HydroX: Hydrogen Doped LXe

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New Directions in the Search for Light Dark Matter Particles
Fermilab & UChicago
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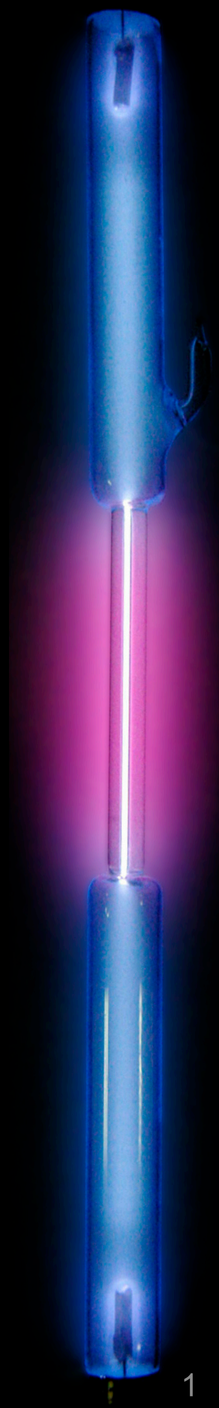
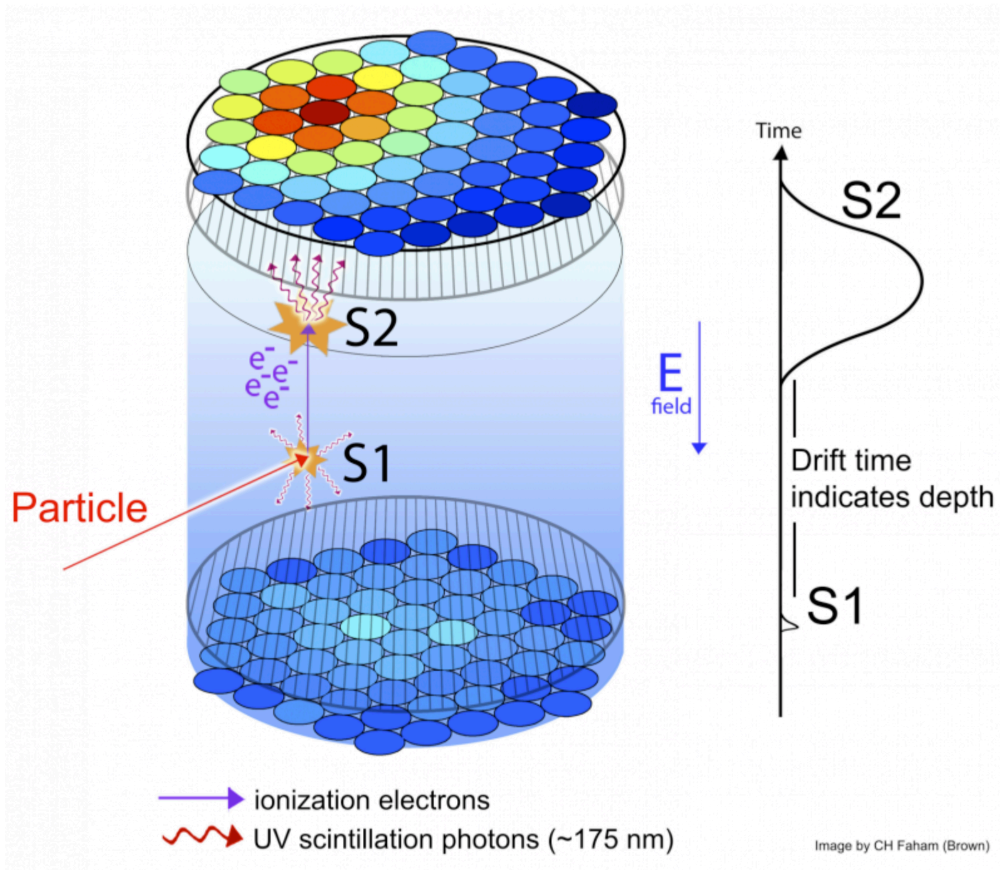


Concept



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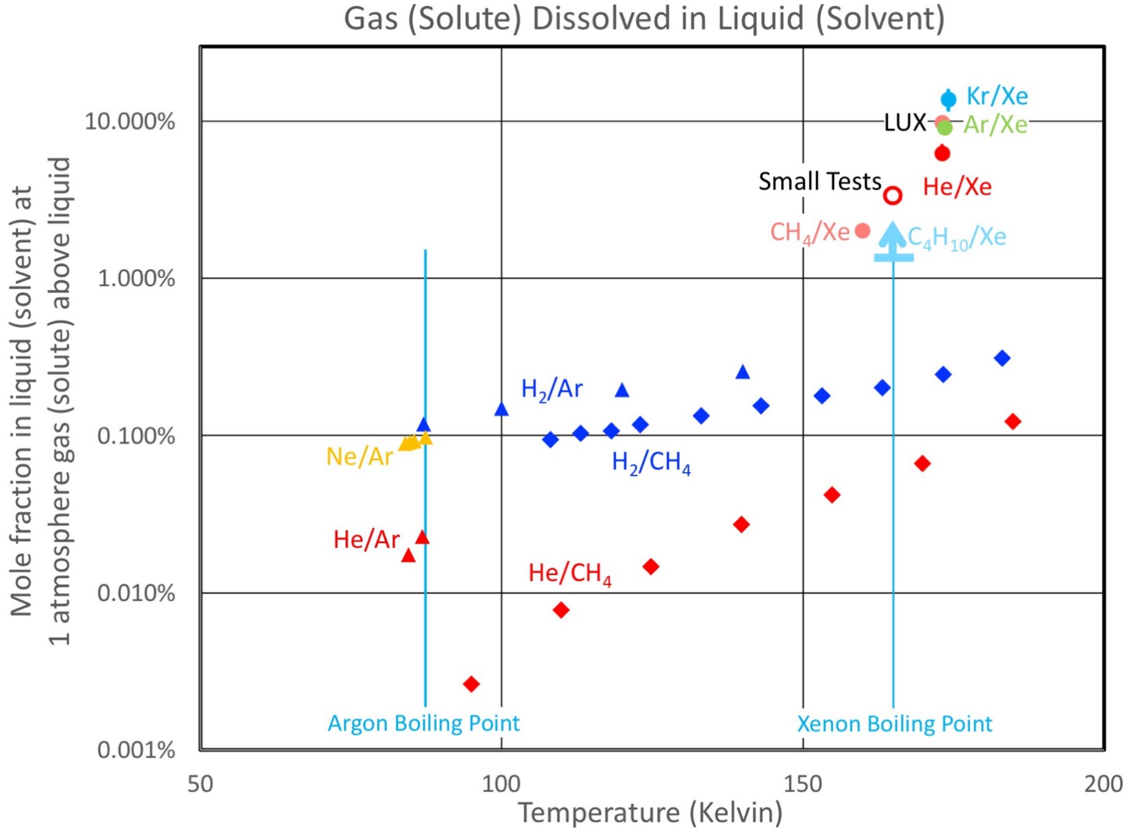


G2 Xe TPCs: LZ, XENONnT, PandaX-4T

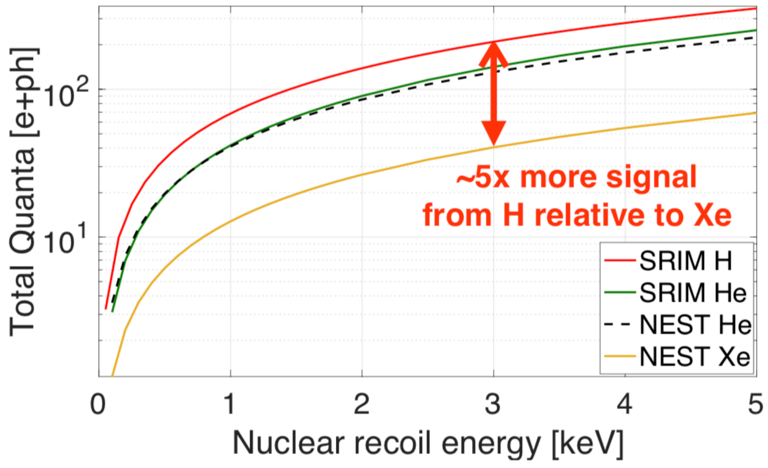
- S2/S1 discrimination between NR/ER
- $m_\chi > 8\ \mathrm{GeV}/c^2$ ($4\ \mathrm{GeV}/c^2$ S2-only)
- Self-shielding (1 MeV γ, 6 cm; 1 keV n, 9 cm)

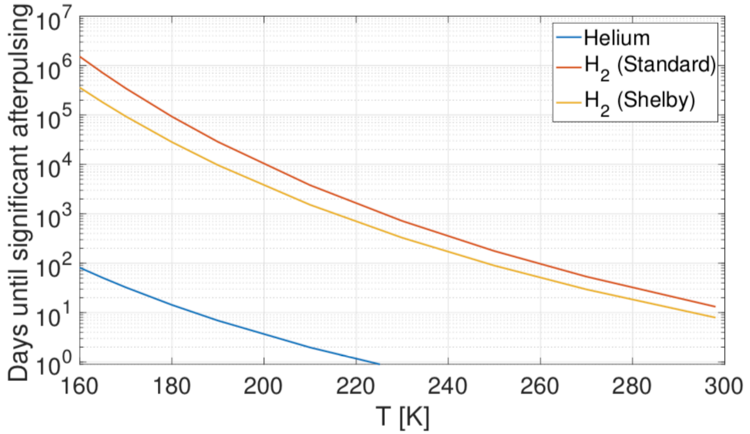
Hydrogen dissolved in Xe:

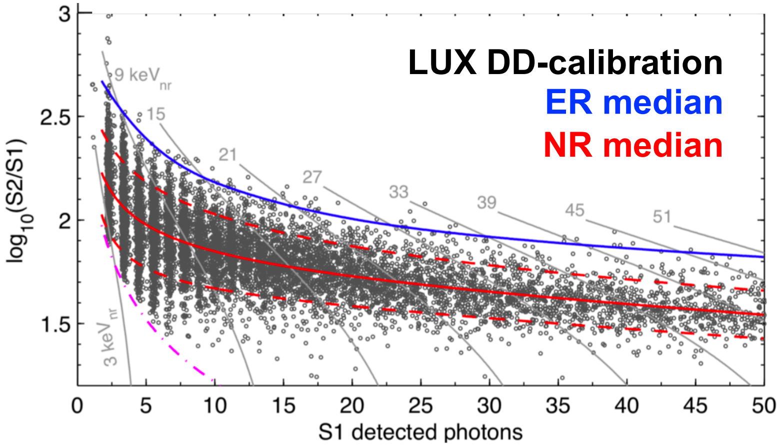
- LXe is excellent solvent for light gases
- Example: 2.6% mol fraction, ~2 kg H2 in LZ
- Better kinematic matching to low mass DM

Detection Techniques

- Dissolve H2 in LXe
- DM-H2 interactions:
  - DM scatters on H2 (proton)
  - Proton transfers energy to Xe ($m_H << m_{Xe}$)
  - Little energy lost to elastic scatters on Xe, more interactions with Xe e^-s: ~5x signal boost
  - Signals read out like any normal Xe TPC
- PMTs are safe: H2 less problematic than He
- Unclear whether H-recoils will have S2/S1 that is ER/NR/in-between-like
- Presence of H2 in the gas phase will negatively affect S2 gain, but allows higher extraction fields before breakdown
  - Garfield sims suggest 40 ph/e- achievable at 120% of the nominal LZ extraction field



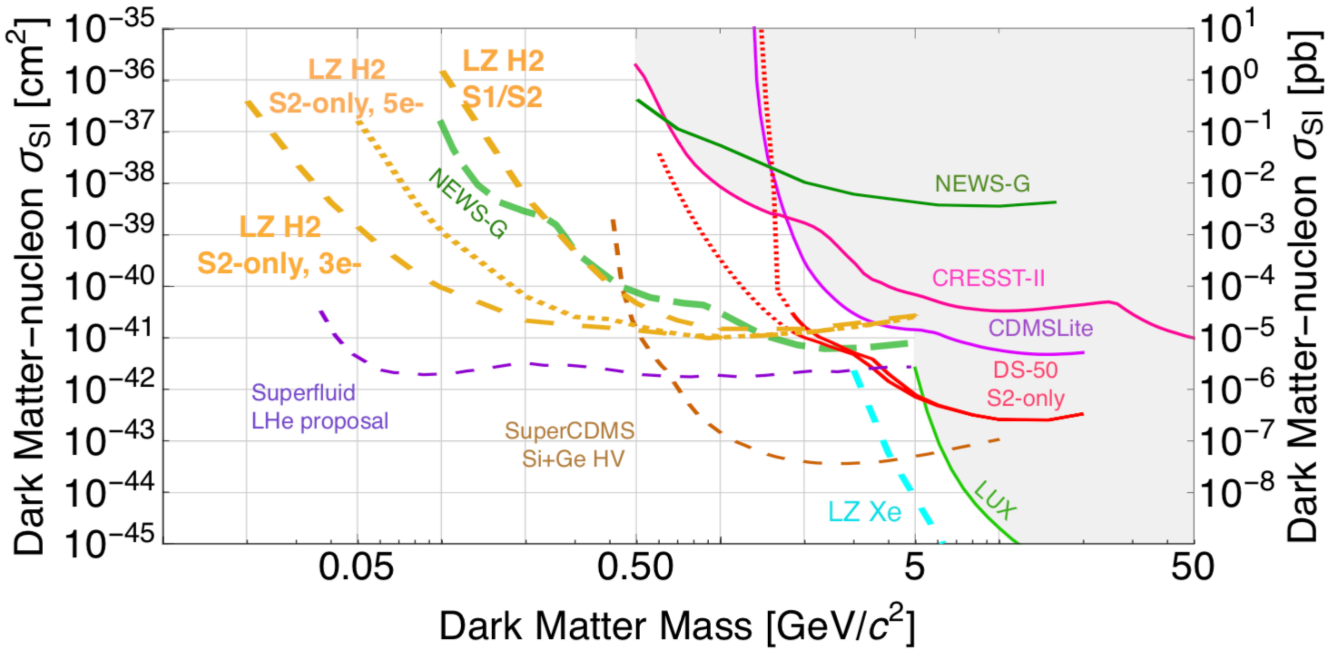


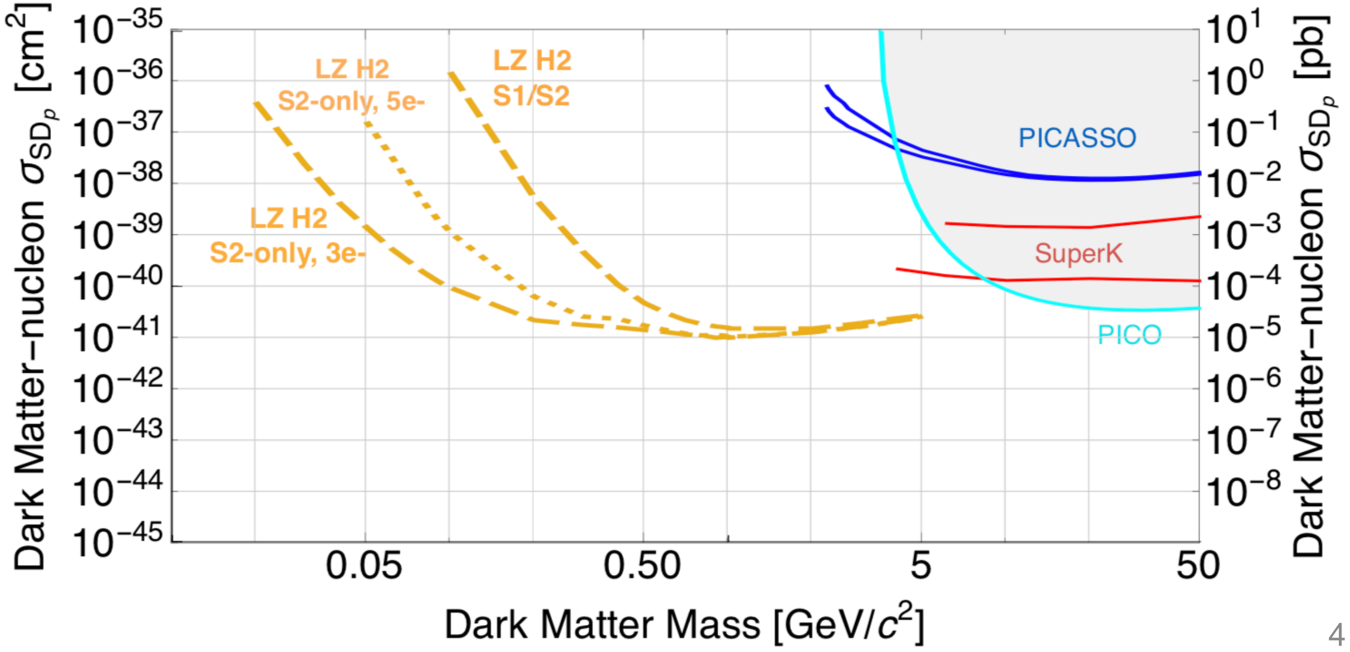


Sensitivity

Assumptions:

- H2 in LZ environment
- H2 mol fraction of 2.6%, 2.2 kg
- S2/S1 is ER-like (no discrimination)
- 250 live-day exposure



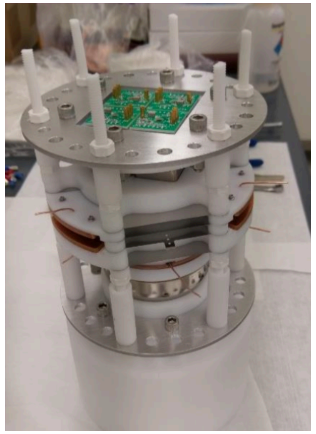


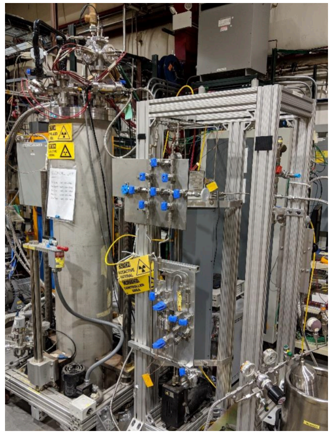
Proposed R&D

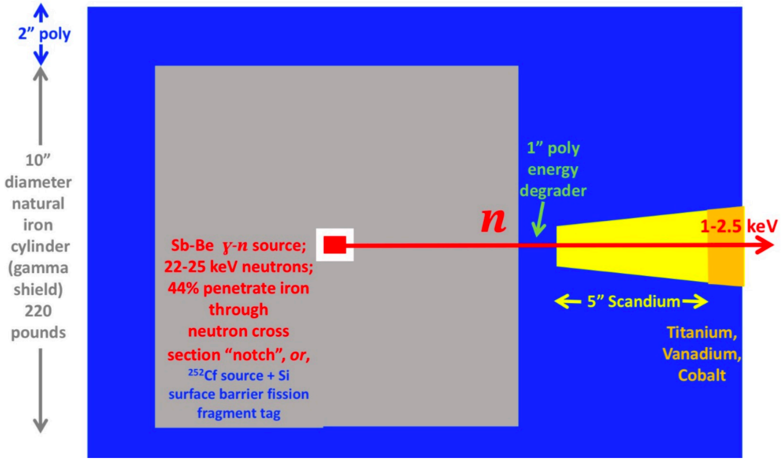
Will it work at all?

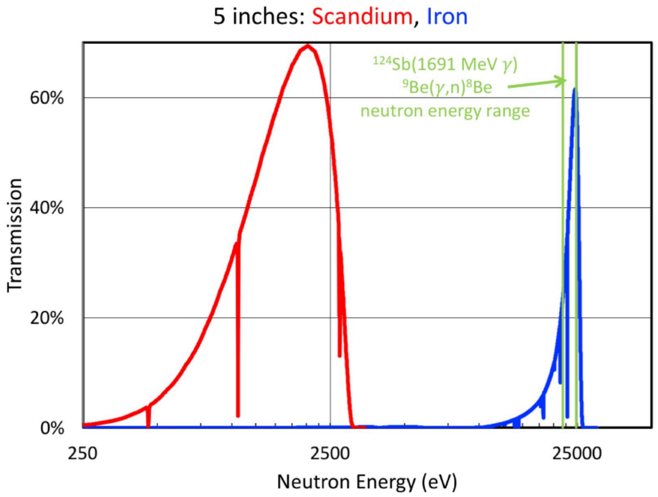
If it works, how do we calibrate it?

If it works and we calibrate it, can we make it work in a G2 Xe TPC?









Proposed R&D

Will it work at all? (XELDA test chamber at Fermilab)

- Measure Henry's coefficient, $H^{xp} \propto x/p$
- Quantify effect of H2 concentration on S1 & S2 yield, S2 gain, and anode breakdown voltage
- Preliminary Xe response to proton recoils

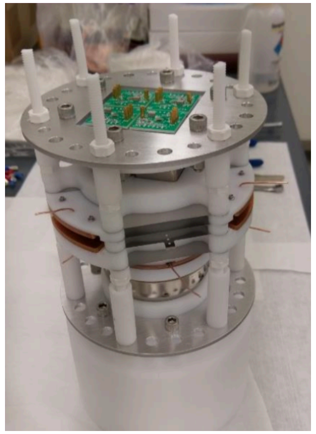
Calibration? Development of a low energy neutron source (UCSB/NU)

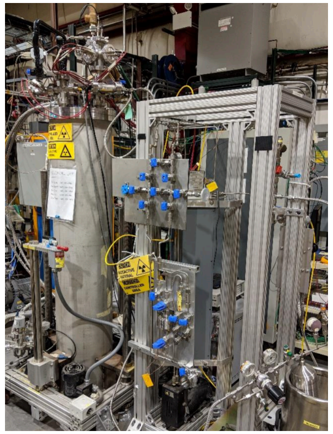
- keV Iron Neutron (keVIN)
- ^{124}Sb-^{9}Be source of 24 keV *n*, iron for γ attenuation and *n* E-selection, scandium conduit gives 1-2.5 keV *n*

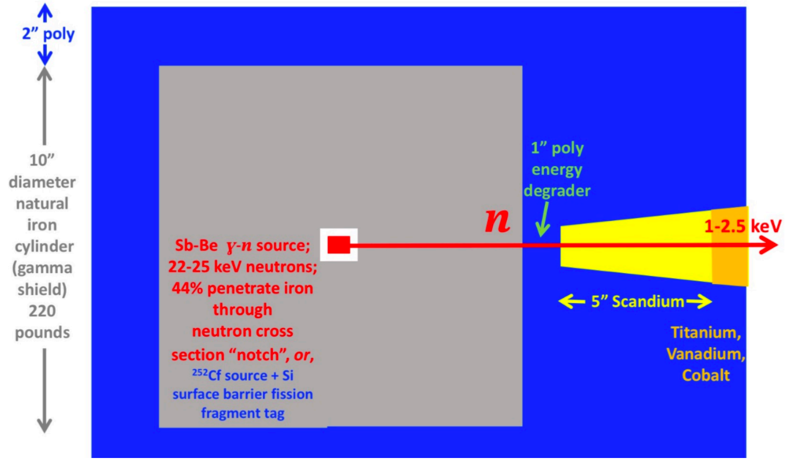
Can it work in a G2 Xe TPC? (cryogenic systems testing, Penn State)

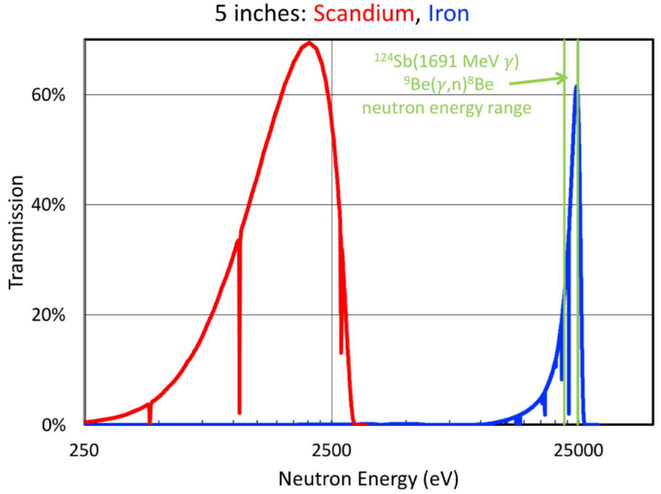
- Alternative purification (can't use Zi getters)
- Measure H2 diffusion in Xe. Requires forced convection?
- Can we efficiently remove H2 from Xe?

Follow up with larger scale circulation testing + low energy proton recoil calibration at SLAC





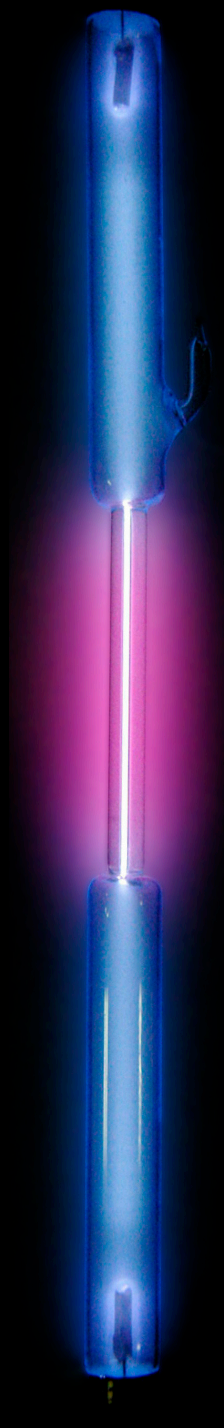




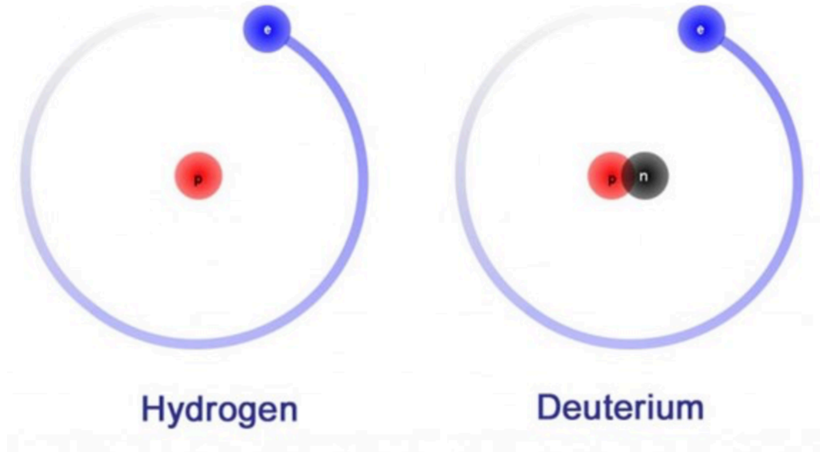
Future Prospects

- H-doping gives new capabilities to existing Xe TPC (LZ, XENON, PandaX)
- Take advantage of existing operations infrastructure
- Xe self-shielding, not available in a conventional low mass experiment
- Detector response and backgrounds will be *well understood* before H-run even starts!
- Probe 100 MeV/c^2 – 5 GeV/c^2 DM masses, with SI and SD sensitivity

Backups



Deuterium



- Only stable p-odd AND n-odd nuclide

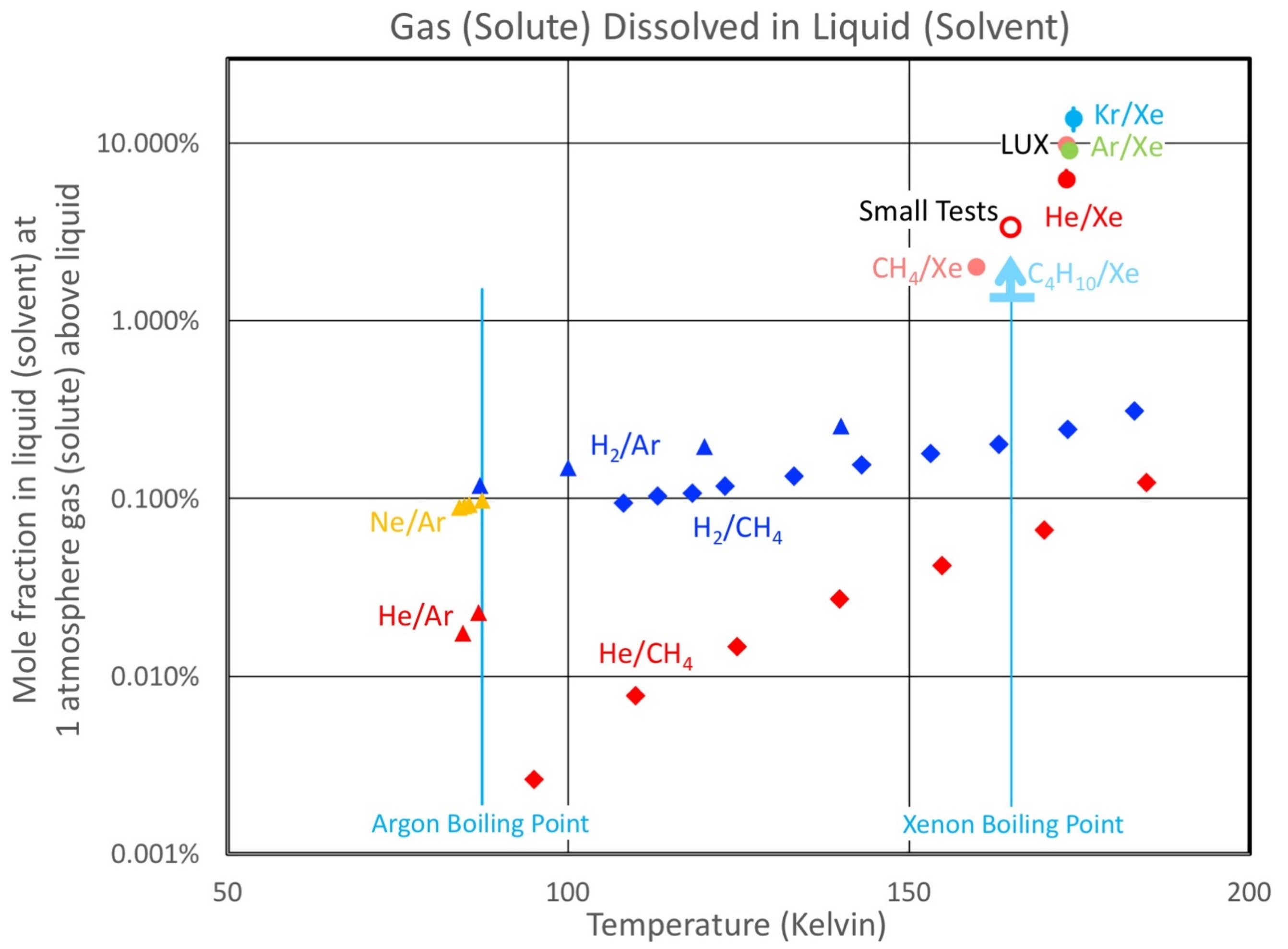
- Substitution of deuterium for H2 (with the same assumptions) shifts SI sensitivities down x4 and to the right by √2

- Provides sensitivity to SD DM-neutron interactions, sensitivity comparable to H2 SD interactions with a shift to the right by √2

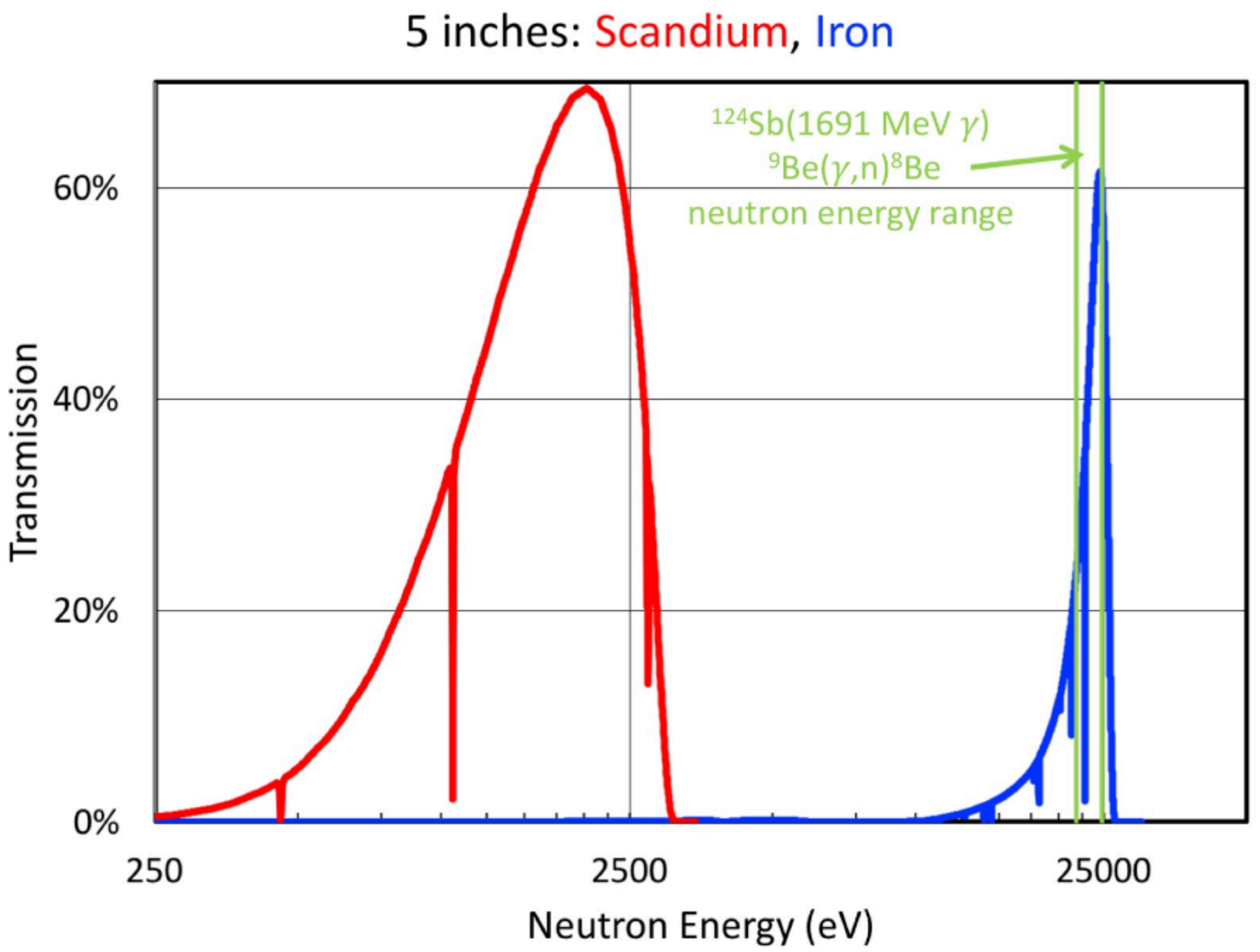
- Plan to do deuterium measurements in parallel with H2

Dissolving H2 in LXe

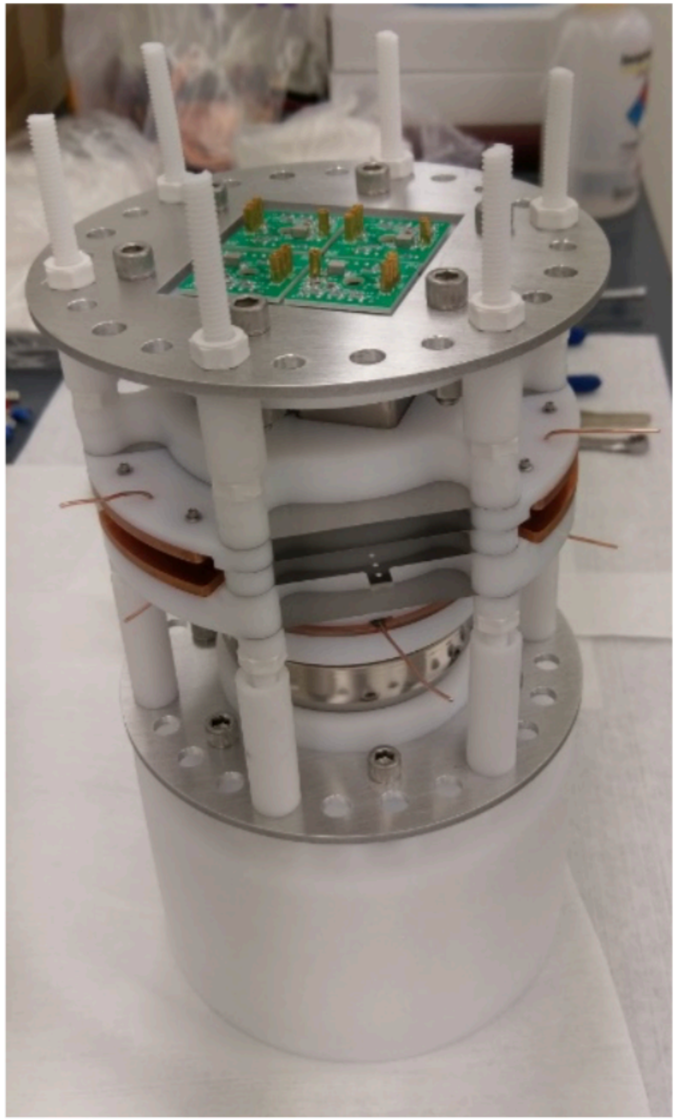
- Henry's law: solute (H2) concentration in liquid (Xe) is proportional to partial pressure in the gas phase
- Increased solubility of a gas in liquid is correlated with a deeper minimum in the Van der Waals potential (H2 is 3x that of He)
- Xe is an efficient solvent because of its deeper VdW potential
- Solubilities increase as a function of temperature
- Extrapolation of existing measurements suggests 5% (2.6% conservative) H2 fraction is achievable

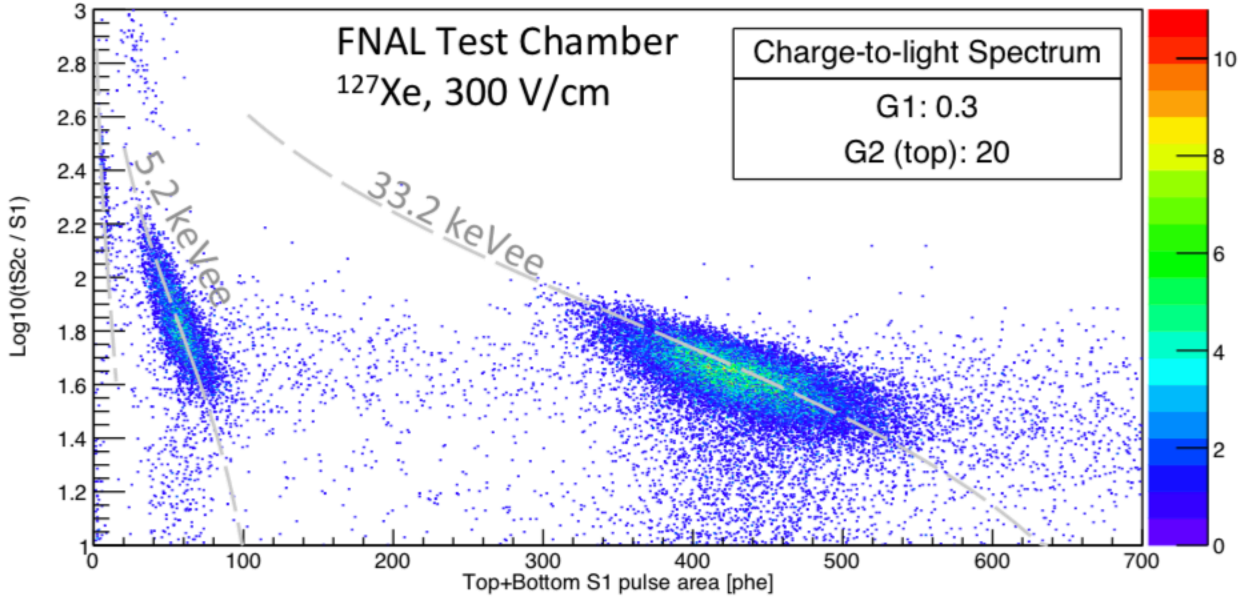


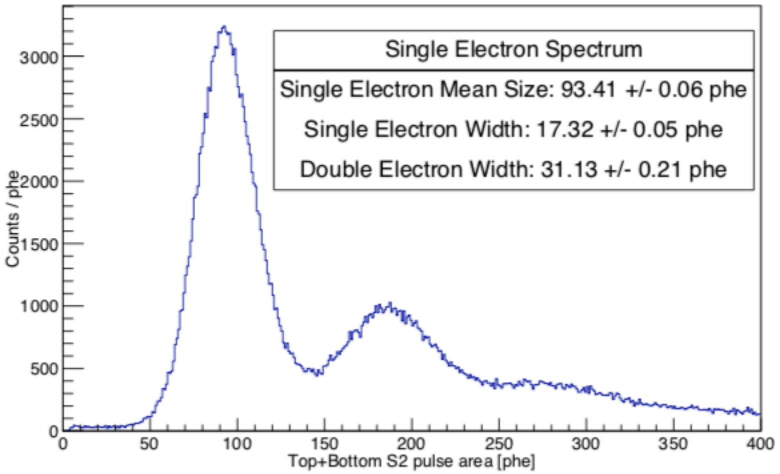
Iron/Scandium Transmission

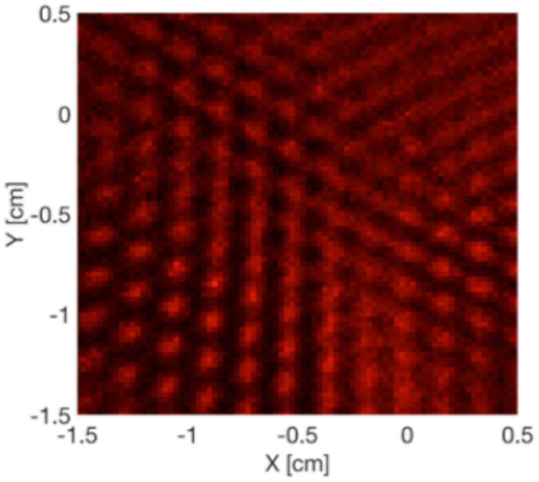


XELDA



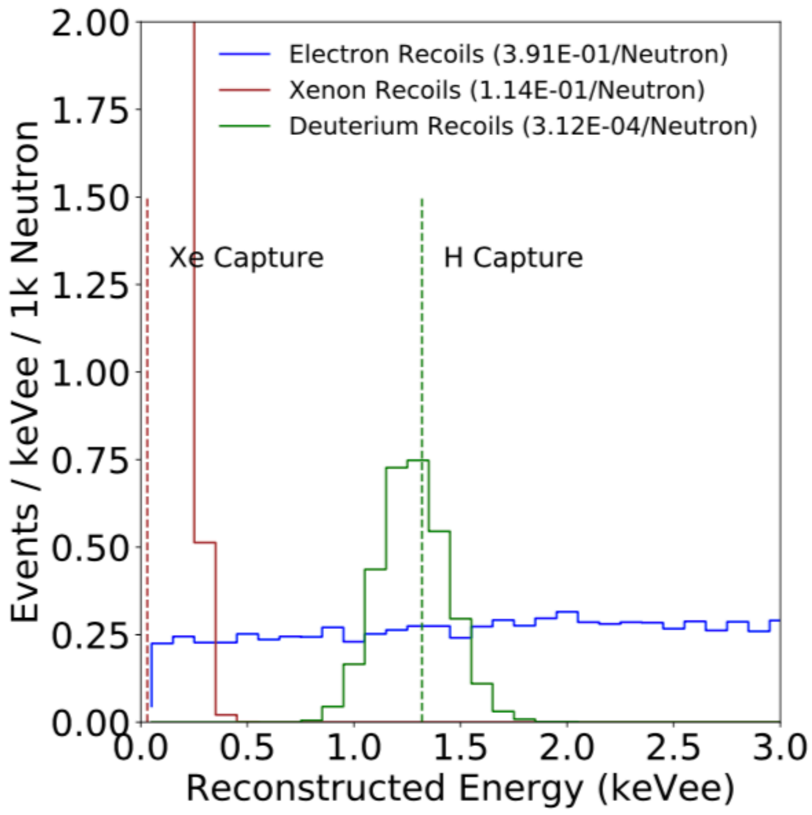

FNAL Test Chamber
127Xe, 300 V/cm
Charge-to-light Spectrum
G1: 0.3
G2 (top): 20
5.2 keVee
33.2 keVee
Log10(tS2c / S1)
Top+Bottom S1 pulse area [phe]

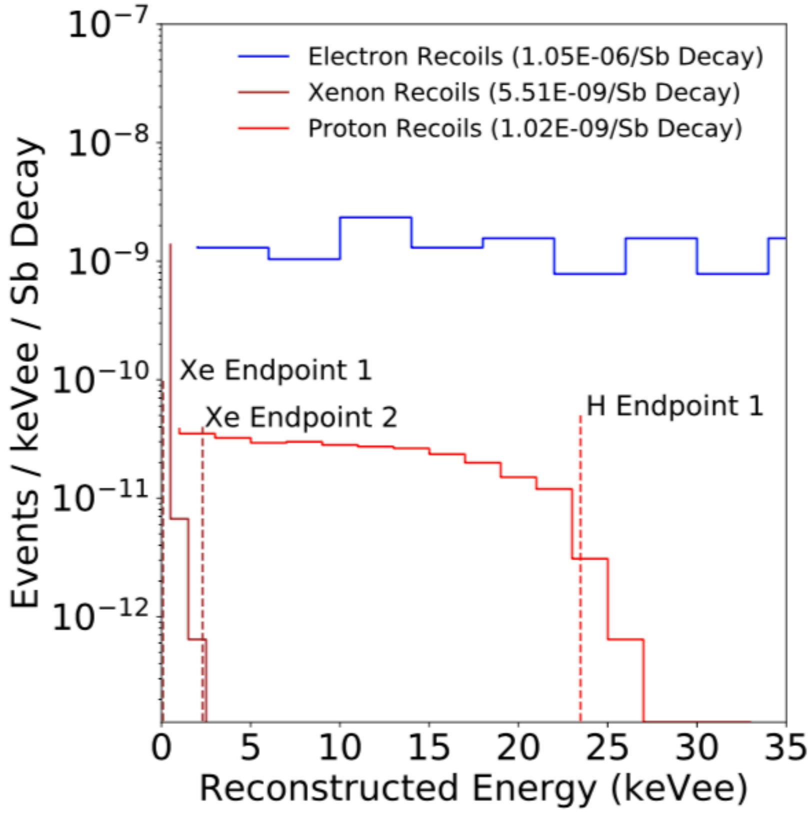

Single Electron Spectrum
Single Electron Mean Size: 93.41 +/- 0.06 phe
Single Electron Width: 17.32 +/- 0.05 phe
Double Electron Width: 31.13 +/- 0.21 phe
Counts / phe
Top+Bottom S2 pulse area [phe]


Y [cm]
X [cm]

XELDA

- MCNPX-Polimi simulation
- Left: thermal neutrons
- Right: simplified keVIN source





- Due to XELDA's size, can get mono-energetic source of 1.3 keV deuterium recoils from neutron capture on protons (gamma escapes)
- Xe capture happens at higher rate, but has very low energy recoil
- Endpoints 1 and 2 correspond to maximum energy recoils for SbBe: 24 keV (98%), 379 keV (2%)

Timeline

- Jun 2020 – Operate Xe TPC with dissolved H2
- Mar 2021 – Measure >1 keV proton recoil yields
- Dec 2021 – Demonstrate efficient injection/removal of H2 from Xe
- Jan 2023 – Operation of H2-doped ~30 kg LXe TPC @ SLAC
- Dec 2023 – Development of project plan and design report
- 2025 – Tentative end of LZ science run