Reflections on a Cosmic Frontier Early Career Award

‘The search for WIMP dark matter with liquid xenon’

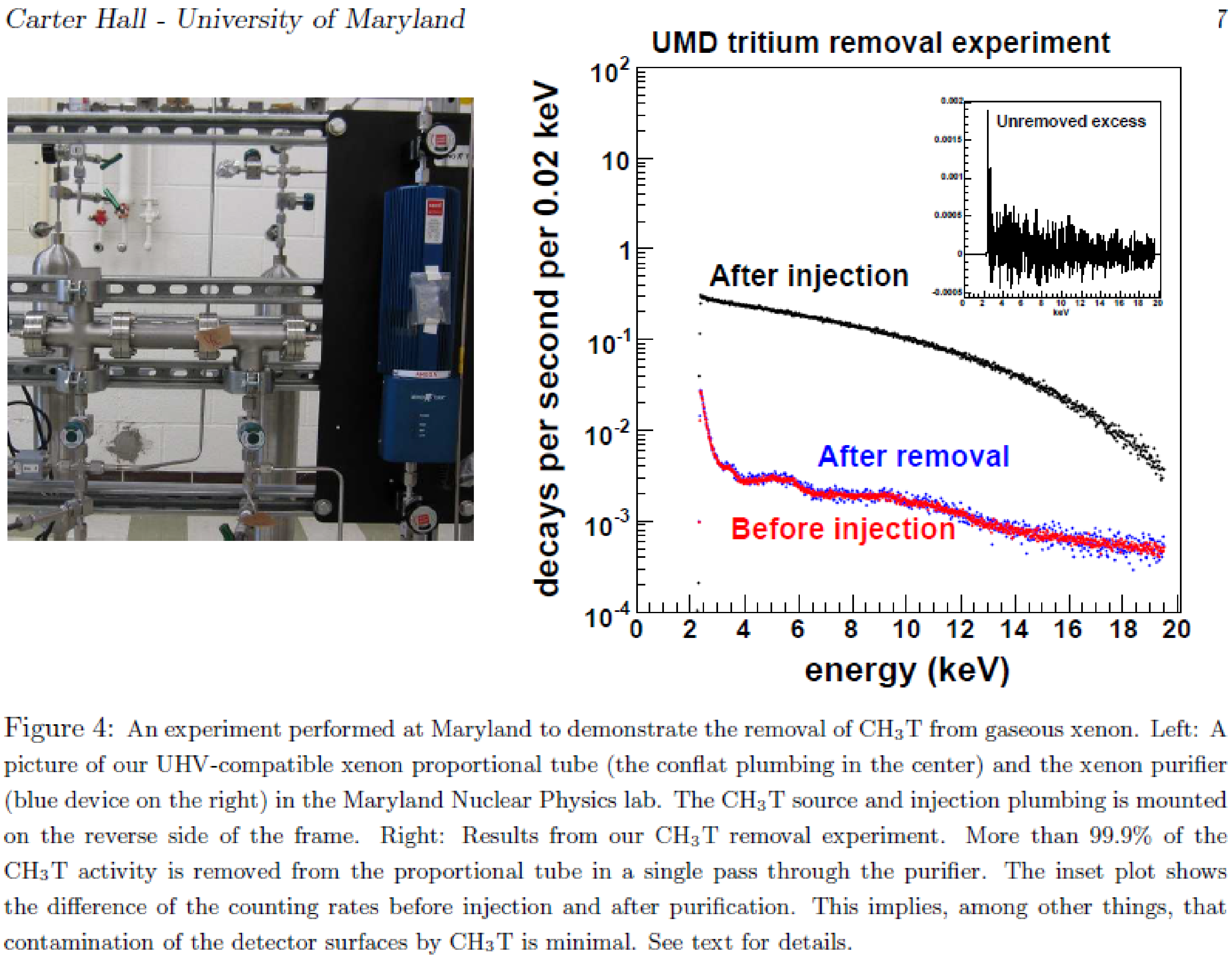
Submitted November 2010
Awarded May 2011 – April 2016

Carter Hall, University of Maryland
ECAN Workshop, Texas A&M
June 9, 2023

Part 1

Tritium Calibration of Liquid Xenon WIMP search experiments

Project Description, November 2010



Carter Hall - University of Maryland 7

Figure 4: An experiment performed at Maryland to demonstrate the removal of CH_3T from gaseous xenon. Left: A picture of our UHV-compatible xenon proportional tube (the conflat plumbing in the center) and the xenon purifier (blue device on the right) in the Maryland Nuclear Physics lab. The CH_3T source and injection plumbing is mounted on the reverse side of the frame. Right: Results from our CH_3T removal experiment. More than 99.9% of the CH_3T activity is removed from the proportional tube in a single pass through the purifier. The inset plot shows the difference of the counting rates before injection and after purification. This implies, among other things, that contamination of the detector surfaces by CH_3T is minimal. See text for details.

First WIMP search results from LUX, October 2013 (ECA year 3)

First results from the LUX dark matter experiment at the Sanford Underground Research Facility

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K.T. Lesko,[5] A. Lindote,[7] M.I. Lopes,[7] A. Lyashenko,[19] D.C. Malling,[1] R. Mannino,[10] D.N. McKinsey,[19]
D.-M. Mei,[18] J. Mock,[13] M. Moongweluwan,[17] J. Morad,[13] M. Morii,[3] A.St.J. Murphy,[15] C. Nehrkorn,[14]
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The Large Underground Xenon (LUX) experiment is a dual-phase xenon time-projection chamber operating at the Sanford Underground Research Facility (Lead, South Dakota). The LUX cryostat was filled for the first time in the underground laboratory in February 2013. We report results of the first WIMP search dataset, taken during the period April to August 2013, presenting the analysis of 85.3 live-days of data with a fiducial volume of 118 kg. A profile-likelihood analysis technique shows our data to be consistent with the background-only hypothesis, allowing 90% confidence limits to be set on spin-independent WIMP-nucleon elastic scattering with a minimum upper limit on the cross section of 7.6×10^{-46} cm^2 at a WIMP mass of 33 GeV/c^2. We find that the LUX data are in disagreement with low-mass WIMP signal interpretations of the results from several recent direct detection experiments.

PACS numbers: 95.35.+d, 29.40.-n, 95.55.Vj
Keywords: dark matter, direct detection, xenon

Convincing evidence for the existence of particle dark matter is derived from observations of the universe on scales ranging from the galactic to the cosmological [1–3]. Increasingly detailed studies of the Cosmic Microwave Background anisotropies have implied the abundance of dark matter with remarkable precision [4, 5]. One favored class of dark matter candidates, the Weakly Interacting Massive Particle (WIMP), may be amenable to direct detection in laboratory experiments through its interactions with ordinary matter [6, 7]. The WIMPs

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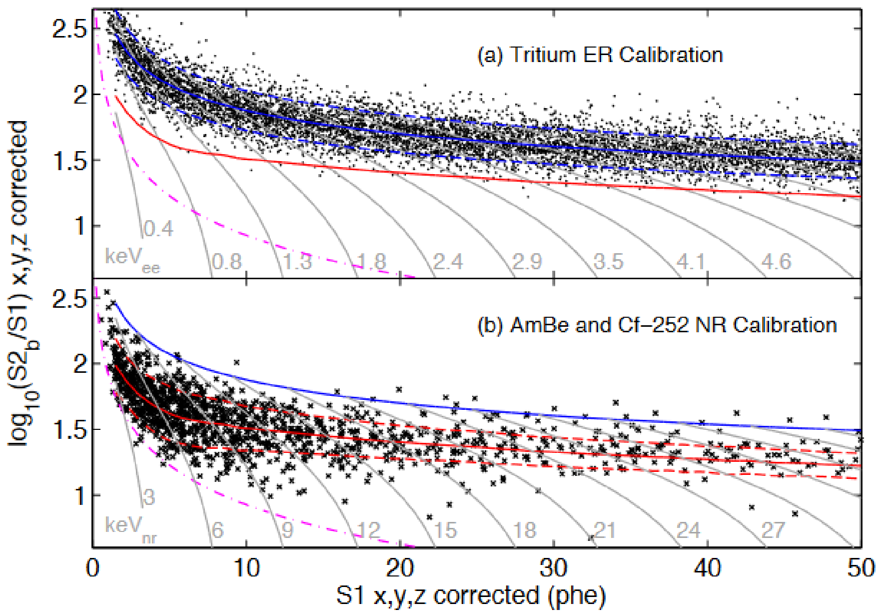
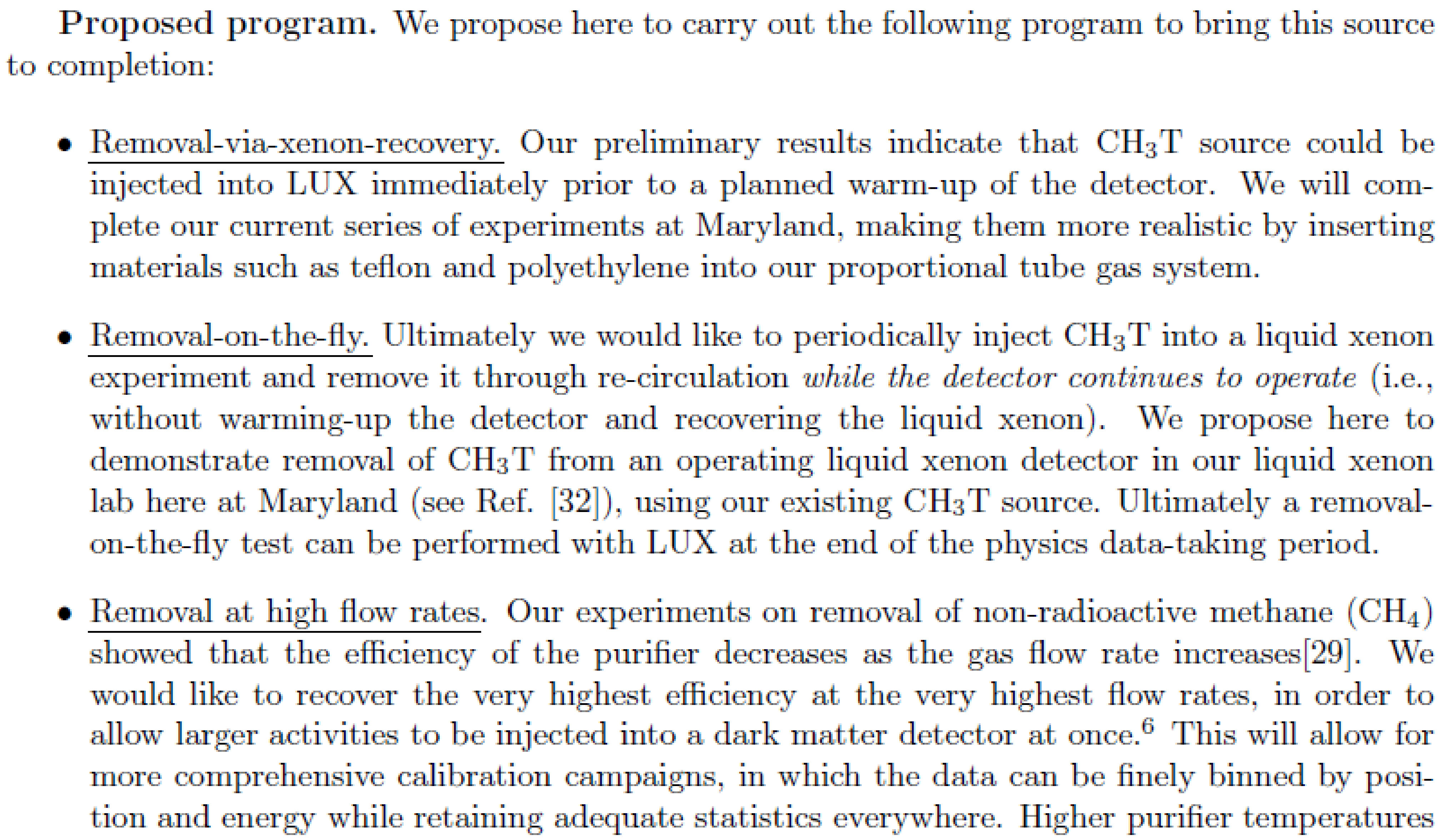


FIG. 3. Calibrations of detector response in the 118 kg fiducial volume. The ER (tritium, panel *a*) and NR (AmBe and ^{252}Cf, panel *b*) calibrations are depicted, with the means (solid line) and $\pm 1.28\sigma$ contours (dashed line). This choice of band width (indicating 10% band tails) is for presentation only. Panel *a* shows fits to the high statistics tritium data, with fits to simulated NR data shown in panel *b*, representing the parameterizations taken forward to the profile likelihood analysis. The ER plot also shows the NR band mean and vice versa. Gray contours indicate constant energies using an S1–S2 combined energy scale (same contours on each plot). The dot-dashed magenta line delineates the approximate location of the minimum S2 cut.

Project Description, November 2010



Proposed program. We propose here to carry out the following program to bring this source to completion:

- Removal-via-xenon-recovery. Our preliminary results indicate that CH_3T source could be injected into LUX immediately prior to a planned warm-up of the detector. We will complete our current series of experiments at Maryland, making them more realistic by inserting materials such as teflon and polyethylene into our proportional tube gas system.

- Removal-on-the-fly. Ultimately we would like to periodically inject CH_3T into a liquid xenon experiment and remove it through re-circulation *while the detector continues to operate* (i.e., without warming-up the detector and recovering the liquid xenon). We propose here to demonstrate removal of CH_3T from an operating liquid xenon detector in our liquid xenon lab here at Maryland (see Ref. [32]), using our existing CH_3T source. Ultimately a removal-on-the-fly test can be performed with LUX at the end of the physics data-taking period.

- Removal at high flow rates. Our experiments on removal of non-radioactive methane (CH_4) showed that the efficiency of the purifier decreases as the gas flow rate increases[29]. We would like to recover the very highest efficiency at the very highest flow rates, in order to allow larger activities to be injected into a dark matter detector at once.[6] This will allow for more comprehensive calibration campaigns, in which the data can be finely binned by position and energy while retaining adequate statistics everywhere. Higher purifier temperatures

Phys. Rev. D 93 072009 (2016) (ECA year 5)

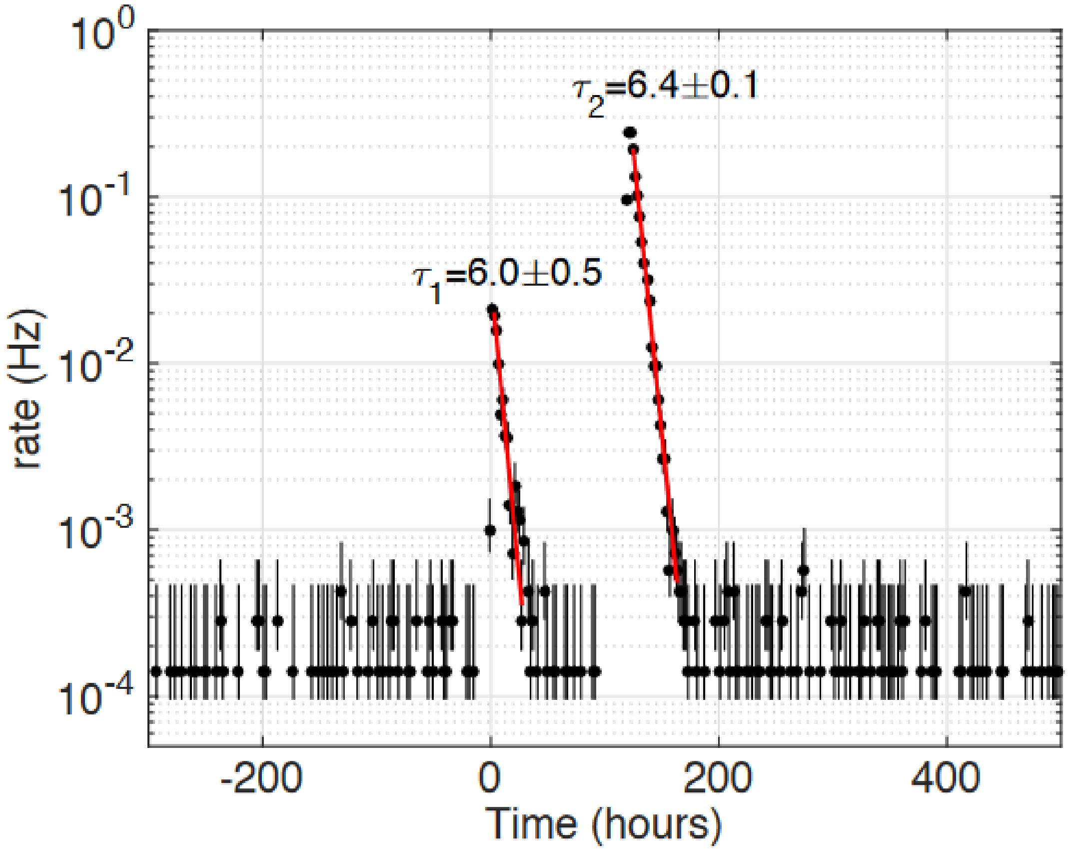


FIG. 2: Rate of single scatter events with S1 below 150 phd in the fiducial volume during the August 2013 CH$_3$T injections. The solid lines are exponential fits to the activity vs. time.

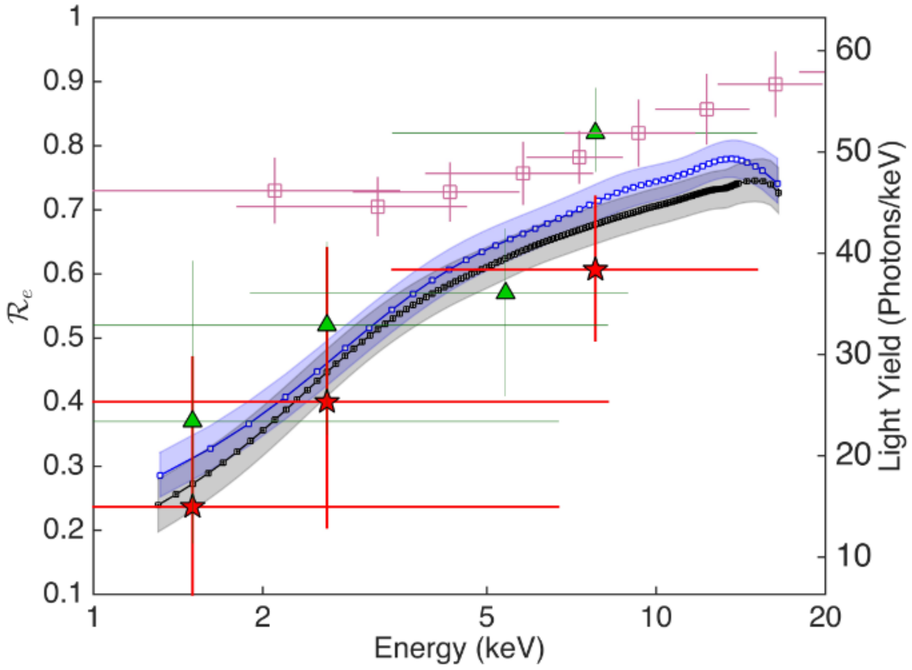


FIG. 8: Light yield measurement from LUX tritium data compared with results from other authors. Left vertical scale: light yield relative to that of the 32.1 keV decay of ^{83m}Kr at zero field. Right vertical scale: absolute light yield measurements. Blue squares represent tritium at 105 V/cm, black squares are tritium at 180 V/cm. The shaded bands are the the systematic errors on the tritium data. Magenta squares represent zero field measurements from [24], green triangles and red stars represent zero field and 450 V/cm from [5]. All non-tritium data is from Compton scatters.

First WIMP search results from LZ – July 2022 (six years post ECA)

First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment

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S. Azadi,[10] A.J. Bailey,[8] A. Baker,[8] J. Balajthy,[11] S. Balashov,[12] J. Bang,[6] J.W. Bargemann,[10] M.J. Barry,[13]
J. Barthel,[14] D. Bauer,[8] A. Baxter,[15] K. Beattie,[13] J. Belle,[16] P. Beltrame,[5,17] J. Bensinger,[18] T. Benson,[7]
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G.M. Blockinger,[20] K.E. Boast,[4] B. Boxer,[11,15] R. Bramante,[1,2] C.A.J. Brew,[12] P. Brás,[21] J.H. Buckley,[22]
V.V. Bugaev,[22] S. Burdin,[15] J.K. Busenitz,[23] M. Buuck,[1,2] R. Cabrita,[21] C. Carels,[4] D.L. Carlsmith,[7] B. Carlson,[14]
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L. de Viveiros,[24] A. Dobi,[13] J.E.Y. Dobson,[5] E. Druszkiewicz,[27] A. Dushkin,[18] T.K. Edberg,[9] W.R. Edwards,[13]
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B. Landerud,[7] E.A. Leason,[17] C. Lee,[1,2] J. Lee,[35] D.S. Leonard,[35] R. Leonard,[26] K.T. Lesko,[13] C. Levy,[20] J. Li,[35]
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K.C. Oliver-Mallory,[8,13,19] J. Orpwood,[36] D. Pagenkopf,[10] S. Pal,[21] K.J. Palladino,[4,7] J. Palmer,[25] M. Pangilinan,[6]
N. Parveen,[20] S.J. Patton,[13] E.K. Pease,[13] B. Penning,[3,18] C. Pereira,[21] G. Pereira,[21] E. Perry,[5] T. Pershing,[34]
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G. Rutherford,[6] D. Rynders,[14] J.S. Saba,[13] D. Santone,[25] A.B.M.R. Sazzad,[23] R.W. Schnee,[26] P.R. Scovell,[4,12]
D. Seymour,[6] S. Shaw,[10] T. Shutt,[1,2] J.J. Silk,[9] C. Silva,[21] G. Sinev,[26] K. Skarpaas,[1] W. Skulski,[27] R. Smith,[13,19]
M. Solmaz,[10] V.N. Solovov,[21] P. Sorensen,[13] J. Soria,[13,19] I. Stancu,[23] M.R. Stark,[26] A. Stevens,[4,5,8]
T.M. Stiegler,[39] K. Stifter,[1,2,16] R. Studley,[18] B. Suerfu,[13,19] T.J. Sumner,[8] P. Sutcliffe,[15] N. Swanson,[6]
M. Szydagis,[20] M. Tan,[4] D.J. Taylor,[14] R. Taylor,[8] W.C. Taylor,[6] D.J. Temples,[28] B.P. Tennyson,[29] P.A. Terman,[39]
K.J. Thomas,[13] D.R. Tiedt,[9,14,26] M. Timalsina,[26] W.H. To,[1,2] A. Tomás,[8] Z. Tong,[8] D.R. Tovey,[36] J. Tranter,[36]
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J. Va'vra,[1] A. Vacheret,[8] A.C. Vaitkus,[6] J.R. Verbus,[6] E. Voirin,[16] W.L. Waldron,[13] A. Wang,[1,2] B. Wang,[23]
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F.L.H. Wolfs,[27] J.D. Wolfs,[27] S. Woodford,[15] D. Woodward,[24,§] S.D. Worm,[12] C.J. Wright,[30] Q. Xia,[13]
X. Xiang,[6,31] Q. Xiao,[7] J. Xu,[34] M. Yeh,[31] J. Yin,[27] I. Young,[16] P. Zarzhitsky,[23] A. Zuckerman,[6] and E.A. Zweig[33]
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arXiv:2207.03764v3 [hep-ex] 27 Oct 2022

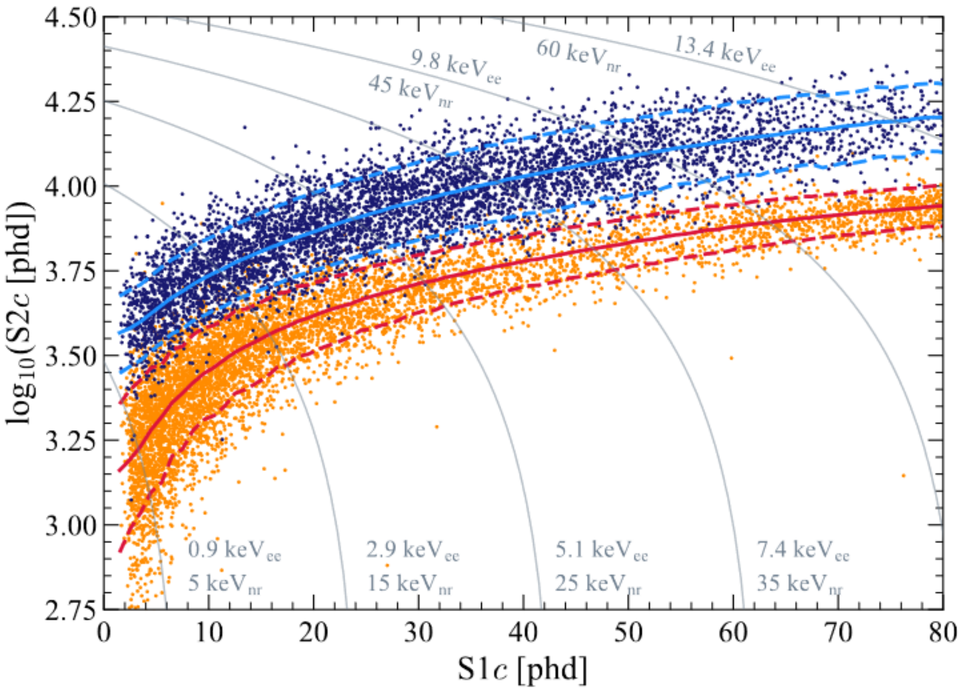
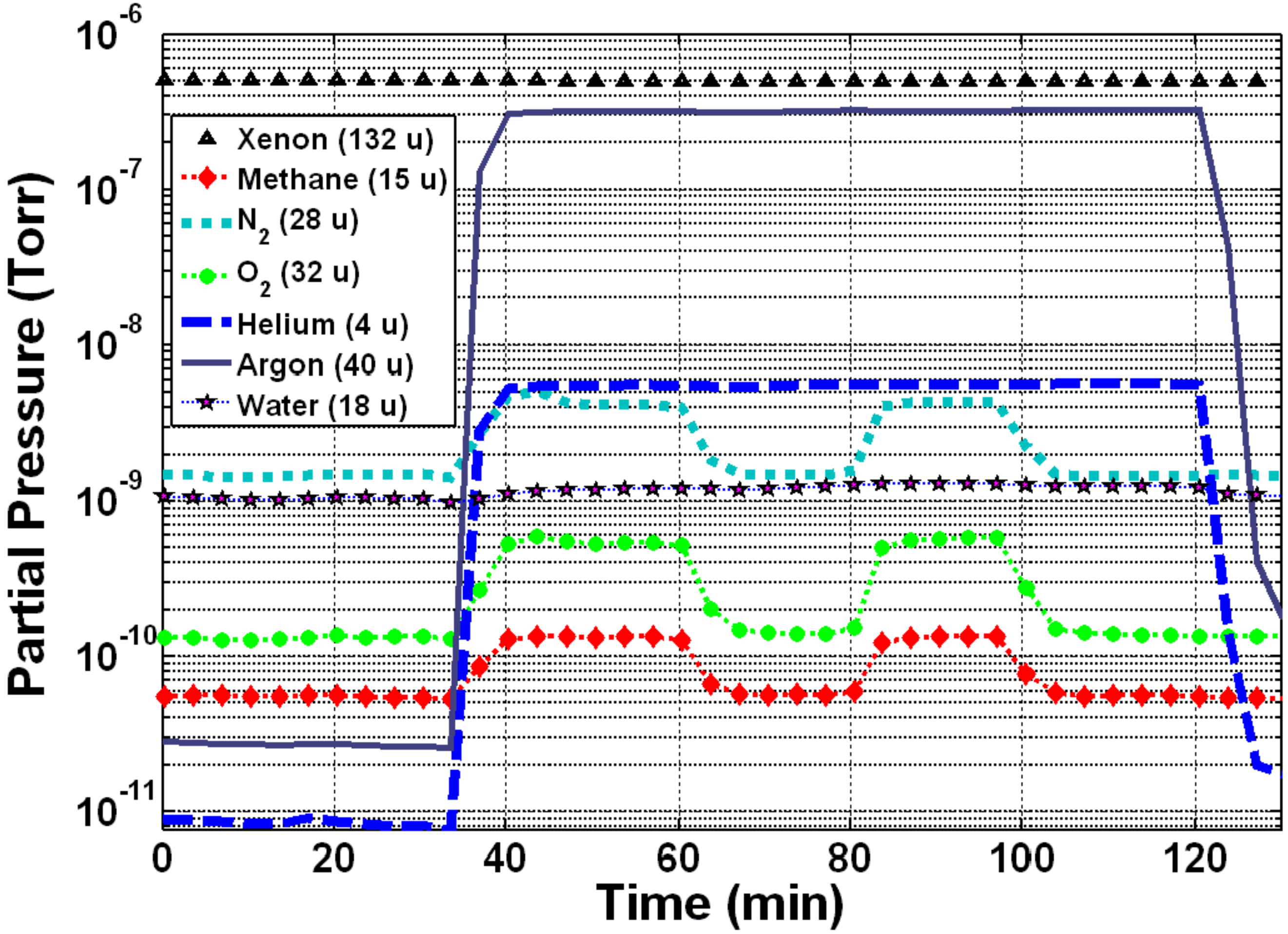


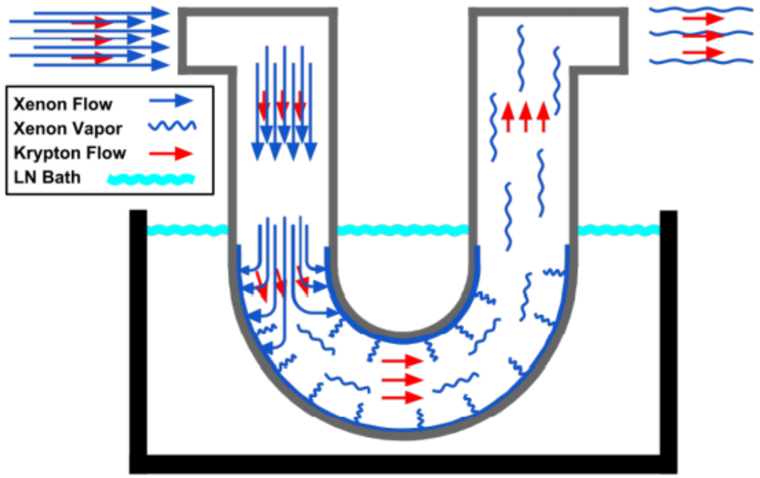
FIG. 1. Calibration events in $\log_{10}$S2c-S1c for the tritium source (dark blue points, 5343 events) and the DD neutron source (orange points, 6324 events). Solid blue (red) lines indicate the median of the ER (NR) simulated distributions, and the dotted lines indicate the 10 % and 90 % quantiles. Thin grey lines show contours of constant electron-equivalent energy (keV$_{ee}$) and nuclear recoil energy (keV$_{nr}$).

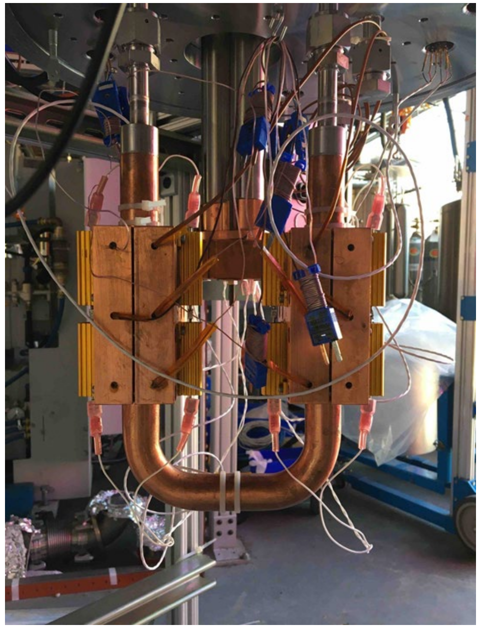
Part 2

Detection of trace impurities in Xe with Mass Spectrometry

Project Description, November 2010







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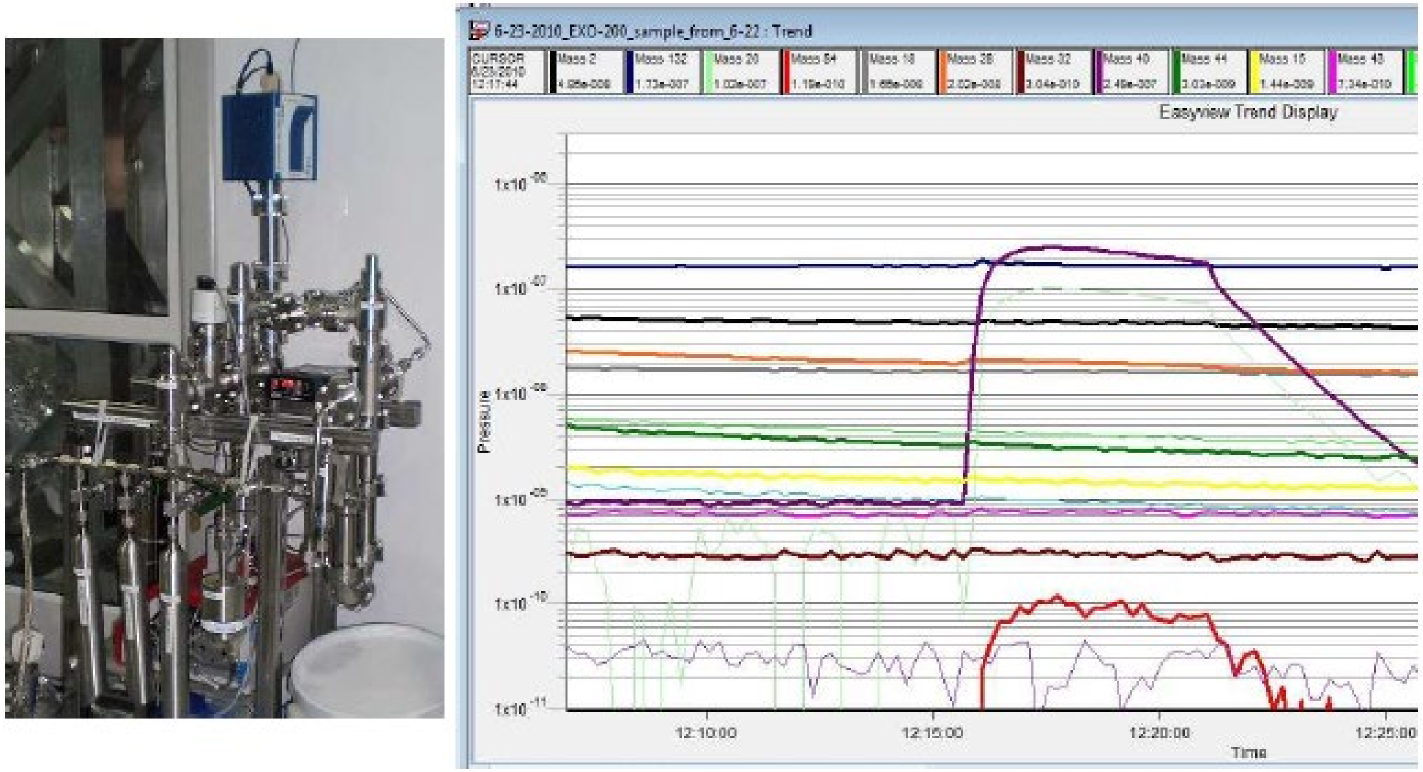
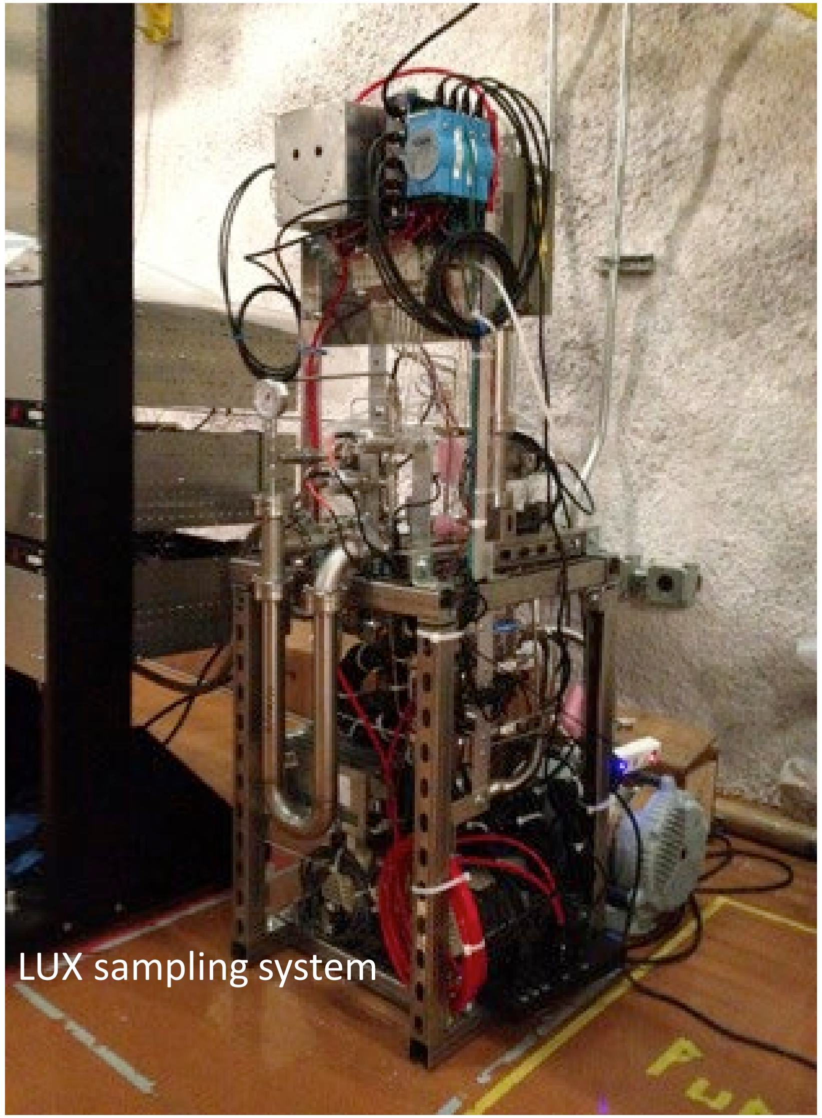
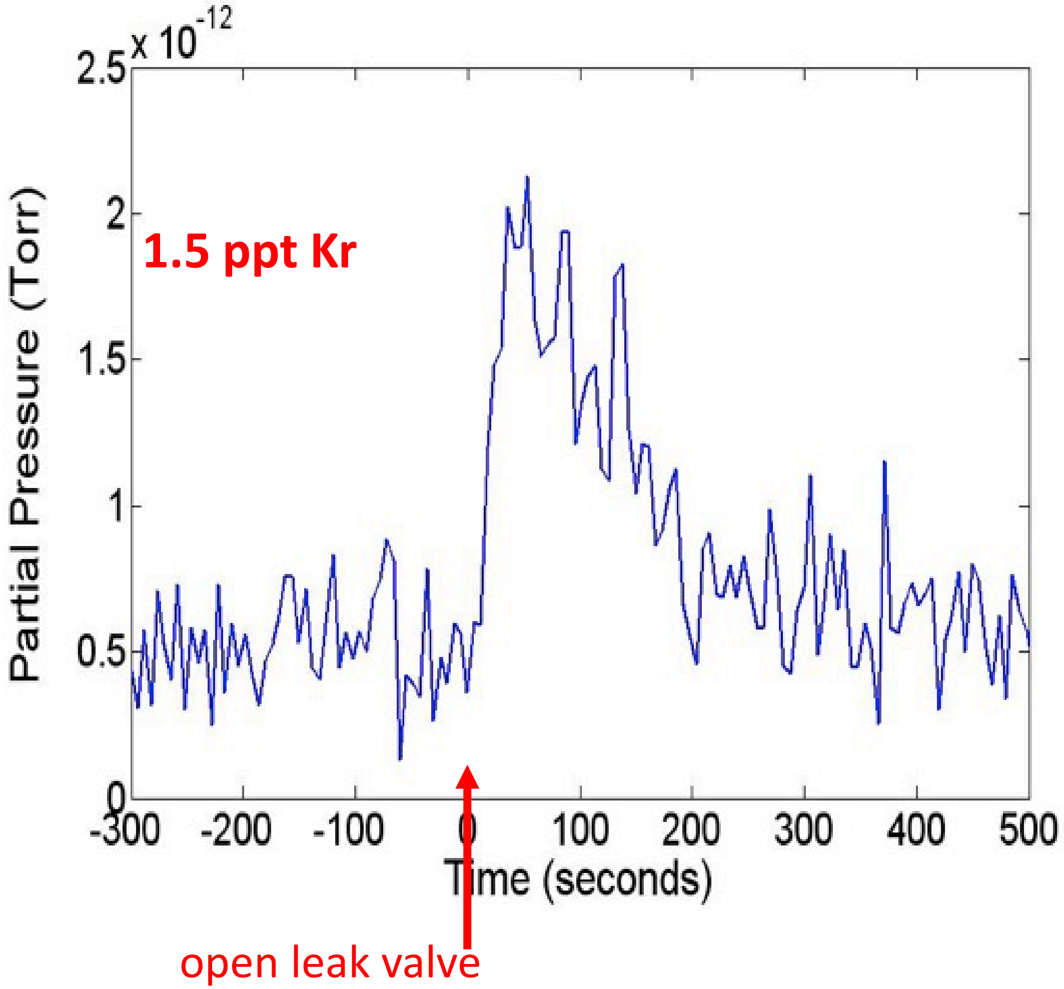


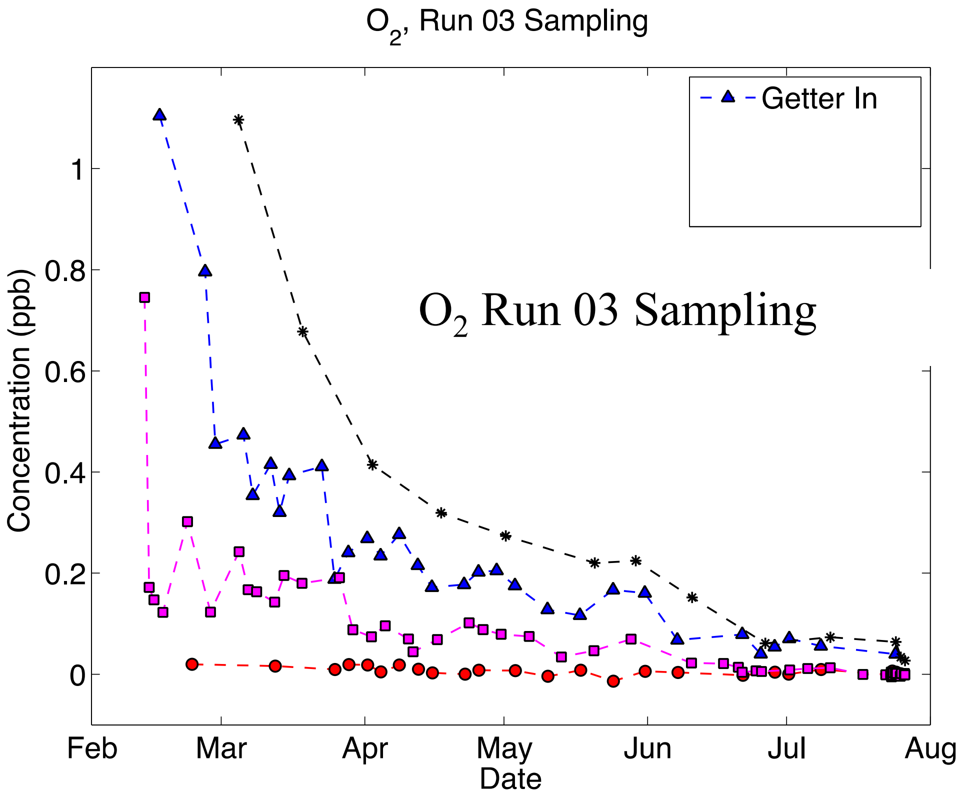
Figure 6: Left: the coldtrap/RGA system constructed by our group for the EXO-200 double beta decay experiment. Right: Coldtrap/RGA results from a xenon gas sample collected from EXO-200 on June 23, 2010. The leak valve is opened at 12:16, and Argon (purple), Neon (light green), and Krypton (red) are observed in the gas sample. Oxygen (brown) does not increase above background levels, and we infer a limit of <0.5 ppb on the oxygen concentration.

Purity monitoring of the LUX Xenon, 2013 (ECA year 3)

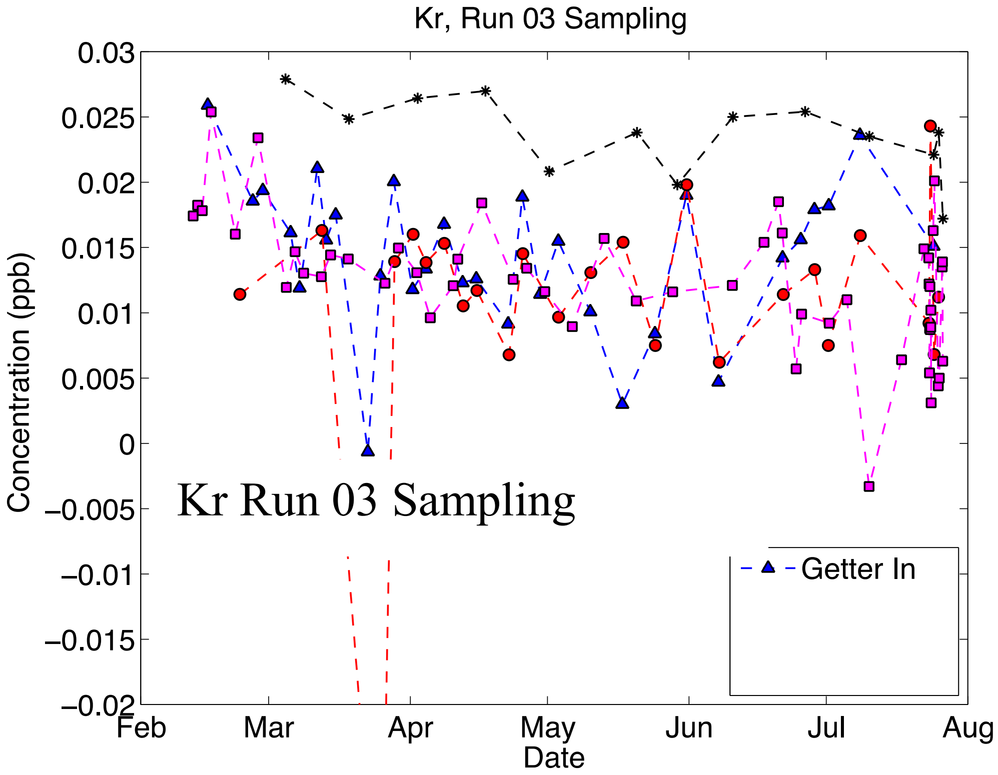




Purity monitoring of the LUX Xenon, 2013 (ECA year 3)

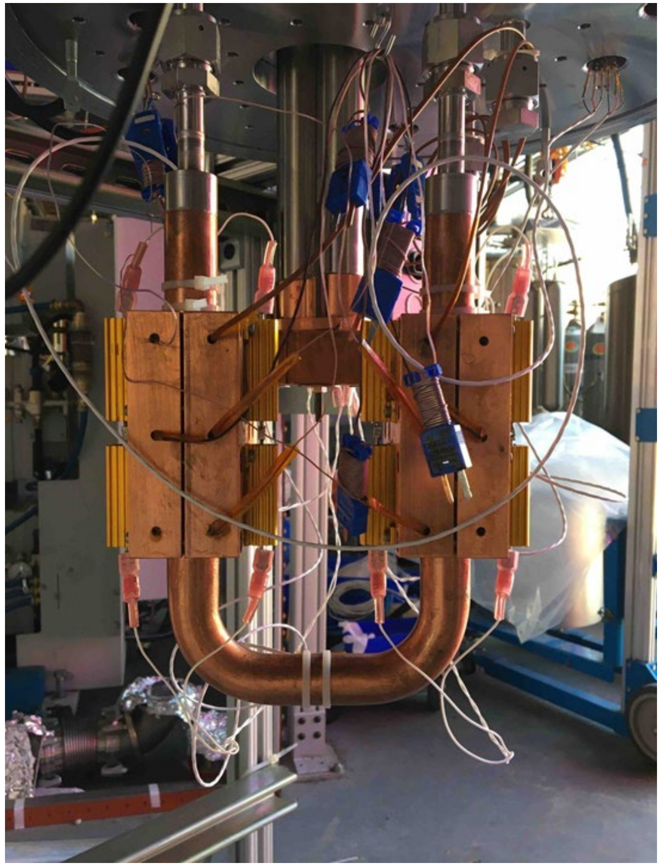


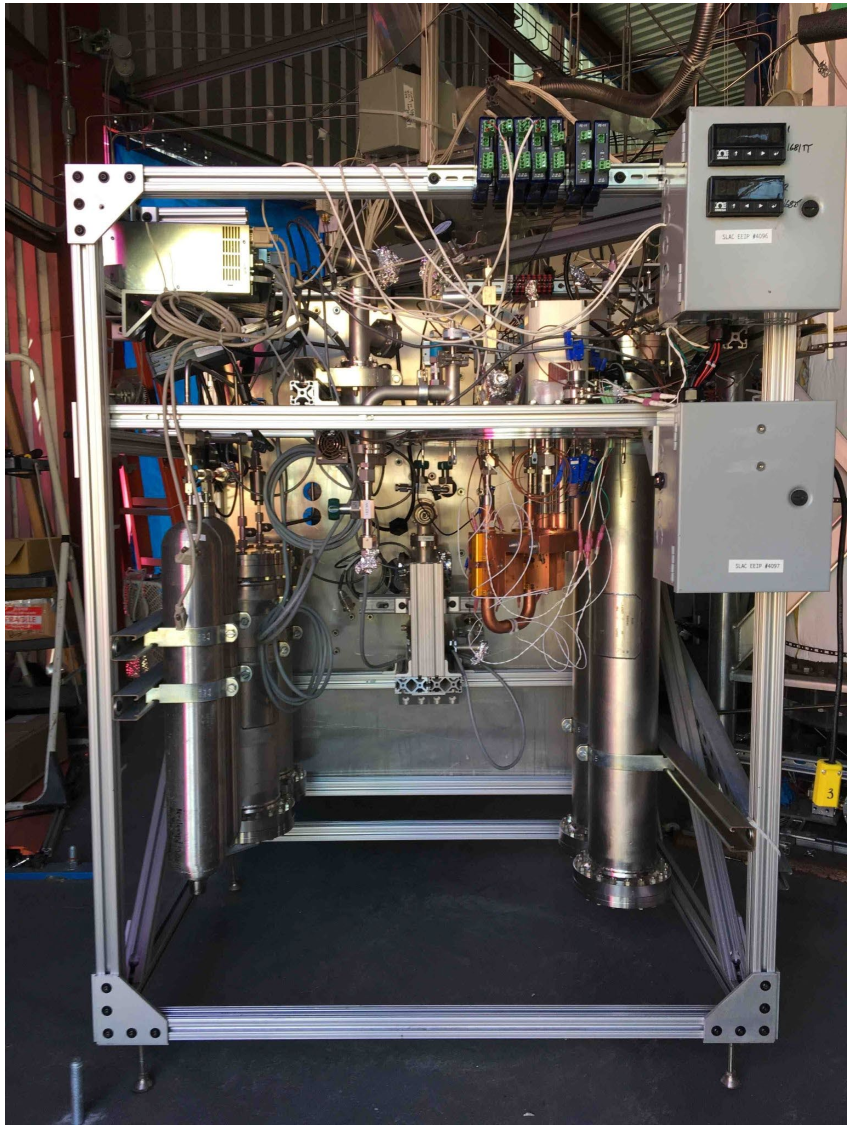
2013

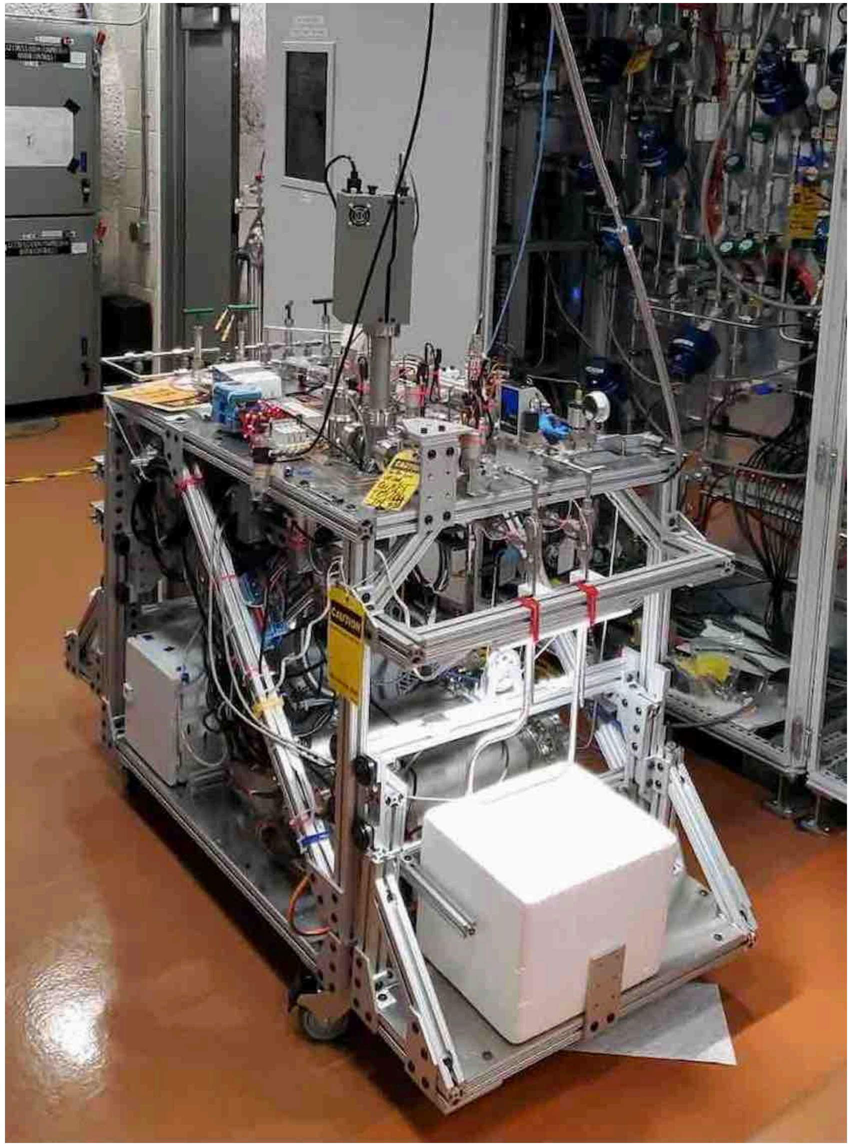


2013

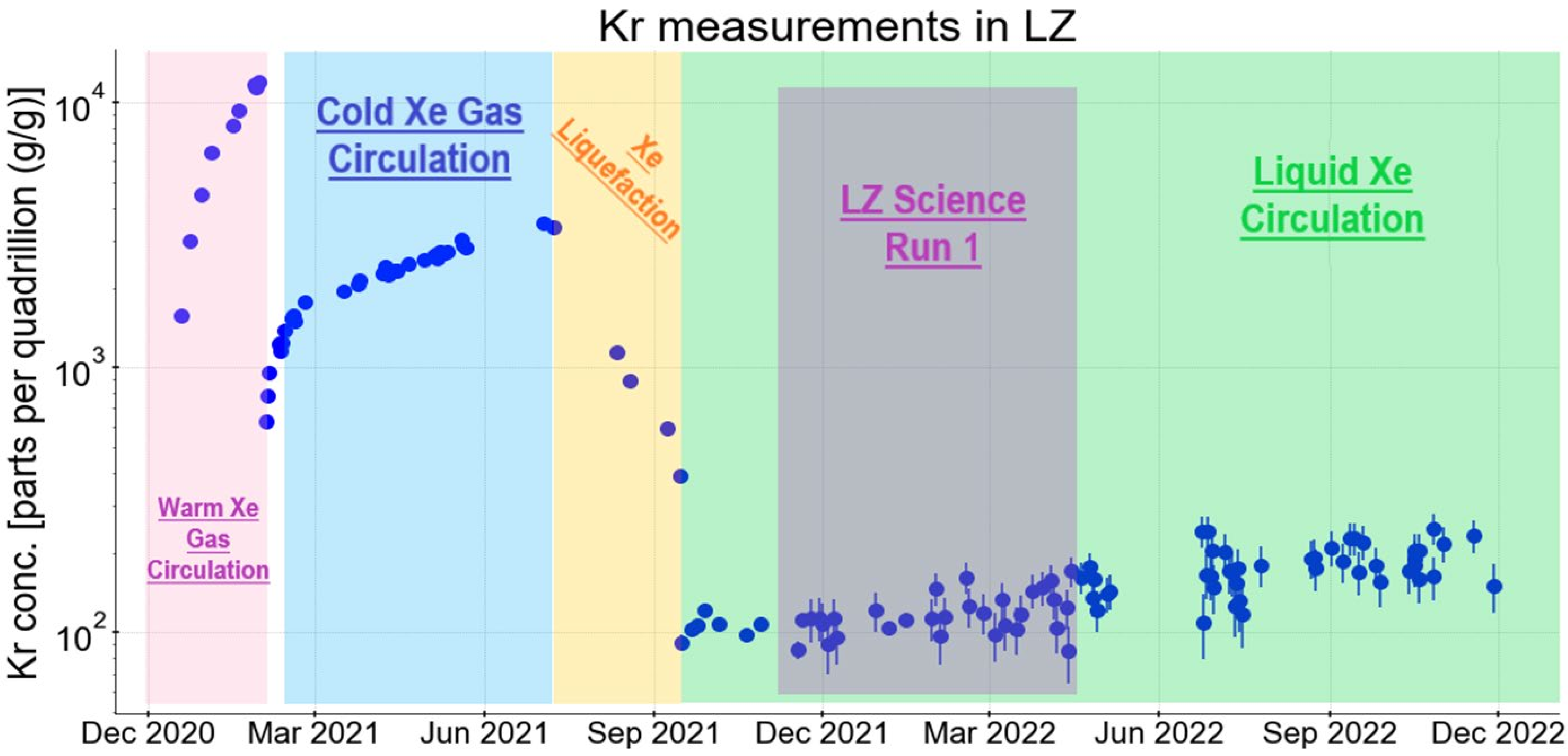
LZ Dark Matter Search, 2020 – 2023 (Four years post-ECA)







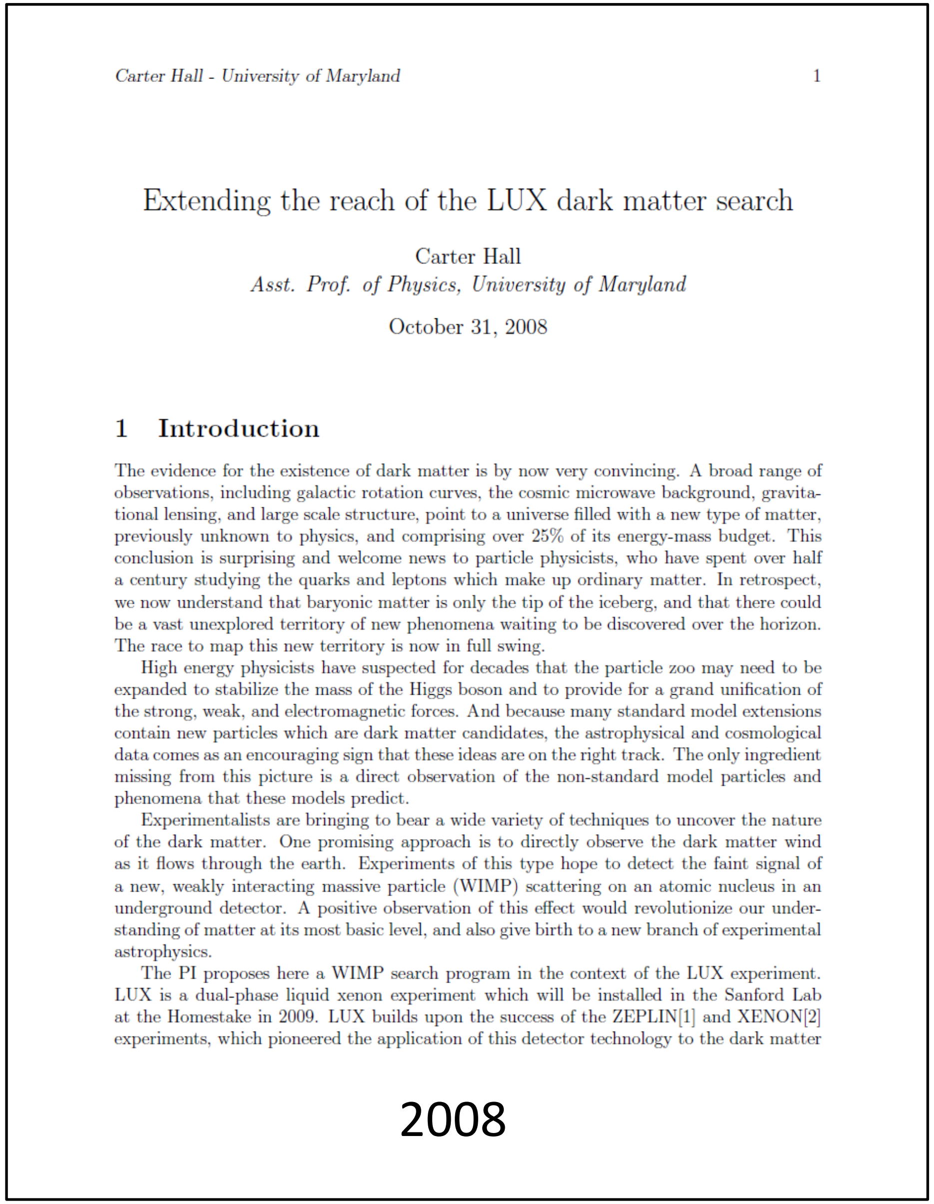
LZ Dark Matter Search, 2020 – 2022 (Four to six years post-ECA)



Proposal Scorecard

- Mass spectrometry detection of impurities
  1. Apply technique to LUX ☑
  2. Extend technique to observe water and CO_2 impurities ☒
  3. Remote control; automation ☑
- Tritium calibration of LUX
  1. Removal via Xe recovery ☒
  2. Removal on-the-fly ☑
  3. Removal at high flow rates ☑
- Mitigation of radioactive noble impurities (Kr and Ar)
  1. Kr and Ar detection via mass spectrometry ☑
  2. Rn removal from Xe ☒
  3. Rn and Kr monitoring with LUX WIMP search data ☒

Unsuccessful attempts – 2008 & 2009



Extending the reach of the LUX dark matter search

Carter Hall
Asst. Prof. of Physics, University of Maryland

October 31, 2008

1 Introduction

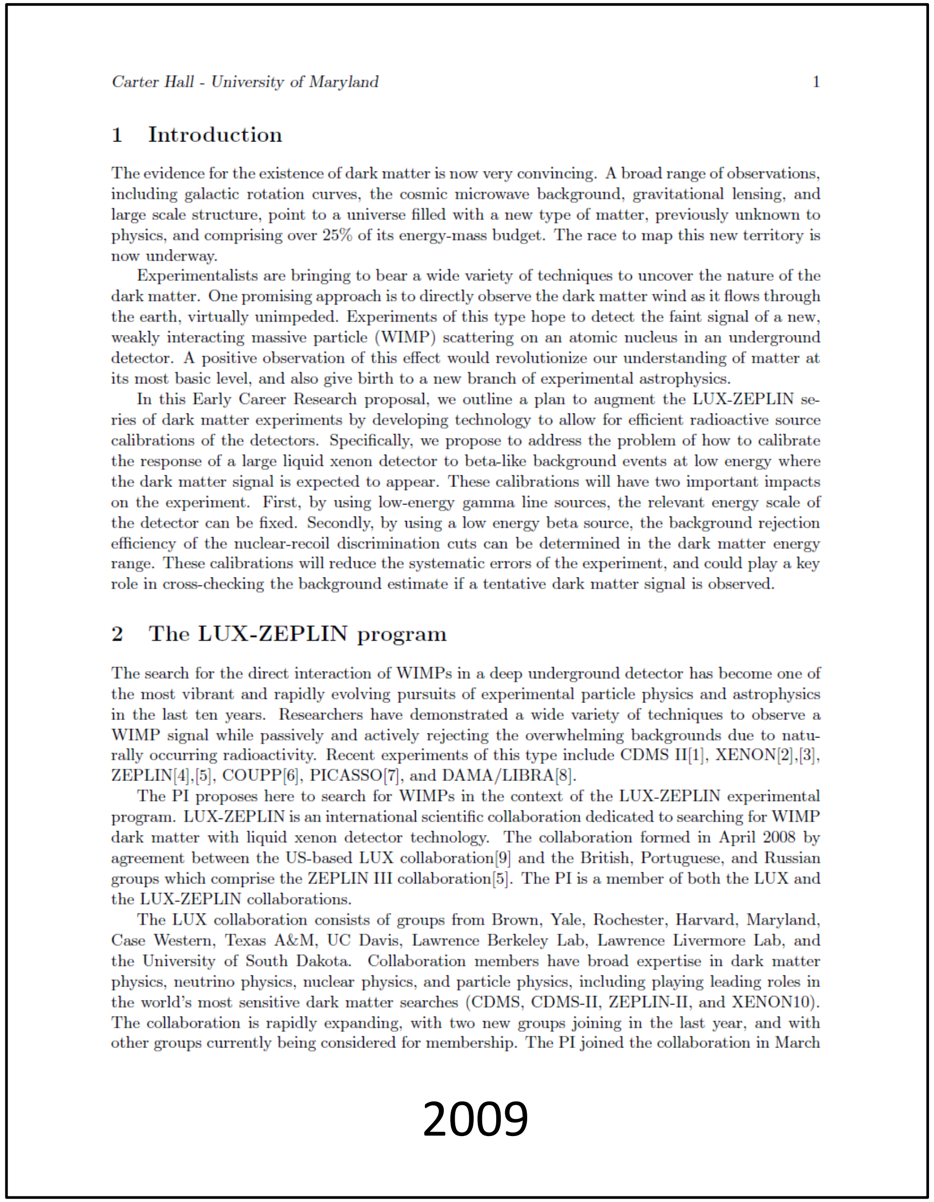
The evidence for the existence of dark matter is by now very convincing. A broad range of observations, including galactic rotation curves, the cosmic microwave background, gravitational lensing, and large scale structure, point to a universe filled with a new type of matter, previously unknown to physics, and comprising over 25% of its energy-mass budget. This conclusion is surprising and welcome news to particle physicists, who have spent over half a century studying the quarks and leptons which make up ordinary matter. In retrospect, we now understand that baryonic matter is only the tip of the iceberg, and that there could be a vast unexplored territory of new phenomena waiting to be discovered over the horizon. The race to map this new territory is now in full swing.

High energy physicists have suspected for decades that the particle zoo may need to be expanded to stabilize the mass of the Higgs boson and to provide for a grand unification of the strong, weak, and electromagnetic forces. And because many standard model extensions contain new particles which are dark matter candidates, the astrophysical and cosmological data comes as an encouraging sign that these ideas are on the right track. The only ingredient missing from this picture is a direct observation of the non-standard model particles and phenomena that these models predict.

Experimentalists are bringing to bear a wide variety of techniques to uncover the nature of the dark matter. One promising approach is to directly observe the dark matter wind as it flows through the earth. Experiments of this type hope to detect the faint signal of a new, weakly interacting massive particle (WIMP) scattering on an atomic nucleus in an underground detector. A positive observation of this effect would revolutionize our understanding of matter at its most basic level, and also give birth to a new branch of experimental astrophysics.

The PI proposes here a WIMP search program in the context of the LUX experiment. LUX is a dual-phase liquid xenon experiment which will be installed in the Sanford Lab at the Homestake in 2009. LUX builds upon the success of the ZEPLIN[1] and XENON[2] experiments, which pioneered the application of this detector technology to the dark matter

2008



1 Introduction

The evidence for the existence of dark matter is now very convincing. A broad range of observations, including galactic rotation curves, the cosmic microwave background, gravitational lensing, and large scale structure, point to a universe filled with a new type of matter, previously unknown to physics, and comprising over 25% of its energy-mass budget. The race to map this new territory is now underway.

Experimentalists are bringing to bear a wide variety of techniques to uncover the nature of the dark matter. One promising approach is to directly observe the dark matter wind as it flows through the earth, virtually unimpeded. Experiments of this type hope to detect the faint signal of a new, weakly interacting massive particle (WIMP) scattering on an atomic nucleus in an underground detector. A positive observation of this effect would revolutionize our understanding of matter at its most basic level, and also give birth to a new branch of experimental astrophysics.

In this Early Career Research proposal, we outline a plan to augment the LUX-ZEPLIN series of dark matter experiments by developing technology to allow for efficient radioactive source calibrations of the detectors. Specifically, we propose to address the problem of how to calibrate the response of a large liquid xenon detector to beta-like background events at low energy where the dark matter signal is expected to appear. These calibrations will have two important impacts on the experiment. First, by using low-energy gamma line sources, the relevant energy scale of the detector can be fixed. Secondly, by using a low energy beta source, the background rejection efficiency of the nuclear-recoil discrimination cuts can be determined in the dark matter energy range. These calibrations will reduce the systematic errors of the experiment, and could play a key role in cross-checking the background estimate if a tentative dark matter signal is observed.

2 The LUX-ZEPLIN program

The search for the direct interaction of WIMPs in a deep underground detector has become one of the most vibrant and rapidly evolving pursuits of experimental particle physics and astrophysics in the last ten years. Researchers have demonstrated a wide variety of techniques to observe a WIMP signal while passively and actively rejecting the overwhelming backgrounds due to naturally occurring radioactivity. Recent experiments of this type include CDMS II[1], XENON[2],[3], ZEPLIN[4],[5], COUPP[6], PICASSO[7], and DAMA/LIBRA[8].

The PI proposes here to search for WIMPs in the context of the LUX-ZEPLIN experimental program. LUX-ZEPLIN is an international scientific collaboration dedicated to searching for WIMP dark matter with liquid xenon detector technology. The collaboration formed in April 2008 by agreement between the US-based LUX collaboration[9] and the British, Portuguese, and Russian groups which comprise the ZEPLIN III collaboration[5]. The PI is a member of both the LUX and the LUX-ZEPLIN collaborations.

The LUX collaboration consists of groups from Brown, Yale, Rochester, Harvard, Maryland, Case Western, Texas A&M, UC Davis, Lawrence Berkeley Lab, Lawrence Livermore Lab, and the University of South Dakota. Collaboration members have broad expertise in dark matter physics, neutrino physics, nuclear physics, and particle physics, including playing leading roles in the world's most sensitive dark matter searches (CDMS, CDMS-II, ZEPLIN-II, and XENON10). The collaboration is rapidly expanding, with two new groups joining in the last year, and with other groups currently being considered for membership. The PI joined the collaboration in March

2009

Project Description, November 2010 (3rd attempt)

1 The search for WIMP dark matter with liquid xenon

The evidence for the existence of dark matter is by now very convincing. A broad range of observations, including galactic rotation curves, the cosmic microwave background, gravitational lensing, and large scale structure, point to a universe filled with a new type of matter, previously unknown to physics, and comprising over 25% of its energy-mass budget. To map this new territory, experimentalists are bringing to bear a wide variety of techniques. One promising approach is to directly observe the Milky Way's dark matter halo as it flows, virtually unimpeded, through the Earth. Experiments of this type hope to detect the faint signal of a new, weakly interacting massive particle (WIMP) scattering on an atomic nucleus in an underground detector. A positive observation of this effect would revolutionize our understanding of matter at its most basic level, while also giving birth to a new branch of observational astrophysics.

In the last ten years, liquid xenon TPC technology has quickly advanced to the frontier of dark matter research. The method was pioneered by the ZEPLIN[1, 2] and XENON10[3] collaborations, and has reached a new level of maturity with the recent results from the XENON100 experiment [4]. XENON100 will be followed in quick succession by the LUX[5, 6, 7] and XMASS[8] experiments, which are expected to produce additional sensitivity gains of an additional two orders of magnitude or more. This heralds the arrival of a new era in which large regions of the WIMP parameter space will be rapidly explored. Most importantly, since these experiments are sensitive to many prominent WIMP models, a direct observation of astrophysical dark matter could be imminent.

In parallel with current efforts, researchers around the world are developing ton and multi-ton liquid xenon proposals[9, 10, 11, 12, 13] which could probe WIMP cross-sections down to 10^{-48} cm^2, roughly four orders of magnitude below current limits. These detectors can be rapidly scaled because the technology has been demonstrated by the pioneering experiments. Nevertheless, we anticipate that new challenges will naturally arise at these new scales, while other issues which carry over from the current generation of experiments must be faced in a more systematic manner. In this Early Career proposal, we outline a strategy to address several of the most important such issues:

1. **Calibration** - *How can massive liquid xenon detectors be calibrated for their response to the dominant electron-recoil backgrounds?* Such a calibration is absolutely required in order extract any meaningful physics from the WIMP search data, but previous calibration strategies based on external gamma sources will fail. We propose to apply a new strategy based on tritiated methane, and we have already made significant progress towards showing that it can be inserted and removed safely from a detector. See Section 2.
2. **Technology** - *How can we reliably and robustly achieve the extremely low concentrations of electronegative impurities which liquid xenon experiments require?* The most common method to identify and correct purity problems in liquid xenon experiments can best be described as "trial and error". The fundamental difficulty, which is faced by all experiments, is a lack of available analytical tools which can provide guidance as to the source of purity problems. We have recently developed a new technique in our lab at Maryland which removes much of the guesswork. We propose to apply this tool to the dark matter problem and extend the method into new areas. See Section 3.
3. **Backgrounds** - *How can we monitor and mitigate the most serious remaining backgrounds which liquid xenon experiments will encounter?* The rapid advances in sensitivity which are now being seen in liquid xenon detectors are made possible primarily through the background rejection power of self-shielding. Radioactive contaminants dissolved in the liquid xenon,

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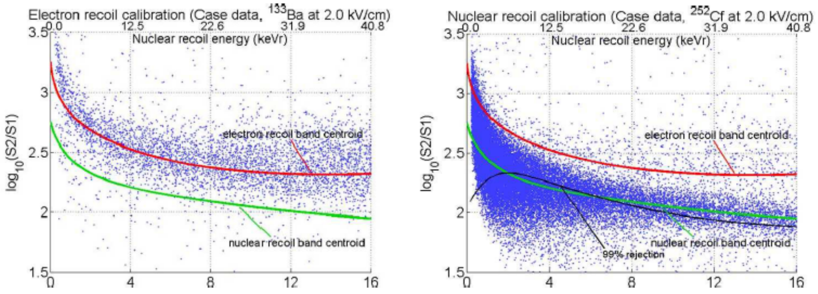

Figure 3: Nuclear recoil discrimination in liquid xenon. These scatter plots show the discriminant variable, $\log_{10}(S2/S1)$, as a function of energy for electron-recoil events (left) and nuclear recoil events (right). WIMP scattering causes nuclear recoils, while the dominant background sources are electron recoils. To collect data of this type, and thereby determine the discrimination factor of the detector, we require both electron-recoil and nuclear-recoil calibration sources. Data courtesy of the LUX group at Case Western.

The importance of calibration. Here we briefly describe why a comprehensive calibration campaign is *absolutely required* for these liquid xenon experiments to be successful. 1) The detector cannot make a reliable energy measurement in either the scintillation or ionization channels without a full-volume calibration dataset. For example, the primary scintillation collection in such a detector varies by as much as a factor of two depending on the event location, and this dependence must be understood[16]. Also, the response of the anode to the charge deposition can also vary by 20% depending on the x-y position of the event[16]. This dependence is due to non-uniformities in the anode electric field, and we must correct for this as well. 2) Dark matter interactions are expected to produce an exponentially-falling recoil spectrum, which means that the energy threshold of the detector must be well characterized with a known source. 3) The recoil discrimination factor (see Fig. 3) of the detector must be determined *in situ* and over the full volume of the detector because it depends on the scintillation and ionization acceptance. Therefore this important background rejection method cannot be employed without a careful calibration campaign. *Note that we must calibrate with both beta-like sources (to induce electron-recoil events) and neutron sources (to induce nuclear-recoil events).* Neutron sources alone are not adequate for our needs.

The power of self-shielding. Dark matter searches benefit from a large target mass in two respects. First, the number of signal events in the detector scales linearly with the target mass and the exposure time. Secondly, at the scale of modern detectors, self-shielding begins to play a dominant role in reducing backgrounds. The reason for this suppression is easy to understand. Gammas and betas in the dark matter energy range (~ 1 - 10 keVee[1]) cannot penetrate into the fiducial volume due to the opacity of xenon material at those energies, while higher energy gammas have difficulty producing single-scatter events at the correct energy. A simulation of the exponential power of self-shielding in the LUX detector is shown in Fig. 2.

Calibration of a large liquid xenon experiment. The fantastic background rejection power of self-shielding, illustrated in Figure 2 is the key feature of modern experiments of this type. On the other hand, having constructed such a background-insensitive instrument, we are faced with a new challenge: how can we calibrate such a device with radioactive sources? Until now, experiments have been calibrated primarily with external, localized gamma sources such as

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[1] "keVee" = keV-electron-equivalent, the energy observed in the detector under the assumption that the interacting particle was a gamma or beta.