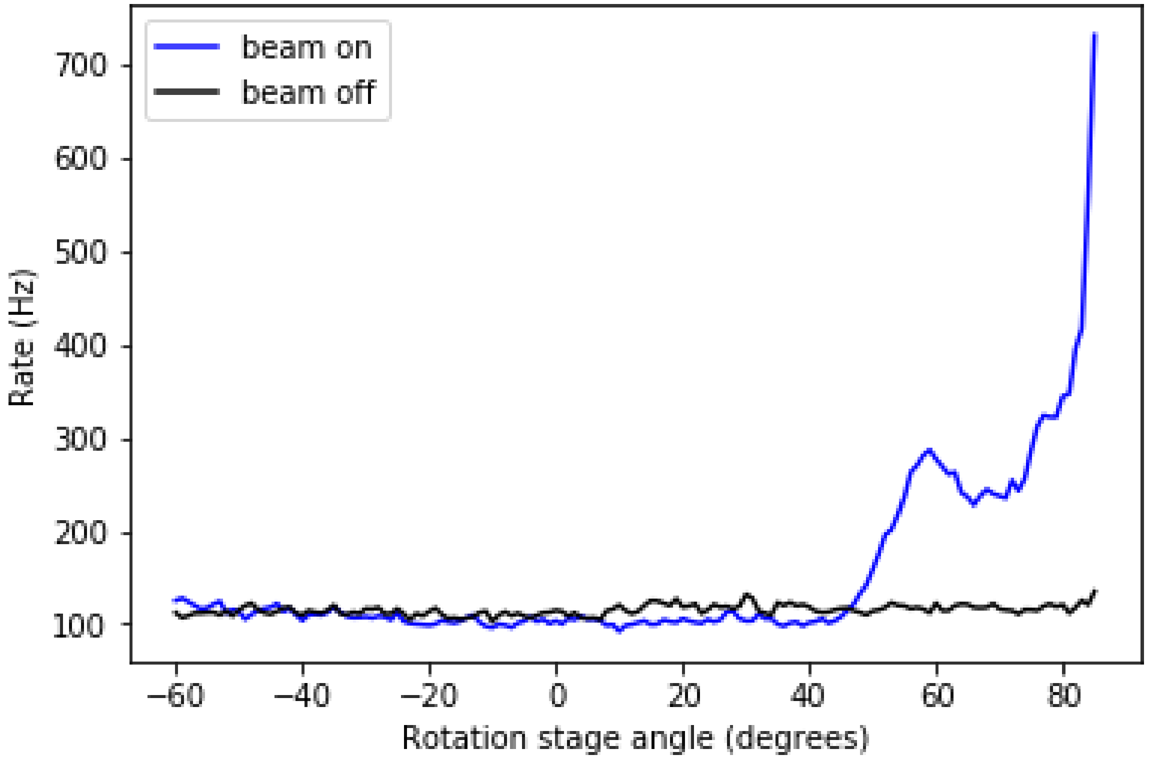




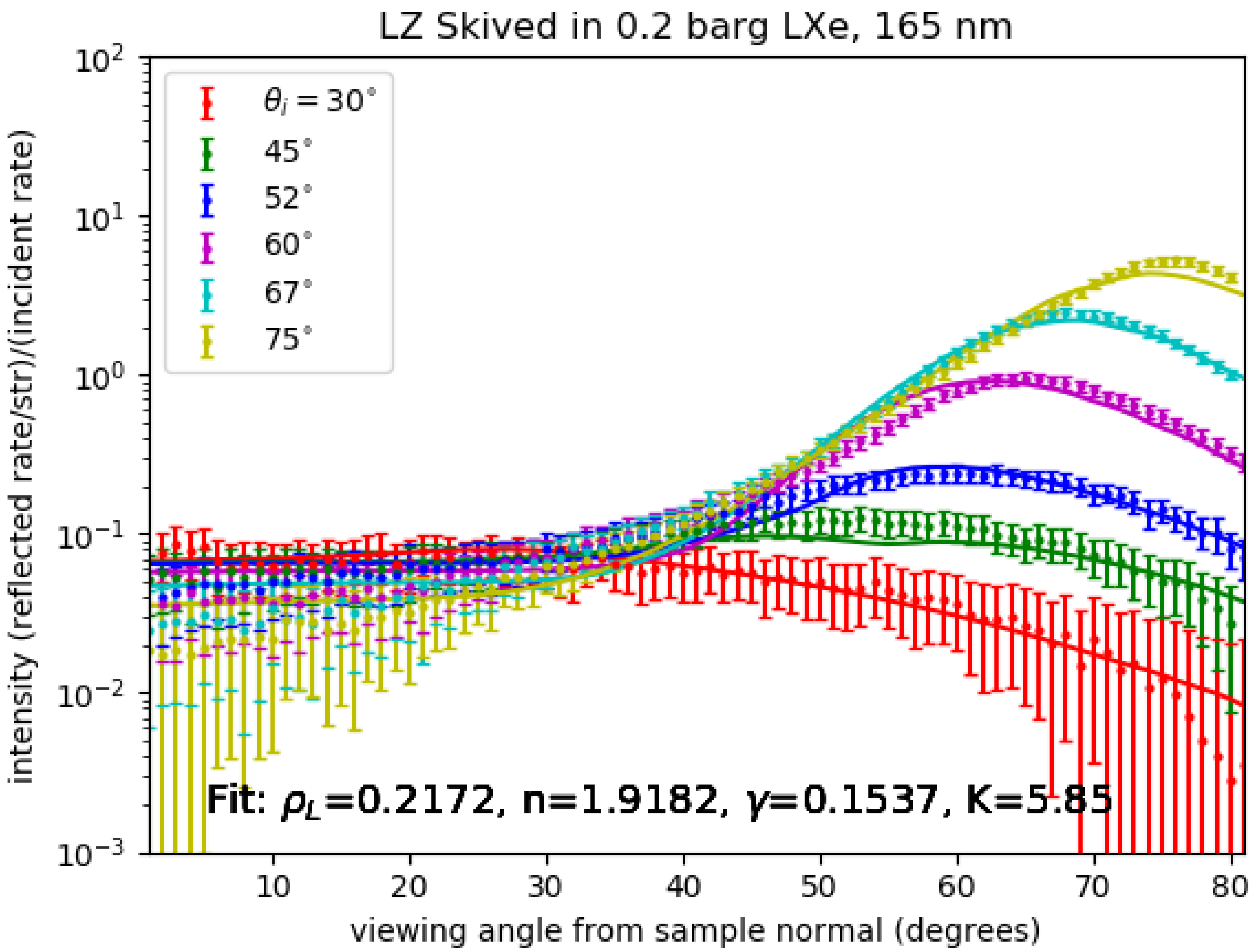
Power correction factor determined from Monte Carlo

Background measurement

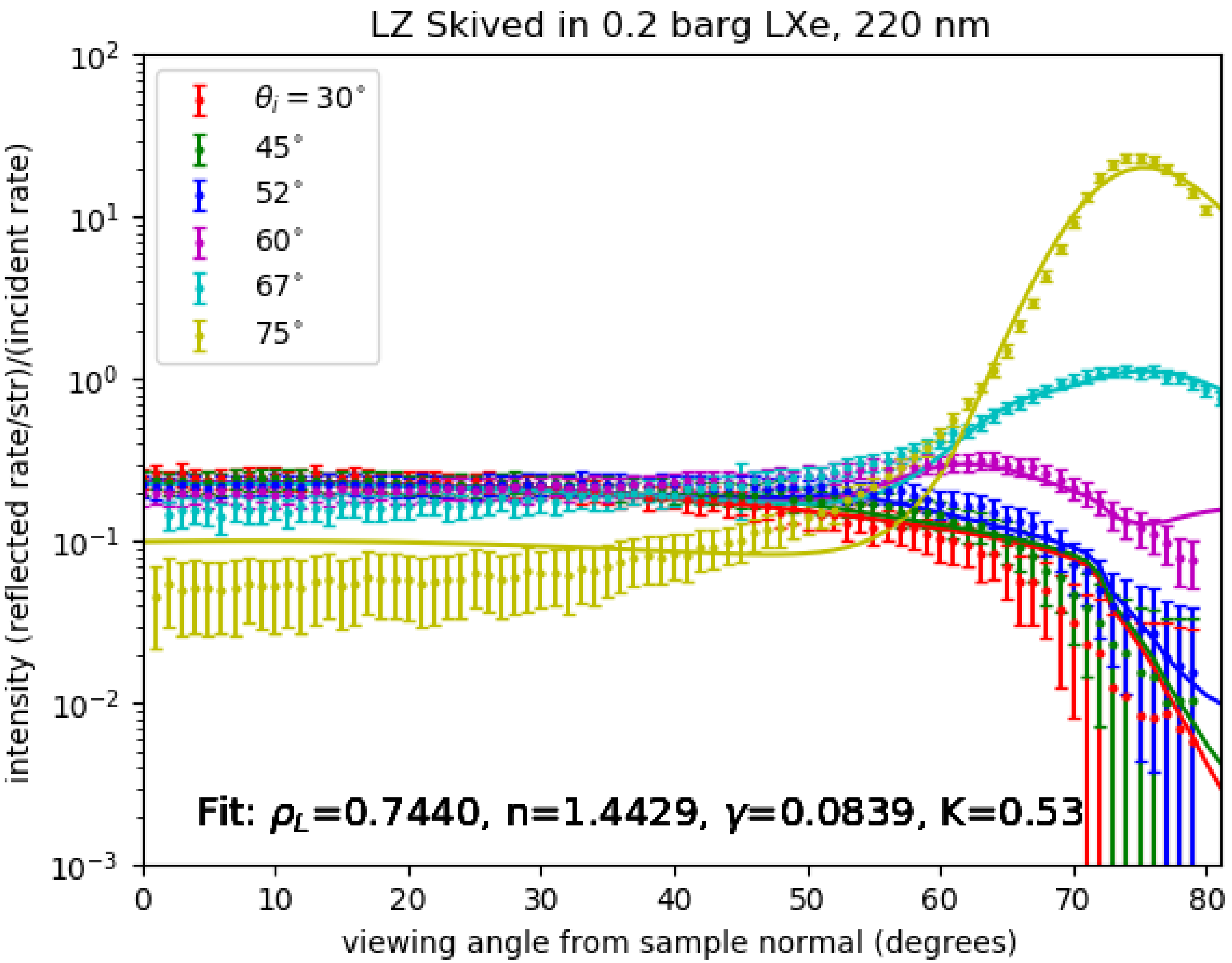
Taken with sample rack out of beam path



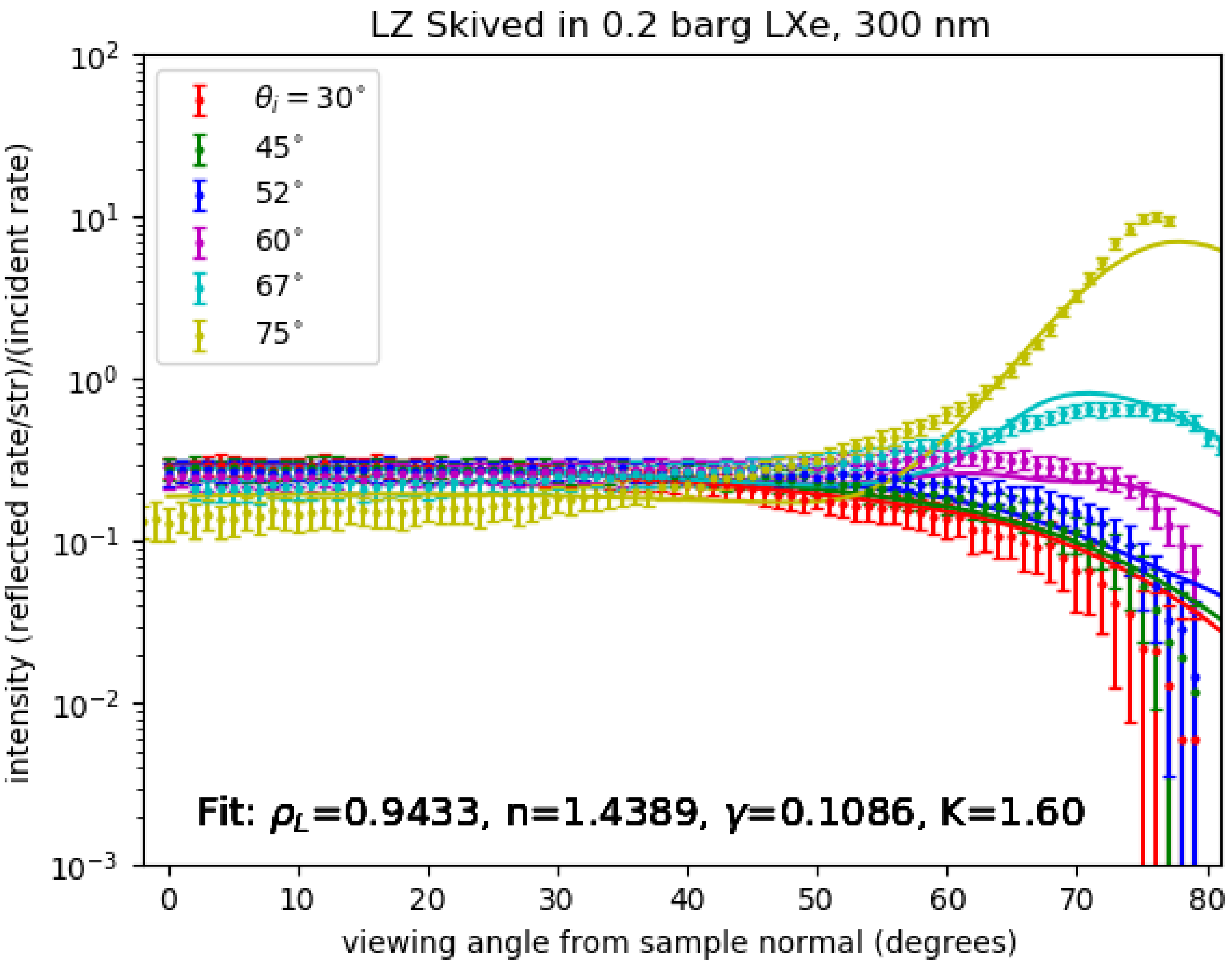
LXe data at other wavelengths



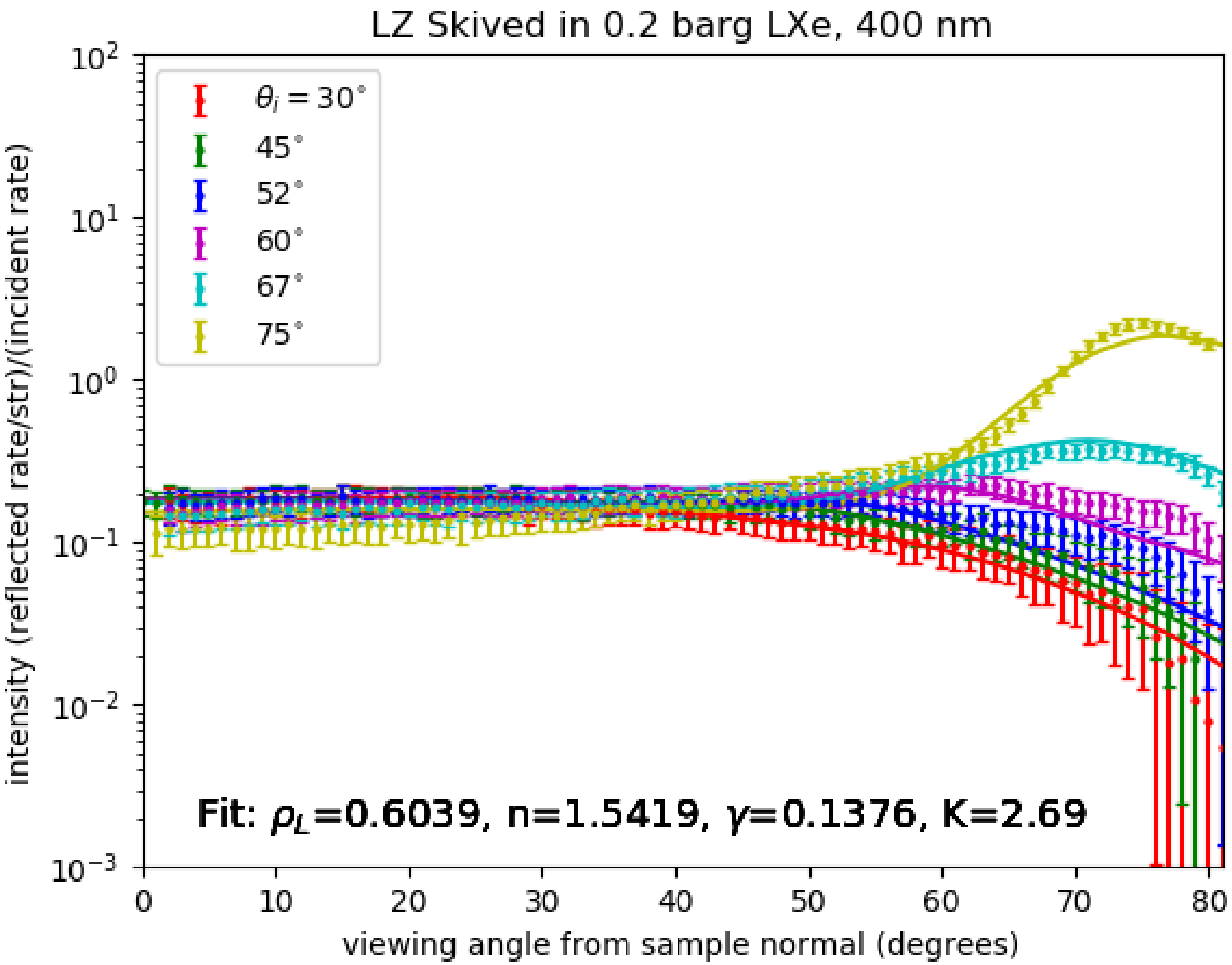
LXe data at other wavelengths



LXe data at other wavelengths



LXe data at other wavelengths

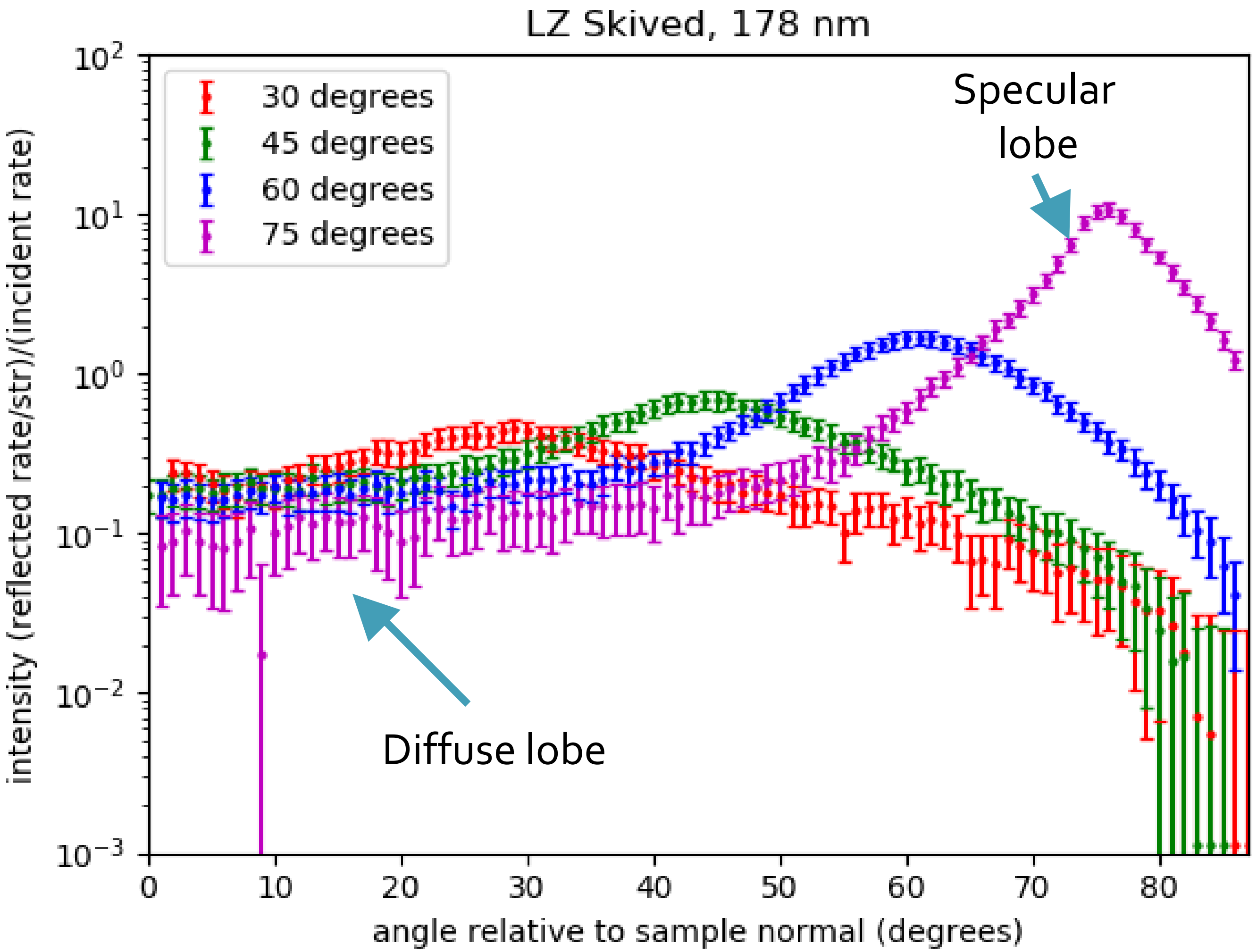


Model

- Based off of Coimbra group's model

$$\varrho = \varrho_D + \varrho_S$$

$$= \frac{\rho_l}{\pi} WN \cos\theta_r + \frac{1}{4\cos\theta_i} FPG$$



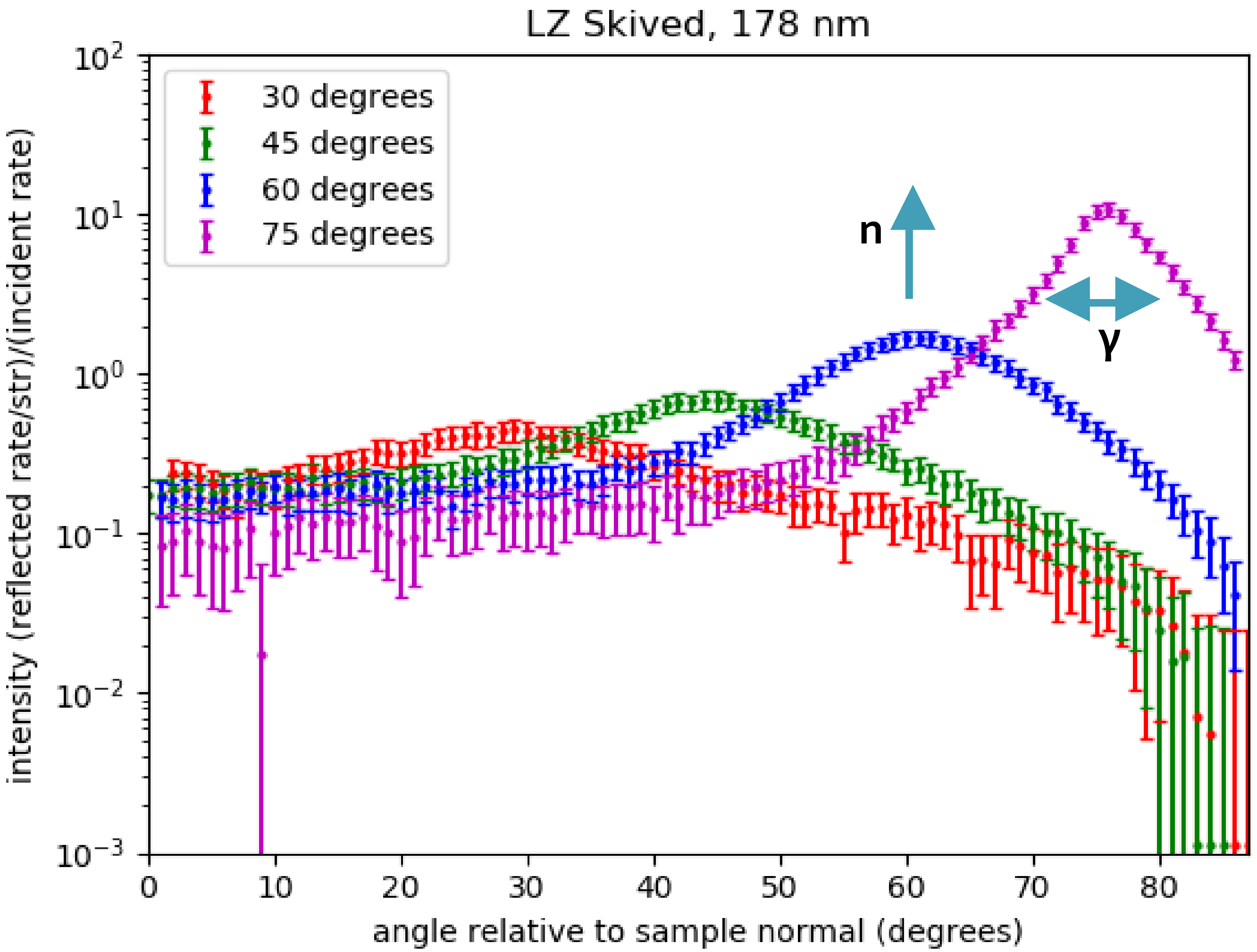
Model

- Based off of Coimbra group's model

$$\varrho = \varrho_D + \varrho_S$$

$$= \frac{\rho_l}{\pi} W N \cos\theta_r + \frac{1}{4\cos\theta_i} F P G$$

Mirror reflection off of microfacets:
Surface roughness modeled using planes at varying angles w/ probability distribution P(γ)
Specular lobe is wider/shorter for larger γ (rougher surface); γ is a free parameter
Scaled by Fresnel coefficient for specular angle, F, and geometric solid angle factors:
Depends on PTFE index, n, also varies in fit
Specular lobe is stronger for larger difference in index between PTFE and surrounding medium, higher incident angles



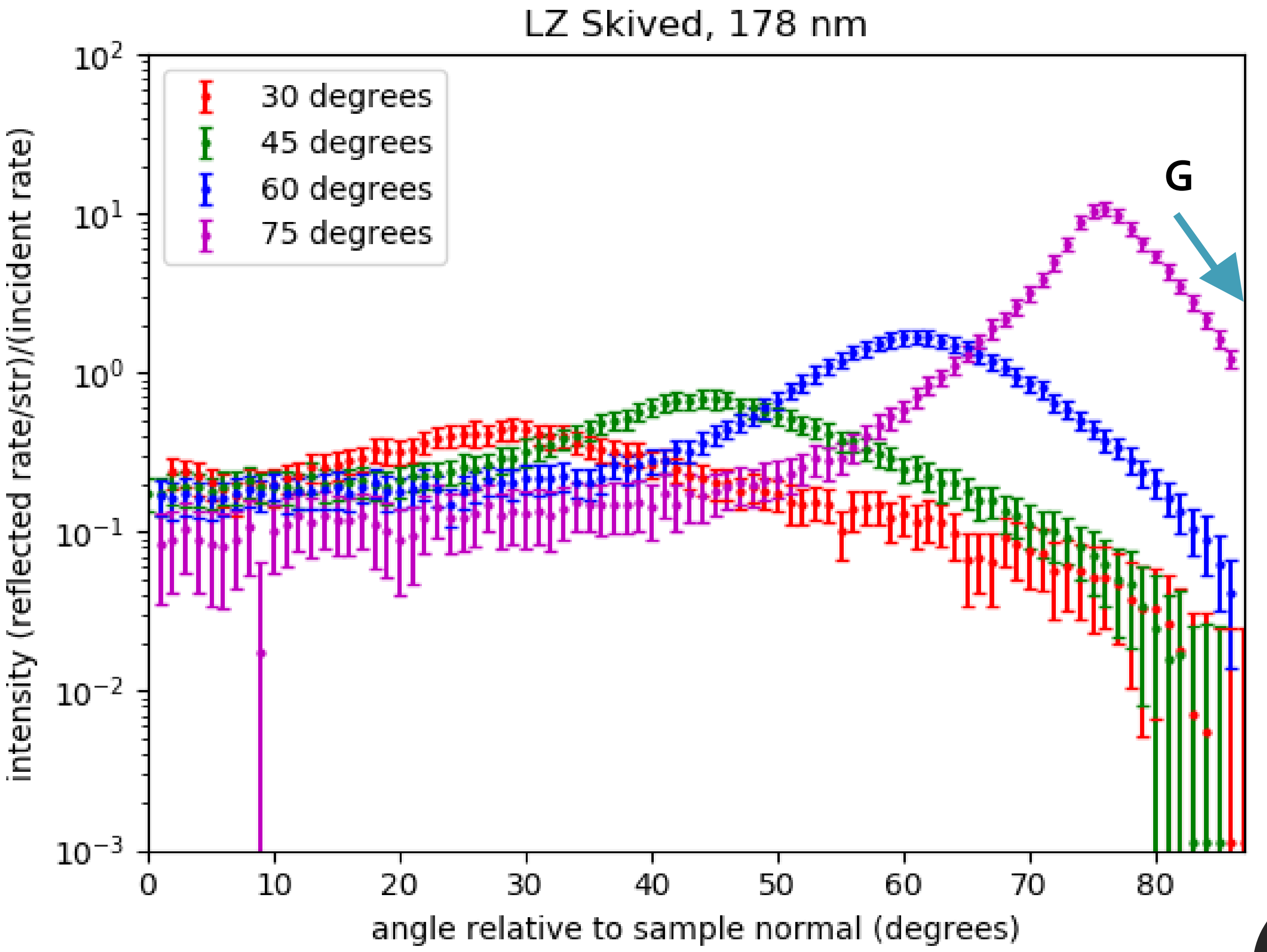
Model

- Based off of Coimbra group's model

$$\varrho = \varrho_D + \varrho_S$$

$$= \frac{\rho_l}{\pi} W N \cos\theta_r + \frac{1}{4\cos\theta_i} F P G$$

Shadowing and masking factor:
Some microfacets prevent light from hitting neighbors at high angles
G accounts for this, depends on P
Reduces specular lobe at very high angles

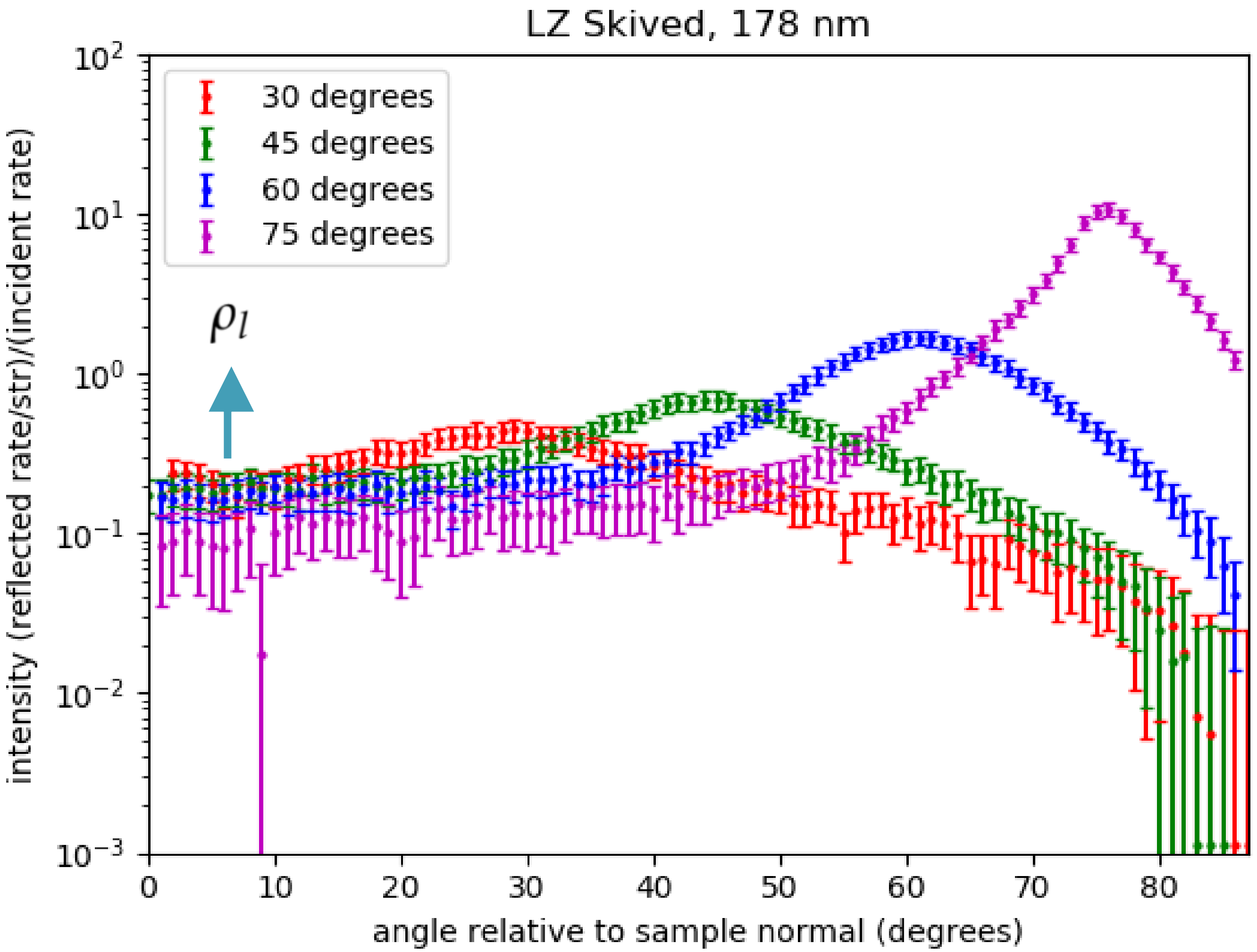


Model

- Based off of Coimbra group's model

$$\varrho = \varrho_D + \varrho_S$$
$$= \frac{\rho_l}{\pi} W N \cos\theta_r + \frac{1}{4\cos\theta_i} F P G$$

Lambertian diffuse reflectivity
(appears equally-bright at all angles)
"Standard" assumption for diffuse materials;
used in many MC simulations
ρ_l (albedo) is also a fit parameter,
sets height of diffuse lobe



Model

- Based off of Coimbra group's model

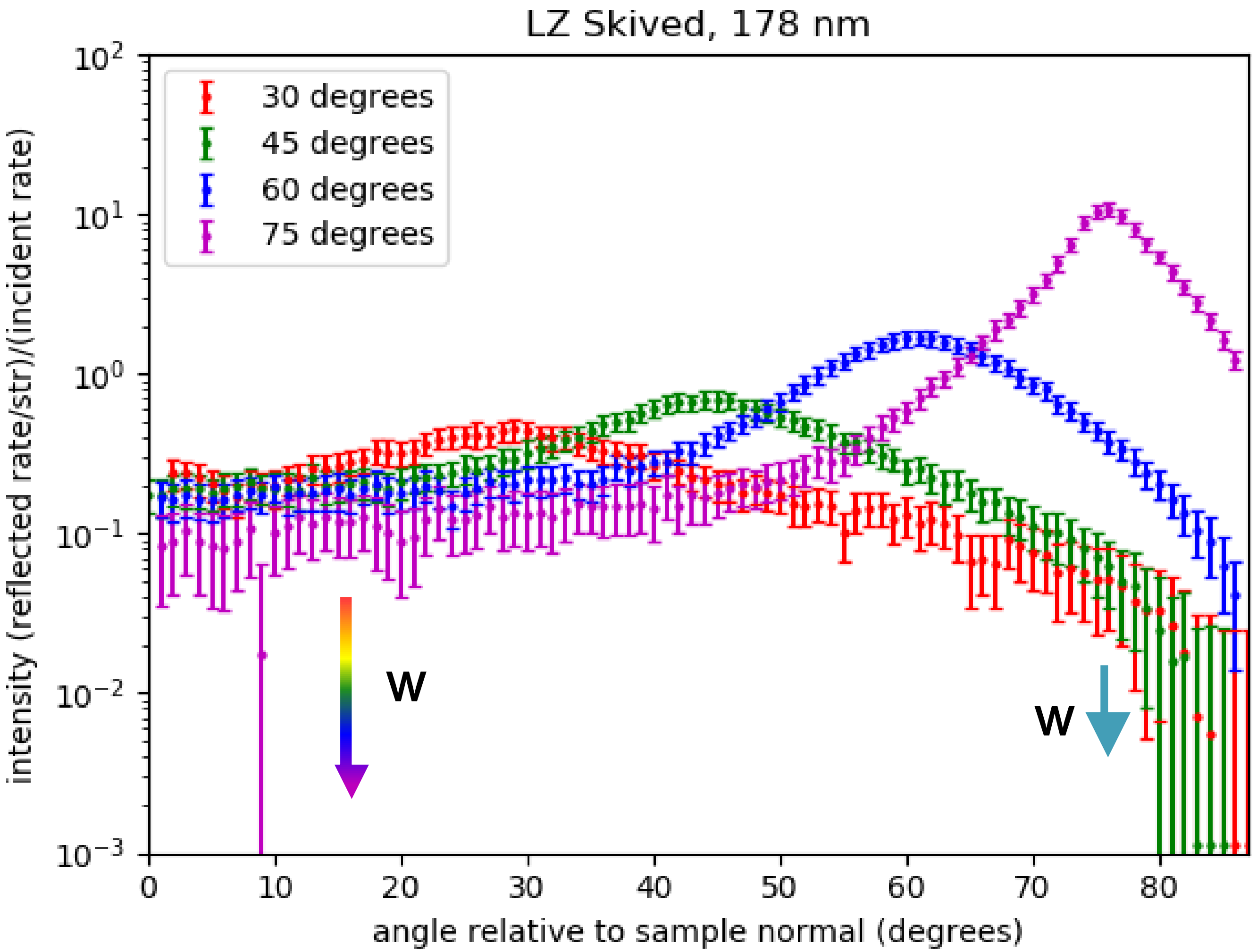
$$\varrho = \varrho_D + \varrho_S$$

$$= \frac{\rho_l}{\pi} W N \cos\theta_r + \frac{1}{4\cos\theta_i} FPG$$

Correction from Fresnel factors:
diffuse light must
enter PTFE, scatter inside, then exit

$$W = \left[1 - F\left(\theta_i, \frac{n}{n_0}\right)\right] \times \left[1 - F\left(\sin^{-1}\left(\frac{n_0}{n}\sin\theta_r\right), \frac{n_0}{n}\right)\right]$$

Reduces diffuse term at high incident
or viewing angles
Depends on n



Model

- Based off of Coimbra group's model

$$\varrho = \varrho_D + \varrho_S$$

$$= \quad \frac{\rho_l}{\pi} W N \cos\theta_r + \frac{1}{4\cos\theta_i} F P G$$

Correction from microfacets:
N integrates diffuse light
distribution over all microfacet angles
Often a small correction