



PRC 108, 045503 (2023)
PRD 113, 032016 (2026)

Development and characterization of xenon-doped liquid argon detectors

CPAD 2026 Meeting
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Adam Tidball, Jingke Xu, LLNL

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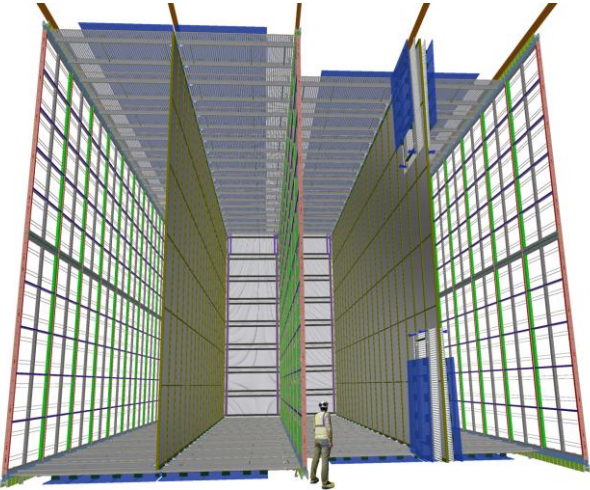
Ar and Xe Detectors Drive Rare Event Searches

Many benefits

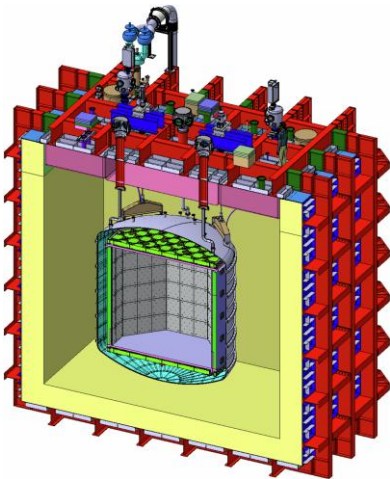
Dual signal channels (scintillation, ionization), high purity, low background, large mass, excellent energy and position reconstruction capabilities...

Many applications

Neutrino physics (CP violation, matter-antimatter asymmetry, neutrino mass hierarchy), dark matter (structure formation, BSM physics)...



DUNE



Darkside-20k



LZ



XENONnT



PandaX-4T

No Perfect Detector Medium

A wish list for Ar

- Longer wavelength
 - ✓ Easier photon collection
- Smaller energy gap
 - ✓ More quanta for same energy deposition
- Shorter decay time
 - ✓ Faster signals

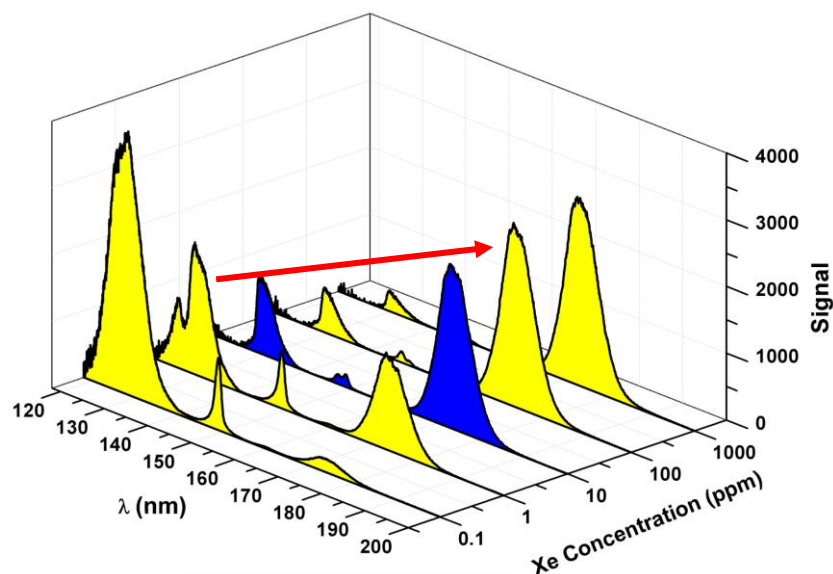
A wish list for Xe

- More abundant
 - ✓ Increased availability
- Lower atomic mass
 - ✓ Easier to recoil
- Colder
 - ✓ Less impurity outgassing

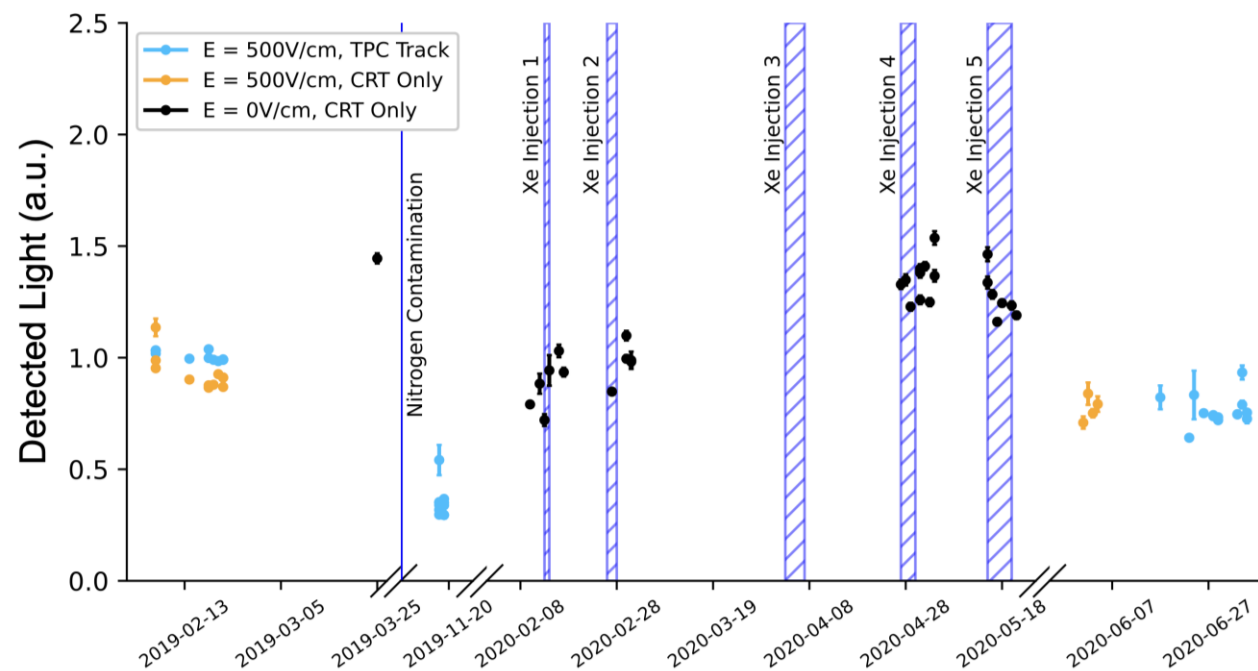
Would it be possible to reap the advantages both media confer?

Benefits of Low-level Xe Doping in LAr

- O(10 ppm) of Xe in LAr can efficiently transfer energy from Ar excitations to Xe
- Longer scintillation wavelength: less attenuation, improved reflectivity, more efficient detection from photosensors
- Demonstrated in both small and large LAr detector systems



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



ProtoDUNE Xe doping test, *JINST 19 P08005 (2024)*

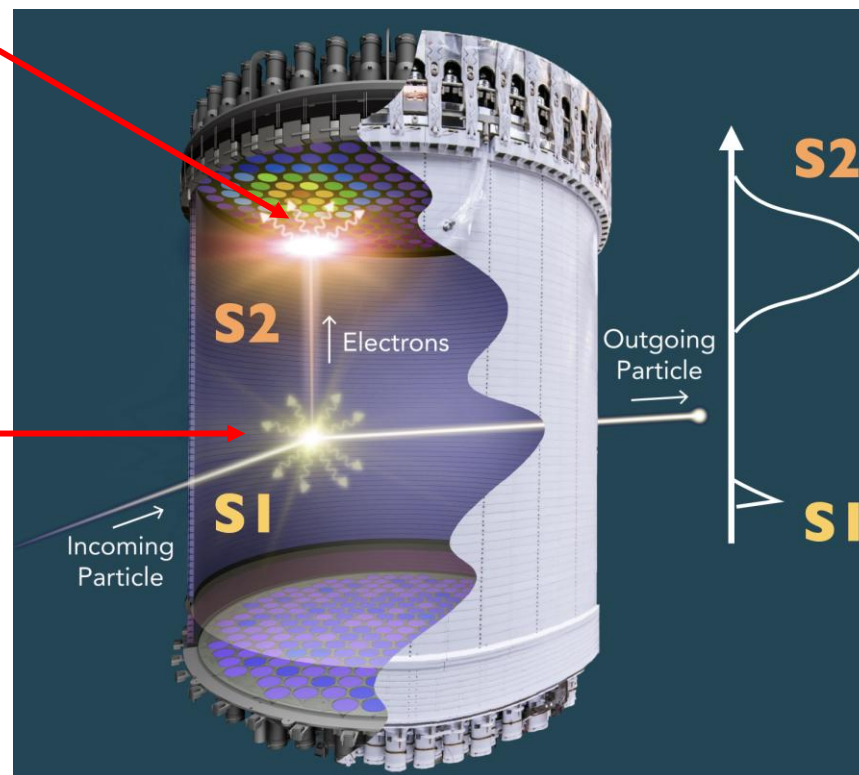
Benefits of high-level Xe Doping in LAr

Gas phase: O(10 ppm) Xe

- [Xe] determined by Henry's law
- Emits Xe wavelength (~ 178 nm) electroluminescence (EL)
- Increases EL yields

Liquid phase: %-level Xe

- Limited by Xe solubility at LAr temperature
- Lower ionization energy than pure LAr
- Shift Ar light to Xe wavelength
- Longer Rayleigh length reduces light attenuation



LAr detector, Xe-like performance

- Efficient light/charge collection
- Better low-energy performance than pure Ar
- Suitable for dark matter, neutrino searches

LAr detector, Xe-rich target

- Broader science from one detector
- e.g. neutrinoless double beta decay using LAr infrastructure

The CHILLAX Program at LLNL

CoHerent Ionization Limit in Liquid Argon and Xenon

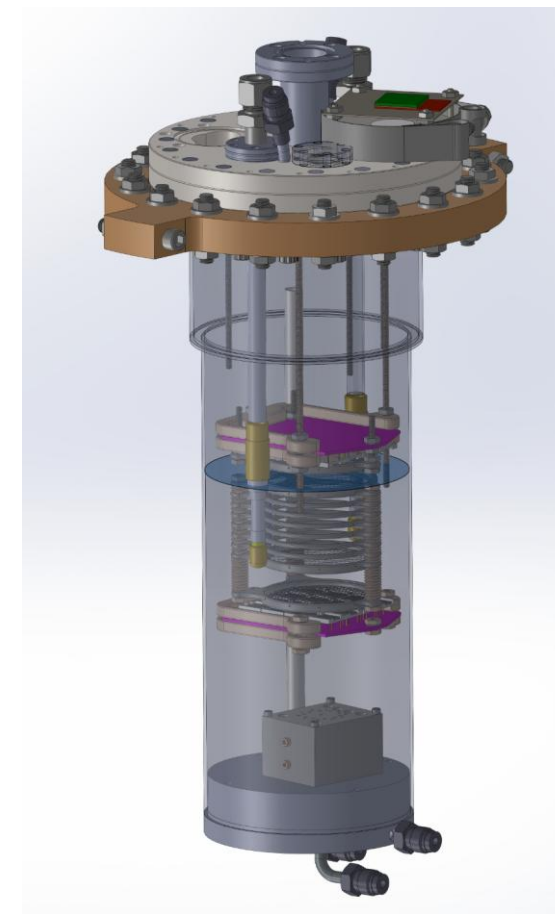
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Questions we seek to answer:

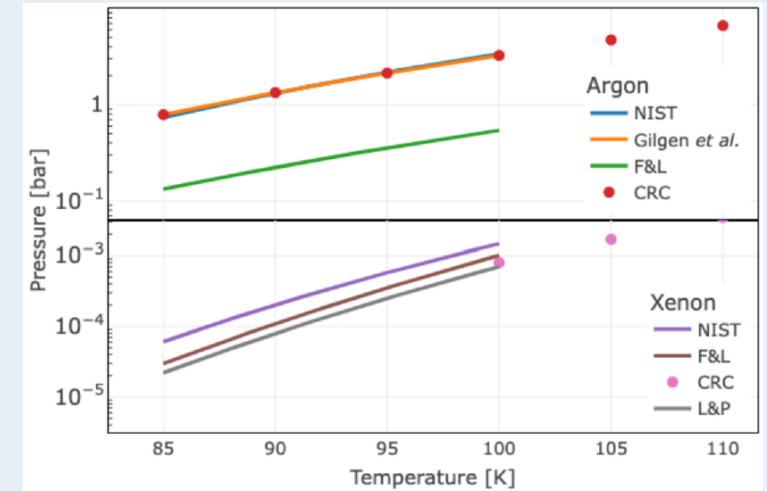
- Up to what [Xe] can LAr sustain?
 - Engineering challenges?
 - Stability over time?
- What benefits can be realized?
 - EL wavelength/gain?
 - How is energy transferred from Ar to Xe?
- To what can this technique be applied?
 - Dark matter, CEvNS?
 - Stability of LArTPCs w/ Xe doping



Kingston (HEPCAT), "HEPCAT Year 1 Report: Progress of the CHILLAX Experiment" (2024)

Operational Challenge- Xenon Ice

- LAr–Xe mixtures are prone to thermodynamic instability: Ar and Xe vapor pressures differ by orders of magnitude at operating temperature
- At 83.8–87.2 K, Xe is a solid with a vapor pressure of only $\approx 25\text{--}40$ ppm relative to Ar
- **Xe ice forms very readily**, making Xe-rich Ar hard to condense and circulate

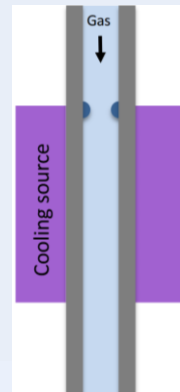


Ar and Xe vapor pressures near LAr temperature

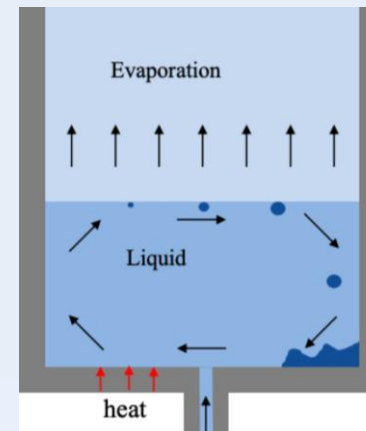
E Mizrachi, *Ph.D. thesis, Univ. of Maryland (2024)*

Three drivers of Xe ice nucleation:

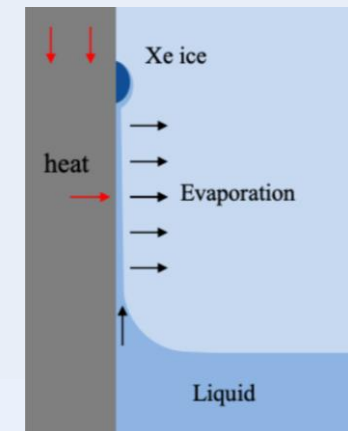
Freeze-out during gas-phase introduction



Distillation during purification and bulk evaporation



Evaporation driven by heat ingress

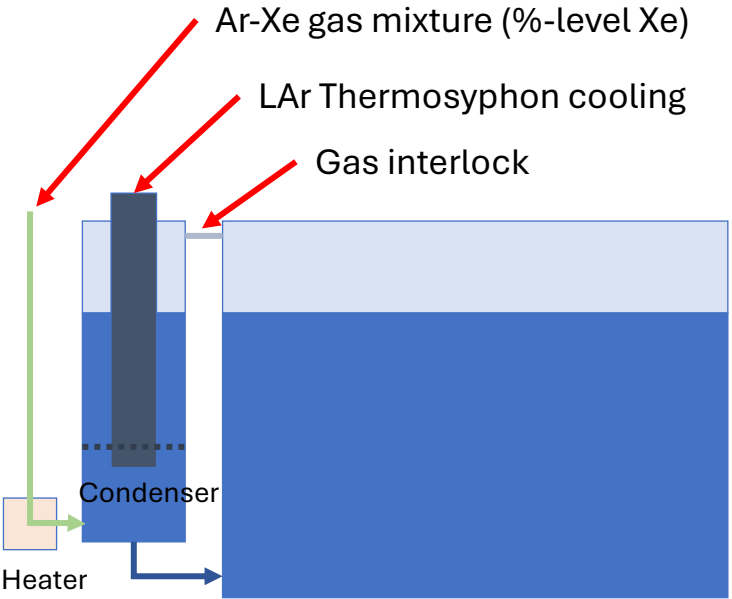


Bernard et al. (CHILLAX), *PRC 108, 045503 (2023)*

Cryogenic Design of CHILLAX

Cryogenics designed to support Xe doping

- Liquify GAr with O(1%) [Xe] introduce to LAr bath
- Deliver liquid mixture via a short path from condenser to detector
- Maintain uniform temperature across entire cryostat
- Avoid heating and evaporating liquid mixture

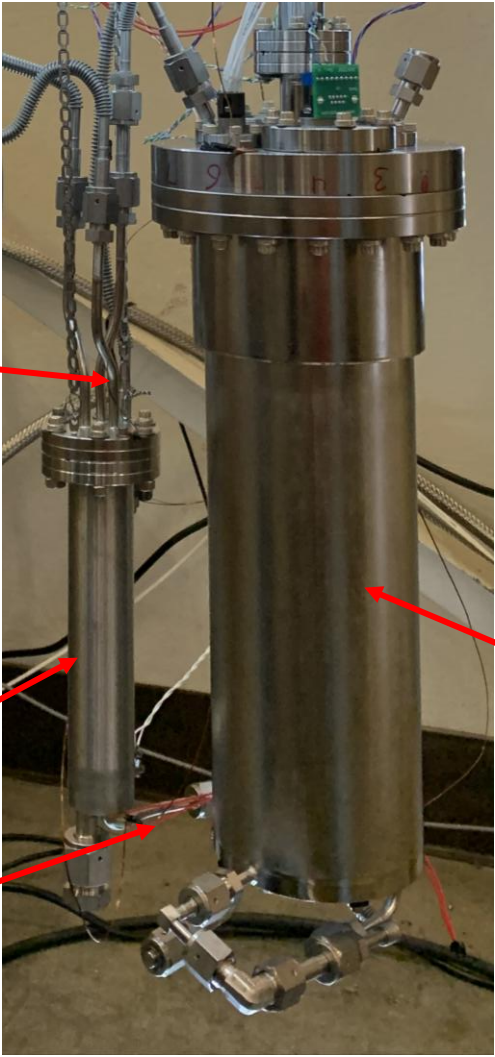


Thermosyphon
Input/output

LAr condenser

LAr delivery
to detector

Detector

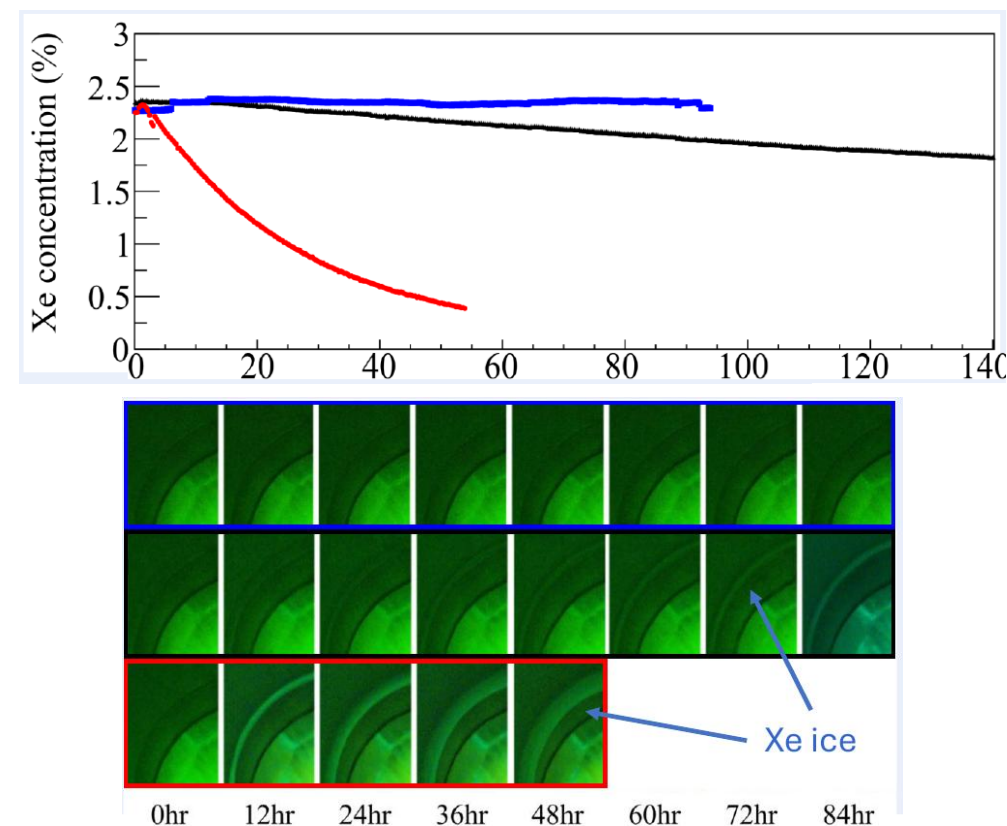


Demonstrated Cryogenic Stability

[Xe] tracked while the top-to-bottom thermal gradient across the detector was held at:

- ~0 K (blue curve)
- 10 K (black curve)
- 75 K (red curve)

[Xe] stable over several days at a ~0 K thermal gradient; larger gradients deplete [Xe] as Xe ice forms

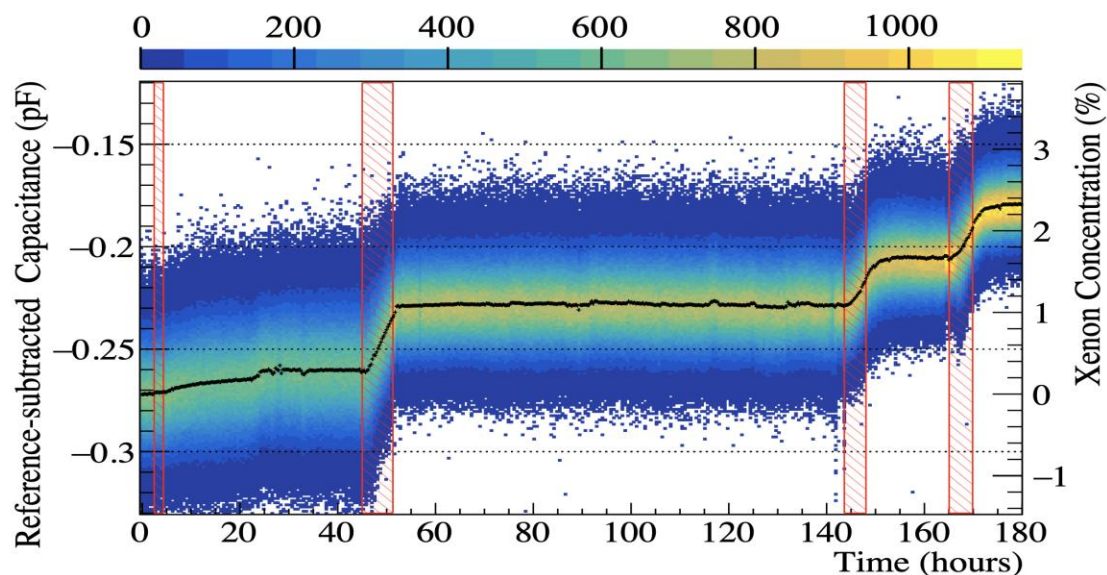


Bernard et al. (CHILLAX), *PRC 108*, 045503 (2023)

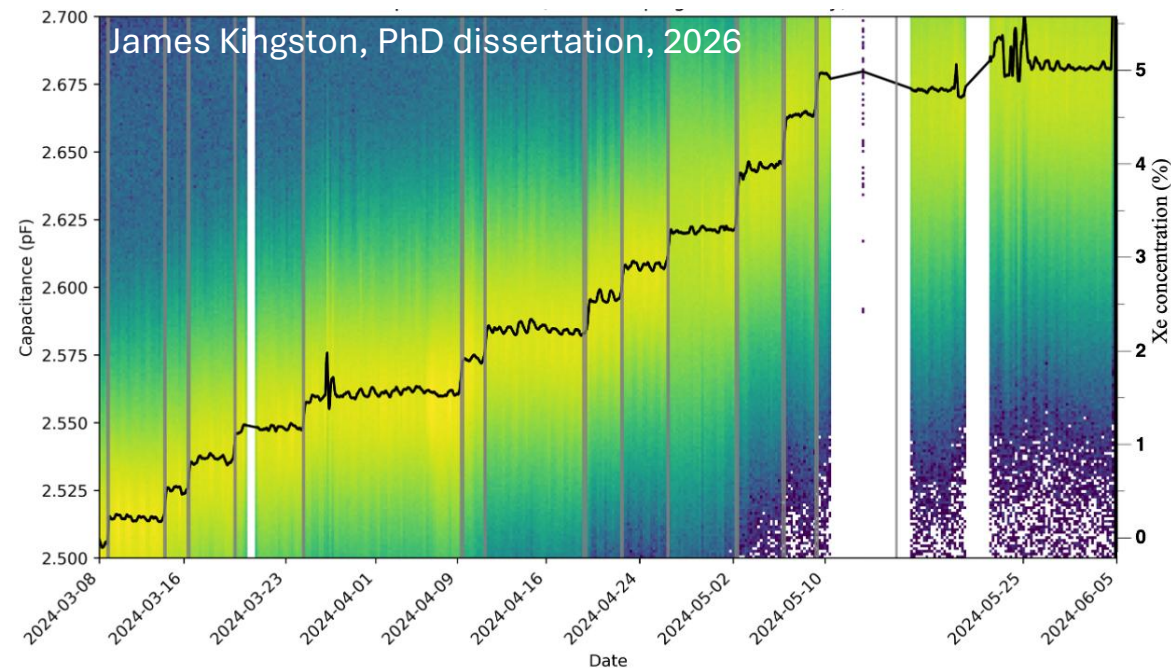
Demonstrated Doping Capability

Xe doping test in 2022

- Reach $\sim 2.35\%$ doping
- $[\text{Xe}]$ stable over several days
- Demonstrated reversal of induced instability modes



Bernard et al., *PRC 108*, 045503 (2023)



Xe doping test in 2025

- Cryogenics unchanged
- Upgraded monitoring, controls, and operation procedure
- Reached $\sim 5\%$ saturation limit of Xe in Lar (1 bar, 87 K)

Experimental Studies of Heavy Doping Benefits

A simple dual-phase TPC with high voltage, VUV photosensors, and wavelength selectivity

Windowed VUV SiPM (S13371)

2x2 Windowless VUV SiPMs (S13370)

Not marked:
RGA “straw”,
capacitor [Xe] meter

LEDs

Liquid
Level meter

Anode (0 kV)

Back view

- Characterize gas electroluminescence (EL) as a function of Xe concentration
- Understand the microphysics of Ar-to-Xe excitation energy transfer

Windowless VUV SiPM (S13371)

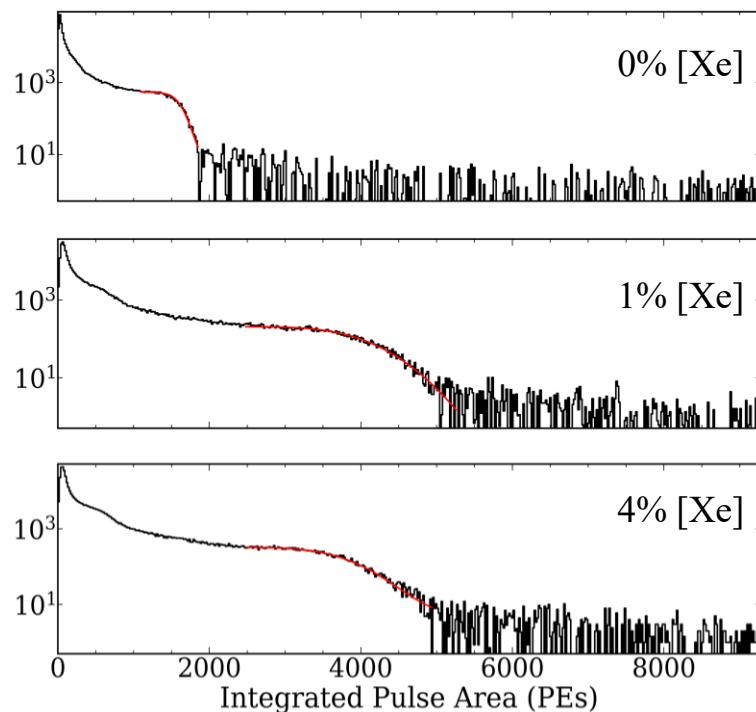
Front view

Shield (0kV)

Cathode (10–14 kV)

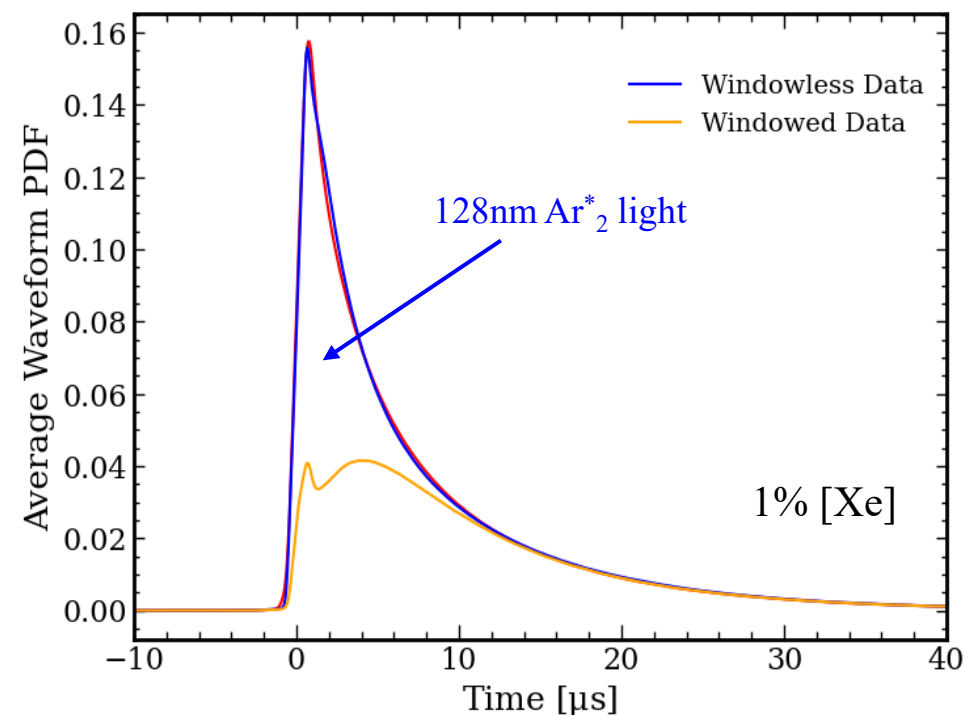
Experimental Observations w/ 0–4% Xe doping

- Ionization signal grows strongly with heavy Xe doping, then plateaus above 1%
- EL pulse shape changes dramatically from 0–3% [Xe]



Energy spectrum

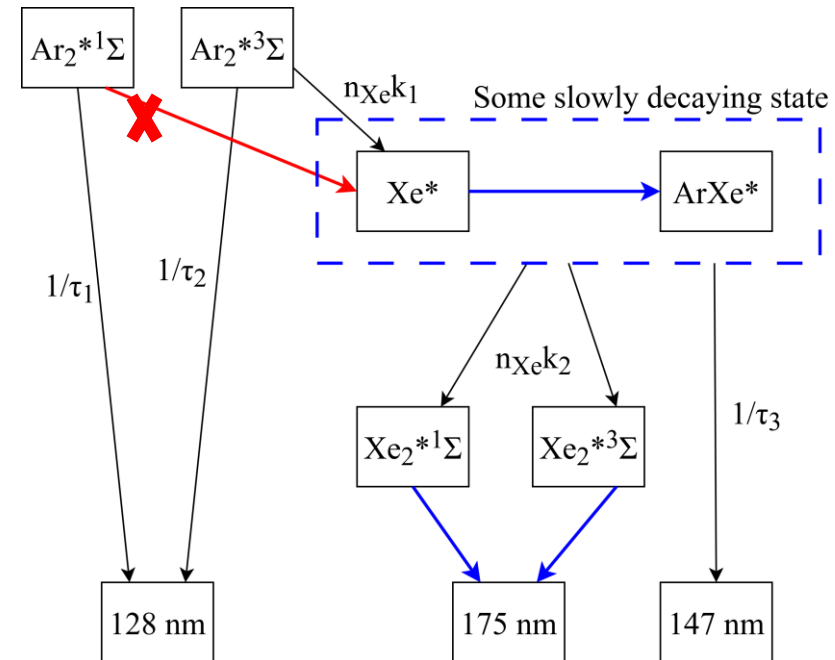
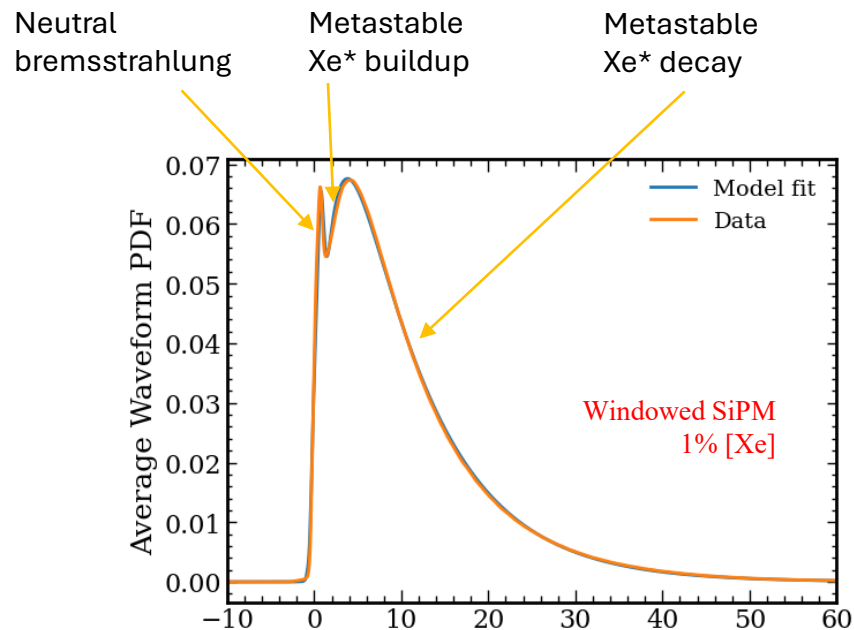
Averaged waveform



Kingston, et al, *PRD* 113, 032016

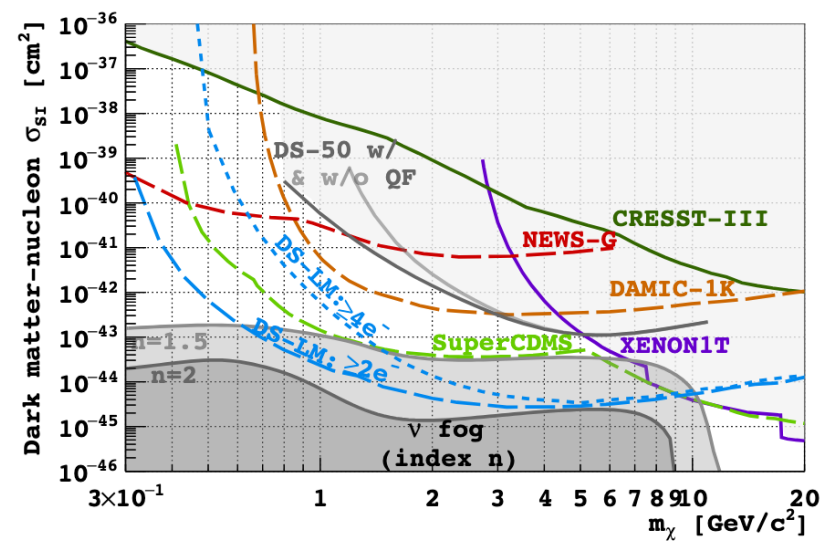
Energy Transfers in %-level Xe-doped LAr

- Simplified model targeting the slow ($\geq \mu\text{s}$) processes
- Reproduces observed pulse shapes for both short and long wavelengths

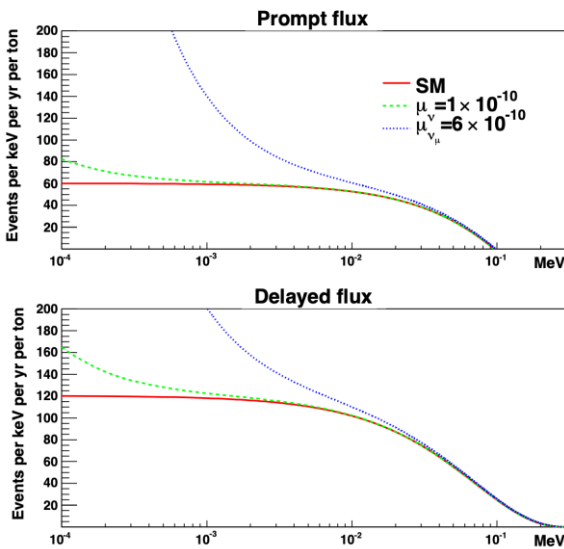


Summary/Potential Applications

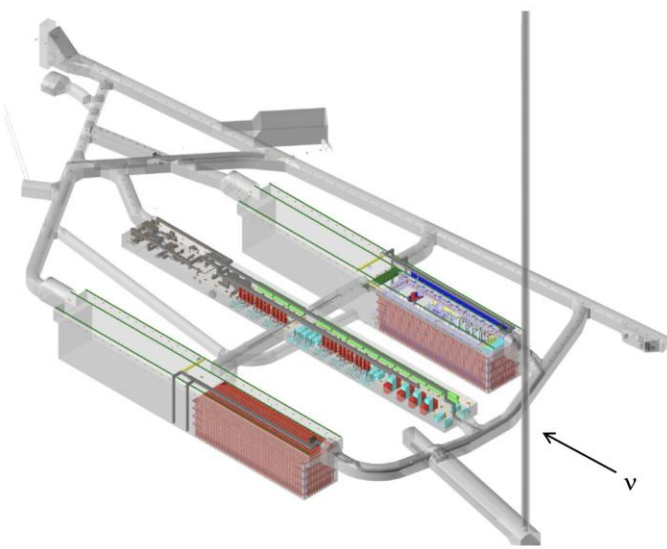
- CHILLAX overcomes substantial challenges and realized high-level stable Xe doping in LAr
- %-level doping substantially enhances ionization signal detection
- We are actively investigating potential applications for this detector technology



Low mass dark matter sensitivity projection (DarkSide-LowMass, PRD.107.112006)



Searches of neutrino magnetic moment using the CEvNS process at SNS, PRD.73.033005



Study of Xe-doping stability in large LAr TPCs such as DUNE vertical drift FD module