47th conference on Plasma Physics

Satellite Meeting

High-field laser-plasma interaction (HIFI)

Laser Driven particle and radiation sources for aplication (LASA)

POLITECNICO MILANO 1863

ERC-2014-CoG No. 647554 ENSURE

NanoLab

Department of Energy

Laser-driven radiation sources for elemental characterization of materials

Matteo Passoni

Politecnico di Milano

June 2021

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

ENSURE erc -2014-CoG No.647554

Exploring the **N**ew **S**cience and engineering unveiled by
Ultraintense ultrashort **R**adiation interaction with matt**E**r

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DIPARTIMENTO DI ENERGIA

❖ Present **team members**:

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Principal investigator

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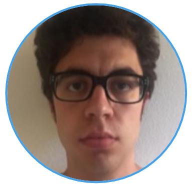

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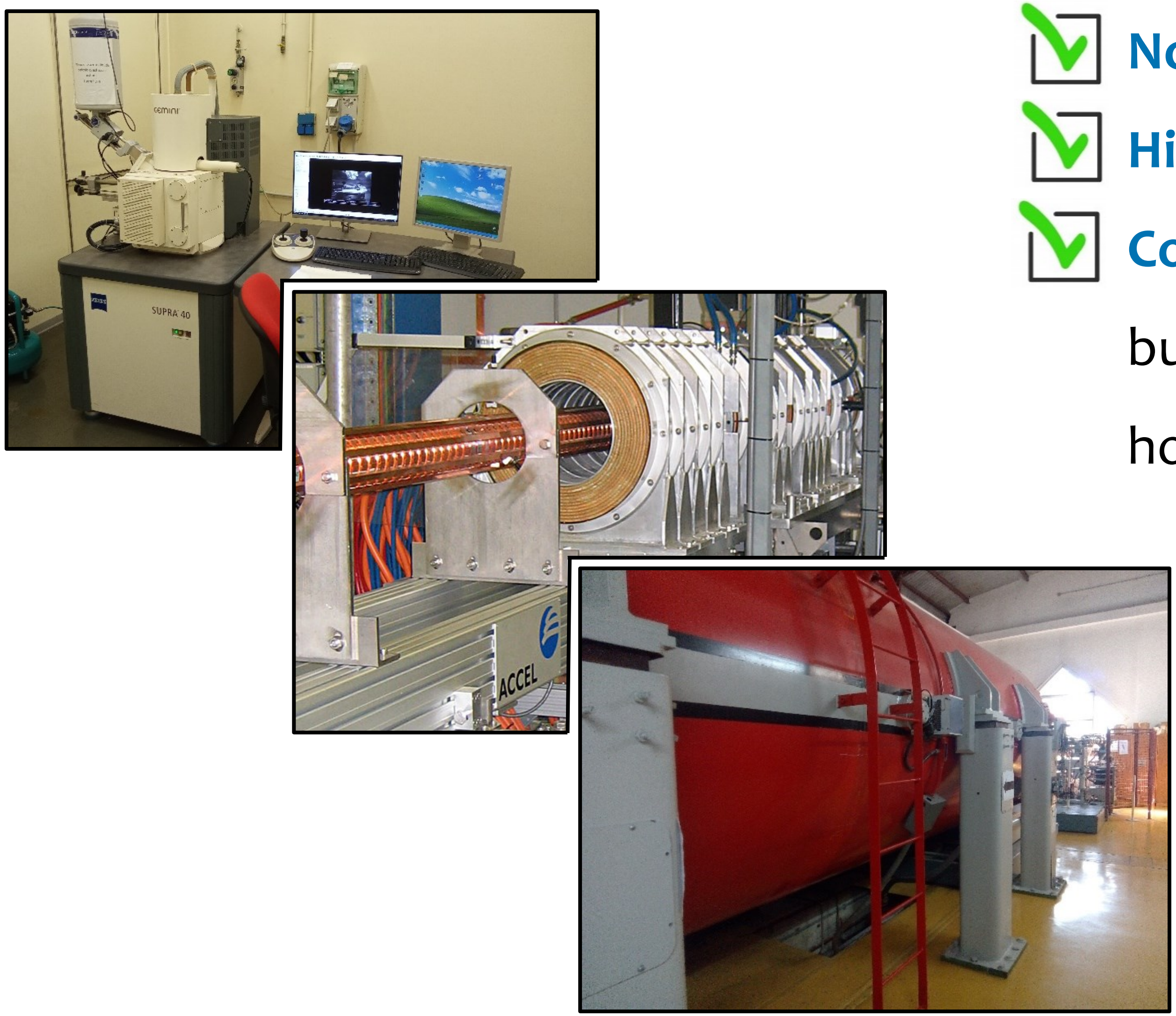
M. Galbiati

D. Orecchia

www.ensure.polimi.it

Atomic and nuclear analytical methods for materials characterization

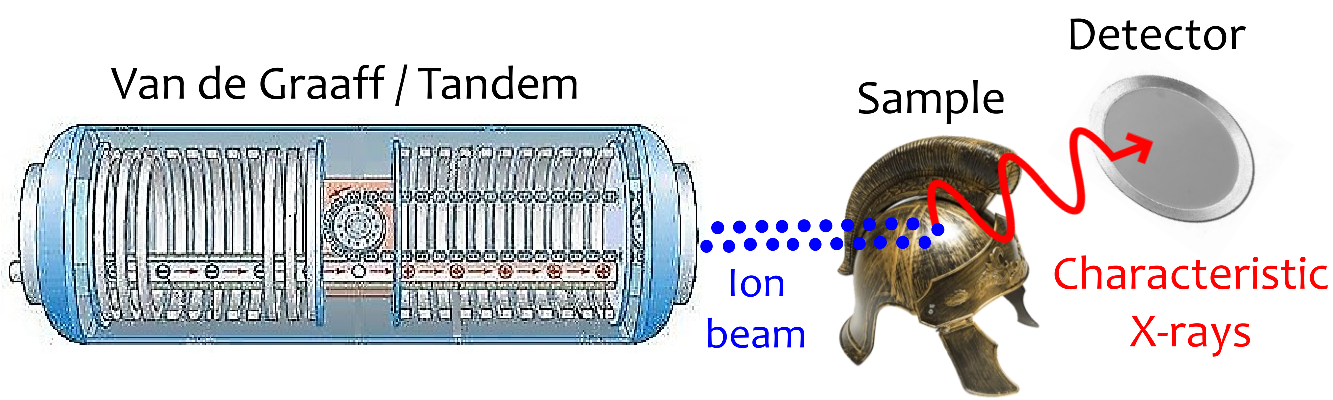


- **Non-destructive**
- **High** detection **capabilities**
- **Complementary** (element/isotope specific, bulk/surface analysis, homogeneous/stratigraphic)

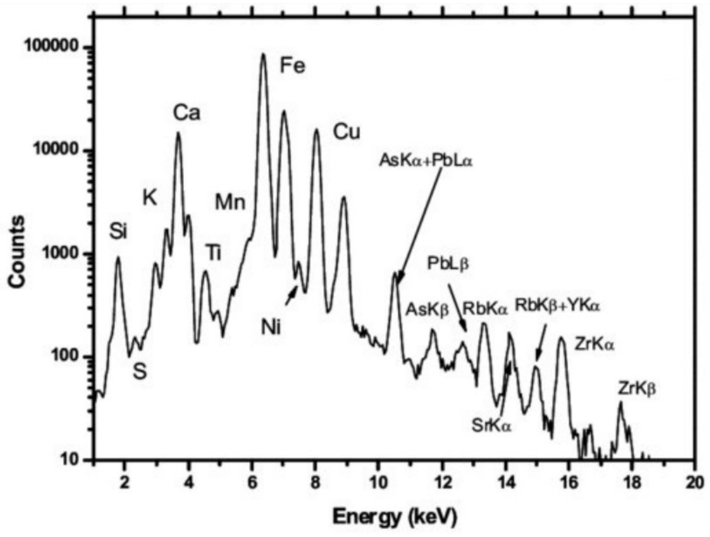
…but often…

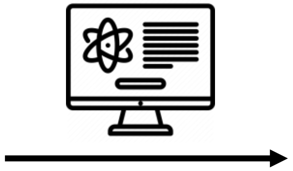
- **Large** and **expensive**
- **Non-tunable** particle energy
- Only **one kind of particle** is provided

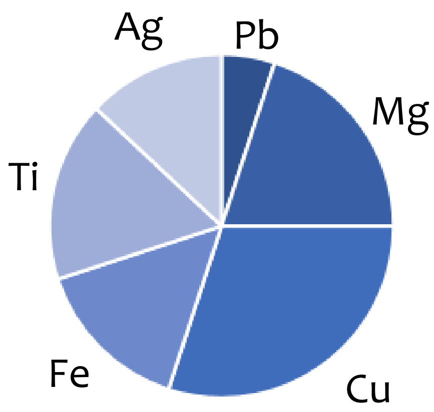
Can laser-driven sources be an option?

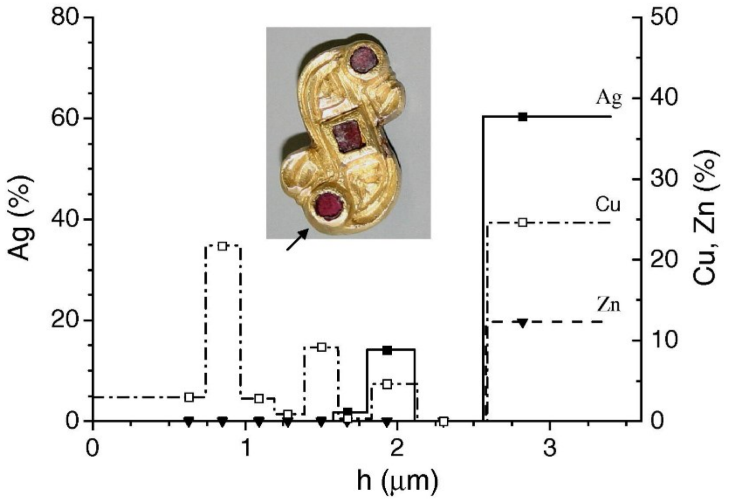


- **2-5 MeV/u** monoenergetic ions
- **Concentrations** & **Depth profiles**
- Cultural heritage, environment, biology, forensic analysis





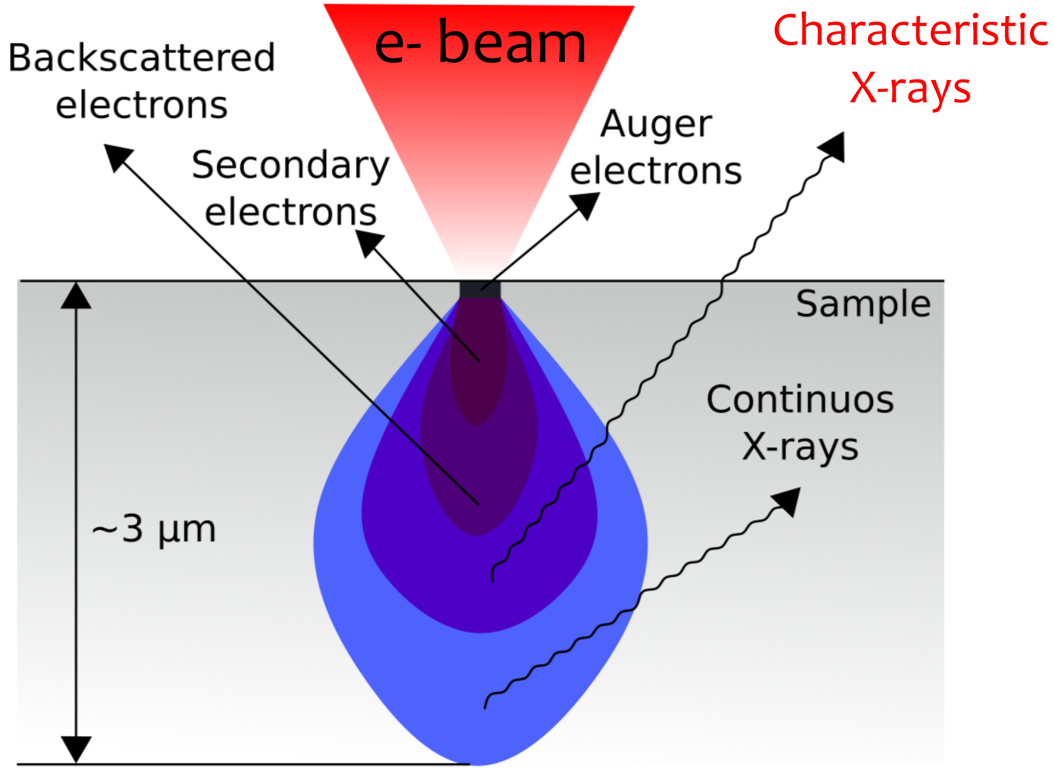




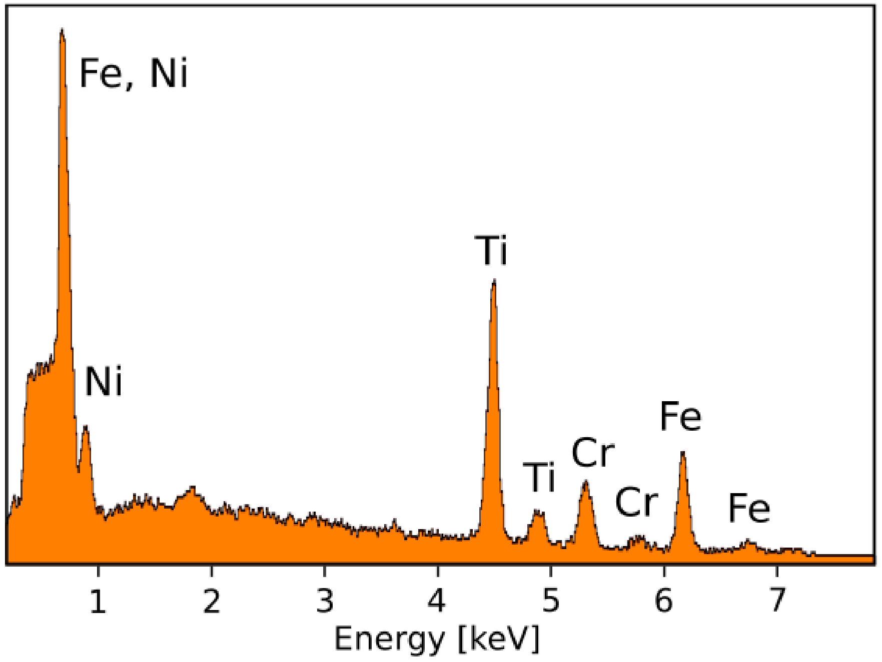
Verma, Hem Raj. Atomic and nuclear analytical methods. Springer-Verlag Berlin Heidelberg, 2007.

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

Materials characterization: Energy Dispersive X-ray (EDX) spectroscopy



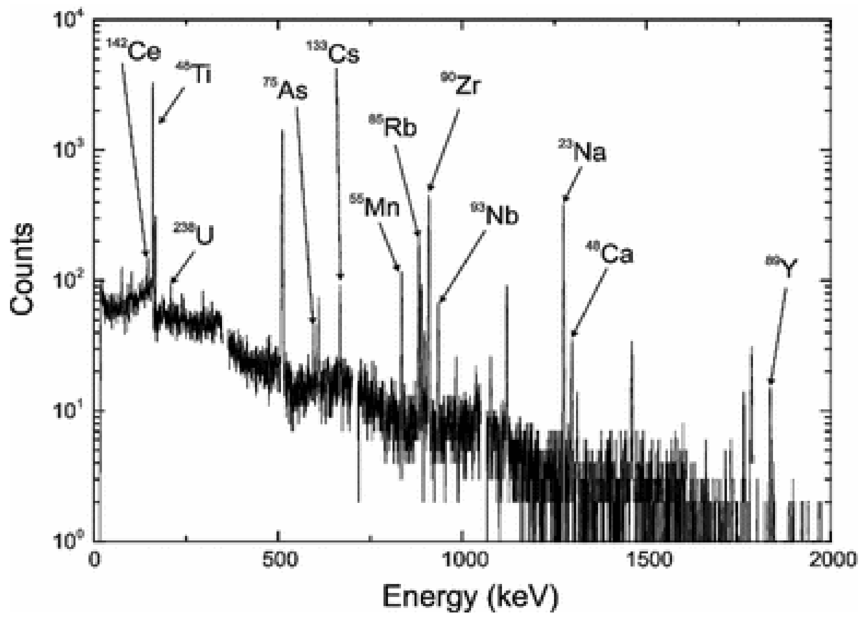
- **KeV** energy **electrons**
- **Small** and solid **samples**
- Fast **identification** of the elements and **concentrations** reconstruction from

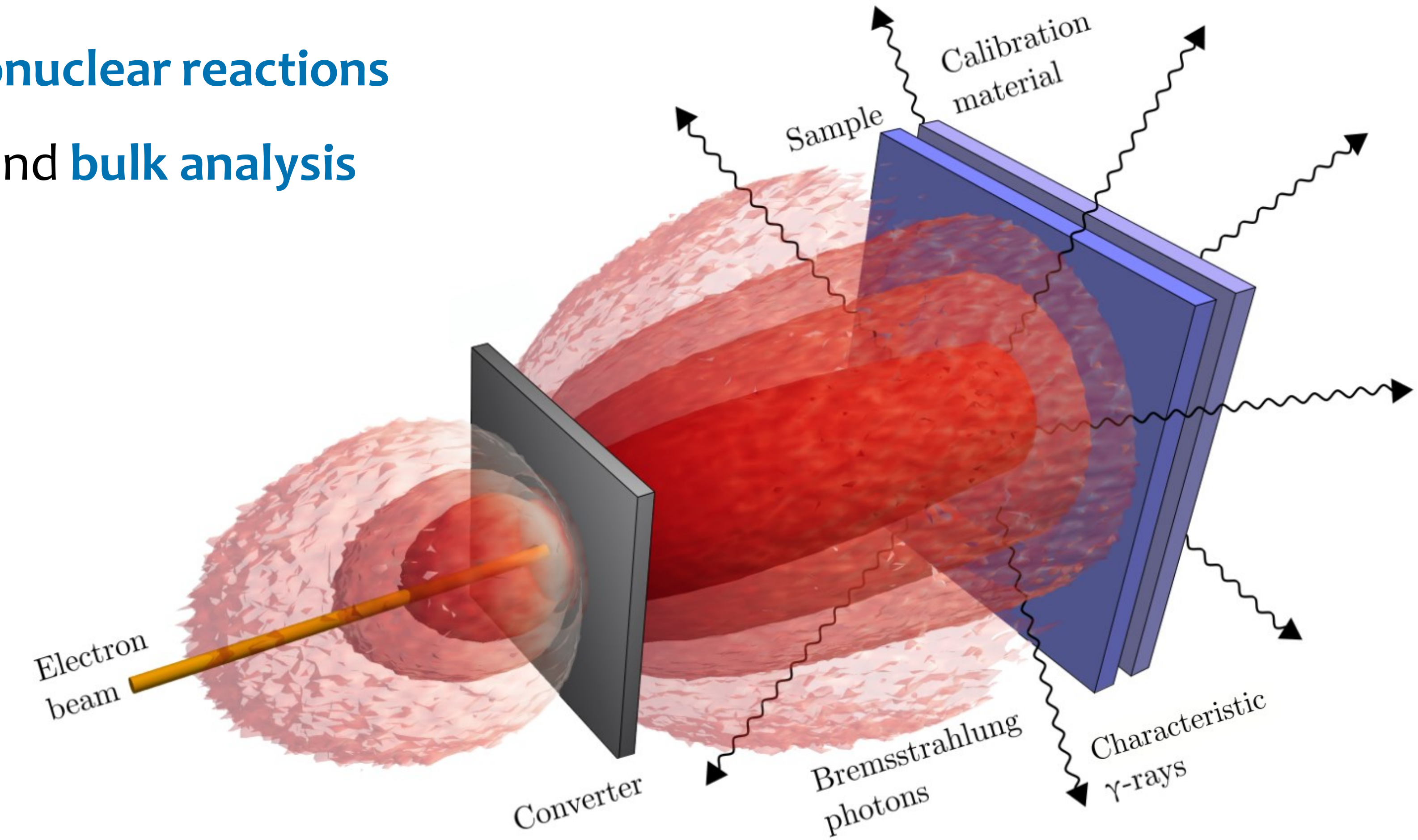


DC Bell and AJ Garratt-Reed. Energy dispersive X-ray analysis in the electron microscope, volume 49. Garland Science, 2003.

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

- **10s MeV e- → bremsstrahlung**
- **Sample activation** due to **photonuclear reactions**
- **Identification** of the elements and **bulk analysis**





Segebade, Christian, et al. "Principles, methodologies, and applications of photon activation analysis: a review." Journal of Radioanalytical and Nuclear Chemistry 312.3 (2017): 443-459.

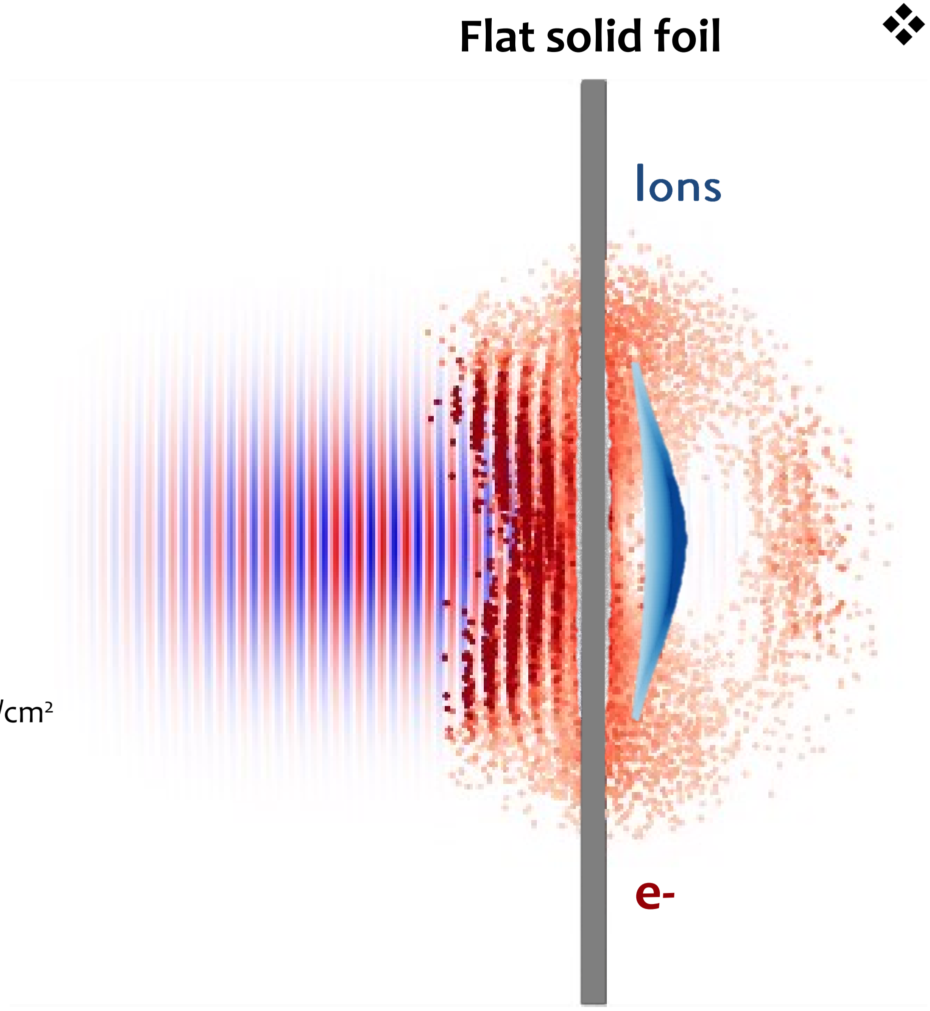
Can laser-driven sources be exploited for PIXE and EDX?

Laser

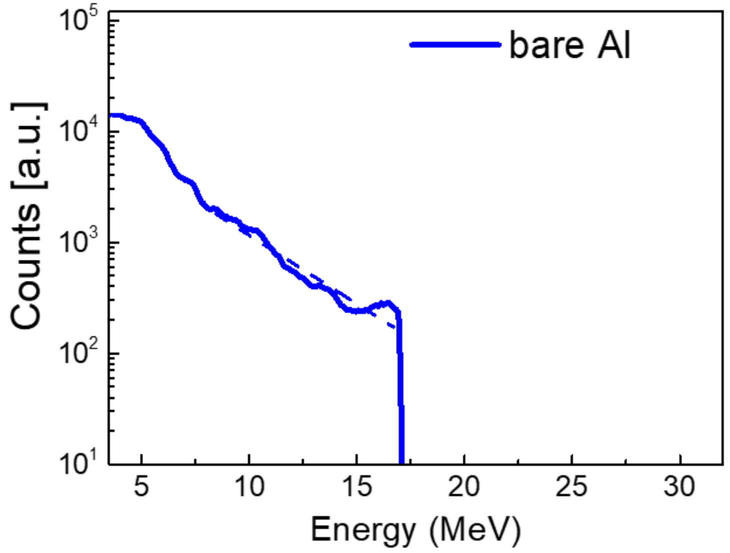
30 fs – 1 ps,

0.1 – 10 J,

10^{18} - 10^{22} W/cm²



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



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

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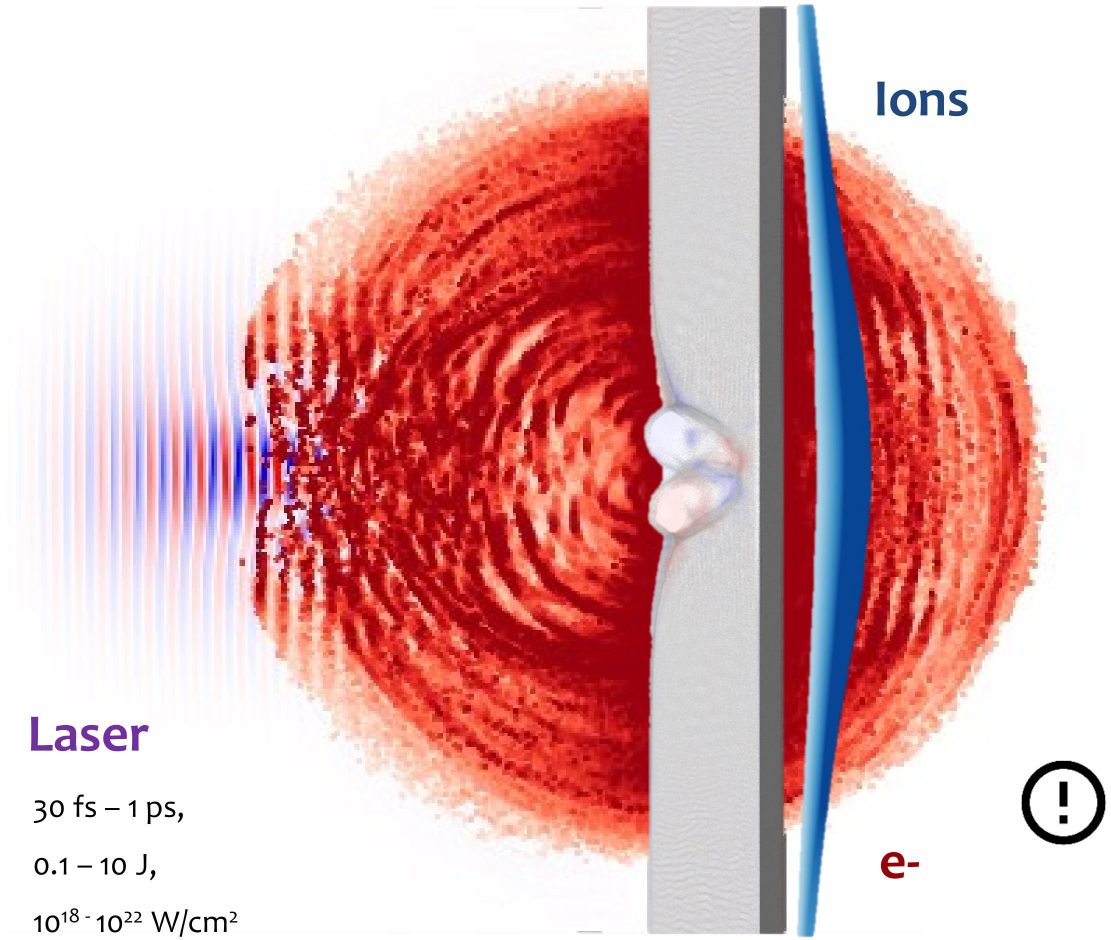
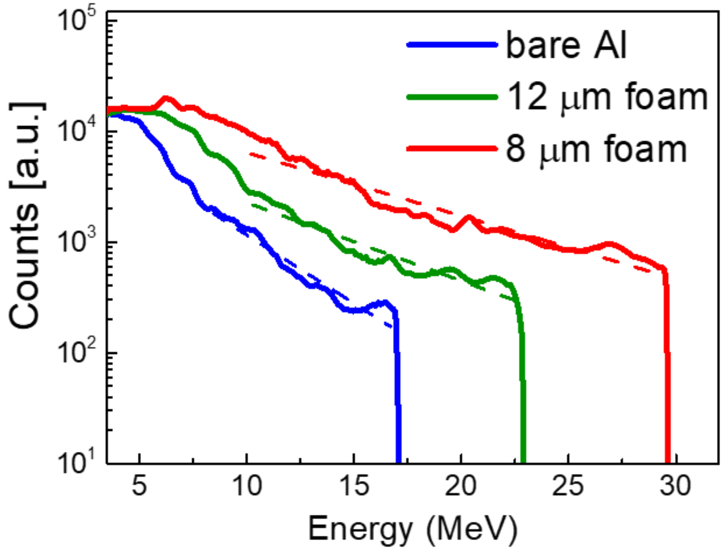
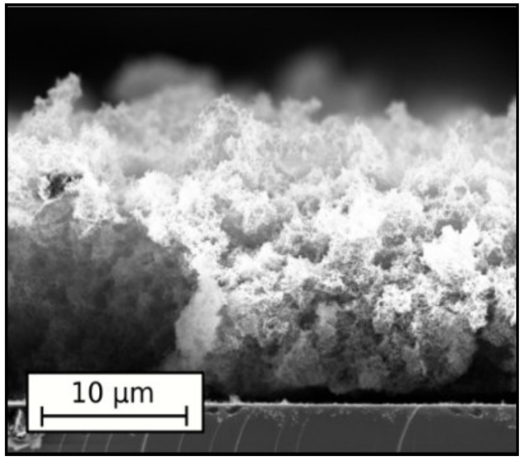
Double Layer Target (DLT)



❖ **DLT** to **enhance** the **acceleration** and mitigation of the laser requirements





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

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Investigation through **theoretical** & **experimental** methods

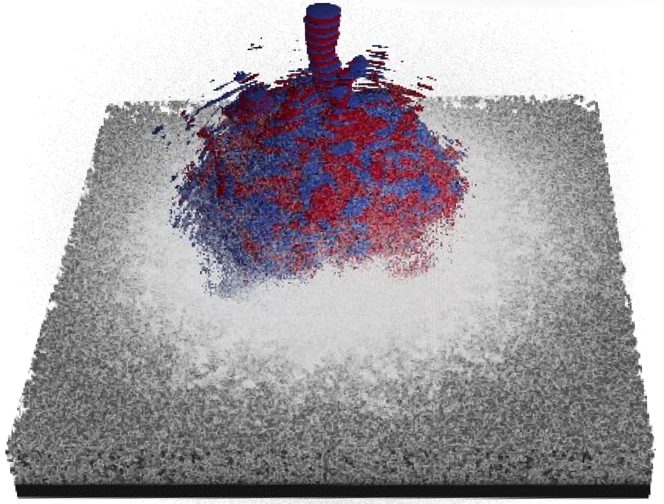
Analytical **models**, **PIC** and **Monte Carlo** simulations

piccante Open Source PIC Code

Smilei

GEANT4 A SIMULATION TOOLKIT

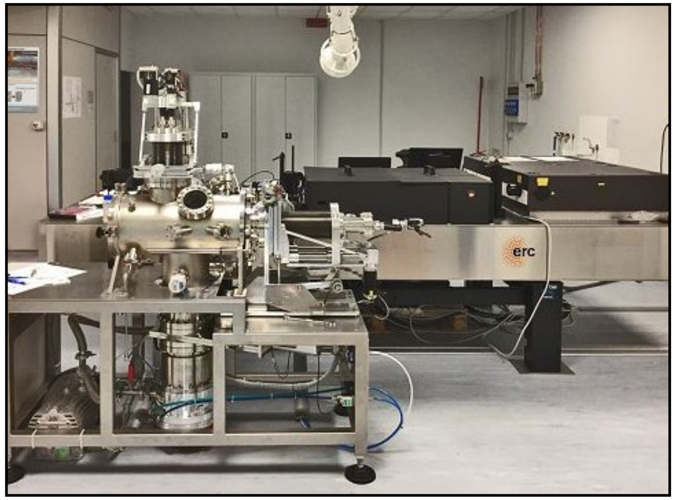
FLUKA



DLTs production with controlled properties

Deposition techniques:

- PLD
- HiPIMS



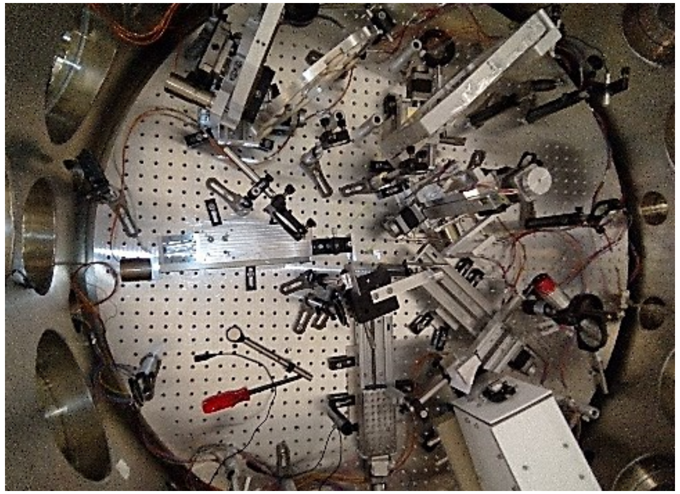
Experimental campaigns

- Test DLTS
- Materials science

CoReLS Center for Relativistic Laser Science

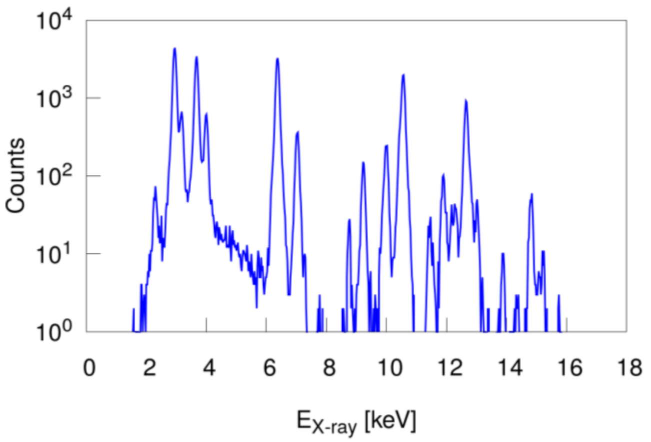
HZDR

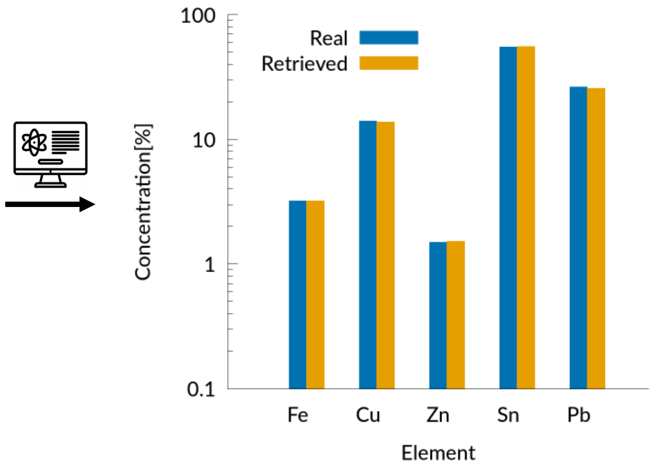
CLPU

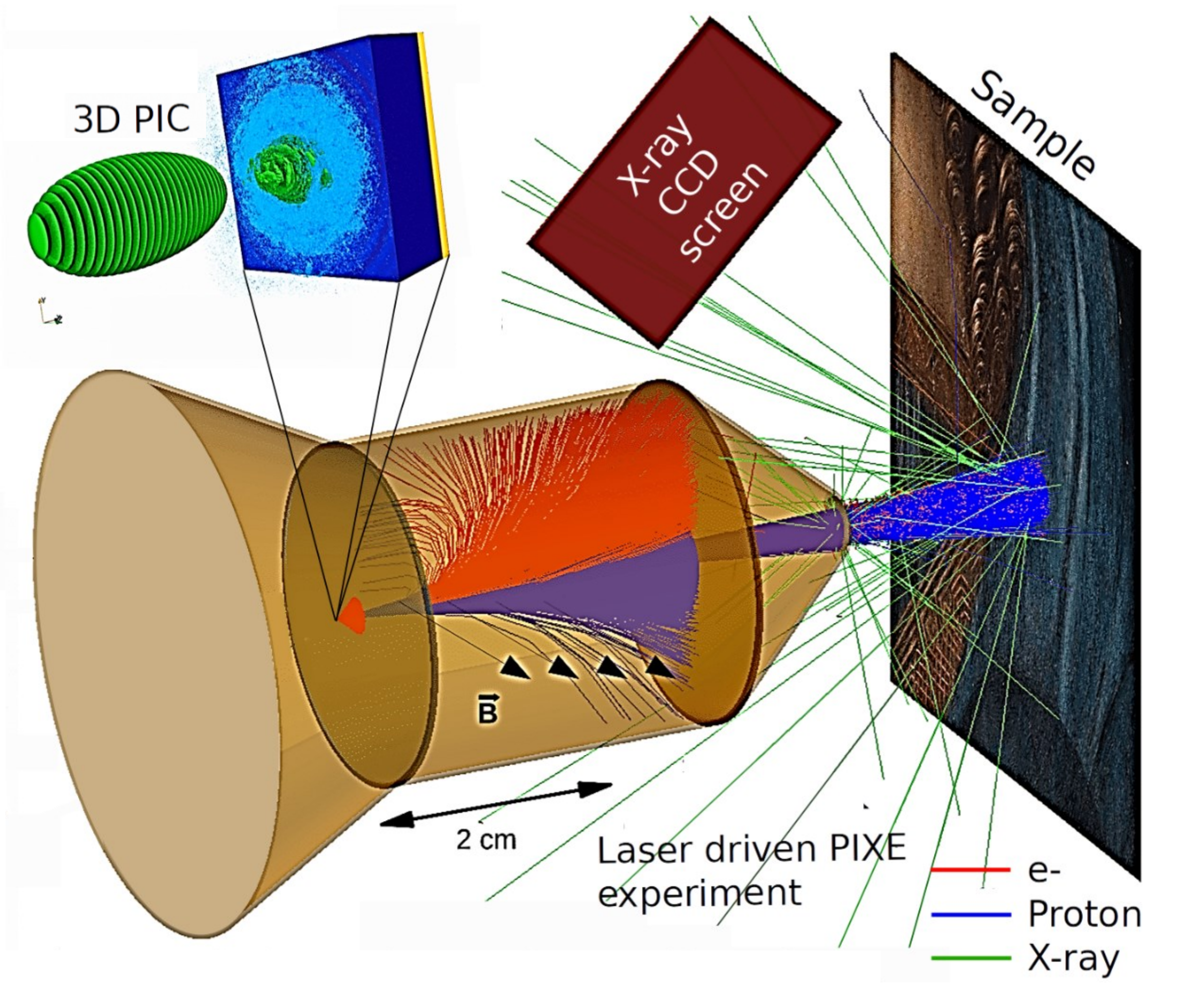


Laser-driven PIXE, a numerical investigation

- Pixe theory with non-monoenergetic proton
- **Simulation** of laser-driven PIXE **realistic scenarios** (piccante , GEANT4)
- **Software** development for the **analysis** of the **X-ray spectra** → Sample composition reconstruction



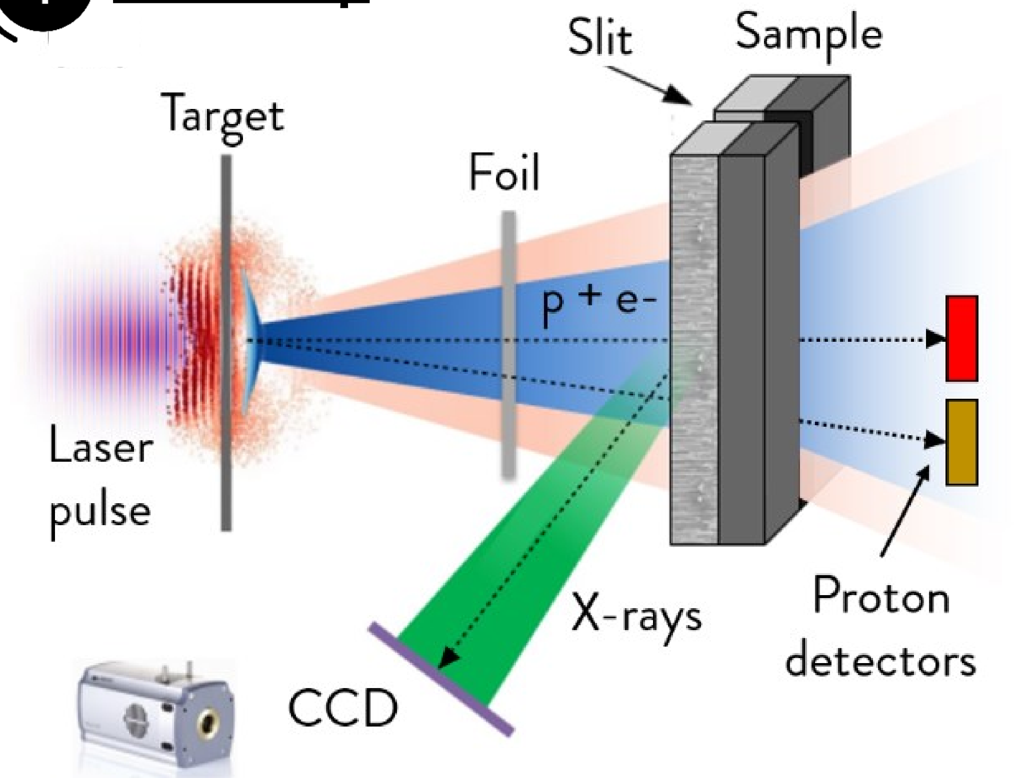




Passoni, Matteo, Luca Fedeli, and Francesco Mirani. "Superintense laser-driven ion beam analysis." Scientific reports 9.1 (2019): 1-11.

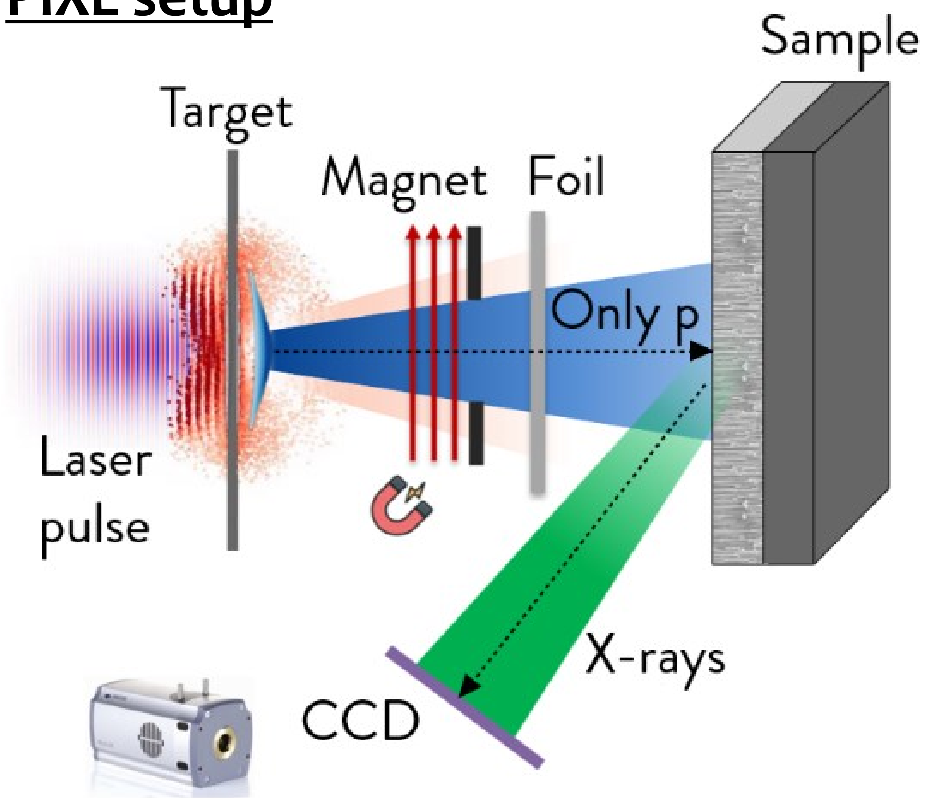
Laser-driven PIXE and EDX experiment @ CLPU

1 EDX setup



- Sample **irradiation** with **both electrons** and **protons**

2 PIXE setup



- Magnet to **remove** the **electrons**

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

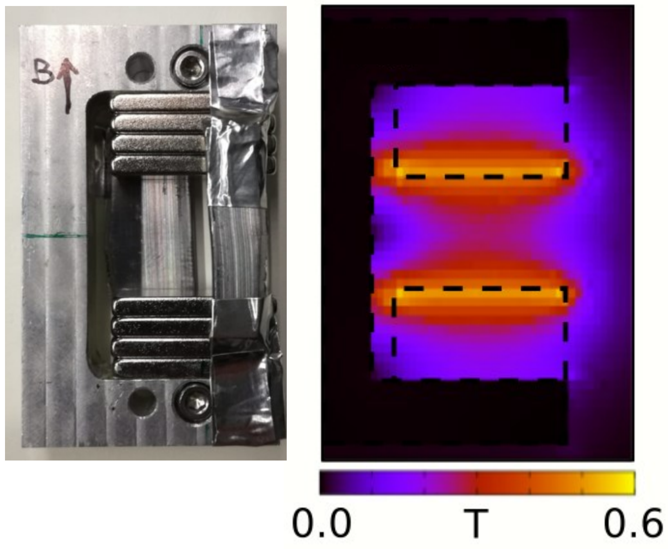
Laser-driven PIXE and EDX experiment @ CLPU

❖ **Electron** and **proton contribution** to the **X-ray production?** GEANT4

Finite Element Analysis

↓

3D **Magnetic field** distribution



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

❖ **Electron** contribution is **dominant**

↓

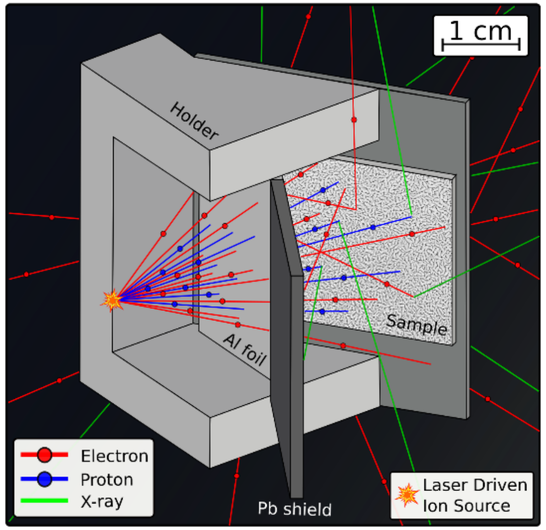
Fast elemental analysis

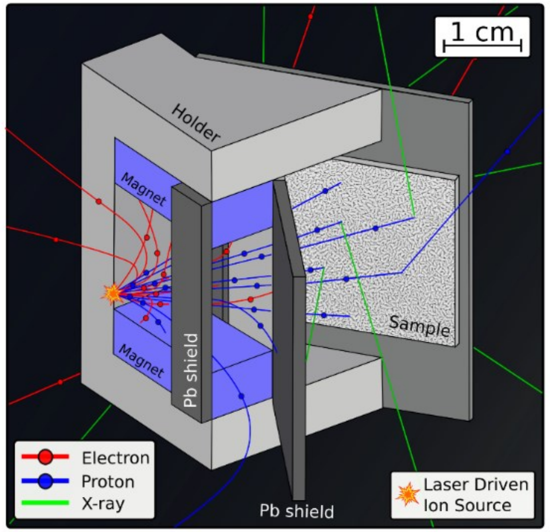
2 PIXE setup

❖ ~98% of **electrons** are **removed**

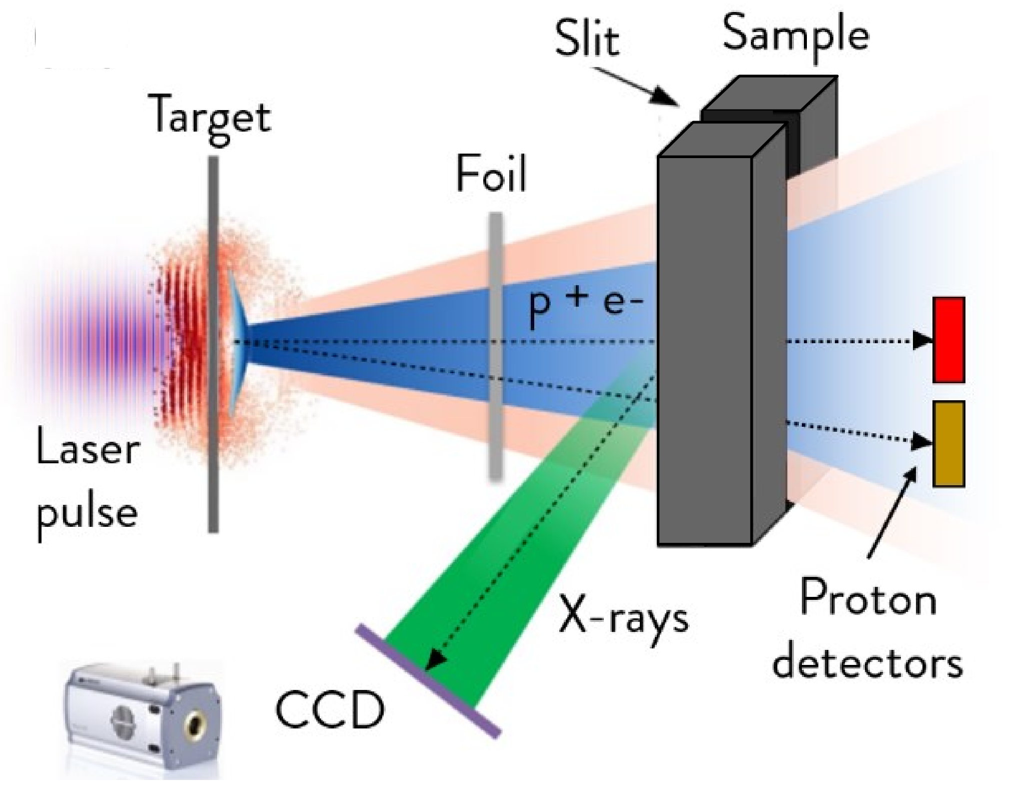
↓

Quantitative analysis

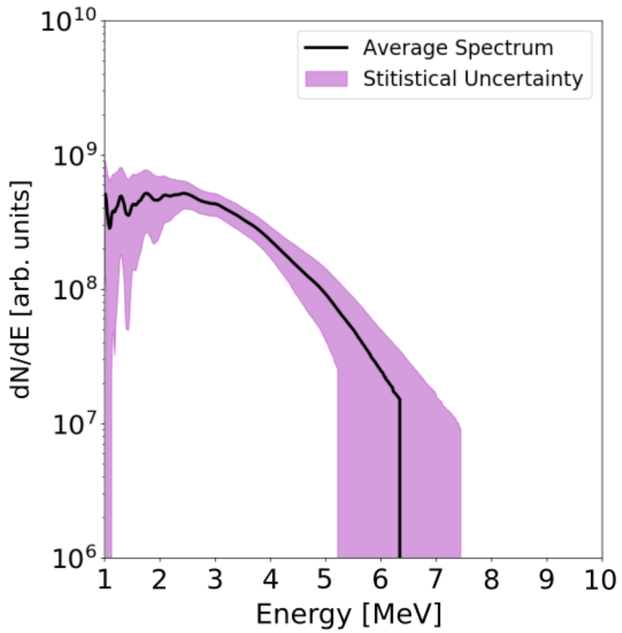


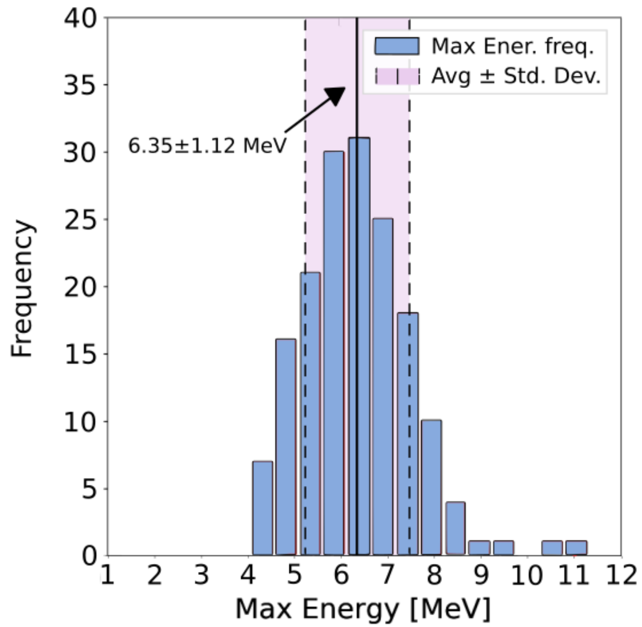


1 **EDX setup** → Sample **irradiation** with **both electrons** and **protons**



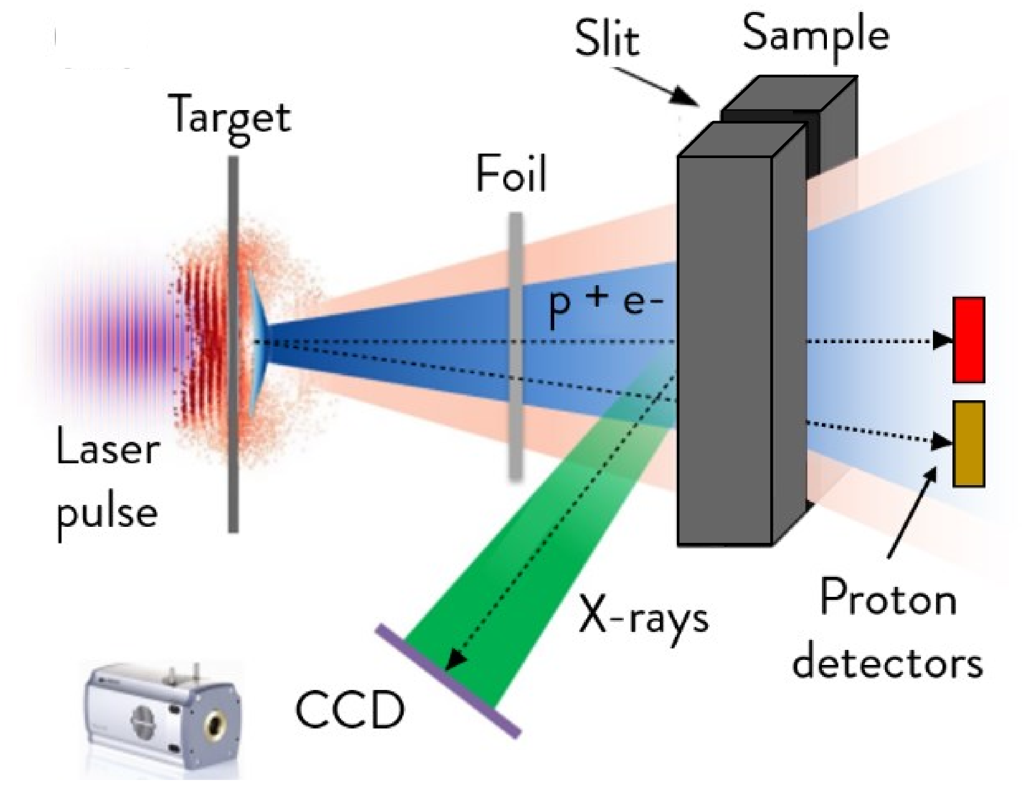
- **Aperture slit** in the middle of the sample
- **Proton** spectrum **characterization** (ToF)



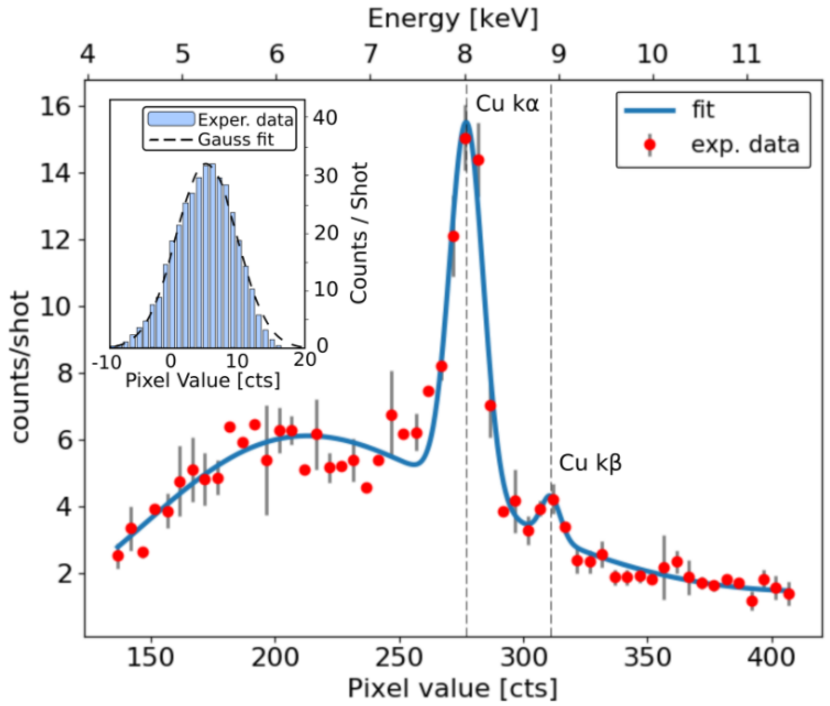


Mirani, F., et al. "Integrated quantitative PIXE analysis and EDX spectroscopy using a laser-driven particle source." Science advances 7.3 (2021): eabc8660.

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



- X-ray **CCD** energy **calibration** (pure Cu sample)



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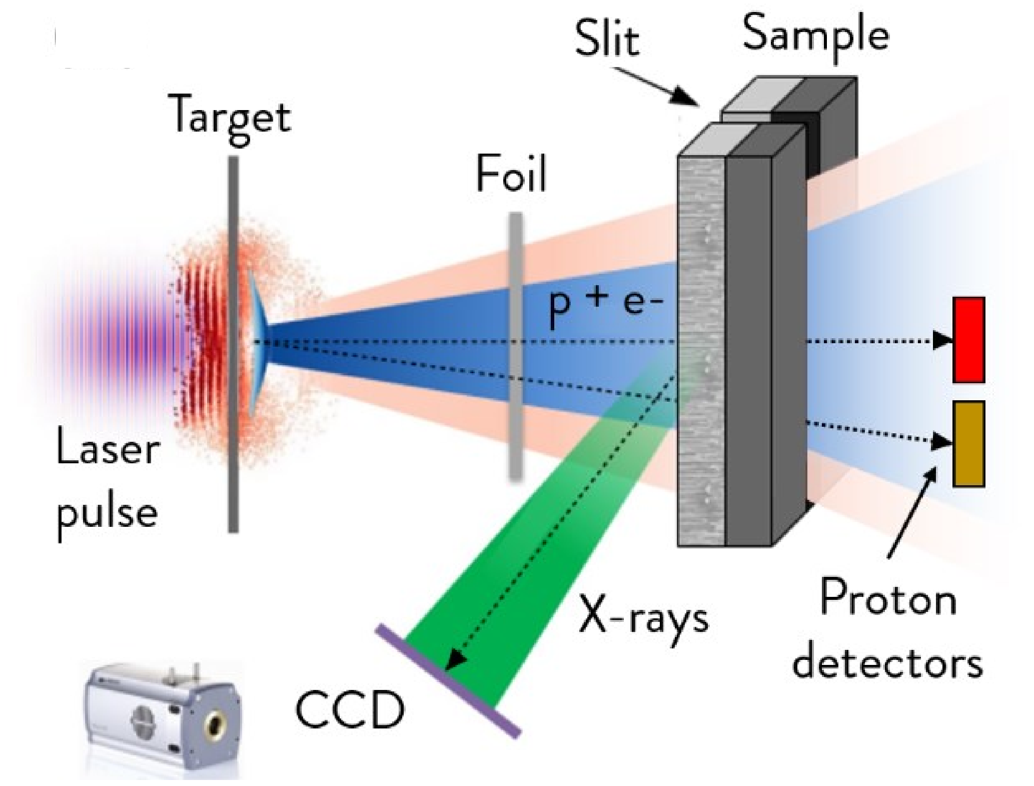
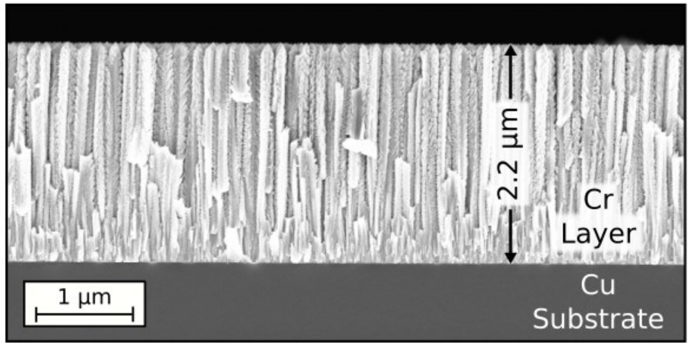
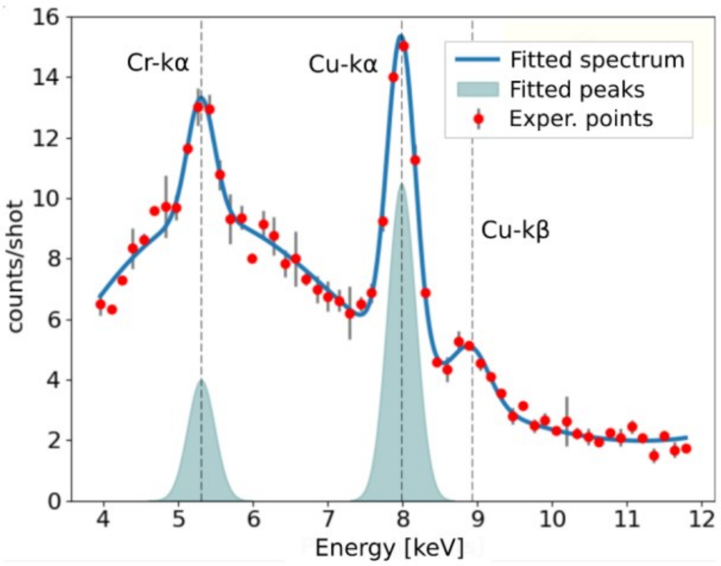
Laser-driven PIXE and EDX experiment @ CLPU

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

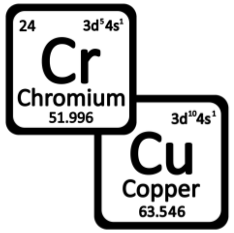






Bi-layer sample (Cr layer + Cu substrate)

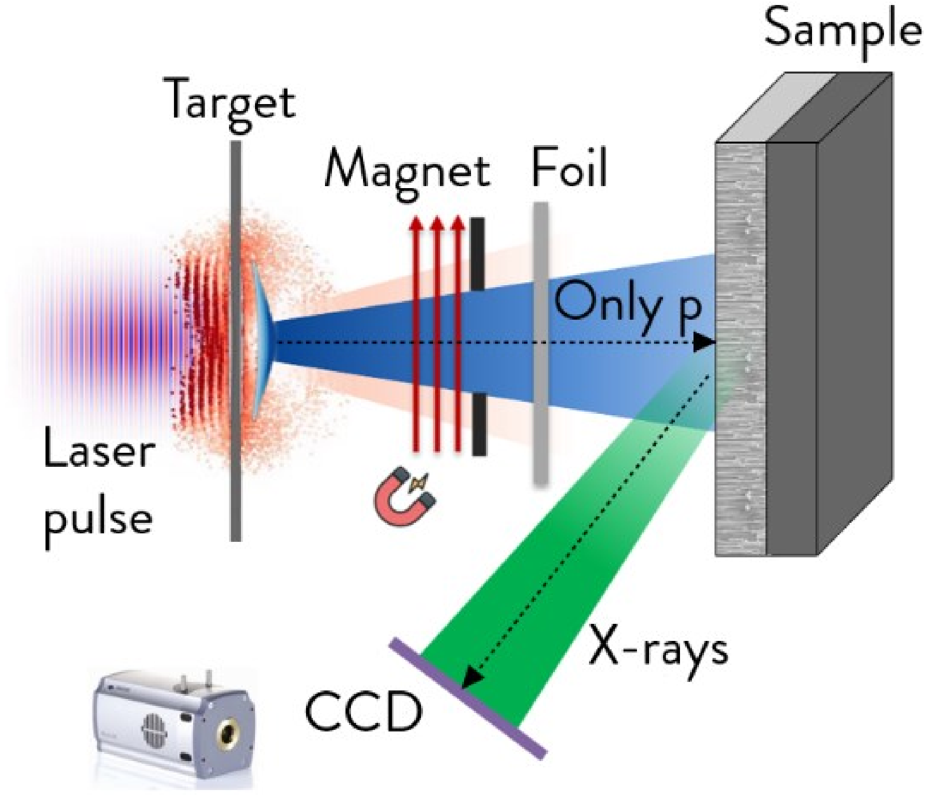
→



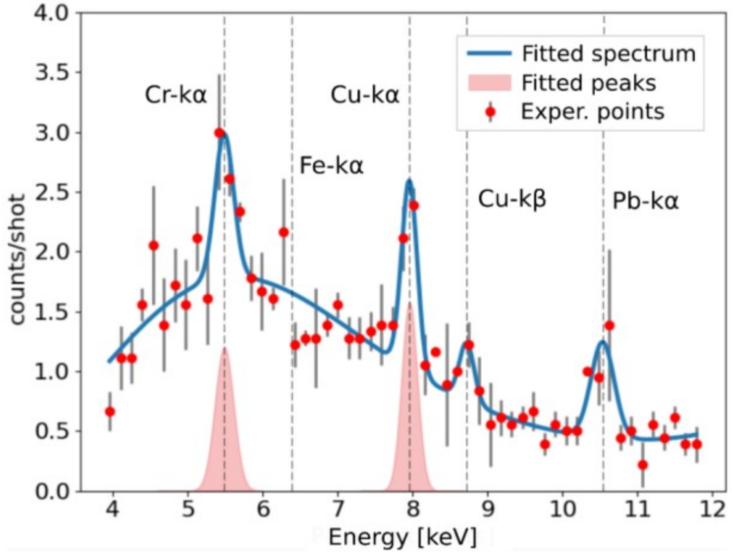
Elements are correctly **recognized**

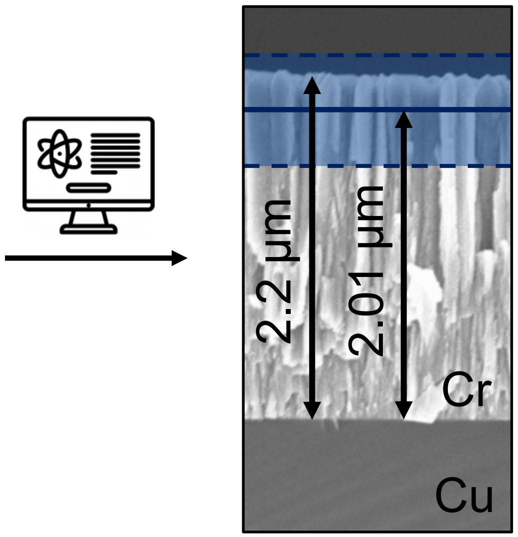
Mirani, F., et al. "Integrated quantitative PIXE analysis and EDX spectroscopy using a laser-driven particle source." Science advances 7.3 (2021): eabc8660.

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



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

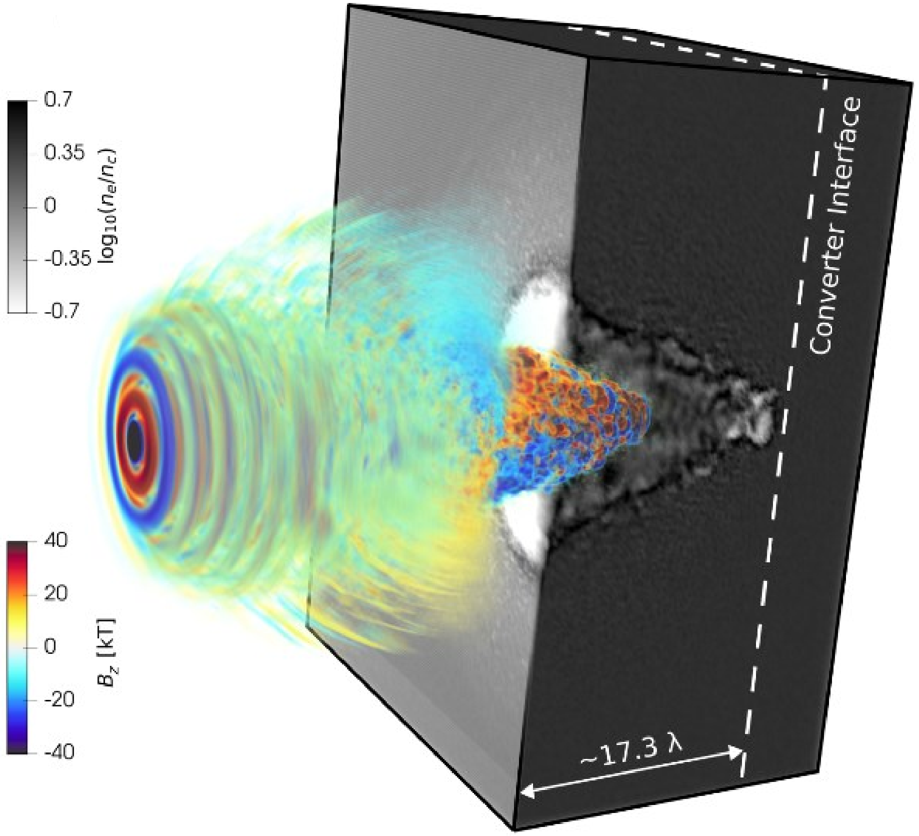




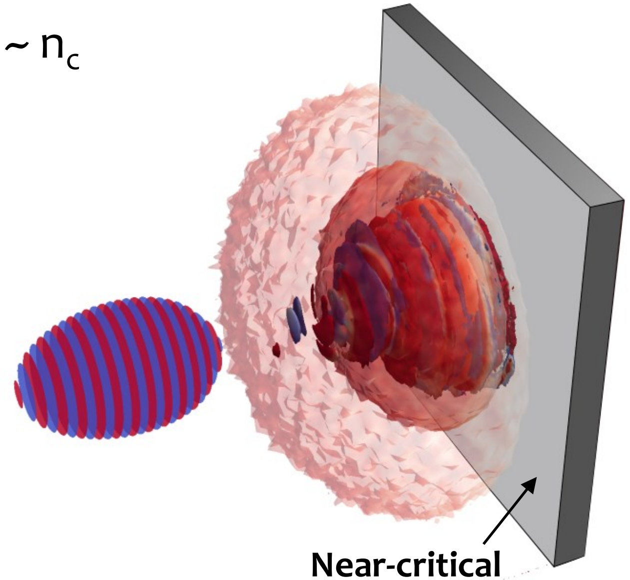
Mirani, F., et al. "Integrated quantitative PIXE analysis and EDX spectroscopy using a laser-driven particle source." Science advances 7.3 (2021): eabc8660.

Laser-driven PAA, a numerical investigation

1) **Laser** interaction with **near-critical** material → **Hot e- generation**



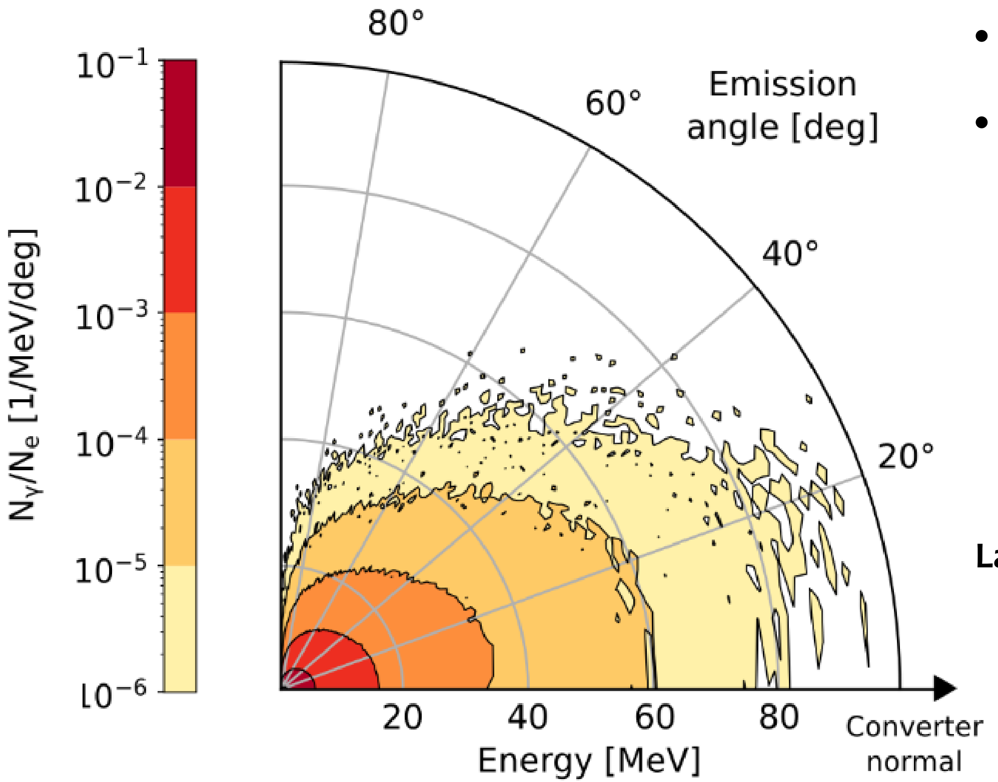
- $a_0 = 20$
- 10 μm foam
- $n \sim n_c$



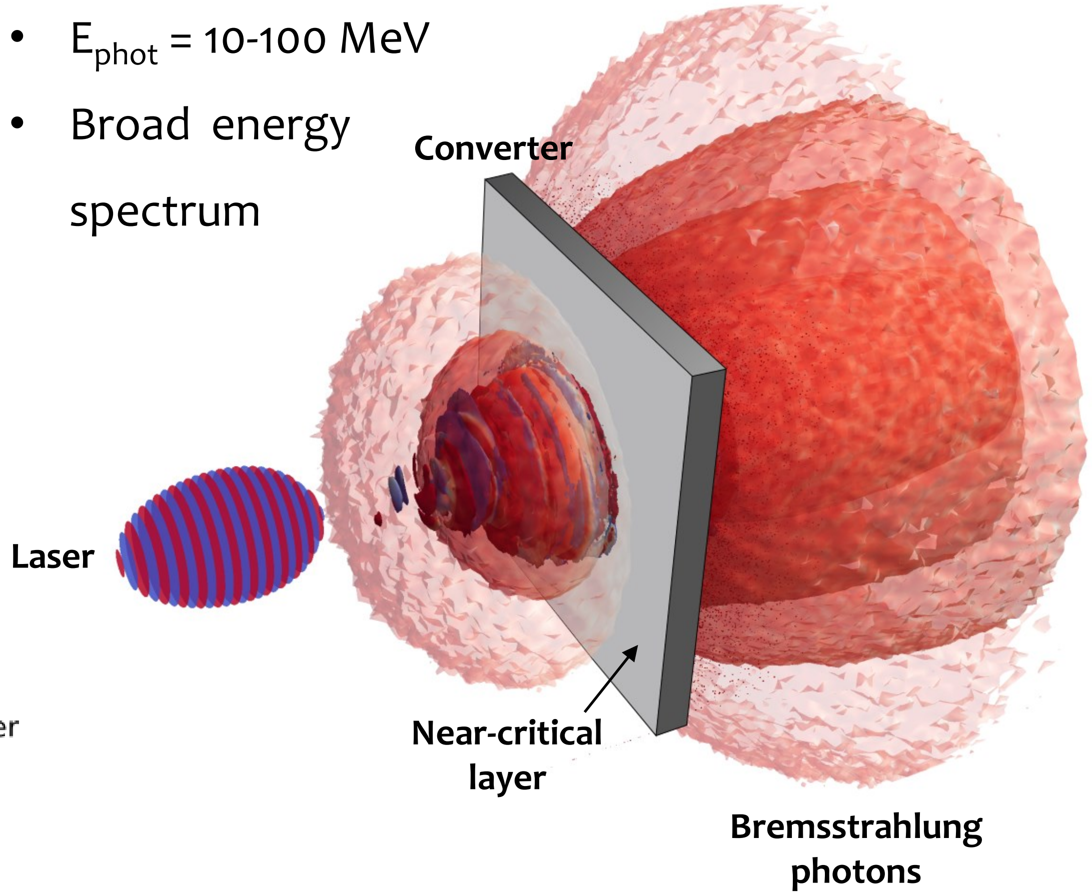
Mirani, F., et al. "Superintense Laser-driven Photon Activation Analysis." Under review at Communications Physics.

Laser-driven PAA, a numerical investigation

2) **Hot e-** interaction with **mm-thick substrate** → Bremsstrahlung **photons** generation

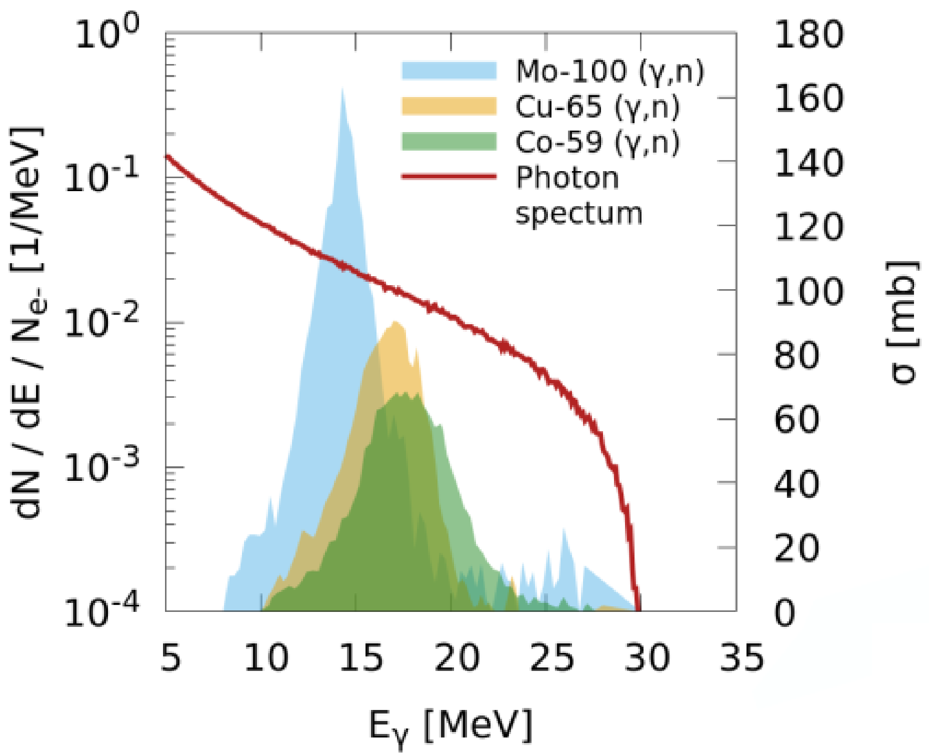


- E_{phot} = 10-100 MeV
- Broad energy spectrum

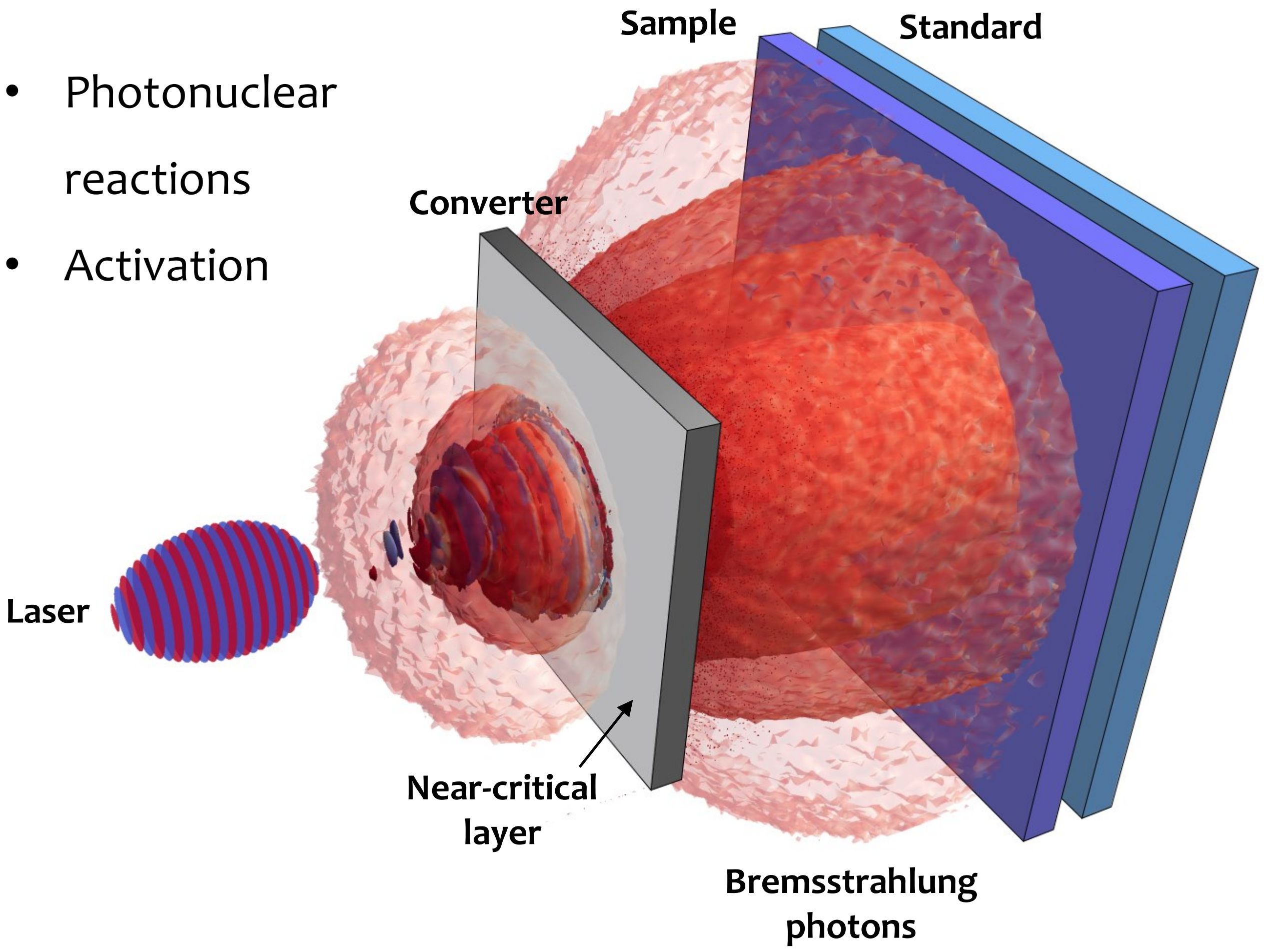


Mirani, F., et al. "Superintense Laser-driven Photon Activation Analysis." Under review at Communications Physics.

3) **Sample** and comparative material **irradiation**



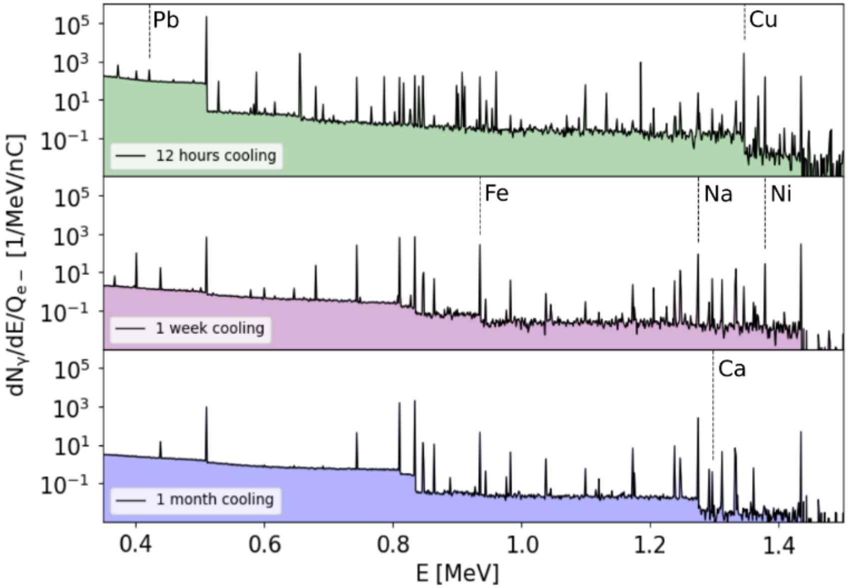
- Photonuclear reactions
- Activation

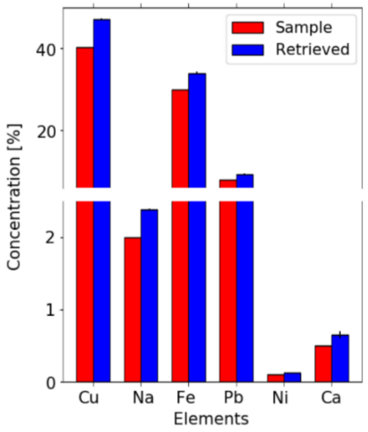


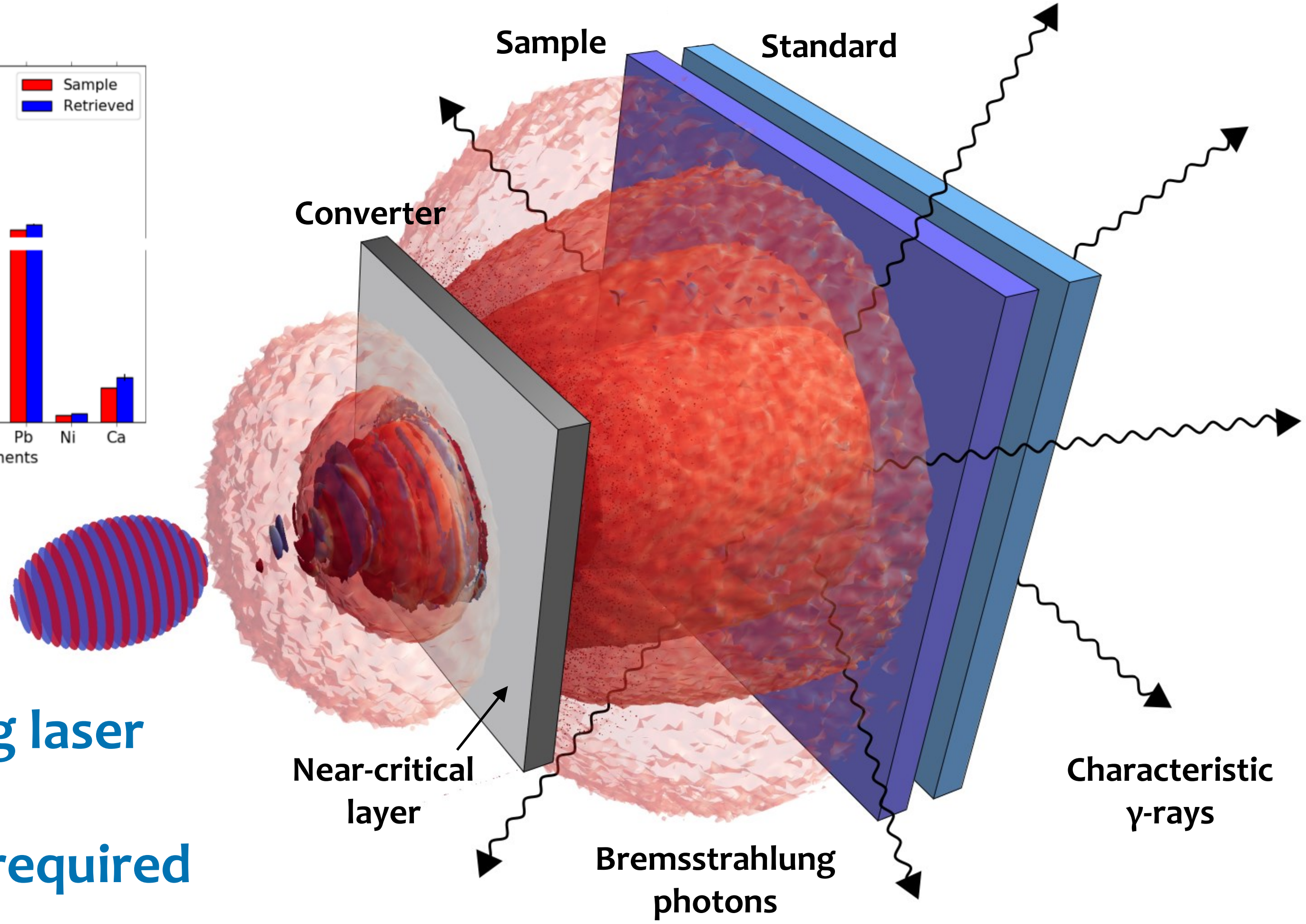
Mirani, F., et al. "Superintense Laser-driven Photon Activation Analysis." Under review at Communications Physics.

Laser-driven PAA, a numerical investigation

3) Delayed emission of **characteristic γ-rays** → **Composition** reconstruction







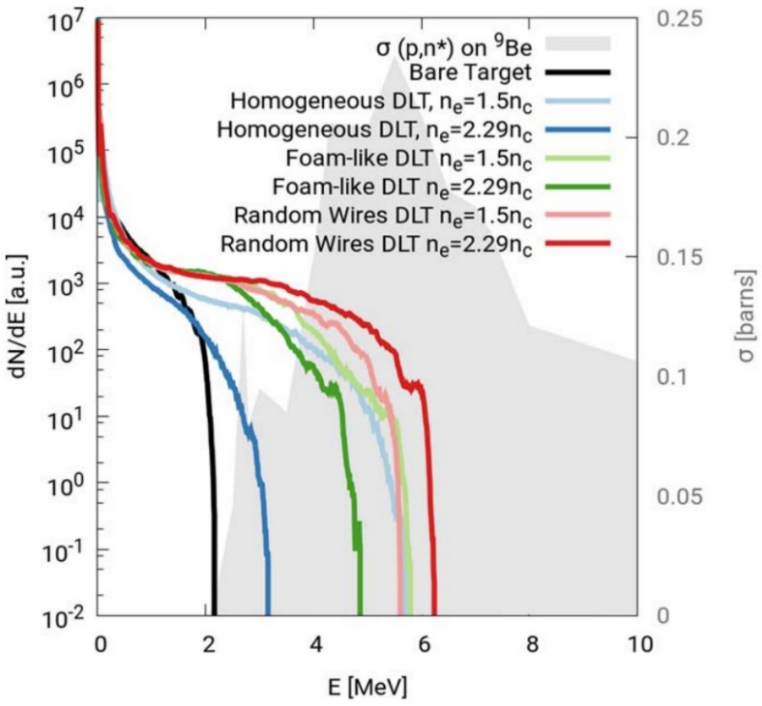
- Laser-driven **PAA achievable** with **existing laser** technology
- Near-critical targets + **100s TW** lasers are **required**

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

Laser-driven neutron sources, a numerical investigation

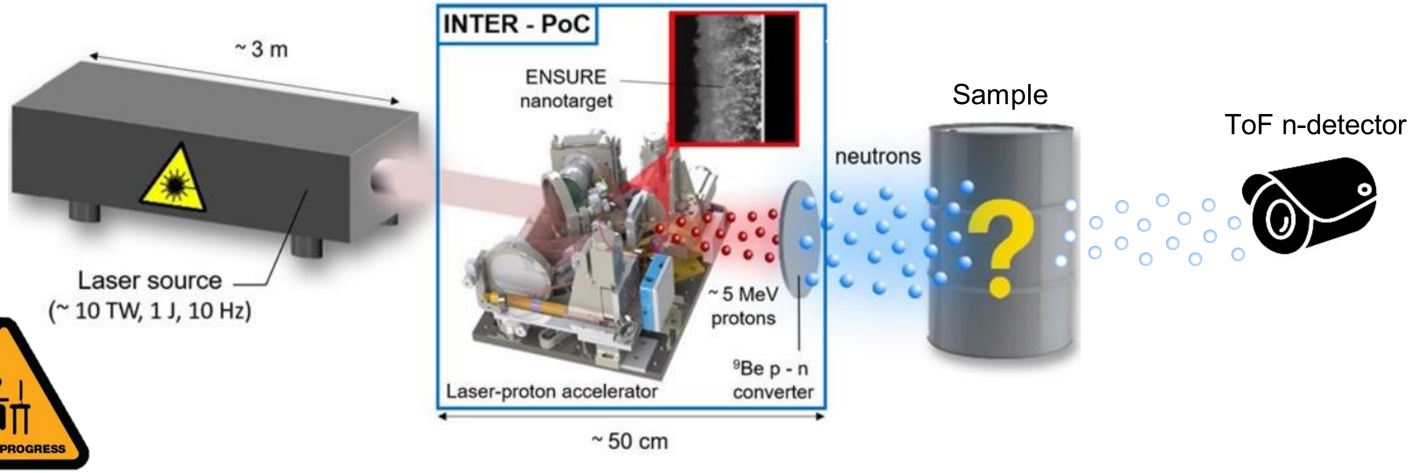
ERC-2016-PoC INTER → Compact **neutron source** (**DLTs** and **Be converters**)

- Collaboration wirth SourceLAB
- piccante and GEANT4 simulations

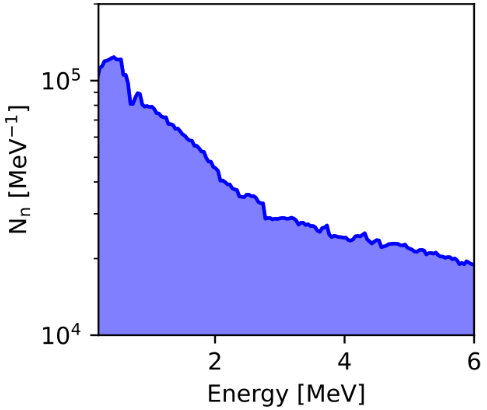


L Fedeli et al 2020 New J. Phys. 22 033045

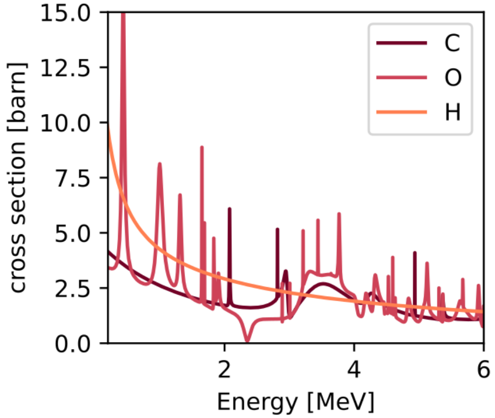
- Fast neutron transmission spectroscopy (**PFNTS**)



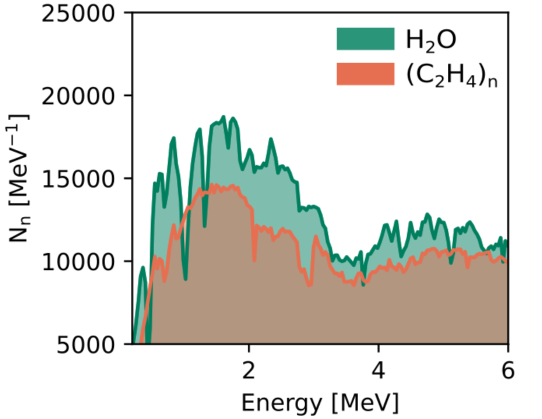
Incident neutrons



Total cross sections

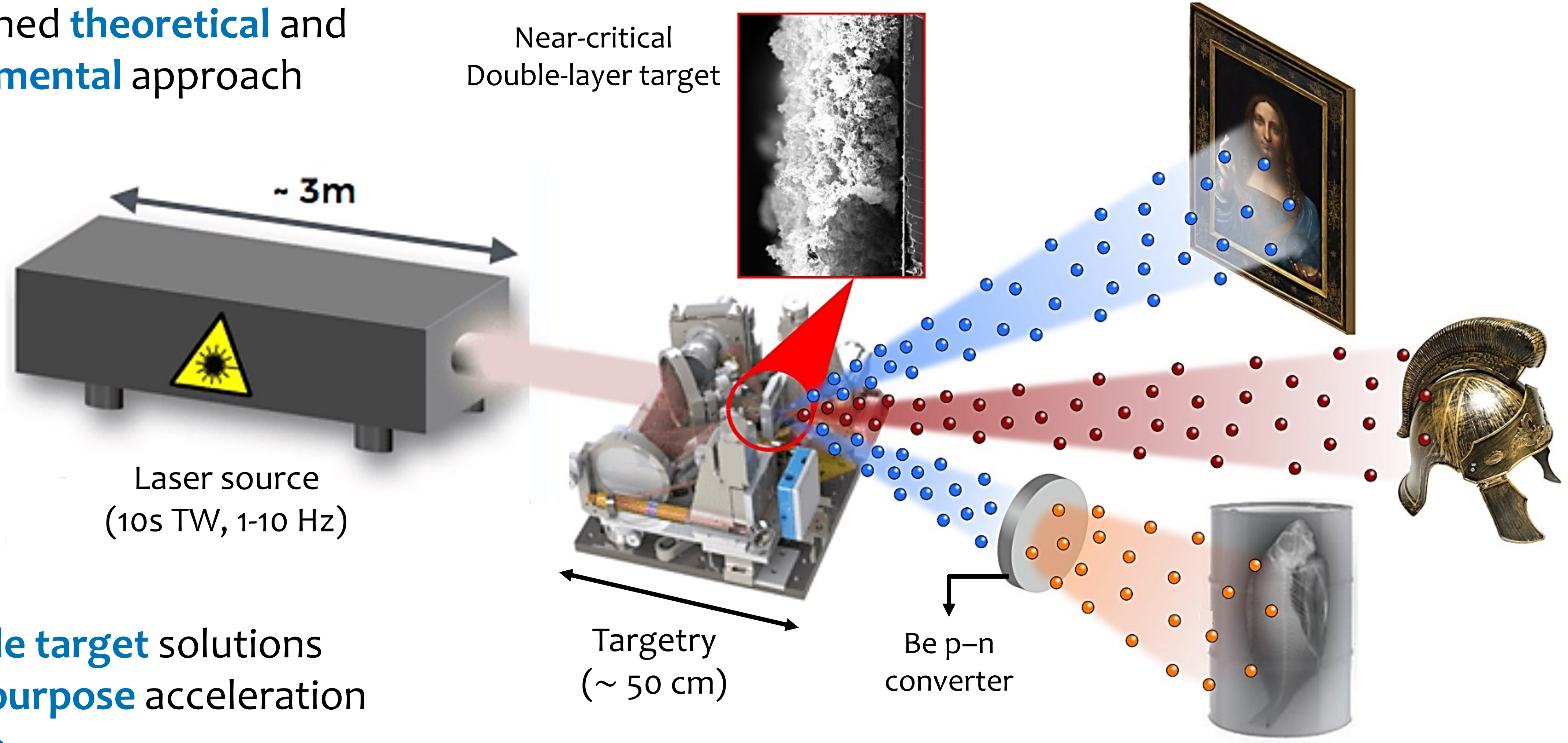


Transmitted neutrons



Conclusions

- Combined **theoretical** and **experimental** approach



- **Suitable target** solutions
- **Multi-purpose** acceleration **system**

Thank you for the attention!

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