



# Non-VUV luminescence in liquid and gaseous argon

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# Introduction

Modern detectors based on argon detect VUV scintillation light from liquid argon at 128 nm, either directly or with wavelength shifter

However, It is known that noble elements, when excited by ionizing radiation, emit light not only in the vacuum ultraviolet (VUV) region but also at longer wavelengths, up to the near-infrared (NIR)

Several studies have been published but questions remain on the nature of this scintillation (origin, light yield, spectral and time structure)

Dedicated experiments have been performed at Fermilab in the past

Near-infrared scintillation of liquid argon: recent results obtained with the NIR facility at Fermilab

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[Journal of Instrumentation](#), Volume 13, March 2018

[Light Detection in Noble Elements \(LIDINE2017\)](#)

Citation C. O. Escobar *et al* 2018 *JINST* 13 C03031

Study of visible-light emission in pure and methane-doped liquid argon

A. Bondar<sup>1,2</sup>, E. Borisova<sup>1,2</sup>, A. Buzulutskov<sup>1,2</sup>, E. Frolov<sup>1,2</sup>, V. Nosov<sup>1,2</sup>, V. Oleynikov<sup>1,2</sup> and A. Sokolov<sup>1,2</sup>

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[Journal of Instrumentation](#), Volume 17, September 2022

Citation A. Bondar *et al* 2022 *JINST* 17 P09009

## Compilation of the results on light emission in liquid Ar in the visible and NIR range

Reference	Excitation source	Electric field (kV/cm)	Spectrum range (nm)	Light yield in visible and NIR range (photon/MeV)	Comments
<a href="#">Heindl 2010</a> <a href="#">Heindl 2011</a>	12 keV e <sup>-</sup>	0	300-1000	Observed	Spectrum measured
<a href="#">Buzulutskov 2011</a> <a href="#">Bondar 2012</a>	25 keV X-rays	0-30	400-1000	510 ± 90	Field independent
<a href="#">Neumeier 2014</a> <a href="#">Neumeier 2015</a>	12 keV e <sup>-</sup>	0	500-1000	Not observed Observed in NIR	
<a href="#">Alexander 2016</a>	511 keV γ-rays	0	715-900	Observed	$\tau_f < 100$ ns $\tau_s \approx 2 - 4$ μs Field independent
<a href="#">Auger 2016</a>	HV breakdown	≤200	400-800	Observed	Spectrum measured
<a href="#">Bondar 2022</a>	25 keV X-rays	0-0.62	400-1000	200 ± 50	$\tau_f < 100$ ns $\tau_s = 1 \pm 0.3$ μs
<a href="#">Jones 2013</a>	5.3 MeV α	0	300-650	Not observed	<10 ph./MeV
<a href="#">Hofmann 2013</a>	0 MeV protons	0	300-1000	Observed	Spectrum measured
<a href="#">Escobar 2018</a>	5.4 MeV α	0	715-900	Observed	
<a href="#">Bondar 2022</a>	5.5 MeV α	0.3-0.62	400-1000	92 ± 23	$\tau_f < 100$ ns No slow comp. Field independent

# Introduction

While there is a large amount of data and theoretical understanding of the scintillation process in liquid argon, much less is known about the scintillation in cold gaseous phase

Molecular densities in low pressure gas phase are three orders of magnitudes lower than in liquid, hence the scintillation dynamics can be very different. Studies of gas scintillation may help with the better understanding of liquid emission, in particular in different spectral ranges

Existing studies by groups of researchers:

Ulrich, Heindl, Neumeier, Bressi, Borghesani, Lindblom, Santorelli...

Current experimental setup consists of an  $^{241}\text{Am}$   $\alpha$ -source and three SiPMs with different spectral sensitivities from VUV to NIR

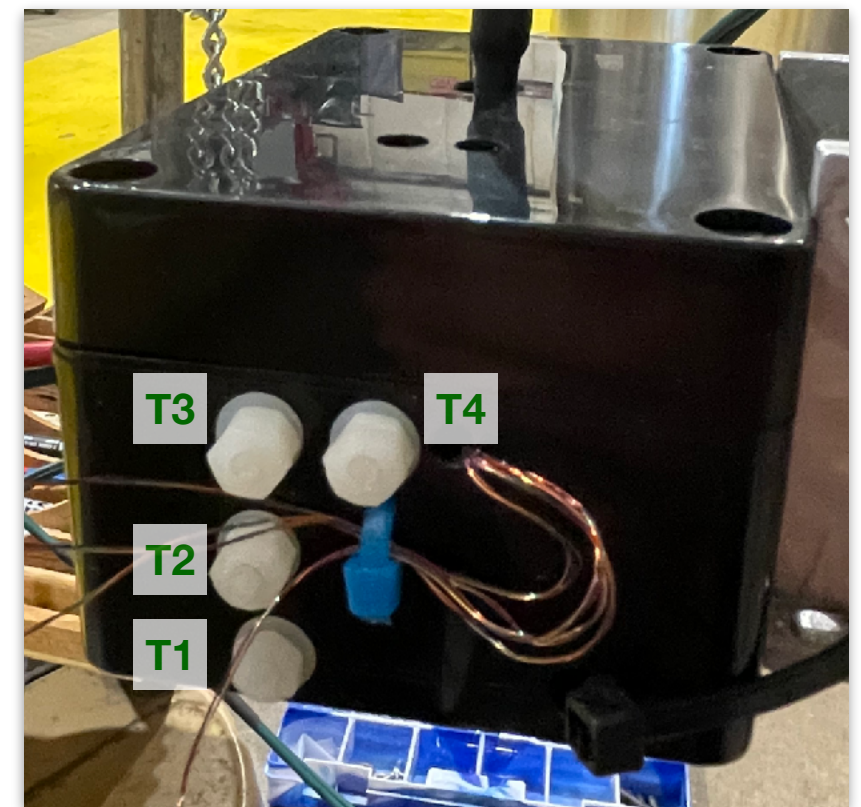
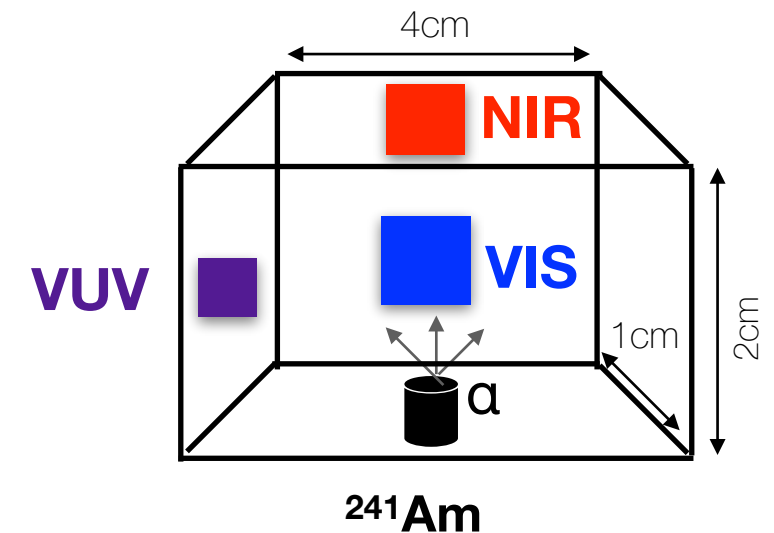
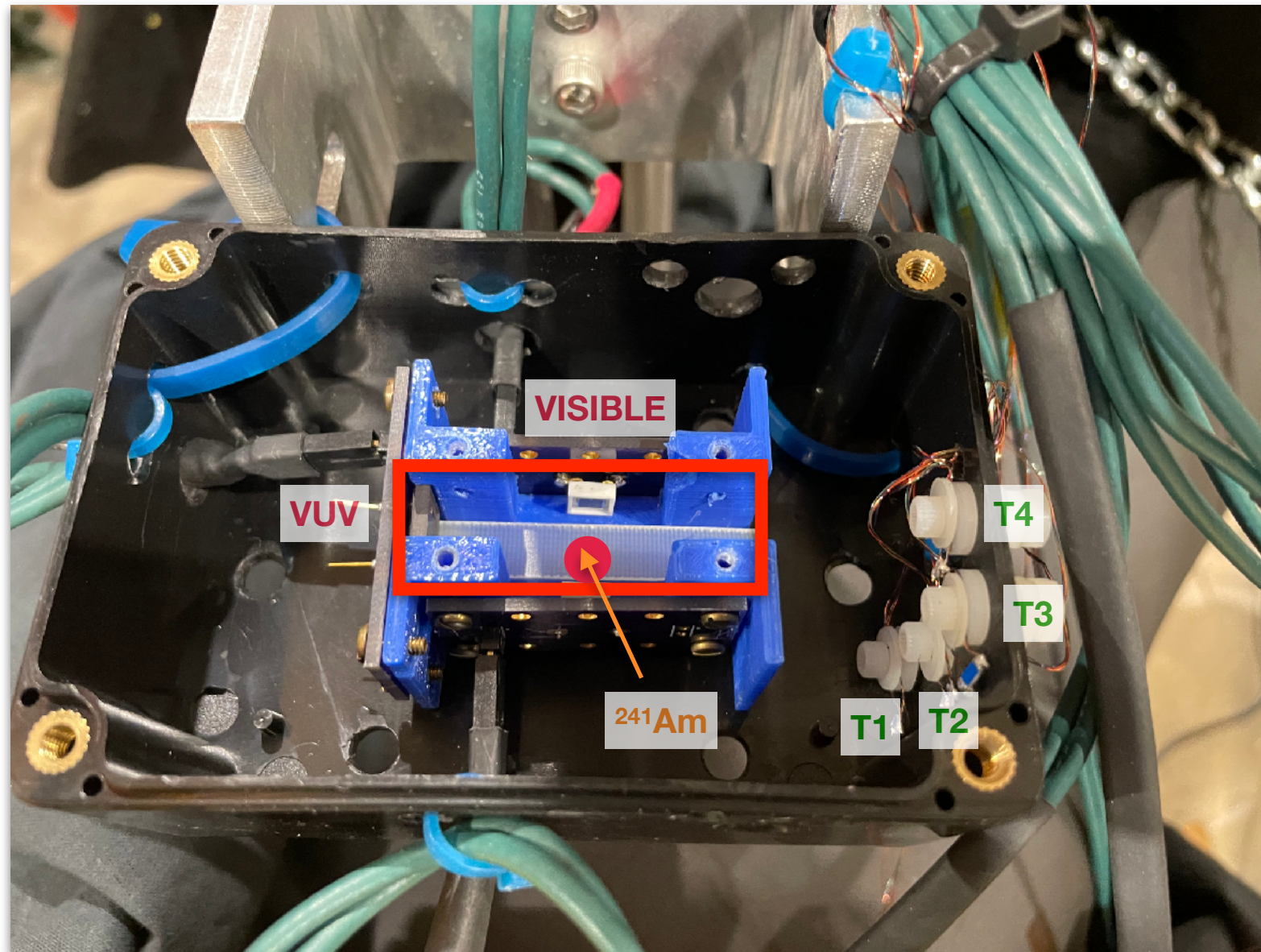


## Experimental setup

An  $^{241}\text{Am}$   $\alpha$ -source (0.1  $\mu\text{Ci}$ ) is installed in a small box, with three photosensors with different spectral sensitivity: near-infrared – top, vacuum ultraviolet and visible on the sides  
Sensors have different dimensions and solid angle coverage

Instrumentation with four temperature probes (Pt-100):

- one at the height of the source
- one at the height of the lateral SiPMs
- two redundant above the height of the active volume



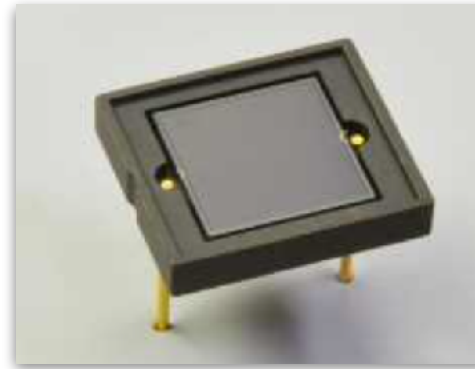


## Spectral sensitivity of photosensors

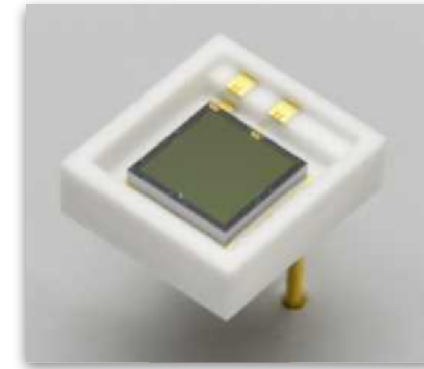
Three sensors from Hamamatsu are used in the experiment

Sensitivities of VUV  $>200\text{nm}$  and VIS & NIR  $<300\text{nm}$  are unknown at this time

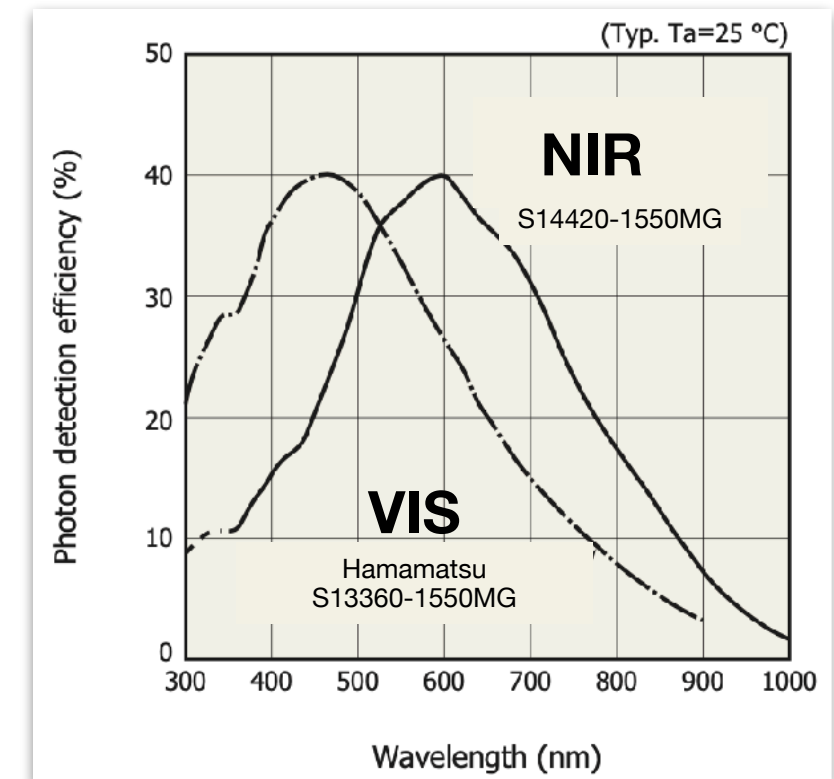
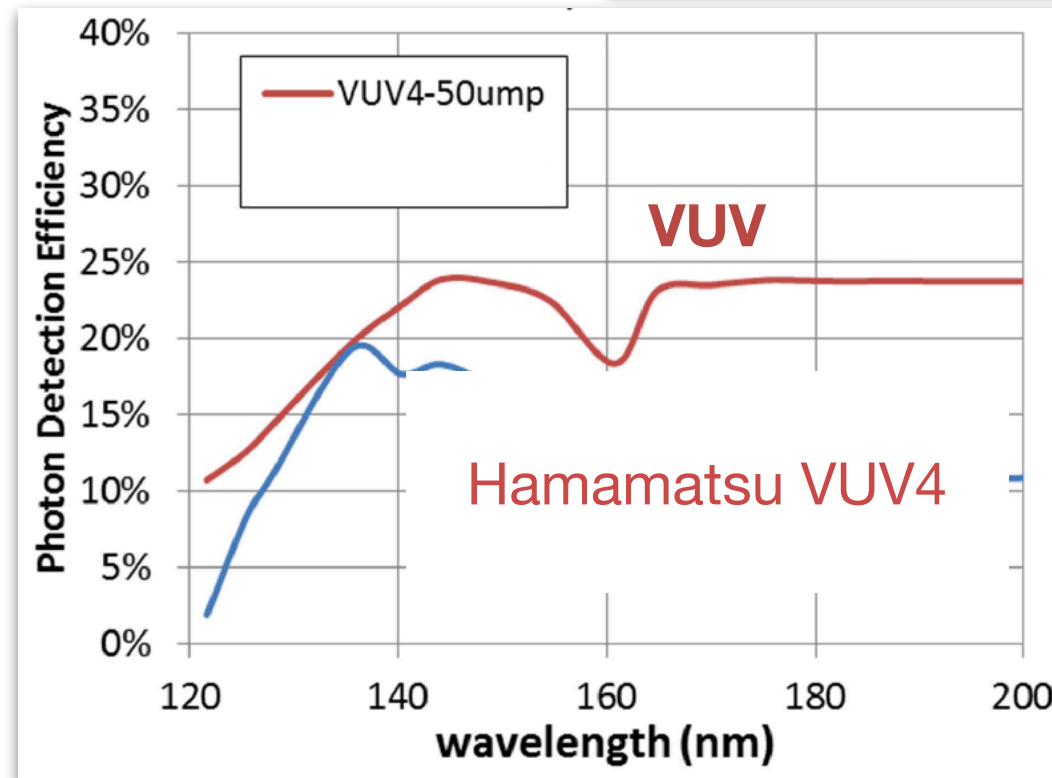
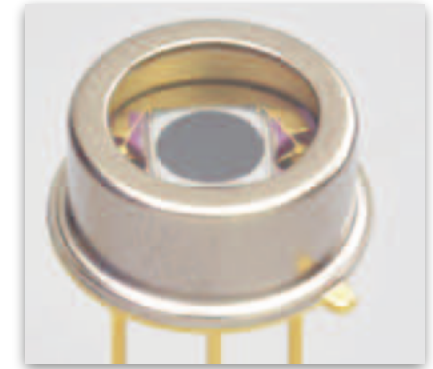
VUV



VIS



NIR



SiPMs register photons produced by scintillation induced by the energy deposition of an  $\alpha$ -particle in the corresponding spectral range

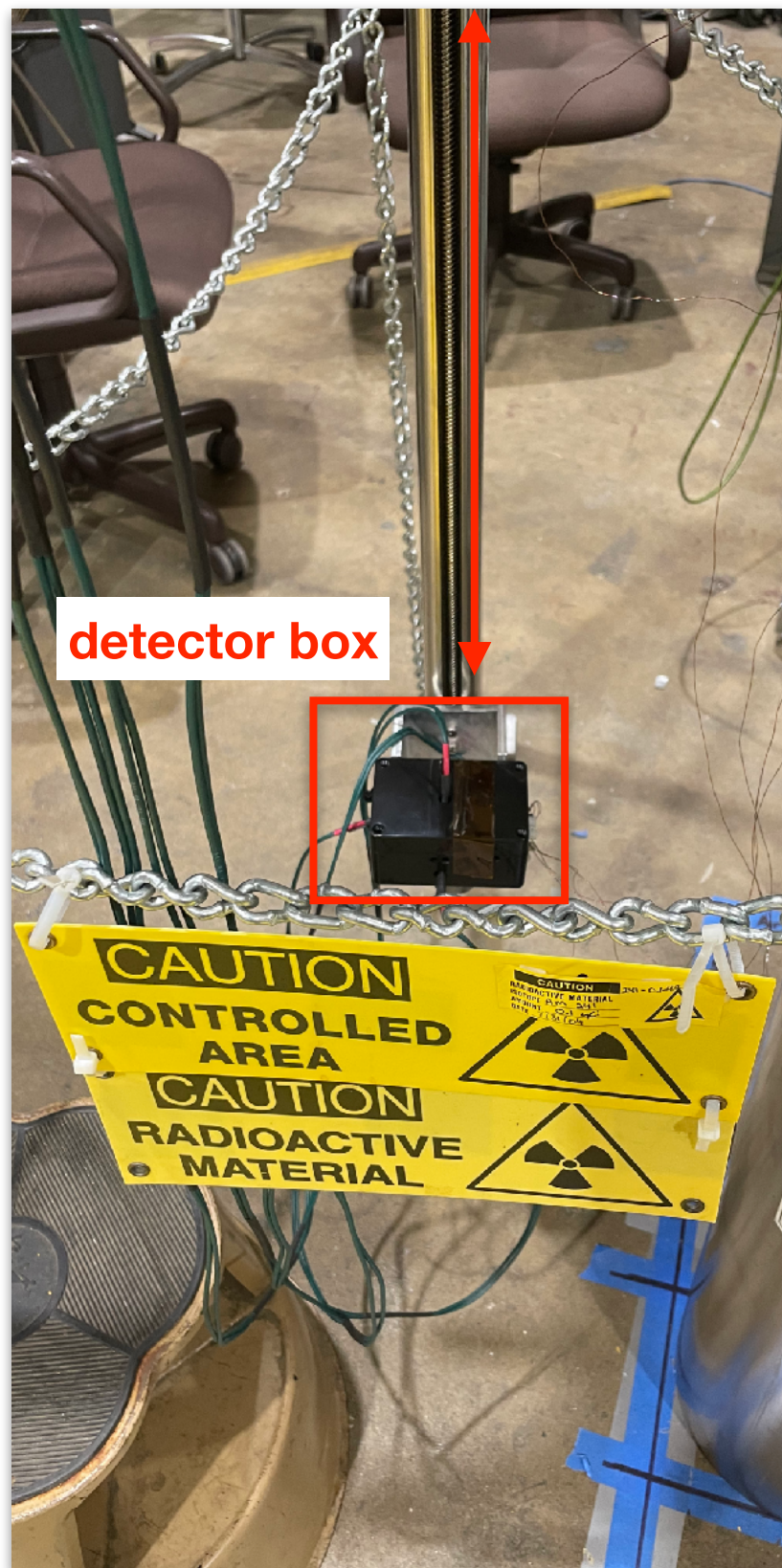
Observed signals reflect a convolution of the scintillation spectrum with SiPM spectral sensitivity and geometrical acceptance

In liquid  $\alpha$ -track is short, hence signal corresponds to the energy deposition of  $\sim 5\text{ MeV}$ . In the gas phase observed signal corresponds to a fraction of the full  $\alpha$ -trajectory



## Setup at the Noble Liquid R&D Facility (PAB)

The detector is installed in a tall cryostat vessel with a long motion feedthrough, which allows to travel to various positions in the cryostat in liquid and gaseous phases

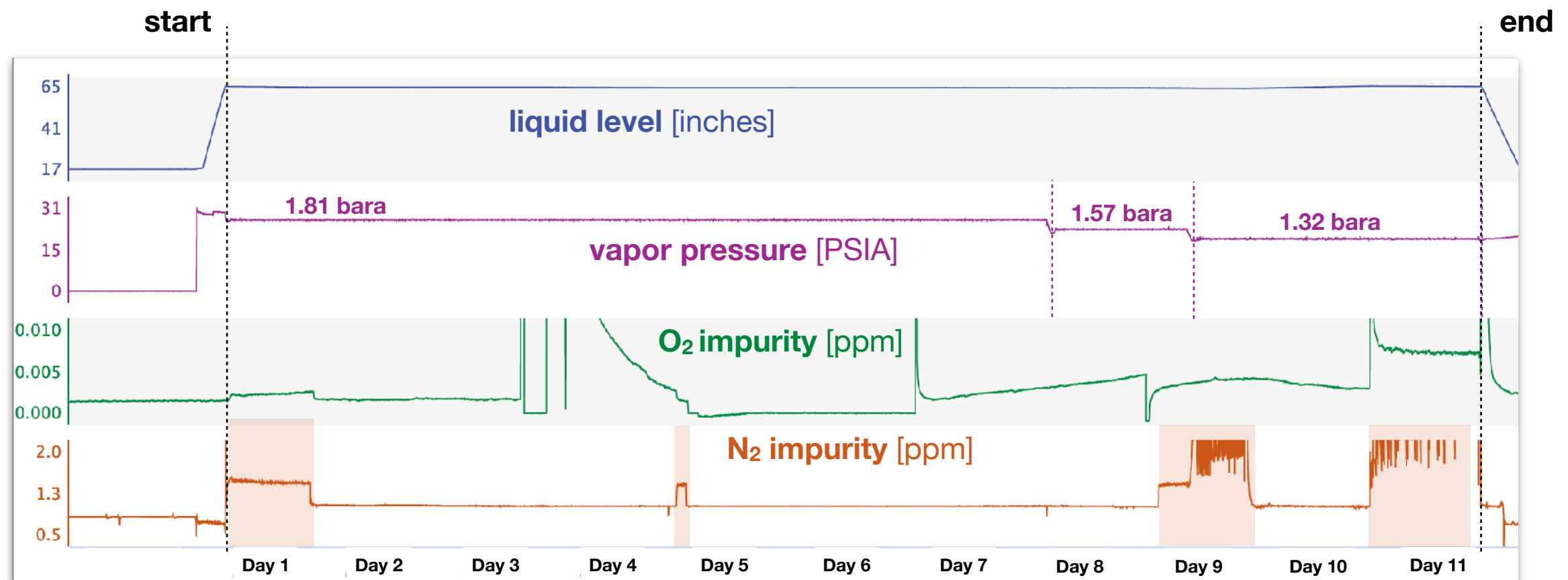




## Experimental conditions

Data acquired varying vapor pressure (1.8, 1.6, 1.3 bars) and vertical position of the box (temperature):

- Liquid argon 92 – 94K
- Cold argon gas 95 – 140K
- Warm argon gas 180 – 190K



Nitrogen and oxygen impurity contamination was measured in the cryostat ullage volume during the experiment:

N<sub>2</sub> contamination on average ~1.4 ppm (three times lower in LAr due to Henry's constant)  
O<sub>2</sub> contamination ~(1.5–4.5) ppb (the same in liquid)

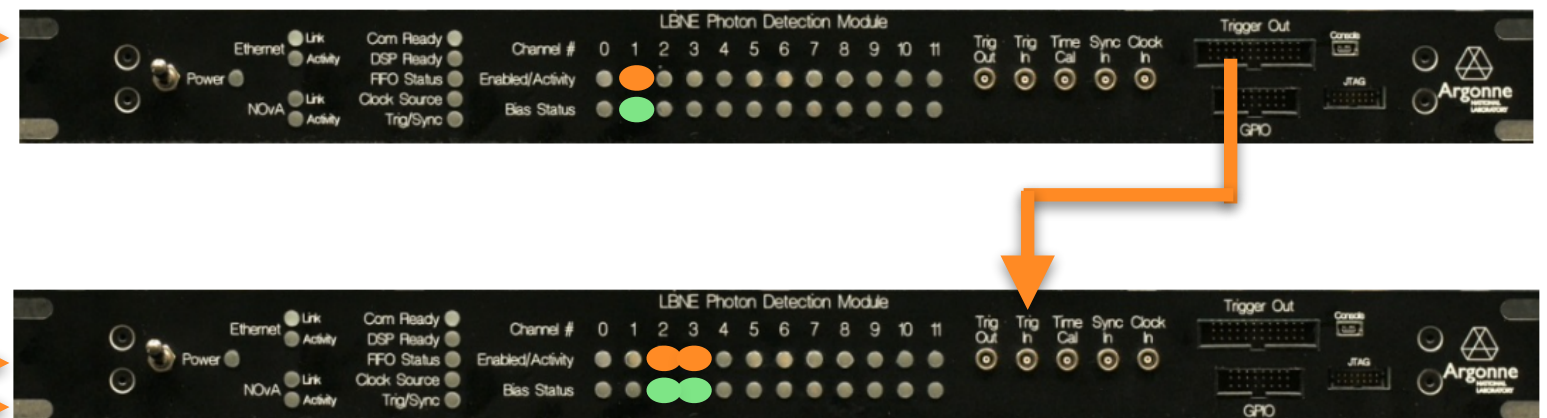
## Data acquisition

Trigger was provided by one of the three channels (NIR, VUV, VIS) with a leading edge discriminator  
Trigger is provided by one channel, and the other two channels are analyzed. The triggered trace is not analyzed to avoid bias due to set trigger threshold

An SiPM signal processor (SSP) is used to bias and readout SiPMs, originally developed at the Argonne National Lab for LBNE (signal amplification and shaping)

Trigger SiPM (e.g. VUV)  
Leading edge discriminator

Two other channels  
(e.g. VIS & NIR)  
→ analysis



The SiPM response and shaping time of the SSP lead to fundamental pulses with the total width of 200–400ns. For this reason we are not attempting studies of the fast and slow components of argon scintillation, but rather focus on the time structure in the microseconds range

Data was acquired with different sampling:

150MHz – 6.6 ns – short 13.3  $\mu$ s traces

37.5MHz – 26.4 ns – long 53.3  $\mu$ s traces

In analysis, the following temporal components are defined:

Fast: < 1.5  $\mu$ s

Slow: 1.5 to 8  $\mu$ s

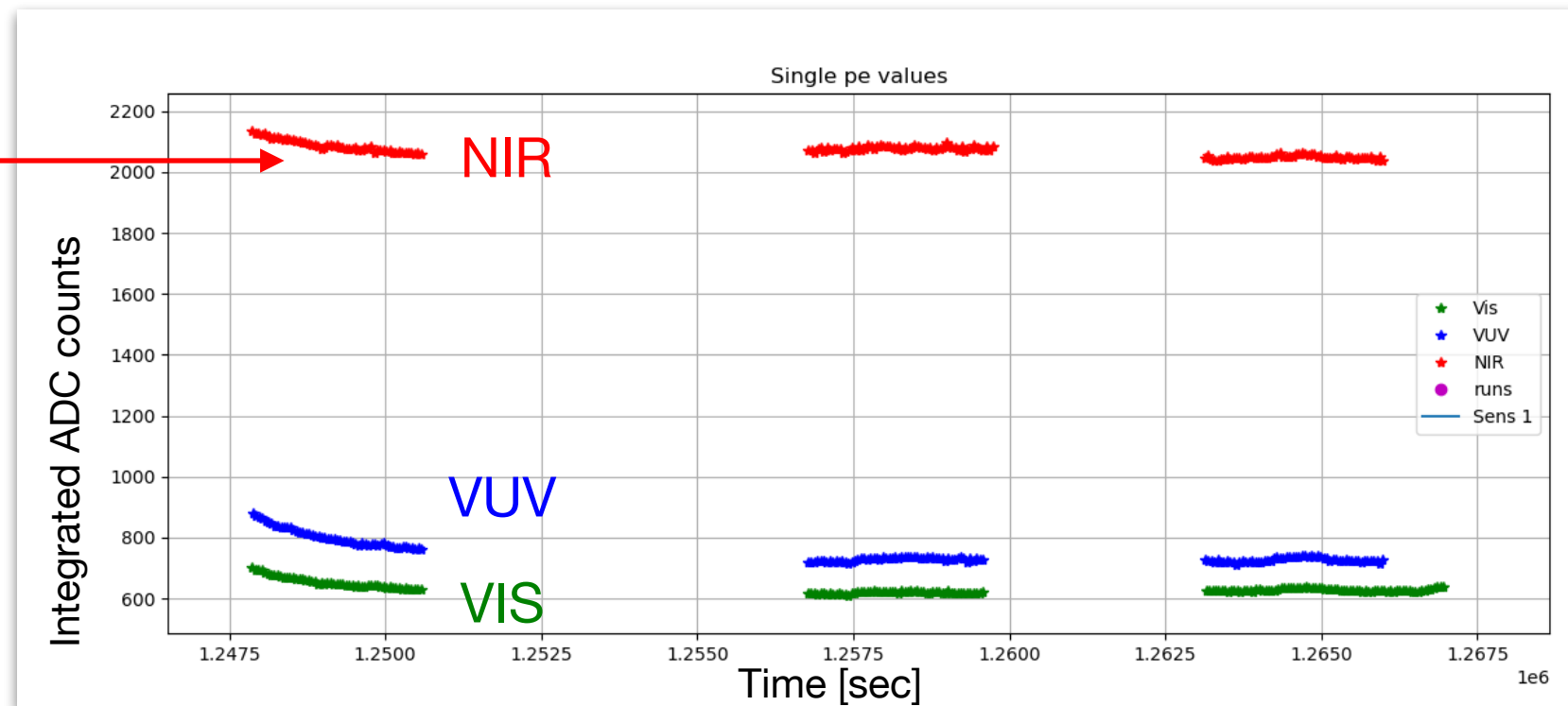
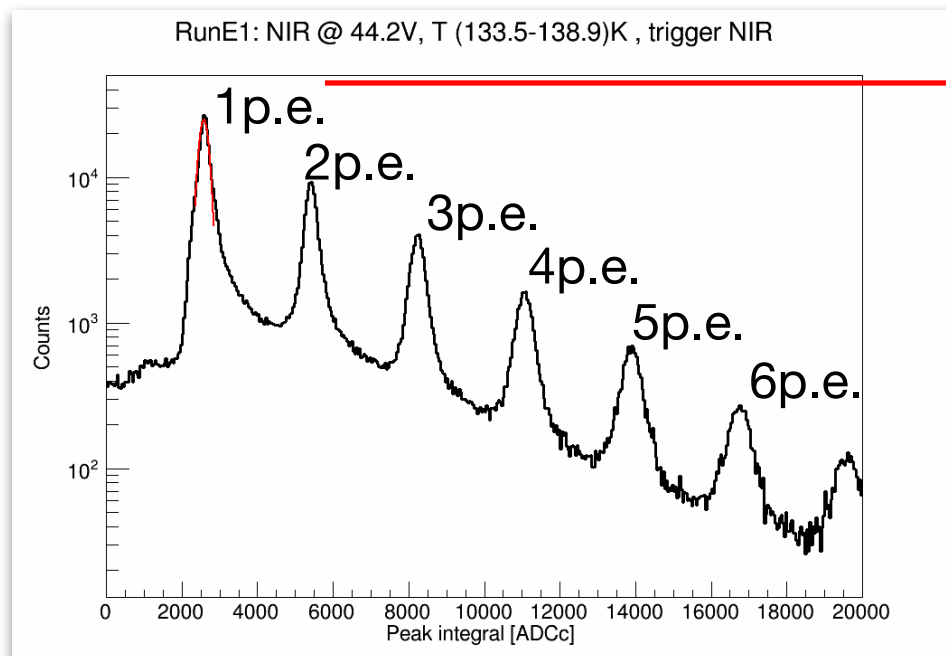
Long: 8 to 12  $\mu$ s

Very long: 12 to 25  $\mu$ s



# SiPM gain calibration

The gain of SiPMs is continuously calibrated in-situ (offline analysis) by tagging pulses with the smallest amplitude/integral (single photoelectron response) to account for temperature-dependence



Two independent data analyses

## Experimental results: VUV signal

(Trigger on visible or NIR sensor)  
(Analysis is based on averaged waveform traces)

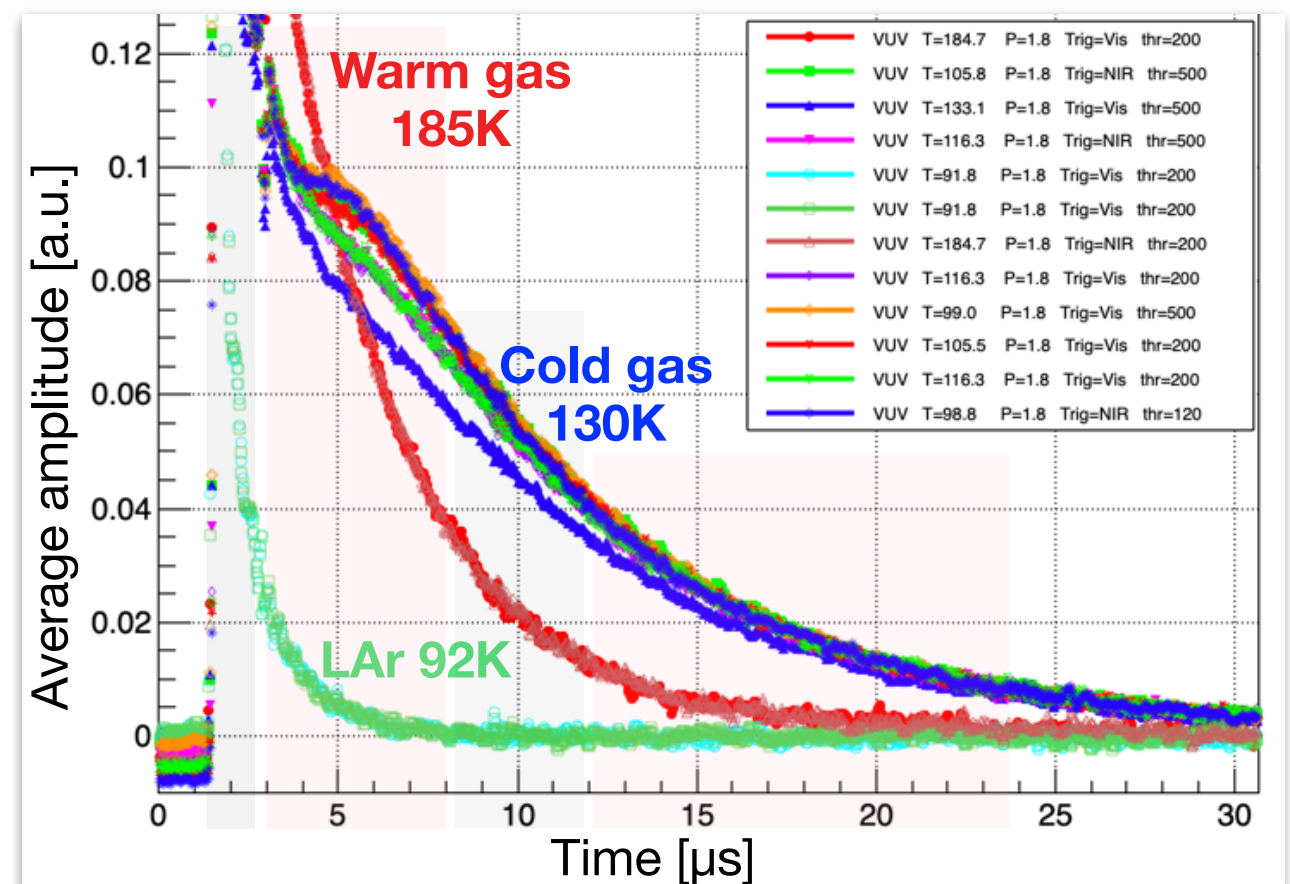
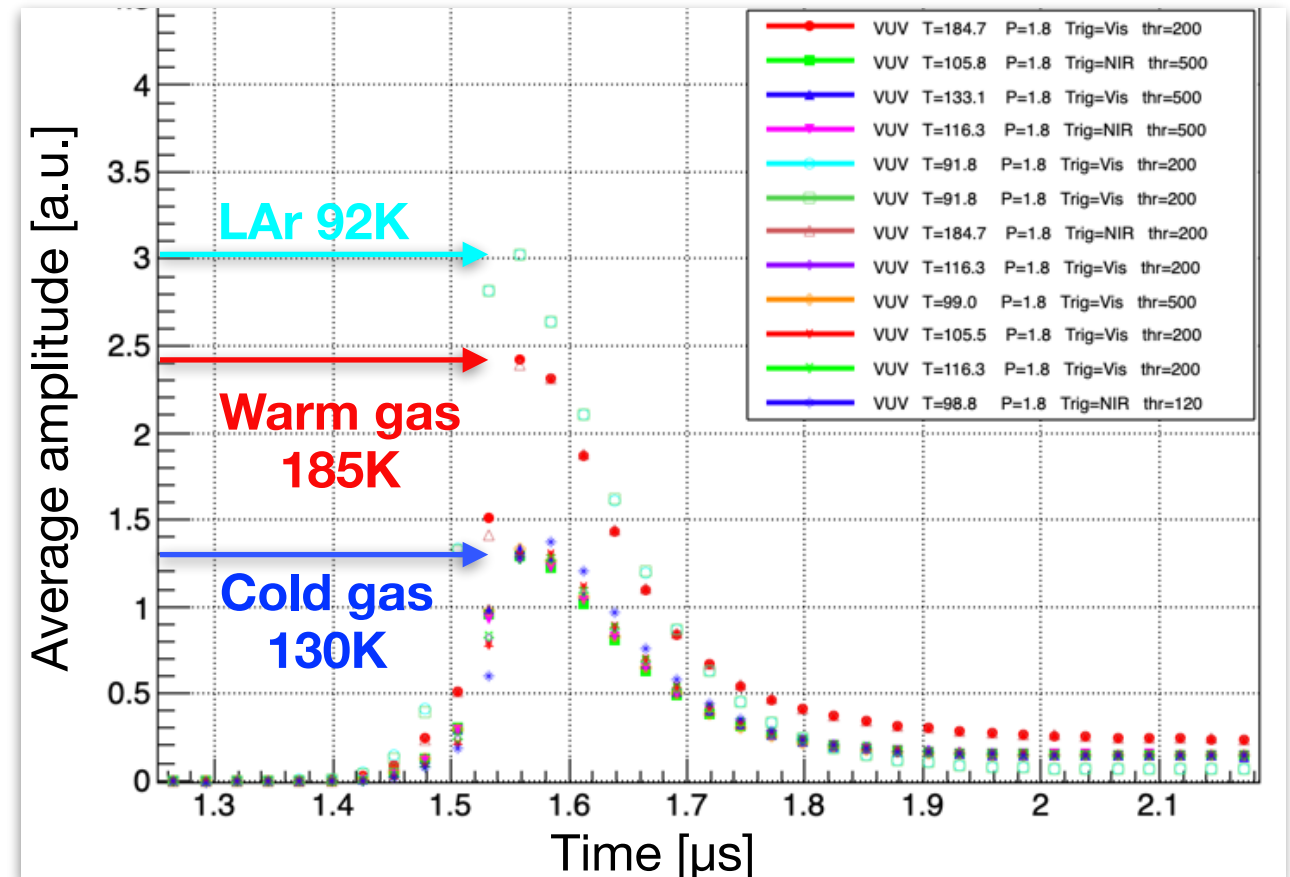
- Observed fast component of the VUV signal reduced in cold gas, compared to the liquid

Fast component in warm gas exceeds signal in liquid by 20% (while the energy deposit is expected to be factor few smaller)

- No slow component beyond  $\tau=1.5\mu\text{s}$  is observed in liquid (as known)

- Signal in cold gas is dominated by the slow component extending up to  $\sim 25\mu\text{s}$

- Slow component of scintillation in warm gas is quite different from the one in cold gas





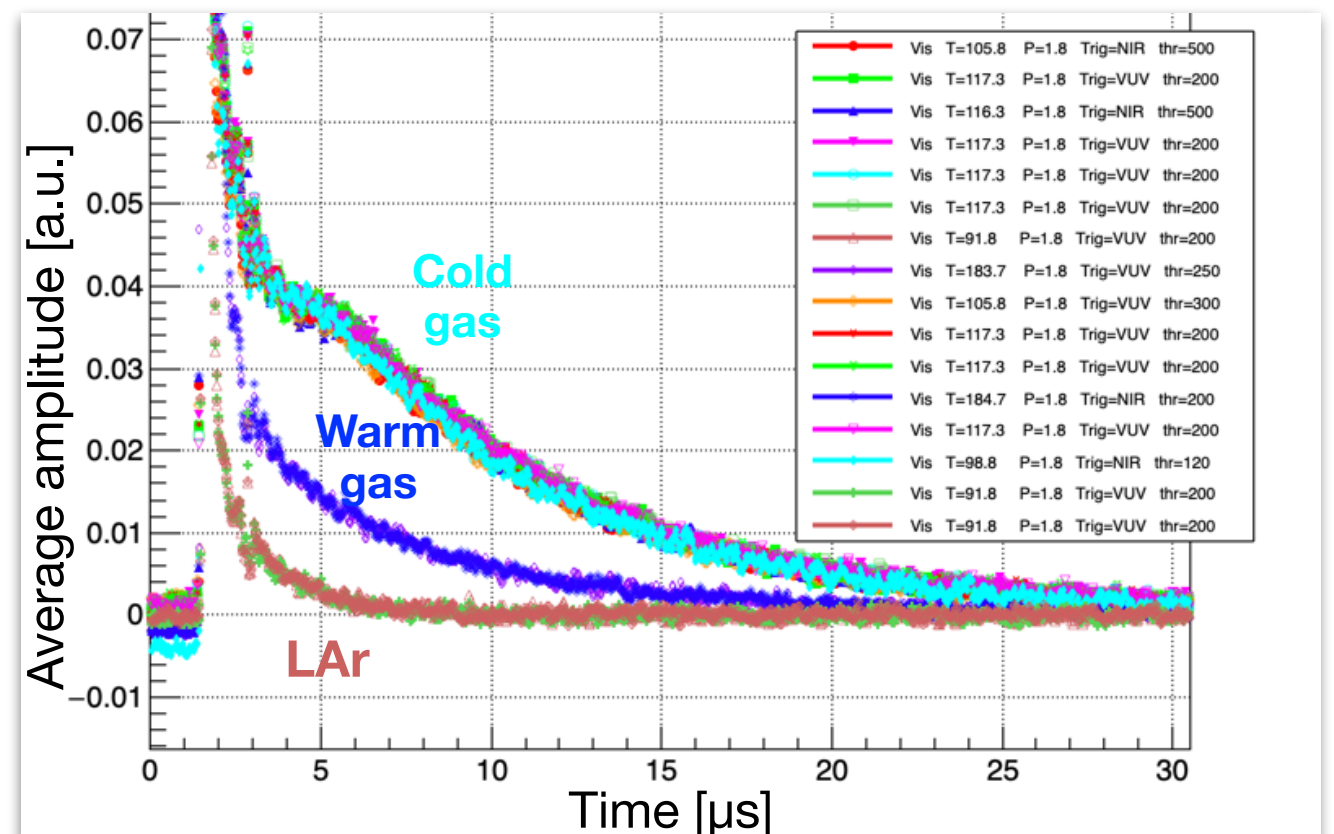
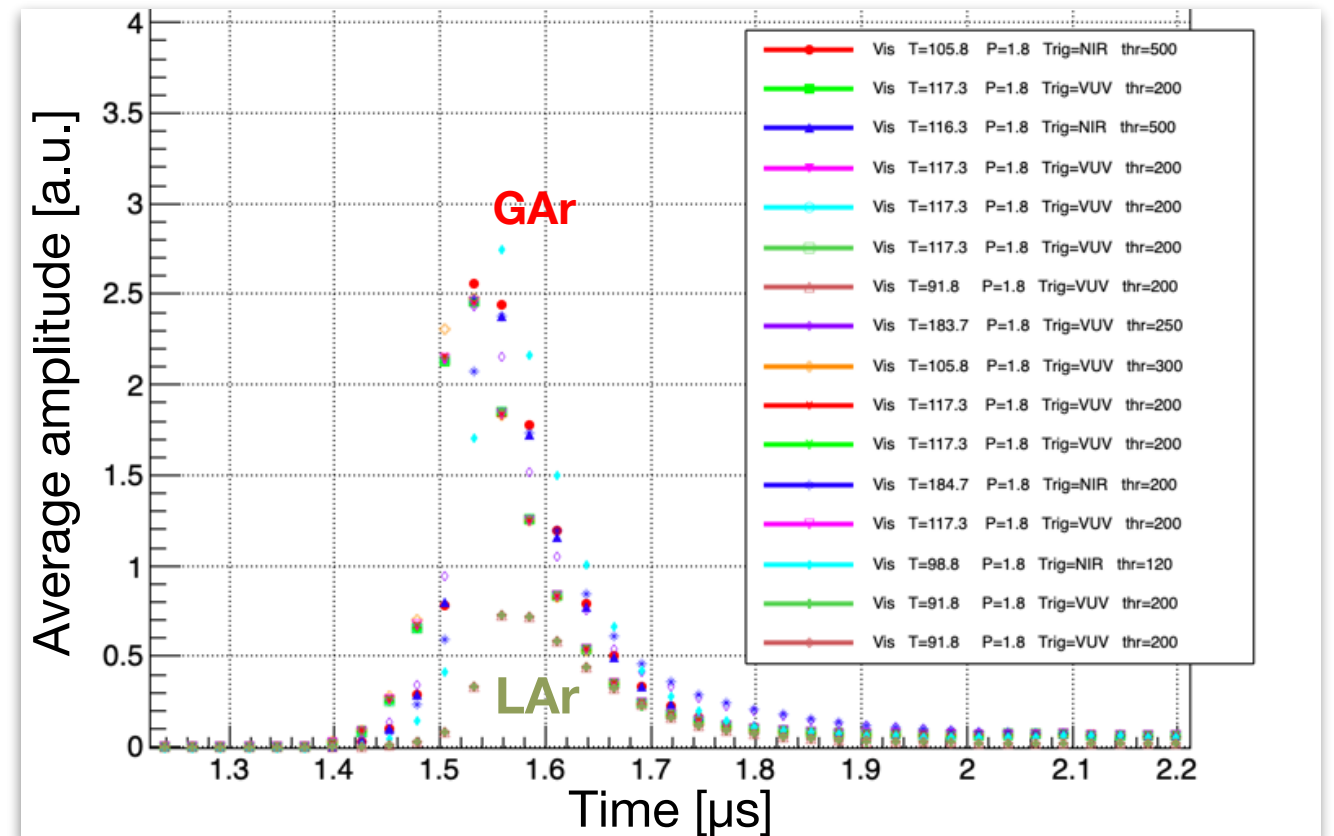
## Experimental results: VIS signal

(Trigger on VUV and NIR signal, shown to produce consistent results)

- Fast signal is observed in liquid, increasing by factor  $\sim 3$  in gas (cold and warm)

Energy deposit in gas is expected to be smaller than in liquid

- Temporal characteristics of the slow component are similar to VUV:
  - absence in liquid
  - presence in cold gas with extension to  $\sim 25\mu\text{s}$
  - reduction in size and different time constant in warm gas



# Experimental results: NIR signal

(Triggered by VUV or VIS channels)

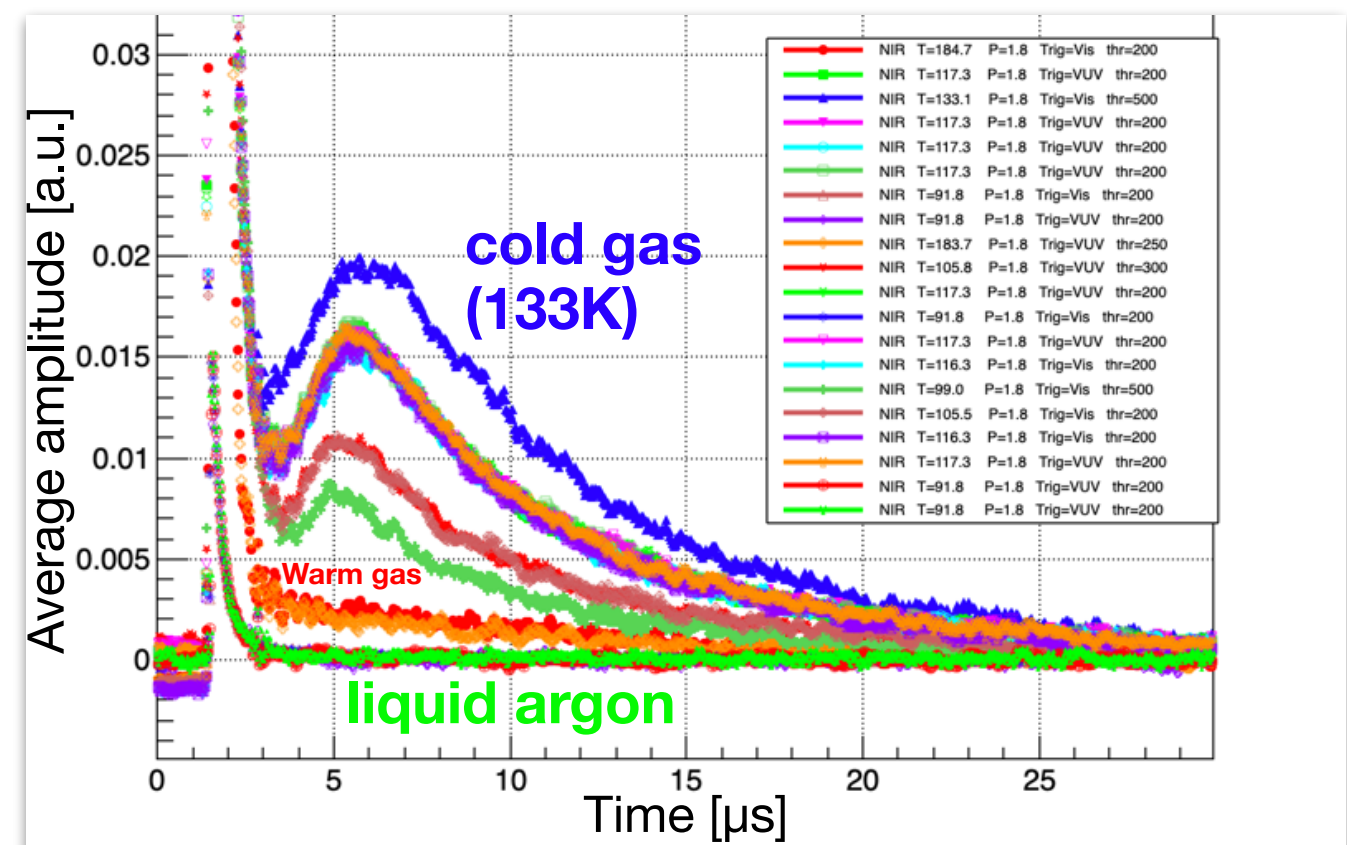
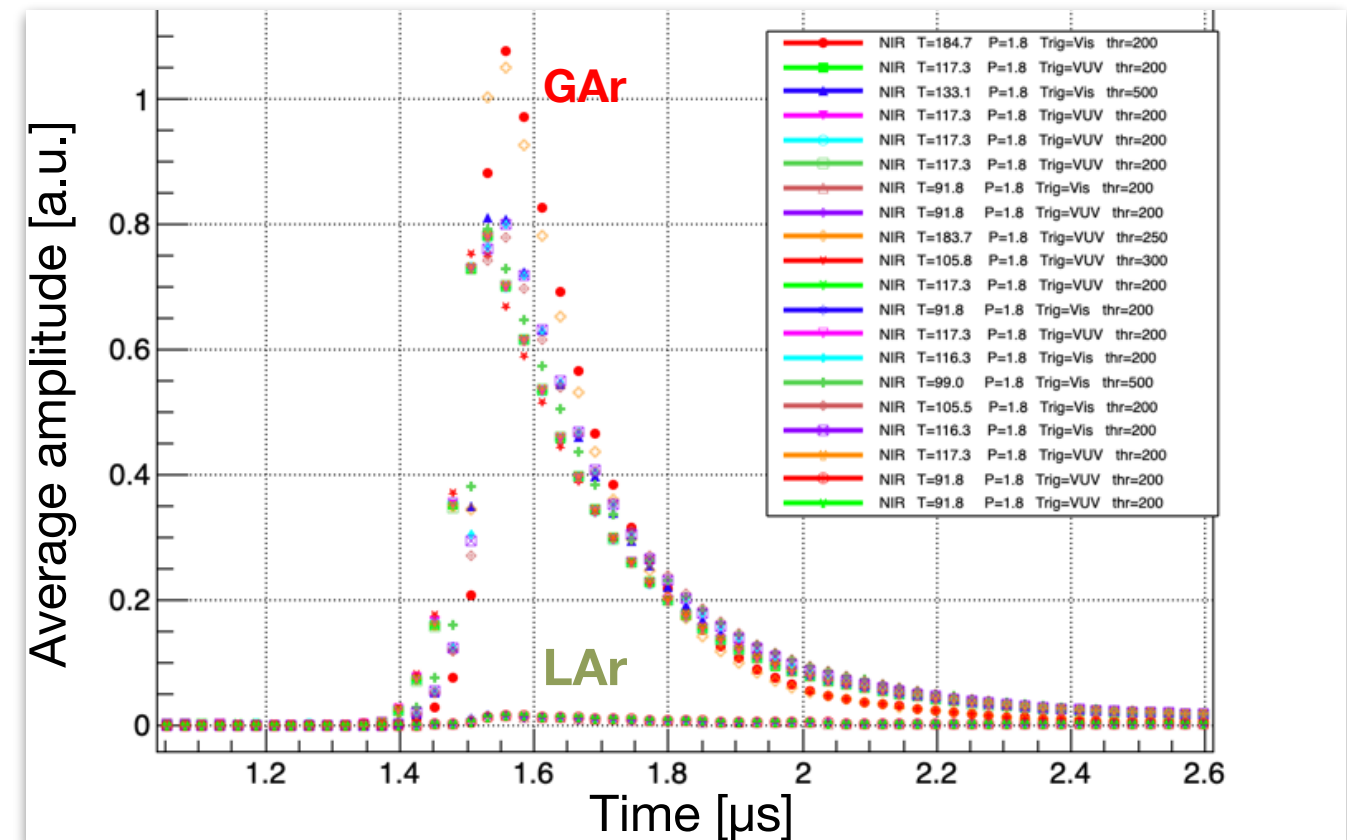
- Fast component is very small in liquid, increasing to ~8PE in gas (cold and warm)

- Slow component is absent in liquid. It appears in cold gas

Temperature-dependent delayed “bump” can be observed

It is peaked around 3-4 $\mu$ s from the start of the fast pulse

This component disappears in warm (185K) gas

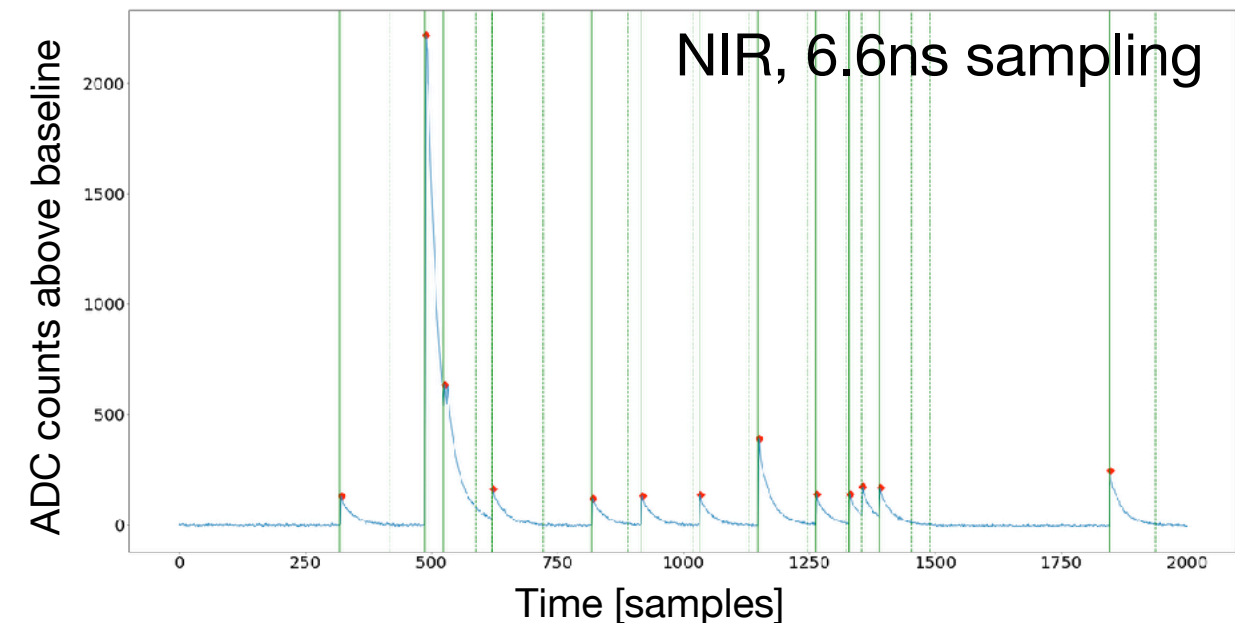




## Experimental results: peak-based analysis

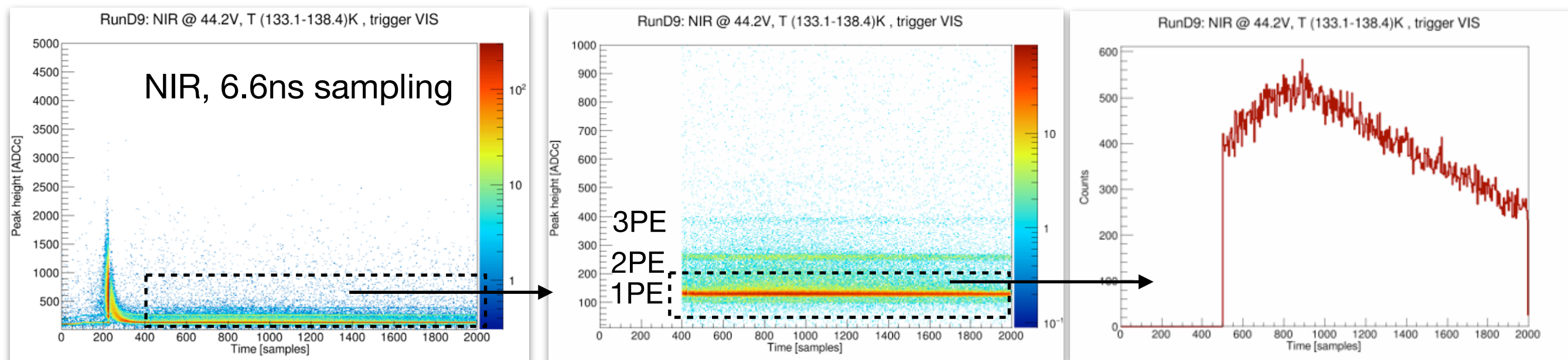
Individual peaks are identified in all traces with find\_peaks/prominence algorithm in Python signal processing package

Example of cold gas run (1.8bara, 133K), trigger VIS



Peak heights are plotted with the start time of peaks

Slow component appears to consist of pulses with small amplitude, mainly SPE signals, clustered in time

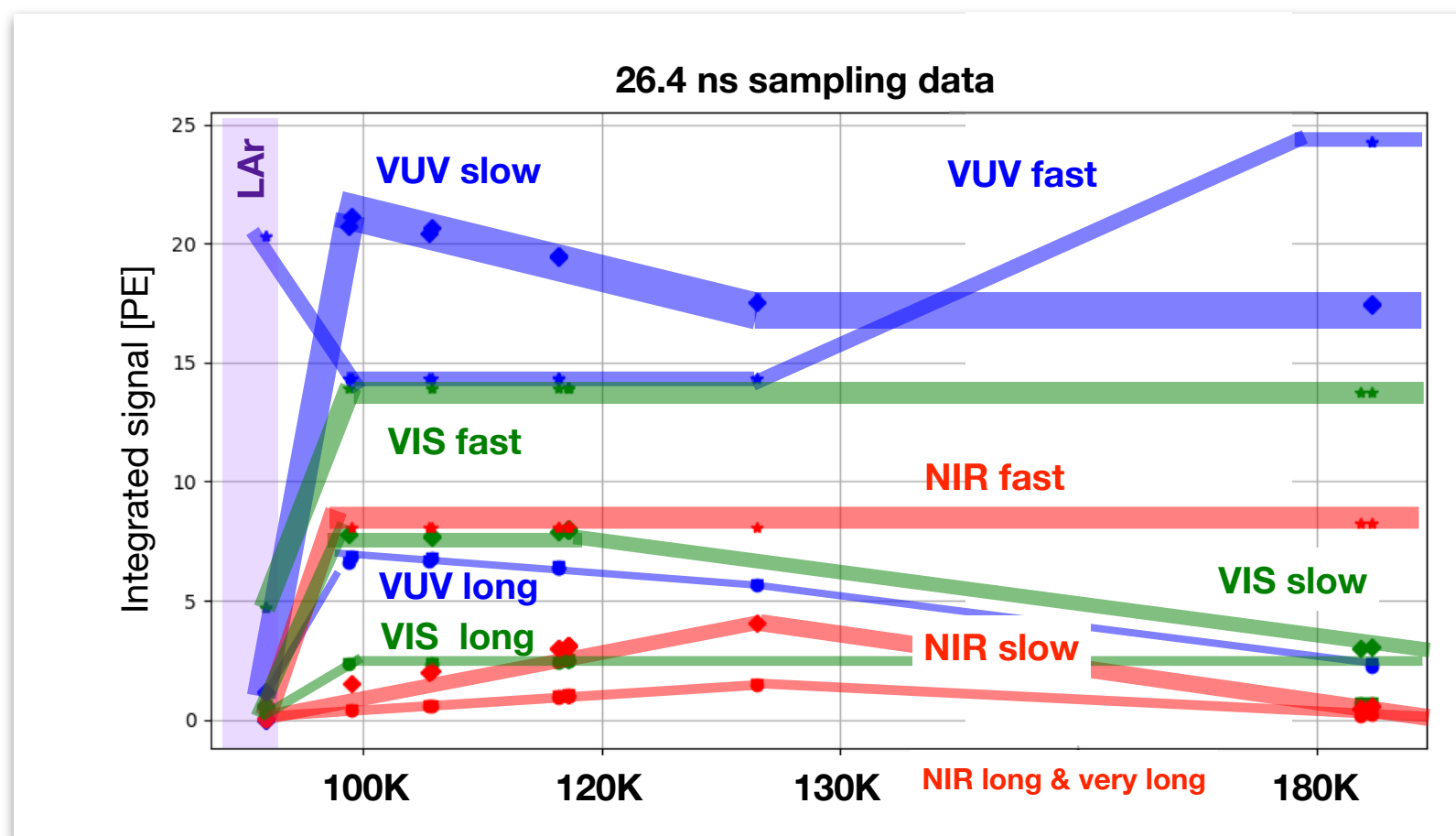


# Experimental results

The results here are based on in-situ temperature-dependent SPE calibration, and shown as integrated signal (averaged trace) in the 4 time ranges:

Fast component: < 1.5  $\mu$ s  
 Slow component: 1.5–8  $\mu$ s  
 Long component: 8–12  $\mu$ s  
 Very long: 12–24  $\mu$ s

NIR signal is absent in liquid argon, and appears in cold argon gas.  
 Slow component is significant in cold gas, disappearing in warm gas



There are slow and long NIR components that increase with the temperature of cold gas

Signal is present in the visible VIS range, consisting of fast, slow, long and very long components in cold gas, and only fast and slow in warm gas

Integrated signal [PE]												
SiPM:	VUV				VIS				NIR			
Integration time:	<1.5 $\mu$ s	1.5–8 $\mu$ s	8–12 $\mu$ s	12–24 $\mu$ s	<1.5 $\mu$ s	1.5–8 $\mu$ s	8–12 $\mu$ s	12–24 $\mu$ s	<1.5 $\mu$ s	1.5–8 $\mu$ s	8–12 $\mu$ s	12–24 $\mu$ s
liquid	20	0	0	0	5	0	0	0	0	0	0	0
cold gas	15	20	7	6	14	8	2.5	2.5	8	4	1.5	1.5
warm gas	24	18	2	2	14	3	0	0	8	0	0	0



## Summary

An experiment was performed at Fermilab in 2022, with an  $^{241}\text{Am}$   $\alpha$ -source and three photosensors with different (but overlapping) spectral ranges, with the data acquired in liquid and gaseous argon without electric field varying the temperature

In liquid argon, we detect the well known VUV signal, and a significant amount of signal in the visible part of the emission spectrum

VUV emission (its fast component) is reduced in cold gas (90–130K), but increased again in warm gas (185K). Signal in cold gas is dominated by the slow component extending up to  $\sim 25\mu\text{s}$

In cold gas, while VUV light is reduced, we observe factor  $\sim 3$  increase of the visible signal

Significant signal is measured in the near-infrared sensitive SiPM in cold gas. Slow ( $1.5\text{--}8\mu\text{s}$ ) and long (8-12, up to  $25\mu\text{s}$ ) components are identified in this emission, with the amount of detected light increasing with temperature in cold gas independently from the other two photosensors

## Conclusions

It is not possible to compare absolute light yields due to not yet calculated photon acceptance of the three photosensors, which depends on the detector geometry, their size and spectral sensitivity

An additional uncertainty arises from the length of the  $\alpha$ -track, which is point-like in liquid argon, and on the order of a few cm in argon gas

→ GEANT4 simulation underway to answer some of these questions

→ Follow-up experiments are being planned

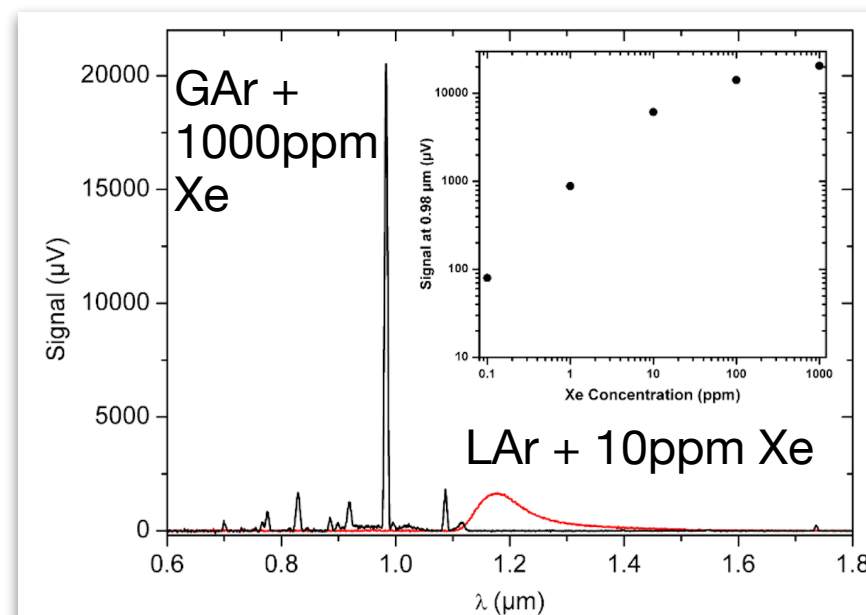
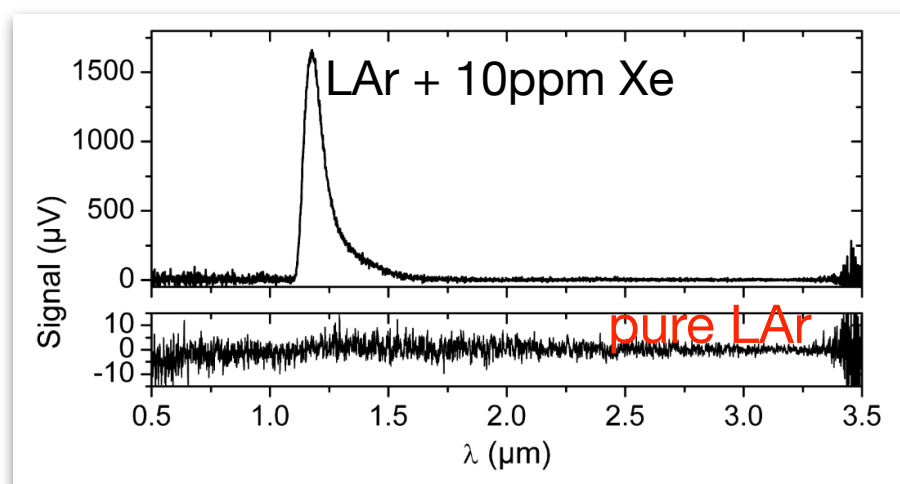
Possible applications of the observed phenomena:

- better understanding of the scintillation in argon, update and improvement of theoretical models
- interpretation of signals in the gas phase of the large-scale surface detectors
- total light yield may improve by detection of signals in visible and infrared ranges
- temporal characteristics of this emission may open new opportunities for particle identification

Very interesting effects are expected in xenon-doped argon:

### Electron beam excitation measurements

A. Neumeier *et al* 2014 *EPL* **106** 32001



A. Neumeier *et al* 2015 *EPL* **109** 12001

