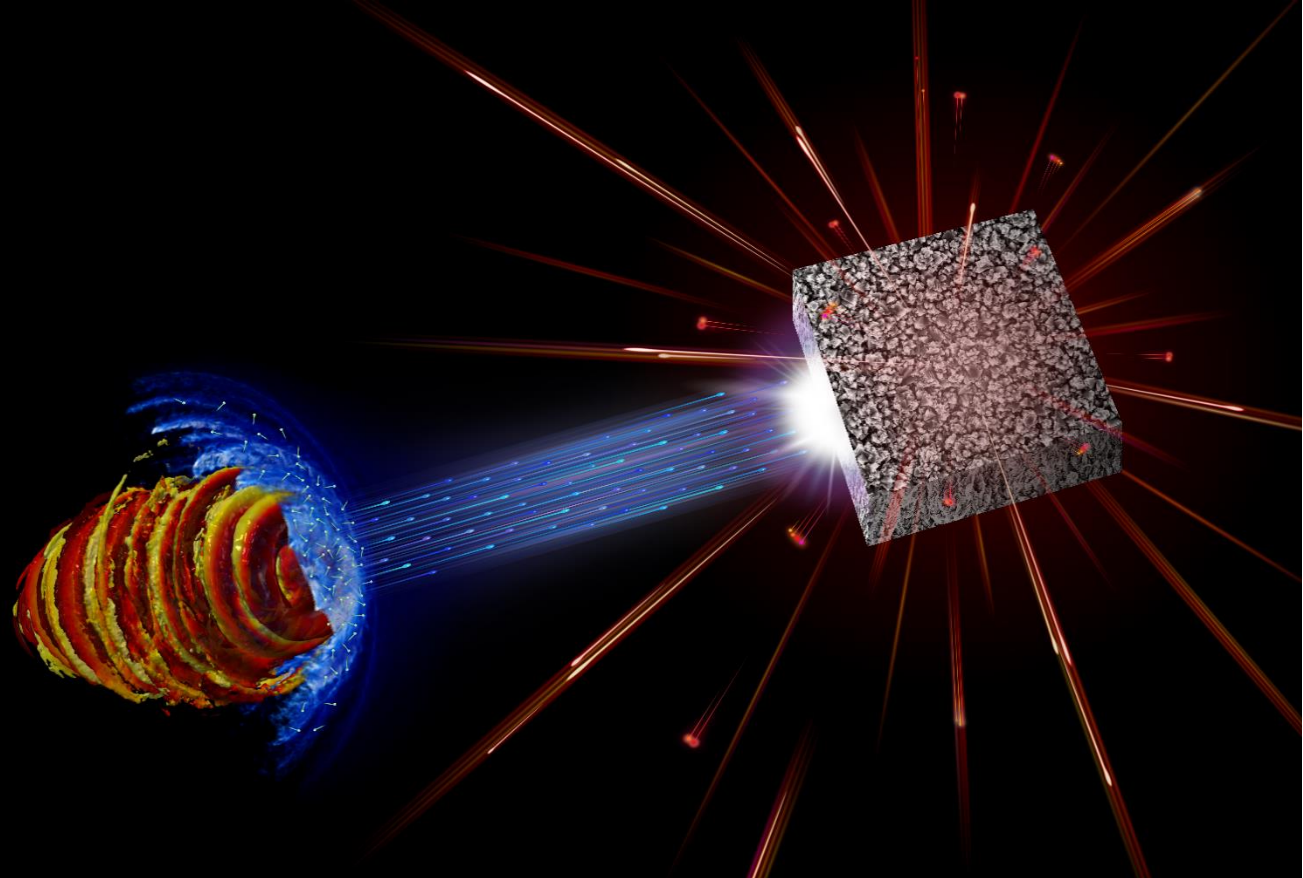
eli beamlines

Multidisciplinary Applications of laser-driven Ions

# Experimental demonstration of laser-driven differential Particle Induced X-ray Emission and Proton Activation Analysis




Francesco Mirani



erc ERC-2022-PoC No. 101069171
PANTANI



POLITECNICO
MILANO 1863

NanoLab
Department of Energy

- Activities performed within the framework of an **ERC-PoC grant** erc ERC-2022-PoC No. 101069171 **PANTANI** at POLITECNICO MILANO 1863
- Present **team** members:


M. Passoni
Principal Investigator


D. Dellasega


M. Zavelani

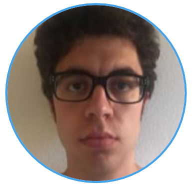

V. Russo


A. Pola


A. Maffini


A. Formenti


F. Mirani


D. Vavassori


M. Galbiati


D. Orecchia

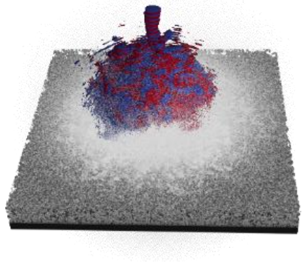

F. Gatti

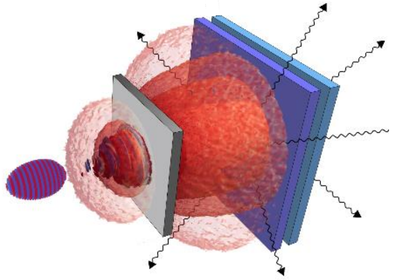
- **Collaboration** with industrial companies: RAYLAB DETECTING INNOVATION spin off POLITECNICO DI MILANO, SourceLAB

www.ensure.polimi.it

# Theoretical & experimental activities @ PoliMi

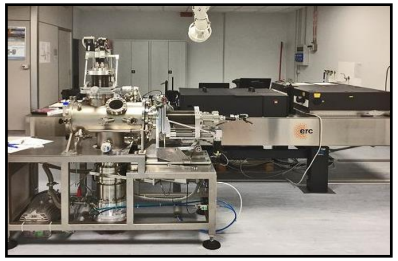
**Theoretical studies** of laser-driven particle acceleration and interaction with matter ( Smilei, FLUKA , GEANT4 )

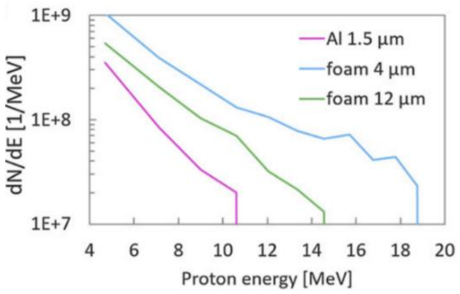




L. Fedeli, et al. *New J. Phys.* 22.3 (2020): 033045.
A. Pazzaglia, et al. *Commun Phys* 3.1 (2020): 1-13.
A. Formenti, et al. New J. Phys. 22.5 (2020): 053020.
A. Formenti, et al. *PPCF* 64.4 (2022): 044009.

Pulsed-Laser Deposition (**PLD**) and **Magnetron Sputtering** to produce advanced materials (e.g. **Double-Layer Targets**)



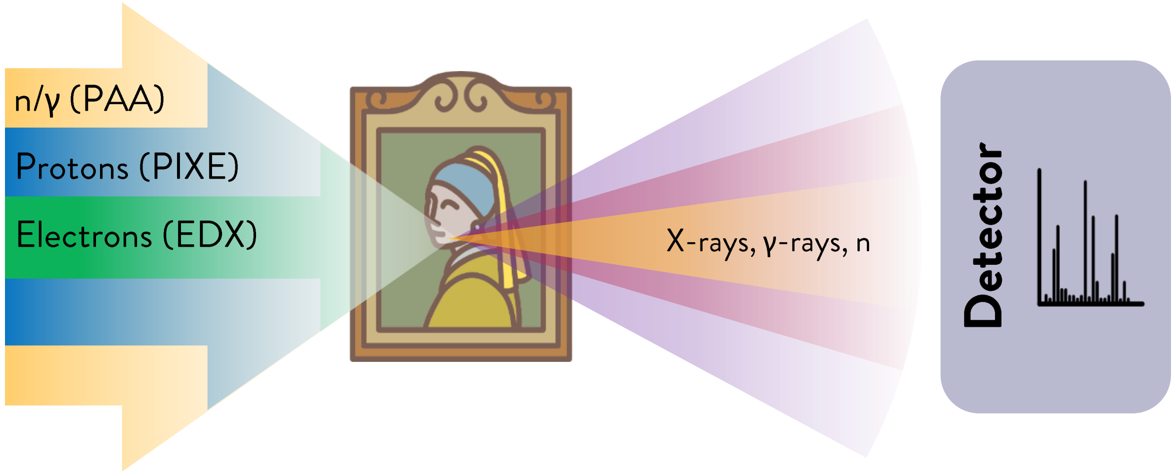


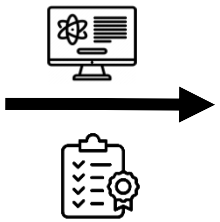

A. Maffini, et al. *Phys. Rev. Mater.* 3.8 (2019): 083404.
I. Prencipe, et al. *New J. Phys.* 23.9 (2021): 093015.
D. Dellasega, et al. *Appl. Surf. Sci.* 556 (2021): 149678.
A. Maffini, et al. *Appl. Surf. Sci.* (2022): 153859.

Study **applications** of laser-driven particle sources in **materials science**

M. Passoni, et al. *Sci. Rep.*, 9.1 (2019): 9202.
F. Mirani, et al. *Commun. Phys.* 4.1 (2021): 1-13.
F. Mirani, et al. *Sci. Adv.* 7.3 (2021): eabc8660.
F. Mirani, et al. Under review at *Phys. Rev. Appl.*

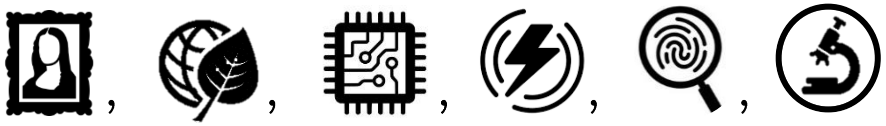
# Characterization of materials via Ion Beam Analysis



- **Concentrations** & **Depth profiles** (differential PIXE) at surface.
- Bulk analysis of **large objects**.
- **Imaging** and **elemental radiography** of non-homogeneous samples.

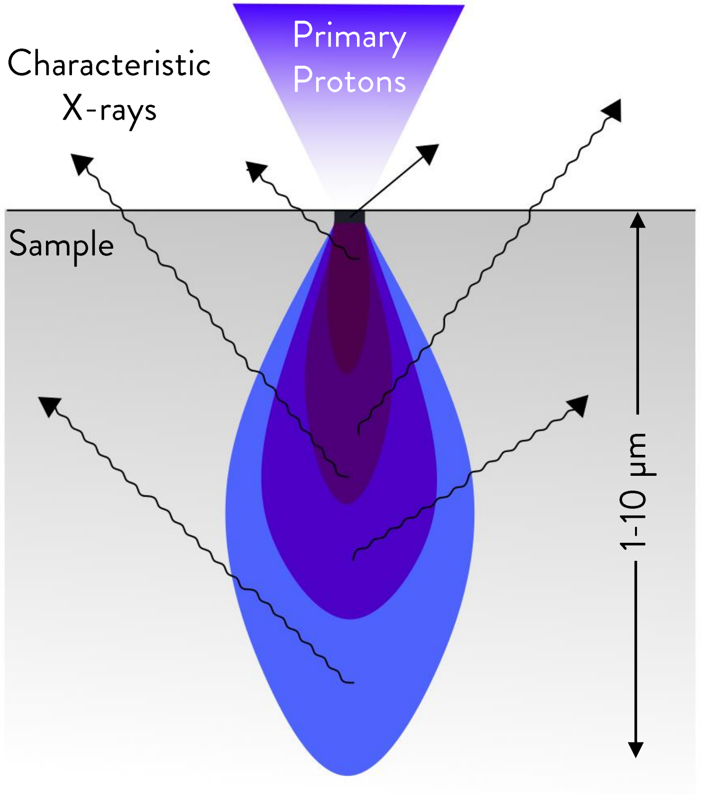
- Broad range of applications:



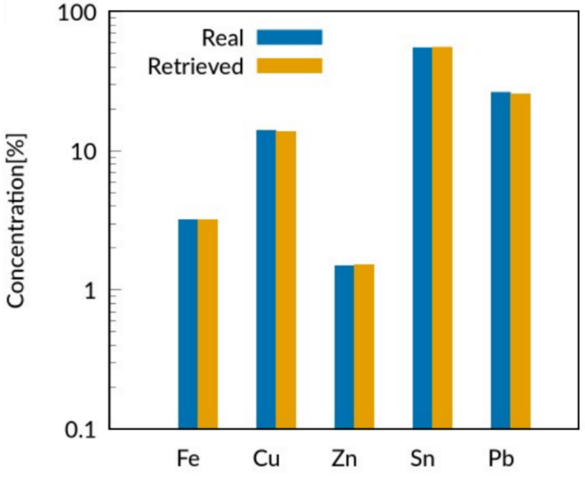
! Different sources / accelerators, **lack of flexibility** (e.g. energy control).

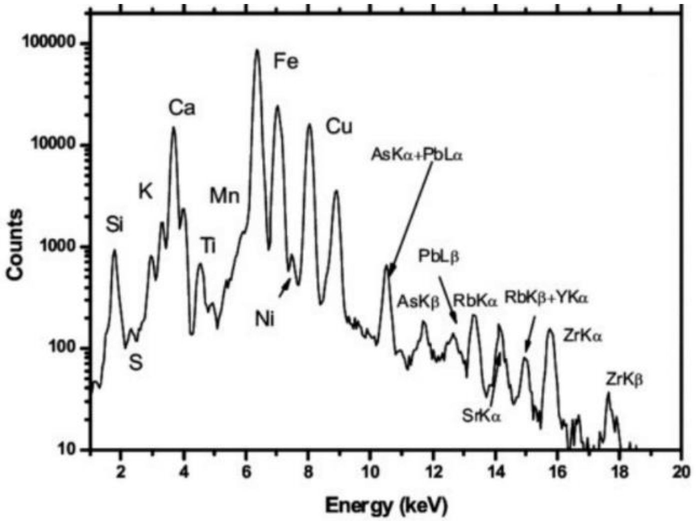
Verma, Hem Raj. Atomic and nuclear analytical methods. *Springer*, 2007.
E. H. Lehmann, *J. Archaeol. Sci. Rep.* 19 (2018): 397-404.
P. A. Mandò, et al. *Nucl. Instrum. Methods Phys. Res. B: Beam Interact. Mater. At.* 239.1-2 (2005): 71-76.
J. Salomon, et al. *Nucl. Instrum. Methods Phys. Res. B: Beam Interact. Mater. At.* 266.10 (2008): 2273-2278.

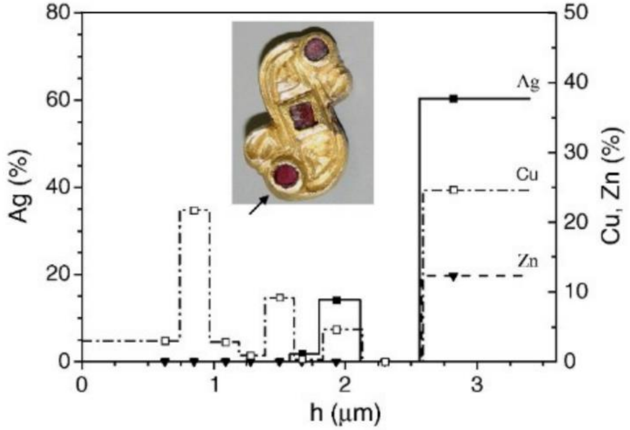
# Particle Induced X-ray Emission (PIXE)




- **2-5 MeV** monoenergetic ions (**protons**).
- Detection of the emitted **X-rays.**
- **Concentrations** & **Depth profiles** (*differential PIXE*)
- Probed thickness up **~ 1 – 10s μm** in solids.



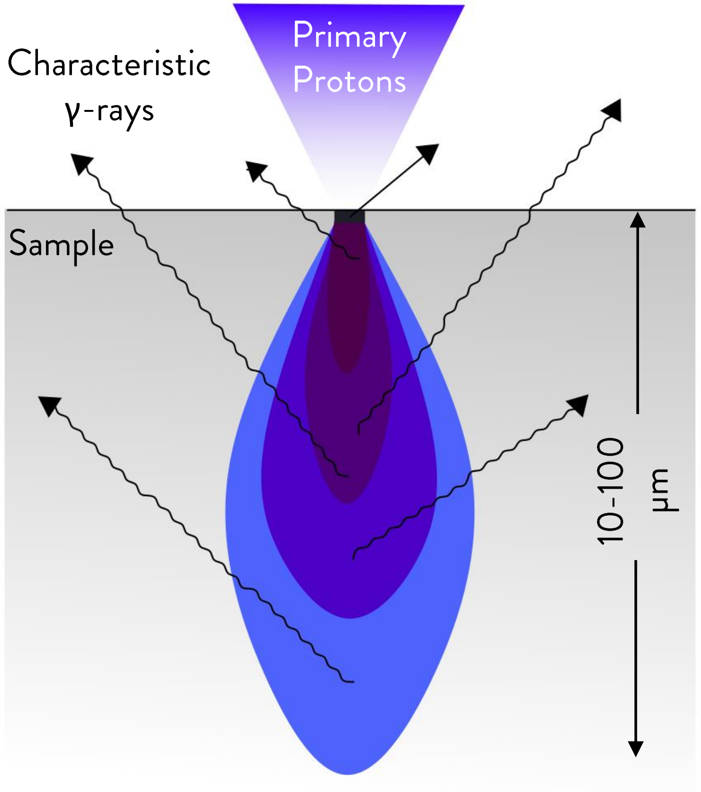



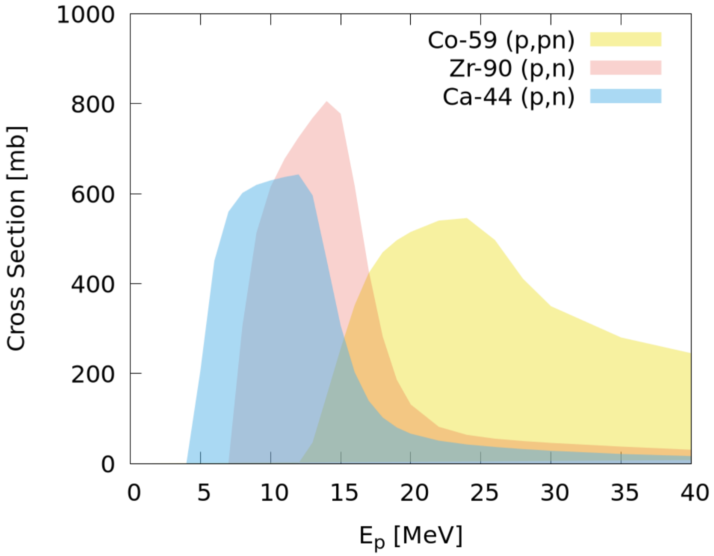

**No standard materials** are required → Spectra analysed with **software** in literature (theoretical description of PIXE).

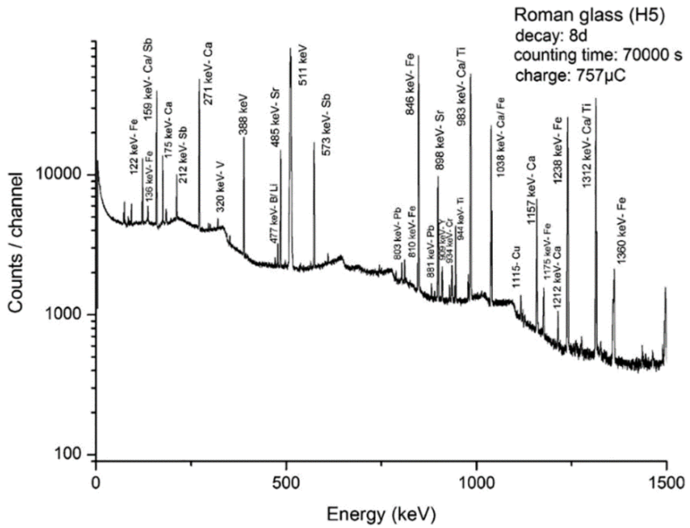
Verma, Hem Raj. Atomic and nuclear analytical methods. *Springer*, 2007.
Ž. Šmit, et al. *Nucl Instrum Methods Phys Res B* 266.10 (2008): 2329-2333.

# Deep Proton Activation Analysis (DPAA)




- **10s MeV** monoenergetic **protons.**
- Detection of the delayed **γ-rays.**
- **Concentrations** of elements and isotope specific.
- Probed thickness up **~ 10 – 100s µm** in solids.





Commonly with **standard materials.**

Proposed also with reference-free **software.**

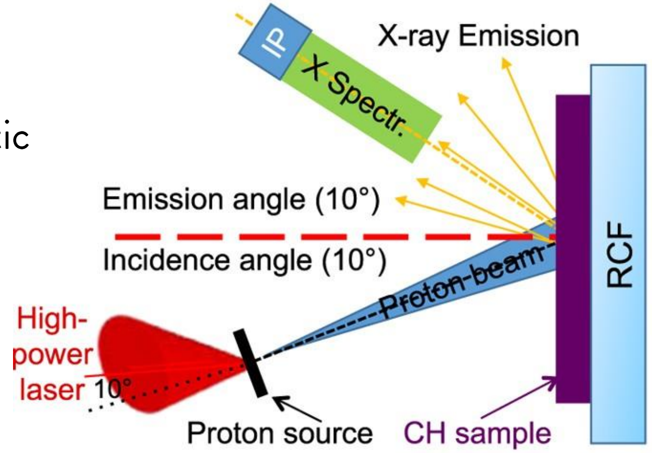

Verma, Hem Raj. Atomic and nuclear analytical methods. *Springer*, 2007.

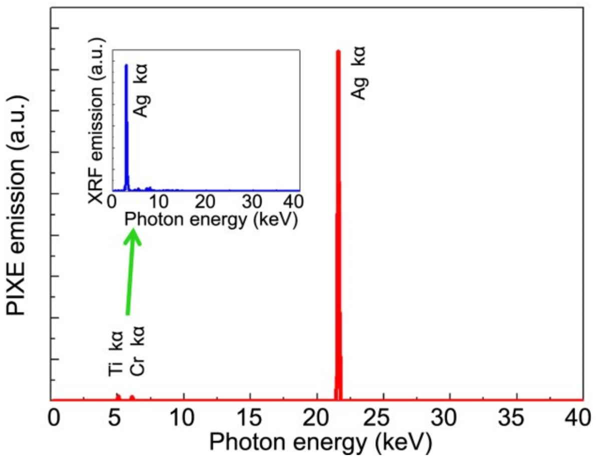
C. S. Sastri, et al. *Nucl Instrum Methods Phys Res B* 467 (2020): 152-155.

# Overview of PIXE with laser-driven sources

**Proof-of-principle experiment** of laser-driven PIXE **elemental analysis.**

- Collect characteristic X-ray spectra.
- Identification of the elements.




- No damage of samples relevant in cultural heritage field.

M. Barberio, et al. *Sci. Rep.* 7.1 (2017): 1-8.

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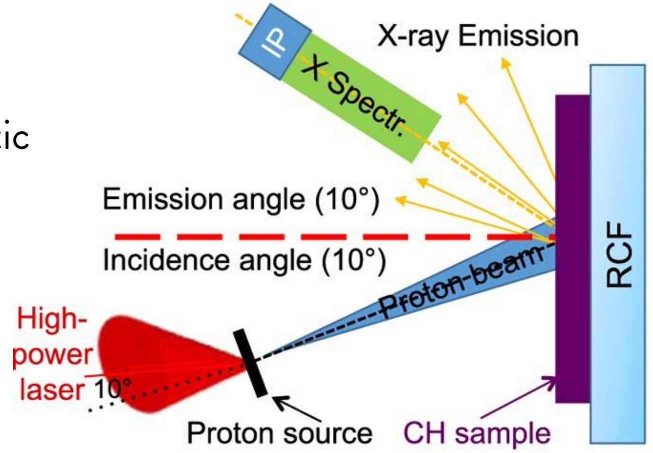
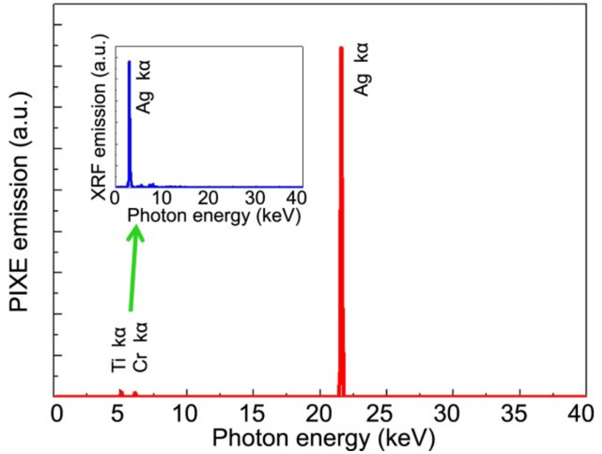


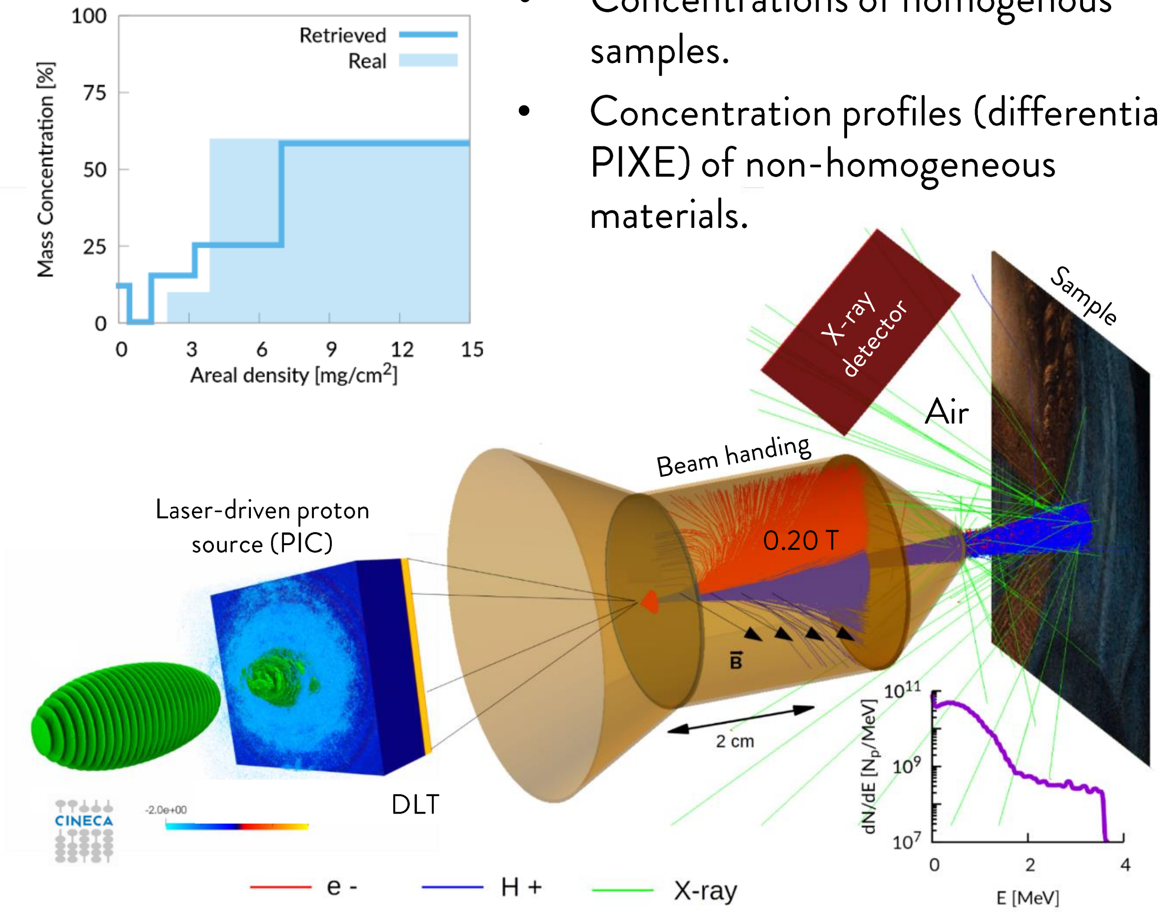




- No damage of samples relevant in cultural heritage field.

M. Barberio, et al. *Sci. Rep.* 7.1 (2017): 1-8.

**Theoretical background** for laser-driven PIXE **quantitative analysis**.

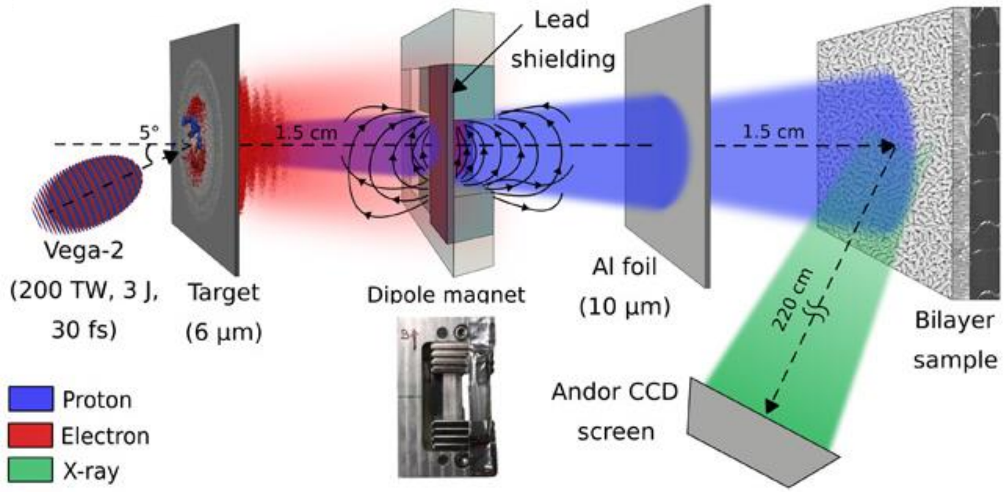
- Concentrations of homogenous samples.
- Concentration profiles (differential PIXE) of non-homogeneous materials.



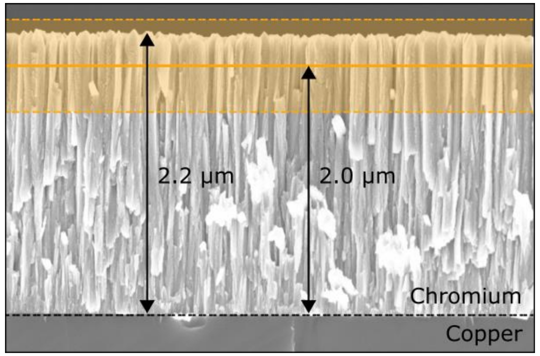

M. Passoni, et al. *Sci. Rep.*, 9.1 (2019): 9202.

# Overview of PIXE with laser-driven sources

**Experiment** of combined laser-driven **PIXE quantitative analysis** & **EDXS.**




- Retrieve the thickness of a micrometric thick layer.
- Faster elemental analysis of thicker samples with PIXE + EDXS.




F. Mirani, et al. *Sci. Adv.* 7.3 (2021): eabc8660.

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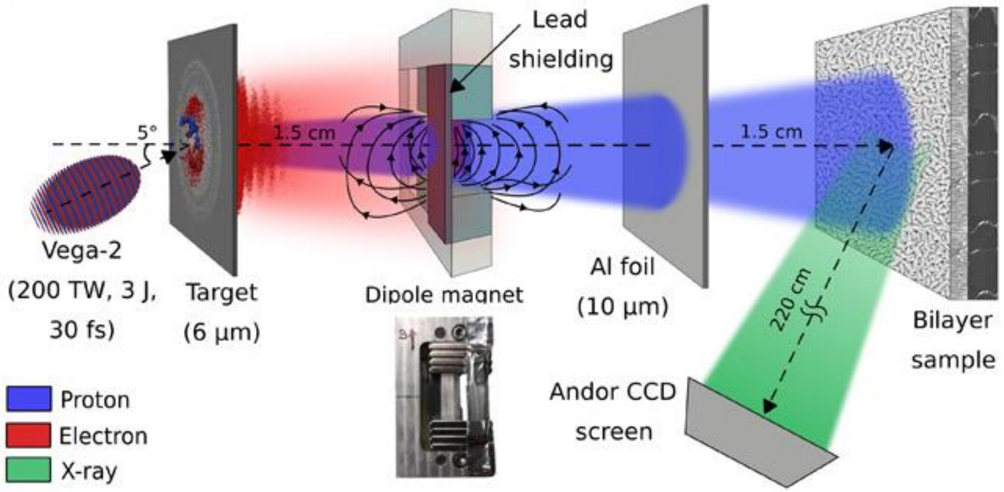


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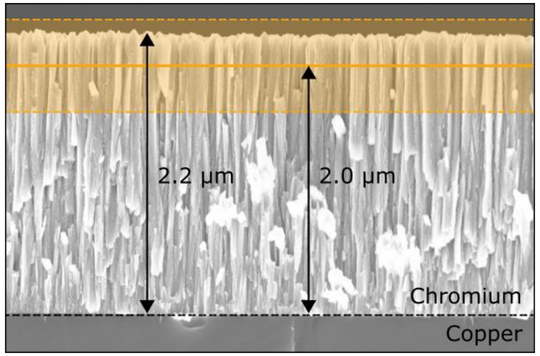
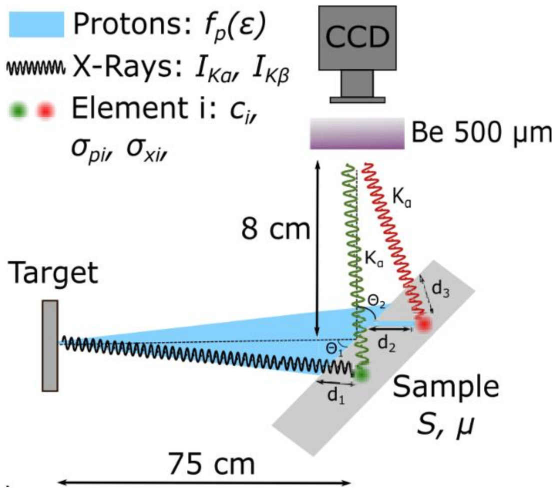
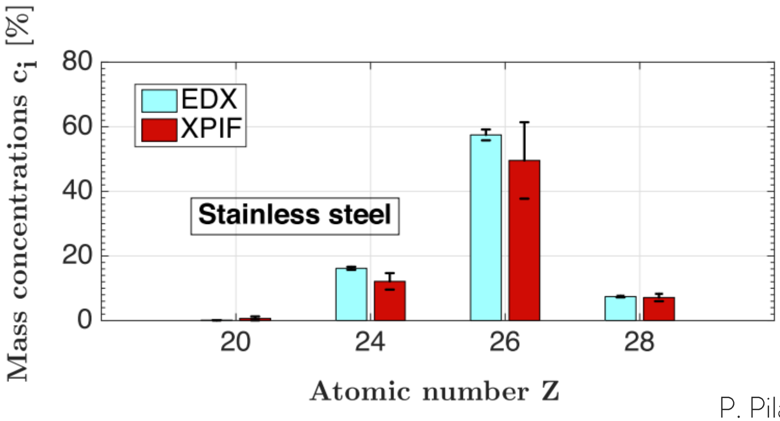



F. Mirani, et al. *Sci. Adv.* 7.3 (2021): eabc8660.

**Experiments** of combined laser-driven PIXE **quantitative analysis** & laser-driven **XRF.**

- Retrieve concentrations in homogeneous samples.
- Faster analysis of thicker samples with PIXE + XRF.



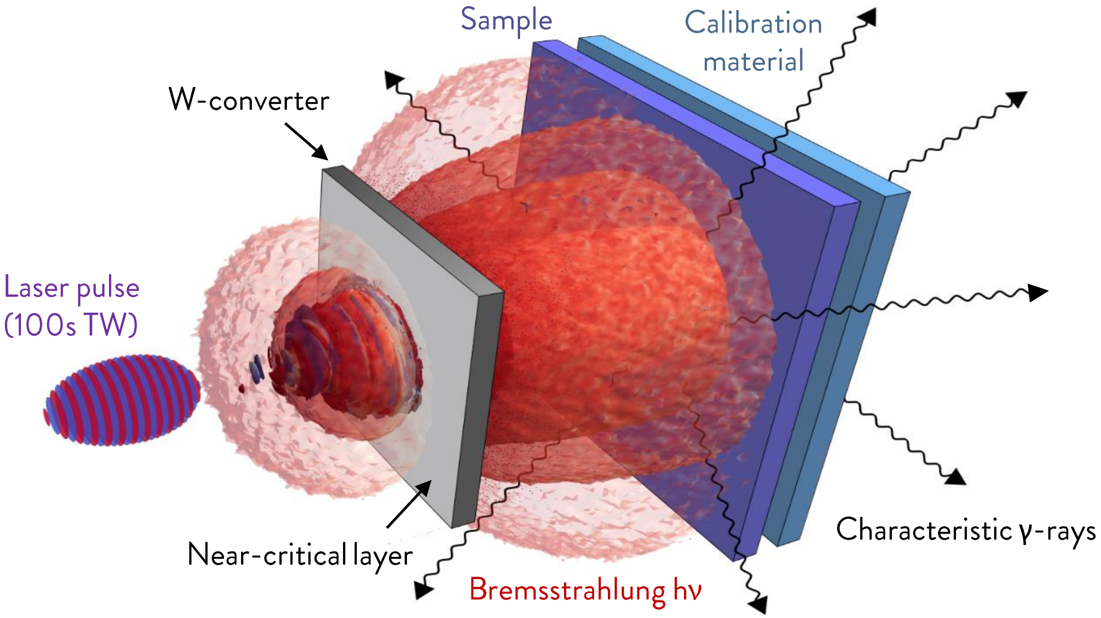



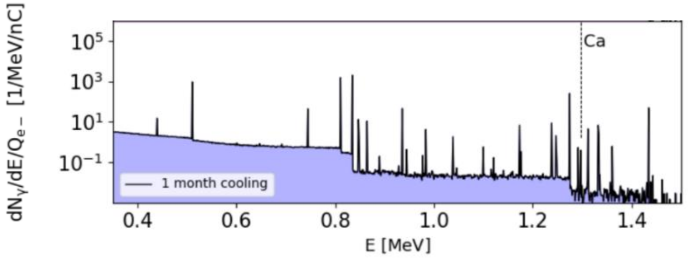

P. Pilar, et al. *Sci. Rep.* 11.1 (2021): 1-10.

F. Boivin, et al. *New J. Phys.* 24.5 (2022): 053018.

# Other materials characterization techniques with laser-driven sources

- Laser-driven **Photon Activation Analysis** for bulk composition (several mm).




- Characteristic delayed γ-ray emission.

F. Mirani, et al. *Commun. Phys.* 4.1 (2021): 1-13.

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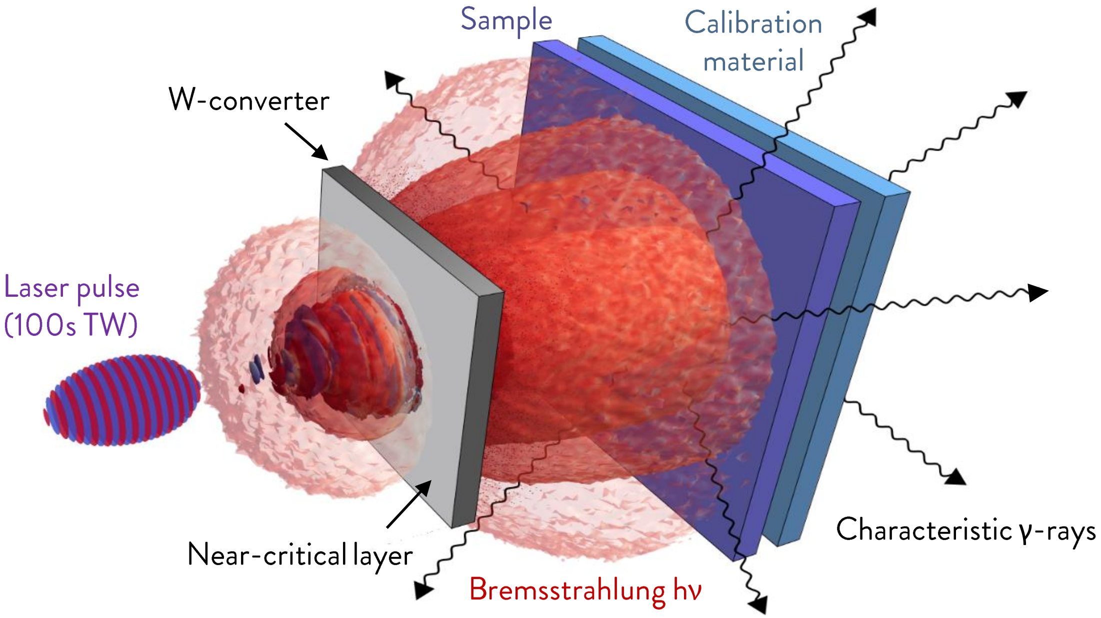
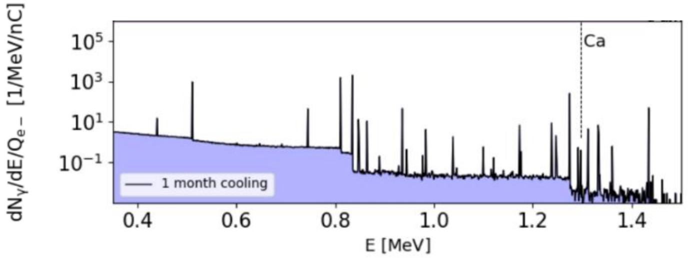
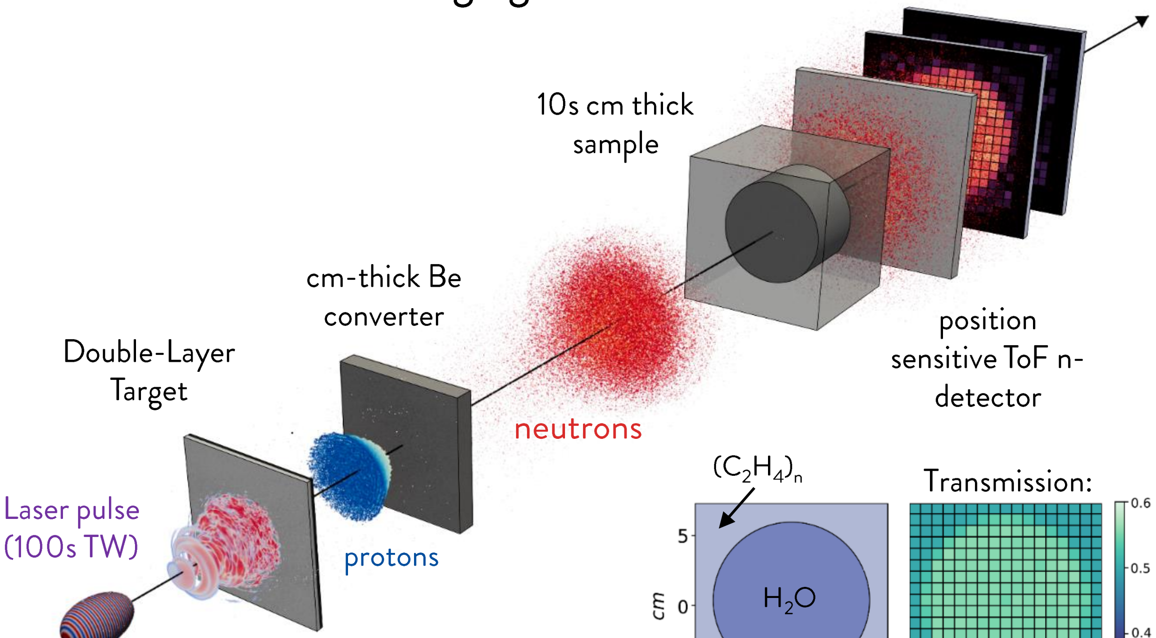
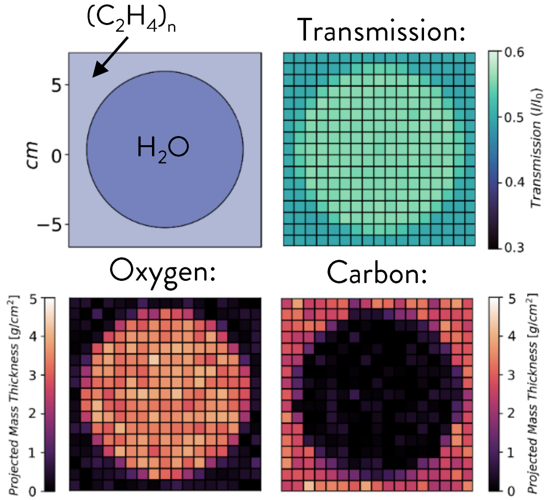



- Characteristic delayed γ-ray emission.

- Laser-driven **Fast Neutron Resonance Radiography** for elemental imaging.




- Irradiation of large samples with 1-10 MeV neutron pulses.

F. Mirani, et al. *Commun. Phys.* 4.1 (2021): 1-13.

F. Mirani, et al. Under review at *Phys. Rev. Appl.*

# Possible experiment @ the ELIMAIA beamline

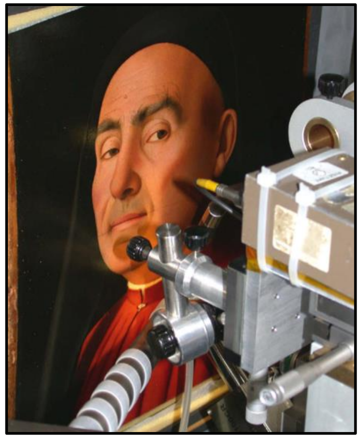
Perform a proof-of-principle **laser-driven differential PIXE experiment** and investigate its full-potential. → Highly relevant for **artworks**!

# Possible experiment @ the ELIMAIA beamline

Perform a proof-of-principle **laser-driven differential PIXE experiment** and investigate its full-potential. → Highly relevant for **artworks**!

- crucial for **restoration** of paintings, canvas (intrinsically composed by several layers) and statues.
- Study of the **painting technique** and **manufacturing of pigments.**



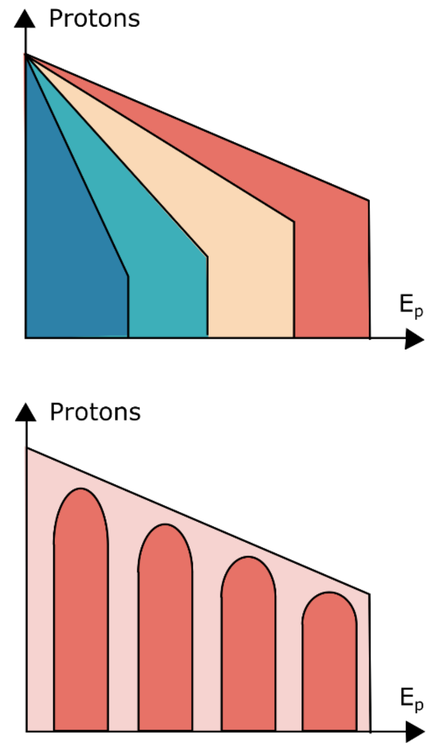


M. Bertasa, et al *JCH* 53 (2022): 100-117.
P. Pouli, et al. *Acc. Chem. Res.* 43.6 (2010): 771-781.
N. Grassi. *Nucl Instrum Methods Phys Res B* 267.5 (2009): 825-831.
P.A. Mandò, et al. *Nucl Instrum Methods Phys Res B* 239.1-2 (2005): 71-76.

# Possible experiment @ the ELIMAIA beamline

Perform a proof-of-principle **laser-driven differential PIXE experiment** and investigate its full-potential. → Highly relevant for **artworks**!

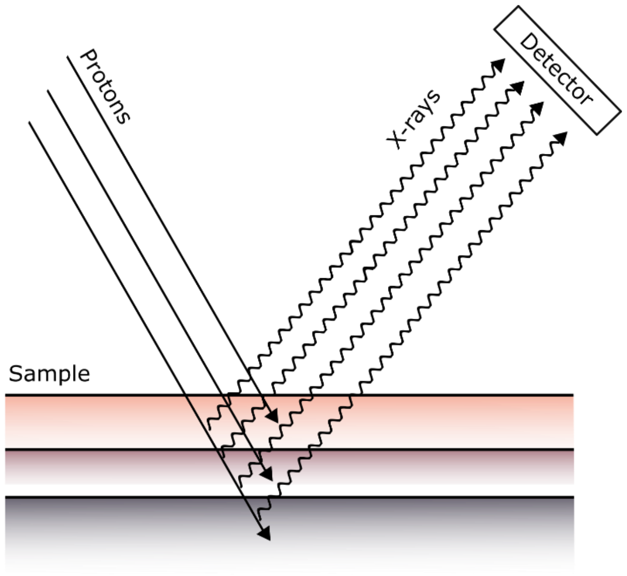
1. Irradiation of **non-homogeneous samples** with **different proton spectra** and collect characteristic X-rays.
2. **Reconstruction**, via theoretical models and codes, of the **concentration depth profiles** of the elements.

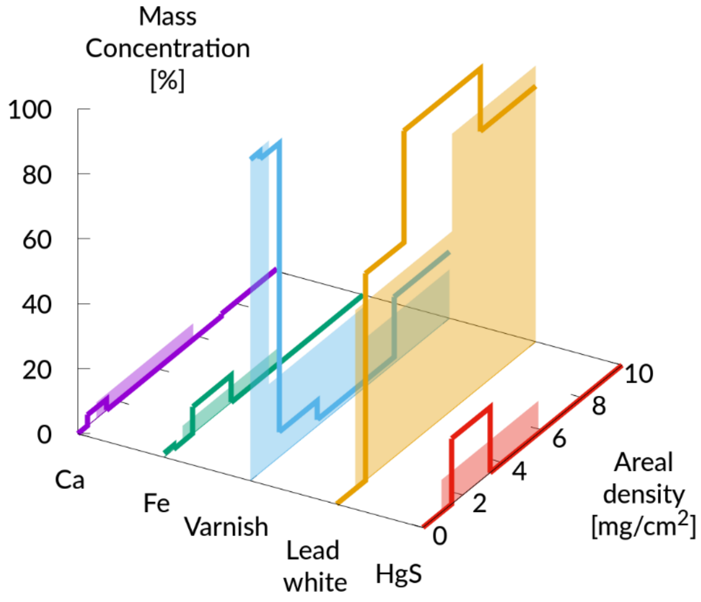



Several spectra from different targets.

VS

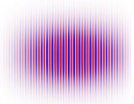
Energy selection from one spectrum.



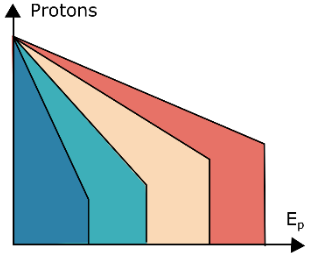
# Possible experiment @ the ELIMAIA beamline

**Technical requirements** for the laser and instrumentation:



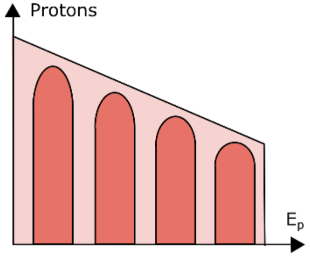
Short term **laser parameter**:

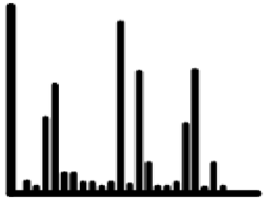
- 30 J energy
- 30 fs time duration
- 0.1 – 1 Hz repetition rate
- $10^9$ – $10^{10}$ protons/shot
- 3-30 MeV energy




**Diagnostics** to measure the **proton** energy **spectra**.

**Energy selector** and transport system.



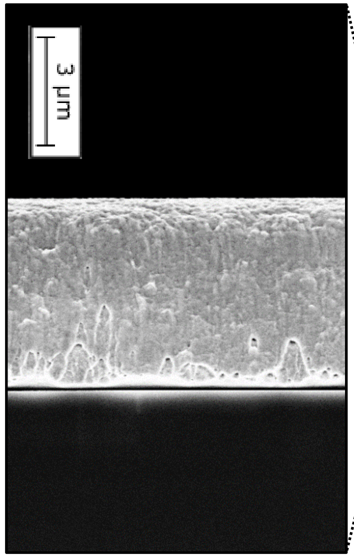
**CCD camera** for X-ray spectroscopy.

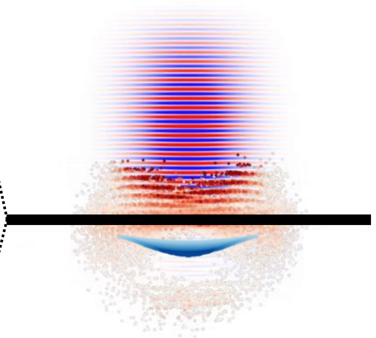
… to perform laser-driven PIXE:

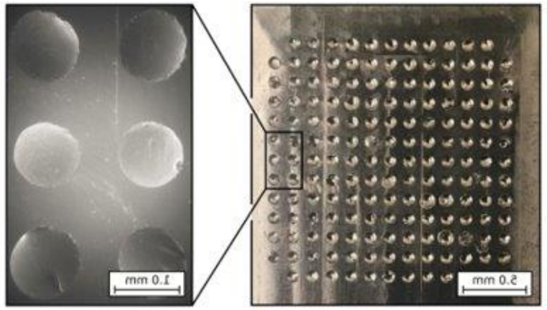
- **No mono-energetic protons** are strictly required.
- **No** knowledge of the **proton number** is required.

# Possible experiment @ the ELIMAIA beamline

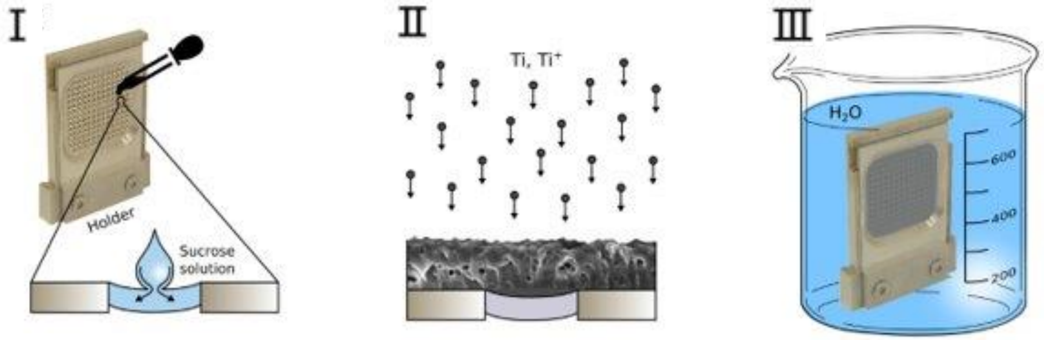
**User-owned equipment** from PoliMi: **metal targets with controlled thickness** produced with Magnetron Sputtering.



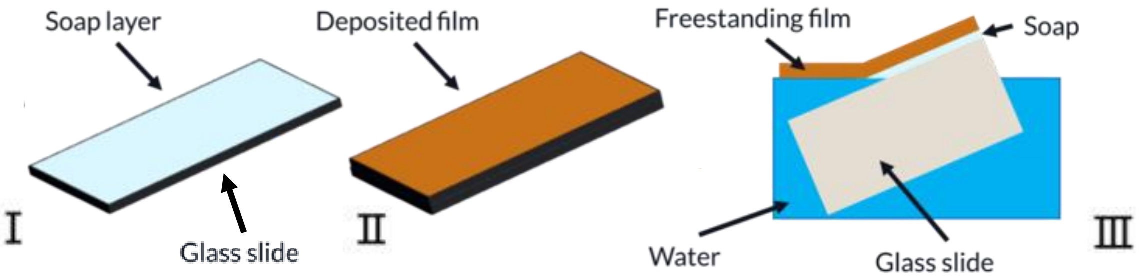



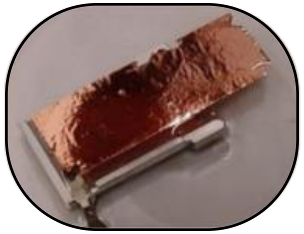



- **First strategy:**




- **Second strategy:**



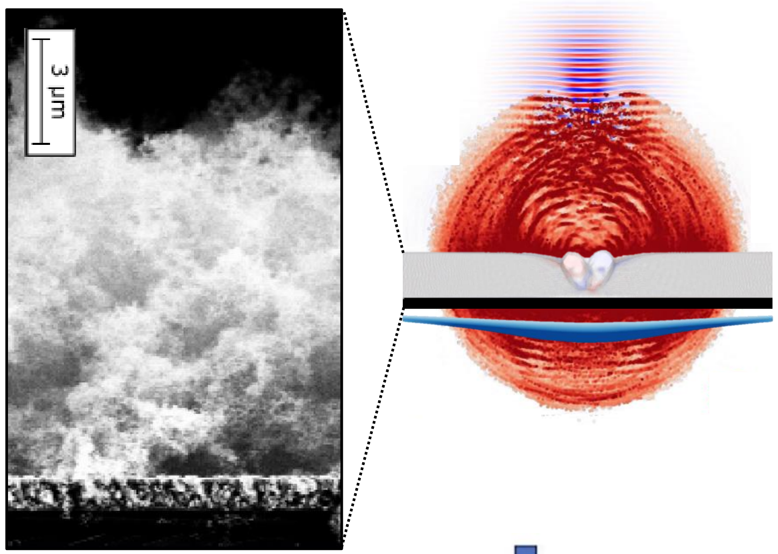



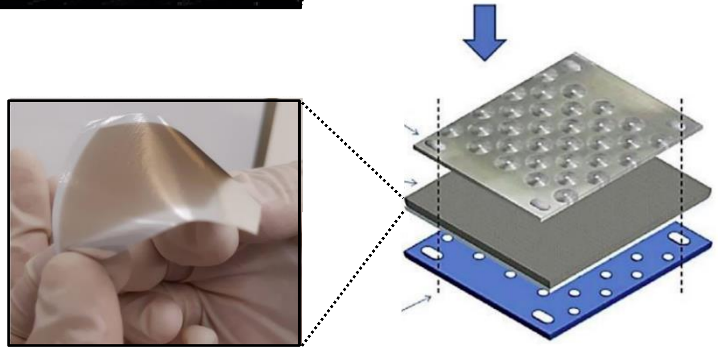
- Different materials, thicknesses from **~ 10s nm** to **microns**.

M. Passoni, et al. *PPCF* 62.1 (2019): 014022.

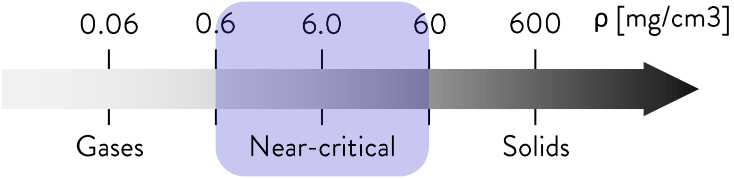
# Possible experiment @ the ELIMAIA beamline

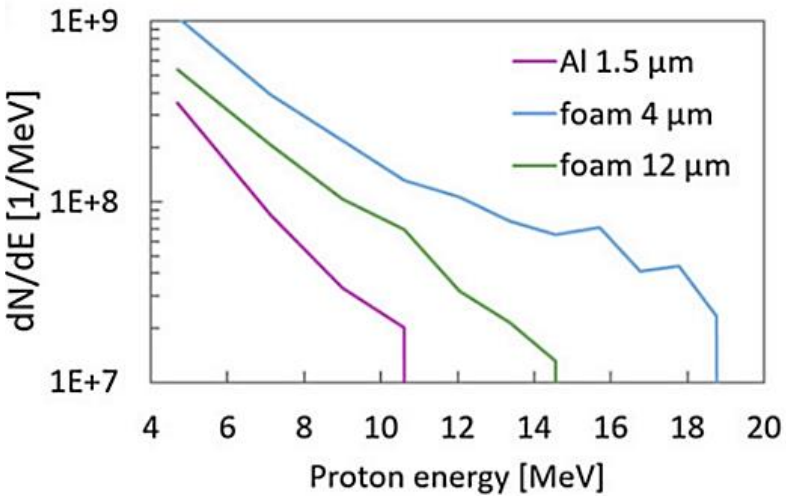
**User-owned equipment** from PoliMi: **near-critical Double-Layer Targets** to control the enhance the energy.

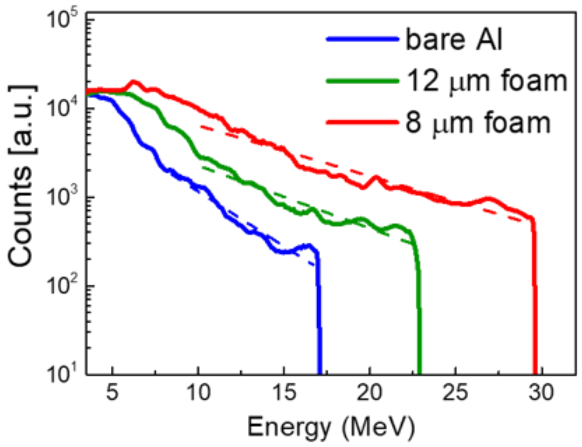


- Production of low-density carbon foams with **Pulsed-Laser Deposition**.
- **Higher conversion efficiency** of laser energy into particle energy.





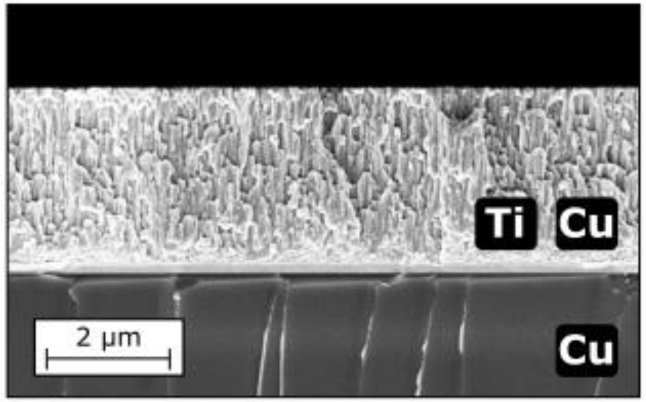
A. Maffini, et al. *Appl. Surf. Sci.* (2022): 153859.
A. Maffini, et al. *Phys. Rev. Mater.* 3.8 (2019): 083404.

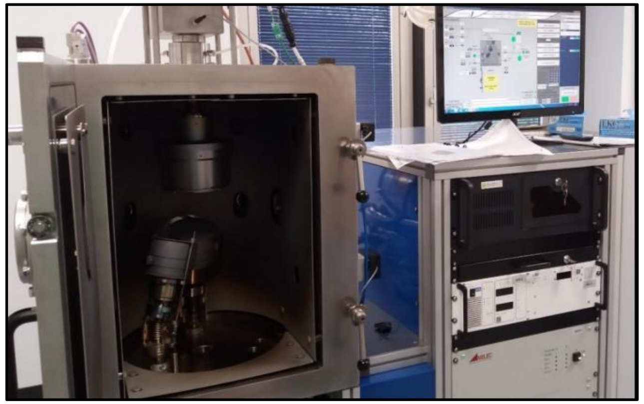
I. Prencipe, et al. *PPCF* 58.3 (2016): 034019.
I. Prencipe, et al. *New J. Phys.* 23.9 (2021): 093015.

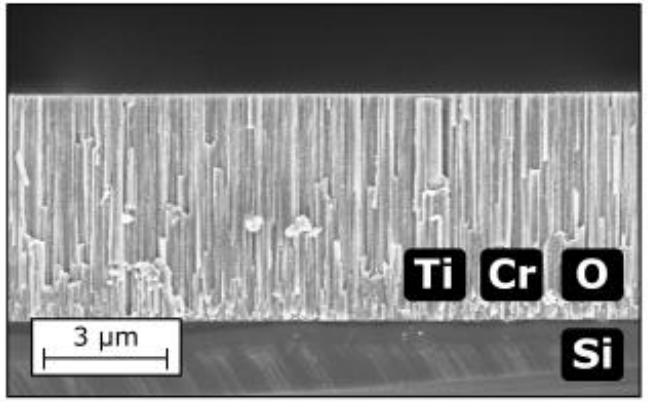
# Possible experiment @ the ELIMAIA beamline

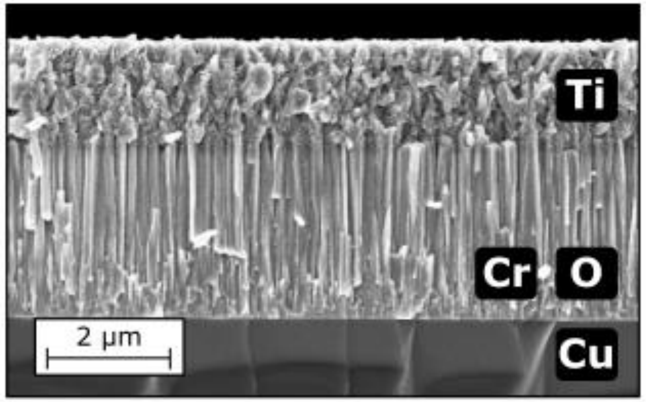
**User-owned equipment** from PoliMi: **multi-elemental**, **multi-layer samples** produced with High Power Impulse Magnetron Sputtering.

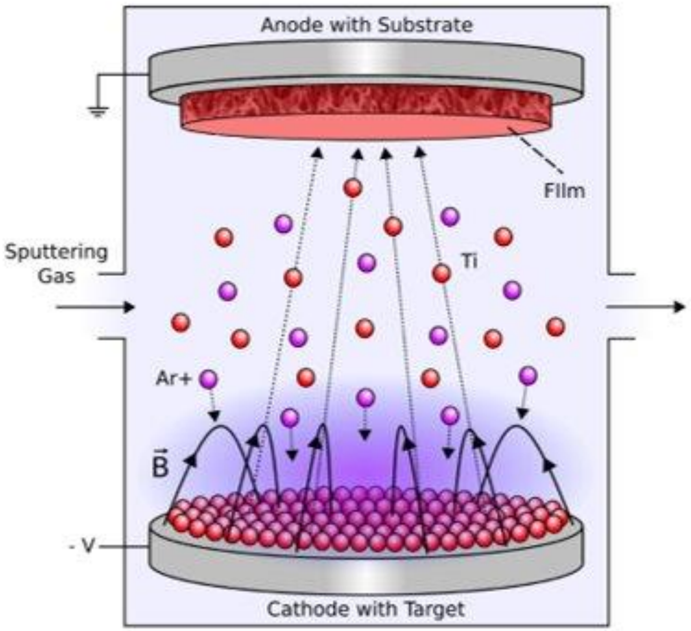
- Control the **deposition time** → **thickness** of the layers
- Control the **applied power** → **concentration** of the elements





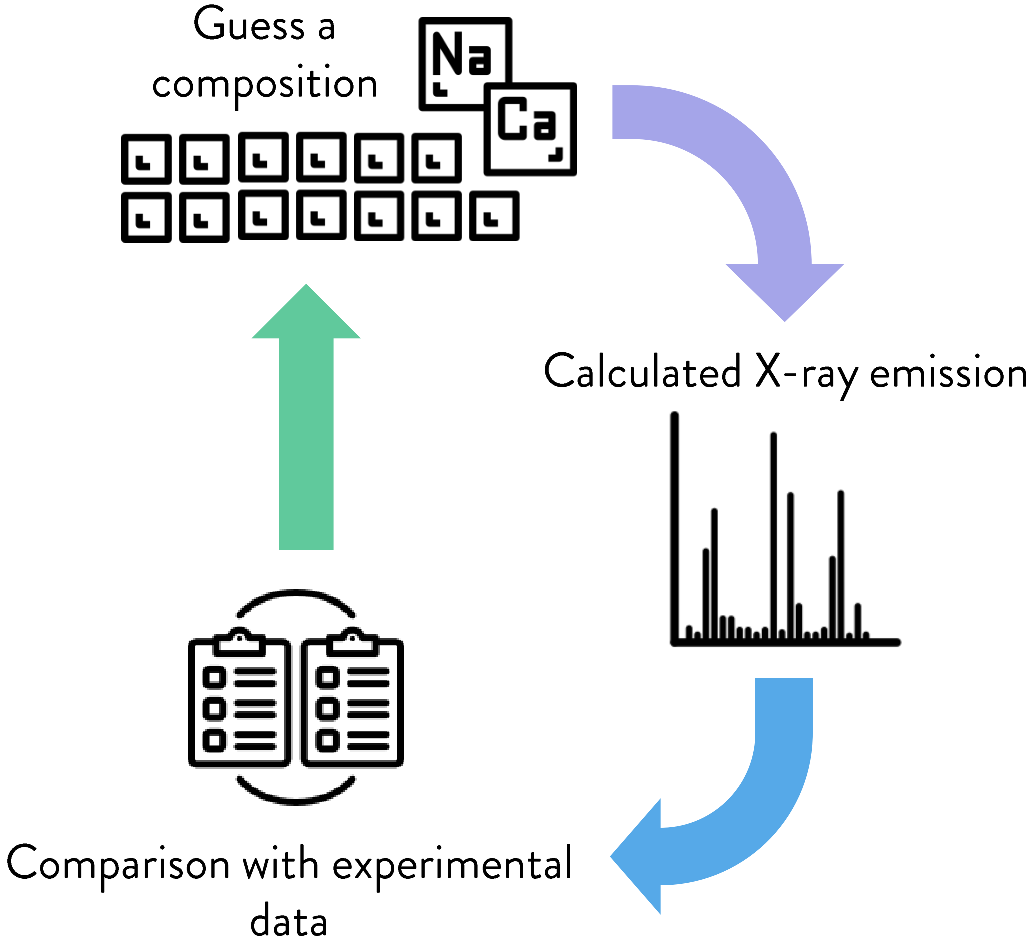



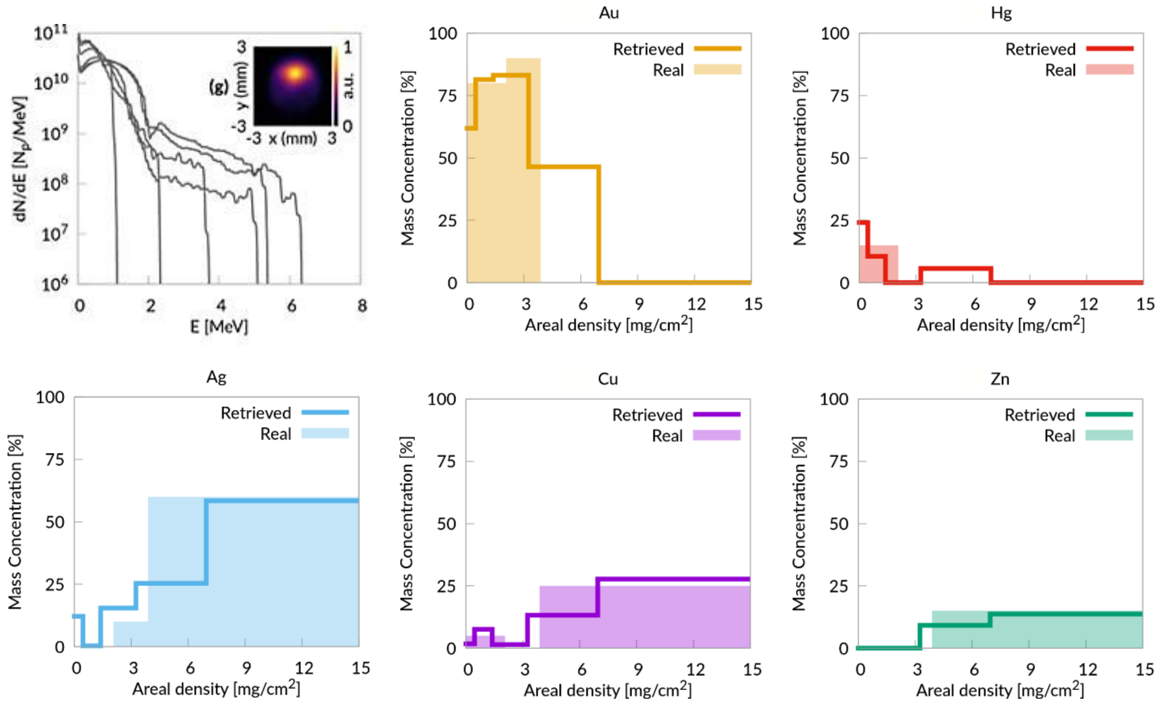

D. Dellasega, et al. *Appl. Surf. Sci.* 556 (2021):149678.

# Possible experiment @ the ELIMAIA beamline

**Software developed at Polimi** for the laser-driven PIXE spectra analysis.



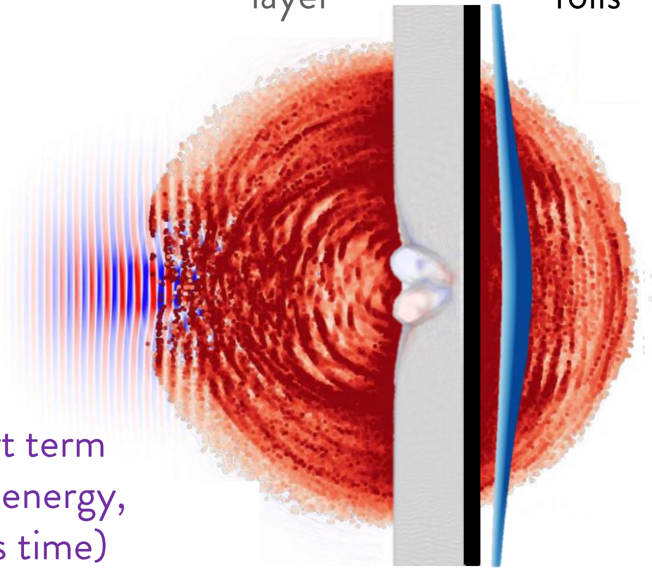

- Already **tested** on Monte Carlo **simulated data** for laser-driven differential PIXE




M. Passoni, et al. *Sci. Rep.*, 9.1 (2019): 9202.

# Possible experiment @ the ELIMAIA beamline

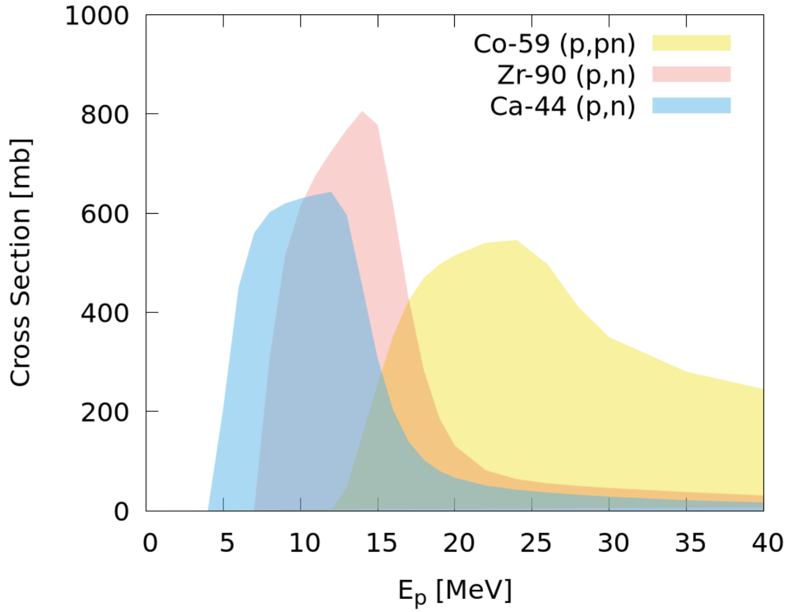
Laser-driven **Charged Particle Activation Analysis** (CPAA)




Short term (30 J energy, 30 fs time)

**Double-Layer Target**

- **> 30 MeV** energy
- **Broad** energy **spectra**
- **> $10^{11}$** protons

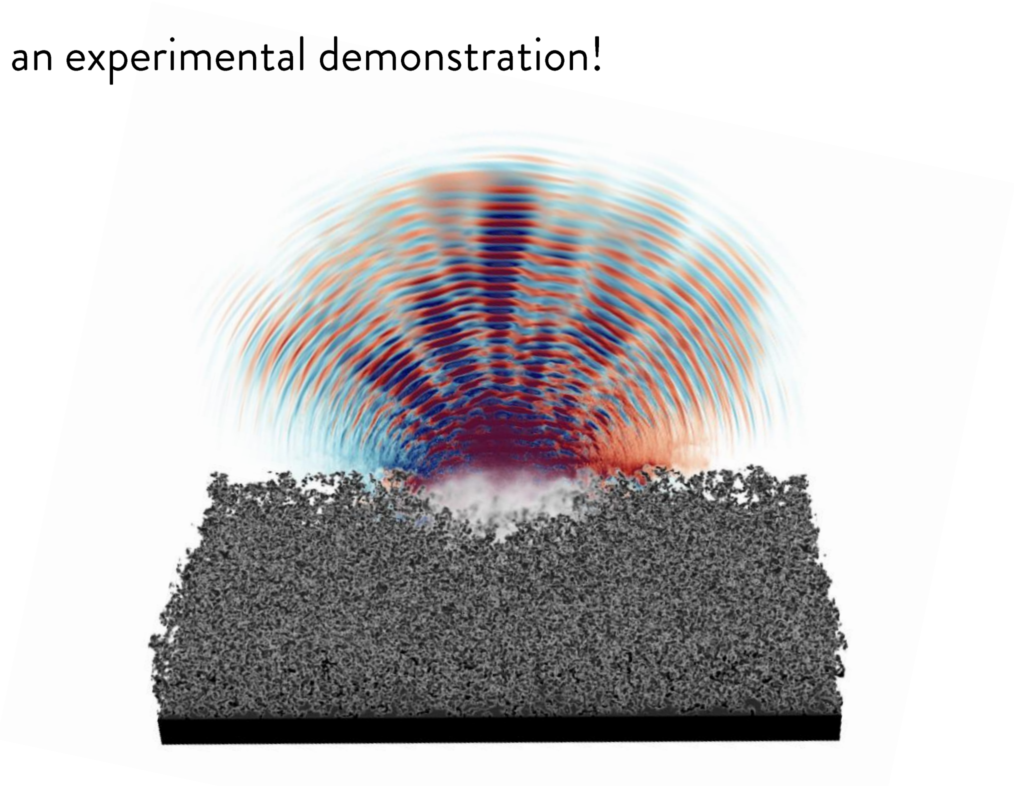



- Irradiation of thick NIST National Institute of Standards and Technology standard materials.
- Possibility to provide γ-ray detectors from POLITECNICO MILANO 1863

- **Enhance** the **proton number** to achieve **high** γ-rays **yields.**
- No need of energy selection.

# Summary & conclusions

- **Laser-driven radiation sources** are **promising** for **materials characterization** and in particular for artworks.
  - **Multiple radiations** → **multi-purpose** (surface, bulk, stratigraphic analysis and imaging).
- **Differential PIXE** (one the most ambitious) and **PAA** still need an experimental demonstration!
- **ELIMAIA beamline** offers **the best chance**:
  - Broad range of proton energies.
  - Energy tunability and selection.
  - High number of particles.
  - High repetition rate.



Thank you for the attention!

POLITECNICO MILANO 1863

ERC-2022-PoC No. 101069171 PANTANI

eli beamlines

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