RADON REMOVAL STUDIES FOR NEXT-GENERATION XENON TPCS

Simran Dave

With Liam Sherman, Tomasz Biesiadzinski and Tom Shutt
(SLAC National Accelerator Laboratory)

simran.dave.23@ucl.ac.uk

LUX-ZEPLIN

World-leading WIMP dark matter experiment

Dual-phase xenon **T**ime **P**rojection **C**hamber

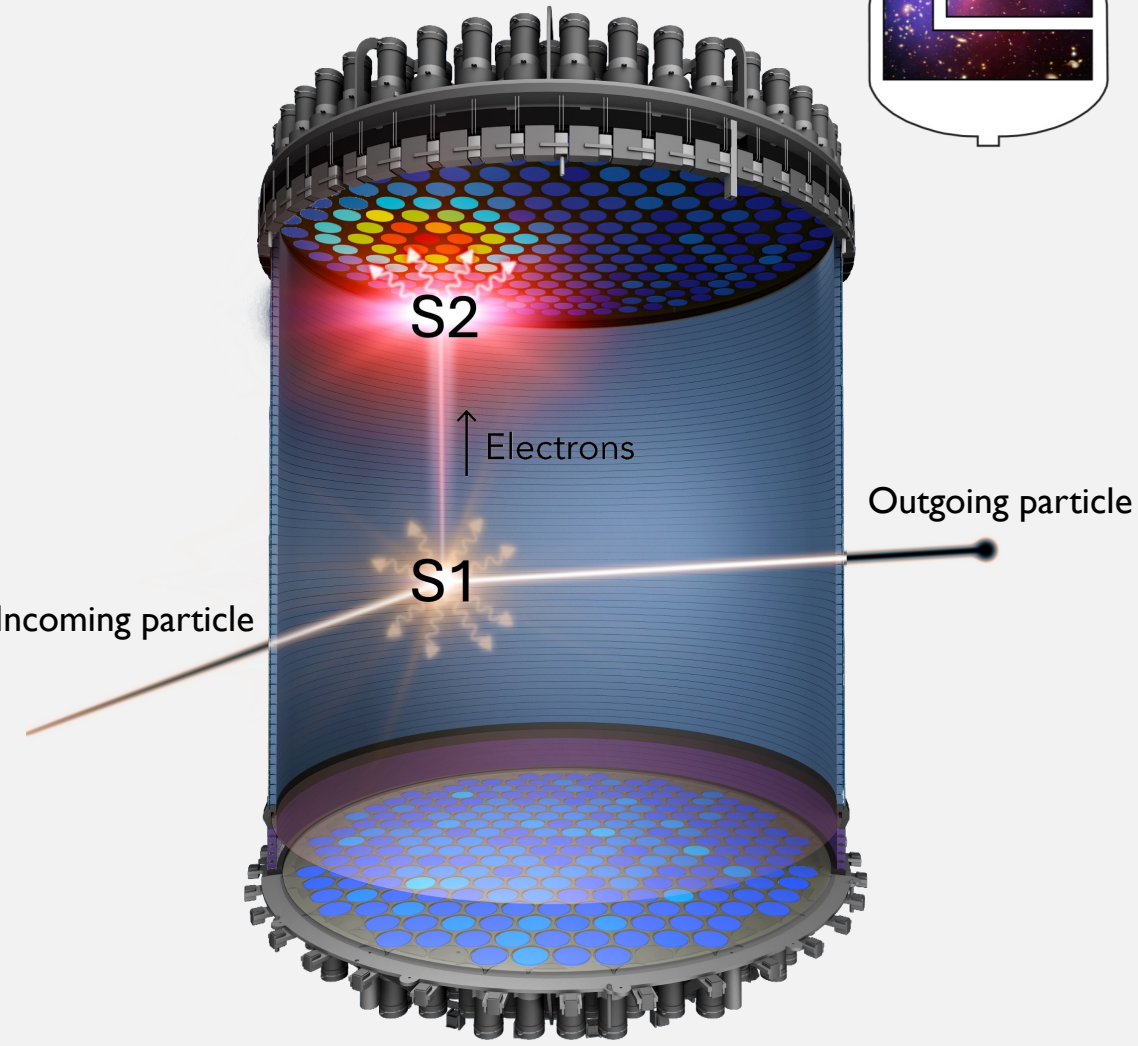
7 tonnes active liquid xenon target

Two signals:

- S1- prompt scintillation photons
- S2- ionisation electrons

S1/S2 ratio → Electronic (ER) / nuclear recoil discrimination (NR)

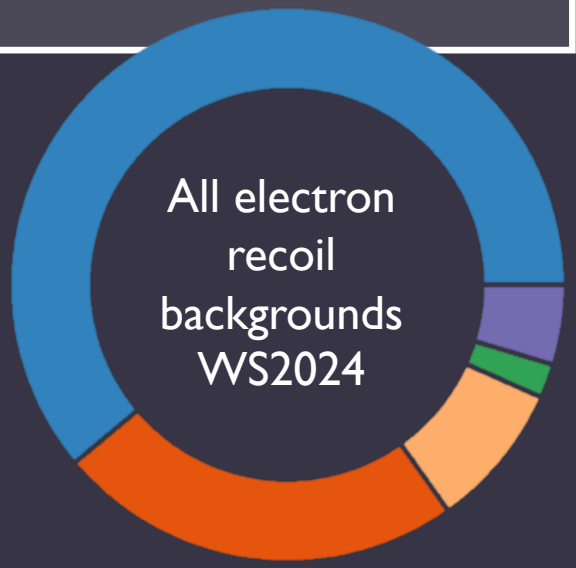
WIMPs expected to interact via NRs

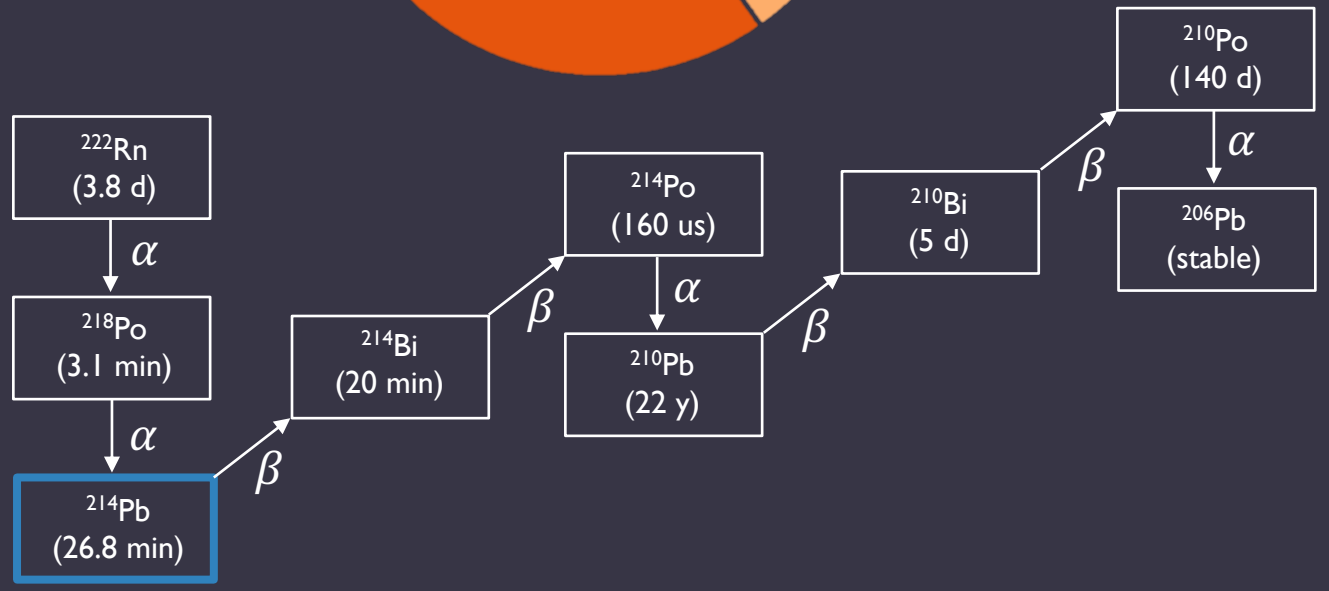


RADON

- ^{238}U naturally exists in most materials
- Decays via a sequence to ^{222}Rn
- Radon is
  - A chemically inert noble gas
  - Hard to shield against
  - Difficult to remove chemically
  - Long half life ($\tau_{1/2}$ ^{222}Rn = 3.8 days)

→ Emanates from detector materials into the active volume





^{214}Pb: Dominant background (~60% of ER)
can appear WIMP-like

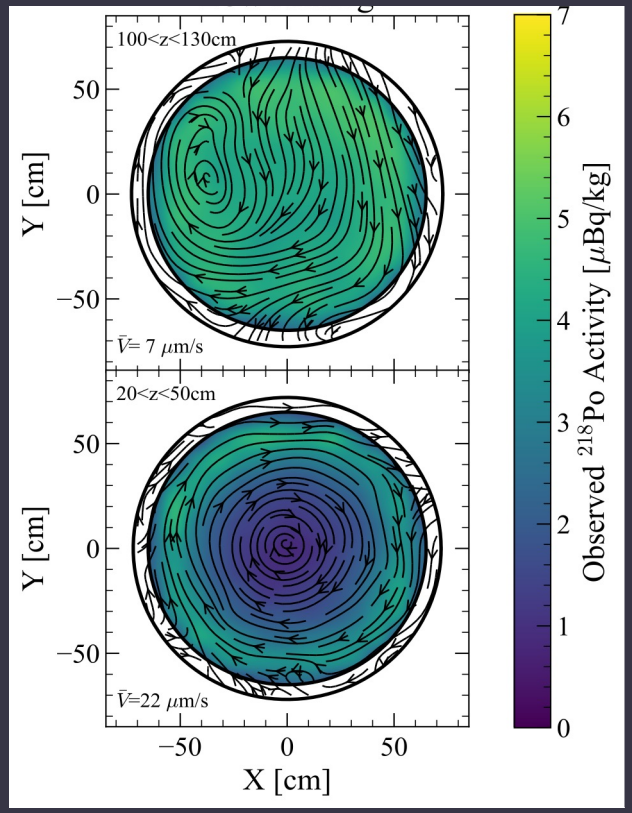
WHAT DO WE CURRENTLY DO?

Multiple strategies employed to target radon background

- 5 year **materials screening** campaign was conducted [1]
- WIMP search 2025 introduced a data-driven technique to our analysis: **flow-based radon tagging** [2]
- **Inline radon removal system** in circulation loop reduces radon concentration in gaseous xenon

Techniques together reach untagged activity levels of 1.8 μBq/ kg

Screening for radon contamination
[1] https://doi.org/10.1140/epjc/s10052-020-8420-x

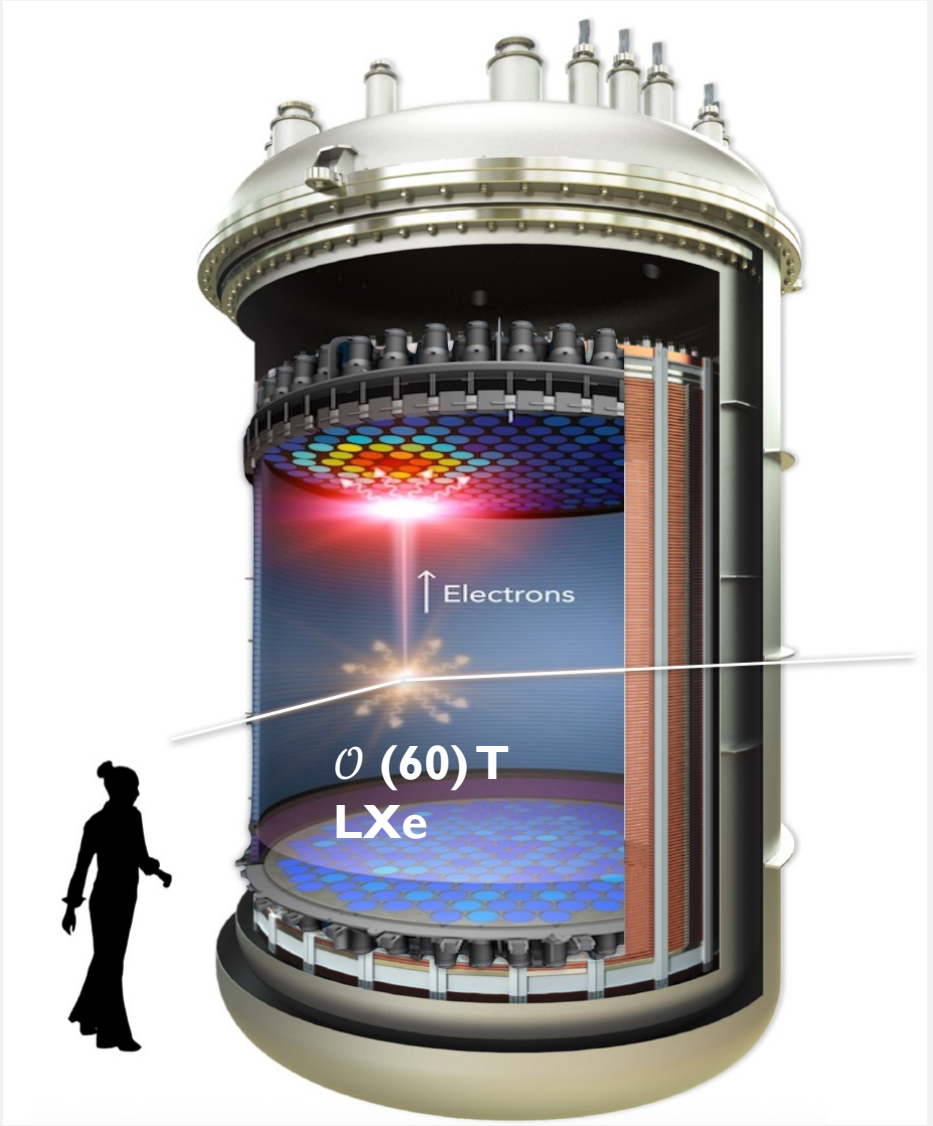


Xenon flow plots – used to track the path of radon decay products
[2]https://doi.org/10.48550/arXiv.2508.19117

XLZD

- Next-generation dual-phase xenon TPC
- Combine the expertise built up by XENON and LZ experiments and the DARWIN R&D project
- $\mathcal{O}(10)$ times the size of current-gen TPCs
- Observatory for rare events- not just WIMP dark matter
- Requires ^{222}Rn activity ~ 0.1 μBq/kg for sensitivity to $0\nu\beta\beta$

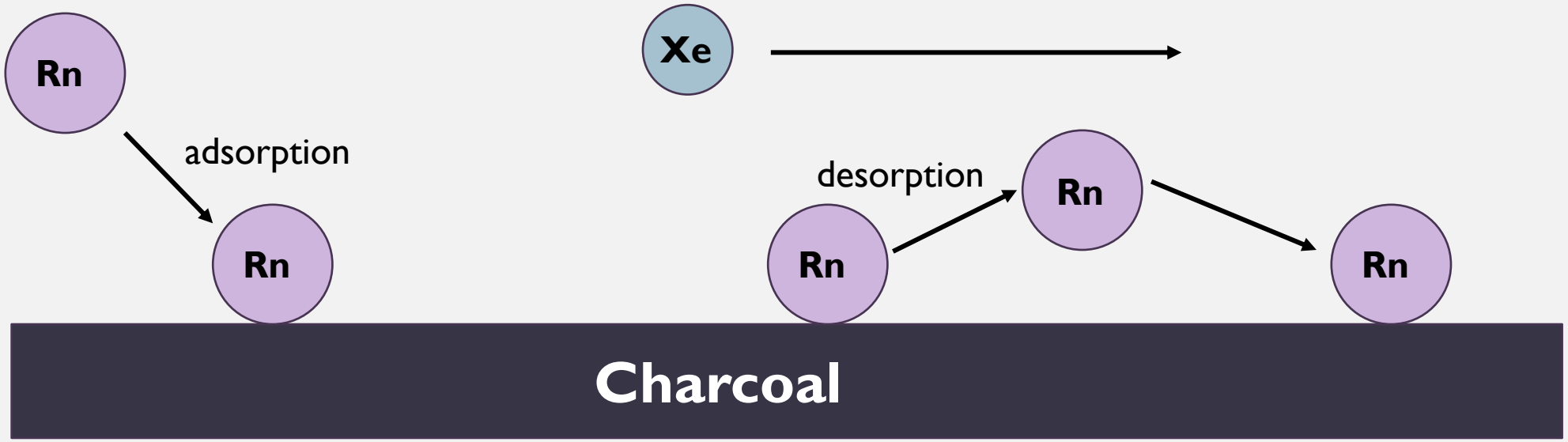
→ More stringent background controls required. One way of achieving this could be upgrading the inline radon removal system (iRRS).



THE IRRS: CHROMATOGRAPHY BASICS

- Chromatography is a technique to separate a mixture into its components
- The different components can interact with a chromatography medium differently, causing some to adsorb (stick) to the surface more than others.
- Radon and xenon interact with carbon via the van Der Waals interaction
- Radon is a larger atom so it is more polarisable → stronger van Der Waals

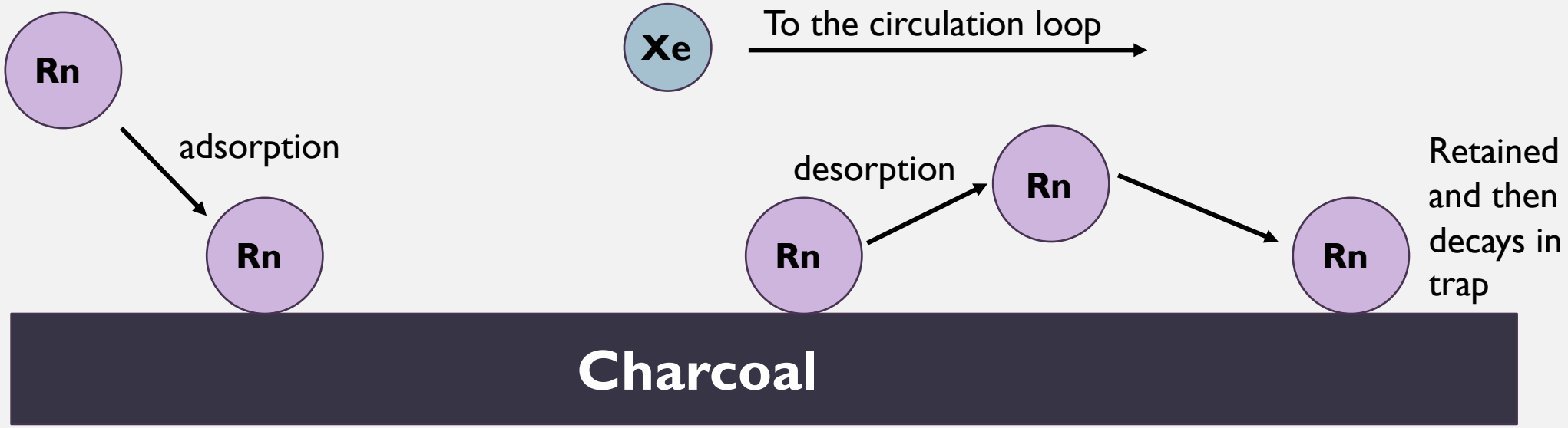
→ **It is adsorbed more easily**



THE IRRS: SCALING UP

- LZ iRRS consists of a single adsorption trap which takes gaseous xenon from the warm regions of the TPC, and passes it through a charcoal chromatography column
  - Radon is retained long enough (~3 half-lives) such that it decays while in the trap
  - Purified xenon is returned to main circulation loop
- Charcoal is also a source of radon! Scaling up the system to XLZD size: charcoal needed would emit more radon than it removes
- Removing radon purely from gaseous regions would not meet XLZD requirements

→ An alternative approach is necessary



SWING SYSTEMS

State 1:

- Radon removed from liquid xenon in one column
- Most of the purified xenon returned to circulation loop
- Some is passed through second column to purge it

State 2:

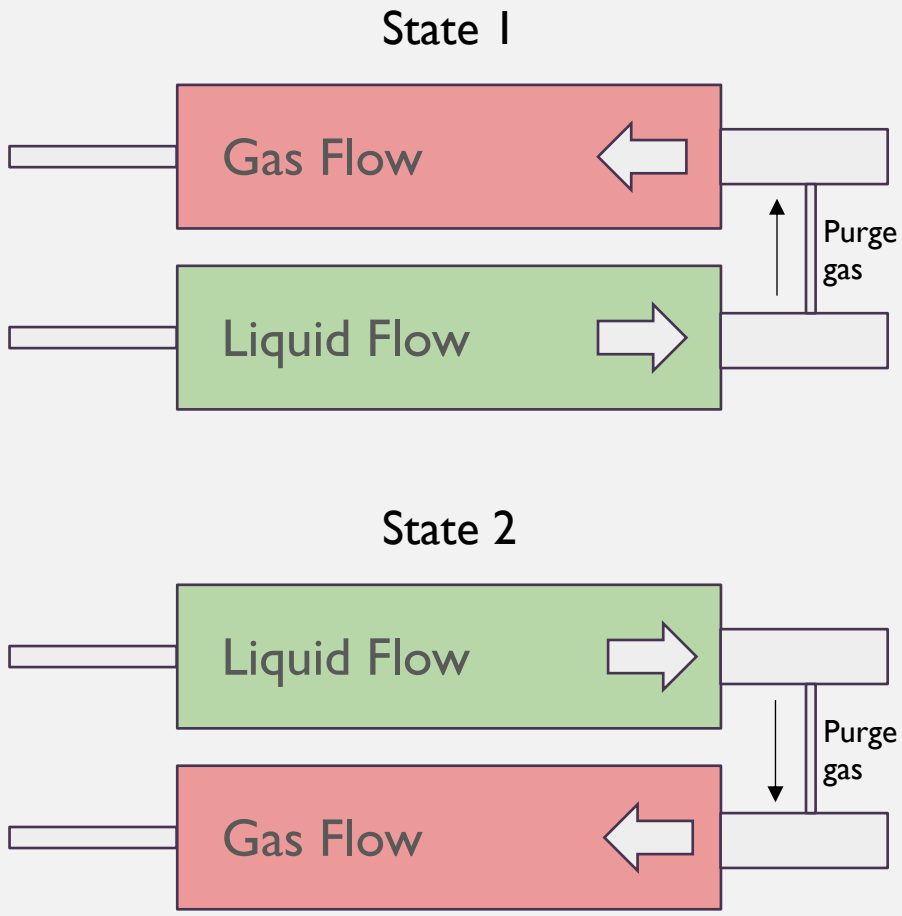
- Flow switches: now purging column where radon was removed and using the other column to purify

✓ Continuous radon removal

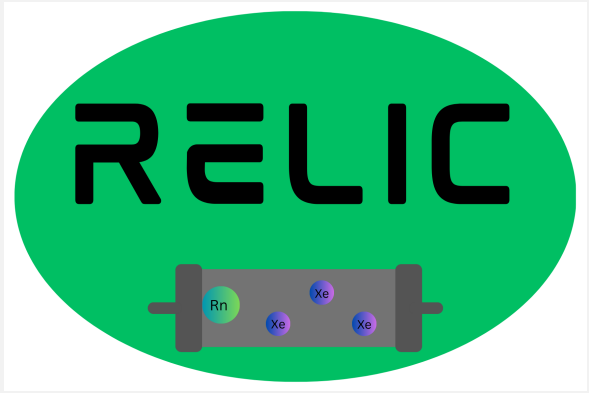
✓ Can be part of main circulation loop

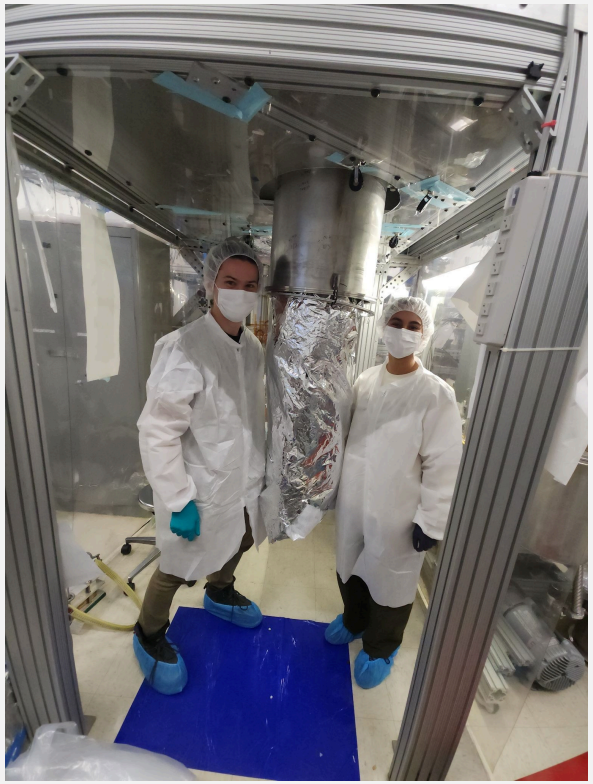
✓ System can be smaller → less charcoal required!

This all rests on the ability to use chromatography to remove radon from *liquid* xenon - which has never been tested before



INTRODUCING: RELIC

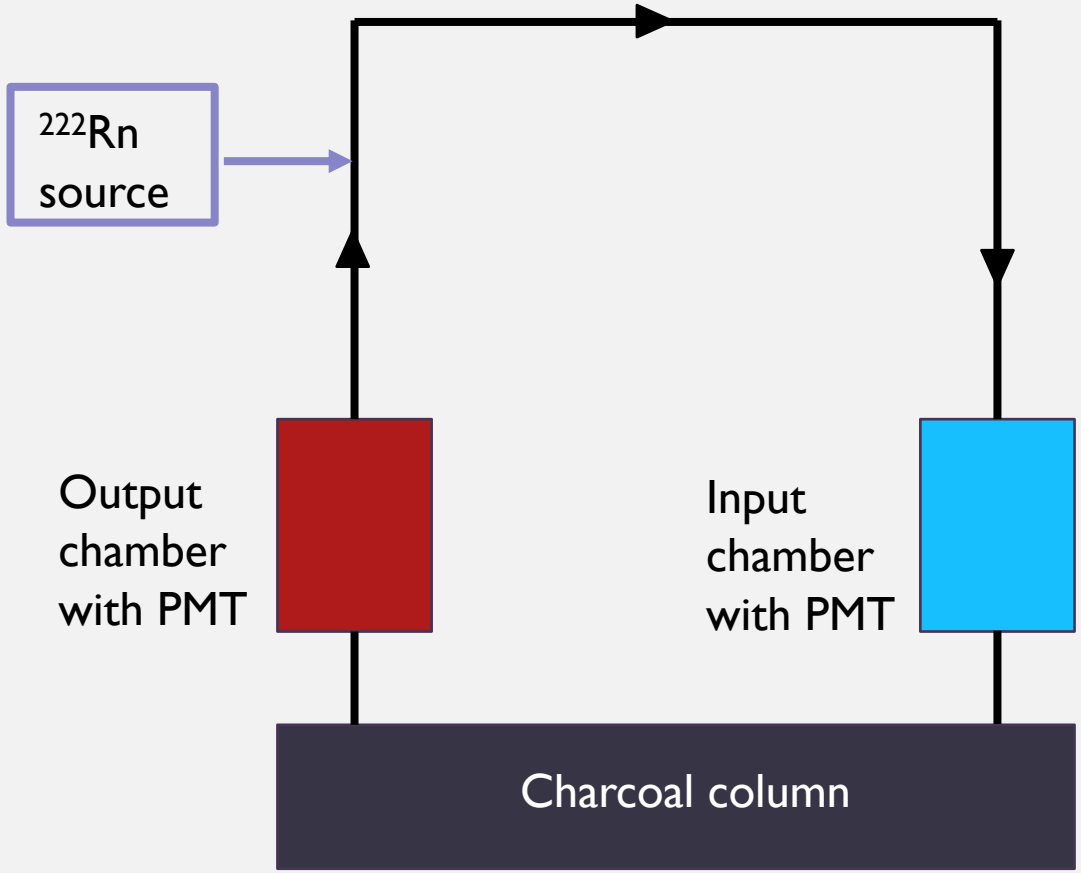




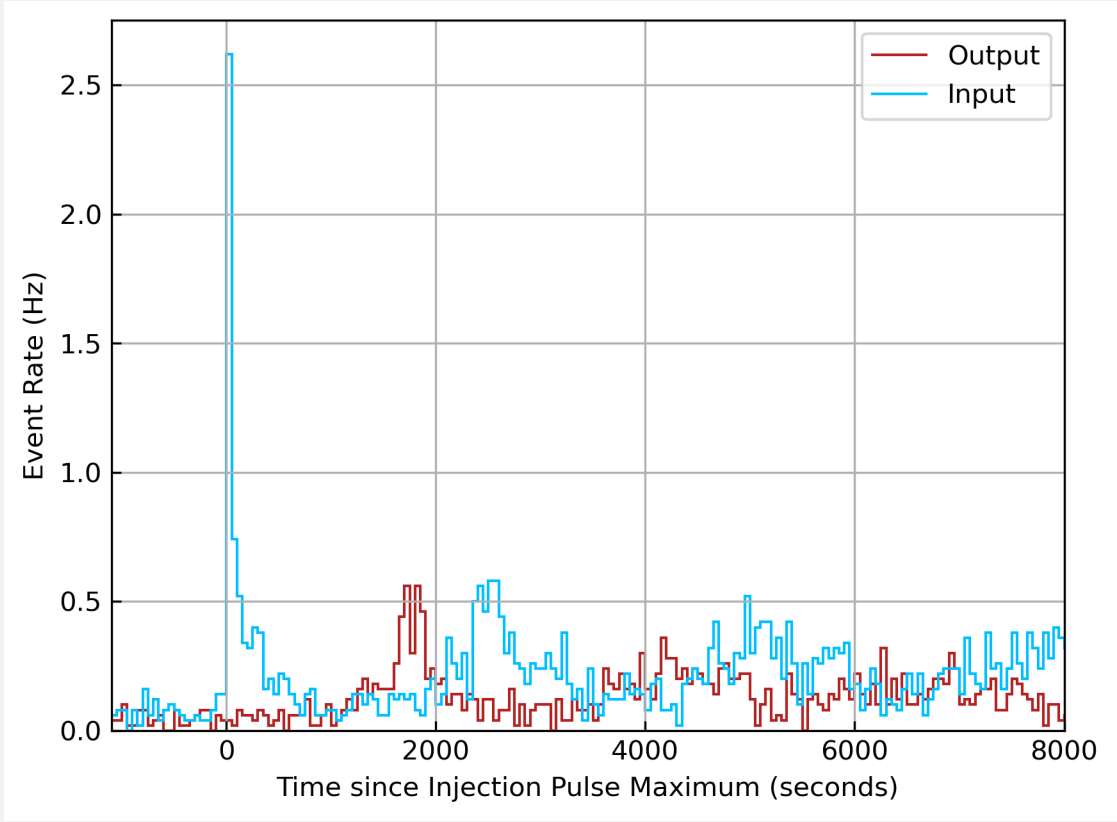
- Efficacy of radon removal is described by the adsorption coefficient, k_a (l/g)
- Measures how well radon binds to charcoal relative to xenon
- ReLIC: **Re**moval of **L**iquid **I**mpurities via **C**hromatography
- Test setup based at SLAC, US National Lab
- Designed to measure k_a

GAS MEASUREMENTS

Circulation loop: continuously flows Xe and Rn through the system

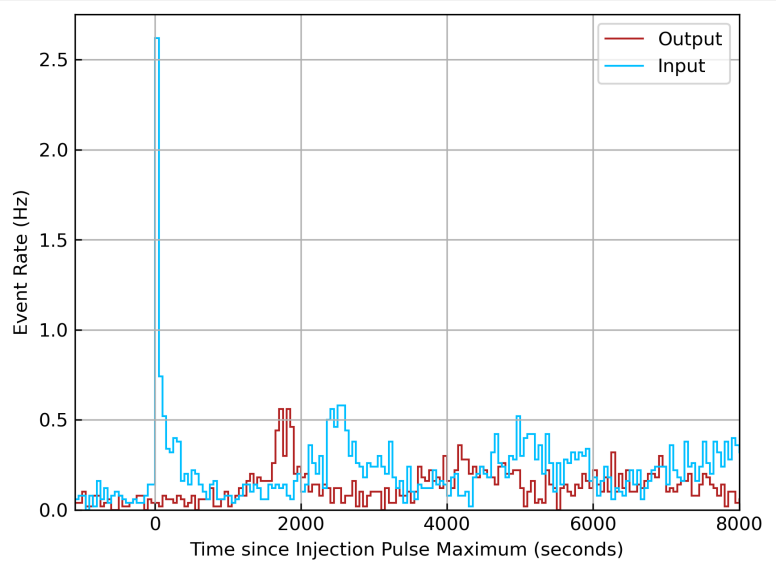


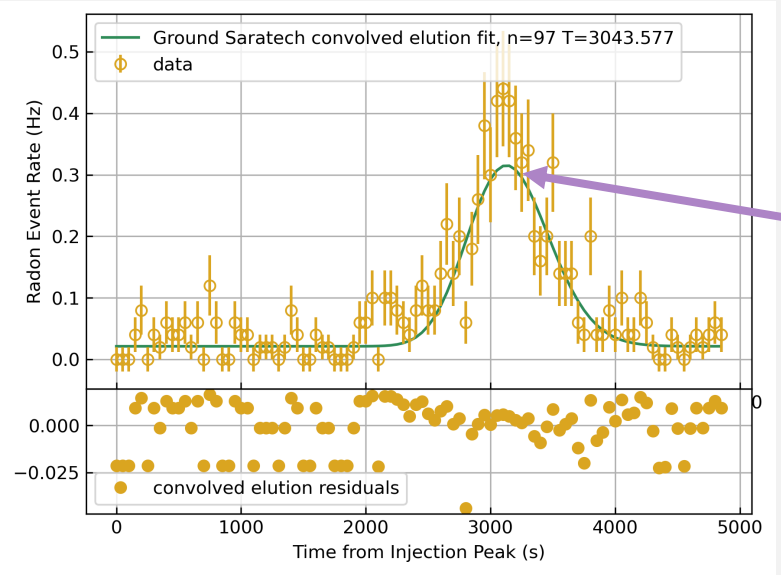
Simplified diagram of the setup



Radon decay rate in the two PMTs
Blue: radon event rate before charcoal column
Red: radon event rate after charcoal column

GAS MEASUREMENTS





- Adsorption coefficient depends on the breakthrough time – how long it takes radon to pass through the column relative to xenon
- This can be extracted from the time difference between the **input** and **output** pulses
- **Input** pulse in gas is sharp- we take this time to be the same as time of injection
- A curve* is fit to determine the time of the **output** pulse. This procedure will be especially useful in the liquid results

* *Elution curve*. A standard curve that material passing through a chromatography column should follow

GAS MEASUREMENTS

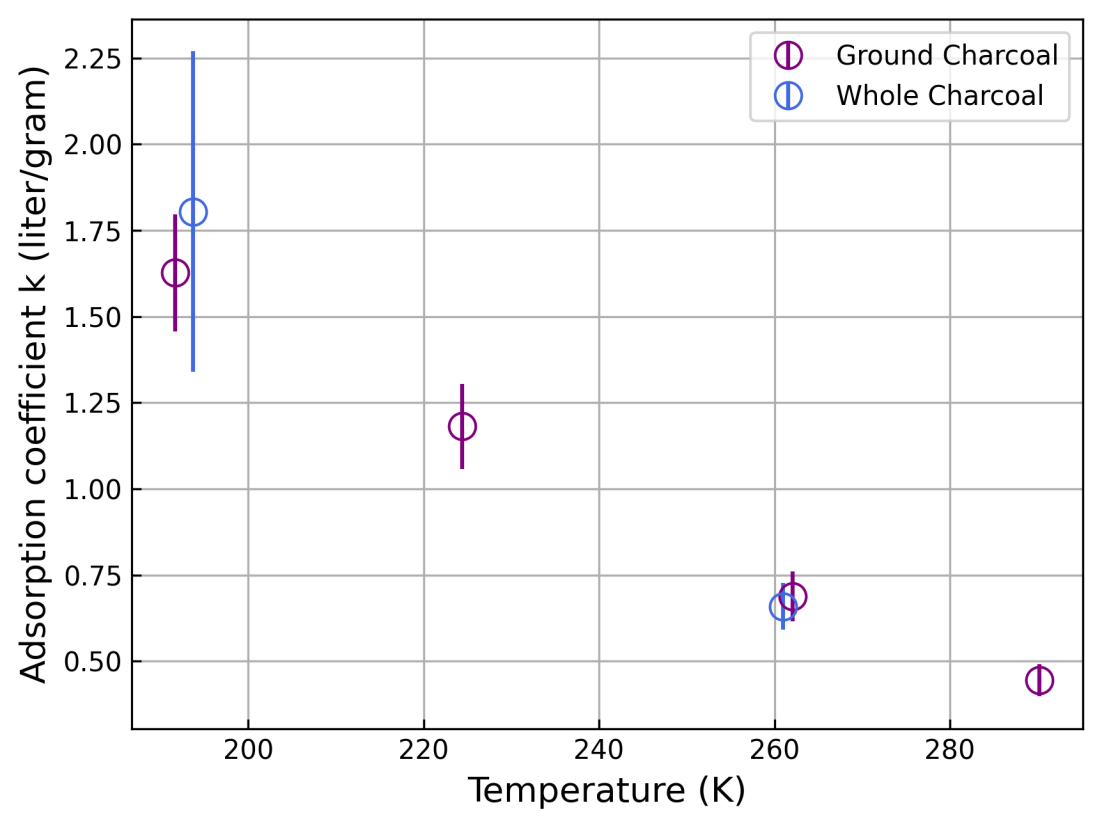
Breakthrough time from elution curve

Xenon flow rate

$$k_{gas} = \frac{T \times \phi}{M}$$

Our parameter of interest!

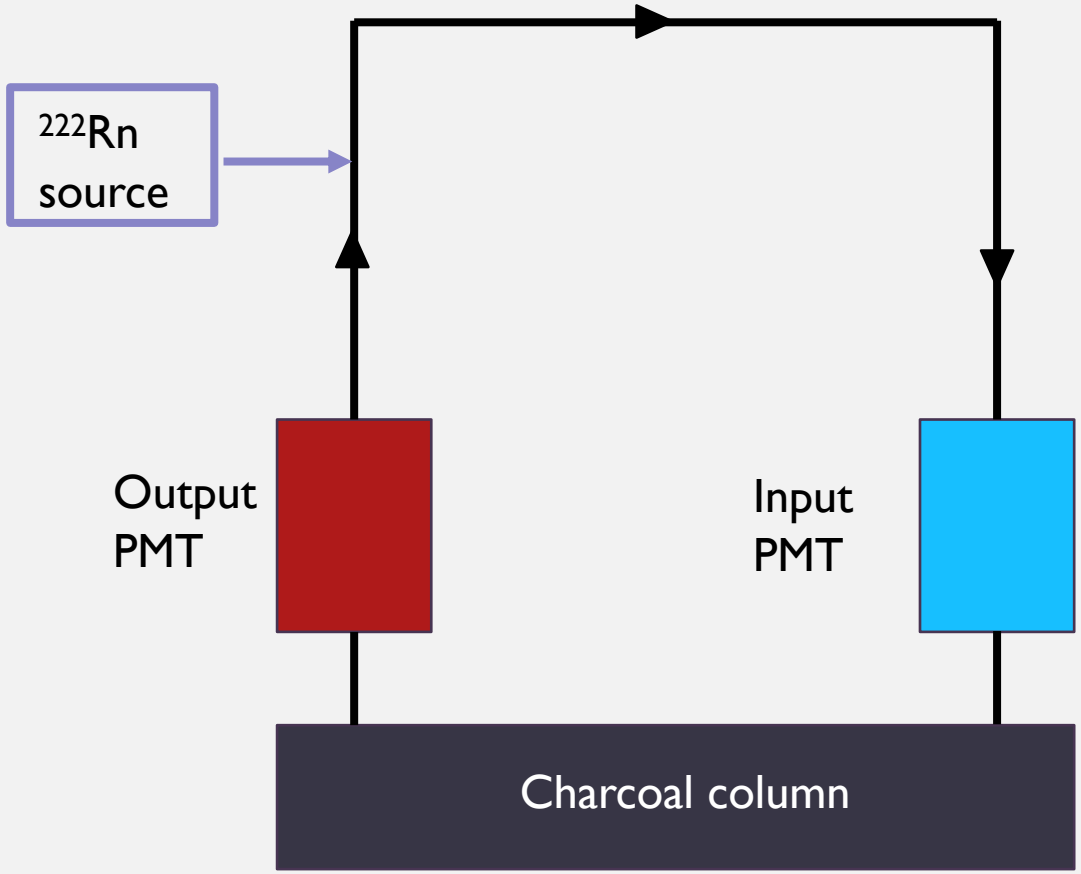
Charcoal mass

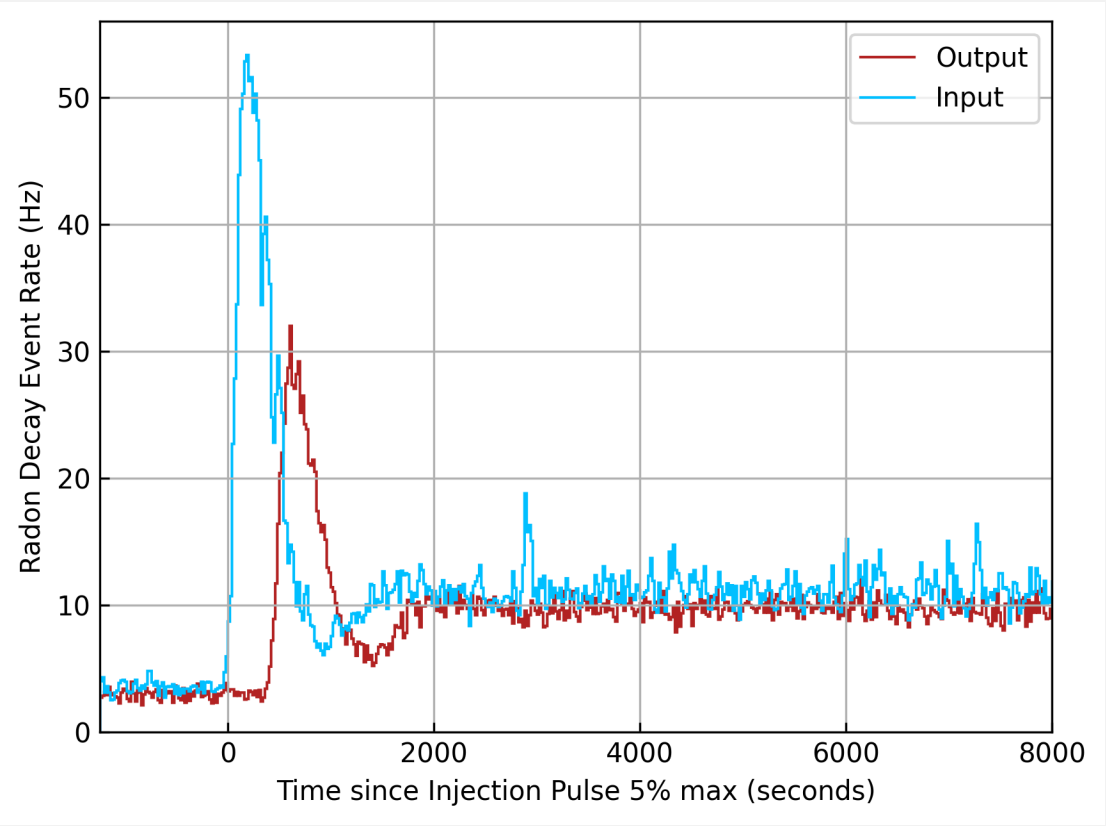


Measured adsorption coefficient as a function of temperature
Two runs with different sizes of charcoal beads are shown, to determine the effect surface area has on k_{gas}

LIQUID MEASUREMENTS

Circulation loop: continuously flows Xe and Rn through the system





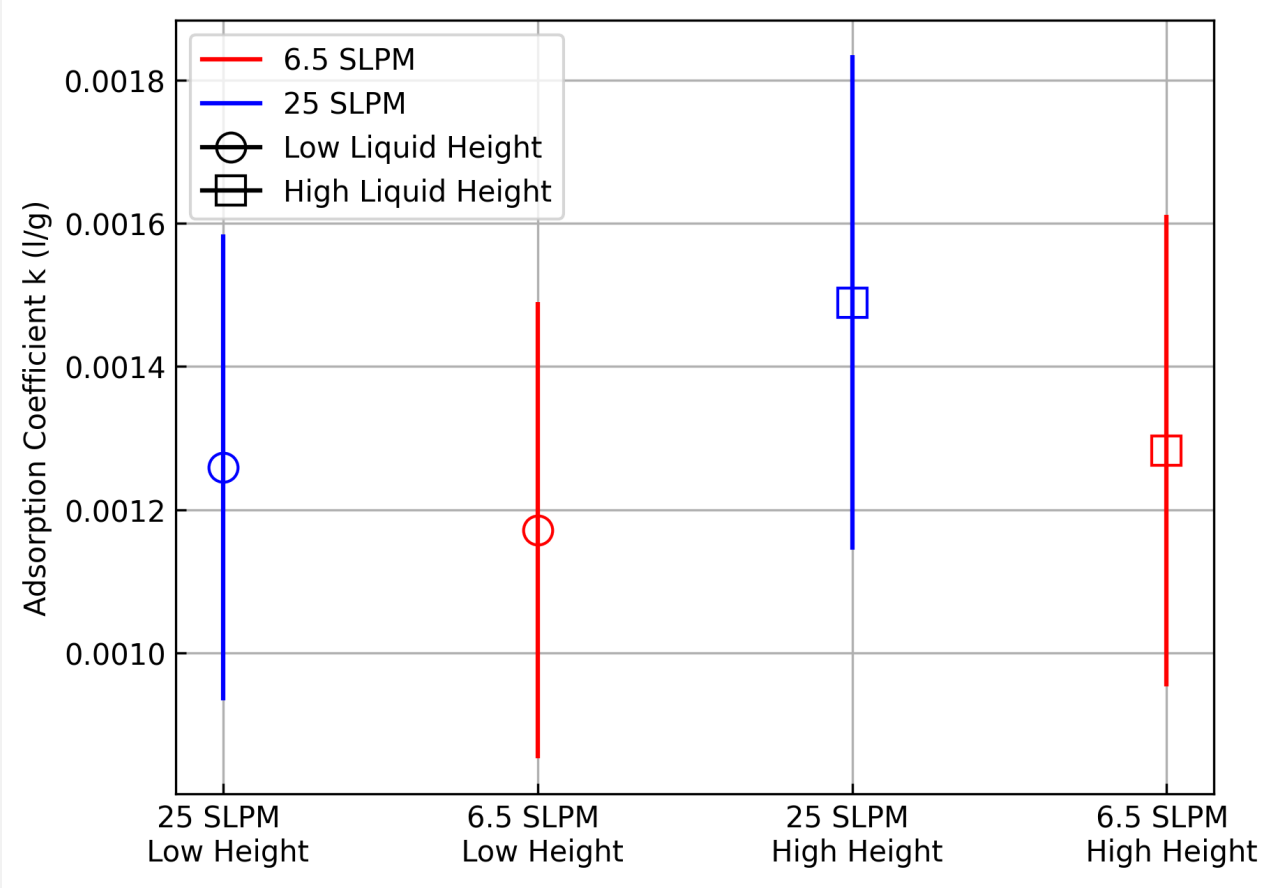
Radon decay rate in the two PMTs

Blue: radon event rate before charcoal column

Red: radon event rate after charcoal column

LIQUID MEASUREMENTS

- Adsorption coefficient 3 orders of magnitude lower than in gas
- No significant effect in changing the flow rate of xenon
- Different liquid heights correspond to different thermodynamic conditions, again no significant effect
- Not enough to make liquid phase radon removal feasible



Adsorption coefficient in liquid xenon for a range of flow rates and liquid heights in the inlet liquid Xe reservoir

REFLECTIONS AND FUTURE WORK

- In gas, chromatography performance increases as we lower the temperature
- Previous studies indicated that at these cold gas temperatures, the density of xenon in the column approaches 1/3 of the density of liquid xenon
- This bolstered the idea that liquid phase radon removal would be feasible and effective. This was not supported by our results
- Ongoing simulations to understand these results better
- Further testing of new, synthetic materials as the chromatography medium
- Paper in preparation

Thank you!

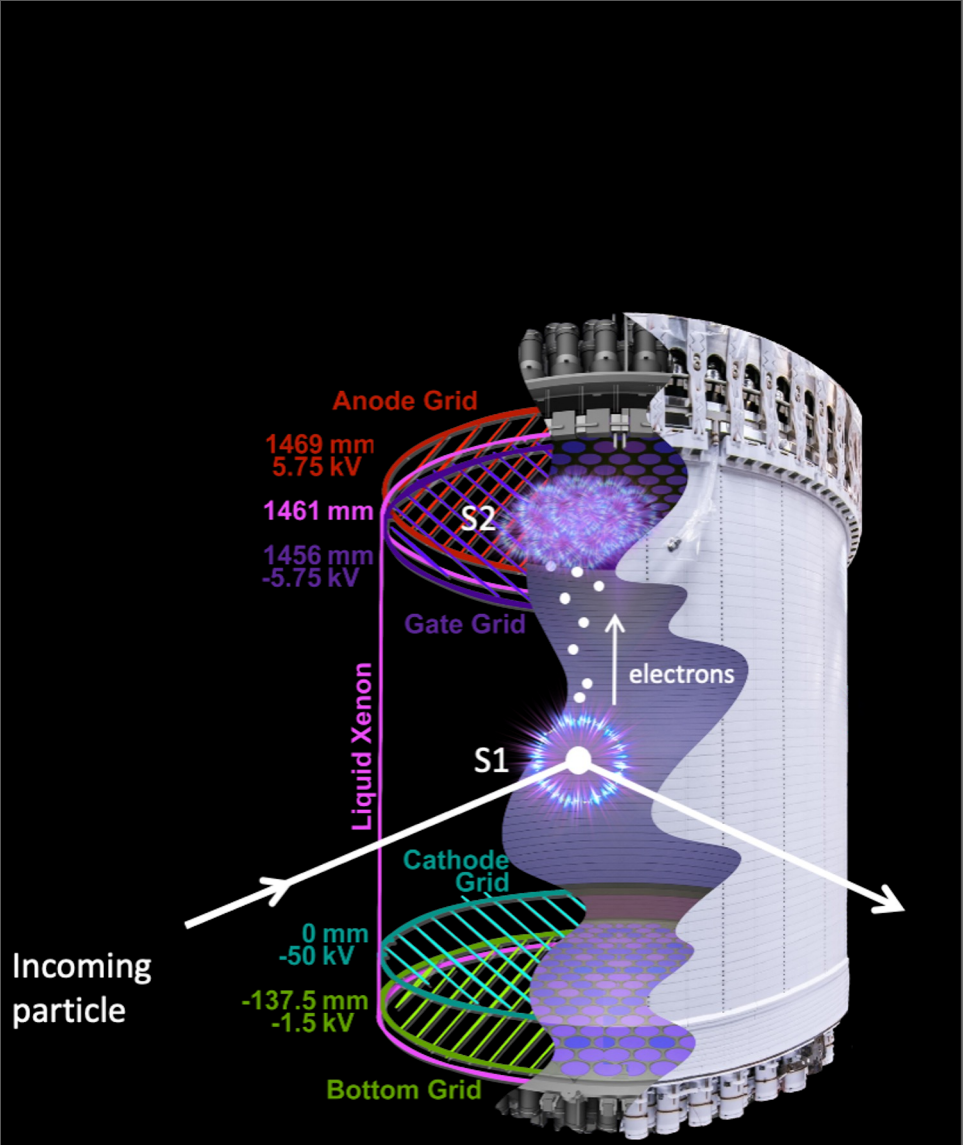


Image by Nicolas A. (Imperial College London)

U.S. Department of Energy
Office of Science

Science and Technology Facilities Council

SANFORD UNDERGROUND RESEARCH FACILITY

Fundação para a Ciência e a Tecnologia

Institute for Basic Science

Swiss National Science Foundation

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

LZ (LUX-ZEPLIN) Collaboration, 38 Institutions

@lzdarkmatter

https://lz.lbl.gov/

250 scientists, engineers, and technical staff

- Black Hills State University
- Brookhaven National Laboratory
- Brown University
- Center for Underground Physics
- Edinburgh University
- Fermi National Accelerator Lab.
- Imperial College London
- King's College London
- Lawrence Berkeley National Lab.
- Lawrence Livermore National Lab.
- LIP Coimbra
- Northwestern University
- Pennsylvania State University
- Royal Holloway University of London
- SLAC National Accelerator Lab.
- South Dakota School of Mines & Tech
- South Dakota Science & Technology Authority
- STFC Rutherford Appleton Lab.
- Texas A&M University
- University of Albany, SUNY
- University of Alabama
- University of Bristol
- University College London
- University of California Berkeley
- University of California Davis
- University of California Los Angeles
- University of California Santa Barbara
- University of Liverpool
- University of Maryland
- University of Massachusetts, Amherst
- University of Michigan
- University of Oxford
- University of Rochester
- University of Sheffield
- University of Sydney
- University of Texas at Austin
- University of Wisconsin, Madison
- University of Zürich

US Europe Asia Oceania

LZ Collaboration Meeting at UCLA, March 2025

Science and Technology Facilities Council

Fundação para a Ciência e a Tecnologia

SANFORD UNDERGROUND RESEARCH FACILITY

Swiss National Science Foundation

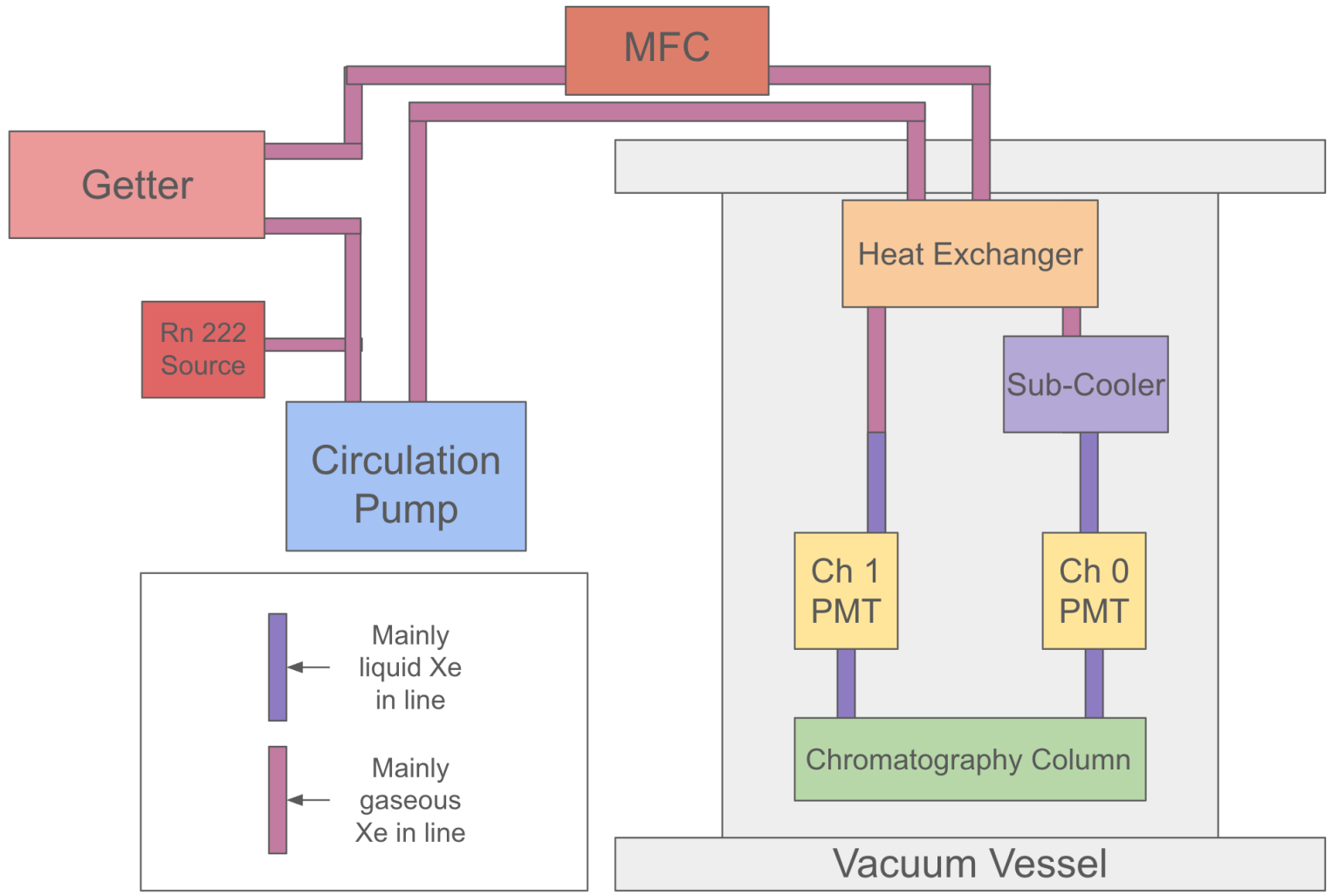
Institute for Basic Science

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

Thanks to our sponsors and participating institutions!

BACKUP

THE SETUP


MFC
Getter
Rn 222
Source
Circulation
Pump
Heat Exchanger
Sub-Cooler
Ch 1
PMT
Ch 0
PMT
Chromatography Column
Vacuum Vessel
Mainly
liquid Xe
in line
Mainly
gaseous
Xe in line