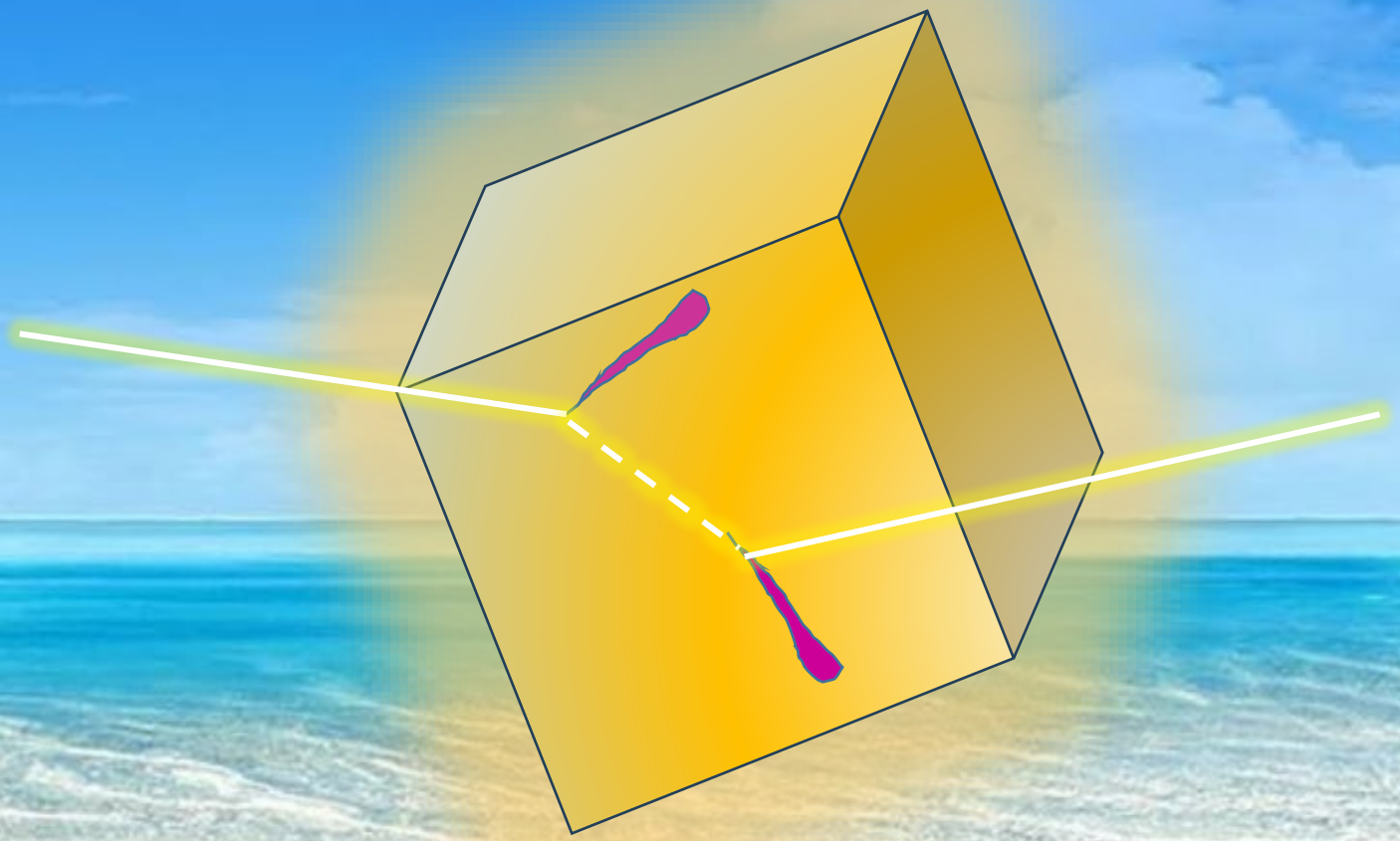
RIPTIDE: Recoil Proton Imaging Detector



Bologna, 10 giugno 2024, Roberto spighi

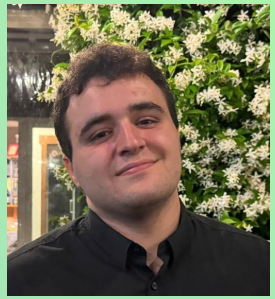
The group (3.8 FTE)

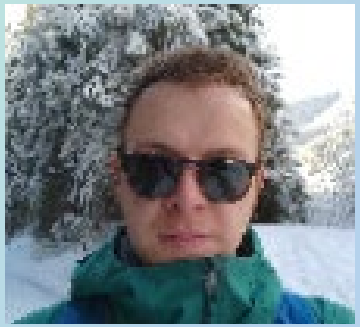
Referees

Simona Giordanengo (TO)

Paolo Cardarelli (FE)

Laureati/ndi





what

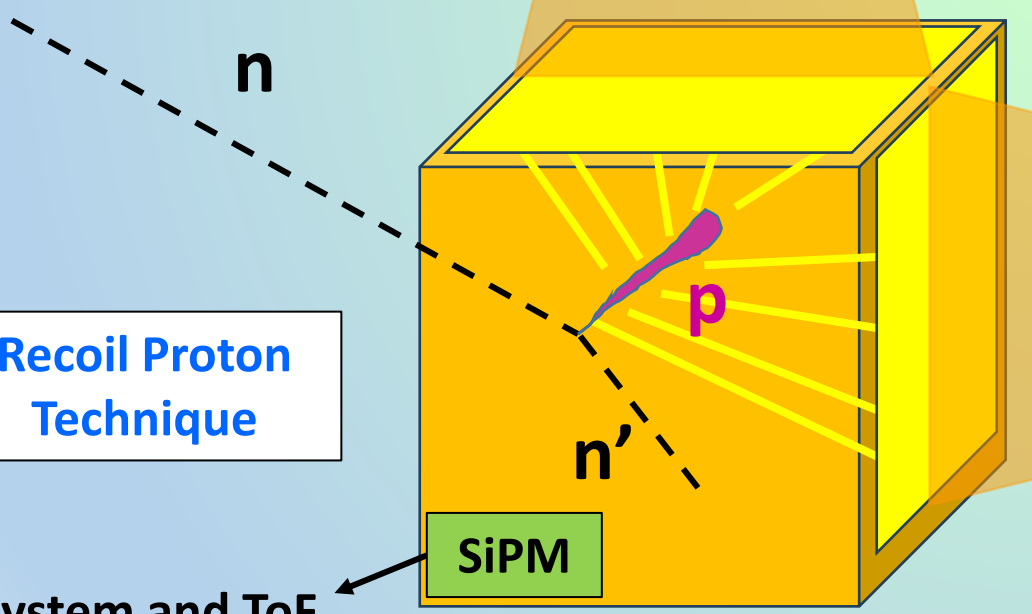
fast image sensor

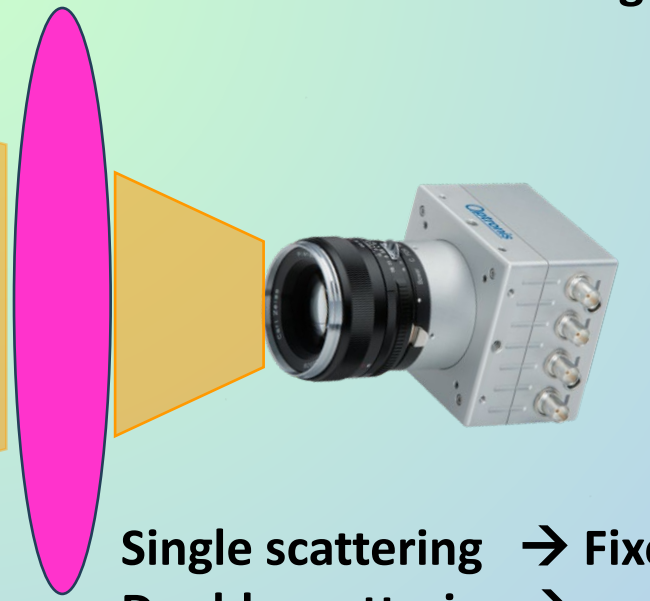
2 bidimensional images

reconstruction

Tridimensional image

Optical system





High frame rate CMOS

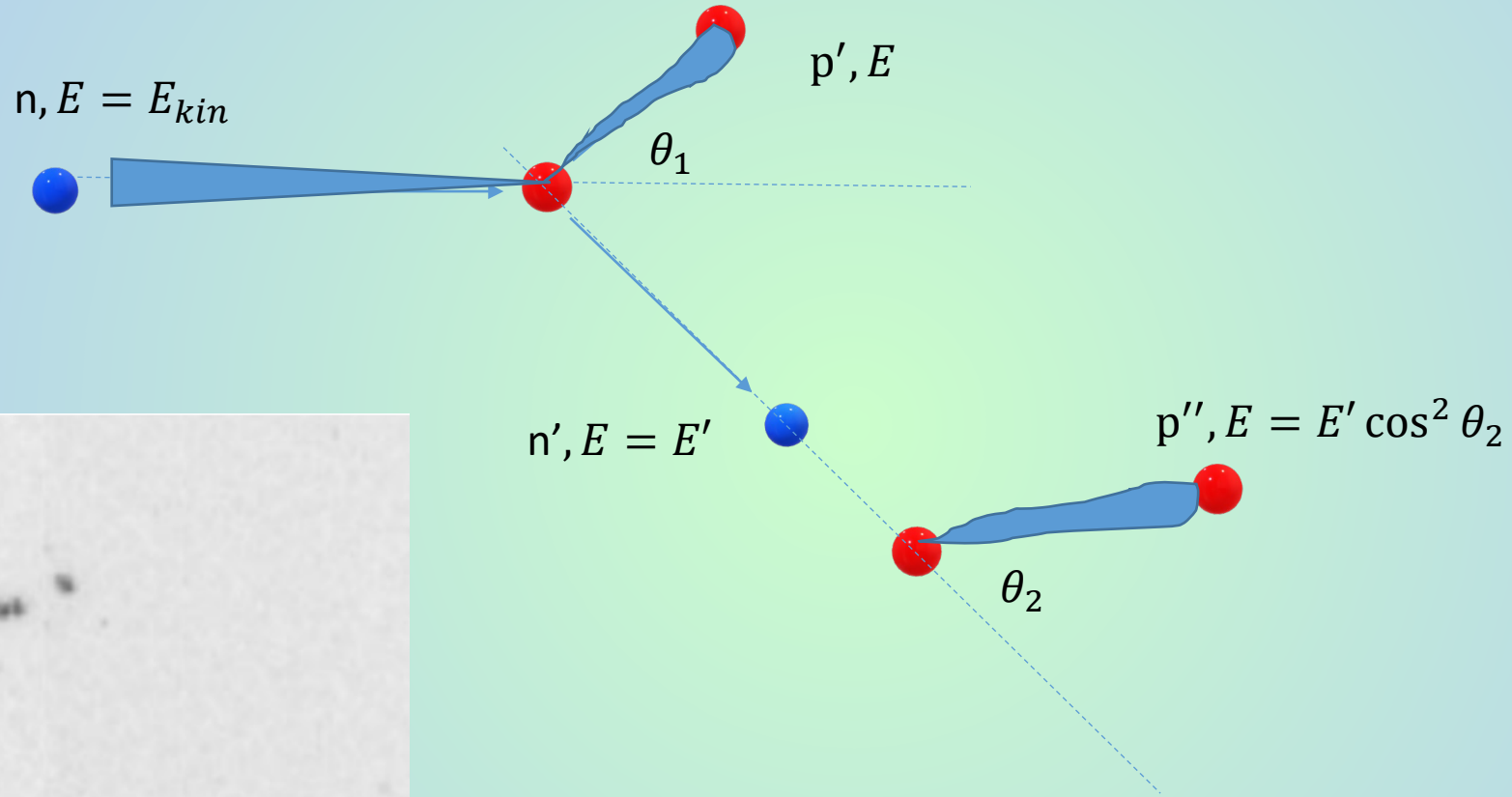
Recoil Proton Technique

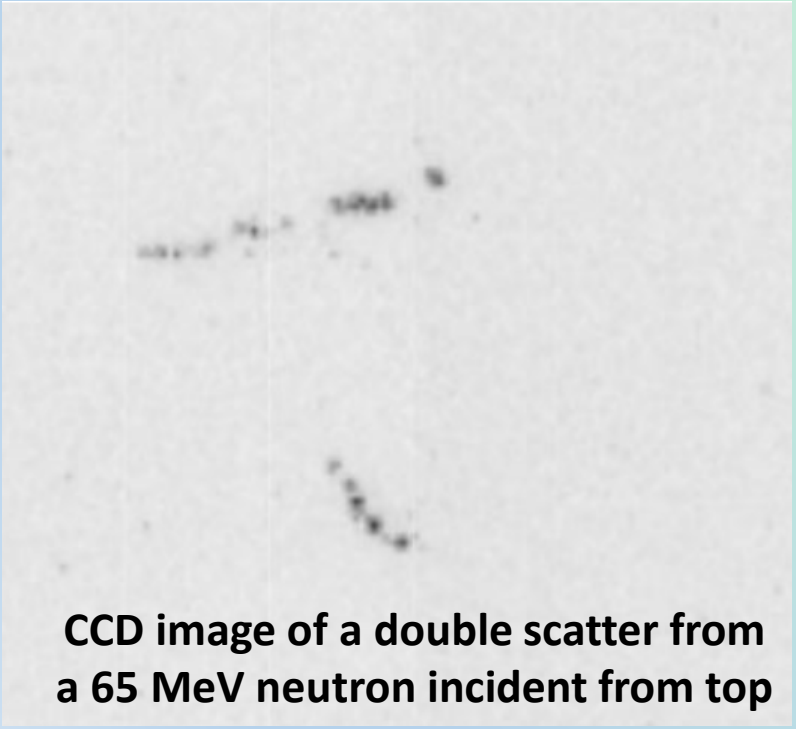
Trigger system and ToF

Single scattering → Fixed target experiment

Double scattering → neutron source not known

Metodology: Recoil proton Tecnique





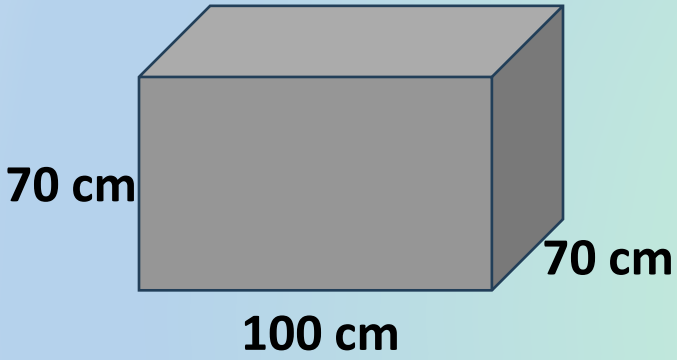
CCD image of a double scatter from a 65 MeV neutron incident from top

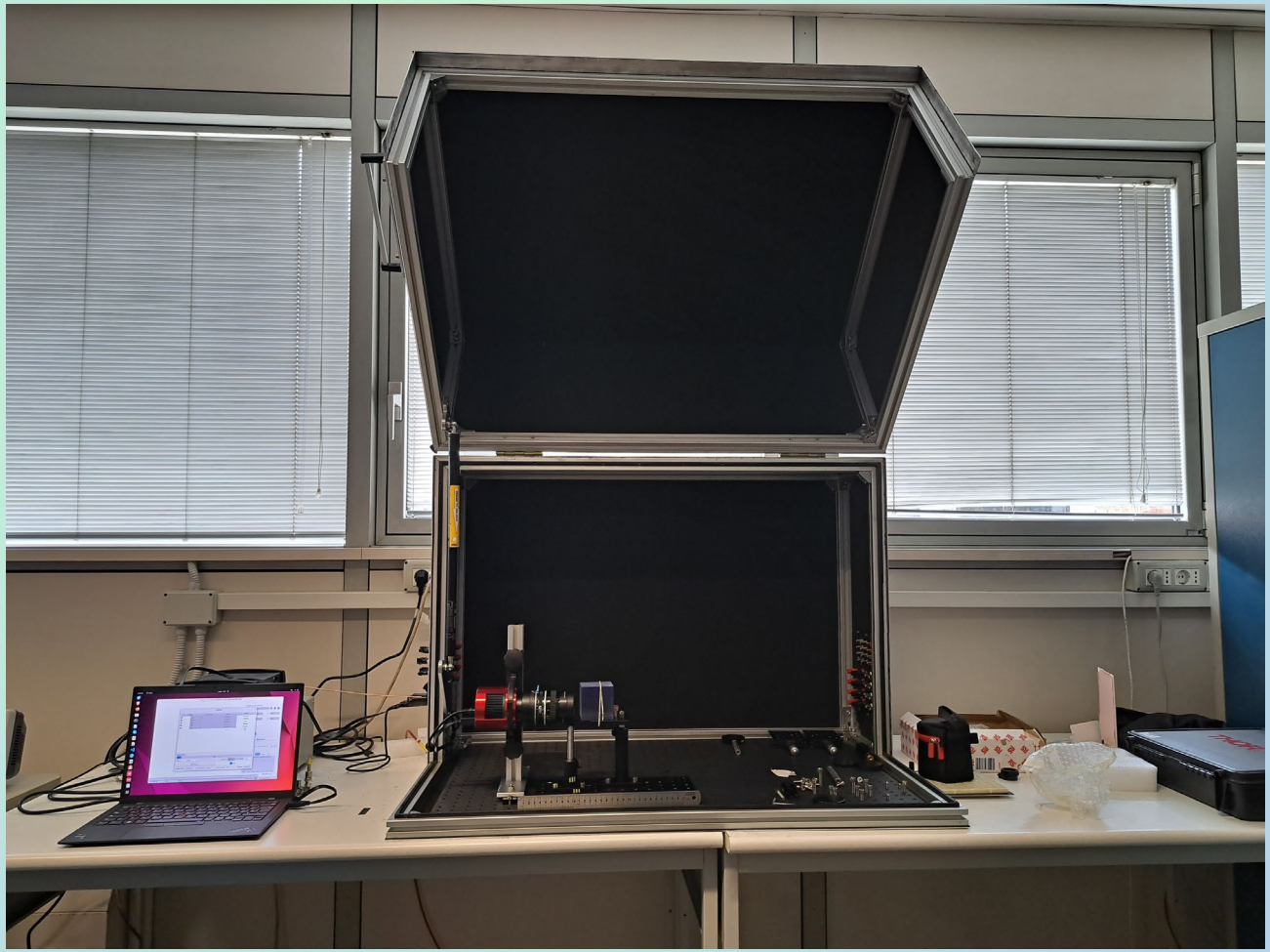
James M. Ryan, et al. «A Scintillating Plastic Fiber Tracking Detector for Neutron and Proton Imaging and Spectroscopy», the conference is available at University of new Empshire Scholar's Repository, https://scholars.unh.edu/ssc/208

The black box

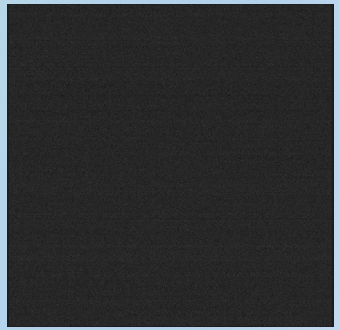
Projected and realized by Officina Service group, INFN Bologna

Sited in the OPH Laboratory (Berti-Pichat Institute)





complete dark



Inside/outside: all different connections (fiber, HV, lemo, …)

Inside equipped with various mechanic supports (Thorlabs)

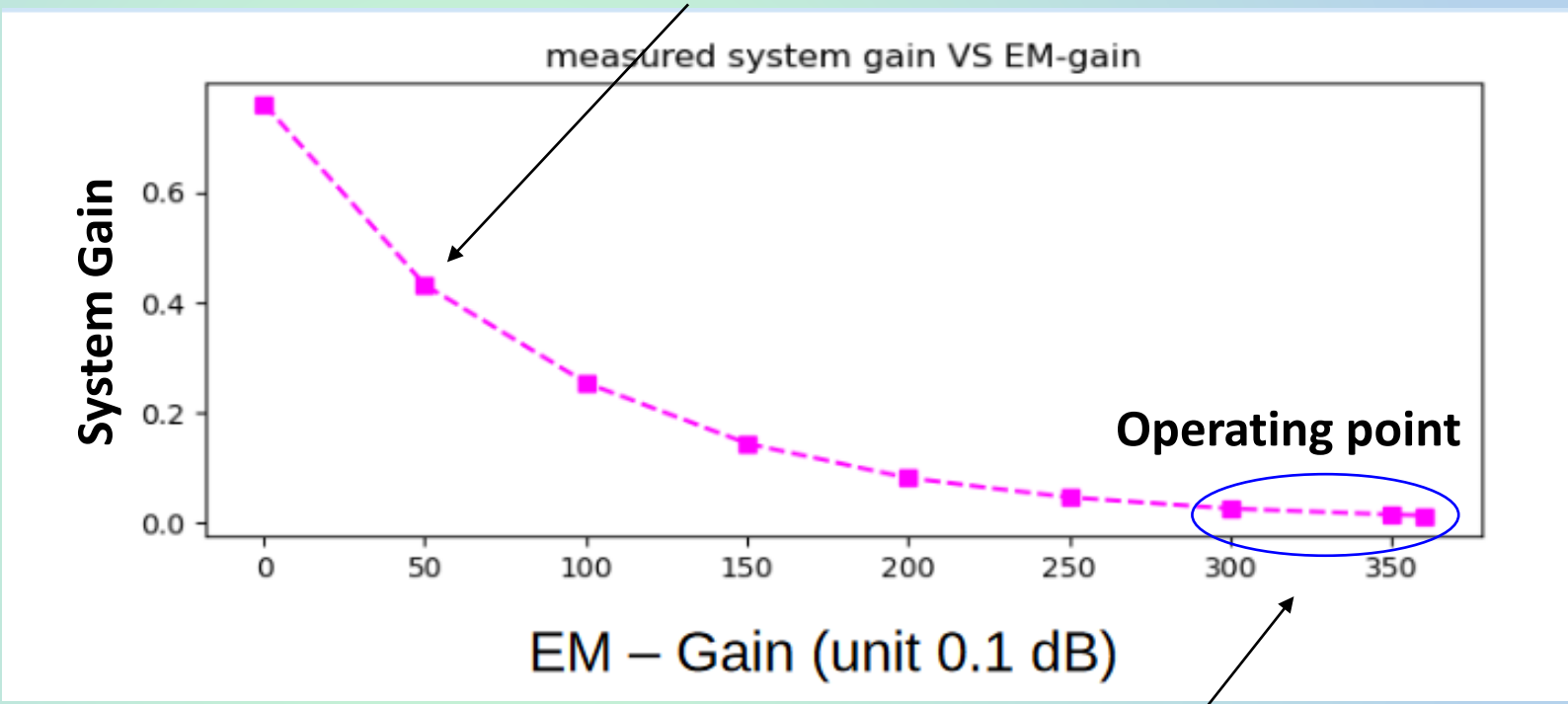
Sensor characterization: sensitivity

Setup

Camera ASI 533 Pro
Sensor: Sony IMX533CMOS

Takes 2 pictures with light (black box open)

0.4 number of e to have a gray level



System Gain: number of electrons per gray level

Number of gray level: 2^{16} = 64000

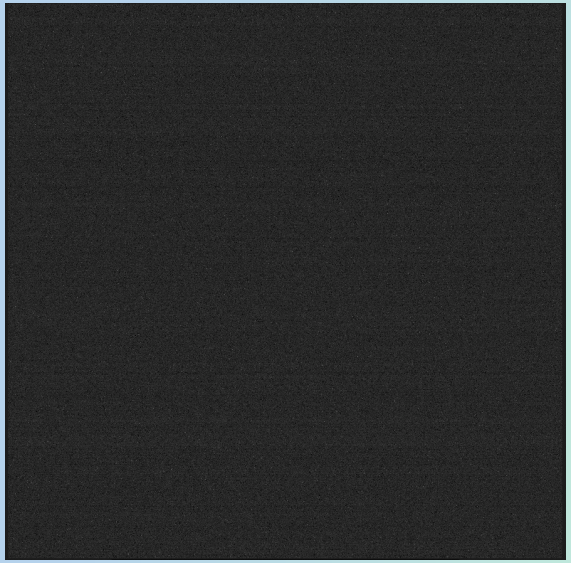
EM (Electromagnetic) Gain: amplification of the number of photoelectrons

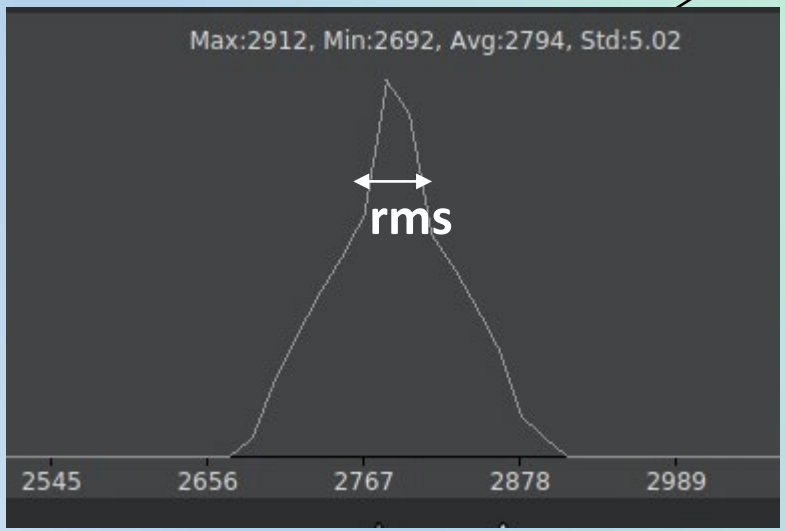
The smaller the number, the greater the sensitivity

1/ 0.02 = 50 → with 1 photoelectrons jump of 50 gray levels

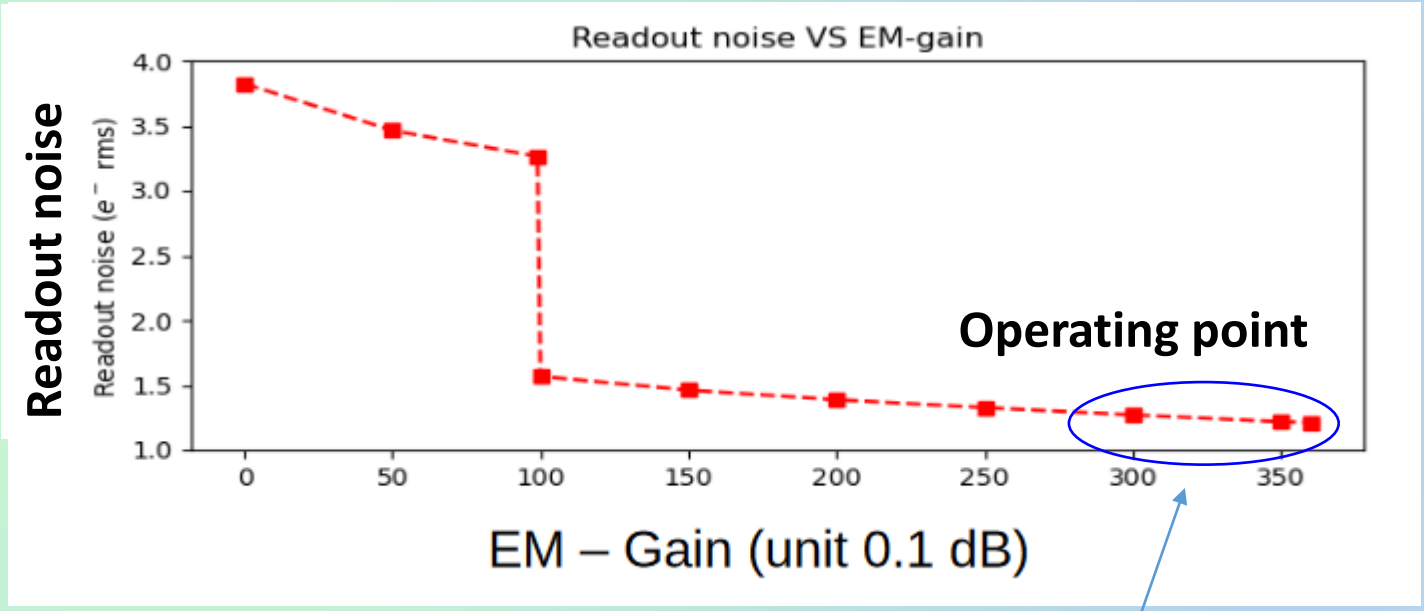
Sensor characterization: noise

Acquisition: complete dark and exposure time = 0 s, EM Gain = 0





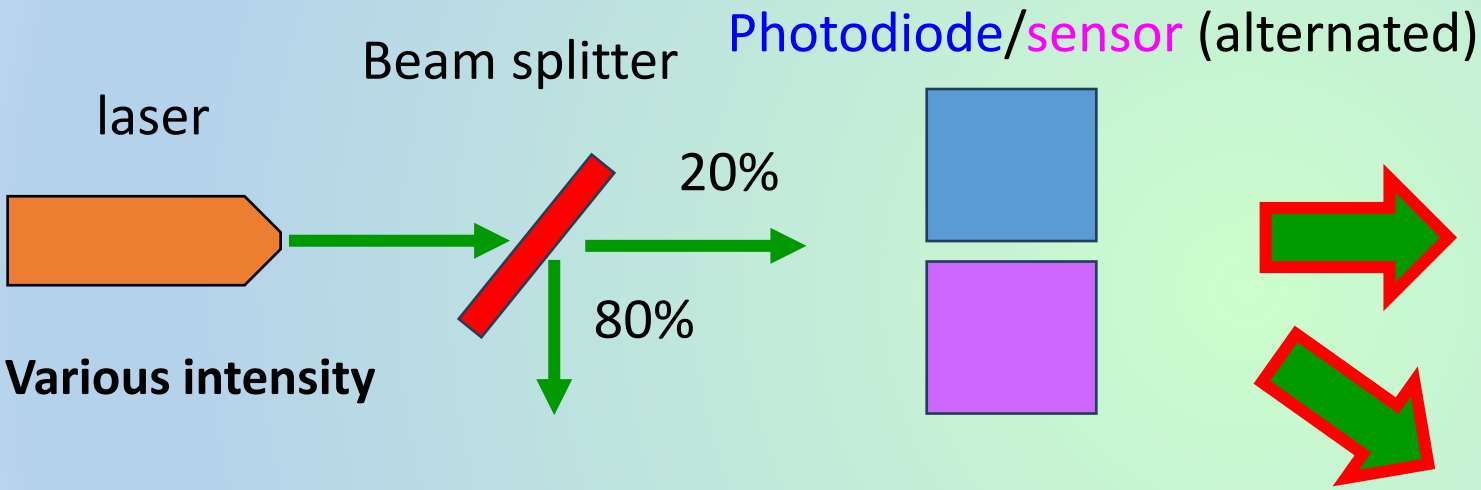
Same setup as previous one, but black box closed

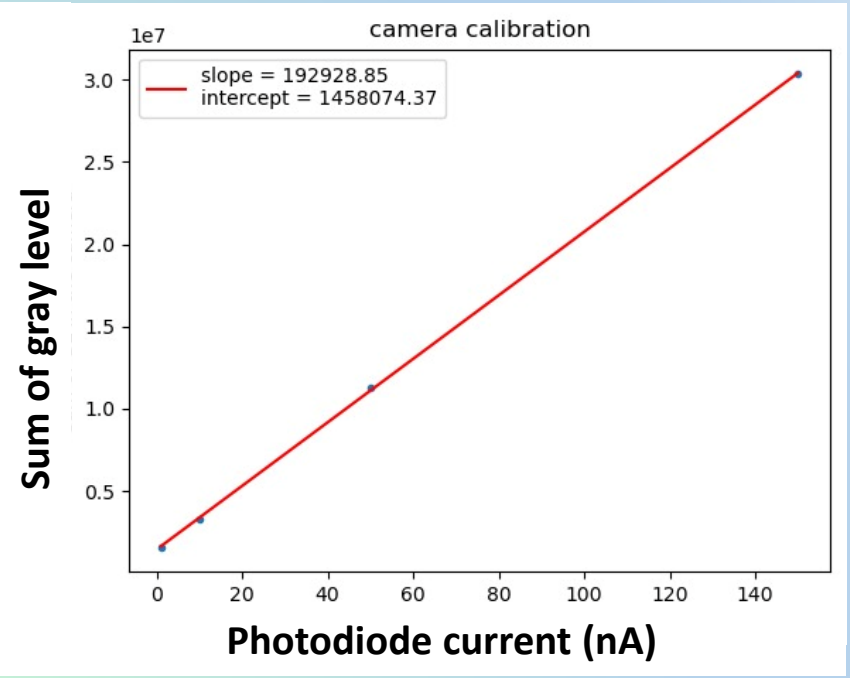


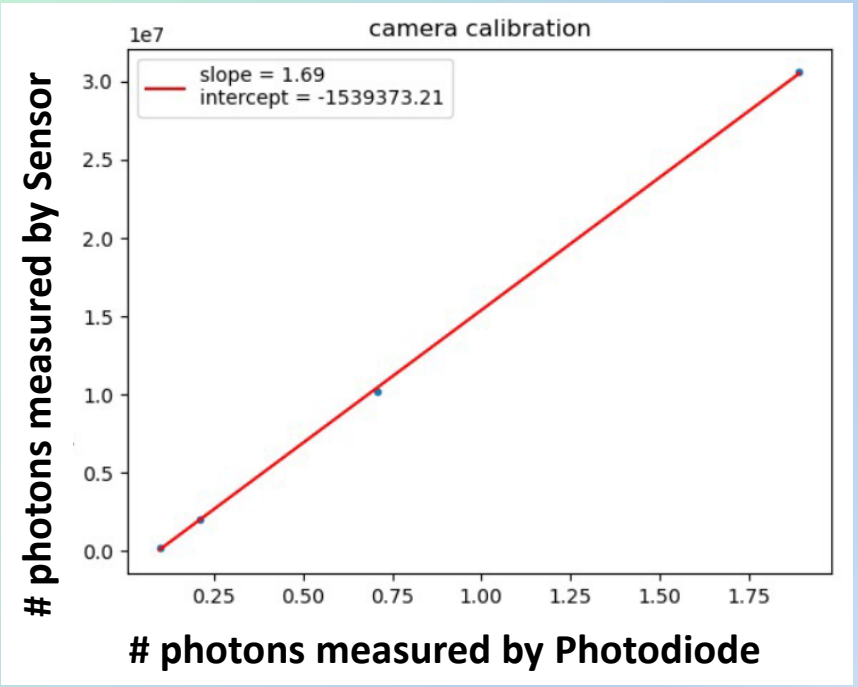
Noise due to electronics:
1.3 e- → +- 1.3

Dark current negligible because it depends on T but we work at -30° wrt extern temperature

Sensor characterization: response linearity





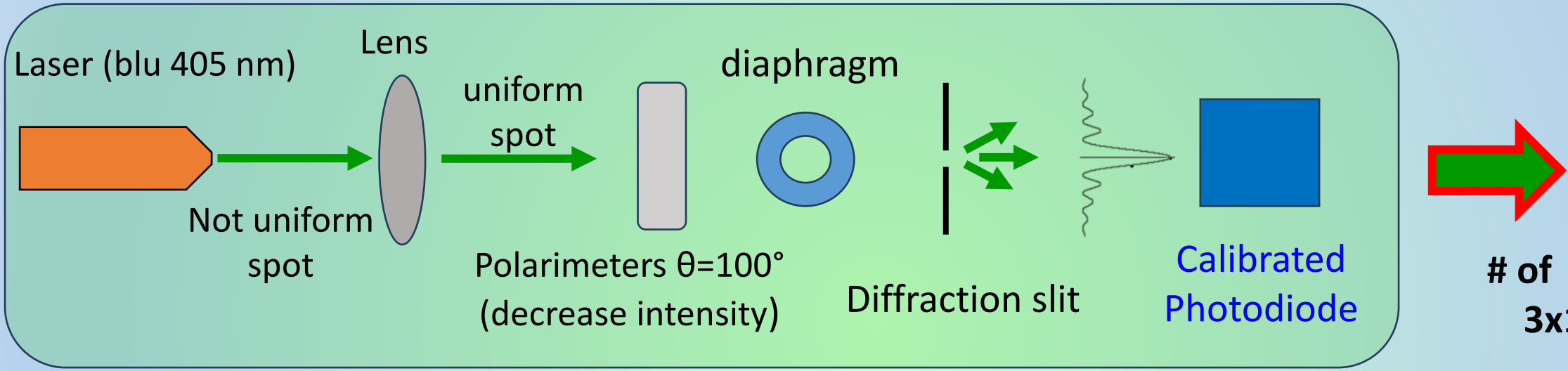


 # photons

- **Camera: (Σ gray levels)*System Gain*Quantum Efficiency**
- **Photodiode**

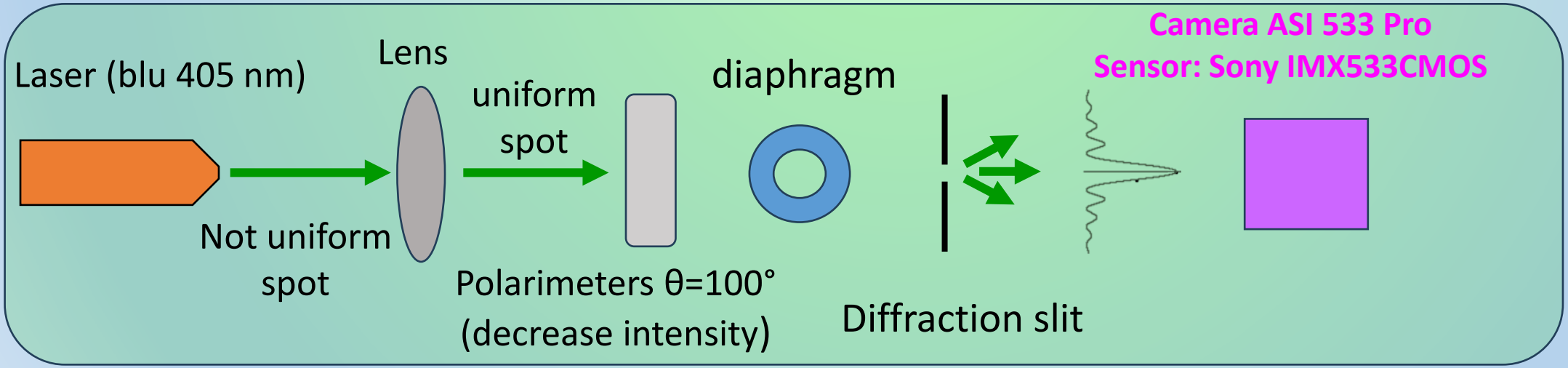
Sensor characterization: sensitivity

decrease intensity → minimum intensity detected

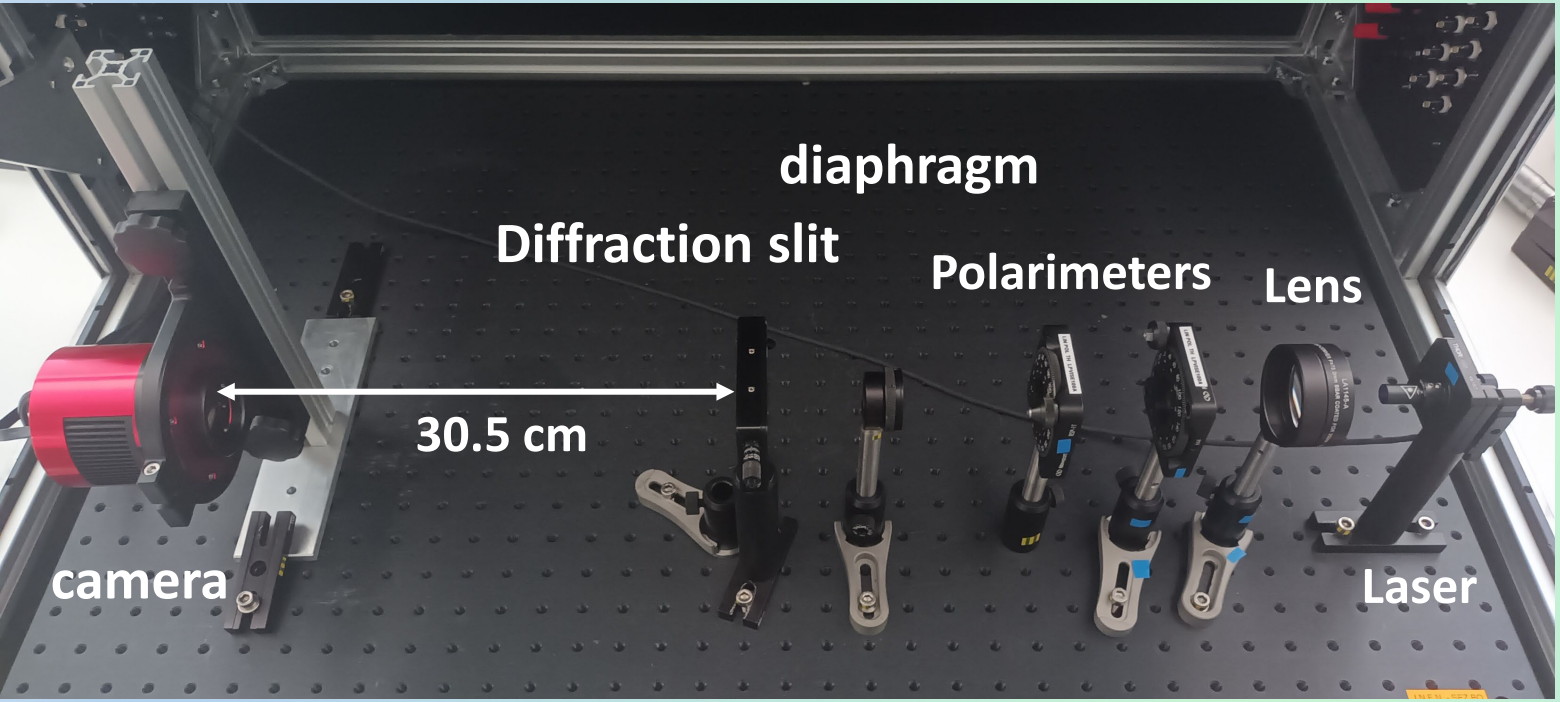


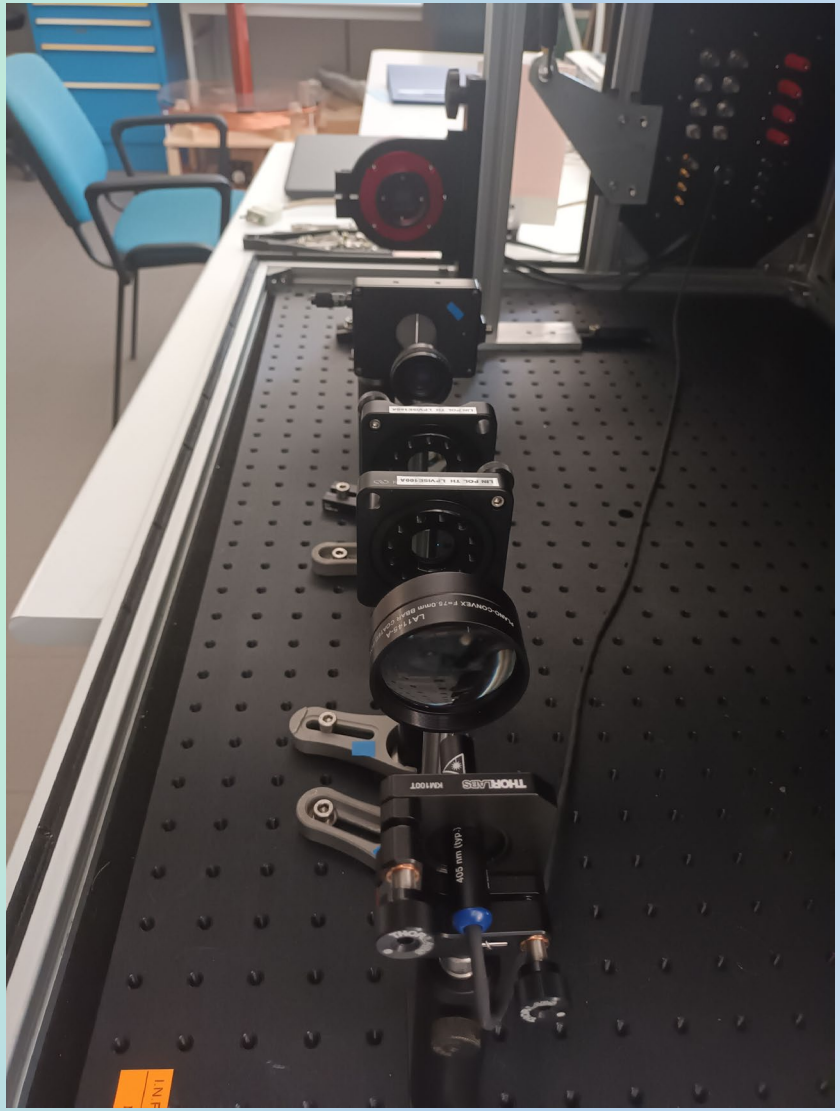
# of photons
$3x10^{12}$ /s

Same setup with our sensor

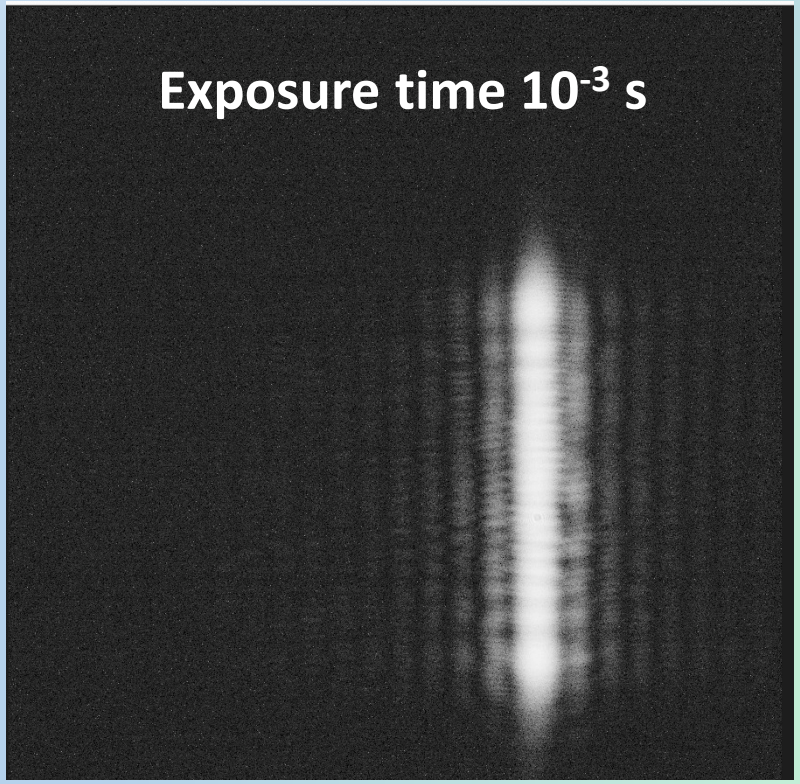


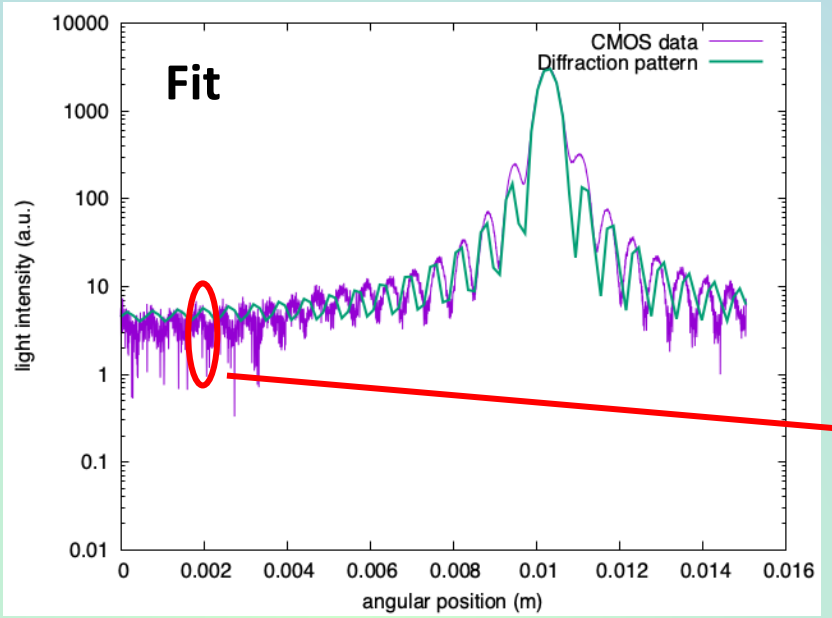
Setup for diffraction figure

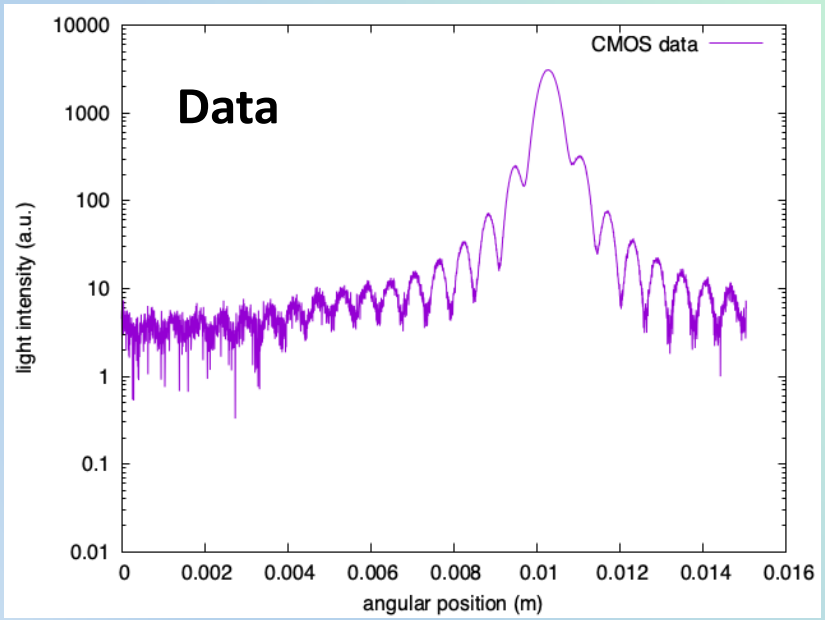


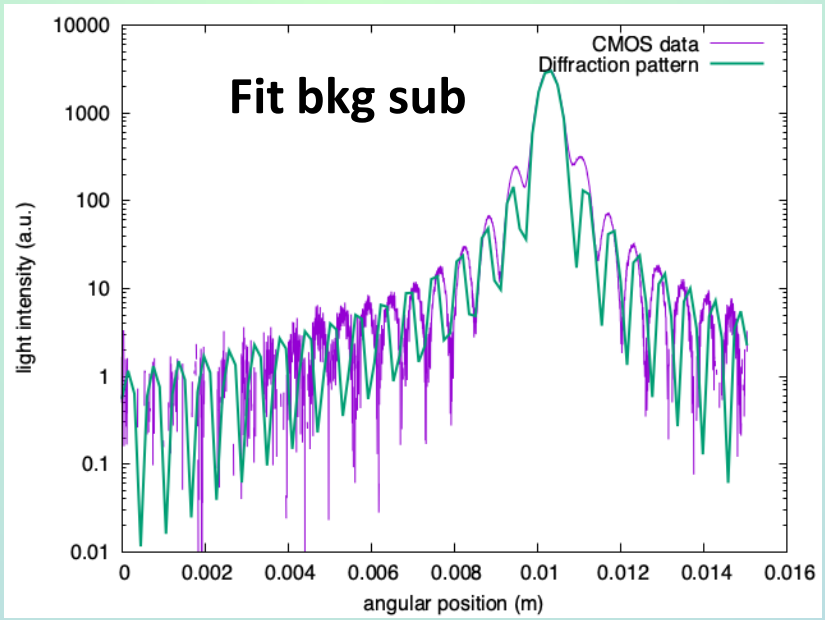


Diffraction figure









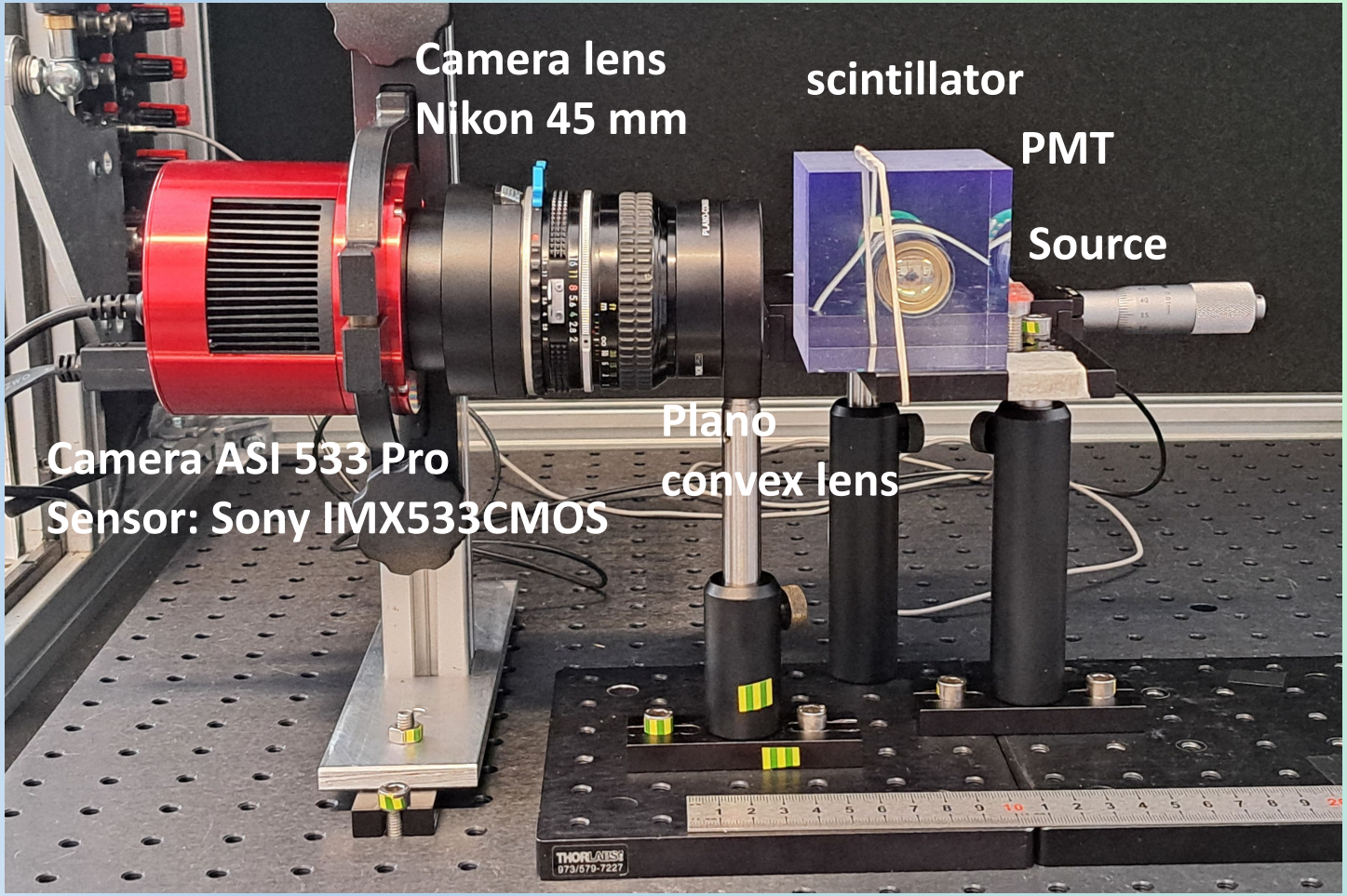
 # pixel = 80 x 1400 = 110 ·10³

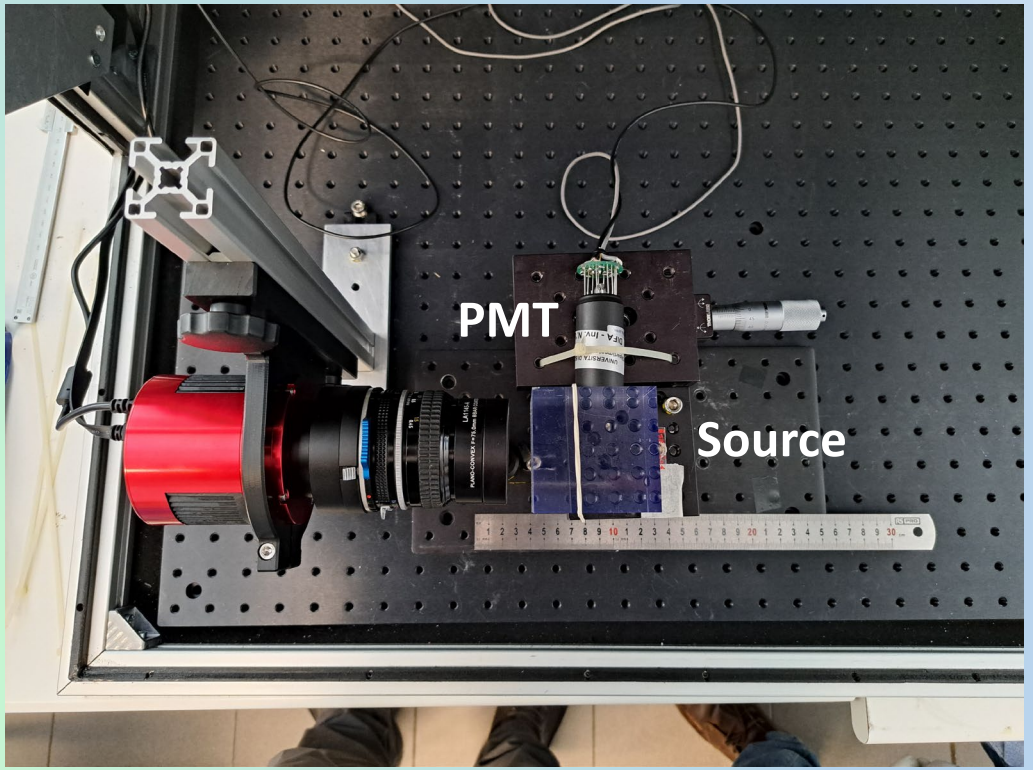
Light is 0.6% of total

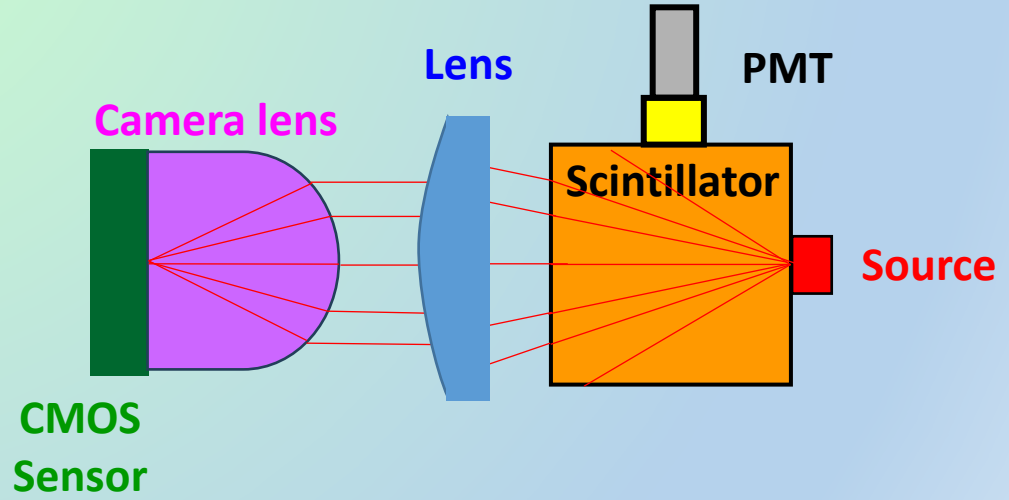
~ 30 photons/pixel

Probably we need MCP

Setup with source







Alpha source

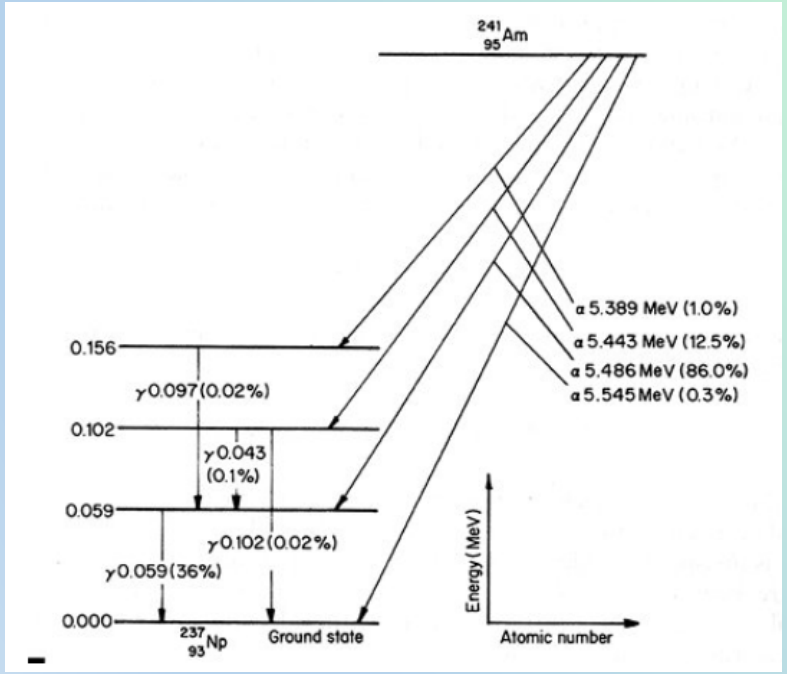
Americium → alpha decay (5.443 and 5.486 MeV)

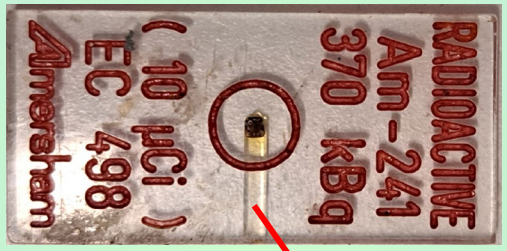
Am(Z= 95, A = 241) → Np (Z=93, A= 237)

Total Activity 370 KBq at the beginning
Solid angle ~ 0.057% (not so easy to evaluate)

Half life 432.2 years

Production of alpha and gamma

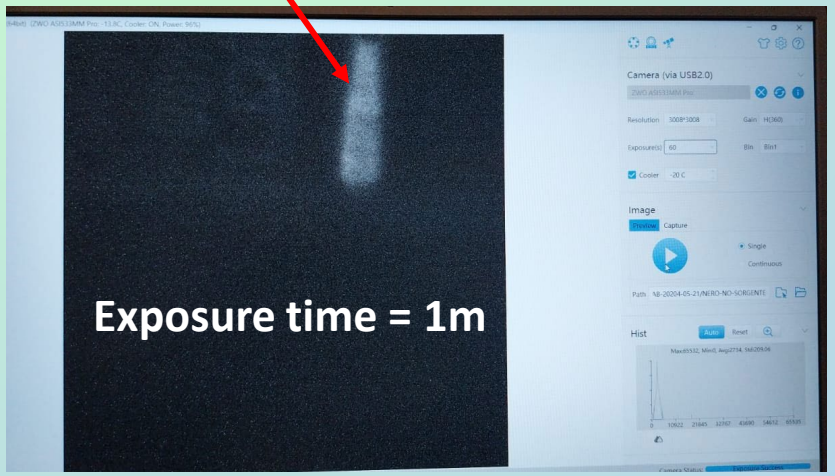


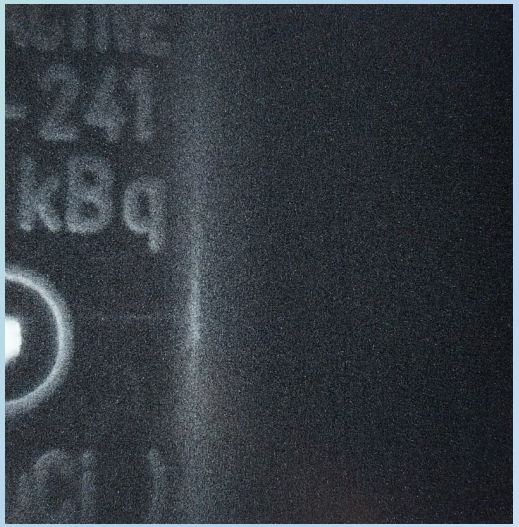


Signal produced by α and γ

Exposure time = 1s

1 mm





Gamma source

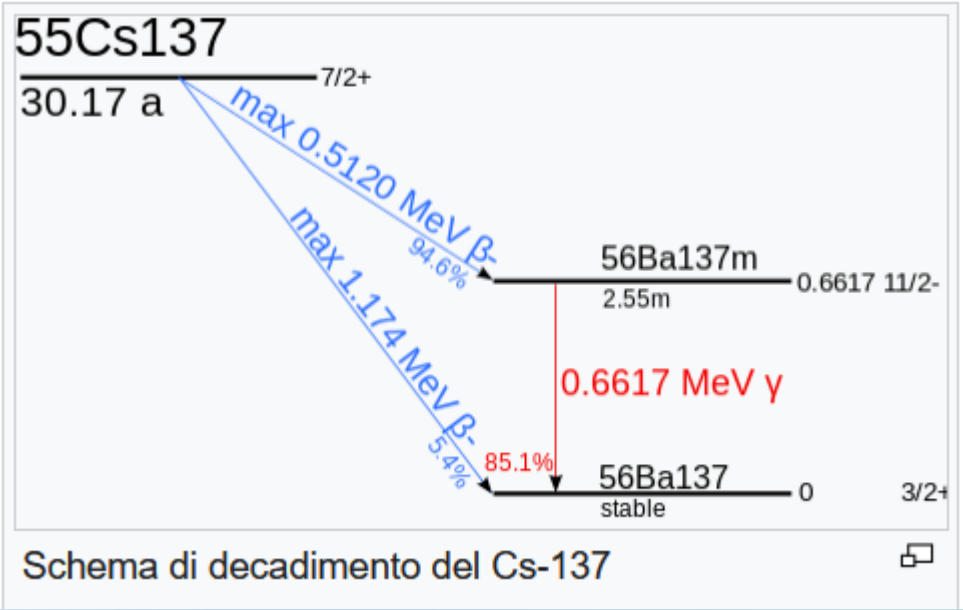
Cesium 137→ beta decay (0.51 and 1.17 MeV)

Cs(Z= 55, A = 137) → Ba* (Z=56, A= 137) + beta

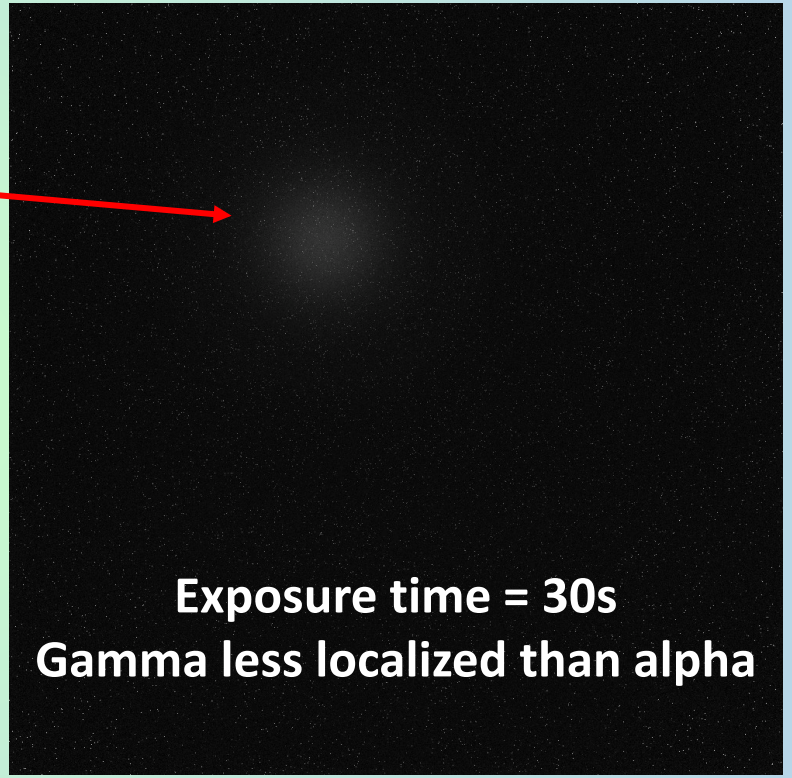
Ba* → Ba + γ (661 KeV)

Source Activity 190 KBq (approx)

Half life 30 years



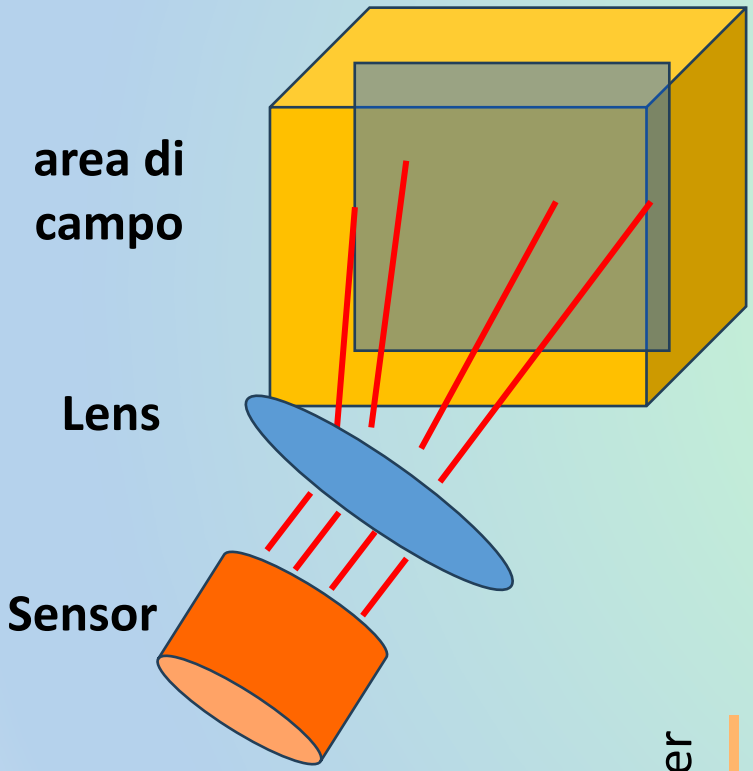
Schema di decadimento del Cs-137



Optics characterization

Measure the Field of View (FOV) and Depth of Focus (DOF) with different Lens Setups

Transverse Area in focus

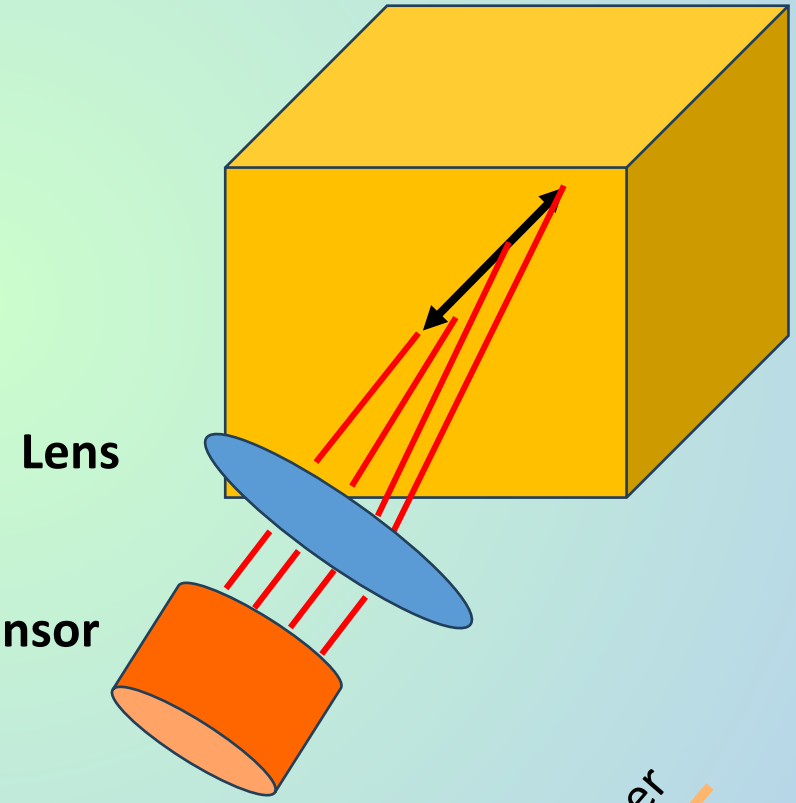


Sensor

Lens system

Graph paper

Longitudinal Area in focus



Sensor

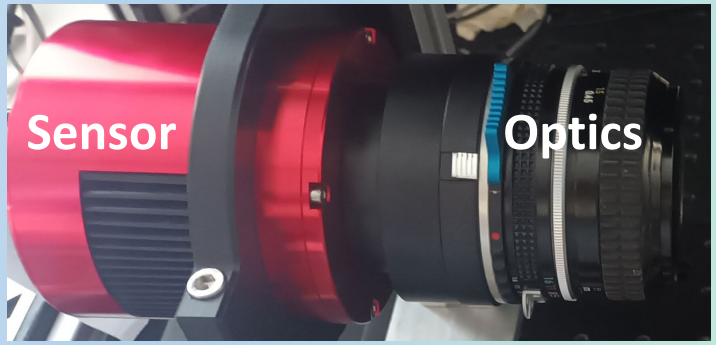
Lens system

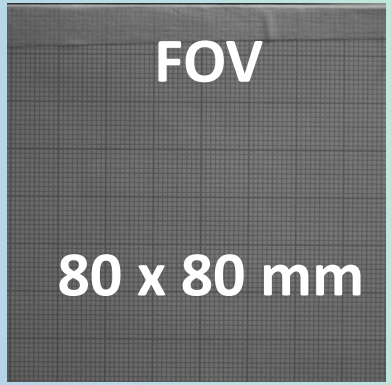
Graph paper

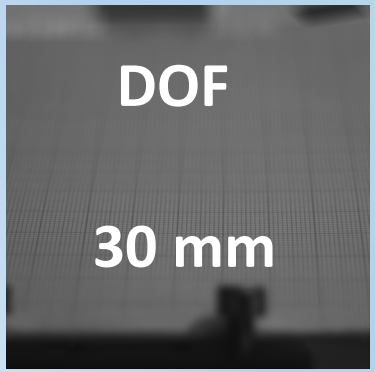
θ=26°

3 different setups

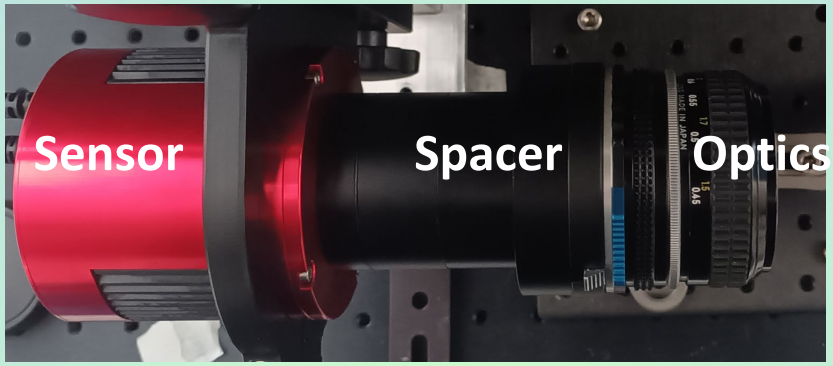
Sensor + Optics (Obiettivo)

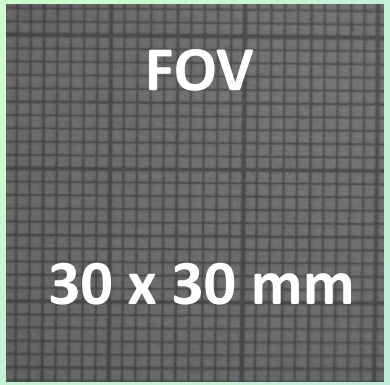


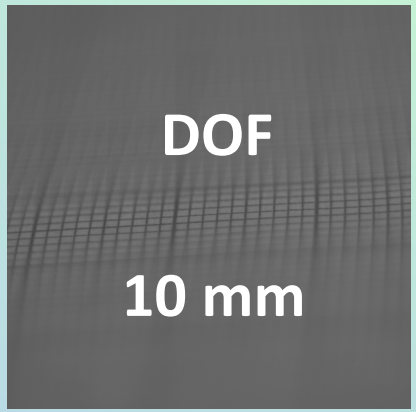




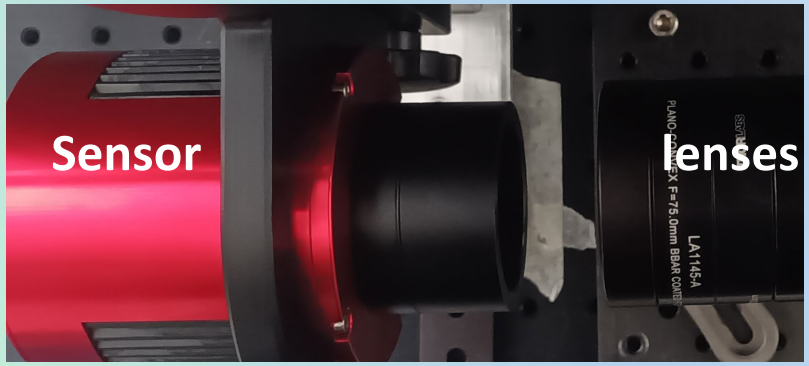
Sensor + Spacer + Optics (Obiettivo)







Sensor + Lenses



Optics characterization: summary

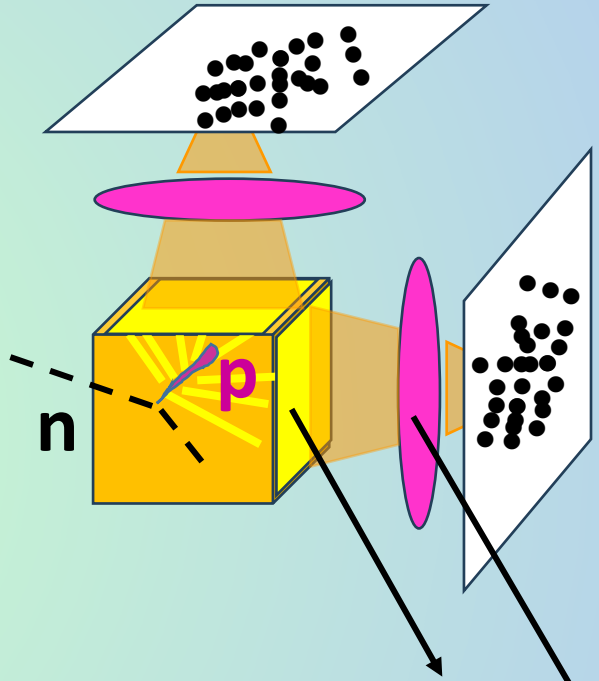
Tipologia lente	FOV (mm^2)	DOF (mm)	Distanza lente sorgente (mm)	Angolo solido (rad)
Obiettivo	80x80	~30	400	~0.004
Obiettivo + distanziatore (21 mm)	30x30	~10	180	~0.02
Due lenti: F75-F100	15x15	~17	~100	~0.19
Due lenti: F75-F125	**20x20**	**~30**	**~125**	**~0.13**
Due lenti: F75-F200	30x30	~40	~200	~0.05

Raggio lente: 25mm
Raggio obiettivo: 15mm

Tracks reconstruction of simulated data

Various methods under study

- **Linear Fit**
- **Principal Component Analysis (PCA)**
- **Hough Transform**
- **Moments method**



Uniform light distribution on the scintillator surfaces

Necessary to have optics to reconstruct the photon directions

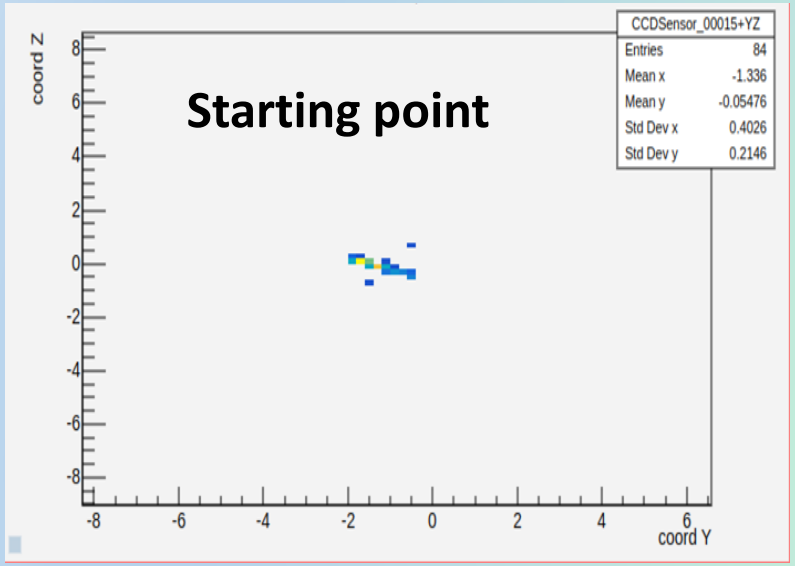
Proton 30 MeV

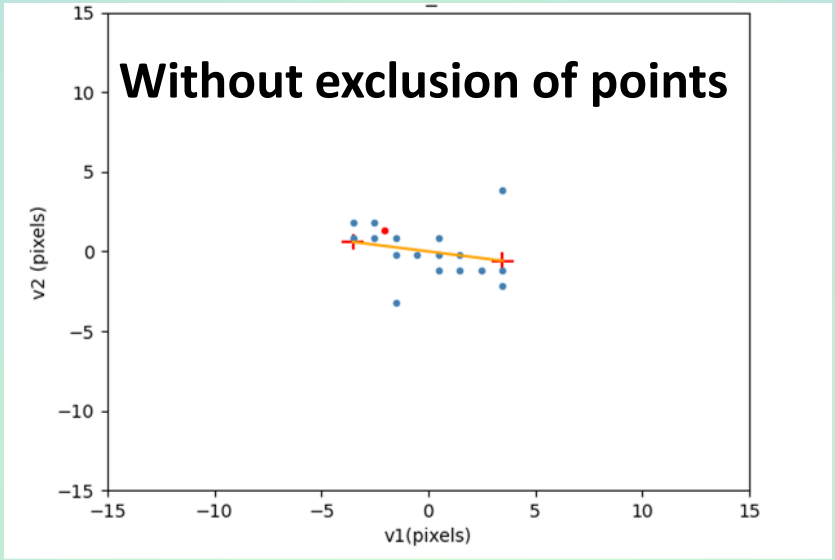
Lens Radius: 0.5 cm

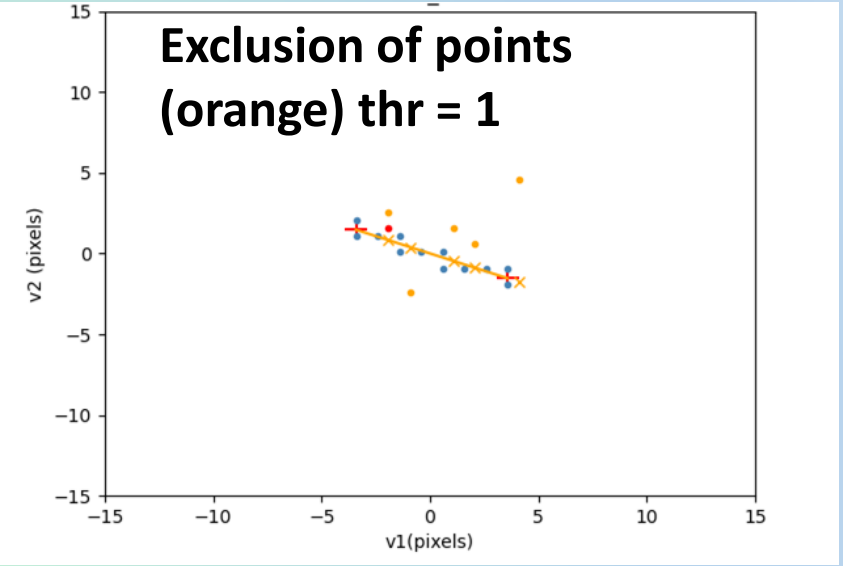
CMOS pixel: 100x100

Linear fit

Excluded points with a # of photons < thr (excluded points = yellow points)

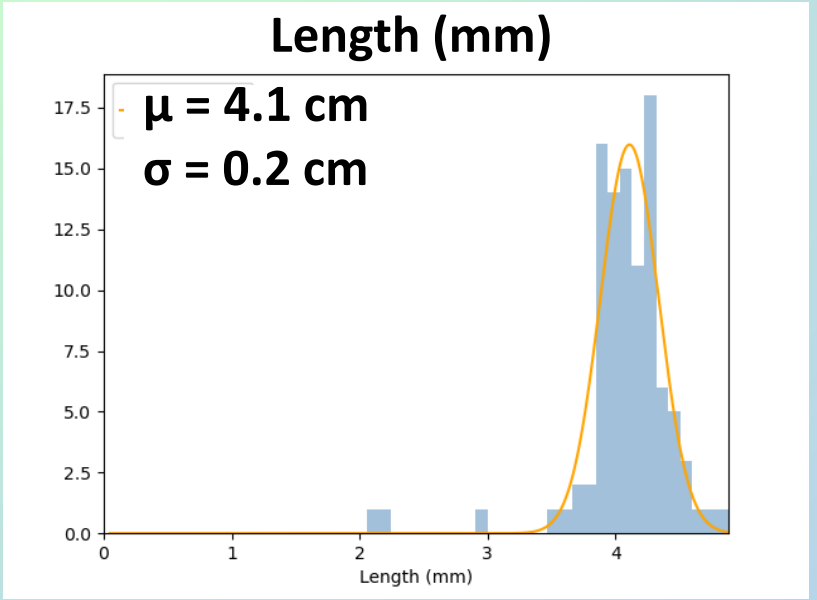






Range depends on the initial-final points

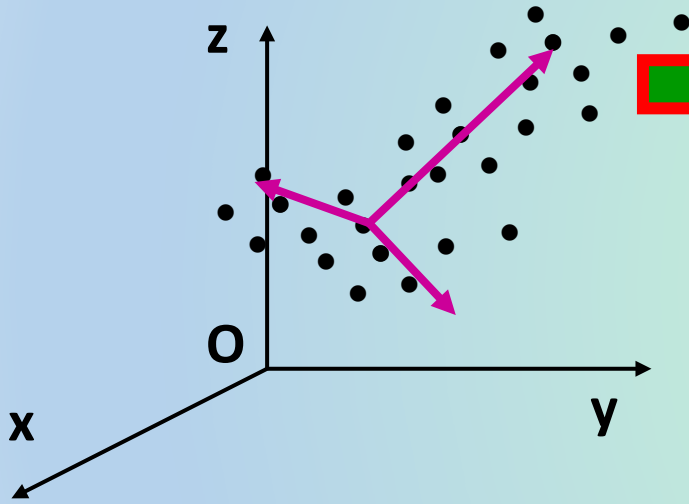
Crucial to identify noise points to discard



PCA Principal Component Analysis

In general (not our case) →

n points (x, y, z) in the space



Covariant matrix

$$\begin{pmatrix} < (x_i - < x >)^2 > & < (x_i - < x >)(y_i - < y >) > & < (x_i - < x >)(z_i - < z >) > \\ < (y_i - < y >)(x_i - < x >) > & < (y_i - < y >)^2 > & < (y_i - < y >)(z_i - < z >) > \\ < (z_i - < z >)(x_i - < x >) > & < (z_i - < z >)(y_i - < y >) > & < (z_i - < z >)^2 > \end{pmatrix}$$

Diagonalization

3 eigenvectors and 3 eigenvalues

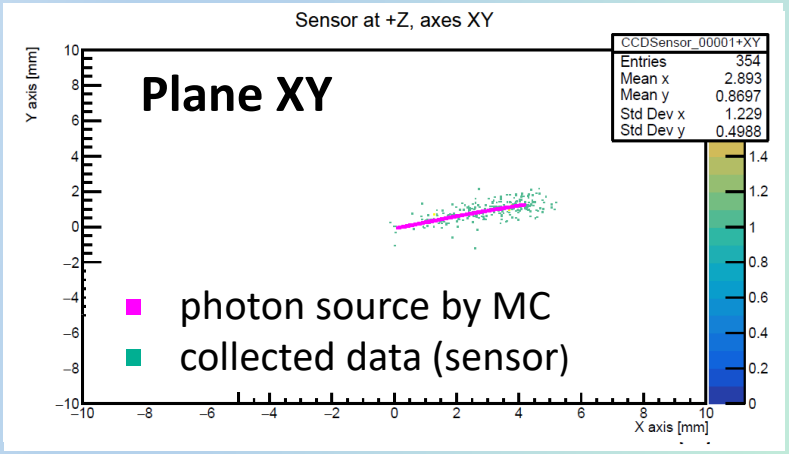
(maximum eigenvalue → principal direction)

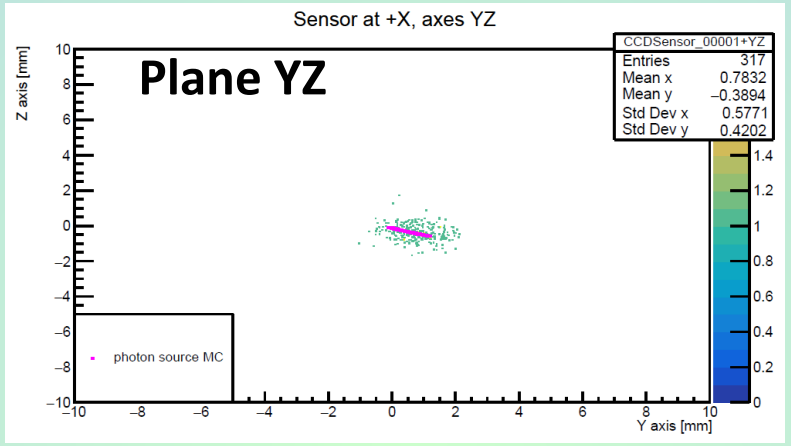
Reduction of dimension
3n points → 3 vectors

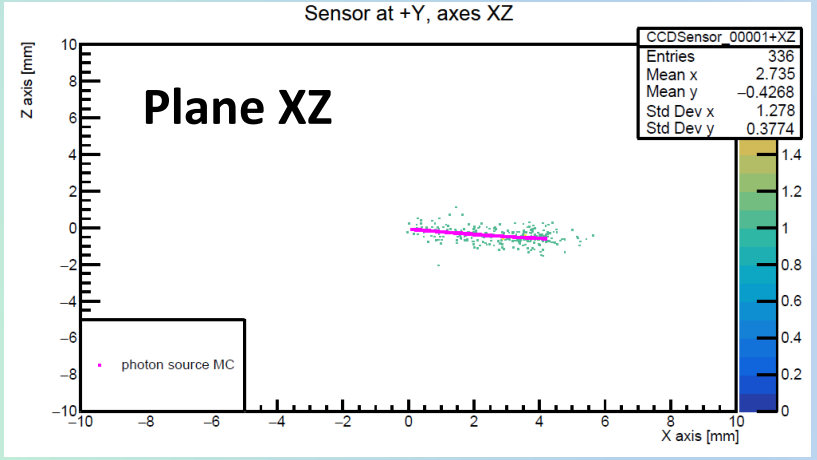
Projecting points on principal eigenvector → Bragg Peak

Source: 30 MeV protons
Generated in (2x2x2)cm³
Isotropic Direction

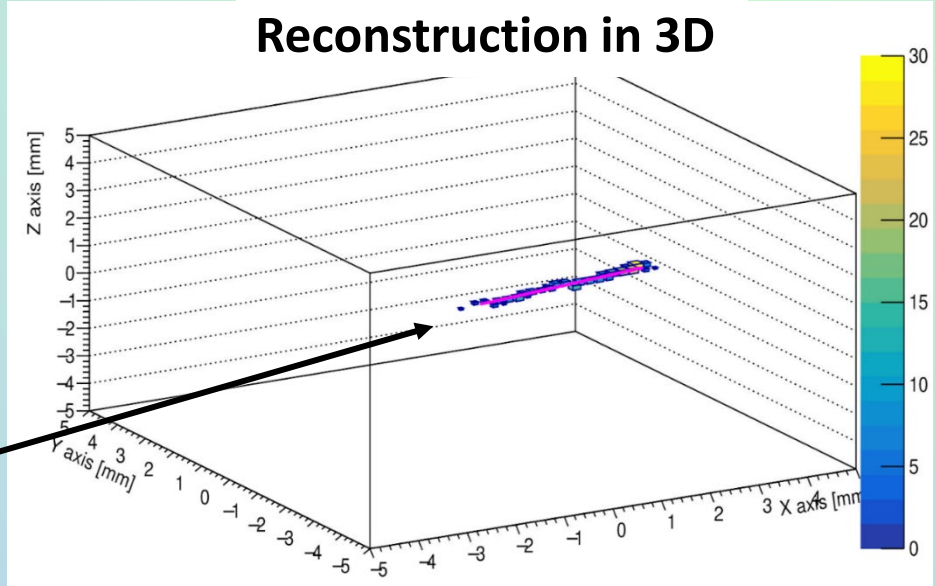
PCA (Principal Component Analysis)



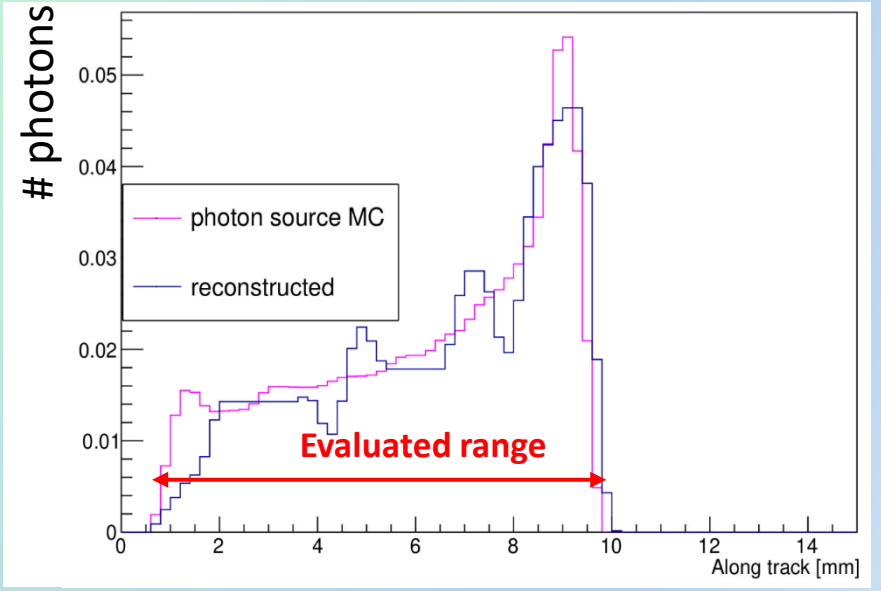




Reconstruction in 3D



proton track
proton reconstructed



Hough Transform

Image Recognition Method (around 1970)

Proton track → straight line

(f(x,y), (m, q))

(x,y) are points IMAGE SPACE

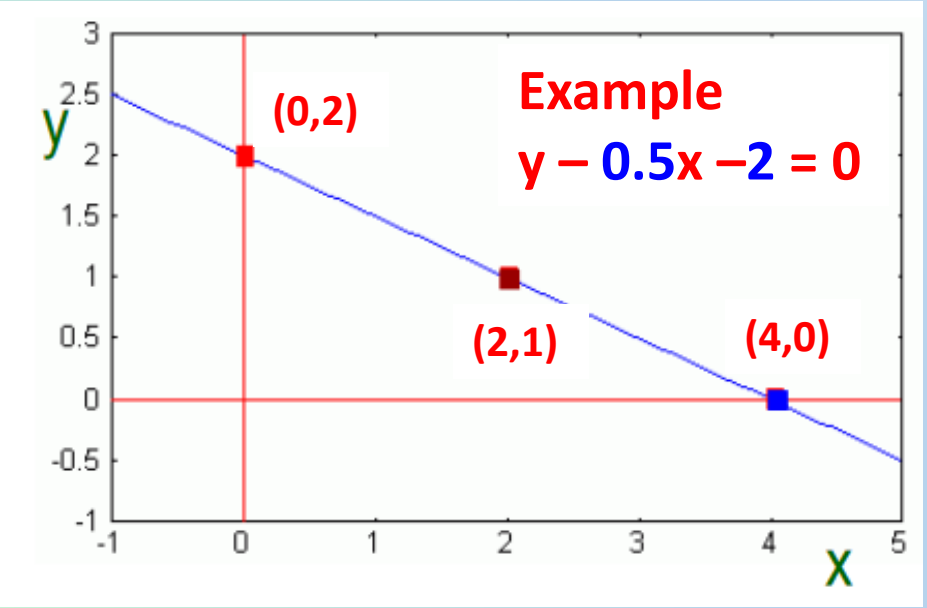
$y - mx - q = 0$

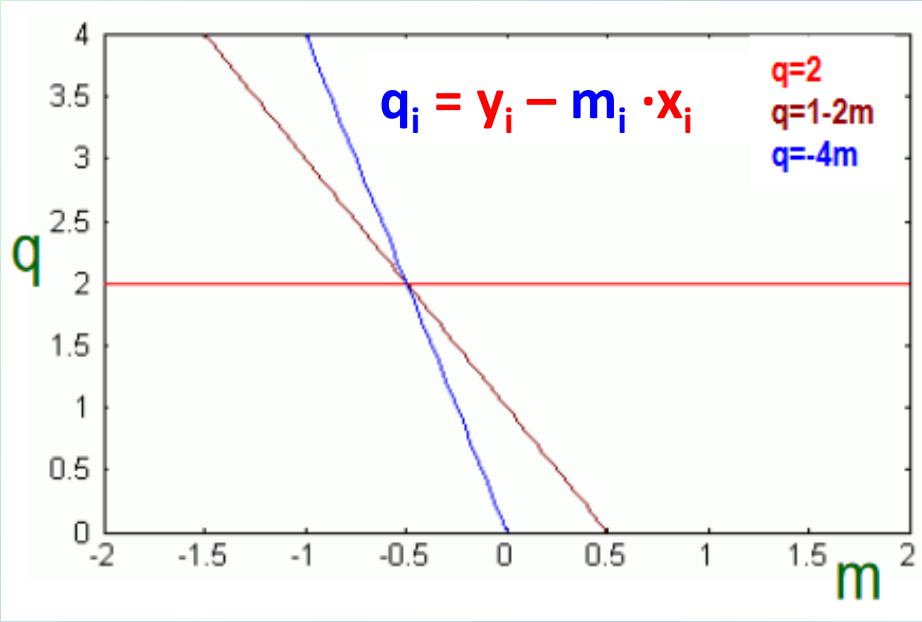
(m,q) PARAMETER SPACE

Each point in the IMAGE SPACE correspond to a point in the PARAMETER SPACE

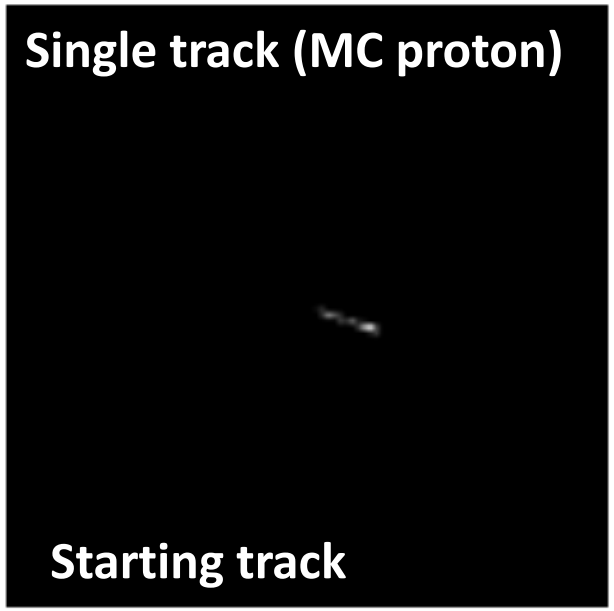
n points that belong to the same line create n surfaces that intersect at the same point

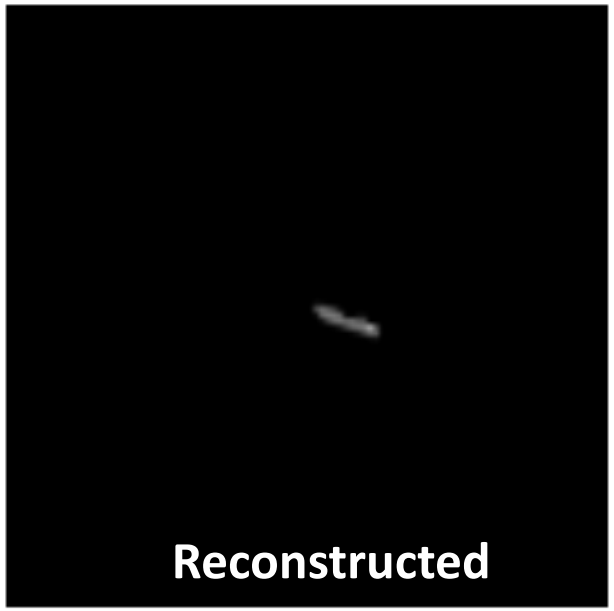
The method is time conuming



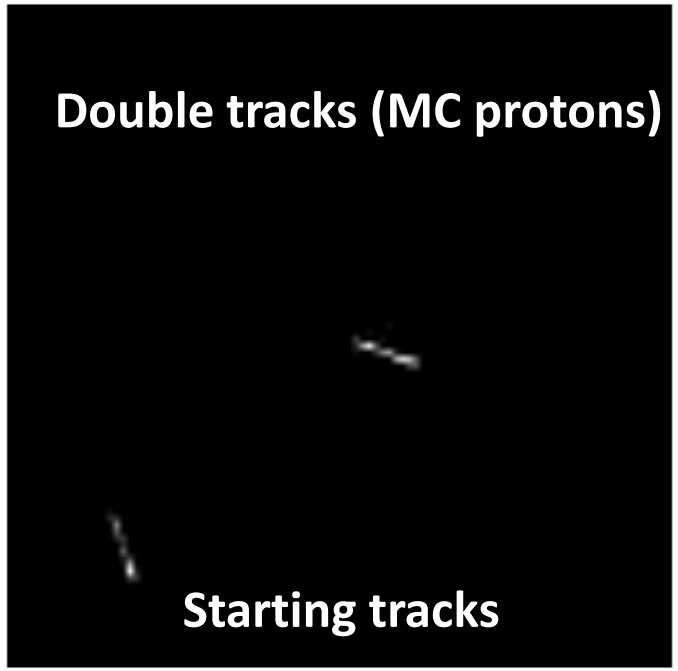


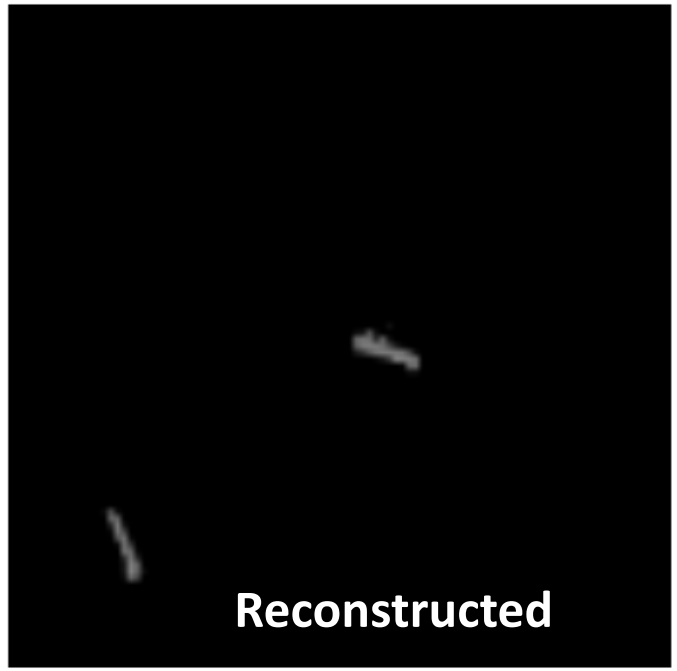
Hough Transform: result





R = 5 mm, 100 x 100 pixels



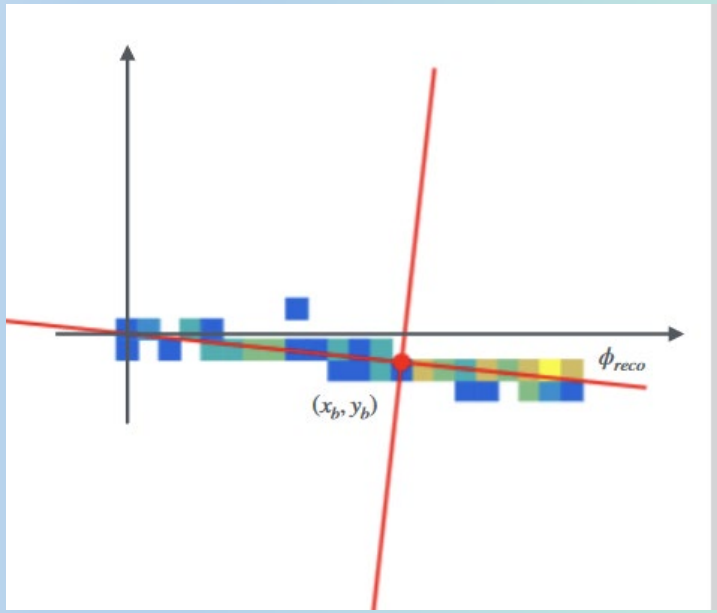


Overlapped 1: R = 5 mm, 100 x 100 pixels

Momenta method, 1

$$\vec{x_b} = \left(\frac{\sum_i Q_i x_i}{\sum_i Q_i}, \frac{\sum_i Q_i y_i}{\sum Q_i} \right)$$

x_b (y_b) center of gravity (first order momentum)



$$\begin{pmatrix} x_i'(\phi) \\ y_i'(\phi) \end{pmatrix} = \begin{pmatrix} cos\phi & sin\phi \\ -sin\phi & cos\phi \end{pmatrix} \begin{pmatrix} x_i \\ y_i \end{pmatrix}$$

Axes Rotation

$$M_2(\phi) = \frac{\sum_i Q_i x_i'^2(\phi)}{\sum_i Q_i} = \frac{\sum_i Q_i (x_i cos\phi + y_i sin\phi)^2}{\sum_i Q_i}$$

second order momentum

$$\frac{\partial M_2(\phi)}{\partial \phi} = 0$$

$$\phi_{max,min} = -\frac{1}{2} arctan \left[\frac{2\sum_i Q_i x_i y_i}{\sum_i Q_i (y_i^2 - x_i^2)} \right]$$

Principal axes

second order momentum ($\phi_{max,min}$)

$$M^{(2)}_{max,min} = \frac{\sum_i Q_i \left(x_i \cos(\phi_{max,min}) + y_i \sin(\phi_{max,min}) \right)^2}{\sum_i Q_i}$$

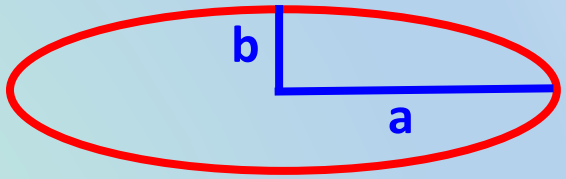
$$R = f(\varepsilon) \sqrt{M^{(2)}_{max}}$$

Range

To be evaluated

Momenta method, 2

For an elliptical distribution (as it is)



$$R = f(\varepsilon)\sqrt{M^{(2)}_{max}}$$

Range

$$\epsilon = \frac{M_2^{max}}{M_2^{min}} = \frac{1}{\sqrt{1-e}}$$

$e = b^2/a^2$

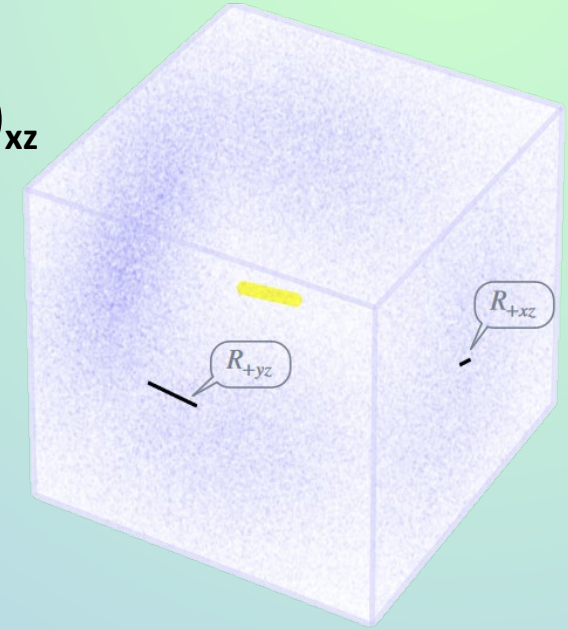
eccentricity

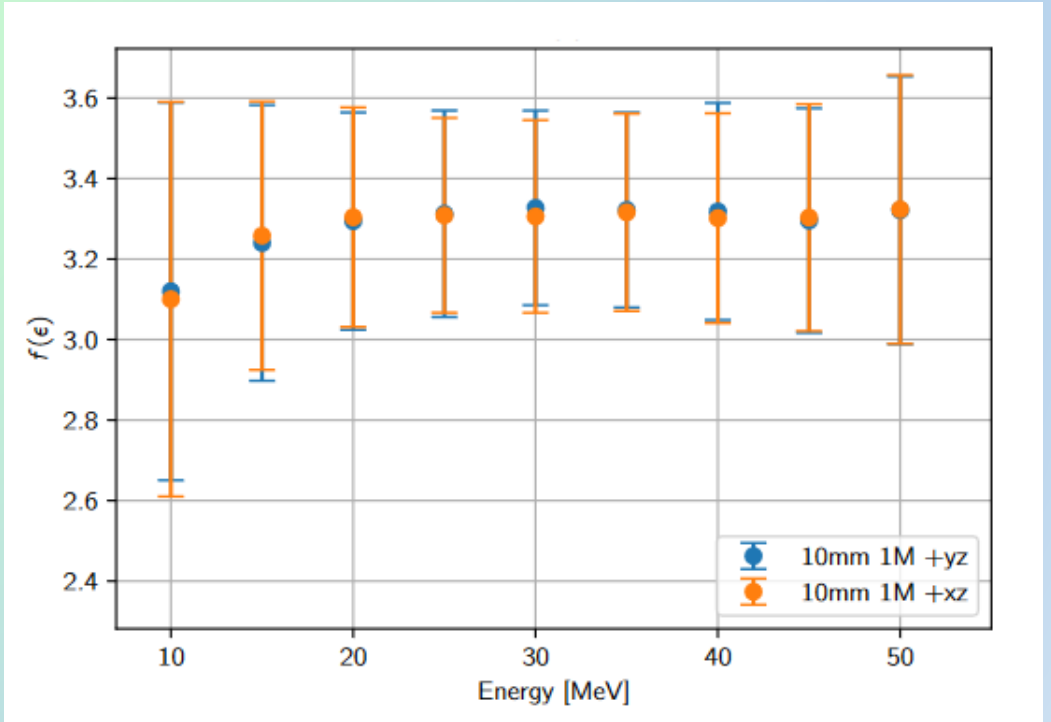
Range is a function of the eccentricity

Evaluated from the simulation

for 2 dimension → $f(\epsilon)_{yz}$ and $f(\epsilon)_{xz}$

$$f(\varepsilon)_{+yz(+xz)} = \frac{R_{+yz(+xz)}}{\sqrt{M^{(2),max}_{+yz(+xz)}}}$$





The work is going on

Sensor and Optics characterization

- sensitivity
- noise
- Linearity
- Signals from γ and α sources
- Field of View (FOV) and Depth of Focus (DOF)

Various methods of track reconstruction under study

- Linear Fit
- Principal Component Analysis (PCA)
- Hough Transform
- Moments method

Next future

- Micro Channel Plate measurements

Service Request (can change)

- Electronics (0.5 MU)
- STG (0.5)

TASK ID	TASK TITLE	START DATE	END DATE	DURATION IN MONTHS	2024											
					Q1				Q2				Q3			
					Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Simulation & Analysis	01/01/2024	31/12/2025	24												M1
2	Optics	01/01/2024	30/06/2025	18												M2
3	Electronics & DAQ	01/07/2024	31/12/2025	18												M3
4	Demonstrator	01/01/2025	31/12/2025	12												
5	Data Analysis	01/07/2025	31/12/2026	18												
6	Test	01/07/2025	30/06/2026	12												

M1: Definition of all the geometry except the image intensifier
M2: Light yield and multianode PMT measurements
M3: Firmware for image acquisition

Backup

GANT

TASK ID	TASK TITLE	START DATE	END DATE	DURATION IN MONTHS
1	Simulation & Analysis	01/01/2024	31/12/2025	24
2	Optics	01/01/2024	30/06/2025	18
3	Electronics & DAQ	01/07/2024	31/12/2025	18
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5	Data Analysis	01/07/2025	31/12/2026	18
6	Test	01/07/2025	30/06/2026	12

2024												2025												2026											
Q1			Q2			Q3						Q1				Q2				Q3				Q1				Q2				Q3			
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
											M1												M5												
											M2																								
											M3						M4						M6												
																							M7												
																													M9						M11
																							M8						M10						

M1: Definition of all the geometry except the image intensifier
M2: Light yield and multianode PMT measurements
M3: Firmware for image acquisition
M4: Image acquisition with external trigger
M5: Reconstruction of the neutron kinematics in double scattering events
M6: Simultaneous acquisition from multiple cameras with external trigger
M7: First prototype realization (without the image intensifier)
M8: First laboratory tests with radioactive neutron source
M9: Analysis of radioactive source data
M10: Data taking with proton and neutron beams
M11: Track reconstruction from beam data

Requests & GANT

CAPITOLO	DESCRIZIONE	2024	2025	2026
Apparati	2ND CMOS high frame rate (~CYCLONE 2000)	**7.5**	3RD CMOS: **7.5** (if required)	
Inventario	2 Canon RF 35mm F1.8 IS MACRO ST	**1.5**	MCP (if necessary) [**30**]	
Consumo	cables, connectors, supports	**1.0**	Lab metabolism: **2**	Lab metab: **2**
	black box to characterize light sensors	**1.0**		
	lens and mirrors	**1.0**		
Missioni	2 in-presence meetings in Bologna	**1.0**	In presence meetings: **1**	data takings: **5**
Totale		**13**	**[3-40]**	**7**

Group Members

RIPTIDE: RecoIl ProTon Imaging DEtector

Nome	Ruolo	FTE 2024
Console Camprini Patrizio	Ricercatore ENEA Bologna	0.5
Giacomini Francesco	Primo Tecnologo CNAF Bologna	0.1
Massimi Cristian	Professore associato UNIBO	0.5
Mengarelli Alberto	Tecnologo INFN Bologna	0.2
Ridolfi Riccardo	Assegnista di Ricerca Bologna	0.5
Spighi Roberto	Dirigente di Ricerca INFN Bologna	0.5
Terranova Nicholas	Ricercatore ENEA Frascati	0.5
Pisanti Claudia	Dottoranda	1.0
Musumarra Agatino	Professore Associato UNICT	0
Pellegriti Maria Grazia	Ricercatore INFN	0
Villa Mauro	Professore Ordinario	0
TOTALE FTE		3.8