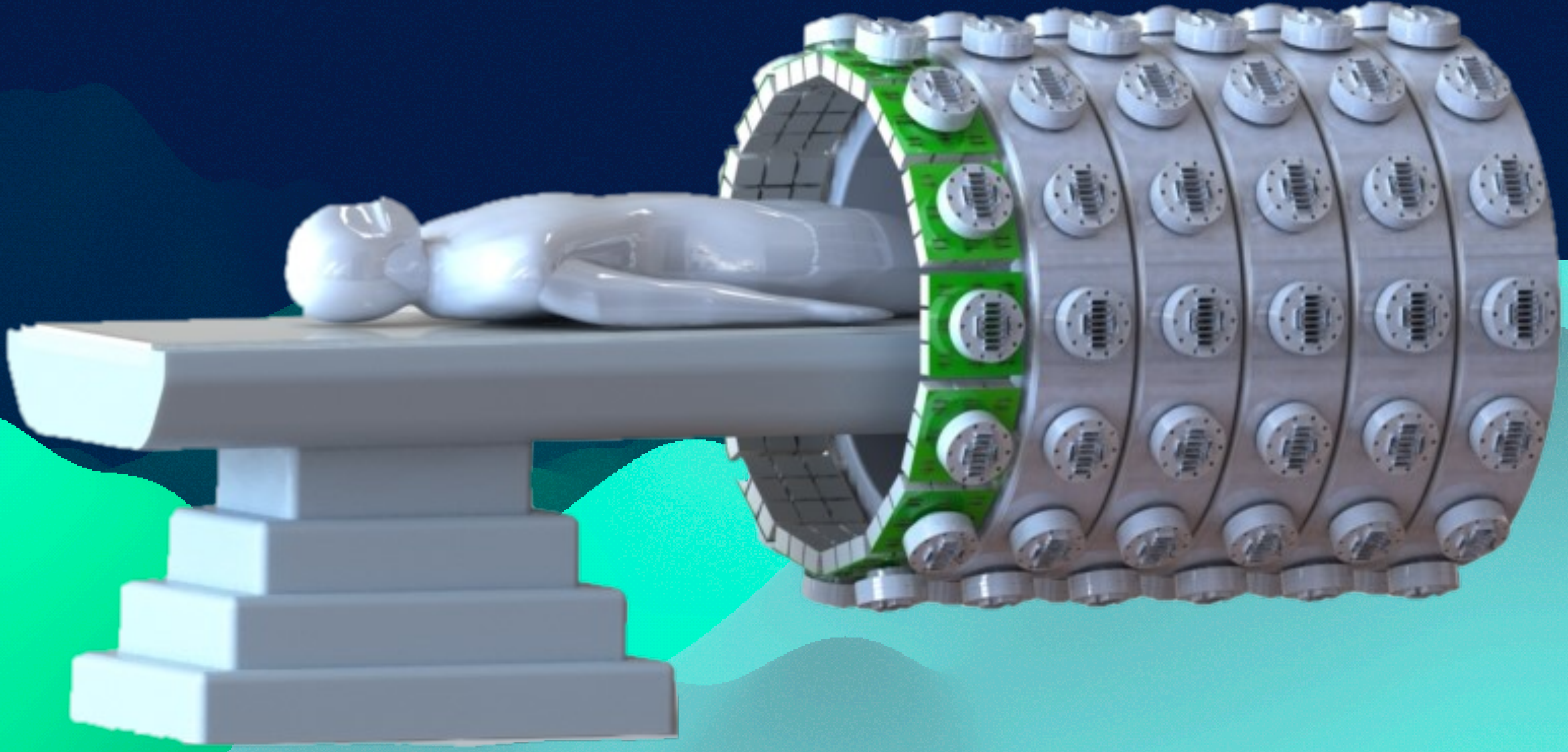

Cryogenic CsI as a potential PET material

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PSMR2024, 23 MAY 2024

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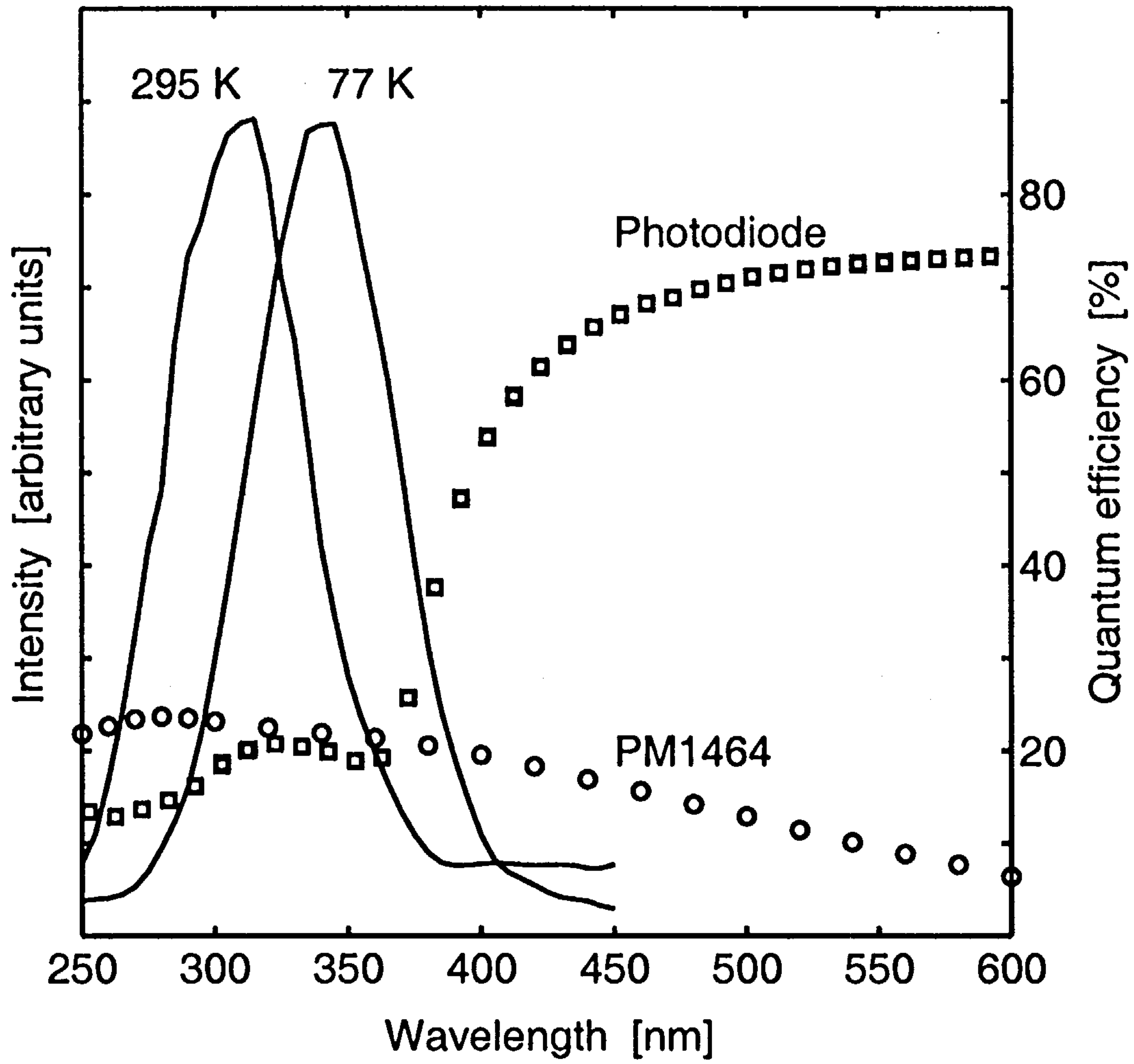
Properties of cryogenic CsI crystals

- Undoped CsI is a UV scintillating crystal with a **relatively small light yield at room temperature** (few thousands γ/MeV, 8% of NaI(Tl)).
  - Used for e.g. the Mu2e calorimeter [1] because of its fast time constant (few ns) and its radiation hardness.
- When cooled near cryogenic temperatures (<110 K):
  - Its **light yield increases** by a factor of ~15 (between 80,000 and 125,000 photons/MeV, depending on stock)
  - A **slow time constant** (O(μs)) dominates the time emission profile.
  - Emission wavelength goes from ~320 nm to **~350 nm**.
  - Being used for detection of coherent elastic neutrino-nucleus scattering experiment.
- Properties of cryogenic CsI have been known since the 90s [2-3].



[1] N. Atanov, et al., *IEEE Trans.Nucl.Sci.* 65 (2018) 8, 2073-2080 arXiv:1802.06346
[2] C.L. Woody, et al., IEEE Trans. Nucl. Sci. NS- 37 (1990) 492.
[3] H. Nishimura, et al., Phys. Rev. B 51 (1995) 2167.

CsI vs other PET crystals

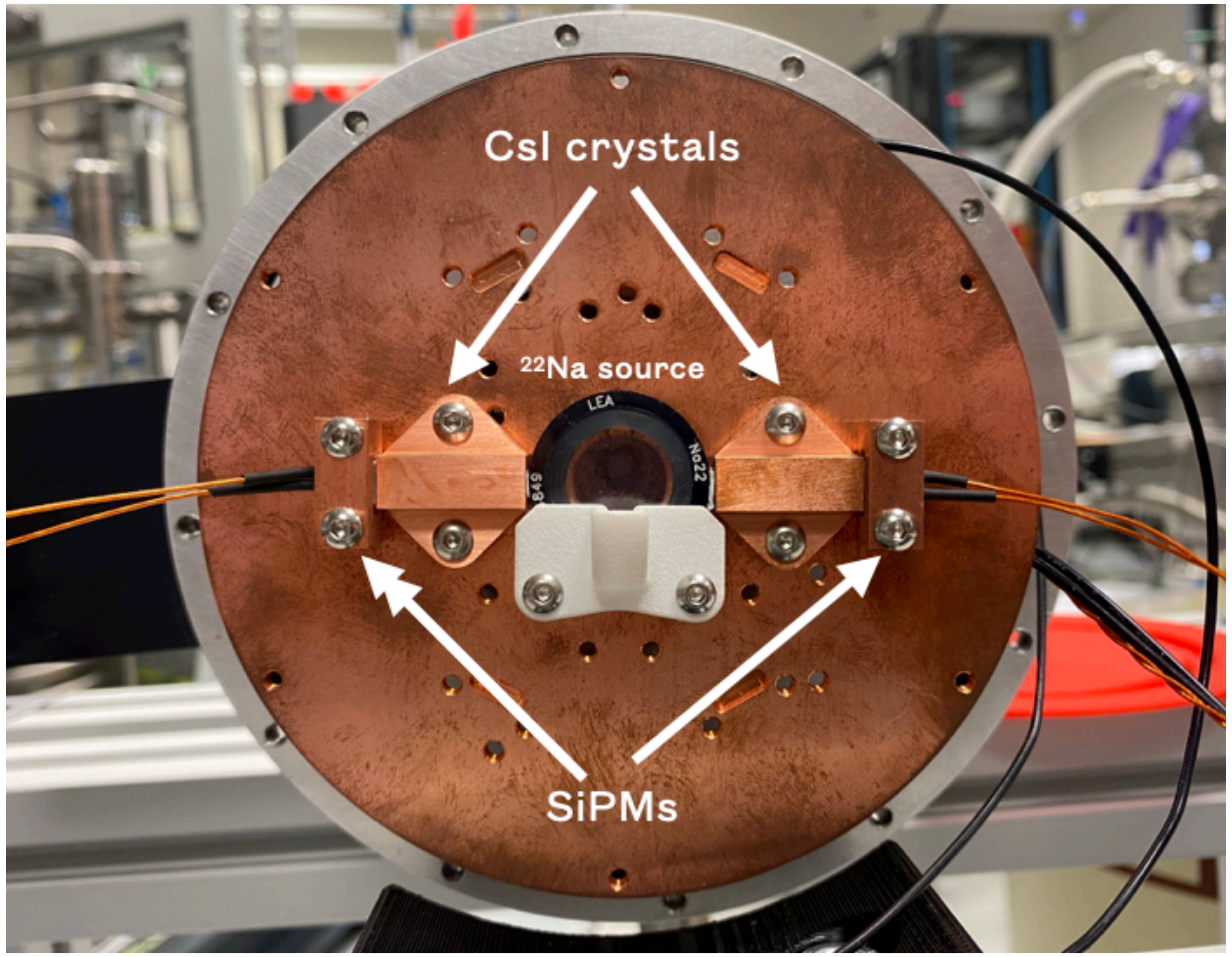
Material	Z_{eff}	X_0 (cm)	Density (g/cm^3)	Light yield (photons/MeV)	Decay time (ns)	Emission wavelength (nm)
LYSO	66	1.14	7.4	35 000	40	420
BGO	74	1.12	7.1	10 000	300	480
CsI(Tl)	54	1.86	4.5	60 000	700	560
CsI @ 100K	54	1.86	4.5	100 000	800	350

CsI vs other PET crystals

Material	Z_{eff}	X_0 (cm)	Density (g/cm³)	Light yield (photons/MeV)	Decay time (ns)	Emission wavelength (nm)	Cost (€/cm³)
LYSO	66	1.14	**7.4**	35 000	**40**	420	**45**
BGO	**74**	**1.12**	7.1	**10 000**	300	**480**	25
CsI(Tl)	**54**	1.86	**4.5**	60 000	700	560	**5**
CsI @ 100K	**54**	1.86	**4.5**	**100 000**	**800**	350	**5**

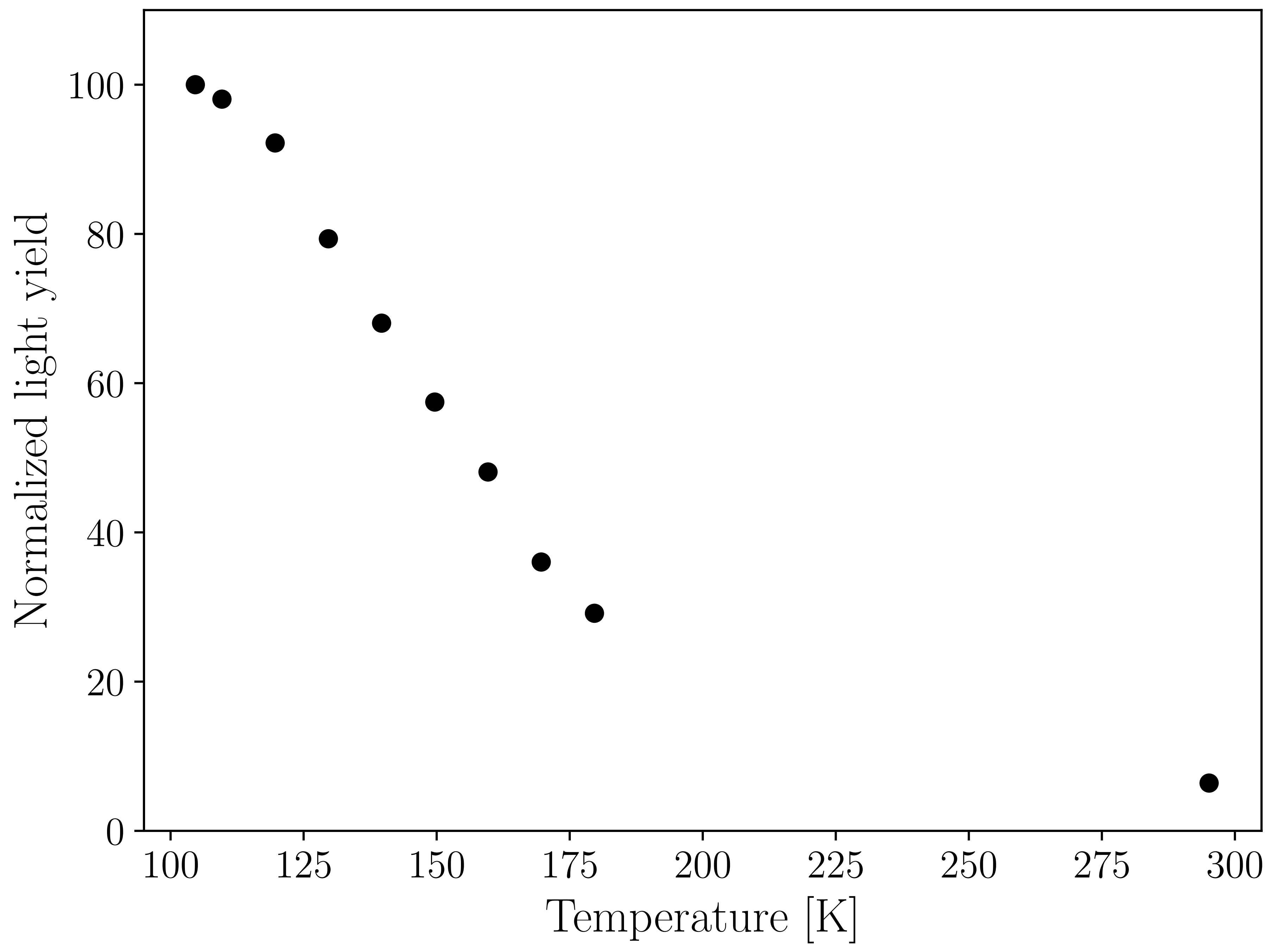
Pixelated CsI crystals measurement

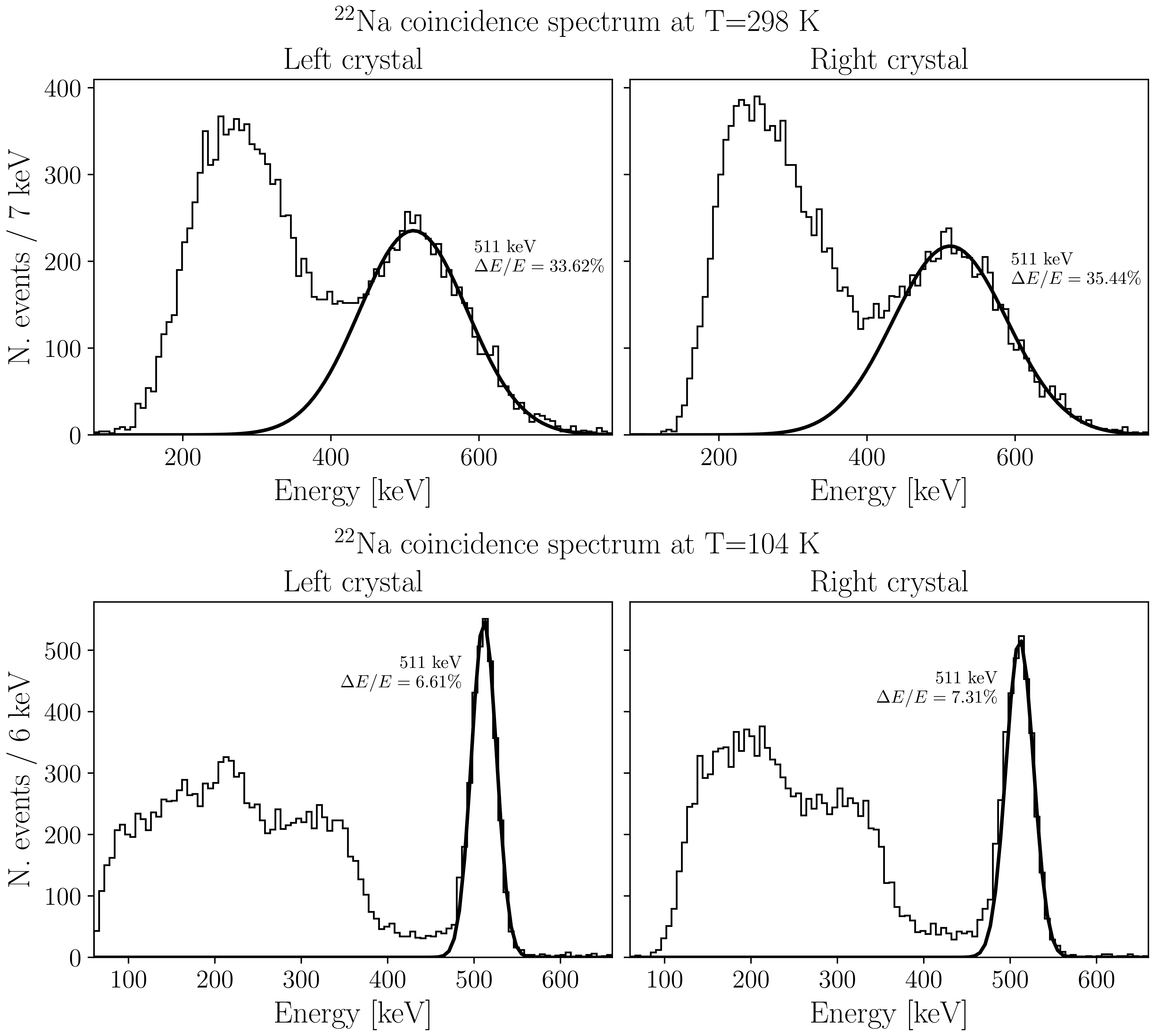
- Our first goal was to measure the **time and energy resolution** at 511 keV of two cryogenic CsI crystals in coincidence.
- Two **3x3x20 mm³ CsI** crystals were wrapped in **PTFE** and placed on a copper plate, connected to a cold finger submerged in liquid nitrogen, and read out by **3x3 mm² Hamamatsu S13360-3025 SiPMs**.
- Temperature was a measured by a PT100 placed behind the plate and can be controlled using two strip resistors.
- Signals were acquired by a scope, triggering in coincidence.



Light yield and energy resolution

- We observe a dependence of the light yield as a function of the temperature which is **in good agreement with [4]**.
- As expected, the energy resolution at cryogenic temperatures is **significantly better** than at room temperature:
  - Light emission is ~15 times higher
  - Quantum efficiency of SiPM is 14% at 320 nm and 18% at 350 nm.





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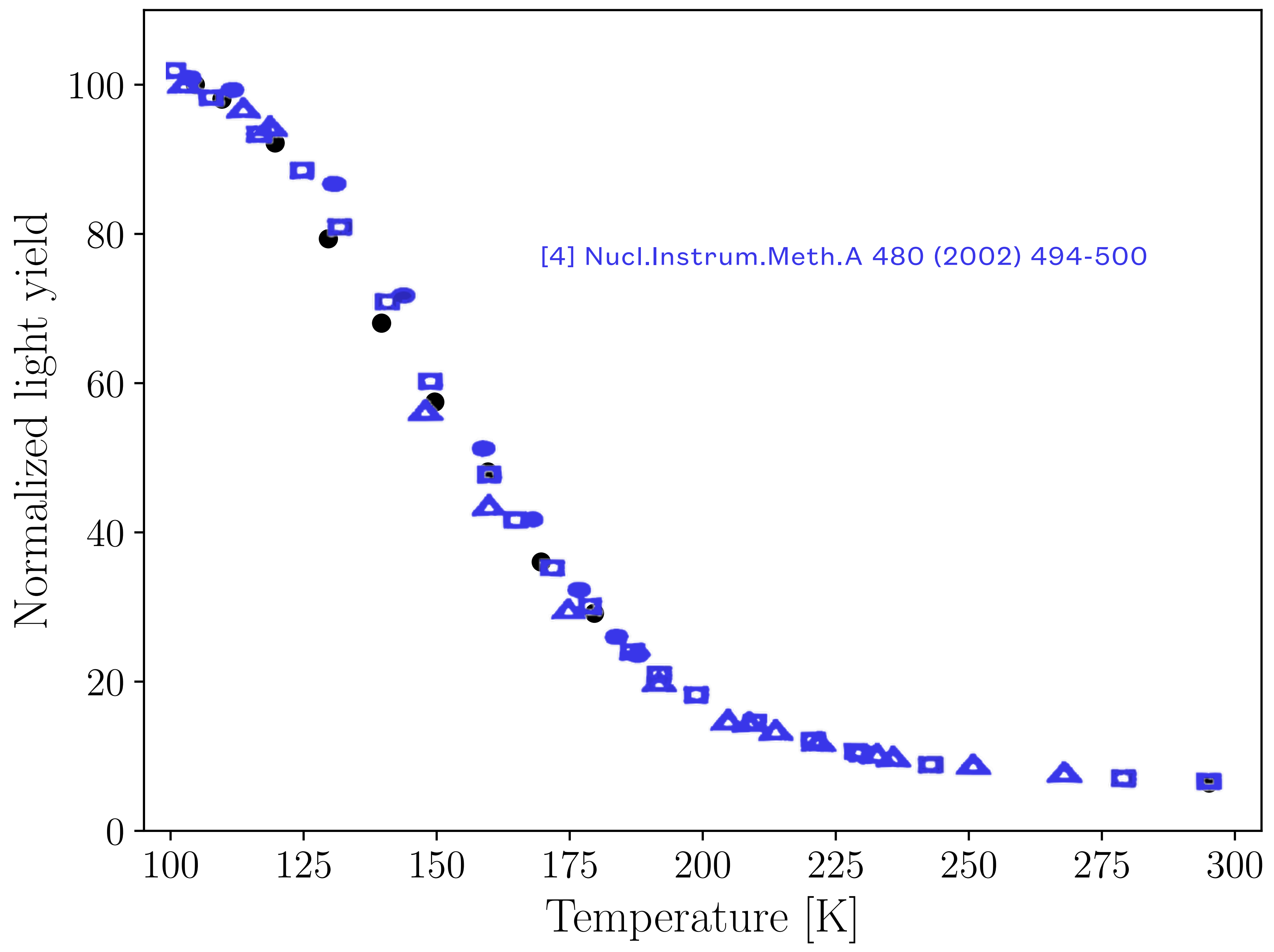
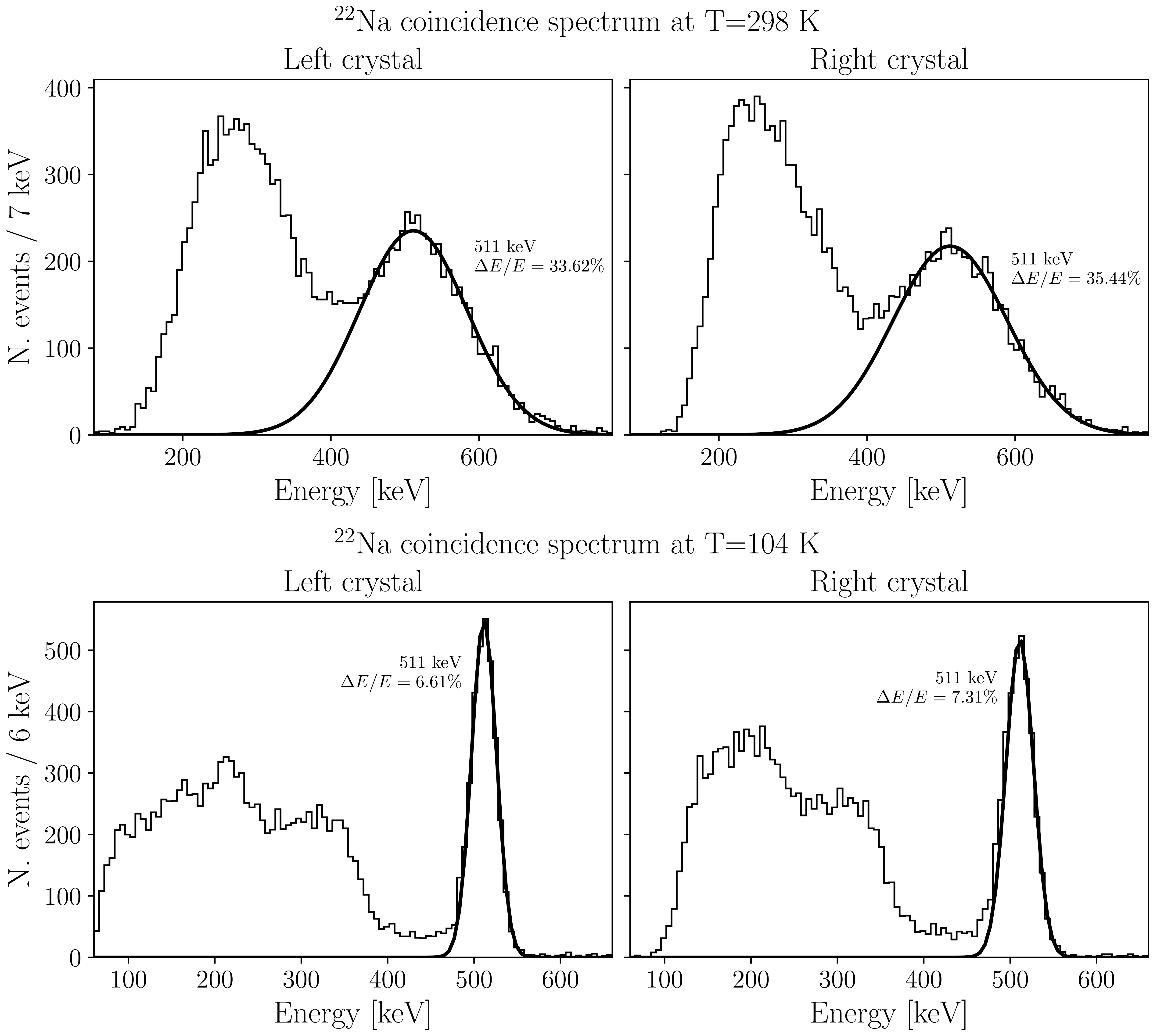
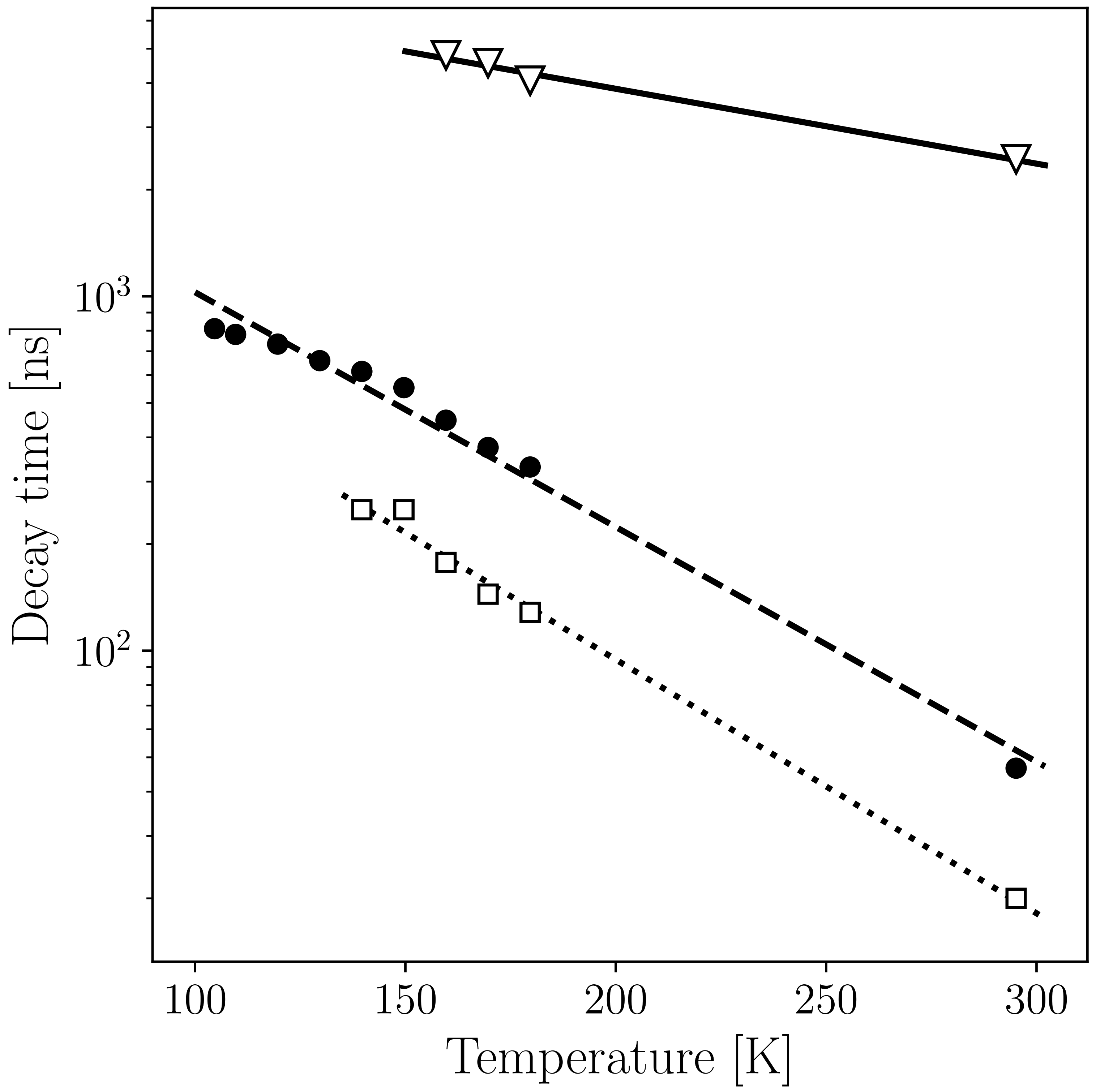
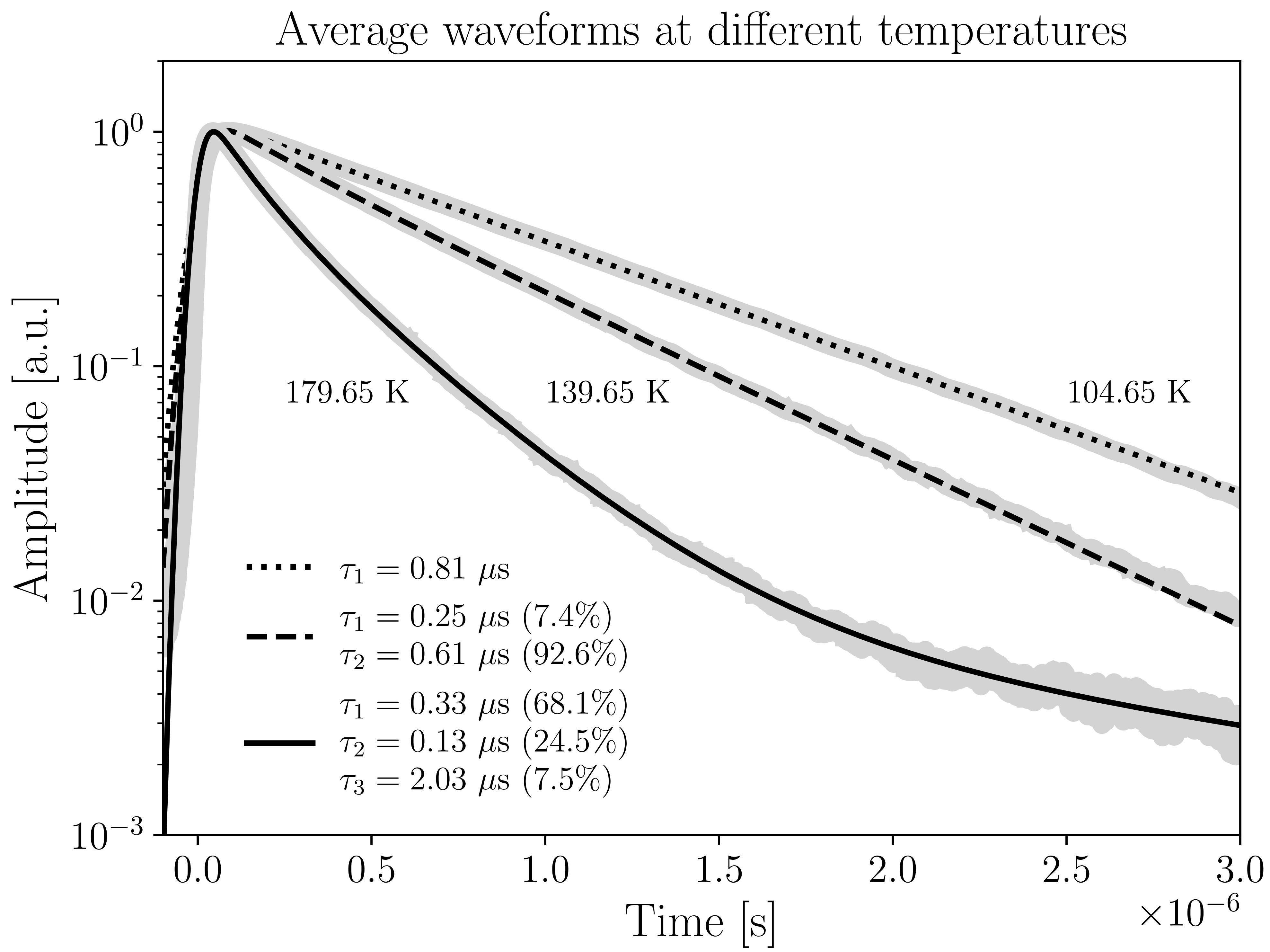




Emission time constants

- We performed several data acquisitions at **different temperatures**.
- As expected, we observe a **slow time component** at lower temperatures, but we see a fast component appearing at colder temperature than in [4].
- Also, we observe a **third, slower component**, which however contributes to <10% of the total light yield and disappears at T < 150 K.





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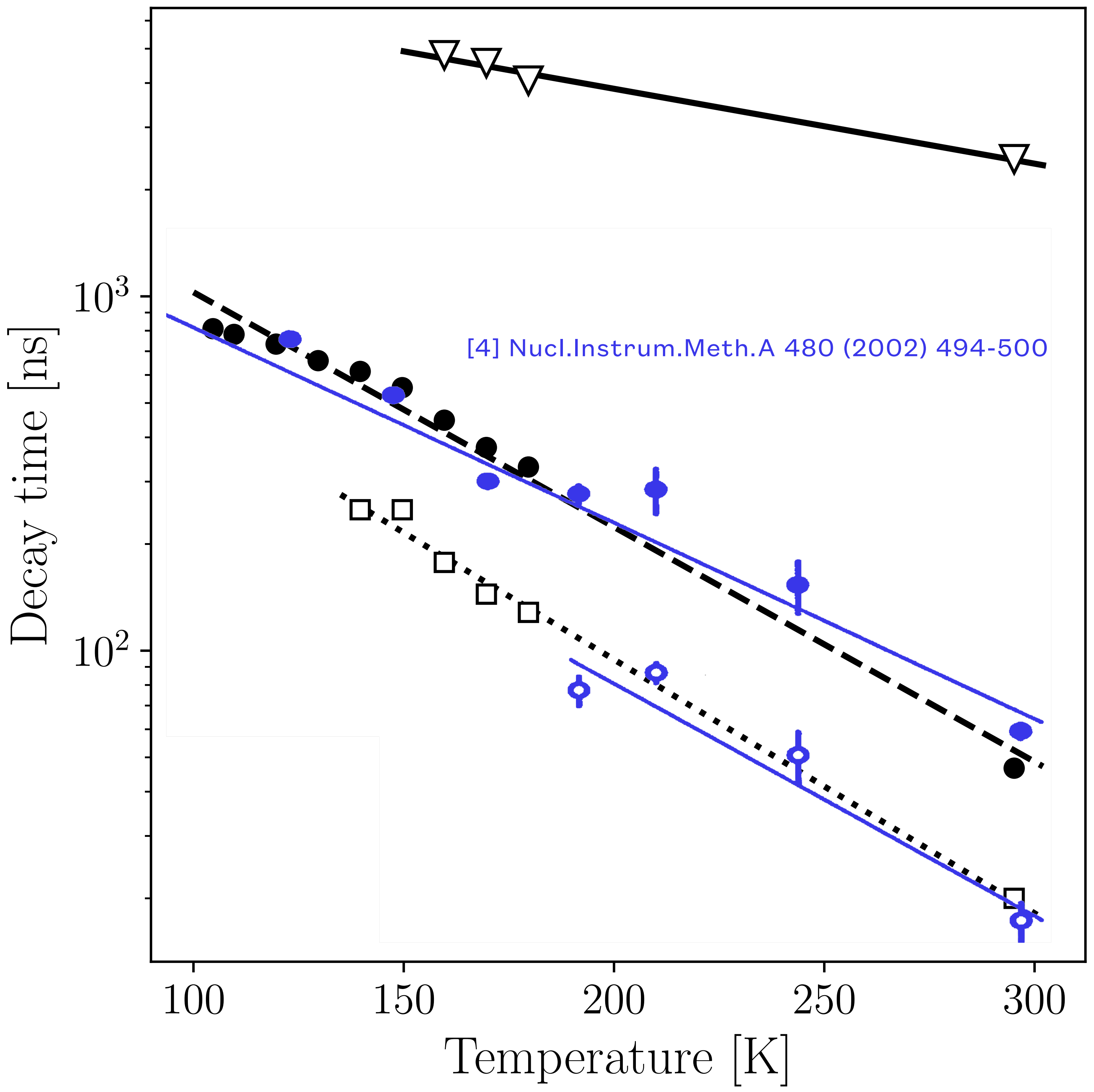
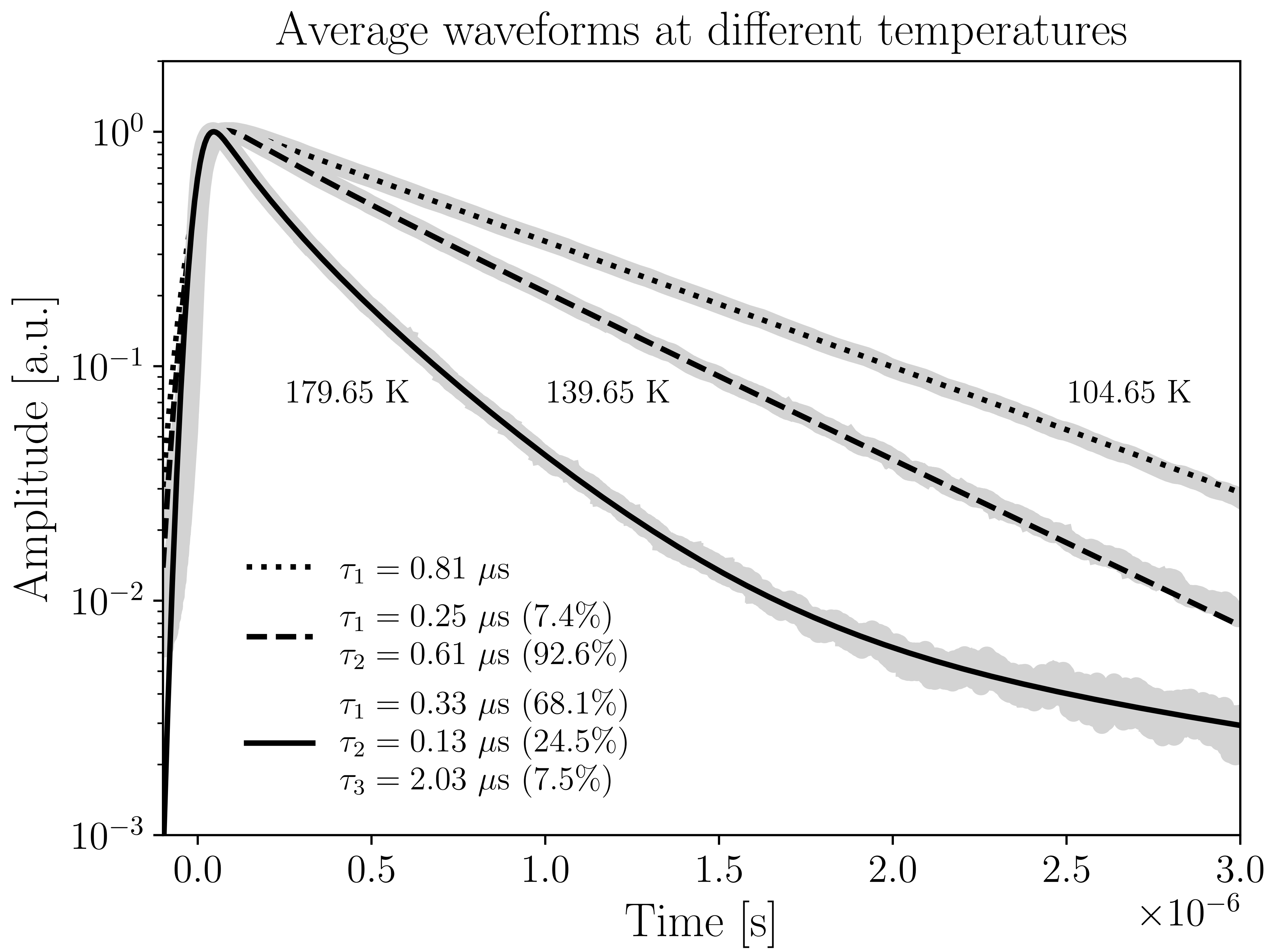
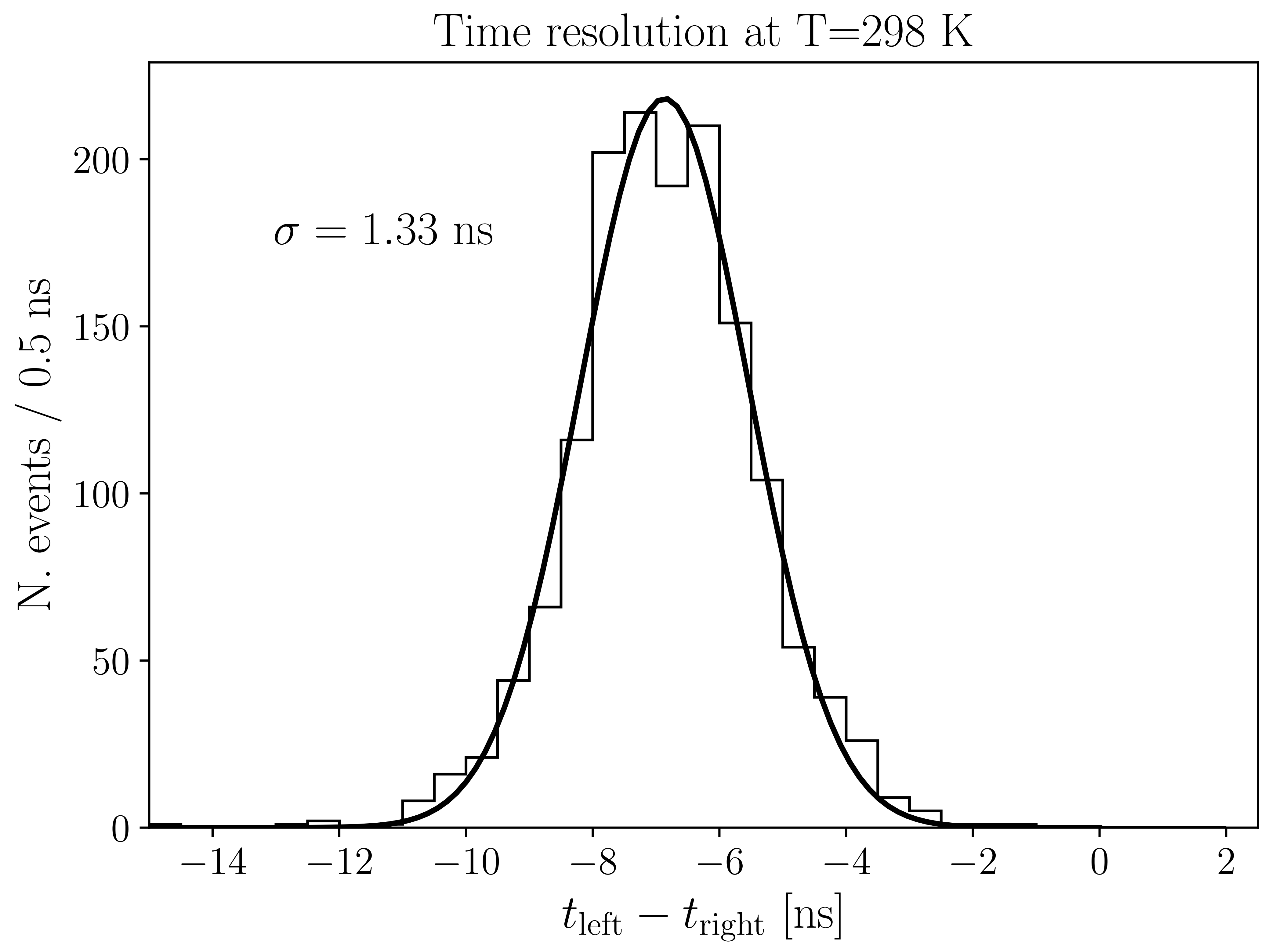
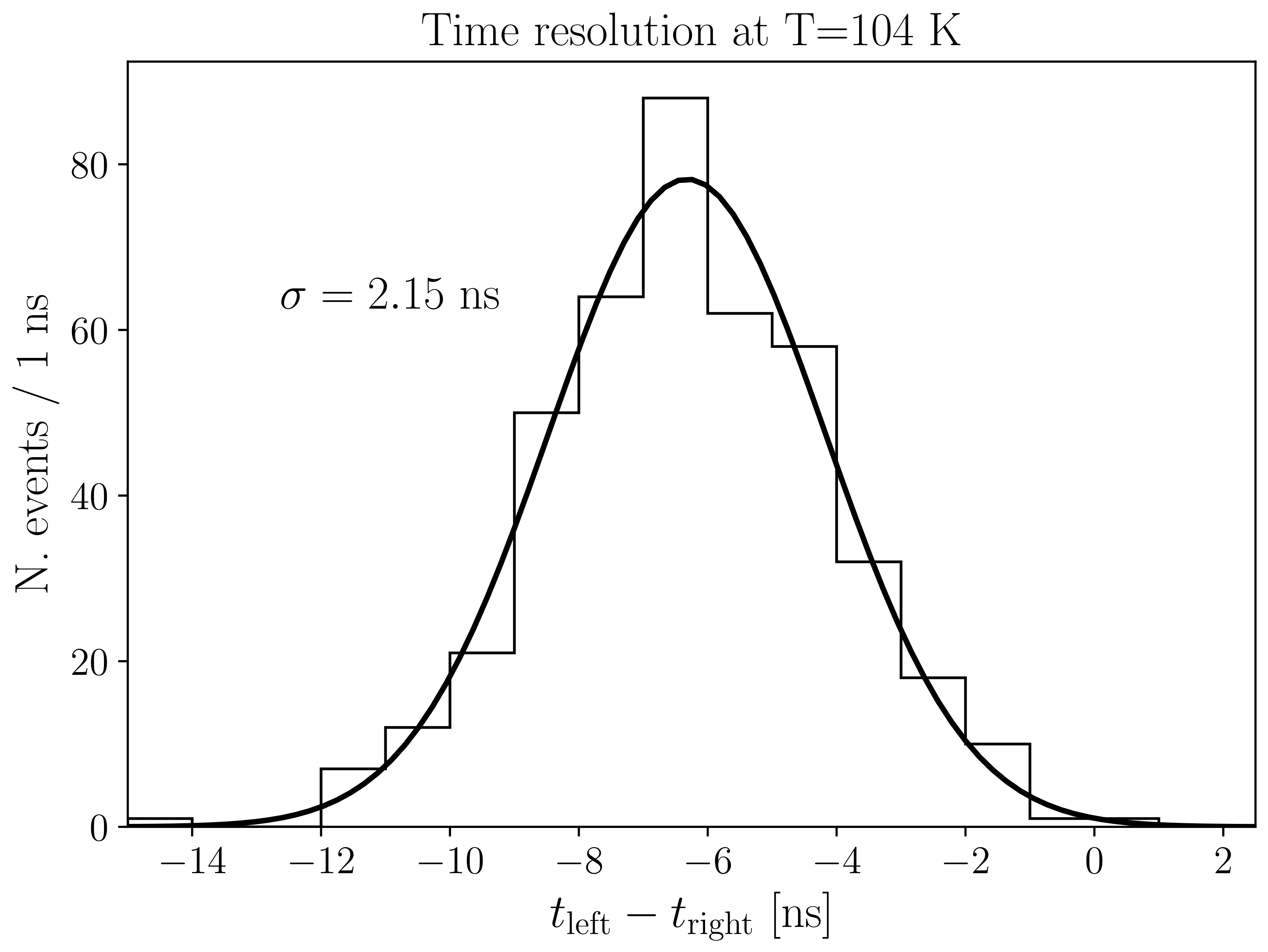




Coincidence time resolution

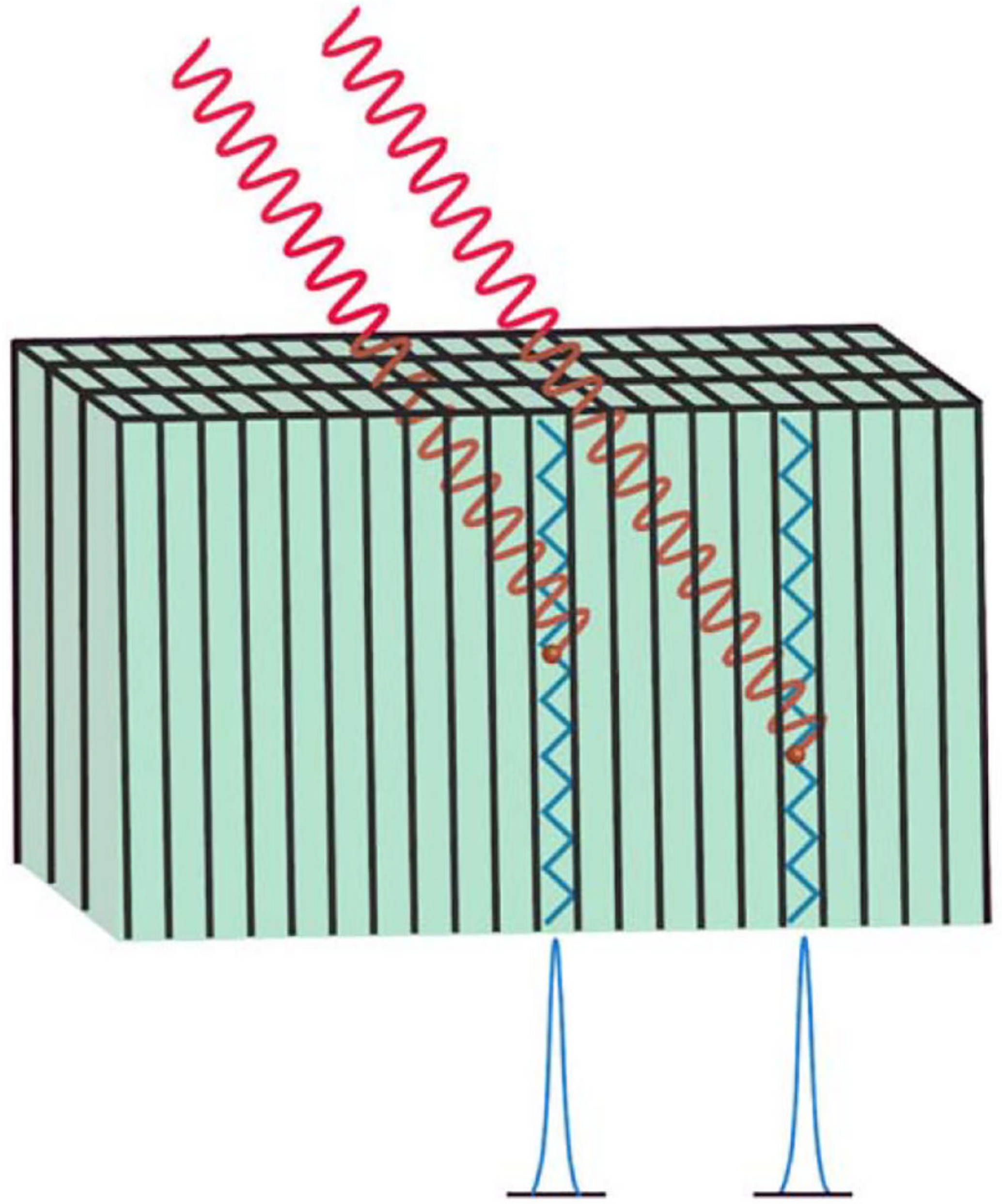
- We measured the coincidence time resolution by calculating the difference between the times when the two waveforms cross a certain threshold.
- Although at cold temperature the emission time is O(µs), the **CTR is still O(ns)**, since the slower emission is compensated by the larger amount of light emitted.





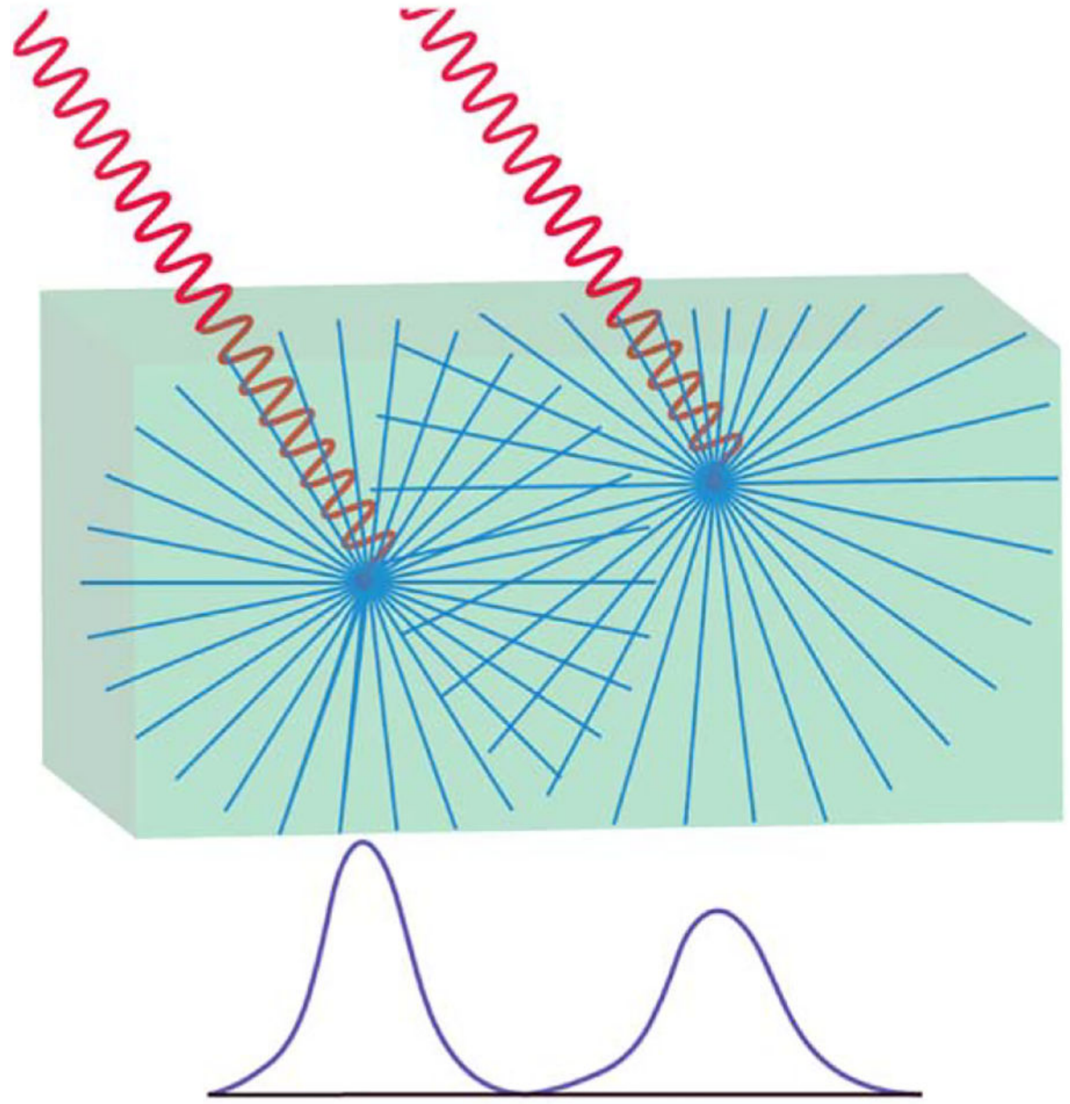
Pixelated

- Each small crystal needs to wrapped with a reflector and read out by **a single photosensor**.
- Position resolution is determined by the **size of the pixel**.
- Light is confined to a single photosensor, **no pile-up**.
- **DOI is challenging.**



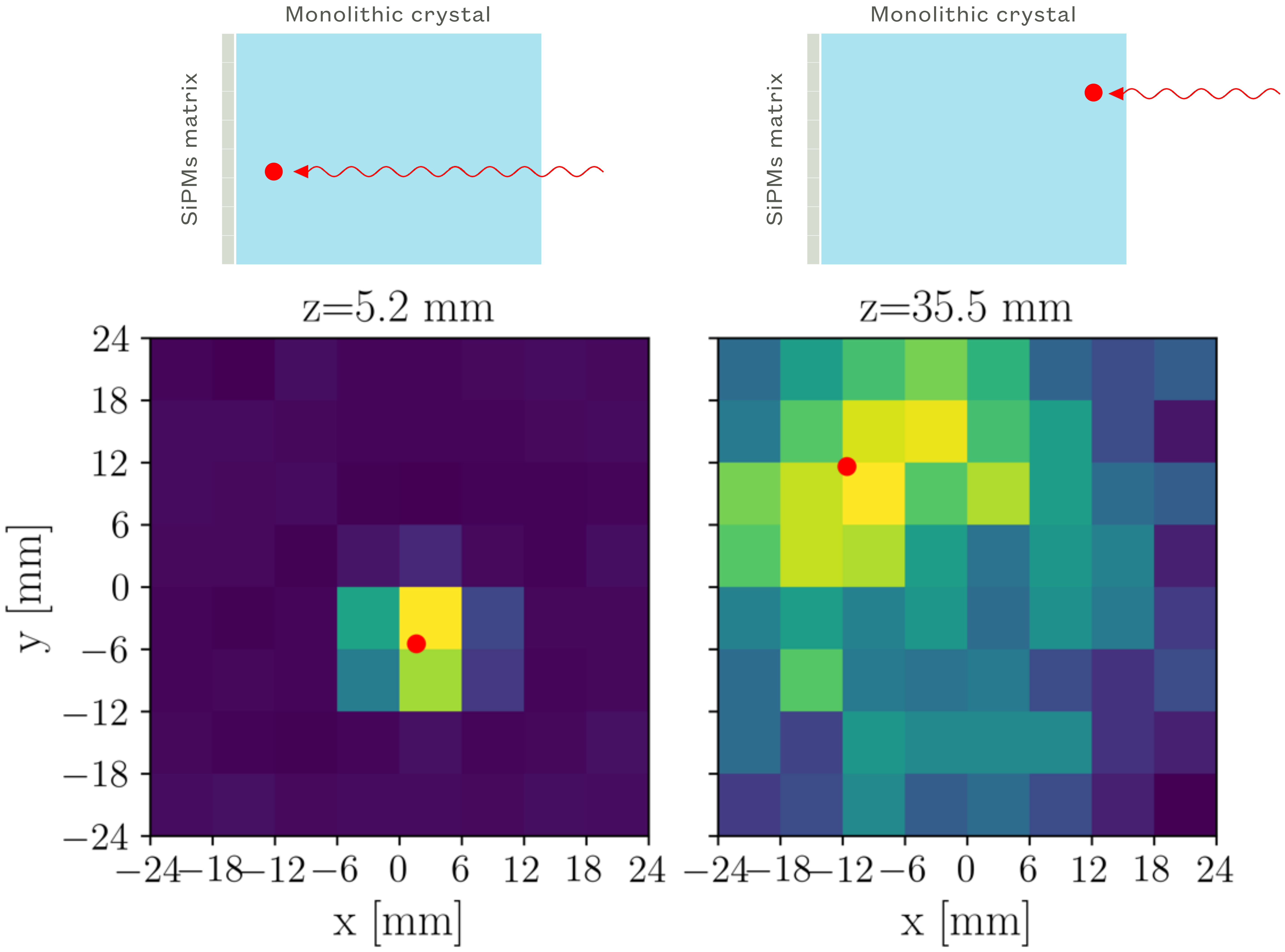
Monolithic

- A single, large crystal is read out by a **matrix of photosensors**.
- Interaction point can be determined by looking at the shape of the light pulse, **including DOI**.
- Possibility of pile-up.
- Simplified manufacturing.
- Minimized dead space.



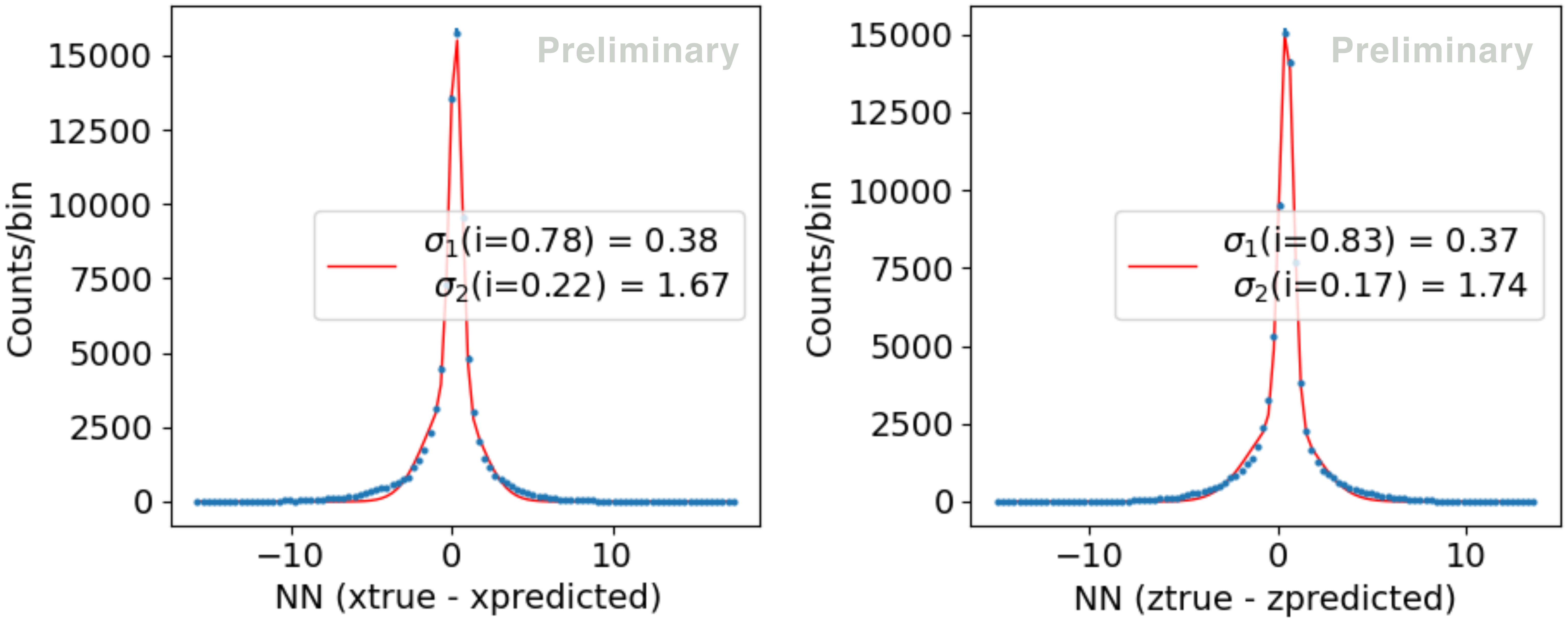
Interaction reconstruction with deep learning

- We developed a deep learning algorithm who is able to reconstruct the **interaction position of the gamma** in a monolithic crystal read out by a matrix of SiPMs.
- The algorithm consists of a **Convolutional Neural Network** trained on 8x8 monochromatic images corresponding to the charge collected by each SiPM.
- Photoelectric interaction is assumed, with the monolithic crystal being **fully wrapped** with PTFE.
- ResNets have also been explored, giving minimal improvement.



Spatial resolution with deep learning algorithm

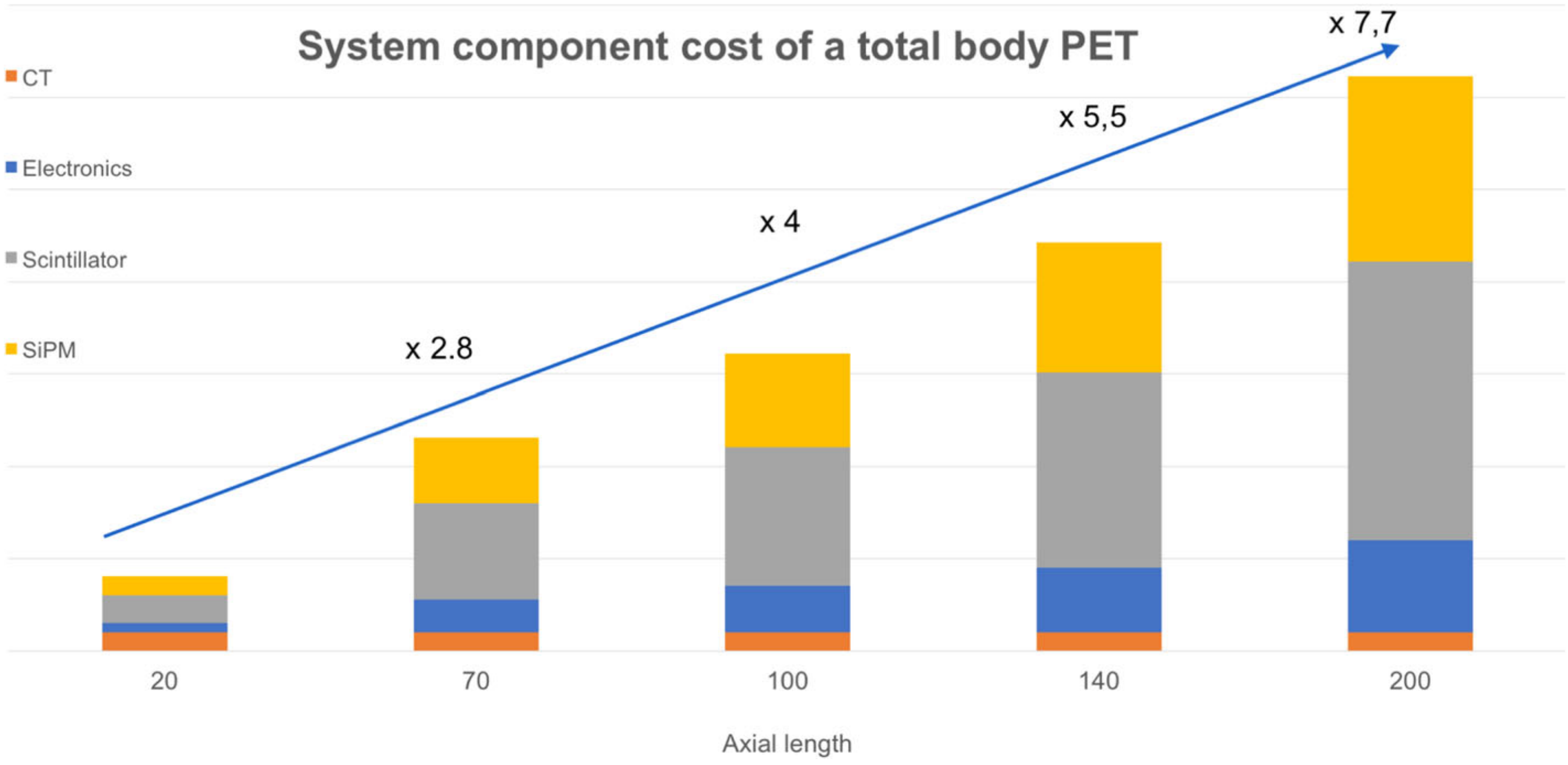
- The deep learning algorithm achieves a resolution with a core of $\sigma < 0.5$ mm.
- The tails correspond to events near the crystal edges.
- This is **comparable** to the naive resolution in x, y of **pixelated crystals** with a 3 mm pitch ($3/\sqrt{12} = 0.87$ mm).

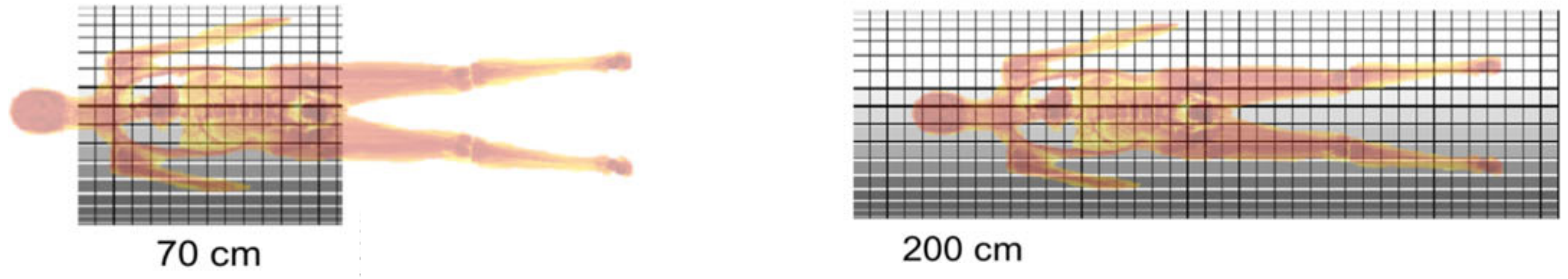


- Most importantly, the resolution on the DOI is **significantly better than 1 mm**, reducing the parallax error especially at large angles (particularly important for full-body PETs).

Why a cryogenic CsI full-body PET?

- The cost of crystals and SiPMs scales linearly with the axial length of the PET.
- For wide and full-body PET these two components dominate the total price.
- Assuming **monolithic crystals** read out by 6x6 mm2 SiPMs can **reduce by x4** the SiPM and electronics component (less sensors and less channels).
- **Cryogenic CsI** crystals are **x5 cheaper** than LYSO (normalizing by Z_{eff} and X_0). Liquid nitrogen cooling is a well known and relatively cheap technique (with a cost that scales slowly with the size).
- This gives a total reduction factor of approximately x4, possibly bringing the cost of a **full-body PET below $3M**.





Adapted from Vandenberghe, S., Moskal, P., & Karp, J. S. (2020). EJNMMI physics, 7, 1-33.

PET scanner simulation and reconstruction

- A PET scanner has been simulated with a custom **Geant4 application**.
- Reconstruction has been performed with `parallelproj` (**GPU-accelerated Python package**).
- In order to fully assess the impact of multiple scattering in a human body, a **modified Jaszczak phantom** has been simulated (larger radius and axial length).
- Two geometries:
  - **30 cm axial length**, 60 cm inner diameter
  - **100 cm axial length**, 60 cm inner diameter
- Two combinations:
  - **LYSO pixelated crystals**
  - **Cryogenic CsI monolithic crystals**

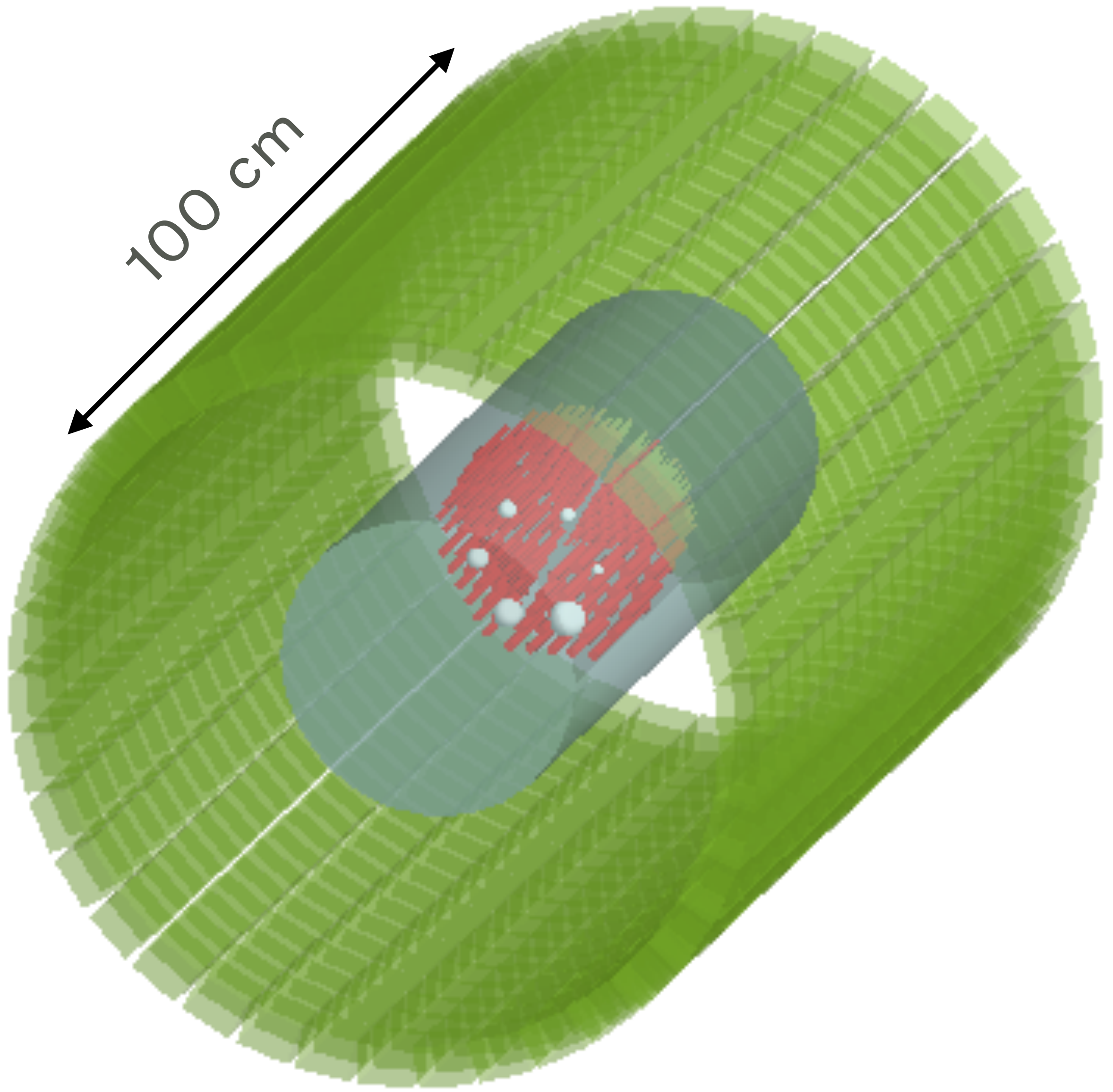
LYSO pixelated crystals

- 3x3x22.8 mm^3
- TOF FWHM of 385 ps.
- E_{res} 12% FWHM

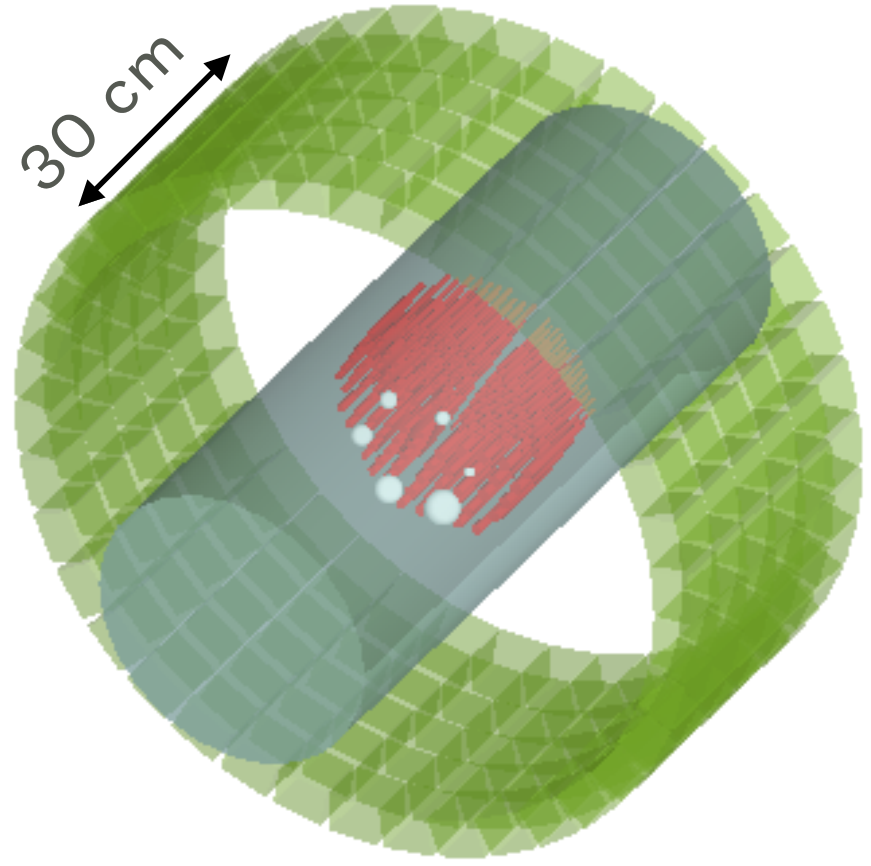
Cryogenic CsI

- 48x48x37.2 mm^3
- No TOF
- Spatial resolution of the deep learning algorithm.
- E_{res} 6.5% FWHM

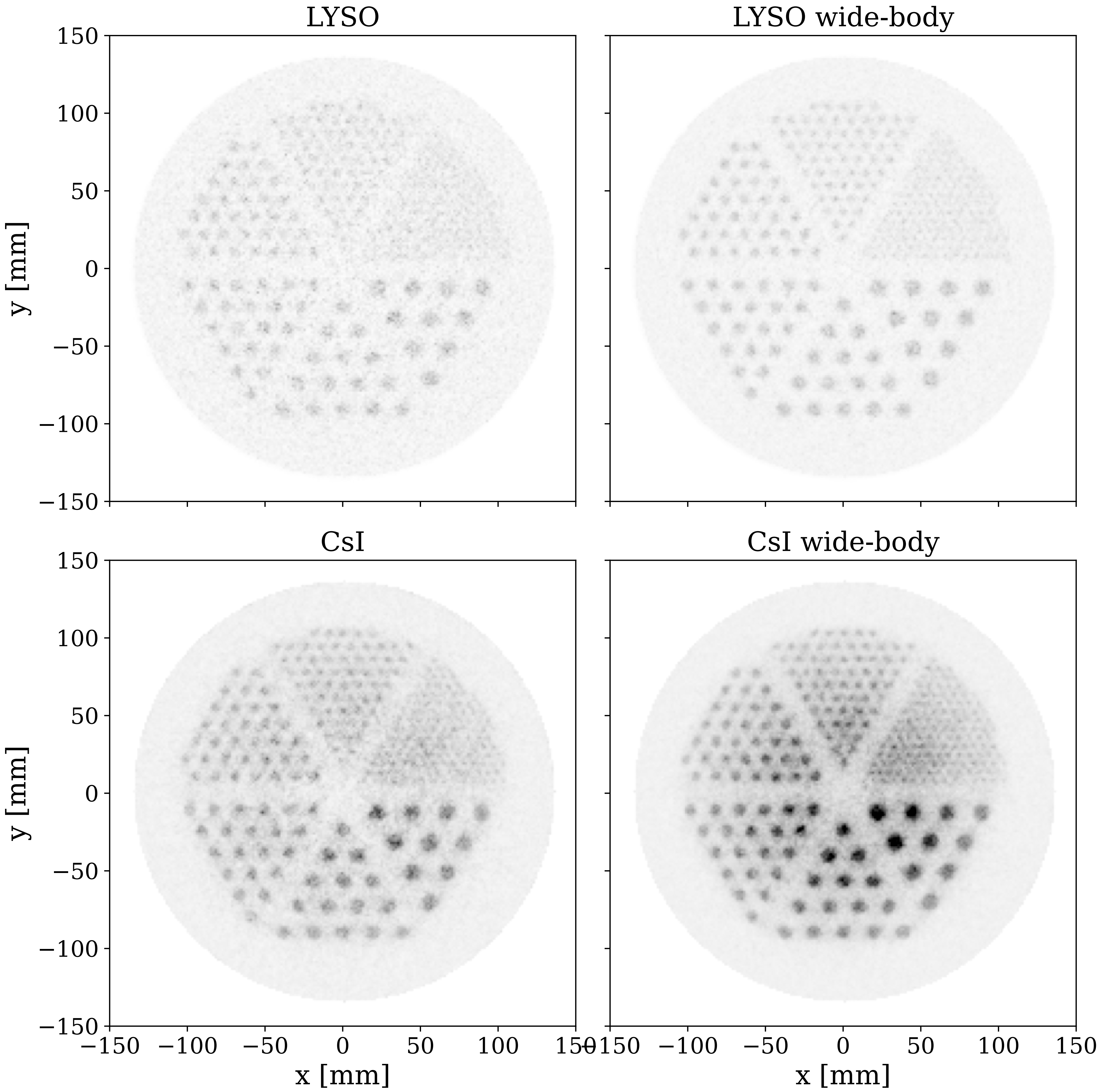
Wide-body geometry



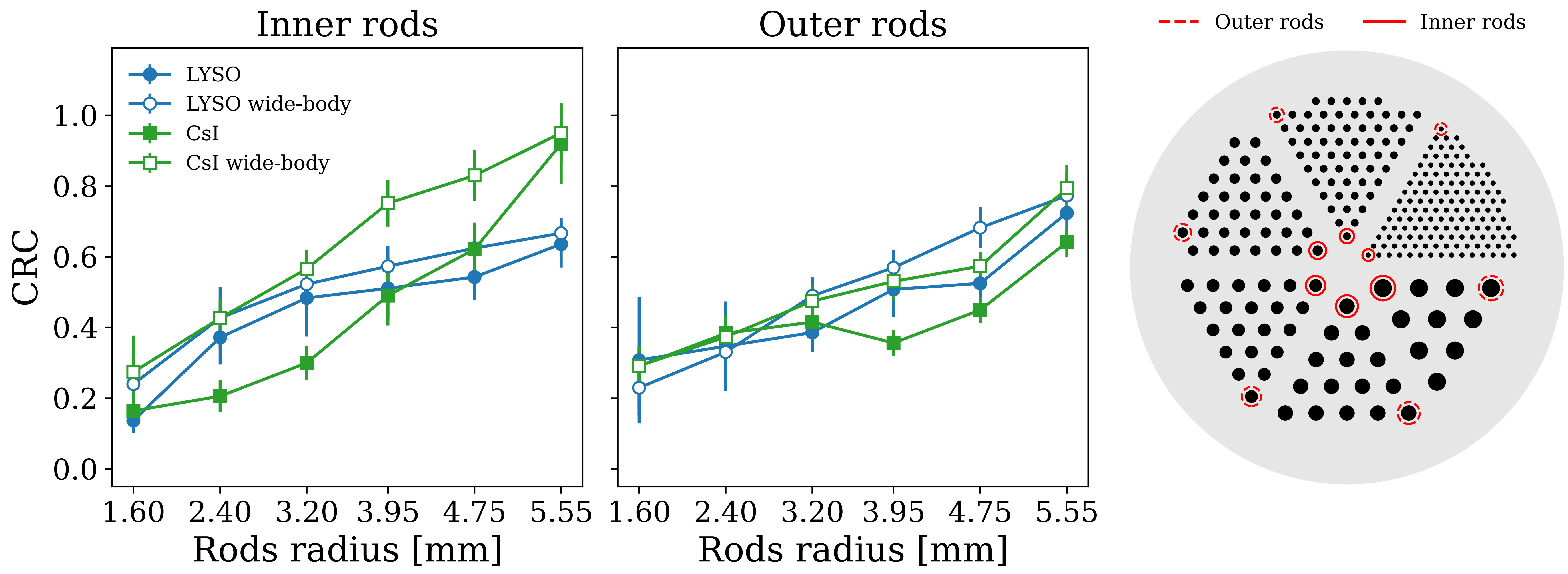
Small geometry



PET scanner simulation and reconstruction



- Equivalent exposure of 10 seconds assuming 240 MBq activity of the rods and 60 MBq activity of the cylinder.
- The CRC of a wide-body PET with **monolithic cryogenic CsI** crystals is **comparable or better** than the one of a PET with **pixelated LYSO crystals with TOF**.
- For the **inner rods** of the phantom, the impact of the better energy resolution is **more visible**, since the scattering probability inside the phantom is higher.

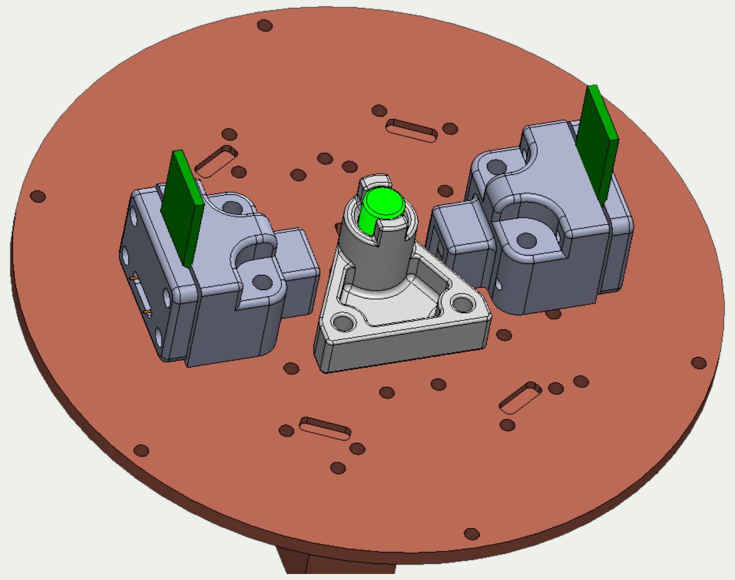


Project roadmap

2023 | 2024 | 2025 | 2026 | 2027

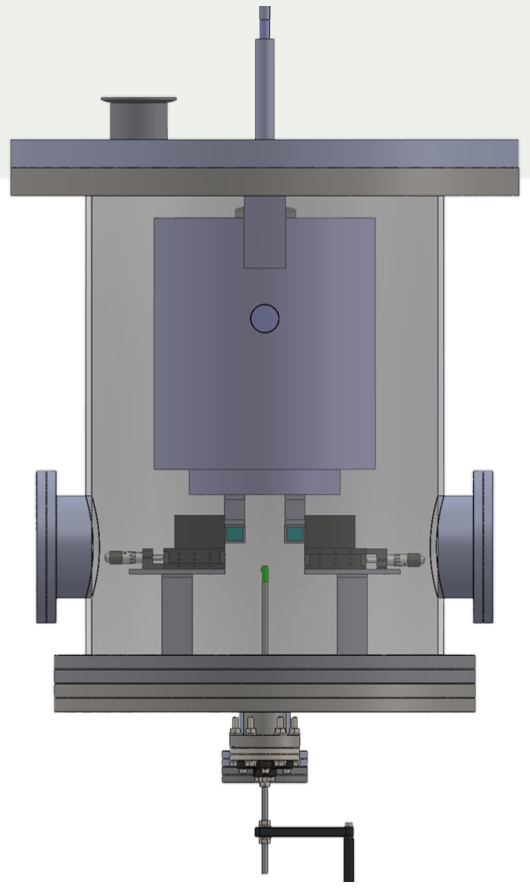
Operation of pixelated cryogenic CsI crystals

Funding secured

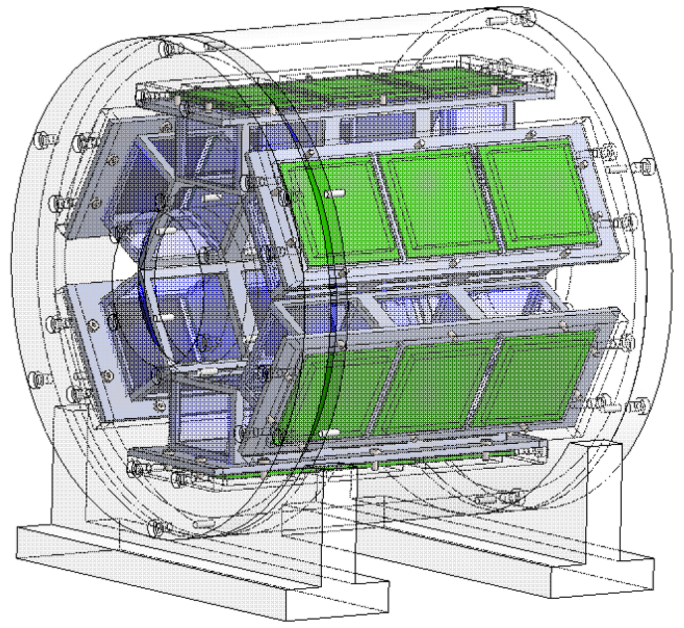


Operation of monolithic CsI(Tl) crystals

Operation of monolithic cryogenic CsI crystals



Construction and operation of small-scale PET with CsI(Tl) crystals



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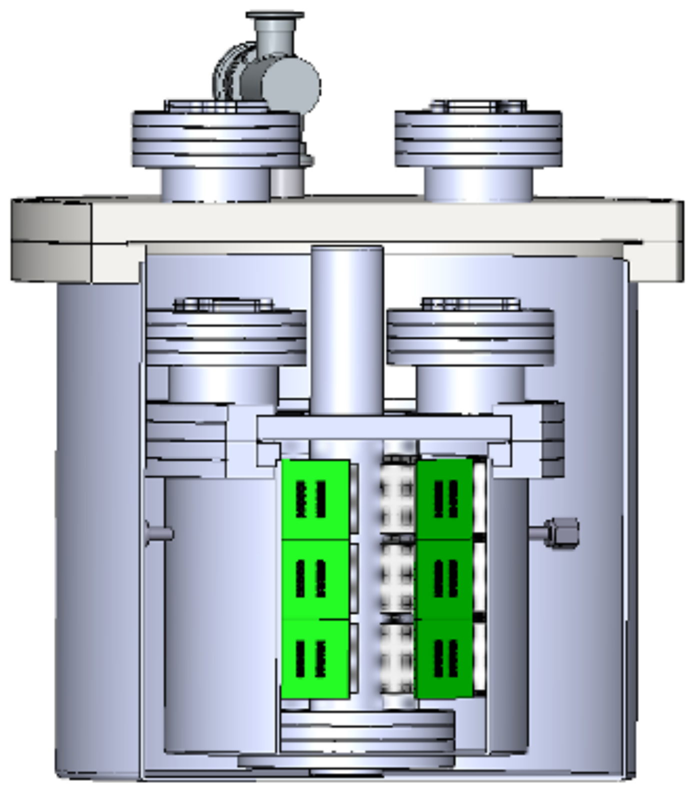
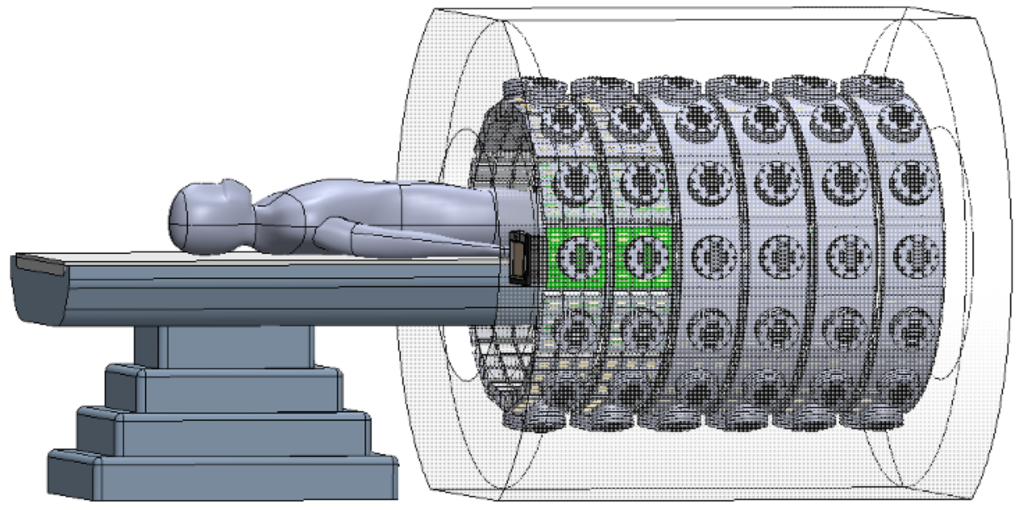
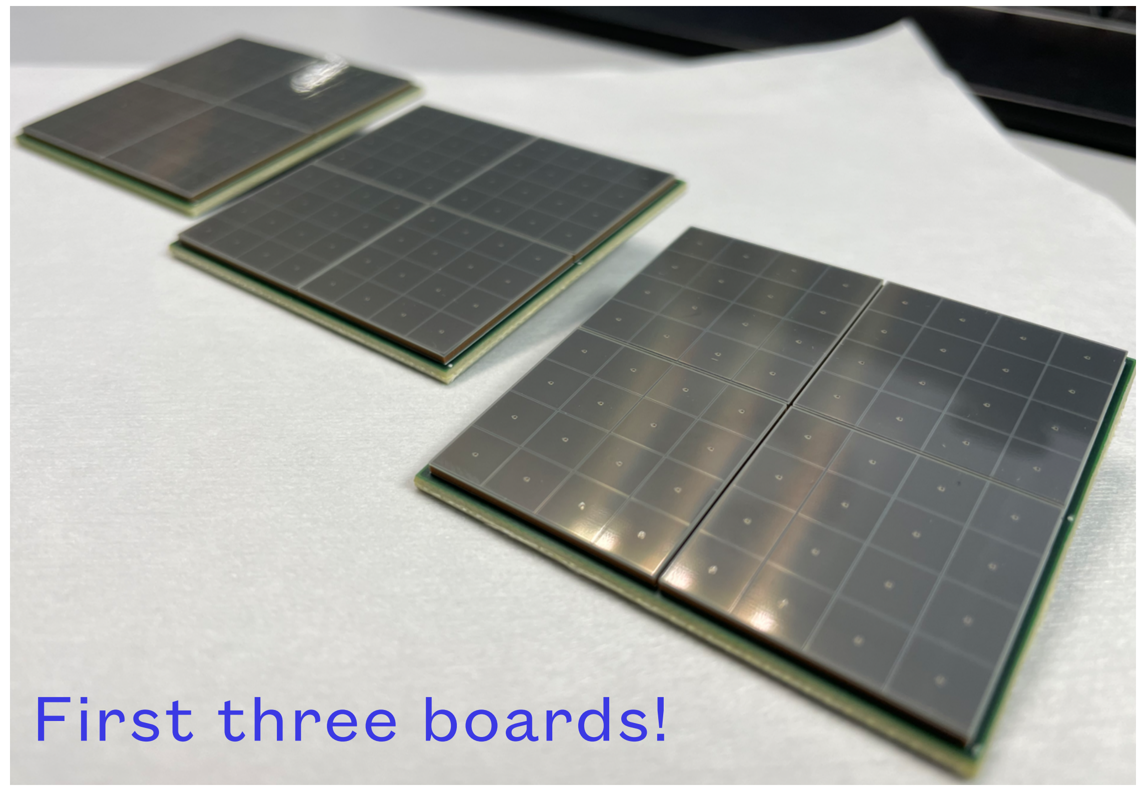




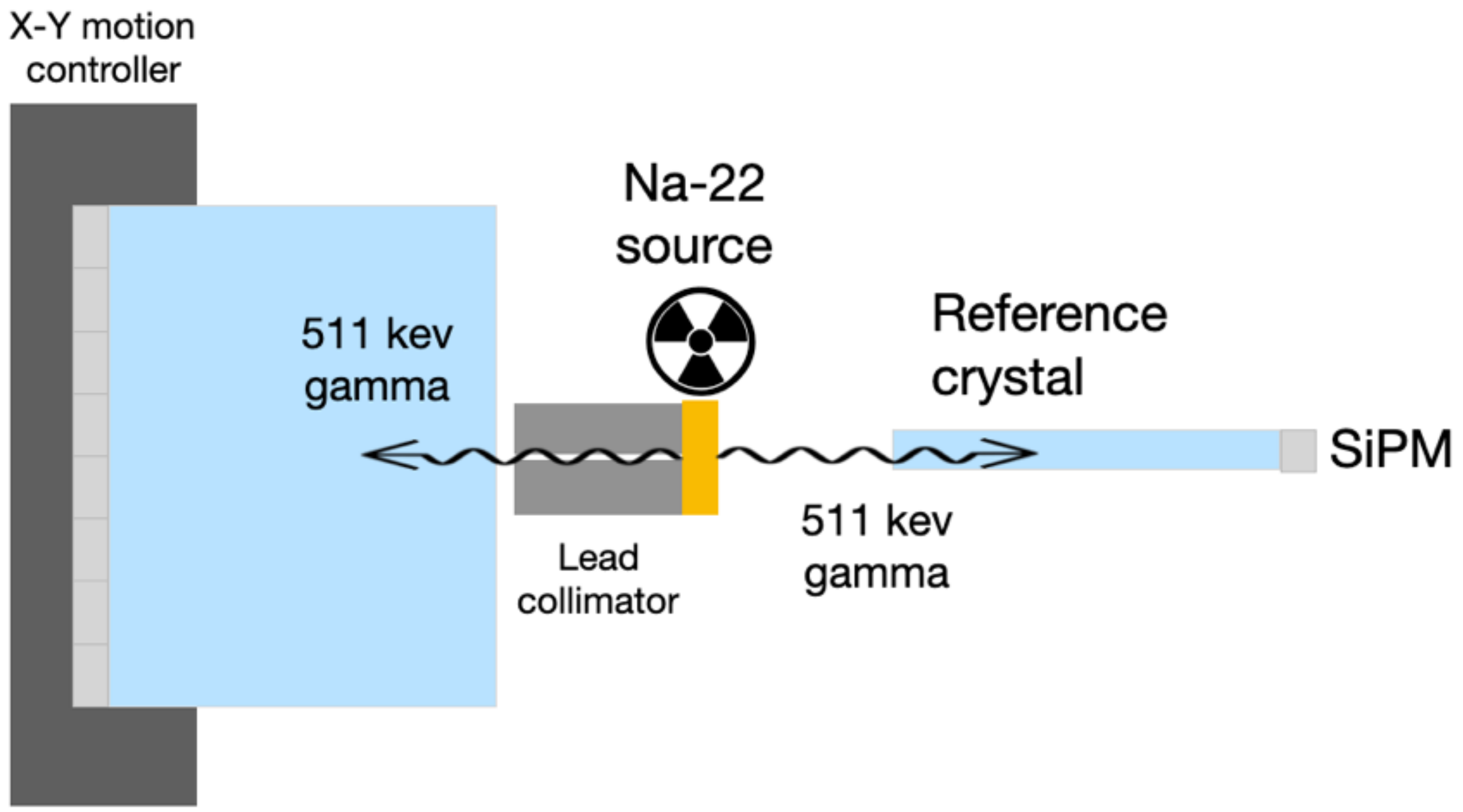
Design and construction of human-sized PET with cryogenic CsI crystals

CsI(TI) R&D

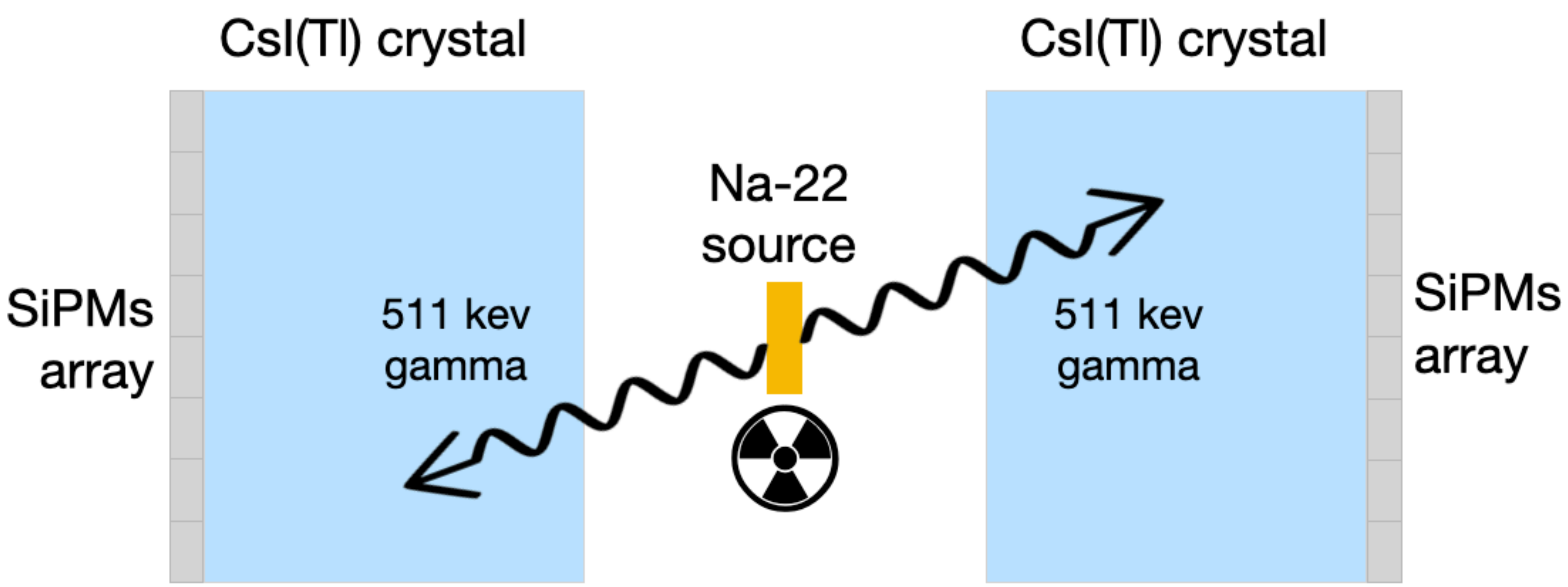
- **Thallium-doped CsI** is a room-temperature alternative to pure cryogenic CsI in terms of performance, but:
  - Slower
  - Non-negligible afterglow
  - x2 less light
  - Hygroscopic
- Operating at room temperature allows us to **decouple** the cryogenic and electronics/DAQ R&D.
- First step will be operating two monolithic CsI(TI) crystals read out by a matrix of SiPMs.
- **PETsys ASIC** or **CAEN QDC** with **Hamamatsu MPPC** 6x6 mm^2 sensors.


First three boards!

Position resolution



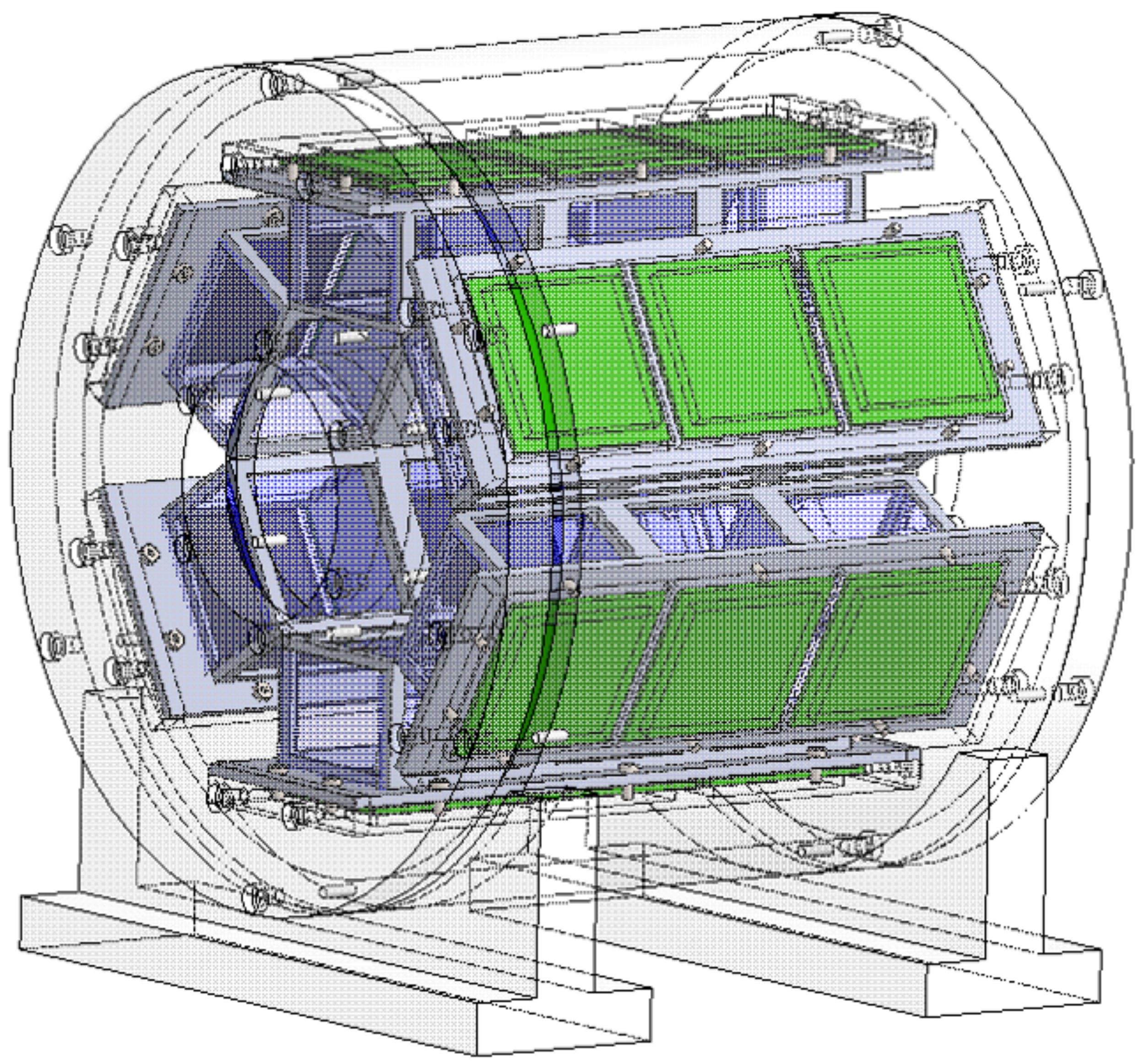
Energy and time resolution



Scaled-down prototype PET

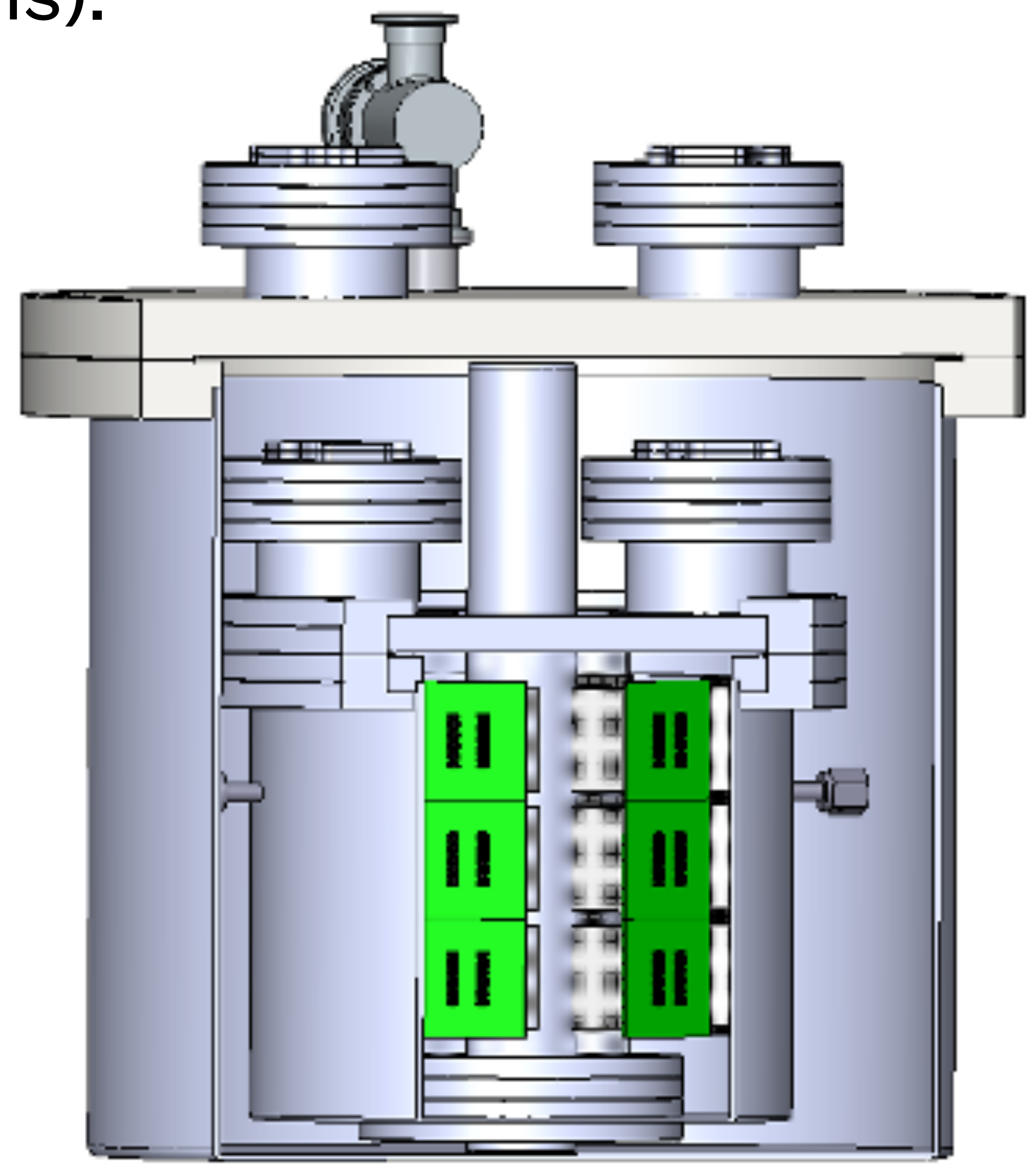
CsI(Tl)

- After operating a pair of monolithic crystals, we will scale up to a small animal PET with **3 rings of 6 CsI(Tl) monolithic crystals** each.
- **PETsys ASIC** and **Hamamatsu MPPC** 6x6 mm^2 sensors.



Cryogenic CsI

- In parallel, we are **developing a cryostat** that can cool CsI crystals at the liquid nitrogen temperature.
- The expertise acquired by our collaborators in the **PETALO project** (LXe PET prototype) will allow us to speed up the design and re-use their solutions (e.g. SiPMs feedthroughs).



Summary

- Cryogenic CsI is an attractive PET material candidate for two main reasons: **exceptionally high light yield** (so very good energy resolution) and **low price**.
- Well known material in particle physics. Cryogenic needs not extreme (100 K, liquid nitrogen is more than enough).
- ML-aided reconstruction algorithm achieves **sub-mm resolution** in three dimensions.
- Cryogenic CsI, combined with a monolithic geometry, could **lower the cost of a full-body PET by x4**, while maintaining performances comparable or better than pixelated LYSO devices.
- Short-term research program aimed at building a small-scale prototype to demonstrate the technology.

Project team

- **PIs: S.R. Soleti, J.J. Gomez Cadenas**
- Researchers: F. Monrabal, D. Zerzion
- Engineers: E. Oblak, A. Castillo, J.M. Benlloch, P. Dietz
- Students: M. Seemann, M. del Barrio-Torregrosa

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- Engineers: J.F. Toledo, V. Herrero