EUV scintillation in pure and xenon-doped liquid argon

PHYSICAL REVIEW D 111, 102001 (2025)

Timothée Hessel

Xenon-doped liquid argon

For particle detection

Xe

- Boiling temperature: 165 K
- Work function: w_i = 15.6 eV
- **Higher atomic mass (131 u) ⇢ higher cross-section with WIMPs.**
- **Very expensive, limited production.**
- **Spin-dependent sensitivity.**

Ar

- Boiling temperature: 87 K
- Work function: w_i = 23.6 eV
- **^{39}Ar contamination** ⇢ solved by using **underground argon.**
- **Abundant ⇢ higher scalability.**
- **Particle identification power.**

Xenon-doped liquid argon

For particle detection

Xe

- Boiling temperature: 165 K
- Work function: w_i = 15.6 eV
- **Higher atomic mass (131 u) ⇢ higher cross-section with WIMPs.**
- **Very expensive, limited production.**
- **Spin-dependent sensitivity.**

Ar

- Boiling temperature: 87 K
- Work function: w_i = 23.6 eV
- **^{39}Ar contamination** ⇢ solved by using **underground argon.**
- **Abundant ⇢ higher scalability.**
- **Particle identification power.**

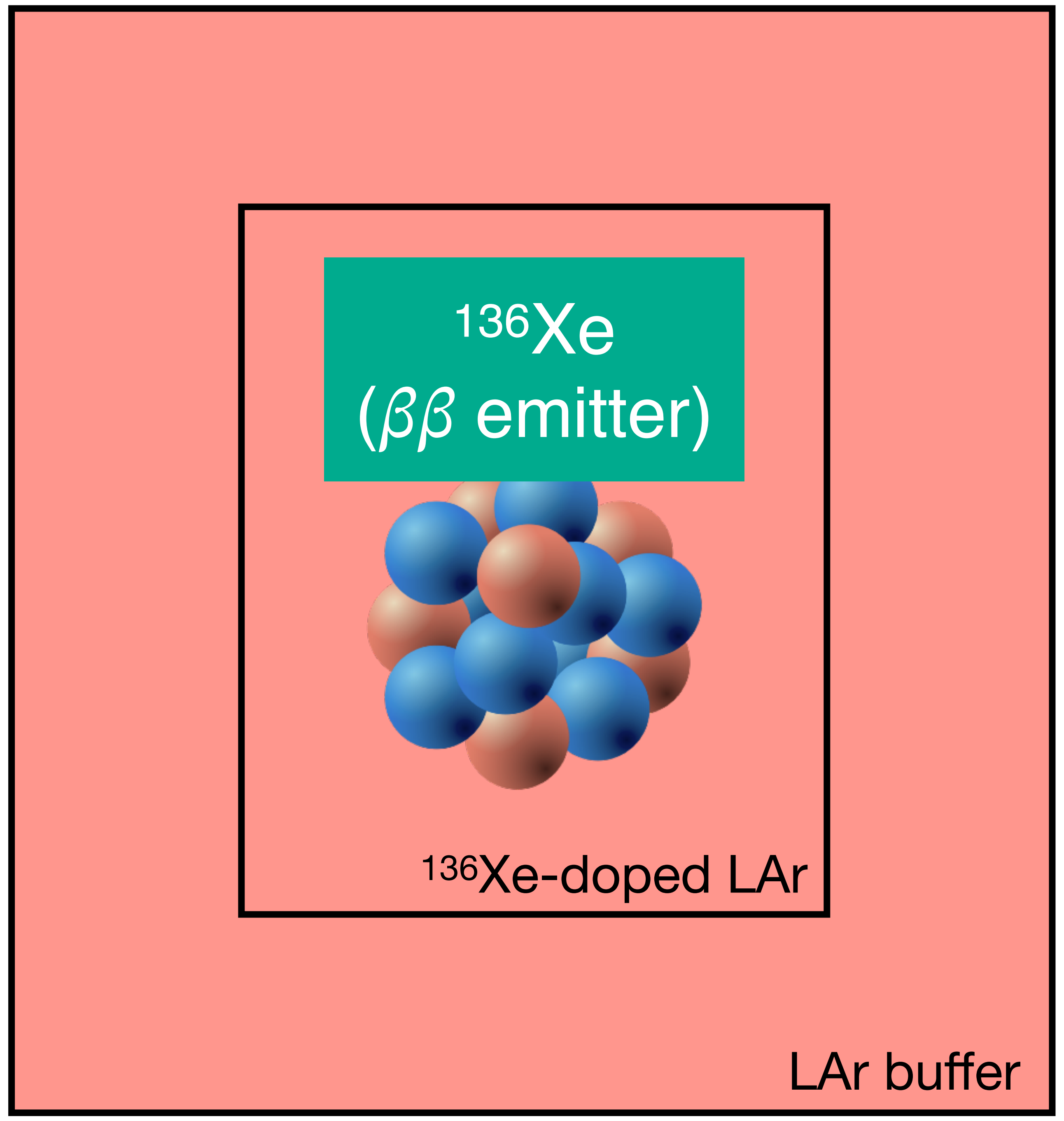
Xe+Ar

- **Higher light yield** for light dark matter search.
- **Better transparency** to improve photo-detection for large-scale detectors (DUNE).
- **Faster scintillation** for better timing resolution.

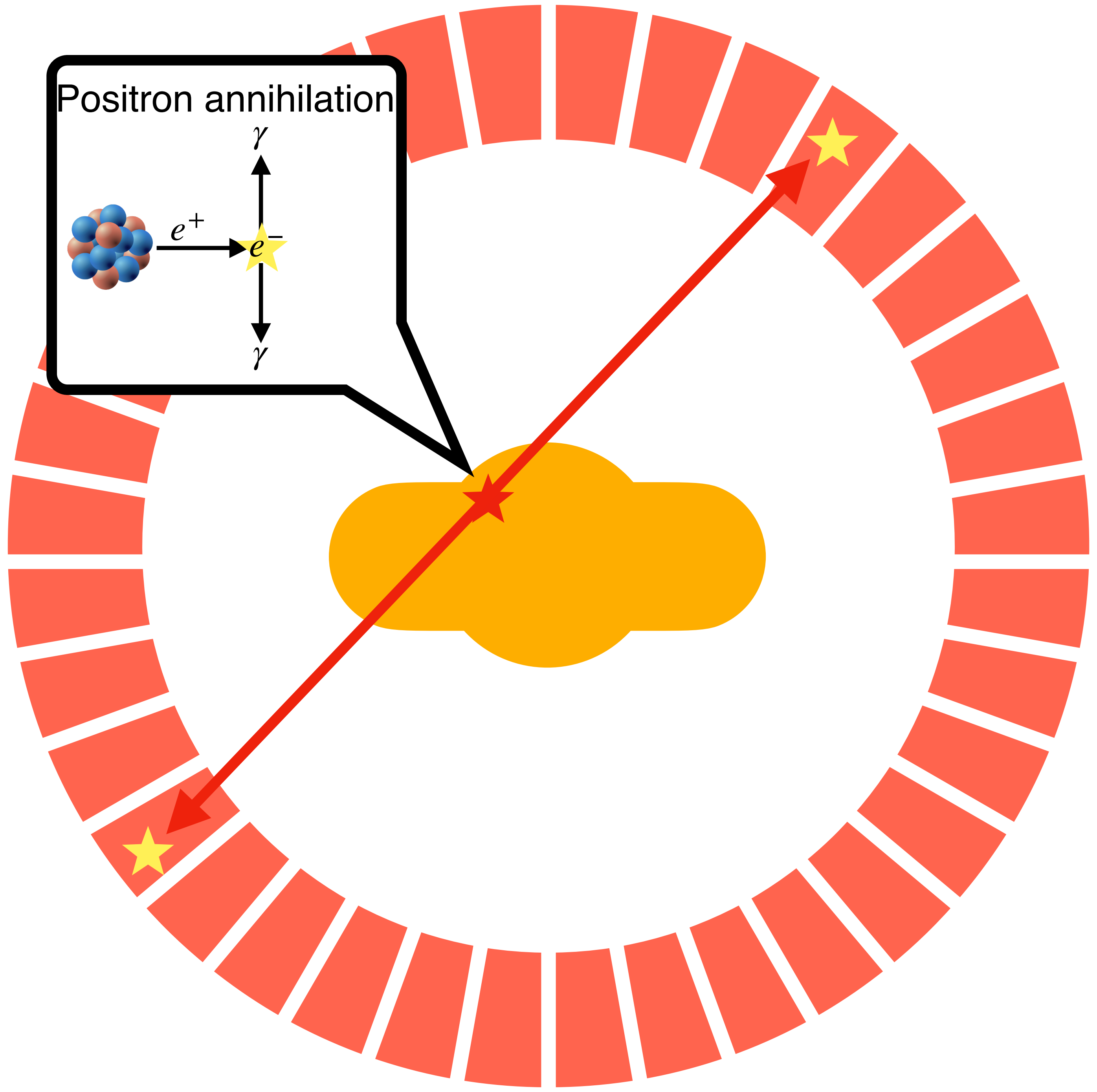
Example of applications of Xe-doped LAr

Dark matter, neutrino physics, medical application

- **Neutrinoless double beta-decay** search with 136Xe-doped LAr.
- Smaller quantity of xenon required.
- Possibility to use a pure LAr outer veto.



- **Positron emission tomography** with Xe-doped LAr.
- Faster scintillation improves position reconstruction.
- With better resolution, the radioactive chemical dose can be reduced.



The X-ArT project

Xenon-Argon Technology

The X-ArT program

- Determine the **phase diagram** of Xe+Ar.
- Developing the **cryogenic** system enabling high Xe-doping.
- Characterising the **Xe-Ar scintillation and ionization** up to maximum solubility.

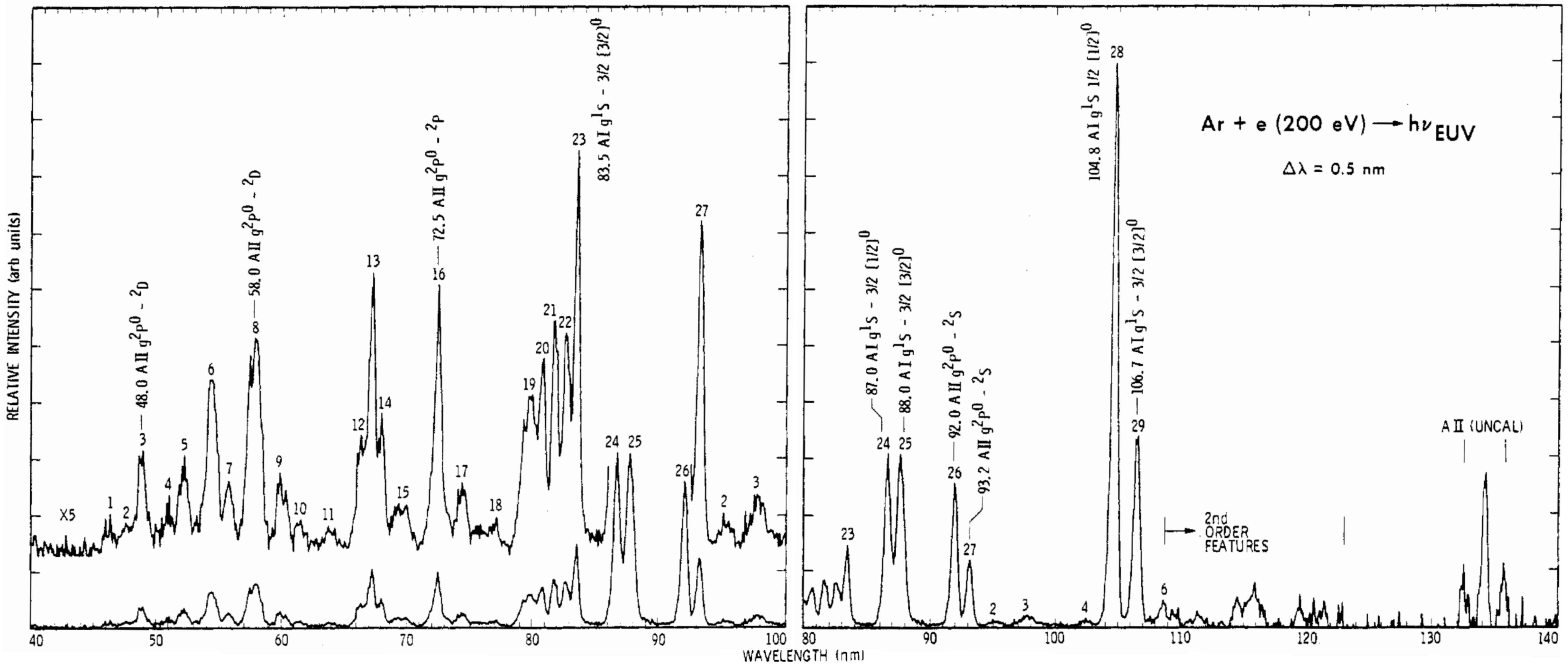
Particle physics

Thermodynamics

Scintillation study of pure and Xe-doped LAr

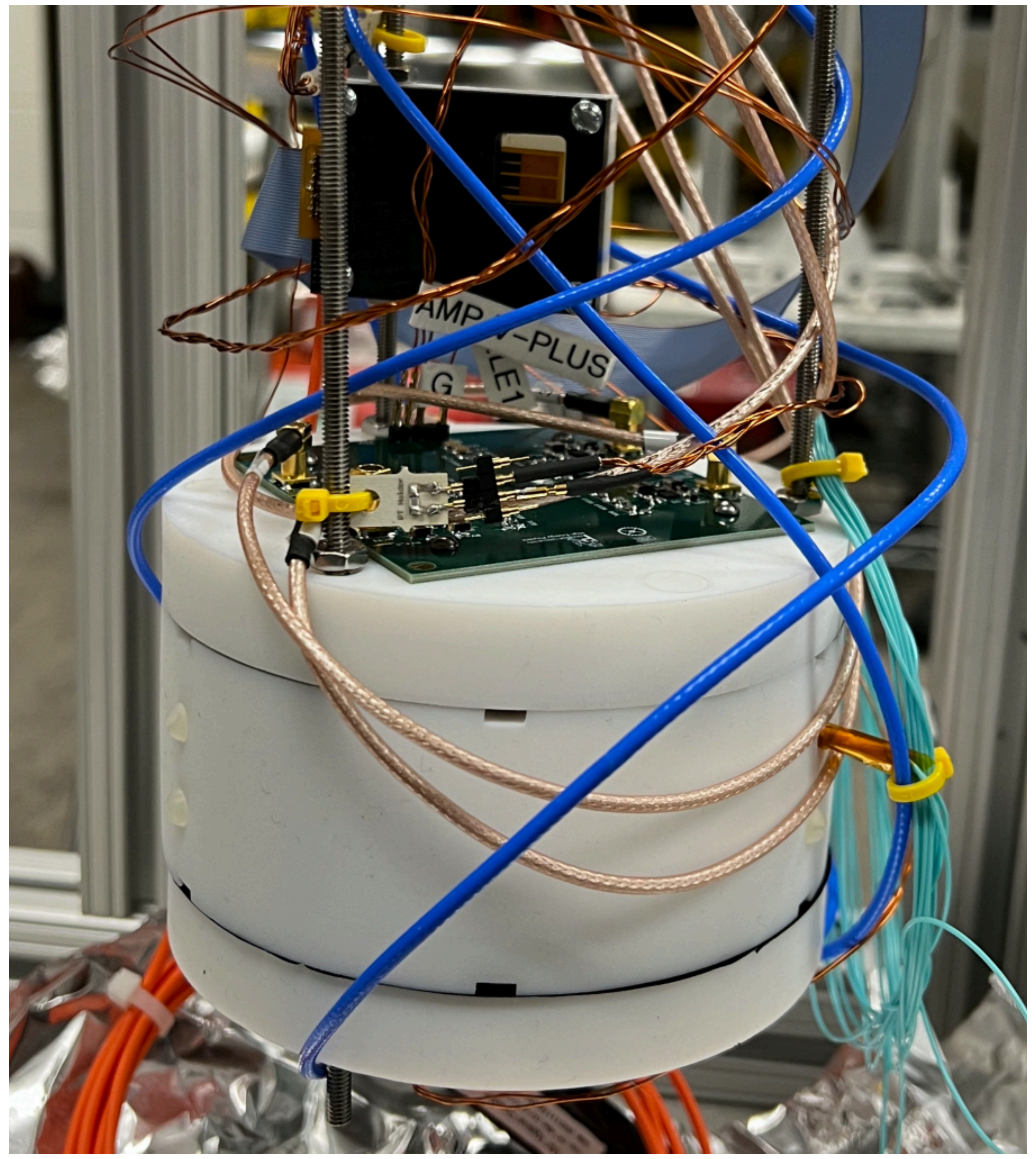
Impact of extreme ultraviolet radiation

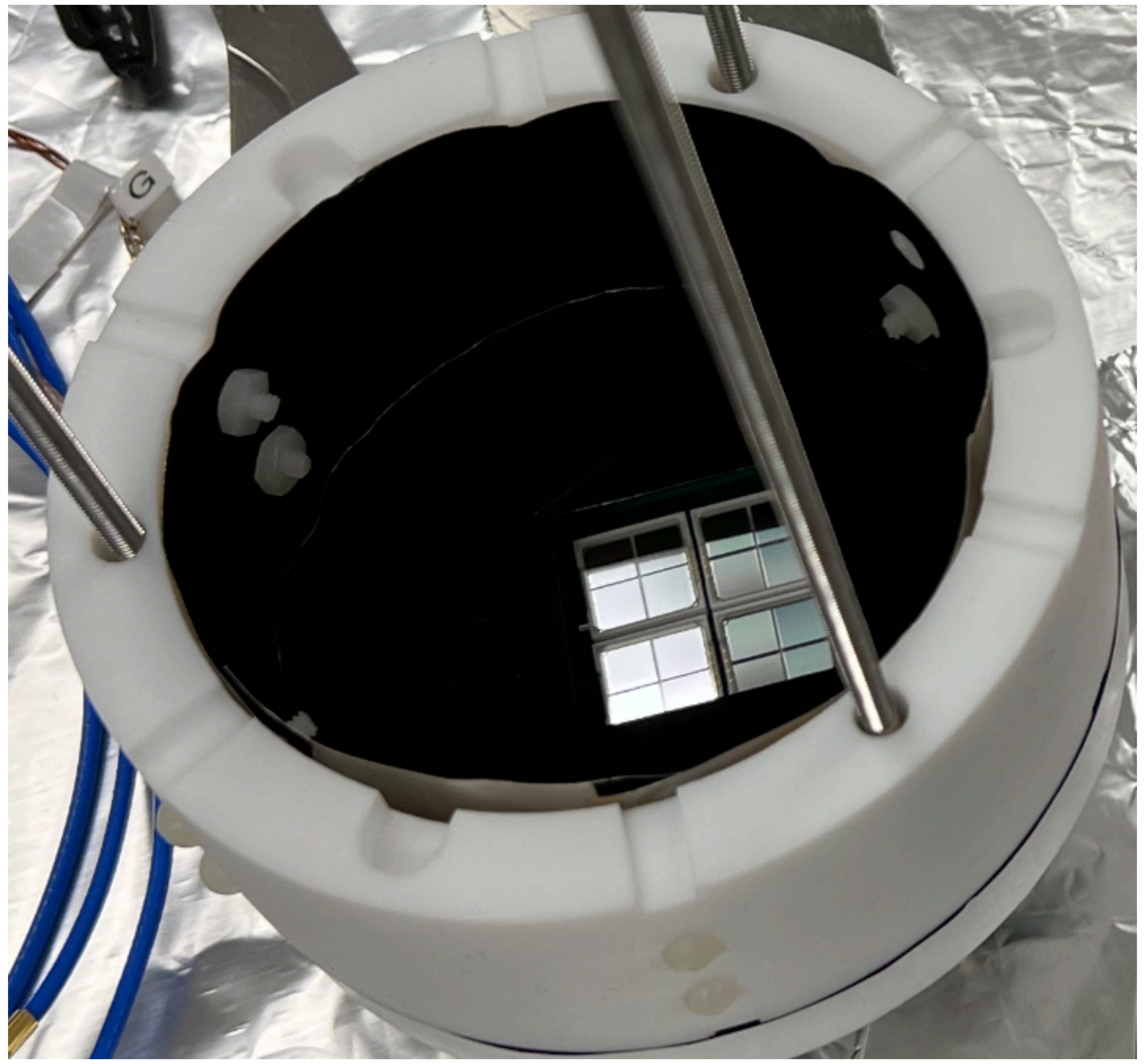
- We show evidences of **extreme ultraviolet (EUV) emission in LAr scintillation**.
- These emissions are attributed to **atomic state excitations** (*J. M. Ajello et al 1990 J. Phys. B: At. Mol. Opt. Phys.* ***23*** *4355*).
- The impact is a **long-lived (O(100 μs)) component** in the scintillation pulse.



Single-phase chamber

Setup in Princeton

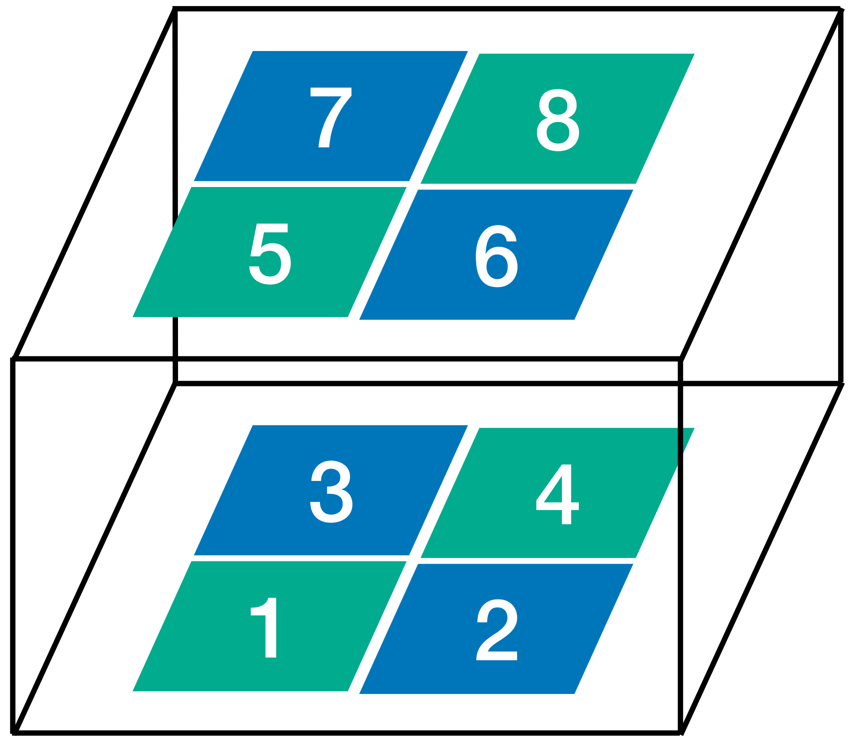




- **Single-phase LAr chamber** (4.5 cm height, 9.5 cm diameter)
- No reflectors, no wavelength shifter.
- **Black absorbing foils**.
- **8 SiPMs channels**.
- Allows for **xenon doping**.

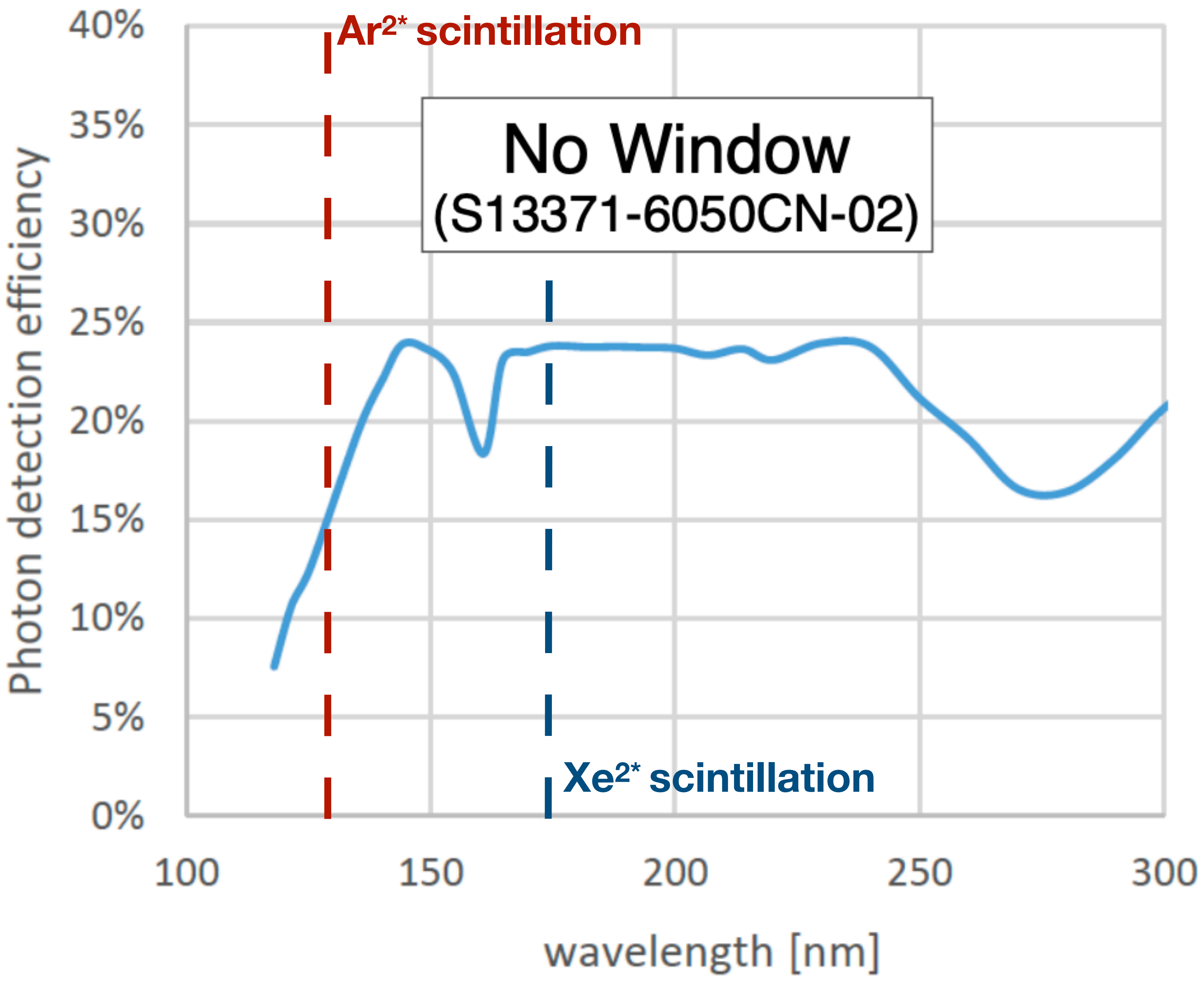
Windowed and windowless SiPMs

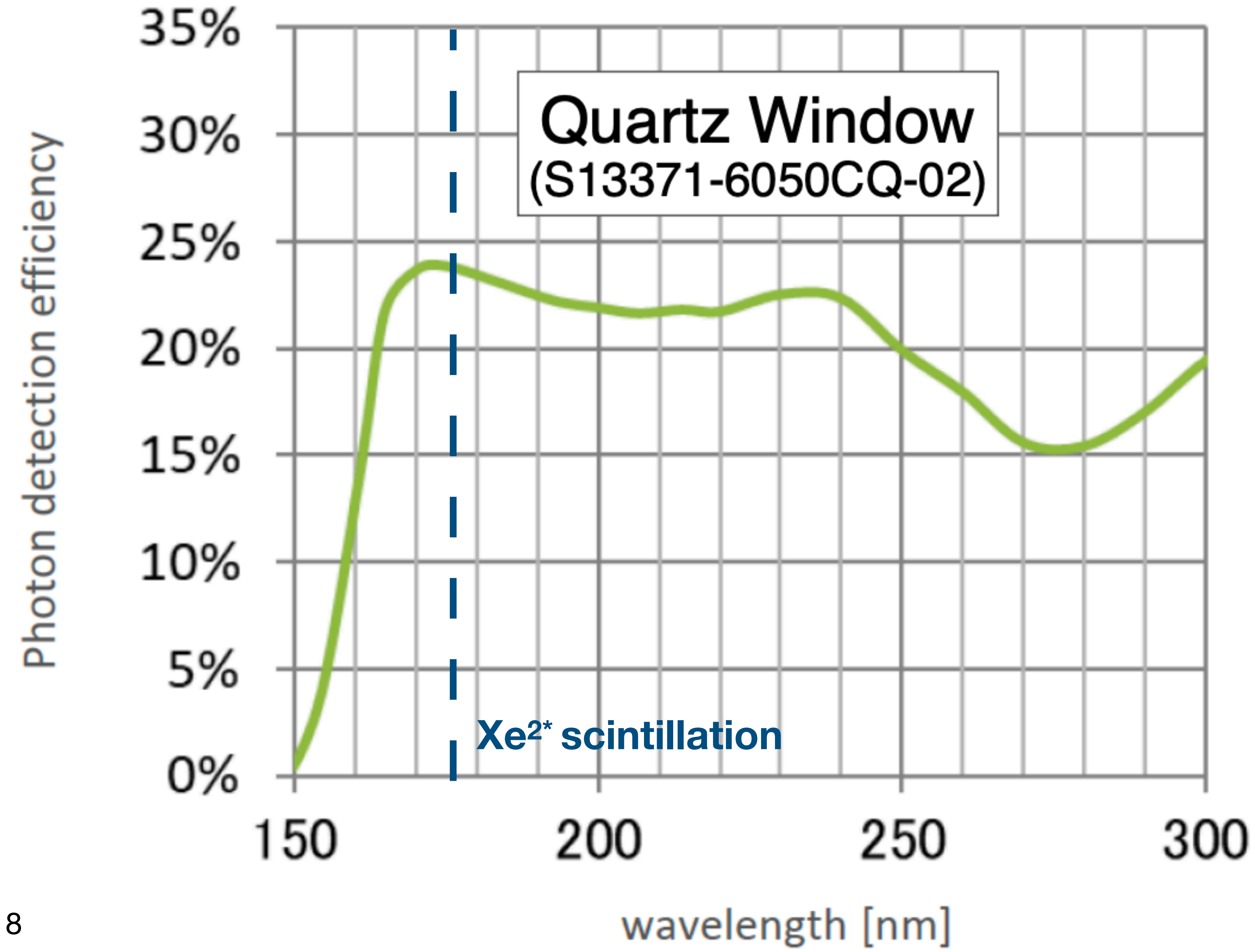
For discrimination between Xe and Ar scintillations



4 channels without window

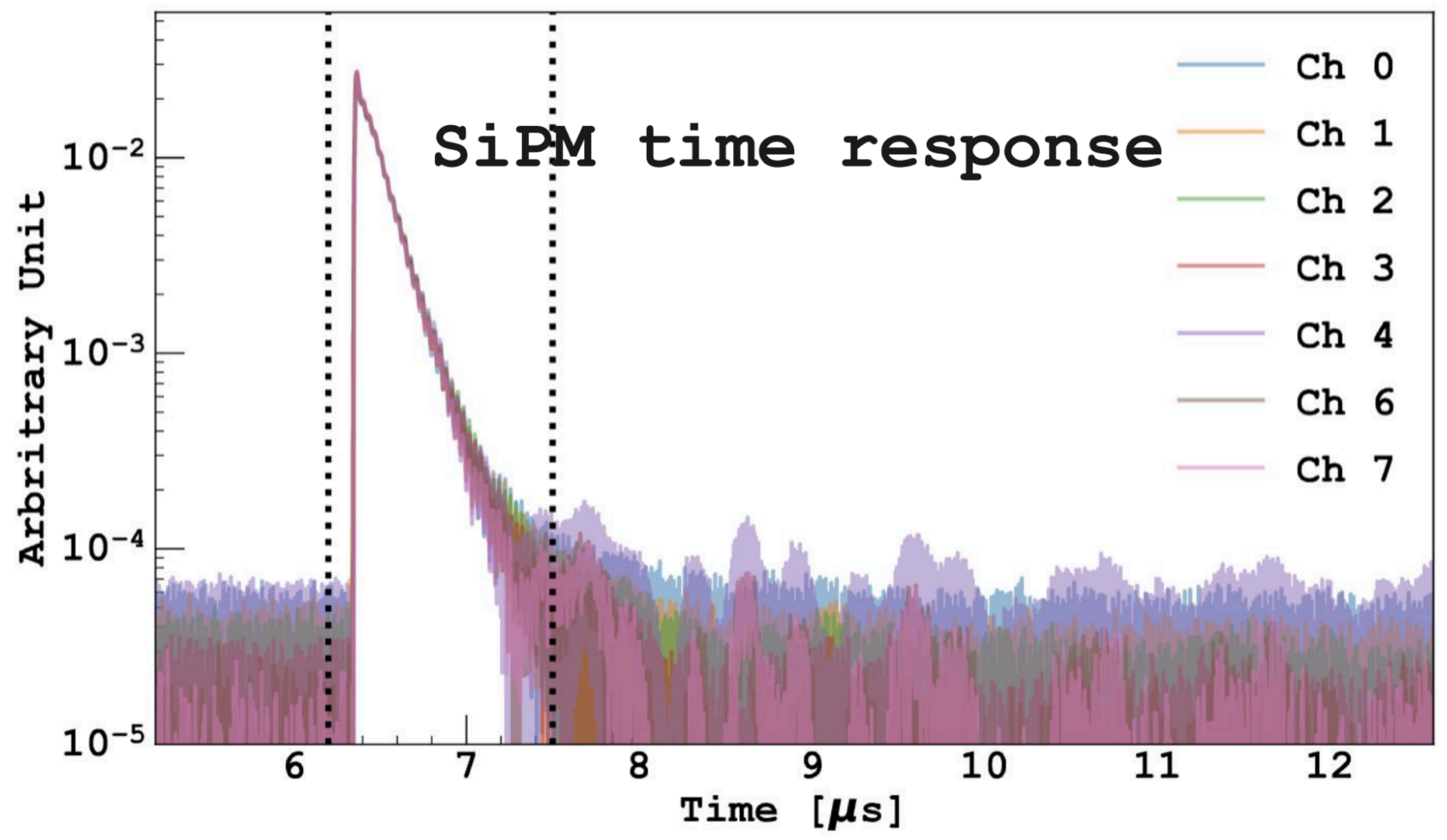
4 channels with quartz window

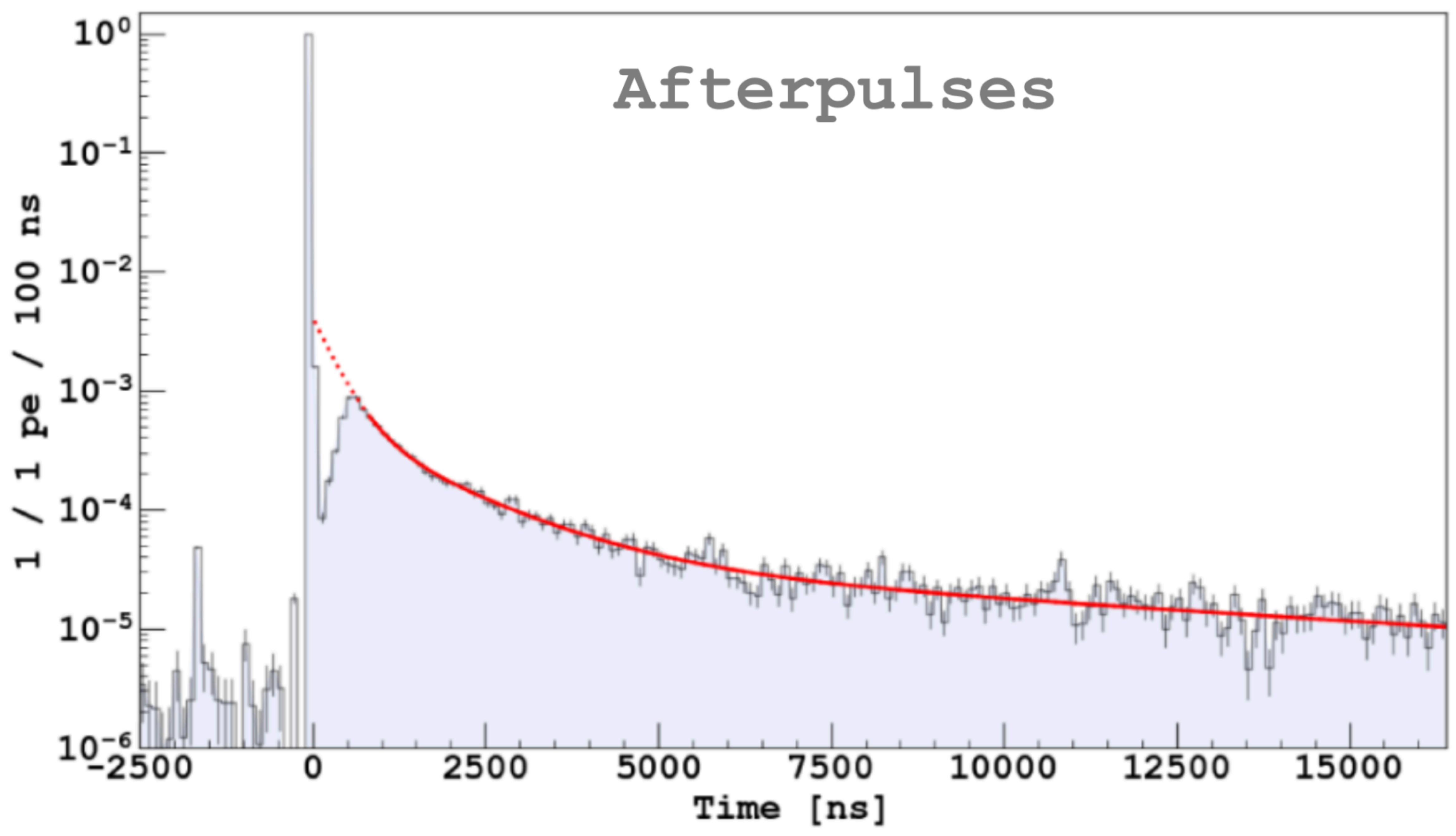




Laser calibration

Single PE resolution and afterpulse characterisation



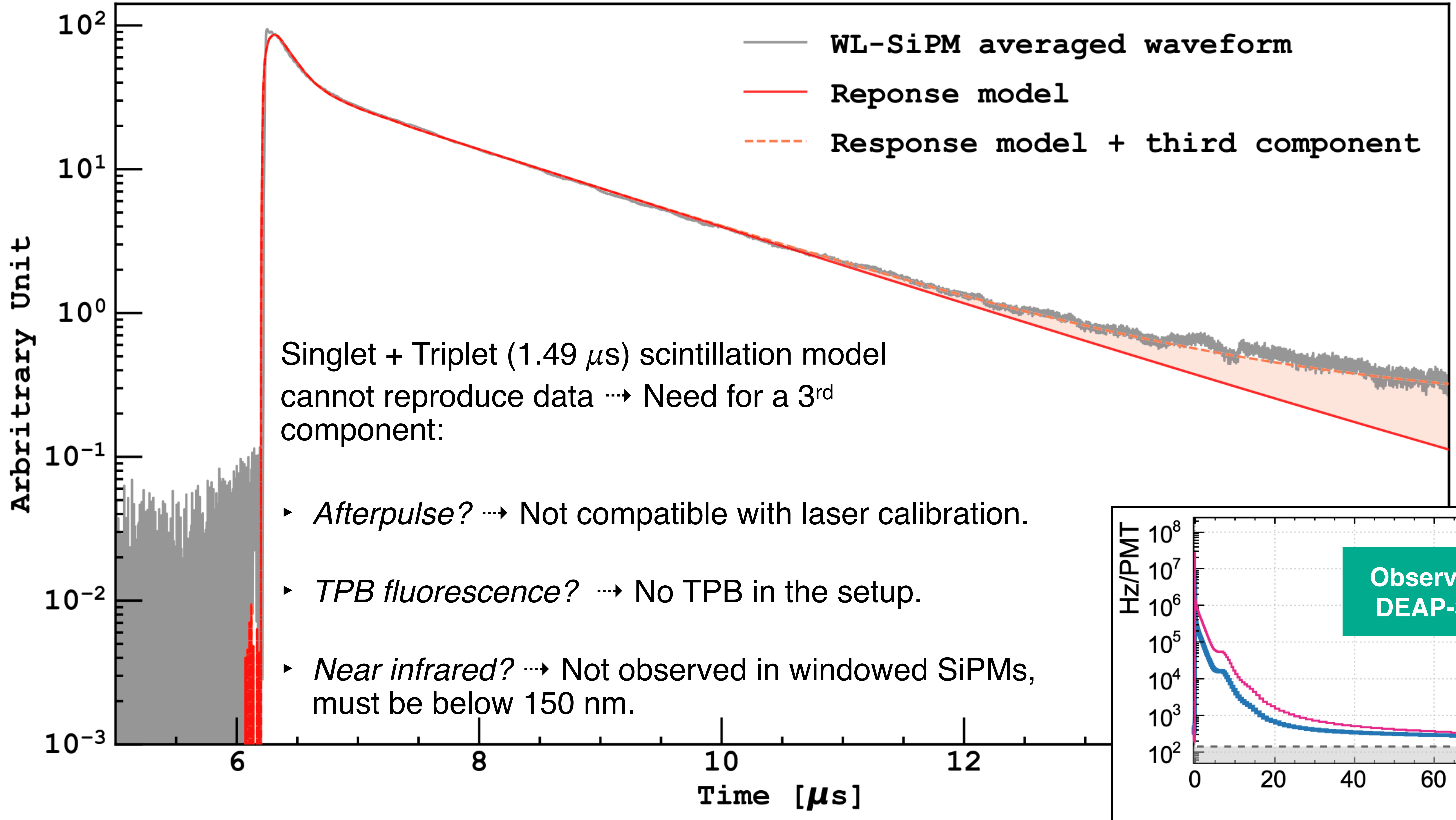


Afterpulse fitted with 3 exponential components:

Characteristic time	80 ± 13 ns	350 ± 30 ns	3010 ± 433 ns
Emission probability	26.8 ± 6.2 %	5.3 ± 0.4 %	1.4 ± 0.4 %

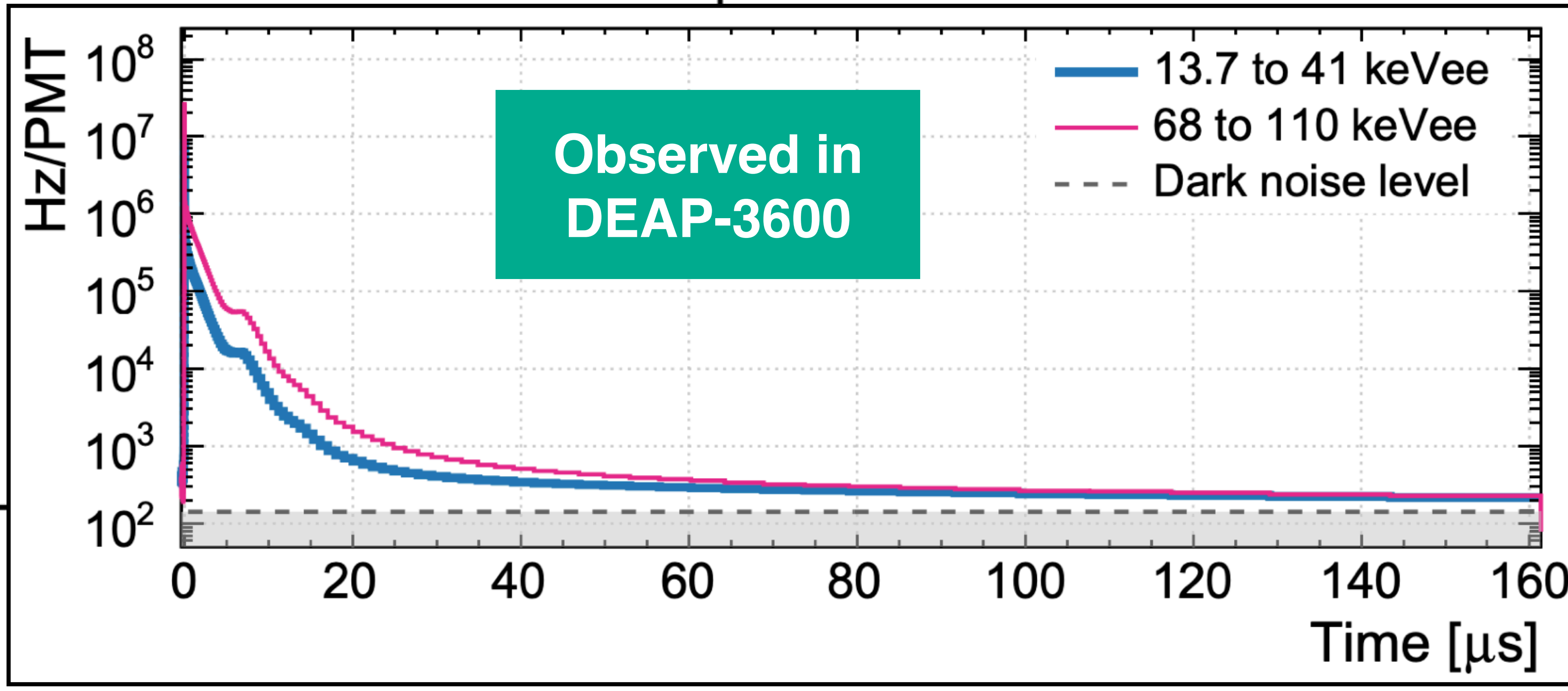
Observation of O(100 us) component

In pure liquid argon, in window-less channels



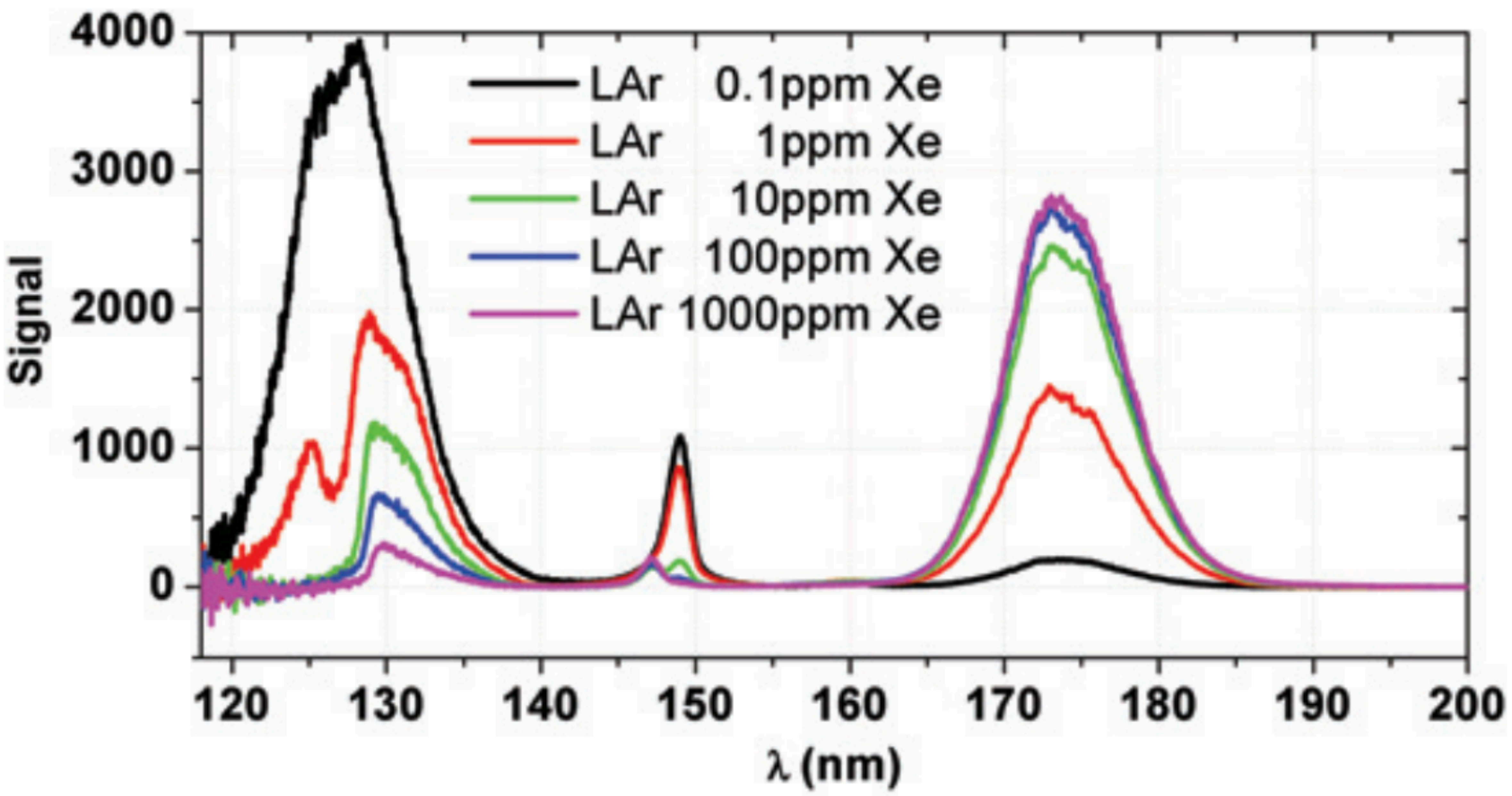
Singlet + Triplet (1.49 μs) scintillation model cannot reproduce data ⇢ Need for a 3rd component:

- *Afterpulse?* ⇢ Not compatible with laser calibration.
- *TPB fluorescence?* ⇢ No TPB in the setup.
- *Near infrared?* ⇢ Not observed in windowed SiPMs, must be below 150 nm.

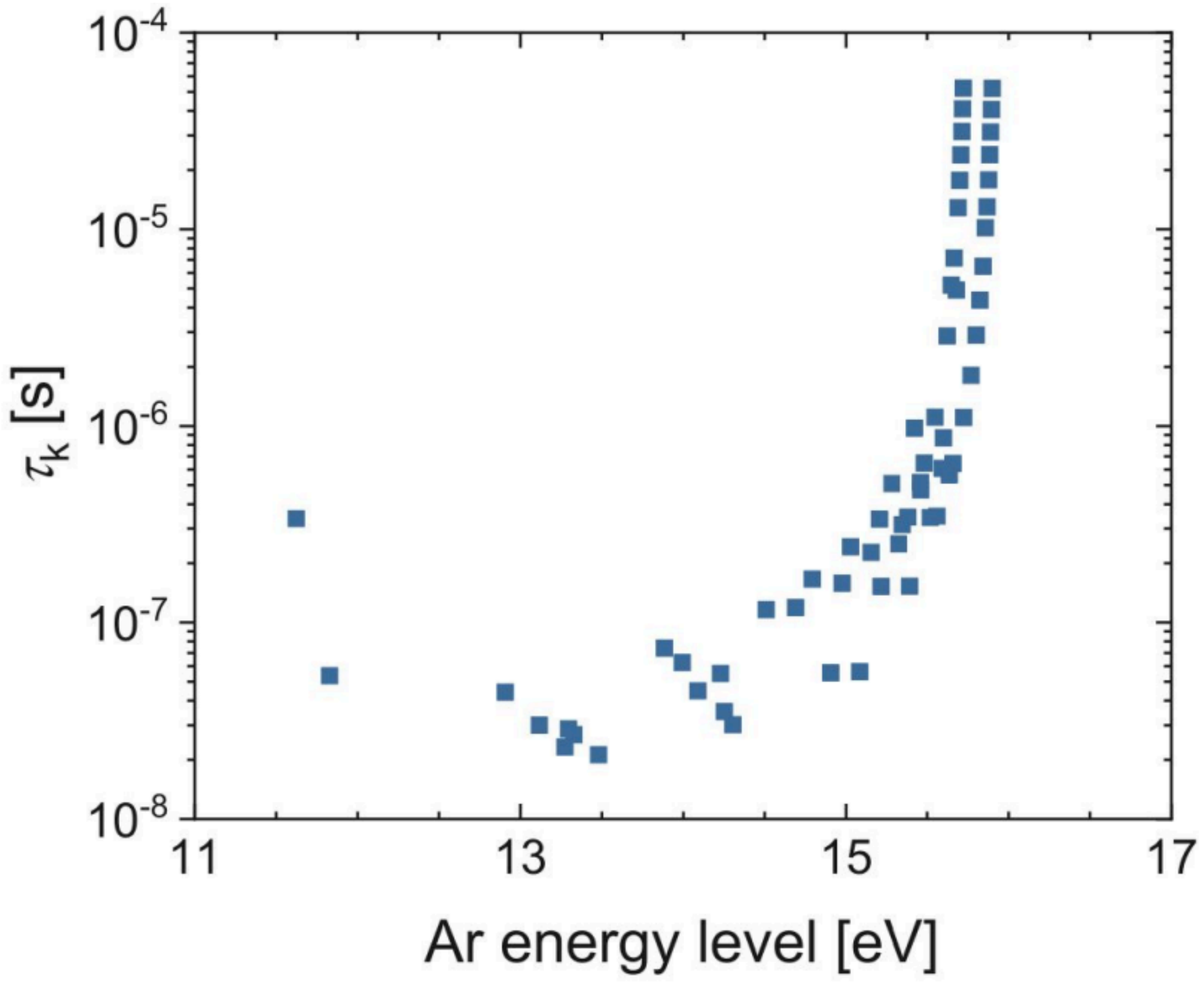


EUV emission in LAr

Spectrum and characteristic times from atomic states



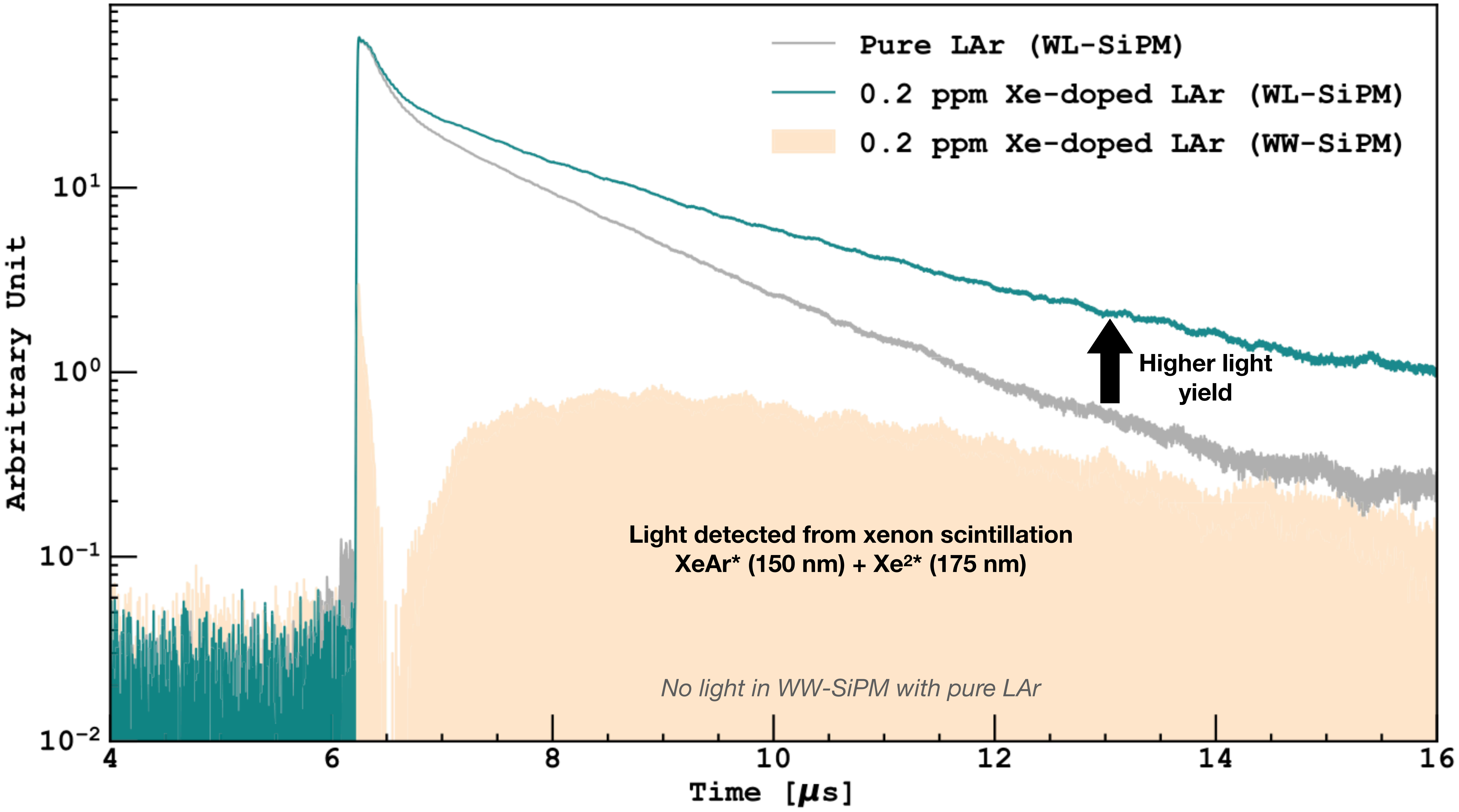
A. Neumeier et al 2015 EPL 109 12001



10.1063/5.0071887

Xe-doped LAr

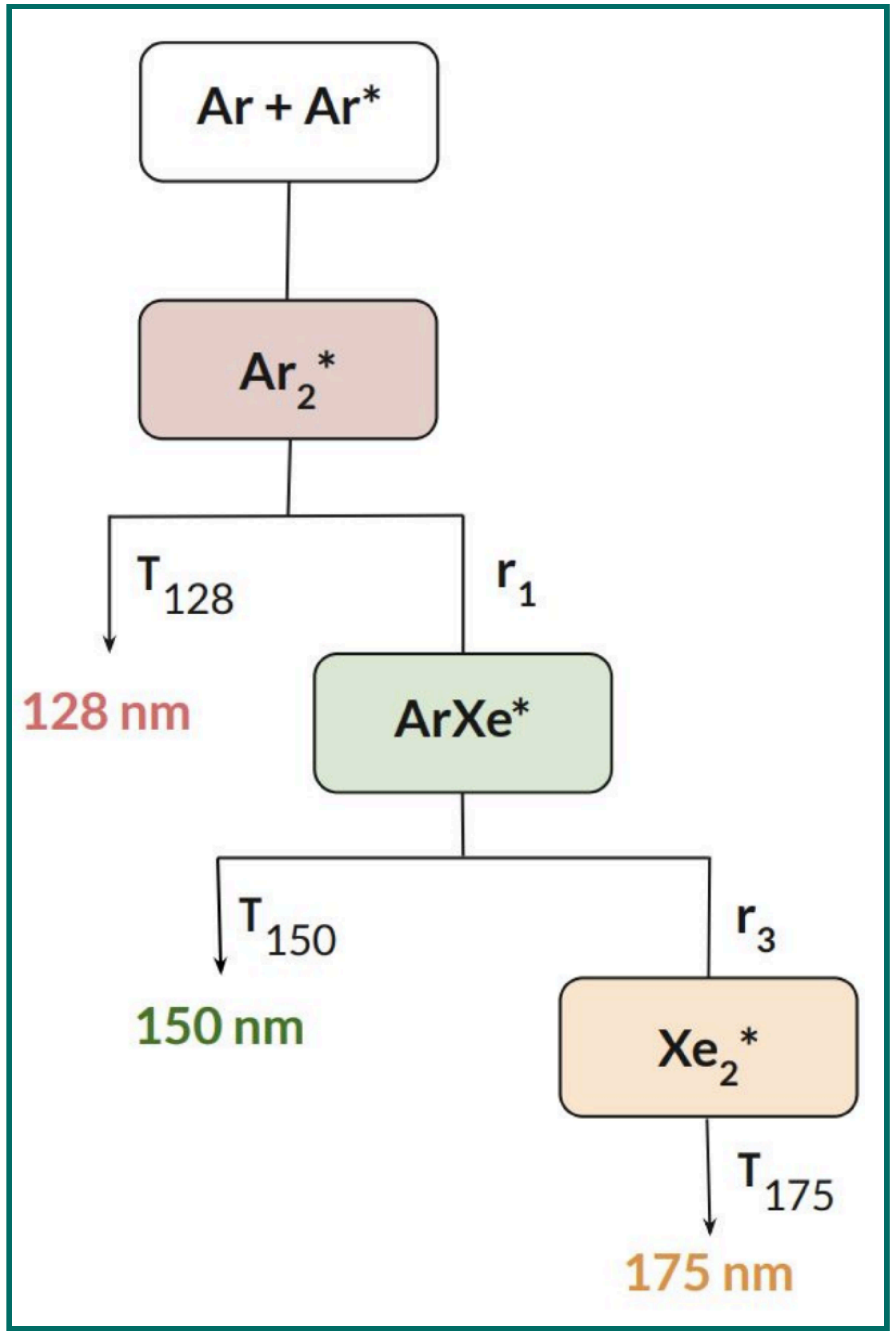
Increasing light yield and wavelength shifting



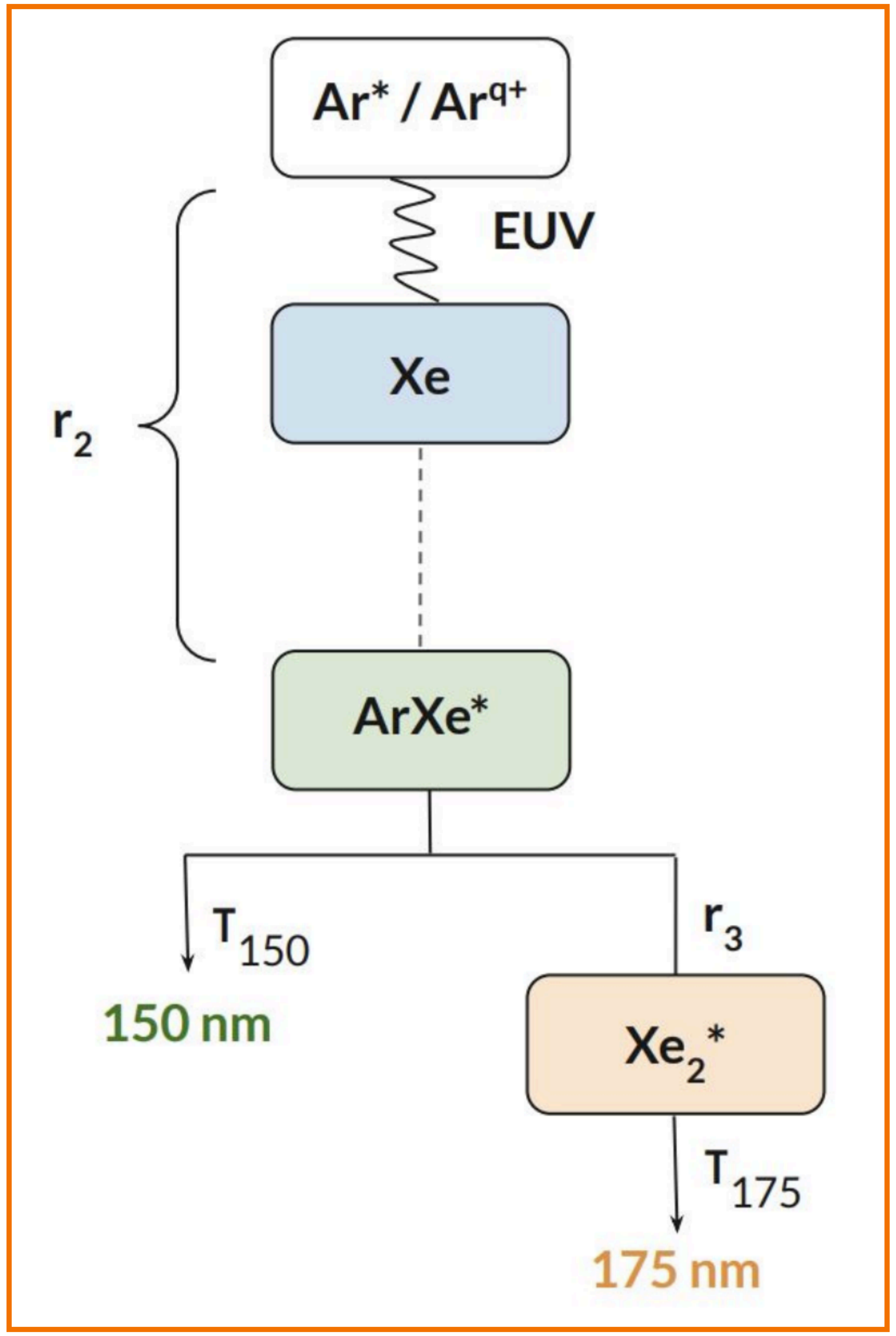
Scintillation model for Xe-doped LAr

Collisional and radiative processes

Collisional branch



Radiative branch



Scintillation model for Xe-doped LAr

Analytical model

	Windowless channels	Windowed channels
Collisional branch	128 nm: $A\left(f_p \frac{e^{-\frac{t}{\tau_s}}}{\tau_s} + (1-f_p)k_1 e^{-k_1 t}\right)$ + 150-175 nm: $B_1 \frac{k_1 k_3}{k_1 - k_3}\left(e^{-k_3 t}(1 - e^{-(k_1-k_3)t}\right)$	175 nm: $B_2 \frac{k_1 k_3}{k_1 - k_3}\left(e^{-k_3 t}(1 - e^{-(k_1-k_3)t}\right)$
+	+	+
Radiative branch	150-175 nm: $C_1 \frac{r_2 k_3}{r_2 - k_3}\left(e^{-k_3 t}(1 - e^{-(r_2-k_3)t}\right)$	175 nm: $C_2 \frac{r_2 k_3}{r_2 - k_3}\left(e^{-k_3 t}(1 - e^{-(r_2-k_3)t}\right)$

- $Ar^{2*} \to ArXe^*$ or $\to 2Ar + 128$ nm:

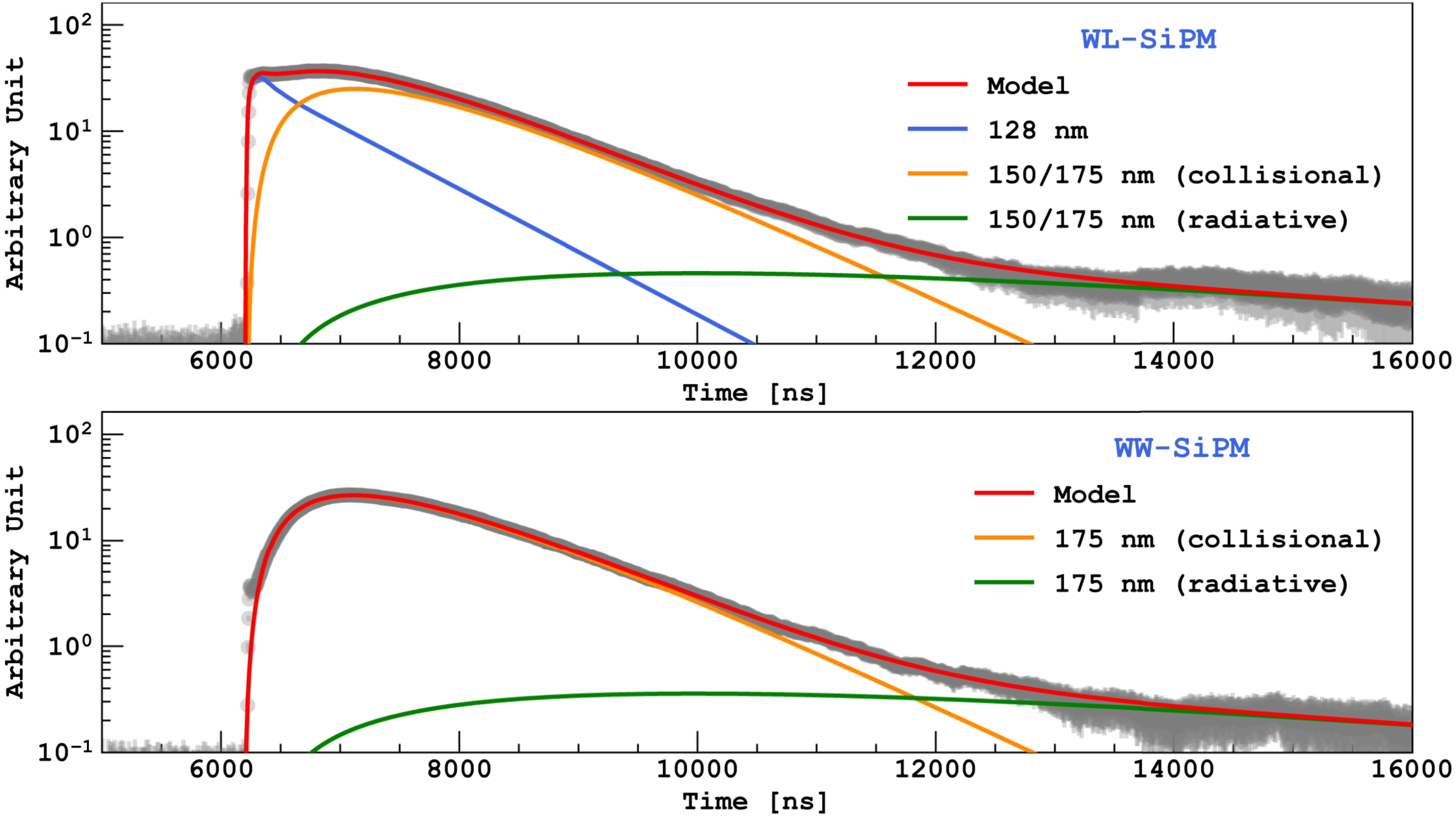
$$k_1 = r_1 + \frac{1}{\tau_{128}}$$

- $ArXe^* \to Xe^{2*}$ or $\to Ar + Xe + 150$ nm:

$$k_3 = r_3 + \frac{1}{\tau_{150}}$$

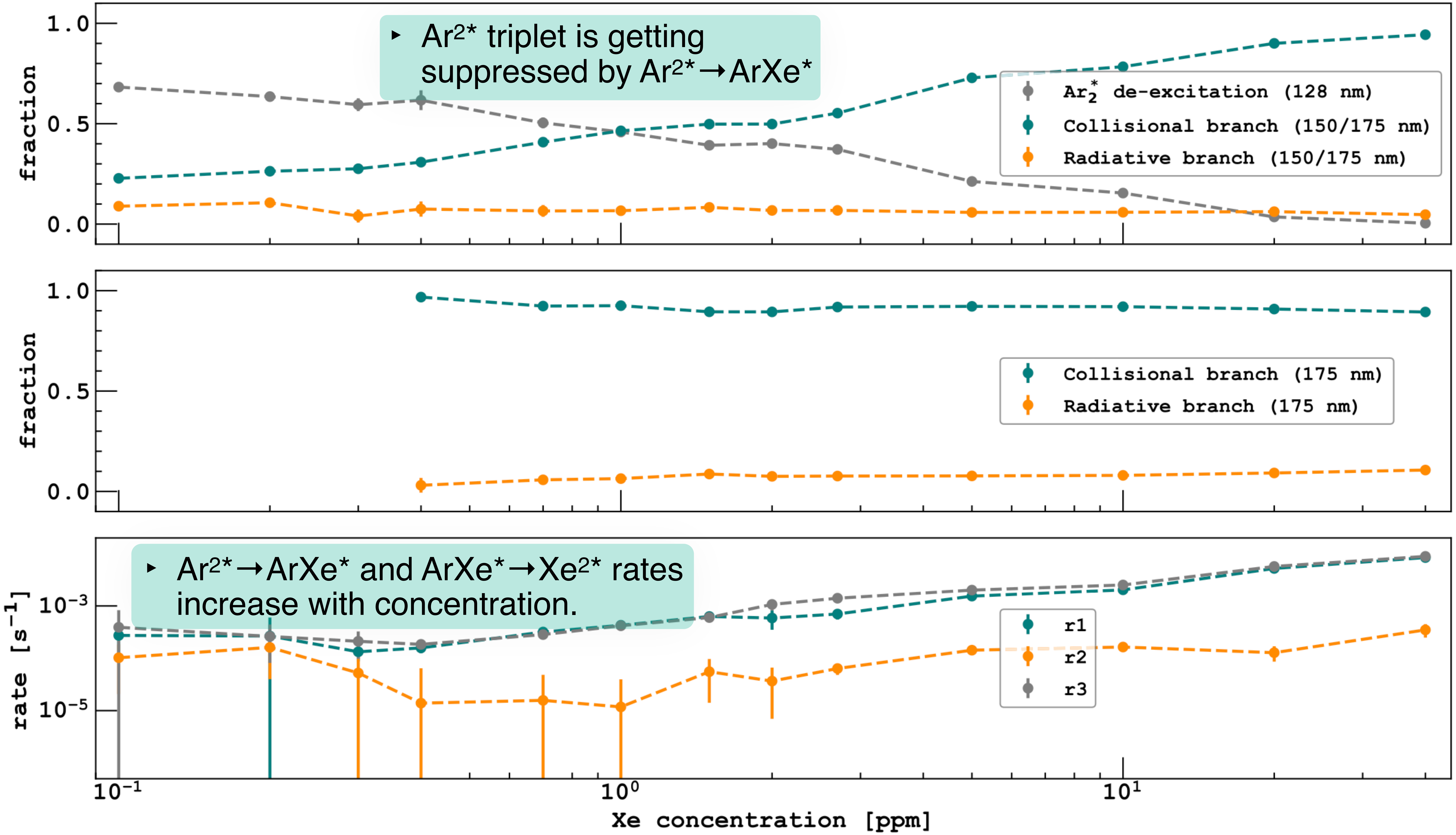
Model fit on summed waveforms

Simultaneous fit of windowed and windowless channels



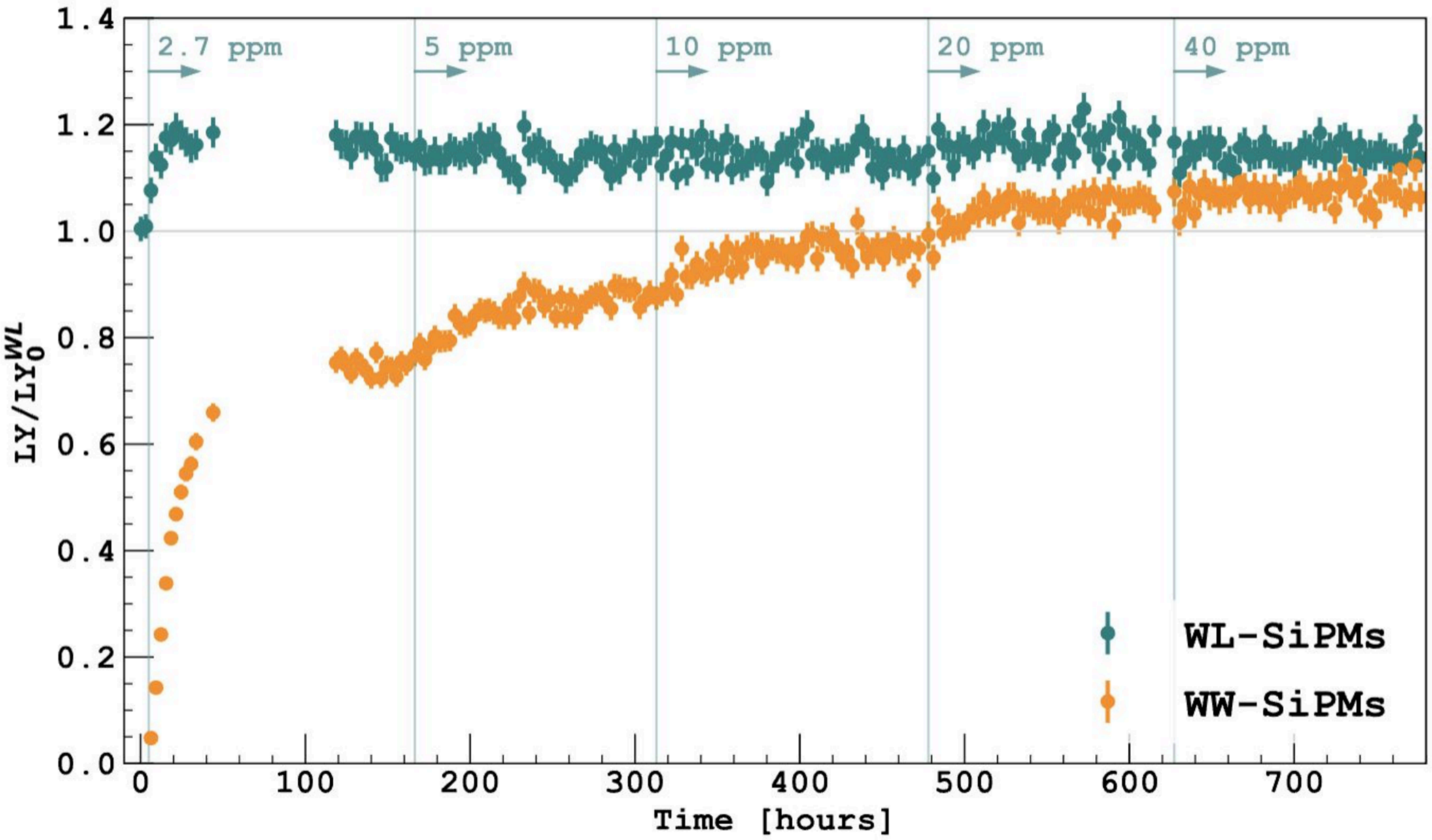
Fit of the summed waveforms

As a function of Xe concentration



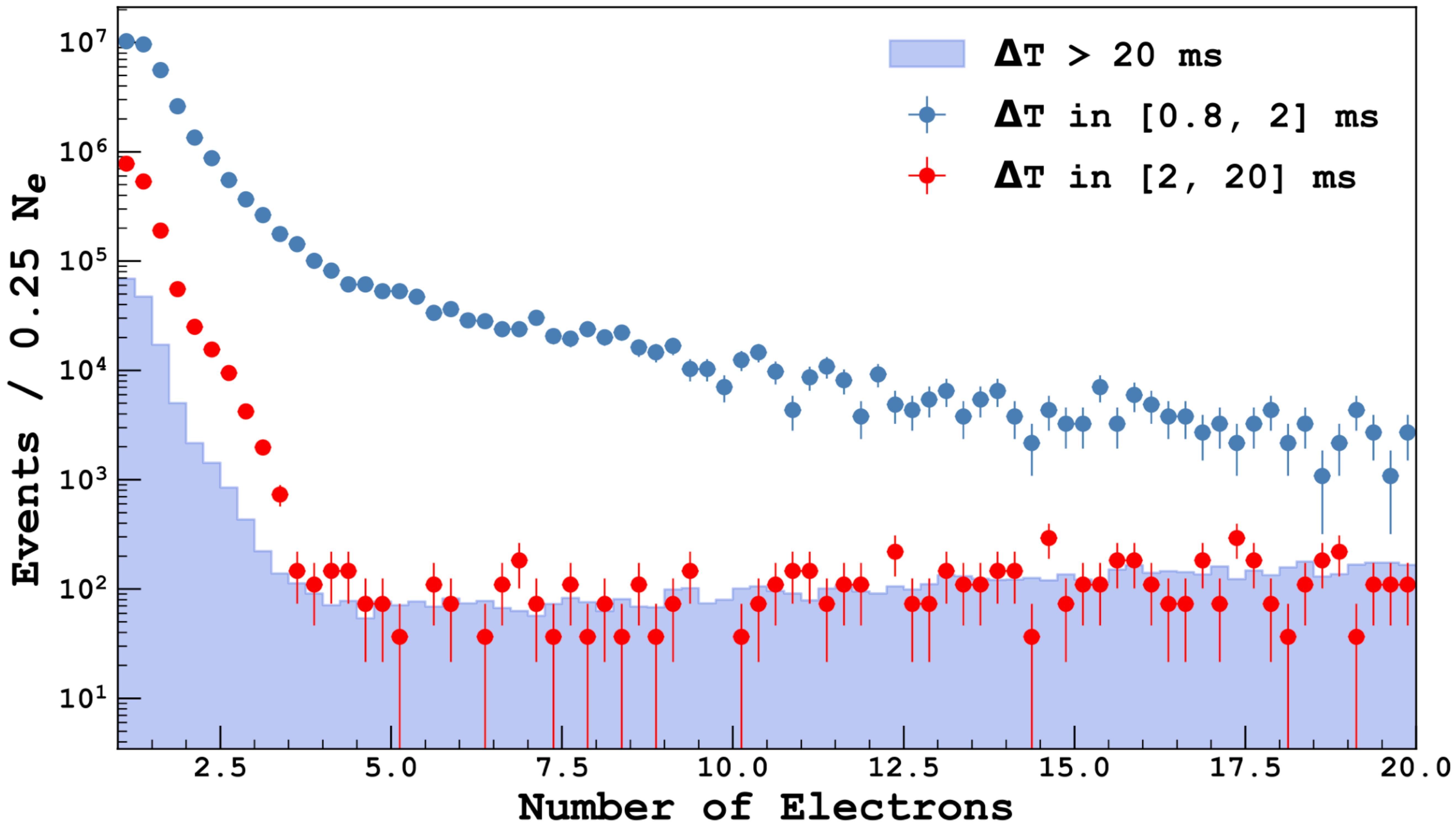
Relative light yield

Dependence on xenon-doping



A possible origin of the spurious electrons

For the light dark matter search



- Excess at number of electrons from unclear origin, limiting the **threshold for light dark matter analysis**.
- Observed to be **correlated with impurity level**.
- **EUV** (expected to go up to 25 eV) could be the source of **ionization of impurities**.
- The multiplicity can increase from **photo-ionization on the grid**.

Impurity	O_2	CH_4	Kr	CO_2	H_2O
Ionization energy	12.1 eV	12.6 eV	14.0 eV	13.8 eV	12.6 eV

Ongoing and future measurements

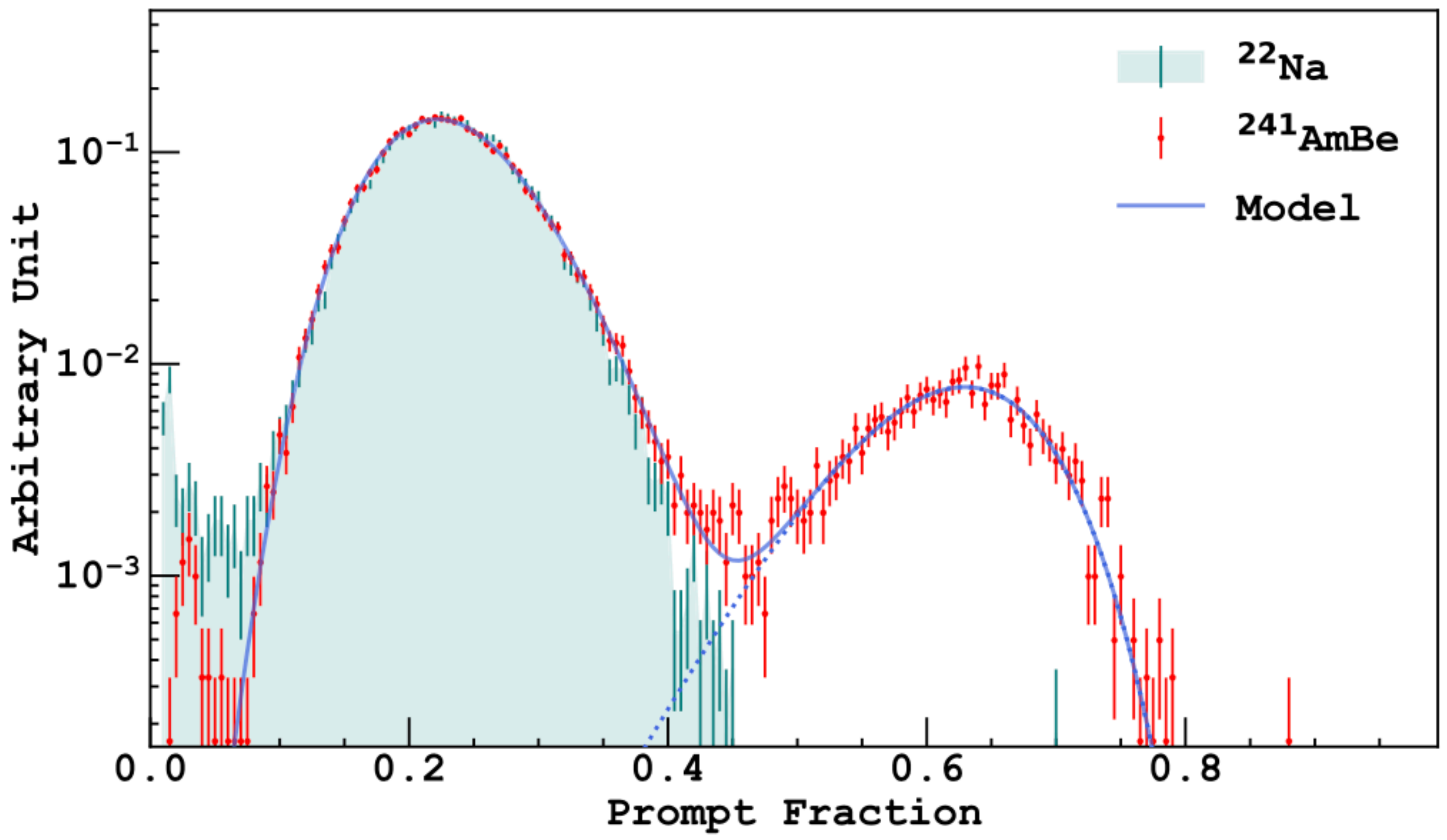
Within the X-ArT collaboration

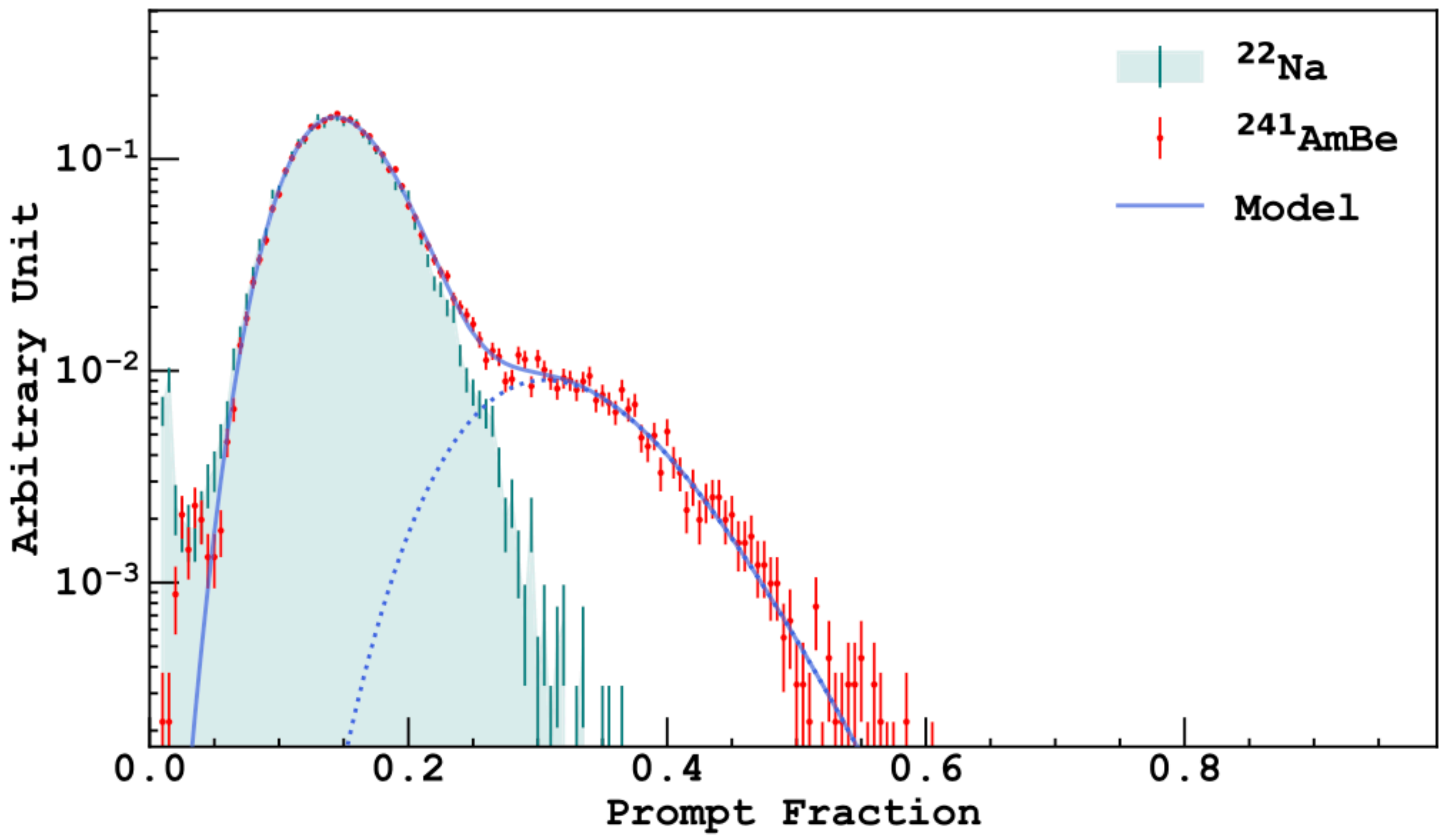
- We demonstrated the **presence of long-lived EUV emission** in LAr scintillation and proposed an **explanation for the spurious electron background** in light dark matter search.
- Data are being acquired with longer acquisition gate to **fully characterise the long-lived component** and the **impact of Xe-doping on rise time**.
- Preparation of a **publication on the phase diagram of Xe+Ar** (thermodynamics measurement and molecular simulation).
- Dual-phase setup for **scintillation+ionization characterisation** of xenon-doped LAr.

Thank you for your attention

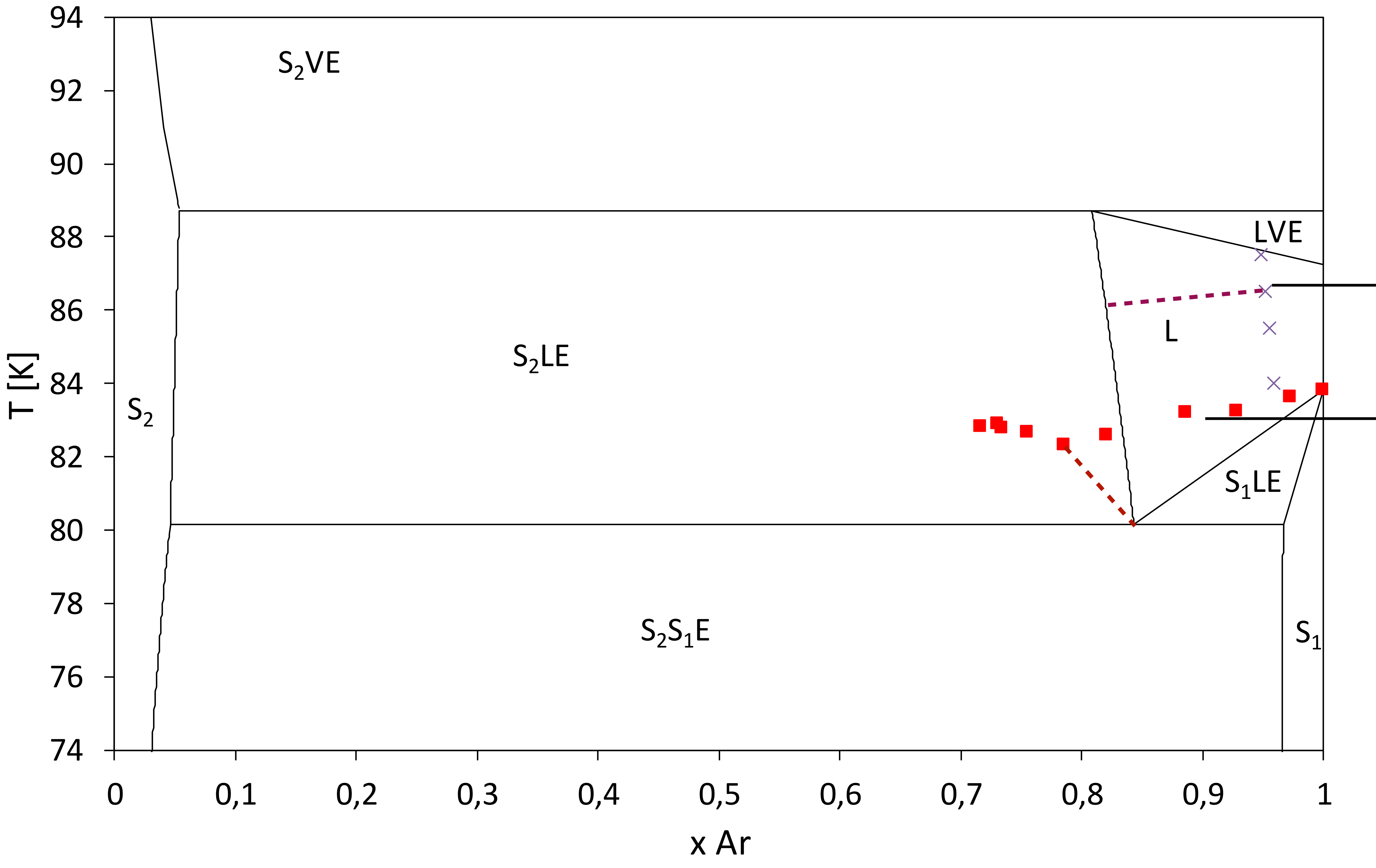
BACK-UP SLIDES

Pulse shape discrimination





Tension in measurement of xenon solubility



- Measured solubility: ~5%
- Measured solubility: ~20%

Phase diagram measurement