



**POLITECNICO**  
MILANO 1863



ERC-2014-CoG No. 647554

**ENSURE**



**Department of Energy**

# Experimental demonstration of quantitative laser-driven PIXE and EDX analysis

Francesco Mirani  
Politecnico di Milano

June 2021

❖ Activities performed within the framework of an **ERC consolidator grant** (2015 - 2020).

# ENSURE



erc -2014-CoG No.647554

Exploring the **New Science** and engineering unveiled by  
**U**ltraintense ultrashort **R**adiation interaction with **mattEr**



**POLITECNICO**  
MILANO 1863

DIPARTIMENTO DI ENERGIA

[www.ensure.polimi.it](http://www.ensure.polimi.it)

❖ Present **team members**:



**M. Passoni**  
Principal investigator



**D. Dellasega**



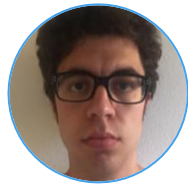
**M. Zavelani**



**V. Russo**



**A. Pola**



**D. Vavassori**



**A. Maffini**

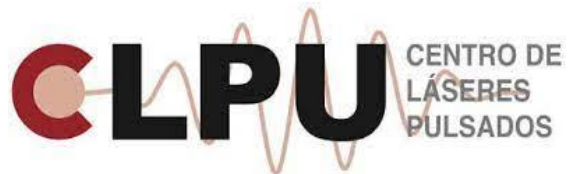


**A. Formenti**



**F. Mirani**

❖ In **collaboration** with:



**M. Galbiati**

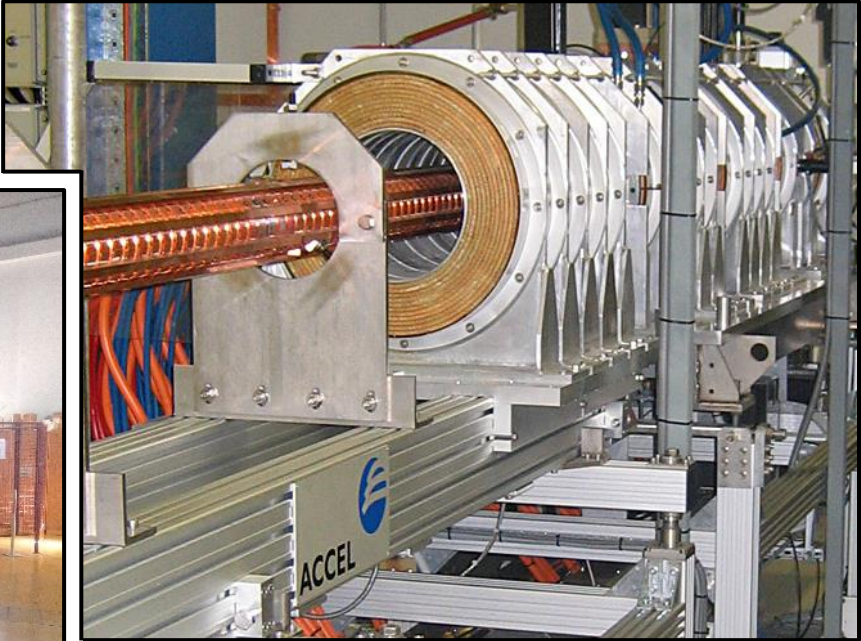


**D. Orecchia**



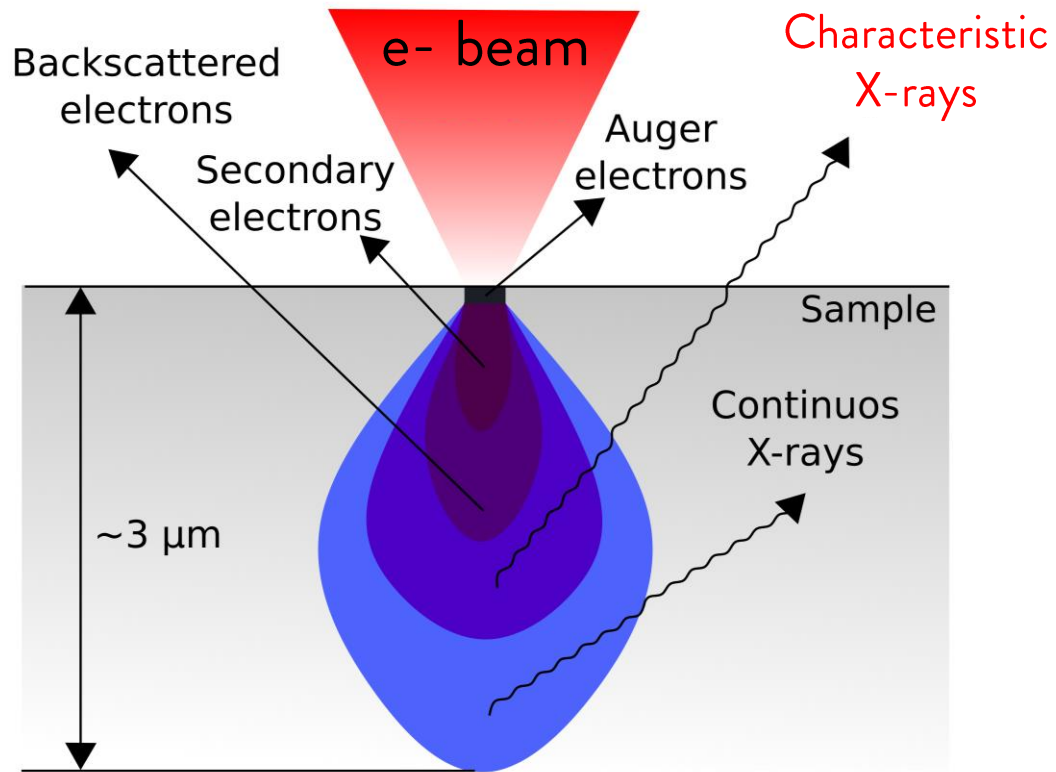
# Atomic and nuclear analytical methods for materials characterization

- ✔ **Complementary** (bulk/surface, homogeneous/stratigraphic)
- ✔ **High detection capabilities**
- ✔ **Non-destructive**

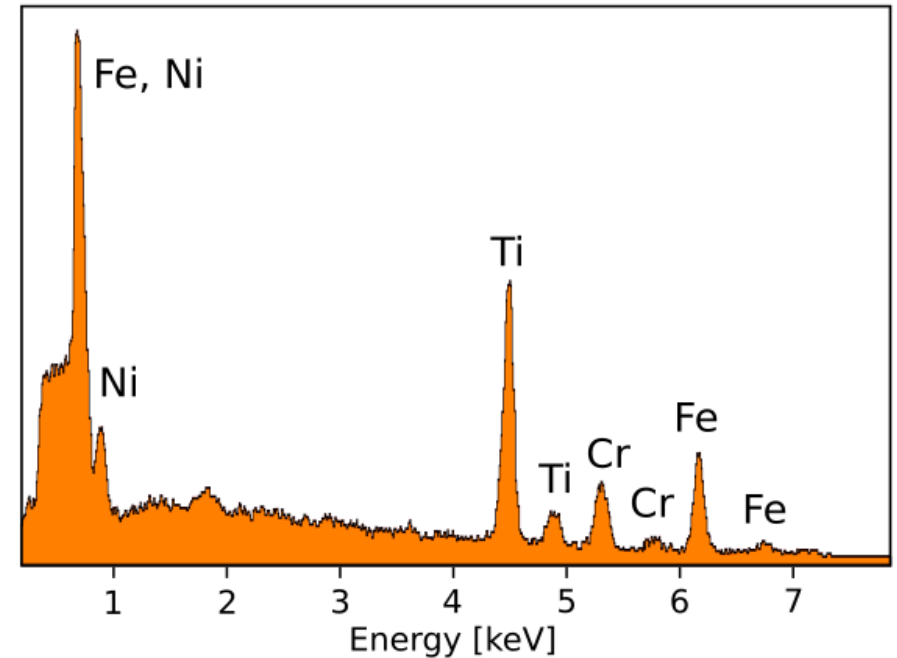


- ✘ **Large and expensive**
- ✘ **Non-tunable energy**
- ✘ Only **one kind of particle** is provided by the machine

# Energy Dispersive X-ray (EDX) spectroscopy



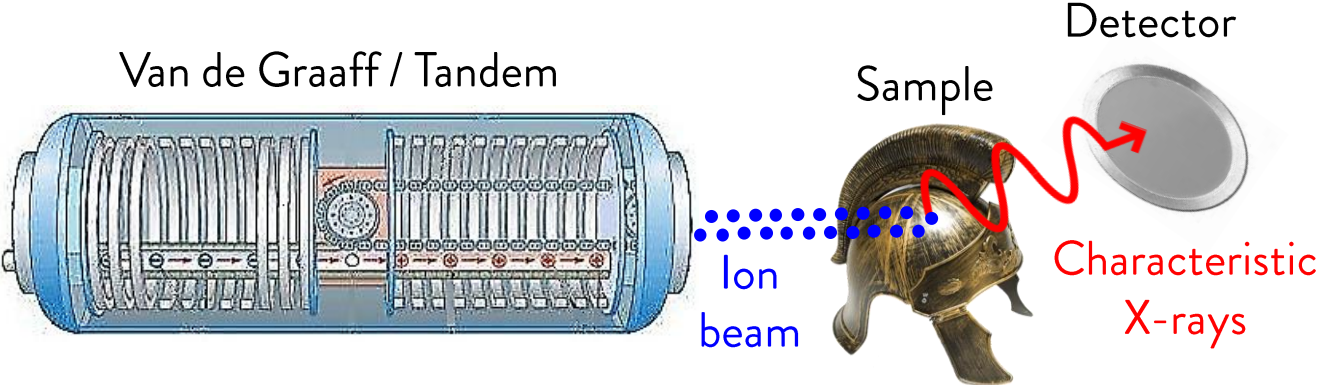
- ❖ **KeV** energy **electrons**
- ❖ **Small** and solid **samples**
- ❖ Fast **identification** of the elements and **concentrations** reconstruction from standards



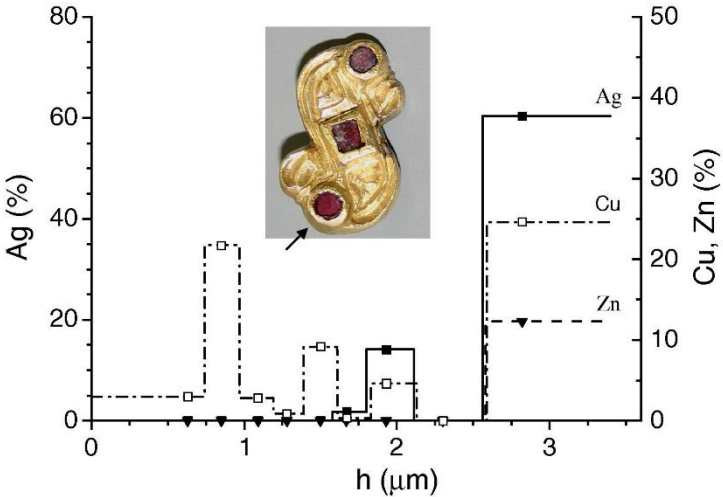
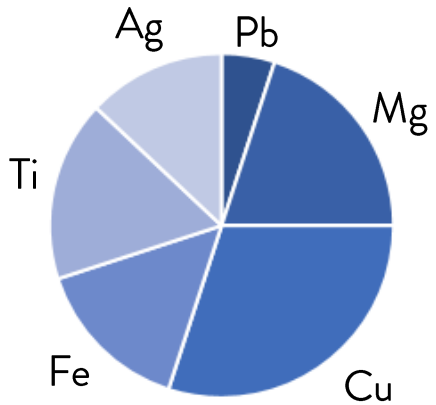
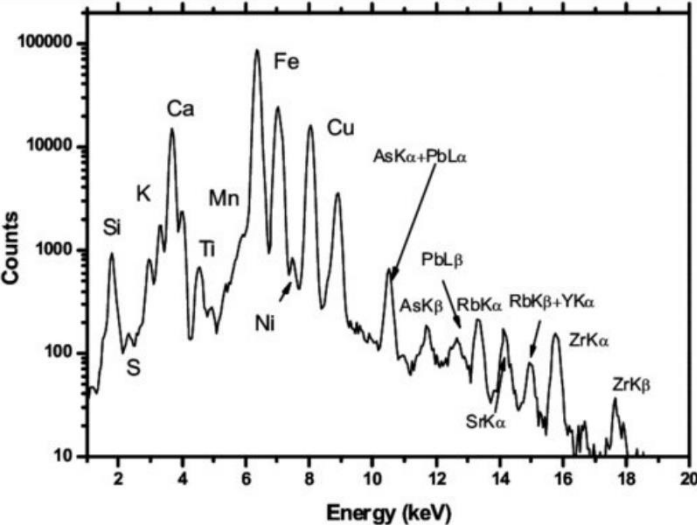
DC Bell and AJ Garratt-Reed. Energy dispersive X-ray analysis in the electron microscope, volume 49. Garland Science, 2003.

A Pazzaglia, et al. Materials Characterization, 153:92-102, 2019.

# Particle Induced X-ray Emission (PIXE)



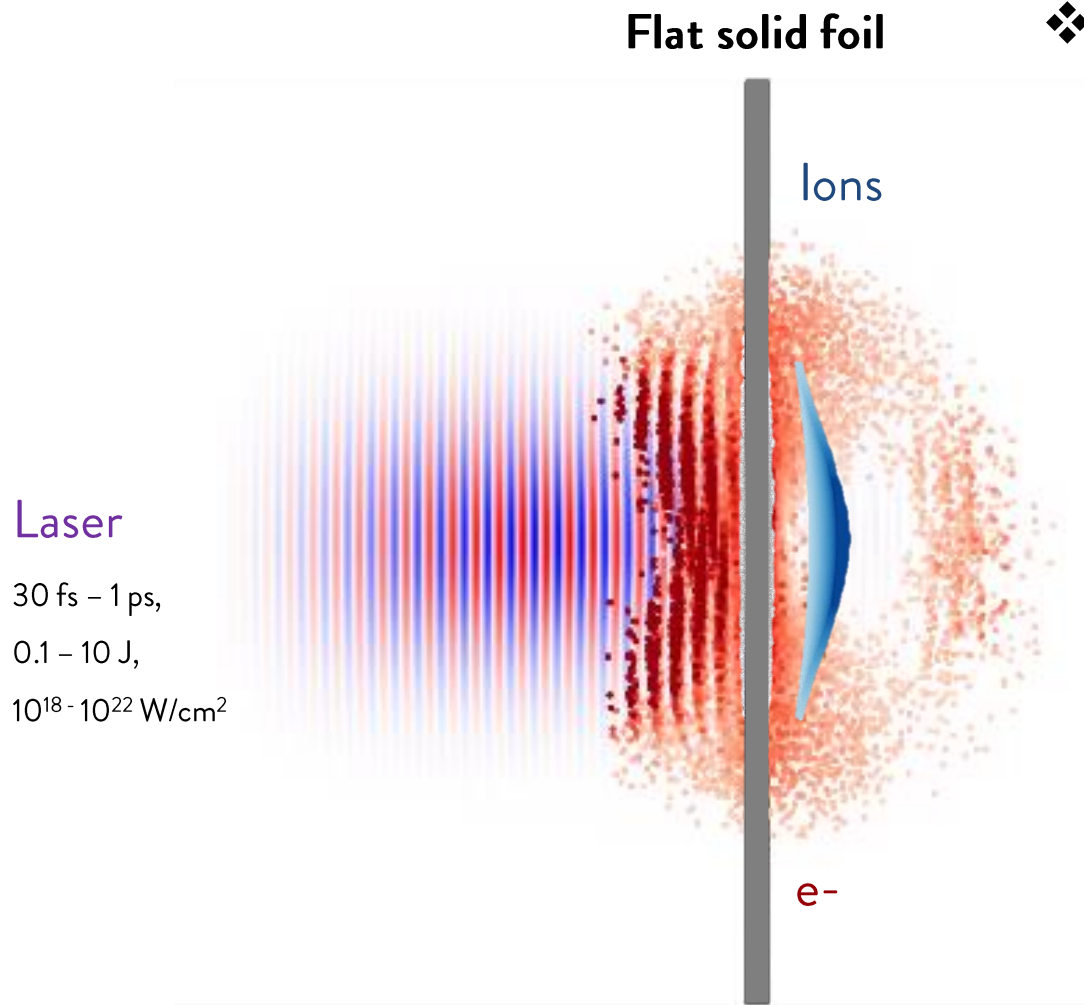
- ❖ 2-5 MeV/u monoenergetic ions
- ❖ Concentrations & Depth profiles
- ❖ Cultural heritage, environment, biology, forensic analysis



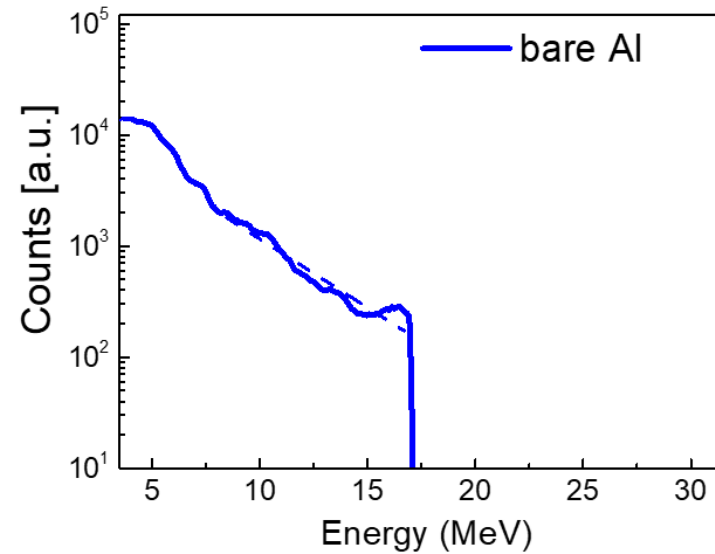
Verma, Hem Raj. Atomic and nuclear analytical methods. Springer-Verlag Berlin Heidelberg, 2007.

Žiga Šmit, et al. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 266(10):2329-2333, 2008.

# Can laser-driven sources be exploited for PIXE and EDX?

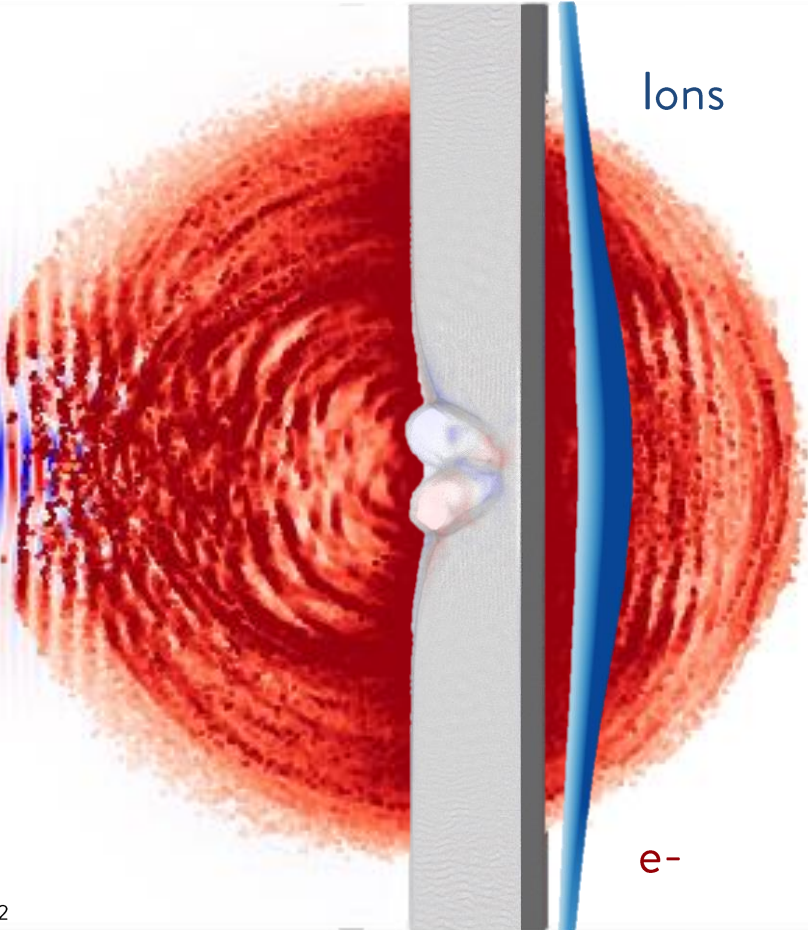


❖ **Solid targets** and **TNSA** acceleration (reliable mechanism, both electrons and ions)



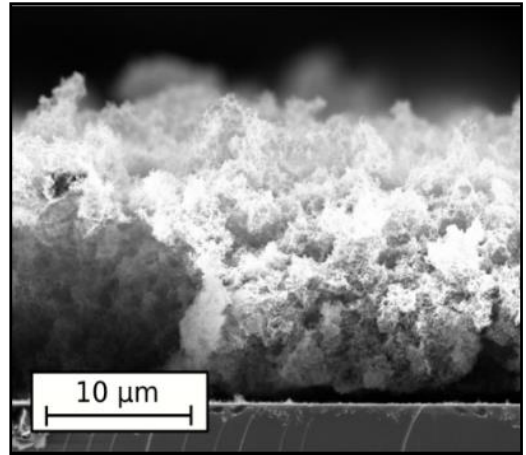
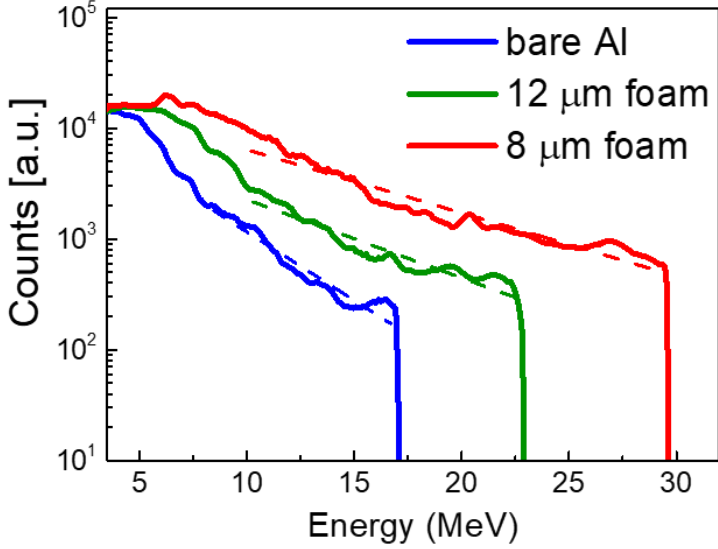
# Can laser-driven sources be exploited for PIXE and EDX?

## Double Layer Target (DLT)



Laser  
30 fs – 1 ps,  
0.1 – 10 J,  
 $10^{18}$  -  $10^{22}$  W/cm<sup>2</sup>



❖ Change the **target** configuration to **enhance** the **acceleration** (e.g. **DLT**)

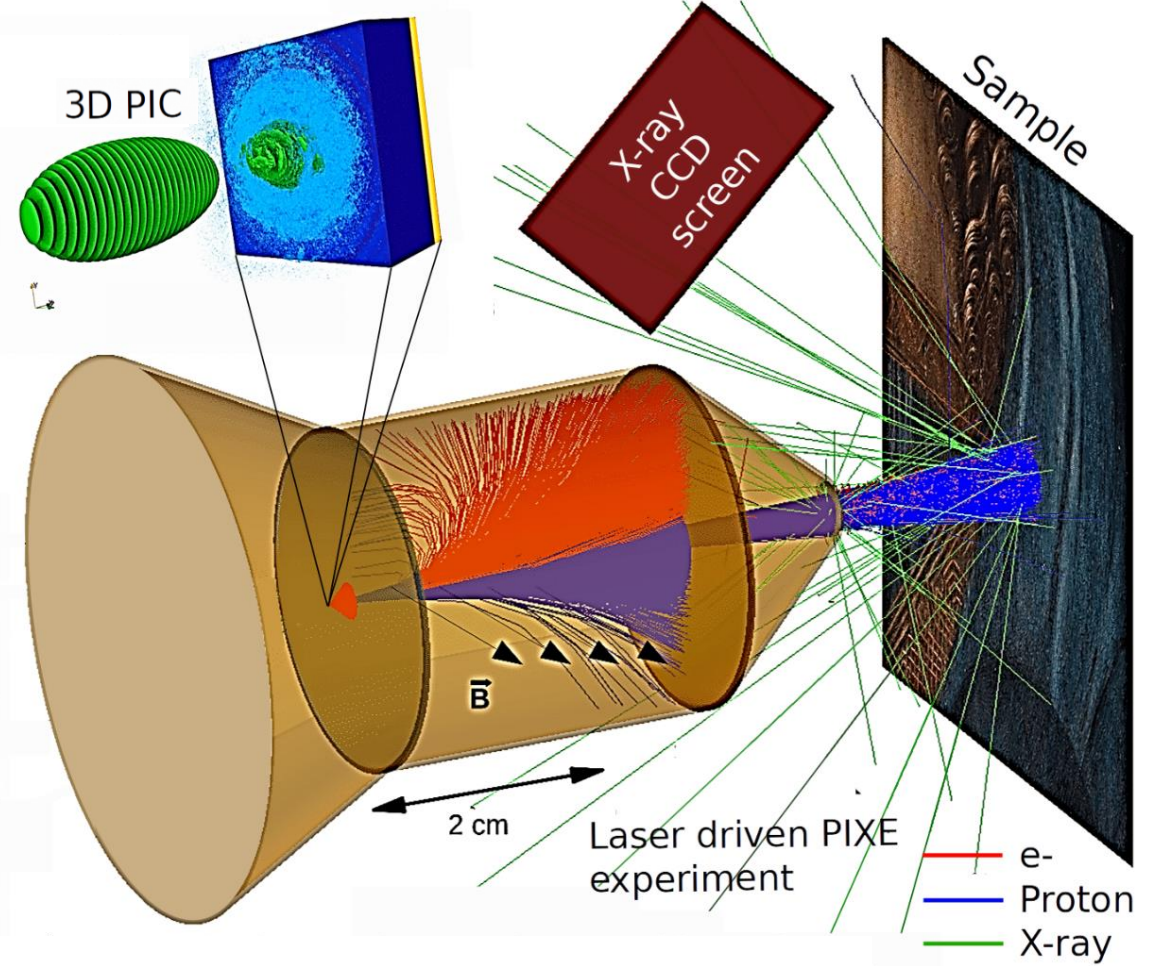
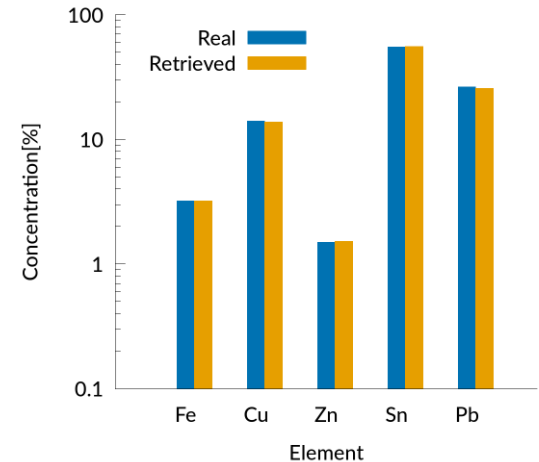
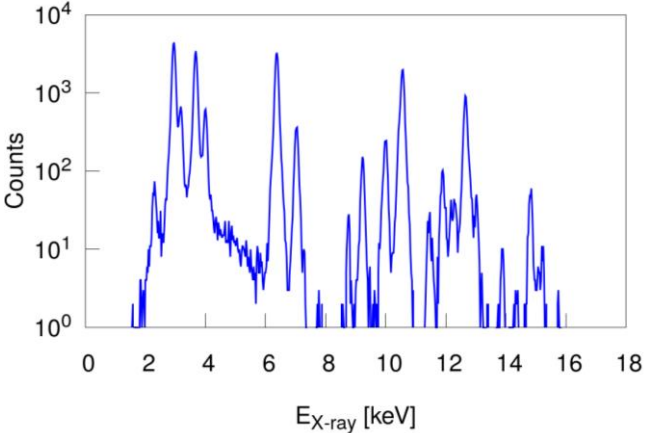


❖ **Unconventional** features of the laser-driven **particles** (e.g. broad energy spectrum)



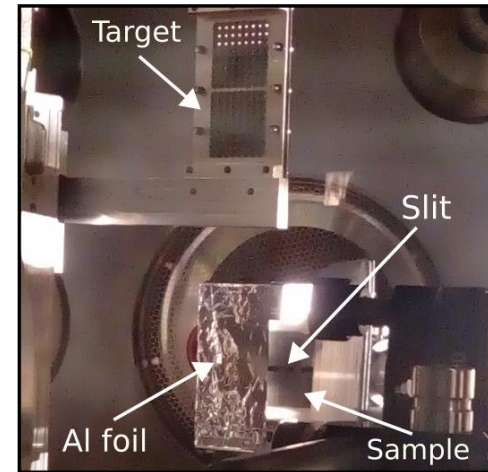
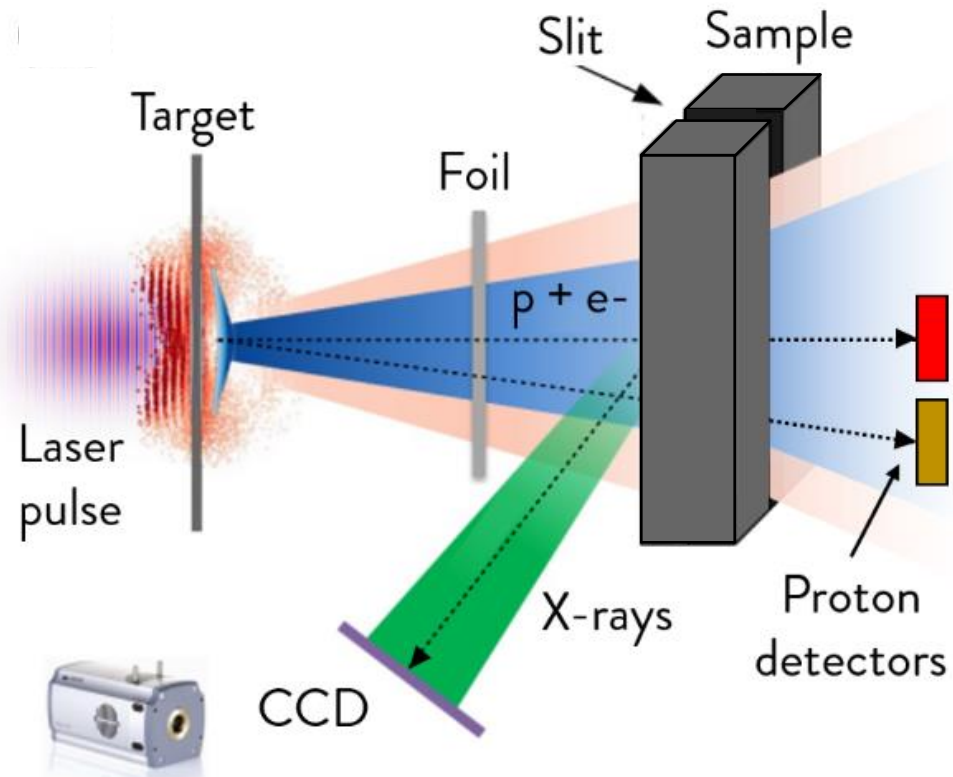
# Laser-driven PIXE, a numerical investigation

- ❖ PIXE theory with non-monoenergetic proton
- ❖ **Simulation** of laser-driven PIXE realistic scenarios (  ,  )
- ❖ **Software** development for the **analysis** of the **X-ray spectra** → Sample composition reconstruction



Passoni, Matteo, Luca Fedeli, and Francesco Mirani. "Superintense laser-driven ion beam analysis." Scientific reports 9.1 (2019): 1-11.

## 1 **EDX setup** → Sample irradiation with both electrons and protons

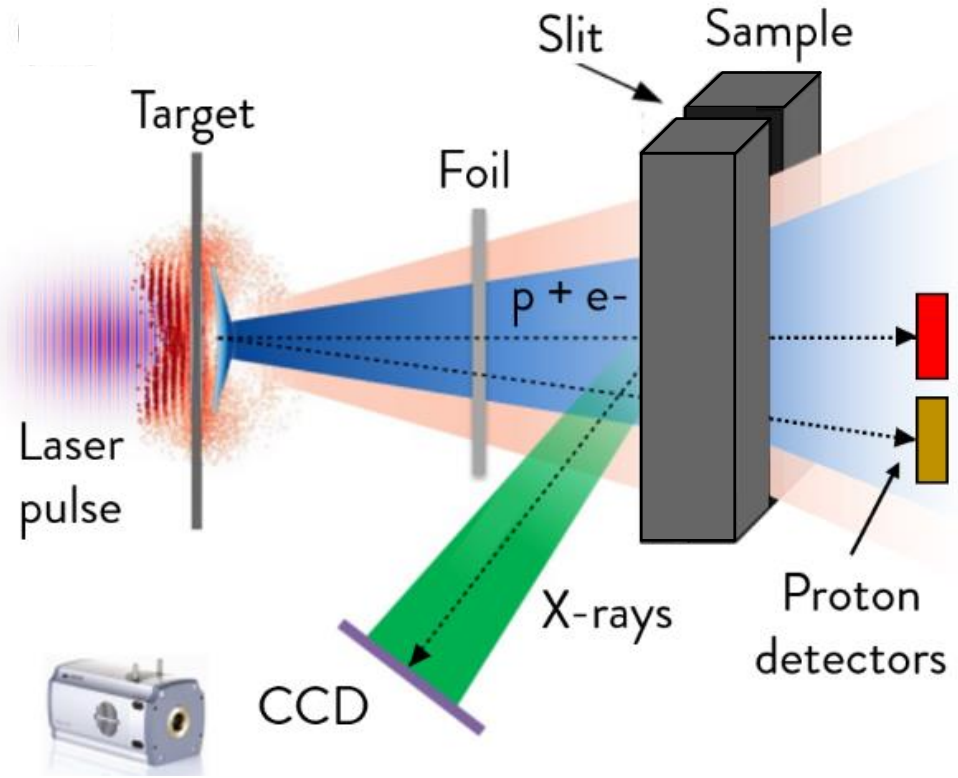


❖ **Vega-2 laser pulse**  
(30 fs, 800 nm, 3 J,  
 $\sim 10^{20}$  W/cm<sup>2</sup>)

- ❖ 6  $\mu\text{m}$  thick Al target
- ❖ 10  $\mu\text{m}$  thick Al → stop debris
- ❖ **Aperture slit** in the middle of the sample

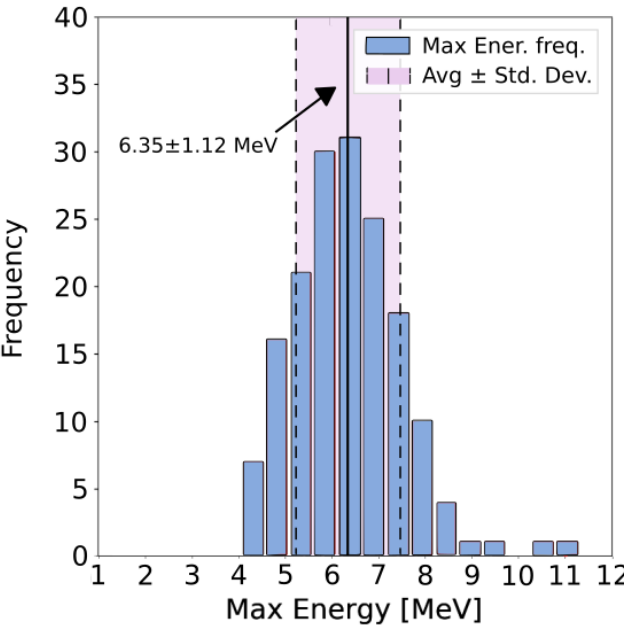
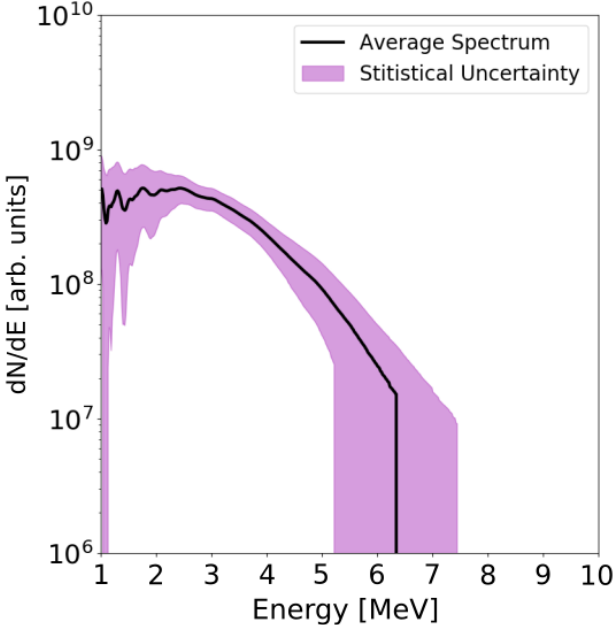
Mirani, F., et al. "Integrated quantitative PIXE analysis and EDX spectroscopy using a laser-driven particle source." *Science advances* 7.3 (2021): eabc8660.

## 1 EDX setup → Sample irradiation with both electrons and protons



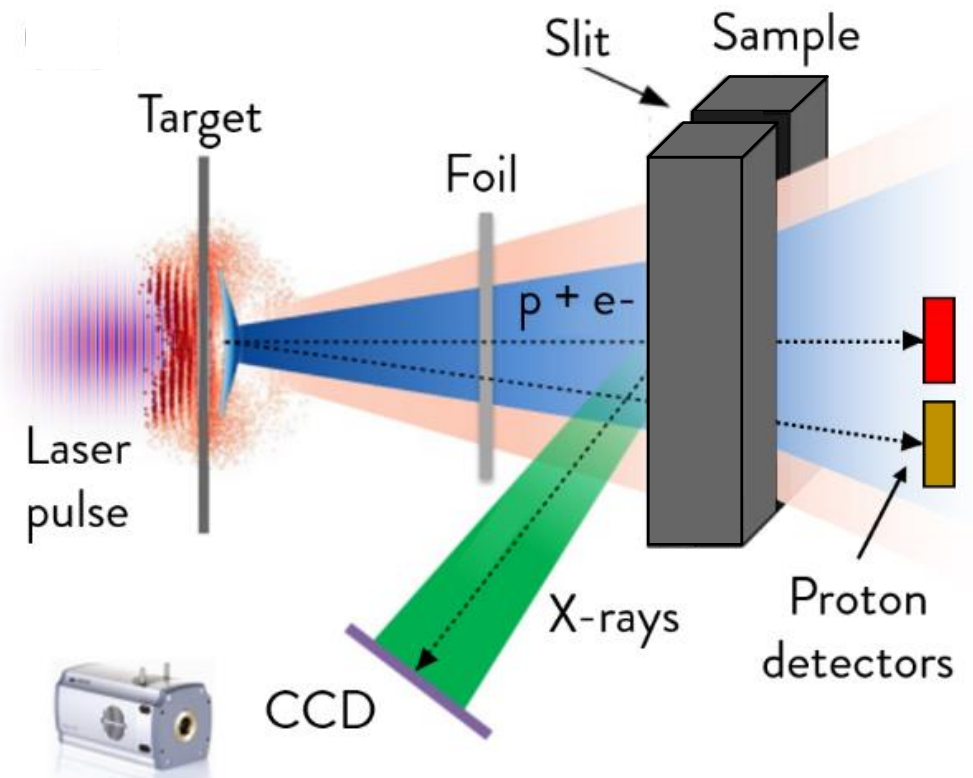
❖ Proton spectrum characterization (ToF)

❖ Maximum energy equal to 6.3 MeV

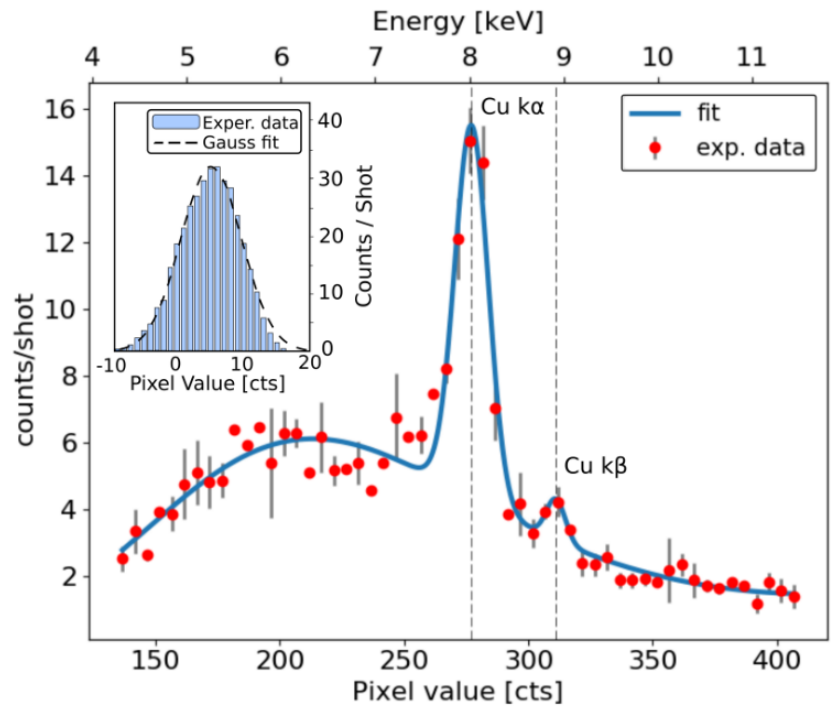


Mirani, F., et al. "Integrated quantitative PIXE analysis and EDX spectroscopy using a laser-driven particle source." Science advances 7.3 (2021): eabc8660.

## 1 EDX setup → Sample irradiation with both electrons and protons

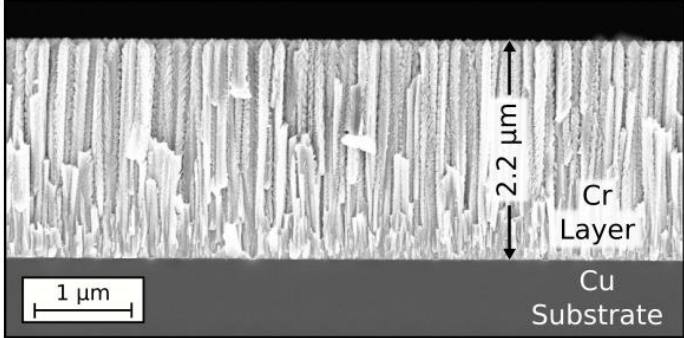
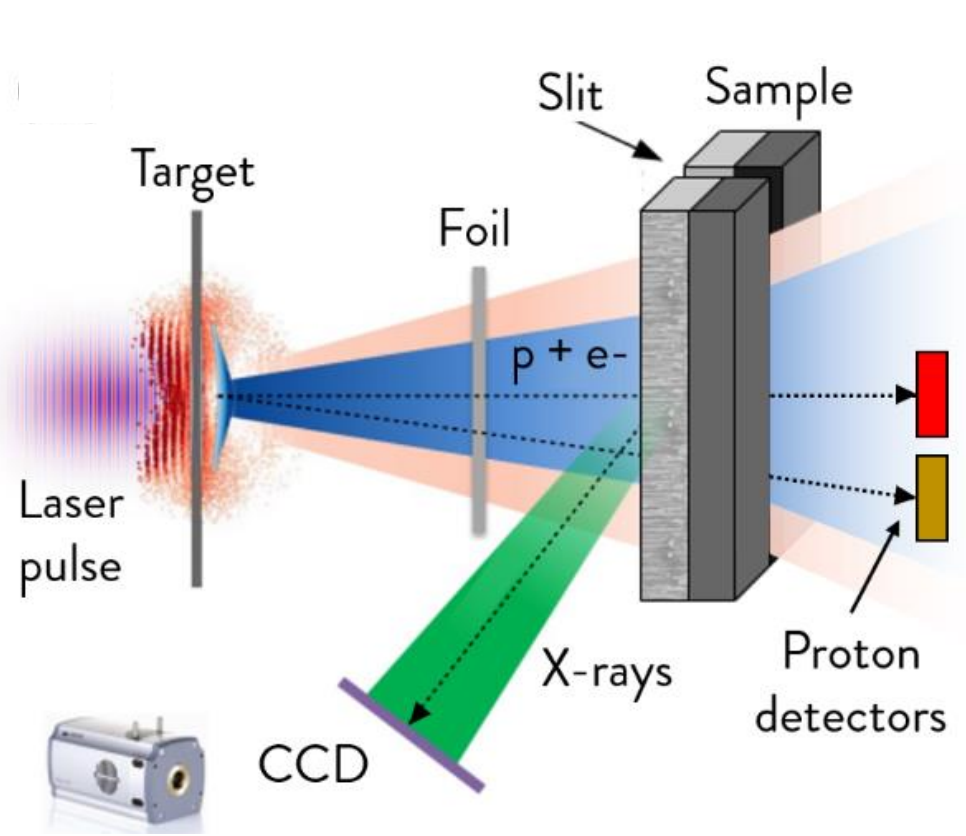


### ❖ X-ray CCD energy calibration (pure Cu sample)



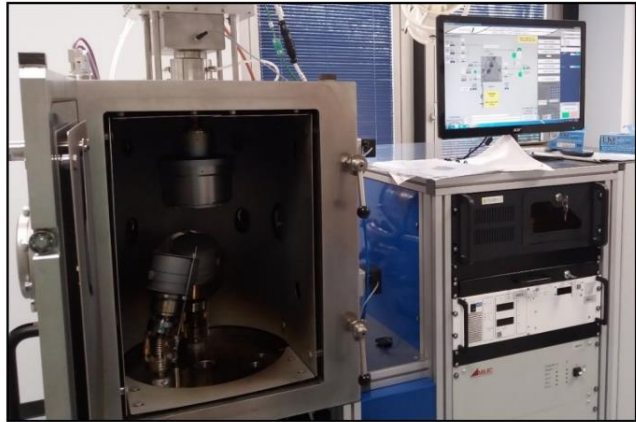
Mirani, F., et al. "Integrated quantitative PIXE analysis and EDX spectroscopy using a laser-driven particle source." Science advances 7.3 (2021): eabc8660.

## 1 EDX setup → Sample irradiation with both electrons and protons



Bi-layer sample (Cr layer + Cu substrate)

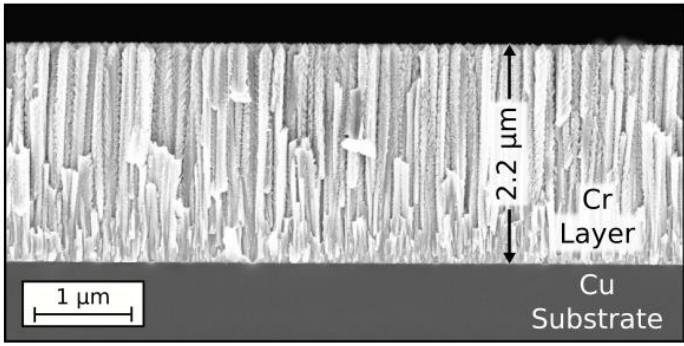
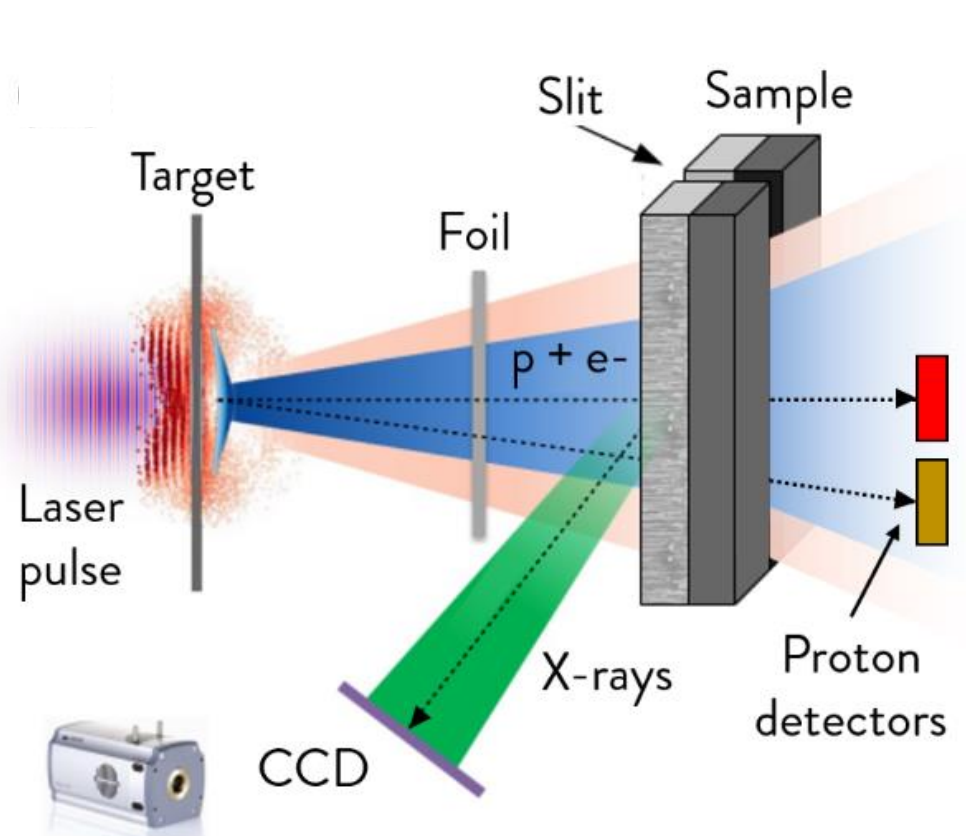
❖ Produced @ [NanoLab](#) with **Direct Current Magnetron Sputtering** (controlled thickness and composition)



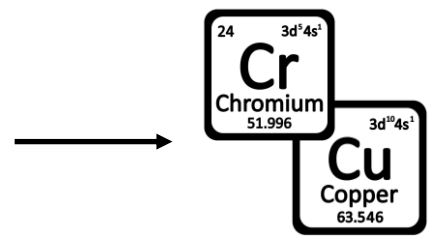
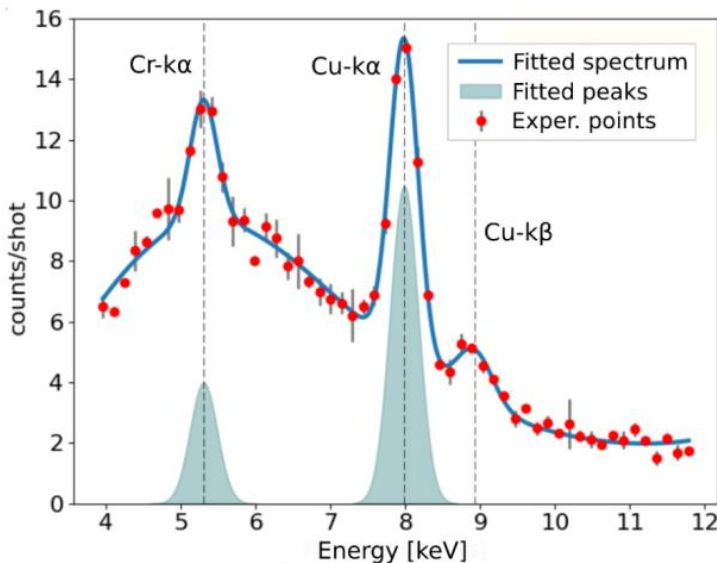
Mirani, F., et al. "Integrated quantitative PIXE analysis and EDX spectroscopy using a laser-driven particle source." *Science advances* 7.3 (2021): eabc8660.

# Laser-driven PIXE and EDX experiment @ CLPU

1 **EDX setup** → Sample irradiation with both electrons and protons



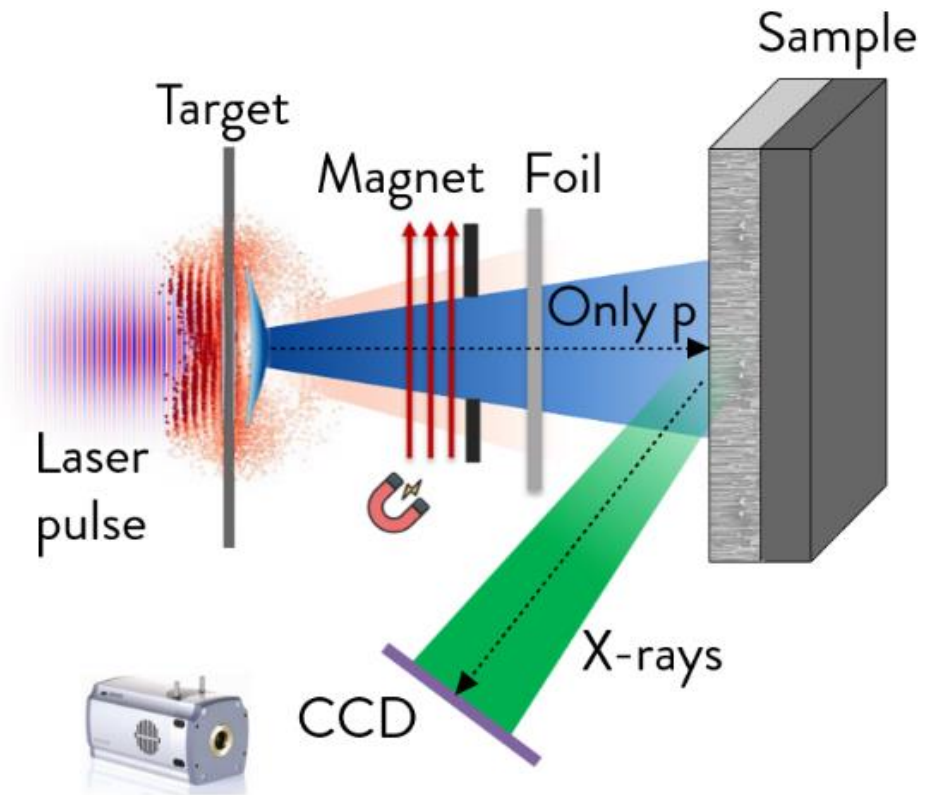
Bi-layer sample (Cr layer + Cu substrate)



Elements are correctly recognized

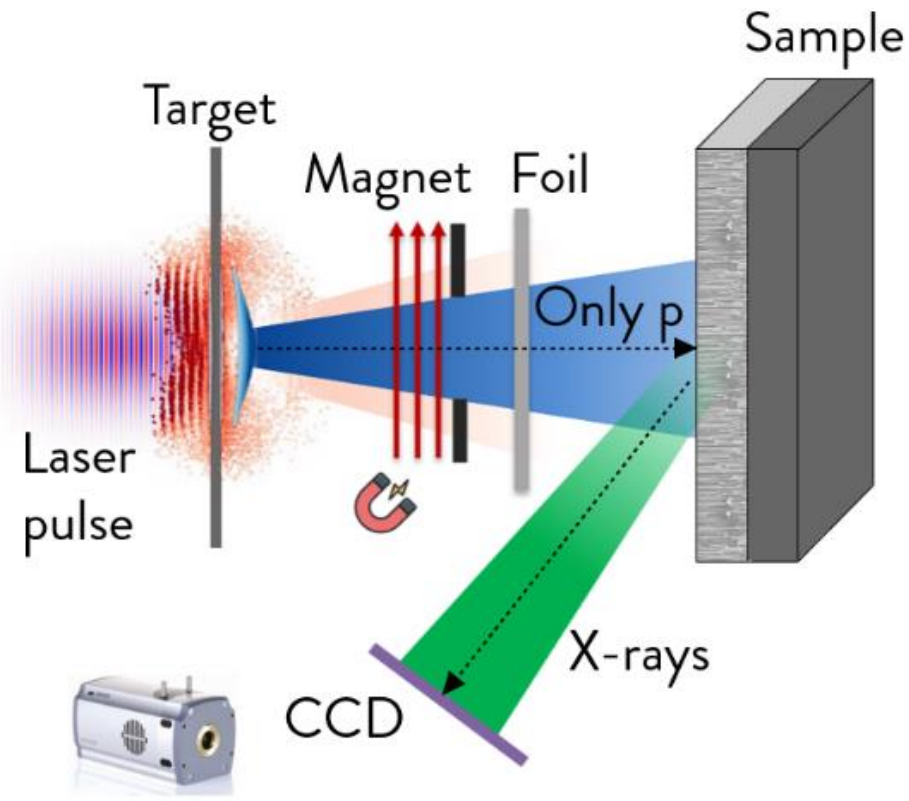
Mirani, F., et al. "Integrated quantitative PIXE analysis and EDX spectroscopy using a laser-driven particle source." Science advances 7.3 (2021): eabc8660.

## ② PIXE setup → Removal of the electrons with dipole magnet (0.26 T) and lead shielding

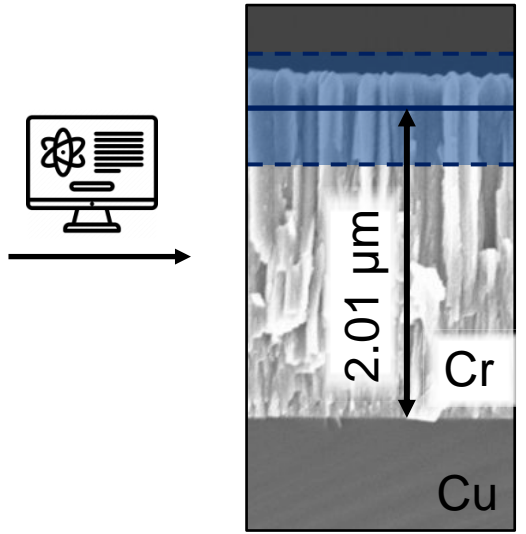
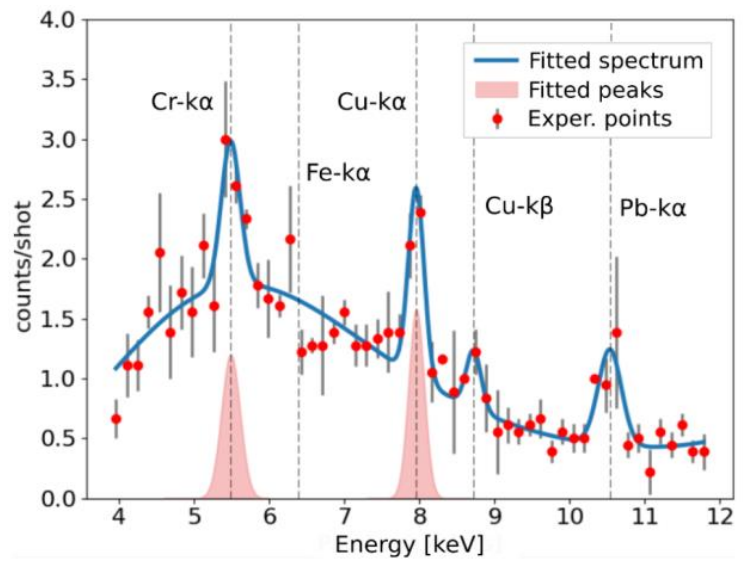


Mirani, F., et al. "Integrated quantitative PIXE analysis and EDX spectroscopy using a laser-driven particle source." *Science advances* 7.3 (2021): eabc8660.

## 2 PIXE setup → Removal of the electrons with dipole magnet (0.26 T) and lead shielding



❖ **Sample thickness reconstruction** exploiting the model developed for the laser-driven PIXE analysis



Mirani, F., et al. "Integrated quantitative PIXE analysis and EDX spectroscopy using a laser-driven particle source." Science advances 7.3 (2021): eabc8660.



# Laser-driven PIXE and EDX experiment @ CLPU

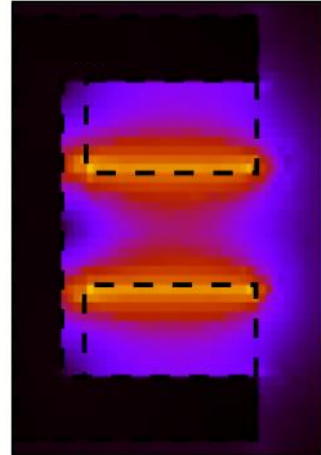
❖ **Electron and proton contribution** to the **X-ray production?**



Finite Element Analysis



3D **Magnetic field** distribution



0.0 T 0.6

## 1 EDX setup

❖ **Electron contribution is dominant**



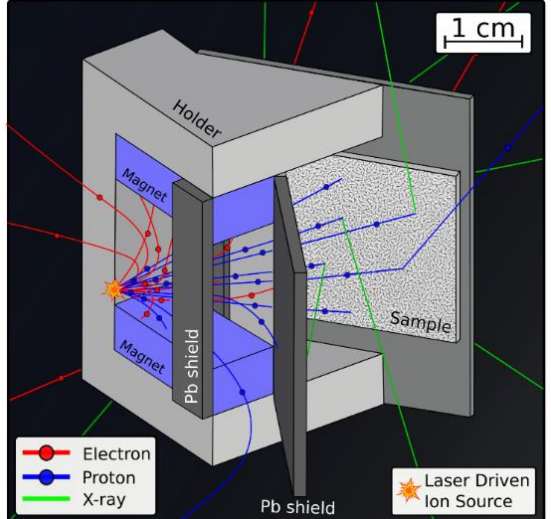
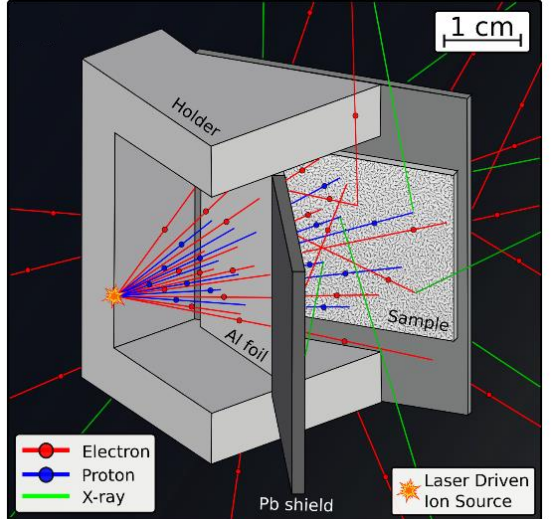
**Fast elemental analysis**

## 2 PIXE setup

❖ **~98% of electrons are removed**



**Quantitative analysis**

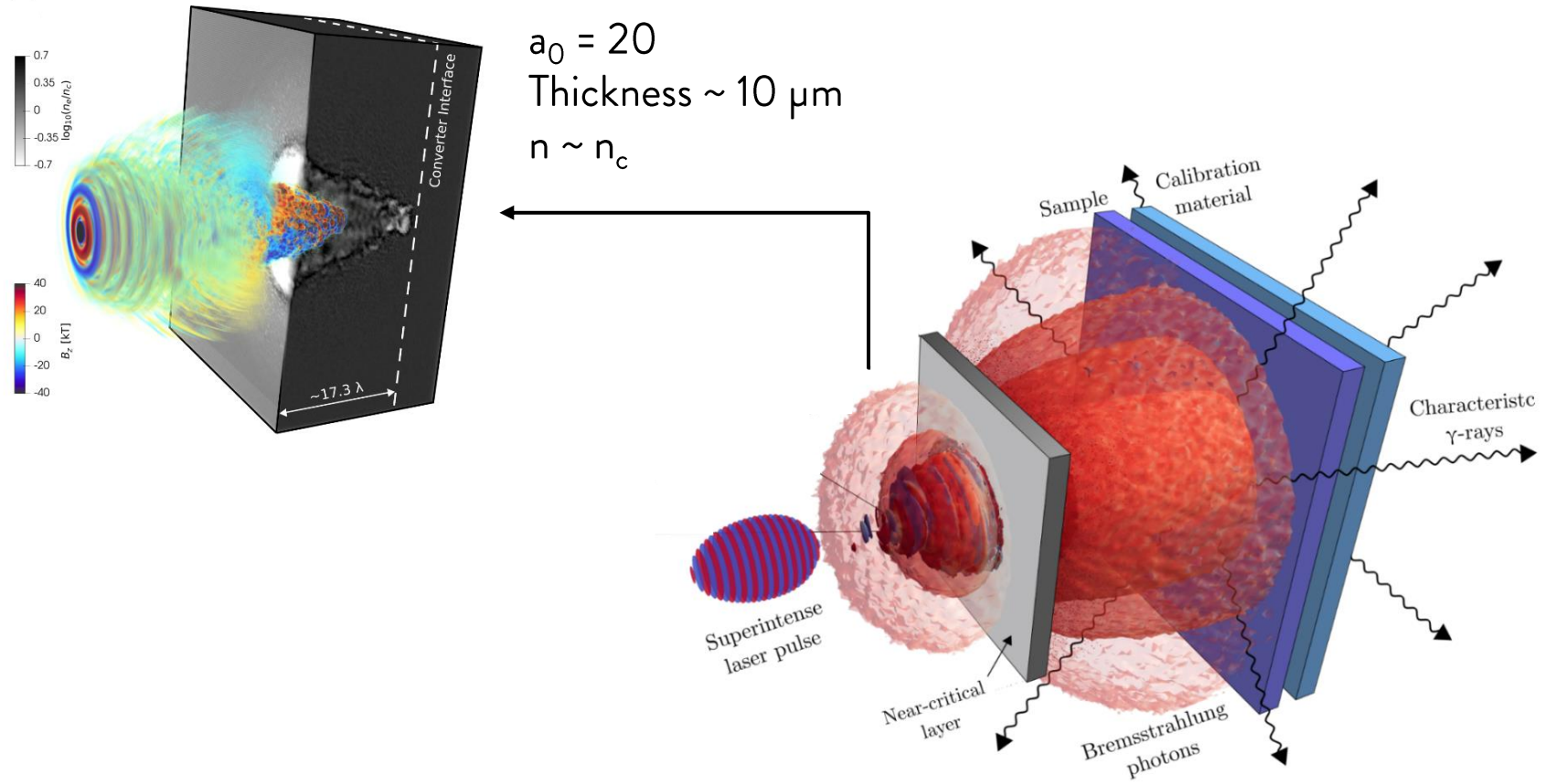


Mirani, F., et al. "Integrated quantitative PIXE analysis and EDX spectroscopy using a laser-driven particle source." Science advances 7.3 (2021): eabc8660.

# Another characterization technique?...Laser-driven Photon Activation Analysis

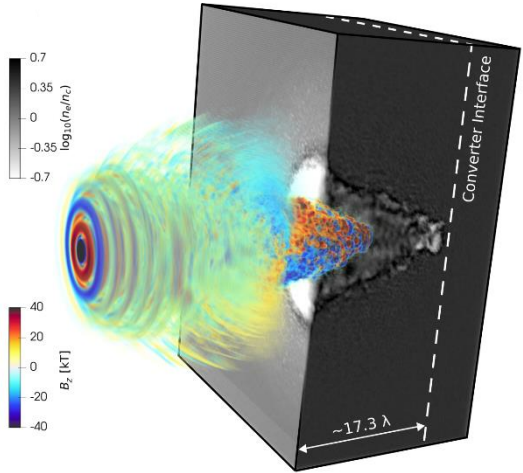
# Another characterization technique?...Laser-driven Photon Activation Analysis

1) Laser + **near-critical** material  $\rightarrow$  **Hot e-**



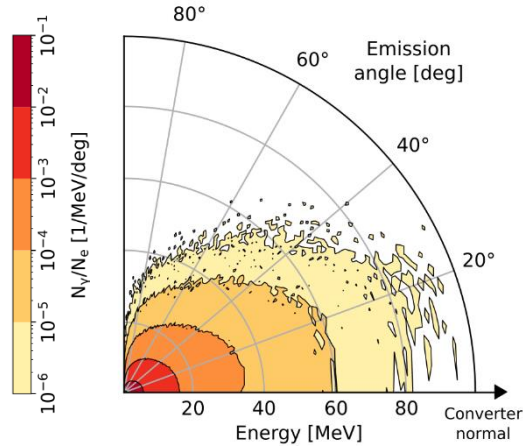
# Another characterization technique?...Laser-driven Photon Activation Analysis

1) Laser + **near-critical** material → **Hot e-**

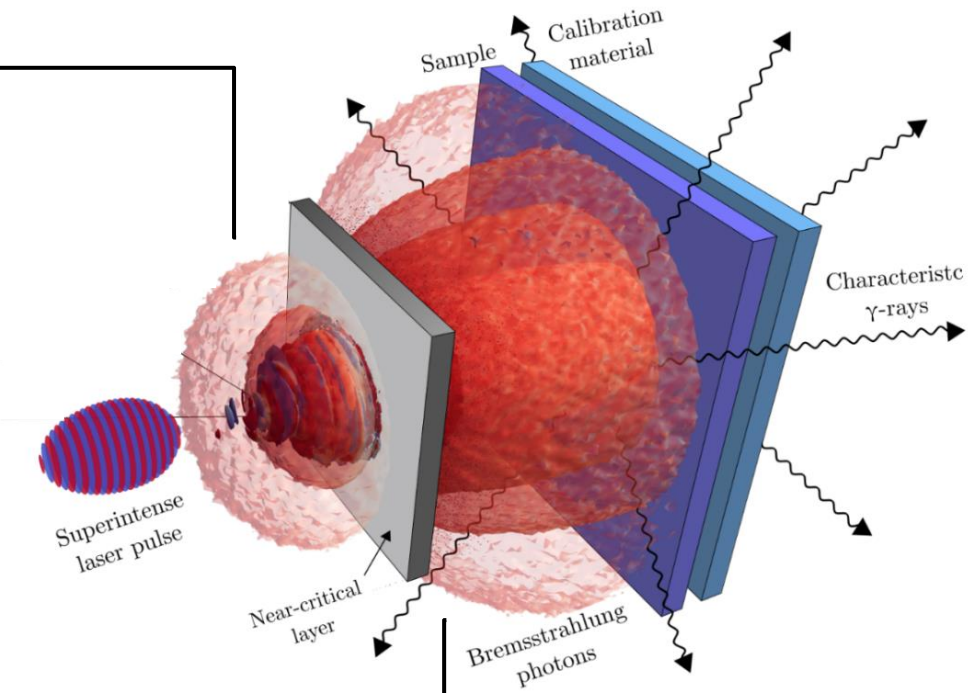


$a_0 = 20$   
 Thickness  $\sim 10 \mu\text{m}$   
 $n \sim n_c$

2)  $e^- + \text{substrate} \rightarrow \text{photons}$

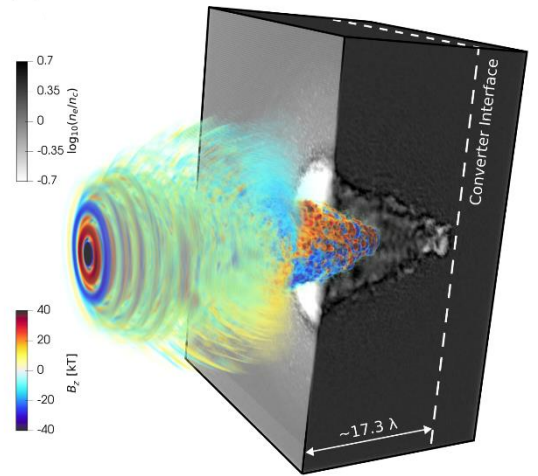


$E_{\text{phot}} = 10\text{s MeV}$



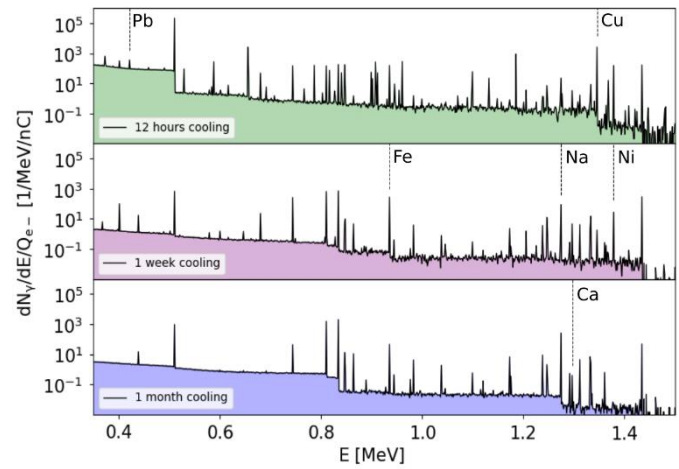
# Another characterization technique?...Laser-driven Photon Activation Analysis

1) Laser + **near-critical** material → **Hot e-**

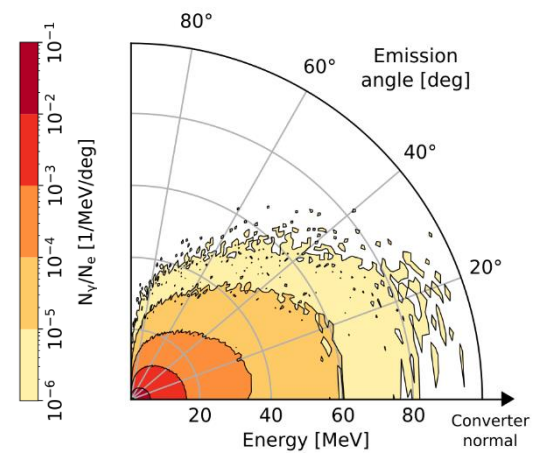


$a_0 = 20$   
 Thickness  $\sim 10 \mu\text{m}$   
 $n \sim n_c$

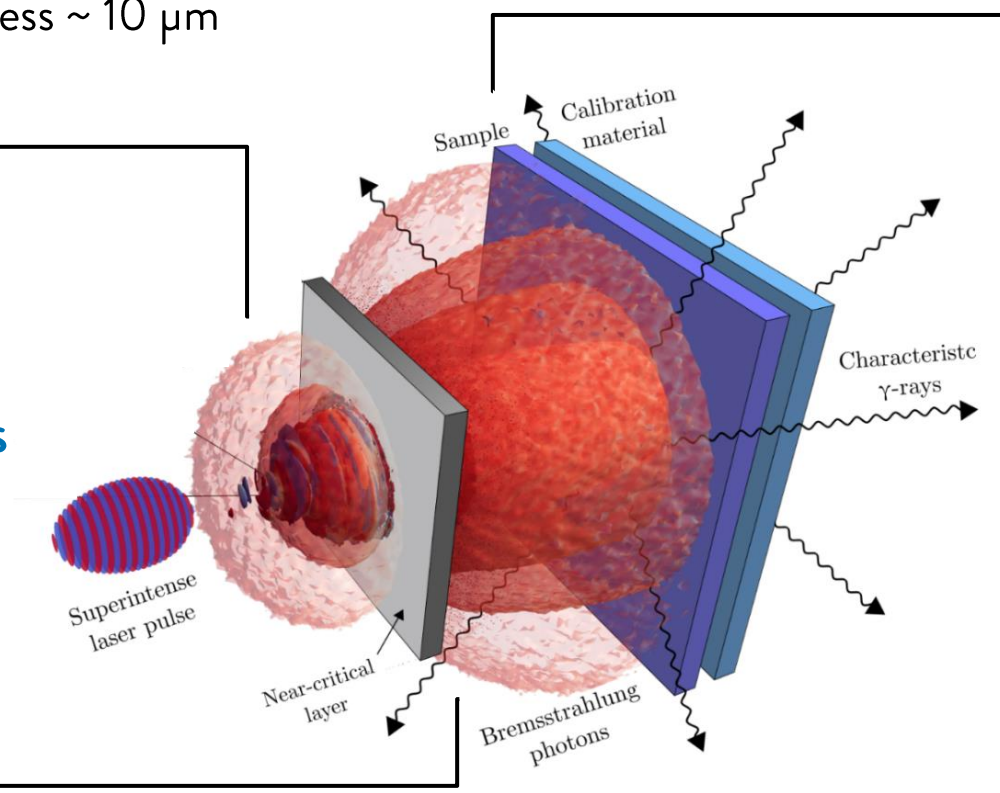
3) BS photons + **sample** → characteristic  **$\gamma$ -rays**



2) **e-** + **substrate** → **photons**

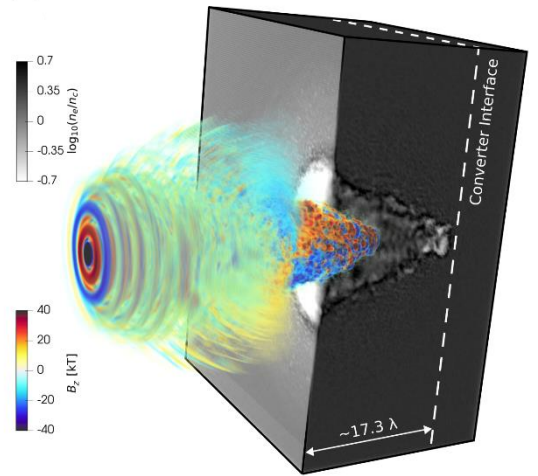


$E_{\text{phot}} = 10\text{s MeV}$



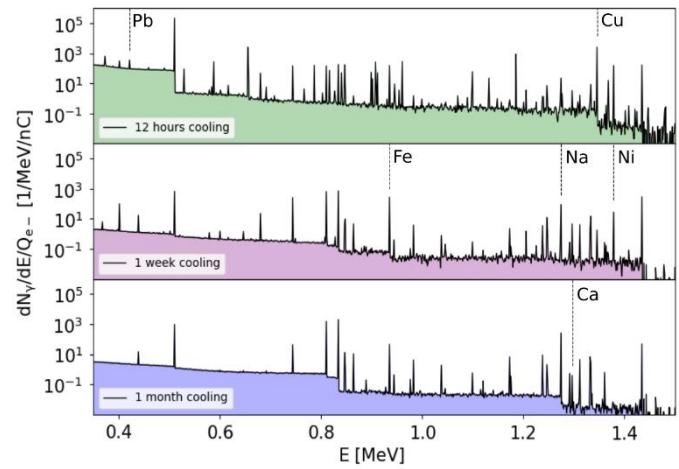
# Another characterization technique?...Laser-driven Photon Activation Analysis

1) Laser + **near-critical** material → **Hot e-**

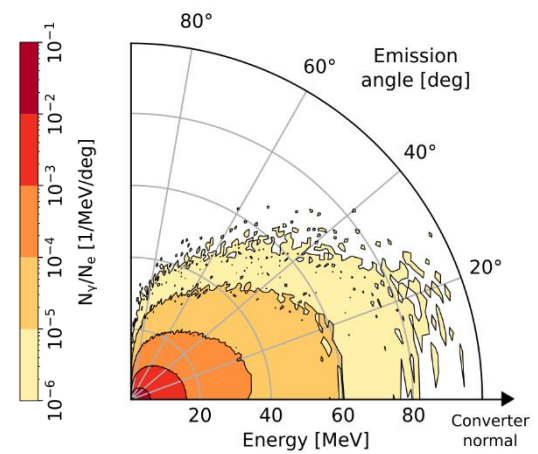


$a_0 = 20$   
 Thickness  $\sim 10 \mu\text{m}$   
 $n \sim n_c$

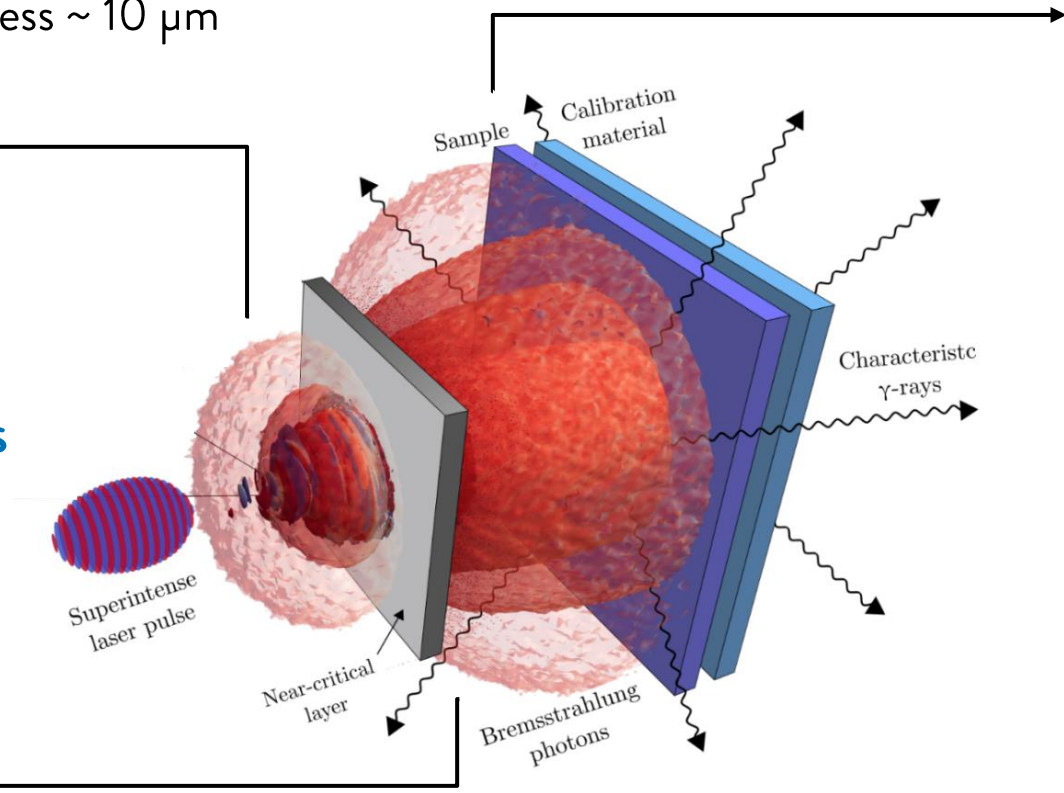
3) BS photons + **sample** → characteristic  **$\gamma$ -rays**



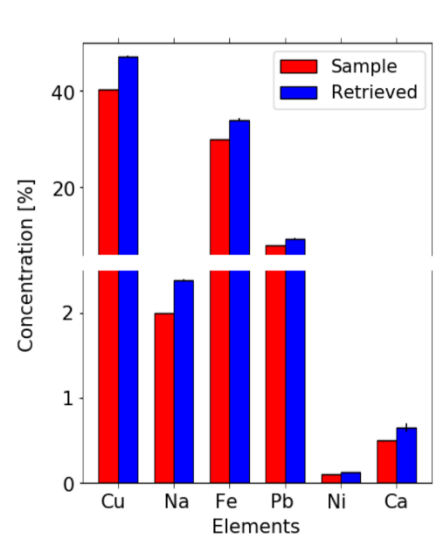
2) **e-** + **substrate** → **photons**



$E_{\text{phot}} = 10\text{s MeV}$

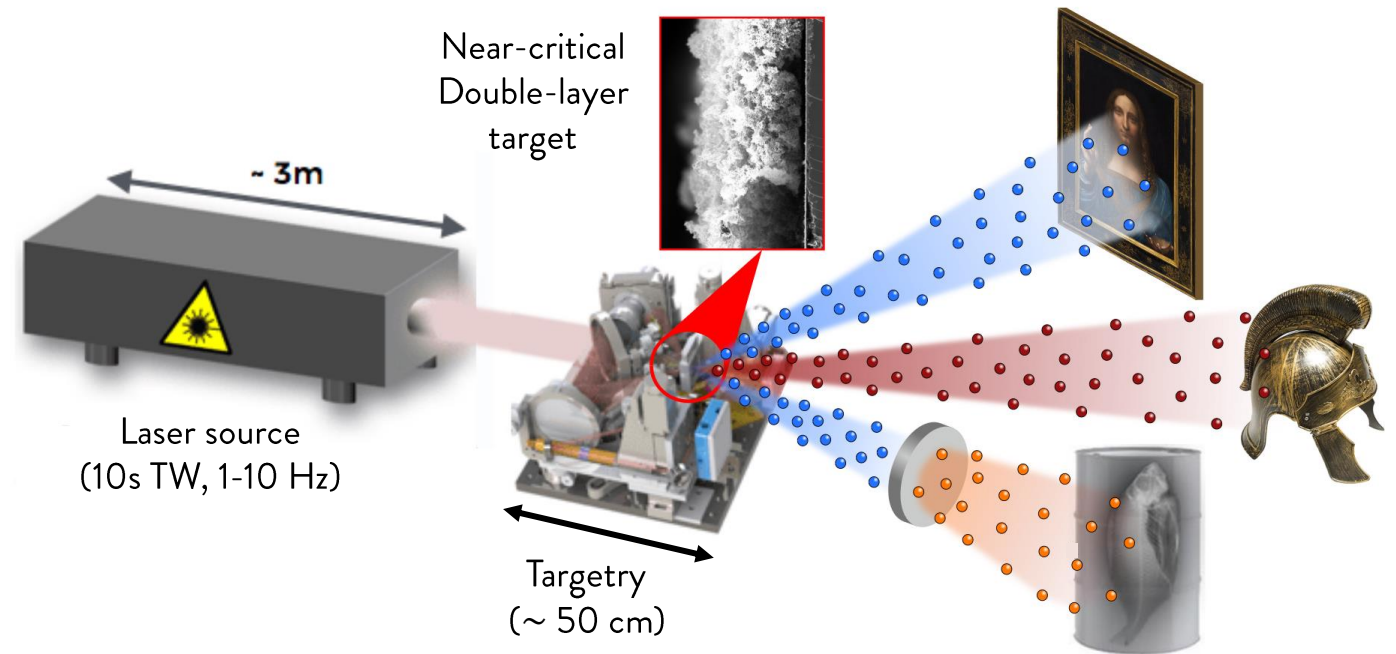


4) Sample bulk **composition**



# What next?

- ❖ Perform laser-driven PIXE and EDX with a **compact laser** and **DLTs**.
- ❖ Investigate **other techniques** (e.g. PAA and FNAA).
- ❖ Design an **optimized laser-based setup** for materials characterization.



Barberio M., et al. Scientific reports 7.1 (2017): 1-8.

Passoni M., et al. Scientific reports 9.1 (2019): 1-11.

Barberio M., et al. Science advances 5.6 (2019): eaar6228.

Passoni M., et al. Plasma Physics and Controlled Fusion 62.1 (2019): 014022.

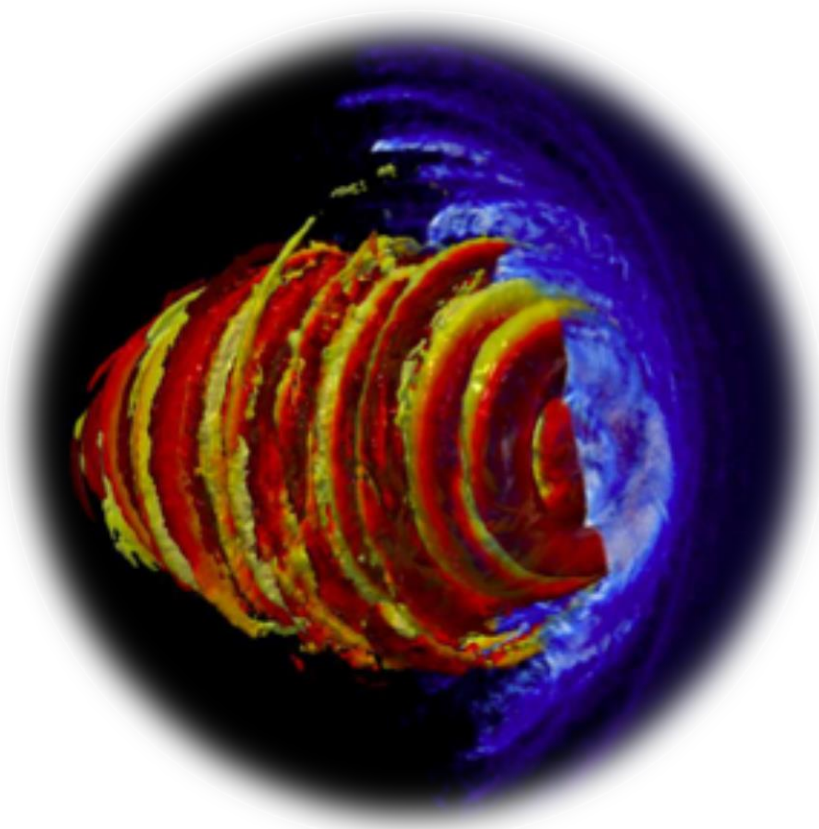
Barberio M., and P. Antici. Scientific reports 9.1 (2019): 1-9.

Morabito A., et al. Laser and Particle Beams 37.4 (2019): 354-363.

Mirani F., et al. Science advances 7.3 (2021): eabc8660.

Puyuelo-Valdes P., et al. Scientific reports 11.1 (2021): 1-10.

Mirani F., et al. arXiv preprint arXiv:2104.07513 (2021).

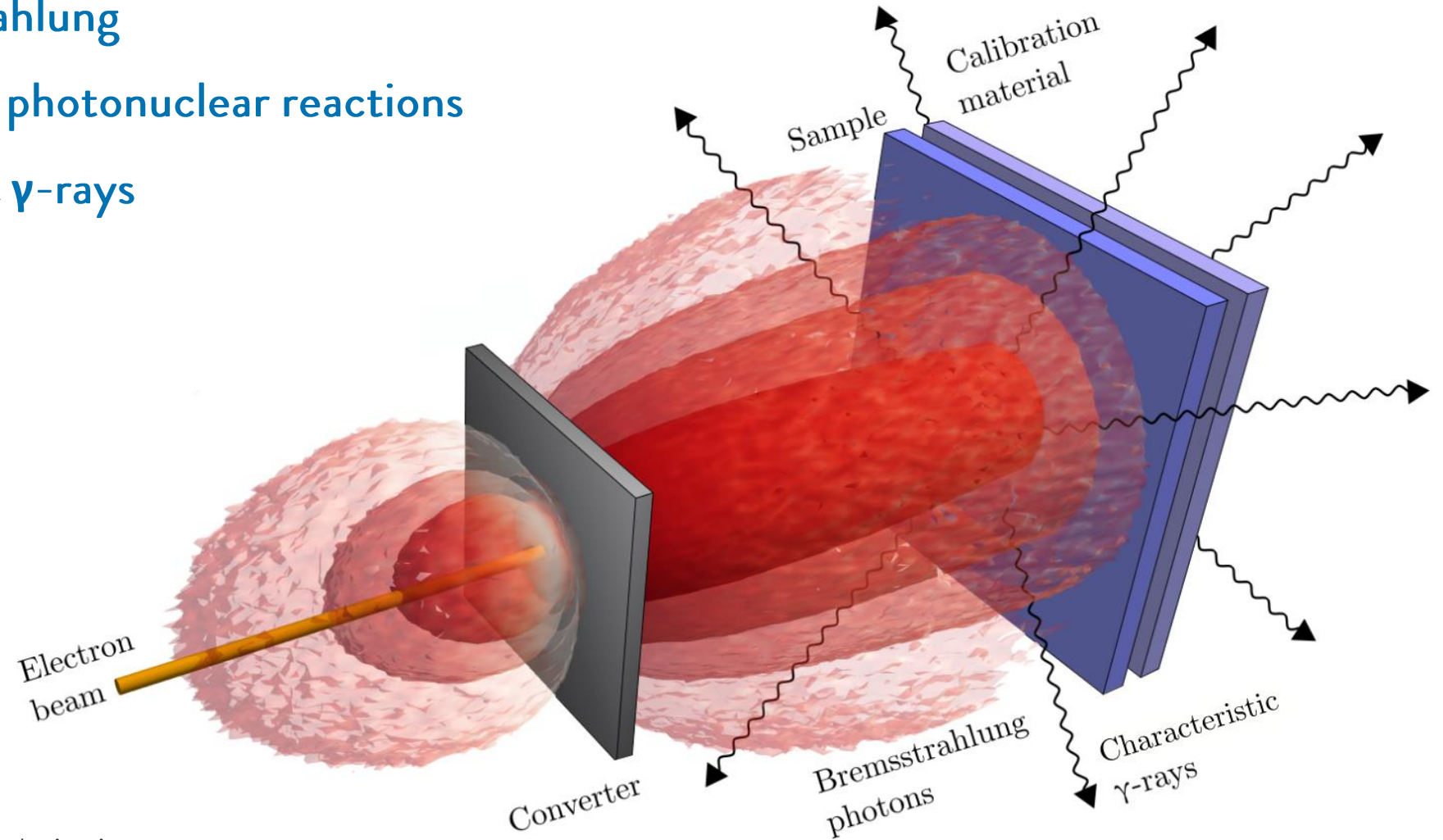


Thank you for the attention!



# Another characterization technique?...Photon Activation Analysis

- ❖ 10s MeV  $e^-$  → bremsstrahlung
- ❖ Sample activation due to photonuclear reactions
- ❖ Emission of characteristic  $\gamma$ -rays



Mirani, F., et al. "Superintense Laser-driven Photon Activation Analysis." Under review at Communications Physics.

