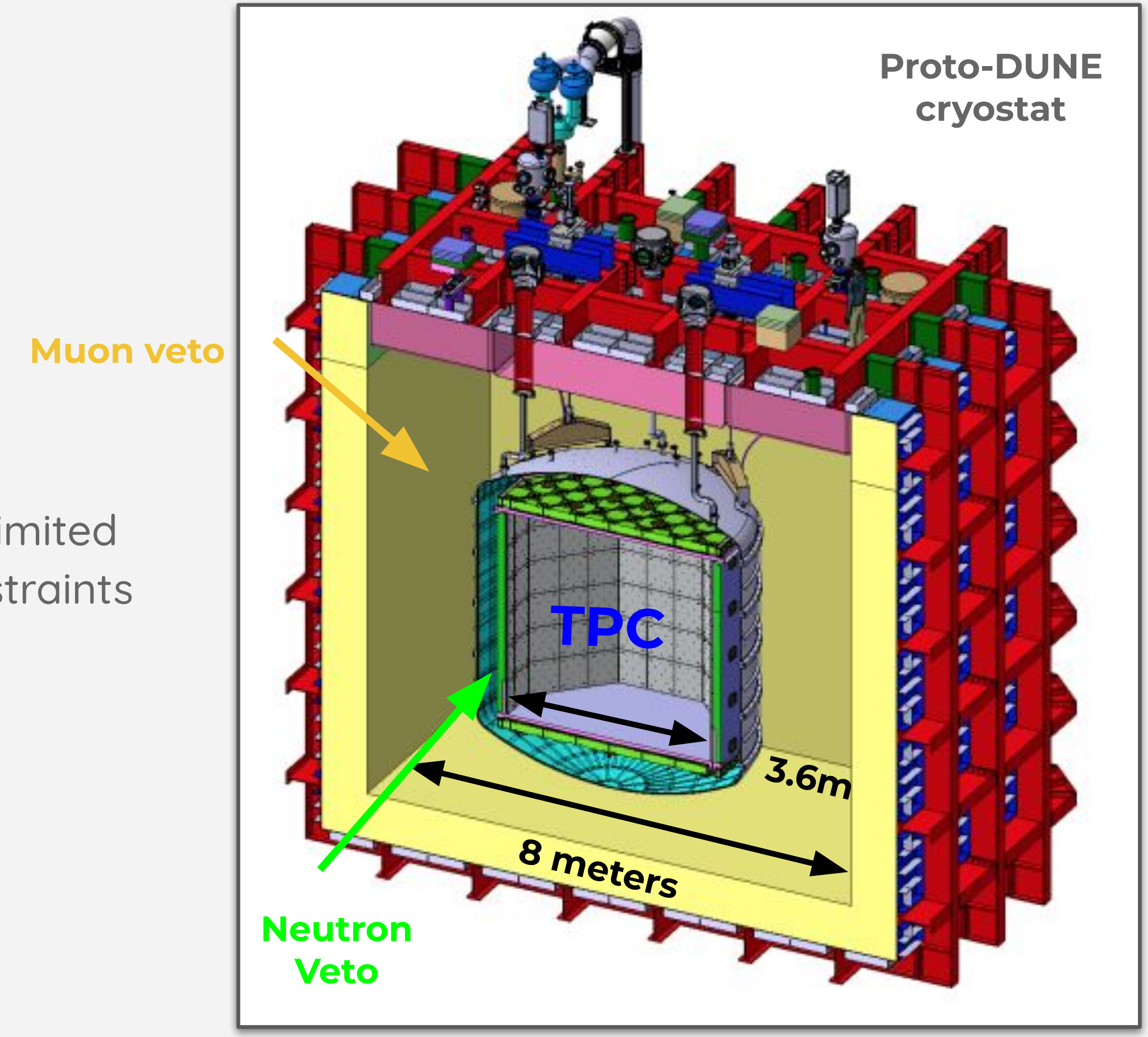
Progress on a novel high-voltage feedthrough concept for Darkside-20k

Tyler Erjavec, UC Davis

UCDAVIS
UNIVERSITY OF CALIFORNIA

Darkside-20k At A Glance

- Two-phase TPC searching for WIMPs
- 20 tons of fiducial LAr
- Main sections
  - Cryostat, titanium vessel
  - Muon, neutron veto, TPC
- 200V/cm drift field
  - Cathode -74kV
- Space allocated for high voltage connection is limited
  - Two active veto detectors induce tight constraints

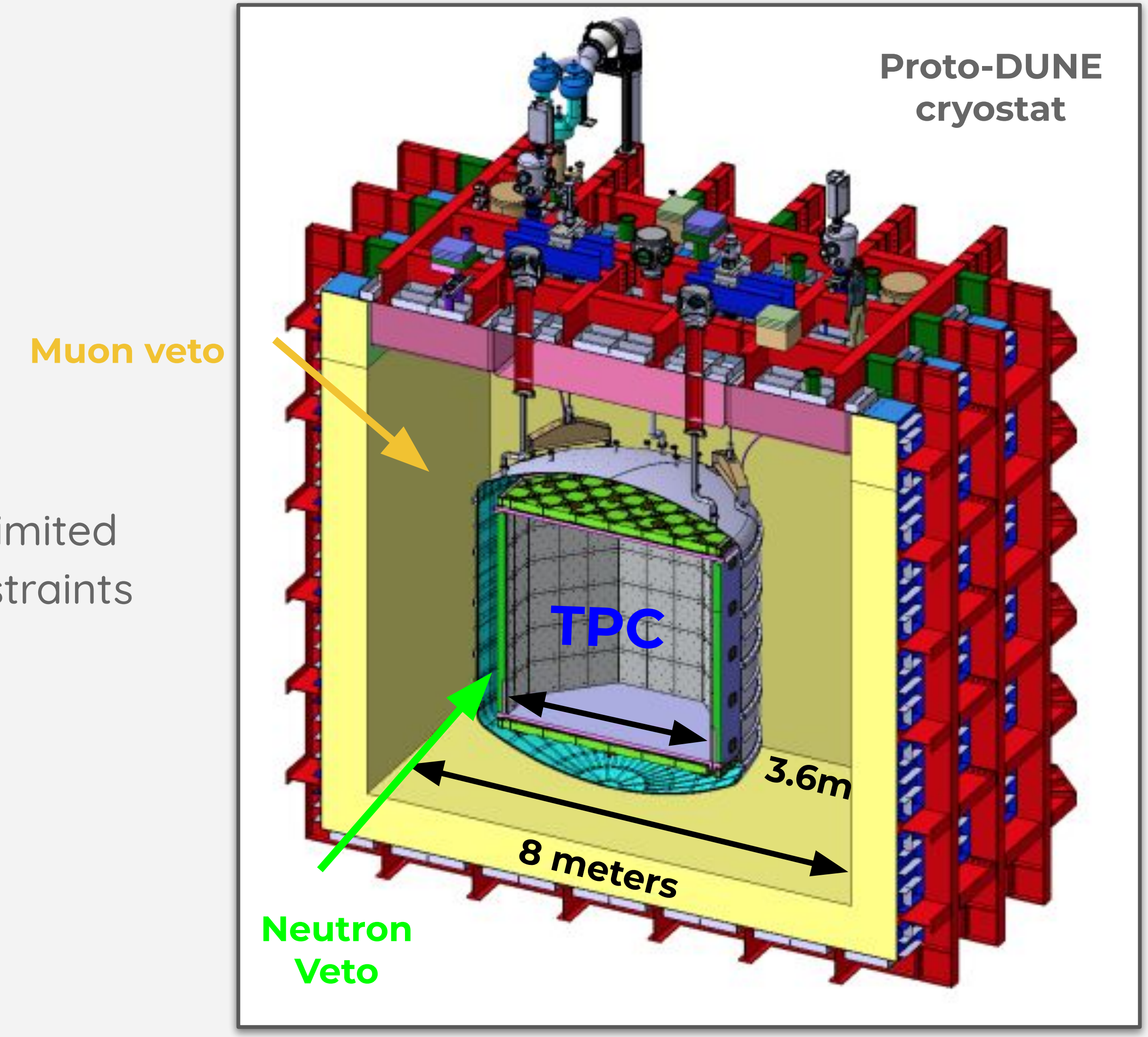


Darkside-20k At A Glance

- Two-phase TPC searching for WIMPs
- 20 tons of fiducial LAr
- Main sections
  - Cryostat, titanium vessel
  - Muon, neutron veto, TPC
- 200V/cm drift field
  - Cathode -74kV
- Space allocated for high voltage connection is limited
  - Two active veto detectors induce tight constraints

Other DS-20k talks:

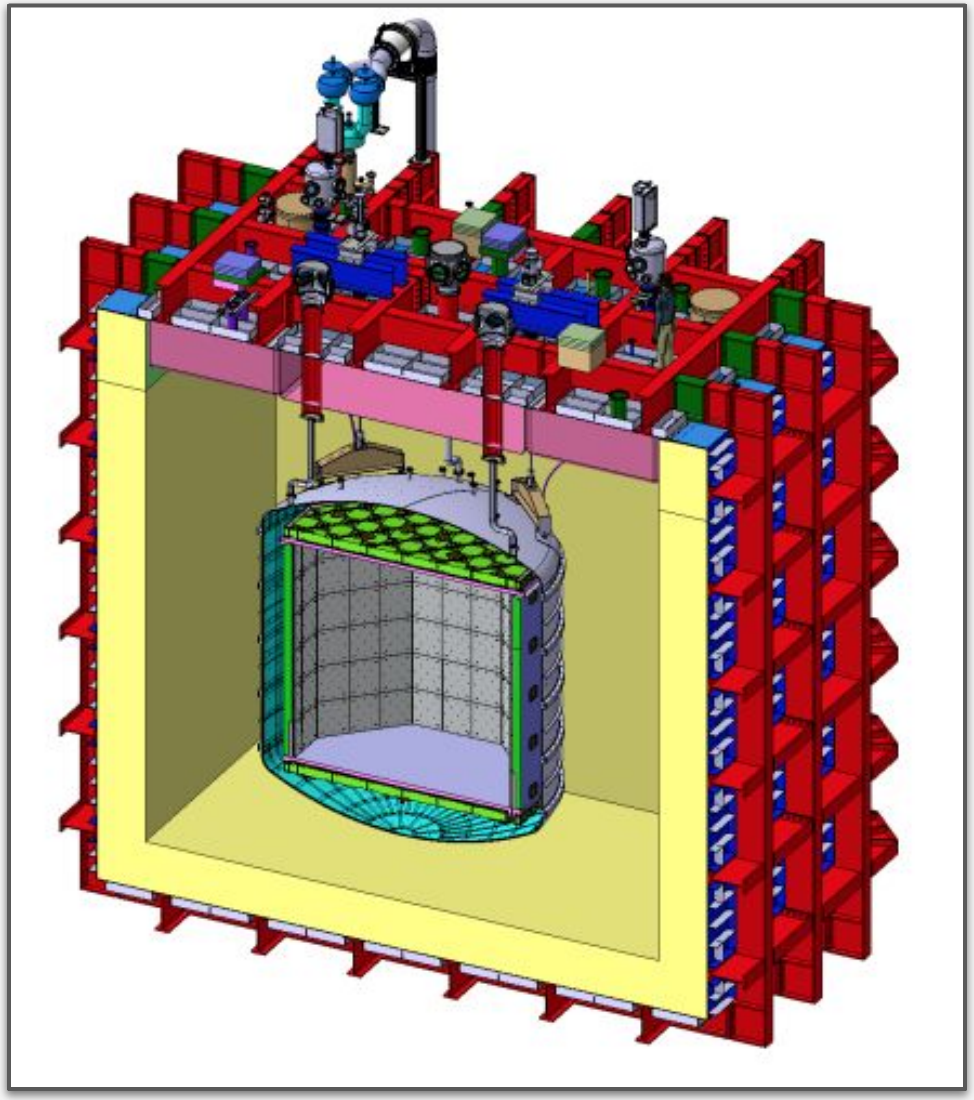
- **Roberto Santorelli, 60 min ago**
- **Yi Wang, tomorrow F3**
- **Francesco Di Capua, tomorrow F3**
- **Priyanka Kachru, tomorrow G1**



Today’s Talk

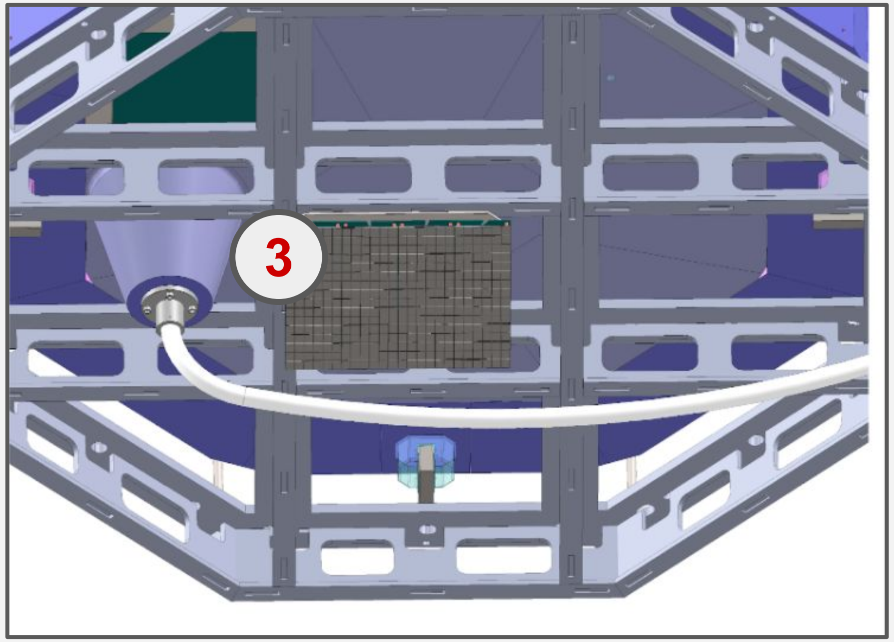
- Will focus on a specific portion of R&D for which our lab at UCDavis is responsible…

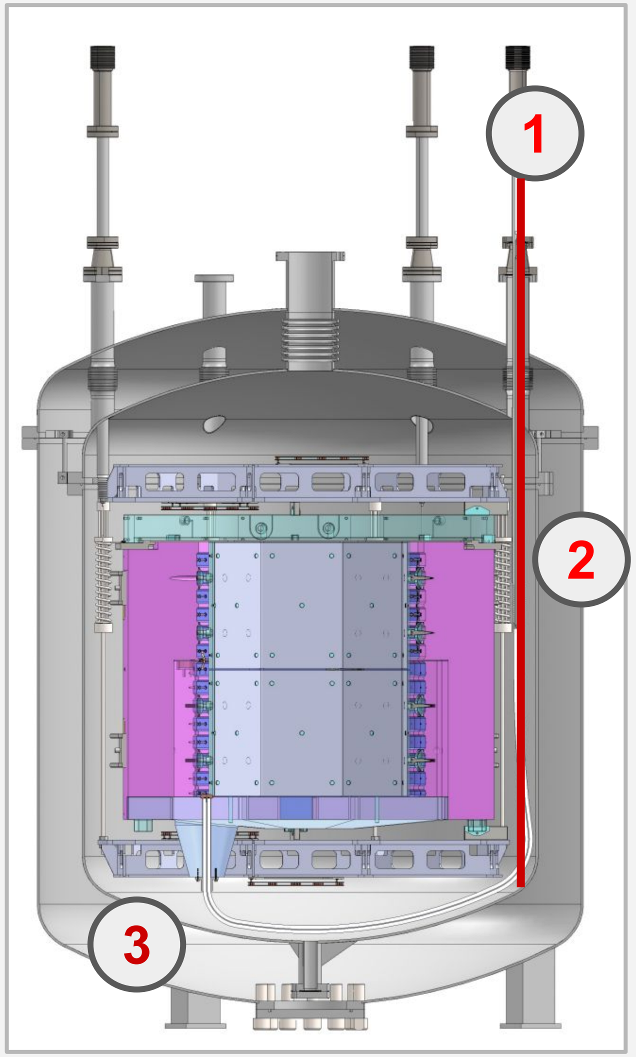
High Voltage Delivery to the Cathode



The Path of the Cable (shown on the mockup detector)

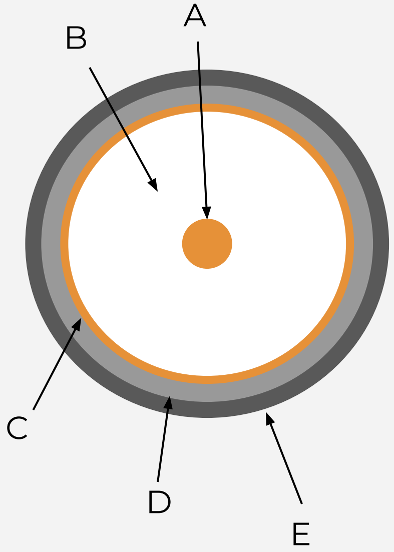
1. Cable enters the cryostat and membrane, into titanium vessel
2. Traverse behind the TPC down ~2m to the bottom
3. Curves and goes through a stress cone
    a. Stress cone held at electrical ground
        i. Reduces electric field stress



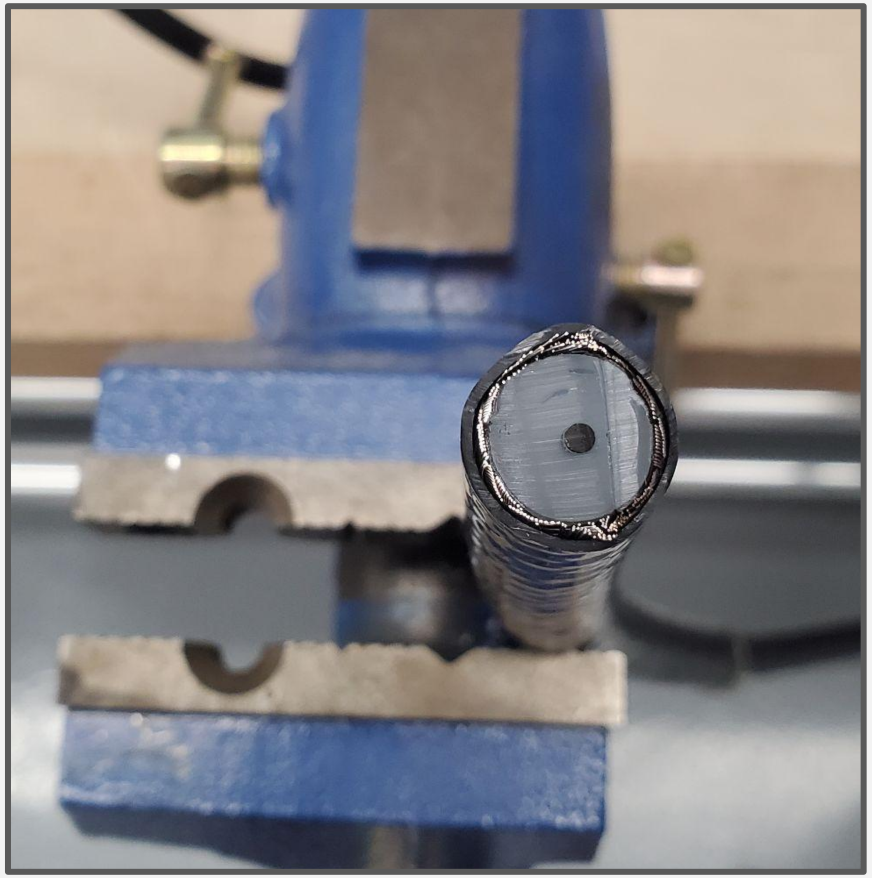


Start With a Fully Plastic Cable

- DS-20k plans to use a fully-plastic, coextruded cable for HV delivery, modified for our needs
- Such cable is useful for a few reasons…
  - Current-limiting, in case of arcing
  - Uniform thermal contraction



- A,C - semi-con PE, carbon doped, ϕ0.08”, 0.010”wall
- B - UHMW PE, to ϕ0.44”
- D - Braided Shield, 34AWG
- E - Polyurethane Jacket,0.



Main R&D Problems

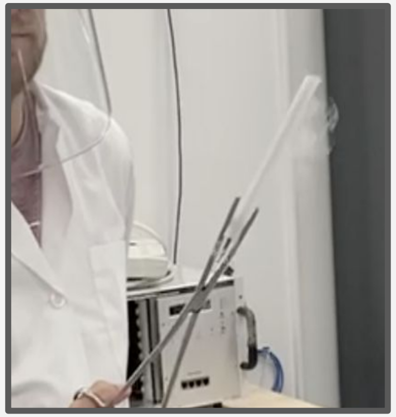
1. **Cable Annealing**
   - The cable experiences spontaneous disassembly at LAr temps
2. **Cathode Termination**
   - How does one reliably attach plastic to metal in cryogen?
3. **Ground Termination**
   - Unconstrained fields create regions of high electrical stress

1. Cable Must Be Annealed

- The coextrusion process induces strong internal stresses inside the cable
    - Internal forces can reach $8 kg/mm^2$ at 84°K ...or **78MPa**

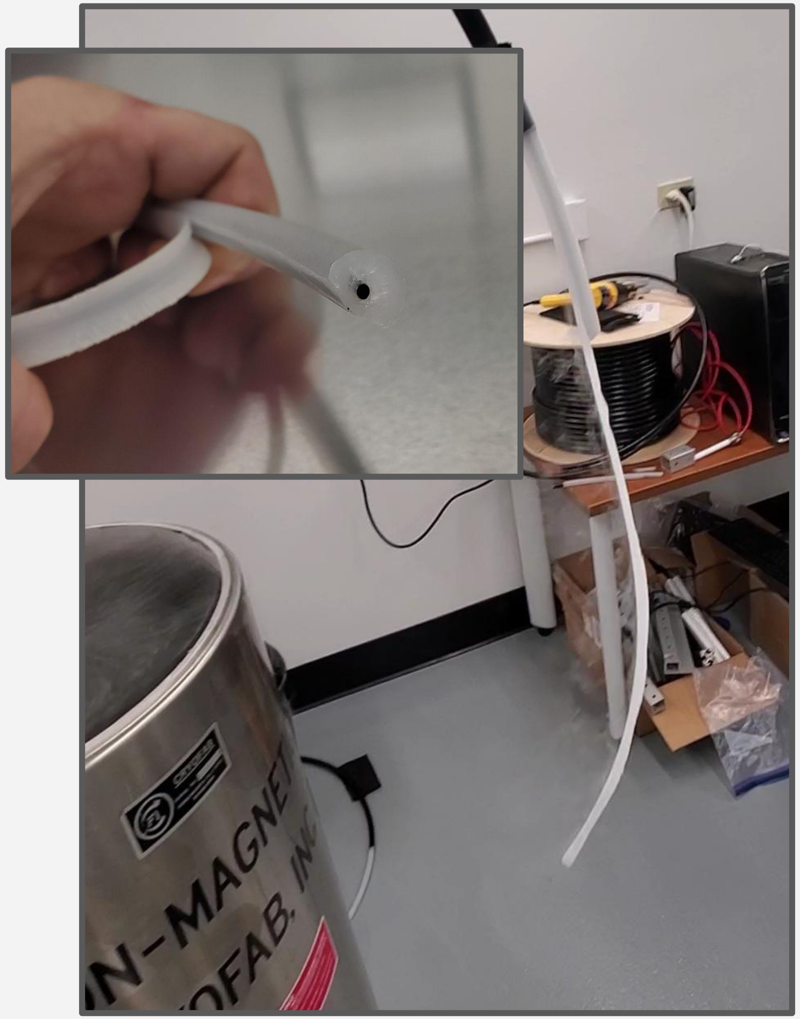
Thermal contraction and cracking of extruded polyethylene electrical insulation at cryogenic temperatures, N. Shimizu et. al

- Yes, it does indeed explode



$1/30^{th}$ second later

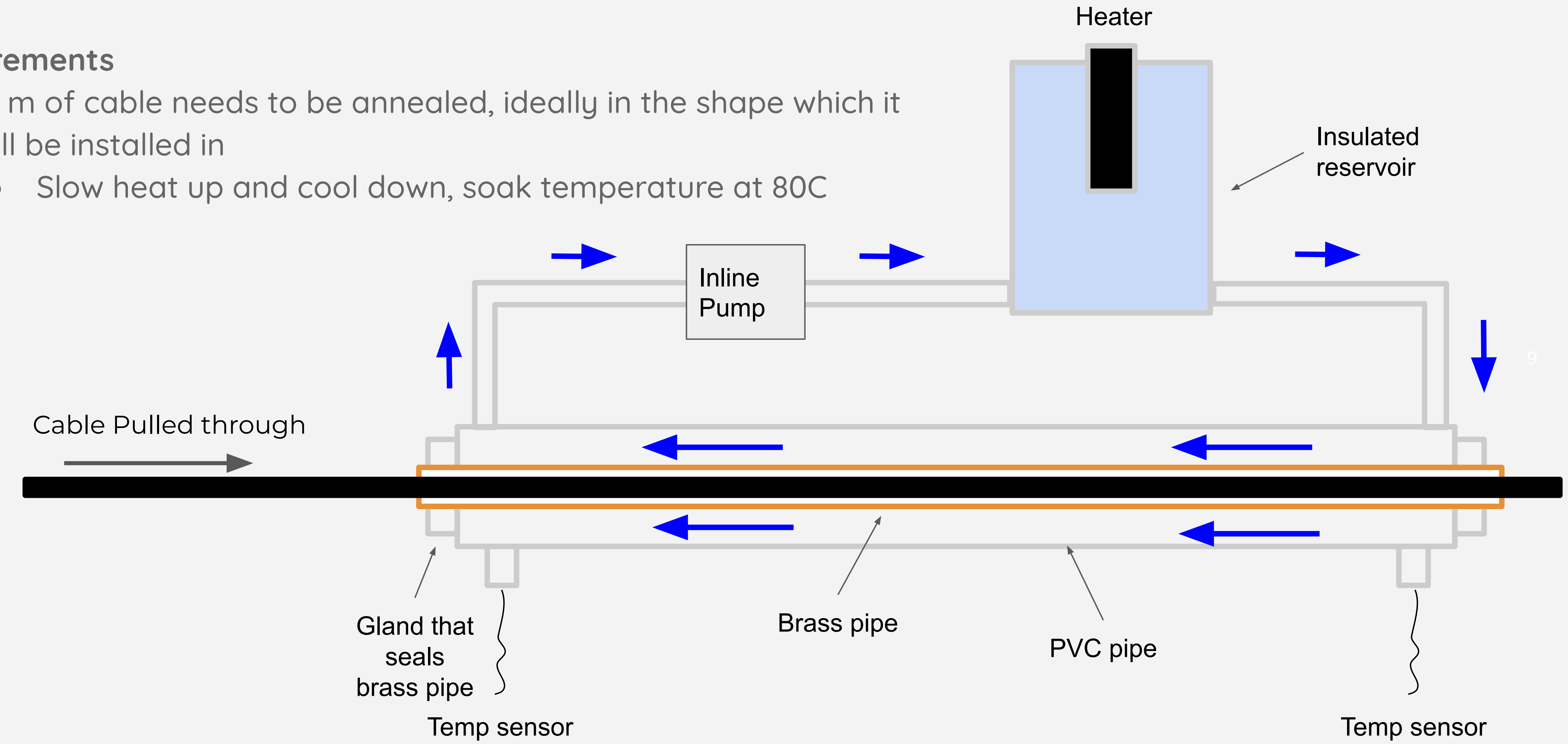
- Therefore annealing is absolutely required
    - A slow, arduous process
    - Could utilize abundant undergrad labor...



Or Make An Annealing Chamber

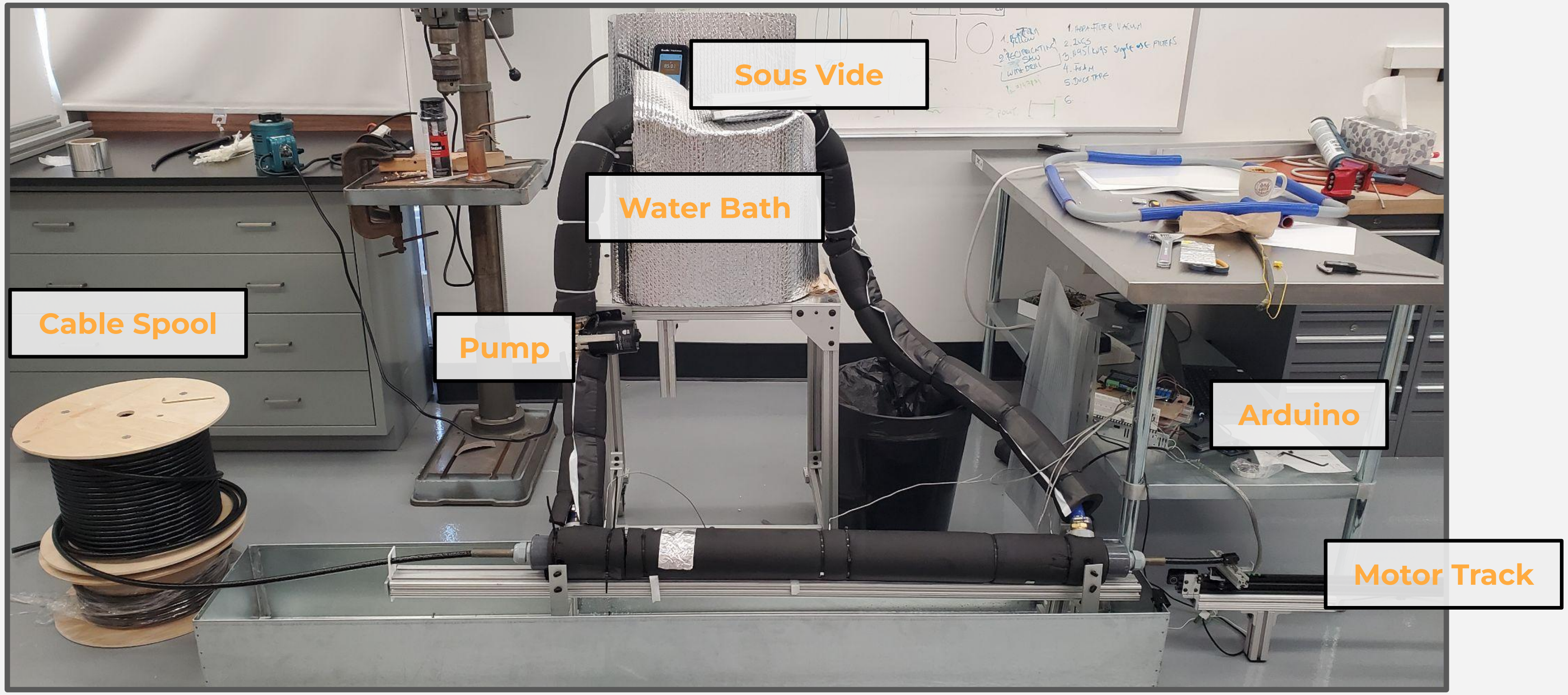
Requirements

- 13 m of cable needs to be annealed, ideally in the shape which it will be installed in
  - Slow heat up and cool down, soak temperature at 80C



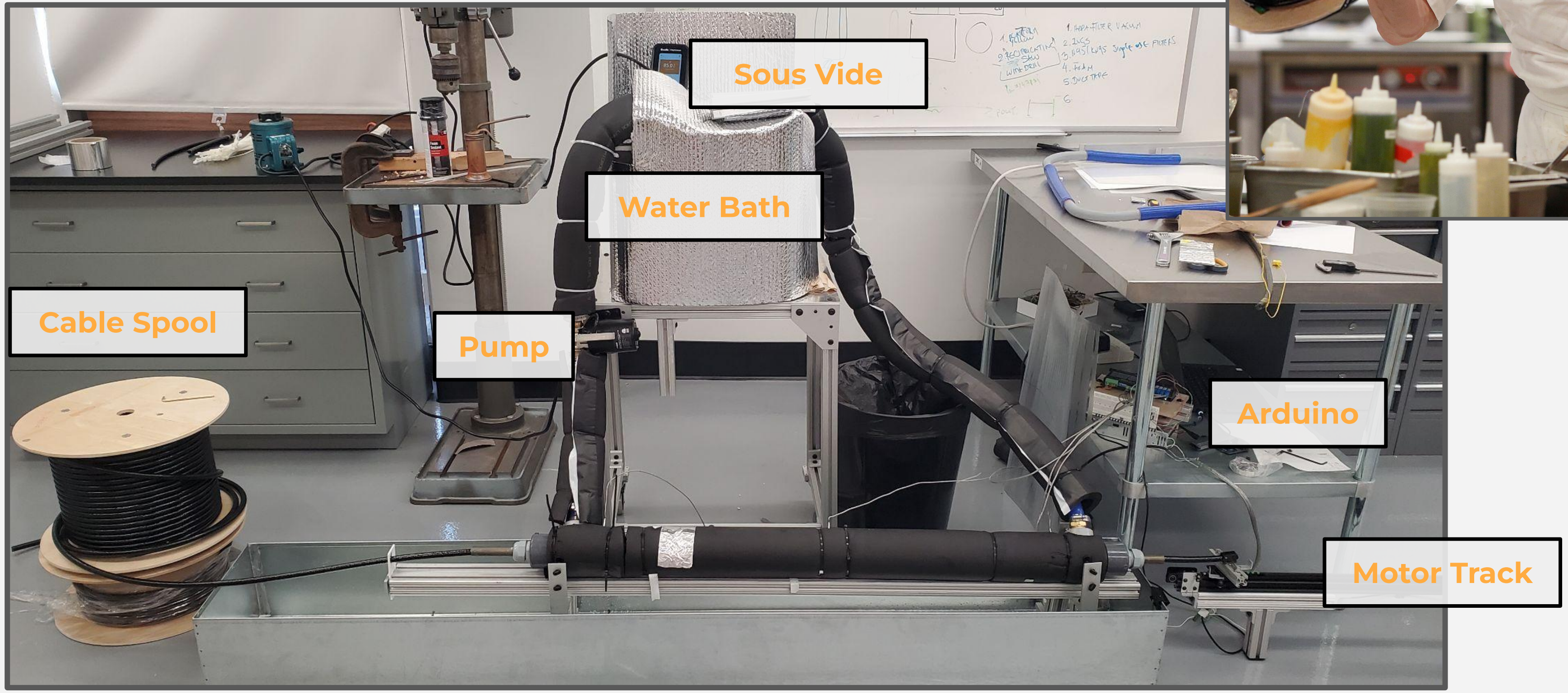
Cookin' With Cable

- 2m long water-heated chamber
- Cable is placed on carriage, which is motor controlled via microcontroller
  - Motor speed is variable
- Water bath temperature maintained via sous vide at temperatures up to 90C
  - Also great for steaks



Cookin' With Cable

- 2m long water-heated chamber
- Cable is placed on carriage, which is motor controlled via microcontroller
    - Motor speed is variable
- Water bath temperature maintained via sous vide at temperatures up to 90C
    - Also great for steaks



2. Cathode termination requires careful consideration

Terminating a *plastic* conductor to metal?

- Soldering/coldwelding not possible
- Thermal contraction problems
  - **Stainless 316:** 16μm/(m ℃), **Polyethylene:** 106-200μm/(m ℃)

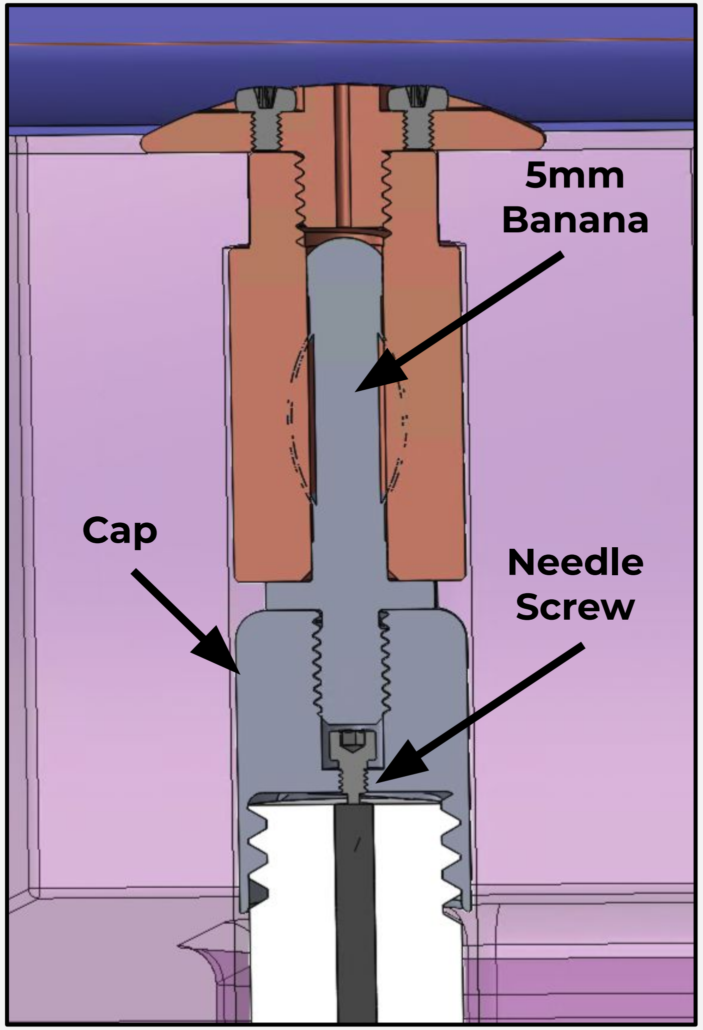
PE shrinks 10x more than SS!

- Ideally have PE contract *around* metal connection
  - Proper strain relief -> connection doesn't break due to shearing forces

Cathode Termination, Mk.I

First Cathode Connection

- Thread the end of the cable, and have a SS screw “cap”
  - Needle screw, inscribed, pierces the CC
  - Banana plug makes connection to cathode



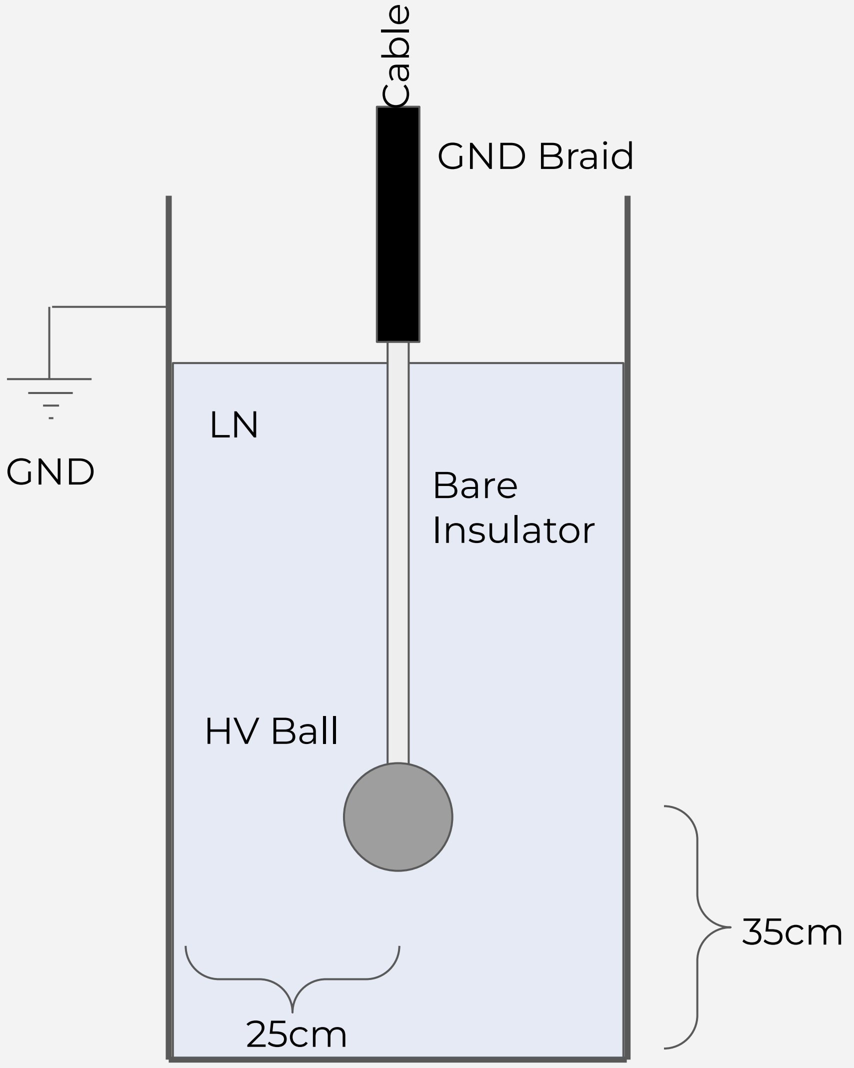
Validate in Cryogenics @100kV

- To verify, the cable and termination scheme was placed into a bath of liquid nitrogen
  - Held for 1 hr at 100kV

- Observed no internal arcing or changes in cable resistance post-cycle

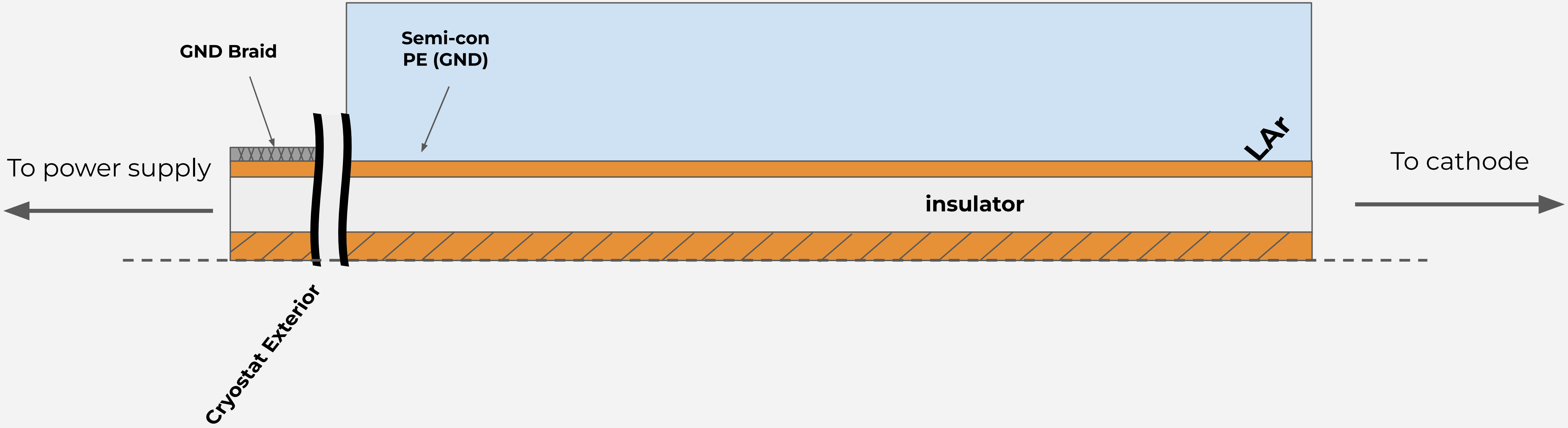
Test successful, but limited

- Test primarily validated annealing and termination scheme
  - “Intra-cable” validation
- Ground is far away from HV, ~ 30cm
  - Due to space constraints, GND in experiment will be ***~5cm*** away from cable
- But why is this bad?



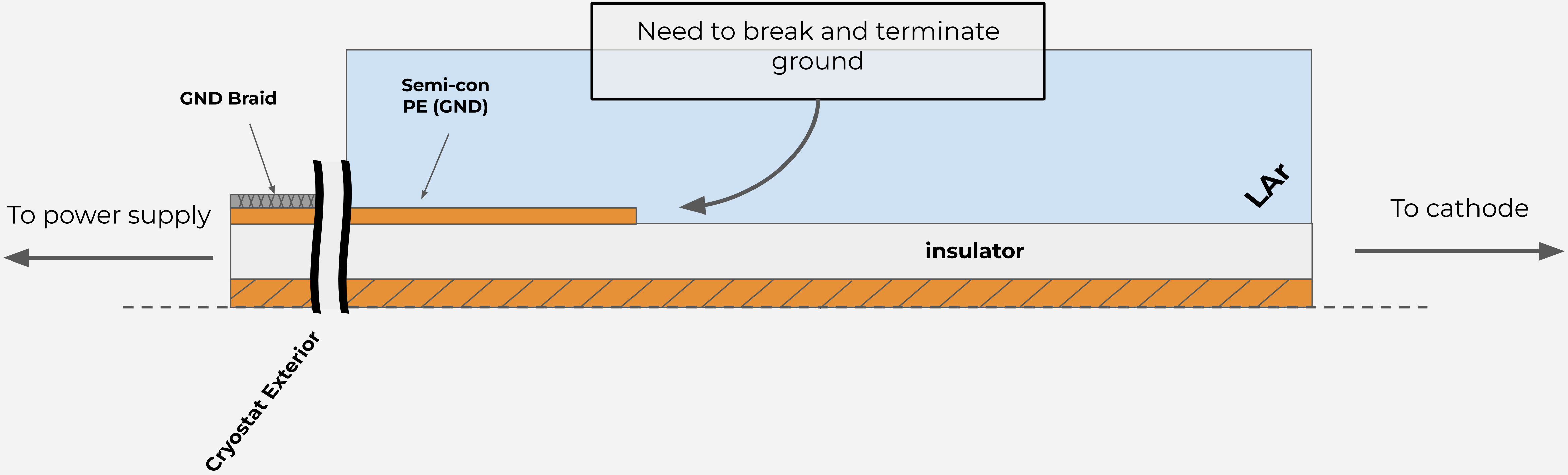
3. Breaking Ground

- Simplified diagram of our cable
  - Cross-section, cut-away



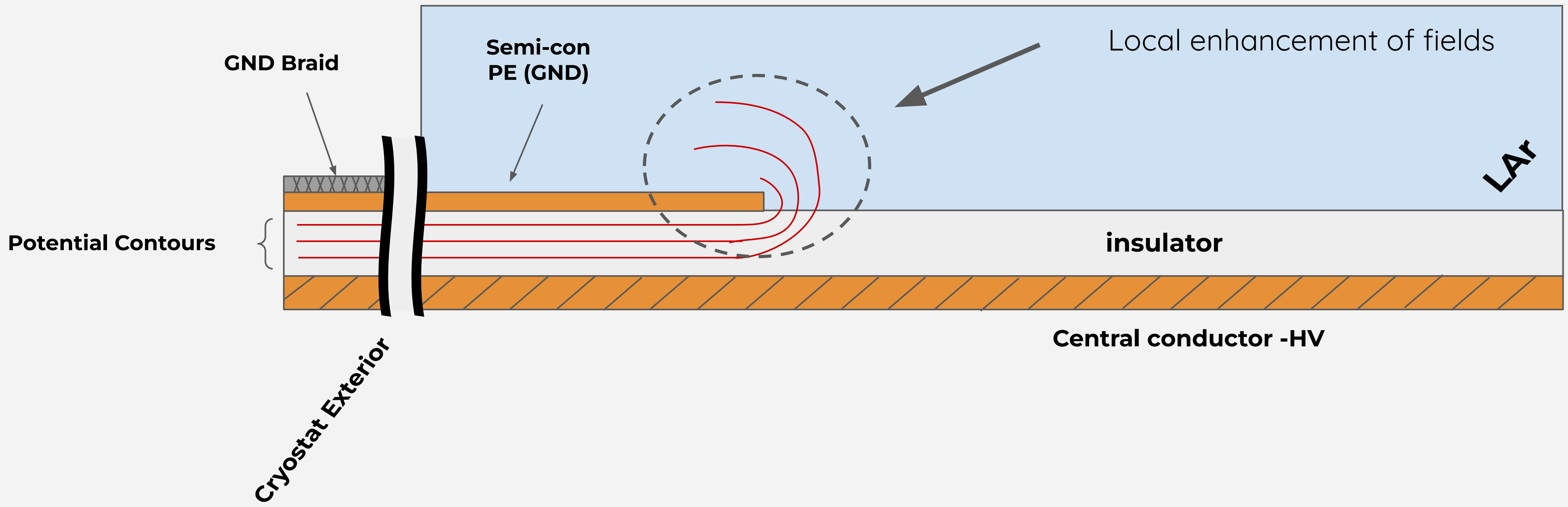
3. Breaking Ground

- Simplified diagram of our cable
  - Cross-section, cut-away



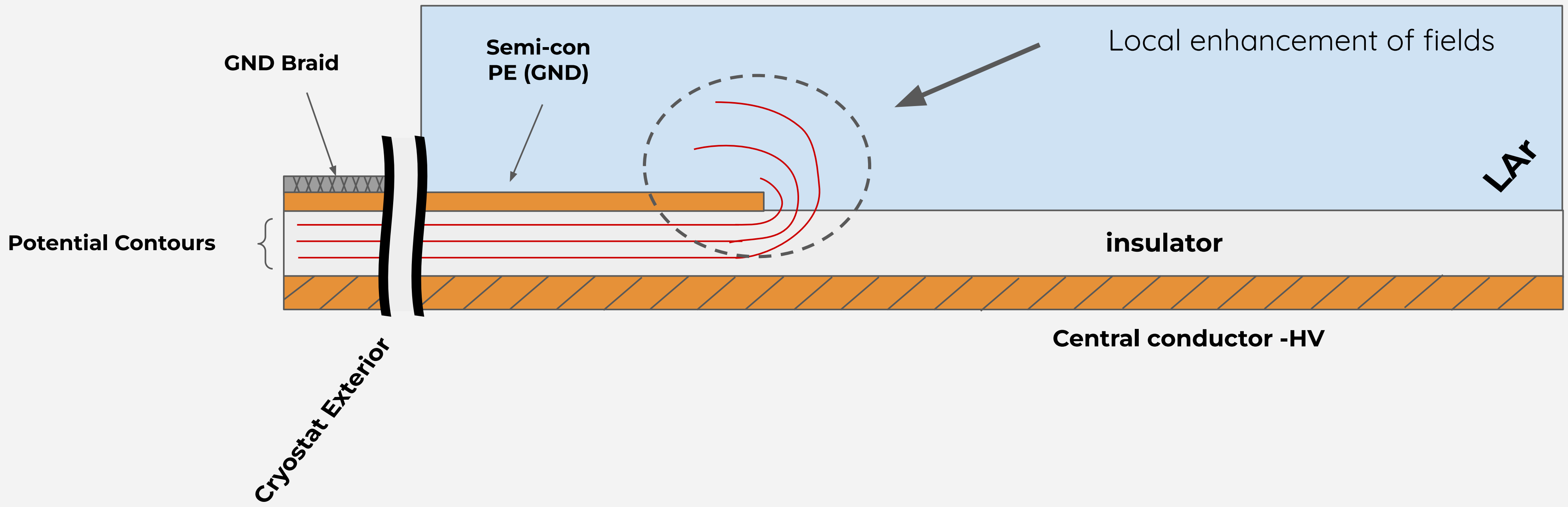
Who Let the Fields Out?

- Removing the ground will cause fields to seek it *elsewhere*
    - Wherever and however
- High field gradients = high electrical stress



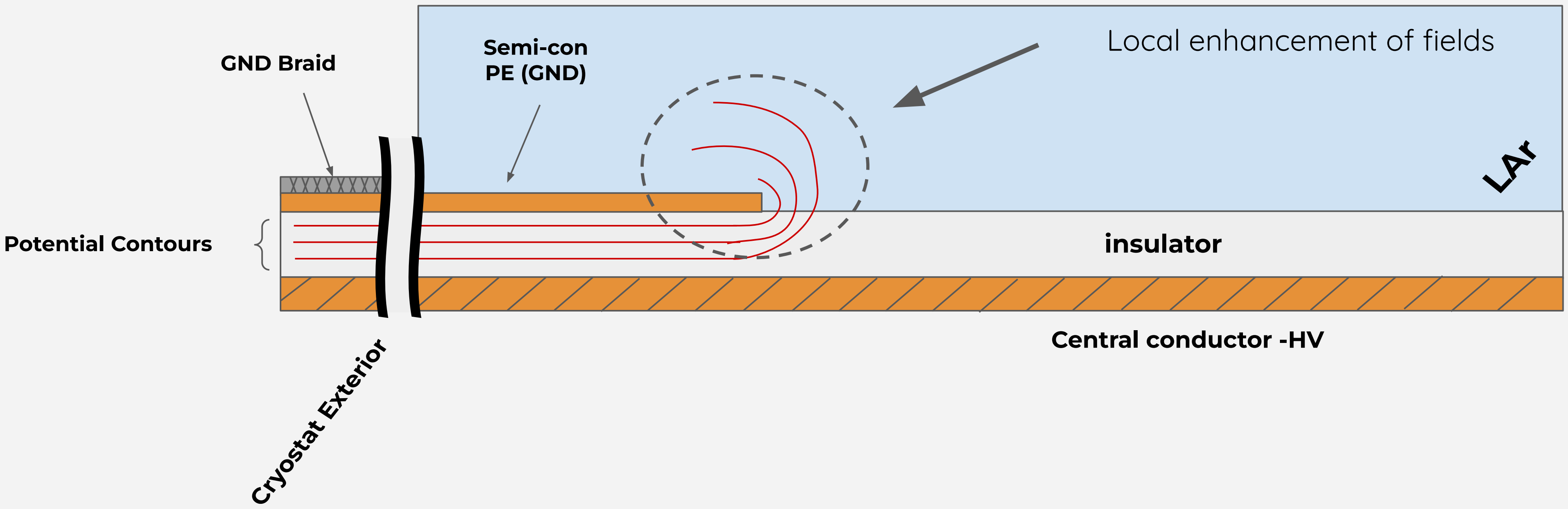
Who Let the Fields Out?

- Removing the ground will cause fields to seek it *elsewhere*
    - Wherever and however
- High field gradients = high electrical stress
- Reports of breakdown *as low as 40kV/cm* *A. Blatter et al 2014 JINST 9 P04006*



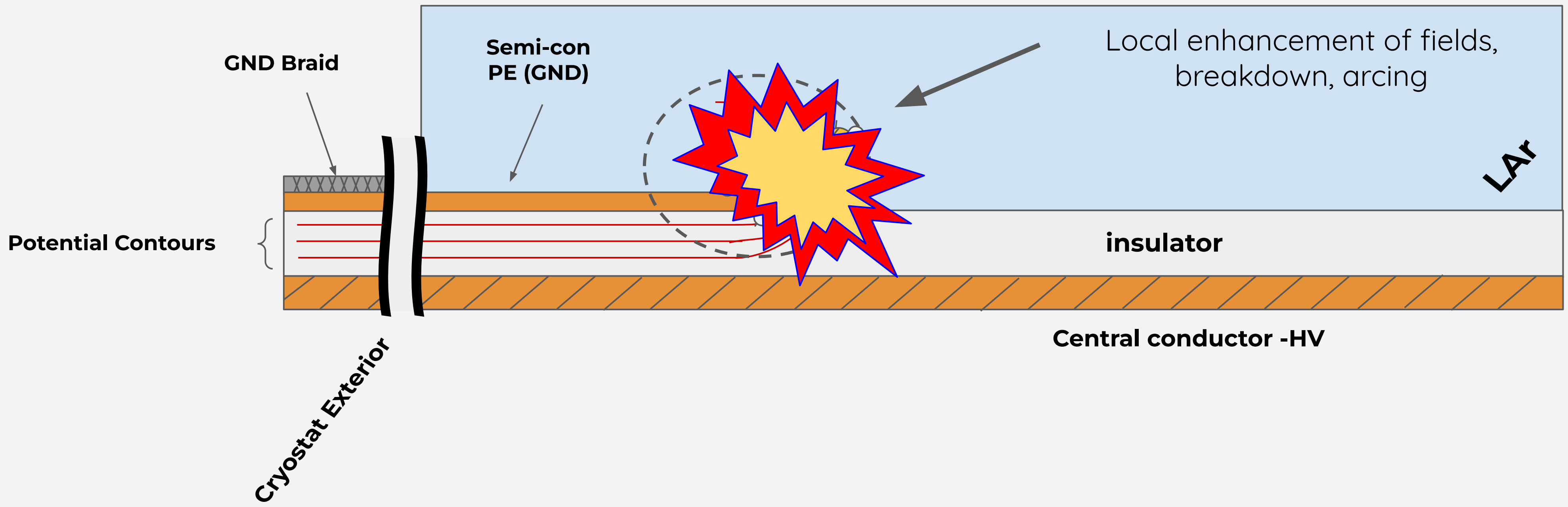
Who Let the Fields Out?

- Removing the ground will cause fields to seek it *elsewhere*
  - Wherever and however
- High field gradients = high electrical stress
- Reports of breakdown *as low as 40kV/cm* A. Blatter et al 2014 JINST 9 P04006
  - Depends ***heavily*** on the stressed area, specific detector geometry



Who Let the Fields Out?

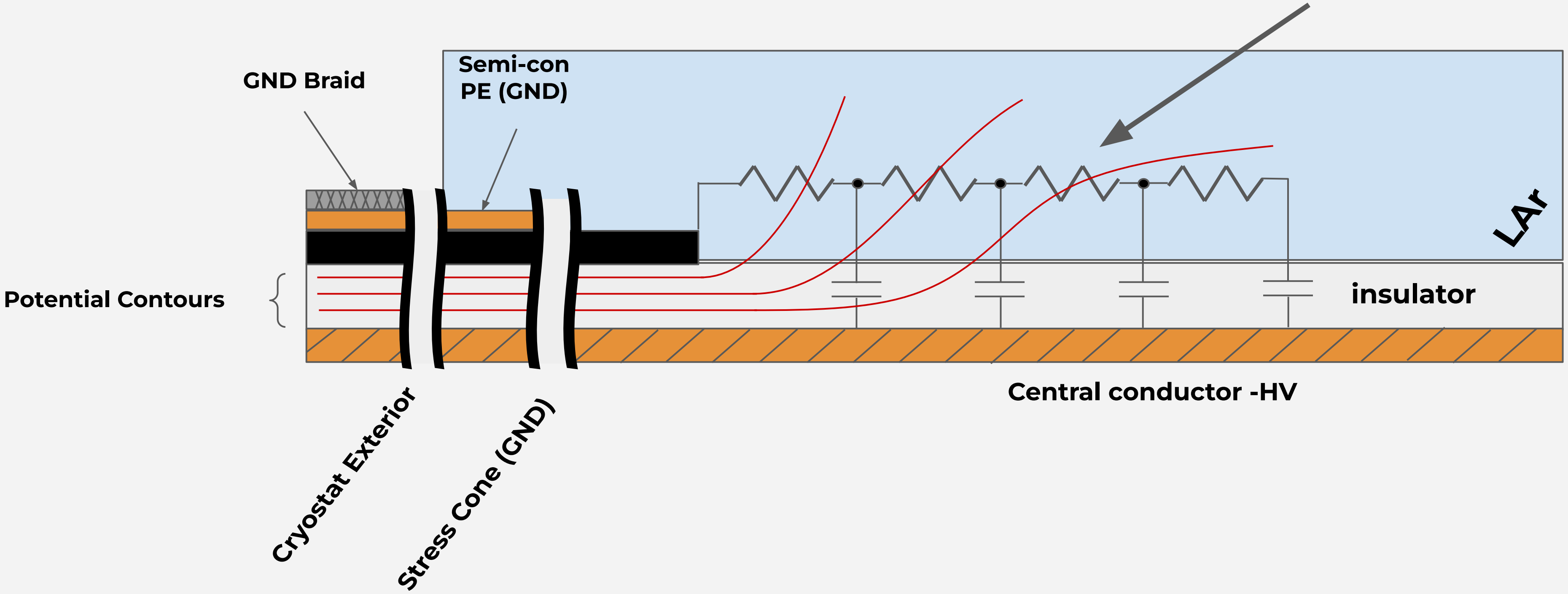
- Removing the ground will cause fields to seek it *elsewhere*
  - Wherever and however
- High field gradients = high electrical stress
- Reports of breakdown *as low as 40kV/cm* *A. Blatter et al 2014 JINST 9 P04006*
  - Depends ***heavily*** on the stressed area, specific detector geometry



Add a Semi-resistive Dielectric Layer

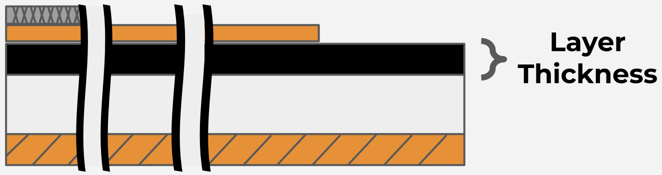
- The addition of an additional semi-resistive dielectric layer in the cable attenuates the field strengths
  - A *resistive field grading*

Tune the resistivity to get desired field attenuation

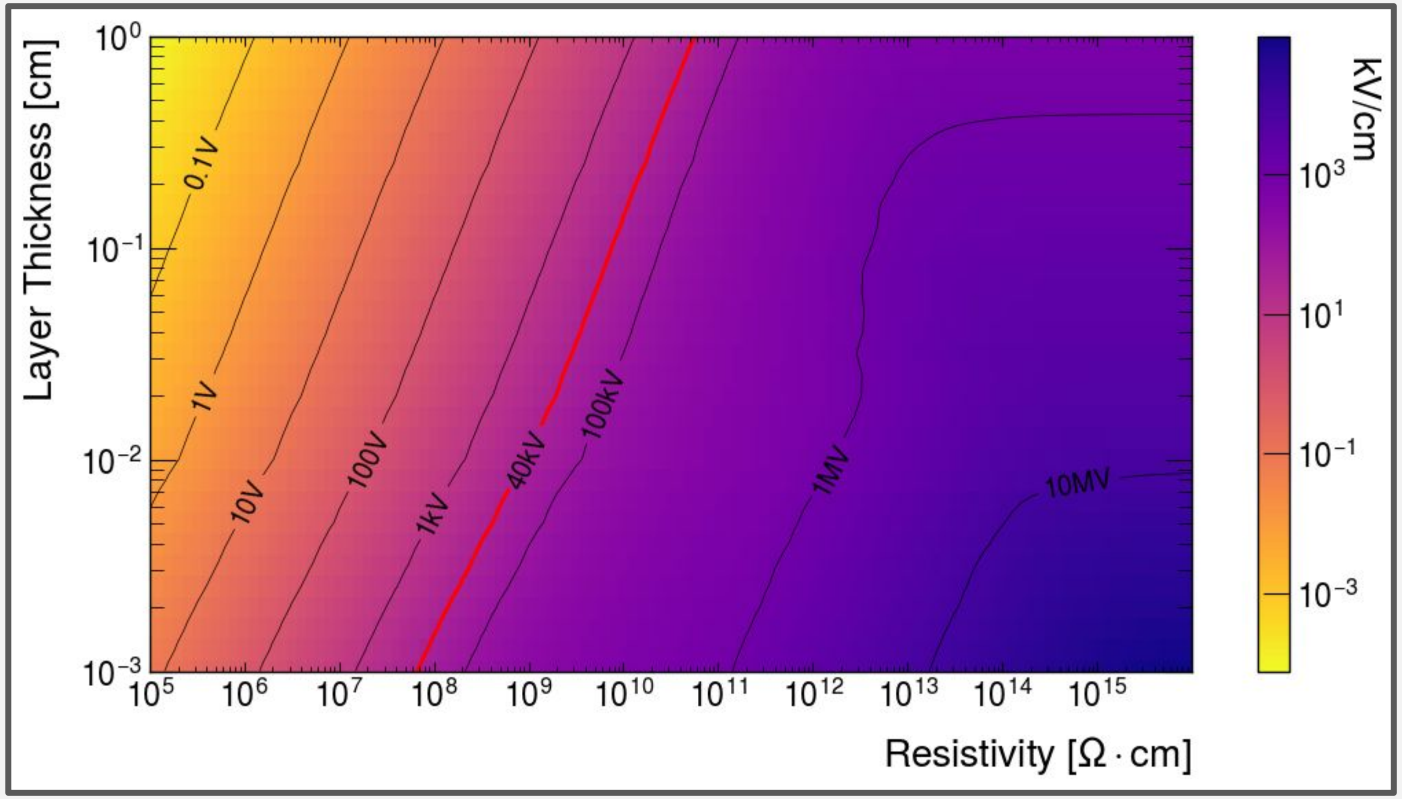


Resistive field grading via carbon black doped PE

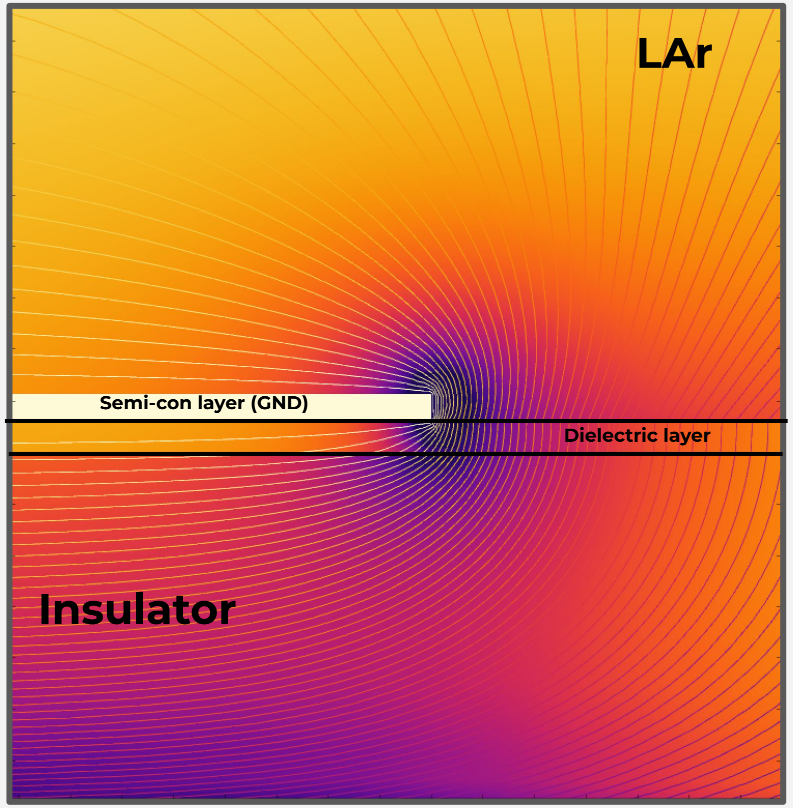
- PE doped with carbon changes its resistivity
  - Can be tuned, evaluate via COMSOL



Maximum Field in LAr Region

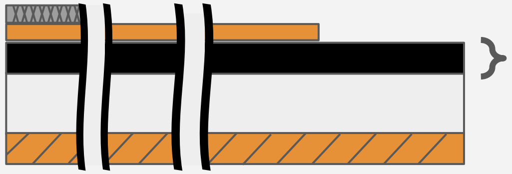


Example, resistivity=1e13

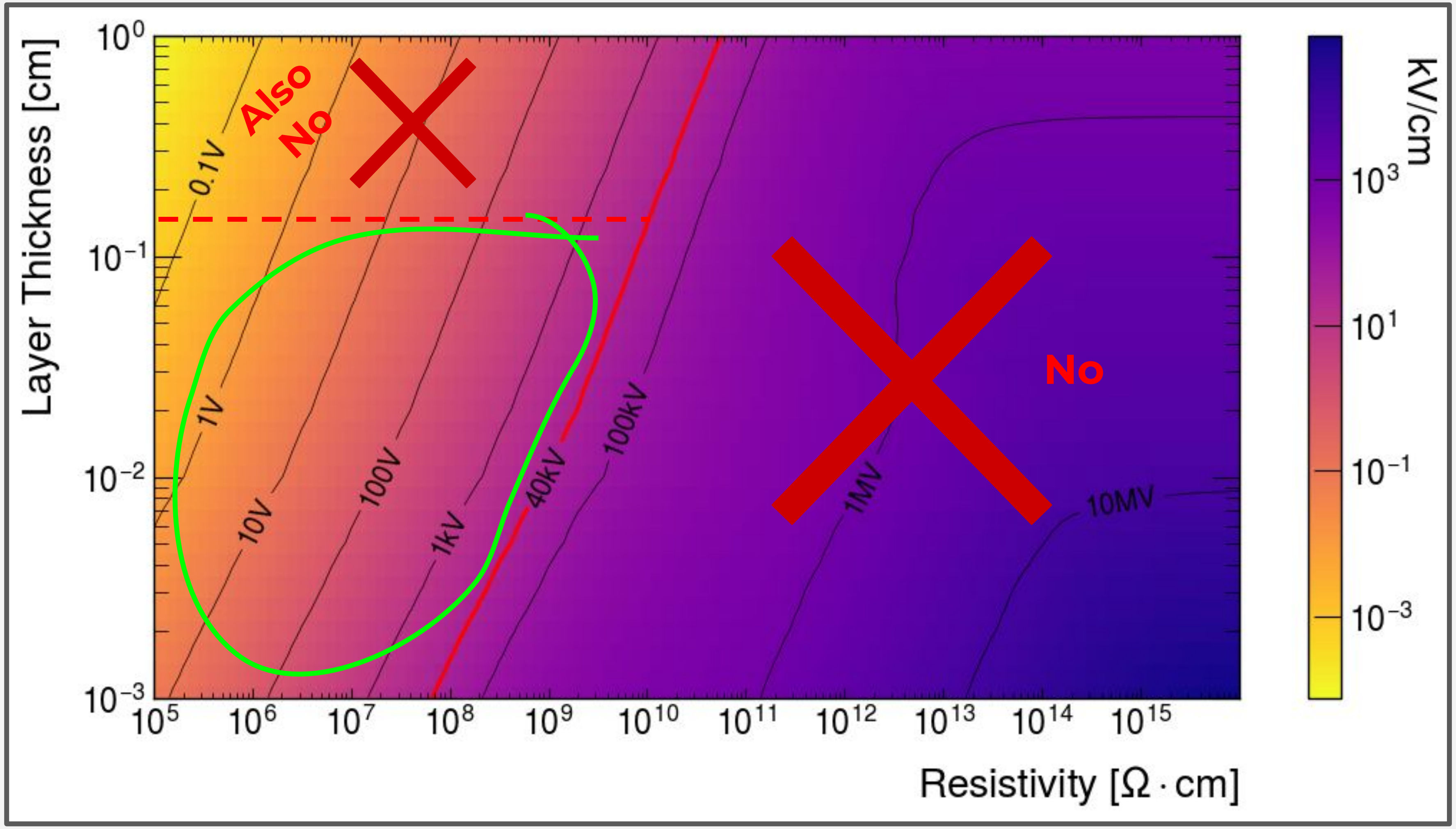


Requirements

- Upper limit of 0.5mm layer thickness
  - Thicker cable has larger bending radius



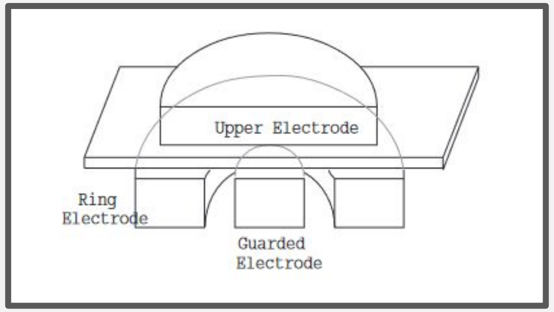
- Resistivity 10^8 Ω □. cm *or less*

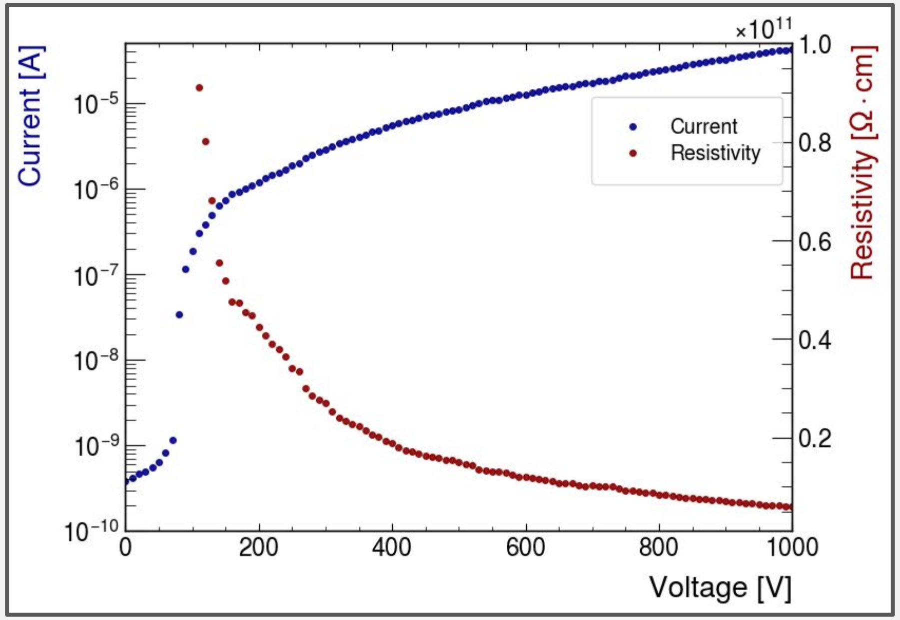


Measuring resistivity of doped PE

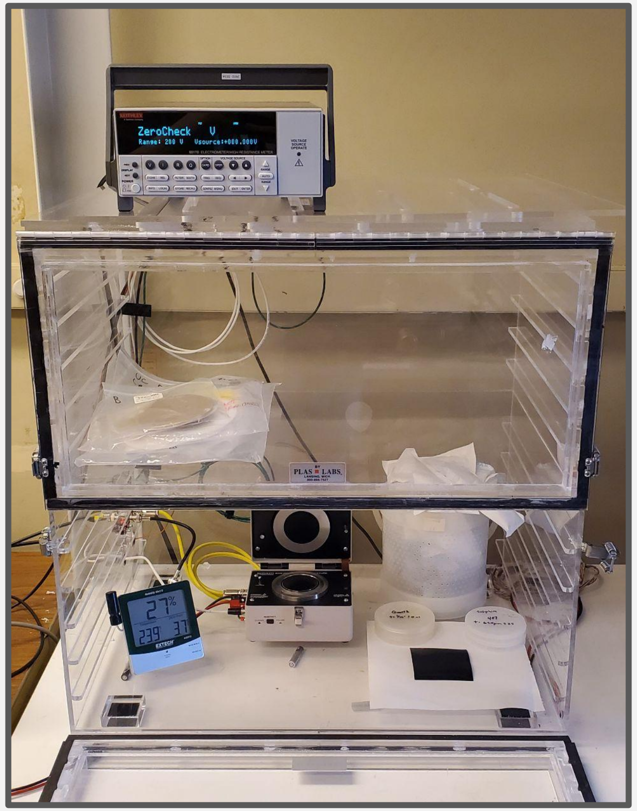
To measure:

- Apply voltage, measure current, calculate resistivity
- Background currents
  - Space charge/charge injection
  - Dielectric relaxation
  - Capacitive elements discharging + more!





Sample C-doped PE from PreMix



Summary

- Proper feedthrough and termination of HV cables become increasingly complex as the HV requirements of liquid noble experiments also increase

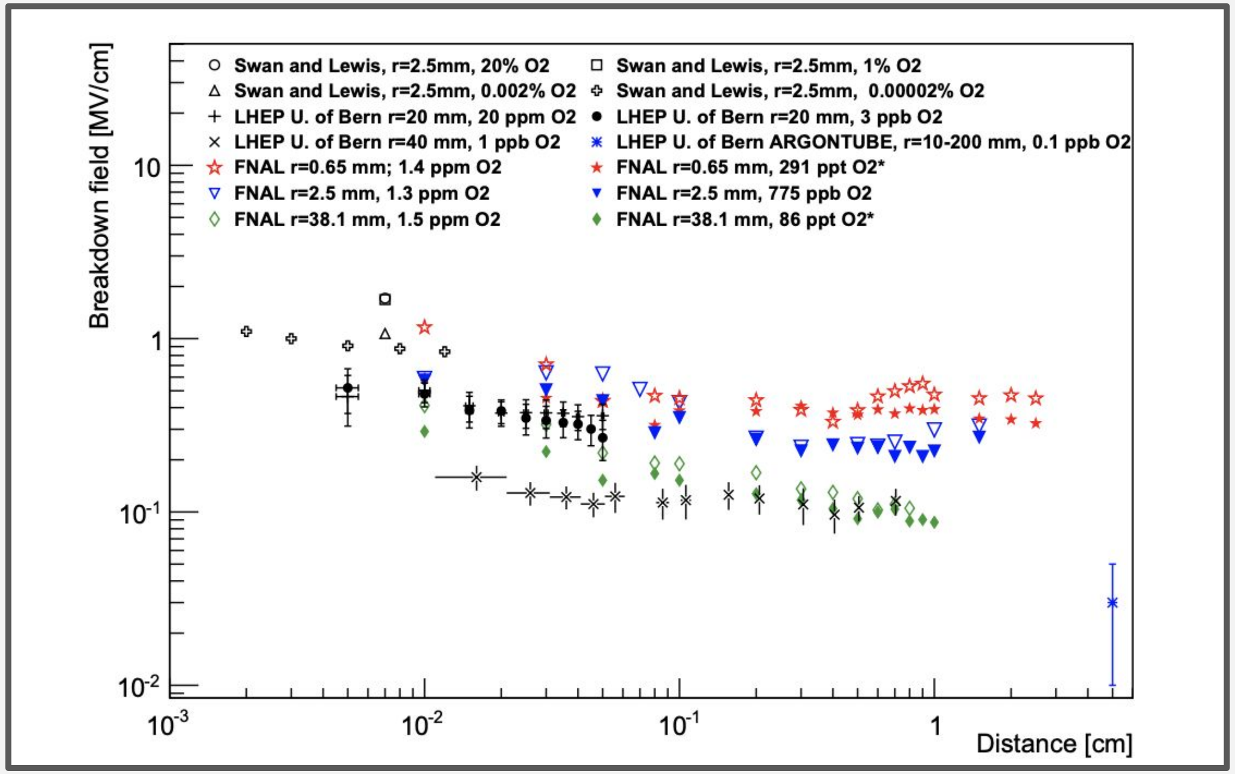
- Use of a novel coextruded fully plastic cable allows for experiment longevity due to cryogenic stability and tunable electrical characteristics
  - But presents unique engineering challenges within the scope of DarkSide-20k design constraints

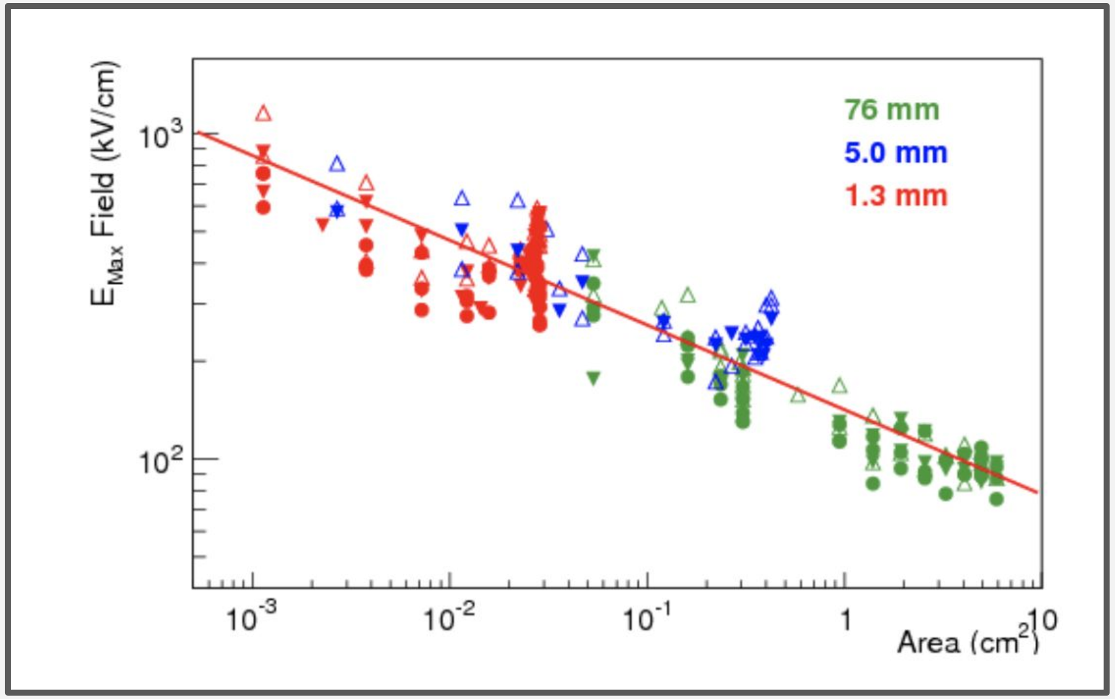
- Work is ongoing to formulate a plastic blend with volume resistivities in the 10^7-10^8 Ω □.cm range

Questions?

LAr Breakdown

- Stressed area
  - Roughly 80% of the max breakdown field

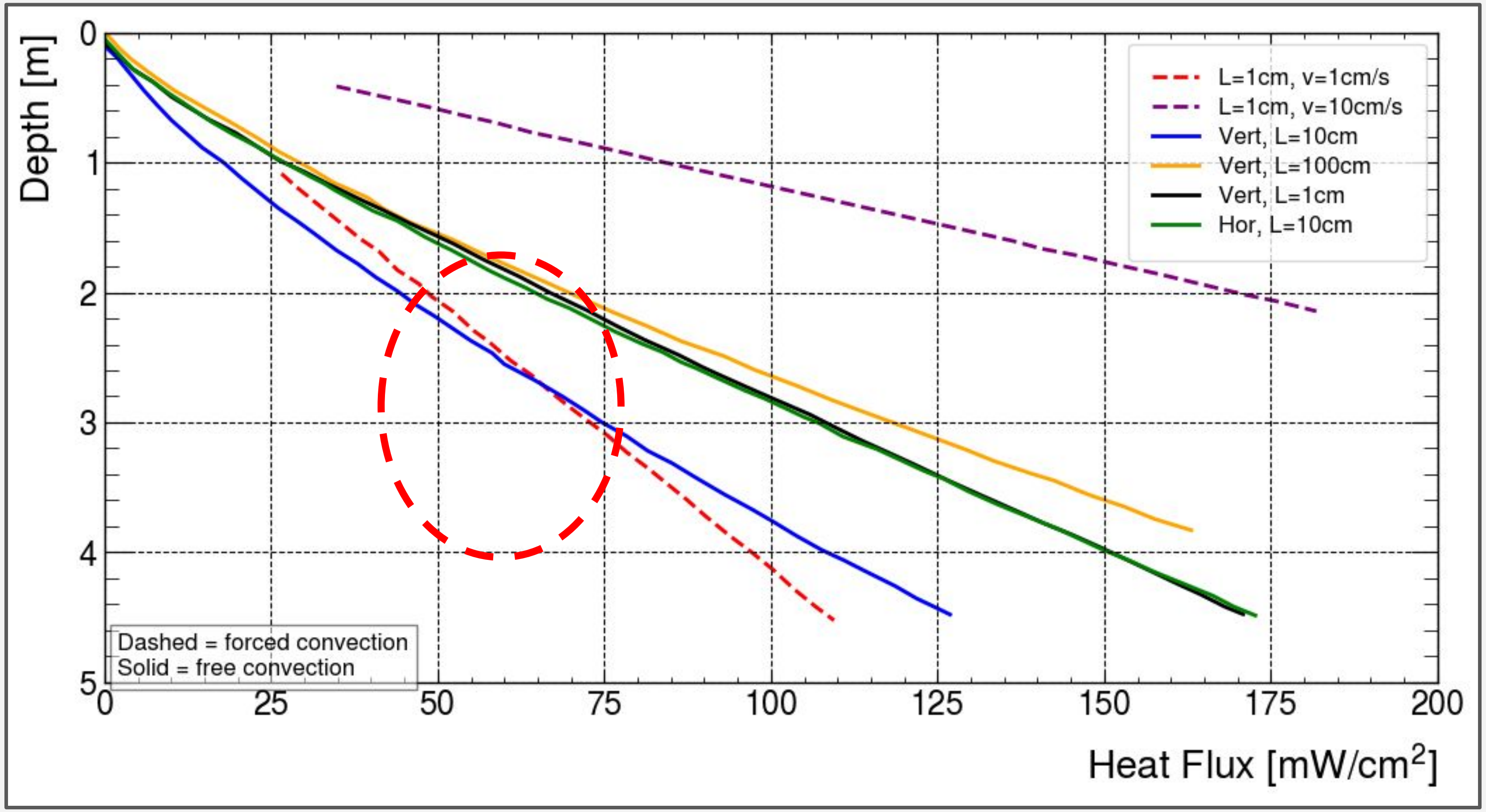




R. Acciarri et al 2014 JINST 9 P11001

But wait...what about resistive heating?

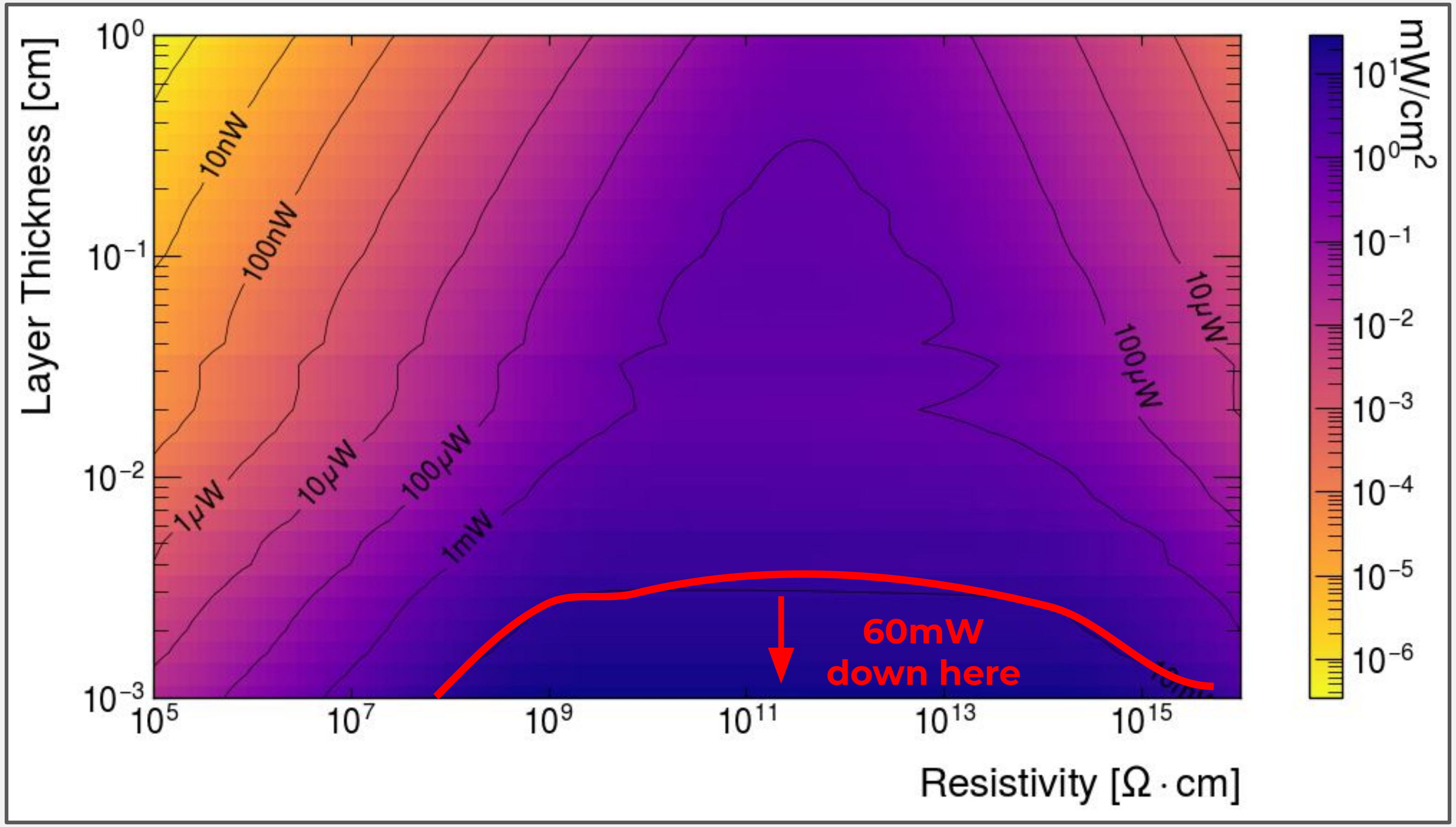
- Another consideration is resistive heating
- Overall current draw is low, but highly stressed areas may be subjected to higher, localized current densities
- HV Cathode ~3m below LAr surface
  - ~60mW/cm^2



Peterson, T., and /Fermilab. Liquid Argon Maximum Convective Heat Flux vs. Liquid Depth. United States: N. p., 1990. Web. doi:10.2172/1031856.

Evaluate in COMSOL, just to be sure

- Sweep through resistivity and layer thicknesses, calculate ***max*** dissipated power per square centimeter
  - Stay below 60mW/cm^2
- Easily stays below for most of the parameter space
  - Thus we can ignore



Custom Compounding

- We require a layer with $\rho_{vol} \sim 10^8\ \Omega \cdot \mathrm{cm}$
- Estimates suggest 22-30% carbon-doped PE
  - Rest is virgin LDPE resin
- Next steps are to compound and extrude test-batches
  - Measure resistivities and adjust accordingly