Development and performance of high voltage electrodes for the LZ experiment

Kelly Stifter
On behalf of the LZ collaboration

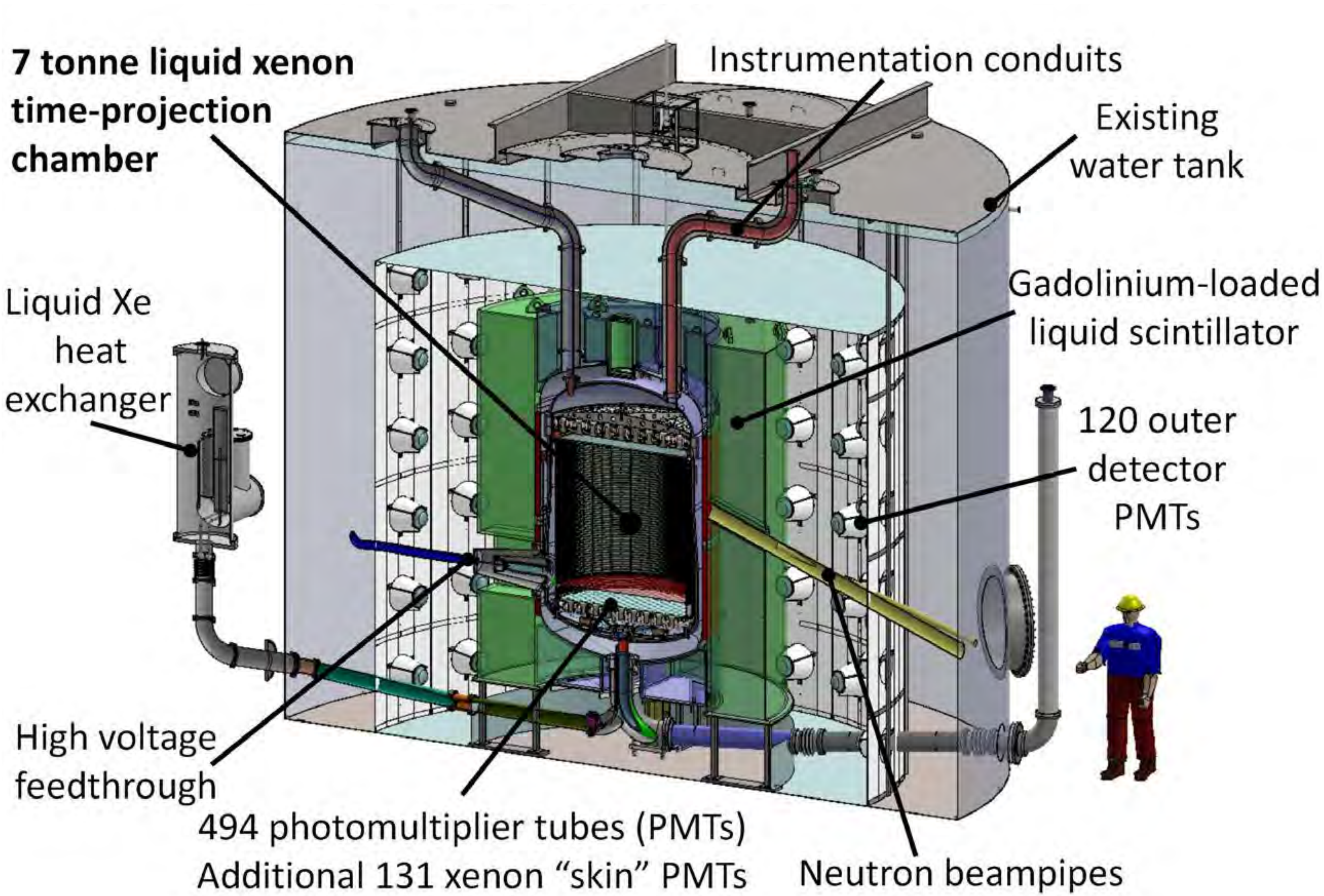
TAUP 2019
Toyama, Japan
9/12/19

KIPAC
KAVLI INSTITUTE FOR PARTICLE ASTROPHYSICS & COSMOLOGY

STANFORD UNIVERSITY

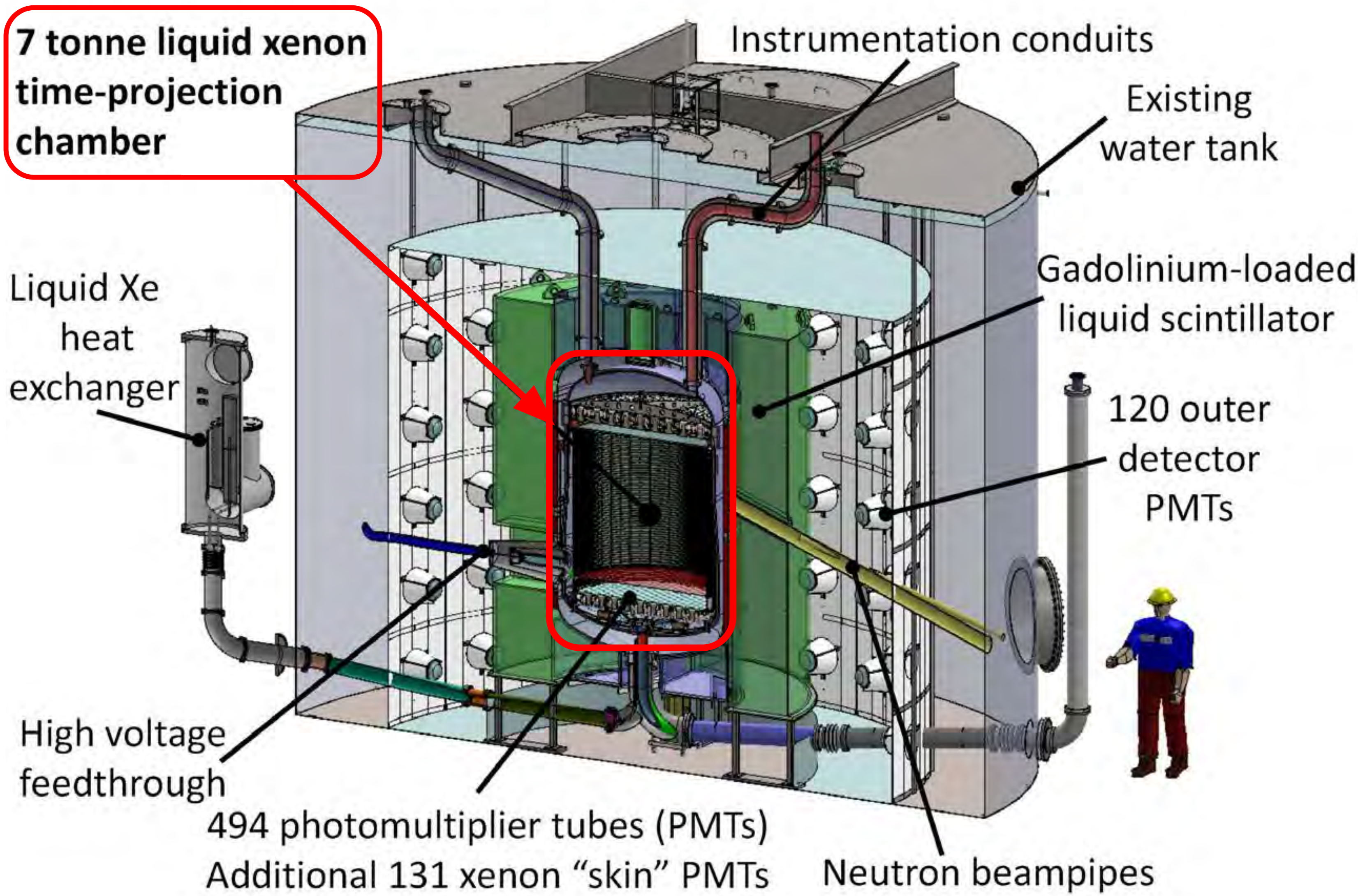
The LZ Dark Matter Detector

LZ TDR: 1703.09144

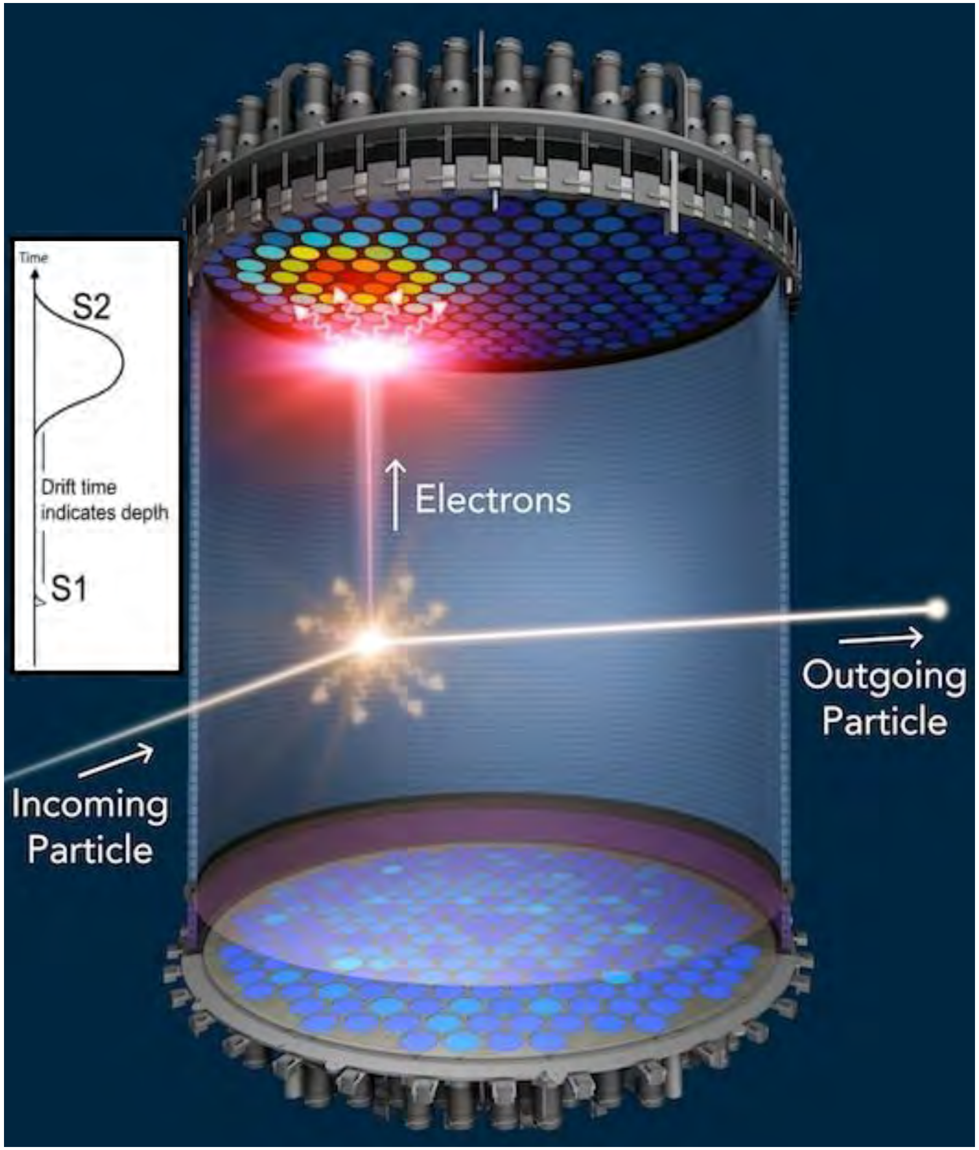


The LZ Dark Matter Detector

LZ TDR: 1703.09144



Time projection chamber (TPC)



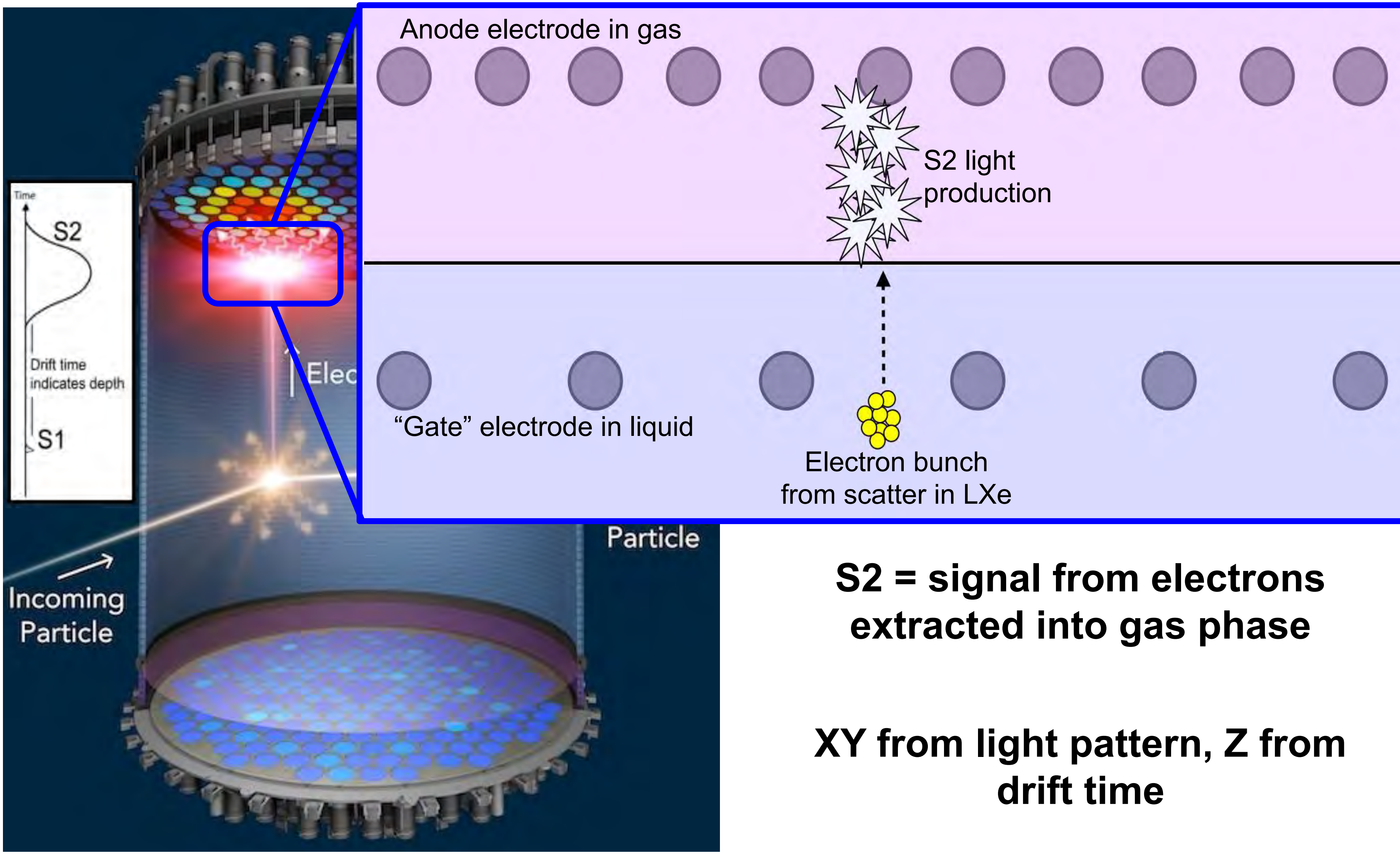
Sensitive to single quanta of light and charge

S1 = prompt scintillation signal from liquid bulk

S2 = signal from electrons extracted into gas phase

XY from light pattern, Z from drift time

“Extraction Region”



S2 = signal from electrons extracted into gas phase

XY from light pattern, Z from drift time

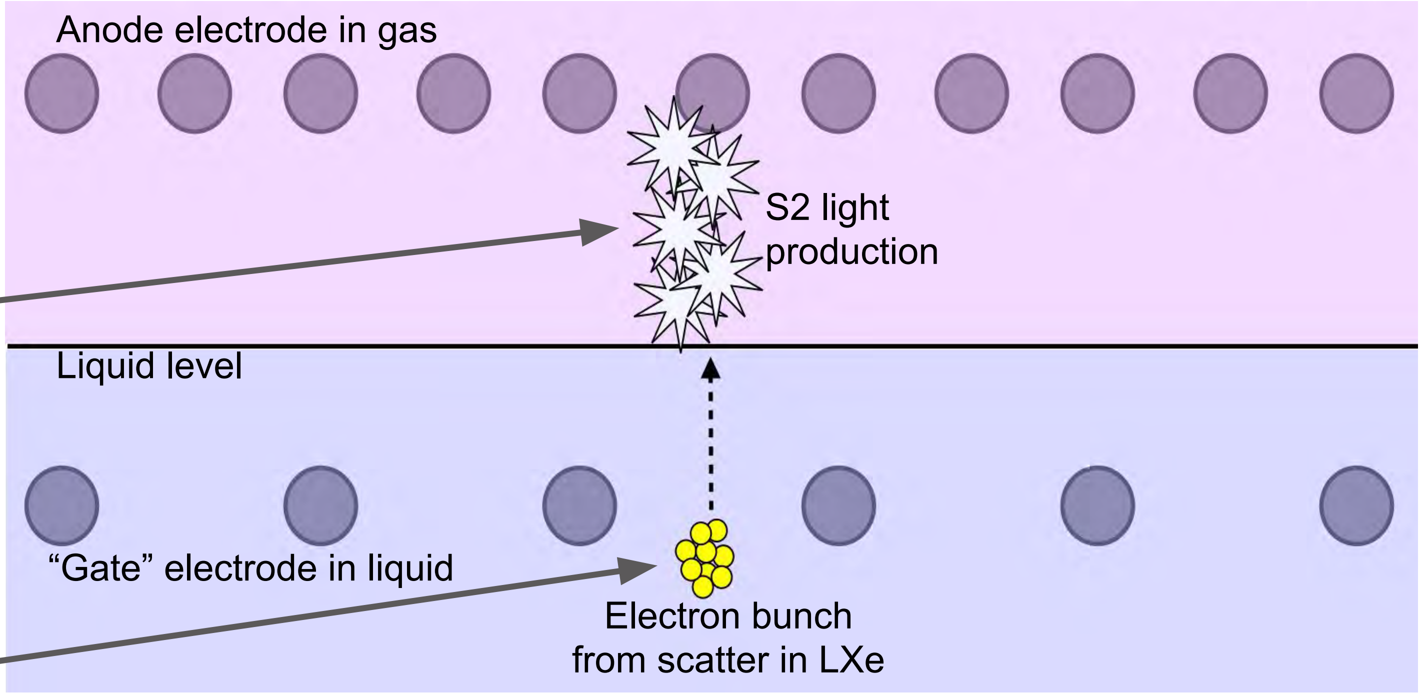
Extraction region design drivers

1. **High electroluminescence (EL) field** for high extraction efficiency and S2 yield

+

2. **Optical** (S1) and **electron** (S2) transparency of electrodes

= Mesh electrodes (grids)



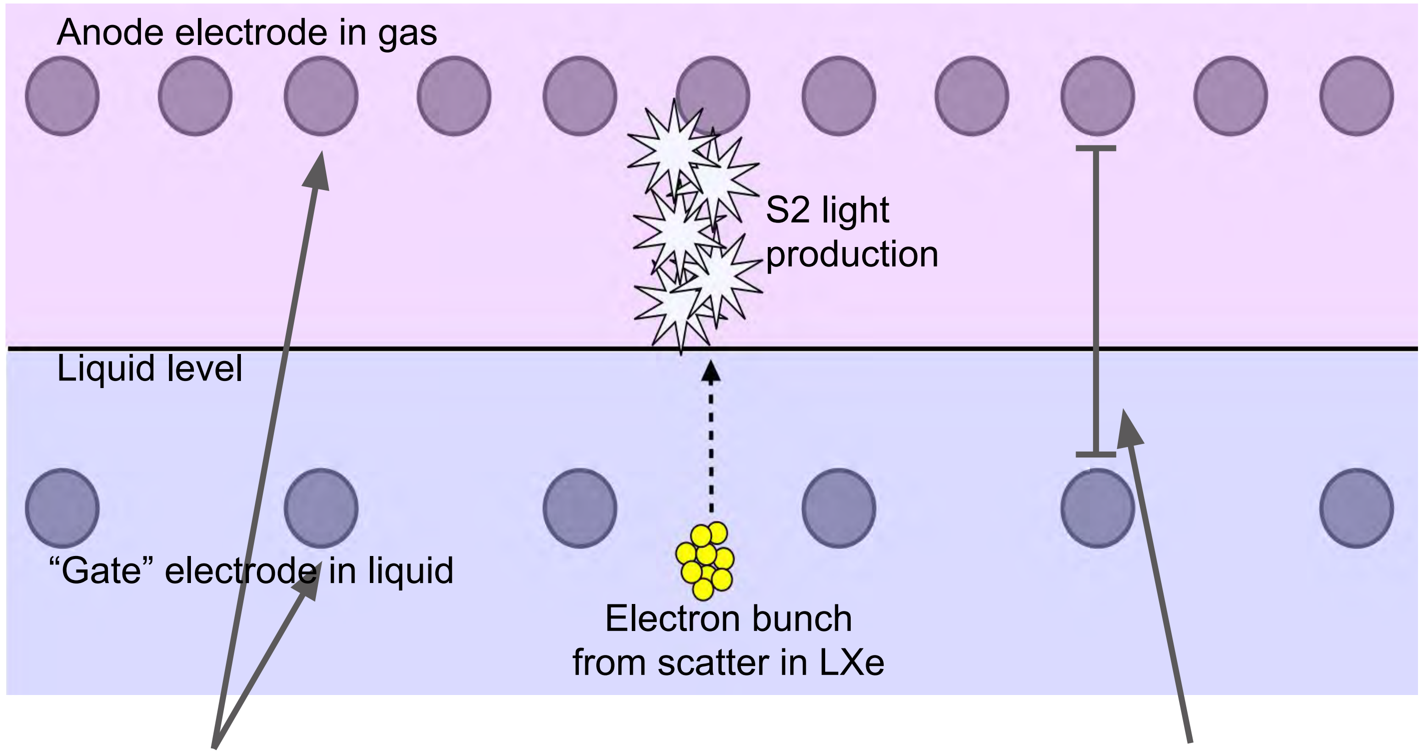
Extraction region design drivers

1. **High electroluminescence (EL) field** for high extraction efficiency and S2 yield

+

2. **Optical** (S1) and **electron** (S2) transparency of electrodes

= Mesh electrodes (grids)



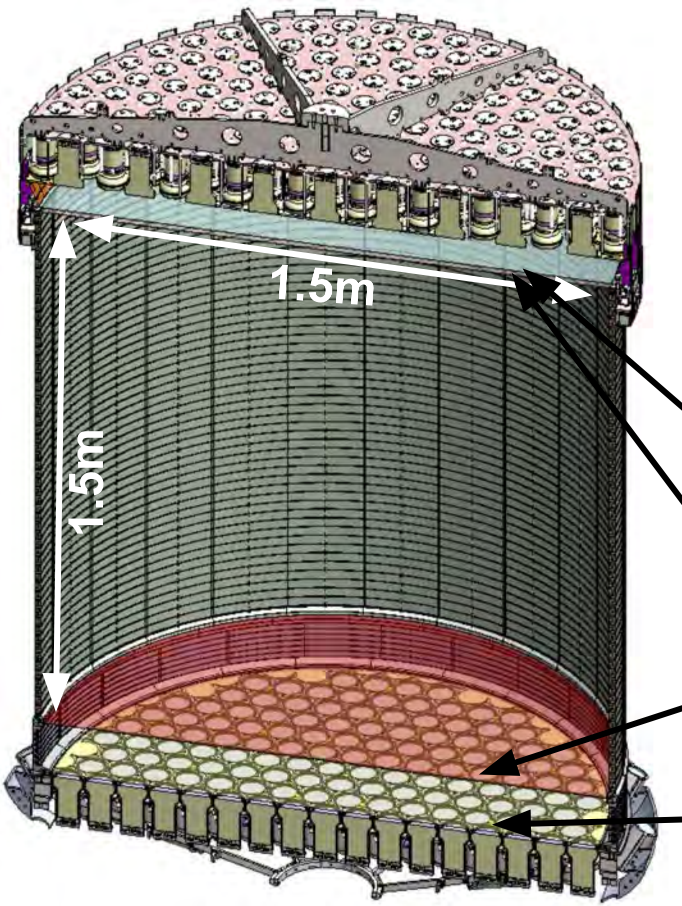
3. **S2 resolution** - optimize gate-anode alignment for electron drift

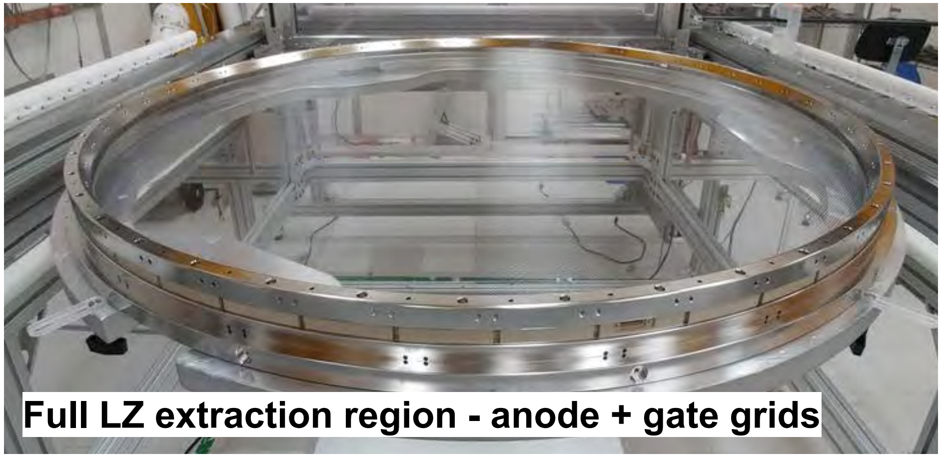
4. **Mechanical constraints** - load on rings, thermal properties, minimize dead material, etc.

5. **Uniformity of EL field** - limit electrostatic deflection of grids, minimize high field points

LZ extraction region and grid design

- Four woven meshes of SS wires glued between SS rings
- Ring geometry designed to limit material and surface fields




Full LZ extraction region - anode + gate grids

Grid	Pitch (mm)	Gauge (um)	Optical transparency	Nominal voltage (max surface field)
Anode	2.5	100	92%	+5.75kV (46.2kV/cm)
Gate	5	75	97%	-5.75kV (-51.8kV/cm)
Cathode	5	100	96%	-50kV (-30.1kV/cm)
Bottom	5	75	97%	-1.5kV (-33.8kV/cm)

11.5kV ΔV: ~80phd/e$^-$

LZ wire grid production at SLAC

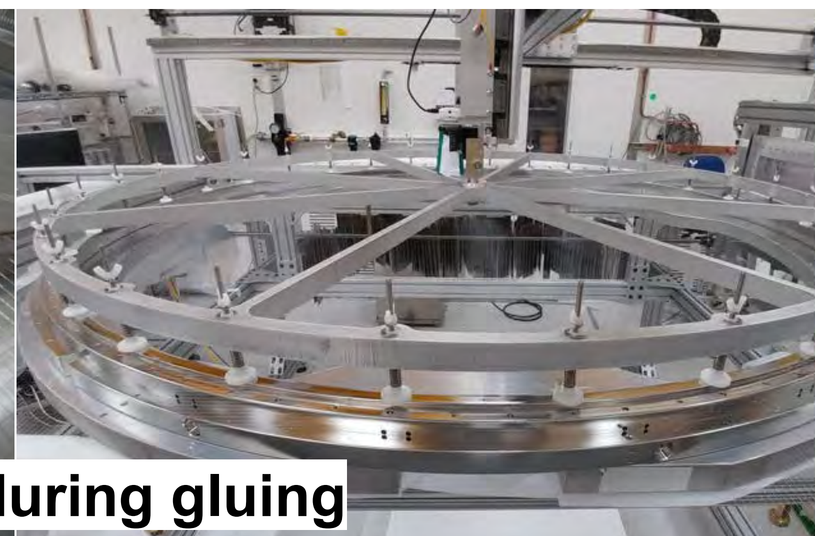
(Link to grid production youtube video)

Custom-built LZ Loom at SLAC

Wires pre-tensioned with weights

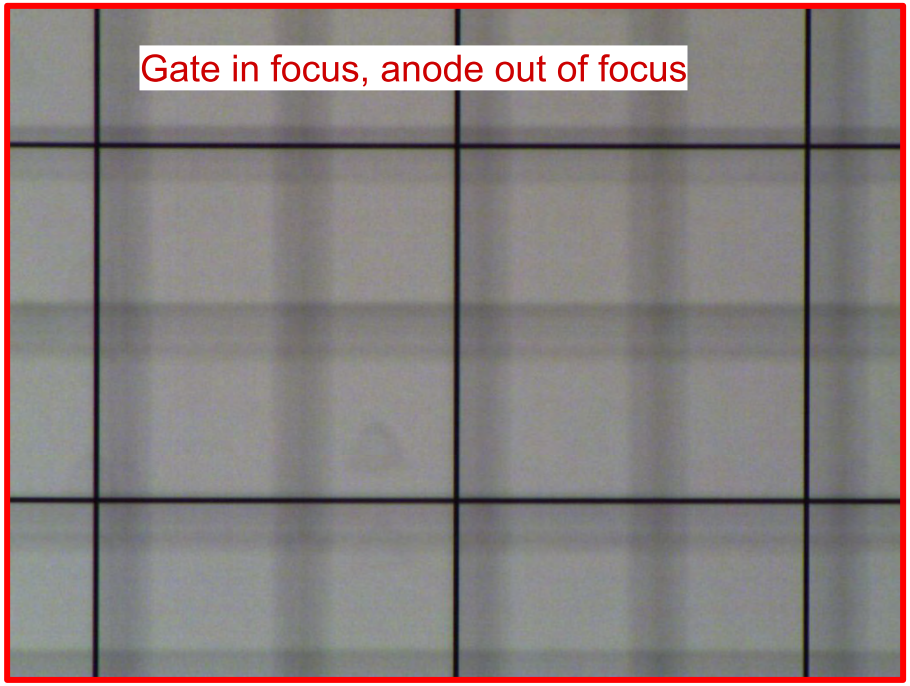
Semi-automated weaving

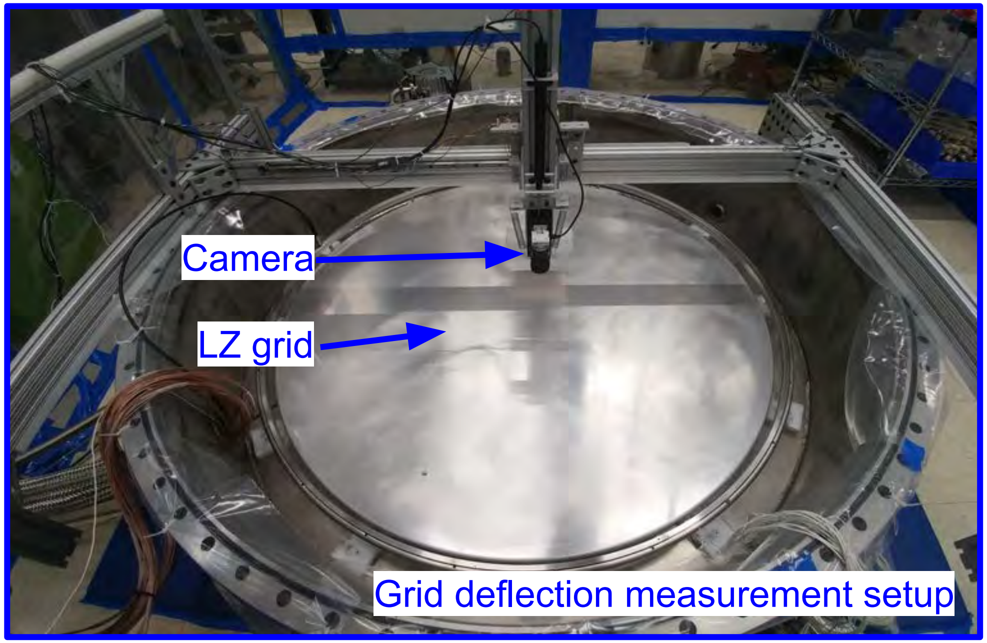
Glue-dispensing robot



Grid during gluing

LZ wire grid production at SLAC



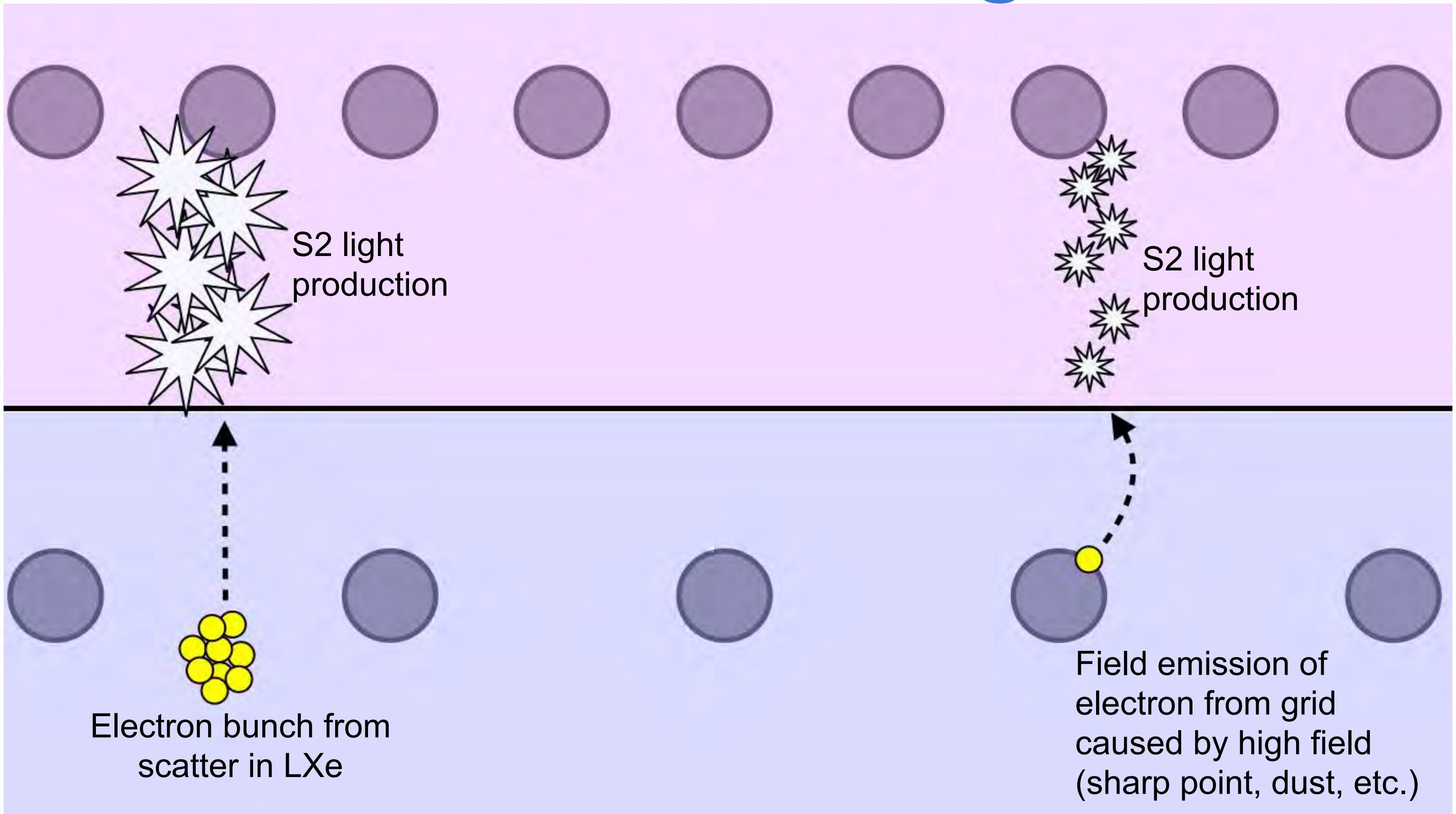


Gate/anode wire alignment mapped for entire extraction region

Electrostatic grid deflection

- Optical measurement at voltage in air using camera's changing plane of focus
- Results mapped to field in liquid, meets requirement of <2mm total deflection

Electron emission from grids



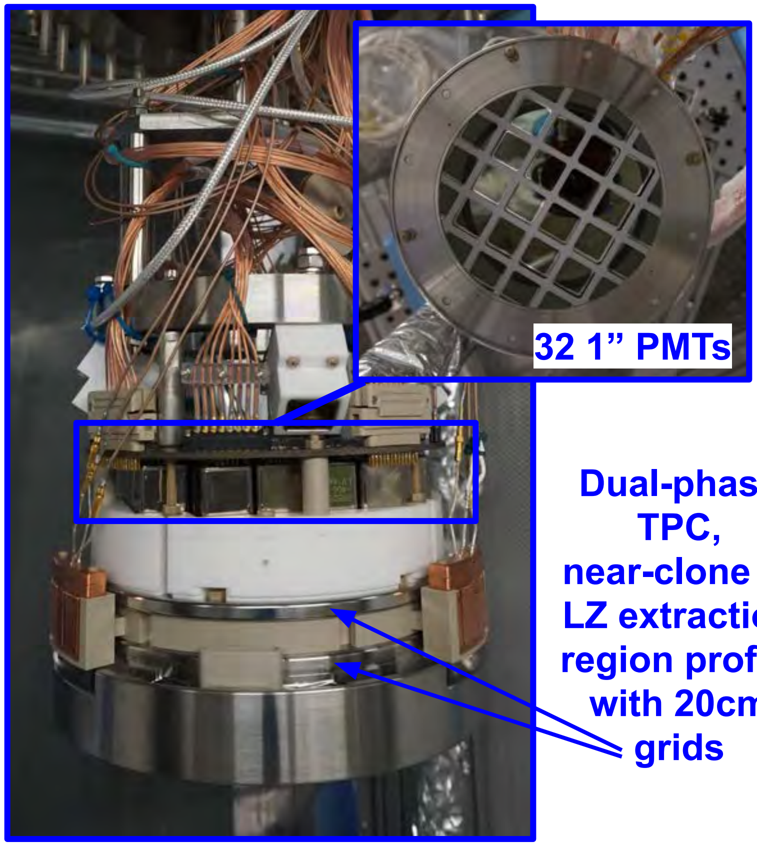
Problematic:

- **LUX extraction voltage limited by emission from grids**
- **High rate = DAQ deadtime**
- **Low energy signal - bad for key physics searches (WIMP search, S2-only, etc.)**
  - **Fiducialization doesn't help: appears in bulk in XY, no S1 → no Z reconstruction**
  - **Compounded by gain in liquid - evidence seen in LUX data [A. Bailey thesis]**

Measuring electron emission in SLAC System Test

Suite of three detectors built to enable comprehensive testing of critical LZ systems

To study physics of electron emission: <u>single electron sensitivity</u> through S2 process, <u>position reconstruction</u> from PMT arrays



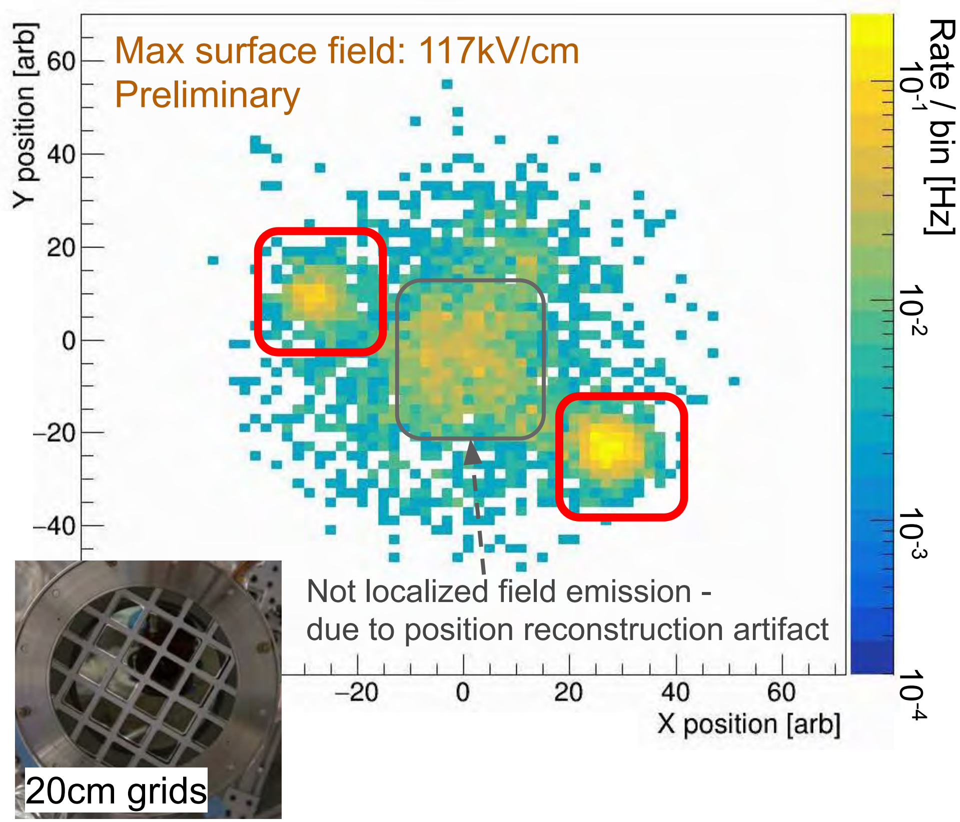
Dual-phase TPC, near-clone of LZ extraction region profile with 20cm grids

Single-phase detector, full LZ extraction region (160cm) installed in vessel

Passivation reduces electron emission

Untreated 20cm grid shows two reproducible electron emission hotspots:

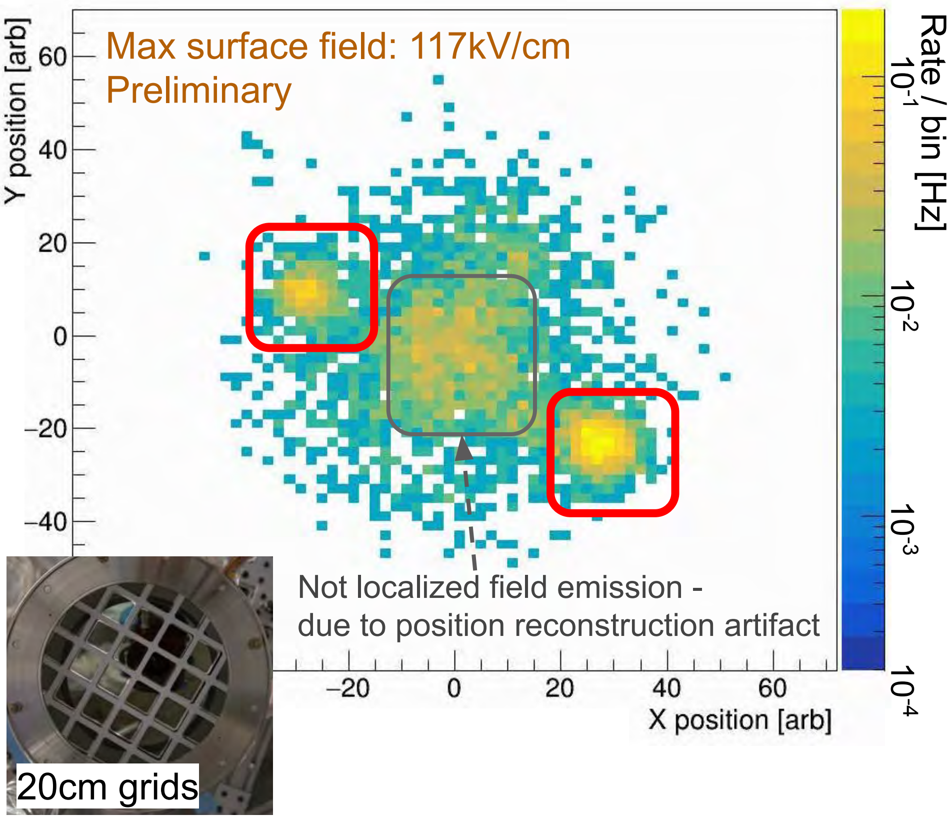
Electron emission rate, by centroid position:



Passivation reduces electron emission

Untreated 20cm grid shows two reproducible electron emission hotspots:

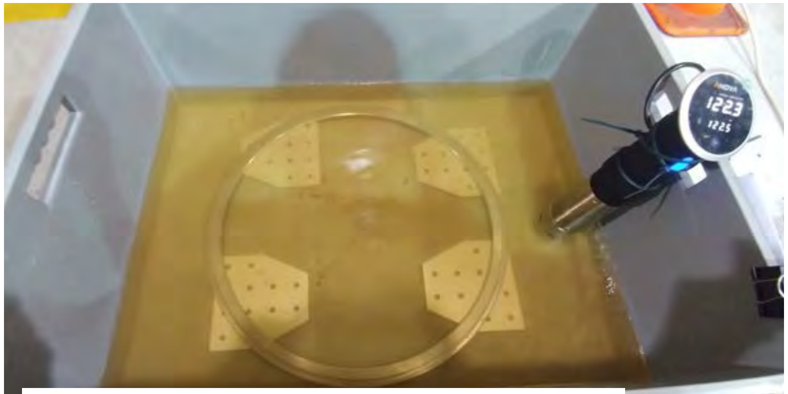
Electron emission rate, by centroid position:



Passivation previously shown to reduce electron emission [arXiv:1801.07231]

Process:

1. **Heated acid bath preferentially etches away surface iron, leaves chromium rich surface**
2. **Thickness of outer chromium oxide increases (30Å → ~70Å, measured by Auger electron spectroscopy)**



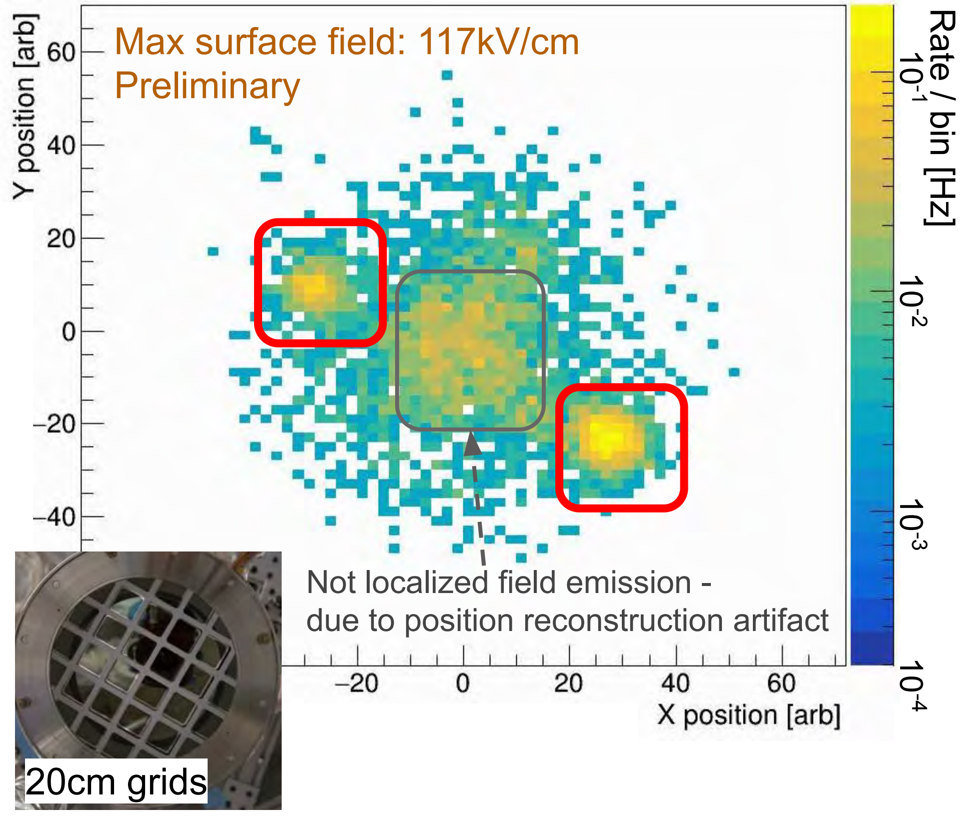
Prototype grid in passivation fluid

Passivation reduces electron emission

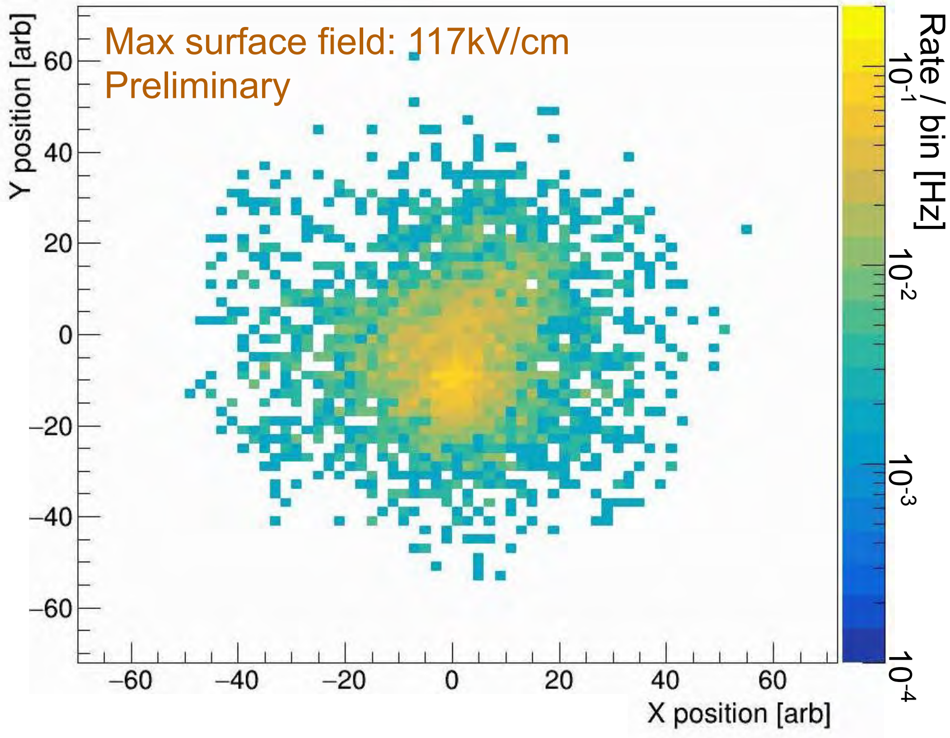
Untreated 20cm grid shows two reproducible electron emission hotspots:

Post-passivation, both hotspots have been removed:

Electron emission rate, by centroid position:



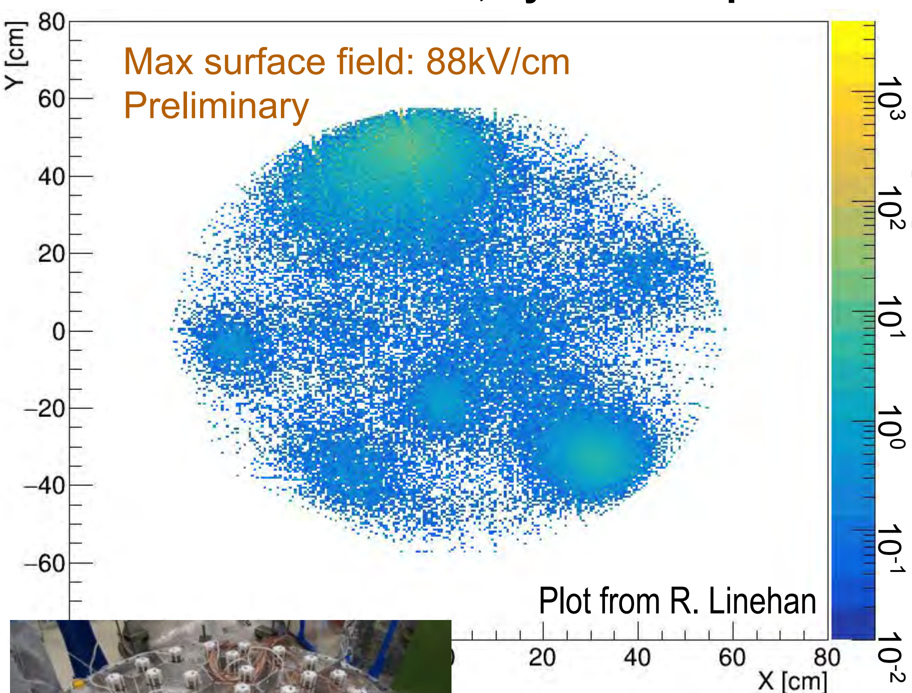
Electron emission rate, by centroid position:

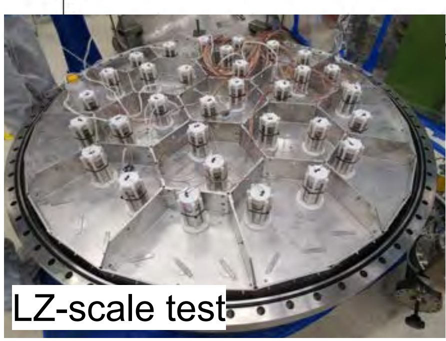


Dust/cleanliness contributes to emission

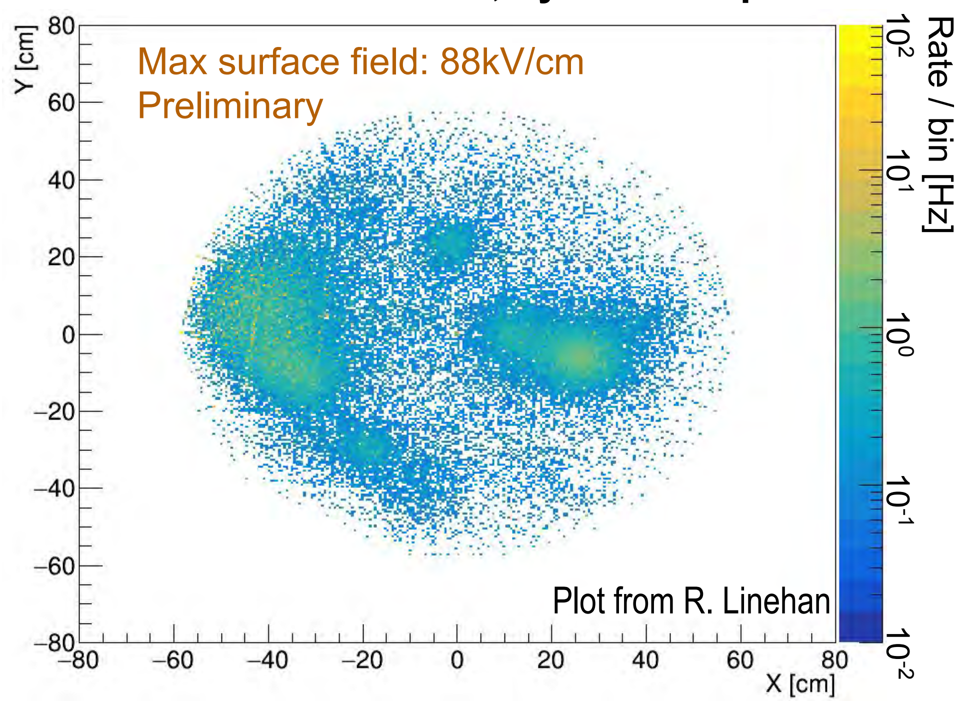
"Transient" electron emission hot spots seen in full-scale LZ extraction region test, moved after dust exposure/removal:

Electron emission rate, by centroid position:





Electron emission rate, by centroid position:



Between tests:

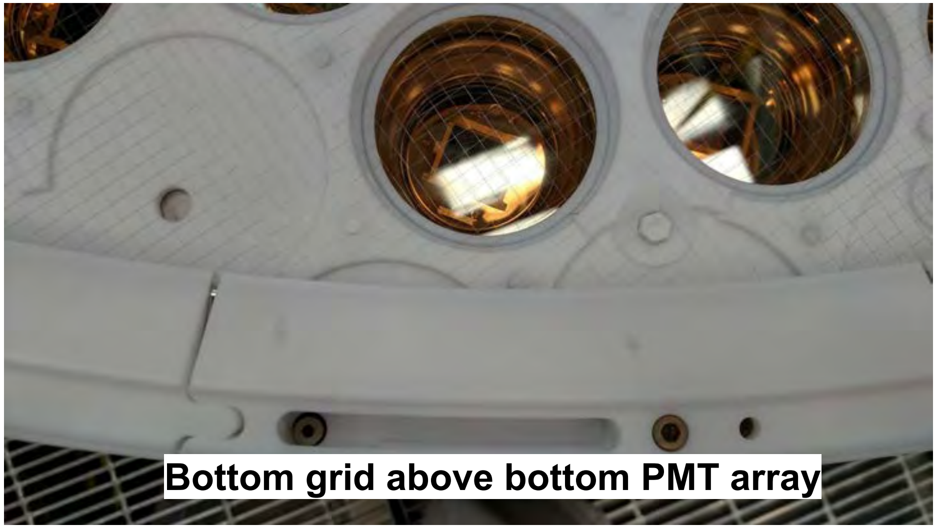
1. Exposure to dust
2. Manual removal of visible dust

LZ grid treatment and cleaning

Citric acid passivation of LZ gate grid

Wash grids with DI water spray prior to installation

Installation of grids into LZ



Bottom grid above bottom PMT array

Bottom and cathode grids installed above bottom PMT array

Assembled extraction region

Attachment of top PMT array

Installation on TPC

Summary

Extraction region performance key to success of LZ

LZ grids designed, fabricated, and tested with single electron sensitivity at SLAC

In order to mitigate the risk of electron emission, we:

1. **Passivated the gate grid**
2. **Recleaned all grids after shipping and prior to installation**

The grids were safely installed in LZ TPC, expecting first science in 2021

Thanks to the LZ Grids/System Test teams

Shaun Alsum
Dan Akerib
Tyler Anderson
Maris Arthurs
Andreas Biekert
Tomasz Biesiadzinski
Jacob Cutter
Alden Fan
Aude Glaenzer
Tomie Gonda
Christina Ignarra
Wei Ji
Scott Kravitz
Nadine Kurita
Wolfgang Lorenzon
Ryan Linehan
Steffen Luitz
Rachel Mannino
Maria Elena Monzani
Eric Miller
Kim Palladino
Tom Shutt
Randy White
TJ Whitis
Ken Wilson

The whole LZ collaboration (see next slide) for all their contributions, help, and advice.

Financial support: DOE, SLAC LDRD, NSFGFP

LZ collaboration, July 2019

5 countries, 36 institutions, ~250 scientists/engineers

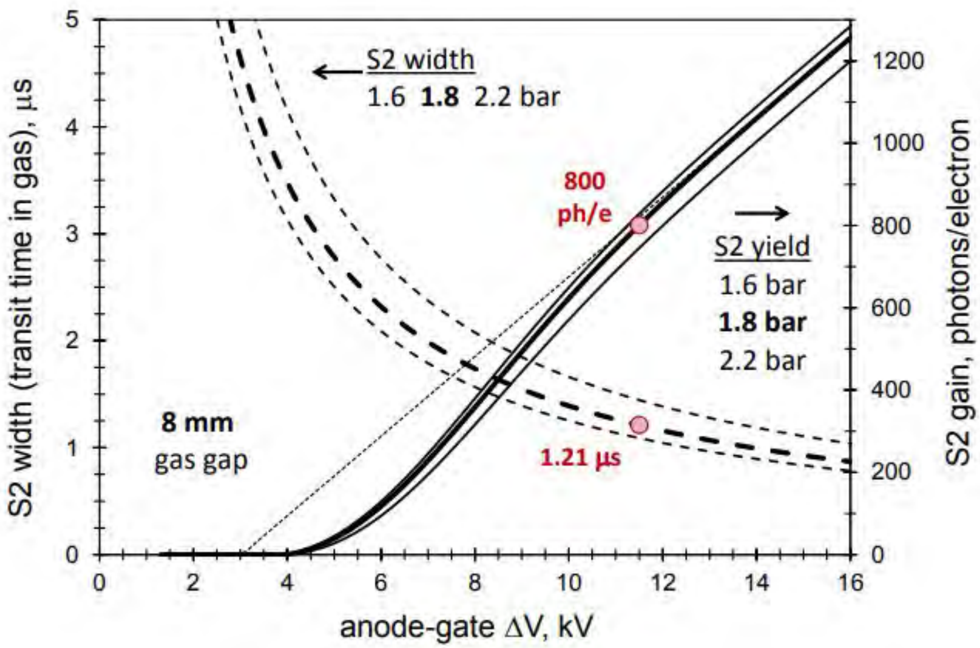
IBS-CUP (Korea)
LIP Coimbra (Portugal)
MEPhI (Russia)
Imperial College London (UK)
Royal Holloway University of London (UK)
STFC Rutherford Appleton Lab (UK)
University College London (UK)
University of Bristol (UK)
University of Edinburgh (UK)
University of Liverpool (UK)
University of Oxford (UK)
University of Sheffield (UK)

Black Hill State University (US)
Brandeis University (US)
Brookhaven National Lab (US)
Brown University (US)
Fermi National Accelerator Lab (US)
Lawrence Berkeley National Lab (US)
Lawrence Livermore National Lab (US)
Northwestern University (US)
Pennsylvania State University (US)
SLAC National Accelerator Lab (US)
South Dakota School of Mines and Technology (US)
South Dakota Science and Technology Authority (US)

Texas A&M University (US)
University at Albany (US)
University of Alabama (US)
University of California, Berkeley (US)
University of California, Davis (US)
University of California, Santa Barbara (US)
University of Maryland (US)
University of Massachusetts (US)
University of Michigan (US)
University of Rochester (US)
University of South Dakota (US)
University of Wisconsin – Madison (US)

Backup slides

Effect of gate-anode ΔV on S2 response



Parameter	value
Gate-Anode separation (and tolerance)	13.0 mm (±0.2 mm)
Gas gap (and tolerance)	8.0 mm (±0.2 mm)
Field in LXe (GXe)	5.2 kV/cm (10.2 kV/cm)
Electron emission probability	97.6 %
S2 photon yield	820 ph/e
S2 width FWHM	1.2 µs
Detailed modeling	
S2 photon yield	910 ph/e
S2 photon *rms*	2.0 %
S2 width FWHM	1.0 µs to 2.0 µs[a]

[a] The larger value is for diffusion-broadened S2 pulses from interactions near the cathode (see Figure 3.6.4).

PMT array	Center	Edge
Top	6.6 % (52 phe/e)	5.4 % (43 phe)
Bottom	2.2 % (18 phe/e)	1.5 % (12 phe)
Top+Bottom	8.8 % (70 phe/e)	6.9 % (55 phe)

S2 photon detection efficiency (photoelectron yield)

LZ TDR: 1703.09144

Dependence of TPC parameters on Cathode HV

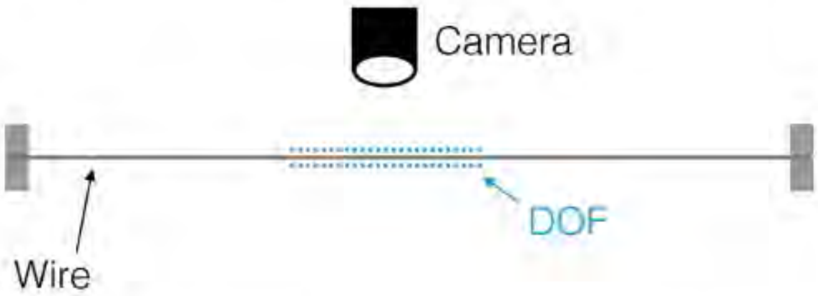
Parameter	−30 kV (LUX)	−50 kV (Base)	−100 kV (Goal)	Comments
TPC drift field, kV/cm	0.17	0.31	0.65	Gate −5.5 kV
ER/NR discrimination	99.6 %	99.7 %	99.7 %	NEST LZ04
Electron drift velocity, mm/μs	1.5	1.8	2.2	[11]
Maximum drift time, μs	970	806	665	Interactions at cathode
Longitudinal diffusion, μs	2.4	2.2	2.0	FWHM, cathode events
Transverse diffusion, mm	2.4	1.8	1.4	FWHM, cathode events
Gate wire field, kV/cm	−64	−62	−58	
Cathode wire field, kV/cm	−18	−31	−63	

LZ TDR: 1703.09144

Deflection tests

Schematic from R. Linehan

Un-deflected Grid



When undeflected, the wire is near the POF of the camera at its original height.

We can focus the camera on the wire and use this to set the initial position of the camera (to some uncertainty).

Deflected Grid

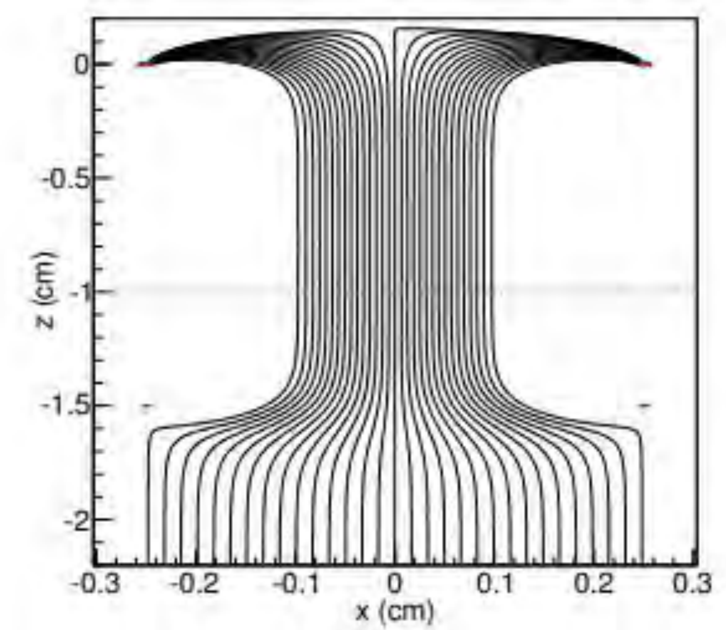
When deflected, the wire causes the POF of the camera to move downward.

We can move the camera downward to re-find the POF. We can use this to find the final position of the camera.

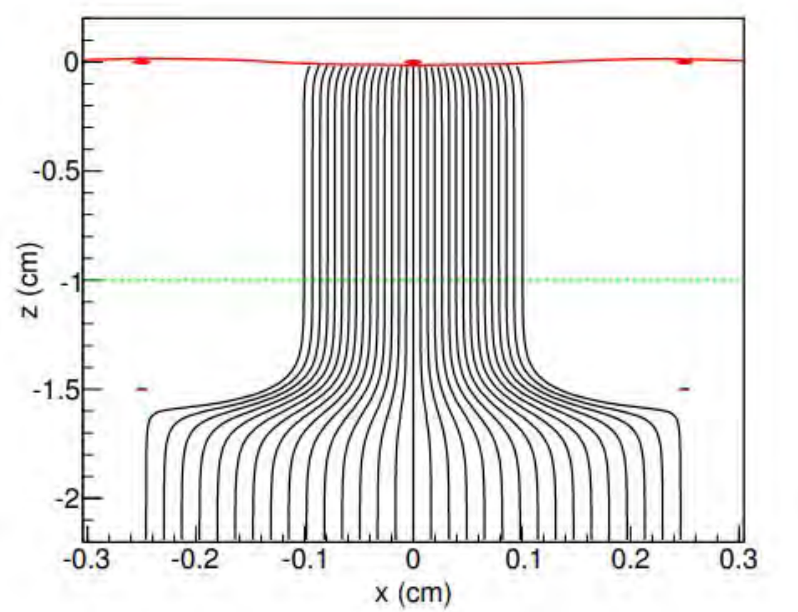
Deflection = (initial position) - (final position)

DOF = depth of field of camera focus
POF = plane of focus

Alignment of gate-anode grids



Electron drift lines for gate (-3.5kV) and anode (+4kV) aligned, 5mm pitch. The green line indicates the liquid surface. The red circles and lines are the locations of the wires in the y = 0 plane.



Electron drift lines for gate (-3.5kV, 5mm pitch) and anode (+4kV, 2.5mm pitch) aligned.

Study from A. Bailey's thesis shows more uniform drift length for electrons through the extraction region for anode pitch equal to half the gate pitch and both grids aligned.

Mid-scale dual-phase TPC at SLAC

<u>Goal:</u> test suite of hardware in conditions closest to LZ

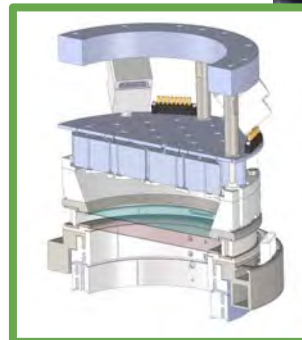
~30kg active volume, liquid xenon dual-phase TPC

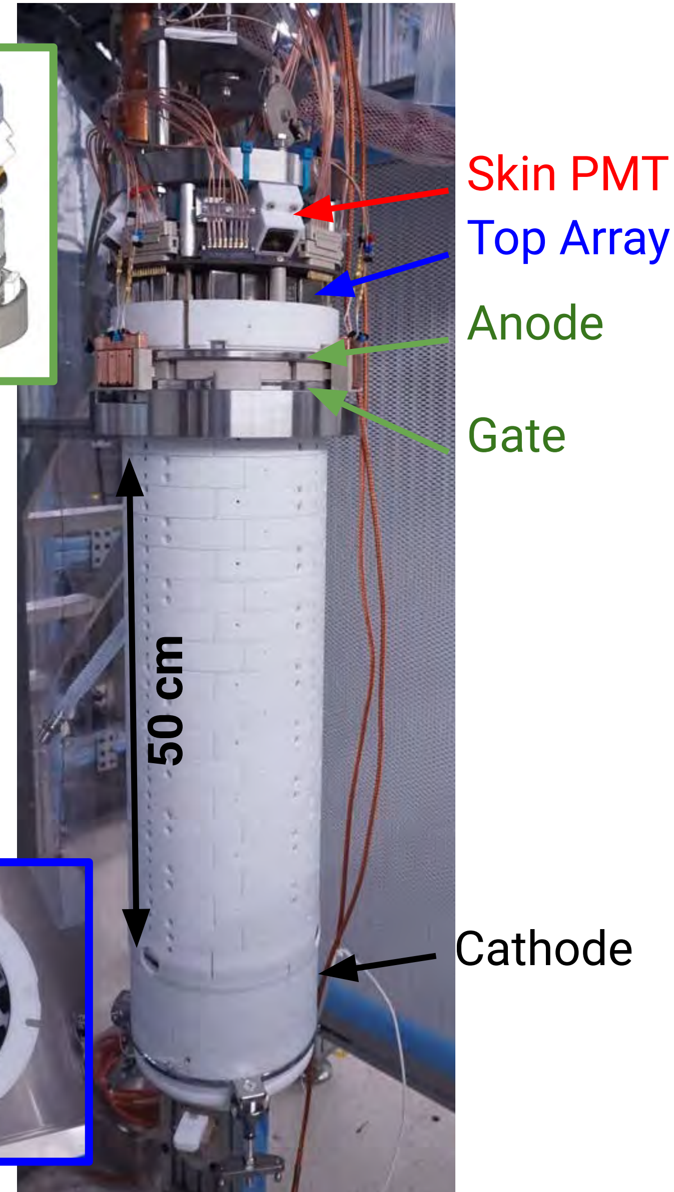
Clone of LZ extraction region, designed to match LZ drift field and extraction field

Xenon circulation path, cryogenics → SLAC scaling up these technologies for LZ

3D position reconstruction

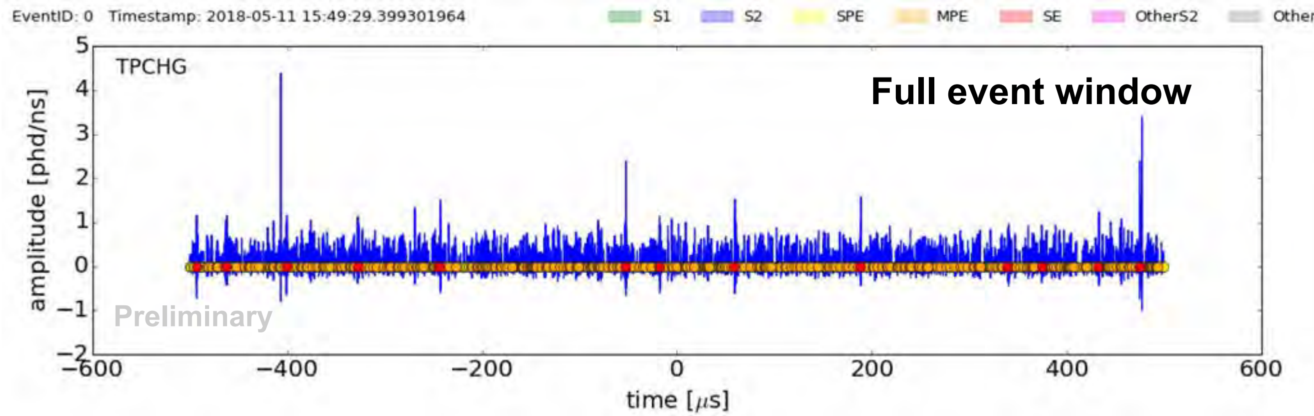
- **32 PMT top array + 6 skin PMTs + 1 bottom PMT**
- **Localize sparking w/ skin PMTs**

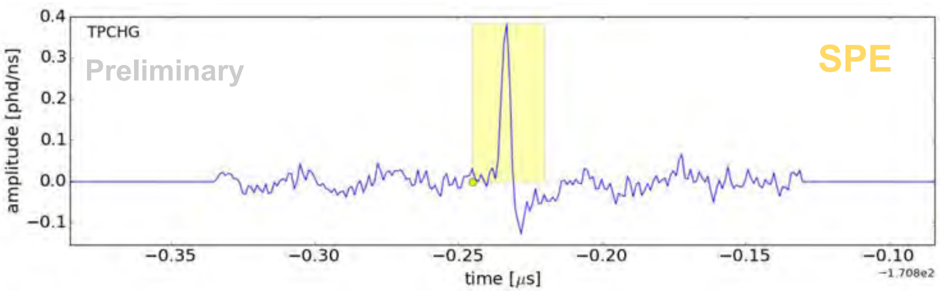


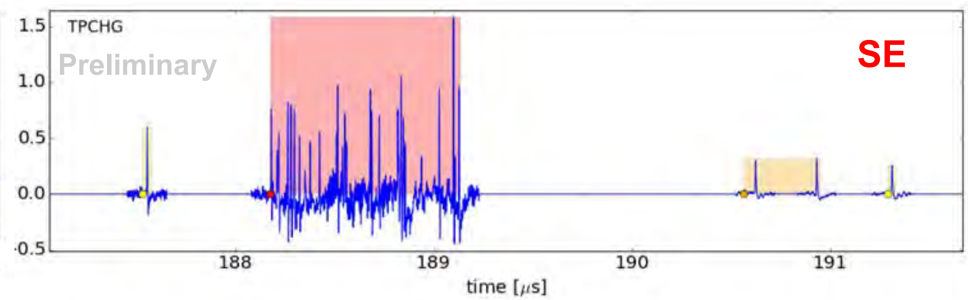


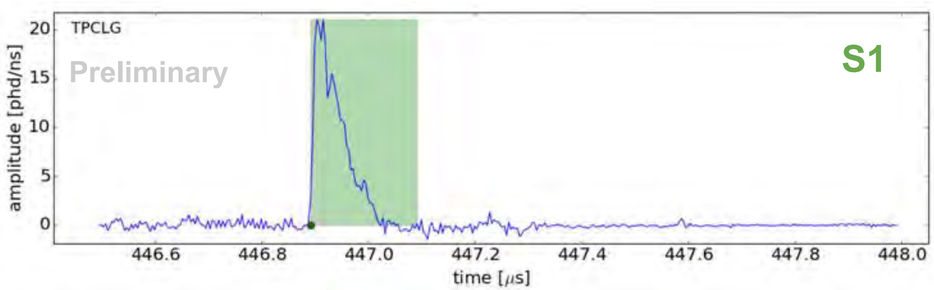
Waveforms

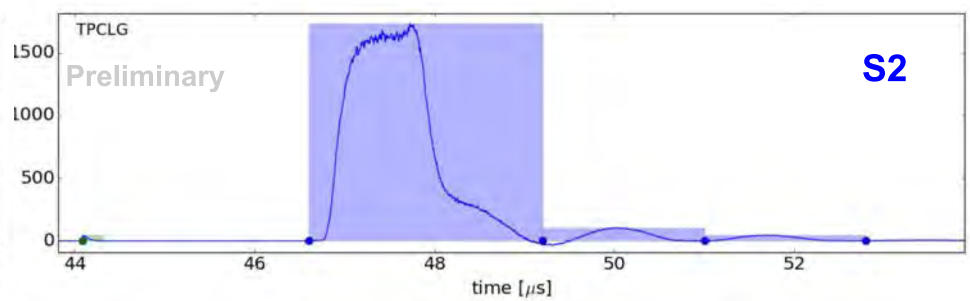
From liquid run of mid-scale detector, ΔV = 12 kV











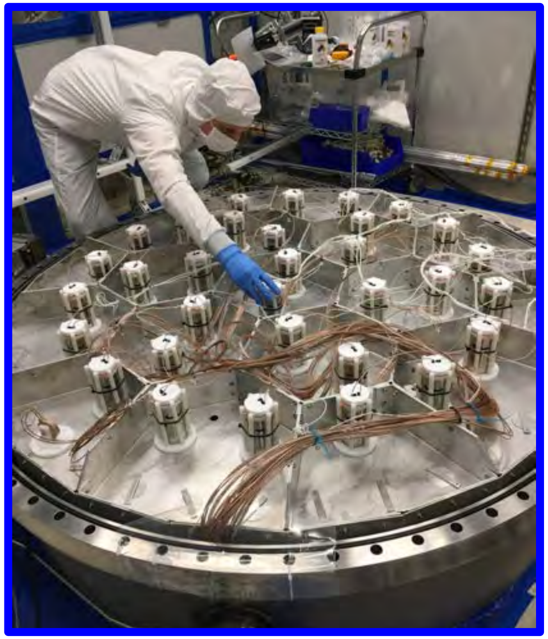
LZ-scale single-phase detector at SLAC

Goal: validate all full-scale grids before shipping to SURF

Sparse 32 PMT array provides 2D position reconstruction in warm xenon gas

Single electron sensitivity for electron emission testing

Full-scale LZ prototype grid installed in vessel



Sparse 32 PMT array

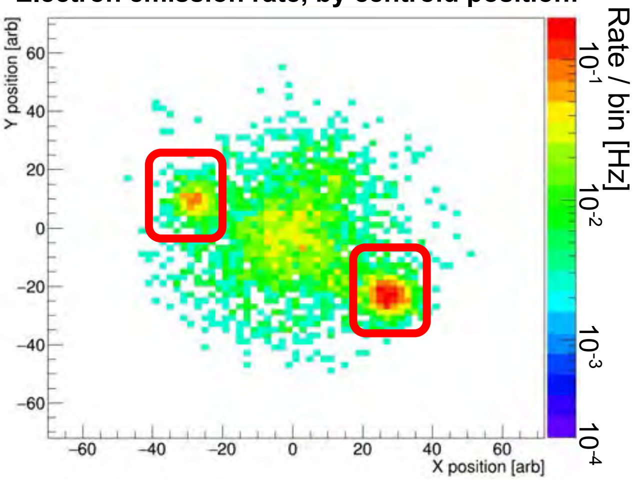
AlMgF2 reflective coating for enhanced LCE

Electron emission reduced via passivation

Electron emission sites were reduced after acid bath, but only eliminated after oxide layer growth:

Untreated grid:

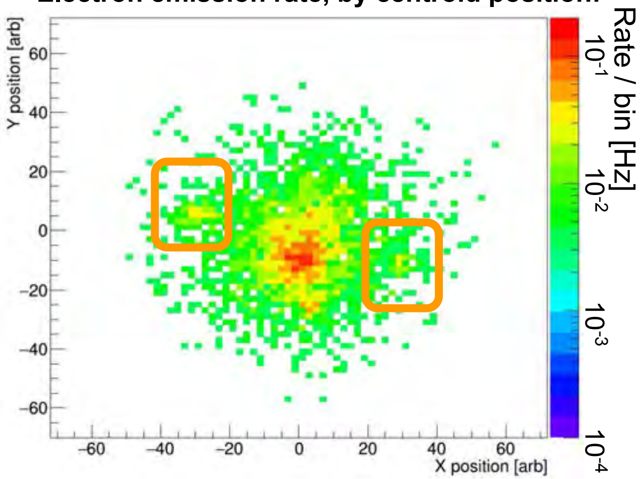
Electron emission rate, by centroid position:



Voltage-dependent hotspots present

Post-acid bath:

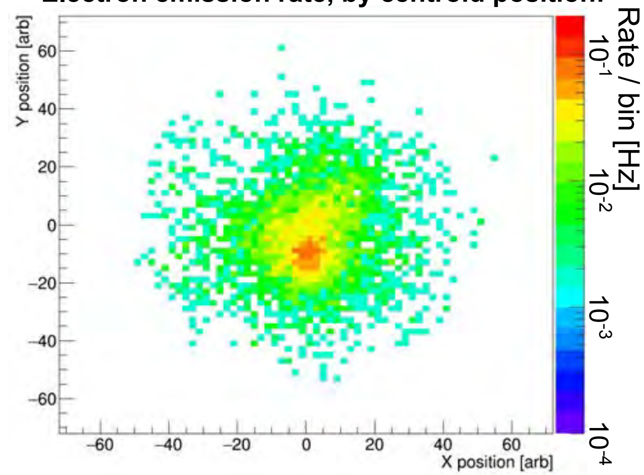
Electron emission rate, by centroid position:



Hotspots reduced

Post-oxidation:

Electron emission rate, by centroid position:



Hotspots eliminated

Gate/anode HV terminations