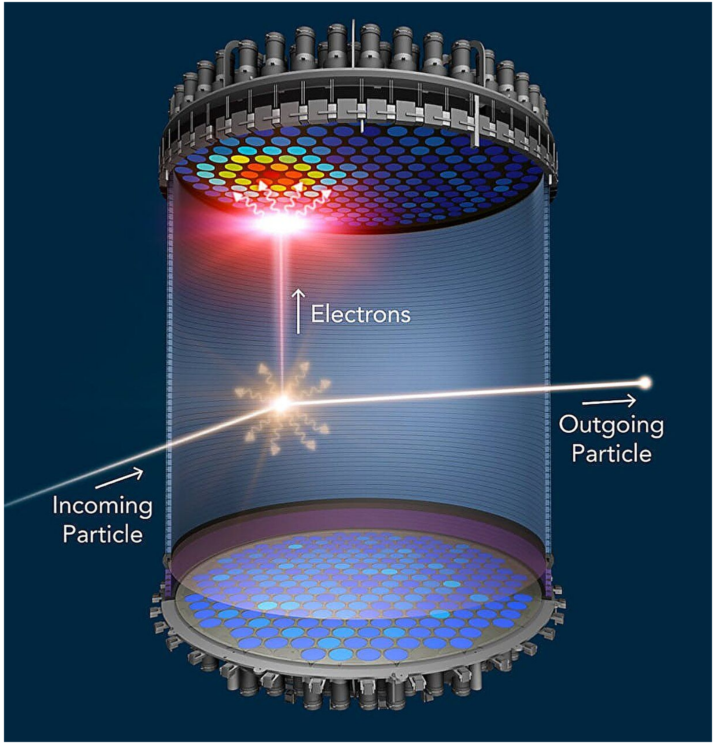
Hydrogen doping in liquid xenon TPCs: HydroX at SLAC

Drew Ames
On behalf of the SLAC HydroX group

CPAD Workshop
8 November 2023

Introduction

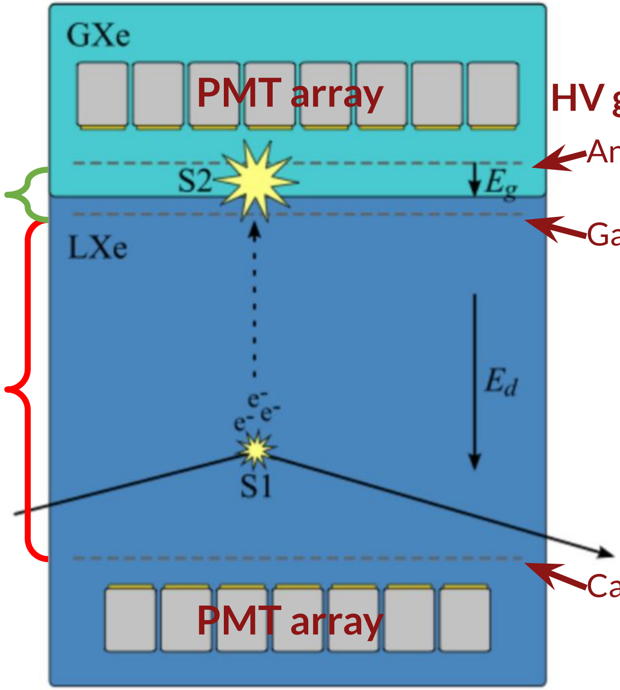
- Liquid xenon time projection chambers (TPCs) lead the search for WIMP dark matter heavier than about 5 GeV
- Xenon TPCs are not sensitive to lower masses - xenon atoms are too heavy (131 GeV)!
- HydroX is testing the addition of a light element such as hydrogen to enhance lower mass sensitivity
- In HydroX, hydrogen acts as dark matter target while xenon produces the signal - best of both elements?



Overview of dual-phase xenon TPCs

Extraction region
Higher field pulls electrons into gas, produce light via proportional electroluminescence (**S2**)

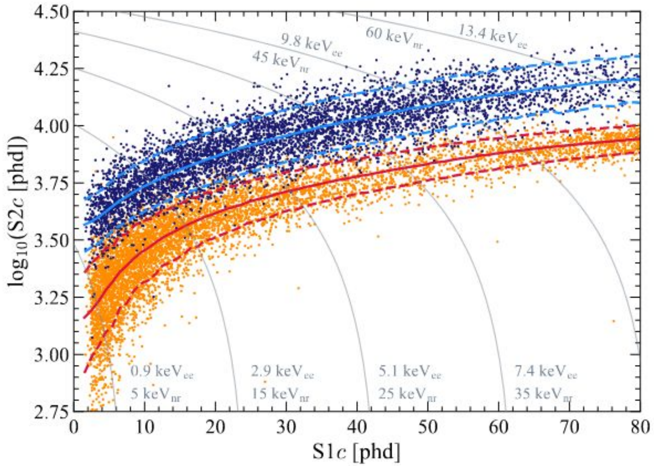
Drift region
Interaction in liquid xenon produces scintillation light (**S1**) and ionization electrons. Applied electric field drifts electrons upward



HV grids:
Anode
Gate
Cathode

S1 + S2:

- 3D position reconstruction
- Interaction energy
- Discrimination: Electron recoil (ER) vs nuclear recoil (NR) - WIMP signal

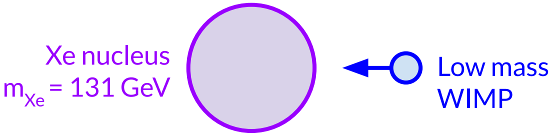


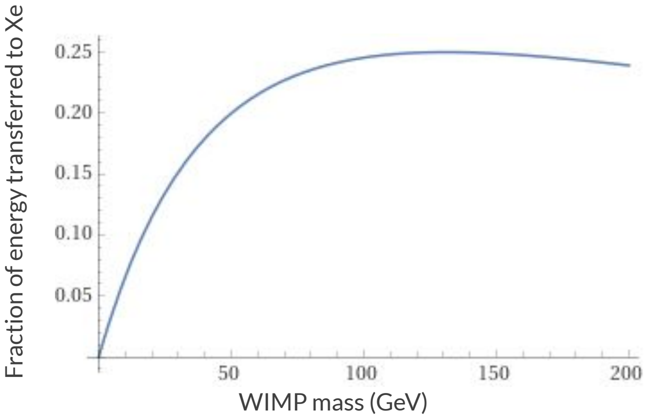
LZ calibration data with tritium (ER, blue) and DD neutron (NR, orange) [arXiv:2207.03764v4]

Kinematic constraints

Sensitivity of xenon target drops off rapidly for WIMP mass <10 GeV - less energy transferred in elastic collision

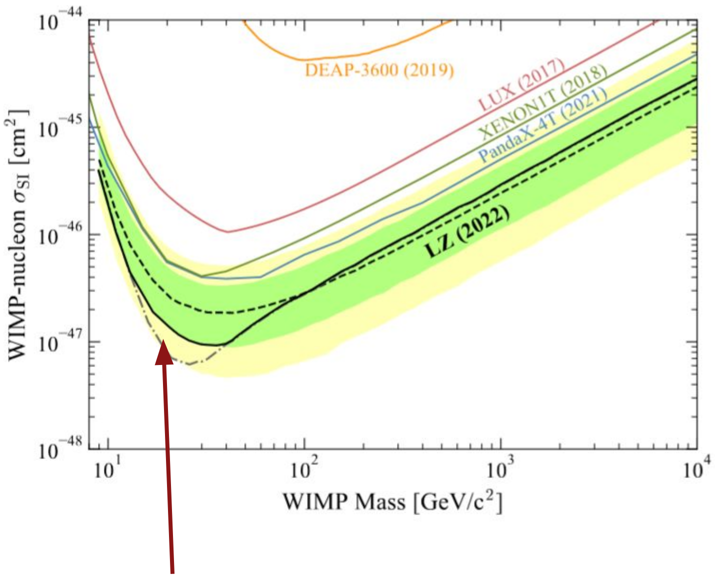
$$E'_{\mathrm{Xe}} = \frac{m_{\mathrm{Xe}}\, m_{\mathrm{W}}}{(m_{\mathrm{Xe}} + m_{\mathrm{W}})^2} E_{\mathrm{W}}$$





m_w	E'_{Xe}/E_W
10 GeV	15.0%
5 GeV	3.5%
1 GeV	0.8%

First LZ WIMP search limit plot
[arXiv:2207.03764v4]



Sensitivity decreases rapidly below ~10 GeV

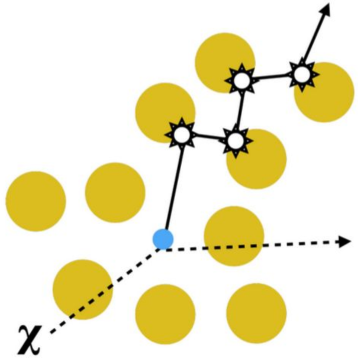
Hydrogen doping

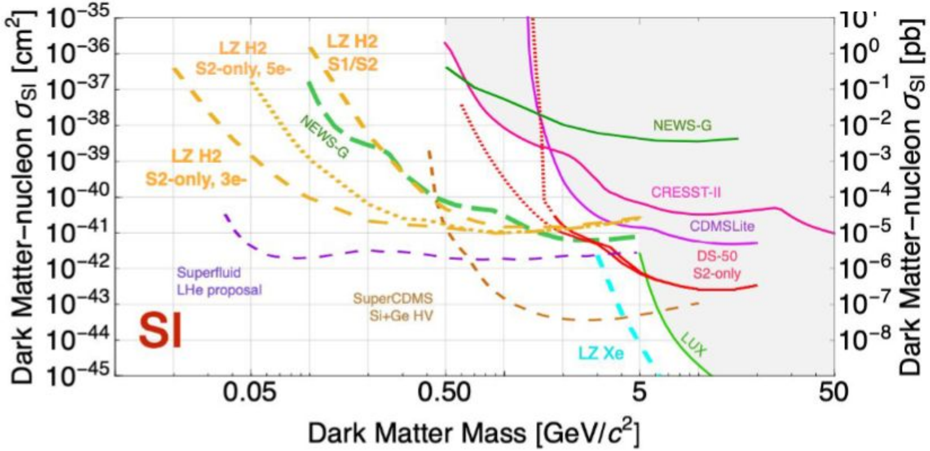
- More favorable kinematics with lighter target (proton, 1 GeV)
- Retain favorable properties of xenon for signal production
    - Self-shielding
    - Low intrinsic radioactivity
    - Familiar, properties are fairly well understood
- Could be deployed in LZ or another existing detector
    - Will already have characterized backgrounds
    - Cryogenic & purification challenges
- Same principles apply to other hydrocarbons

Signal production:

WIMP collides with proton

Proton transfers energy to electrons of xenon atoms in inelastic collisions





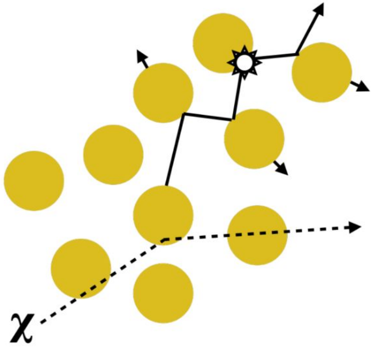
Projected sensitivity for various hydrogen doping scenarios (spin-independent interactions) compared to past & current WIMP search experiments

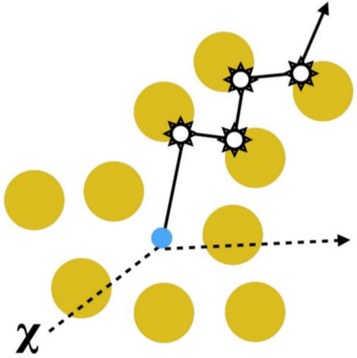
Hydrogen and signal production

Expect hydrogen to enhance signals

Xenon recoil: most energy transfer is kinetic - lost as heat (unobservable)

Proton recoil: too small to transfer kinetic energy to xenon, most is converted into electron excitations (observable)





Doping may also degrade signals

Quenching

Dopant (hydrogen or hydrocarbon) molecules carry away energy from excimers before photon is produced

Absorption

Molecular dopant absorbs photons after production

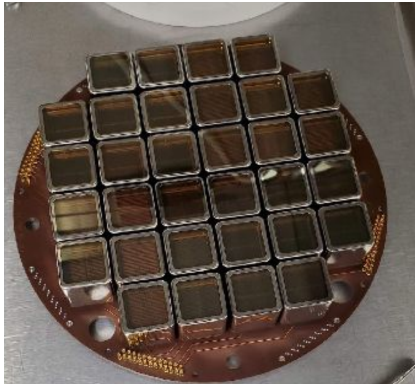
Electron cooling

Electrons in the extraction region lose energy in collisions with dopant molecule

Tradeoffs between dopant types:

- Hydrocarbons more likely than H_2 to cause degradation, due to molecular structure
- Some hydrocarbons may have significantly better thermodynamic properties than H_2

HydroX test stands



Test setups at several institutions to measure:

- Solubility and Henry's constant of hydrogen in LXe
- Signal effects - light and charge yields in gas and liquid phases, quenching, calibration
- Effect of hydrogen on ER/NR discrimination
- Infrastructure - cryogenics, circulation, addition and removal of hydrogen, purification, material compatibility

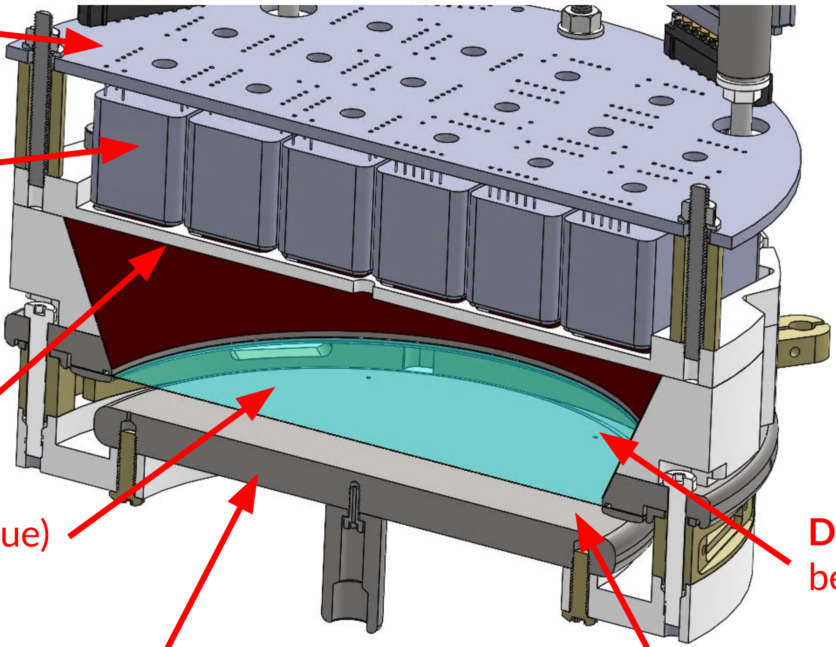
HydroX collaborators:

UCSB	SLAC
Penn State	Imperial College London
LBL	SURF
Michigan	Northwestern

Current efforts at SLAC:

- Measure effects on S2 signal as a function of hydrogen concentration in xenon gas
- Develop gas handling system compatible with hydrogen / hydrocarbons
- Test effects of hydrogen on PMTs

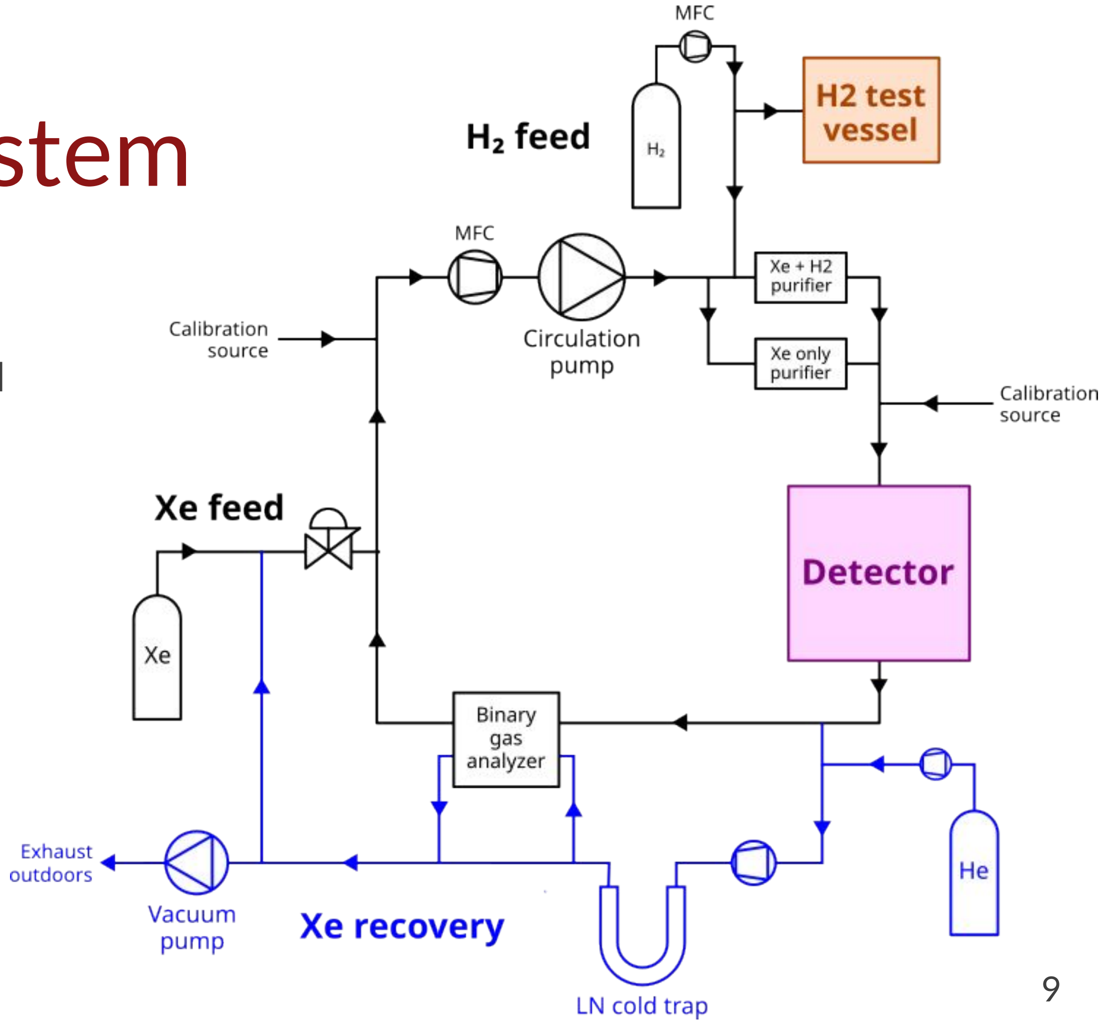
SLAC HydroX TPC



- Reconfigured TPC from LZ system test at SLAC
- Currently set up for gas phase testing
- “Upside down” configuration (extraction region on bottom) minimizes dead volume
- 32 channel CAEN digitizer + LUX amplifier boards

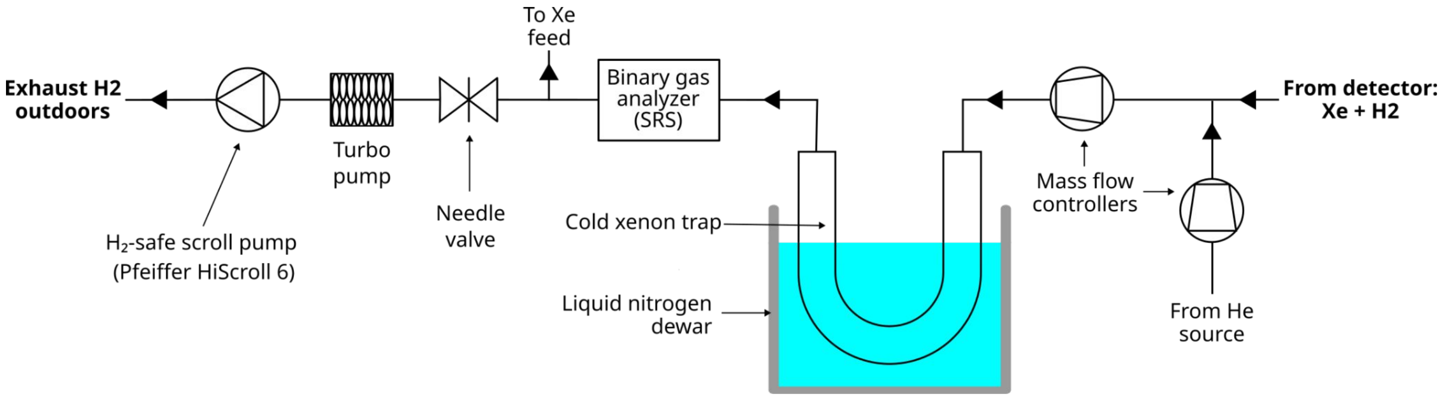
Gas circulation system

- New gas system compatible with hydrogen (and hydrocarbons)
- Designed around hydrogen safety and compatibility
- All pressure relief devices and pumps that see hydrogen exhaust outside
- Hydrogen embrittlement
    - Hydrogen can cause brittleness and cracking in metals, including nickel & alloys
    - Nickel VCR gaskets cannot be used
    - Nickel alloys are common in many instruments
- No hot filaments used anywhere



Xenon recovery

- Gas mixture passes through a cold trap in LN
  - Xe freezes onto trap walls
  - H_2 passes through and gets pumped away
- MFC and needle valve set pressure and flow
- Flow driven by scroll pump (Pfeiffer HiScroll) rated for flammable gas
  - Exhausts outside the building
  - Diluted with inert gas via ballast
- After recovery, xenon warms up into buffer volumes (not shown)
  - Cryopumped back to feed bottle for next run
- BGA downstream of trap
  - Monitor trap outlet
  - Measure residual H2 after warm up
- He source upstream for dilution if necessary



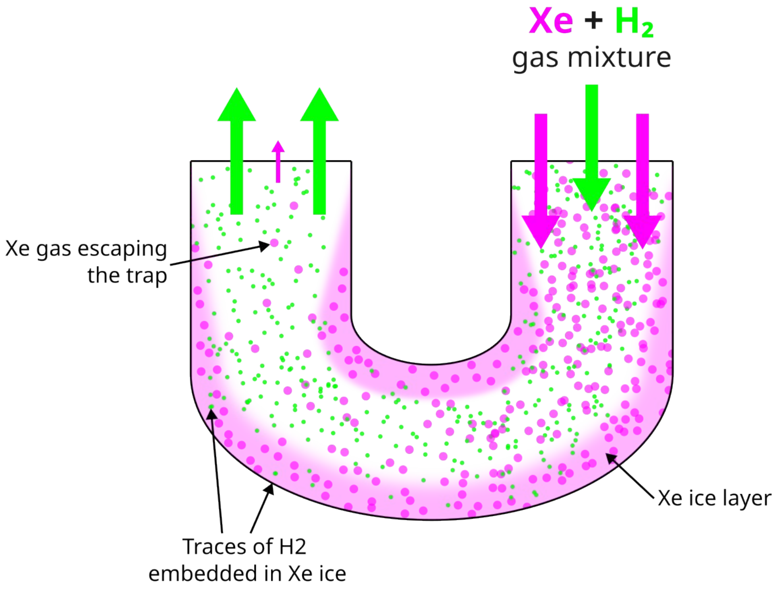
Challenges of xenon recovery

Xenon breakthrough:

- Too much xenon makes it through the trap and gets pumped out
- Need reliable cooling + optimize flow and pressure
- BGA allows monitoring of trap outlet

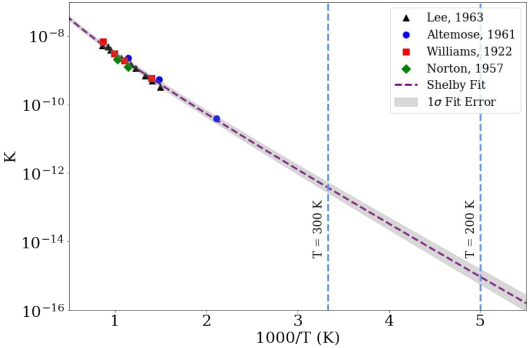
Trap clogs:

- At high concentrations, xenon ice freezes too quickly and can form plug
- May be possible to mitigate with lower flow rate
- Option is available to dilute with helium, but:
  - Helium (and H_2) can become entrained in xenon ice
  - BGA can't measure concentration with >2 gases

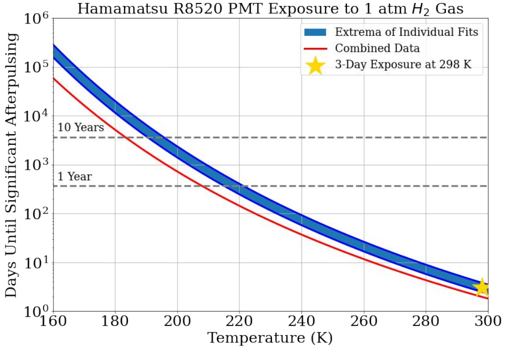


PMT testing

Afterpulsing: residual contaminants in PMT vacuum are ionized by photoelectrons. Ions impinge on the photocathode to release more electrons, which looks like a photon signal



Extrapolation of historical hydrogen diffusion measurements taken at high temperatures (Ruben Coronel)



Diffusion prediction translated into prediction of PMT lifetime in pure hydrogen (Ruben Coronel)

- Helium is known to diffuse readily through silica PMT windows and cause afterpulsing
- Does H_2 behave similarly?
- Historical data exists on H_2 diffusion in silica, but only at high temperatures
- TPC will initially be run with cold gas - extrapolation predicts >10 year lifetime for temps below 180 K
- Test this prediction by measuring afterpulsing rate vs time of a PMT in the hydrogen test vessel (pure hydrogen atmosphere)

Status and outlook

Current status:

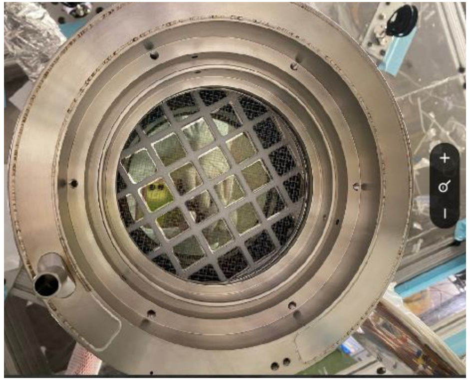
- Modification of TPC from system test is complete
- Construction and testing of gas system is nearing completion
- Developing data processing software in python based on Strax framework from XENON

Next steps: Commissioning

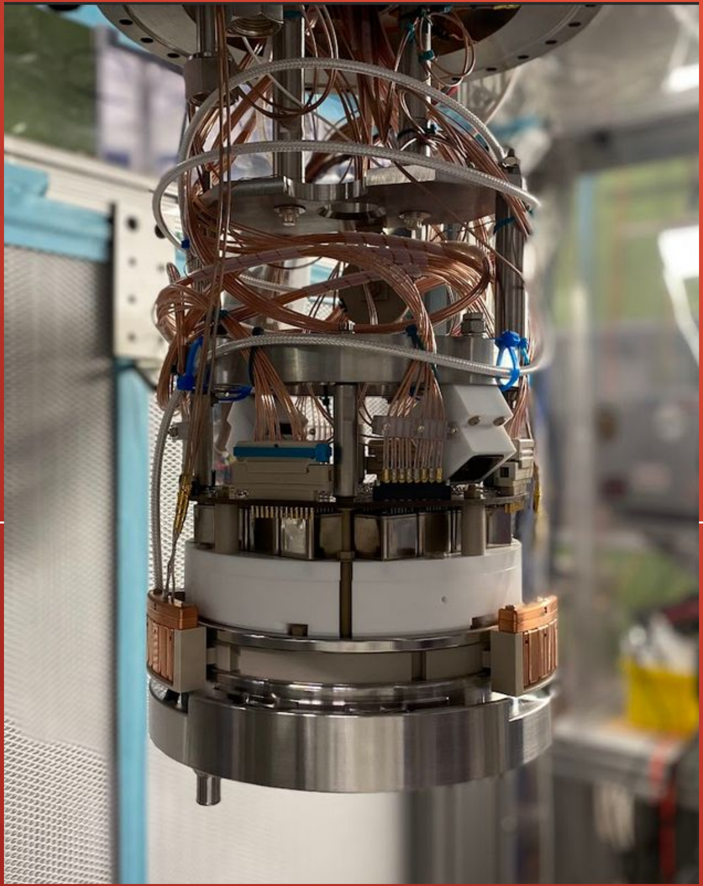
- Test circulation and cooling with xenon gas
- Start hydrogen testing of PMTs
- Testing of the recovery system
- **Begin taking data with hydrogen!**

Future:

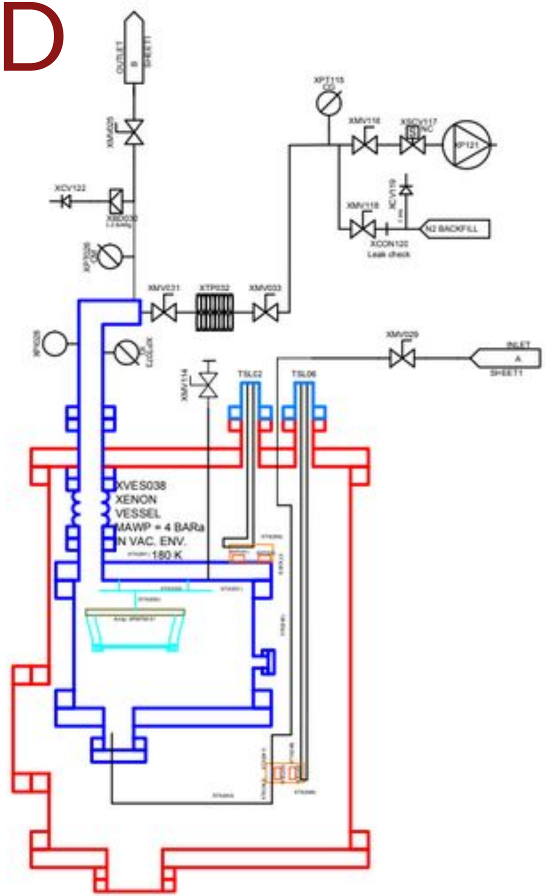
- Take data with hydrocarbons for comparison with hydrogen
- R&D for liquid handling system compatible with doping
- Take data with doped liquid xenon to characterize effects on S1 signals

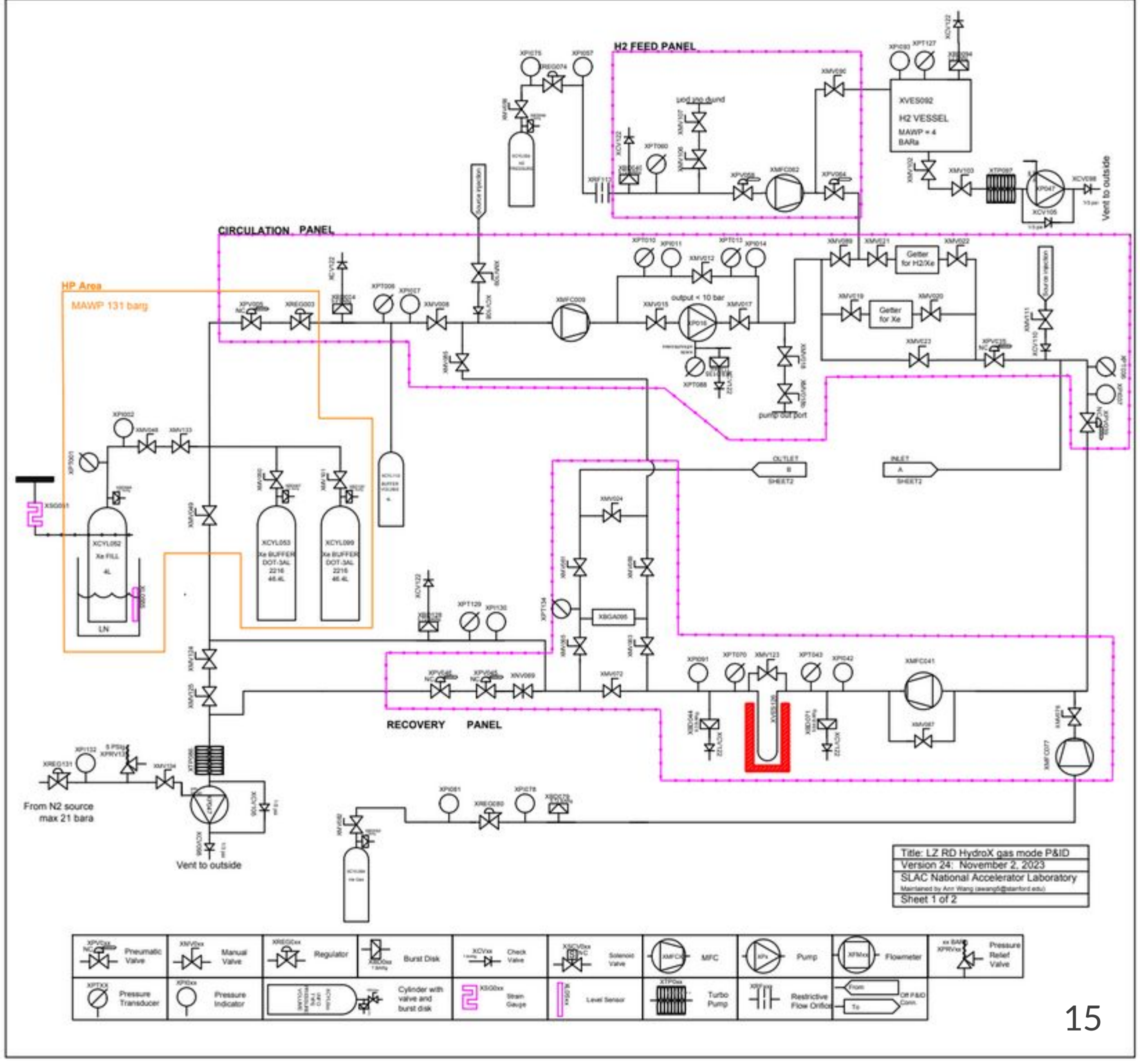


Questions?

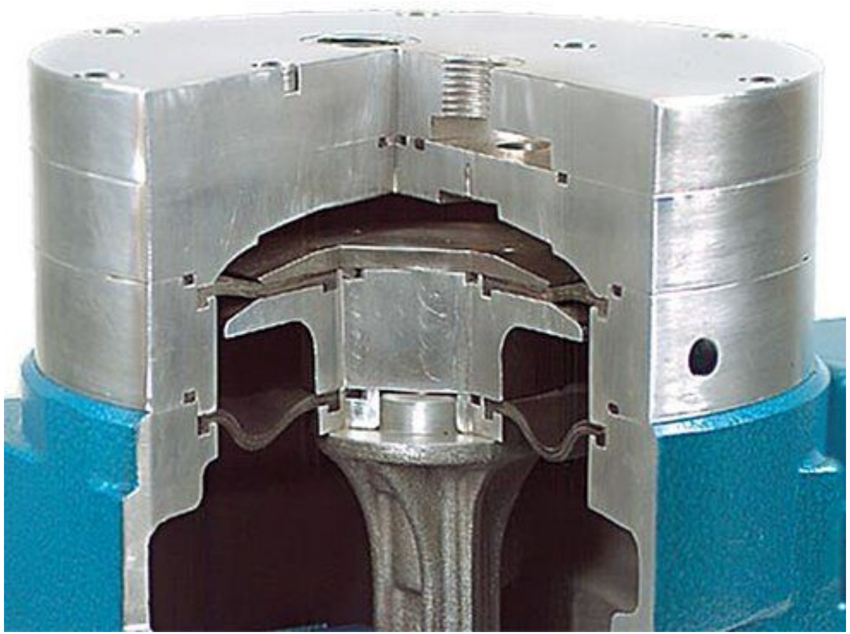


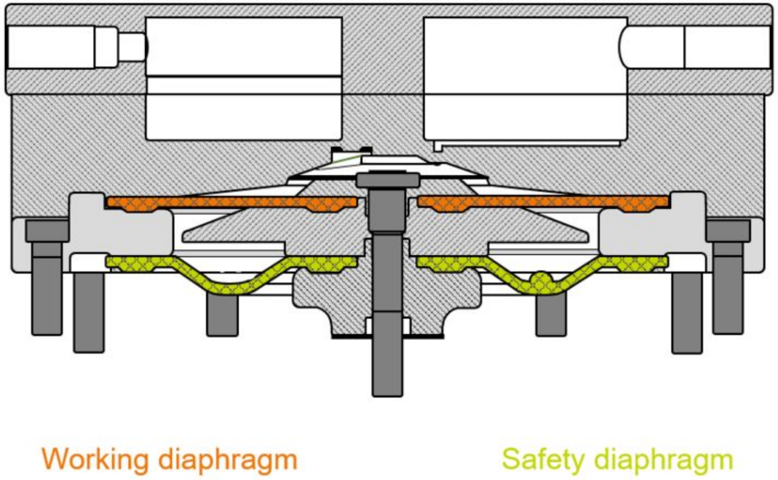
P&ID


XVES038
XENON
VESSEL
MAWP = 4 BARa
IN VAC. ENV.
180 K
INLET
A
SHEET1
XCON120
Leak check
N2 BACKFILL


H2 FEED PANEL
CIRCULATION PANEL
HP Area
MAWP 131 barg
RECOVERY PANEL
From N2 source
max 21 bara
Vent to outside
Title: LZ RD HydroX gas mode P&ID
Version 24: November 2, 2023
SLAC National Accelerator Laboratory
Sheet 1 of 2

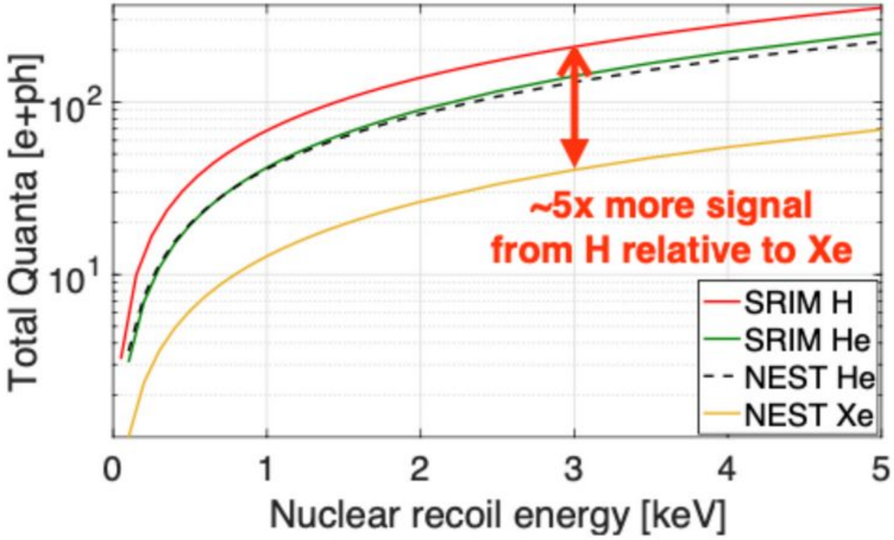
KNF double diaphragm system





Hydrogen signal enhancement

Simulation of light & charge yield with hydrogen doping



Pics