Scintillating light track reconstruction for fast neutron detection based on deep-learning techniques

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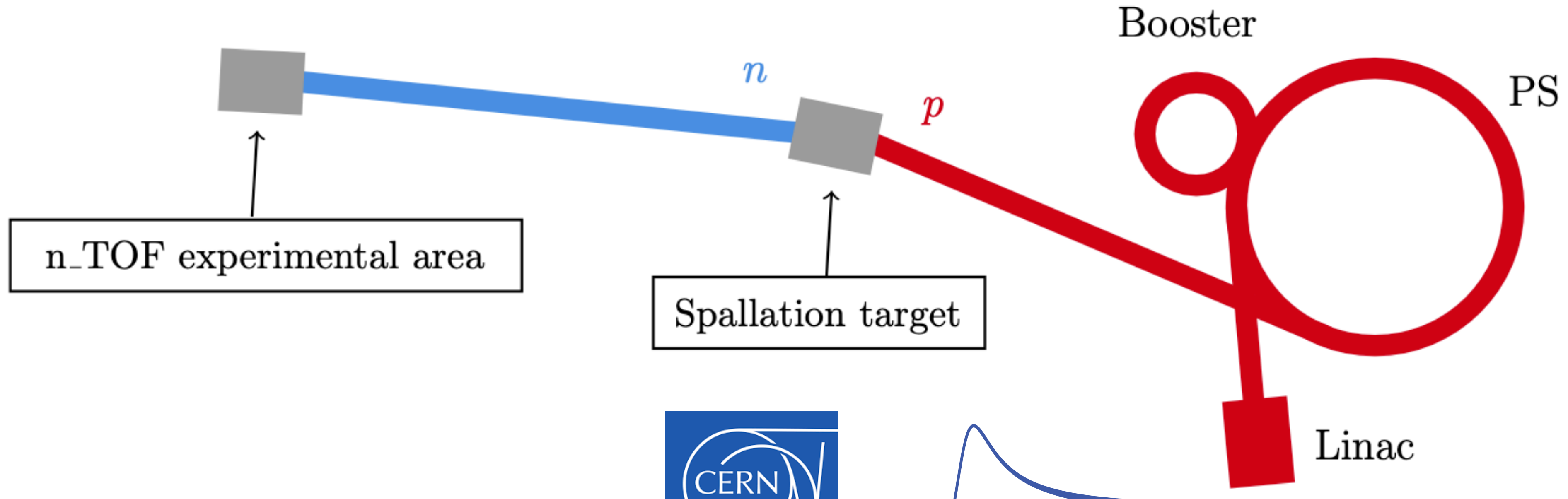
Outline

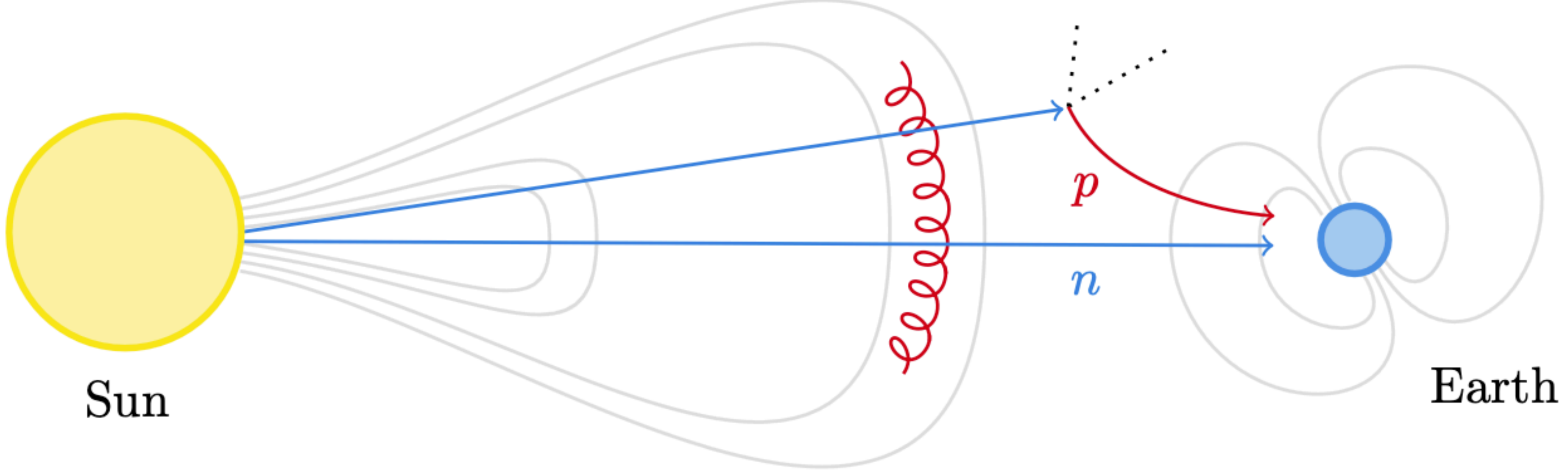
- Motivations for neutron tracking
- RIPTIDE detector concept
- Current experimental setup
- Monte Carlo simulations
- Track orientation reconstruction algorithms
- UNet model for track length reconstruction
- Preliminary results
- Conclusions

Motivations for neutron tracking

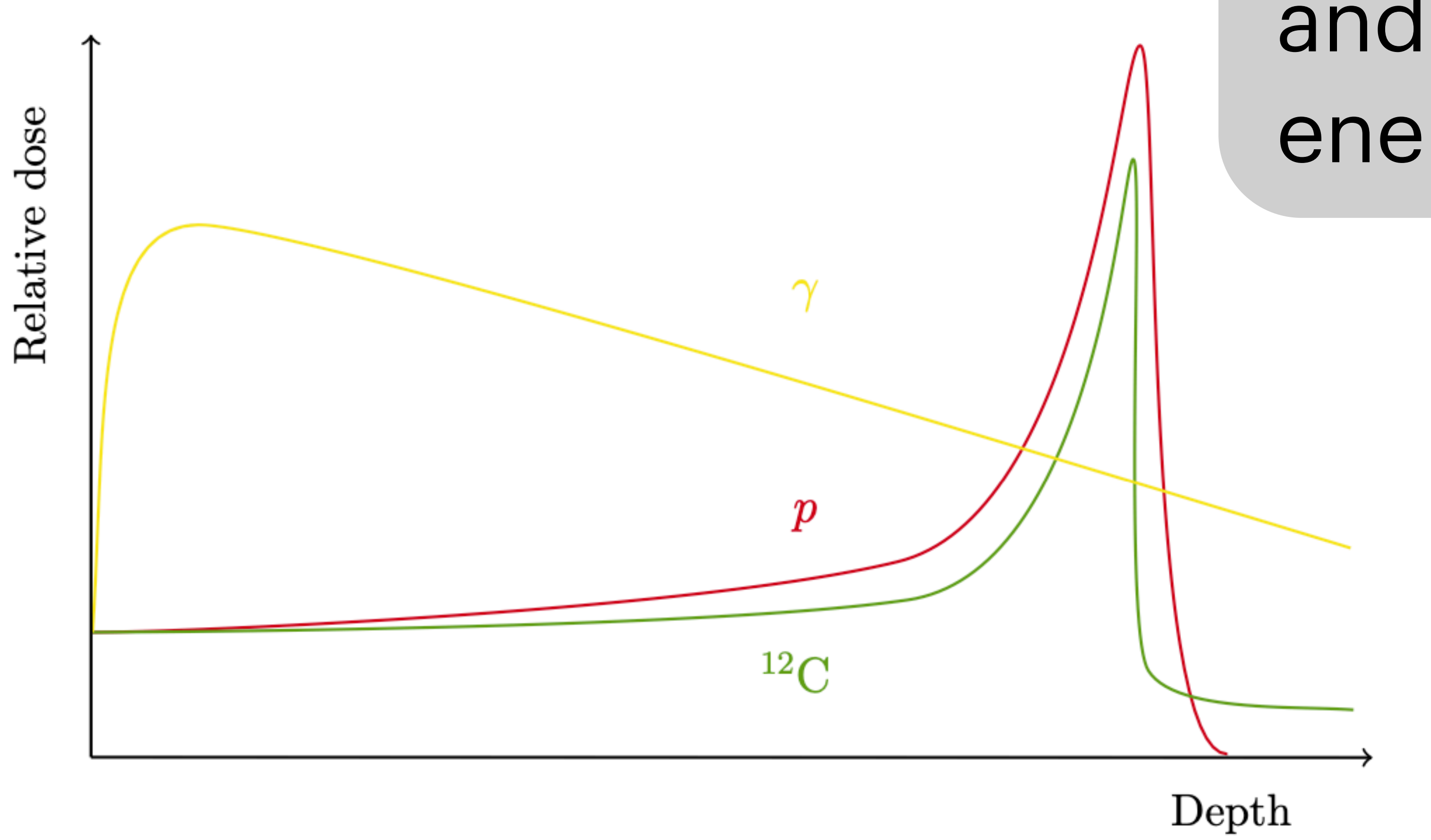
Experimental nuclear physics



Solar neutrons

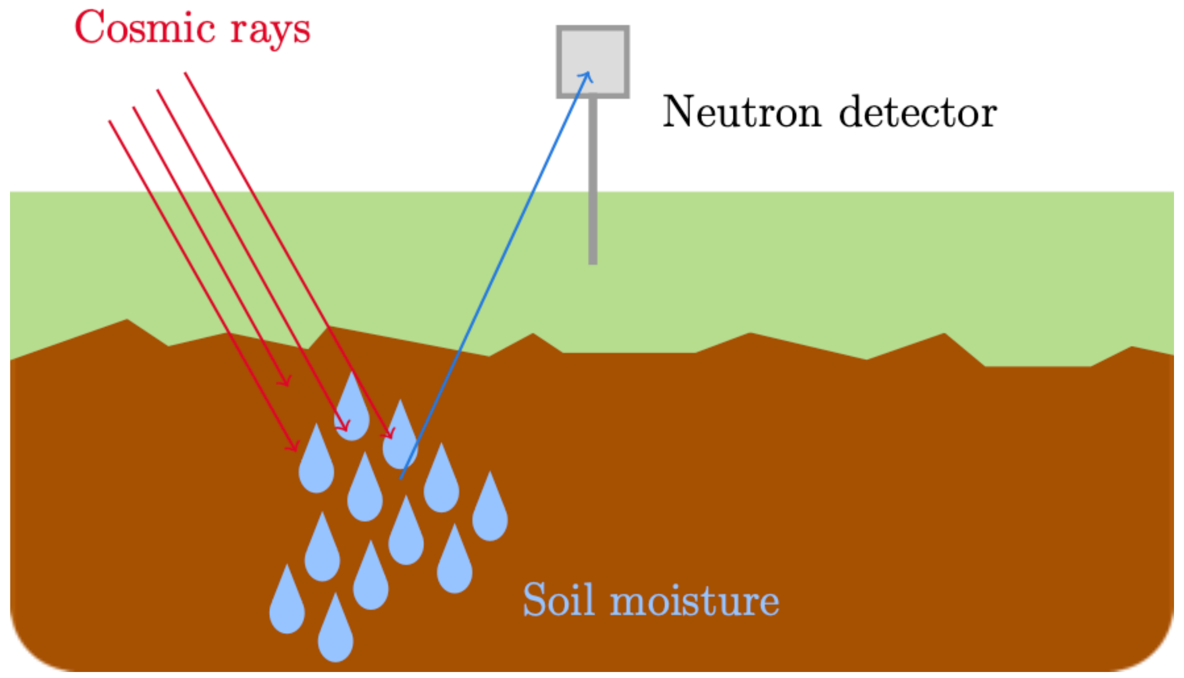


Neutron trackers are crucial for both fundamental and applied research, as they provide not only the energy but also the direction of incoming neutrons



Hadrontherapy

Space radio-protection

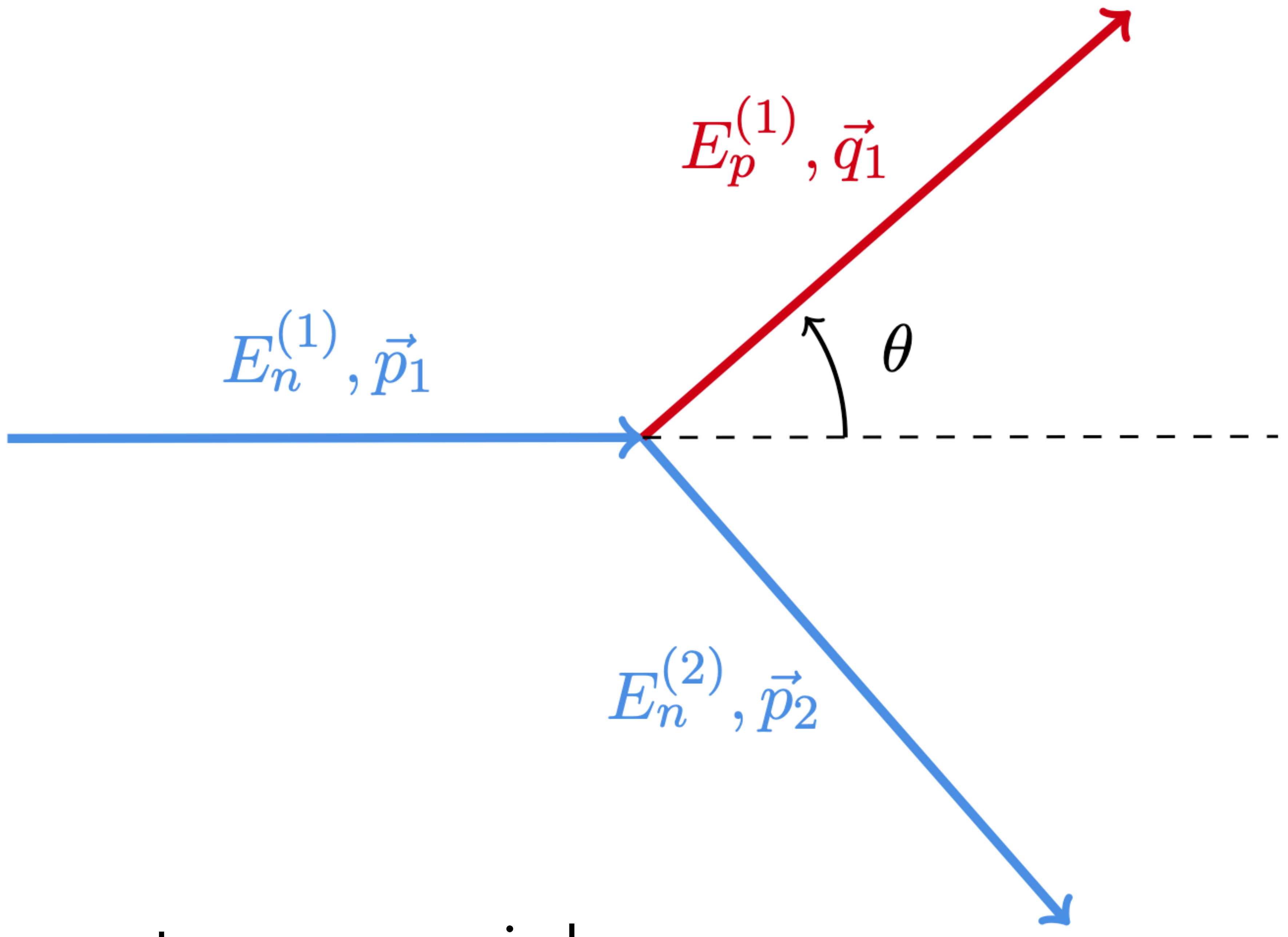


Environmental physics

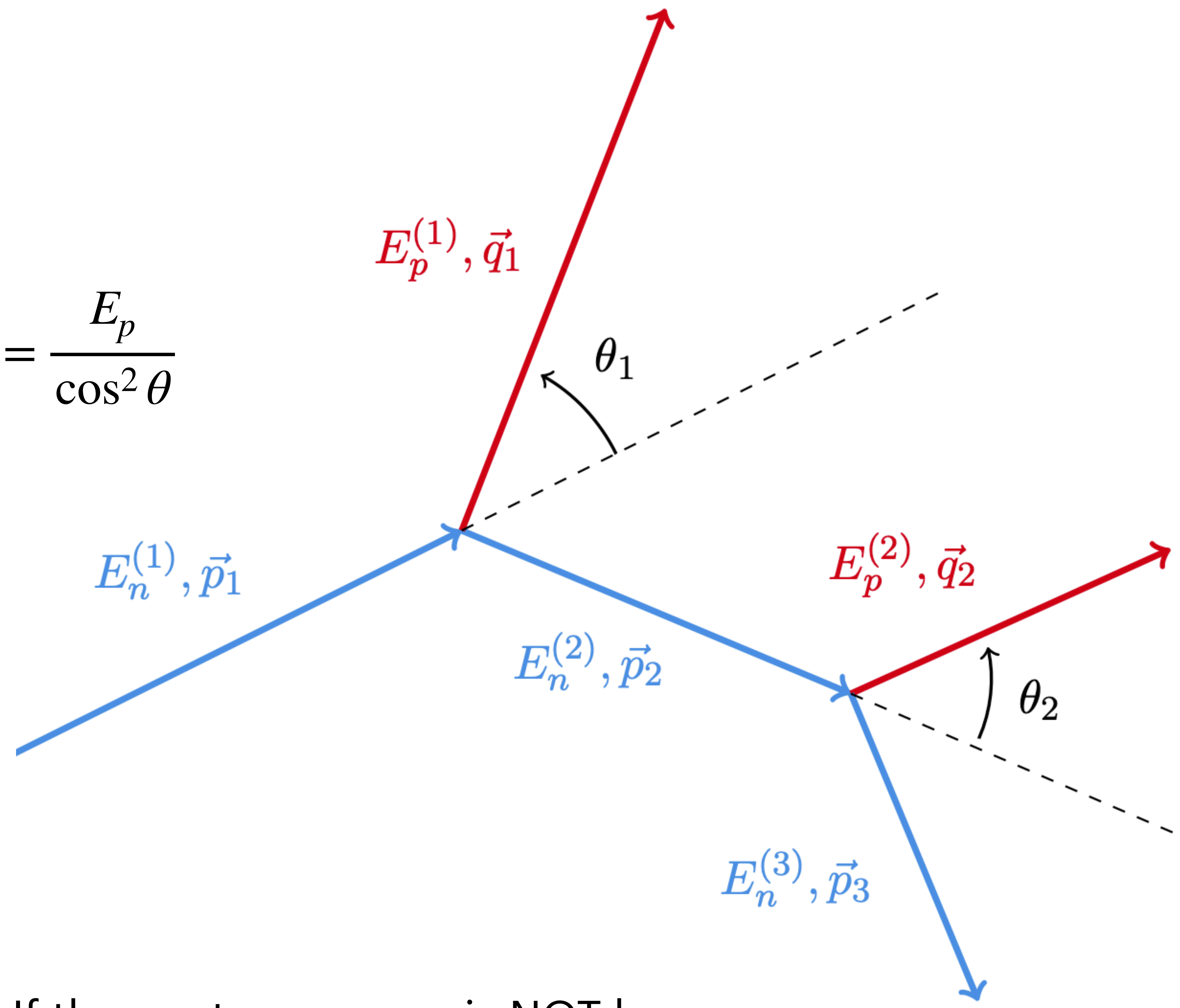
Techniques for Recoil Proton Track Imaging

Fast neutrons scatter like **billiard balls** with **protons** but are **invisible** because they have no charge and don’t ionize matter directly

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



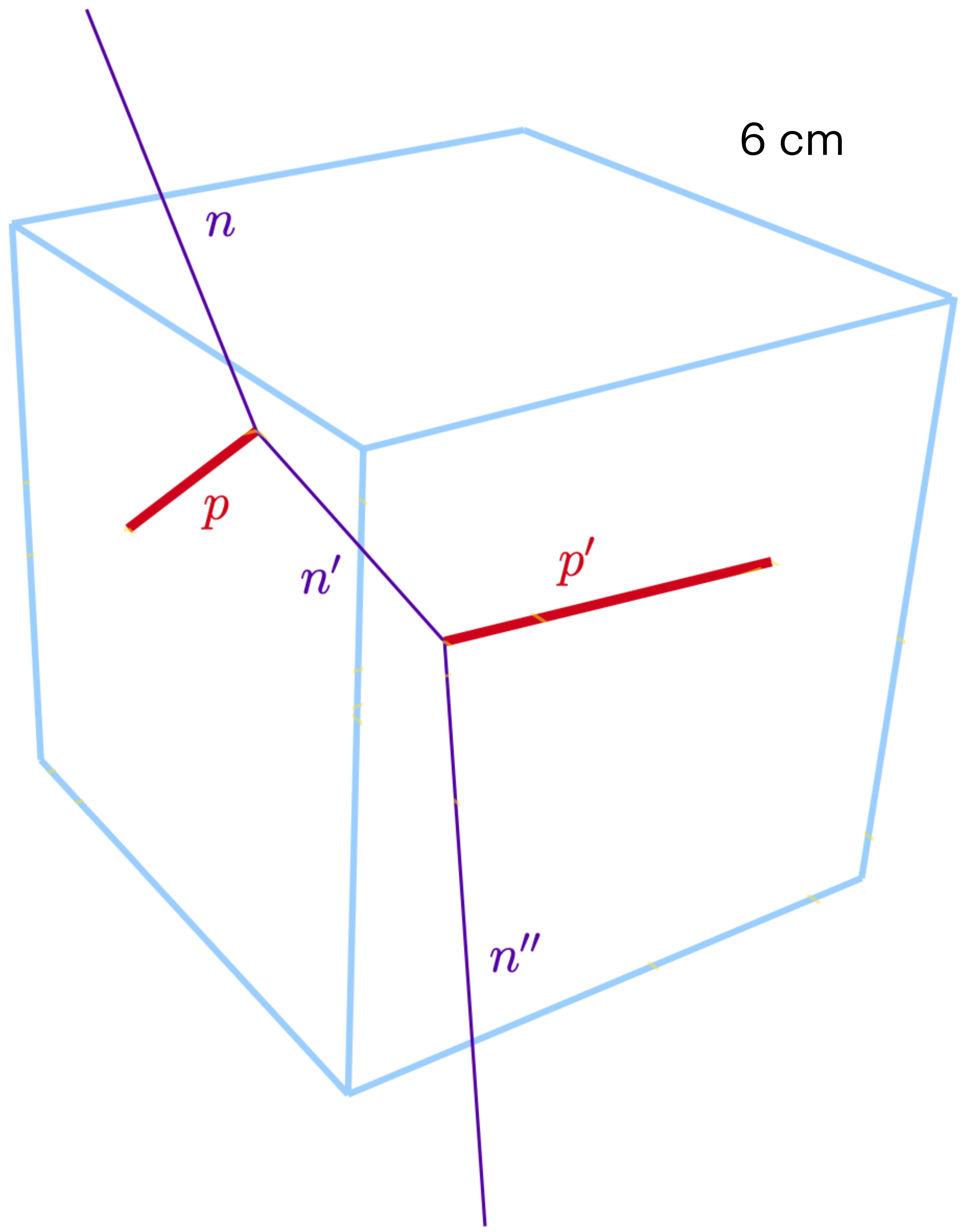
If the neutron source is known a **single scattering** is sufficient



If the neutron source is NOT known a **double scattering** is needed

RIPTIDE detector concept

A **plastic scintillator** is ideal for n-p reactions; protons from hydrogen atoms become visible through the emitted **scintillation light**



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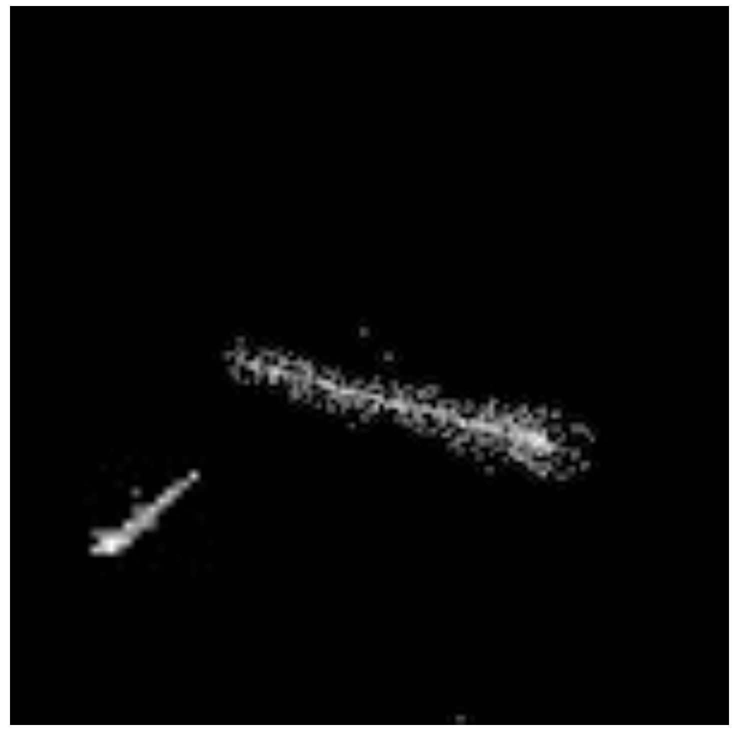
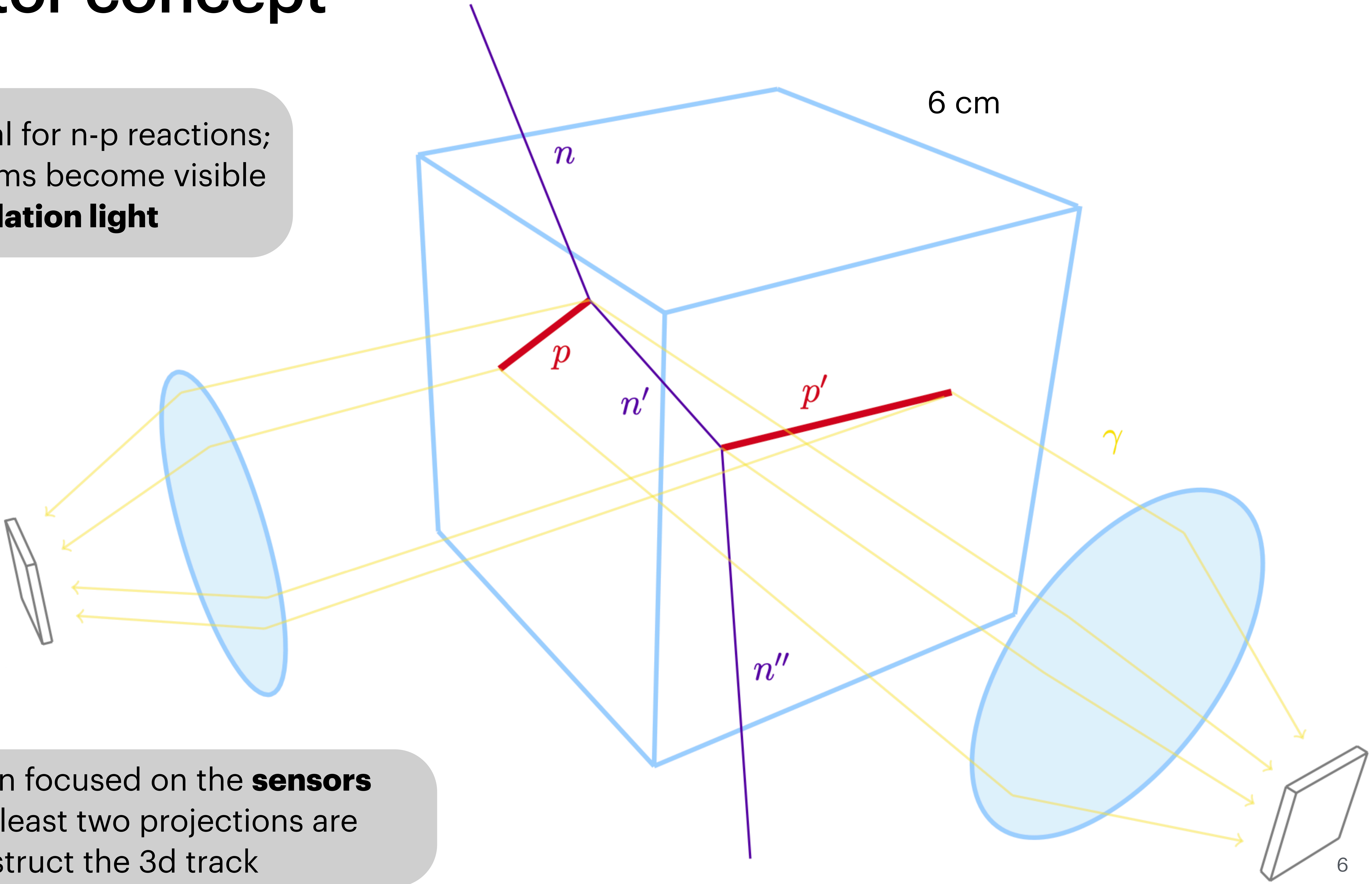
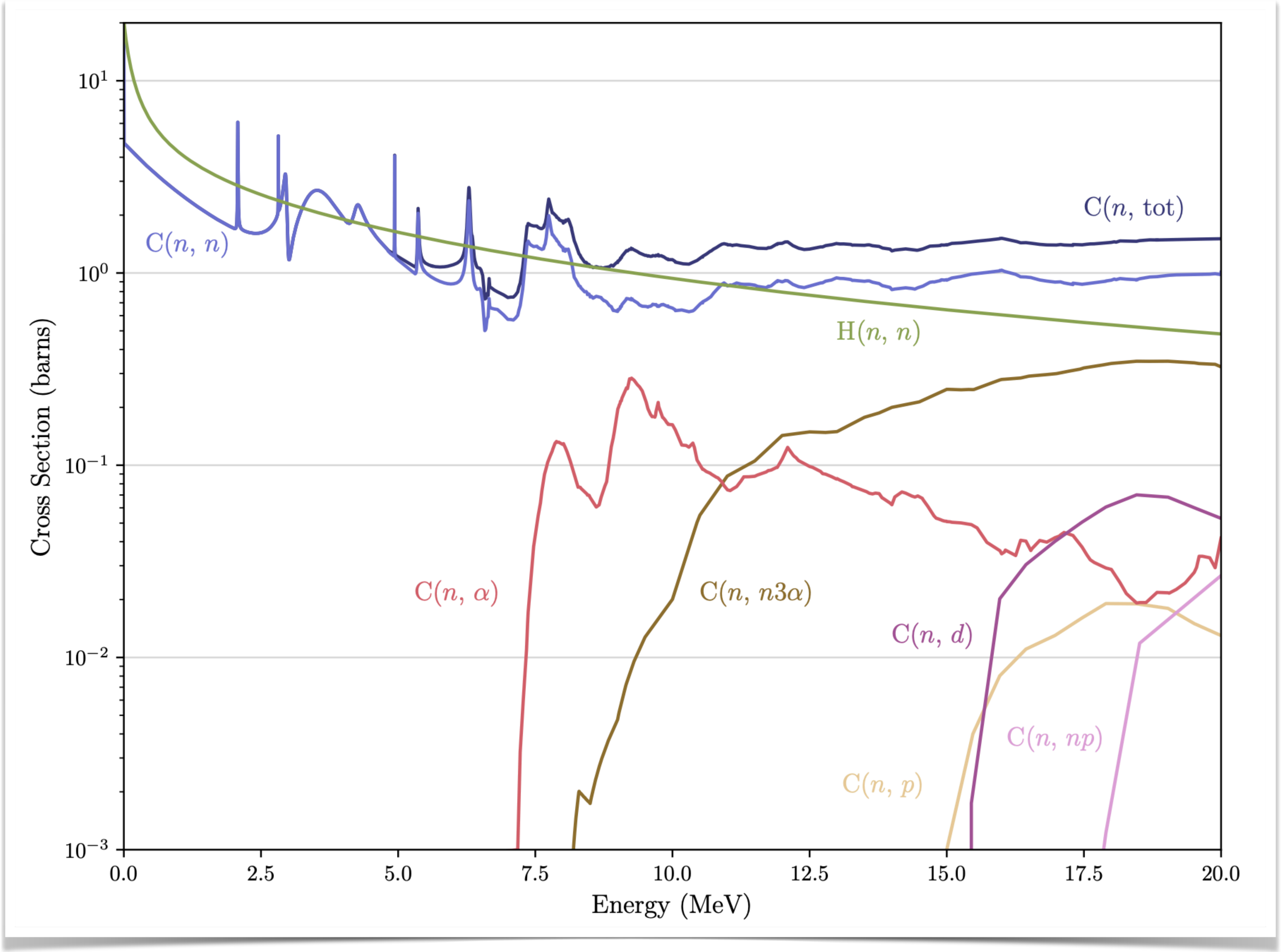




The generated light is than focused on the **sensors** through **lens systems**; at least two projections are needed in order to reconstruct the 3d track

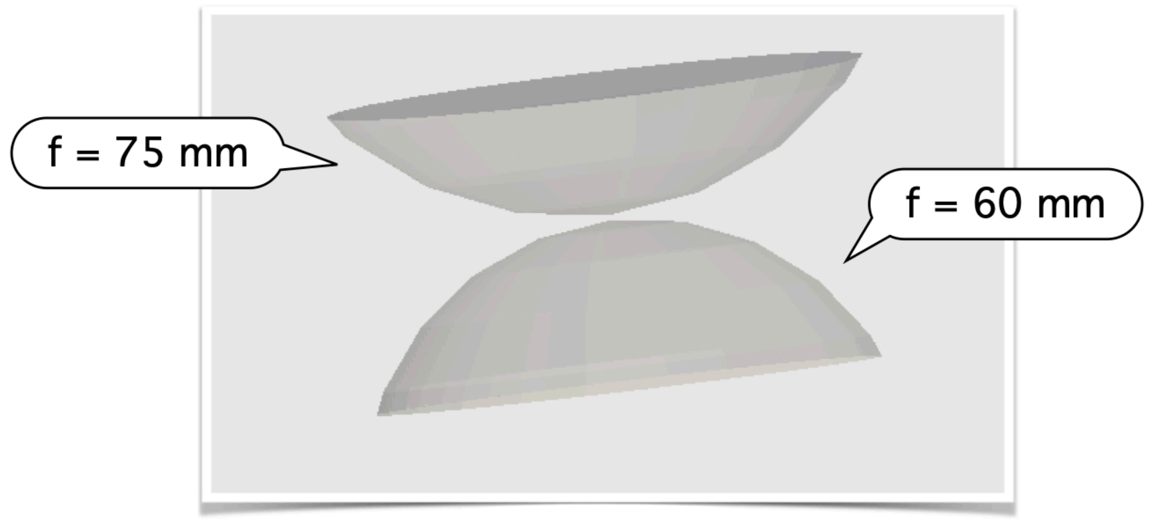
Not only n-p scattering

In a plastic scintillator n-C reactions can also occur but **carbon ions** are hard to see due to short range



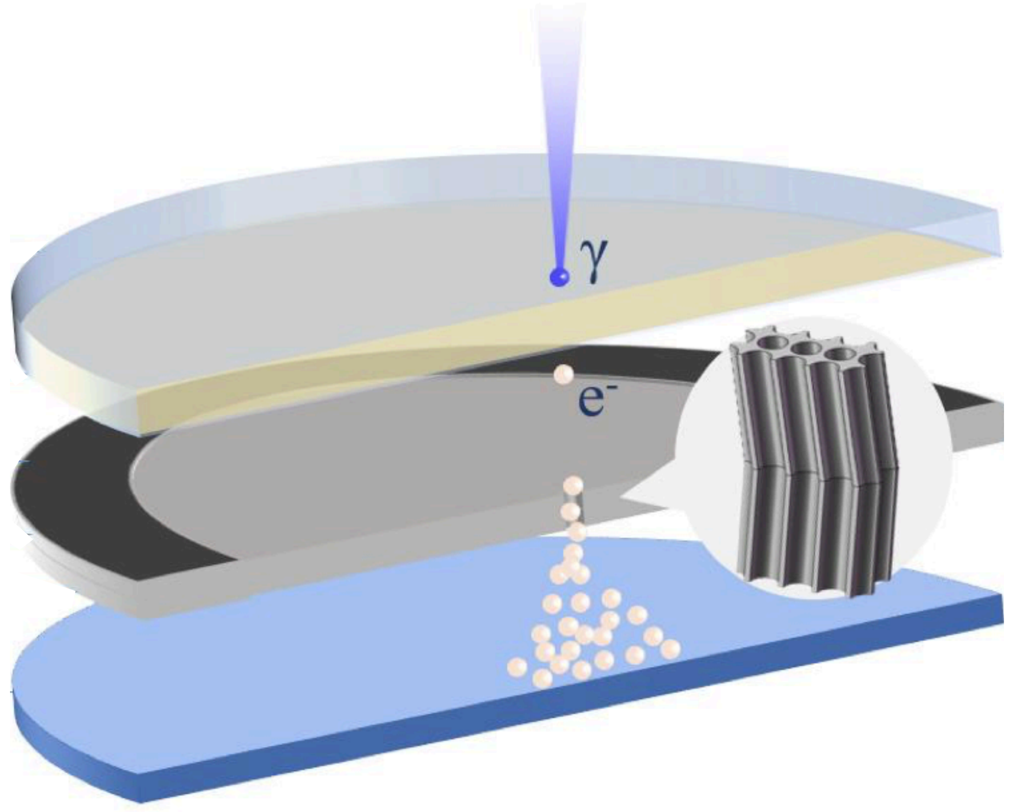
RIPTIDE: current status

Lens system



Ramsden eyepiece

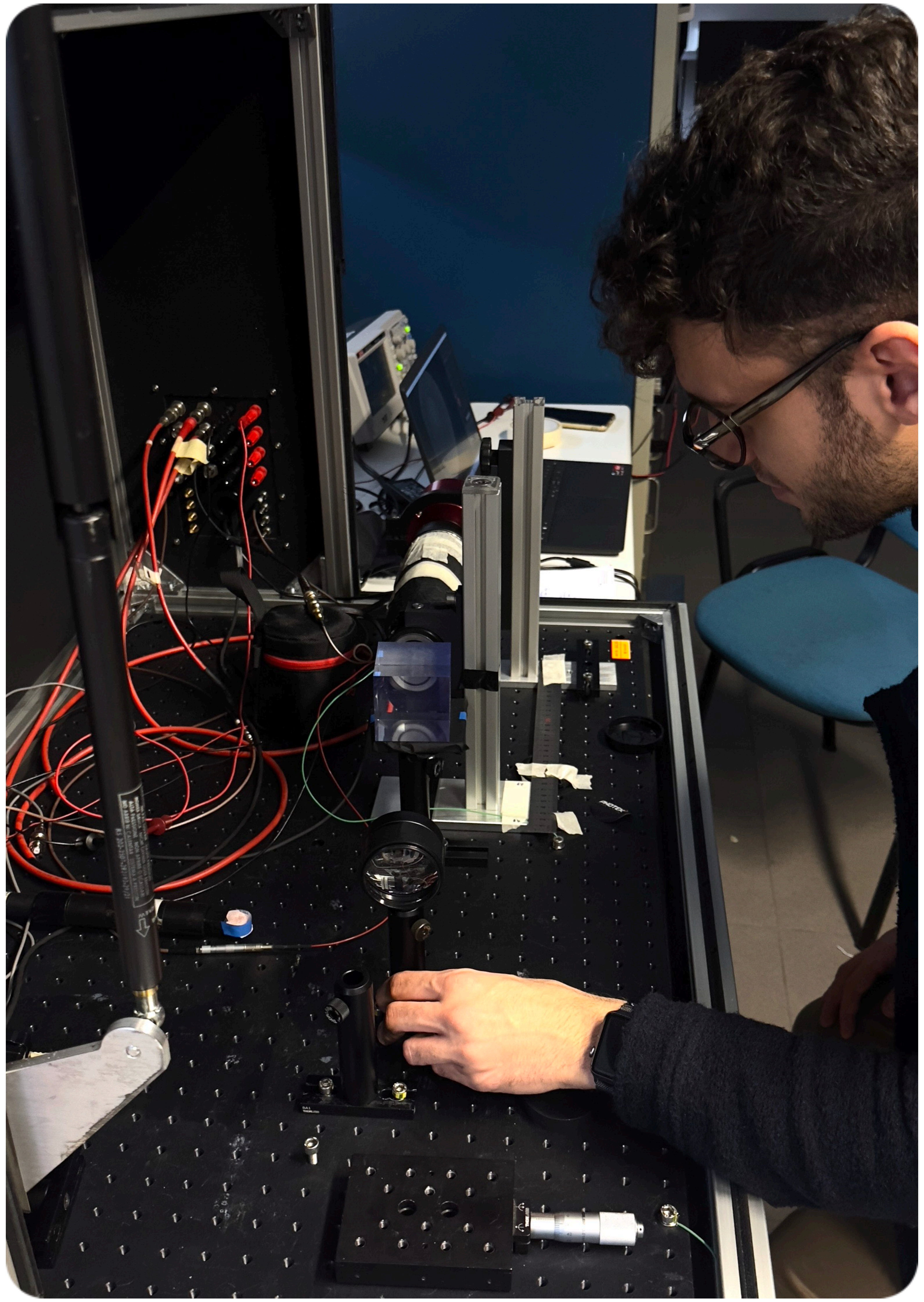
Image intensifier



Photek MCP 40mm

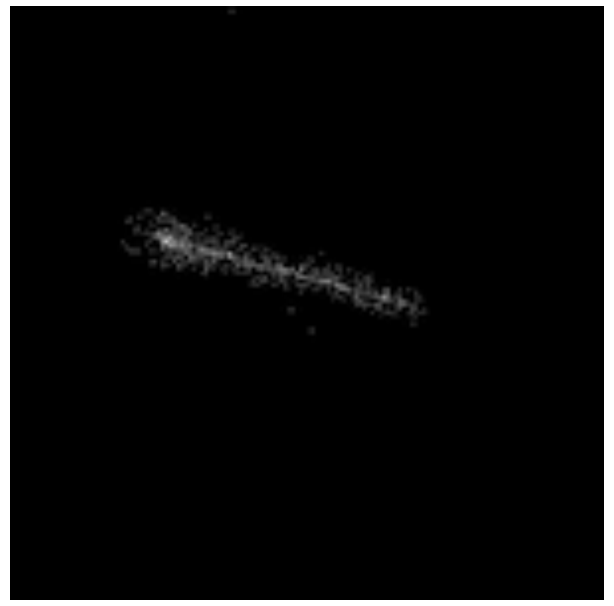
CMOS camera

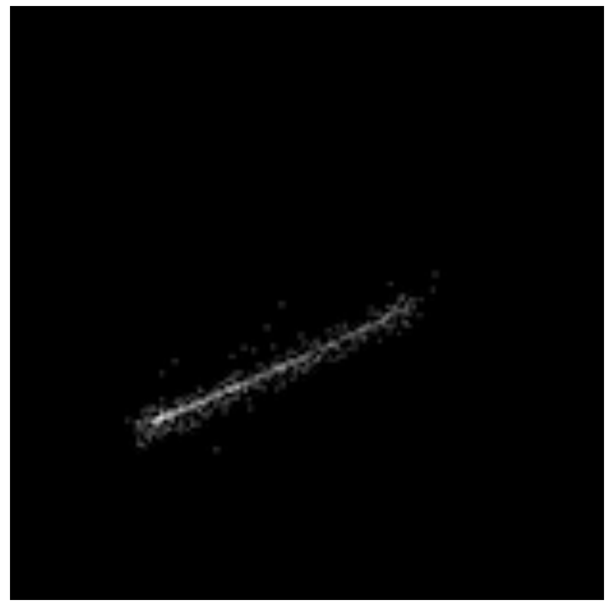
Cyclone 2 2000 M



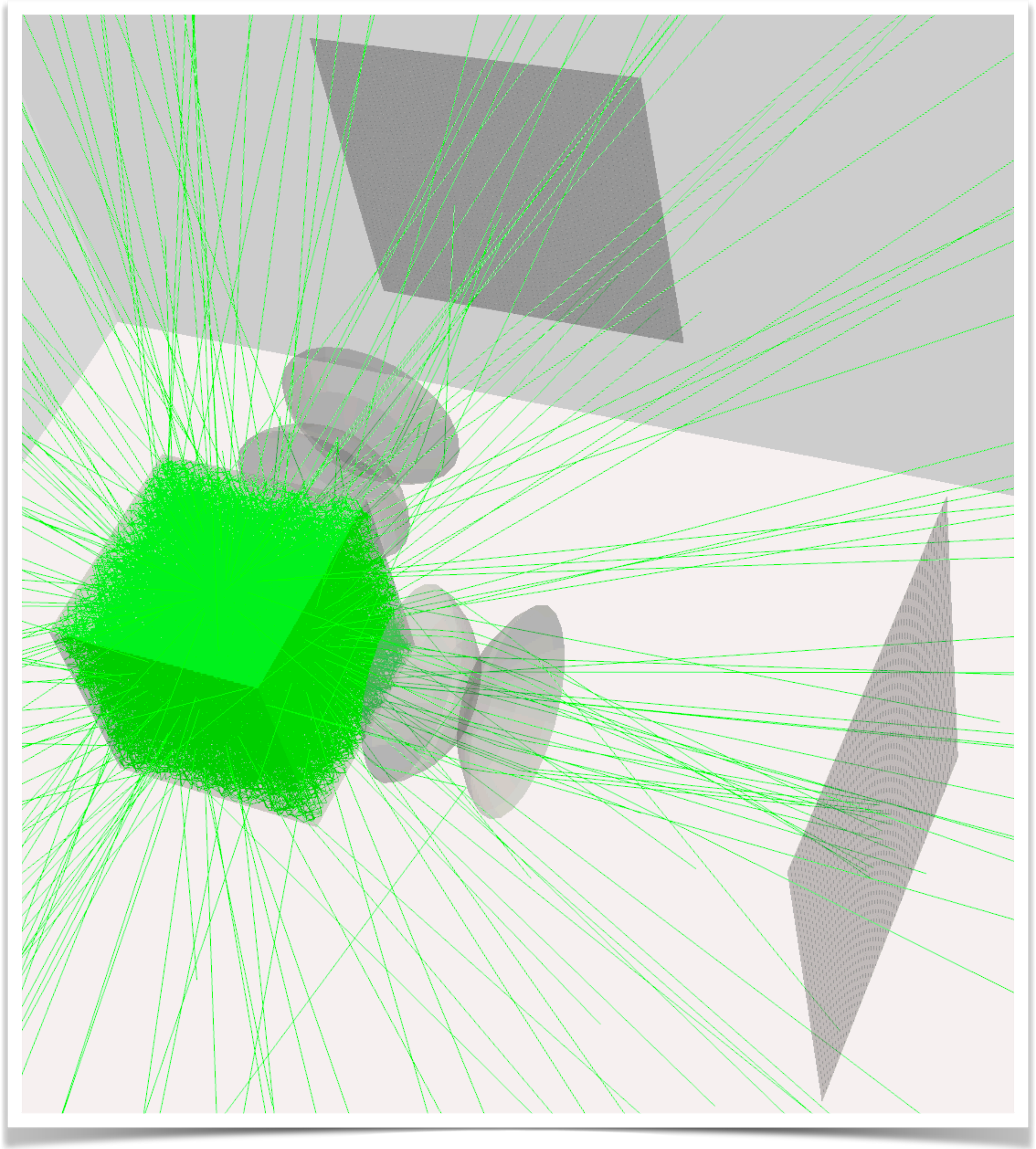
Monte Carlo simulations

To test the viability of the experiment, a **Geant4 simulation** has been developed to optimise the detector components and the geometric parameters





The outputs of the simulation are **two orthogonal projections** of the proton track



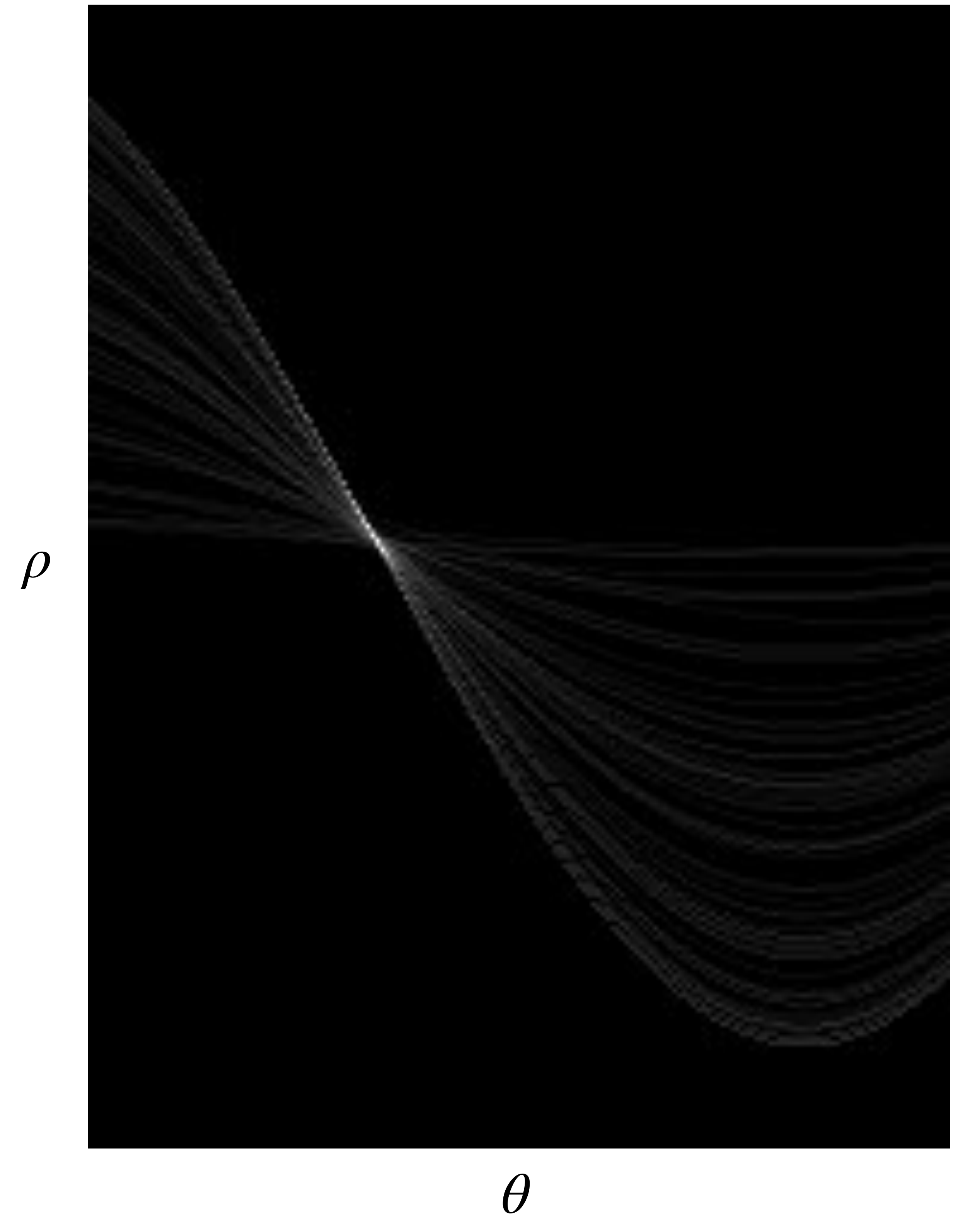
To estimate neutron energy and direction, we need to analyze the proton recoil track by estimating its **direction**, **orientation**, and **length**, which is correlated to the energy.

Track direction

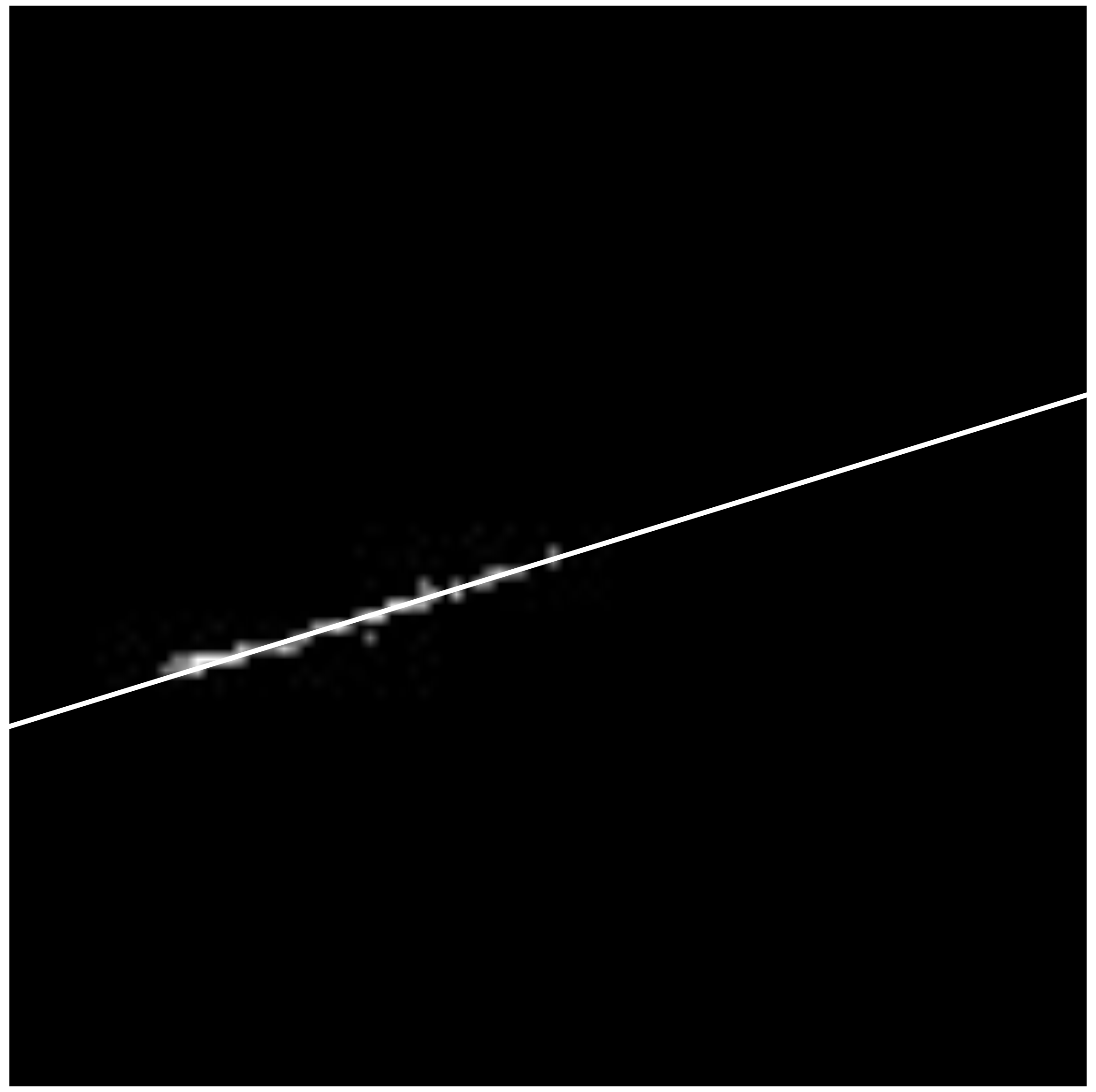
Find the 2D direction of the projected tracks with the **Hough transform**

Each (u, v) is mapped using

$$\rho = u\cos\theta + v\sin\theta$$



Fill the (ρ, θ) space and find the peak



How to resolve the ambiguity in the orientation?

Track orientation

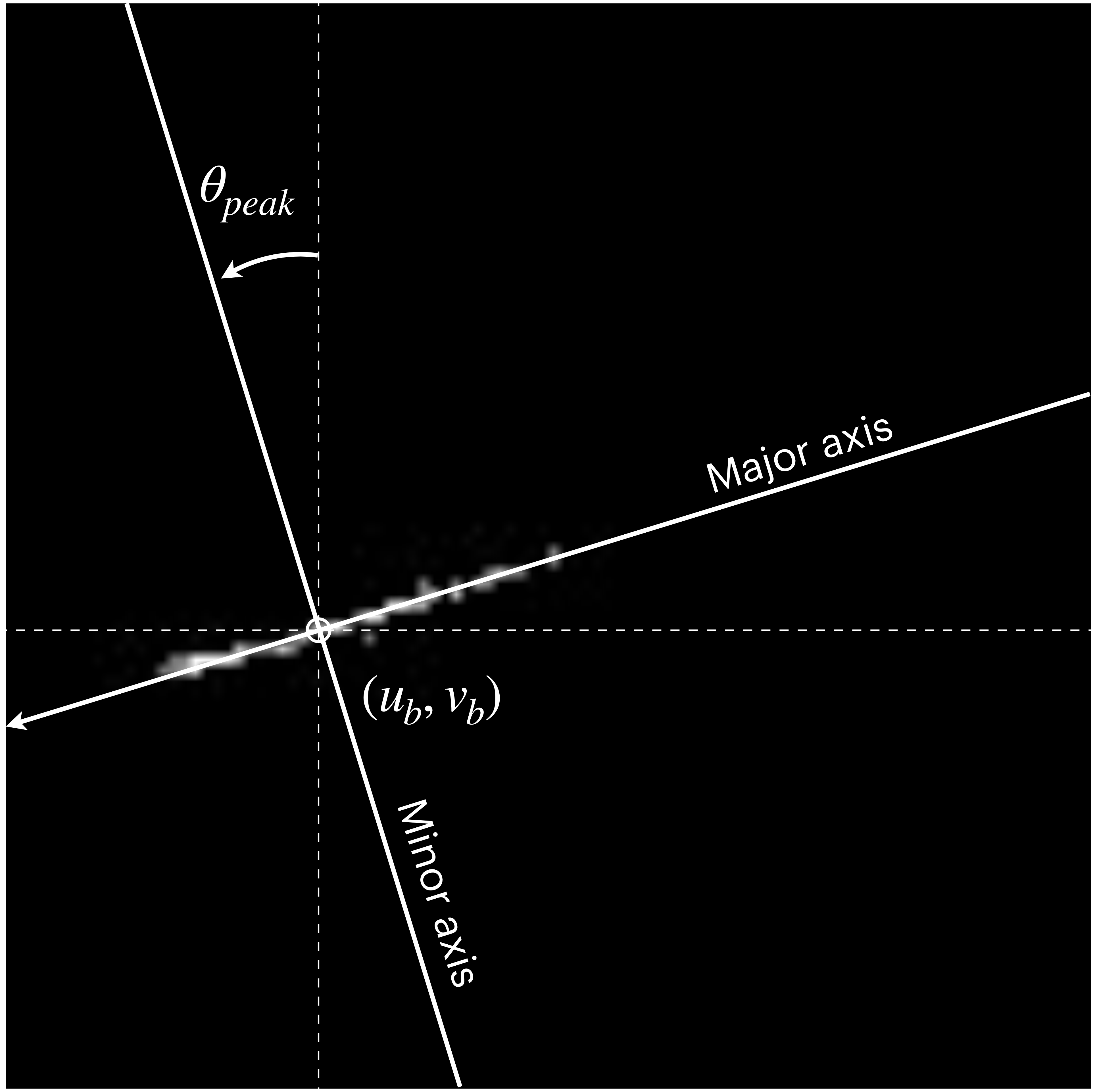
Barycentre

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

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

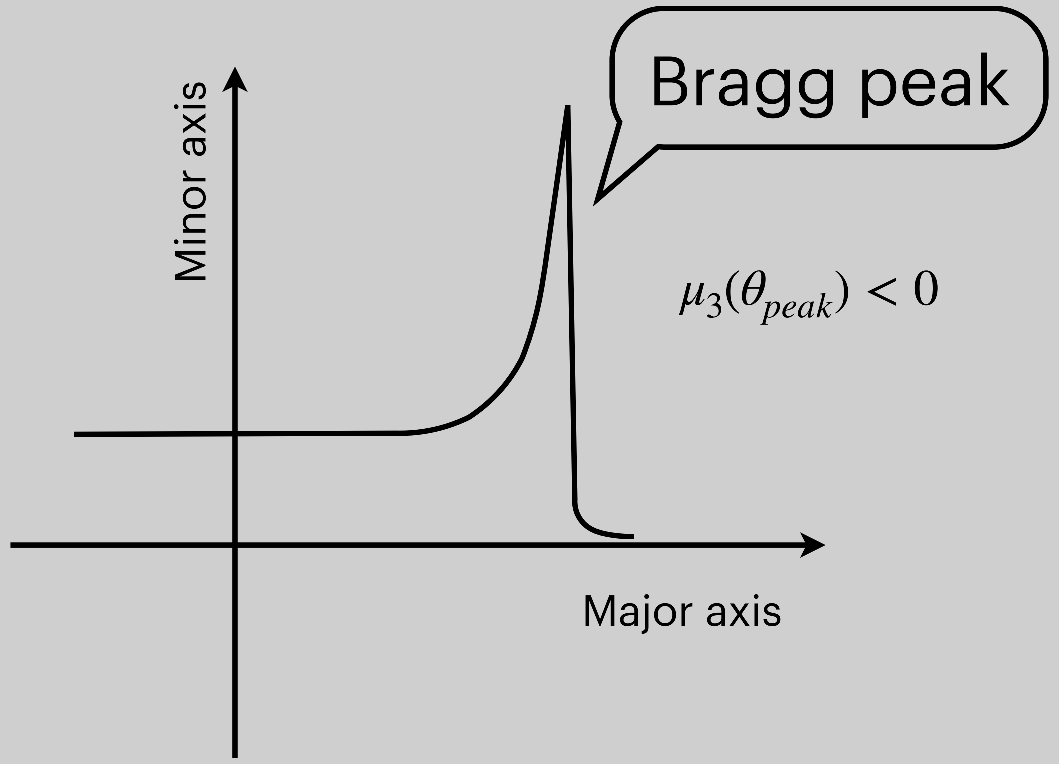
Rotation

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



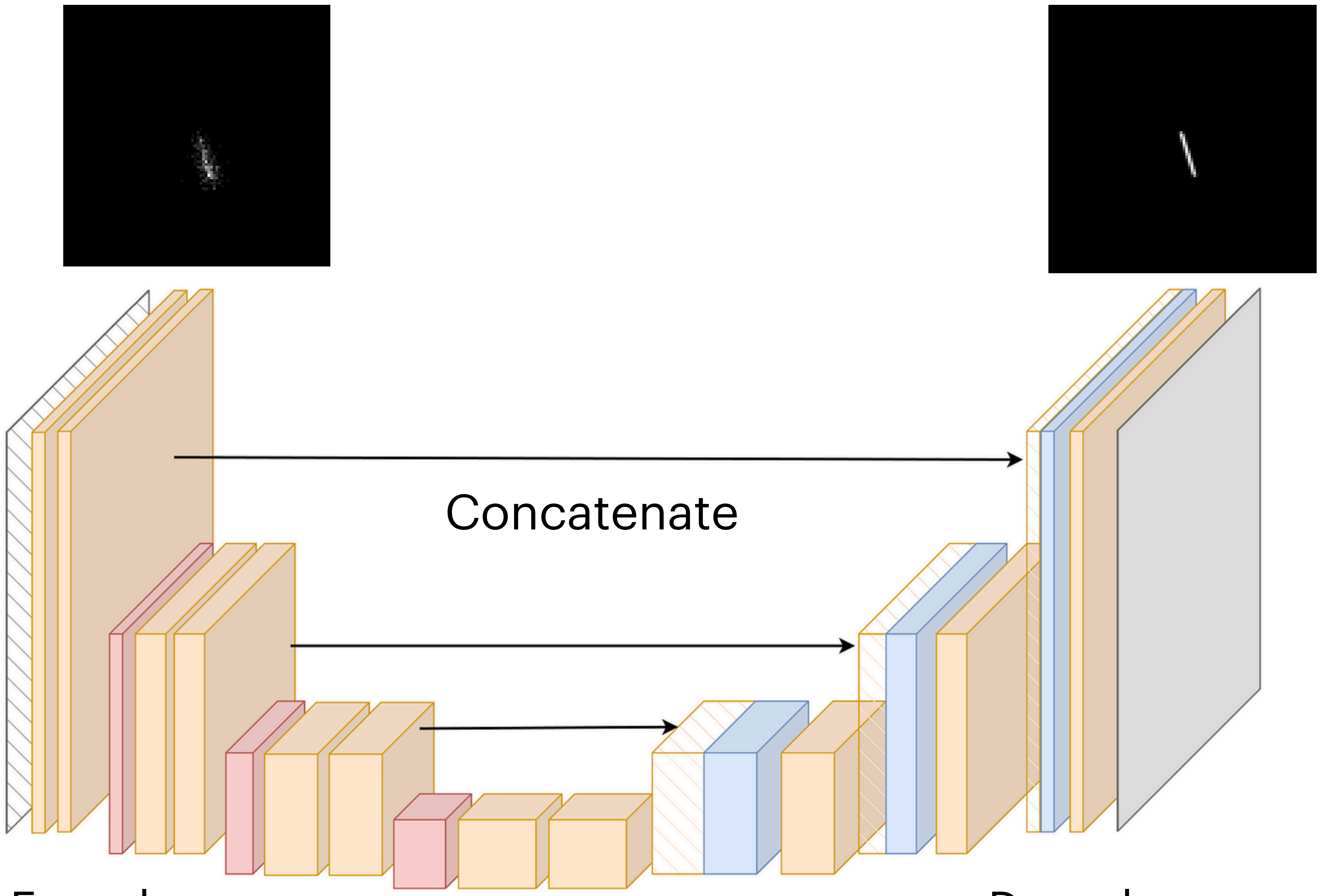
Skewness

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



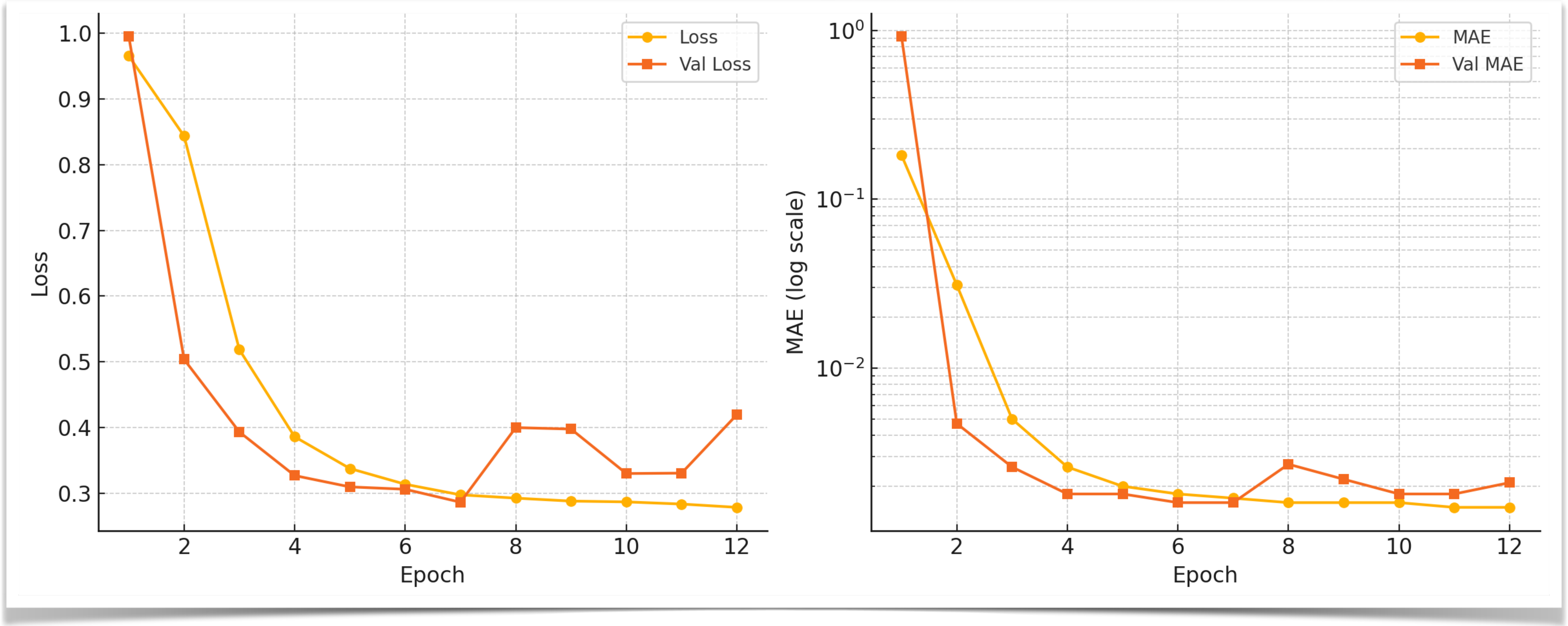
Track length - Remove optical aberration using a UNet

A **UNet** is used to correct optical aberrations in the track projection image caused by the lens system



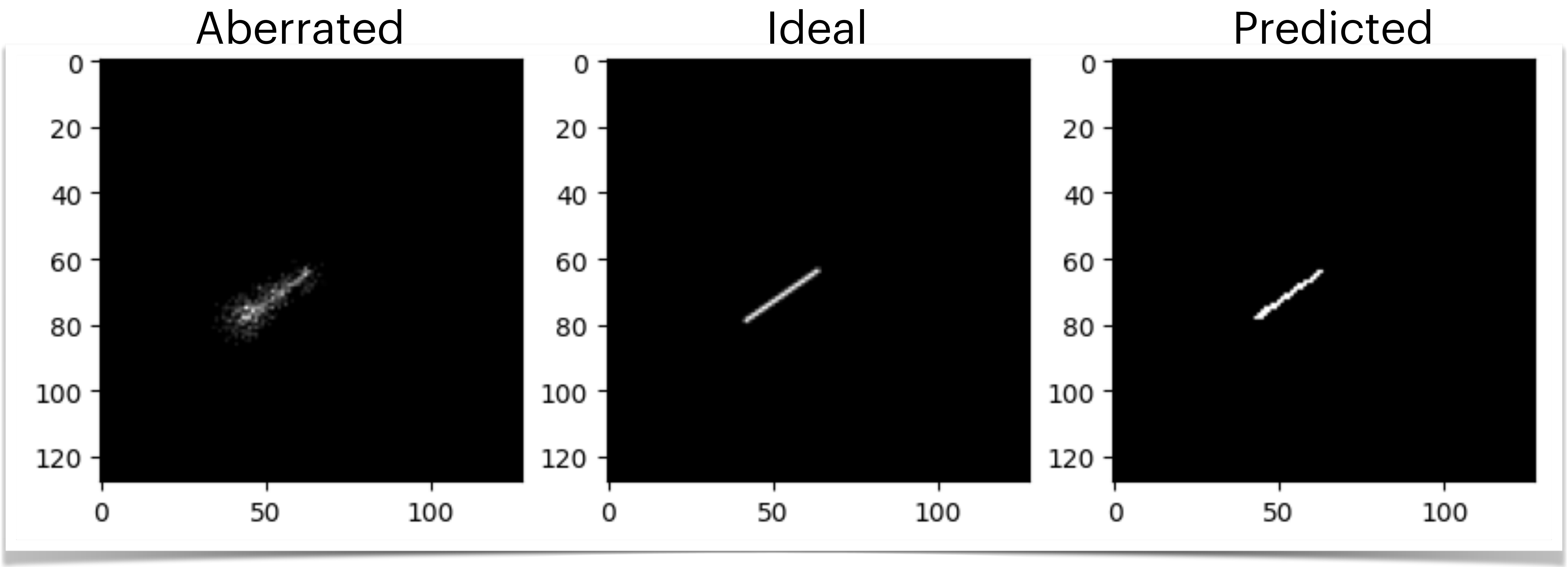
Phase	Main Blocks	Output Shape	Param #
Input	Input Layer	(128, 128, 1)	0
Encoder	Conv2D + BN + Dropout (x2)	(128, 128, 64)	37,824
	MaxPooling2D	(64, 64, 64)	0
	Conv2D + BN + Dropout (x2)	(64, 64, 128)	221,952
	MaxPooling2D	(32, 32, 128)	0
	Conv2D + BN + Dropout (x2)	(32, 32, 256)	886,272
	MaxPooling2D	(16, 16, 256)	0
	Conv2D + BN + Dropout (x2)	(16, 16, 512)	3,539,968
	MaxPooling2D	(8, 8, 512)	0
	Conv2D + BN + Dropout (x2)	(8, 8, 1024)	14,157,824
Decoder	Conv2DTranspose + Concat (x4)	Variable	2,786,240
	Conv2D + BN + Dropout (x2 per block)	Variable	9,403,496
Output	Conv2D (1 filter)	(128, 128, 1)	65
Total			**31,054,145**

Track length - Remove optical aberration using a UNet

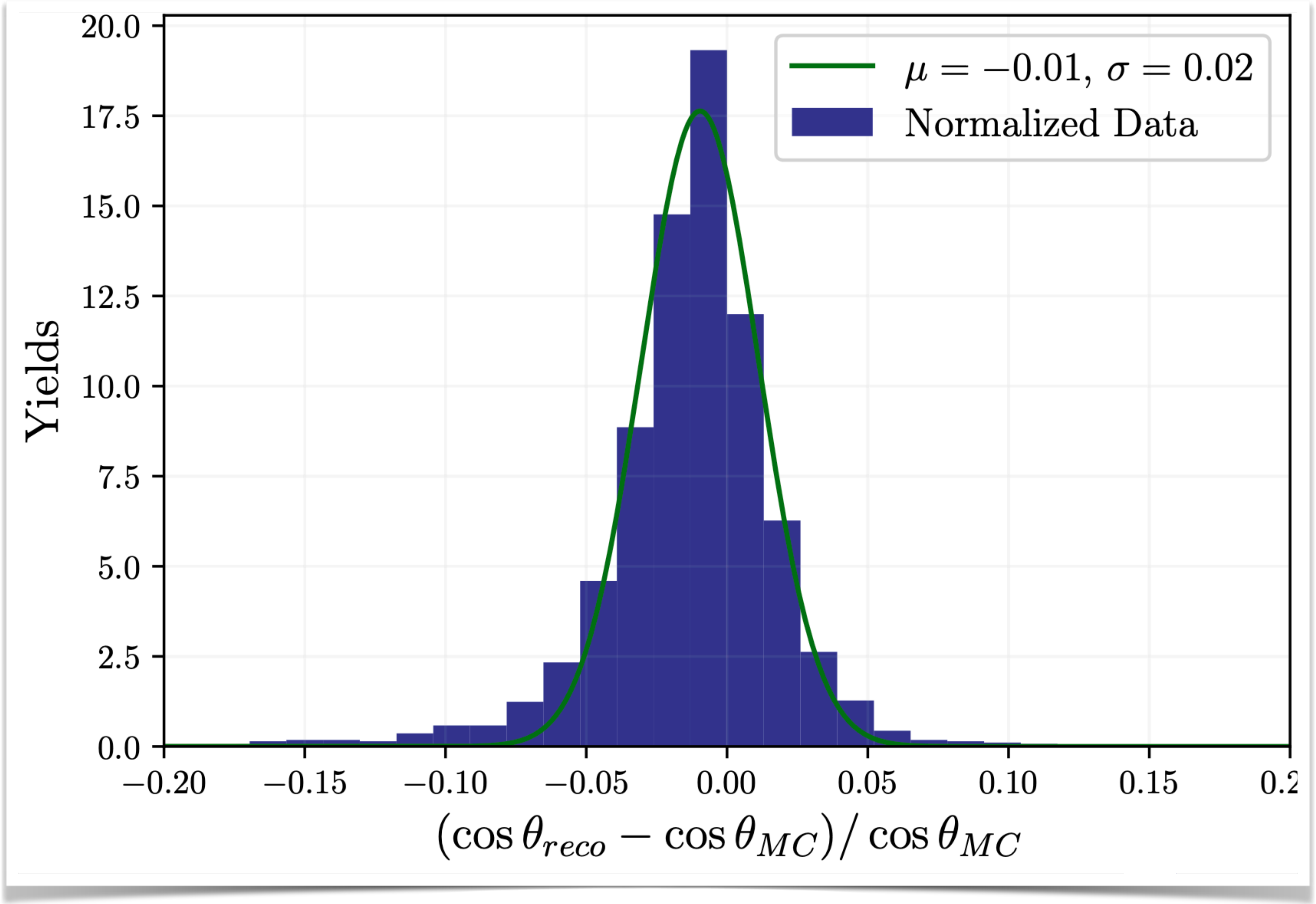


Training results

Inference

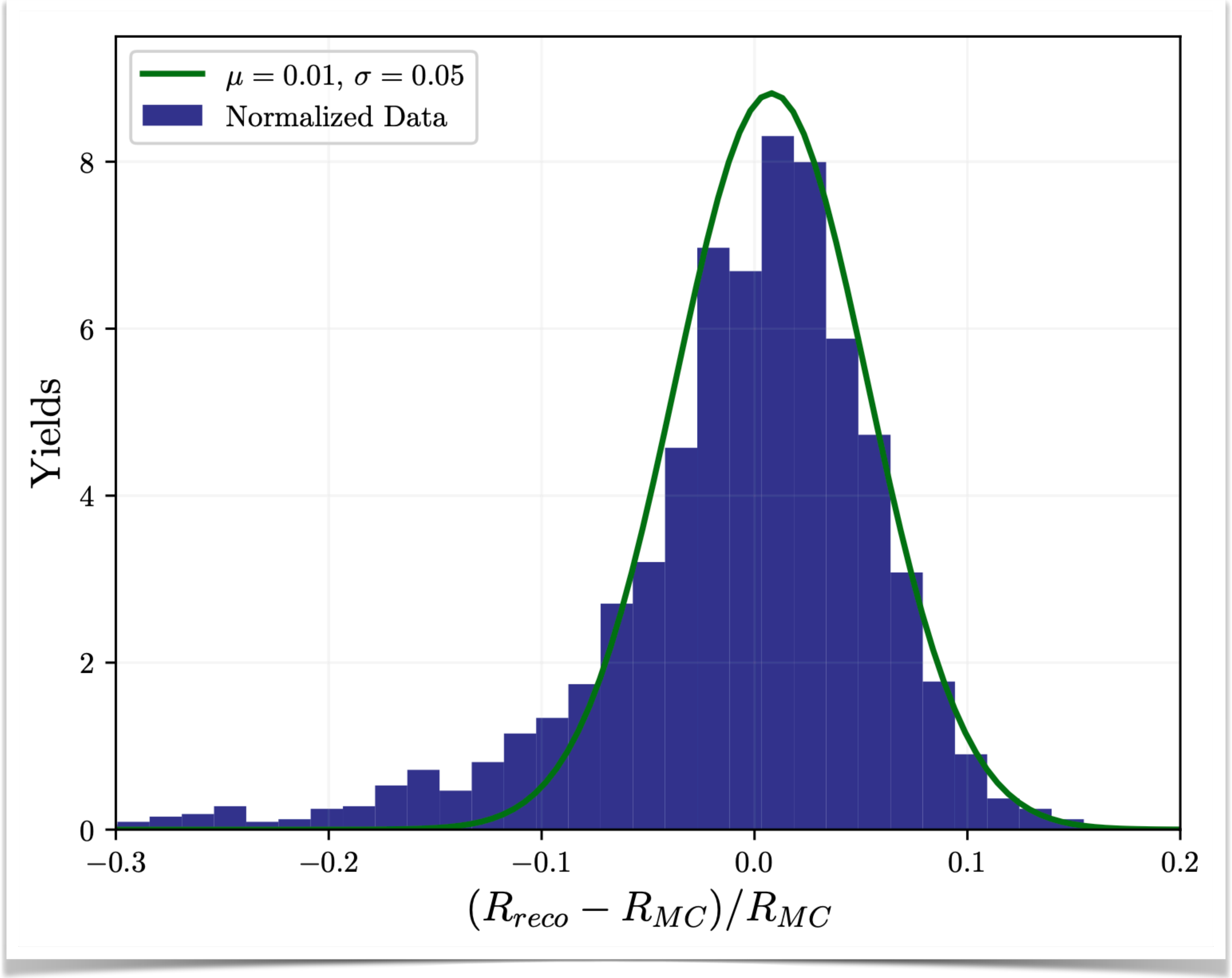


Results

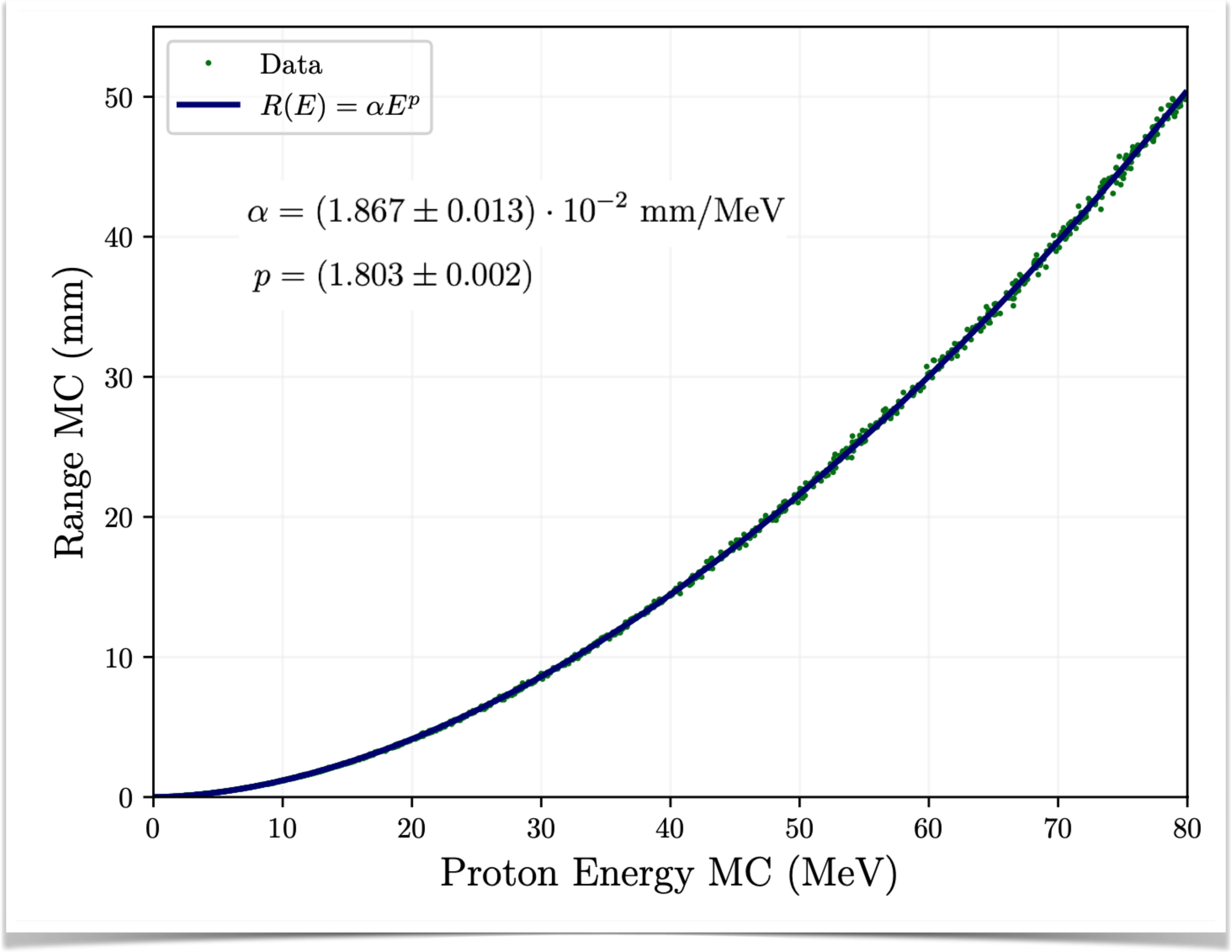


Reconstructed **direction** compared to MC truth

Reconstructed **proton range** compared to MC truth

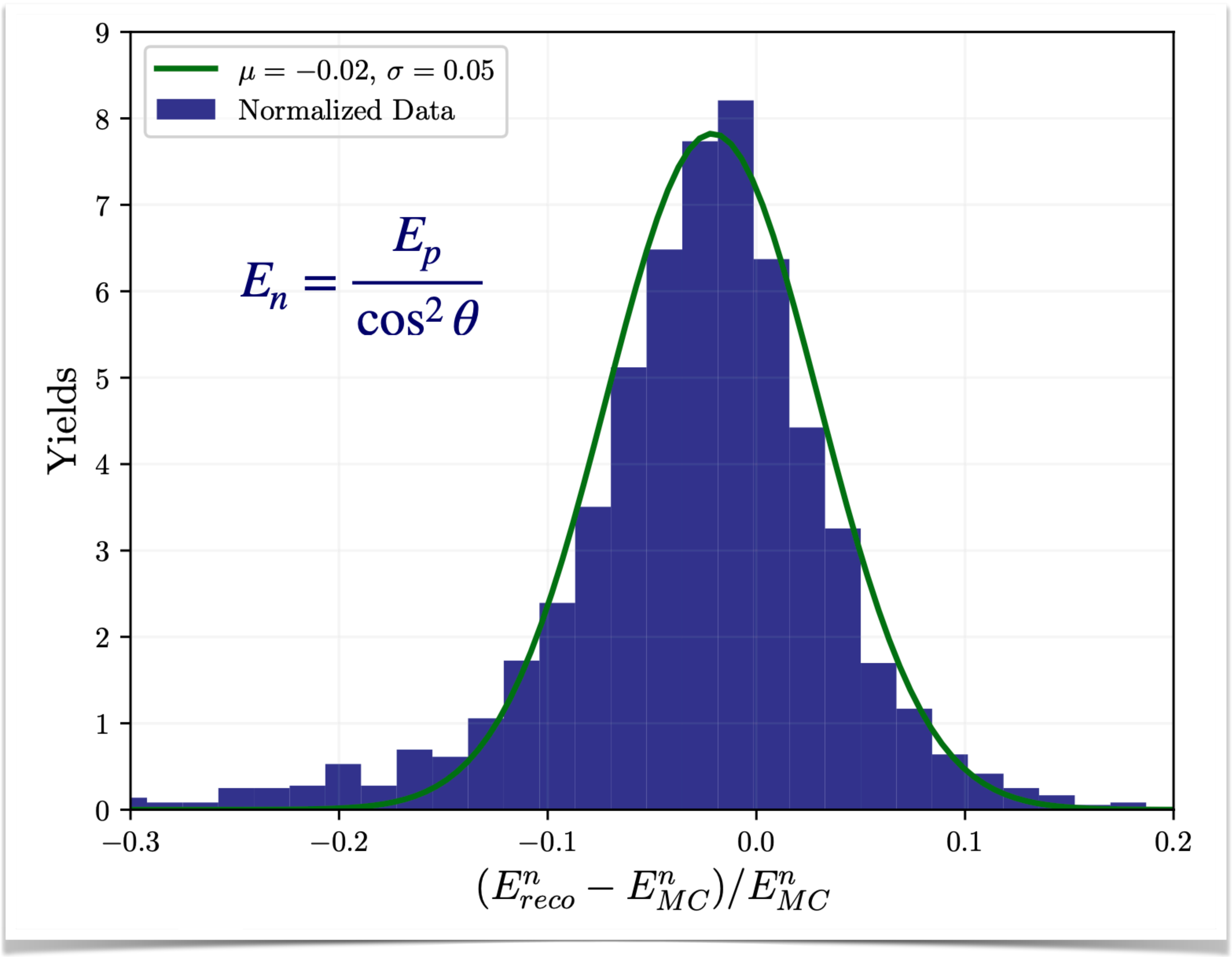


Results



Relationship between **proton energy and range** based on MC simulations

Reconstructed **neutron energy**, obtained combining reconstructed proton energy and direction, compared with MC truth



Conclusion & Future developments

- The method for measuring the **energy** and **direction** of **neutrons** incident on the scintillator appears promising based on Monte Carlo data when the source position is known

- **Hough transform** and the **momenta method** are used to determine direction and orientation

- A **UNet model** is used to reconstruct the track length more precisely

- The neutron energy is estimated by combining these methods

- Extending this approach to double-scattering events would enable the determination of the source position when it is unknown.

- Once experimental data become available, these techniques will be applied and validated