This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

LLNL-CFPRES-2025874

Condensed-matter effects in advanced detectors
Surface charging in dual-phase noble liquids

CPAD 2026

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LLNL, Rare Events Detection Group

Condensed-matter effects shape backgrounds, sensitivity, and stability in advanced detectors.
Surface charging and physisorbed films: mechanisms, observations, and experimental tests.



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Hidden parameters: reservoirs of stored energy and charge

Detector-response models need additional state variables for stored energy and charge, together with mechanisms for their accumulation and release.

Focus: unextracted electrons at the liquid–gas interface and charging of solid physisorbed films on electrodes. These films strongly affect emission alongside oxides and defects; bulk-liquid effects also contribute.

Consequences: electron/photon backgrounds, sensitivity modulation, instabilities, and breakdown.

Scaling: larger detectors have longer surface equilibration/relaxation times. At fixed cosmogenic intensity, surface energy/charge flux density grows with contributing volume per unit area.

The relative importance of instability modes can change with scale—a serious design and operation risk.

This talk: experimental examples, diagnostics, suppression tests, and design options for larger detectors.

Vladimir Peskov, Paul Leiderer, and Valeri Shikin made large experimental and theoretical contributions in these areas.

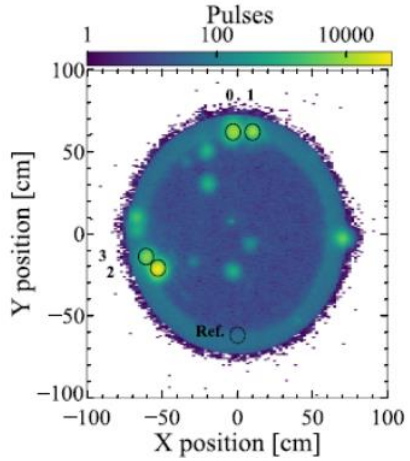
Intermittent electrode emission and physisorbed films

LZ and LUX report intermittent electron and photon emission from electrode grids.
LZ's hotspot veto reduces emission backgrounds (≈1% additional exposure loss, WS2025).

Strongest effects are appearing from trapping positive charges in physisorbed films

My experience with physisorbed film charging began at the Kapitza Institute.
In Leiderer's lab, I observed a ≈1 eV reduction in the Ag photo-efefct threshold with a positively charged He film (1994, unpublished).
Vladimir Peskov experimentally studied sporadic cathode emitters across many gaseous detectors and cathode materials.
He observed jets of a few to 10^5 electrons and memory after irradiation. Positive-ion charging of dielectric or adsorbed films activate emission.
Refs: Jacobaeus et al., physics/0112013; Peskov and Fonte, arXiv:0911.0463.

Broader statement: Solid layers form on immersed electrodes, trap charges and alter electrodes resistivity, capacitance, work function, and photoemission.

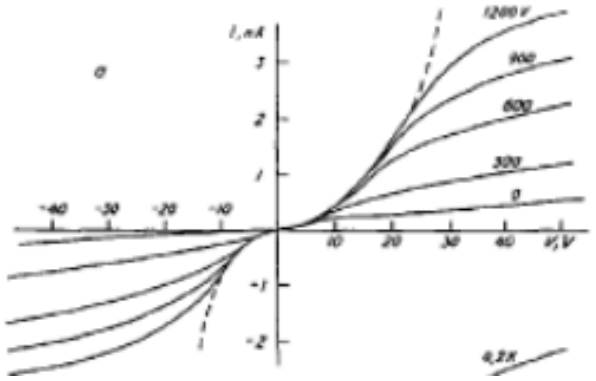


LZ gate-emitter map; electron pulses often have coincident photons.
Akerib et al., PRD 113, 072018 (2026), §IV.
LUX: Bailey (2016).
Veto: LZ WS2025 webinar, 8 Dec 2025, slide 49.

Emission from charged physisorbed layers cannot be eliminated by treating metal oxide films alone.

AC fields and charge transport in surface films

From the Kapitza Institute helium experiments to initial XeNu tests

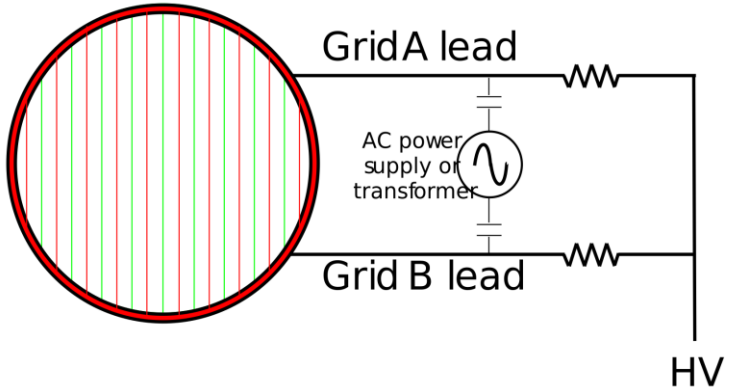


Liquid He: an AC voltage of up to 1.2 kV at 100 kHz across a 1 mm gap reduced near-source recombination and removed charging hysteresis.

S. V. Pereverzev and A. Ya. Parshin, Physica B 197, 347–359 (1994).

DOI: 10.1016/0921-4526(94)90232-1

XeNu dual-phase detector at LLNL



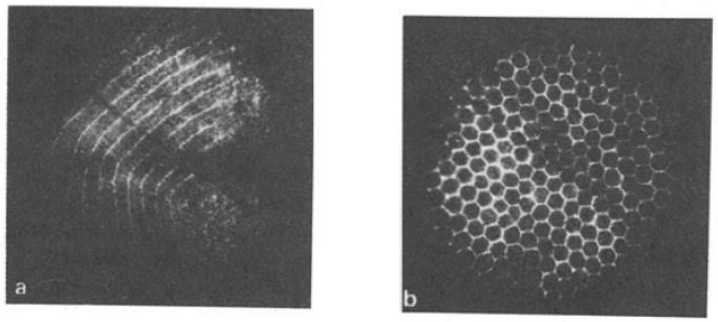
XeNu: 100 kHz, up to 2 kV peak-to-peak between alternating wires at 1 mm pitch enhanced emission for several seconds.

No steady-state reduction in single-electron emission was observed.

Further tests are needed to determine whether AC-driven charge removal suppresses electron emission bursts.
I designed XeNu at LLNL as a small, flexible platform for controlled studies of charge transport, surface phenomena, and detector response.

Charged-liquid surface instabilities: established physics

P. Leiderer, J. Low Temp. Phys. 87, 247–278 (1992).



Electron-charged ^{4}He at 3.5 K. Shadowgraphs approximately 2 s and 6 s after the field exceeds the instability threshold. Bright regions mark local surface maxima.

$\lambda c \approx 0.24$ cm.

Capillary length: $a = \sqrt{[\sigma / ((\rho_l - \rho_v)g)]}$

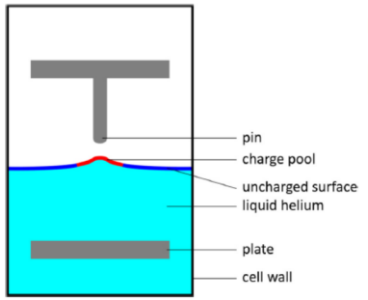
Ideal planar onset wavelength: $\lambda c \approx 2\pi a$

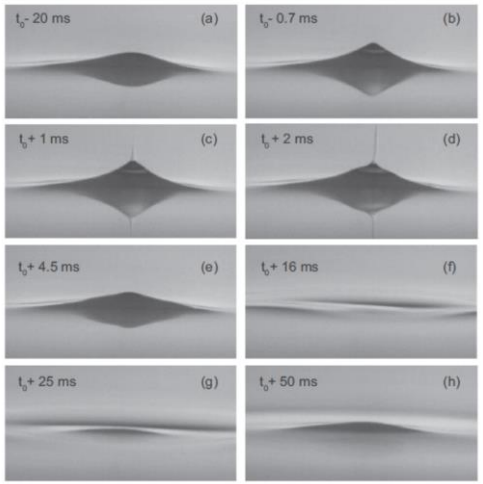


Dimples and hillocks can coexist.

Taylor-cone jet emission from helium charged with metallic particles from below.

T = 2.1 K. Frame interval ≈ 0.19 ms.





P. Moroshkin et al.

Phys. Rev. E 95, 053110 (2017).

Charged droplet extraction in He and N_2: Boyle and Dahm, J. Low Temp. Phys. 23, 477–486 (1976).

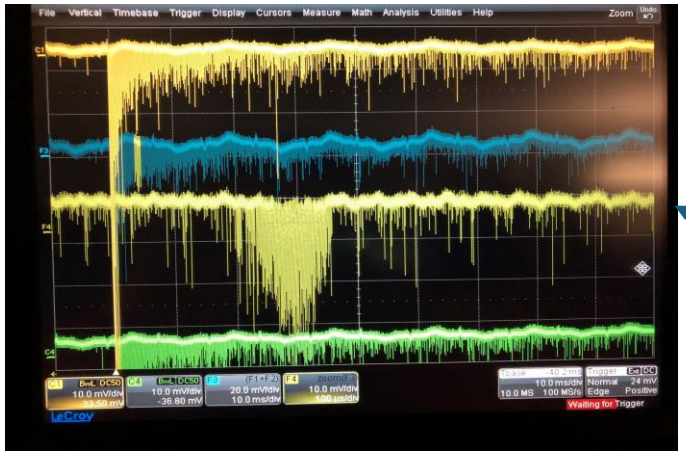
Charged-He surface instabilities: established experiments and theory. Shikin, Phys. Usp. 54, 1203 (2011).

In He and N_2, droplet extraction couples to surface motion and cell-mode excitation (Boyle & Dahm, 1976).

Ferrofluid analogy: Rosensweig instability in a perpendicular magnetic field (Cowley & Rosensweig, 1967).

Xe ($\varepsilon_r \approx 1.85$) and Ar (≈1.50) require dielectric polarization, which can lower critical fields in a normal electric field.

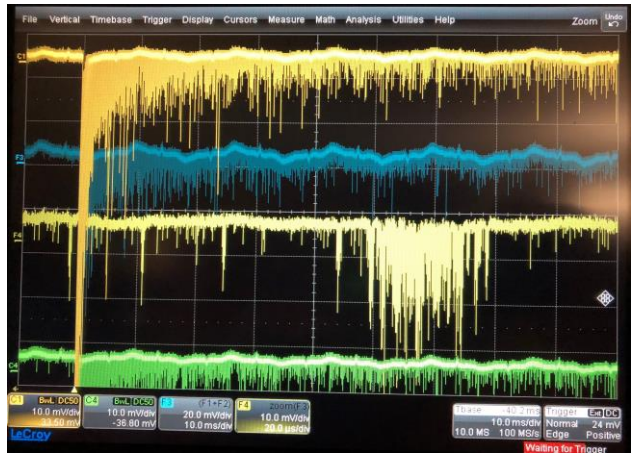
XeNu e-bursts follow extended S2 pulses

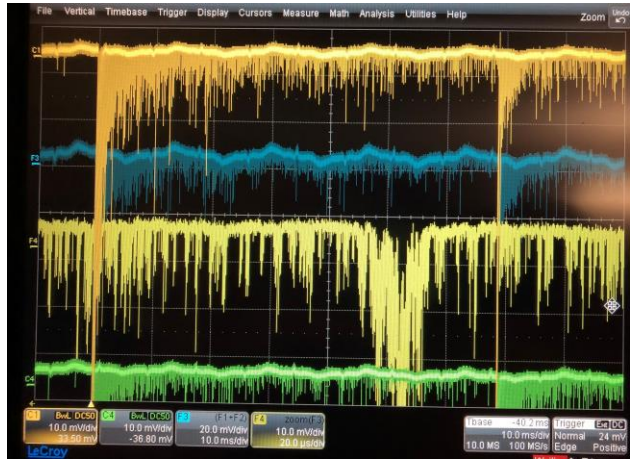


10 ms/div

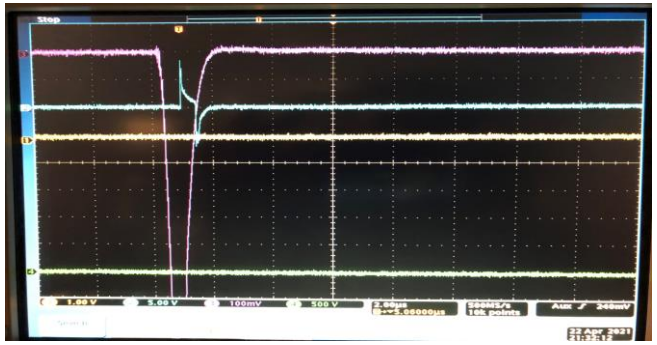
100 µs/div

20 µs/div



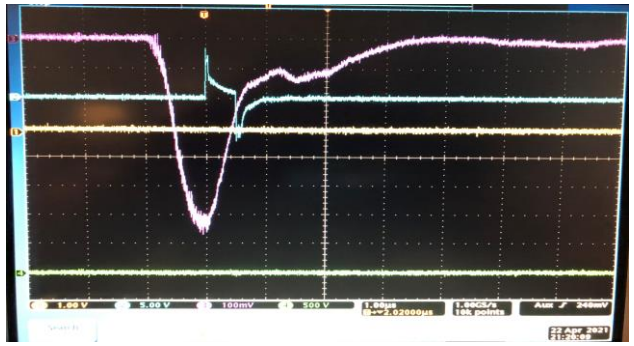


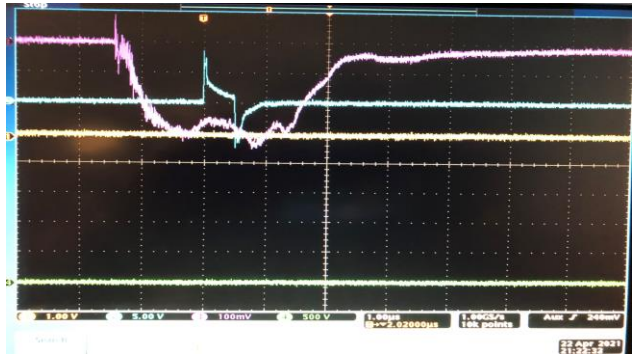
Blue (f3): sum of four top PMTs. f4: zoom of f3. Acquisition window: 100 ms.



2 µs/div

1 µs/div





Pink: bottom PMT operated at low gain. No e-bursts were observed after the short, localized S2 events studied.

One or more e-bursts can follow extended S2 pulses with delays up to 20 ms in these examples.

Hypothesis: extraction along muon tracks excites waves that trigger surface-charge release.

Surface waves and electrode geometry change the instability

Geometry and surface deformation

Uniform fields can produce dimples or hillock lattices.
Wire fields and boundaries can favor ridges and localized charge accumulation.

Localized emission

Below the capillary length, instability changes.
EHD printing demonstrates micro- and nanodroplets.
Proposed Xe extension: localized droplet or single-electron emission.

Can wave suppress S2 signal?

A large transient crest can reduce gas amplification by shortening the gas gap. Near extraction saturation, increased extraction provides little compensation. The calculation must include field redistribution at fixed electrode voltages.

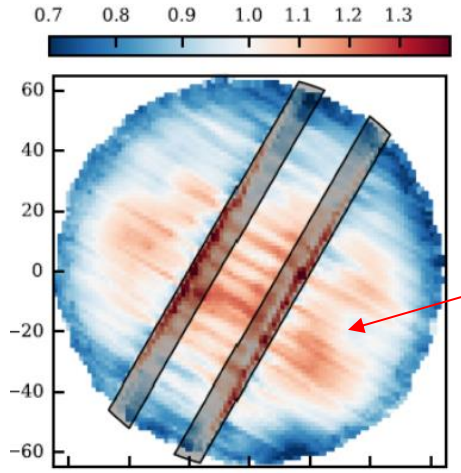
Other wave sources include seismic, building, or cryostat vibrations, droplets, and mechanical stress release.

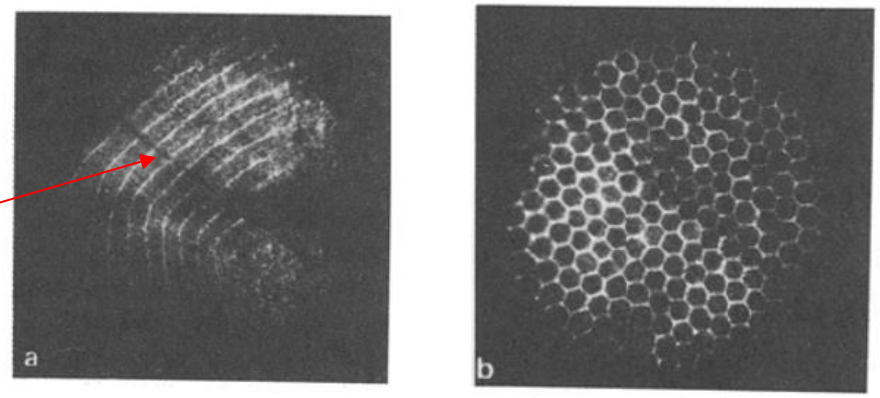
Möller et al., J. Low Temp. Phys. 202, 431–443 (2021): nonuniform fields and localized charge pools.
Boyle & Dahm, J. Low Temp. Phys. 23, 477–486 (1976): extraction coupled to surface motion.
Richner et al., Nanoscale (2016), doi:10.1039/C5NR08783J: electrohydrodynamic NanoDrip printing.

Surface-charge dynamics in XENONnT

XENON detectors report delayed electron emission and emission episodes (10, 100, 1T, nT).
XENONnT has a continuous PTFE perimeter at the liquid surface.

Observed: enhanced S2 near support wires, anomalous pulse shapes, increased electron emission at high fields, and response changes over days.





Helium images: analogy to test

P. Leiderer, J. Low Temp. Phys. 87, 247 (1992).

Hypothesis: enhanced-response regions have the greatest surface elevation and charge density. Local fields below the capillary scale may support droplet or single-electron emission (EHD-printing analogy).

Large ionization events replenish surface charge and renew relaxation. Averaged spatial and temporal corrections may miss this history dependence. The resulting systematic uncertainty is not determined by the averaged maps alone.

Mitigation: actively remove injected surface charge.

Charge removal and surface monitoring in LUX/LZ

LUX: two perimeter openings

Localized e-bursts follow large S2 signals at their previous positions.

No bursts on the half facing the copper-weir opening (Jingke Xu, private communication).

Flow and collection by metal may remove surface charge.

LZ: six openings, three weirs

Six precision capacitive level sensors near the weir channels may also collect surface charge.

No LUX-like e-bursts reported in the reviewed studies.

Charge collection may add sensor noise. Longer averaging could then limit fast-wave detection.

Suppressing e-bursts does not establish stable extraction or amplification.

Charge drainage may suppress bursts while waves still modulate response.

LUX: Akerib et al., Phys. Rev. D 102, 092004 (2020). Weir-side observation: Jingke Xu, private communication.
LZ: Akerib et al., NIM A 953, 163047 (2020), §2.4; few-electron backgrounds, arXiv:2510.06500.
Charge-removal design comparisons: RED1, ZEPLIN-III, RED100 (supporting slide 13).

Design options for controlling charge accumulation

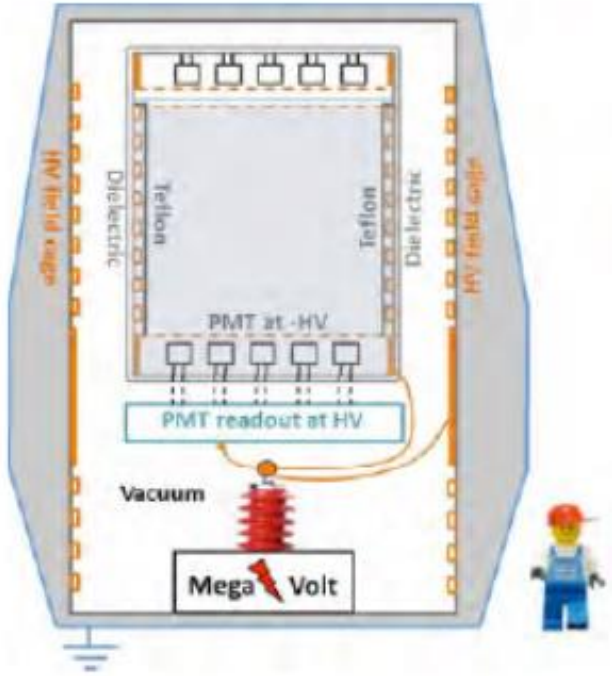


Figure 1: Possible design for a large dielectric cryostat.

An "inverted Van de Graaff" concept would use a strong drift field extending to the extraction region.

Removing the extraction grid would remove that emission source.

AC bias between cathode wires could drive charge transport in surface films to suppress burst emission.

An anode with a tangential field could direct unextracted electrons to a collector. A traveling potential is another option.

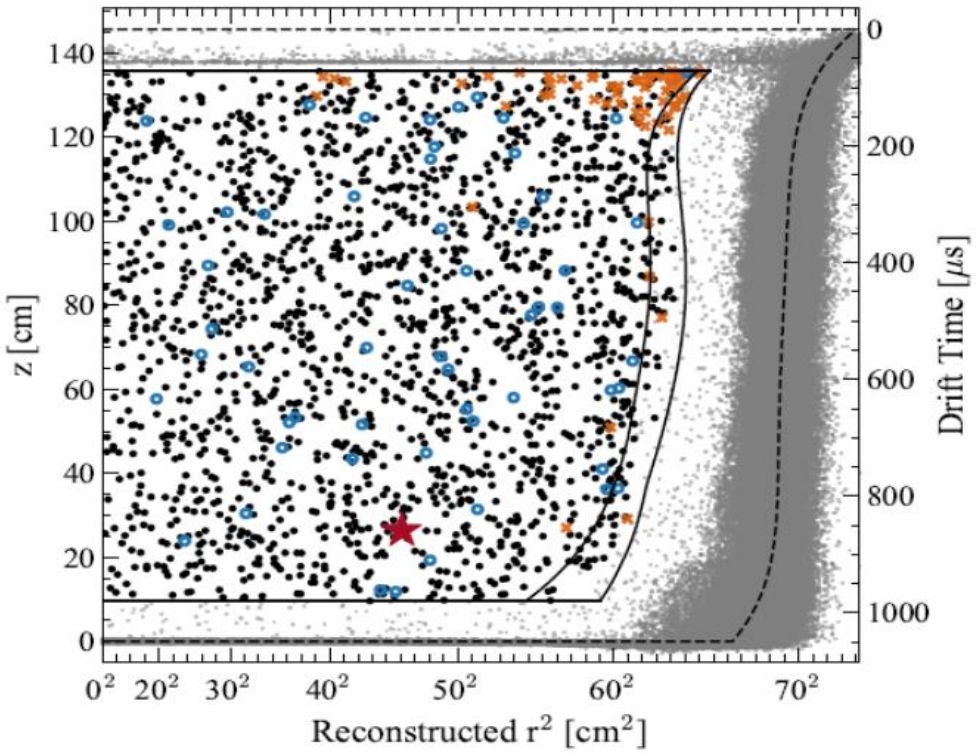
Additional benefit of stronger drift fields– suppression of electron trapping /release by density fluctuations in liquid Xe (Dmitri Akimov @ RED100) -required additional testing

Concept discussed in B. Rebel et al.,

High Voltage in Noble Liquids for High Energy Physics, JINST 9, T08004 (2014).

These tests fit a small XeNu-scale apparatus. In my experience, support for focused noble-liquid materials studies has fallen between HEP/NP detector programs and BES. Coordinated support would reduce risk for XLZD.

A testable surface-wave hypothesis



LZ reports one high-energy nuclear-recoil-like event.

Could a transient surface deformation reduce the S2 signal of an electron recoil enough to enter this S2/S1 region?

LZ finds the candidate's S2 shape consistent with a local single-site template. For deep events S2 length increased by diffusion- compression by short liquid drift not seen

Are level sensors affected by electrons escaping surfaced can not detect waves ?

LZ extended nuclear-recoil search

arXiv:2609.02823 (2026)

Surface dynamic is important to monitor. Do we have data /models to connect perimeter level sensors and accelerometer @ microphone information to wave picture/distribution?

Conclusions and proposed tests

Surface charge and adsorbed films can create memory in detector response.

A small dual-phase apparatus can test:

1. Charge-removal paths at the liquid perimeter
2. Surface-wave excitation and delayed electron bursts
3. Ion-driven grid emission and AC suppression
4. High field drift suppression of delayed electron emission

The blind spot is the evolving material state. Research on these effects falls between disciplines, institutions, and funding programs.

Within current sponsor and laboratory priorities, I have not been able to secure support to continue the XeNu experimental program on evolving material effects.

"Studies of excess background mechanisms are Blue Sky projects"

Helmut Marsiske, in response to my question after his CPAD2024 presentation

Coordinated support for small experiments could test these mechanisms and reduce design and operating risks for XLZD.

Additional Slides

Charged liquid surfaces: Shikin references

[1] V. B. Shikin. Instability and reconstruction of a charged liquid surface.
Physics–Uspekhi 54, 1203–1225 (2011). Comprehensive review, 23 pages.

[2] P. Leiderer, W. Ebner, and V. B. Shikin. Macroscopic electron dimples on the surface of liquid helium.
Surface Science 113, 405–411 (1982).

[3] V. Shikin. On the phase diagram of the development of an instability of a massive charged surface of liquid helium.
Low Temperature Physics 29, 382–385 (2003).

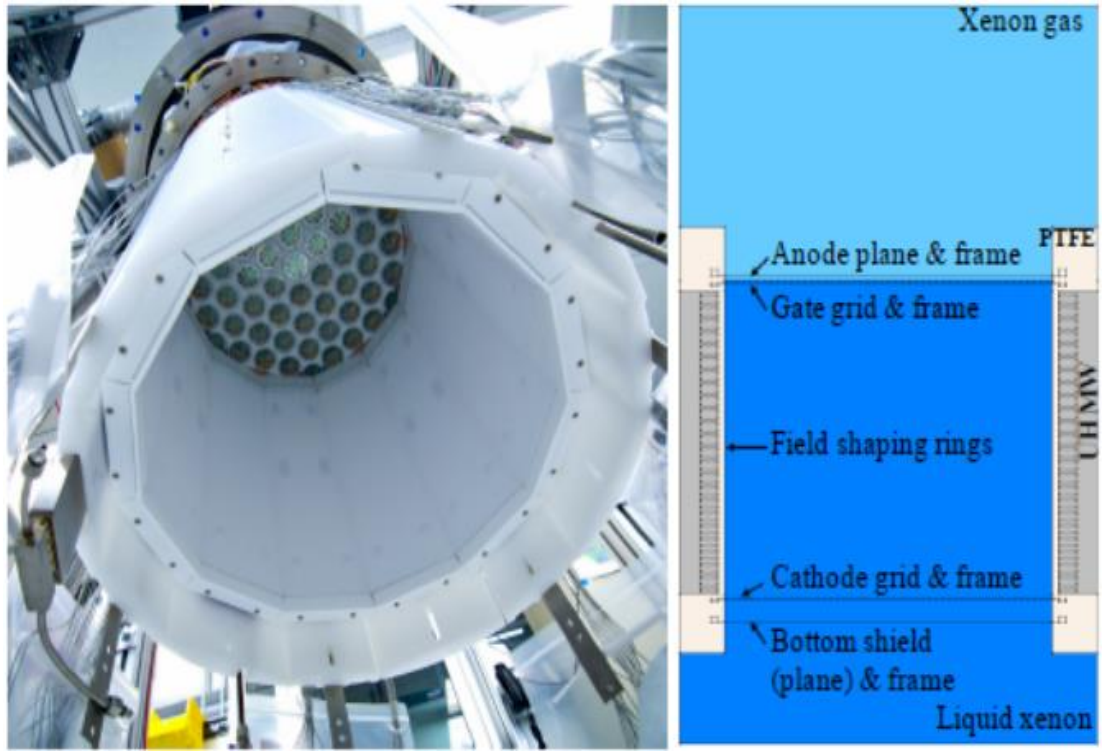
[4] V. Shikin. On the stability of a weakly charged surface of liquid helium.
JETP Letters 78, 461–465 (2003).

[5] V. Shikin and E. Klinovaya. A mixed scenario for the reconstruction of a charged helium surface.
Low Temperature Physics 36, 142 (2010).

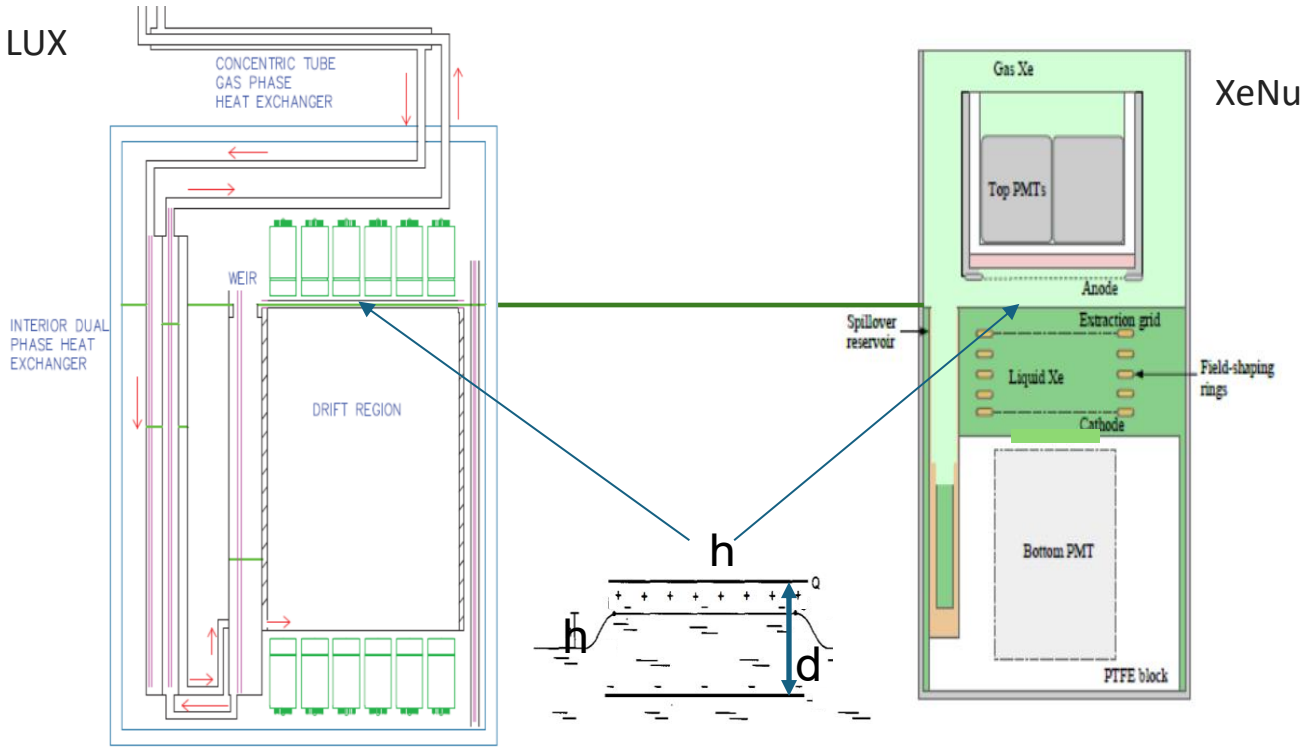
[6] I. Chikina and V. Shikin. Instability of the Liquid Dielectric Surface in a Perpendicularly Applied Electric Field.
Journal of Low Temperature Physics 195, 319–326 (2019).

Xe and Ar require finite dielectric polarization in the helium-based models.
In a normal electric field, polarization adds a destabilizing contribution
and can lower the critical fields for surface instabilities.

Escape paths for surface electrons



PTFE around the active surface can restrict lateral escape.
Openings and nearby metal may provide charge-removal paths.



$h \approx E_o^2 \varepsilon_o(\varepsilon - 1)/(\rho g)$ $E_o = V/d$

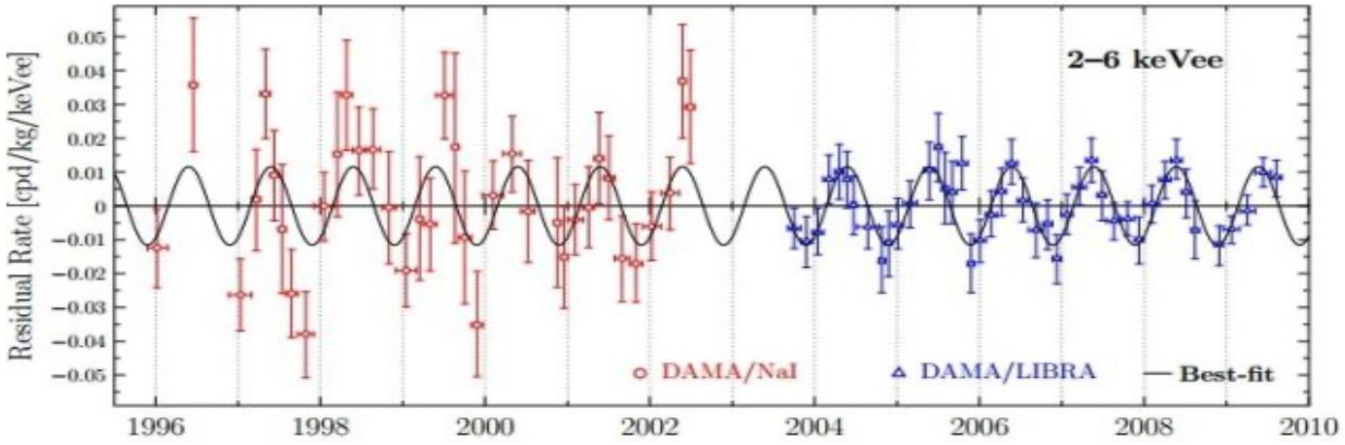
XeNu estimate: h ≈ 0.12 mm for 10 kV across a 10 mm grid gap.

Anode sagging drives surface electrons inward; extraction-grid buckling drives them outward.
With identical grids and a centered liquid level, the electrostatic force is stronger on the anode in gas than on the gate in dielectric liquid. Greater anode sagging therefore produces net inward confinement.

Scaling concern: larger spans can increase grid deformation and the time needed for surface charge to reach a collector.

NaI(Tl) afterglow and the DAMA/LIBRA question

DAMA/LIBRA reports annual modulation at Gran Sasso.
Independent NaI(Tl) experiments have not confirmed it.
ANAIS-112's six-year result challenges the modulation.





D. Nygren: a testable stored-energy hypothesis
arXiv:1102.0815 (2011).

Optical pumping and quenching
F. Sutanto et al., Phys. Rev. D 107, 032010 (2023).

Hypotheses to test

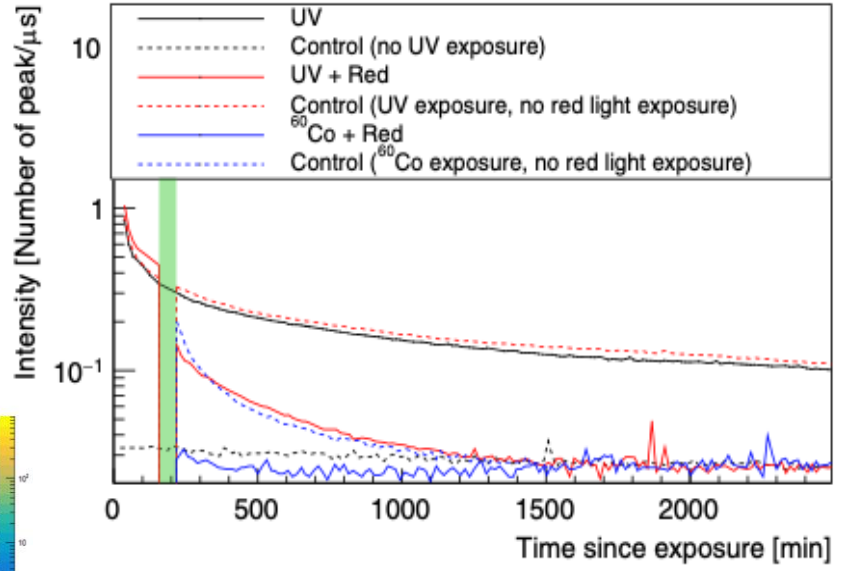
Environmental changes may alter trap populations and lifetimes.

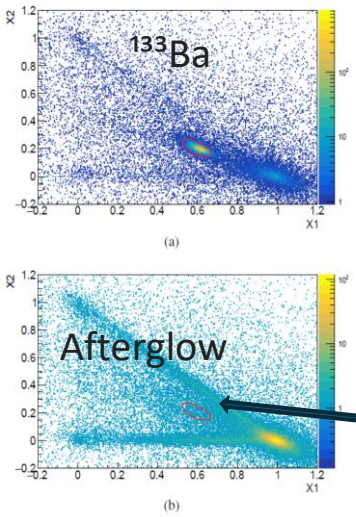
Radiation can populate or quench different traps.

A low-energy recoil may release stored energy.

Test these processes with optical pumping, quenching, and neutron exposure.







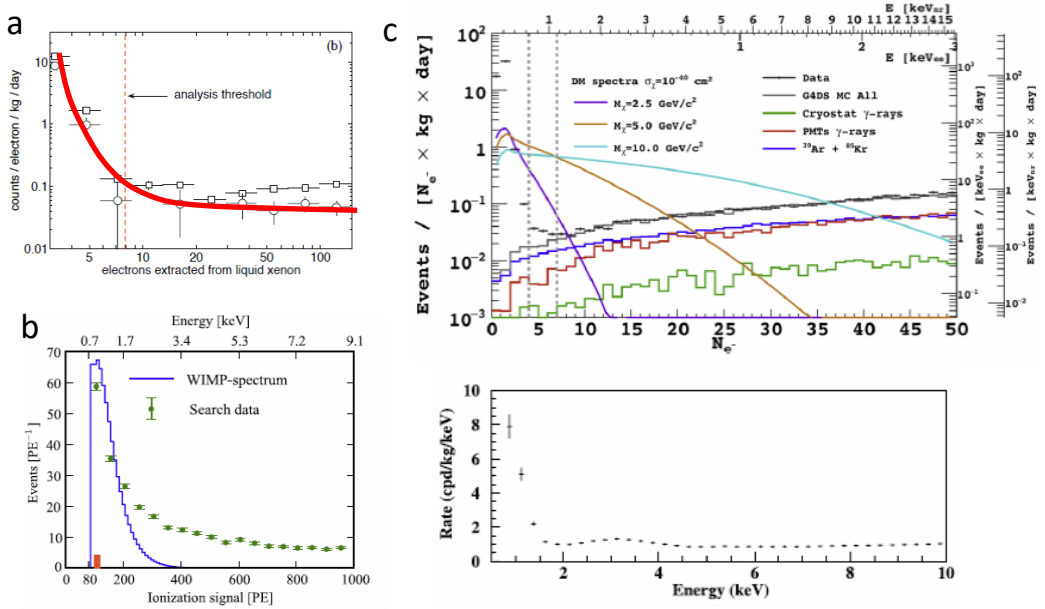
Most afterglow photons are uncorrelated. A quantitative rate and acceptance study is needed for pulse-like coincidences.

$$X_1 = \frac{A[100,600]\,ns}{A[0,600]\,ns}, X_2 = \frac{A[0,50]\,ns}{A[0,600]\,ns}$$

Could stored energy provide internal amplification in NaI(Tl)?

Low-energy excesses across detector materials

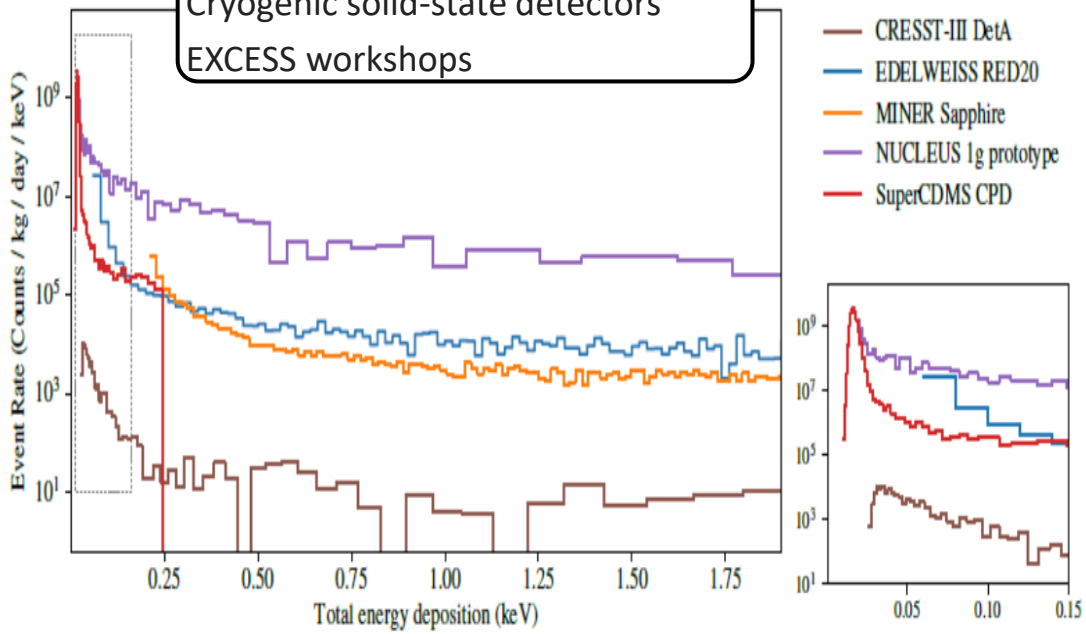
Examples of low-energy excess spectra



a: XENON10 | b: XENON100 | c: DarkSide-50 | d: DAMA/LIBRA

Cryogenic solid-state detectors

EXCESS workshops



Many spectra rise toward lower energies.

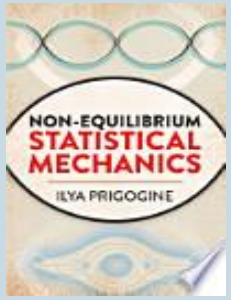
Stored-energy release is one possible source of electron, photon, phonon, or quasiparticle signals.

Similar spectra alone do not establish a common microscopic mechanism.

Driven systems and avalanche models motivate tests of event clustering, relaxation, and sensitivity to controlled excitation.

Driven systems and self-organized criticality





Ilya Prigogine

Nobel Prize in Chemistry, 1977

Systems with energy flow

Energy flow can sustain collective structures.

Interactions can correlate release events.

Classical avalanches alone do not establish quantum entanglement.

Related detector perspectives

S. Pereverzev, Phys. Rev. D 105, 063002 (2022), arXiv:2107.14397.

S. Pereverzev, SciPost Phys. Proc. 12, 009 (2023), arXiv:2212.13964.

Energy storage and release:

Thermally stimulated luminescence, electron emission, and conductivity

NaI(Tl): a relevant example





Possible avalanche signatures

Power-law event sizes

Broad relaxation times

1/f-like noise in some models

Small triggers, larger releases

Suppression through faster relaxation

SOC requires tests of scaling and correlations.

Per Bak, Chao Tang, and Kurt Wiesenfeld

Phys. Rev. Lett. 59, 381 (1987).

Detector models need the relevant excitations, their populations, and their interactions.