Challenges for High Voltage in Noble Liquids

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CPAD, October 14, 2017

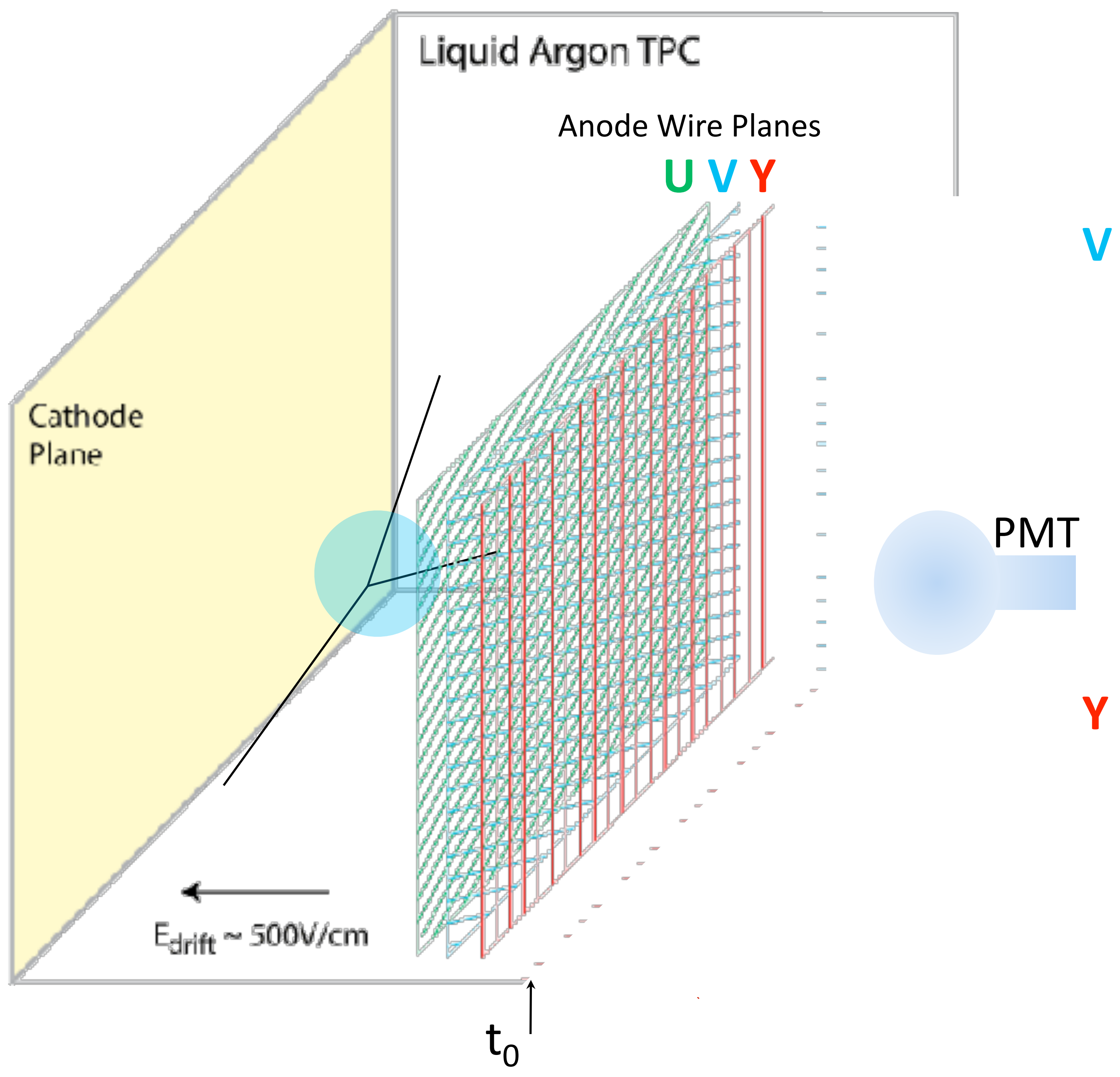
Warning/Disclosure

- Giving a talk on HV in liquid nobles
- I work on high voltage (HV) for ν liquid argon time projection chamber (LArTPC) experiments
- I have never worked with Xe or on dark matter experiments, but I did want to highlight some of the work being done in that area

Why HV

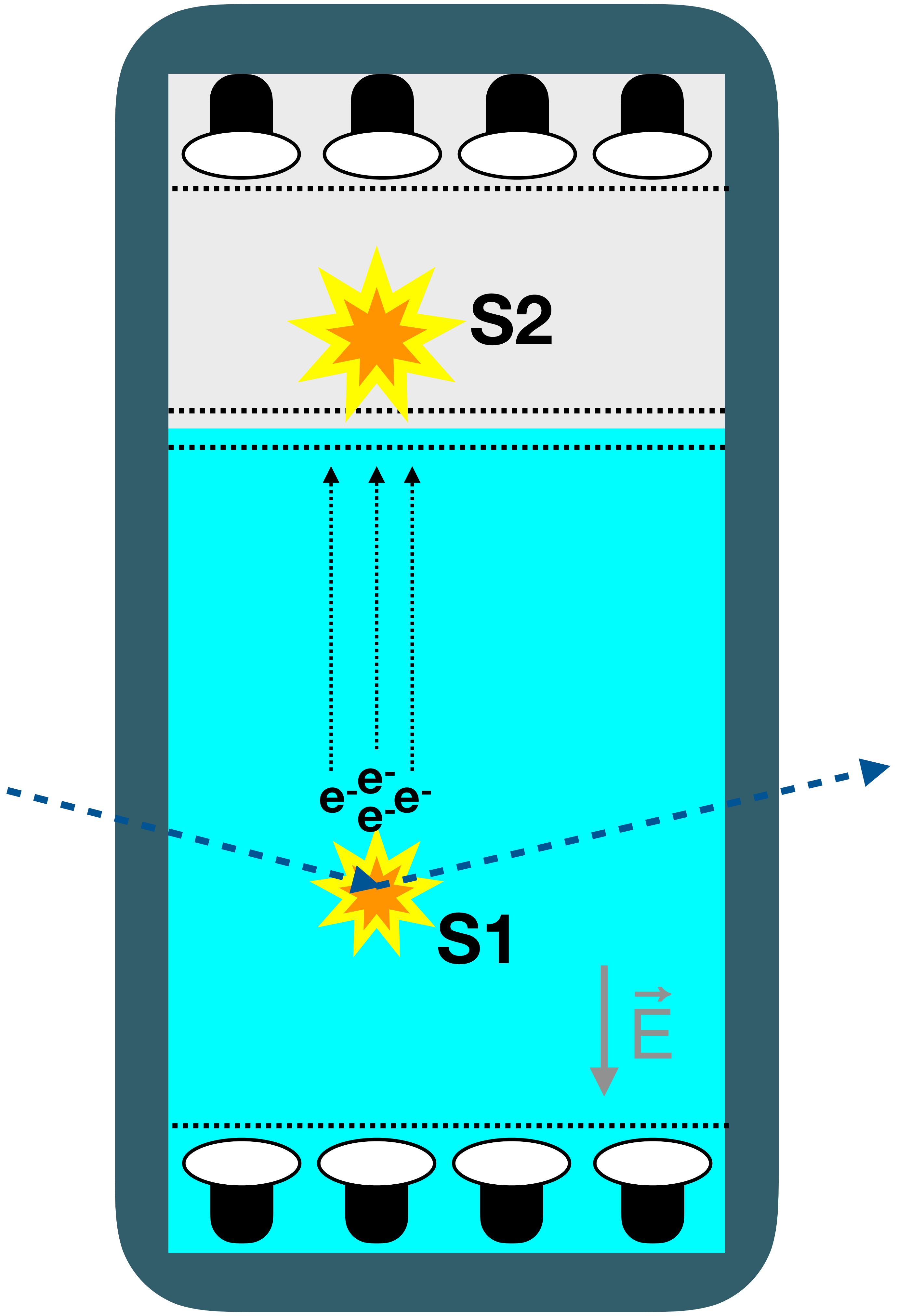
- In single phase (SP) TPCs, HV voltage on a cathode creates the field to drift the signal electrons from ionization to sense wires (or pixels).

- In dual phase (DP) experiments, there is also an HV applied to a cathode to drift electrons.
  - There is additionally an HV applied to the gate wires to amplify the electrons in the gas phase



Why HV

- In LArTPCs, HV voltage on a cathode creates the field to drift the signal electrons from ionization to sense wires (or pixels).
- In dual phase experiments, there is also an HV applied to a cathode to drift electrons.
  - There is additionally an HV applied to the gate wires to amplify the electrons in the gas phase



Why HV: Physics Reach

- SP LArTPCs: More signal electrons!
  - For those with significant cosmics: faster drift leads to less background
- DM: Better electronic recoil and nuclear recoil discrimination
  - Dependence on field is not as strong as once thought
  - More signal electrons & greater extraction efficiency

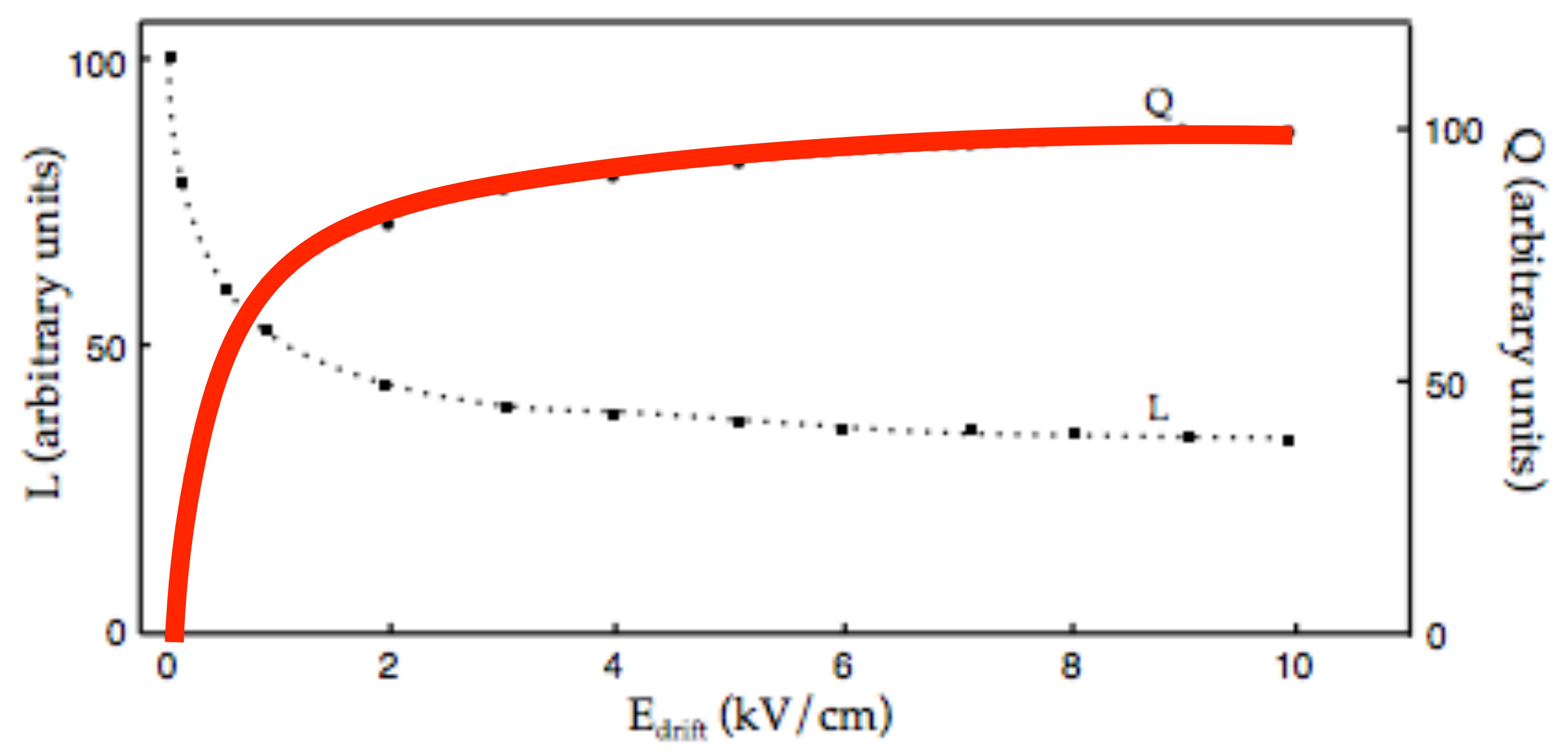


Figure 3.7: The graph shows the behaviour of the luminescence light intensity and of the collected charge as function of the electric field strength. The y axis scales

L. Grandi Dissertation, p. 85

What level of HV are we talking about?

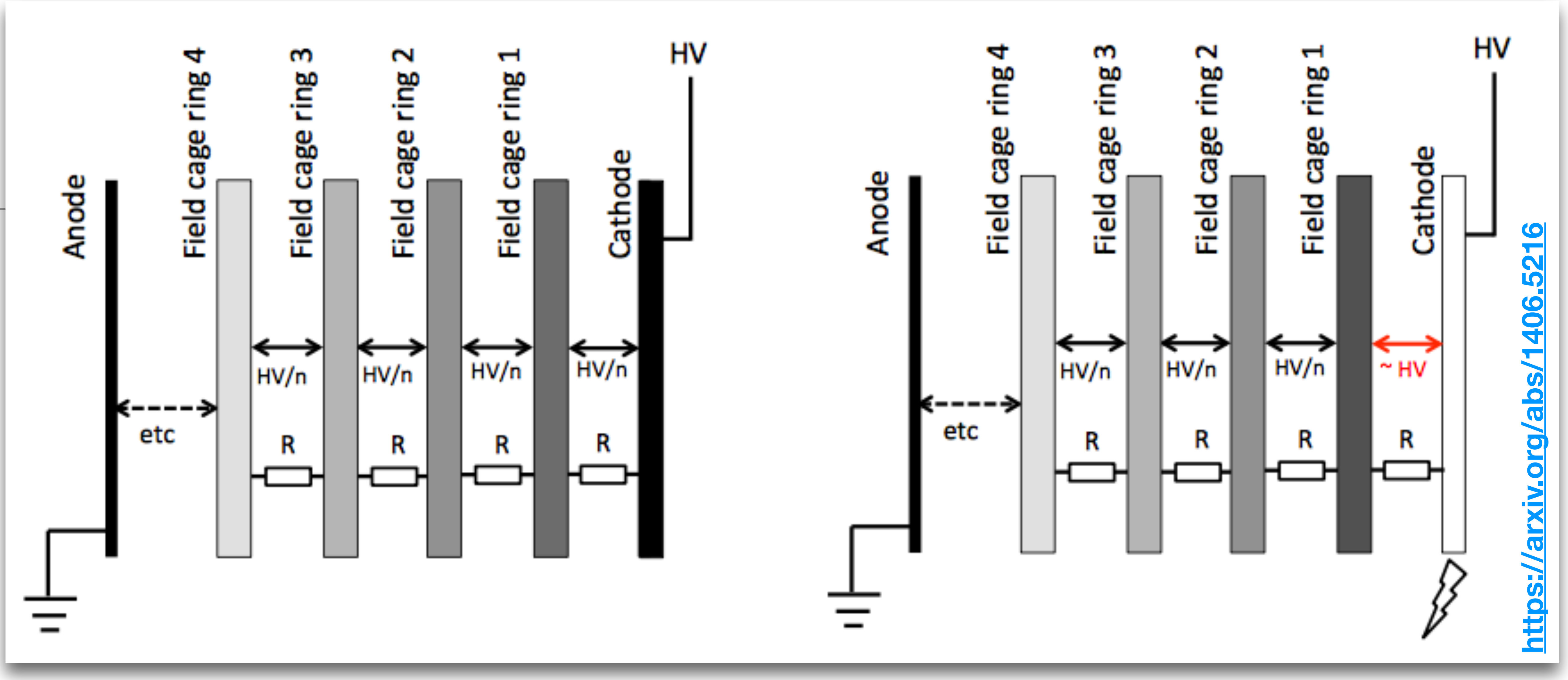
I'm neglecting DP wire voltage here

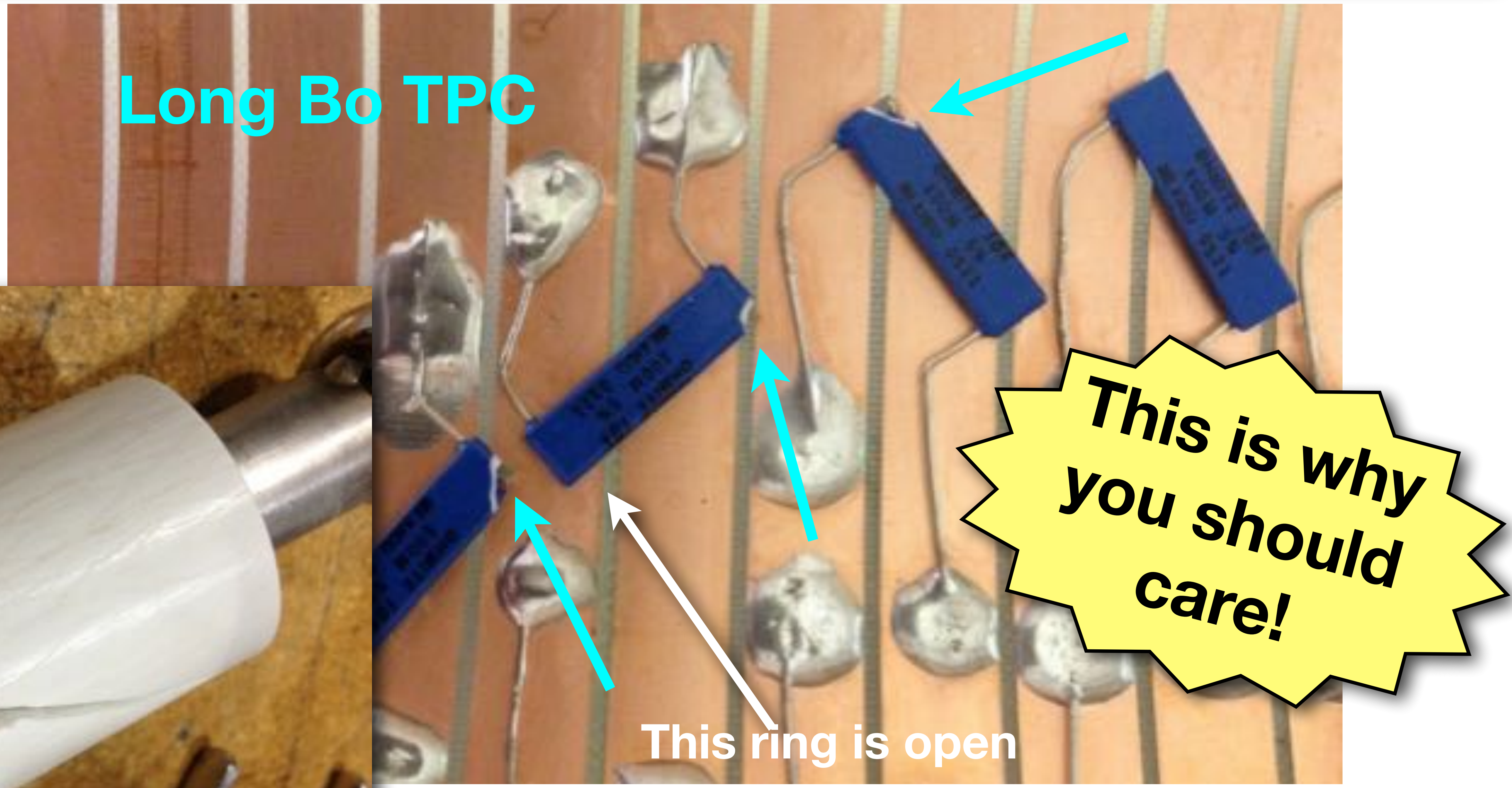
Experiment	Detector	Target or Maximum Cathode V (kV)	Operation
ICARUS	SP Ar	75	75 (150)
MicroBooNE	SP Ar	128	70
DarkSide-50	DP Ar	60	12.7
ProtoDUNE-DP	DP Ar	300	-
DUNE-SP	SP Ar	180	-
DUNE-DP	DP Ar	600	-
EXO-200	SP Xe	75	8, 12
Xenon100	DP Xe	30	16
LUX	DP Xe	up to 100	8.5
LZ	DP Xe	50	-

Challenges/Issues/Concerns/Problems

Breakage

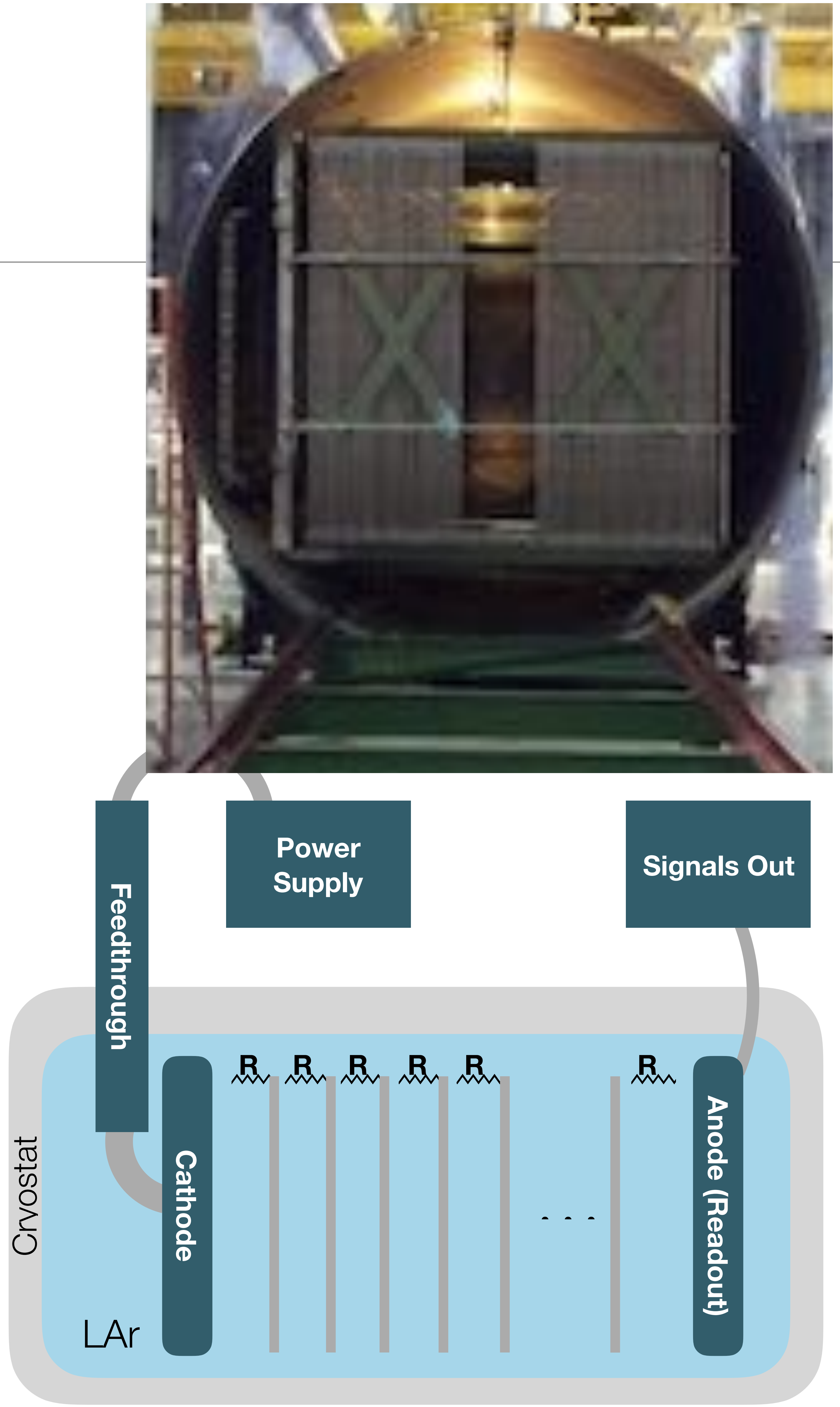
- Resistors can break due to an over-voltage condition
  - Cathode (or some field cage component near the cathode) can discharge to ground putting a large voltage across the resistor
  - Also, breakdowns can break components:





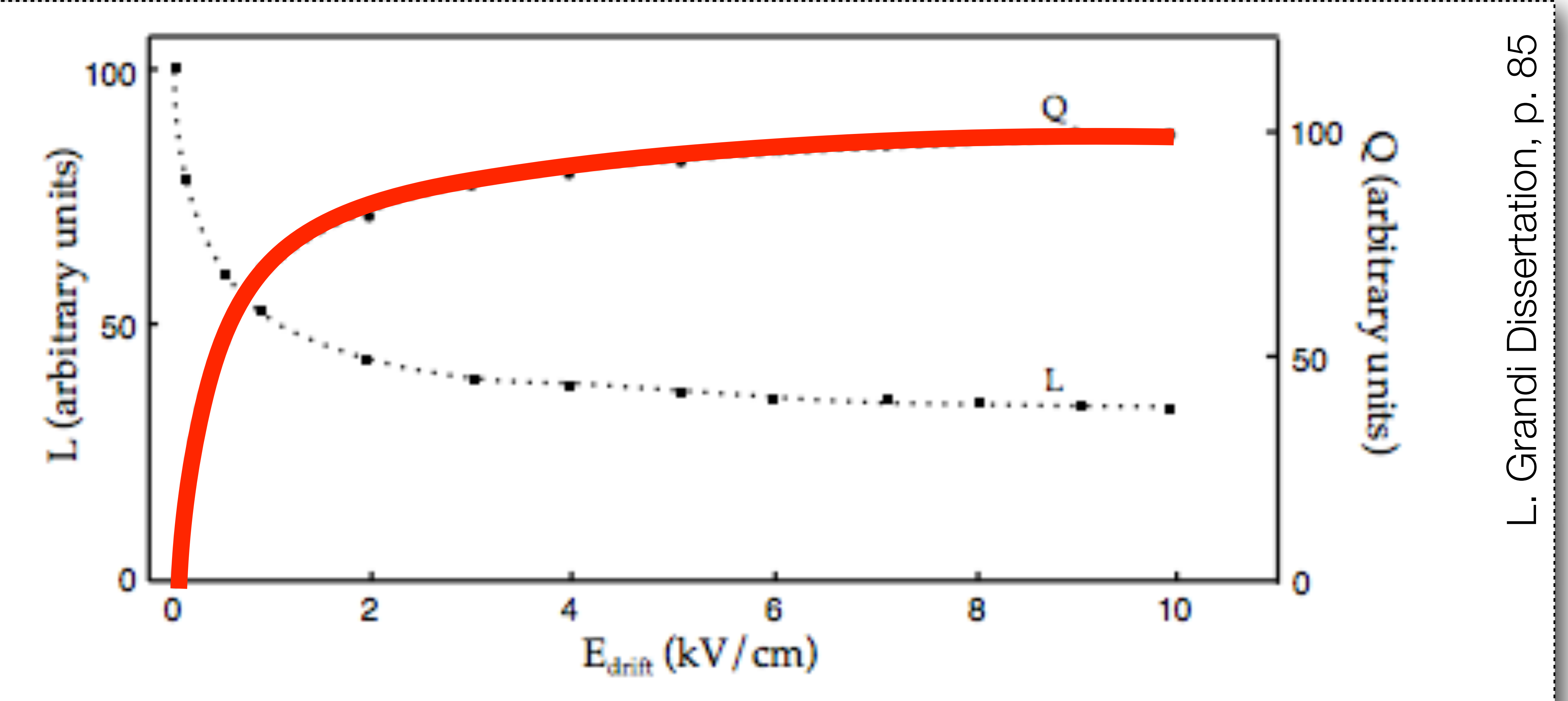
Electronics (Breakdowns continued)

- The cathode is capacitively coupled to the anode
- Cathode can be many square meters in area (µB is ~2.5 m x 10 m)
- A discharge can induce a large current on the anode and damage electronics



Physics Reach

- One breakdown or glitch can set the operating threshold of an experiment limiting the physics reach
- Downtime — time when the detector isn't collecting data
  - PS trips from discharge
  - Sustained irregular current draw leads to irregular voltage on the cathode (and likely noise on the electronics).



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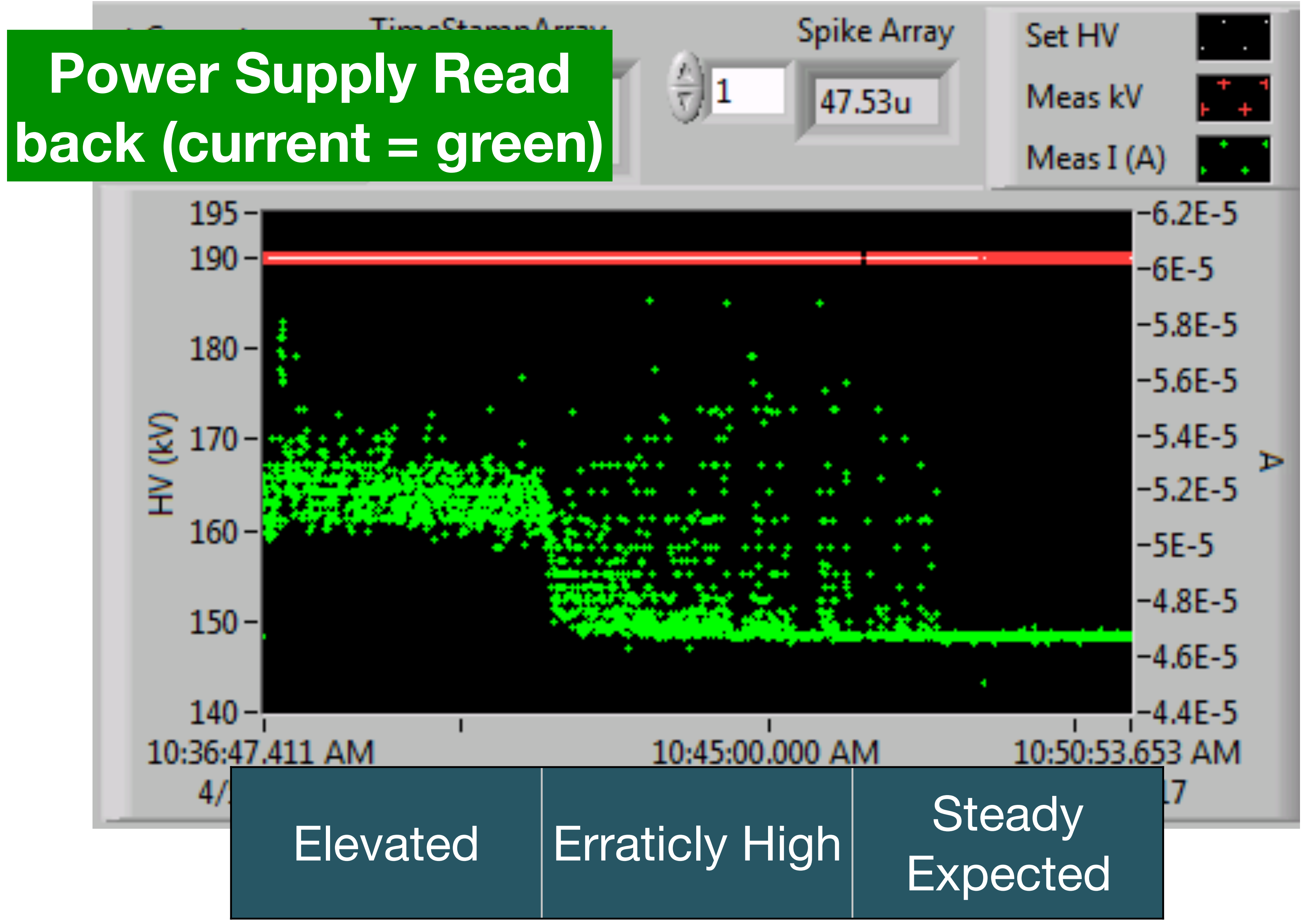

Light & Charge

- The DP experiments are especially sensitive to problems arising from unintended electroluminescence & spurious electron emission
- Light and charge from the grids hurt discrimination ability
- Theoretical threshold is ~400 kV/cm, but in practice experiments impose limits of 50-60 kV/cm

How to tackle some of these issues

Supression: Coating

- LHEP Bern has investigated increasing the max field a component can withstand under HV with a polymer coating (http://arxiv.org/abs/1406.3929v1)
- Prevents streamer from starting!
- Fields as high as **412 kV/cm** were reached over several mm before breakdown
- Similarly, DUNE-SP has metal profiles capped with polyethylene


physics.ins-det] 16 Jun 2014

A method to suppress dielectric breakdowns in liquid argon ionization detectors for cathode to ground distances of several millimeters

M. Auger, A. Ereditato, D. Goeldi, S. Janos, I. Kreslo, M. Luethi, C. Rudolf von Rohr, T. Strauss, T. Tolba and M. S. Weber

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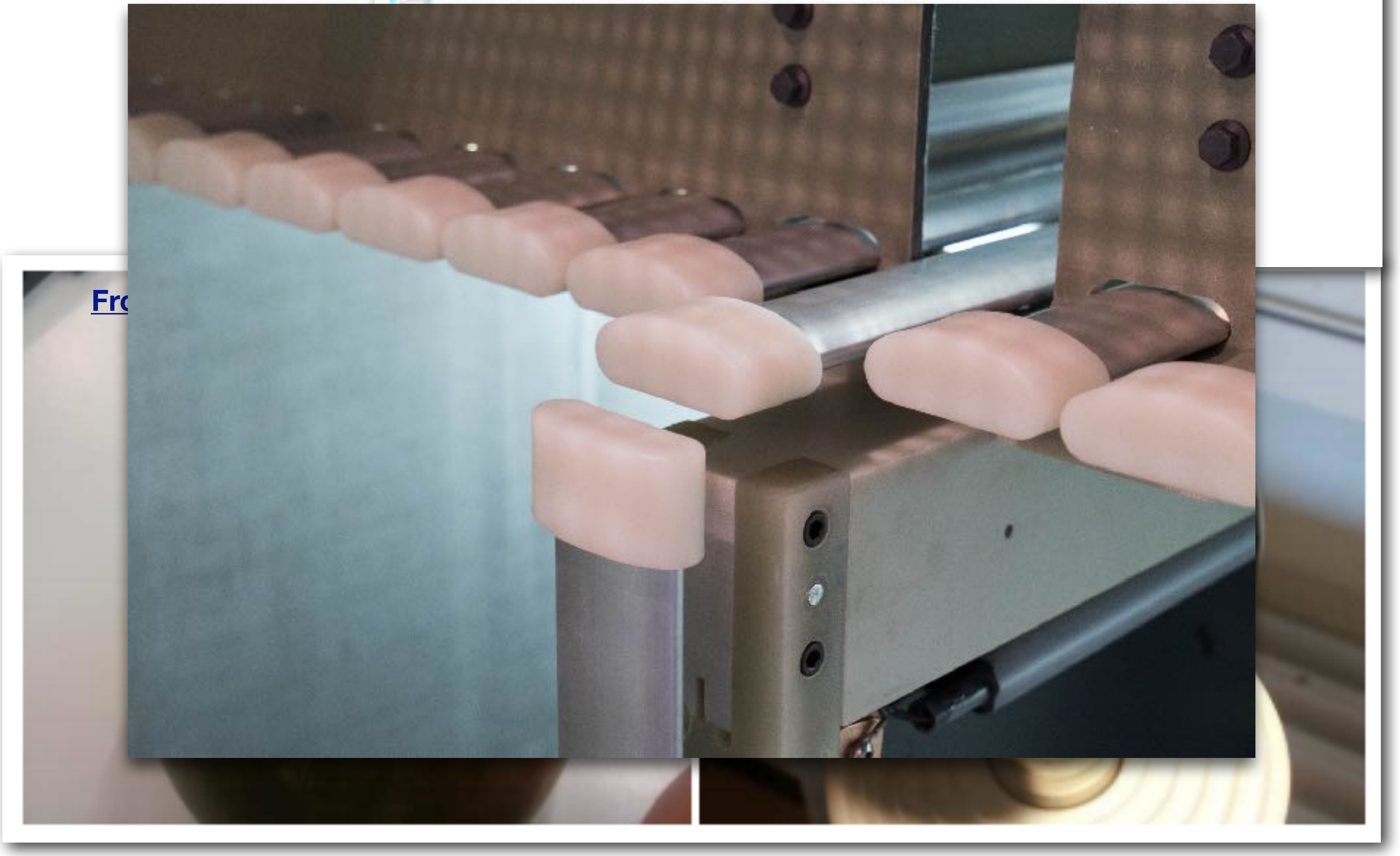


Better Understanding: Dielectric Strength (LAr)

- As of ~5 years ago, experiments for LAr were being designed using a dielectric strength of ~1 MV/cm
    - With this, even factors of 10 in safety weren't that hard
- We then realized after seeing sparks/ discharge/breakdown at fields less than MV/cm that this value was inappropriate
- It turns out that it came from studies from the 1960s using 5 mm balls at sub-mm spacing.

Vol. 107, No. 3 ELECTRODE SURF

Table II. Mean strengths for liquified gases (mv/cm)

	Platinum electrodes		Stainless steel electrodes	
	from Fig. 2	from ref. (2)	from Fig. 3	from ref. (2)
Argon	1.10	0.86	1.42	1.00
Oxygen	2.00	0.93	2.38	1.04
Nitrogen	2.26	0.93	1.88	1.00

time, and platinum electrodes, in order to make di-

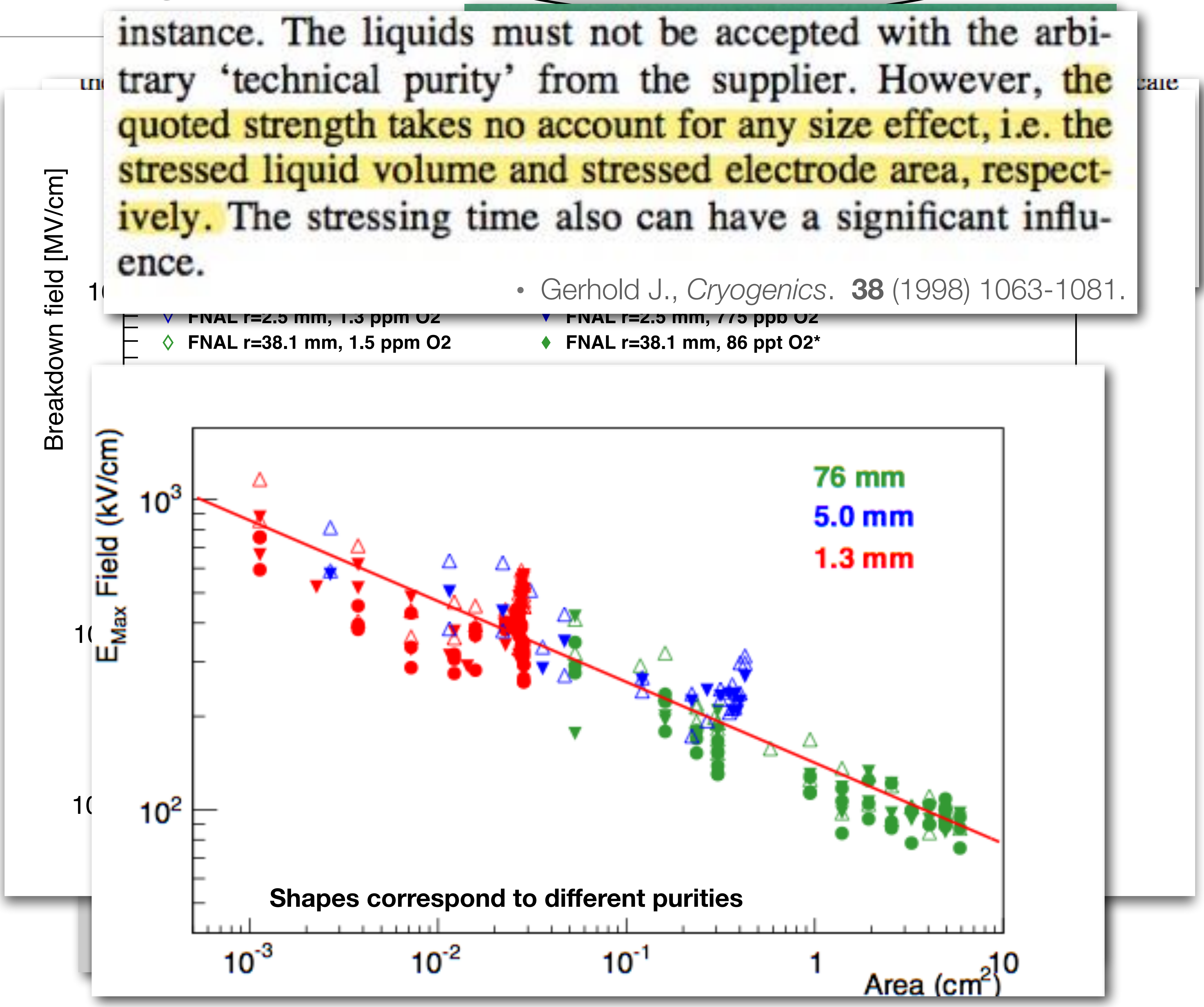
planation of the effect. The nonlinear plot for argon and stainless steel suggests that the strength of argon for really large spacings (> 100 μ) would be much less than that quoted in Table II, and any increase for smaller

D. Swan and T. Lewis, *J. Electrochem. Soc.* 107 (1960) 180.

Better Understanding: Dielectric Strength (LAr)

Breakdowns at fields as low as **40 kV/cm**

- Studies at Bern using a ball-plate observed breakdowns as low as 40 kV/cm
- The ETH Zurich group studied breakdowns between two plates
  - Observed breakdowns in boiling argon as low as 40 kV/cm
- Fermilab also used a ball plate geometry and got similar results to the Bern group
  - Literature suggested that stressed area or volume could be a parameter of interest
  - Using stressed area unified the trend across our data and is currently the best metric for predicting breakdown voltage

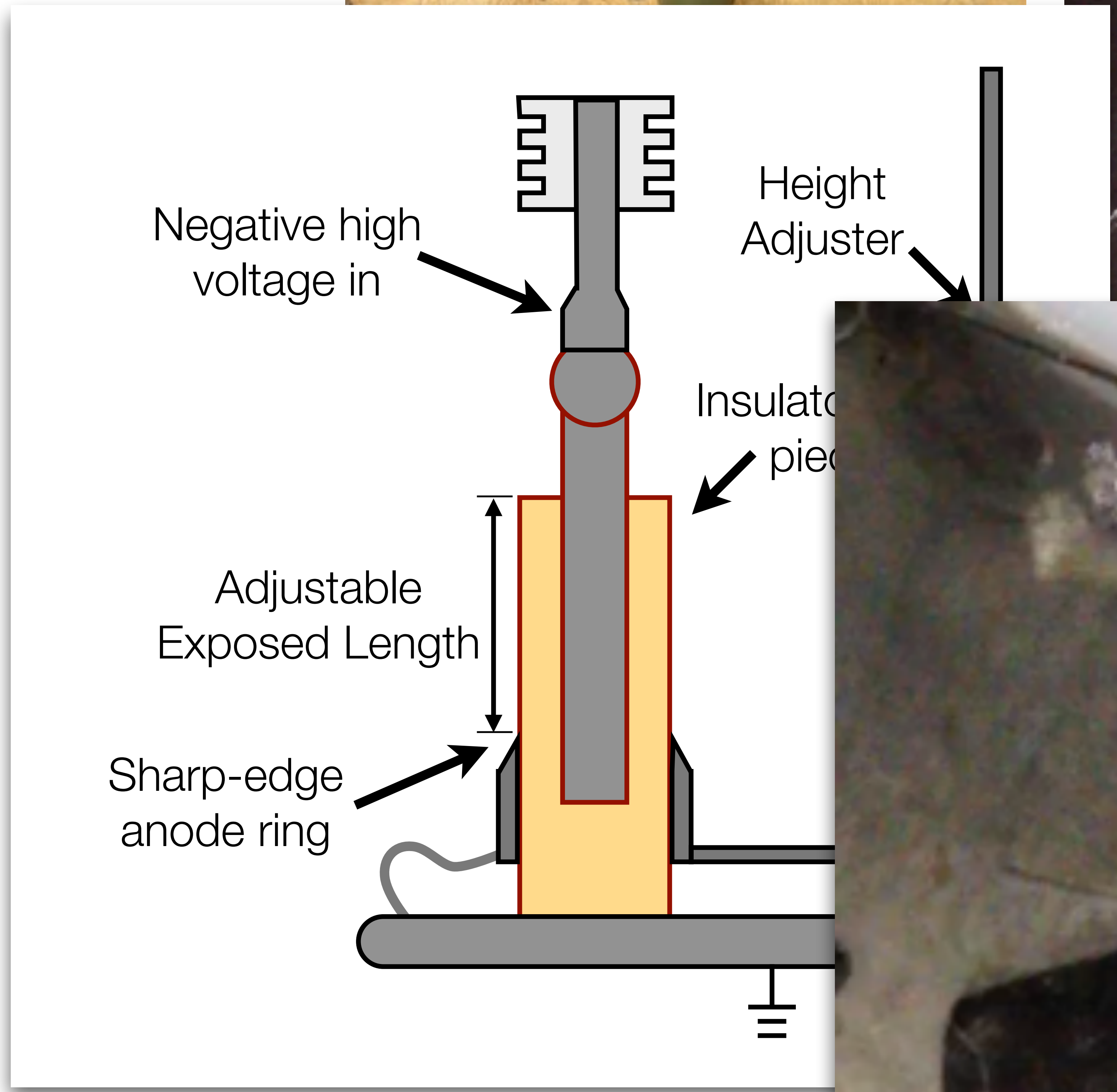


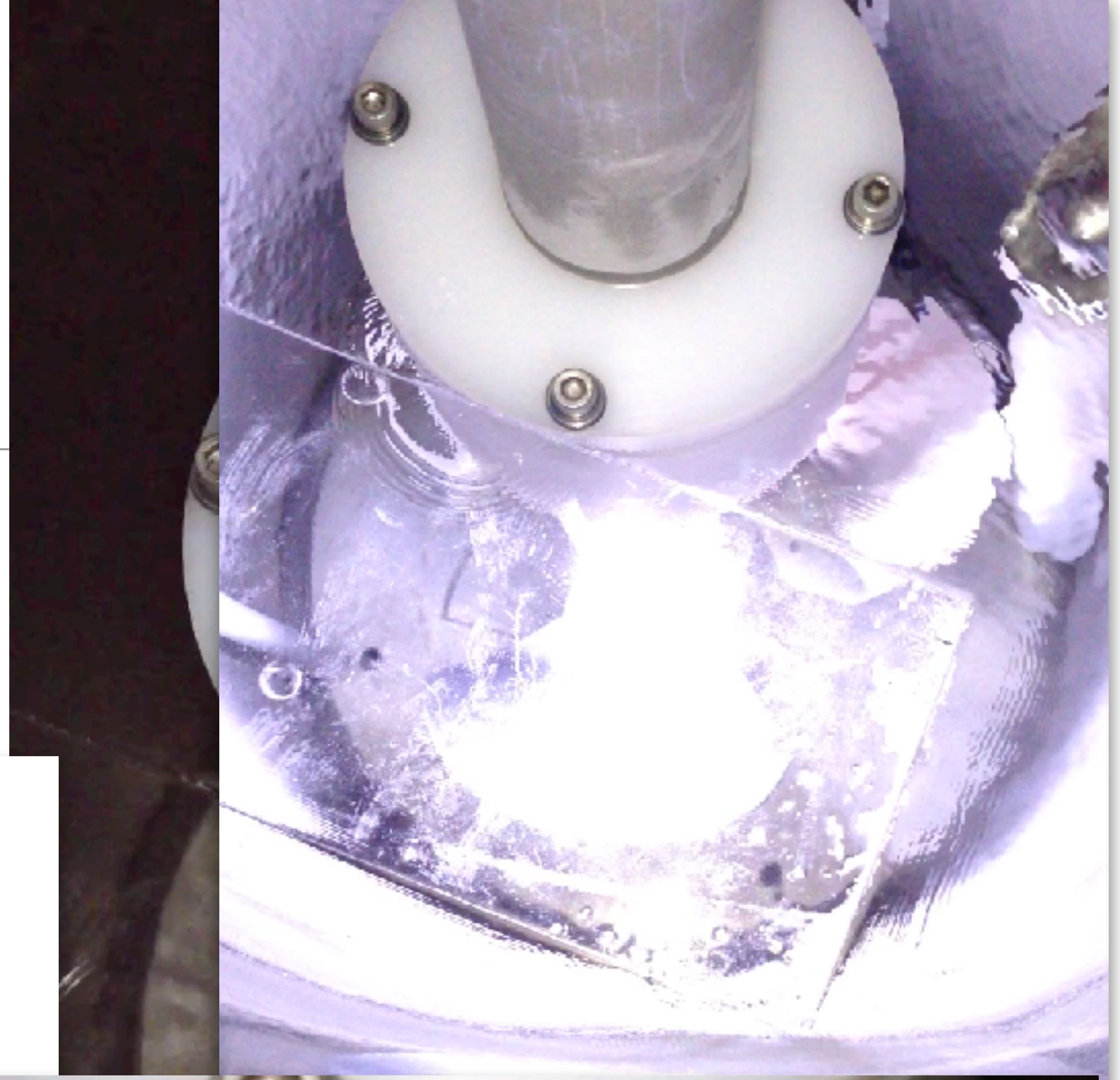
Light & Better Understanding in LXe

- Studies have been done on spurious electron emission from wires
  - Effects of passivation, electropolishing at Imperial College London. See A. Tomas' talk at last year's conference.
  - See Ch. 6 in A. Bailey's Thesis, 2016
- nEXO has test beds at Carleton U., SLAC, and LLNL
- LZ has tests at SLAC (see A. Fan's and W. Ji's talks from yesterday), ICL,
  - LBL: See L. Tvrznikova's talk at LIDNE describing a new versatile LXe and LAr test stand
- R&D for high voltage effects on a number of noble liquid experiments was reported at a 2013 workshop at FNAL (https://arxiv.org/abs/1403.3613)

Better Understanding: Feedthrough Design

- Test of insulator performance in a feedthrough-like geometry
  - Insulator surrounding a conductor
- Evaluate materials, length, grooves/ profiles
- Caveat: this was done in an open cryostat
  - N2 kills late light, O2 eats electrons, impurities can perturb the local field.



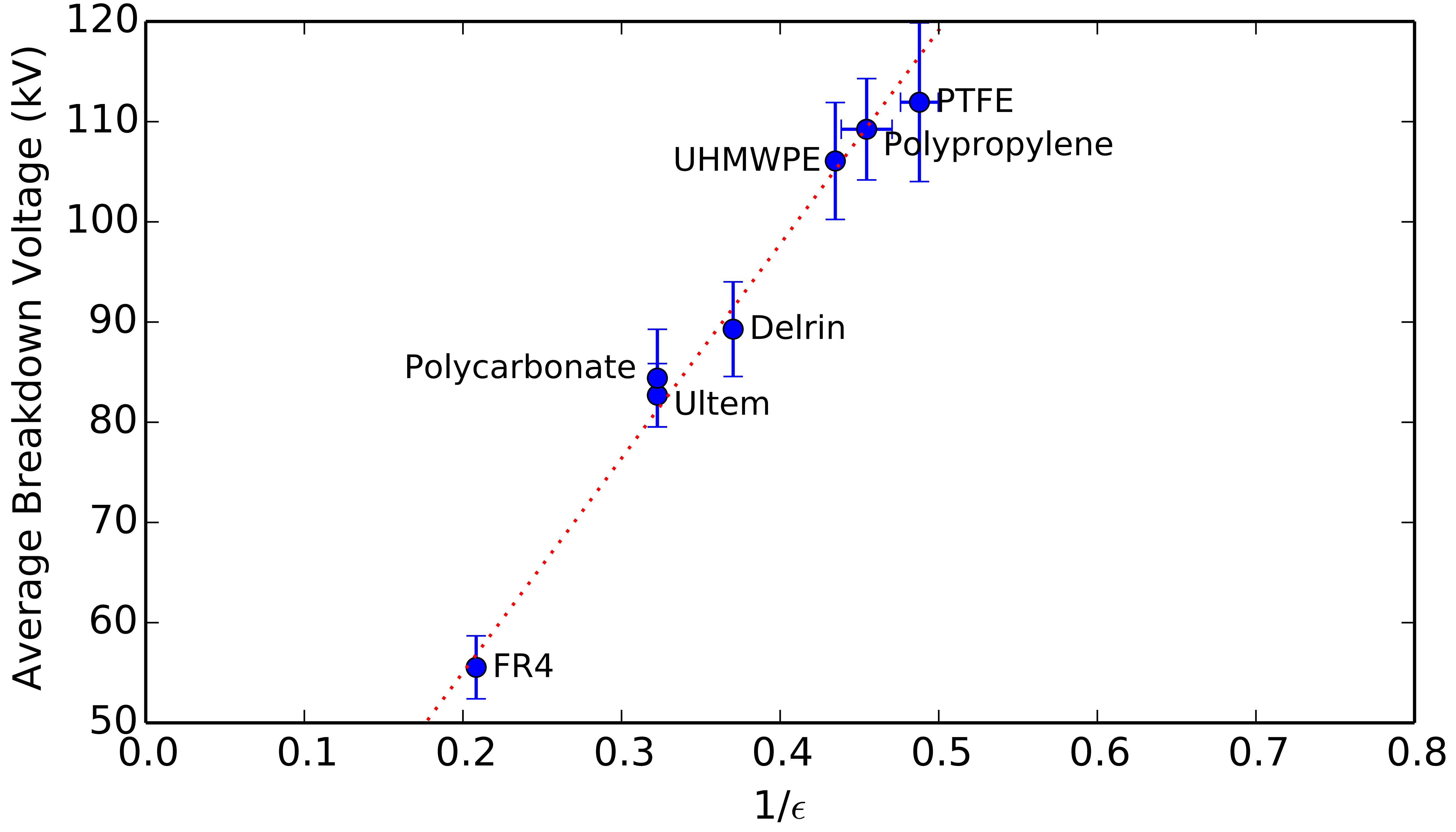


2016_JINST_11_P03026, http://arxiv.org/abs/1506

Insulator Study: Materials

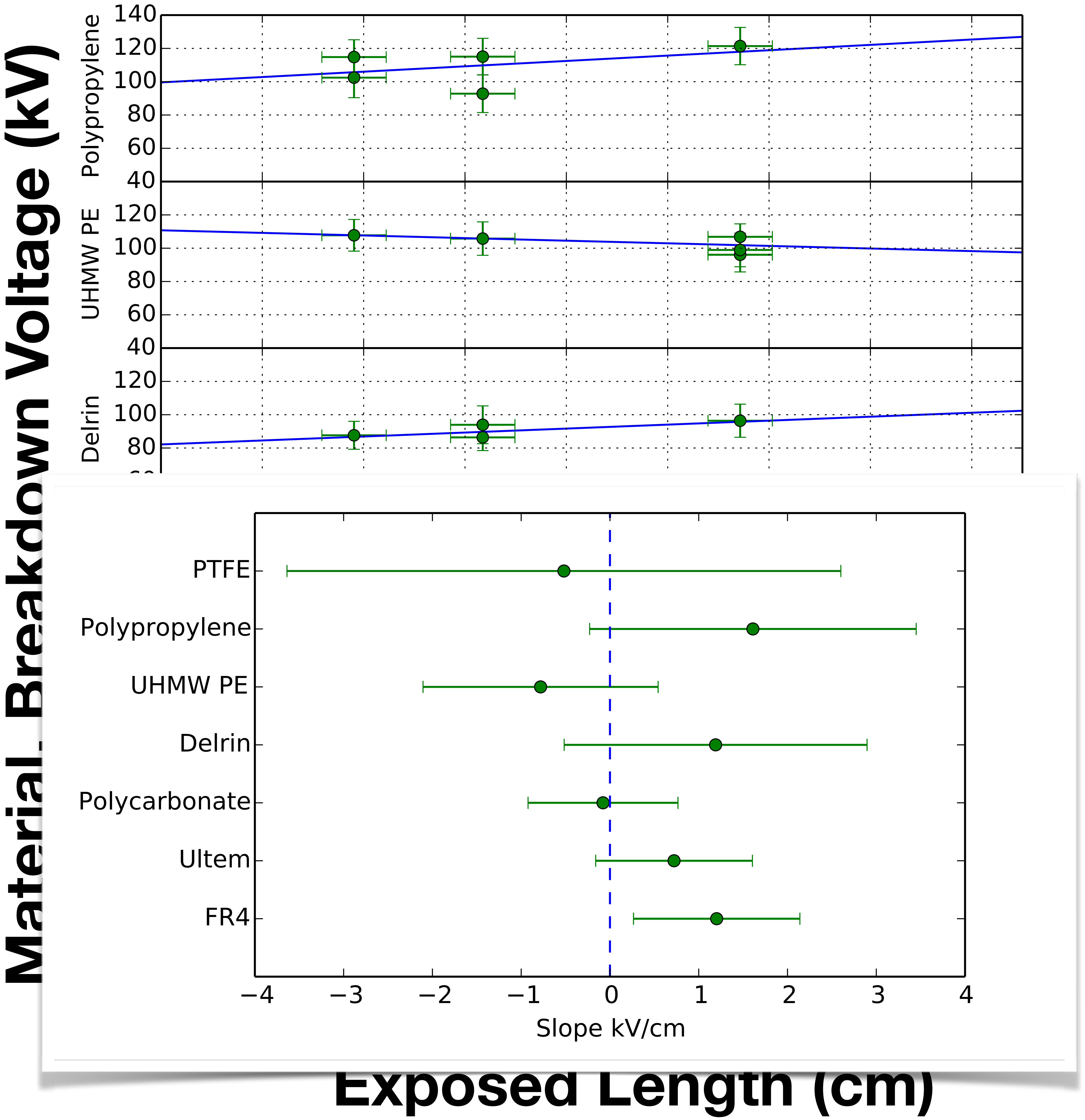
- There was lore that certain materials had surface properties that allowed electrons to skate along the surface

- We found that <u>differences in breakdown voltage between **materials** could be explained by differing permittivities</u> (—> resulting electric field at the insulator surface)



Insulator Study: Length

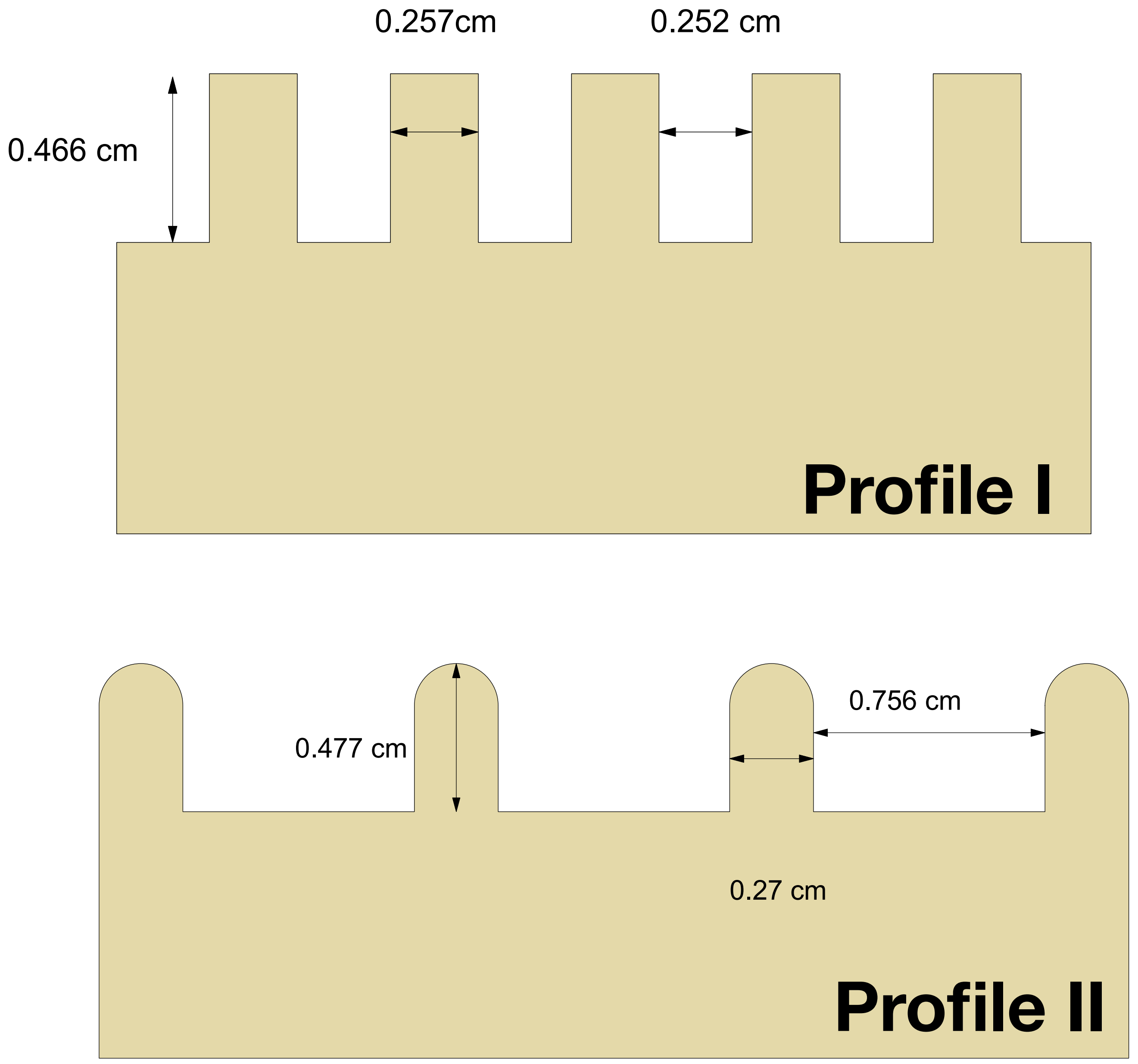
- We considered the exposed insulator length:
- Broad experience at room temperature generally relates an *increase in path* to an *increase in breakdown voltage*
- However, we found exposed insulator **length** had little, if any, effect on breakdown voltage (~1-12 cm)



Insulator Study: Grooves

- Grooves are sometimes added to the surface of insulators to improve HV performance
  - This is seen frequently in HV bushings & standoffs
  - There, the idea is to increase the creepage path
  - In liquid argon, it's less clear
    - Surface with a component anti-parallel to the E field to inhibit travel?
    - Islands where charges collect reducing the local field?

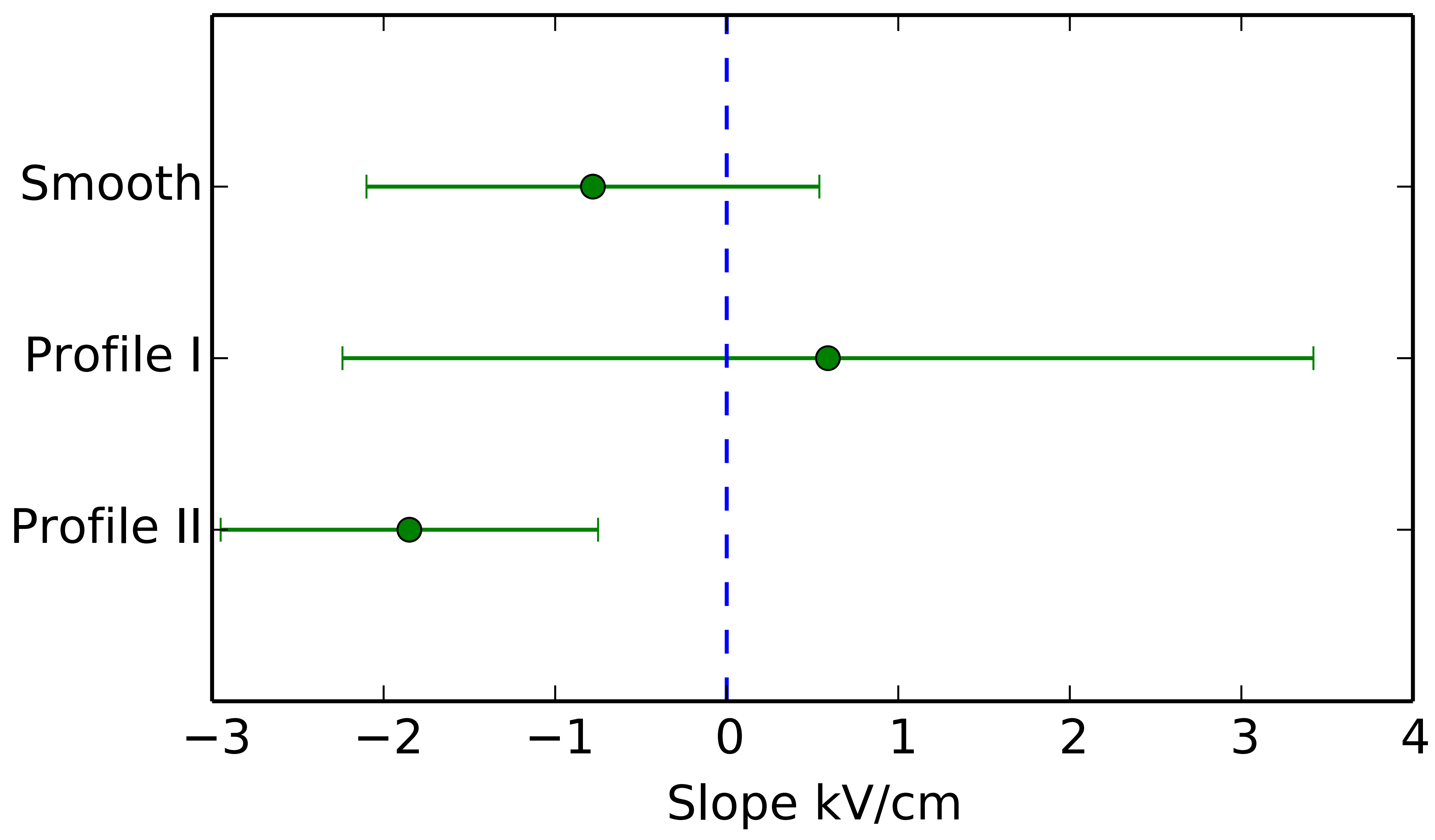
HV bushing from the Baltimore Museum of Industry

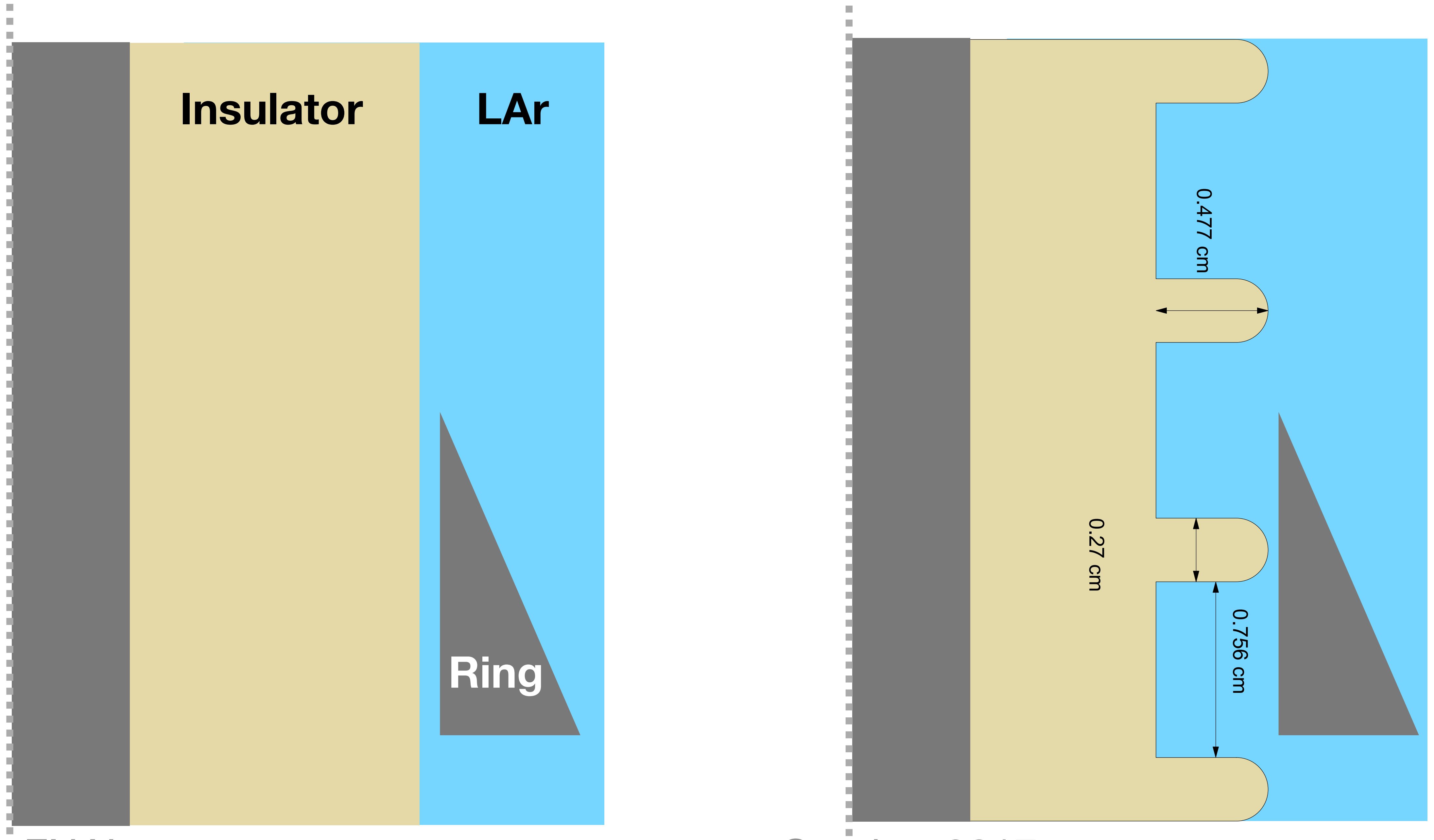


Insulator Study: Grooves

- However, an initial test of the effect of adding **grooves** to the surface showed little effect on breakdown voltage (at most ~10%).

- The effect could be explained by the change in electric field simply by removing material (different permittivity changes the local field)





Insulator Study: Implications for HV Feedthroughs

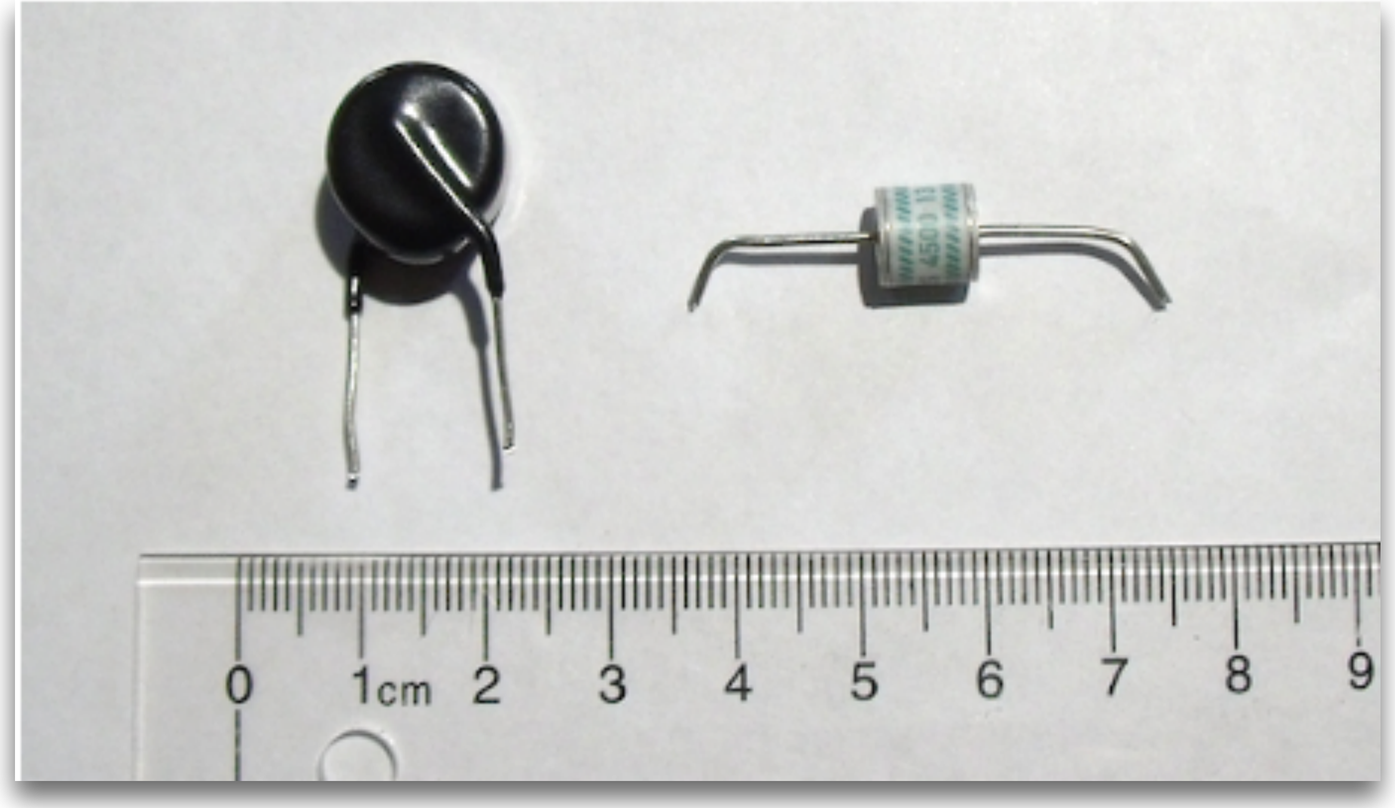
- The length independence is supportive of a narrative where once the streamer starts, it can be self-sustaining
- This along with the material independence suggests that the key parameter is the **peak electric field**
  - One can reduce this with
    - Selection of material
    - Careful design of the ground tube
    - Increasing the insulator radius

ETH Zurich successfully tested a feedthrough to 280 kV!! — larger radius

Protection

- Experiments have implemented surge protection for over-voltage conditions (JINST 9 (2014) P09002)
  - Varistors
  - Gas Discharge Tubes
  - Protect resistors
- Robust resistors

Figure 10. The Metallux HVR 969.23 resistors mounted on the 16 field cage loops closest to the cathode.



Reduce Capacitive Effects

- Slow down discharge
  - [Proto]DUNE-SP has implemented a resistive cathode
- Partition energy
  - Rings of field cage are now "profiles"
    - If one profile discharges, it's now releasing only a fraction of the energy

Open Issues

- Insulator charge up and surface currents
- Time component
  - Also note that the area/volume/BD studies were done to immediate BD
    - One can get to a voltage & BD after some time
- Detailed purity understanding
- Surface conditions/treatments
  - Also evidence of surface effects on electrical connections (press fit)
- (somewhat academic but) The mechanisms of breakdown or more generally HV phenomena
  - Roles bubbles play

https://arxiv.org/pdf/1709.00095.pdf

PREPARED FOR SUBMISSION TO JINST

3D Modeling of Electric Fields in the LUX Detector

LUX collaboration. D.S. Akerib,[a,b,c] S. Alsum,[d] H.M. Araújo,[e] X. Bai,[f] A.J. Bailey,[e]

K. Yazdani,[e] S.K. Young,[u] C. Zhang,[m]

ABSTRACT: This work details the development of a three-dimensional (3D) electric field model for the LUX detector. The detector took data during two periods of searching for weakly interacting massive particle (WIMP) searches. After the first period completed, a time-varying non-uniform negative charge developed in the polytetrafluoroethylene (PTFE) panels that define the radial boundary of the detector's active volume. This caused electric field variations in the detector in time, depth and azimuth, generating an electrostatic radially-inward force on electrons on their way upward to the liquid surface. To map this behavior, 3D electric field maps of the detector's active volume were built on a monthly basis. This was done by fitting a model built in COMSOL Multiphysics to the

field. At that moment another pulse will start building up.

This process is possible when a bubble of gas with a diameter of some μm is produced around the tip. The energy required to create the bubble comes from the frictional dissipation of electrons emitted from the tip into the liquid; this results in

Bressi, G., Carugno, G. & Ptohos, F. Il Nuovo Cimento D (1991) 13: 979. https://doi.org/10.1007/BF02457160