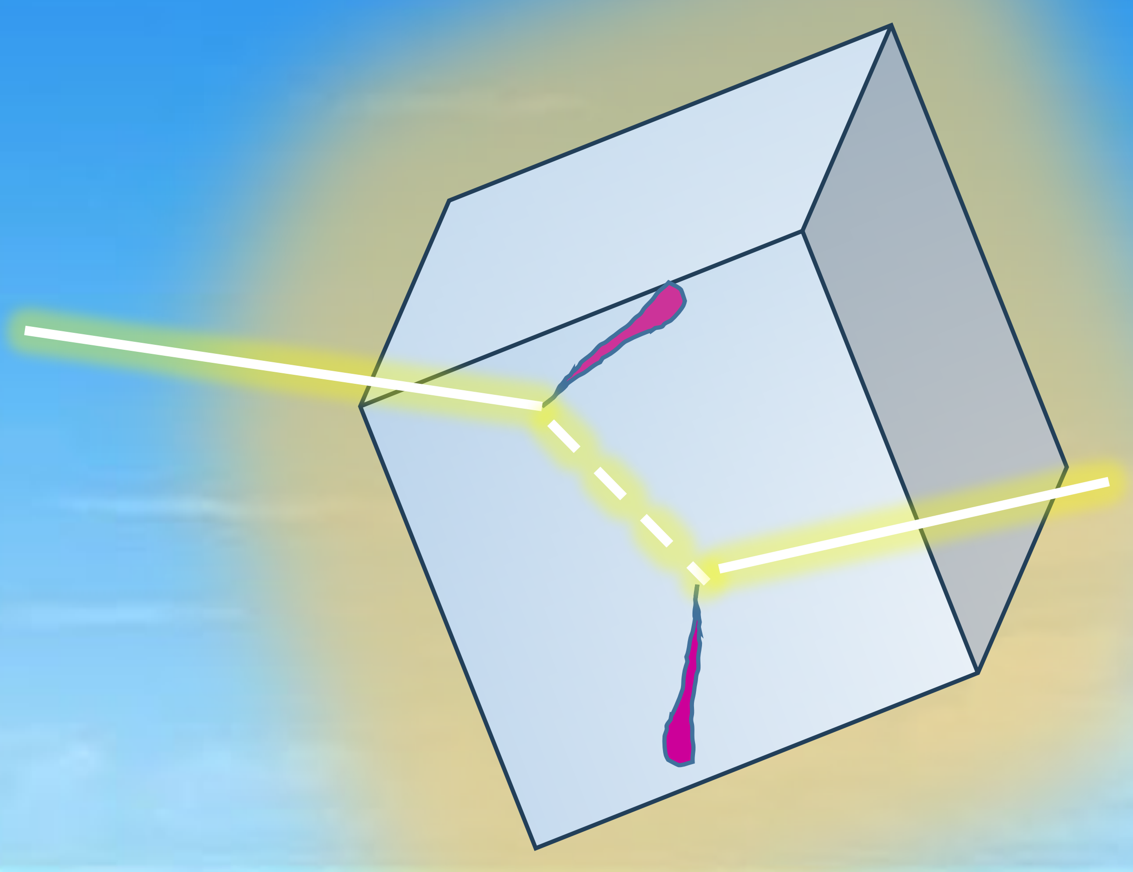
RIPTIDE: Recoil Proton Imaging Detector

Il gruppo (3.8 FTE)



Nome	Ruolo	FTE
Console Camprini P.	Ric ENEA	0.2
Giacomini Francesco	Pr Tecn CNAF	0.1
Lanzi Samuele	Dott	0.5
Massimi Cristian	Prof Ass	0.3
Mengarelli Alberto	Tecn INFN	0.2
Pisanti Claudia	Dott	1.0
Ridolfi Riccardo	Ass Ric	0.5
Spighi Roberto	Dir Ric INFN	0.5
Terranova Nicholas	Ric ENEA	0.5
Villa Mauro	Prof Ord	0
TOTALE FTE		3.8

Bologna, luglio 2025

RIPTIDE concept

Neutron detectors are crucial for nuclear/particle physics, astroparticle studies, radiotherapy, and radiation protection. Since neutrons do not ionize directly, detection relies on **nuclear reactions producing charged particles** (e.g. recoil protons from n-p scattering). Key challenges include:

- **Detection efficiency** depends on interaction probability and secondary particle escape.
- **Track imaging of recoil protons** remains a challenge due to high photon sensitivity requirements

RIPTIDE (RecoIl Proton Track Imaging DEtector) is a fast neutron tracker. It reconstructs neutron energy and momentum from proton tracks via single or multiple n-p scatterings, using two-body kinematics from the recoil angle and energy

$$E_n = \frac{E_p}{\cos^2\theta}$$

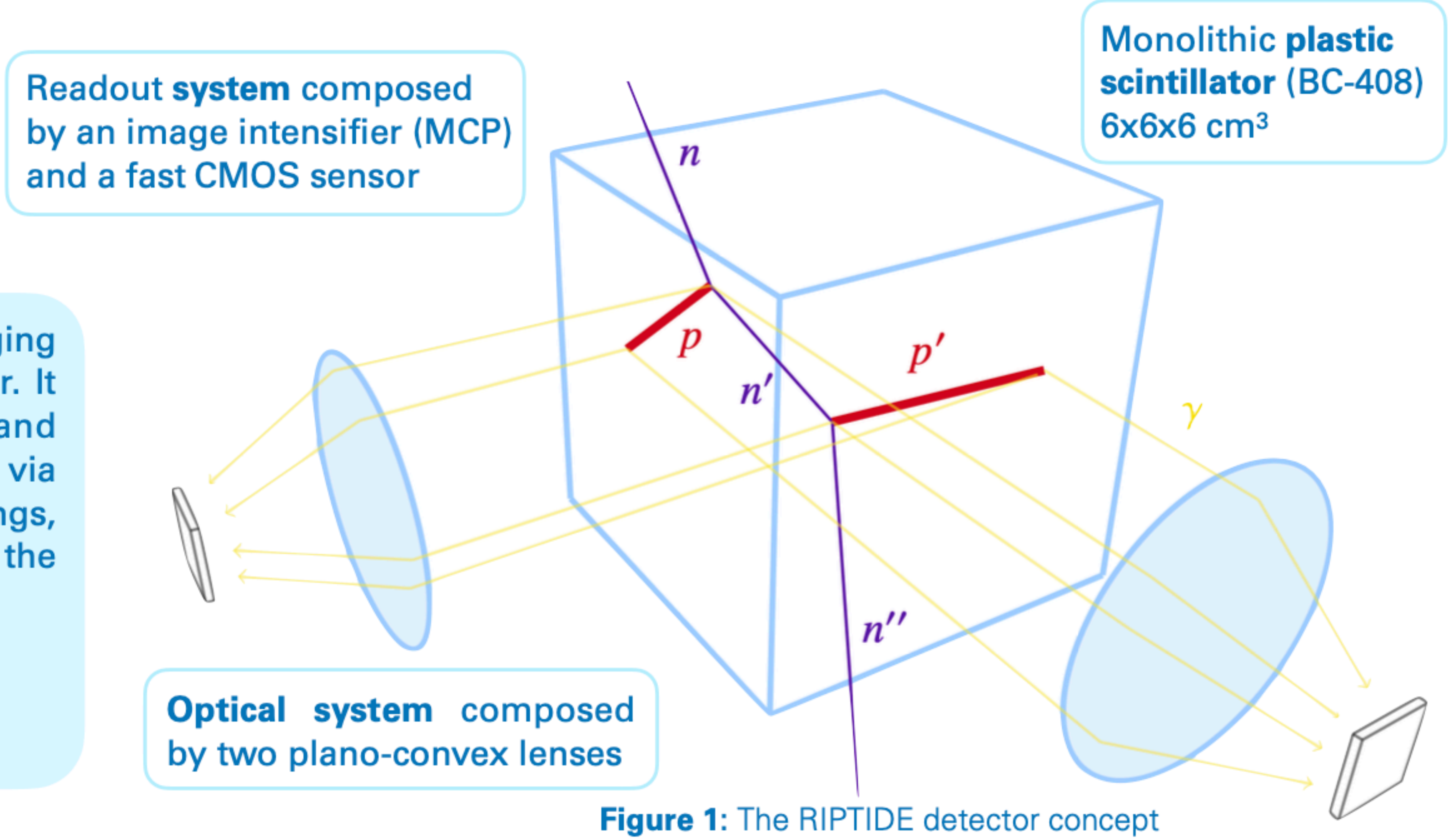
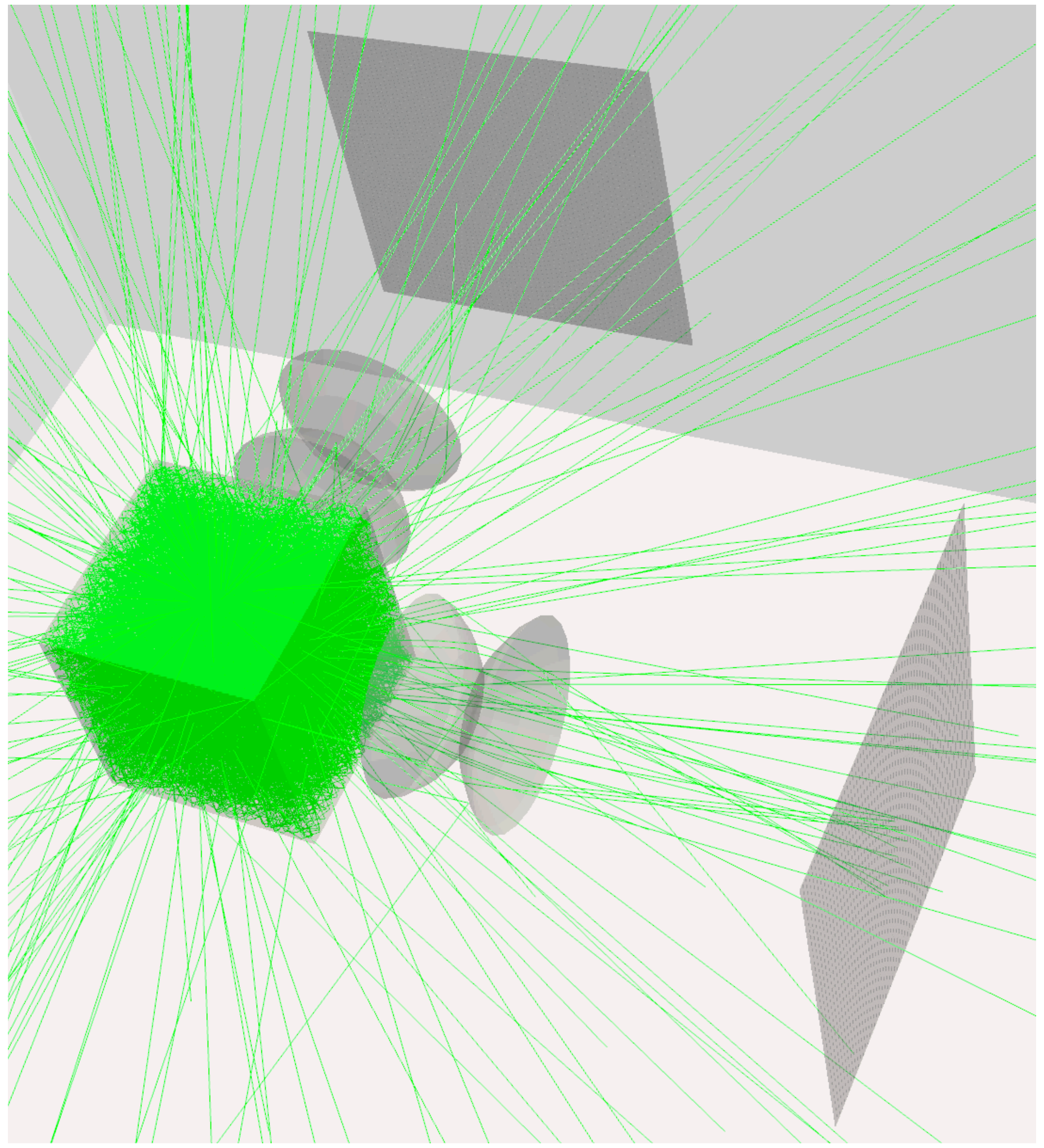


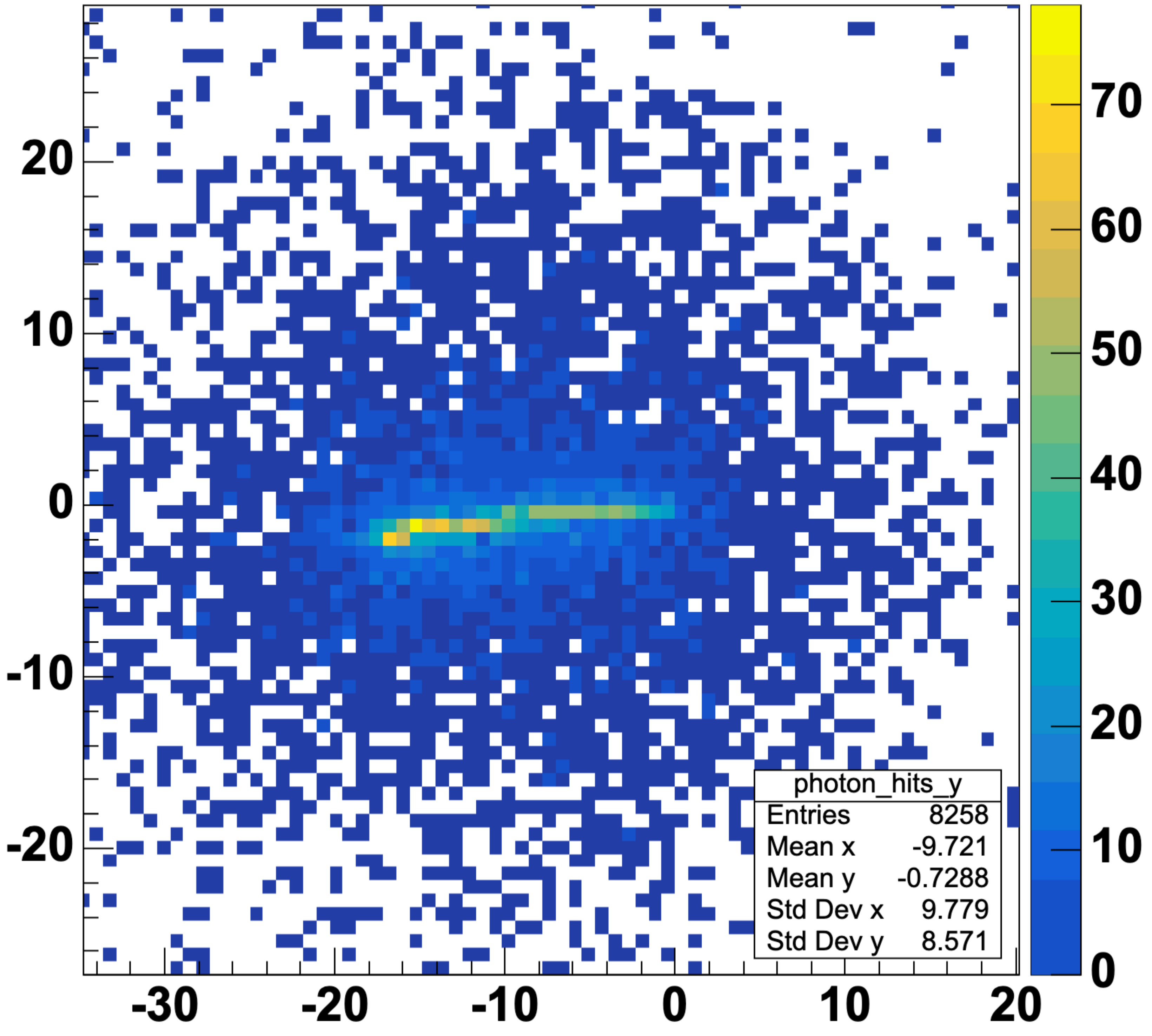
Figure 1: The RIPTIDE detector concept

Geant4 simulation

The detection concept was validated with Geant4 Monte Carlo simulations using appropriate physics lists. Key parameters, like cube-lens and sensor-lens distances, are configurable at runtime via macros



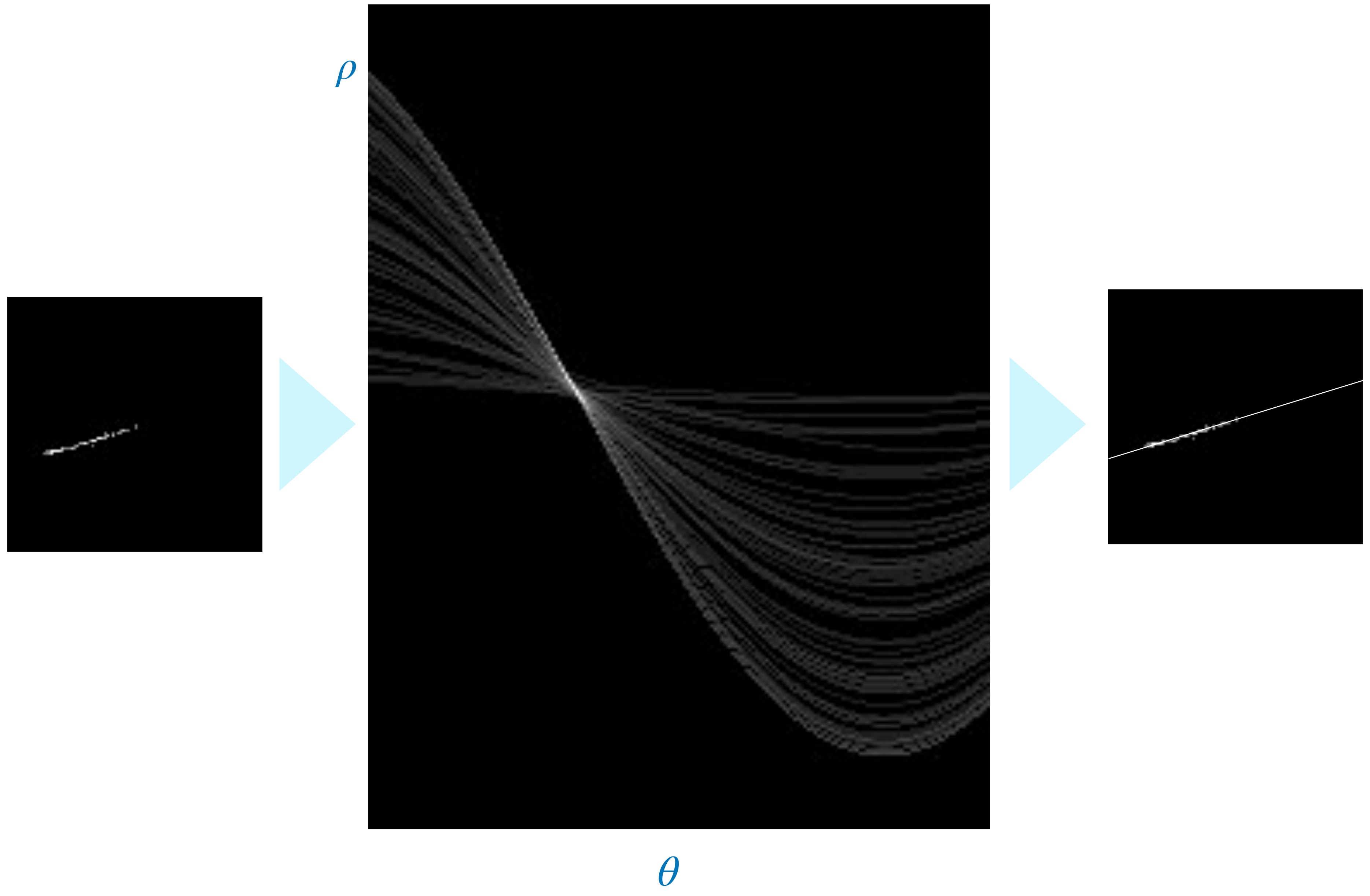
Visualisation of the Geant4 parametric simulation



Example of a simulation output showing a 30 MeV recoil proton

Reconstruction

Hough transform for direction



Each pixel is mapped into a parameter space where the most voted pixel corresponds to the best parameters for the line

Momenta method for orientation

1) find the barycentre

$$(u_b, v_b) = \left(\frac{\sum_i w_i u_i}{\sum_i w_i}, \frac{\sum_i w_i v_i}{\sum_i w_i} \right)$$

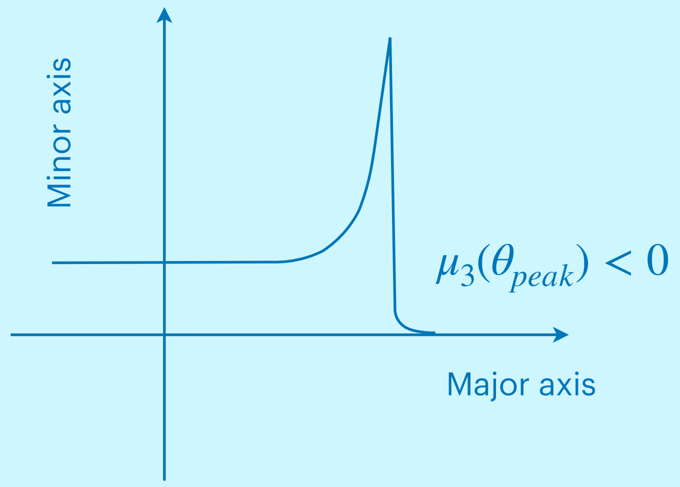
$$u_i \to u_i - u_b \qquad v_i \to v_i - v_b$$

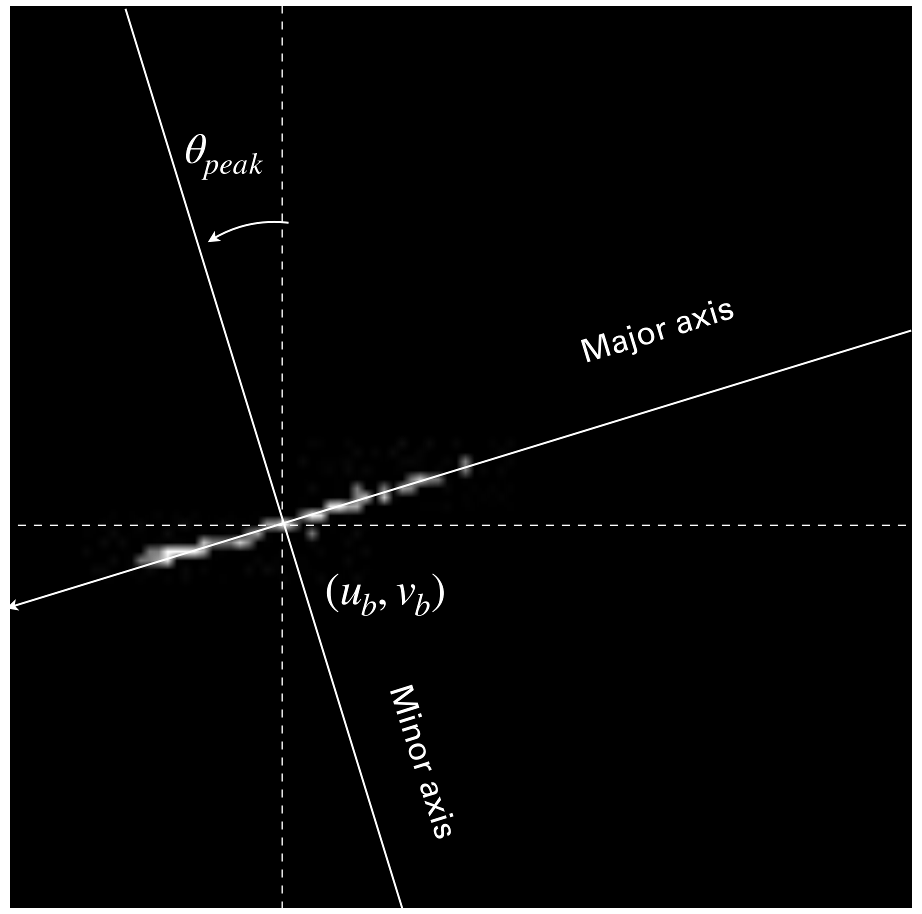
2) rotate the axes

$$\begin{pmatrix} u_i'(\theta) \\ v_i'(\theta) \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} u_i \\ v_i \end{pmatrix}$$

3) evaluate the skewness

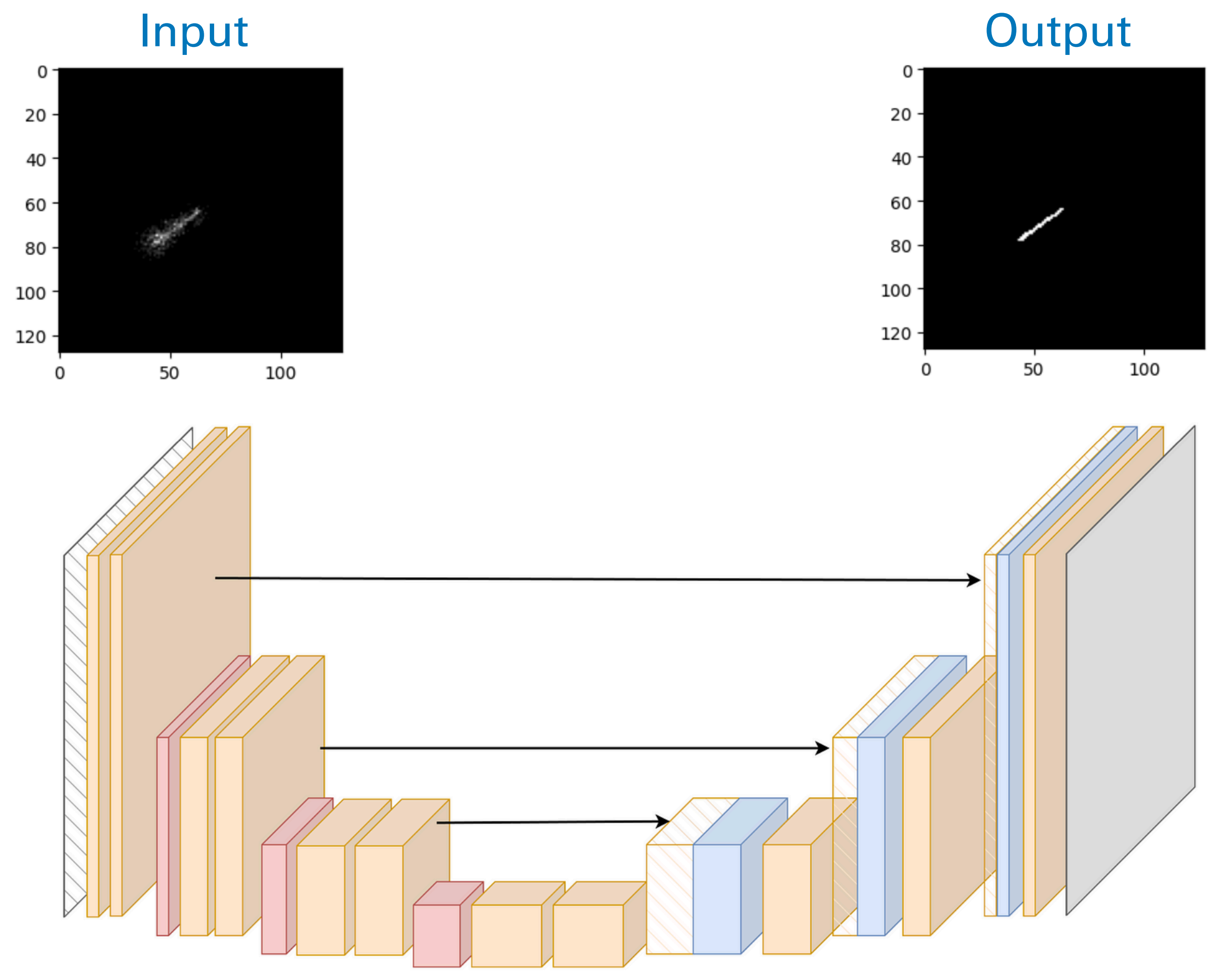
$$\mu_3 = \frac{\sum_i w_i (u_i \cos\theta_{peak} + v_i \sin\theta_{peak})^3}{\sum_i w_i}$$





Reconstruction

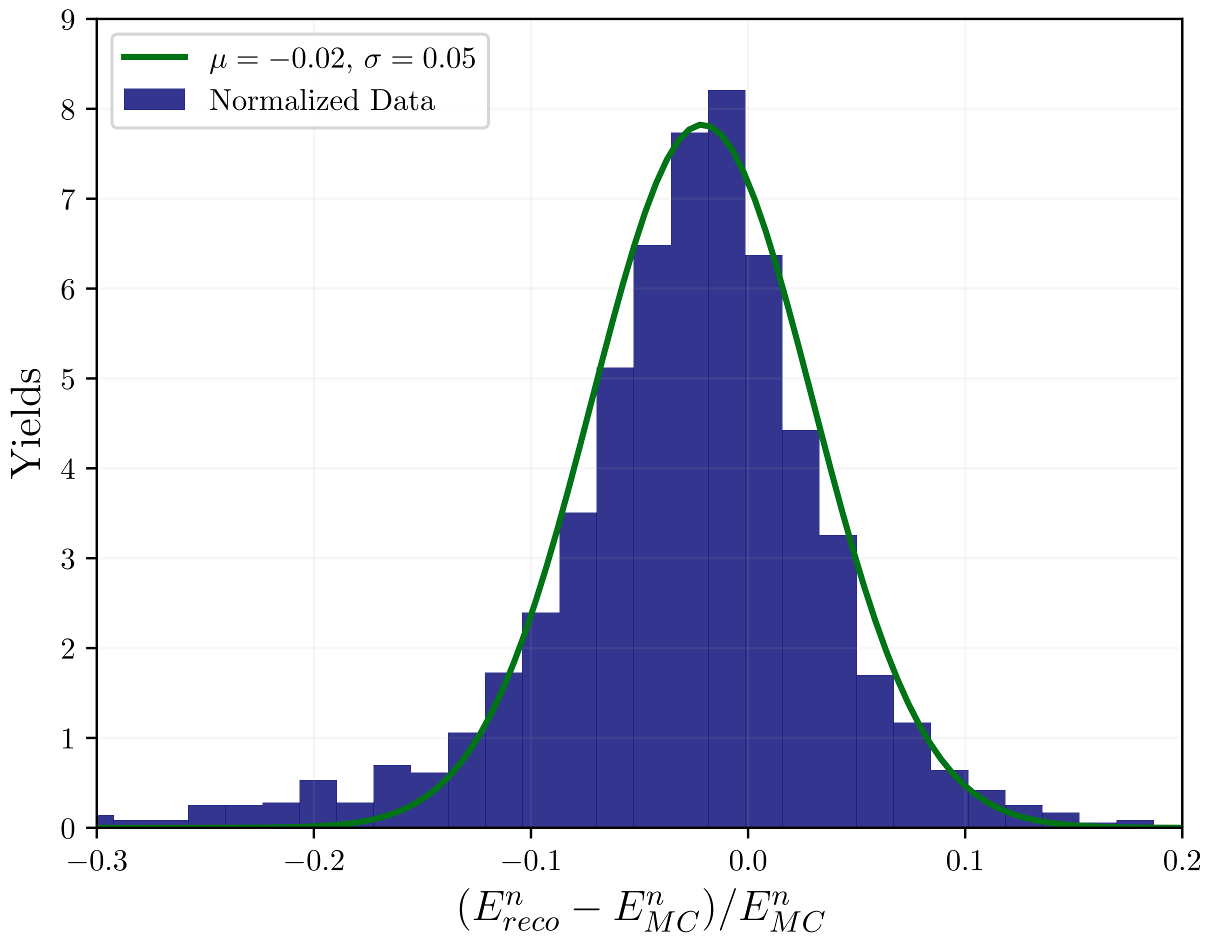
UNet model fot track restoration

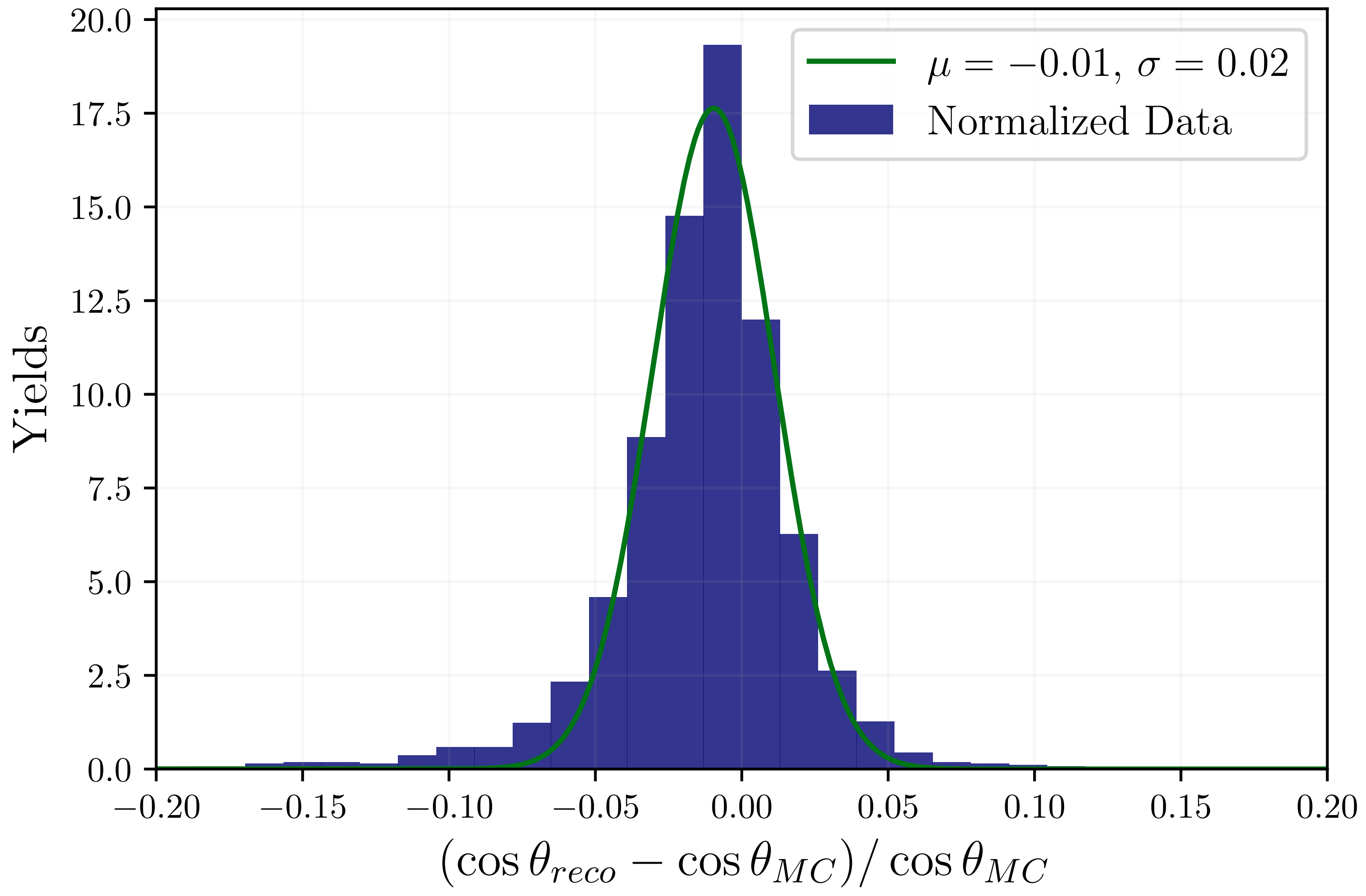


The UNet model, a convolutional neural network for image segmentation, is used to facilitate **proton range** estimation by correcting optical aberrations

Results on MC data

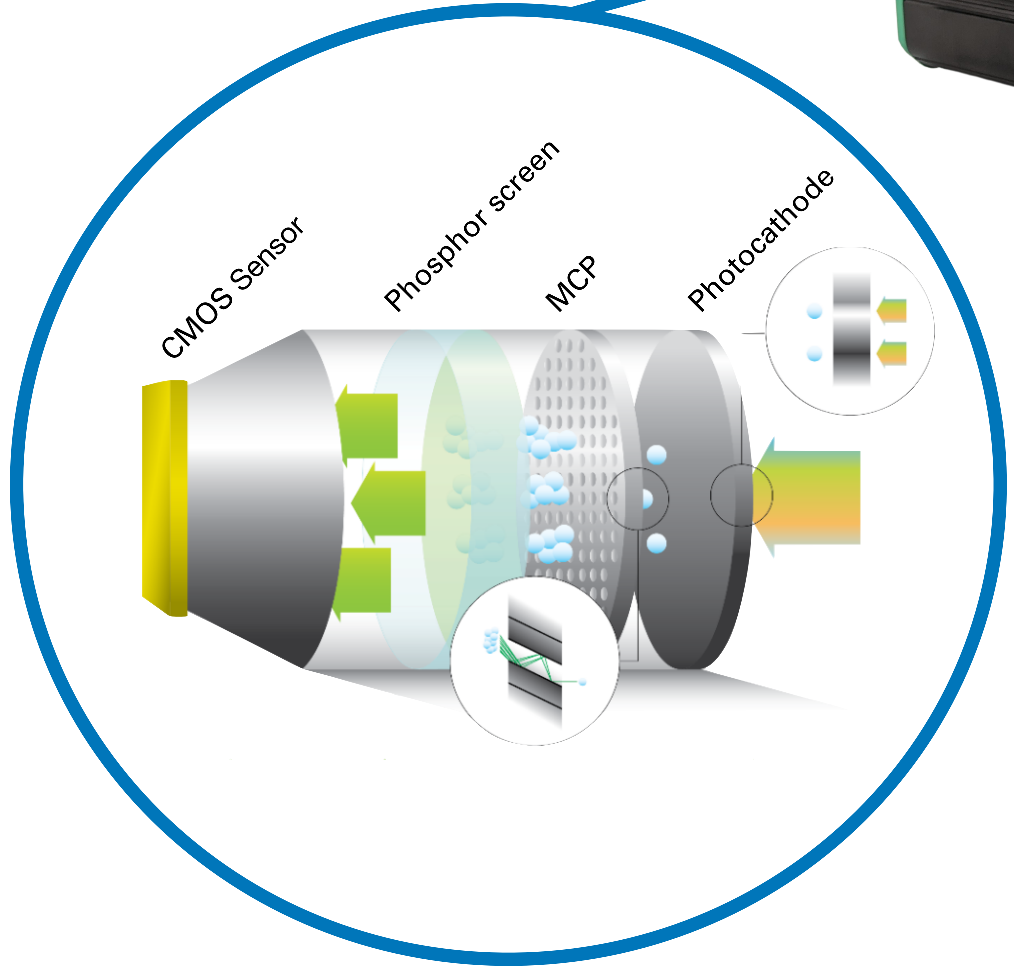
Reconstruction results with simulated monochromatic neutrons show a 2% resolution on the reconstructed angle cosine and 5% on neutron energy



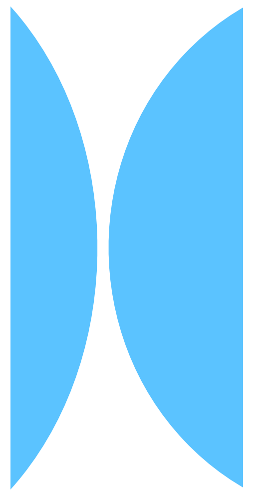


Experimental Setup

HiCAM FLUO (Lambert)

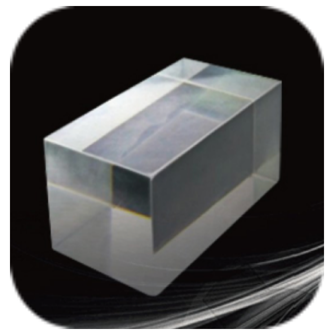


Optical system



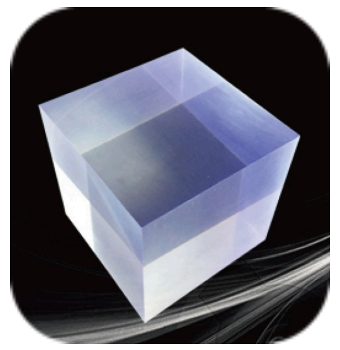
$f = 75$ mm $\quad f = 60$ mm

Scintillators



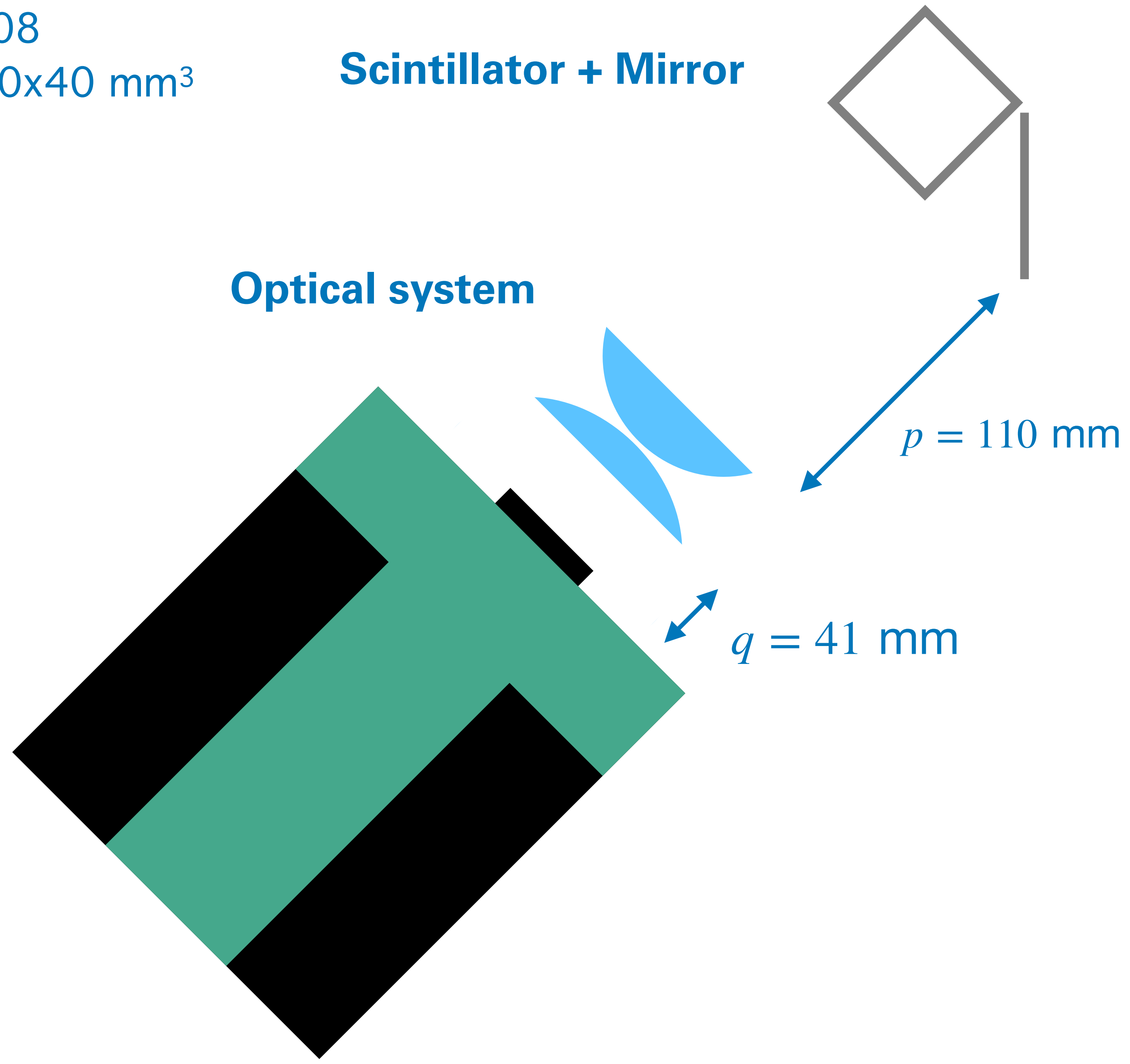
CsI(Tl)
20x20x20 mm^3

GAGG
10x10x10 mm^3

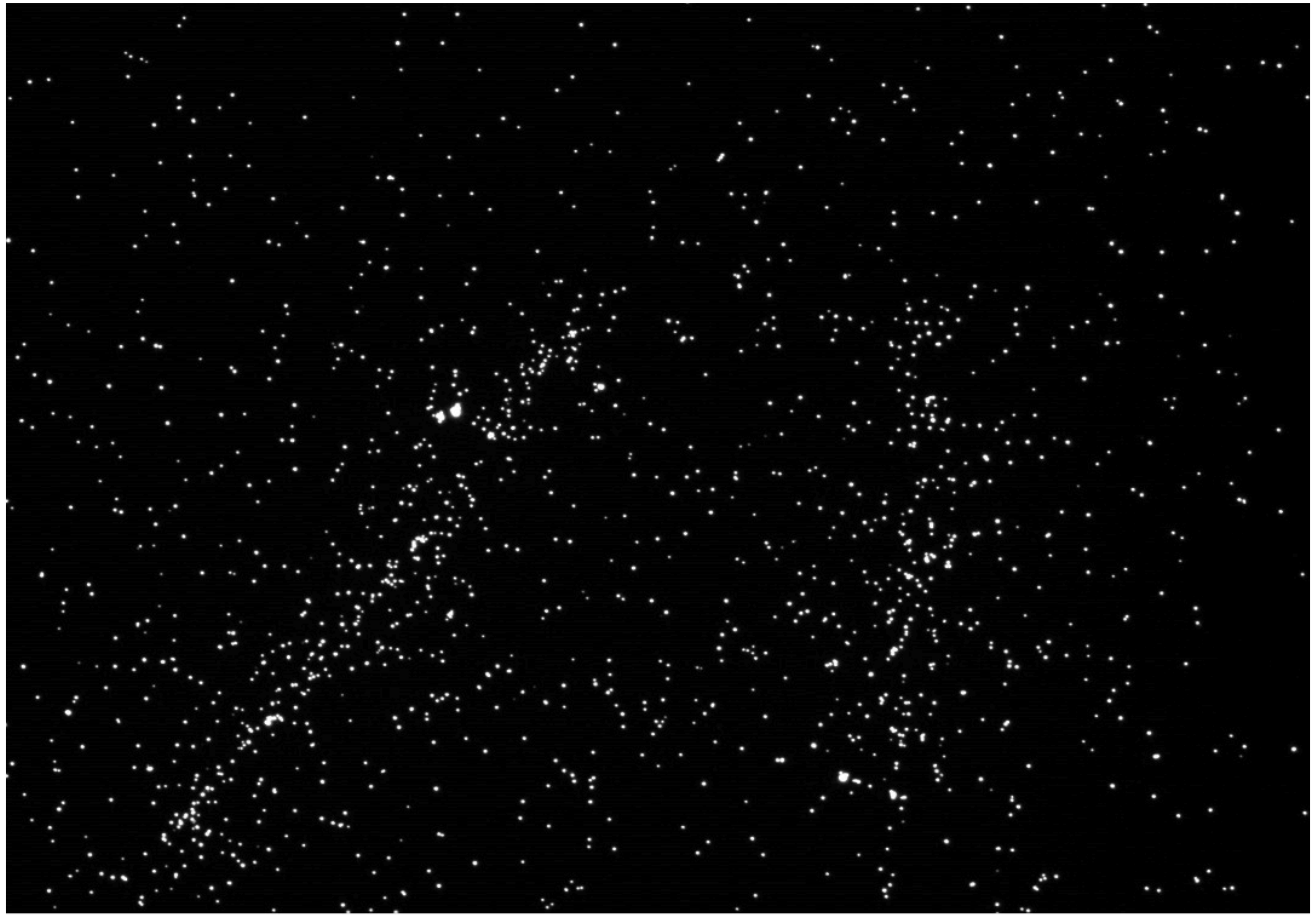


BC-408
40x40x40 mm^3

We used the HiCAM FLUO camera from Lambert, which integrates all the necessary readout components for our detector. It includes an **image intensifier** optically coupled via fiber optics to a **fast CMOS camera**, connected to a computer through a frame grabber. The optical system consists of **two plano-convex lenses** with focal lengths of 75 mm and 60 mm, both two inches in diameter. This setup allows us to capture scintillation light images from muon tracks in various scintillators, including **CsI(Tl)**, **GAGG**, and **BC408**. To enable **stereoscopic 3D reconstruction** of the tracks, a **mirror** was placed beside the scintillator cube



First observation



First image of a cosmic muon track passing through the CsI(Tl) scintillator. Two tracks are visible: the direct track and its mirrored image due to the reflection

Conclusions

- RIPTIDE is an innovative detector designed to perform neutron tracking through the scintillation light produced by recoil protons, without the need for charge readout or segmentation
- Direction and orientation of proton tracks are reconstructed using the Hough transform and the momenta method. A U-Net deep learning model is used to enhance the reconstruction of the track length
- The neutron energy is estimated by combining the reconstructed direction and track length. Monte Carlo simulations show promising results when the neutron source position is known, achieving angular and energy resolutions of approximately 2% and 5%, respectively
- First muon tracks have been successfully observed in the laboratory using a CsI(Tl) scintillator
- The same reconstruction techniques will be applied to real data