HydroX: Signal production in an ethane-doped liquid xenon time projection chamber for light dark matter detection

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CPAD

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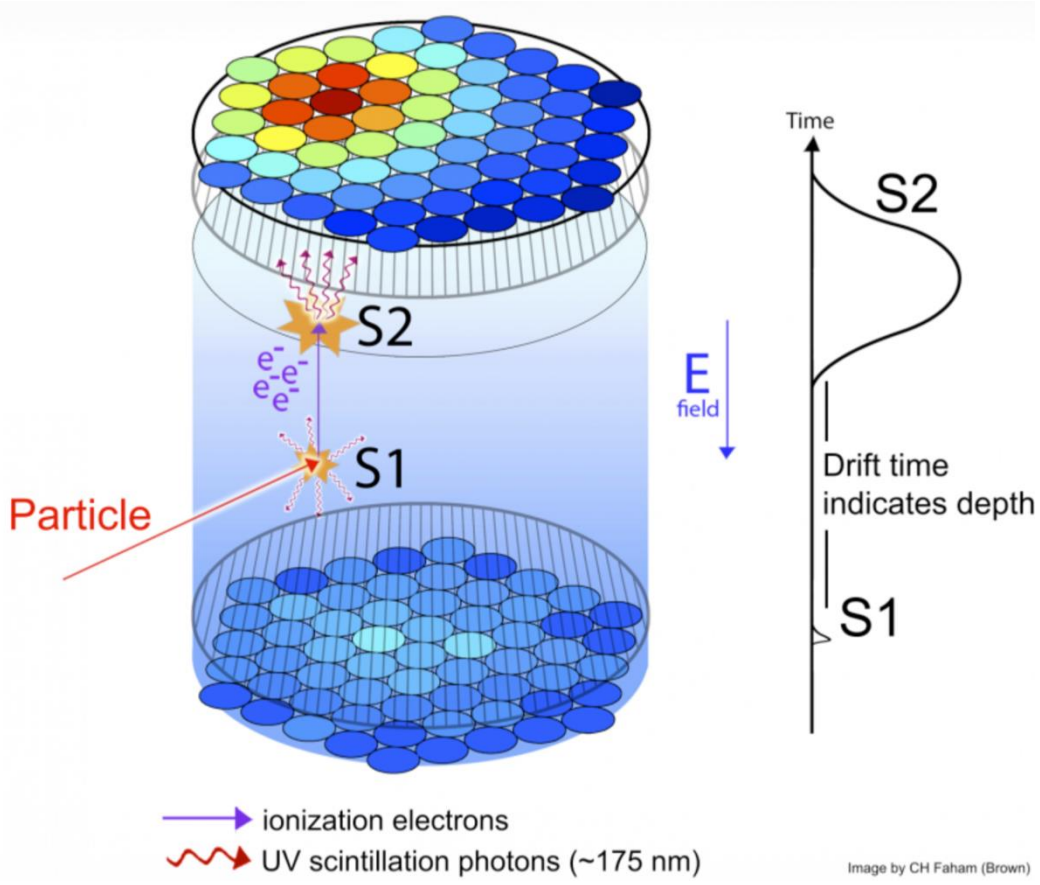
Stanford University

U.S. DEPARTMENT of ENERGY

Introduction: Dual-phase Xe TPCs

Recoil events with Xe atom and incoming particle produce light signals that we can detect using PMTs:

- S1: photons from deexcitation of Xe dimers in LXe
- S2: Electroluminescence photons from extracted e-



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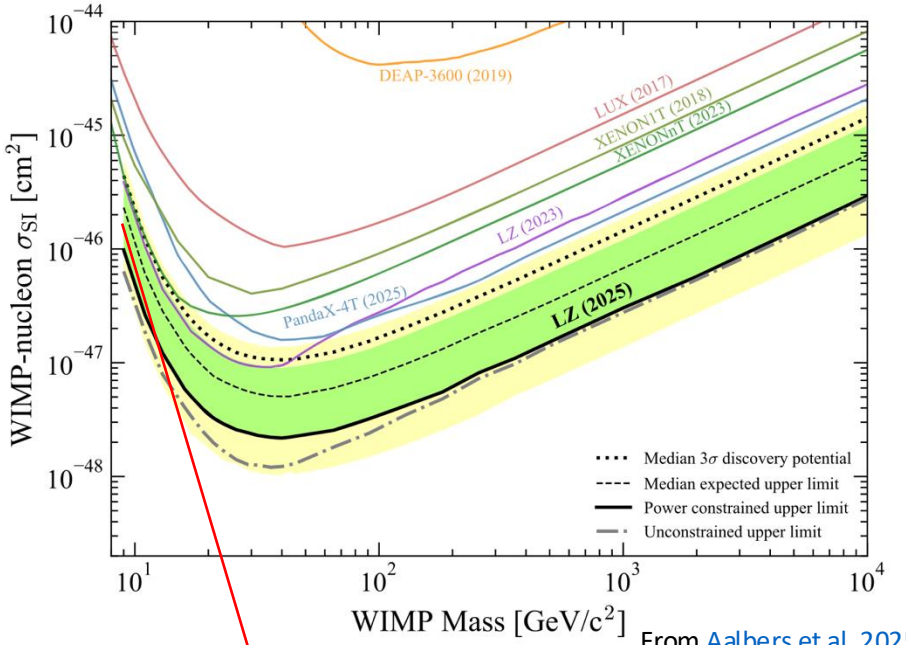
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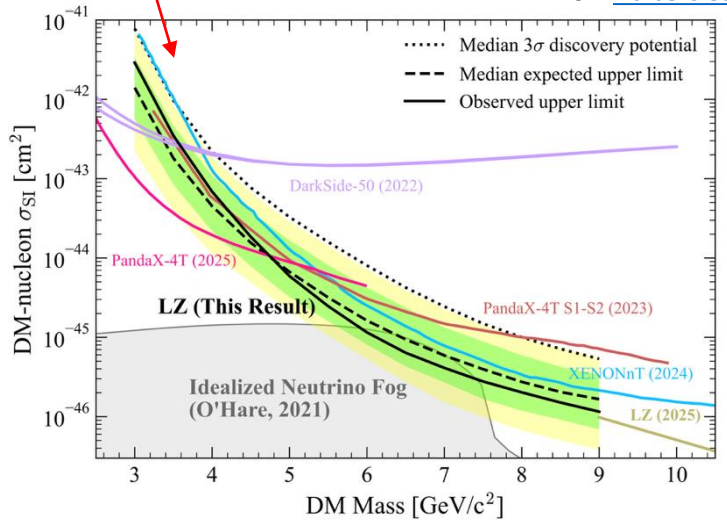
Minimum mass sensitivity depends on mass of target mass *A* and nuclear recoil energy threshold E_{NR}.

LZ is sensitive to ~GeV mass particles.

Low mass sensitivity is constrained by kinematics of elastic collision between incident. Xenon atom is less kinematically matched with sub-GeV mass dark matter.



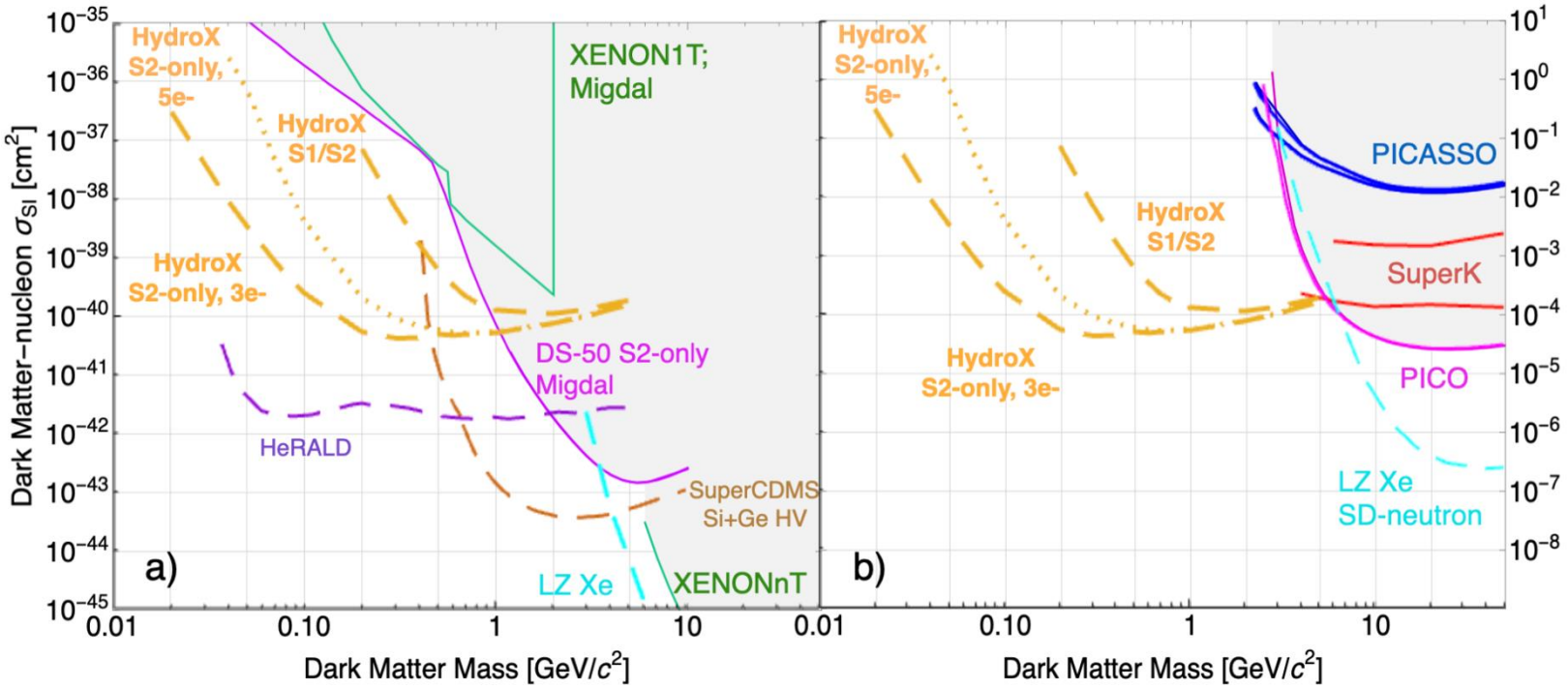
From Aalbers et al. 2025



From Akerib et al. 2025.

HydroX: Hydrogen Doped Xenon TPC

Lower LZ mass reach down to sub-GeV dark matter by doping with 1.1% H_2 by number density relative to the LZ fiducial volume (□0.95kg H_2).



Projected sensitivity of HydroX. Left: SI. Right: SD.
From [Lippincott et al.]

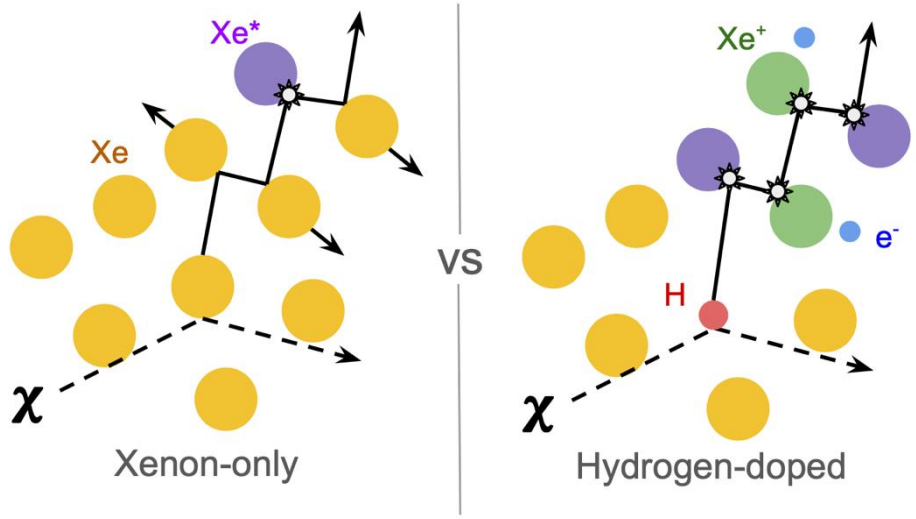
Hydrogen's Effects on Signals

Pros:

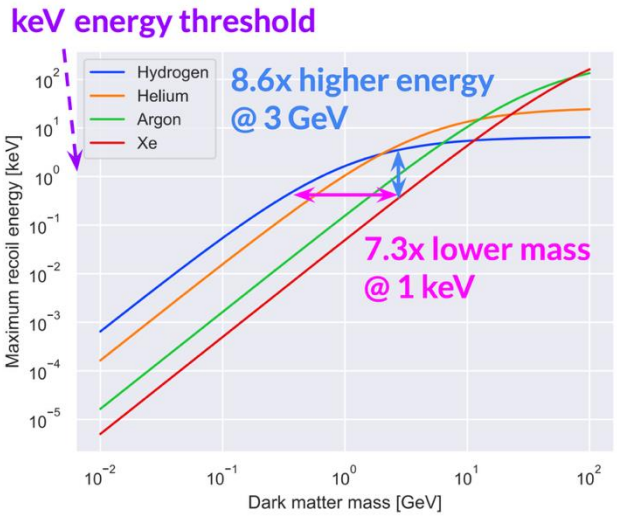
- In pure Xe: ~80% of energy in Xe excimers is lost to heat from collisions.

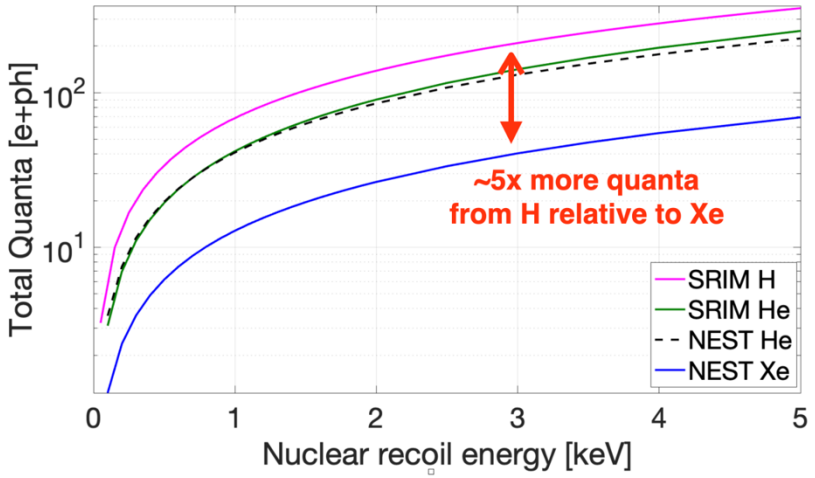
  In Xe + hydrogen: Nearly all of recoil energy is observable via electronic excitations.

- Hydrogen can lower mass reach to sub-GeV light dark matter.



*Drawing from R. Coronel





*From Lippincott et al.

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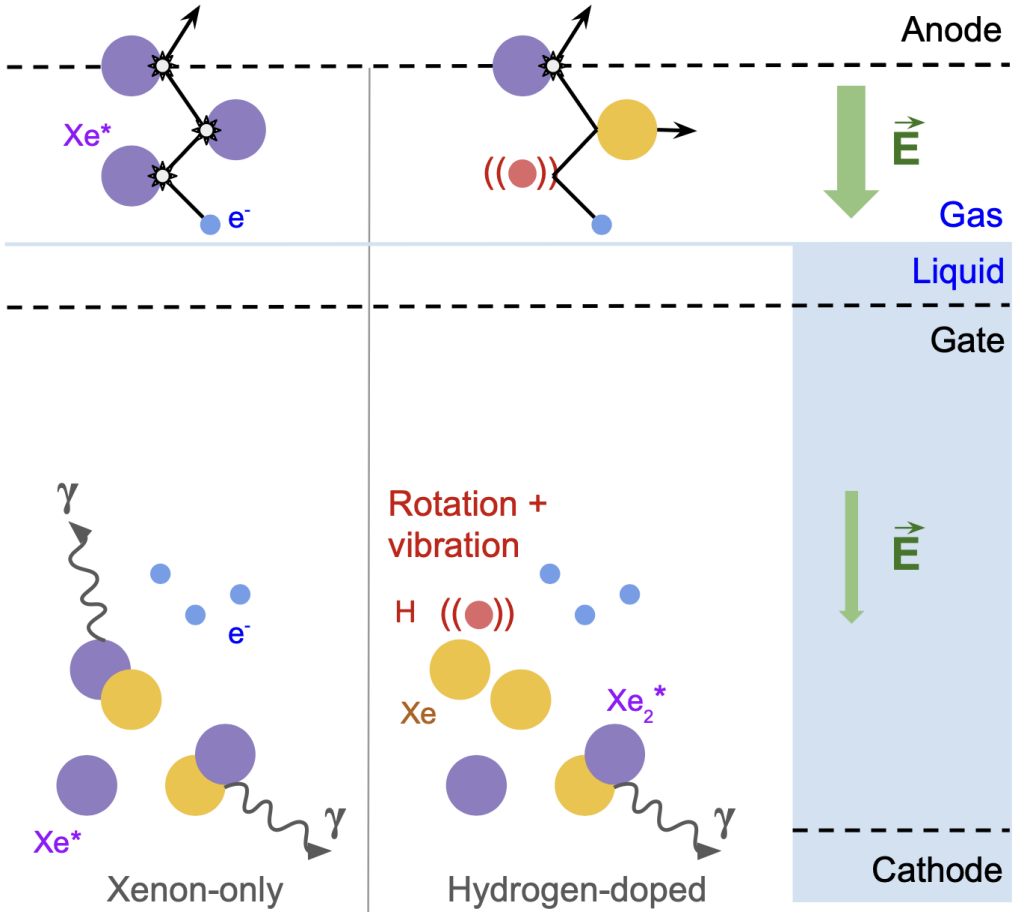
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- Hydrogen can lower mass reach to sub-GeV light dark matter.

Cons:

- Energy can be lost to dopant molecule's vibrational and rotational modes
- H in liquid quenches S1s.
- H in gas cools e- and quenches excimers, reducing S2s.

Requires lab measurement to see composite result of these opposing effects.



*Drawing from R. Coronel

Previous Results

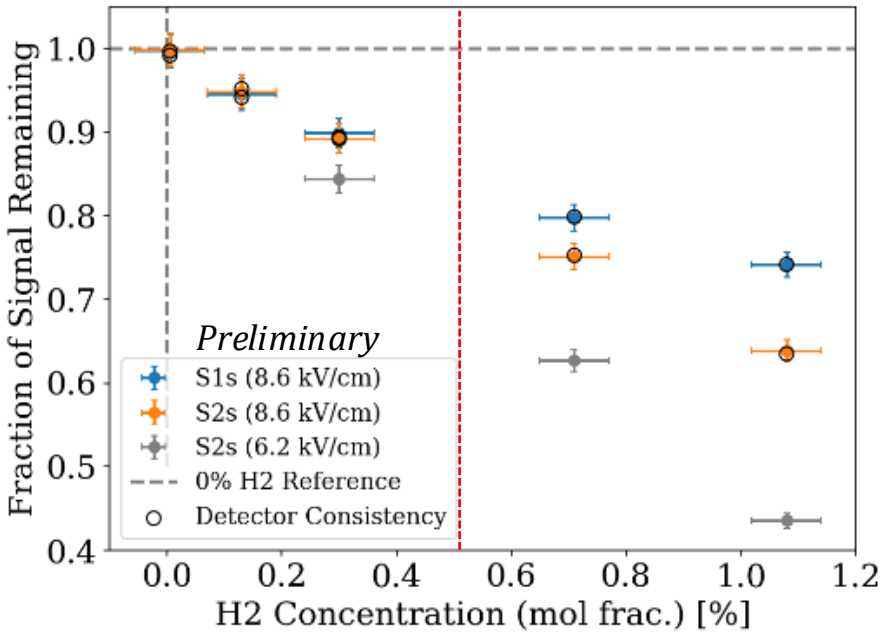
Solubility of Hydrogen

- Henry's law states that amount of gas dissolved in liquid is proportional to the partial pressure of that gas above the liquid.
- Previous measurements of H_2 in Xe at SLAC and UCSB showed poor solubility of H_2 in LXe and an unviable reduction of S2s in GXe.

Hydrocarbons as potential dopants

- Hydrocarbons have better solubility in liquid Xe than H_2.
- Ethane liquifies around the same temperature as Xe at the same pressure.
- In particular: "Xenon + ethane is the simplest system which exhibits negative values for all three major excess molar functions" i.e. ethane is stable in LXe and doesn't 'escape' to GXe. (Filipe et al.)

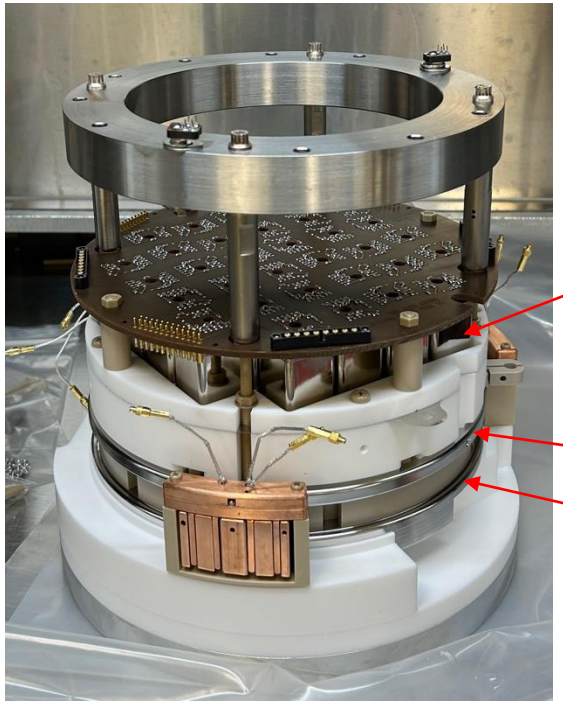
1% H by mole

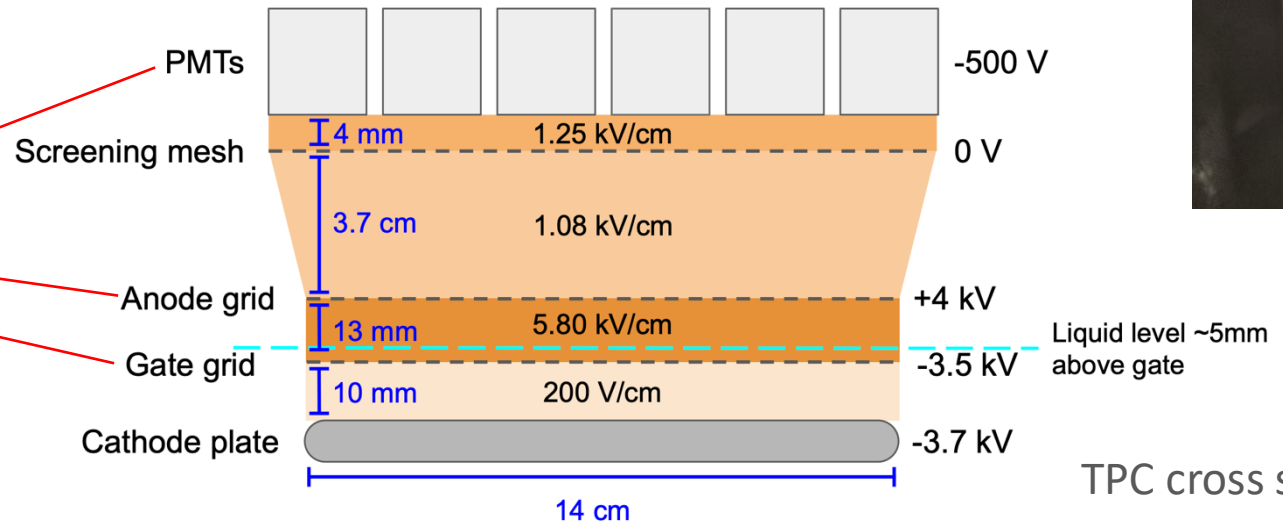


Gas HydroX results from SLAC showed unfavorable reduction of S2s below a desired H_2 concentration.
(Figure from R. Coronel et al. in preparation)

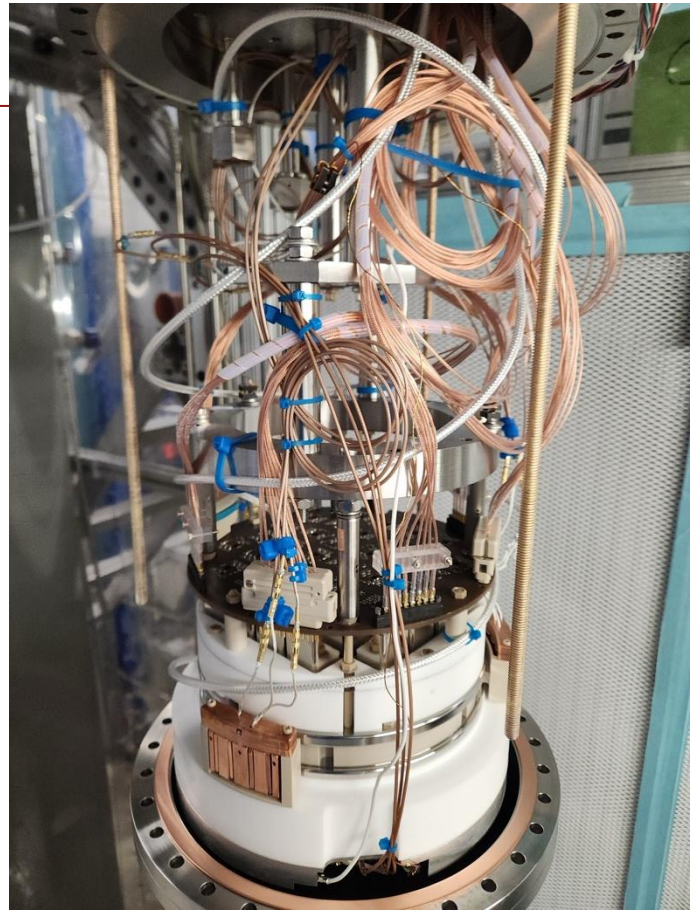
SLAC Test-Stand Overview

- 15 cm-diameter anode/cathode/gate grids at high voltage.
- 32 1-inch PMT array on top.
- 13 mm extraction region (matching LZ)
- Roughly 4.1 kg Xe in the circulation path with 1 kg being in gas phase.

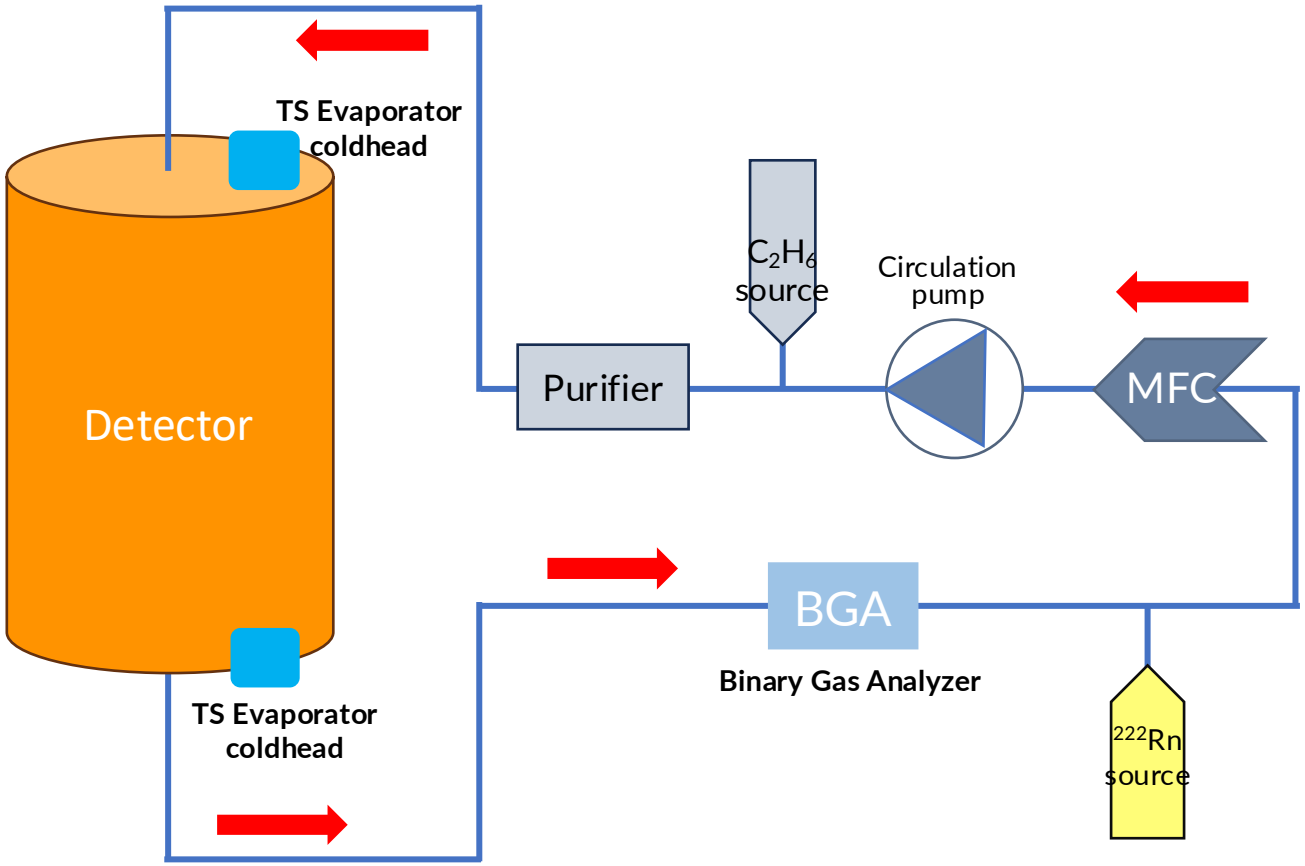




TPC cross section.



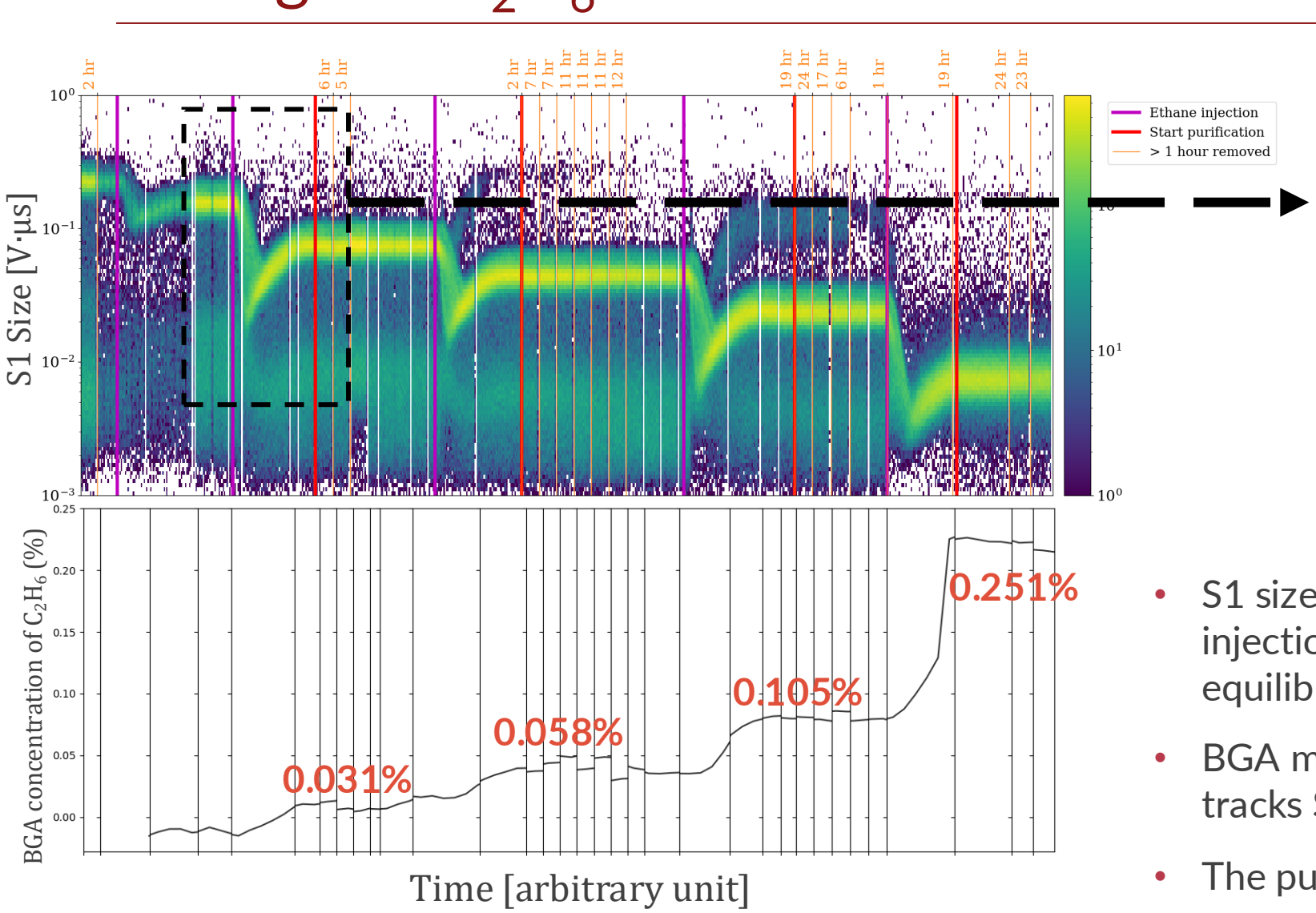
Circulation & Purification

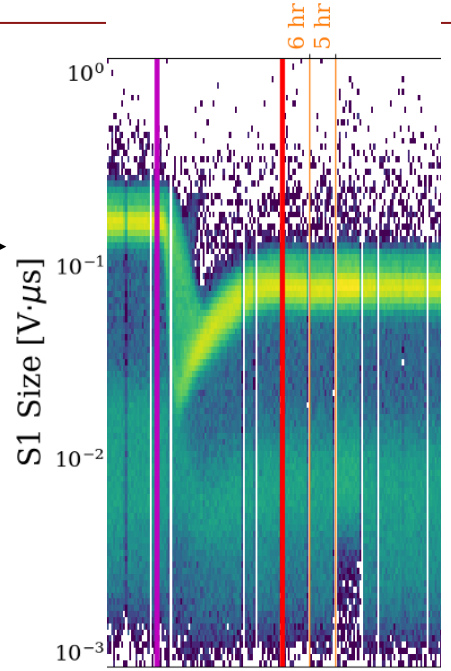


Bottom liquid draw – BLD

- Liquid is removed from the bottom of the TPC and boils in the line. It reenters the detector space from the top and condenses via the coldhead.
- Electronegative impurities (O_2, H_2O etc.) can degrade signal by attracting electrons. Xe + C_2H_6 mixture is purified using the purifier without absorbing significant amount of neither.
- The BGA reads the concentration of ethane in gas Xe → sets a lower bound for ethane concentration in liquid.

BGA gives C_2H_6 concentration



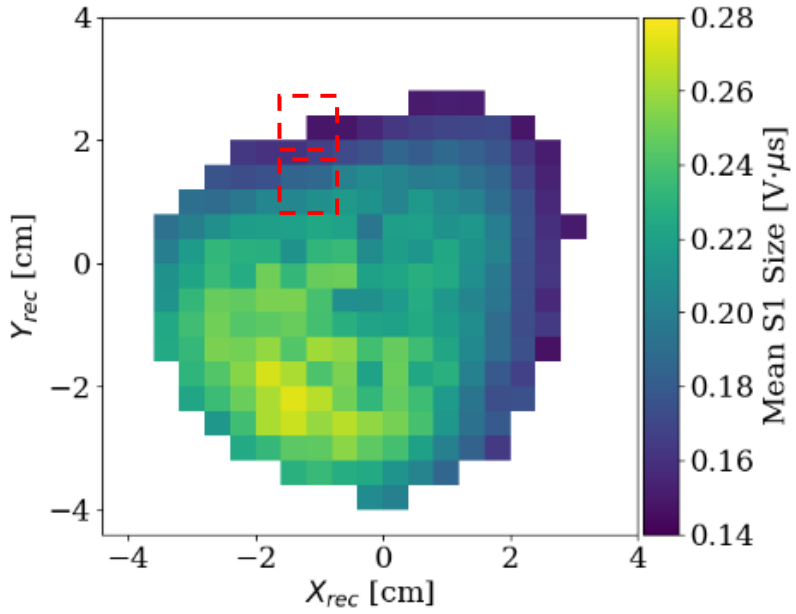


2nd ethane injection effect on S1 size.

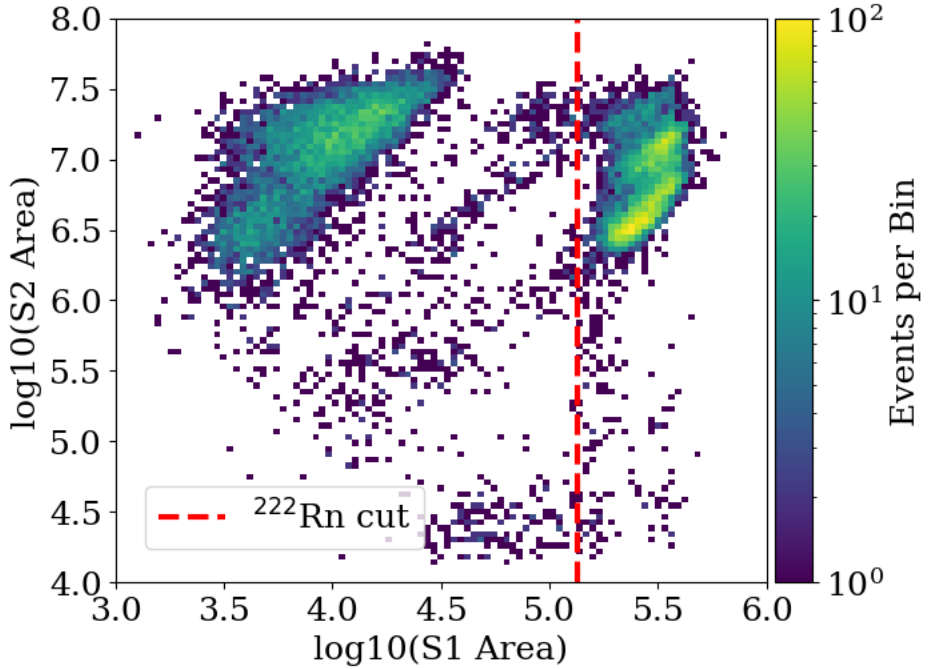
- S1 size drops and then increases after ethane injection, points to thermodynamic equilibration.
- BGA measurement of ethane concentration tracks S1 size reduction.
- The purifier maintains signal size.

Detector Calibration with ^{222}Rn source

- Injected isotropic 222Rn source which produces 5.6 MeV alpha decays.
- Calibrated pulse areas based on reconstructed center-of-mass XY distribution (Note: 2 PMTs are off)



Pulse calibration in XY space to account for PMTs not being gain-matched. 2 PMTs approximately in the location of the dashed red boxes are off.

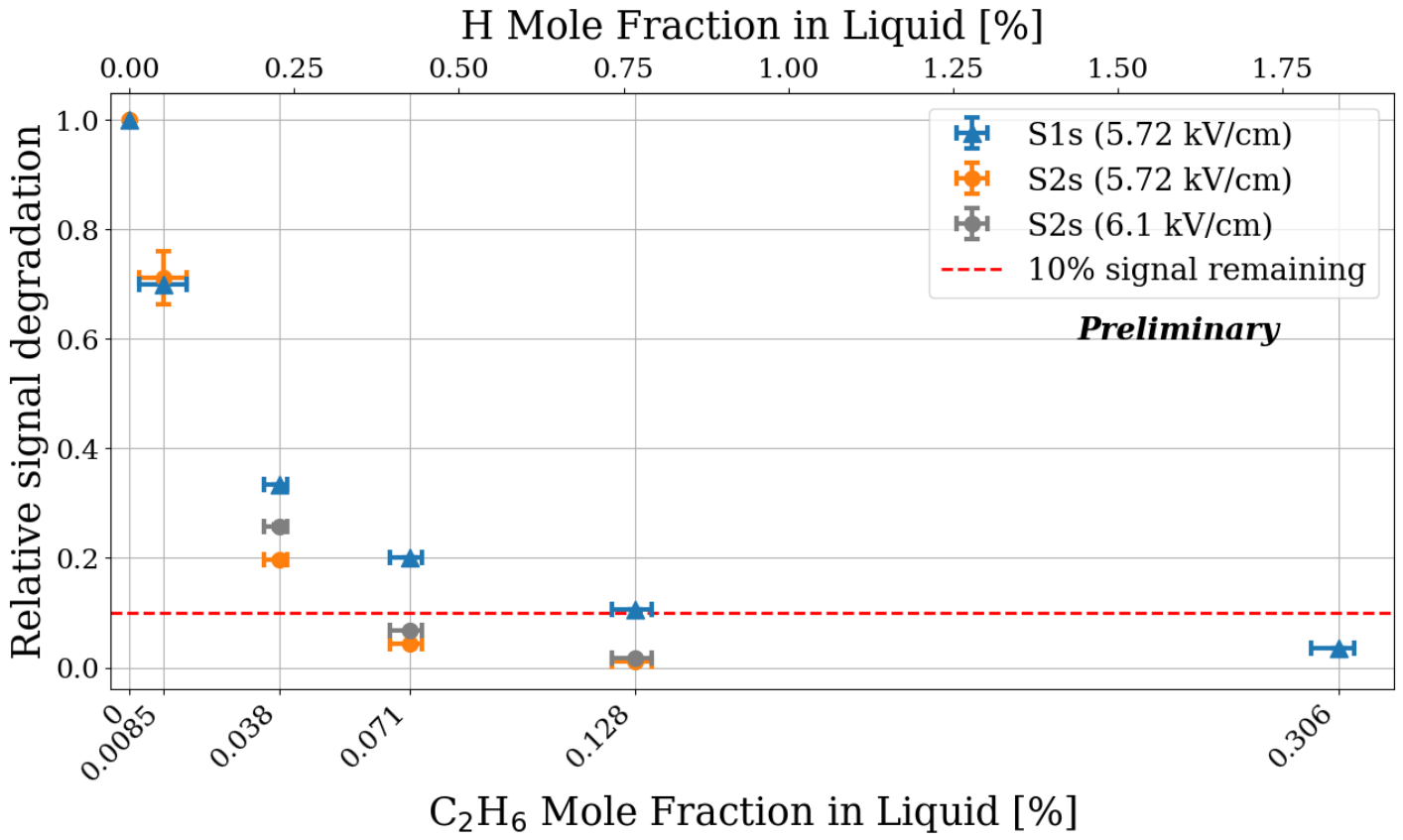


^{222}Rn alpha events to the right of the red dashed line in log(S1-S2) space compose about 70% of all events. No other cuts are applied.

Preliminary Results

Calculated signal reduction relative to pure Xe:

- S2s degrade faster than S1s.
- On average, 46% of S2 is regained after increasing extraction E field by 6.6%.
- As an upper-bound on ethane: A 3e- S2o analysis is feasible at ~10% S2 remaining → 0.0527% C_2H_6 = 0.316% H = 136 g H in LZ
  (based on preliminary rate law fit)



Conclusion and Future Work

We started a feasibility study of ethane-doping in LZ for sub-Gev DM searches.

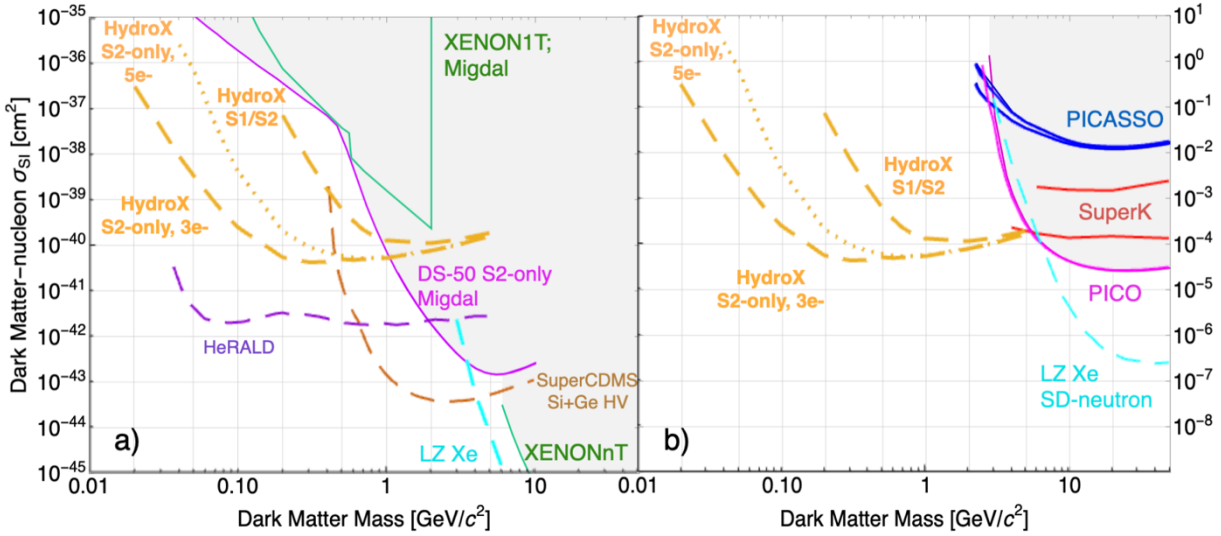
We measured S1 and S2 degradation in a dual phase Xe TPC due to doping with ethane C_2H_6.

- We can regain ~half of S2 by increasing field strength by ~6%.
- A 3e- S2o analysis gives a conservative ethane upper bound of 0.0527% C_2H_6 equivalent to 136 g H in LZ FV.

HydroX remains a possible detector technology to probe the unexplored low mass DM parameter space.

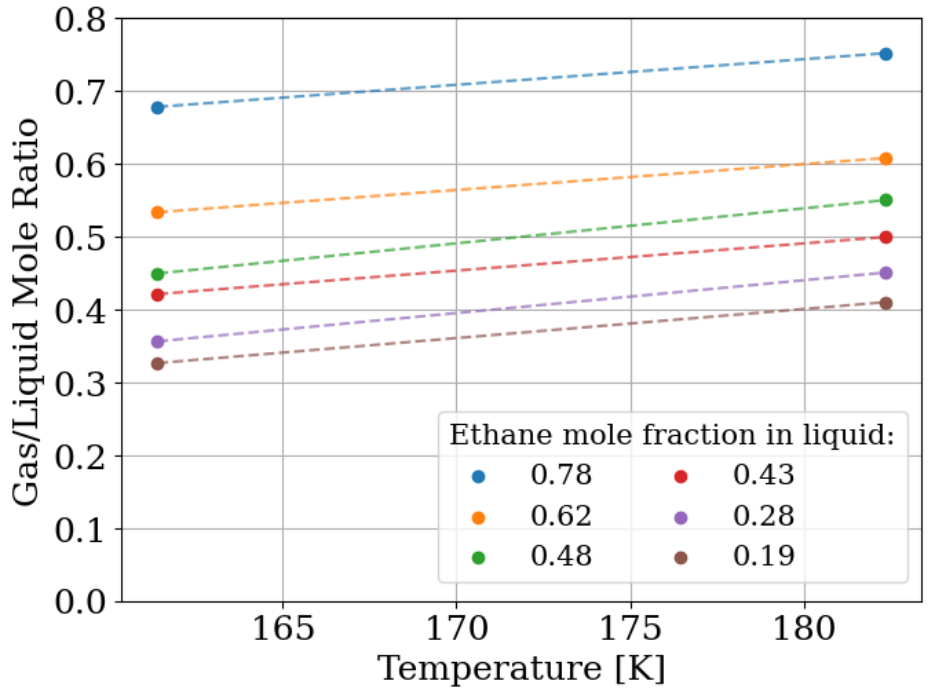
Future work:

- New run to refine measurements,
- Measure extraction efficiency of ethane-doped Xe,
  - Will inform of HV need for a HydroX run in LZ.
- Decouple different signal degradation mechanisms,
- A PLR sensitivity study based on empirical data.

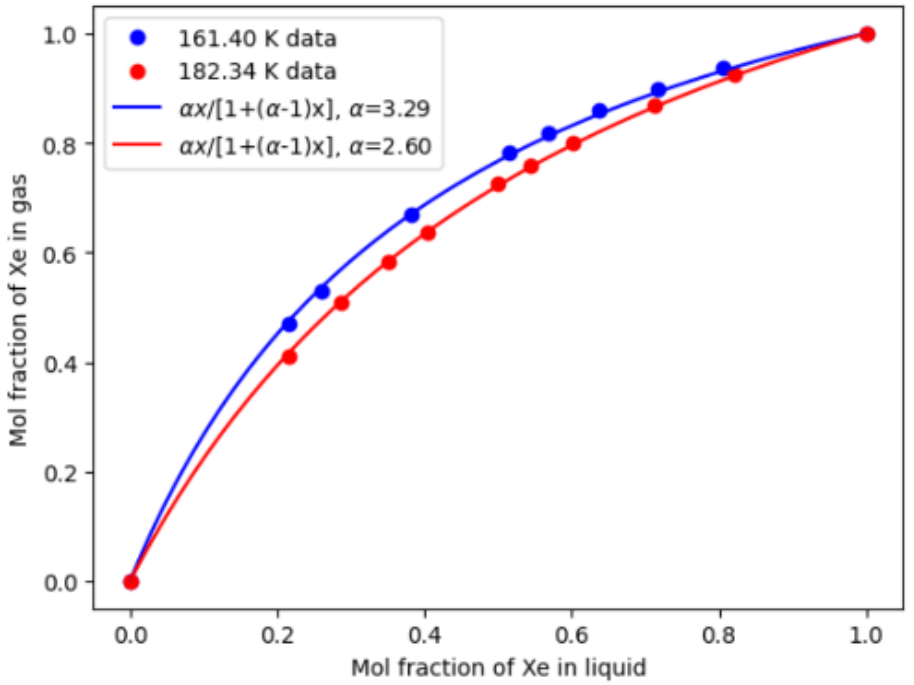


Backup slides

Ethane solubility



Gas/liquid ratios of ethane in Xe+ethane mixure at various ethane concentrations at two different temperatures. Note that all values are <1, i.e. there is more ethane in the liquid than in the gas.
Values from Filipe et al.



Mol fraction of Xe in gas vs Mol fraction of Xe in liquid in a Xe+ethane mixure at various ethane concentrations at two different temperatures. We fit a constant relative volatility equation to the data points to extrapolate ethane concentration in liquid in our experimental values.
Values from Filipe et al.

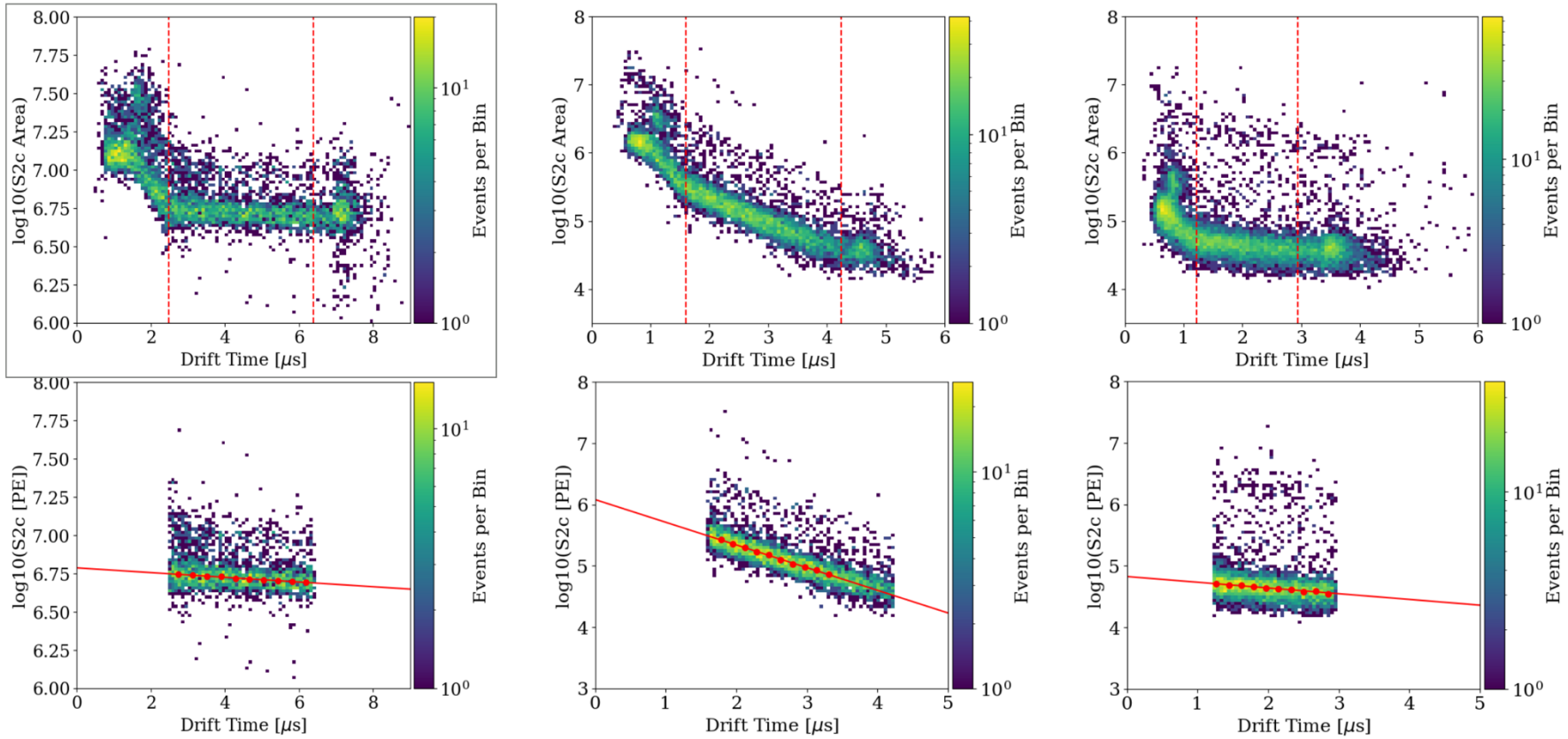
Ethane Injections

Injection	Total Ethane in System [number density %]	Total Ethane in Liquid [number density %]	Total H in Liquid [number density %]	Mass of p+ in LZ's 5.6-tonne Fiducial Volume [gram]
1	0.0070 ± 0.0006	0.0085 ± 0.008	0.051 ± 0.0048	22 ± 2.1
2	$0.031^{+0.002}_{-0.004}$	$0.038^{+0.003}_{-0.006}$	$0.228^{+0.018}_{-0.036}$	$98^{+7.7}_{-15.5}$
3	$0.058^{+0.003}_{-0.005}$	$0.071^{+0.004}_{-0.007}$	$0.426^{+0.024}_{-0.042}$	$184^{+10.3}_{-18.1}$
4	$0.105^{+0.004}_{-0.006}$	$0.128^{+0.005}_{-0.007}$	$0.768^{+0.030}_{-0.042}$	$333^{+12.9}_{-18.1}$
5	$0.251^{+0.004}_{-0.007}$	$0.306^{+0.005}_{-0.009}$	$1.836^{+0.030}_{-0.054}$	$804^{+12.9}_{-23.2}$

2.18% H = 958 g H in LZ FV

*Percent mole concentration in liquid is calculated using constant relative volatility equation and partial pressures.

Calculating S1 and S2 size at zero drift



Pure xenon | Second injection + purification | Third injection + purification

We apply a linear fit to the drift region in log(S2 area) vs drift time space. The y-intercept gives us ‘S2 size at 0 drift’ which we use to set S2 size degradation.

Did a simple rate law fit (α = 1) and an adjusted fit with density exponent to predict S2 size reduction at variable ethane concentration.

$$\mathrm{S2}([\mathrm{C_2H_6}]) = \frac{\mathrm{S2}(0)}{1 + k[\mathrm{C_2H_6}]^{\alpha}}$$

Simple rate law fit: k= 100

With density exponent: k=1000, α = 1.6.

