

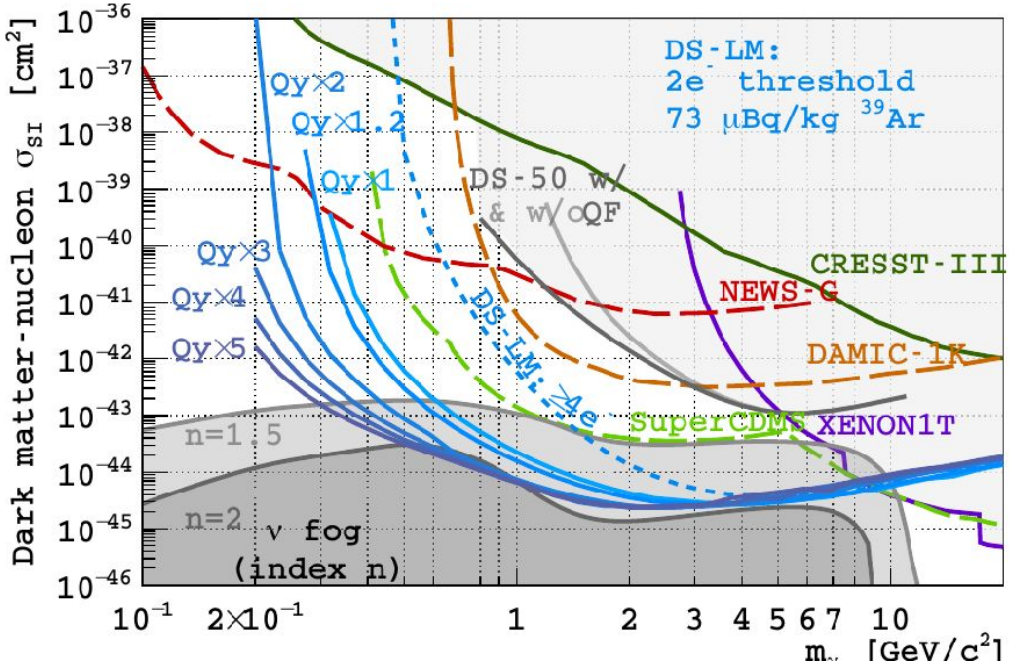
Developing low-threshold liquid argon TPCs with photo-sensitive dopants for rare-event experiments

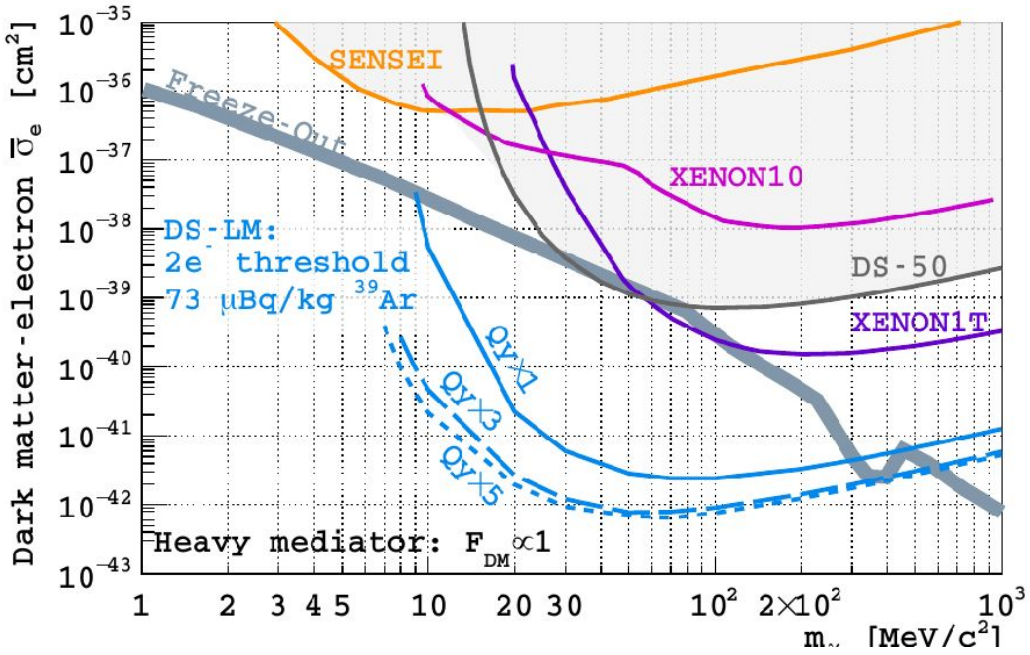
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CPAD | October 20, 2026 | Seattle

Rich physics lies between 10 and 1000 eV, below LAr thresholds

- **Light dark matter**
  - Sub-GeV candidates scatter on nuclei or electrons
  - WIMP searches (10 GeV–10 TeV) are approaching their **final sensitivity**
- **Reactor CEvNS**: Sub-keV nuclear recoils;
  - 10–100 eV thresholds test the weak mixing angle and sterile neutrinos
- **Why LAr can't reach it:** 23.6 eV per electron–ion pair, 70–80 % of recoil energy lost as heat
  - Raising the ionization yield (Qy) pushes the reach to lower masses
- **Goal**: Tonne-scale LArTPCs with the 5–20 eV thresholds of solid-state detectors (**SENSEI, DAMIC, SuperCDMS**)

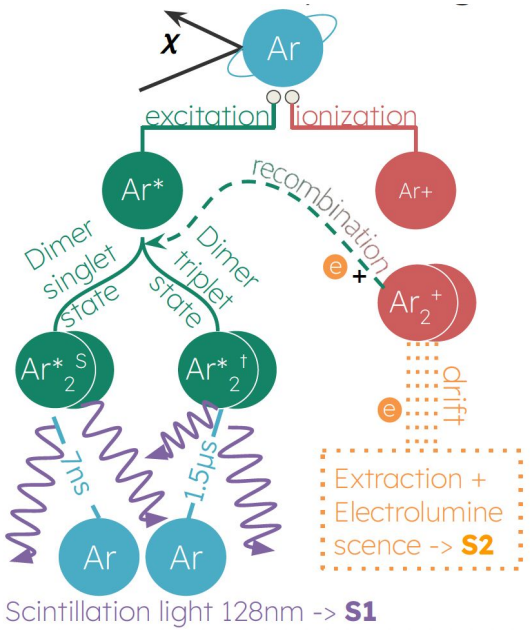


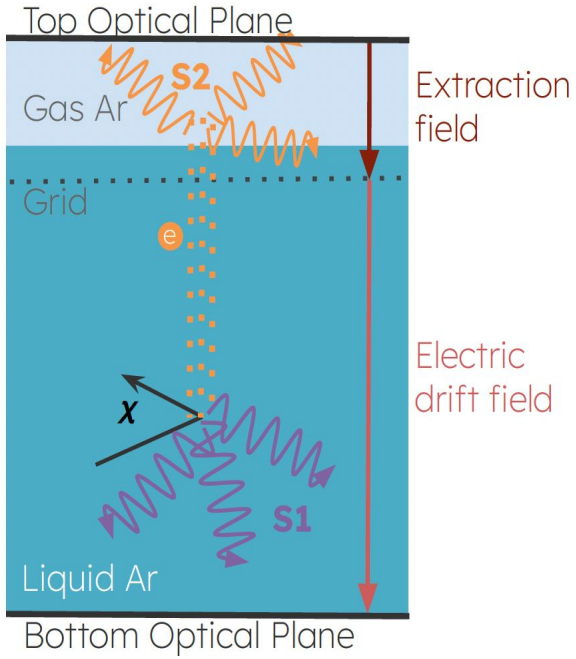


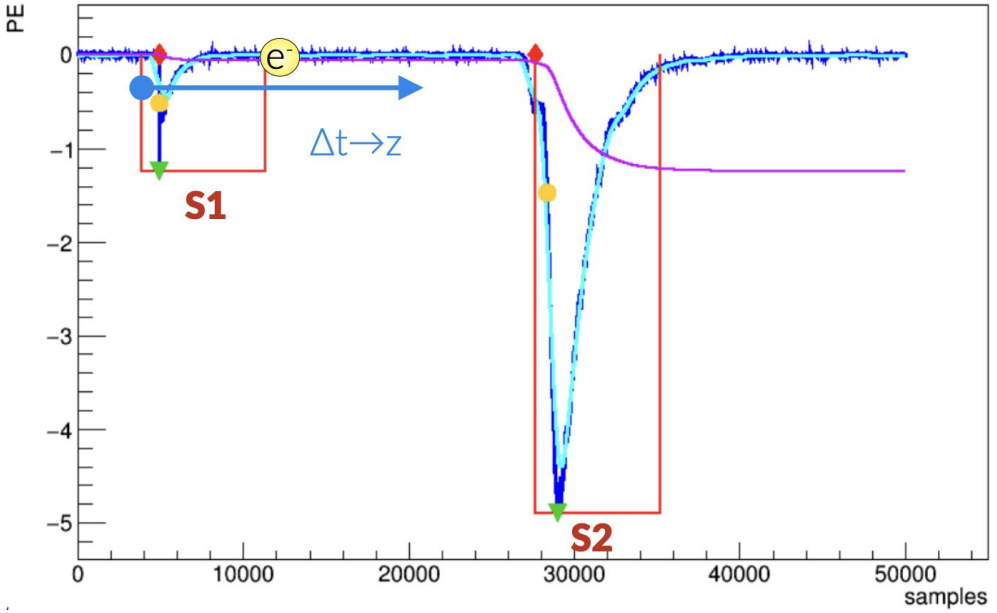
GADMC Phys. Rev. D 107, 112006

Dual-phase LArTPCs

- Detection of two signals:
  - **S1:** Primary scintillation in liquid
    - Triggering requires several photons to be detected, many more to be produced
  - **S2:** Proportional secondary light signal from ionization electrons accelerated in gas pocket
    - Can efficiently detect every ionization electron
- **LAr**: cheap, ultra-purifiable, scalable (**DEAP-3600, MicroBooNE, ICARUS, ProtoDUNE**)







- S2-only allows sensitivity to single-electron events
  - As a consequence, S2 can access lower energies than S1
  - Low-threshold LArTPC via S2-only channel
- **Challenges:**
  - Cannot measure Δt; Can't fiducialize in z
    Timing resolution limited by max e- drift time
  - No PSD; No ER discrimination
  - Spurious electron backgrounds

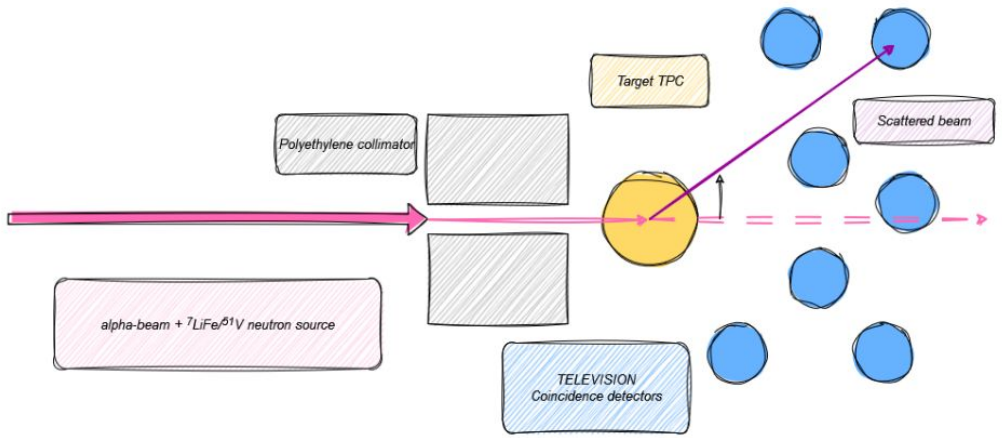
Designing novel low-energy detectors

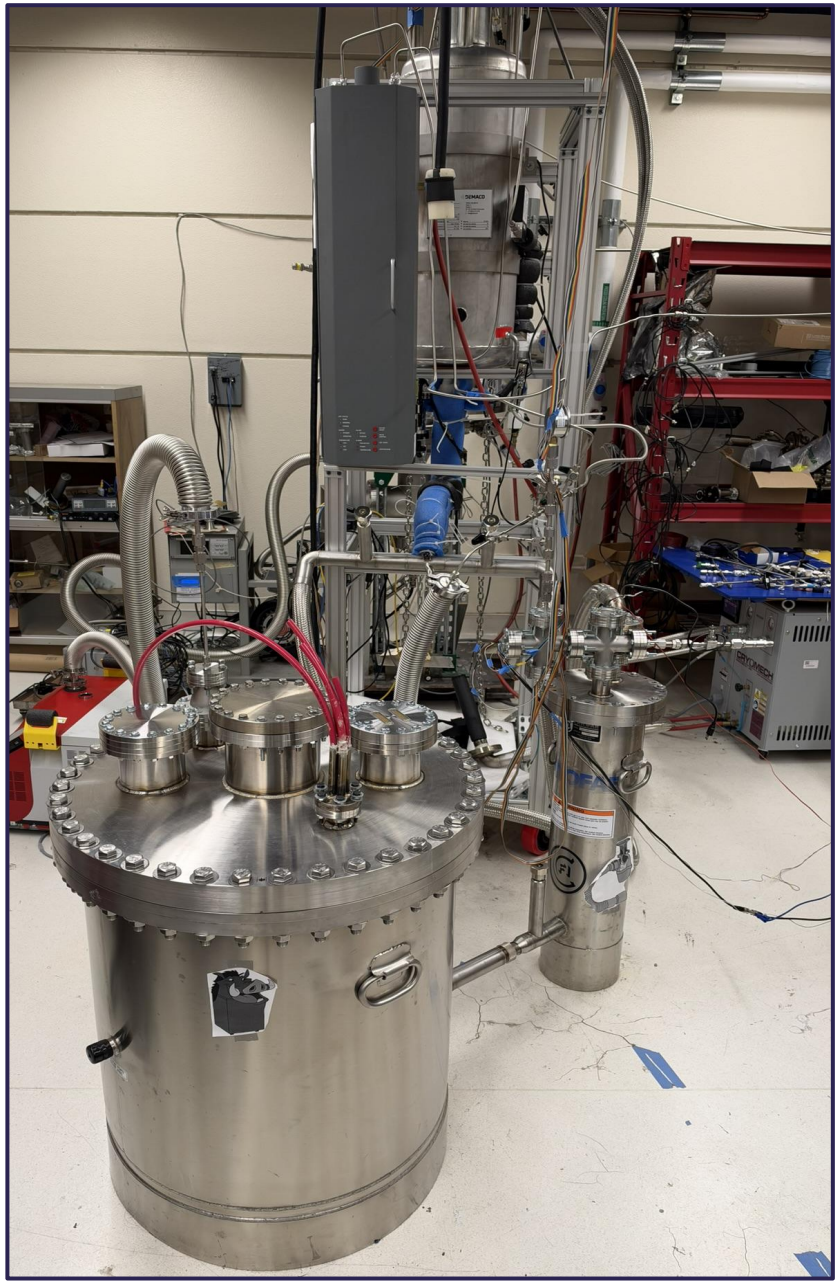
- **Cryogenic system:** liquefy argon and dope it stably and purely
  - **Argon:** inexpensive; light nucleus suits light dark matter
  - **Xenon:** lower ionization energy, more easily detected light
  - **Photo-sensitive dopants:** lowest ionization energy, lightest nuclei; turn photons into electrons

- **LOADED(Low-energy Optimization And Doping for Enhanced Detectors)**

  A small, customizable TPC to

  - Study spurious backgrounds at the lowest energies
  - Measure the effect of Xe and photosensitive dopants
  - Calibrate pure and doped LAr to very low-energy signals





Dopants turn lost energy into countable electrons

- **Dopants**: ionization energy ≤ 9.8 eV, at 10–1000 ppm
- **Light → charge:** scintillation photons ionize the dopant, up to 2× yield
- **Recover the heat:** recoils keep ionizing below argon's 15.8 eV
- **^{1}H target:** 40× more recoil energy for light dark matter
- Never measured at the eV scale or in a dual-phase TPC

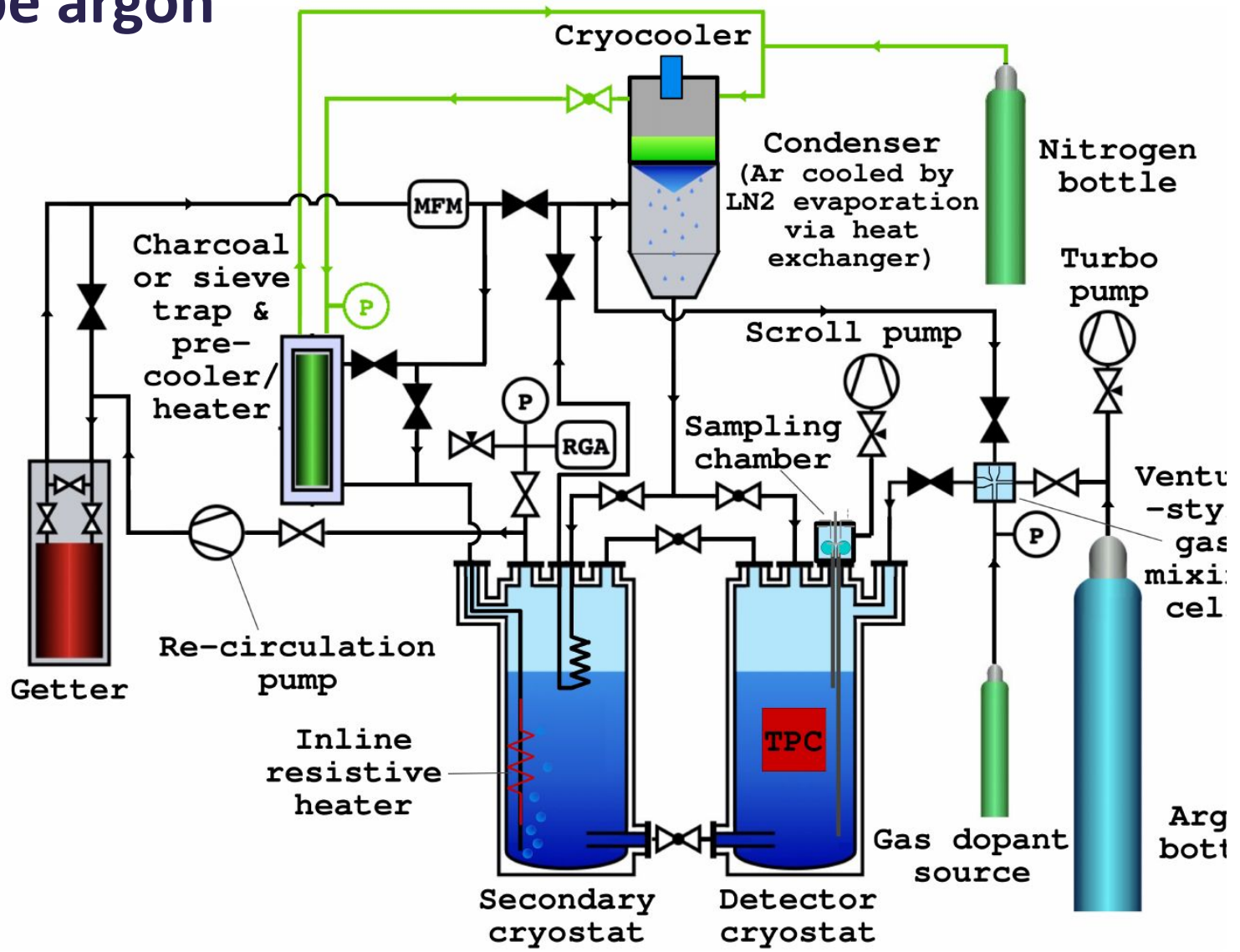
Dopant	Formula	Ion. E	QE	Max conc.	Melts
Allene	C_3H_4	9.5 eV	70 %	250 ppm	137 K
Isobutylene	C_4H_8	9.2 eV	-	16 ppm	133 K
TMG	$(CH_3)_4Ge$	9.3 eV	45 %	15 ppm	185 K
TMA	$(CH_3)_3N$	7.8 eV	35 %	100 ppm	156 K

Four candidate dopants, three engineering challenges

- **Allene:** best studied, proven purification, safest
- Dopants are solids at LAr temperature, so little reaches the gas
- **Challenge 1, stable and pure:** >10 ms electron lifetime, uniform for a month
- **Challenge 2, no new backgrounds:** purify the dopant; PEN instead of TPB
- **Challenge 3, no S2 feedback:** S2 light re-ionizes the dopant, which causes ringing or an avalanche

A two-cryostat system to dope argon

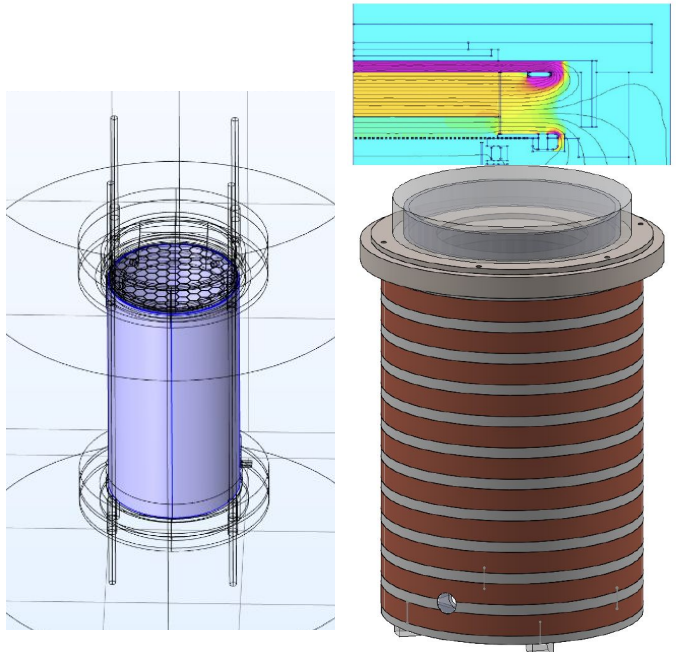
- **Fill:** purified argon condenses into the detector cryostat; dopant is metered into a mixing cell
- **Operate:** a secondary cryostat cools by thermosiphon, and the warmer detector side keeps dopant at the TPC
  - Same approach reached 2 % Xe in LAr without ice
- **Purify:** molecular sieves remove O_2 and H_2O but not dopant
- **Check:** RGA, depth sampling and S1/S2 response with a γ source track concentration
- **Status:** built on DS-50, DEAP-3600 and LLNL Xe-doping system; all parts running at UCR



Recirculation, purification and doping loop

LOADED: a 0.5 kg dual-phase TPC built for electron counting

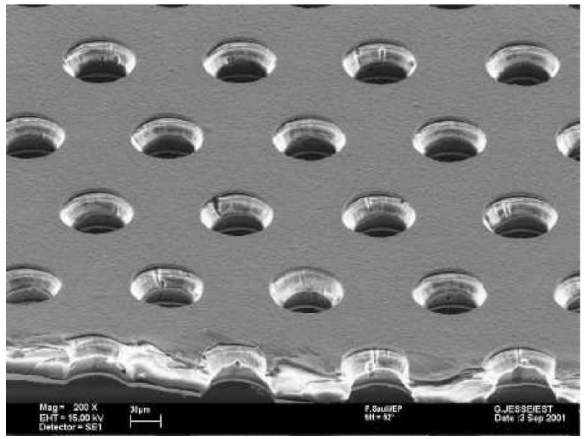
- Based on DS-50, SCENE and ReD; field optimized for S2-only measurements
- S2 gain target g_2 ~75 PE/e
- **Glass barrel:** 5 mm borosilicate, no hydrogen, so calibration neutrons don't scatter
- **Electrodes:** ITO-coated glass cathode and anode, resistive Kapton field cage
- **VEIL:** blocks S2 light that would re-ionize the dopant, passes electrons (two misaligned PEN layers, 0.2 mm holes)
- **Readout:** SiPM arrays top and bottom, DarkSide-20k electronics
  - Top SiPMs read individually for 6× better S/N



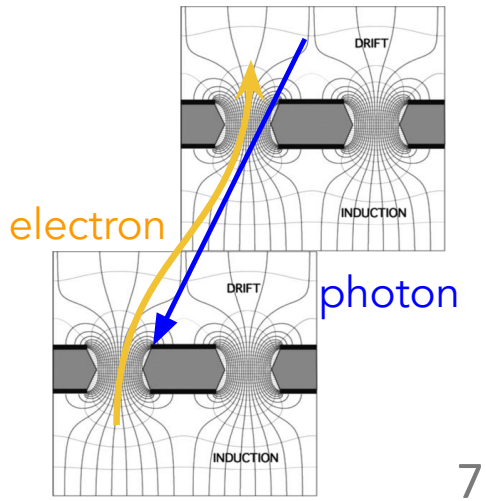
Design + field simulation



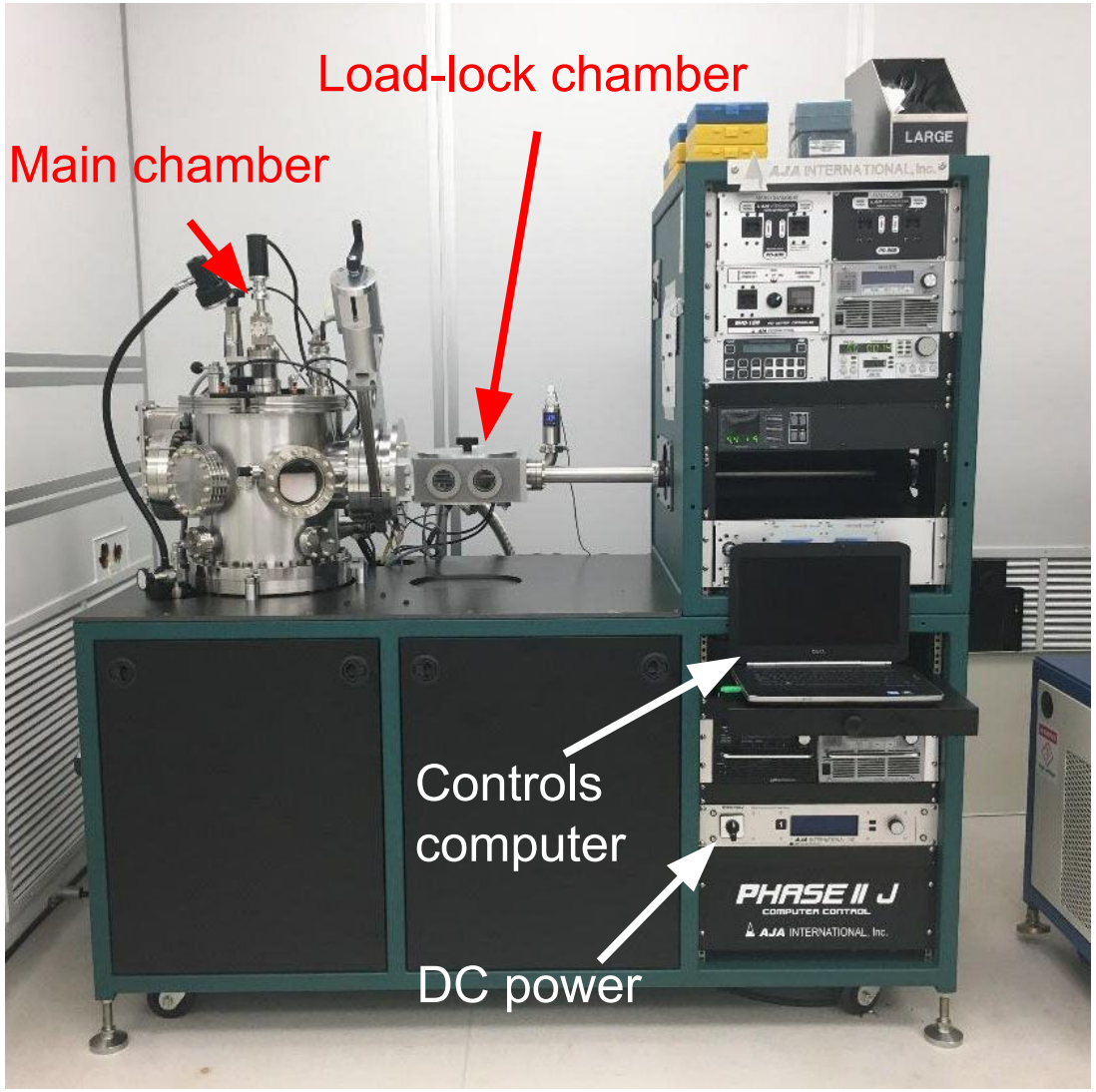
Built borosilicate barrel



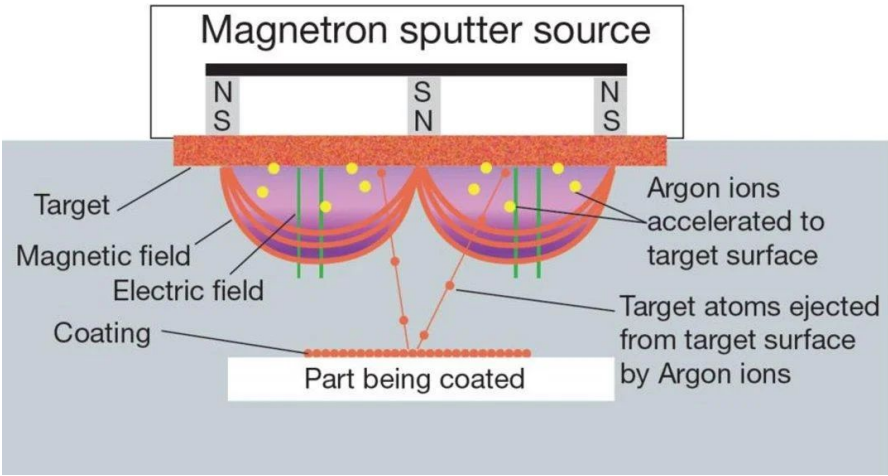
GEM foil (Sauli, NIM A 805, 2015)



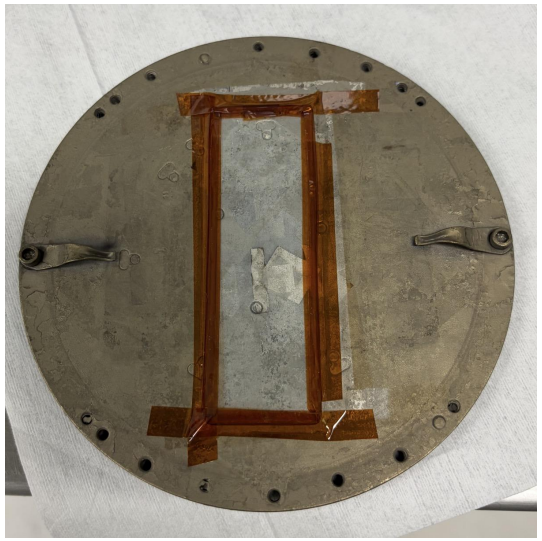
AJA magnetron sputtering machine





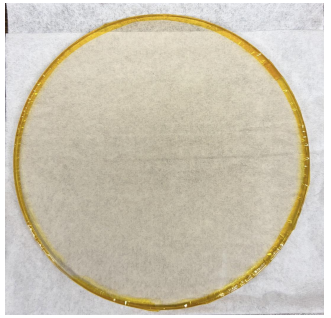






Electrodes and field cage: ITO coatings and resistive Kapton

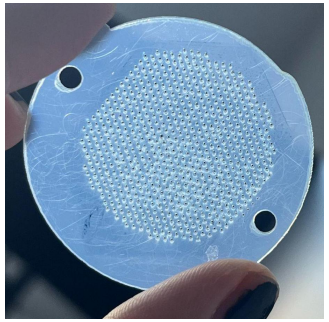
- **ITO glass cathode:** sputtered at UCR, ~5 kΩ/sq, ~91 % transparent
  - Anode next, with a bilayer recipe
- **Kapton field cage:** 4–6 × 10^8 Ω/sq, near-linear voltage drop
  - COMSOL: the measured gradient has a negligible effect on the field
- **VEIL prototypes:** laser-cut PEN, coating 11 kΩ/sq, ~48 % visible transmittance
  - Simulations (COMSOL, Garfield++): electron transparency grows with layer spacing
- **Next:** VUV opacity at 128 nm, then a two-layer VEIL test in LOADED



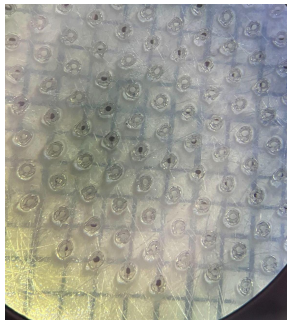
ITO cathode



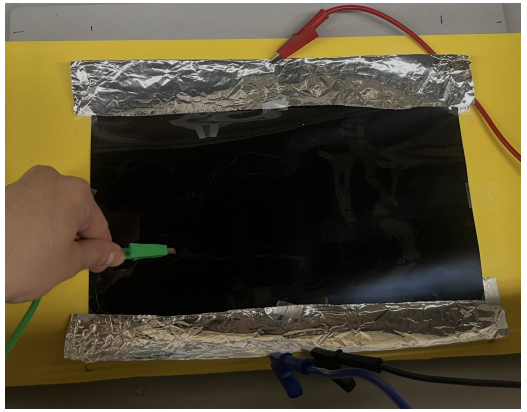
anode

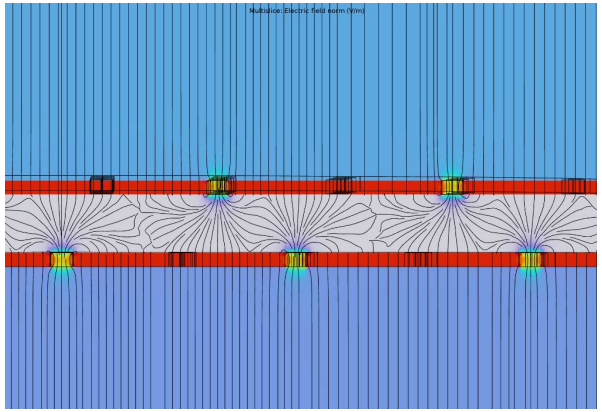


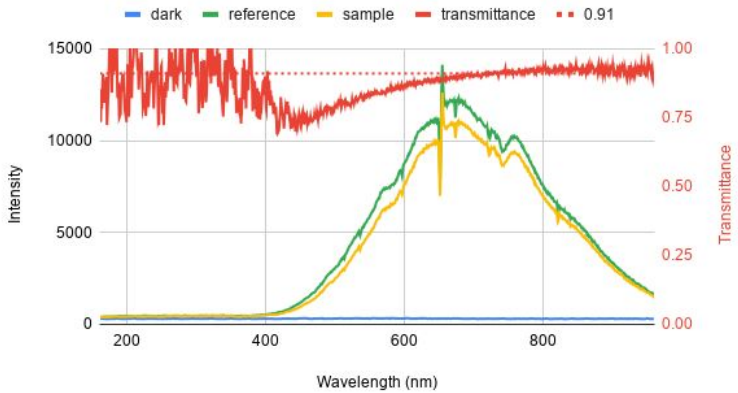
Laser-cut PEN VEIL



Holes under microscope

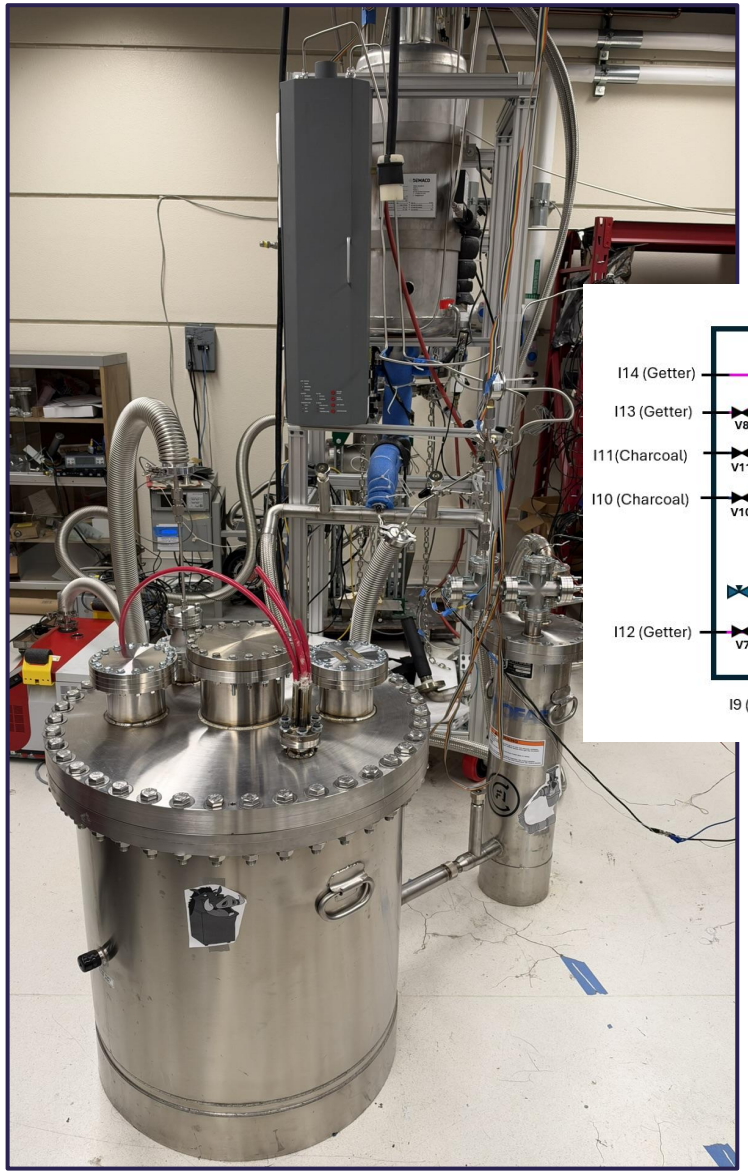


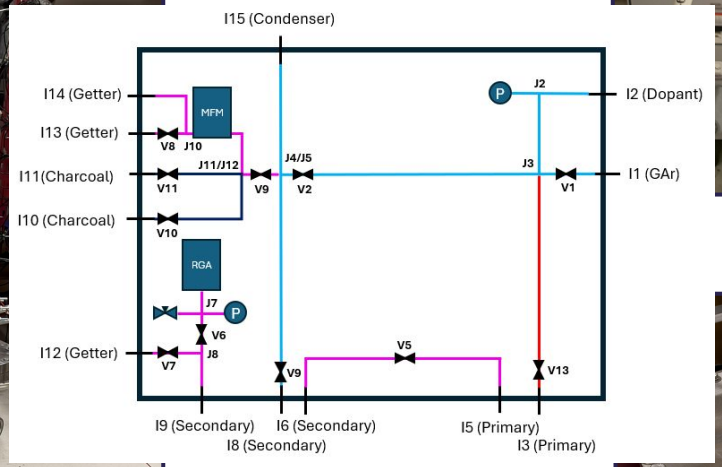


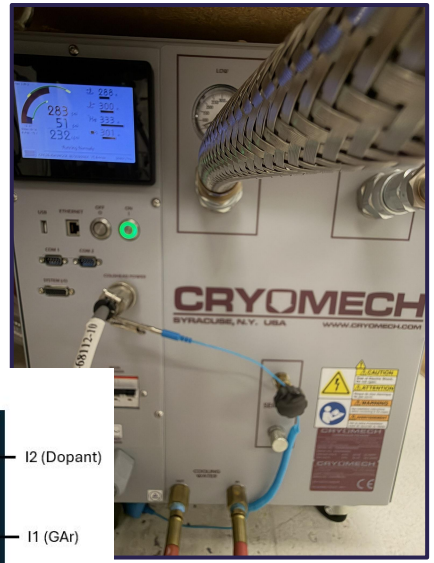


Cathode transmittance (~91 %)

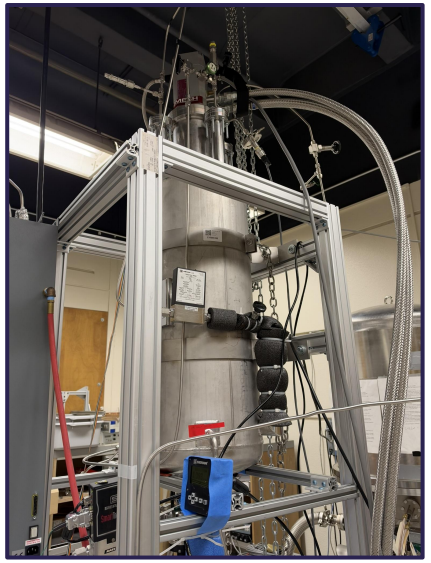
Cryogenic system in the UCR lab







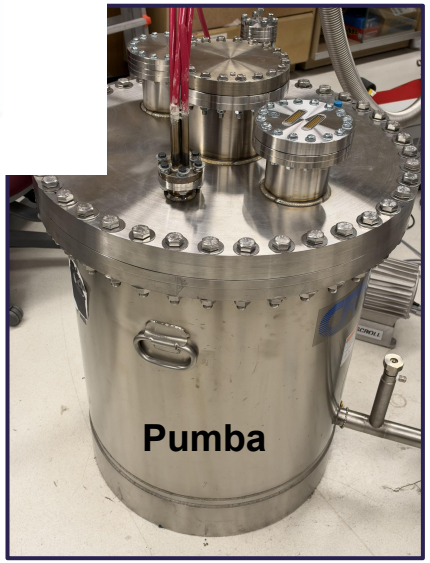
Cryomech



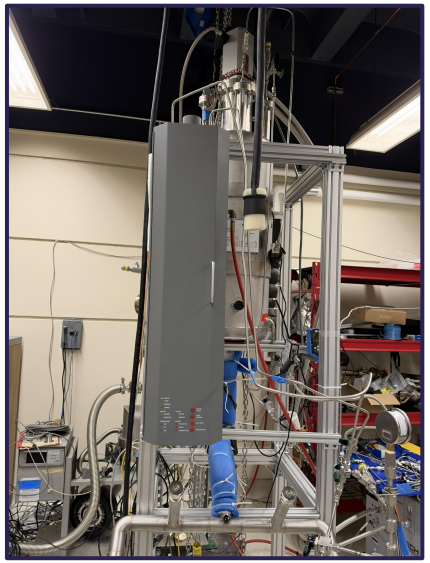
Condenser



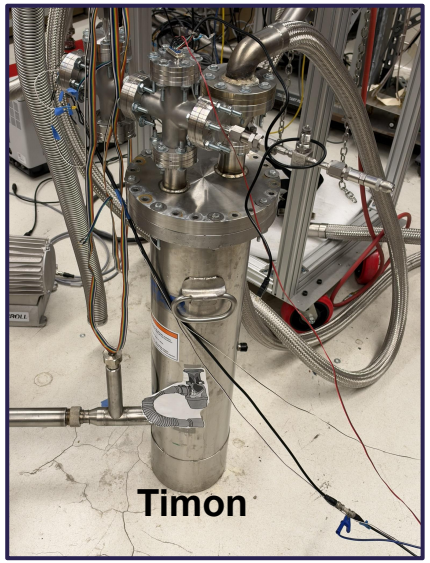
Argon and nitrogen gas bottles



Cryostat for hosting TPC



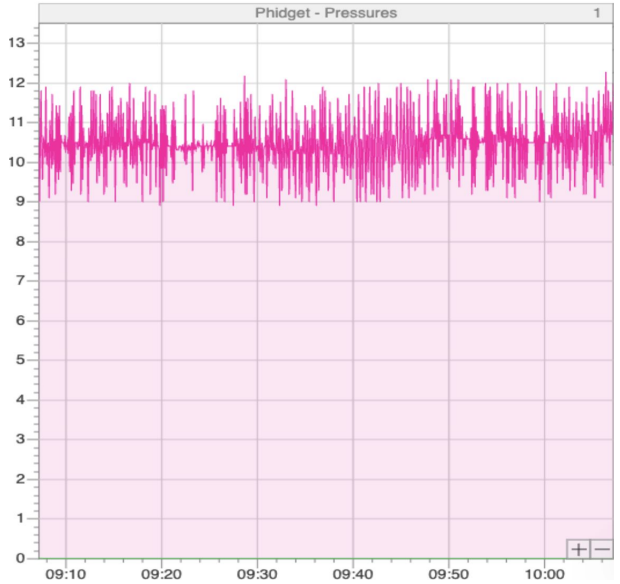
Getter

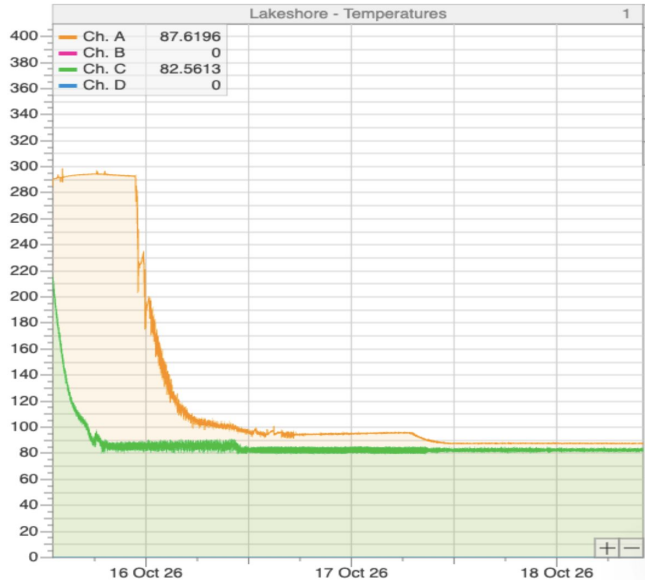


Cryostat for doping LAr

Milestone 1: argon liquefied and held stably

- **Two-stage cooldown in the UCR lab**
  - Nitrogen gas cools the system: ~5–6 h
  - Argon gas then condenses to liquid: another ~5–6 h
- **Stable for weeks**
  - N_2 side: ~82 K at 11 psi; Ar side: ~87 K at 15 psi
  - Argon flow ~1.6 scc/s
  - Heaters at a fixed set point prevent ice formation
- **Lessons learned:** leaks, valves, heaters, cooldown and warm-up procedures
- **Why it matters:** a stable, pure liquid is the baseline for every doping test







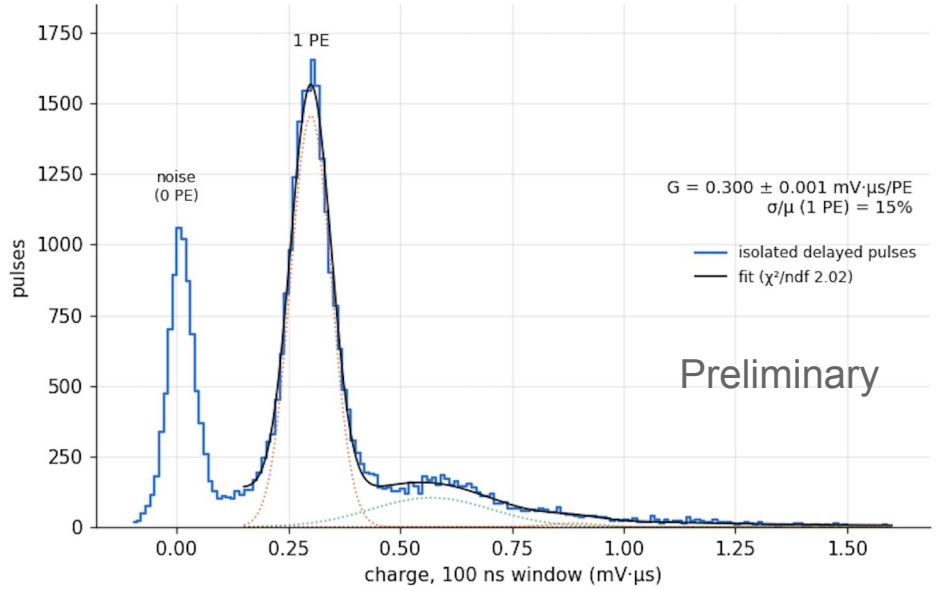
Argon ice during condensation, added a heater to avoid

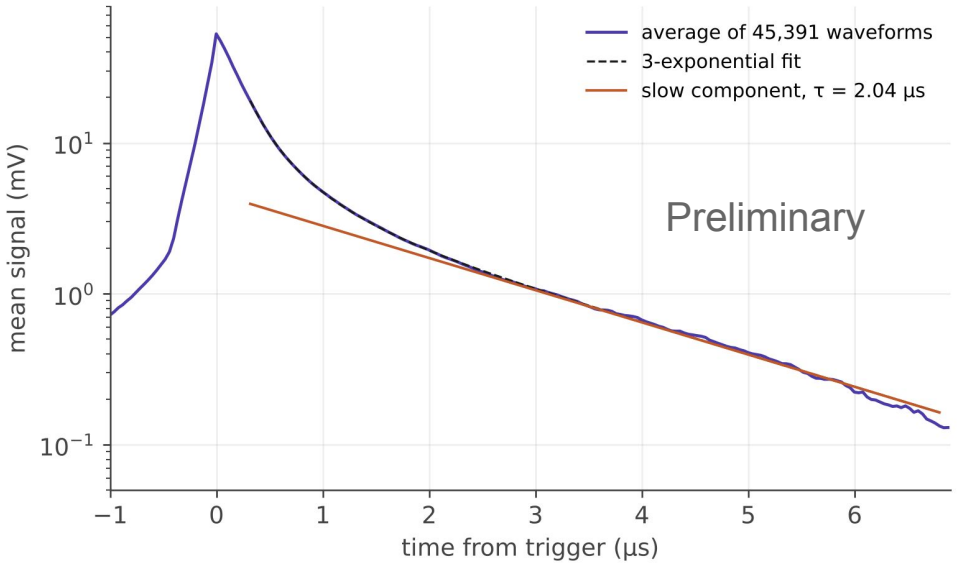
Milestone 2: first SiPM data in liquid argon

- **Setup:** SiPM in LAr, ^{60}Co source, PEN shifter, Lumirror as reflector, camera and LED at the top of the cryostat

- **Single photoelectrons resolved at 87 K**
  - Gain 0.30 mV·µs/PE, σ/µ 14 %, S/N 13
  - 1 PE ≈ 8 mV
- **Pulse shape:**
  - Slow component ≈ 2.0 µs
  - Longer than pure LAr (≈1.5 µs): no quenching seen; SiPM afterpulsing likely adds a tail







Summary and next steps

- Photo-sensitive dopants could bring tonne-scale LArTPCs to ~10 eV thresholds
  - Light dark matter down to ~MeV via ^{1}H, reactor CEvNS, DUNE neutron tagging
- **Approach:** a two-cryostat doping system plus LOADED, a glass TPC with VEIL to stop S2 feedback

- **Status**
  - Argon liquefied and stable for weeks
  - SiPM resolves single photoelectrons in LAr (gain 0.30 mV·μs/PE)
  - ITO cathode coated, Kapton mapped, VEIL prototyped and simulated

- **Next**
  - Finish LOADED and run it with pure LAr
  - Dope with allene: >10 ms electron lifetime, no added impurities
  - Calibrate electronic and nuclear recoil yields vs. dopant concentration, down to ~15 eV
  - Develop high-purity doping techniques; need to add dopant w/o adding impurities

Thank you and
Stay tuned!