Impact of extreme ultraviolet radiation on the scintillation of pure and xenon-doped liquid argon

LIDINE 2025 Hong Kong

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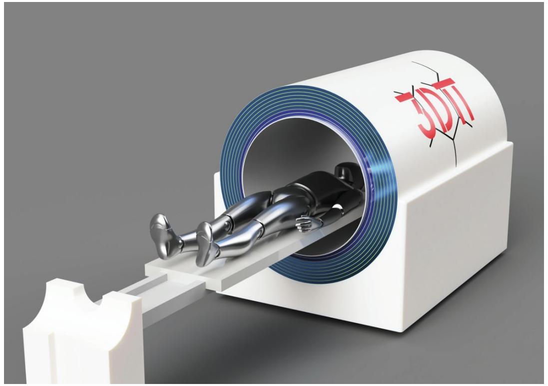
Université Paris Cité

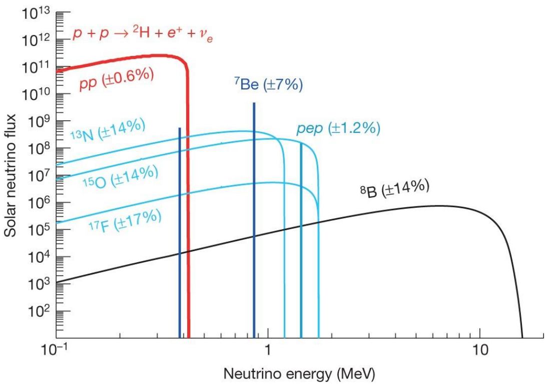
DARKSIDE

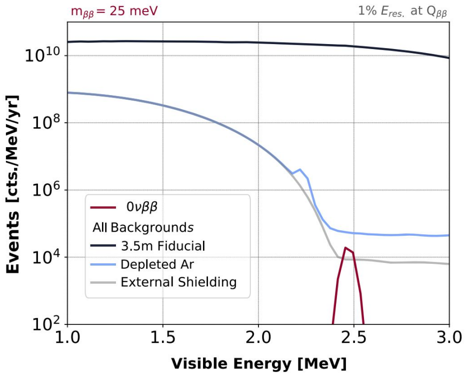
X-ArT

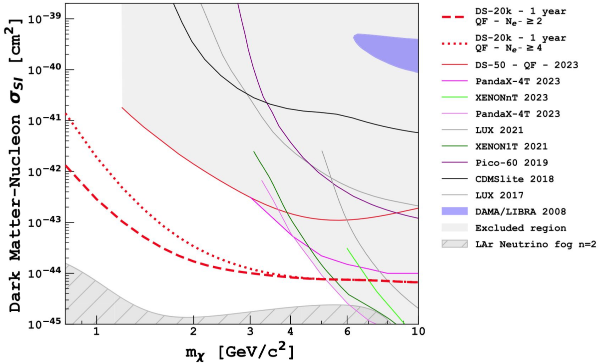
Xenon doped liquid argon

- **faster** scintillation: sub-nanosecond timing resolution
- **higher** photon and ionization yield
- **longer** photon attenuation length
- lower energy **thresholds**
- cost effective
- argon boiling **temperature**









X-ArT: Xenon-Argon Technology

1. Study the **thermodynamic** properties :
   a. Ar-Xe **phase diagram**
   b. Maximum Xe **solubility** in LAr
2. Characterize the **Ar-Xe response** in scintillation and ionization up to the maximum Xe solubility
   a. phase 1: **scintillation** only up to 40 ppm of xenon concentration
   b. phase 2: **ionization** up to maximum solubility

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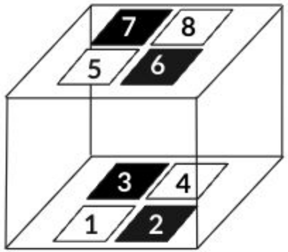
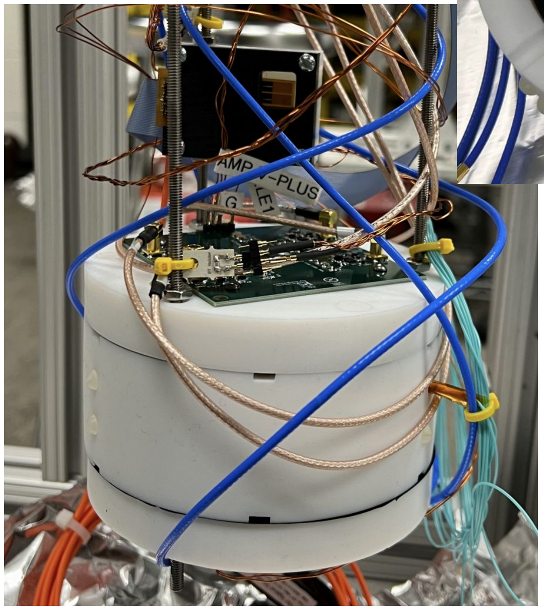
Experimental setup at Princeton

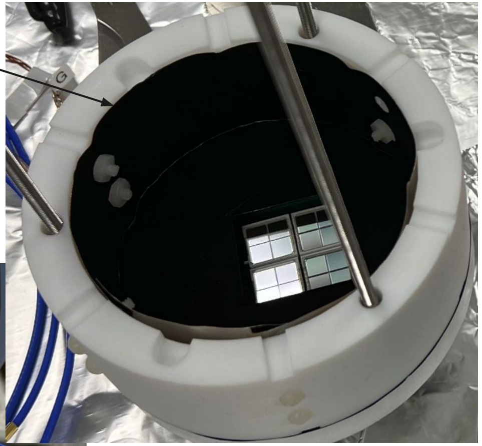
PHYSICAL REVIEW D 111 102001 (2024)

Single phase LAr cylindrical chamber

- 4.5 cm height / 9.5 cm diameter
- **no TPB** wavelength shifter
- **black foil** to prevent reflections
- 32 VUV-sensitive Hamamatsu S13371 SiPMs
  - 4 SiPMs per channel (8 channels)
  - 4 channels **with quartz window** (**WW**)
  - 4 channels **without window** (**WL**)







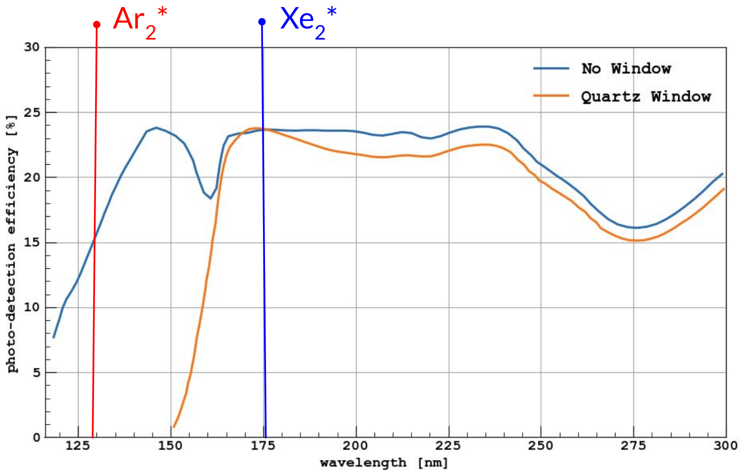
Detection channels

WW channels: sensitive above ~**150 nm**

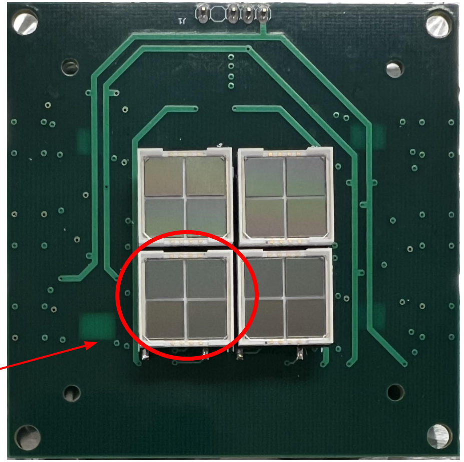
→ detect only Xe_2^* photons (175 nm)

WL channels: sensitive above ~**60 nm**

→ detect both Xe_2^* (175 nm) and Ar_2^* (128 nm) photons



one channel



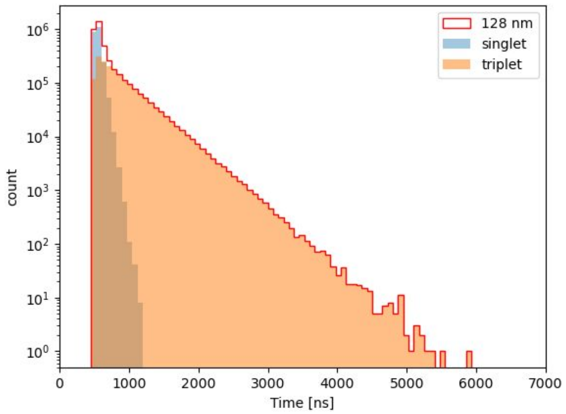
readout board

Characterization of the LAr response

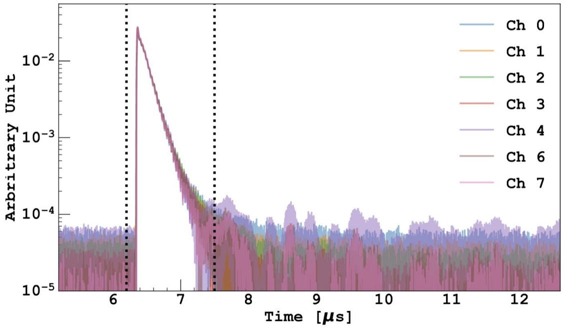
Pure LAr measurement (WL-SiPMs only) to constrain the Ar_2^* **triplet lifetime** and characterize the **LAr purity**.

<u>LAr scintillation response model:</u>

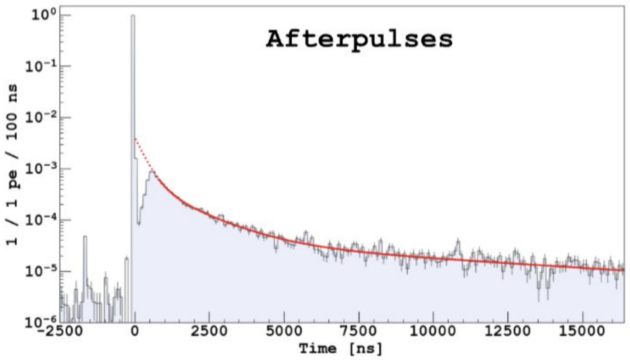
sum of singlet and triplet state exponentials ⊗ SiPM time response ⊗ SiPM AP time profile



Ar$_2$ excited states:
singlet (**6 ns**)
triplet (**1600 ns**)



from laser calibrations

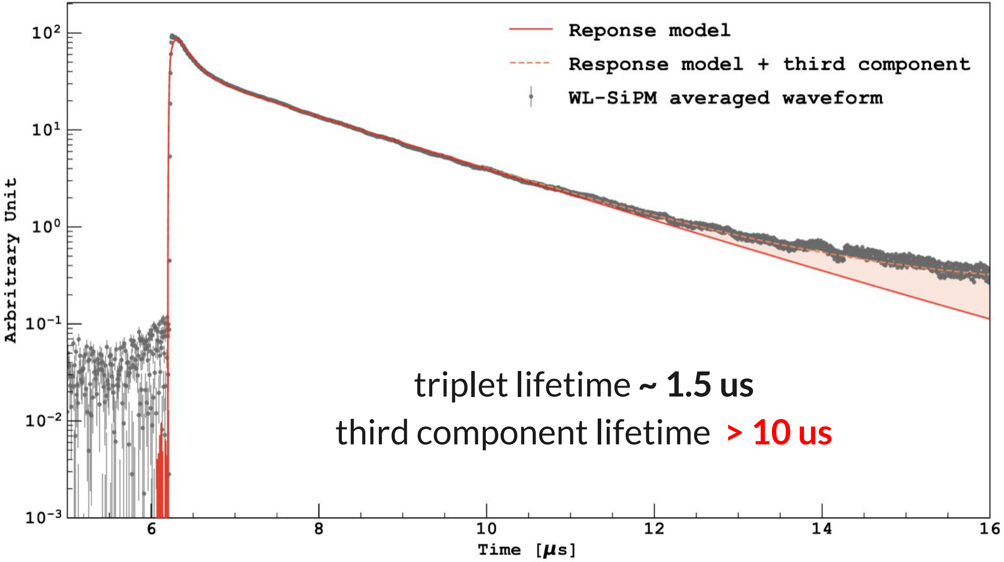


three exponential model

Characterization of the LAr response

Long component observed with WL-SiPMs:

WINDOWLESS SIPMS



triplet lifetime ~ **1.5 us**

third component lifetime **> 10 us**

In literature it is assigned to:

- TPB fluorescence
- Teflon fluorescence
- Near-infrared photons (> 800 nm)

TPB fluorescence ? → NO

- no TBP in the X-ArT setup

Teflon fluorescence ? → NO

- all teflon components covered with black foil

Near-infrared photons ? → NO

- detected at < 150 nm

Afterpulses ? → NO

- APs only cannot explain the long tail

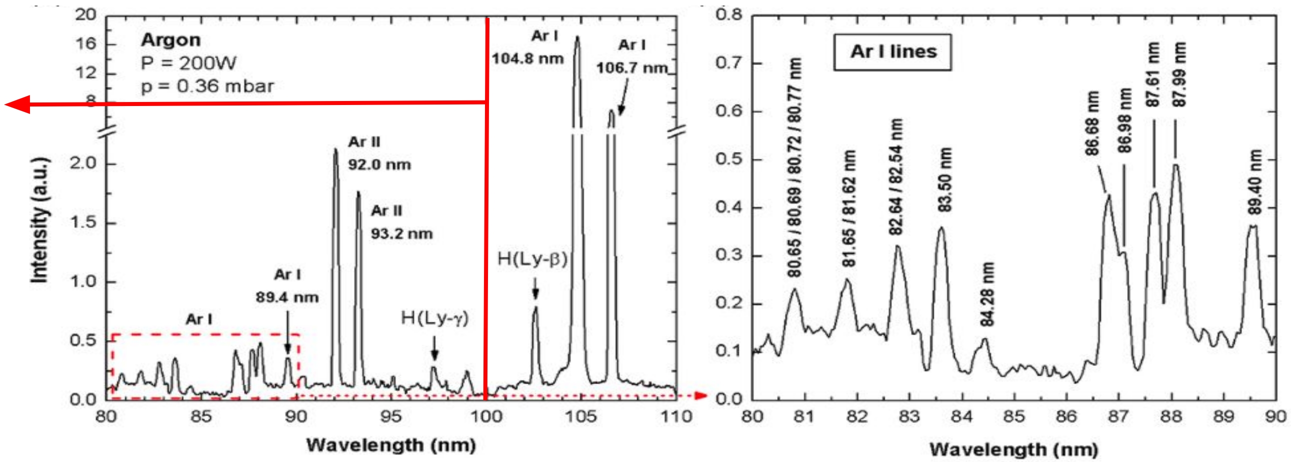
EUV emission in LAr

Ar-I: neutral argon (Ar*)
Ar-II: singly or multiple ionized argon (Ar^{q+})

EUV range: ~10-100 nm
Emission from metastable states: ms to s

1. It is well known from atomic physics that Ar-I and Ar-II emit EUV photons from metastable levels.
2. EUV photons with wavelength < 100 nm or energy > 12.1 eV can ionize Xe atoms.

Xe ionization threshold



Lis K. Nanver DOI: 10.5772/15396

EUV detectable with SiPMs? → YES

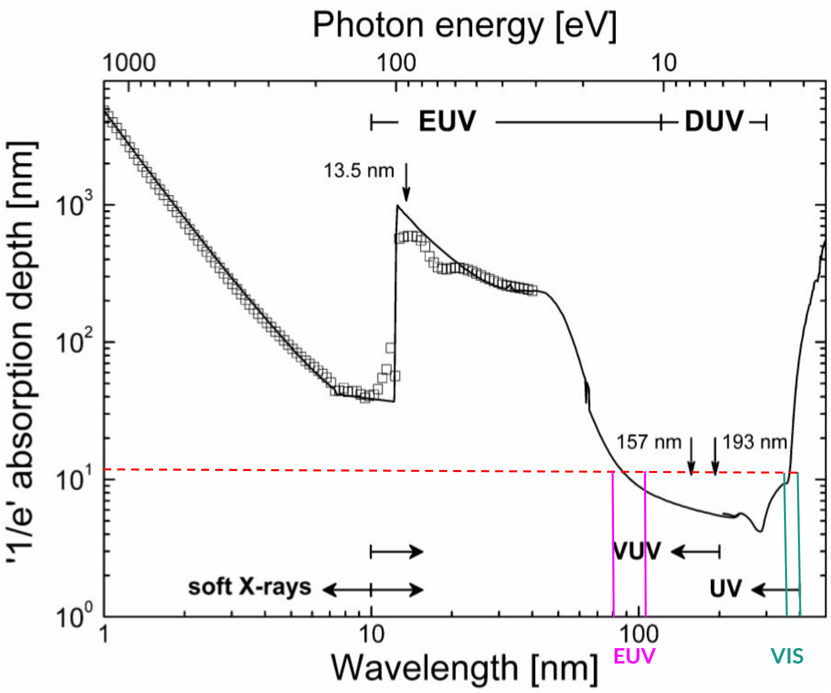


Fig. 7. '1/e' absorption depth in Si as a function of incident radiation wavelength (Palik, 1985; Henke data).

EUV and VIS have almost the same absorption length in silicon.

EUV detectable with TPB/PMTs? → YES

Eur. Phys. J. C (2018) 78:329

TPB is efficient at EUV.

Eur. Phys. J. C (2018) 78:329

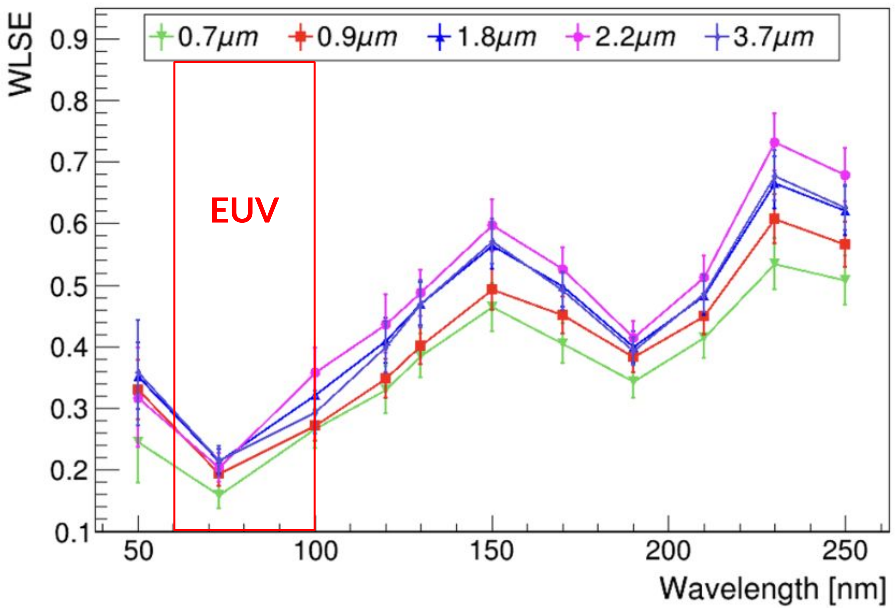


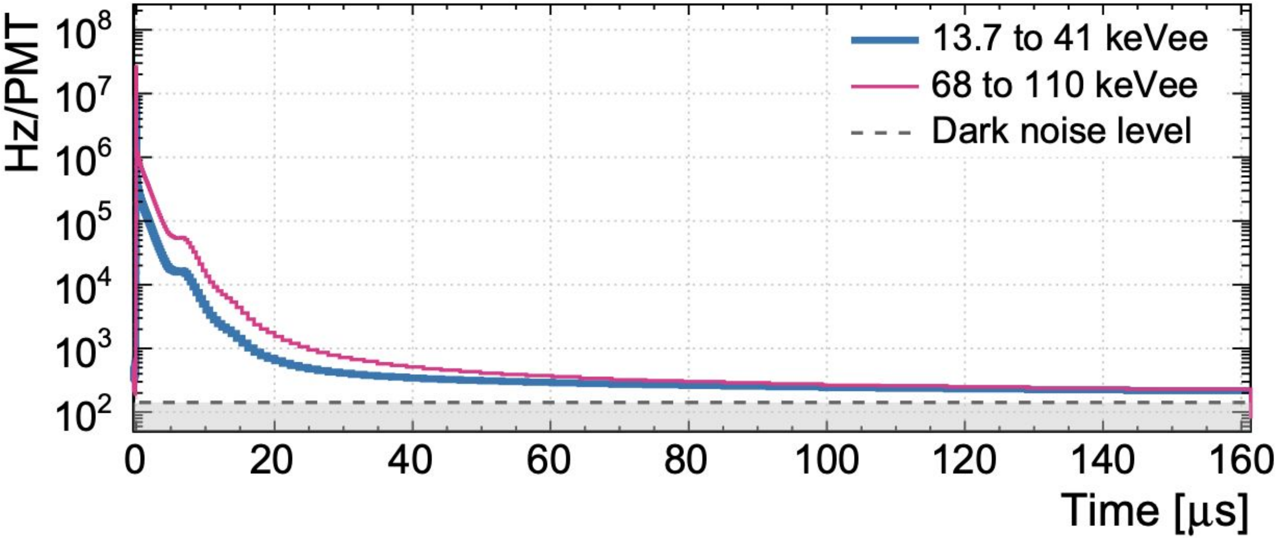
Fig. 16 Absolute WLSE efficiency for several samples of various thickness

Eur. Phys. J. C 80, 303 (2020)

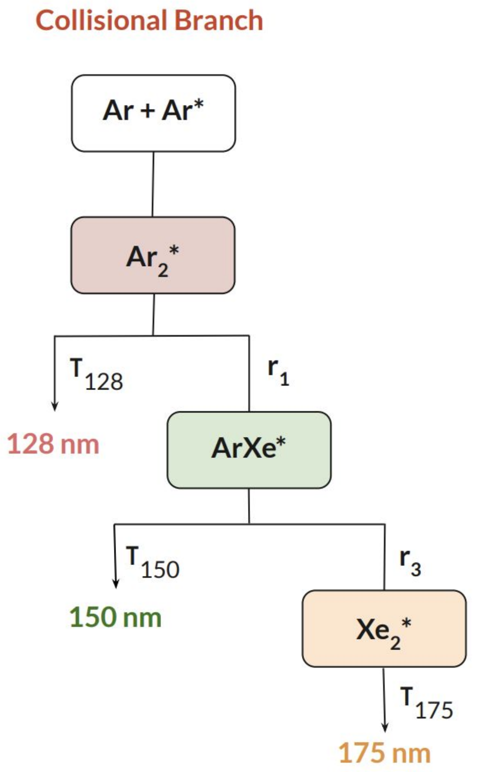
Long component in DEAP-3600

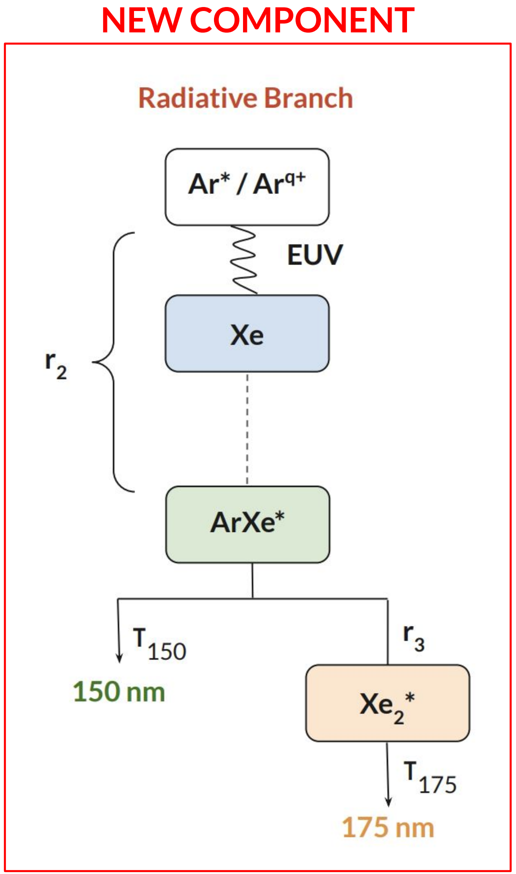
DEAP-3600:

- **liquid argon** detector for dark matter searches
- uses **TPB** wavelength shifter (UV to VIS conversion) and **PMTs** to detect the scintillation light



The Xe-Ar scintillation model





$r_1 \rightarrow$ rate of **ArXe*** formation

$r_2 \rightarrow$ rate of **EUV-induced** ionization and subsequent **ArXe*** formation

$r_3 \rightarrow$ rate of **Xe_2*** formation

Two competitions between:

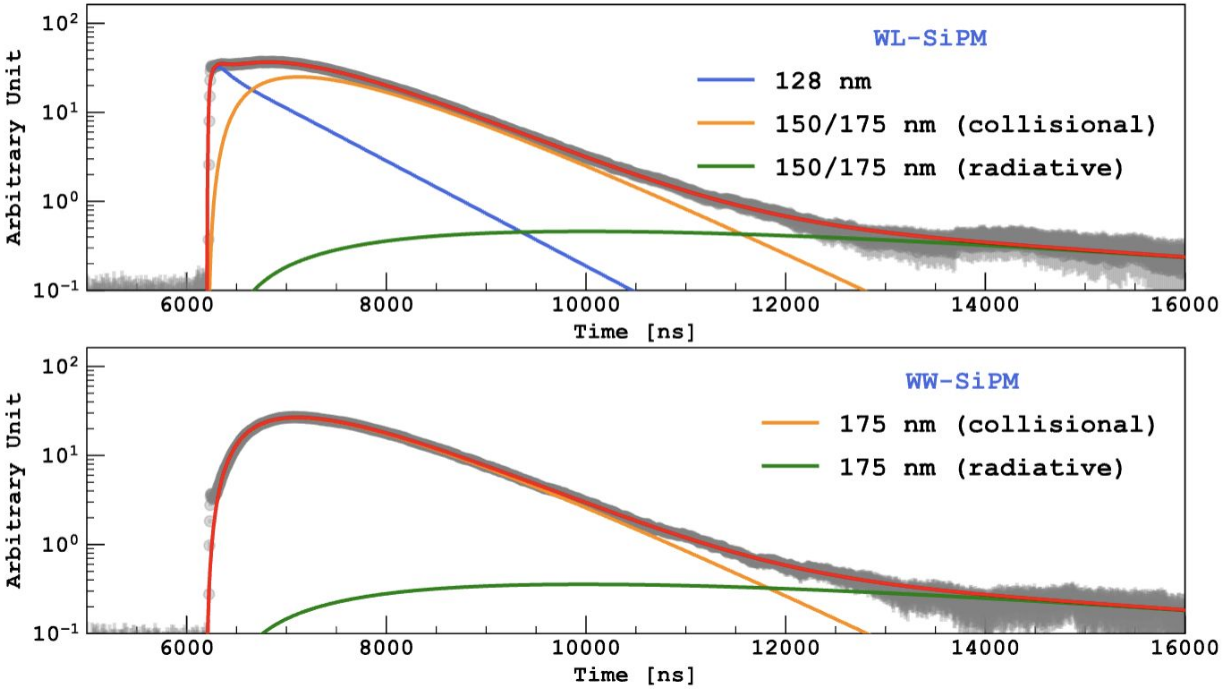
- triplet decay and ArXe* formation
- ArXe* de-excitation and Xe_2* formation

The analytical model

	WW-SiPMs	WL-SiPMs
collisional	128 nm $$A \cdot [f_p \cdot \frac{e^{-\frac{t}{\tau_s}}}{\tau_s} + (1 - f_p) \cdot \frac{e^{-k_1 t}}{1/k_1}]$$ 150 nm/175 nm $$B_1 \cdot \frac{k_1 k_3}{k_1 - k_3} \cdot [e^{-k_3 t} \cdot (1 - e^{-(k_1 - k_3)t})]$$	175 nm $$B_2 \cdot \frac{k_1 k_3}{k_1 - k_3} \cdot [e^{-k_3 t} \cdot (1 - e^{-(k_1 - k_3)t})]$$
radiative	150 nm/175 nm $$C_1 \cdot \frac{r_2 k_3}{r_2 - k_3} \cdot [e^{-k_3 t} \cdot (1 - e^{-(r_2 - k_3)t})]$$	175 nm $$C_2 \cdot \frac{r_2 k_3}{r_2 - k_3} \cdot [e^{-k_3 t} \cdot (1 - e^{-(r_2 - k_3)t})]$$

Simultaneous fit of WL- and WW-SiPM waveforms

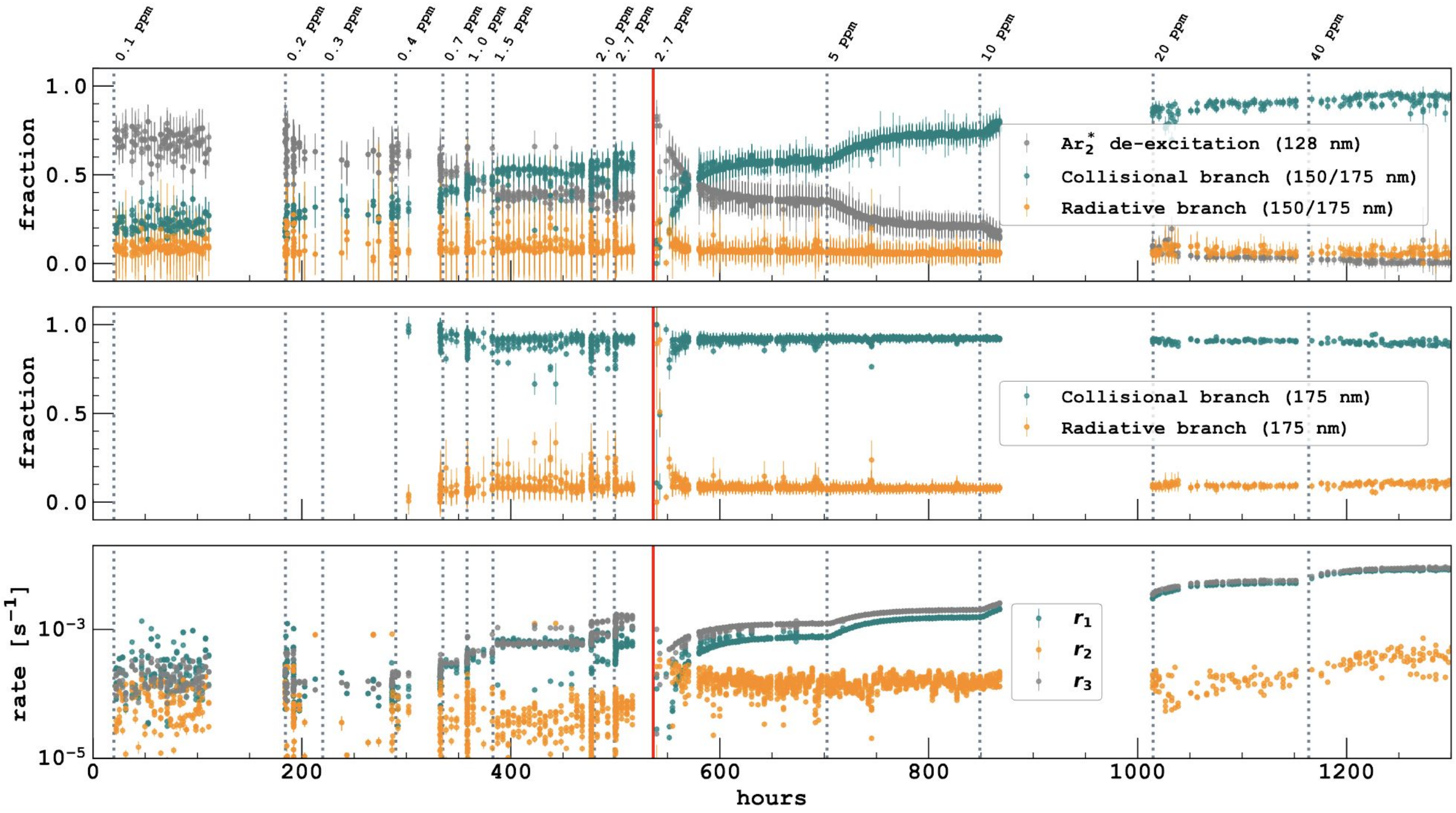
2.7 ppm of Xe and ^{60}Co source



rate parameters (r_1, r_2, and r_3) are constrained between the two fits

- **Non-zero contribution from the radiative process.**
- **The collisional process alone, cannot explain the data.**

Effects of the Xe concentration



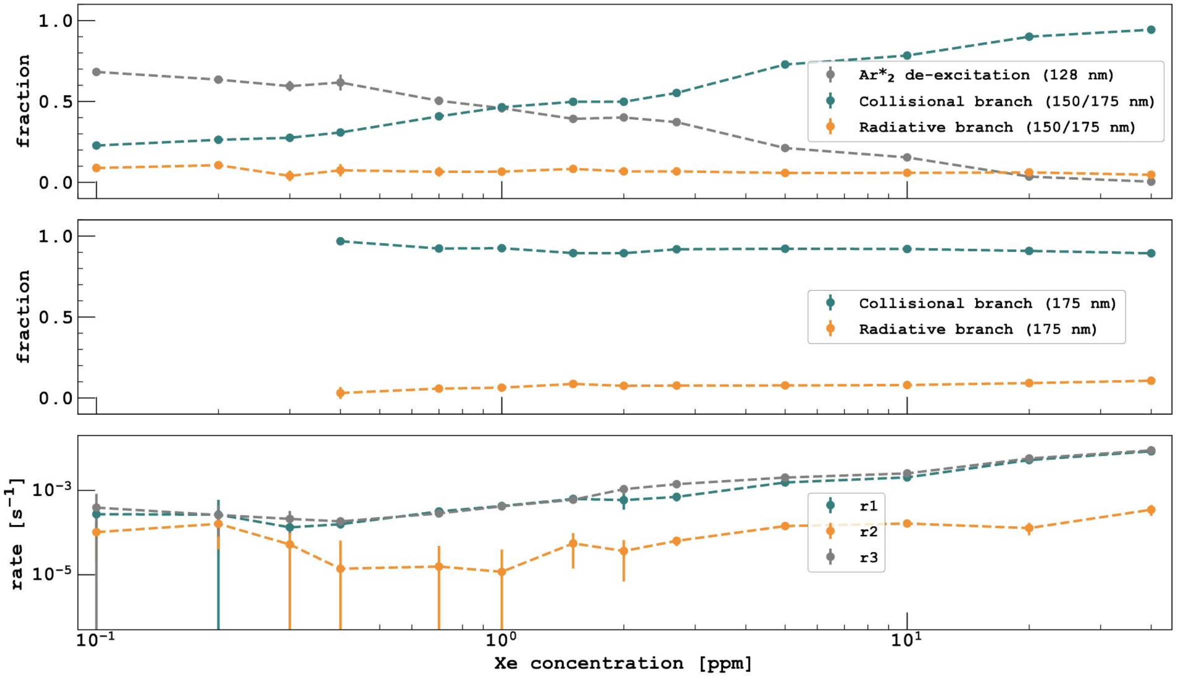
Effects of the Xe concentration

Collisional branch increase with Xe:

- increasing probability of collisional energy transfer

Radiative branch is constant:

- depends on atomic Ar excitation
- mean EUV - Xe scattering length is negligible with respect to the chamber size

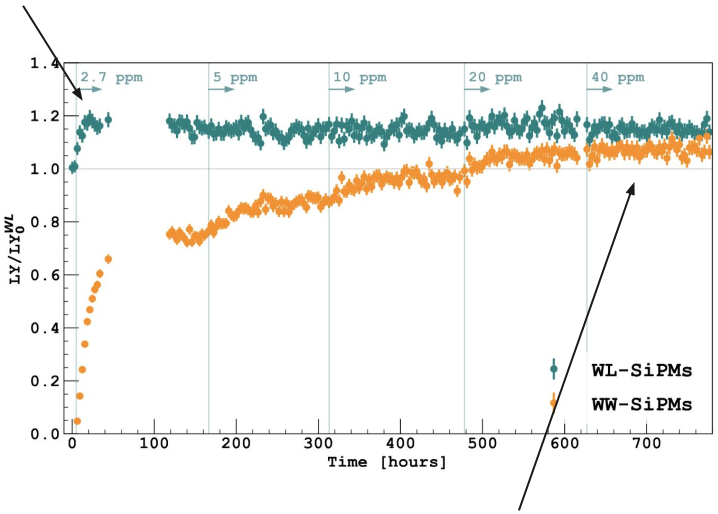


Xe-doped liquid argon light yield and PSD

LY increases with increasing Xe concentration.

overall LY = sum of Ar_2^*, Xe_2^* and ArXe* photons

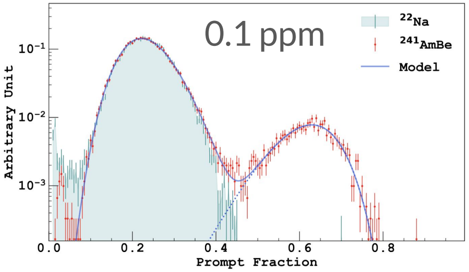
increase due to the radiative component

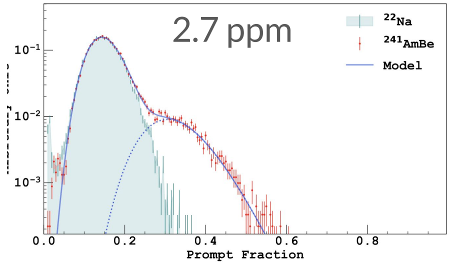


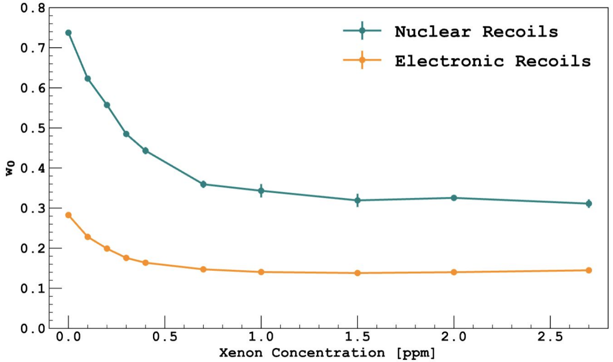
128 nm becomes negligible

PSD degrades with increasing Xe concentration.

PSD observable **w**: the fraction of light in the first 300 ns







EUV as natural source of spurious electrons

<u>**Spurious electrons:**</u>

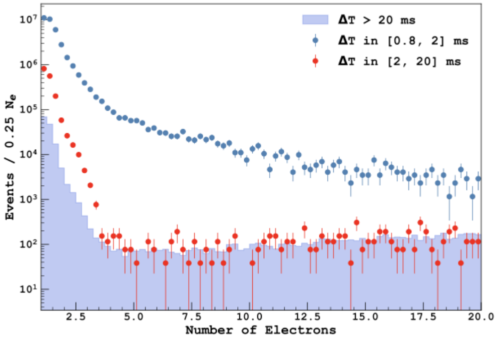
Electroluminescence pulses of unknown origin equivalent to one or few electrons, **correlated** (ms scale) with **preceding events** in the TPC and with **impurities**.

EUV can photo-ionize Xe as well as impurities,

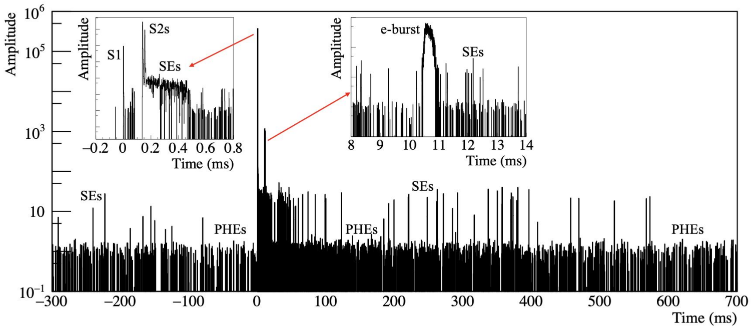
for instance: O_2 (12.1 eV), CH_4 (12.6 eV) and Kr (14.0 eV)

- correlation with preceding events exciting atomic Ar states
- time delays dominated by metastable atomic Ar states

LAr:



LXe:

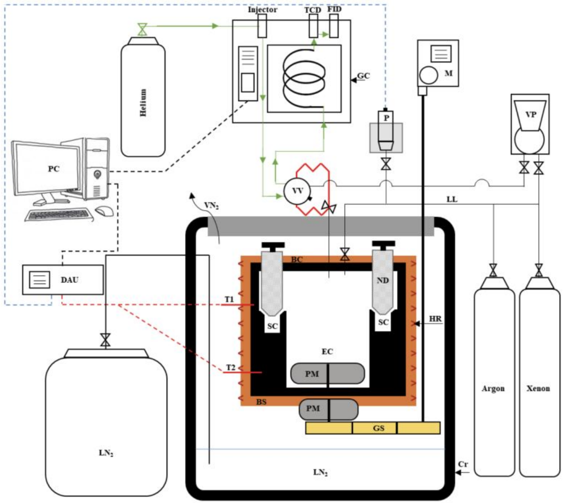


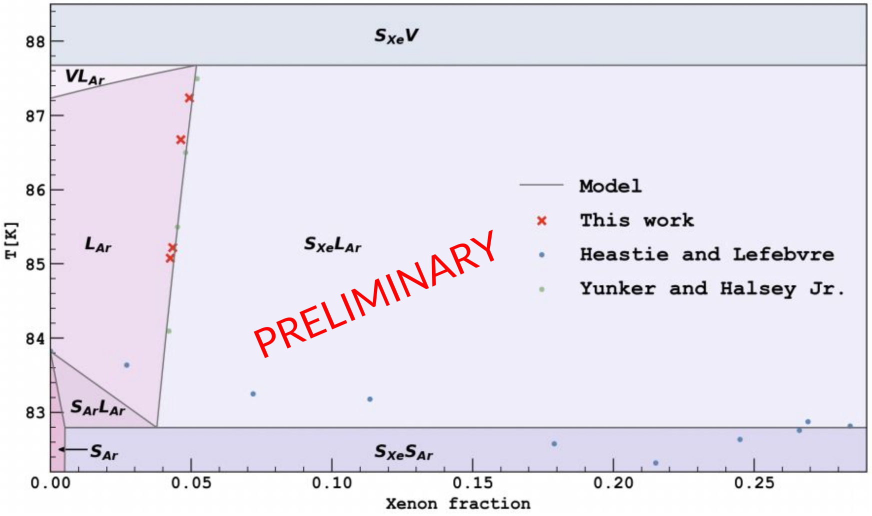
Bonus: first phase-diagram

Study of the solid-vapor and solid-liquid phase equilibrium in the 85-150 K temperature range.

Observations:

1. decrease of xenon solubility in the vapor phase with decreasing temperature
2. higher but decreasing solubility of xenon in the liquid phase with decreasing temperature: maximum at **4.2%**
3. measurements in very good agreement with model expectations





Conclusions

1. The **radiative component** addition models pure and xenon-doped liquid argon scintillation.
2. In the xenon-doped system we observed an increase in **LY** up to 15 % and a degradation in **PSD** with increasing Xe concentration.
3. EUV photon emission can explain the **spurious electrons** in pure LAr, through photoionization of impurities.
4. Maximum solubility and phase diagram of the xenon-argon mixture was measured.

Next steps:

- ❏ new campaign for investigation of the long component of LAr scintillation
- ❏ characterization of the ionization response of Xe doped LAr
- ❏ thermodynamics paper by the end of the year.

Backup

Argon and xenon as scintillators

	+	−
Ar	+ scalability + radio purity: UAr + excellent PSD + low dark count rate SiPM	− not directly detectable wavelength − long scintillation times − short attenuation length
Xe	+ higher WIMP cross section + spin-dependent sensitivity + fast response + directly detectable wavelength	− expensive and limited − higher dark count rate SiPM − poor PSD

SiPM specifications

WW-SiPMs

■ Electrical and optical characteristics

(Typ. T = 25 deg C, Vr = Vop unless otherwise noted)

Parameters	Symbol	Value (typ.)	Unit
Spectral response range	λ	155 to 900	nm
Peak sensitivity wavelength	λp	500	nm
Photon detection efficiency at λp *2	-	32	%
Photon detection efficiency at 175nm (in vacuum) *2	-	24	%
Breakdown voltage	V_{br}	53 +/- 5	V
Recommended operating voltage *3	V_{op}	V_{br} + 4.0	V
Dark count rate / channel	DCR	4.0 (MAX:12)	Mcps
Crosstalk probability	P_{CT}	3	%
Terminal capacitance at Vop / channel	Ct	1200	pF
Gain	M	2.55×10^6	-
Temperature coefficient of reverse voltage Around room temperature	ΔTV_{op}	54	mV/deg C

*2 : Photon detection efficiency does not include crosstalk and after pulse.

*3 : Refer to the data attached for each products.

WL-SiPMs

■ Electrical and optical characteristics

(Typ. T = 25 deg C, Vr = Vop unless otherwise noted)

Parameters	Symbol	Value (typ.)	Unit
Spectral response range	λ	120 to 900	nm
Peak sensitivity wavelength	λp	500	nm
Photon detection efficiency at λp *2	-	32	%
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Temperature coefficient of reverse voltage Around room temperature	ΔTV_{op}	54	mV/deg C

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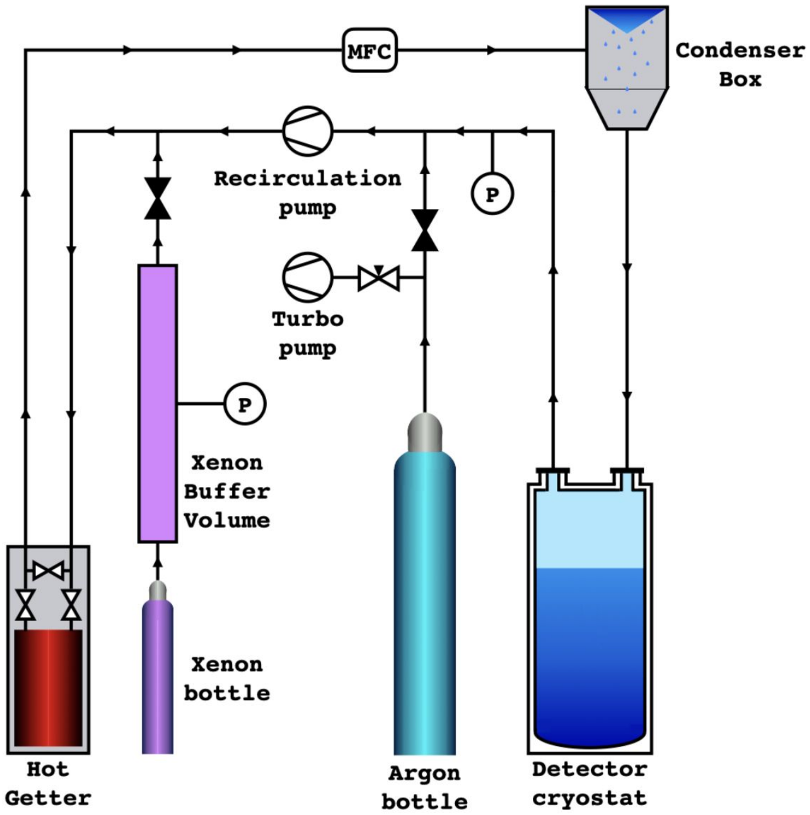
*3 : Refer to the data attached for each products.

Custom-designed cryogenic system at Princeton



Xe-doped liquid argon scintillation

We fit the waveforms of WW and WL channels simultaneously to disentangle the contributions of components with different wavelengths.

1. Direct Ar scintillation: $$Ar_2^* \rightarrow Ar + Ar + \gamma_{128}$$

2. When Xe is added, ArXe is formed: $$Ar_2^* + Xe \rightarrow ArXe^* + Ar$$

At ~ 0.2 ppm of Xe:

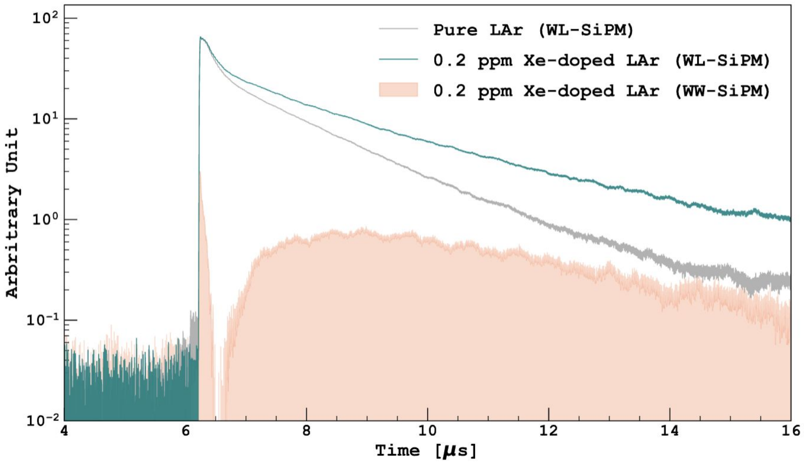
- slow component observed with WL-SiPMs with lifetime ~ 5 ms from ArXe* de-excitation that emits 150 nm photons:

$$ArXe^* \rightarrow Ar + Xe + \gamma_{150}$$

At increasing Xe concentration the Xe_2^* reaction dominates:

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

Xe_2^* decays emitting 175 nm light



6.3 hours after injecting 2.7 ppm of Xe

The Ar-Xe scintillation model

Probability density functions (pdfs) describing the signals observed by the WL and WW channels:

$$f_{WL}(t) = \frac{A}{\varepsilon_{128}} f_{128}(t) + \frac{B_1}{\varepsilon_{150/175}} f_c(t) + \frac{C_1}{\varepsilon_{150/175}} f_r(t)$$

$$f_{WW}(t) = \frac{B_2}{\varepsilon_{150/175}} f_c(t) + \frac{C_2}{\varepsilon_{150/175}} f_r(t)$$

(convoluted with SiPM response)

Amplitudes

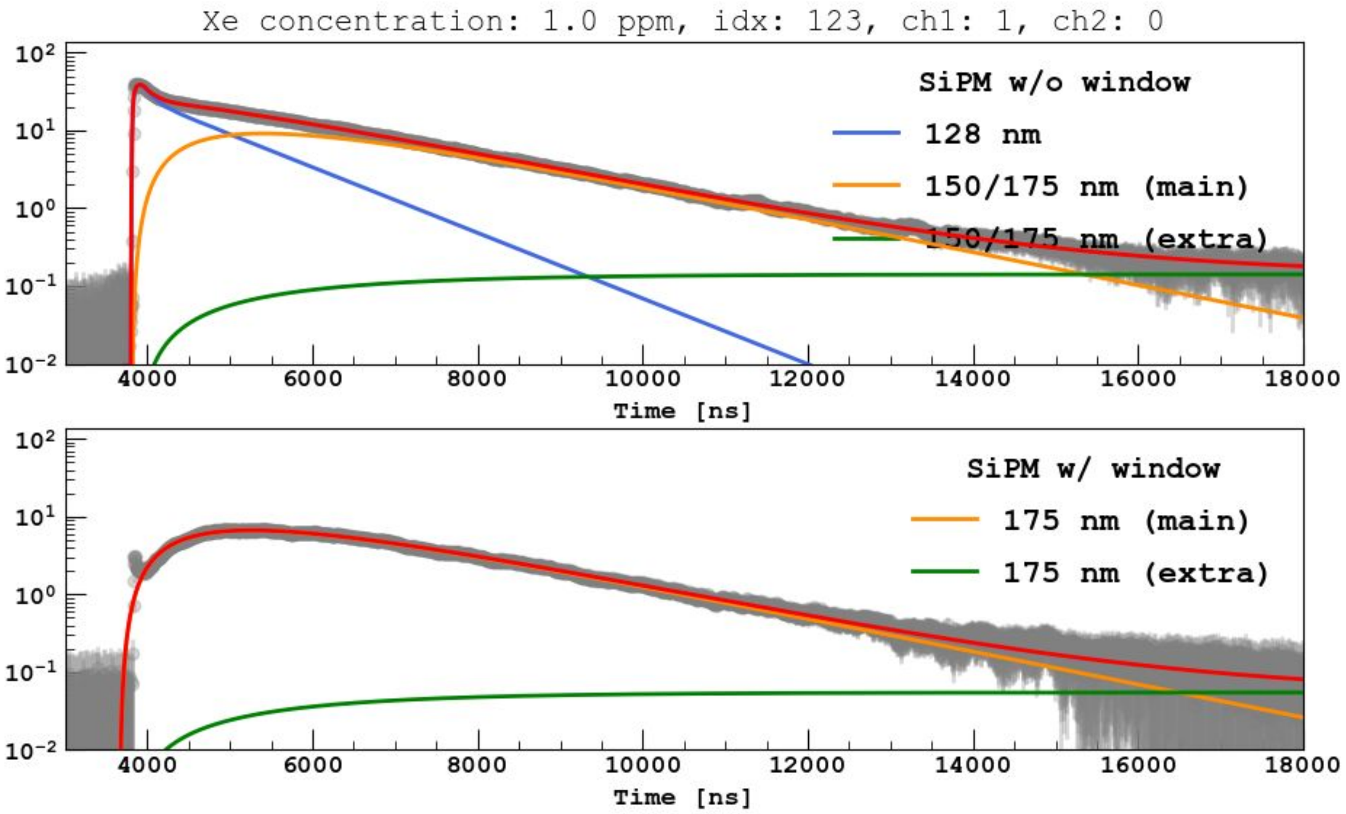
A: Ar_2^* de-excitation

B1: collisional component in WL
C1: radiative component in WL

B2: collisional component in WW
C2: radiative component in WW

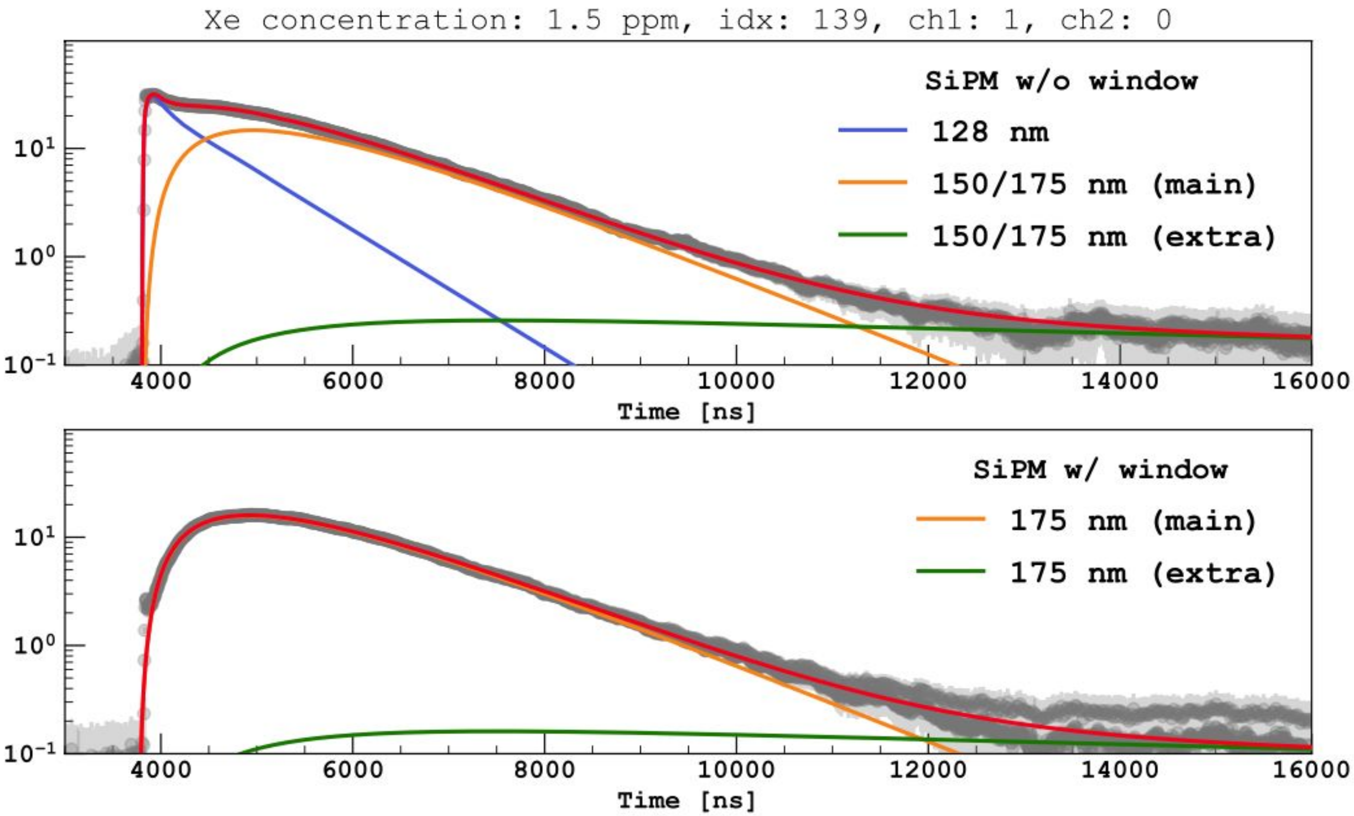
ε: photodetection efficiencies at different wavelengths

1.0 ppm



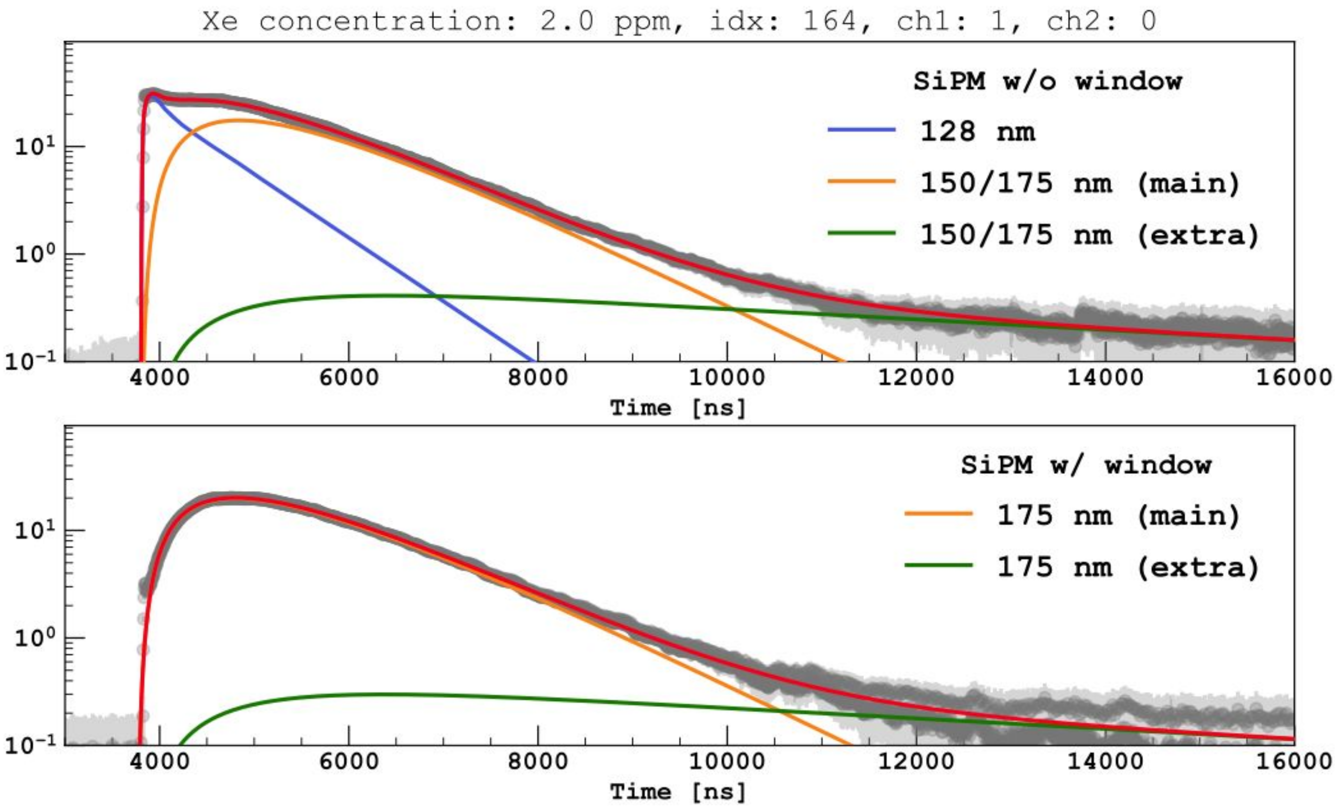
Xe concentration: 1.0 ppm, idx: 123, ch1: 1, ch2: 0
SiPM w/o window
128 nm
150/175 nm (main)
150/175 nm (extra)
Time [ns]
SiPM w/ window
175 nm (main)
175 nm (extra)
Time [ns]

1.5 ppm



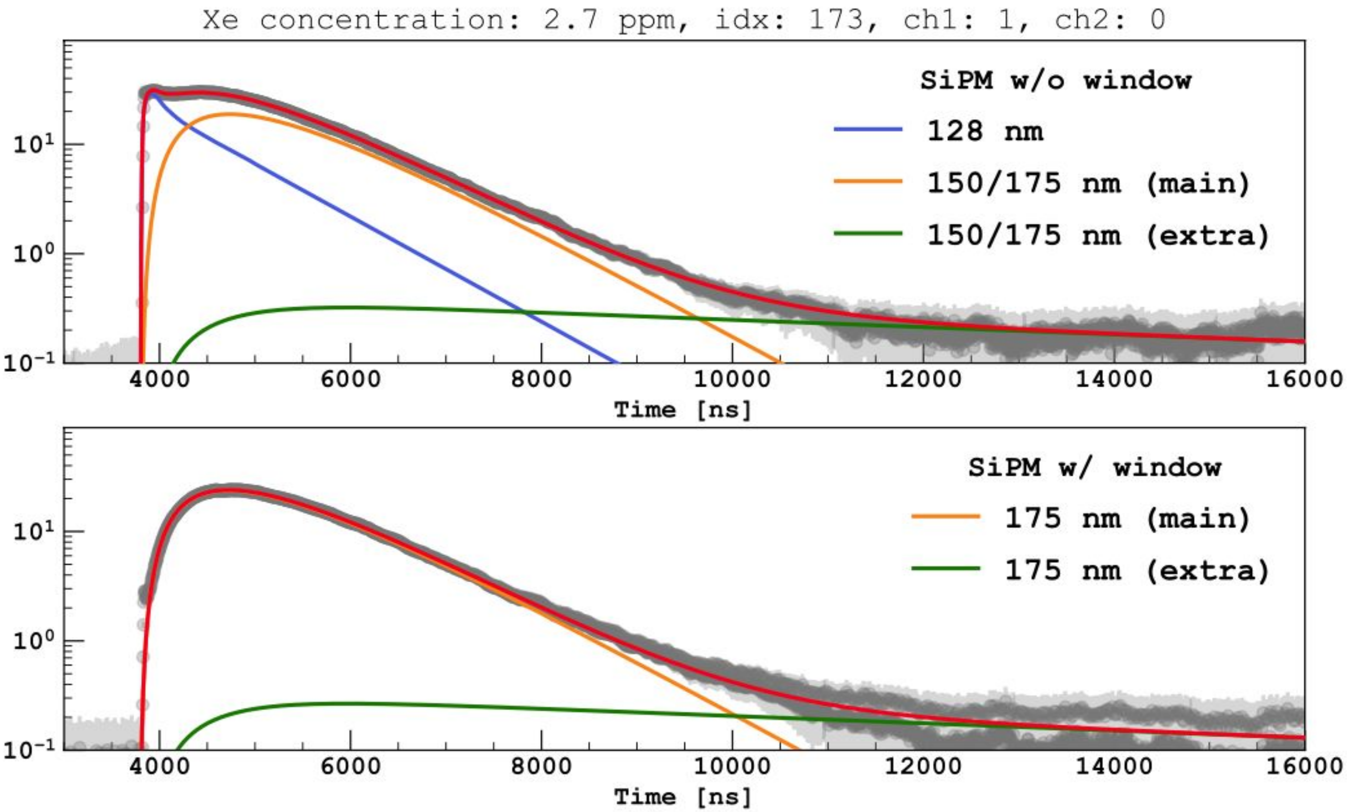
Xe concentration: 1.5 ppm, idx: 139, ch1: 1, ch2: 0
SiPM w/o window
128 nm
150/175 nm (main)
150/175 nm (extra)
10^1
10^0
10^{-1}
4000
6000
8000
10000
12000
14000
16000
Time [ns]
SiPM w/ window
175 nm (main)
175 nm (extra)
10^1
10^0
10^{-1}
4000
6000
8000
10000
12000
14000
16000
Time [ns]

2.0 ppm



Xe concentration: 2.0 ppm, idx: 164, ch1: 1, ch2: 0
SiPM w/o window
128 nm
150/175 nm (main)
150/175 nm (extra)
10¹
10⁰
10⁻¹
4000
6000
8000
10000
12000
14000
16000
Time [ns]
SiPM w/ window
175 nm (main)
175 nm (extra)
Time [ns]

2.7 ppm



Xe concentration: 2.7 ppm, idx: 173, ch1: 1, ch2: 0
SiPM w/o window
128 nm
150/175 nm (main)
150/175 nm (extra)
10¹
10⁰
10⁻¹
4000
6000
8000
10000
12000
14000
16000
Time [ns]
SiPM w/ window
175 nm (main)
175 nm (extra)
10¹
10⁰
10⁻¹
4000
6000
8000
10000
12000
14000
16000
Time [ns]