Studies of Xenon-Doped Argon with the CHILLAX Experiment

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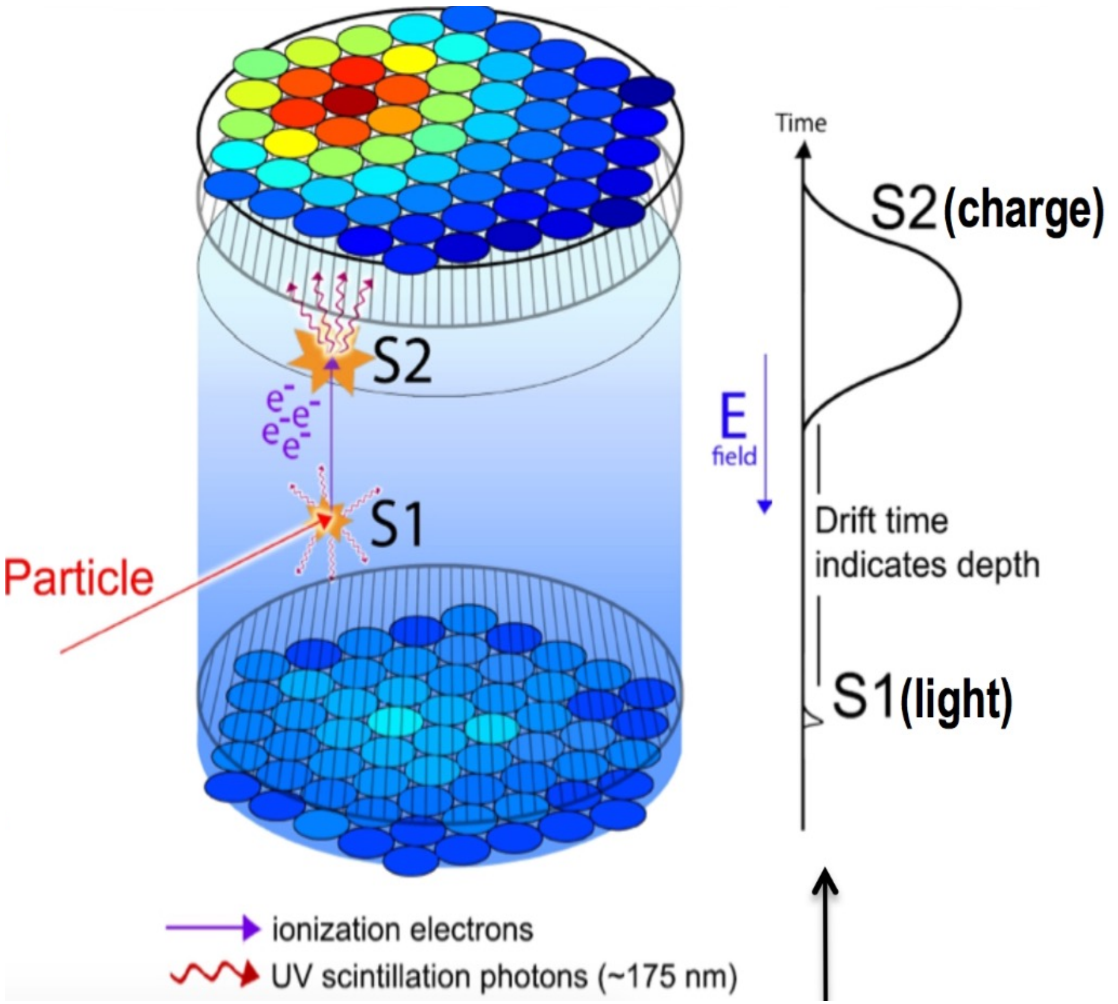
Review of Xenon and Argon Time Projection Chambers (TPCs)

A noble element dual phase TPC contains a noble element in the liquid and gas phase. An electric field is established to drift electrons. Photosensors detect scintillation light.

An energetic particle will generate:
- Scintillation light (S1)
- Ionization (S2)

The time between the S1 and S2 reveals the Z position of interaction.
The S2 pulse hit pattern on array of top photosensors reveals (X,Y) position.
S1/S2 ratio and pulse shape discrimination can be used for particle ID.



Comparison of Xenon and Argon for Detection Experiments

Argon and xenon are the two prominent noble element detection media.

Both noble elements have their advantages and disadvantages, and have produced world-leading results in the field of dark matter and neutrino physics.

Property	Argon	Xenon
Scintillation wavelength	128 nm	178 nm
Kinetic Match to Light Particles	A = 39.95	A = 131.29
Liquid phase ionization energy	14.3 eV	9.28 eV
Excitation Energy	11.8 eV	8.4 eV
Scintillation lifetime	1.5 us	22 ns
Price	Cheap	Expensive

Chemistry of Xenon-Doped Argon

Fast e- + Ar → slow e- + Ar*

Threshold 11.8 eV

Fast e- + Xe → slow e- + Xe*

Threshold 8.4 eV

Example: Electrons inelastically colliding with xenon or argon

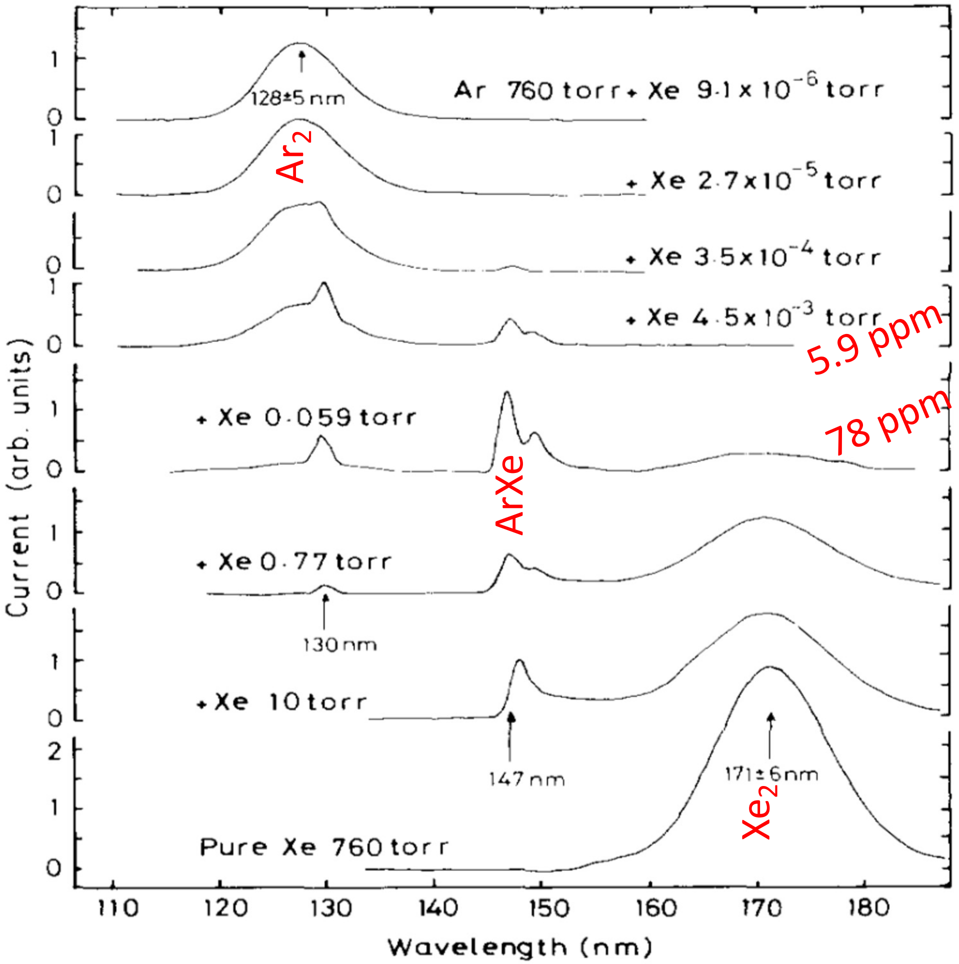
$Ar^* + Ar \rightarrow Ar_2$
$Ar^* + Xe \rightarrow ArXe$
$Xe^* + Xe \rightarrow Xe_2$

Argon and xenon form metastable excimers

$Ar_2 \rightarrow 2\,Ar + h\nu$ (128 nm, 1.6 us)
$ArXe \rightarrow Xe + Ar + h\nu$ (147 nm, ~300 ns(?))
$Xe_2 \rightarrow 2\,Xe + h\nu$ (178 nm, 22 ns)

Excimers decompose and release scintillation light

Xenon-Doping in Gaseous Argon

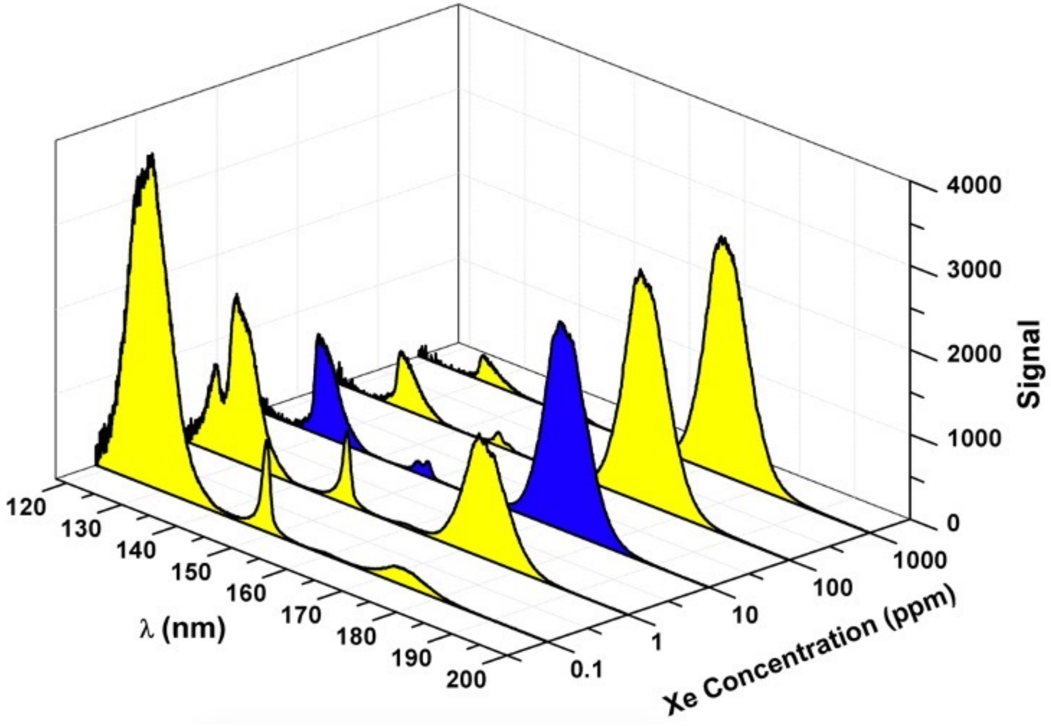


Emission spectra of xenon-doped argon gas mixtures at 1 atm in a gas proportional counter*

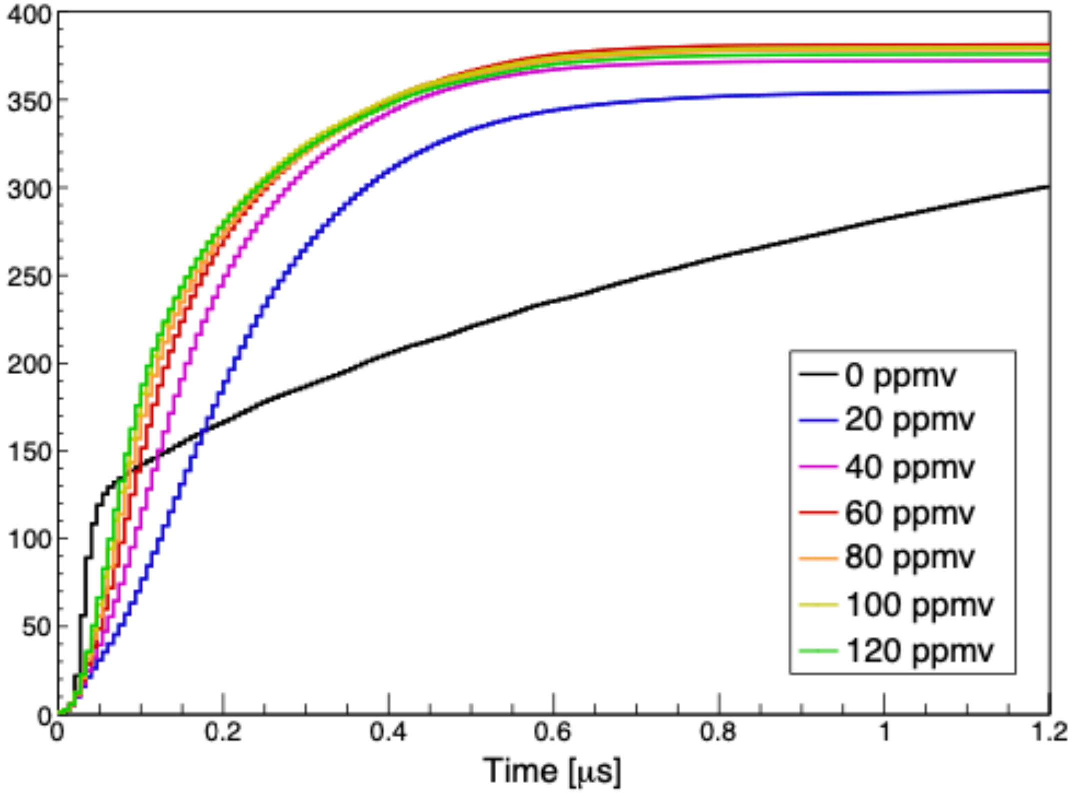
We expect most of the S2 light will be wavelength-shifted to 147 nm by ~50 ppm of Xe addition to Ar gas.

* T. Takahashi et al.
NIM **205** 591-596 (1983)

Xenon-Doping of Liquid Argon



Neumeier et al., EPL 109 12001 (2015)



D. Whittington, JINST 11 C05019 (2016)

Applications of Xenon-Doped Argon

- WIMP dark matter detection
  - Darkside-20K / GADMC
  - Especially important for extending the reach of ionization-only analysis
- Neutrino physics via the CEνNS channel*
  - Sterile neutrino searches
  - Neutrino magnetic moment searches
  - Non-standard interactions and new light mediators
  - Flavor-blind observation of supernovae, including potential insight into the neutrino mass hierarchy**
- Anti-proliferation technology
  - Reactor fuel cycle monitoring with CEνNS***

Low energy nuclear recoils

Energy spectra are weighted toward lower energies.

Small ionization signal improvements result in large sensitivity gains.

- Large-Scale argon TPC improvements****
  - Shift liquid scintillation light to more easily sensed wavelength
  - Narrower timing of liquid scintillation light
  - Reduced Raleigh scattering of scintillation light
  - Increased charge yield?

High energy hadrons and leptons

Simplify scintillation optical signal channel

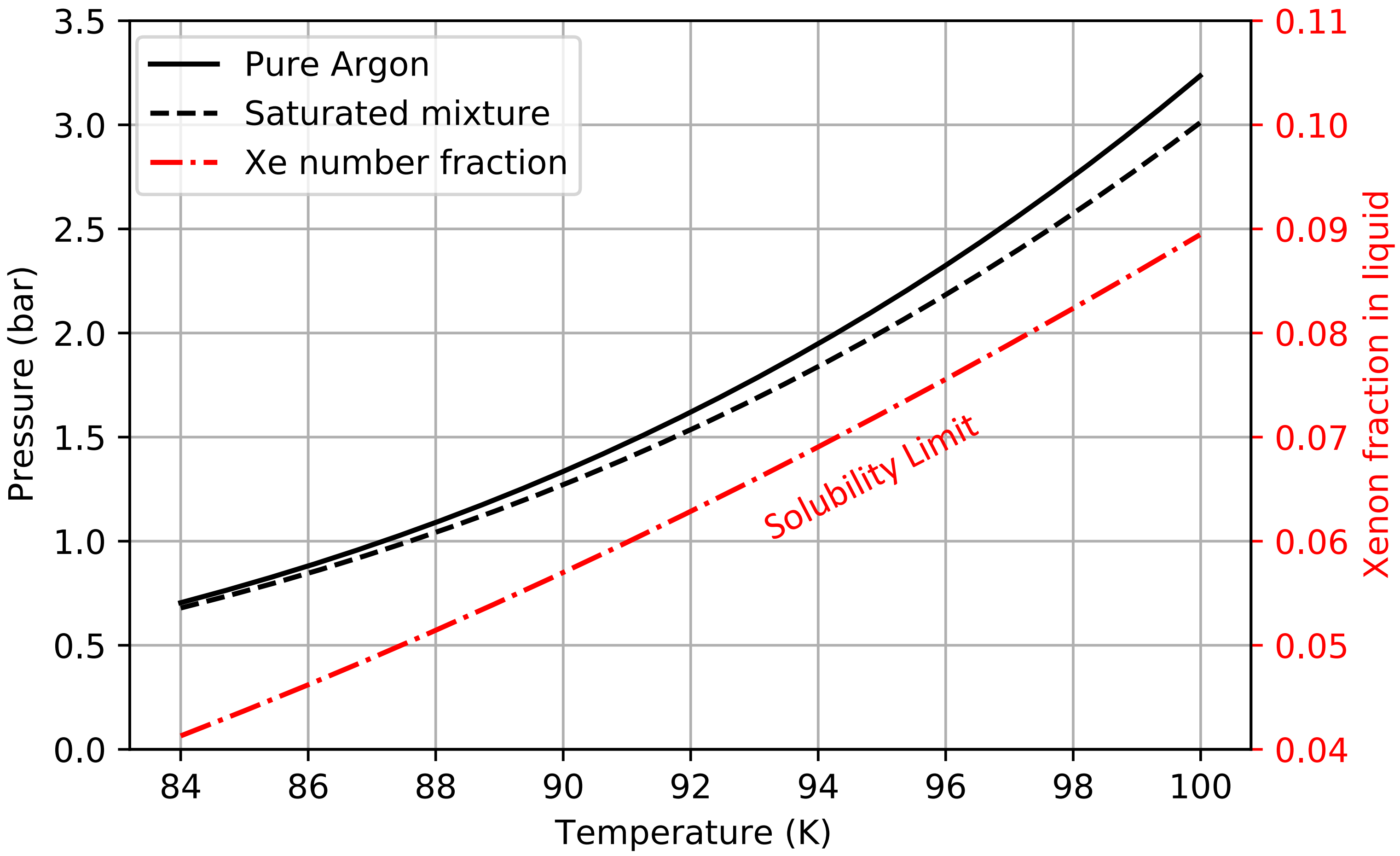
* O.G. Miranda et al., arXiv:2003.12050 ; L.J. Flores et al. arXiv:2002.12342 ; C. Blanco et al. arXiv:1901.08094

** P. Agnes et al., arXiv:2011.07819 ; *** C. Hagmann and A. Bernstein, arXiv:nucl-ex/0411004 ; **** D. Whittington, JINST **11** C05019 (2016)

Thermodynamics of Xenon-Doped Argon

Xenon-argon miscibility is highly dependent on temperature

Xenon-doping past the solubility limit results in unwanted xenon solid formation



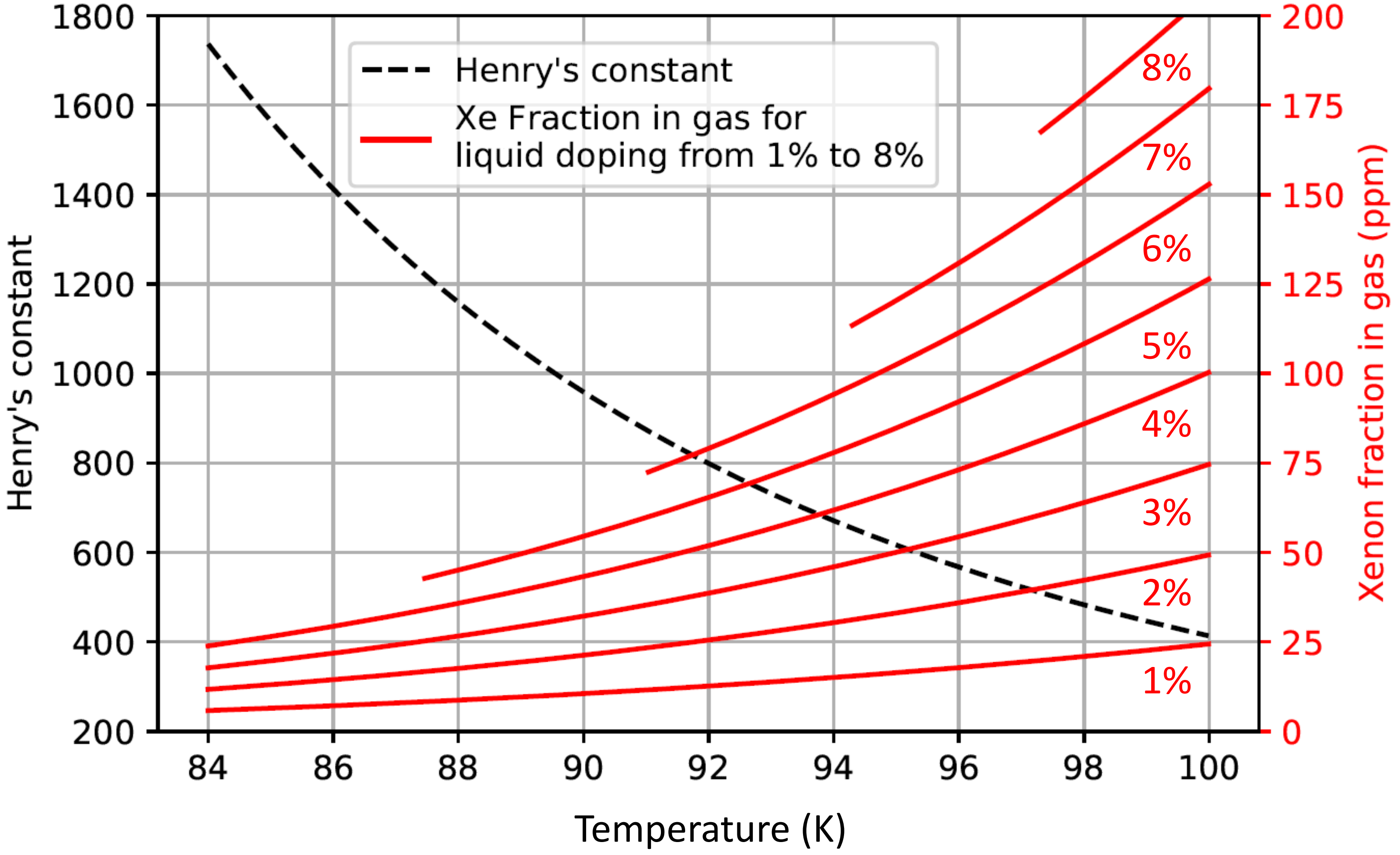
Thermodynamics of Xenon-Doped Argon

Recall: S2 light becomes "xenon-like" at O(10 ppm) level

For an operating temperature of 92 K and a desired xenon concentration in gas of 50 ppm, one needs ~4% xenon in the liquid.

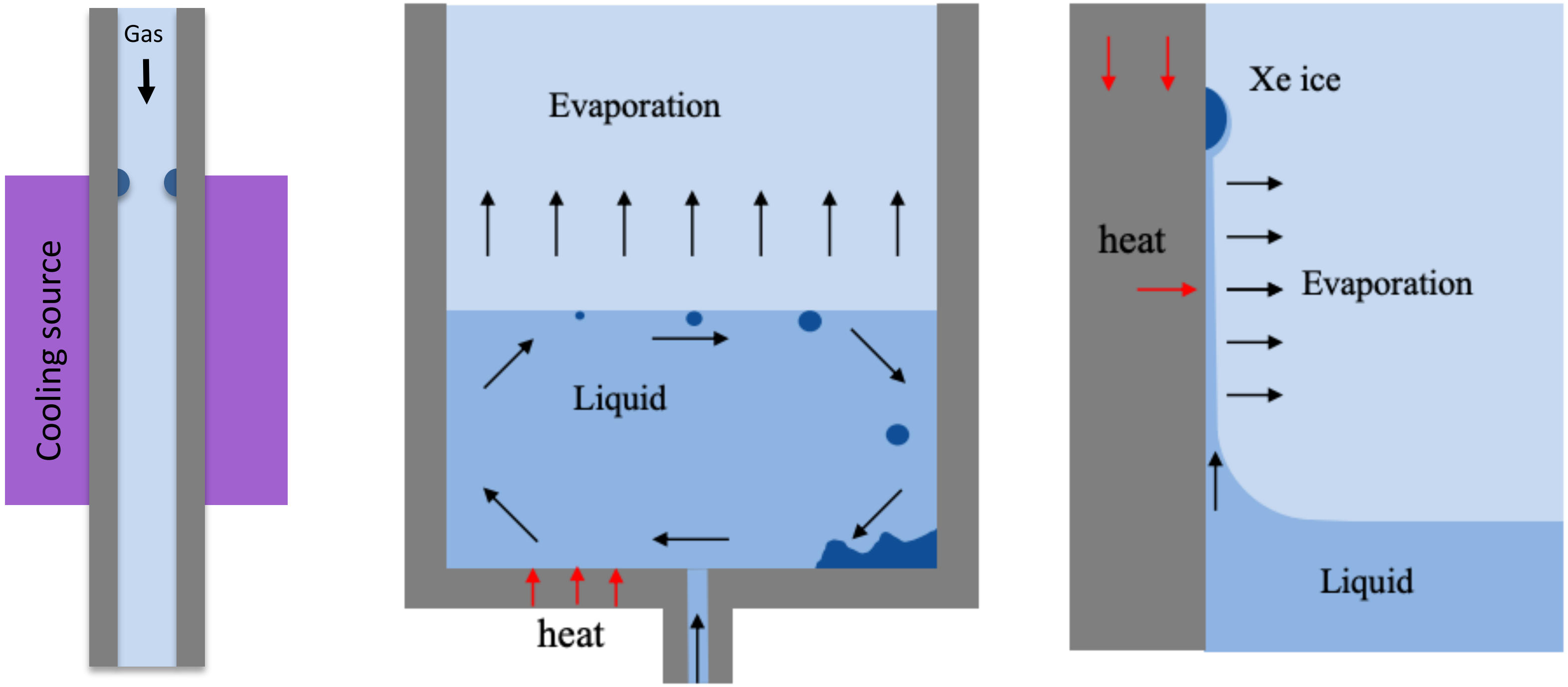
Solubility limit at 92K: ~ 6%

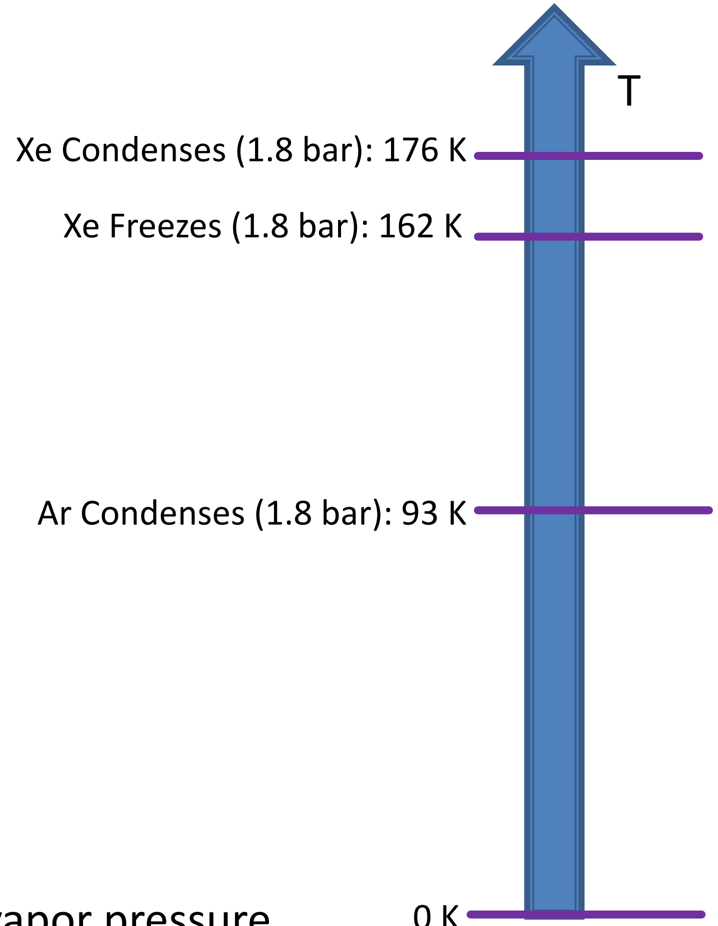
Doable in theory!



Complications from Xenon-Doping

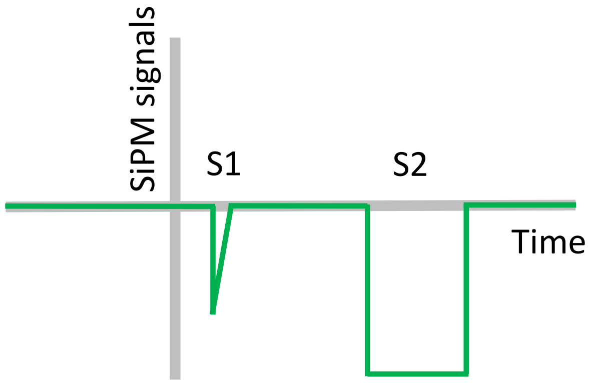
The large temperature discrepancy between xenon and argon boiling points are a major source of system instability



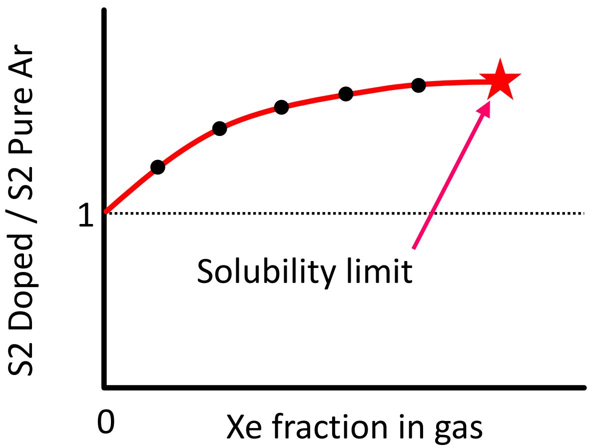


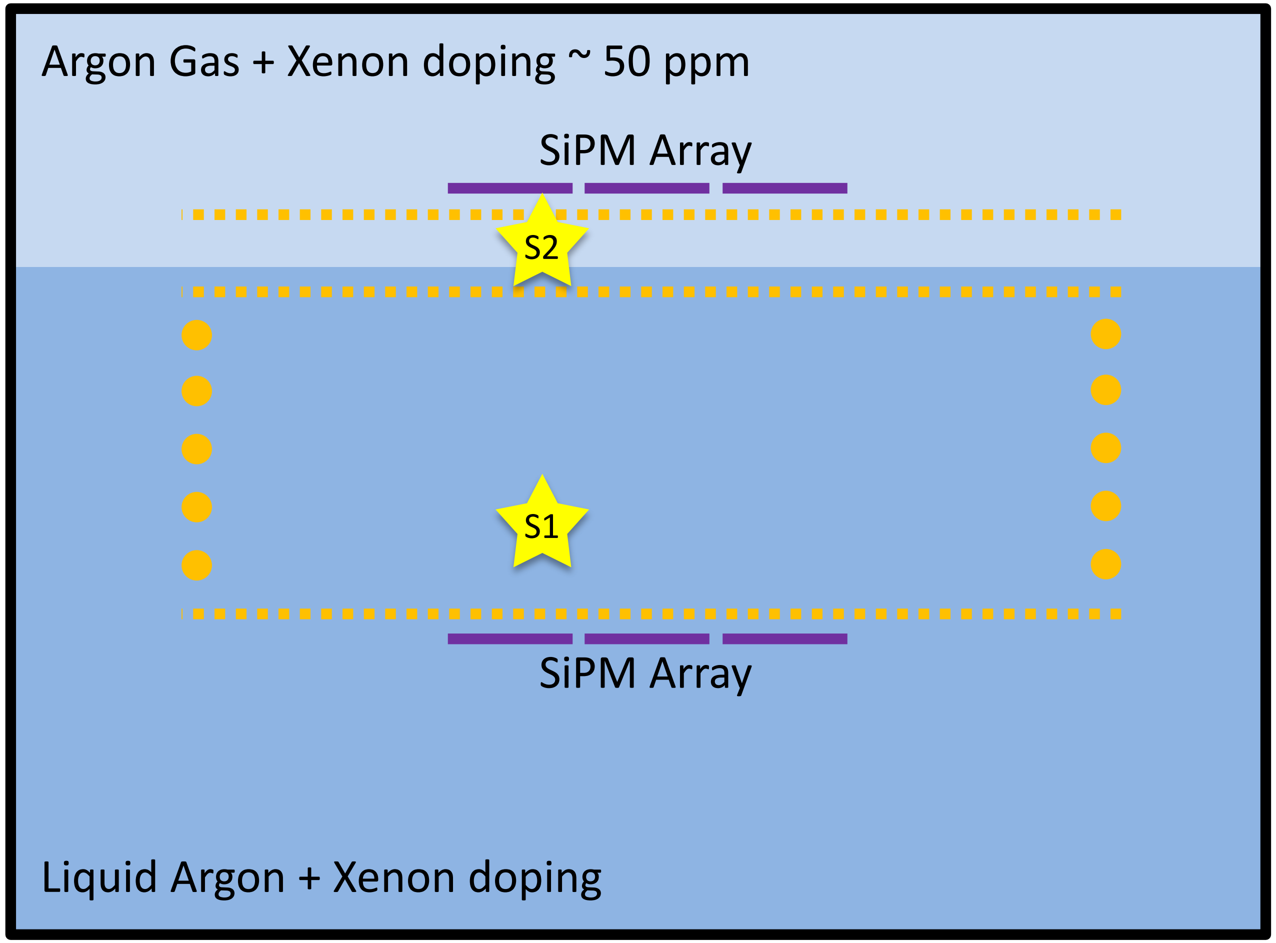
Left: Condensation of Xe-rich Ar gas causes Xe to freeze if Xe pressure exceeds saturation vapor pressure
Middle: Evaporation of liquid mixture causes Xe concentration to increase in the liquid
Right: Unintended evaporation of liquid isolated by surface tension can cause Xe ice to form

Xenon-Doped Argon S2 Experiment



Anticipated data





Detector Vessel

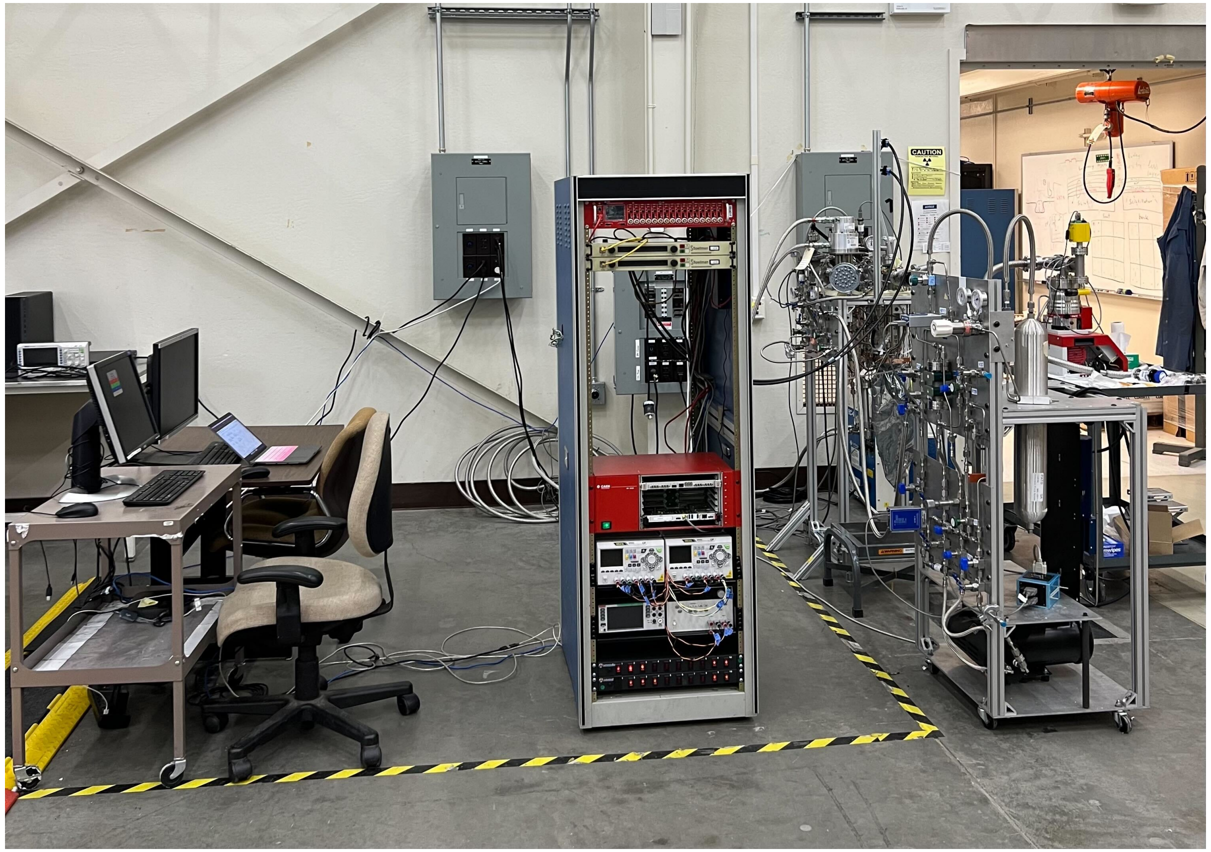
CHILLAX: CoHerent Ionization Limit of Liquid Argon and Xenon

Concept: A liter-scale dual phase xenon-doped argon TPC

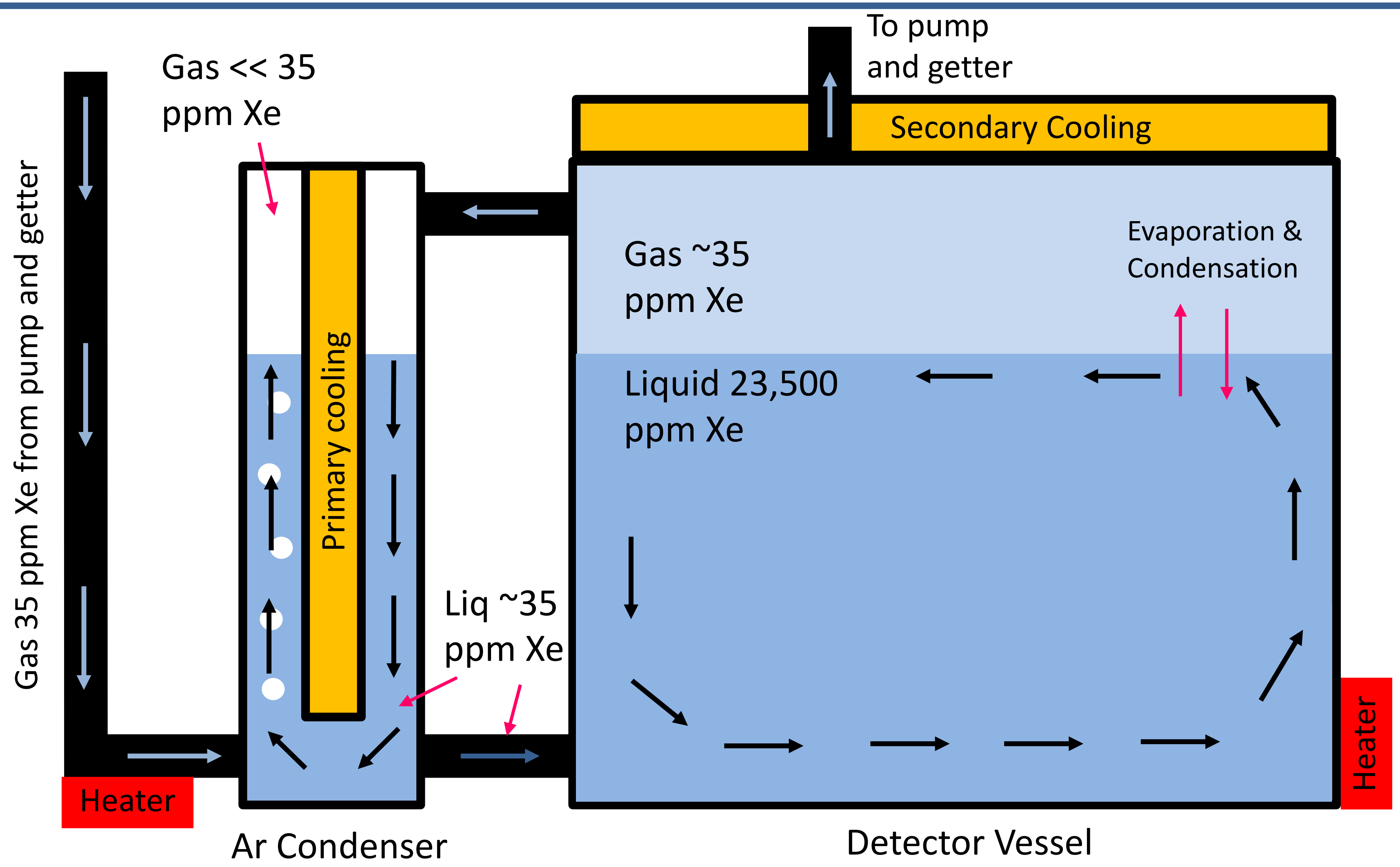
<u>Goals</u>

Investigate stability concerns from xenon-doped argon, develop system architecture that can address these challenges.

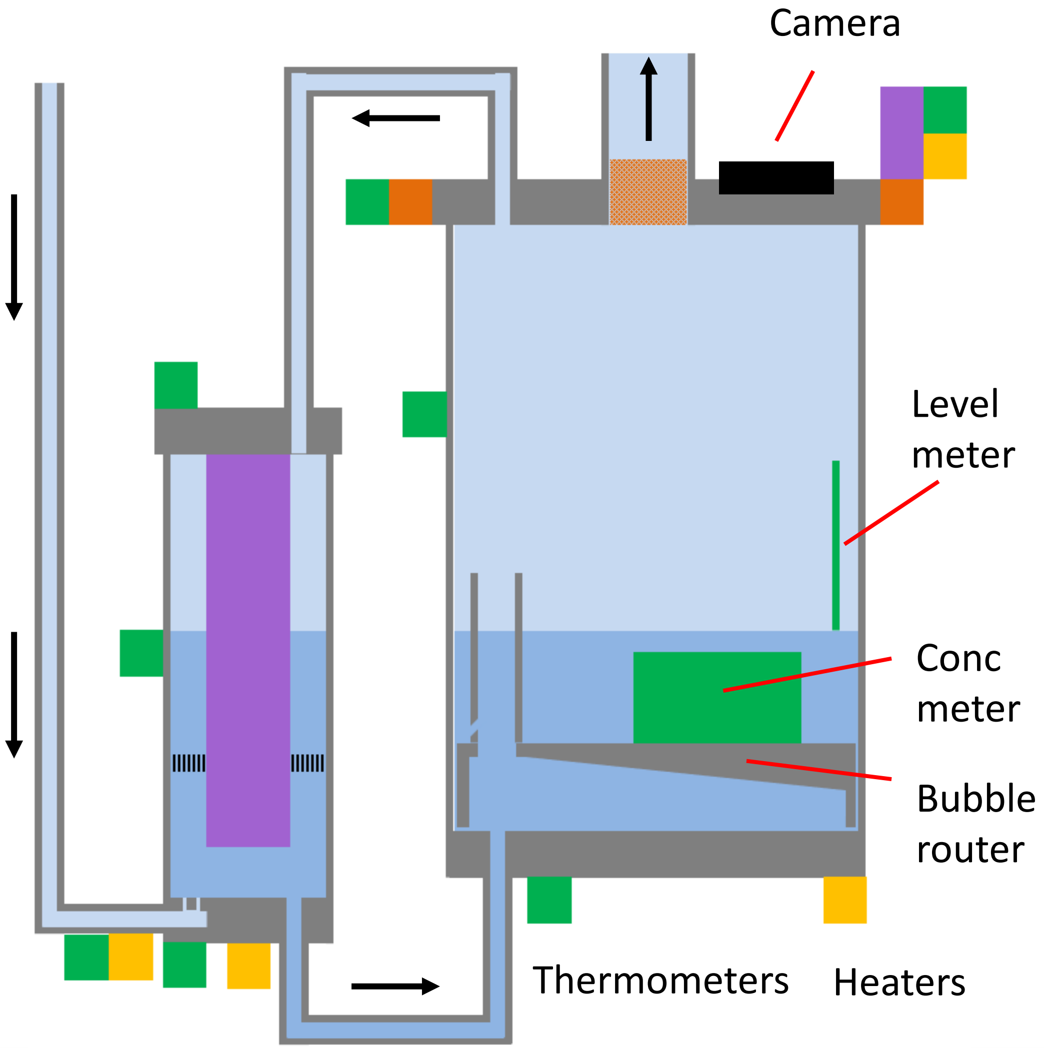
Quantify benefits to an argon TPC's ionization signal from xenon doping

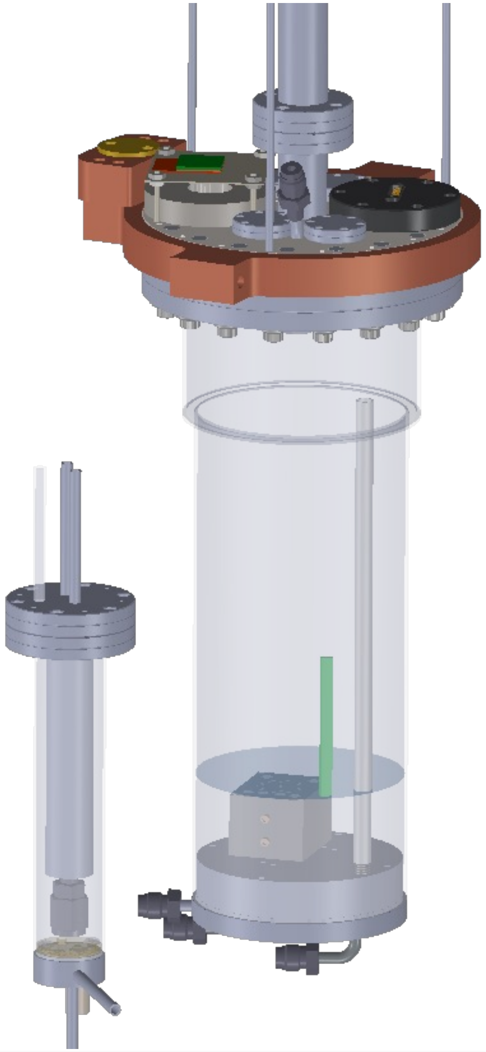


Circulation Design



Circulation Design





Capacitive Technique to Measure Xenon Concentration in Argon

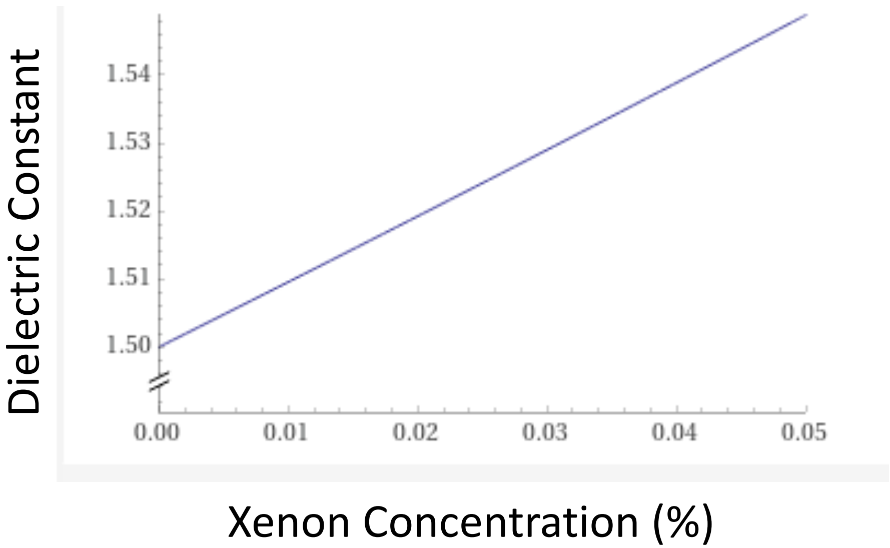
The dielectric constant of xenon-doped argon can be determined by the Clausius-Mossotti equation:

$$\frac{\varepsilon_r - 1}{\varepsilon_r + 2} = \sum_{i=1}^{2} \frac{n_i \alpha_i}{3\varepsilon_0}$$

n_i: number density of molecule (or atom) type i

α_i: atomic polarizability of molecule type i

One can derive a nearly linear dependence of ε_r on F_{Xe}:

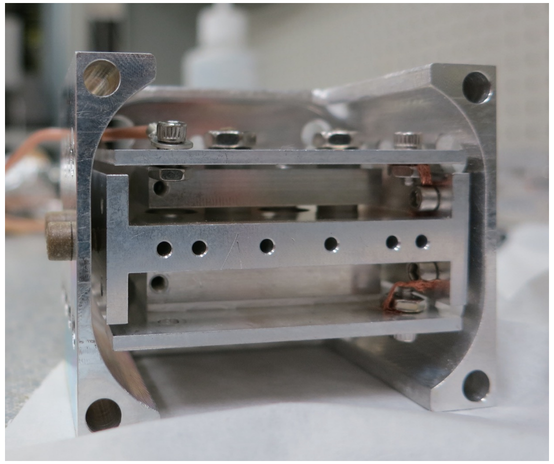


Then the capacitance of a capacitor with a xenon-doped argon dielectric medium is linearly dependent on the xenon concentration

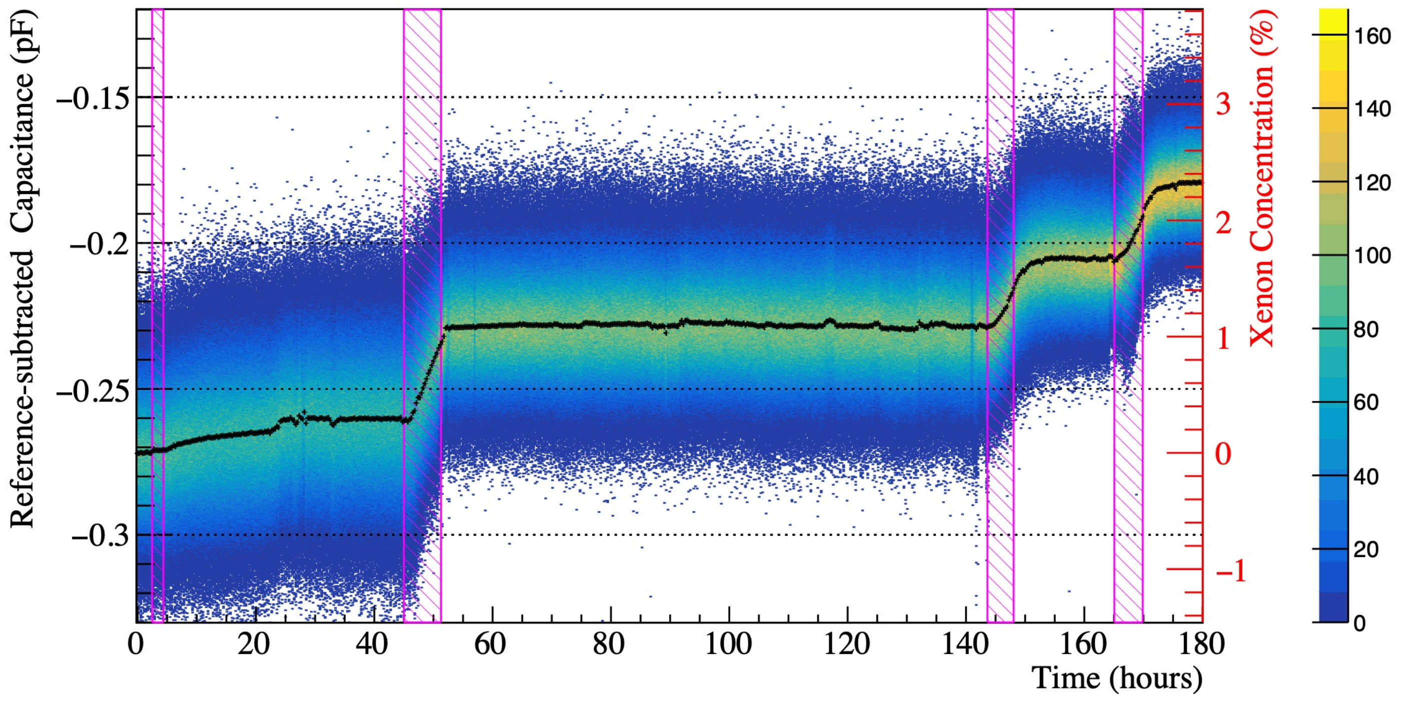
Capacitance and Xenon Concentration in Response to Doping

The CHILLAX capacitor tracks xenon concentration throughout the doping process with 0.05% precision

The capacitor is sensitive to variations in doping conditions (fast vs slow introduction of xenon)



Drifts in capacitance should be attributed to changes in xenon concentration or temperature

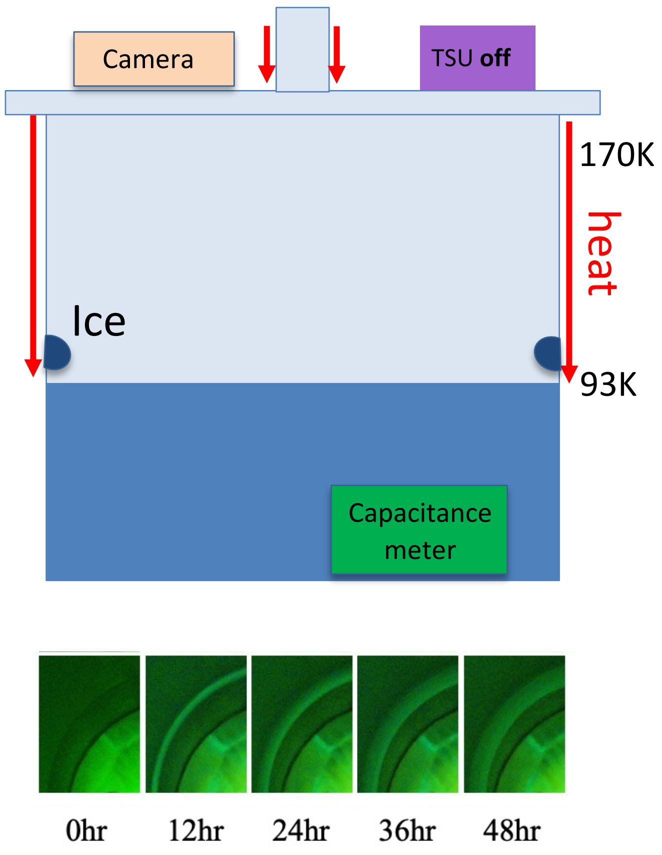


Capacitance and xenon concentration in CHILLAX over time, with doping stages highlighted in pink

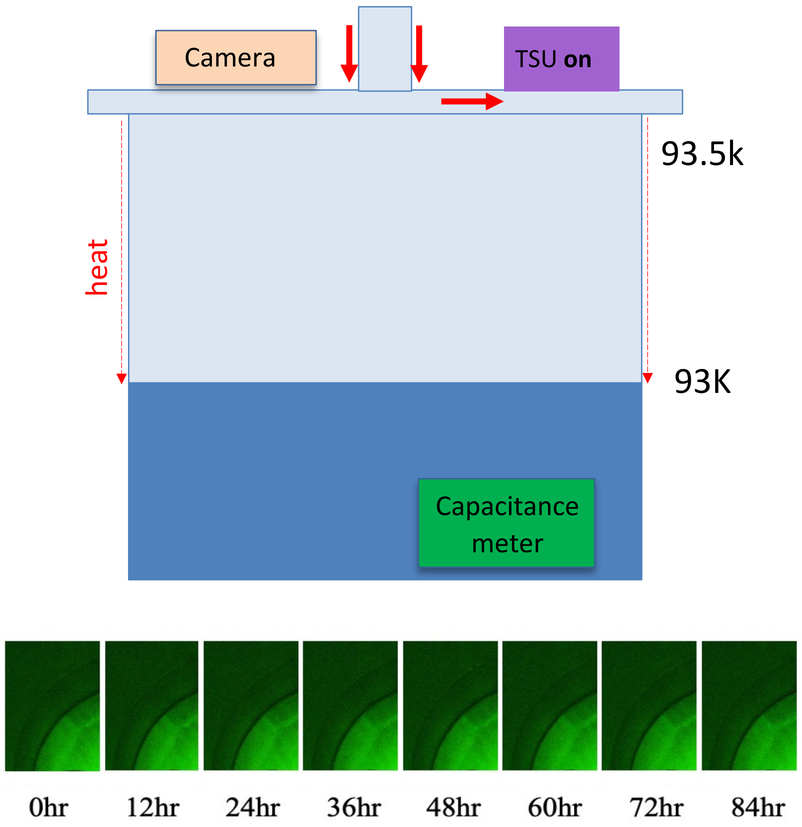
Stability Tests with Controlled vs Uncontrolled Detector Temperature Gradient

Controlling thermal profile with thermosiphon at top of detector greatly enhances xenon stability in detector volume

Change in xenon concentration results in change in signal characteristics. Detrimental for any detector's performance!

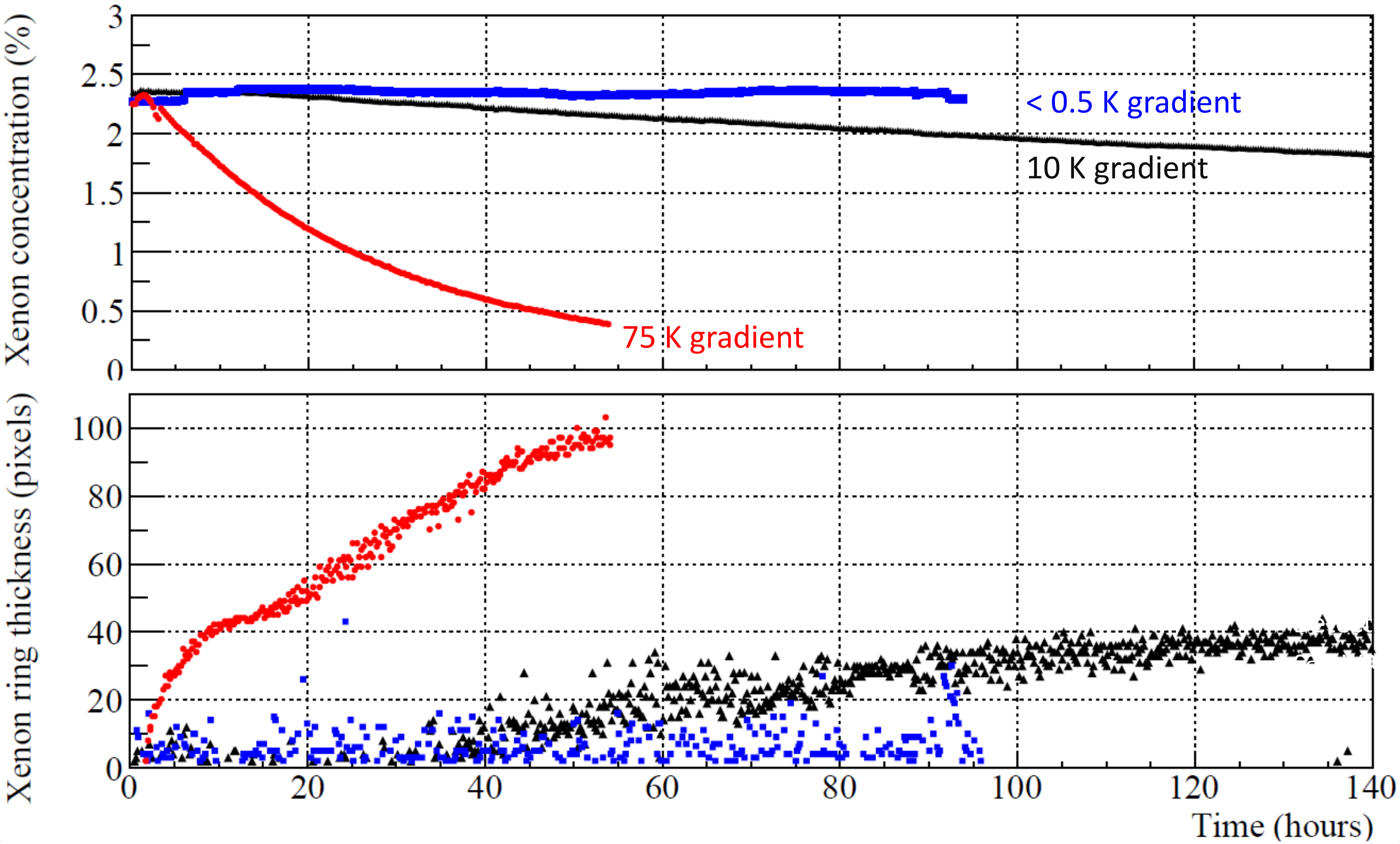


A 95 K temperature gradient results in rapid ice buildup



Maintaining a 0.5 K temperature gradient prevents ice buildup for at least 3.5 days

Capacitive and Pixel Measurements of Xenon Stability Tests



Development of a Dual Phase Xenon-Doped Argon TPC

CHILLAX is not actually a detector… yet!

Phase 1: Successfully stabilize 2.35% xenon-doped liquid argon at the liter scale inside a cryostat **[Complete]**

Phase 2: Design and install a TPC inside the cryostat to generate and measure ionization signals from xenon-doped argon **[Ongoing]**

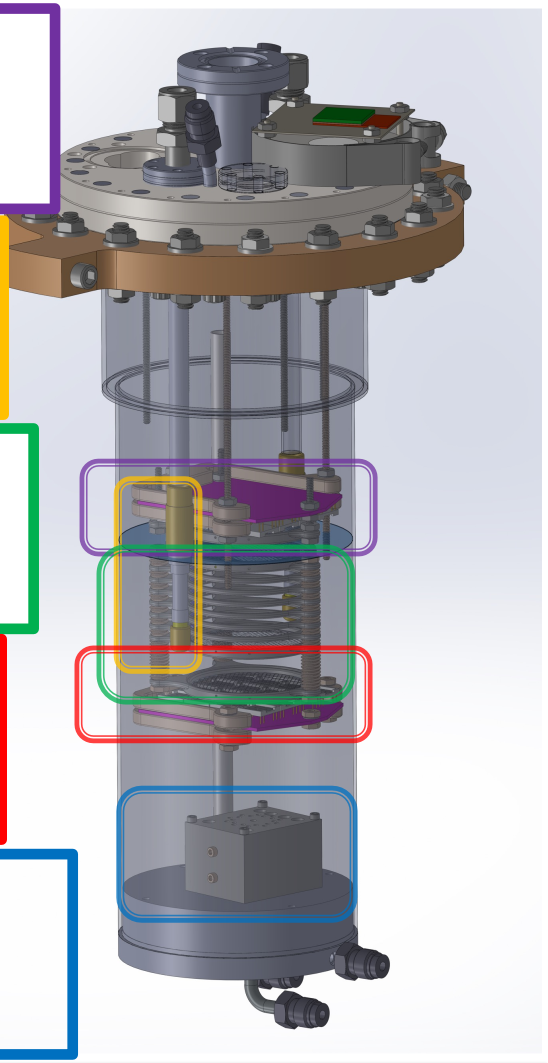
The **Top Silicon Photomultiplier (SiPM) Array** will capture S2 light and allow for XY position reconstruction.

High-Voltage (HV) feedthroughs will deliver high voltage for establishing an electric field to drift ionized electrons.

Field-Shaping rings surround the target volume to maximize electric field uniformity.

The **Bottom SiPM Array** will capture additional S1 prompt light.

The **Capacitive Meter** quantifies xenon concentration by measuring the dielectric constant (already implemented!)

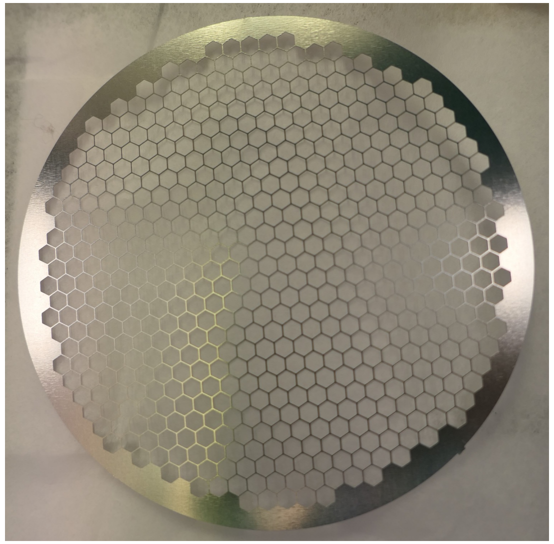


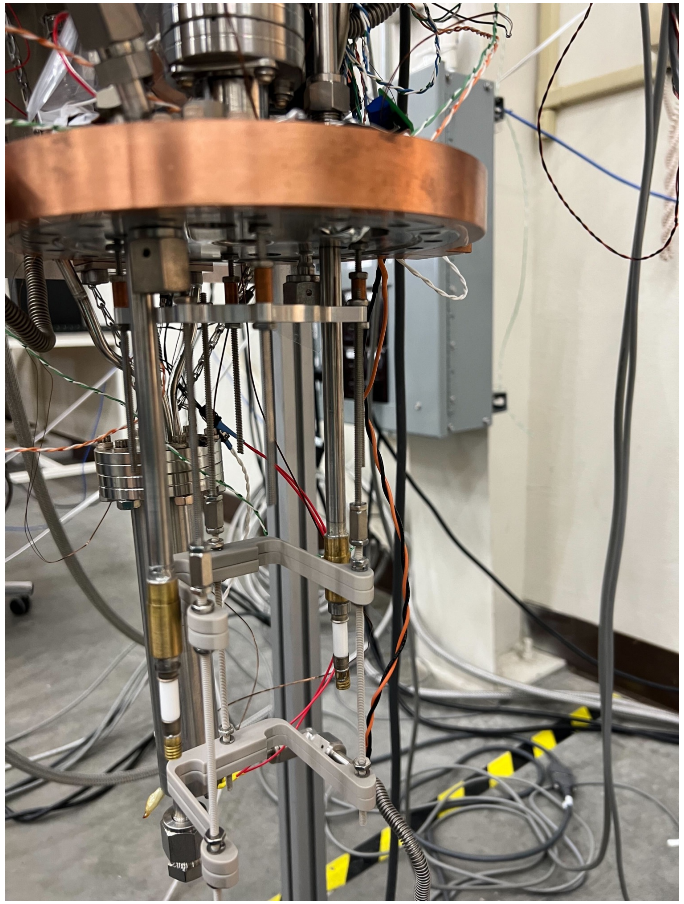
Near-term plans for CHILLAX

Fabrication, Assembly, and Testing of TPC Parts

Installation and Testing of HV Feedthroughs

We will then transition to quantifying the improvements to a dual phase argon TPC from xenon-doping.





Conclusion

Xenon-doping of argon has potential for achieving new sensitivities in noble element detectors, but maintaining stability is nontrivial.

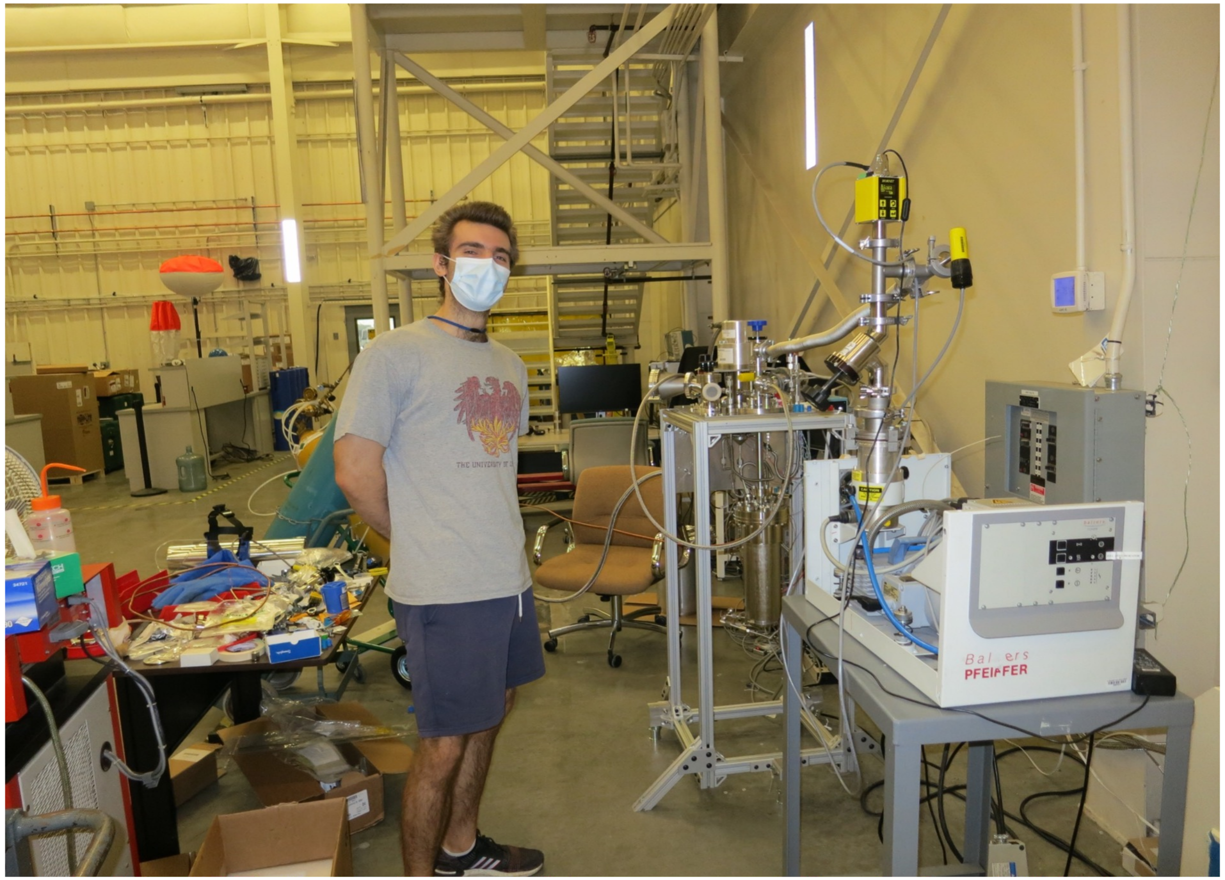
We can establish stable concentrations of xenon of up to 2.35% in liquid argon and can monitor the concentration in the liquid with both a capacitive meter and a camera.

Xenon ice formation can be controlled with proper thermal design.

TPC design for CHILLAX is in mature stages, components are being fabricated and tested.

Measurements of improvements to S2 light and ionization yield forthcoming…

Thank you! Questions?



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