

Characterizing signal production in hydrogen-xenon gas mixtures

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On behalf of the HydroX test stand @ SLAC team

Motivation: HydroX

Dissolve hydrogen in an existing liquid xenon time projection chamber (like LZ) to improve sensitivity to **light dark matter**

- LXe TPCs have **~keV energy thresholds**; need enough $\gamma + e^-$ for reliable detection
- Hydrogen is a better **kinematic match** for \sim GeV DM \rightarrow larger recoil energy \rightarrow better detection efficiency!
- Keep desirable properties of LXe detectors: self-shielding, particle discrimination, radiopurity, known backgrounds

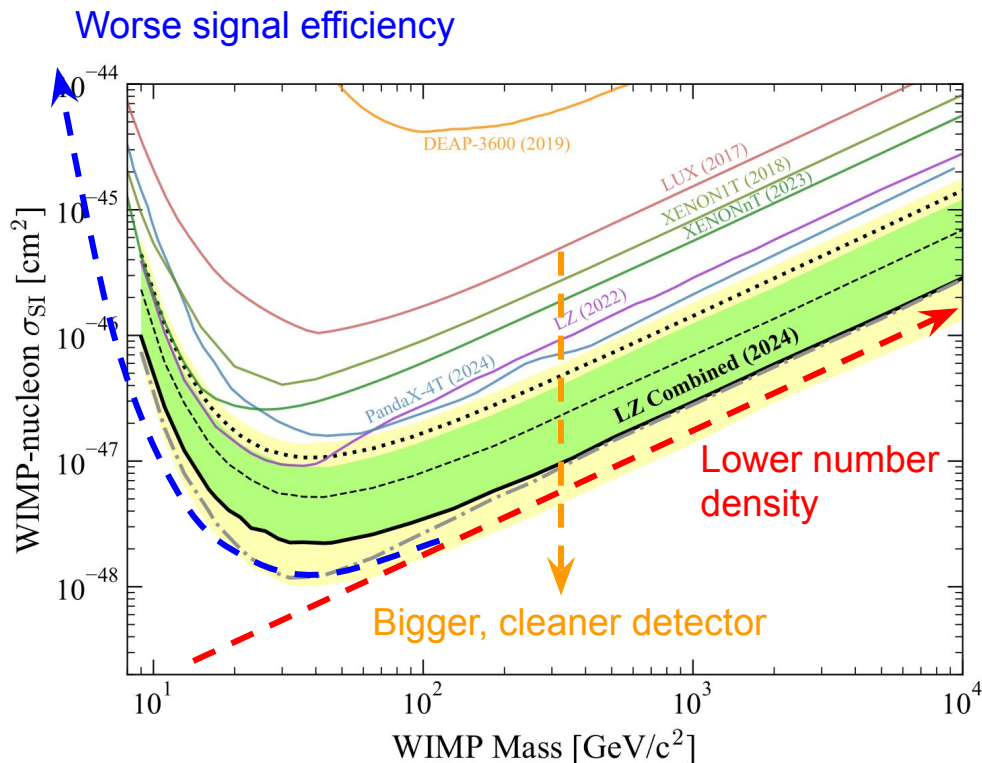
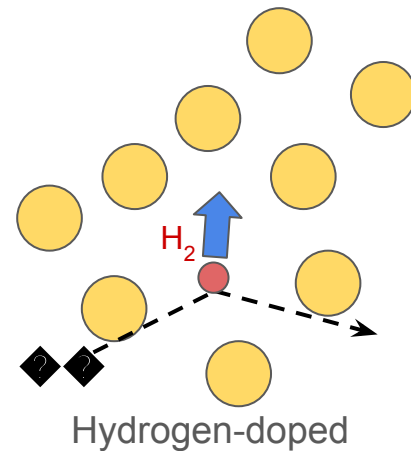
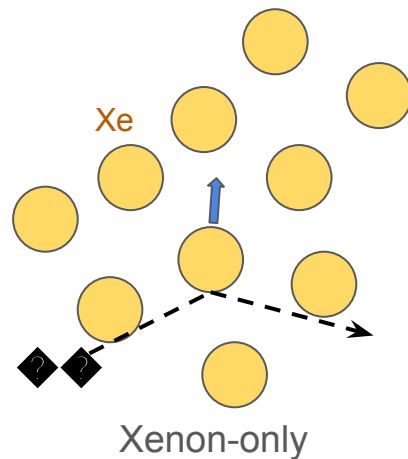
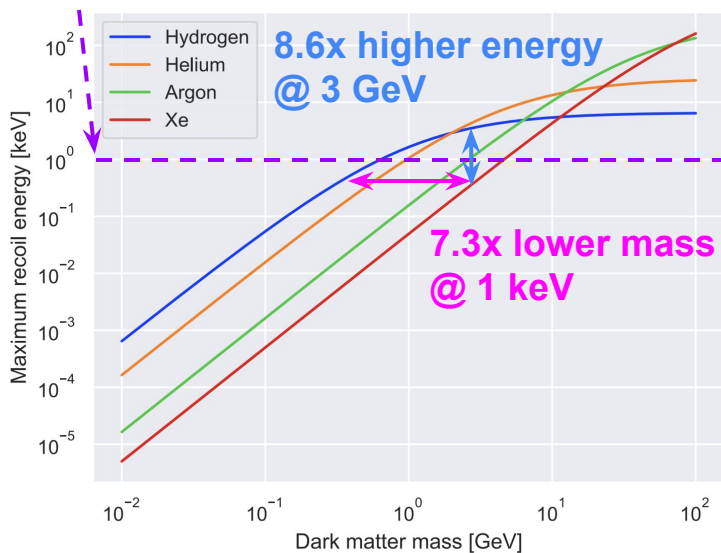


Figure from [Aalbers et. al.](#)

A Balancing Act

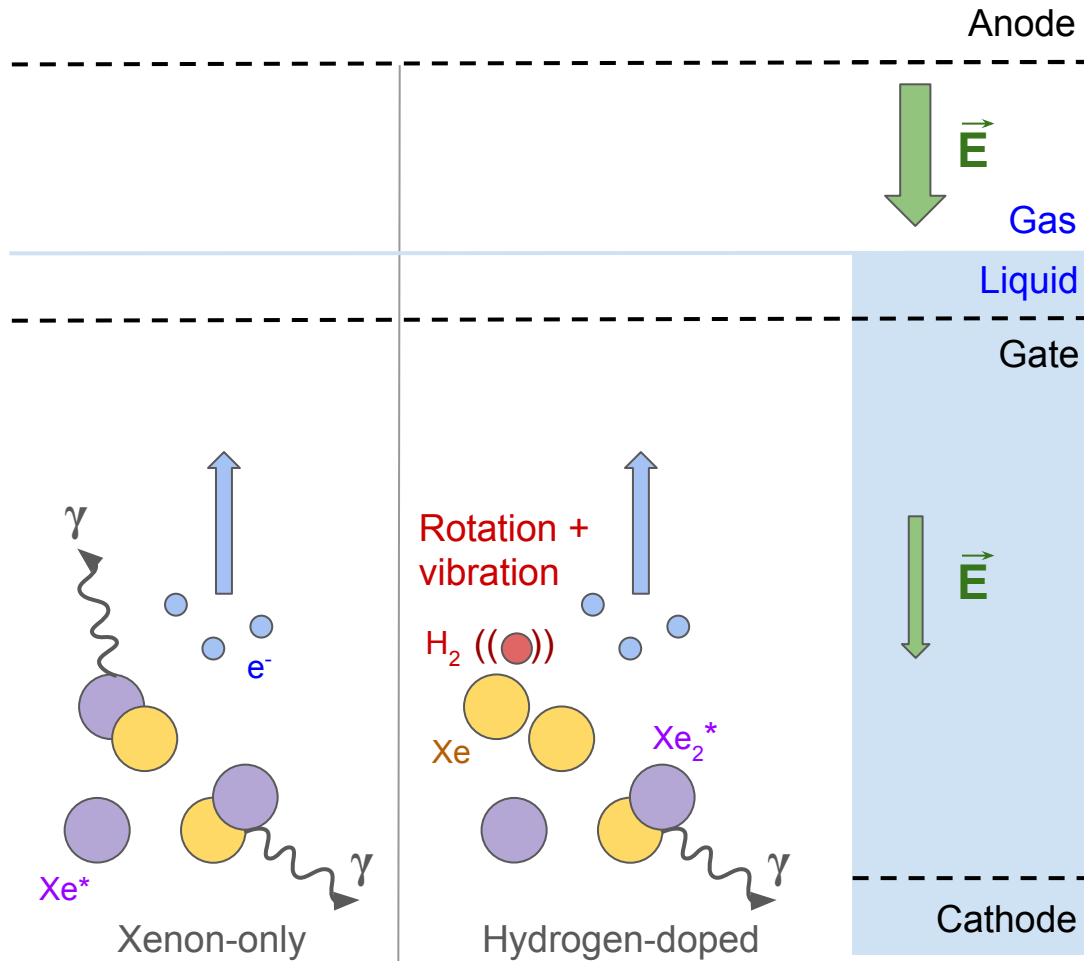
- ~GeV WIMPs produce more energetic recoils on hydrogen than xenon

keV energy threshold



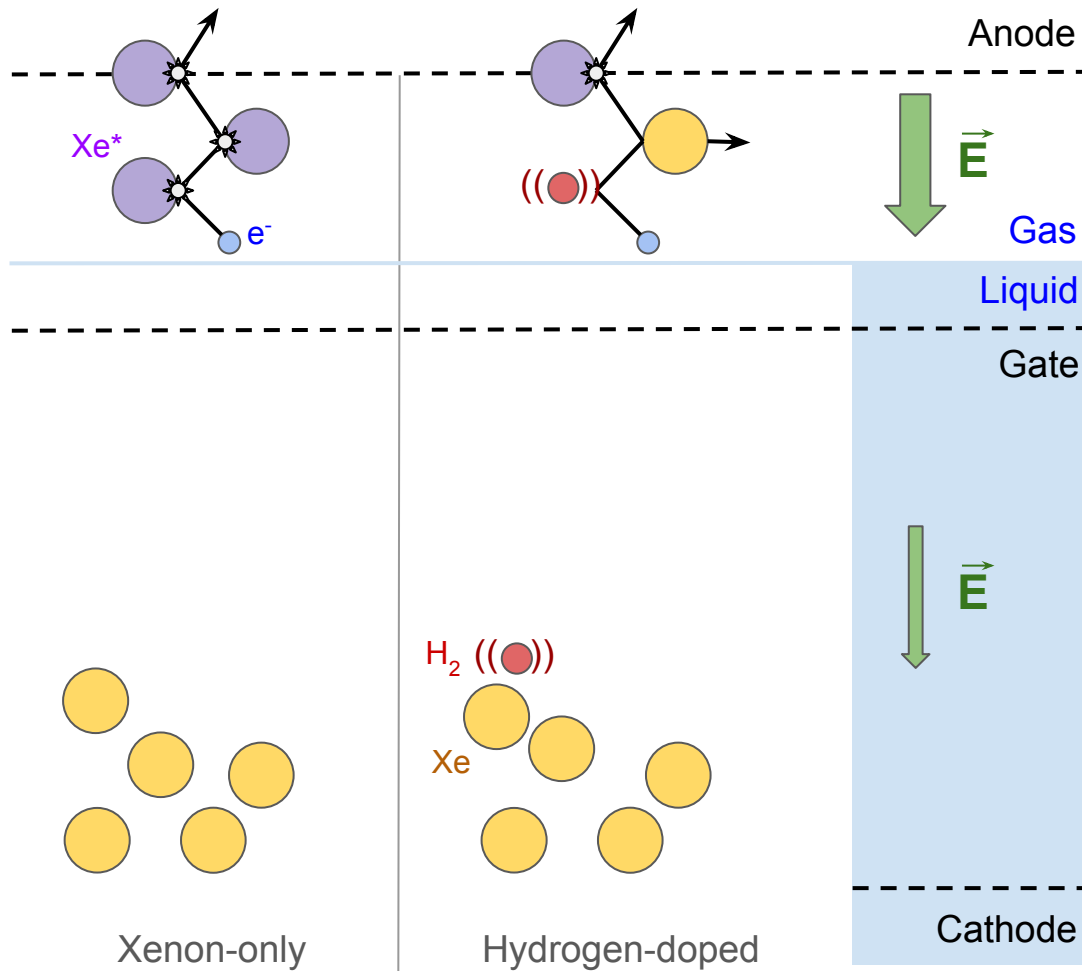
A Balancing Act

- H_2 quenches xenon excimer states (Xe_2^*), reducing primary scintillation signal (**S1**)
- Liberated e^- drift to top of detector, extracted at liquid/gas interface



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- Liberated e^- drift to top of detector, extracted at liquid/gas interface
- In *gas*, e^- accelerated by a ~ 10 kV/cm E-field, producing secondary scintillation signal (**S2**)
- H_2 cools e^- and quenches excimers, reducing S2 signal



The Tally

	+	-
Kinematics		
→	1. Higher energy recoils	1. Xe ₂ * quenching (S1 + S2)
→	2. More Xe ⁺ /Xe* per energy	2. Electron cooling (S2)
Simulation: SRIM (Stopping and Range of Ions in Matter)		

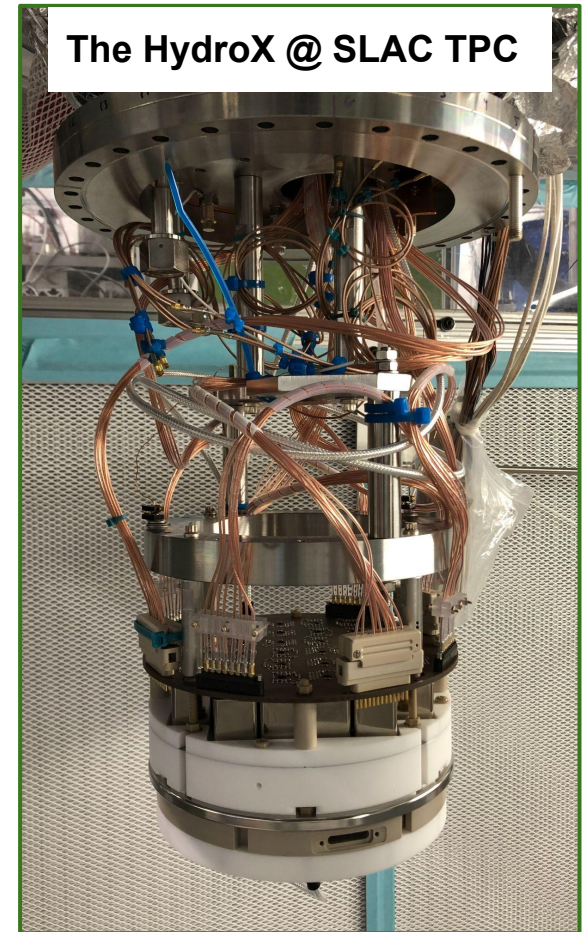
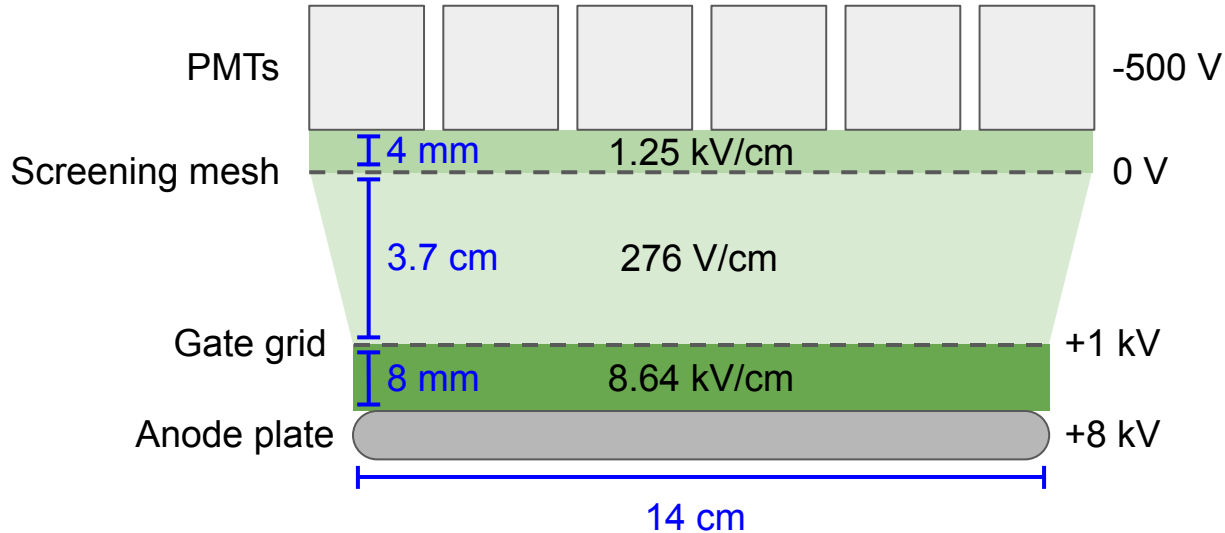
**55% quenching @ 26 bara
with 1.1% H₂ (Tezuka et. al.)**

**Simulation:
(Garfield++)**

Can we dissolve enough hydrogen to improve sensitivity to light DM while maintaining a large enough S1/S2 signal?

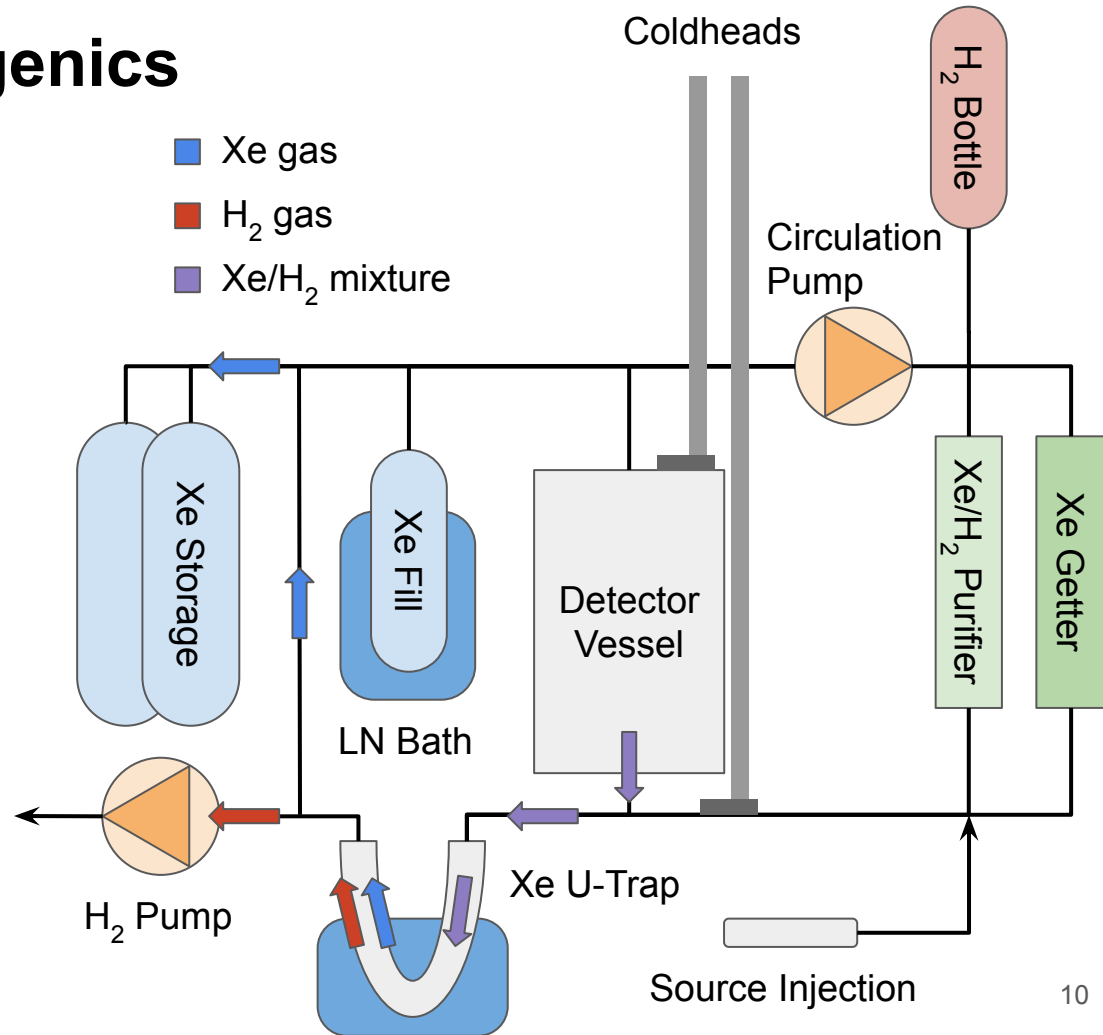
Test Stand @ SLAC

- **TPC:** modified from LZ system test
 - 32-PMT array for accurate XY reconstruction
 - Extraction region designed to replicate LZ
 - LXe capability, gas phase for now
- **DAQ:** custom reconstruction based on [strax](#) analysis framework



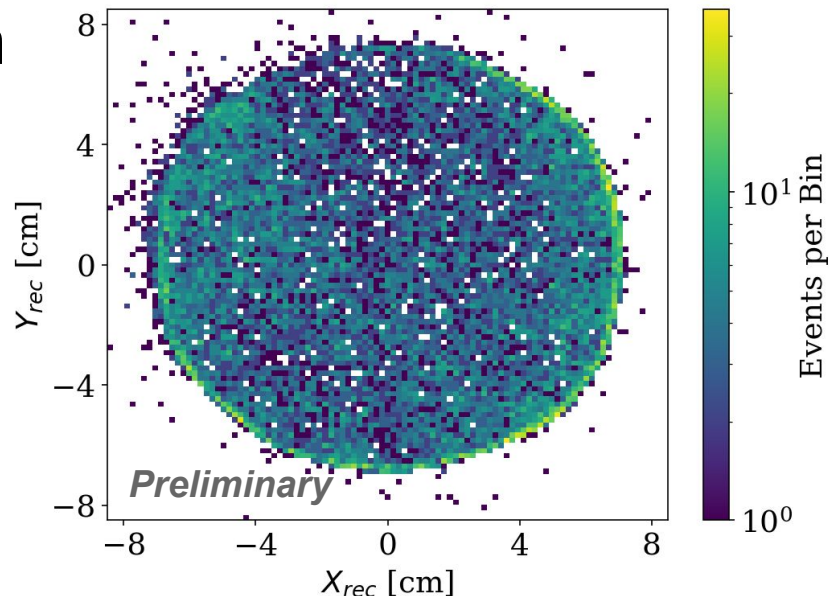
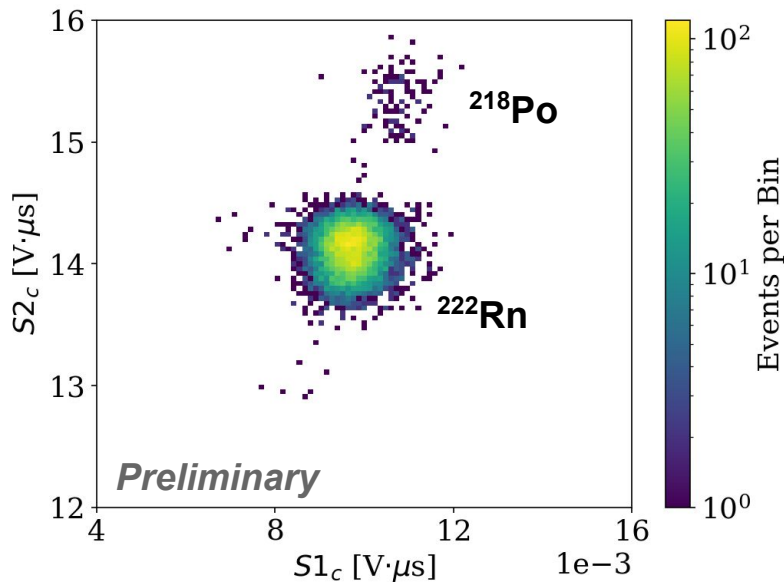
Gas Handling & Cryogenics

- Detector vessel and incoming gas cooled to 190 K to prevent H₂ permeation through PMT windows
- Circulation to maintain Xe/H₂ mixing
- Xe/H₂ mixture cleaned with Entegris ambient-temperature purifier
- LN-cooled U-trap freezes xenon, H₂ evacuated outdoors



Detector Calibration with ^{222}Rn

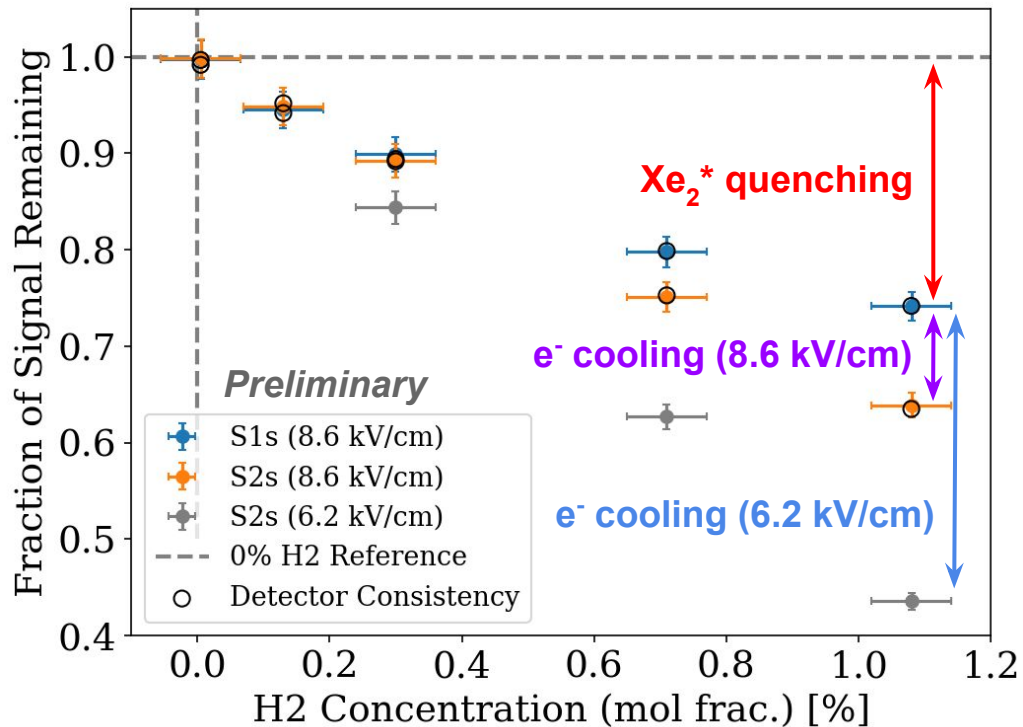
- Isotropic ^{222}Rn source \rightarrow **5.6 MeV alpha decays**
- DAQ trigger tuned for ^{222}Rn S1 signals
- **Great XY reconstruction using center-of-mass algorithm!**



- Fiducial cut applied to ensure alpha tracks fully contained in TPC
- After corrections, ^{222}Rn and ^{218}Po (6.1 MeV) decays well-localized in S1/S2 space!

Preliminary Results

- **S2(S1) signals are reduced by 36%(26%)* at 1.1% mol fraction H₂**
- Fraction of S2 remaining decreases more rapidly at reduced extraction field
- May retain larger S2 signal by increasing extraction field - predicted by Garfield++ electroluminescence simulation



*May be affected by gas contamination (next slide)

Electron Drift Velocity...

- H_2 expected to increase e^- drift velocity and decrease longitudinal diffusion
- Observe **$\sim 2x$ faster drift velocity** in “pure” Xe than literature \rightarrow hypothesize **nitrogen contamination** from improper purifier conditioning
- Effect of contamination on S1/S2 signal is uncertain

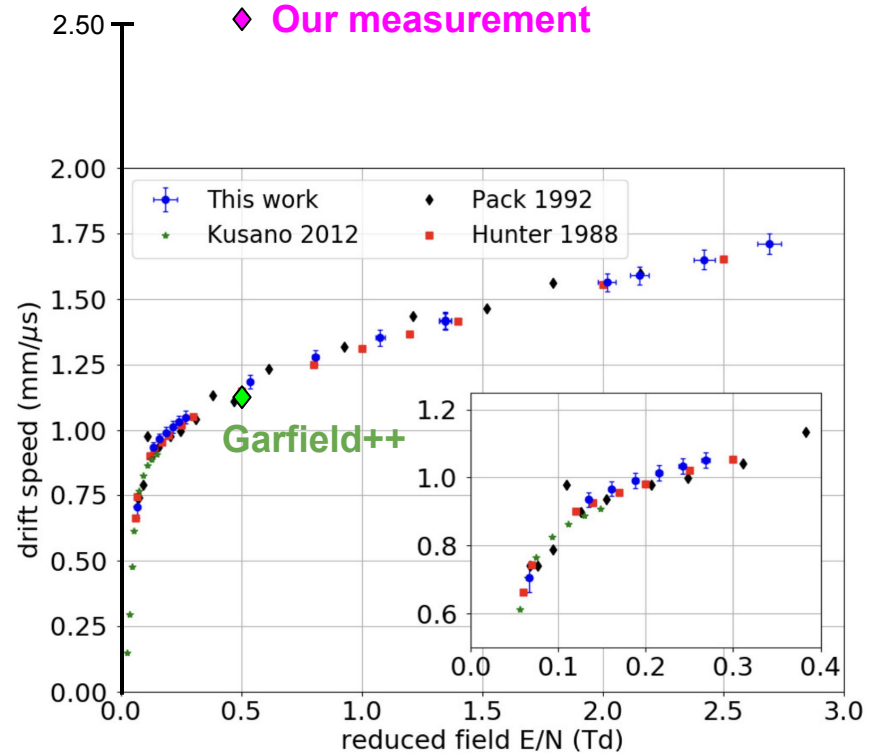


Figure from [Njoya et. al.](#)

Ongoing Work & Future Plans

Initial measurement indicates significant S2 reduction at 1.1% mol fraction H₂

- Effects of Xe₂* quenching and e⁻ cooling are comparable
- Run cut short due to discovery of contamination in Xe/H₂ mixture
- Clean xenon, then continue H₂ injections until <10% of S2 signal remains - expect ~5% mol fraction H₂
- Compare e⁻ cooling results with Garfield++ simulation

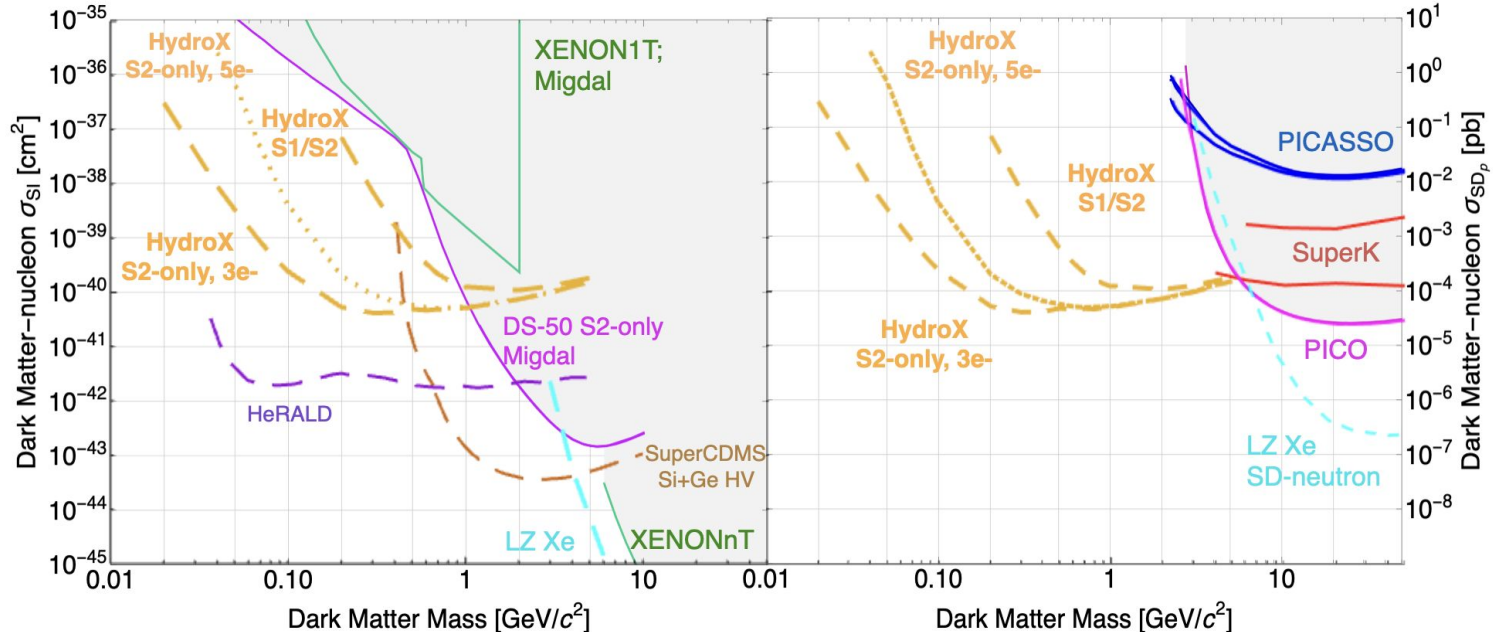
Are there other dopant gases that might provide a better balance of 1) signal amplification and 2) solubility in LXe?

- Solubility (Henry's coefficient) of H₂ in LXe is unknown

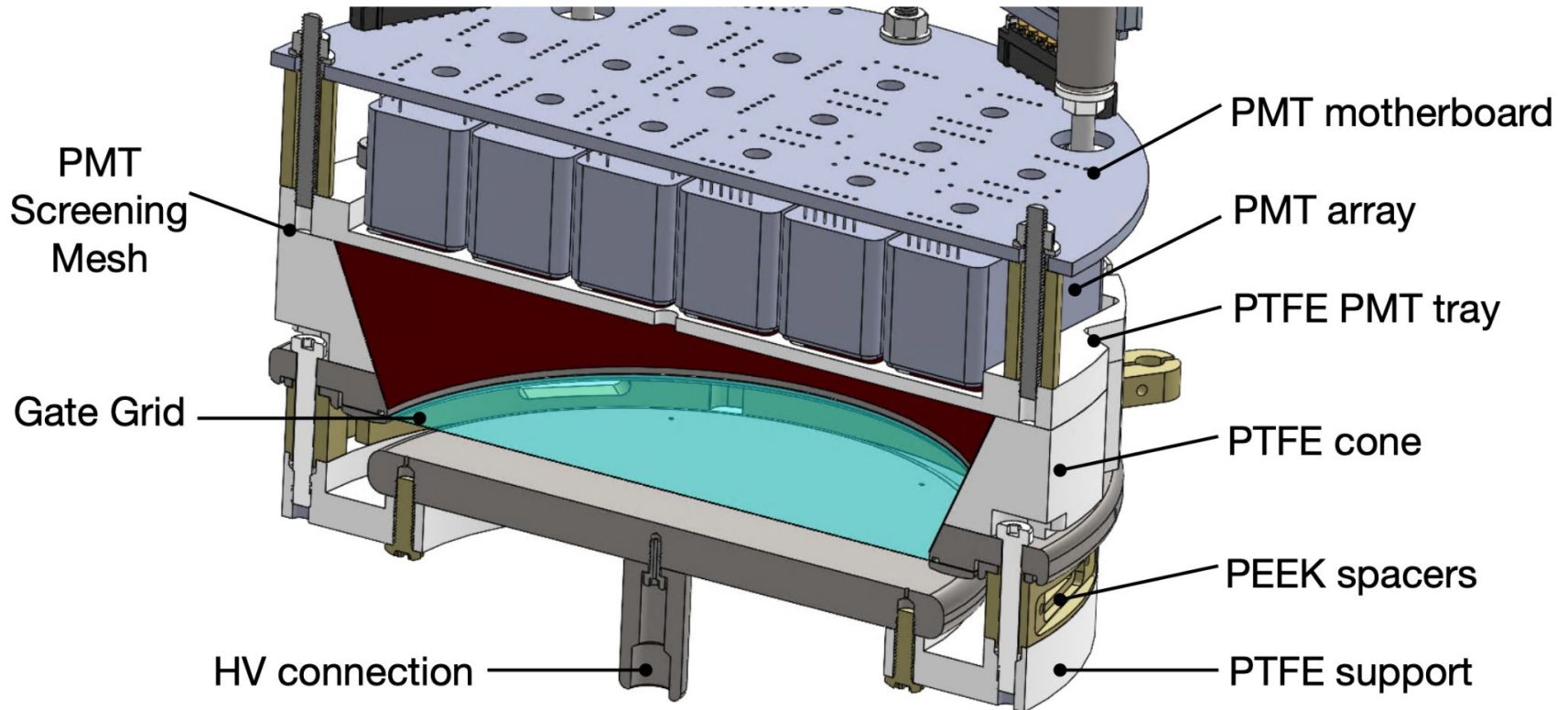
Backup

Projected Sensitivity

- Projected HydroX limits using the LZ detector
- **Assumptions:** 1) 500 day exposure @ 1.1% H₂ mol fraction, 2) S1/S2 partitioning is similar to electronic recoils, 3) 50% of S1 signal is lost to Xe₂* quenching, and 4) S2 yield of 240 photons per e⁻

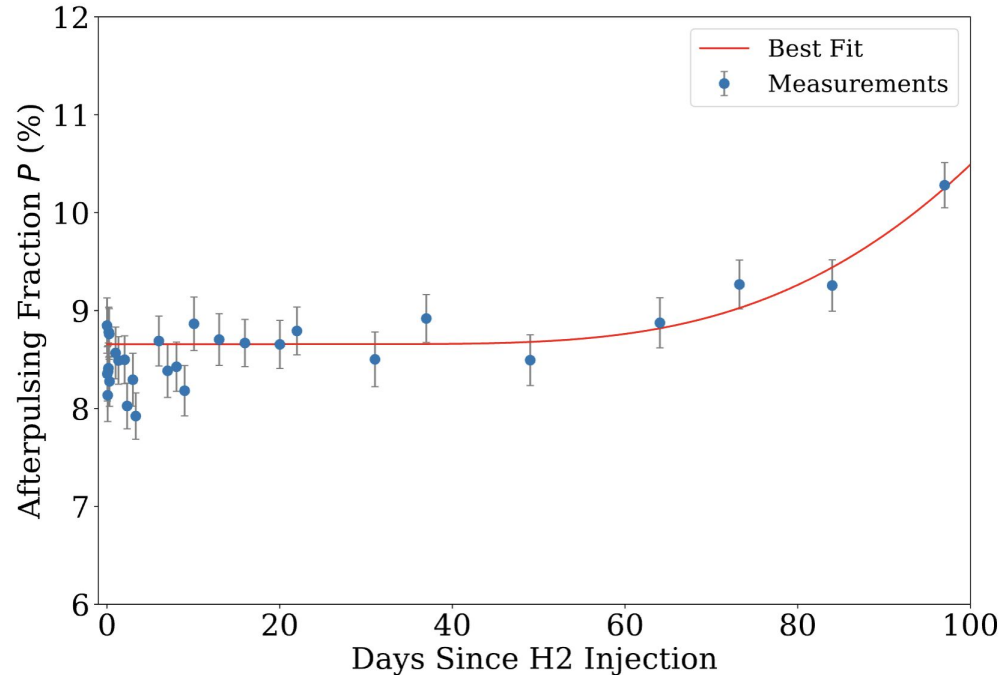


TPC Details



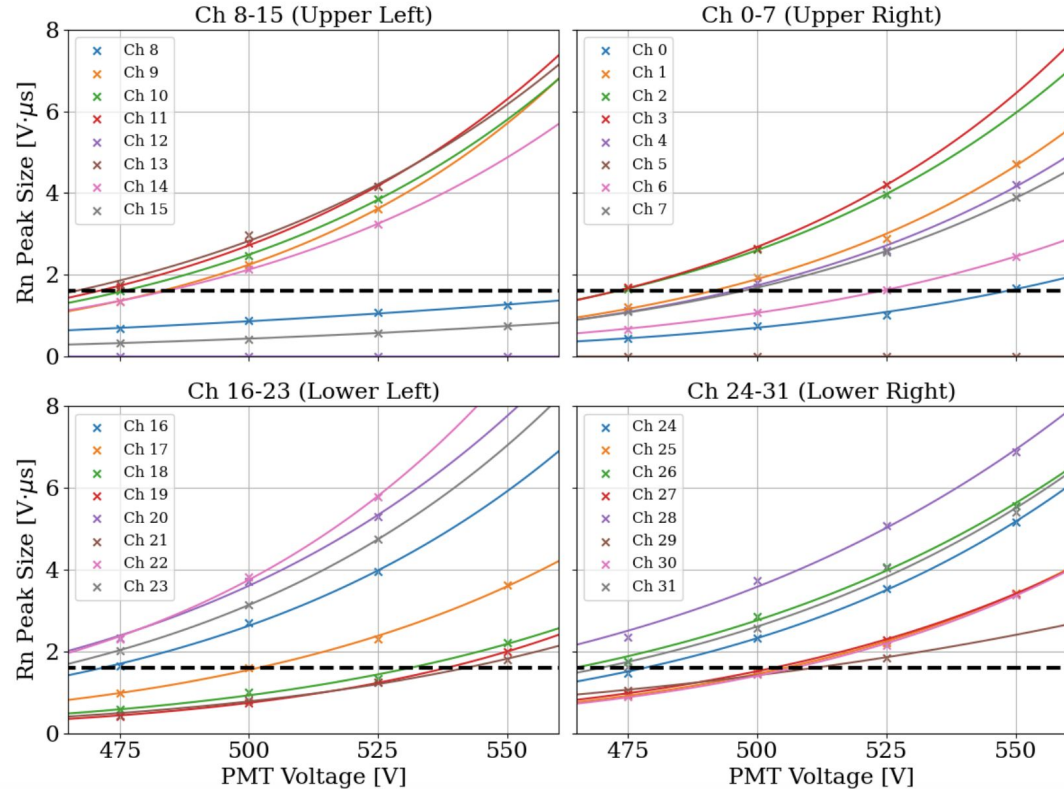
Hydrogen Permeation

- Performed experimental verification of H₂ permeation rate through silica glass
- Hamamatsu R8520-406 1-inch PMT exhibited a significant increase in afterpulsing after ~100 days exposure to 1 atm H₂ @ 293 K
- As a result, detector and incoming gas cooled to 190 K to ensure longevity of 32-PMT array



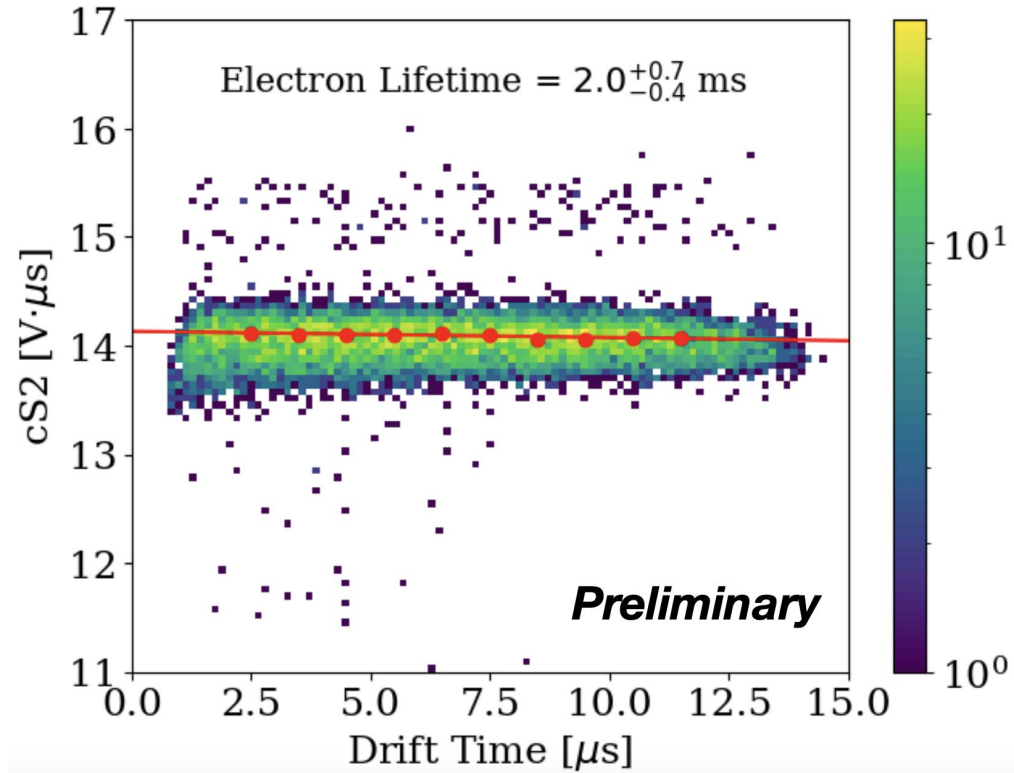
PMT Calibration

- Measured biggest ^{222}Rn S2 areas in each PMT between 475 and 550 V
- Fit function $G = A^{10}V^k$ with A, V fit parameters
- Set PMT voltages to equalize maximum ^{222}Rn response at $1.6 \text{ V} \cdot \mu\text{s}$



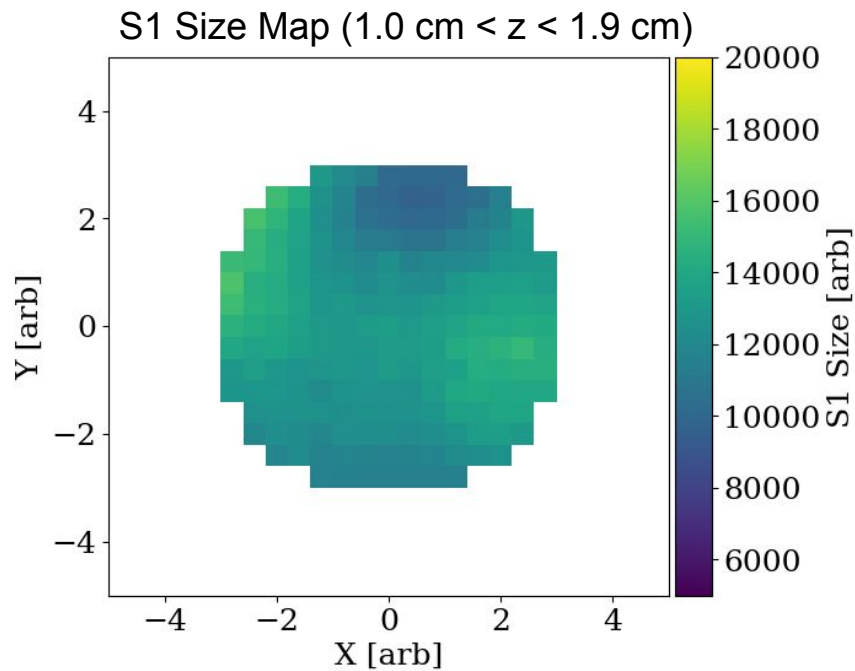
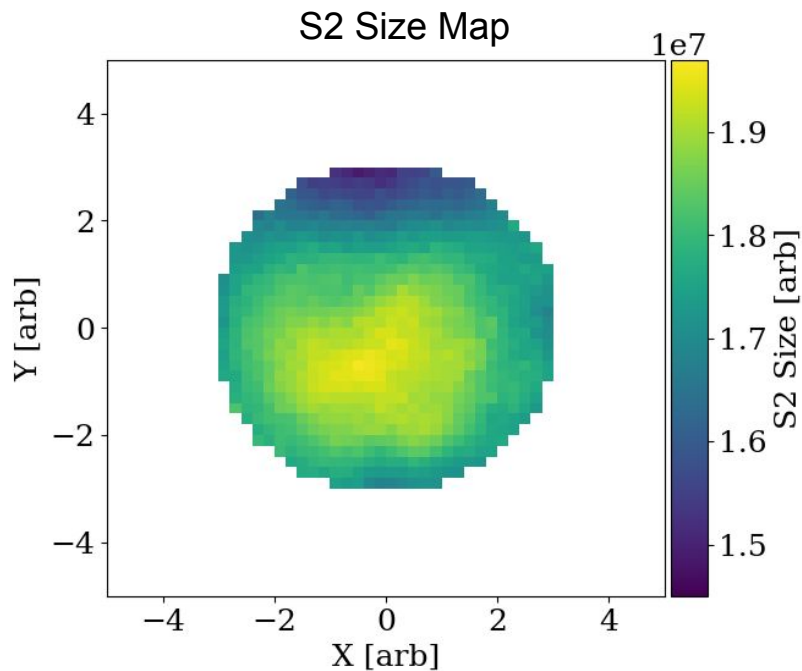
Electron Lifetime

- e^- lifetime many times longer than maximum drift time of TPC
- S2 correction based on drift time was negligible and thus not implemented



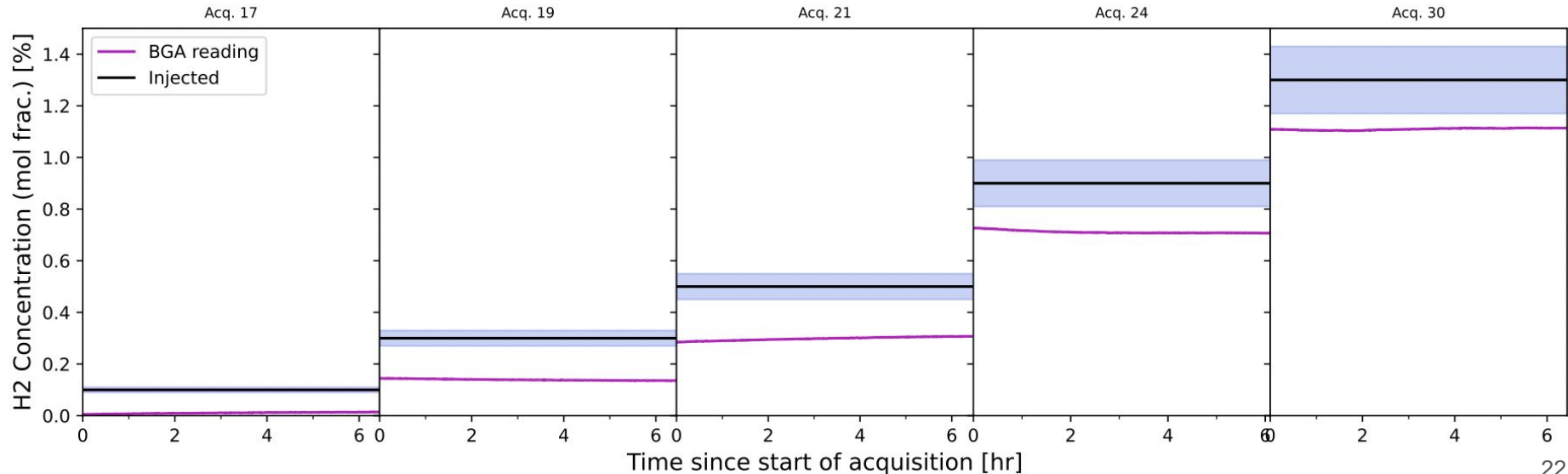
Position Corrections

- S2s corrected by equalizing the average S2 area in each XY pixel (left)
- S1s corrected by equalizing the average S1 area in each XYZ voxel (one z-slice shown right)



Hydrogen Injections

- Series of **five H₂ injections** to target concentrations of 0.1%, 0.3%, 0.5%, 0.9%, 1.3% (mol fraction)
- Two independent measurements of H₂ concentration:
 - Volume + pressure of injection line, also estimate total volume of system to 10% accuracy
 - SRS binary gas analyzer (BGA) reading during circulation
- Observe **disparity between volume + BGA measurements** → use BGA



^{222}Rn Contours in S1/S2 Space

