CHILLAX – developing a xenon-doped dual-phase argon detector for rare event searches

Jingke Xu, LLNL

Neutrino seminar, Fermilab

April 7th, 2022

LLNL-PRES- 833531
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

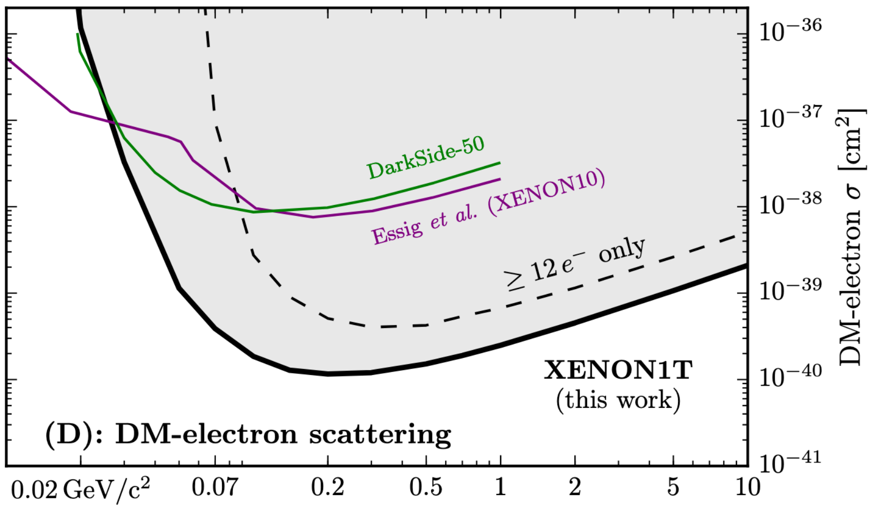
Outline

- Introduction
  - Physics motivation for CHILLAX
  - Benefits of xenon doping in dual-phase argon detectors
- CHILLAX detector development
  - Xenon doping cryogenics
  - CHILLAX design features
  - Preliminary xenon doping test results
  - Direct VUV light readout with SiPMs
- Conclusion and outlook

Low-mass dark matter searches

Liquid argon and xenon ionization detectors also lead low-mass dark matter searches

- Extremely low background rates in the keV energy region
  - < 1 event/ton/keV/day in xenon
  - ~0.1 event/kg/keV/day in argon
- Large detector mass
- Low energy threshold
  - Single ionization electron sensitivity
  - < 1keV threshold in Ionization only mode
  - << 1keV threshold assuming Migdal effect



Dark matter-electron scatter cross section limits obtained with argon and xenon experiments
Phys. Rev. Lett. 123, 251801

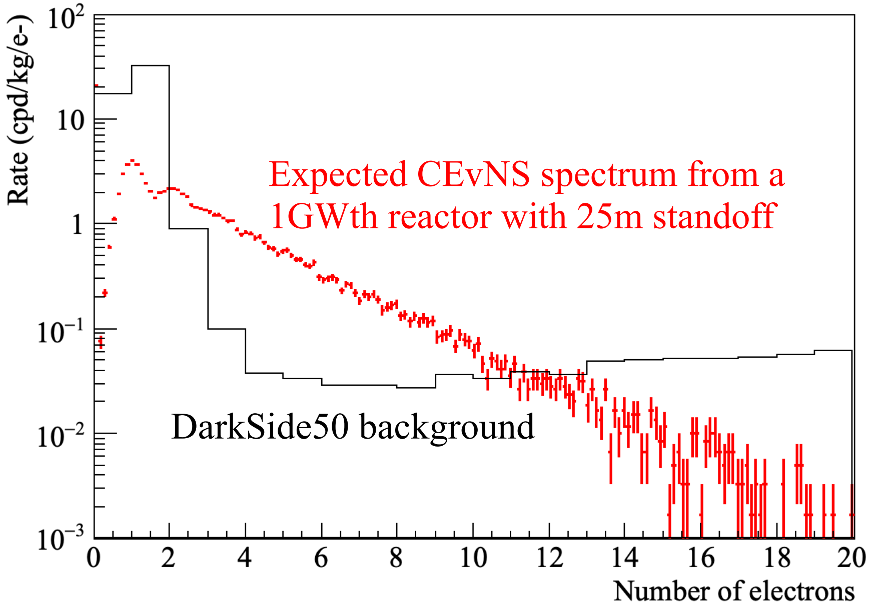
CEvNS detection with noble liquids

Coherent Elastic neutrino-Nuclear Scatter (CEvNS) is a rare process analogous to low-mass WIMP dark matter interactions

- A new probe into BSM physics
- Complementary to IBD-based reactor monitoring programs

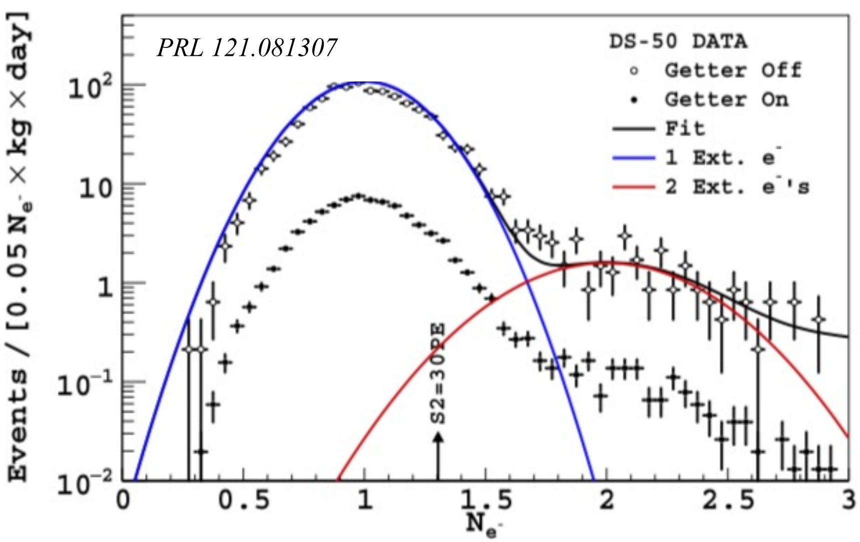
Liquid argon and xenon ionization detectors are good candidates for CEvNS detection

- Sufficiently low energy threshold
- Low background rate
- Large target mass achievable

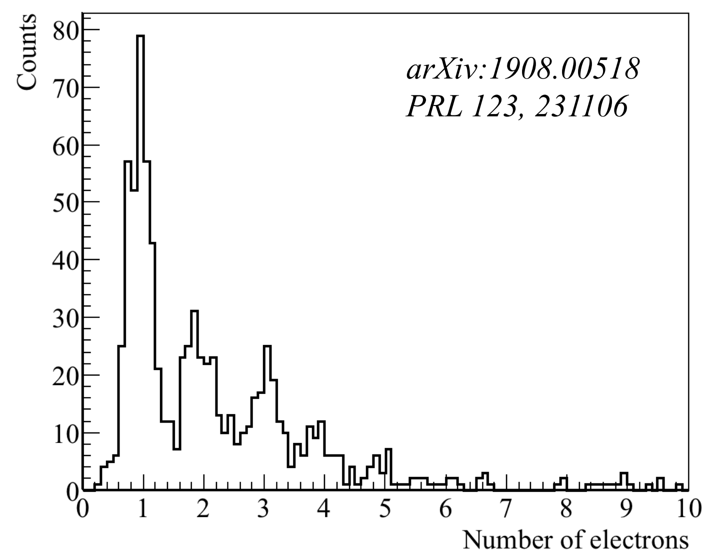


Can one combine advantages of Ar and Xe?

- Argon is a preferred target for kinetic coupling to neutrinos and low-mass DM
- Argon detectors may have a lower ionization background rate
  - Impurity outgassing is a main source for few-electron background (LAr is colder)
  - Unextracted electrons from liquid into gas is another (reduced in LAr)
- Xenon detectors have outstanding energy resolution in the few-electron region
  - Longer wavelength light reduces complexity of signal collection



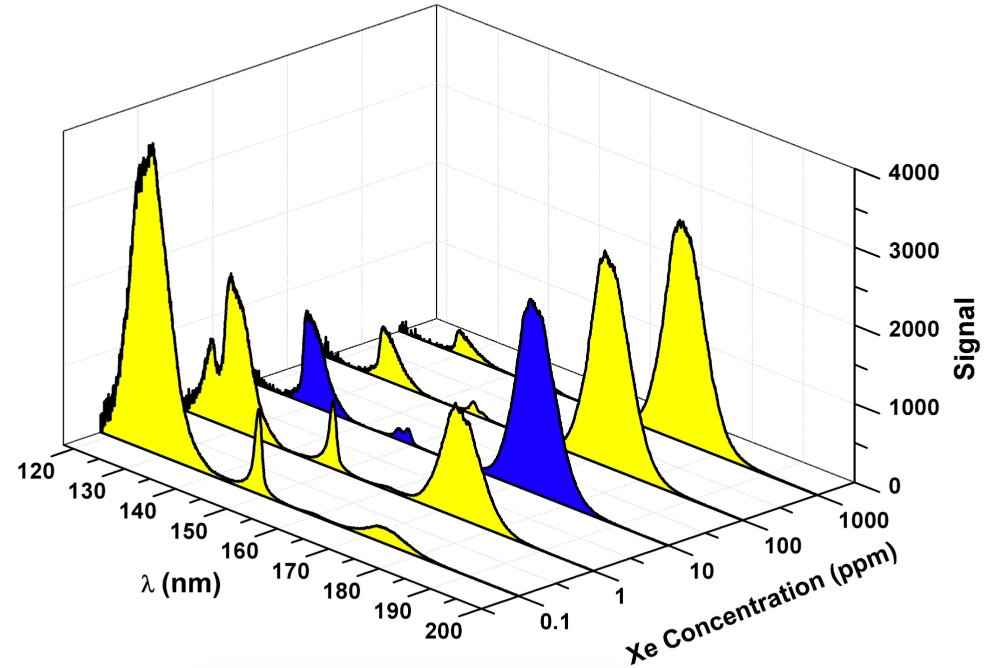
Single and double electron spectrum in DarkSide50



Few-electron spectrum (400eV Xe recoils) in LLNL XeTPC

Xenon-doping in liquid argon (as is usually discussed)

- Low-concentration xenon doping in liquid argon is well studied for “wavelength shifting” of argon scintillation light
  - Energy transfer from Ar* to Xe
  - Wavelength shifting of 128nm light
  - Longer wavelength, shorter decays
  - 10ppm xenon in LAr almost completes the “wavelength shifting” process
- This technique may have significant application in large LArTPCs such as DUNE

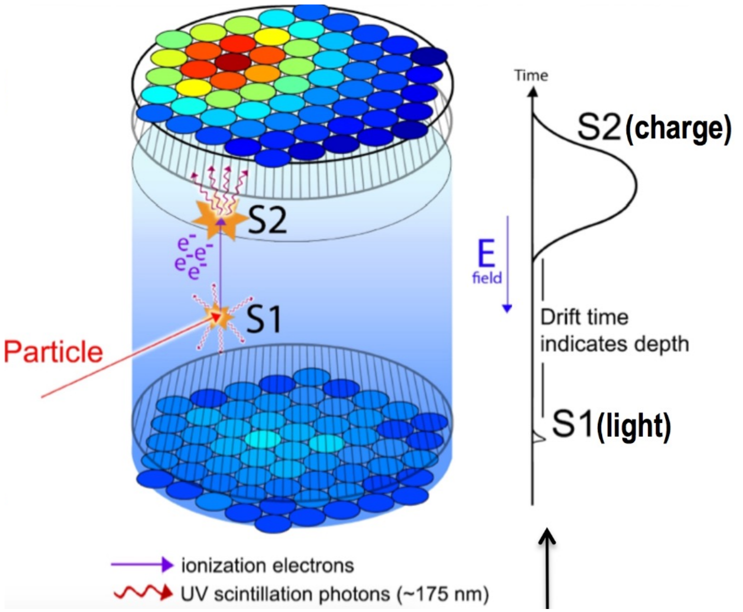


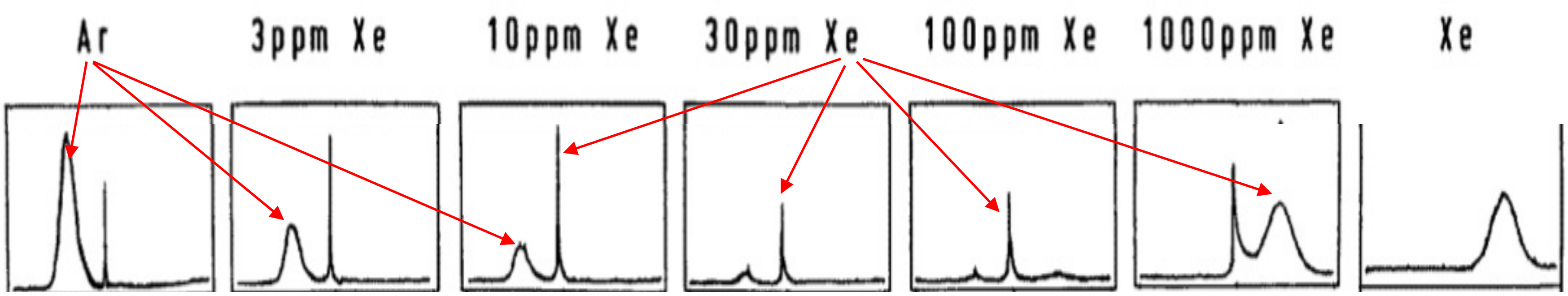
Spectra of scintillation light emission in liquid argon-xenon mixtures
A. Neumeier et al., Europhys. Lett. 109 12001 (2015)

Xenon-doping for better ionization detection?

Xenon doping may enhance electron signal amplification in a dual-phase argon detector

- Electron signals are amplified through electroluminescence in the gas phase
- 10s of ppm xenon in gaseous argon can shift a large fraction of argon electroluminescence to longer (xenon) wavelengths
  - Possibly **higher photon yield**
  - Longer wavelength → **easier detection**
  - Shorter decay → **improved timing**



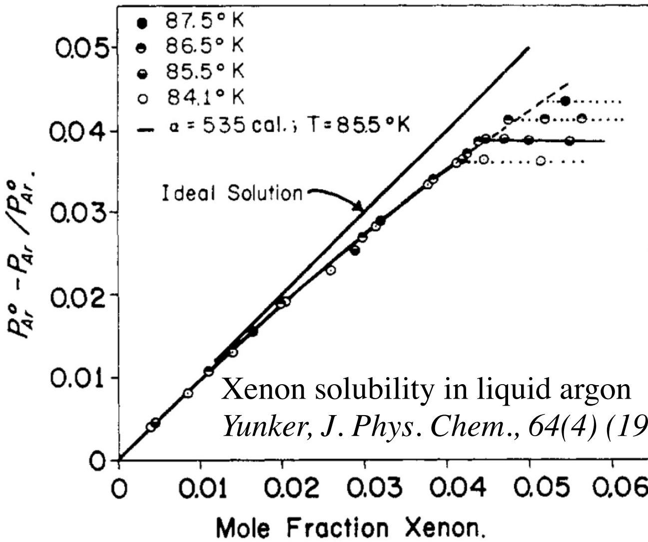


T Efthimiopoulos et al 1997 J. Phys. D: Appl. Phys. 30 1746

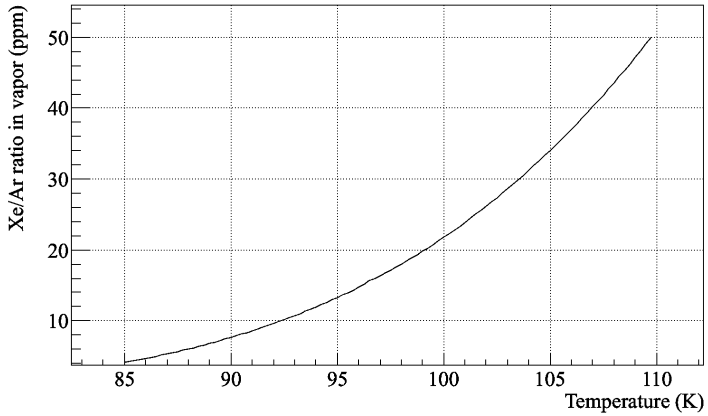
Xenon-doping for better ionization detection?

Can we get 10s of ppm gaseous xenon in a dual-phase argon detector?

- Xenon has high solubility in liquid argon
  - 4.5% by mole fraction at 87.5K
  - 7% by mole fraction at 95K (extrapolation)
- Xenon has appreciable vapor pressure at liquid argon temperature
  - 1e-4 bar at 87.5K, and 5e-4 bar at 94K
  - A few percent of xenon doping in the liquid may give 10s of ppm of xenon in the gas based on Raoult's law
  - Chemical potential argument predicts higher xenon concentration in gas



Xenon solubility in liquid argon
Yunker, J. Phys. Chem., 64(4) (1960) 484.

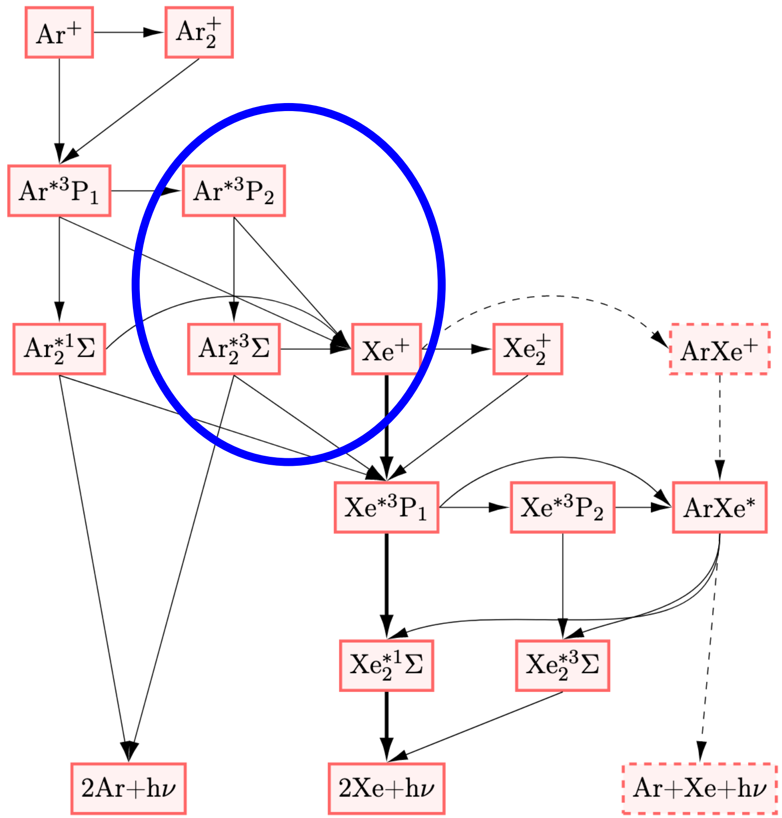


Calculated Xe concentration in a dual-phase argon detector with 4% xenon doping (Raoult's law/ideal solution)

Xenon-doping to boost ionization signal?

For detection of small ionization signals, xenon doping may lead to more ionization electrons per energy deposition

- Some Ar excitation states have higher energy levels than Xe ionization
- Penning ionization of argon excitations could lead to xenon ionization and additional electrons
- May require high electric field to observe significant effect
- Effect to be confirmed experimentally



Energy transfer processes in xenon-dopped argon
C. Galbiati et al 2021 JINST 16 P02015

Outline

- Introduction
  - Physics motivation for CHILLAX
  - Benefits of xenon doping in dual-phase argon detectors
- <u>CHILLAX detector development</u>
  - Xenon doping cryogenics
  - CHILLAX design features
  - Preliminary xenon doping test results
  - Direct VUV light readout with SiPMs
- Conclusion and outlook

Technical challenges of xenon doping

High-concentration xenon doping poses serious technical challenges

- How to mix a lot of xenon into liquid argon in a reasonable period of time?
  - ~100ppm of xenon may be introduced to argon gas stream in a typical condensation scheme
  - 1% doping of xenon takes ~100 times more time than the condensation of argon

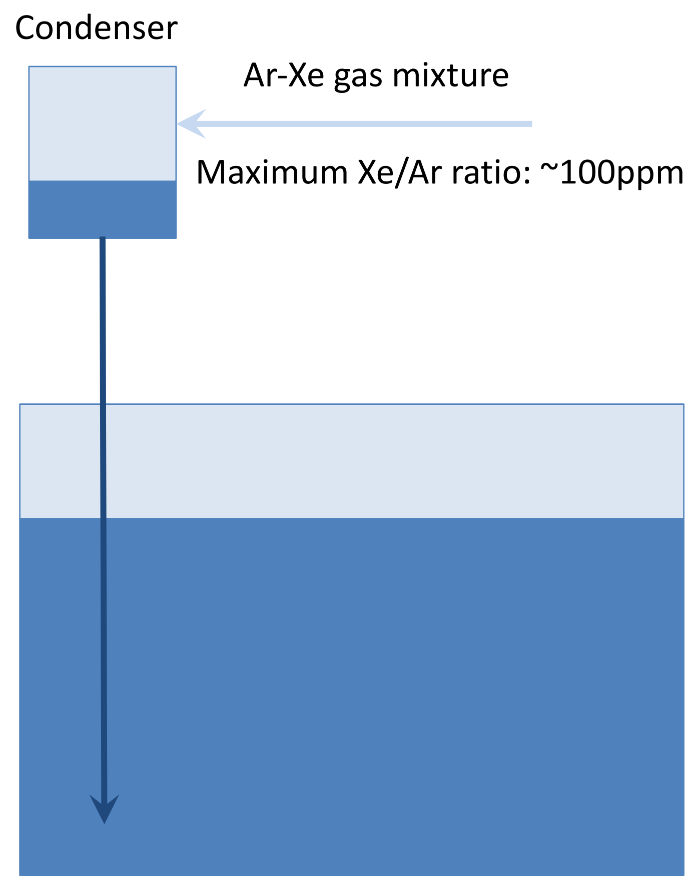


Illustration of a typical gas condensation scheme for dual-phase noble liquid detectors

Technical challenges of xenon doping

High-concentration xenon doping poses serious technical challenges

- How to mix a lot of xenon into liquid argon in a reasonable period of time?
  - ~100ppm of xenon may be introduced to argon gas stream in a typical condensation scheme
  - 1% doping of xenon takes ~100 times more time than the condensation of argon
- How to circulate the Ar-Xe mixture to maintain liquid purity for detector operation?
  - A distillation scenario is created when the liquid mixture turns into gas
  - Where liquid boils, ice forms!

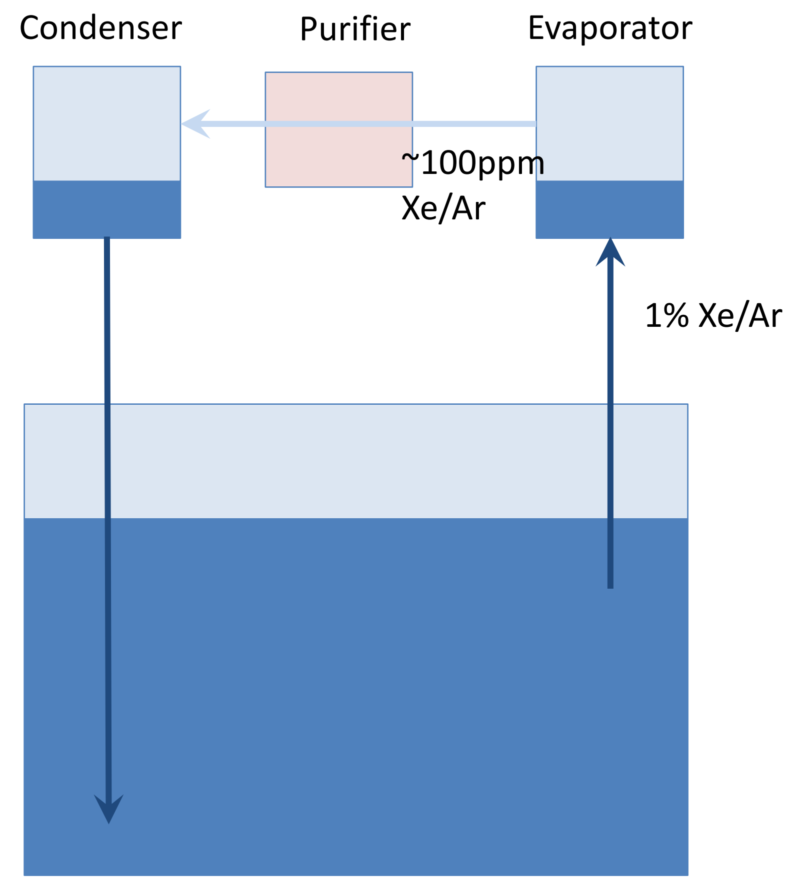
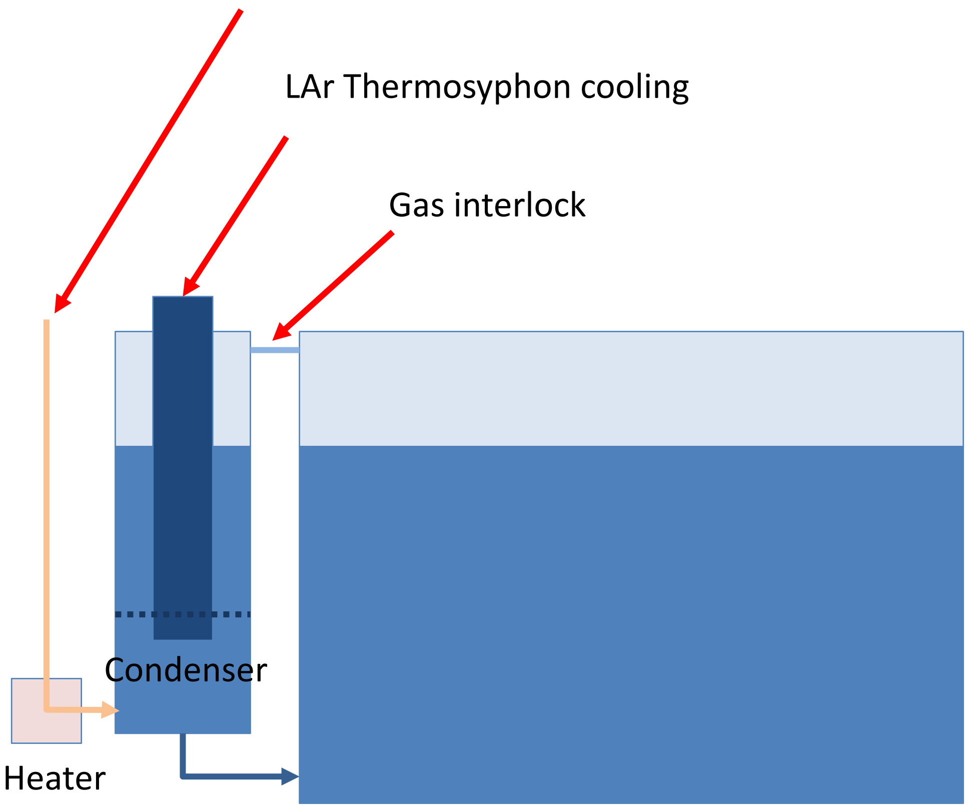


Illustration of a typical gas circulation scheme for dual-phase noble liquid detectors

Xenon delivery in CHILLAX

To obtain %-level xenon doping, CHILLAX adopts a different condensation scheme

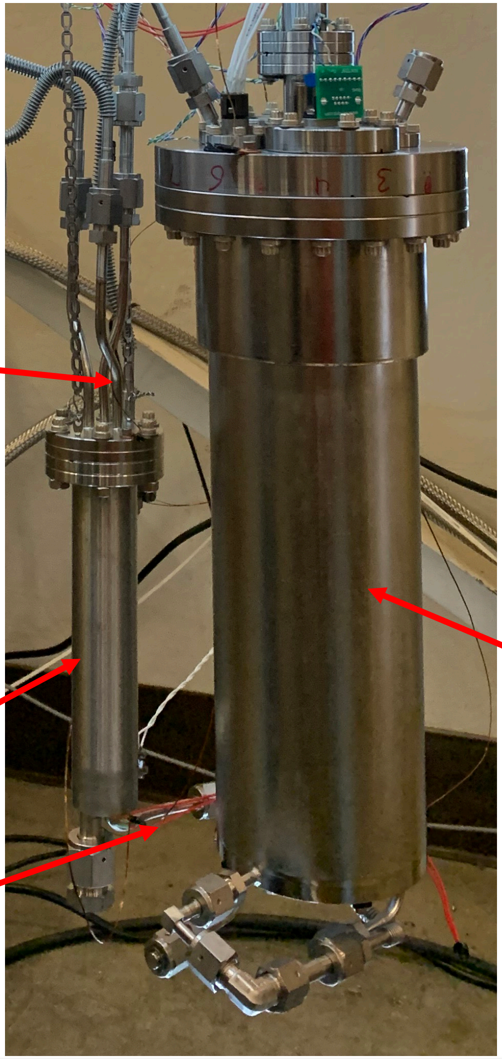
- Introduce 1-2% Xe-Ar mixture gas directly into liquid argon
- Full xenon capture in liquid (ice can dissolve if it forms)
- Direct cooling applied to liquid argon (through thermosyphon) next to detector
- Pre-heating Xe-Ar gas before entrance to condenser



Xenon delivery in CHILLAX

To obtain %-level xenon doping, CHILLAX adopts a different condensation scheme

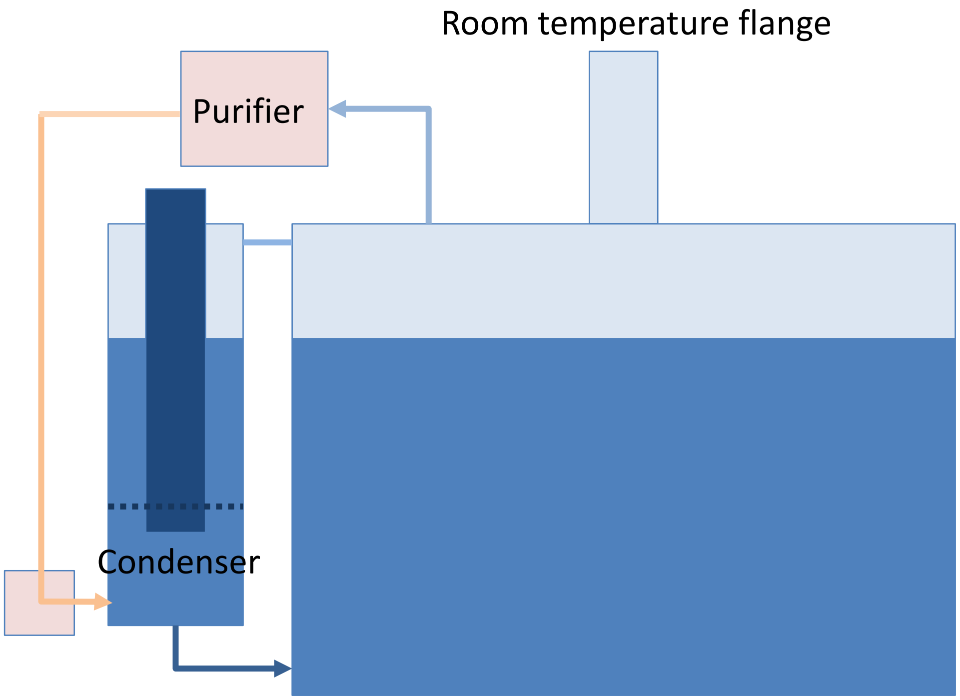
- Introduce 1-2% Xe-Ar mixture gas directly into liquid argon
- Full xenon capture in liquid (ice can dissolve if it forms)
- Direct cooling applied to liquid argon (through thermosyphon) next to detector
- Pre-heating Xe-Ar gas before entrance to condenser



Circulation-purification in CHILLAX

Continuous circulation and purification are needed to keep the target clean

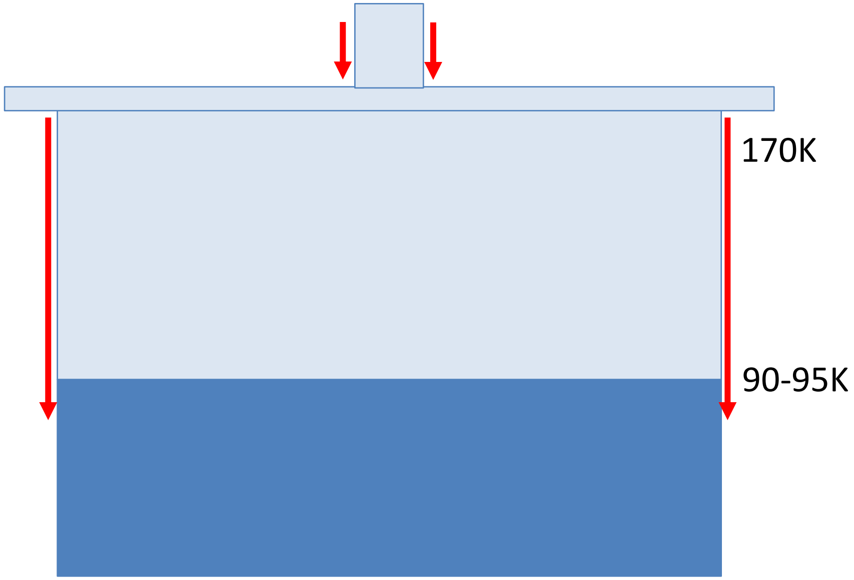
- Ideally, we would move liquid through purifier
  - No phase transition/distillation
  - No xenon congregation
- We are currently testing circulating gas from detector volume
  - No xenon congregation outside detector argon volume
  - Liquid convection could prevent xenon ice forming

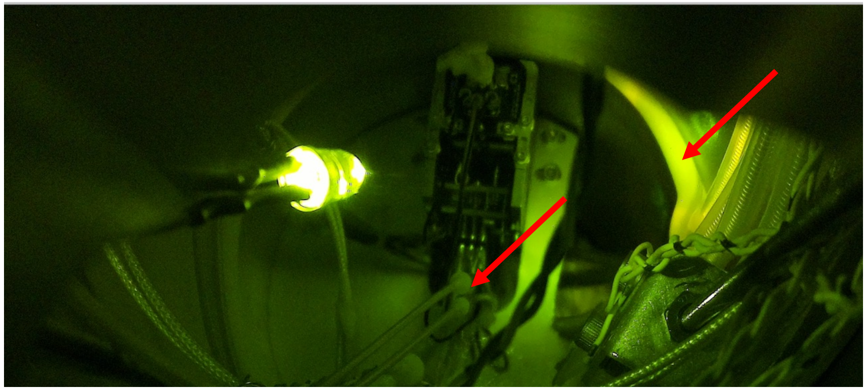


Retaining xenon in liquid mixture

Thermal leaks into liquid mixture will cause boiling and distillation

- Detector support structure is mounted on room temperature flanges
- Heat traveling down detector can cause liquid next to detector wall to boil and local xenon concentration to increase
  - Liquid splashed/capillary-drawn onto walls boils off and leaves behind xenon ice
  - Xe-saturated argon might produce saturated Xe gas that can condense on wall surfaces near by

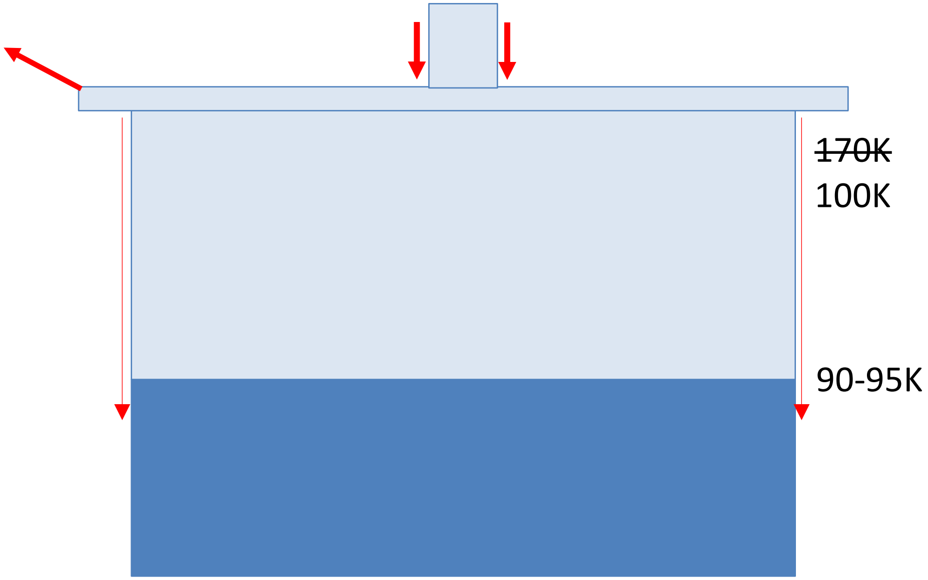




Retaining xenon in liquid mixture

We added a thermal link to the cryocooler to intercept heat leak down the support

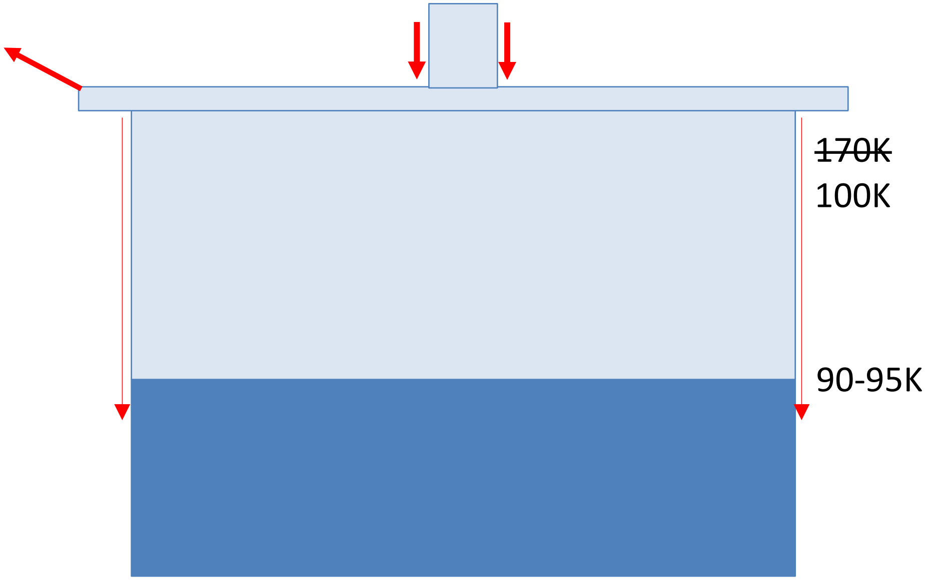
- Detector flange cooled to ~100K while liquid mixture stays at 90-95K
- Xenon ice forming is much slowed
- Will add thermosyphon for stronger cooling (possibly produce Ar reflux on walls)

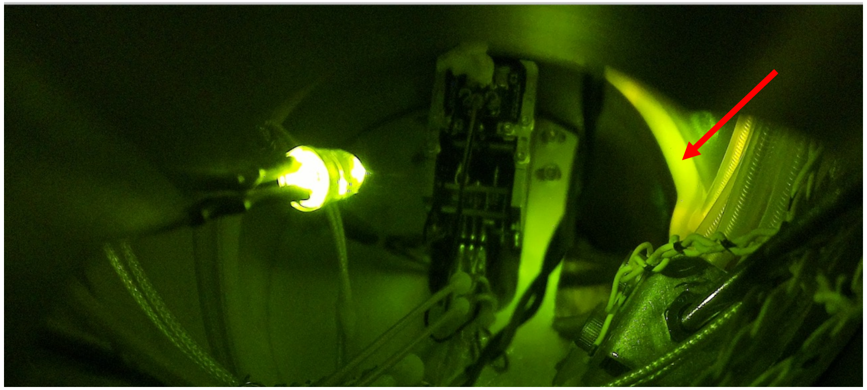


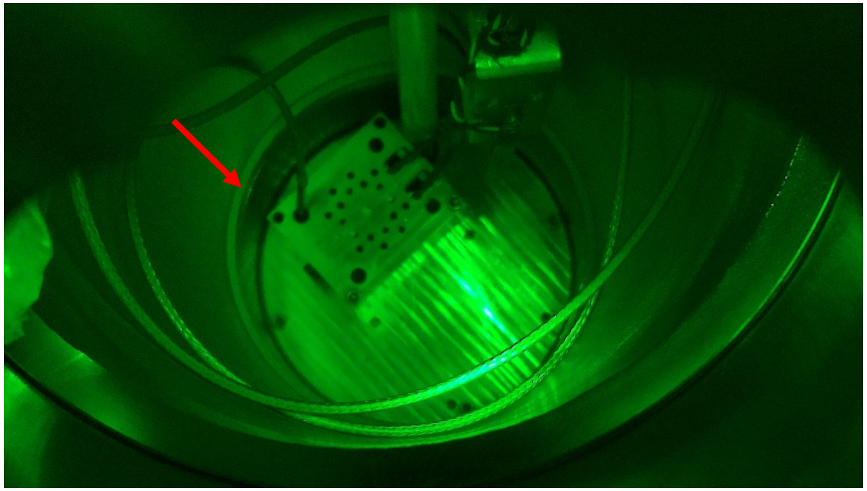
Retaining xenon in liquid mixture

We added a thermal link to the cryocooler to intercept heat leak down the support

- Detector flange cooled to ~100K while liquid mixture stays at 90-95K
- Xenon ice forming is much slowed
- Will add thermosyphon for stronger cooling (possibly produce Ar reflux on walls)



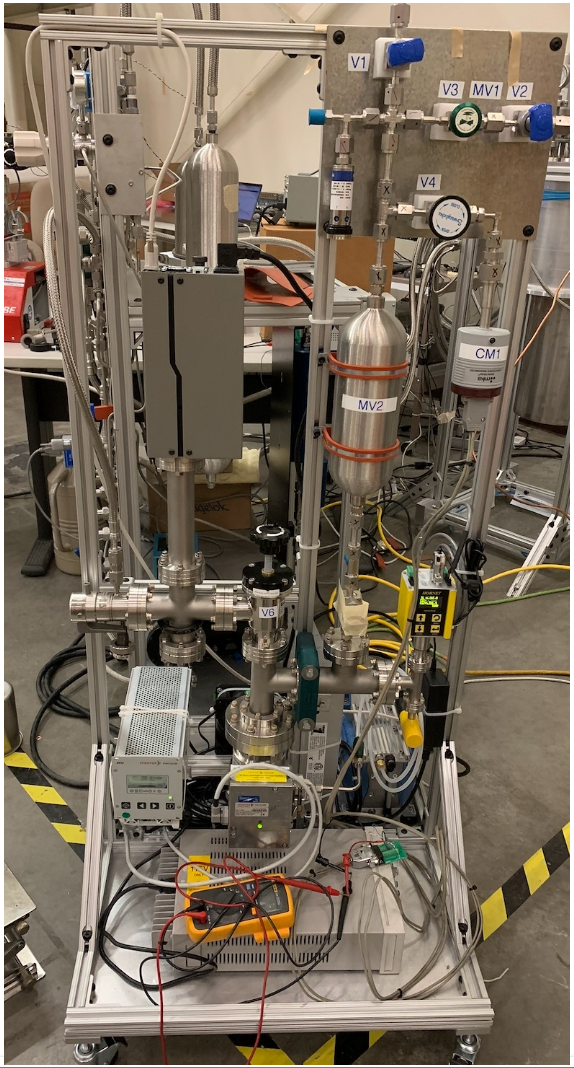




Xenon concentration measurement in the gas

To gain benefits of xenon doping for electron signal amplification, we need 10s of ppm Xe/Ar in the gas

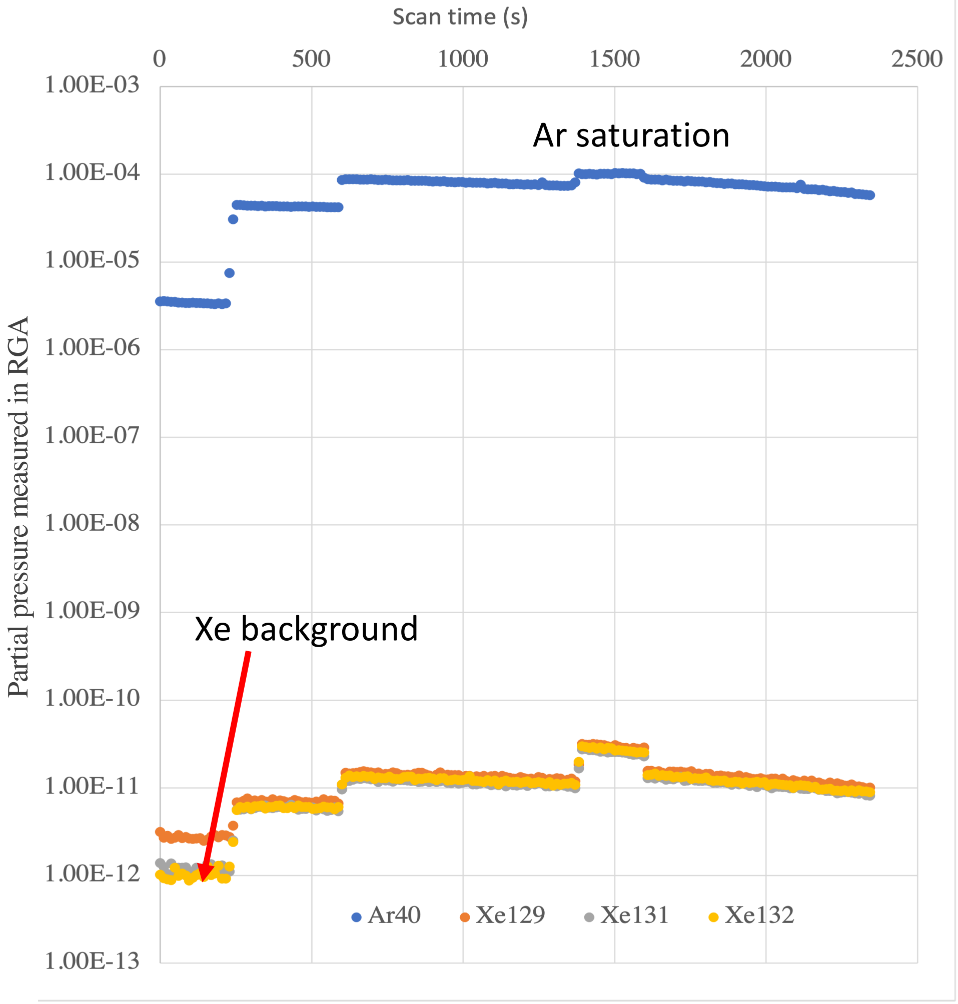
- Goal is to achieve ~30-50ppm Xe/Ar
- Gas composition sampled with RGA200
- Gas dilution through volume expansion, pressure bleeding, pinhole and leak valve control
- Ar-Xe gas mixture in the ppm level can be prescribed for system calibration



CHILLAX Sampling system calibration

RGA scan of prescribed Ar-Xe mixture

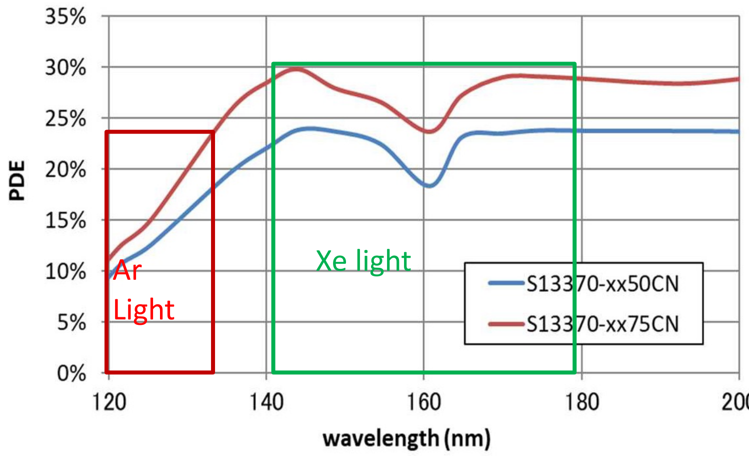
- Sample contains 2ppm Xe/Ar
- Scan used both FC and CEM
- RGA measured ~0.6 ppm
- Complete calibration curve under development
- We observed gaseous xenon concentration in the 10s of ppm region for liquid doping of ~1-2%
- High voltage system to measure electroluminescence gain in preparation

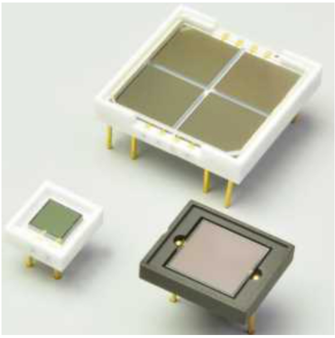


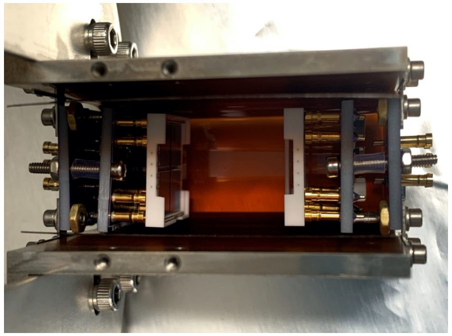
CHILLAX detection of VUV photons

At ~10s of ppm Xe/Ar ratio in the gas, electroluminescence signal may contain Ar^*_2, $ArXe^*$ and possible Xe^*_2 light

- Light detection system needs sensitivity to 128, 147 and 175nm light
- Hamamatsu VUV4 SiPMs are chosen based on their specs
- In-house, onboard, cold amplifiers were built for two types of VUV4 SiPMs (with quartz window and without)
- SiPM modules deployed in CHILLAX (both pure argon and argon-xenon mixture)



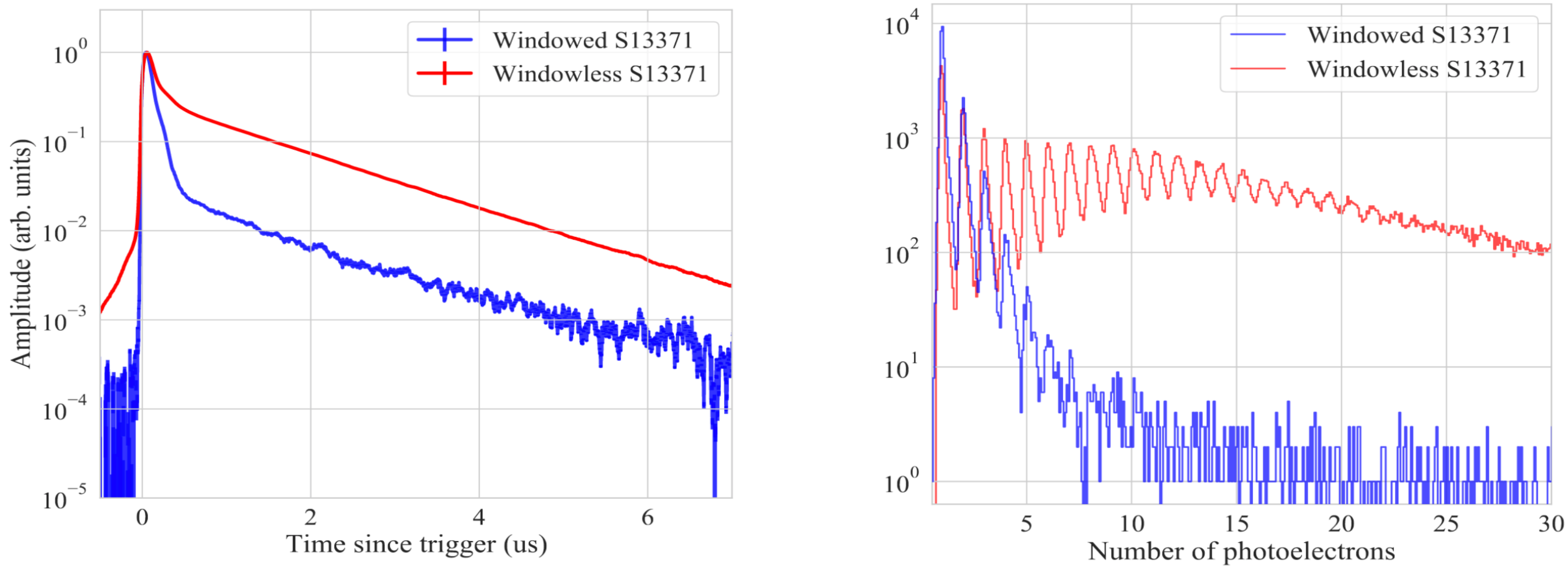




Direct detection of 128nm light

We designed control experiments using VUV4 SiPMs with and without quartz windows (160nm cutoff) to verify direct UV sensitivity

- VUV4 SiPMs with quartz window detected < 1% of light compared to windowless ones
- VUV4 SiPMs with quartz window observed weak argon triplet scintillation component

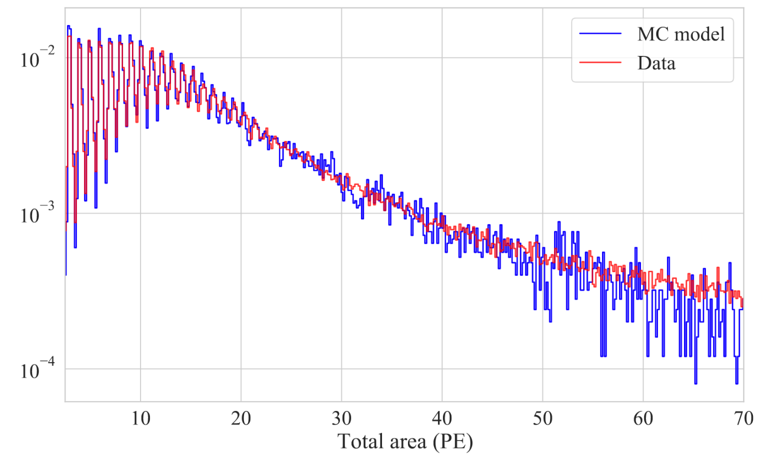


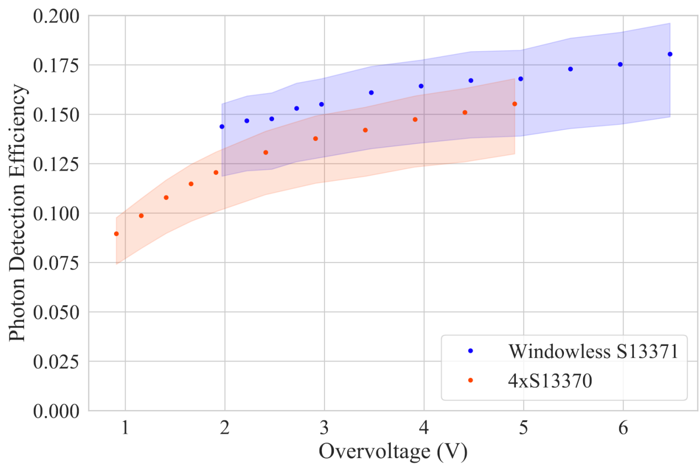
Average SiPM waveforms (left) and energy spectra measured with windowed (blue) and windowless (red) VUV SiPMs for 241Am radiation in pure liquid argon, confirming 128nm sensitivity

Detection efficiency for 128nm light

We measured appreciable PDE values for VUV4 SiPMs at 128nm

- MC simulation tracks data well
- ~15% PDE at 128nm
- Previous characterizations of VUV4 SiPMs at 175nm reported lower than quoted PDE (possibly due to quartz window)
- VUV4 SiPMs are suitable for direct liquid argon light detection!
- Publication arXiv:2202.02977, accepted by JINST





Fitted SiPM spectra for pure argon scintillation (top) and the evaluated SiPM PDE (bottom)

Conclusion and Outlook

- Xenon doping in liquid argon detectors has promising benefits
- High-concentration xenon doping, despite challenges, can substantially improve performance of dual-phase argon detectors
- CHILLAX has demonstrated preliminary success in introducing and maintaining high xenon concentration in liquid argon
- We have demonstrated direct 128nm sensitivity of VUV4 SiPMs
- We are ready to measure the effects of xenon-doping on electron signal amplification in a dual-phase configuration
- We will study possible increase of ionization yield of argon by xenon doping
- A lot of interesting results to expect this year -- stay tuned

Relevance to low-level xenon doping efforts

- A liquid argon body dopped with xenon is not stable
- Where liquid boils, ice can form
- A uniform temperature profile throughout the cryogenic system is crucial
- Small thermal leaks can cause xenon to deplete from active volume
- Even in systems with low xenon concentration, slow thermal processes could lead to xenon non-uniformity over time
- Further discussions and collaboration on xenon doping studies will be welcomed!

Lawrence Livermore National Laboratory

Disclaimer
This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor Lawrence Livermore National Security, LLC, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.