SLAC NATIONAL ACCELERATOR LABORATORY

KIPAC
KAVLI INSTITUTE FOR PARTICLE ASTROPHYSICS & COSMOLOGY

Studying hydrogen-xenon mixtures for direct dark matter detection

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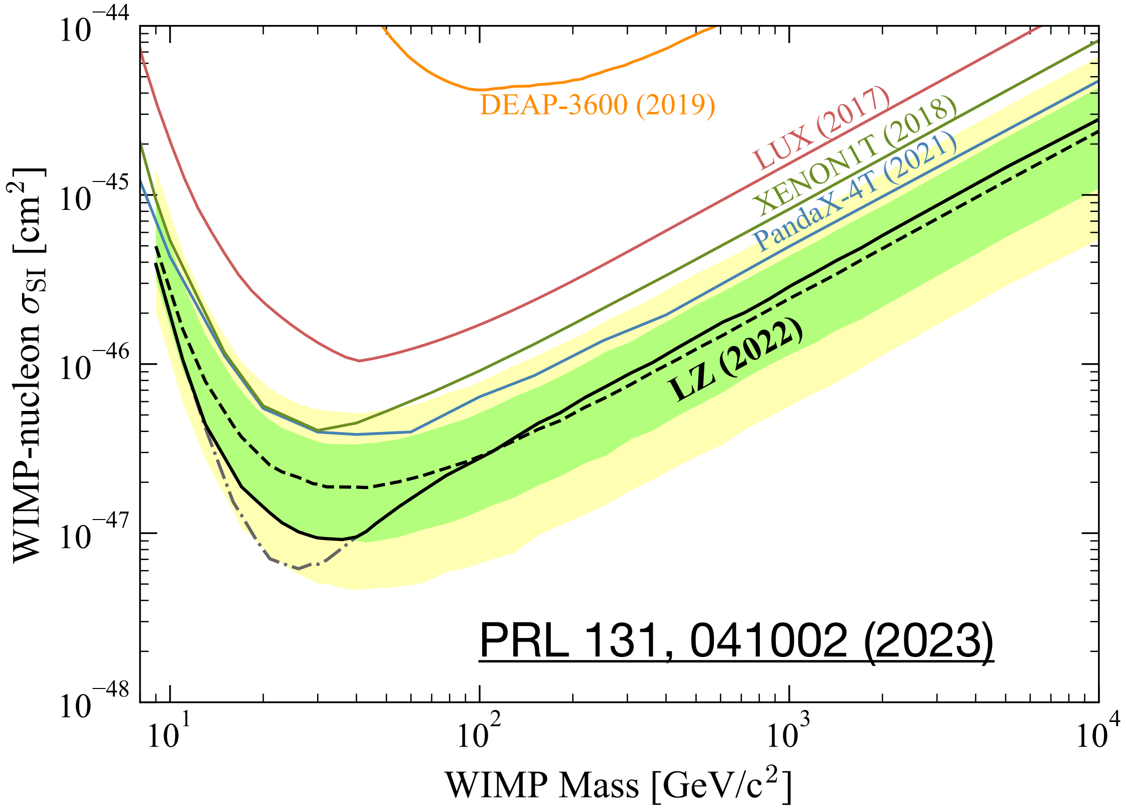
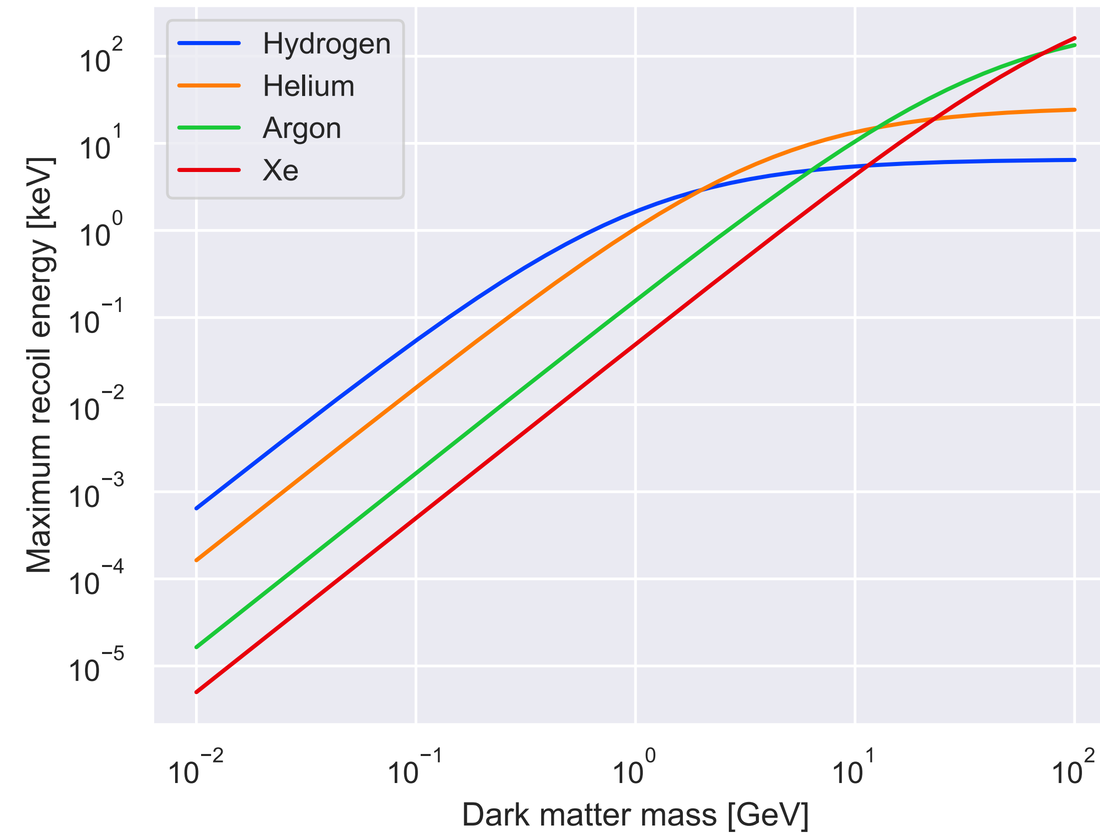
On behalf of the HydroX test stand @ SLAC team

Motivation for HydroX

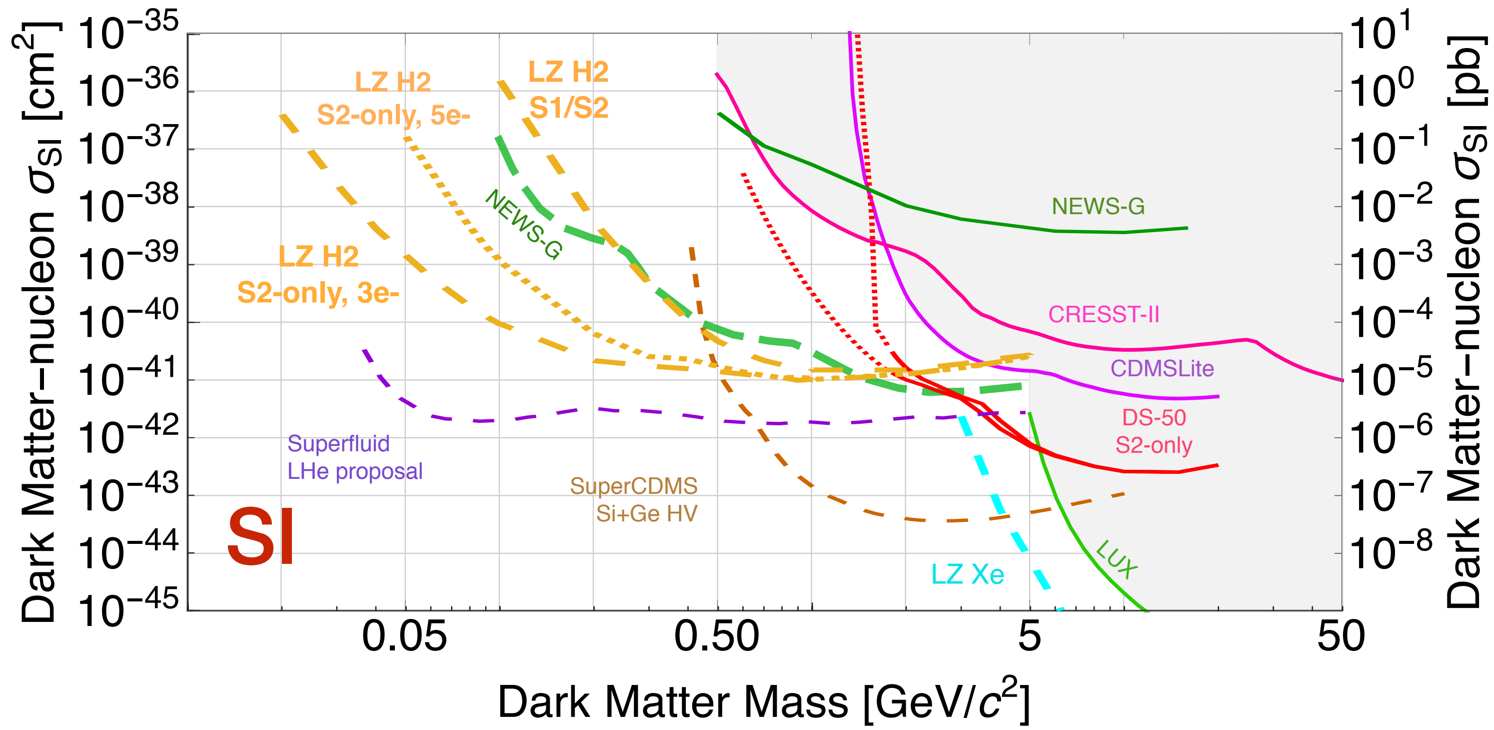


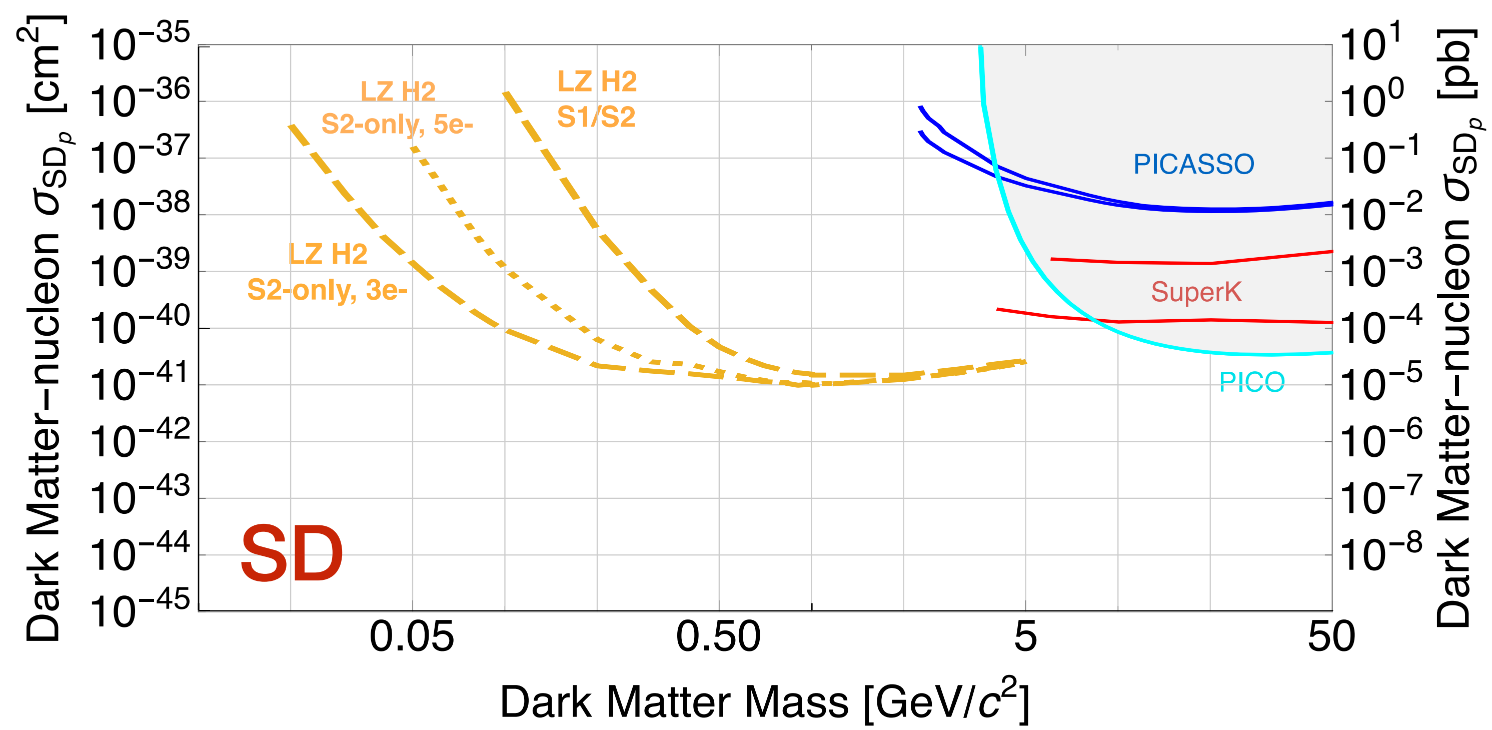


- Sensitivity of xenon-based TPCs to dark matter candidates drops rapidly below O(10 GeV)
  - Typically have keV energy threshold
  - Maximum recoil energy from ~GeV WIMP is < 100 MeV —> no detectable signal!
- **Basis of HydroX: add light target to xenon-based detectors to improve light DM sensitivity!**
  - Larger recoil energy for hydrogen atom, recoil energy is then transferred to Xe for visible signal
  - Keep desirable properties of Xe while providing a better kinematic match for light DM particles

Projected sensitivity

- Pro: we can upgrade a **pre-existing xenon-detector**
  - Successful program with well-understood backgrounds
- Sensitivity projections with LZ show a competitive reach for low masses
- Projected limits assume 2.6% mole fraction of H2 in xenon and 250 live-days
- Excellent sensitivity to spin-dependent interactions (hydrogen is an unpaired proton)



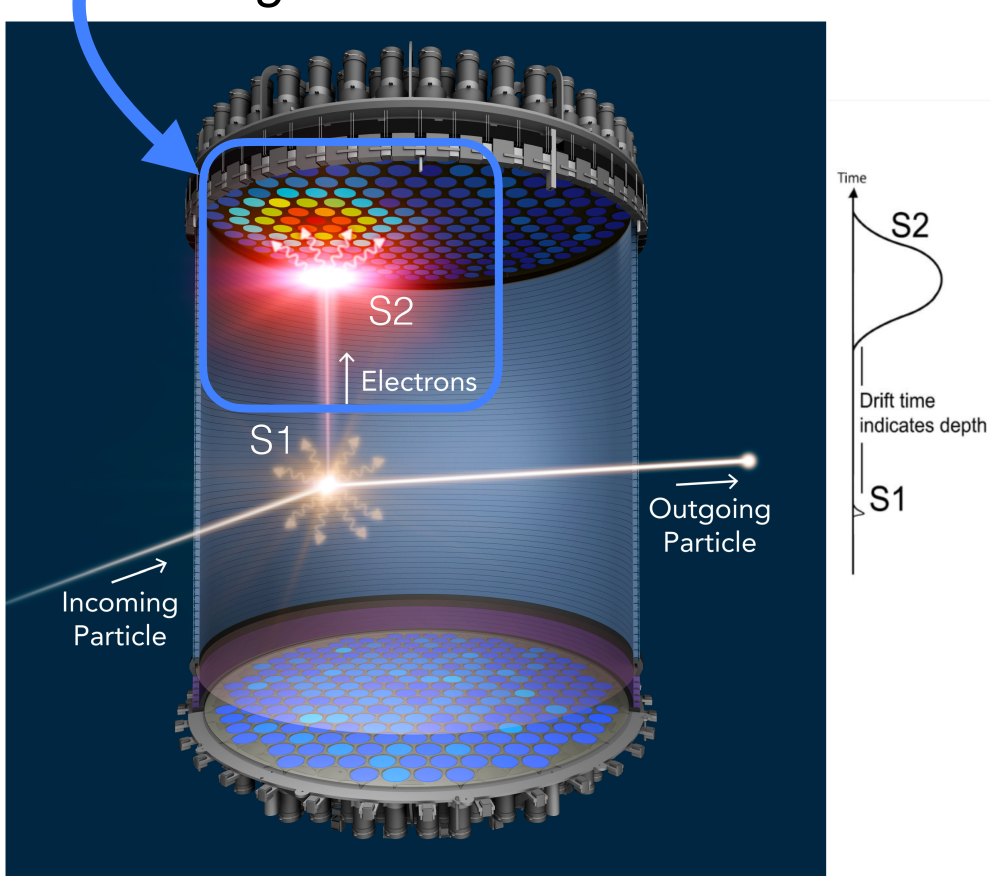


Plots by H. Lippincott

Unknowns about hydrogen doping

- Several questions need to be explored to understand the feasibility of hydrogen-doped xenon detectors
  - How much hydrogen can we dissolve in liquid xenon?
  - How will adding hydrogen affect ER/NR discrimination?
  - **Does hydrogen degrade the Xe scintillation signal?**
    - H2 can cool the electrons or absorb energy from the excited Xe states

Figure from LZ TDR



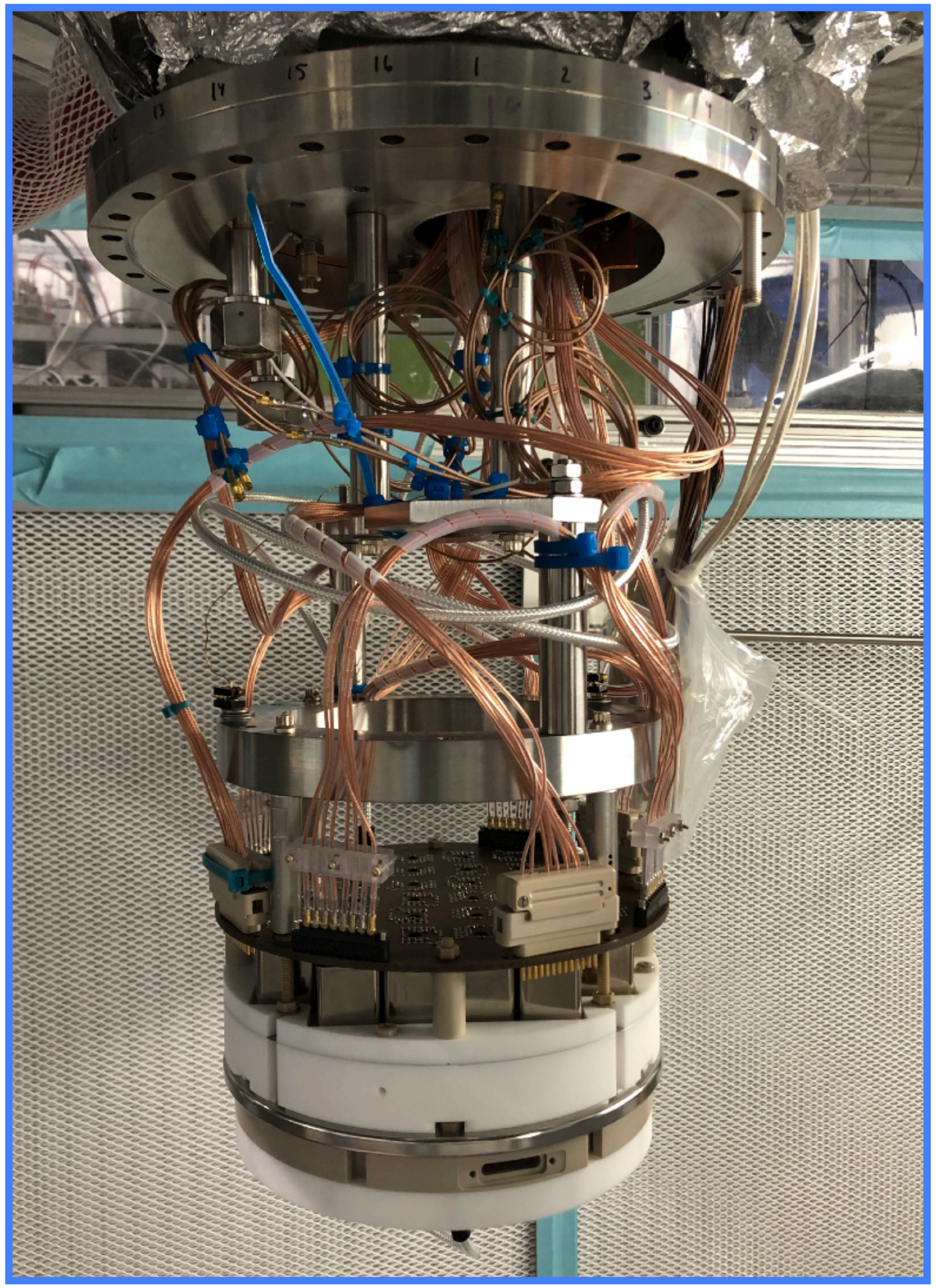
→ Focus of the test stand at SLAC at the Liquid Noble Test Facility (LNTF)

- Measure S2 as a function of H2 concentration
- Gain experience with handling H2-Xe mixtures

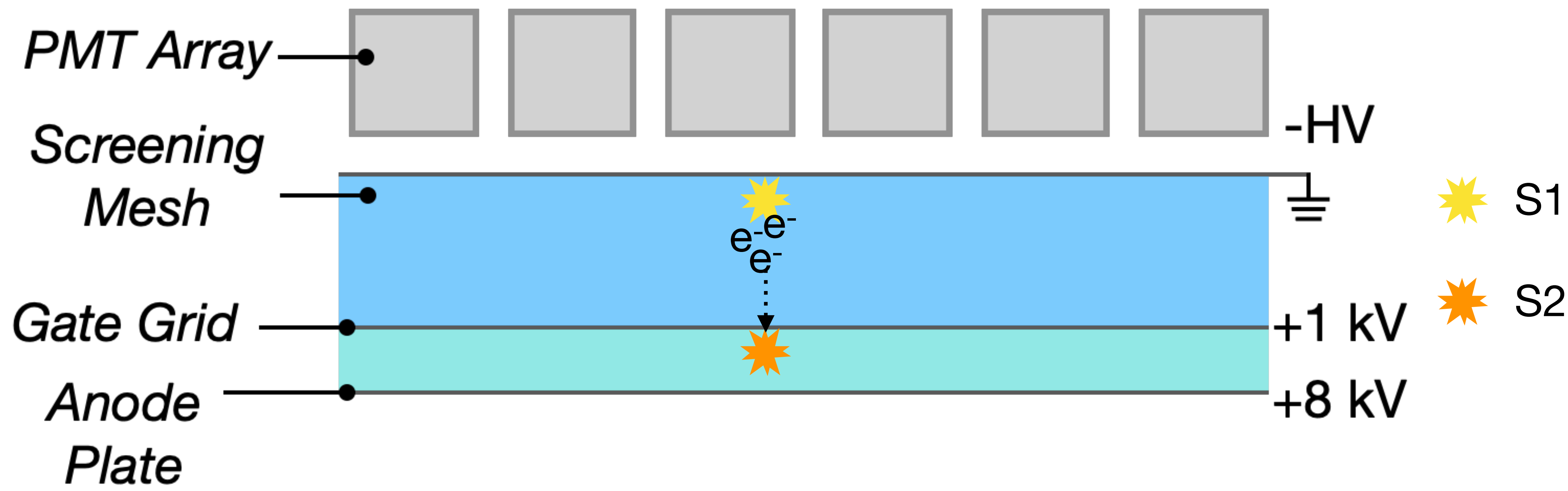
<u>HydroX institutions:</u>
UCSB, LBL, SLAC, Penn State, Michigan, SURF, Imperial College London, Northwestern, Rochester

Status of test stand @ SLAC

- Spent past ~year constructing system for these measurements
- **TPC** with ~800 g of xenon (modified LZ System Test TPC)
- **32-PMT array** with 1-inch Hamamatsu R8520-406
- **Gas handling systems** for feeding, circulating, and recovering xenon and hydrogen
- Extensive instrumentation to **monitor temperature and pressure** across the system
- **Custom DAQ and reconstruction** package based on the strax analysis framework



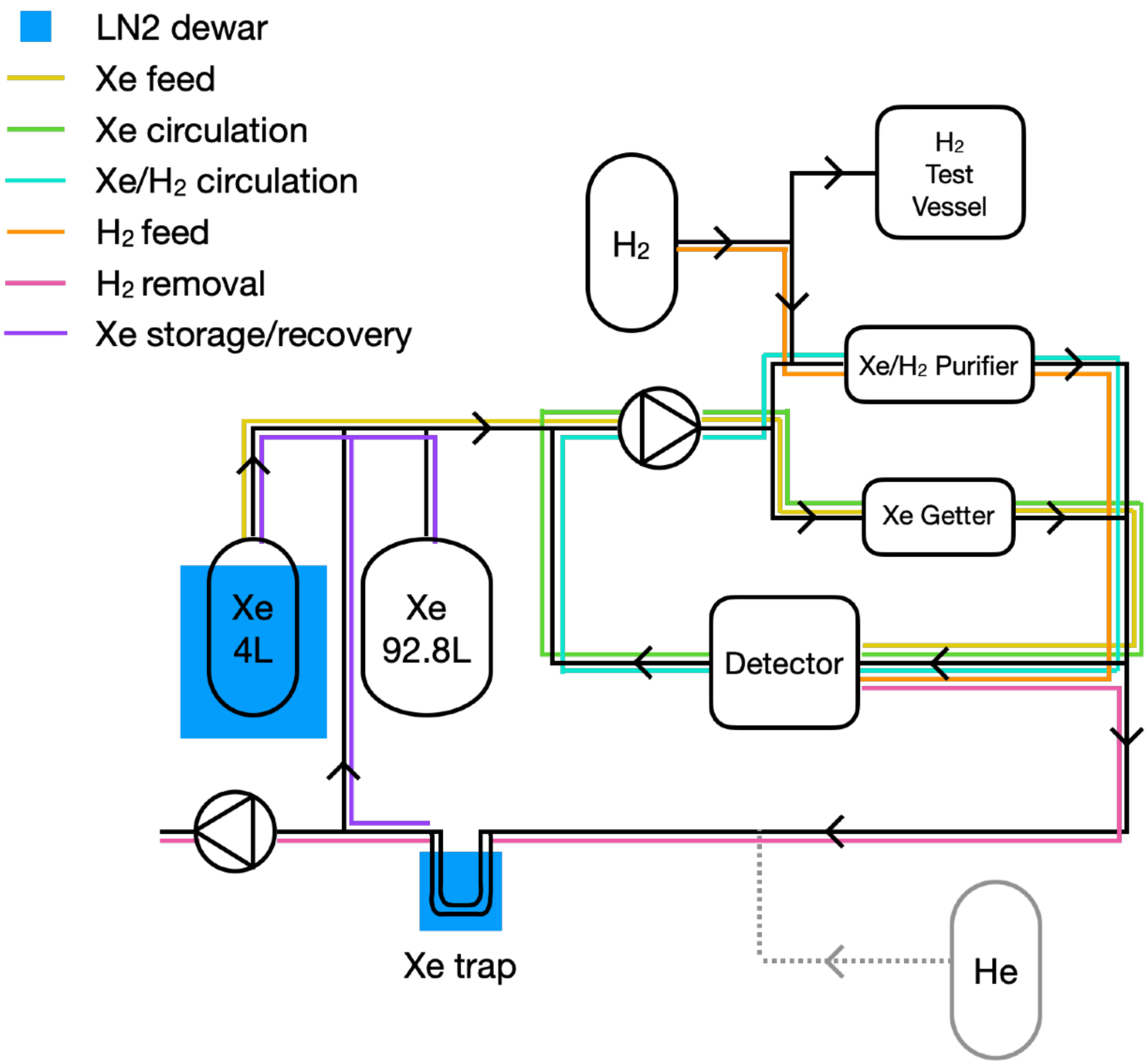
TPC Configuration & Detection



- Run in gas phase with both a gate and anode plate
- Particle interactions will produce two observable signals:
  - **S1** - “light” signal
  - **S2** - “charge” signal
- Focus is to measure the effect of H2 on the S2, but we will also measure the S1 (in gas)

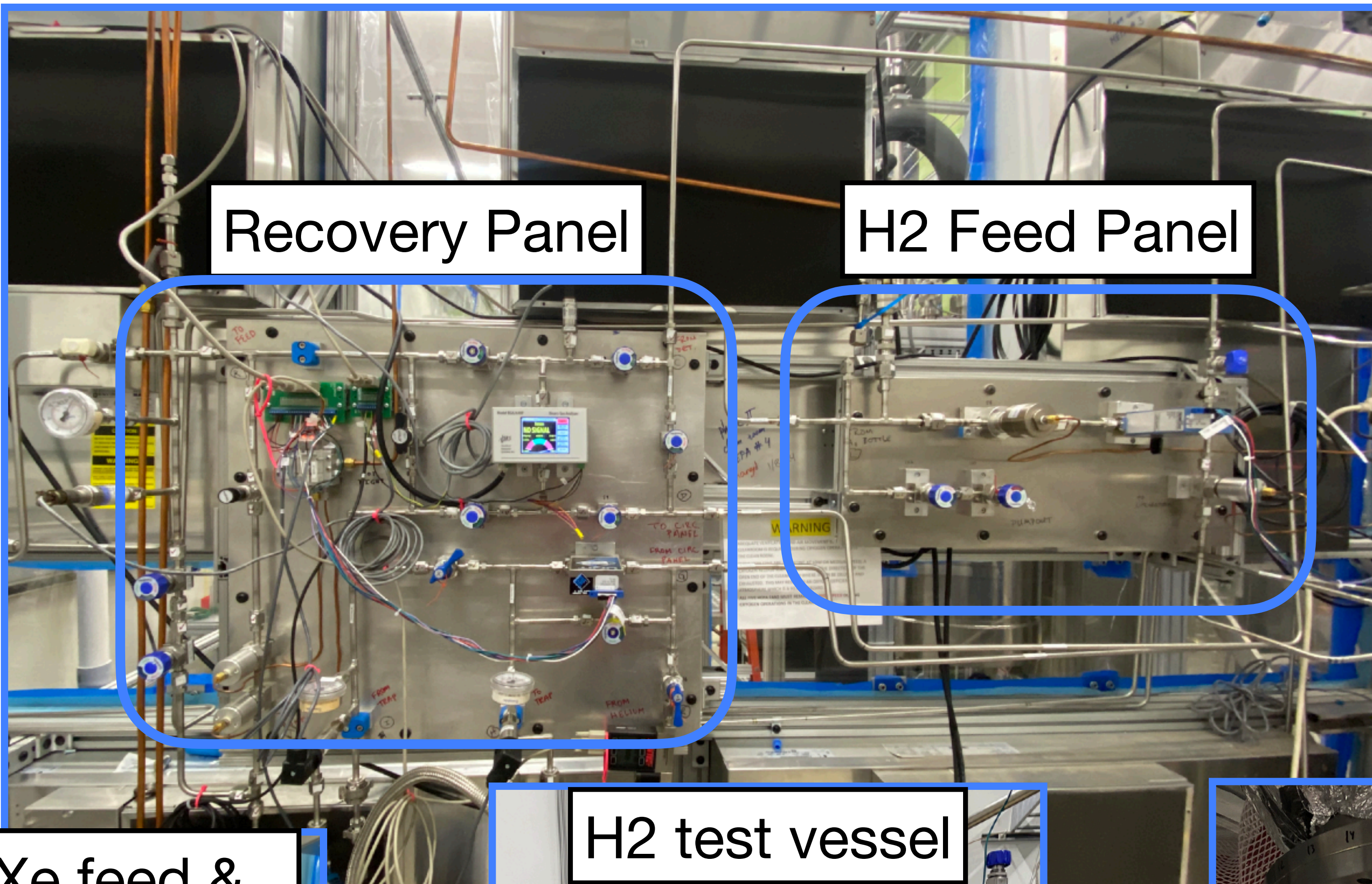
Detector Parameters	
Drift region height	3.7 cm
Drift region diameter	14 cm
Extraction region height	8 mm
Average drift field	276 V/cm
Average extraction region field	8.64 kV/cm

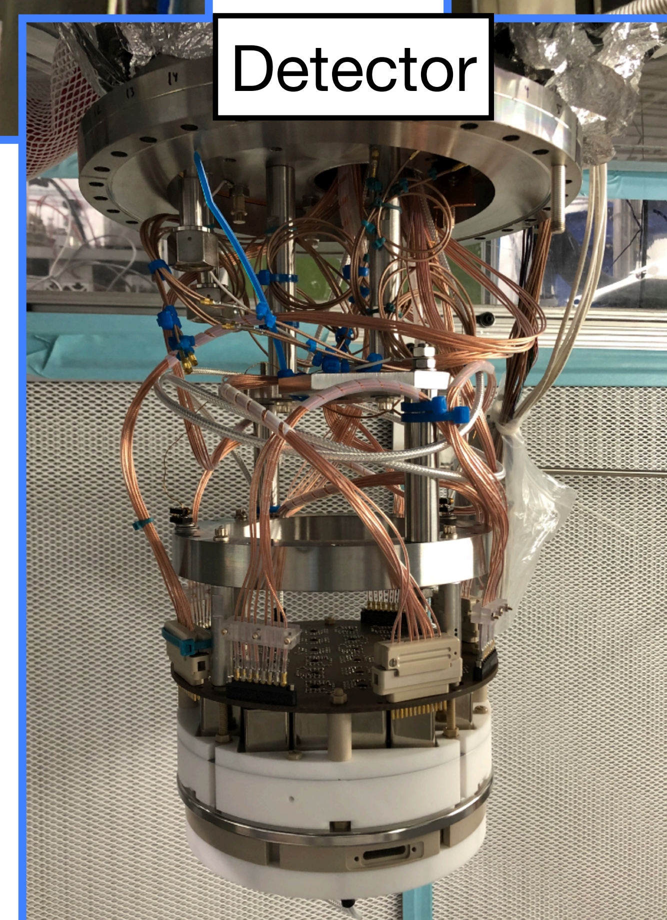
Gas handling system



- Built H2 feed system with separate line to H2 test vessel (PMT after pulsing tests)
- Gas circulates @ 5 SLPM with KNF double diaphragm pump through a purifier from Entegris for H2/X2 mixtures
- Design incorporated solutions to deal with H2 safety/ material concerns:
  - Pressure relief exhaust routed to outdoors due to flammability concerns
  - Detector is cooled with a LN thermosyphon system to run with cold gas

Photos of gas system & detector



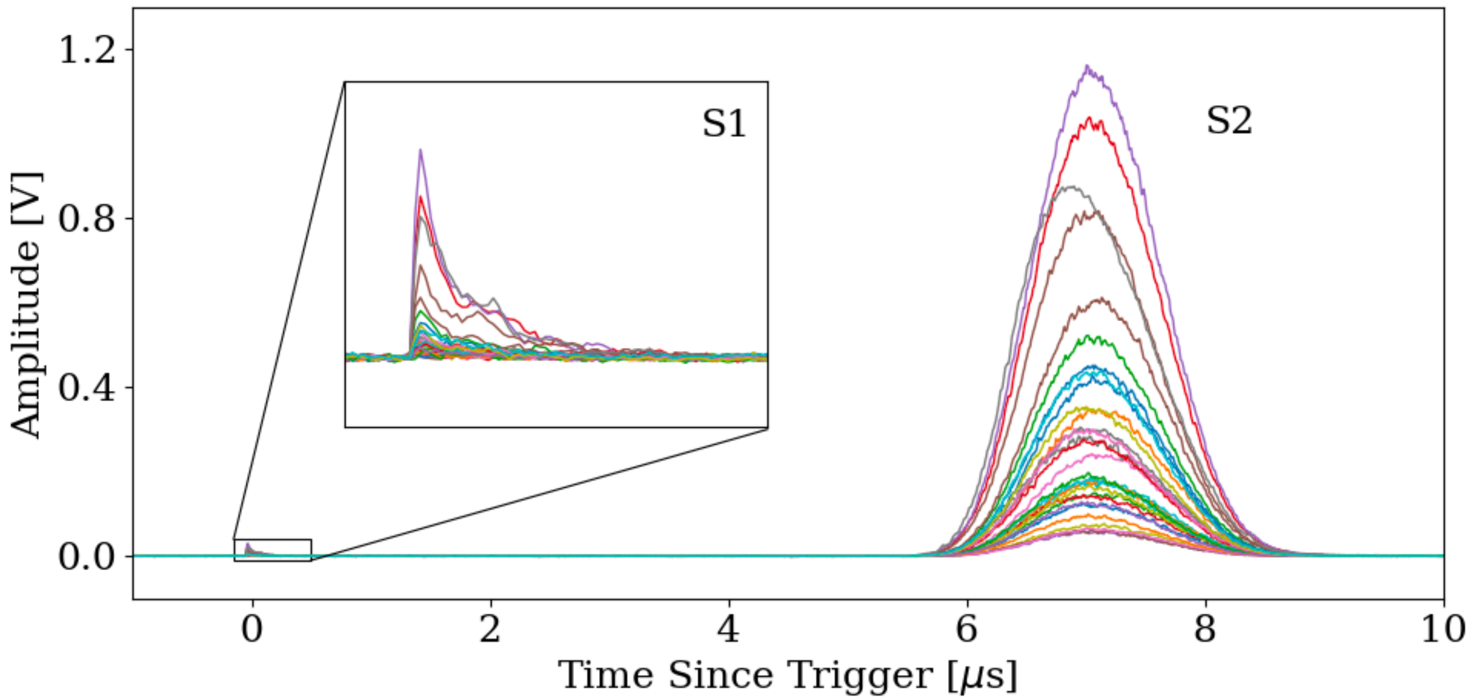


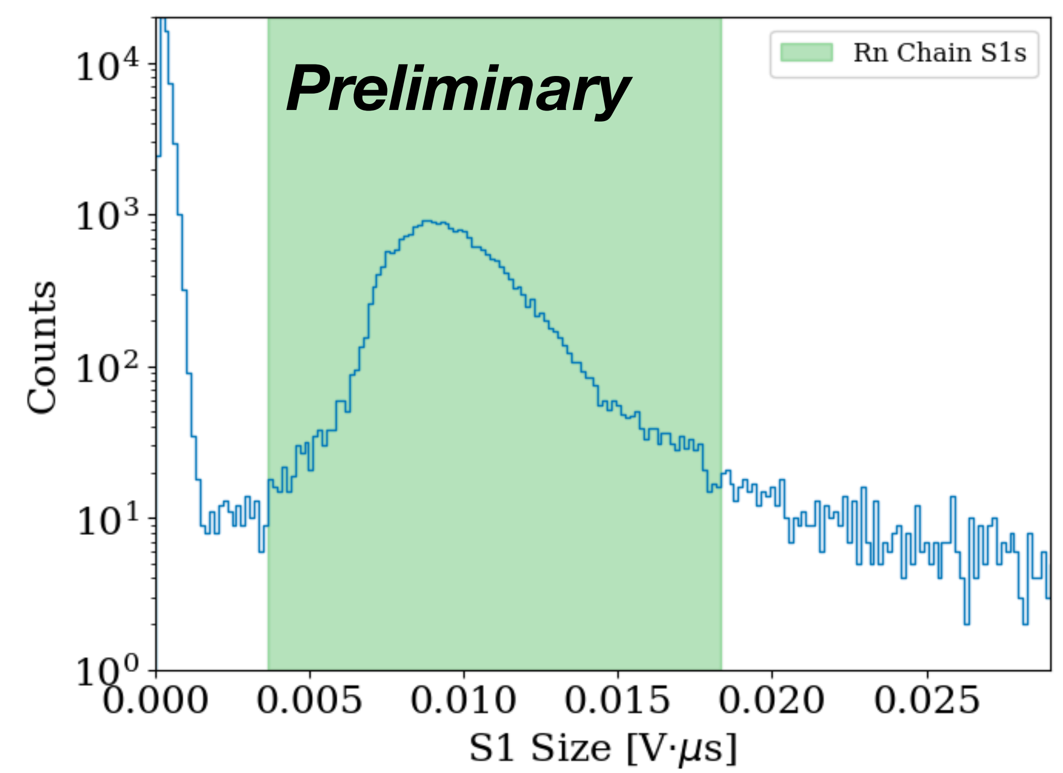
Major construction effort for gas handling

Xenon-only Rn-222 measurements

- First demonstrate understanding of detector with Xe only measurements
- Use a radioactive source to calibrate our signal & detector
- **Rn-222 decay** has a 3.8 day half life with 5.6 MeV alpha, track length ~1 cm
- Large energies, but provides clear signal (& was readily available)
- Injected a Rn-222 internal source with ~kHz of triggers
- Analysis:
  - See peak in our spectrum and we apply a very loose selection around peak in S1 pulse area to select Rn events

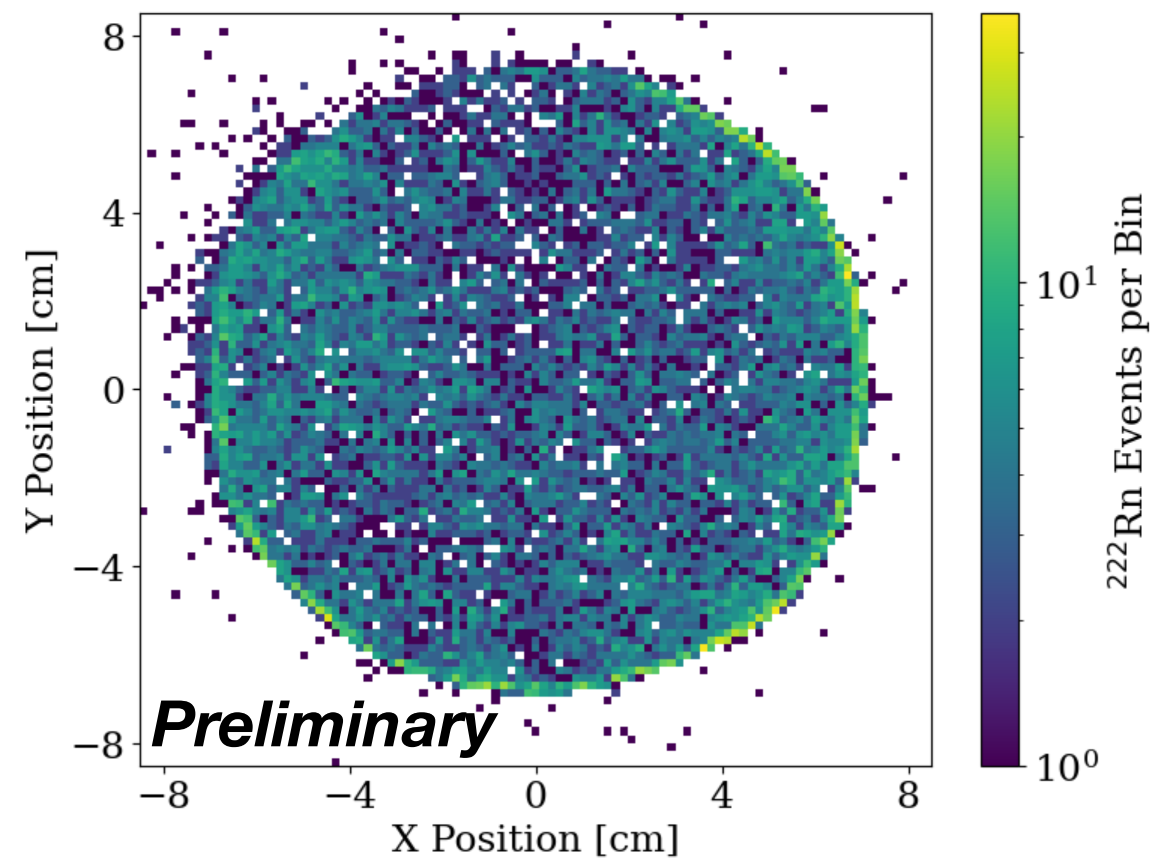
Example event

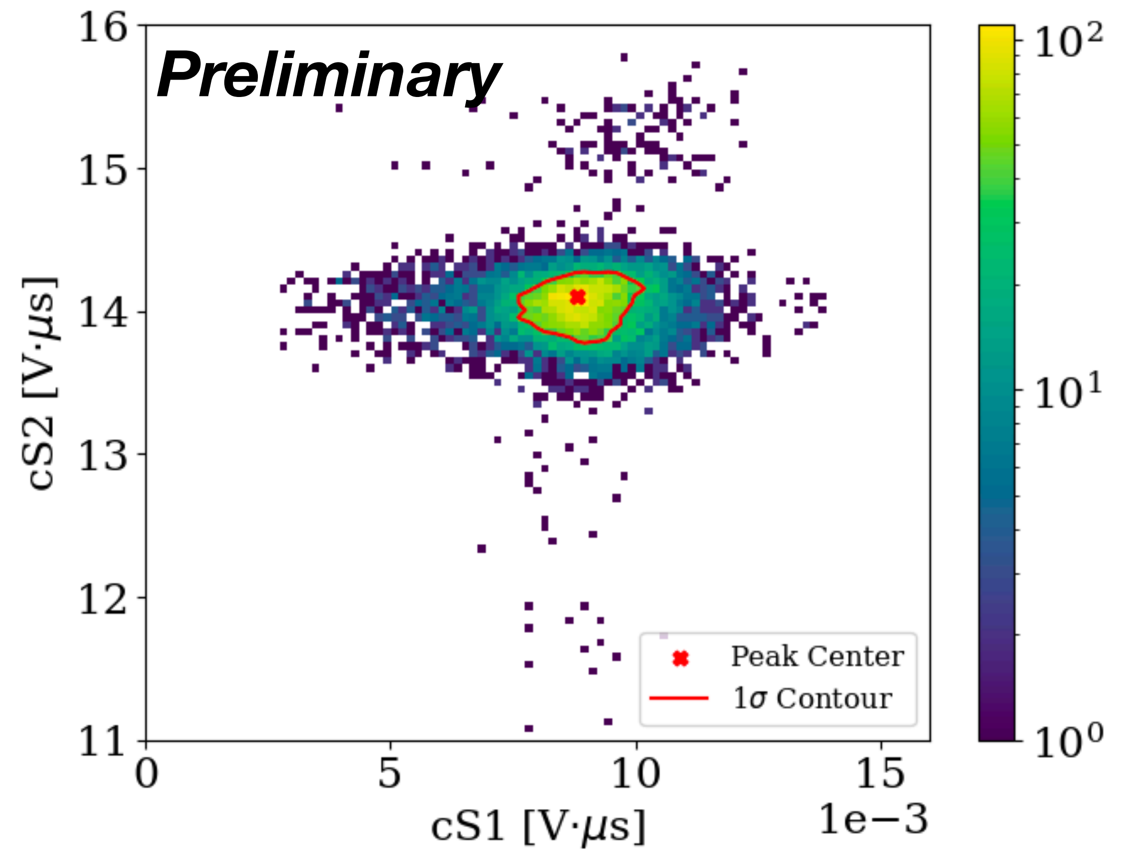




Xenon-only Rn-222 measurements

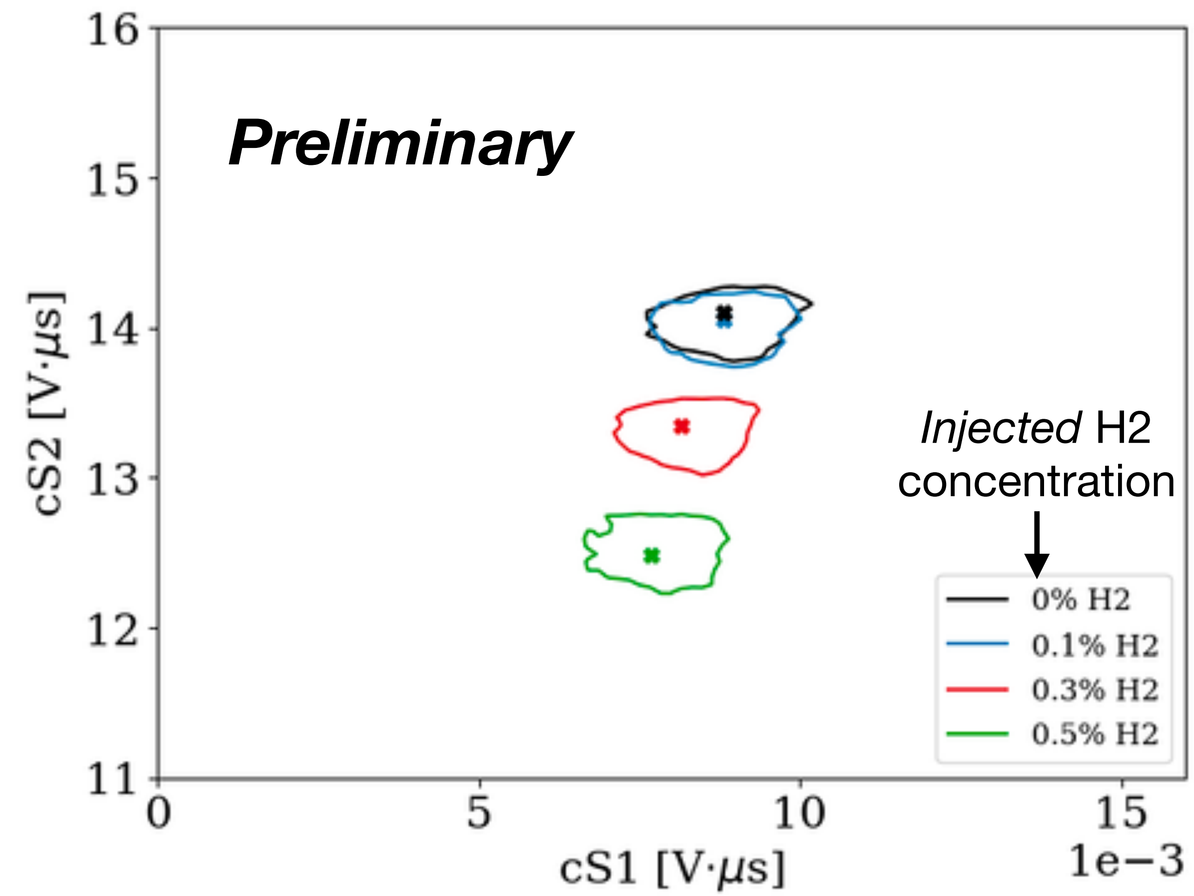
- Analysis - continued
  - Relatively uniform population of Rn S2s using centroid position reconstruction (despite 2 disabled PMTS)
  - We then apply a rough fiducial volume cut (~6 cm radius and drift time cut), as well as S1 and S2 position corrections
  - S1 vs drift time corrections
  - S2(x,y) corrections
- Resulting peak in S1 vs S2 space is pretty localized!

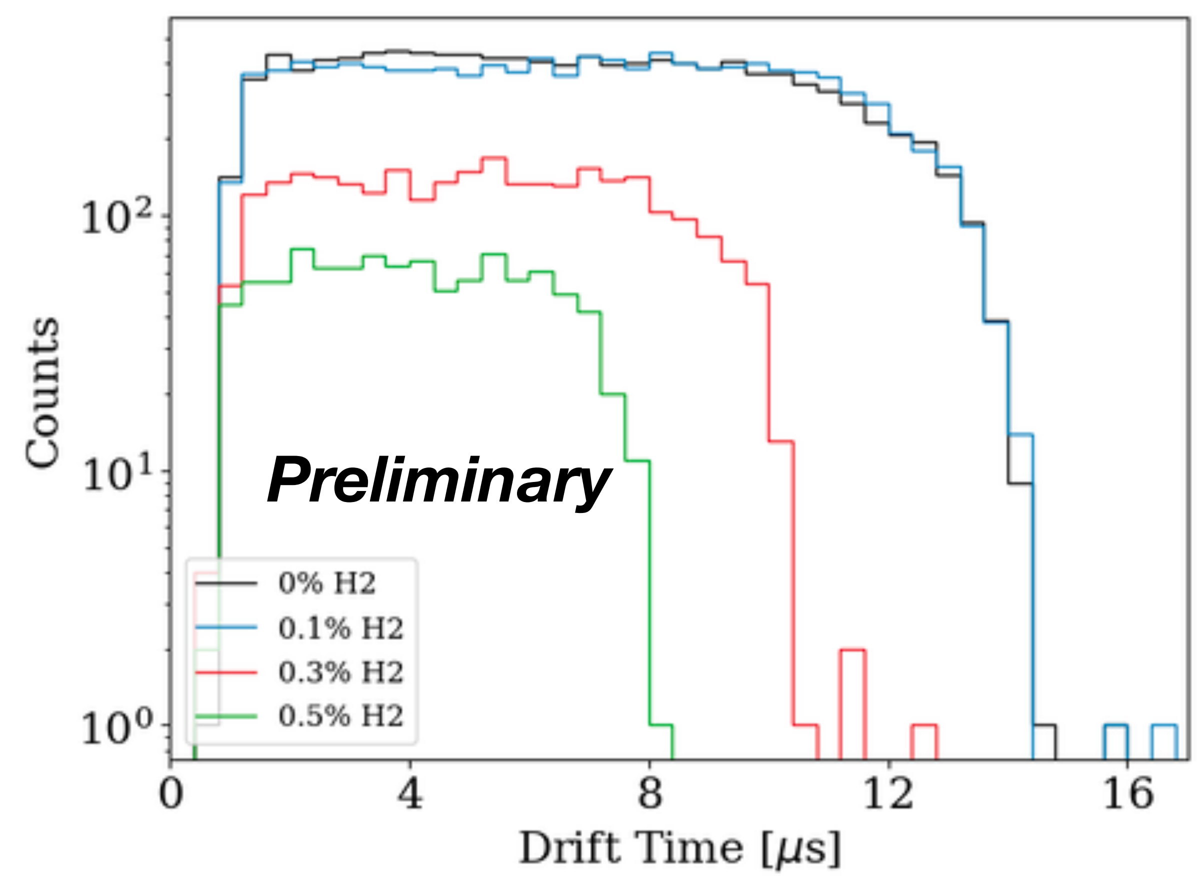




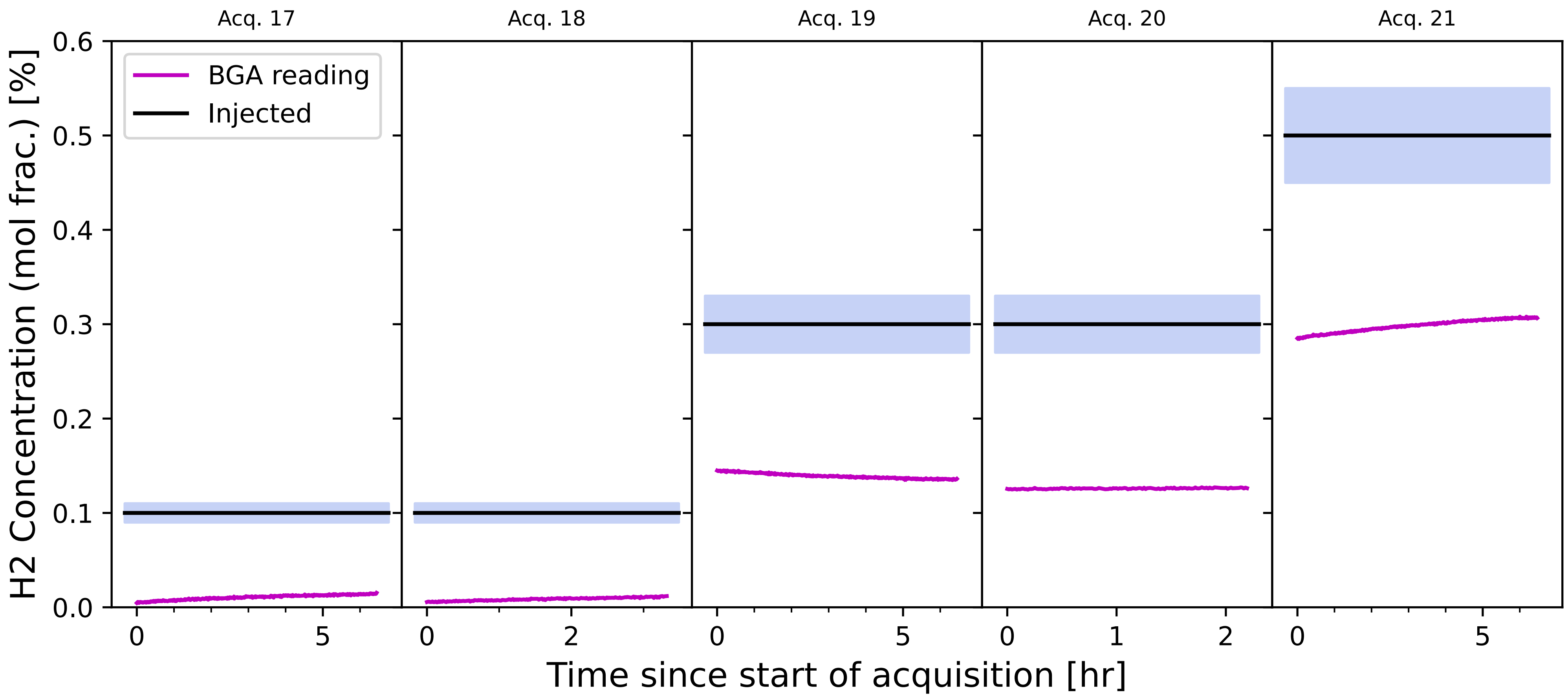
Preliminary observations

- Disclaimer: data was recently collected and requires further investigation & validation
- After the Xe-only run, we injected H2 at three concentrations using a known volume with ~10% uncertainty: **0.1%, 0.3%, 0.5%** (by mol fraction)
  - *See next slide for a comment on the measured H2 concentration*
- We observe a significant decrease in both S2 size and maximum electron drift time as a function of injected hydrogen concentration





H2 concentration measurements



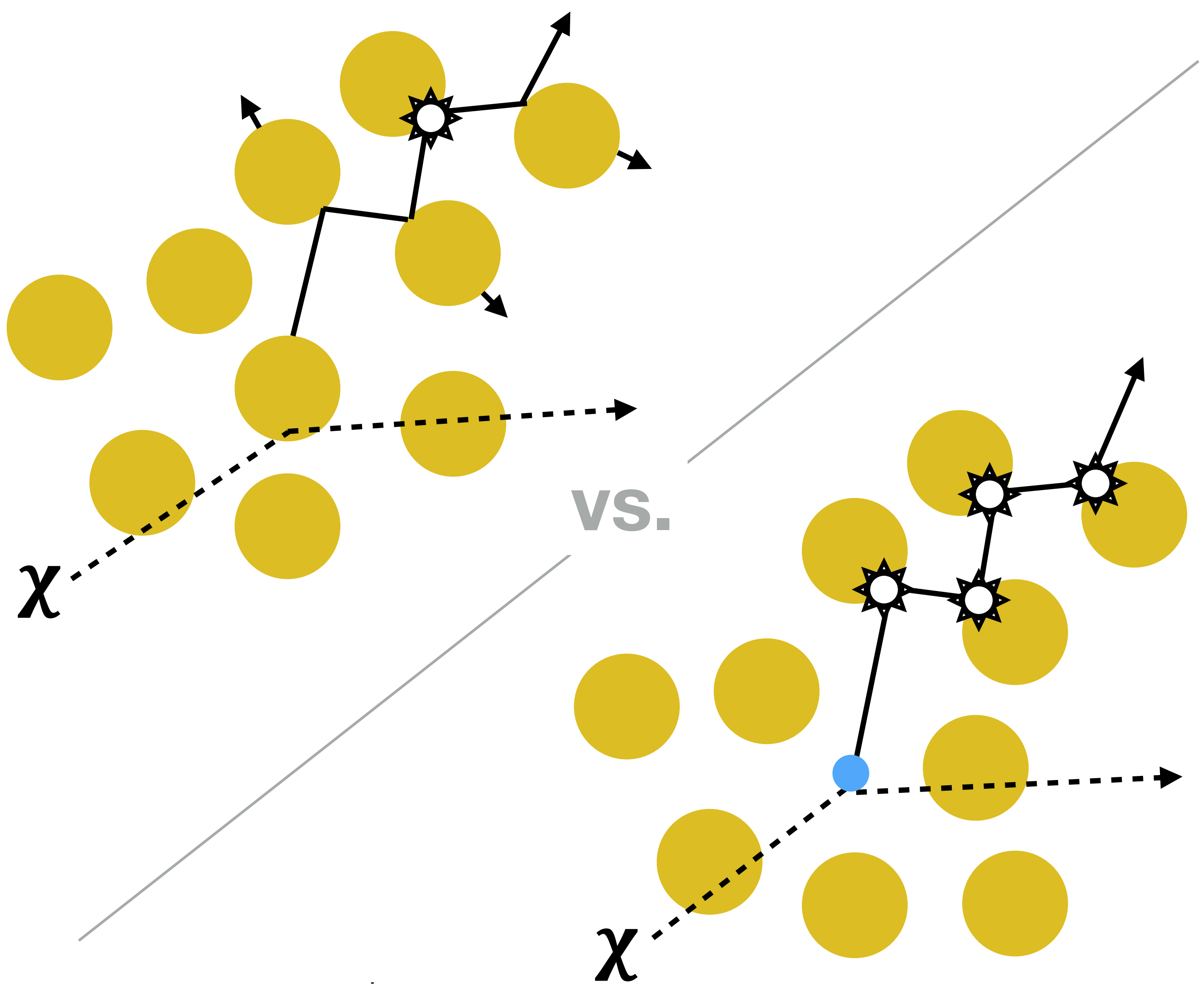
- H2 concentration is measured by a SRS binary gas analyzer built into the circulation gas panel
- We also take two datasets across different days for the 0.1 and 0.3% H2 concentration points to monitor stability (these datasets give consistent S1 vs S2 peaks)
- However, we see a discrepancy between our injected concentration and the concentration measured with the BGA—> *under investigation*

Summary & future plans

- Our system is up and running!
- We observe an effect of injecting hydrogen on the S2 signal and maximum drift time
  - More precise quantification to come
- Continue Rn-222 measurements with increased H2 concentrations
- Repeat measurements with other sources: e.g. Kr-83m (41 keV) and Co-57 source (122 keV)
- Measure effect of H2 on the single electron S2 signal

Backup

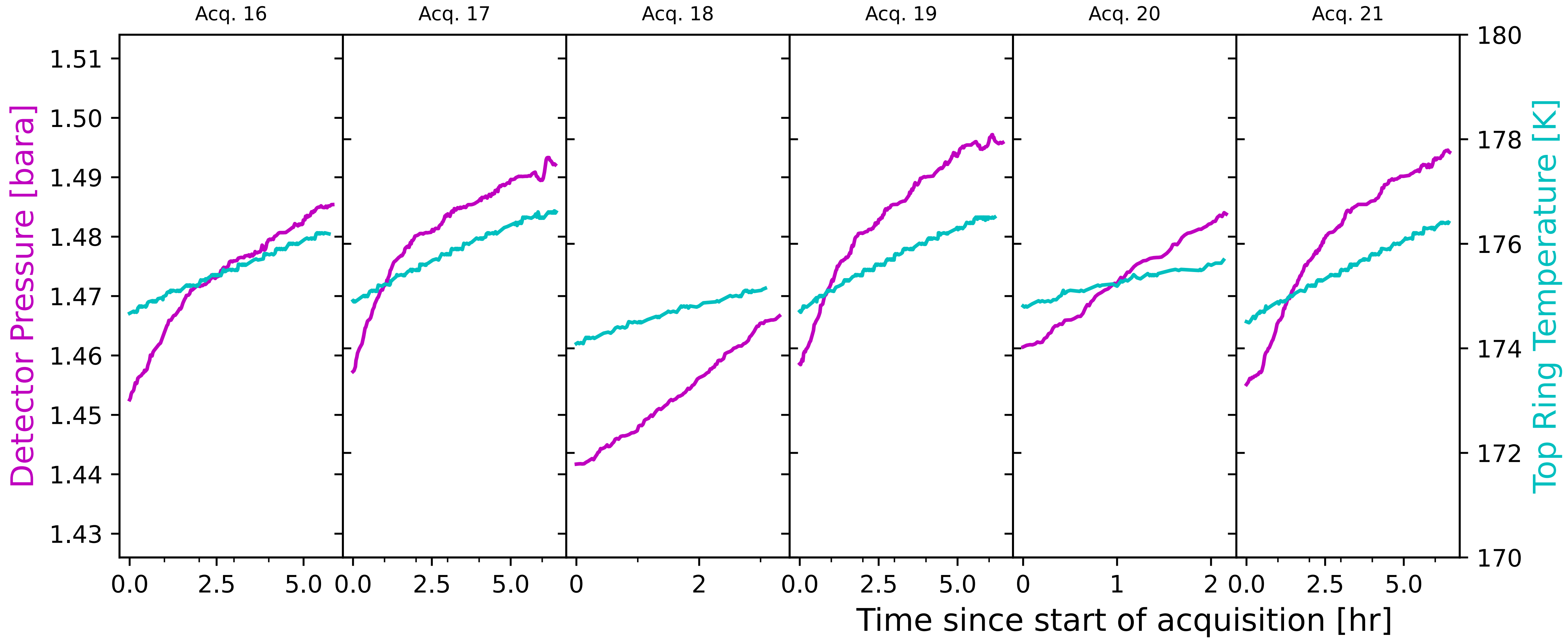
HydroX principles



- Hydrogen atom serves as the target
- Bonus! Xe-Xe collisions lose energy to heat through the Lindhard effect (~0.2), H-Xe collisions should have a Lindhard factor of ~ 1

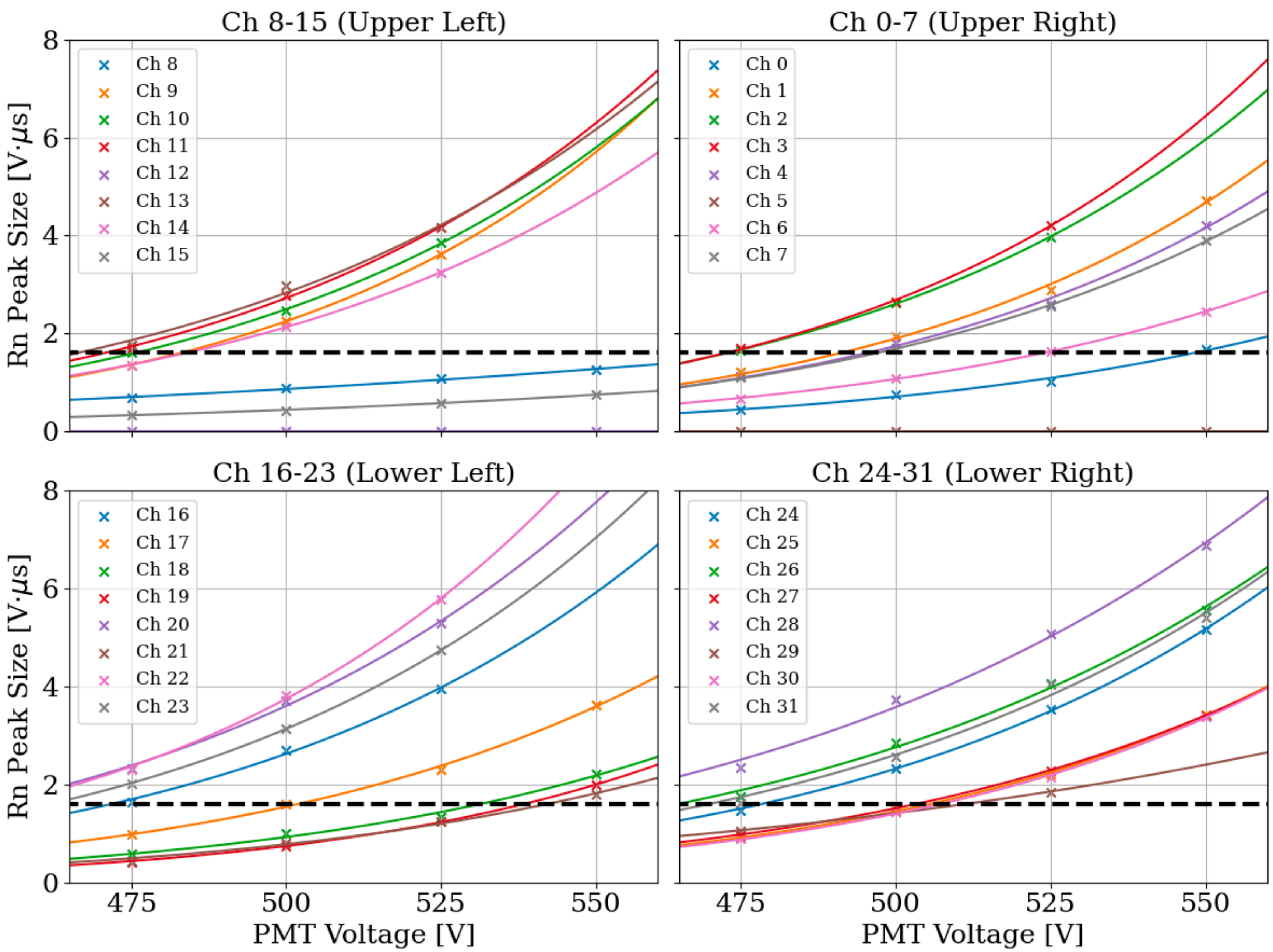
Cartoon from A. Fan's CPAD talk

Detector Stability



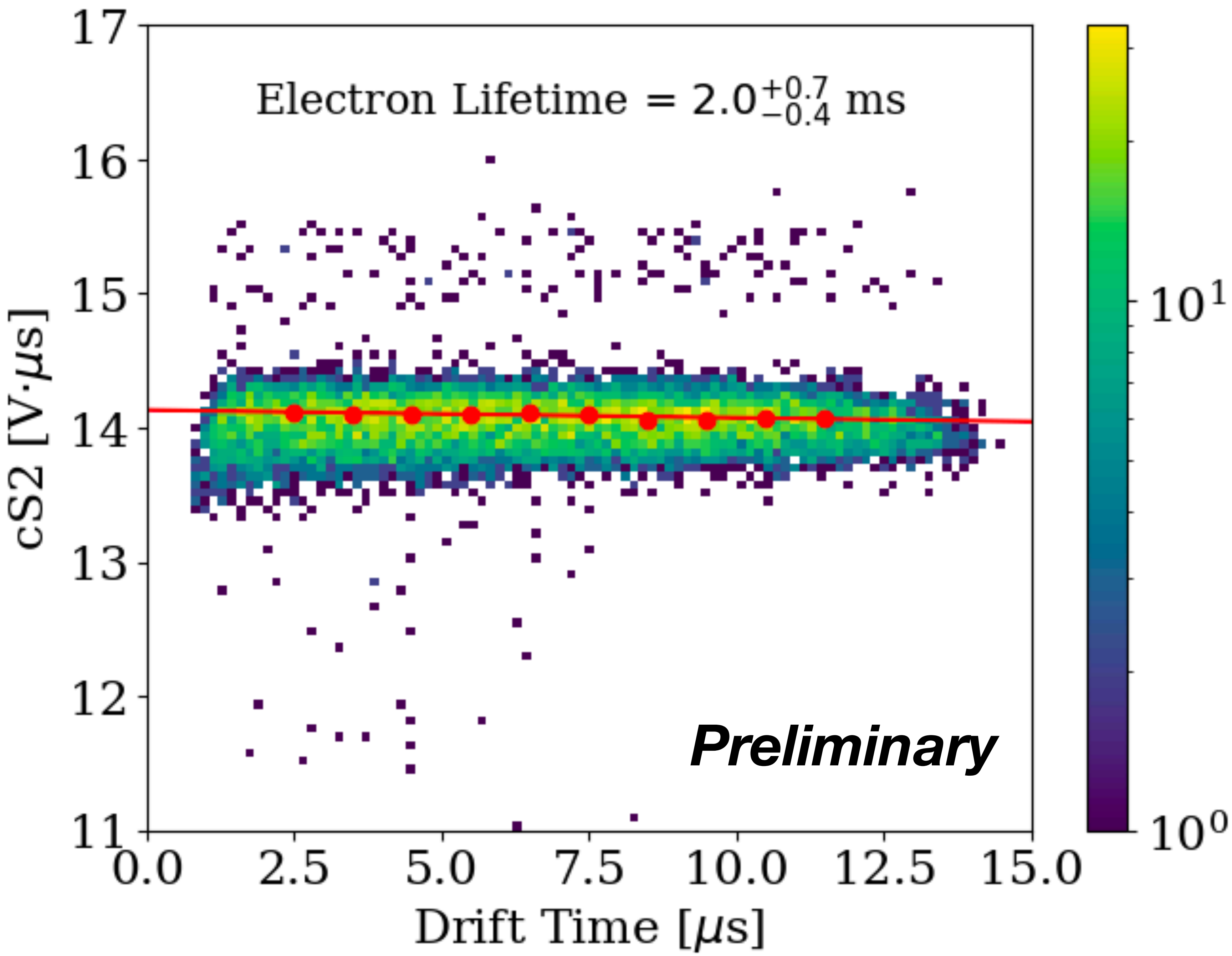
- Detector pressure and temperature sensors are consistent across different acquisitions within ~few percent
- Note here the top ring temperature should be significantly colder than the temperature of the gas (RTD is placed on SS support ring for the TPC)
- From the pressure measurement estimate the detector is ~220 K

PMT HV vs Rn Peak Size

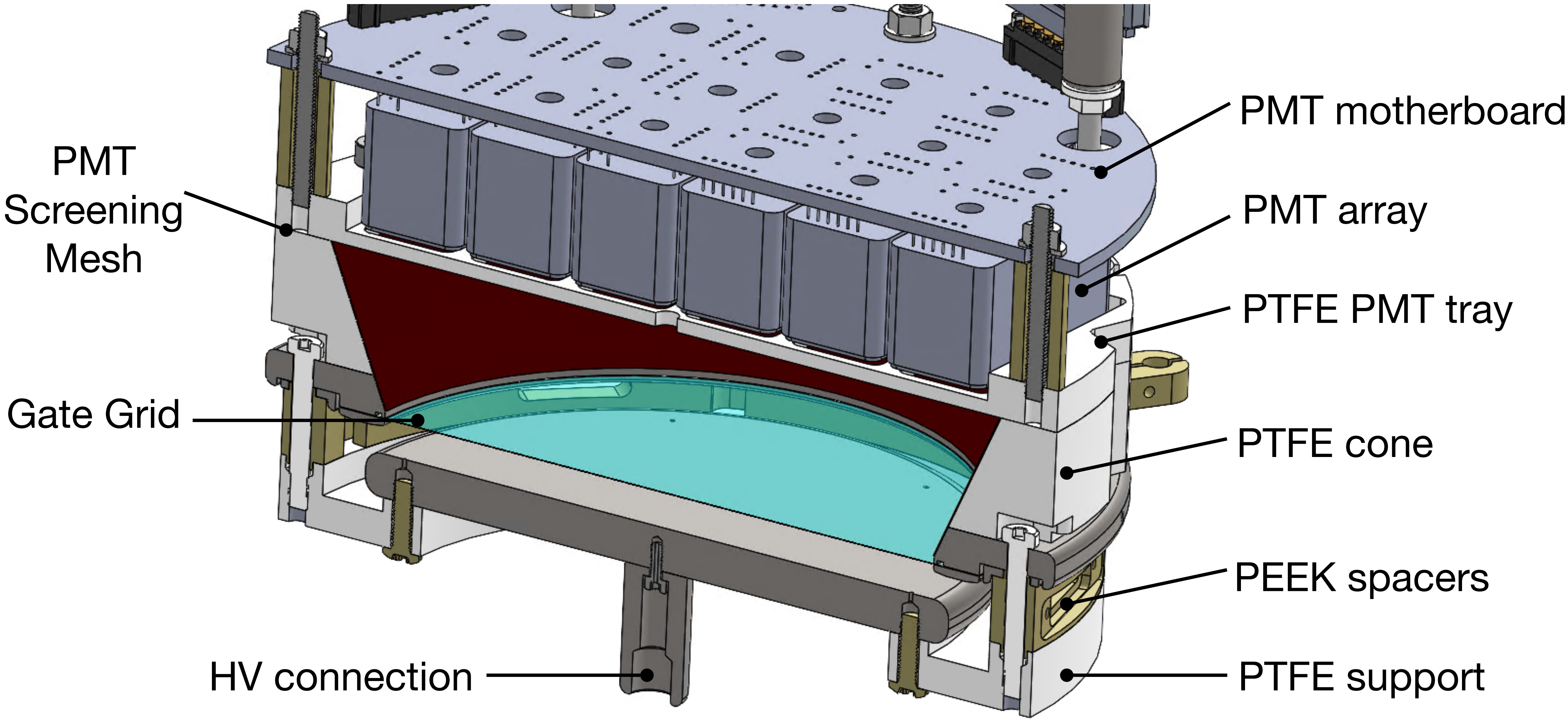


- Scanned PMT HVs to equalize Rn peak across PMTs

Electron lifetime



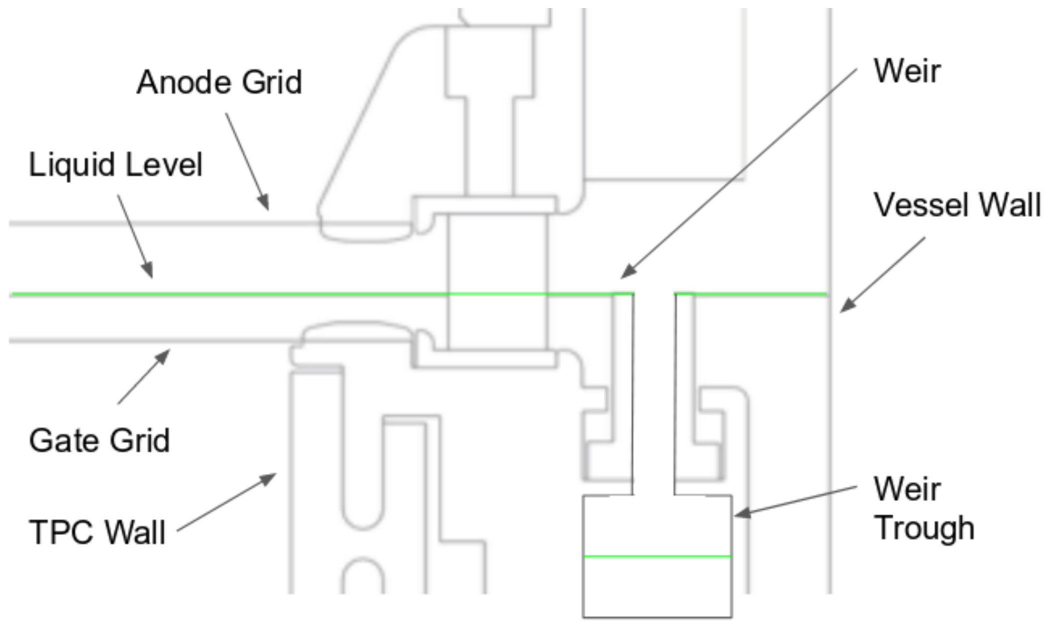
TPC design



- Modified version of LZ System Test TPC

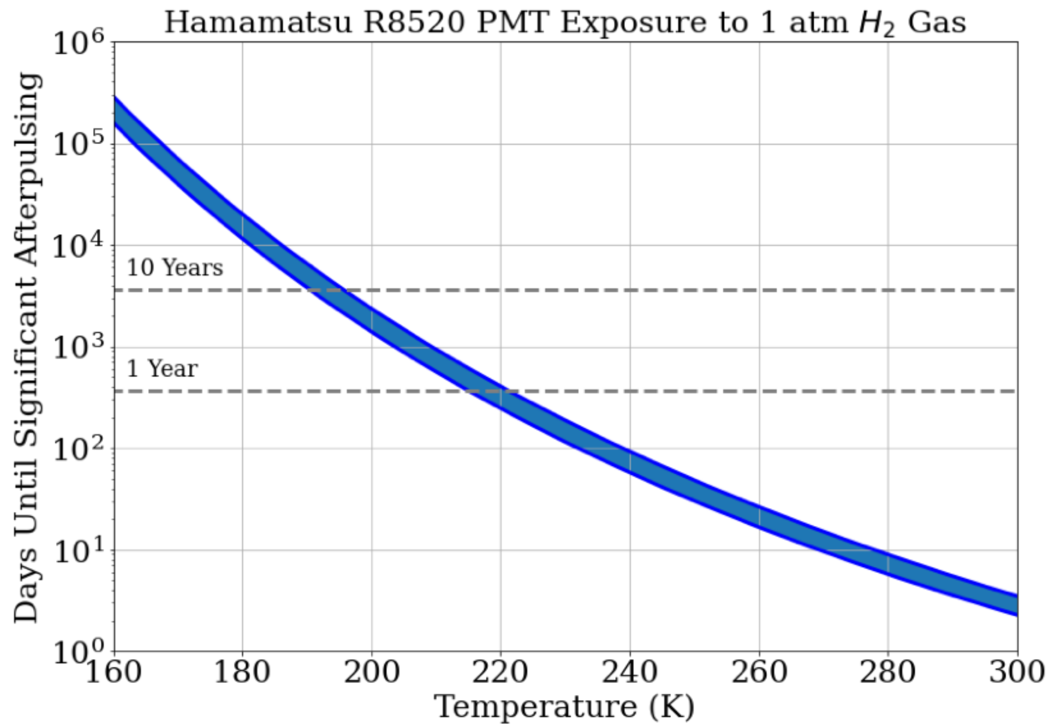
Grid specifications

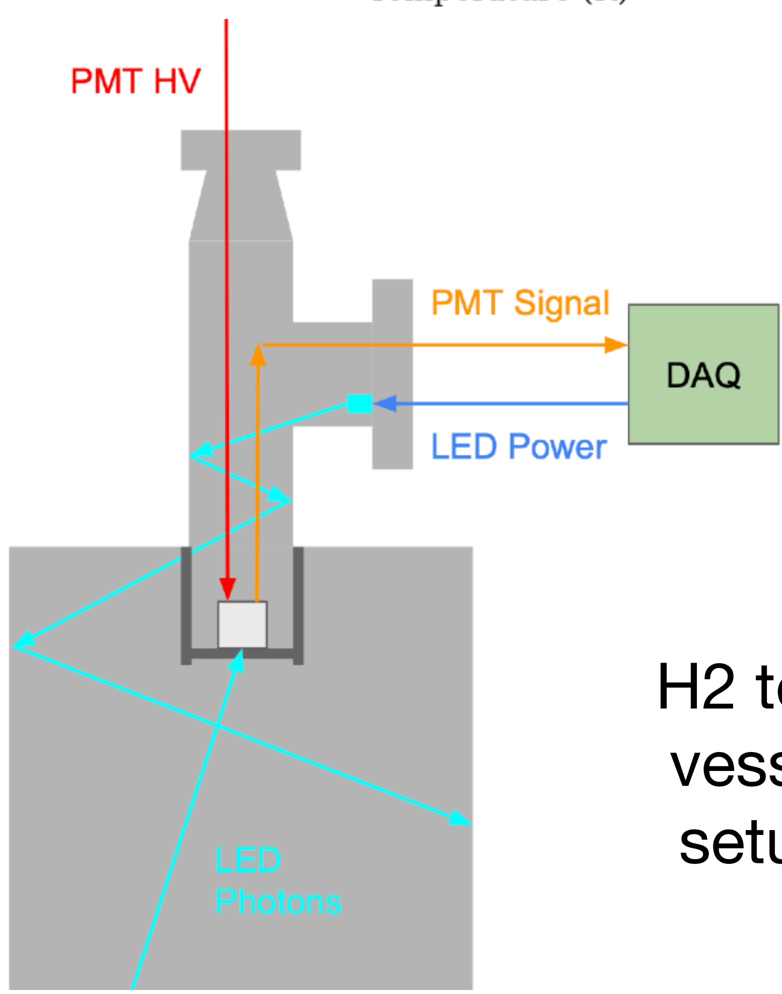
- Woven stainless steel grids of diameter 14.1 cm
- Wire: 2.5, 5 mm pitch, 700, 100 microns diameter
- Glued between SS rings



Credit: TJ Whitis

H2 after-pulsing test





H2 test vessel setup

- Plot shows projected effect of temperature on time to after-pulsing (assume after-pulsing begins at 1e-3 torr)
- Uses projection from high temperature diffusion data through silica
- Experimentally test effect on PMT using LED with a vessel filled with 1 bar of H2 gas
- Meanwhile for PMT safety we cool our detector gas for measurements