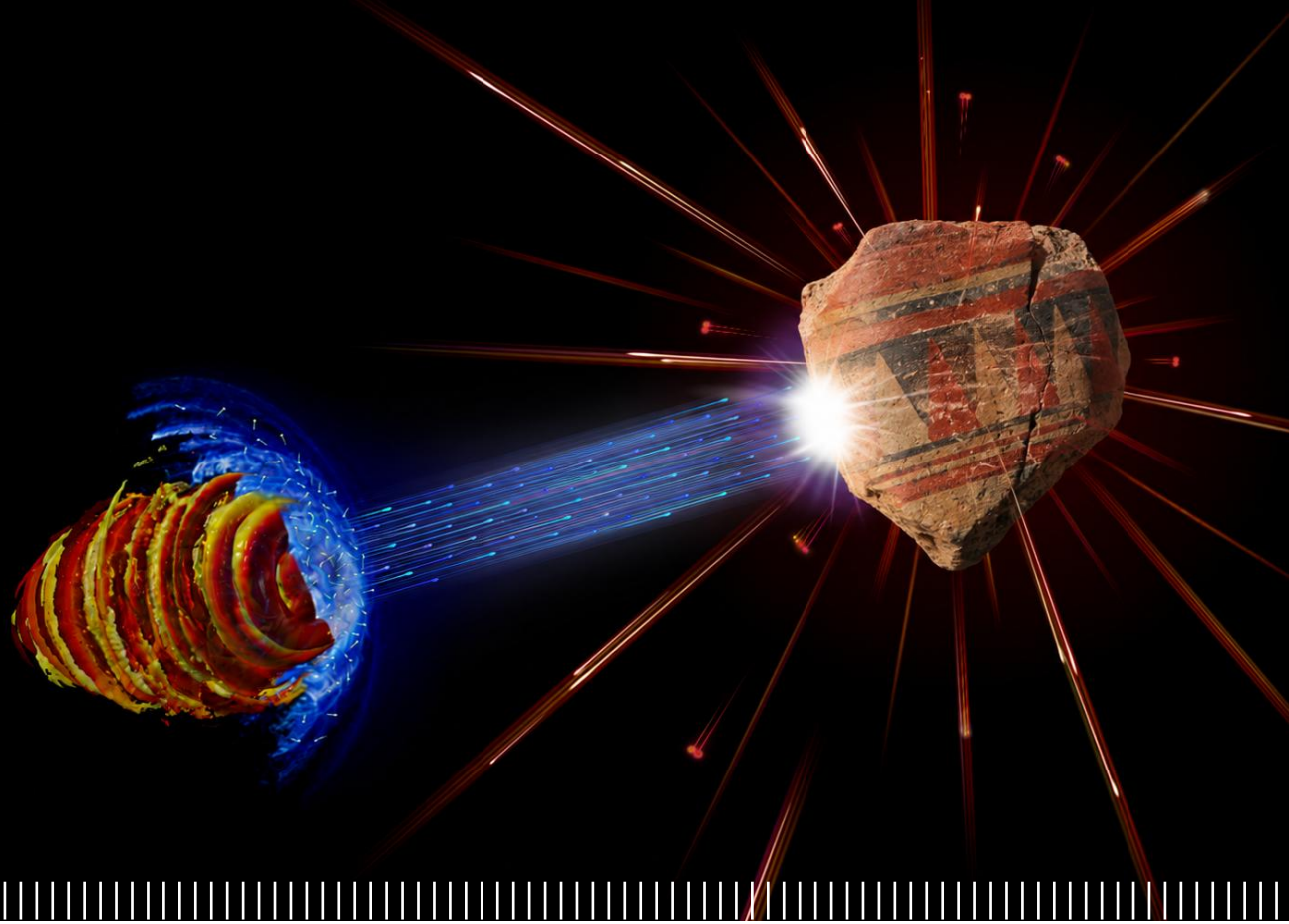
Experimental Application of Laser–Plasma Radiation Sources to Cultural Heritage Studies at ELI Beamlines

Francesco Mirani

30th June 2026



POLITECNICO MILANO 1863

EPS 26
PLASMA PHYSICS EDINBURGH

NanoLab
DIPARTIMENTO DI ENERGIA

- Activities performed within the framework of a collaboration between:

- Our group from POLITECNICO MILANO 1863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- The research was carried out at the ELIMAIA beamline of the Extreme Light Infrastructure ERIC, eli Beamlines facility
  - Access to the facility through the 5th User call
  - Internal team: Vasiliki Kantarelou, Francesco Schillaci, Lorenzo Giuffrida and Daniele Margarone

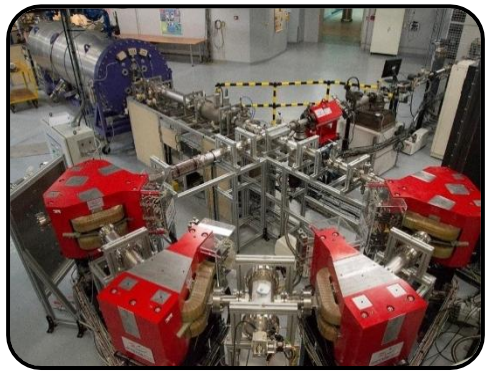
- The Consiglio Nazionale delle Ricerche | ISPC Istituto di Scienze del Patrimonio Culturale
  - Team leaders: Claudia Conti and Francesco Paolo Romano

- The RAYLAB DETECTING INNOVATION company with


D. Rastelli

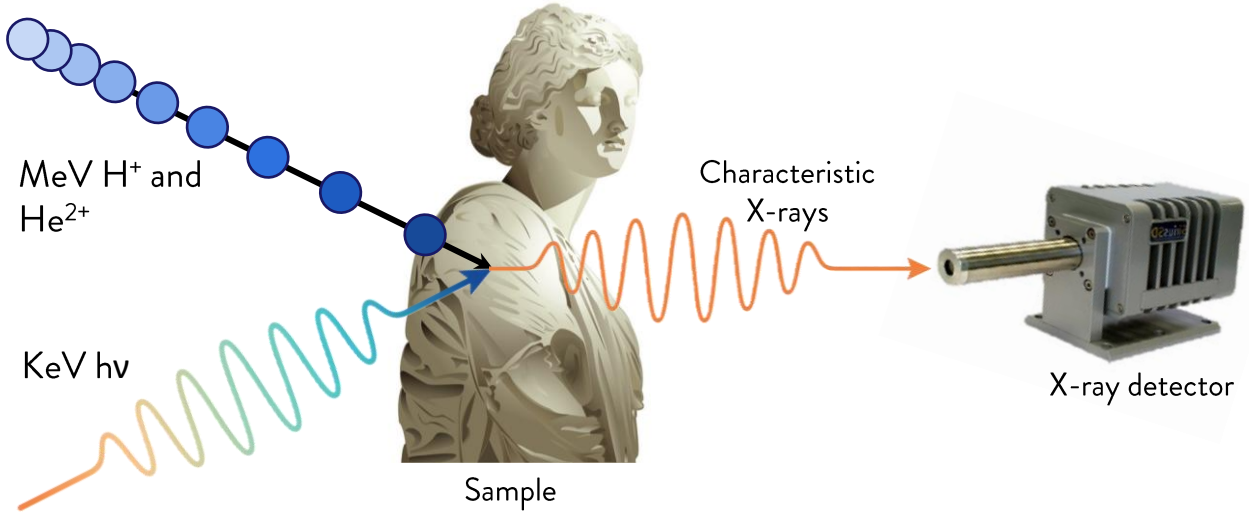
What are the materials analysis techniques used in cultural heritage studies?

- Ion **accelerators**

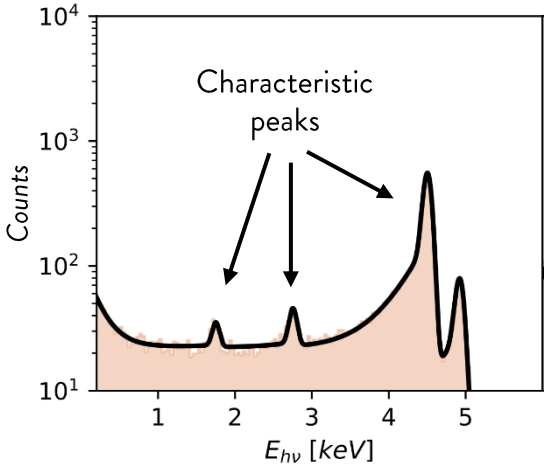


Particle Induced X-ray Emission (PIXE)

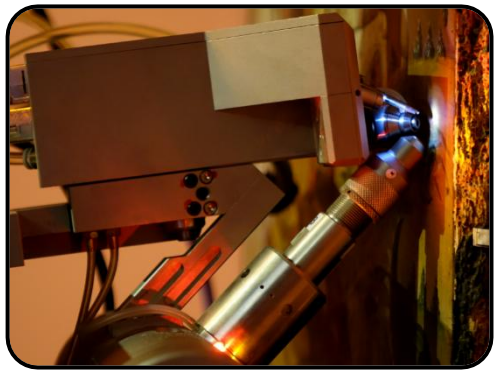
- Monoenergetic particles
- Higher detection limit



Quantification of elements from X-ray spectrum analysis



- Portable **X-ray tubes**



X-Ray Fluorescence spectroscopy (XRF)

- Broad energy spectrum
- Portable configurations

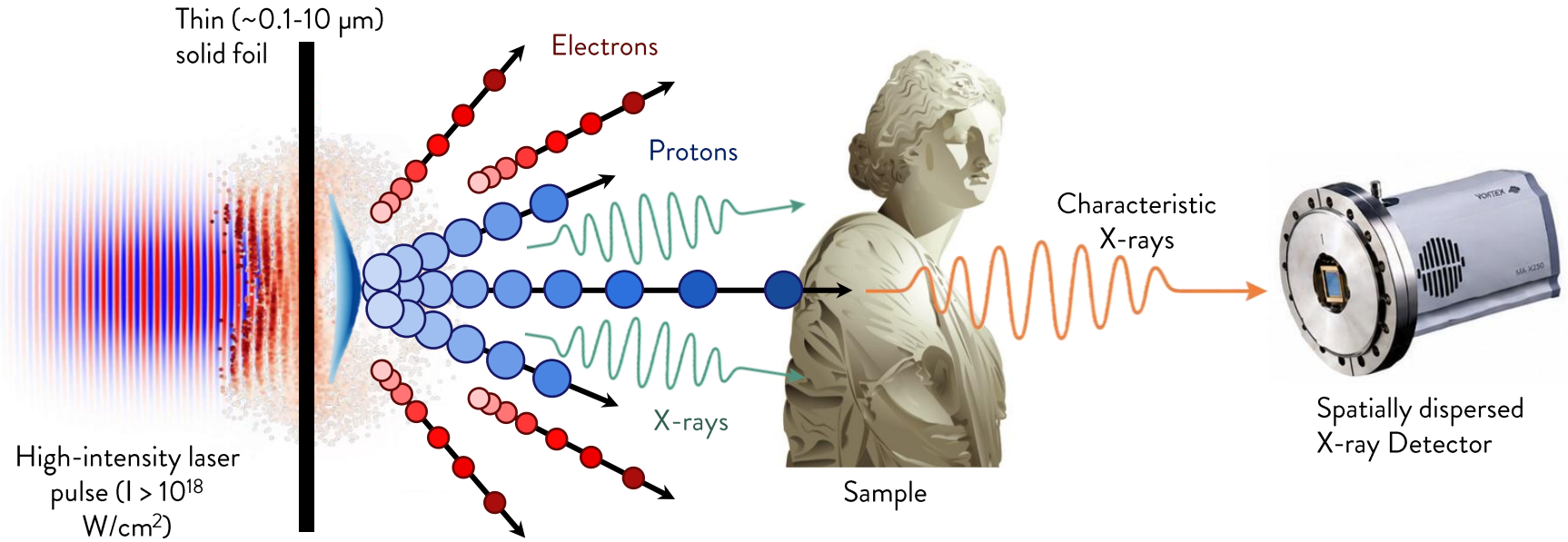
- Electron accelerators and **neutron sources** for **activation** analysis and **radiography**
- **Different conventional sources** for specific techniques
- **Laser-plasma** accelerators are potentially **compact** and **multi-purpose.**

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

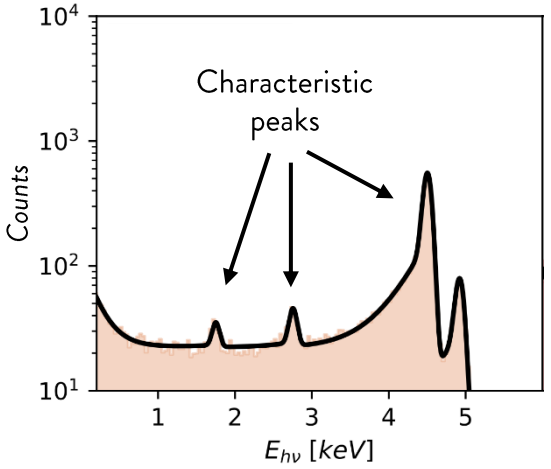
P. A. Mandò, et al. *Nucl. Instrum. Methods Phys. Res. B: Beam Interact. Mater. At.* 239.1-2 (2005): 71-76.

Laser-plasma radiation sources for cultural heritage studies

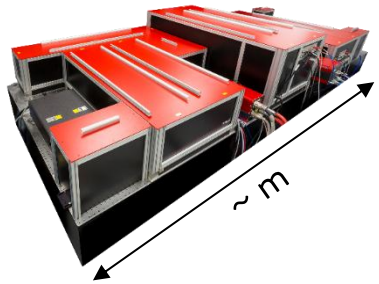
- **Super-intense** ultra-short **laser pulse** + Micrometric thick **foil** → **Target Normal Sheath Acceleration** (TNSA)

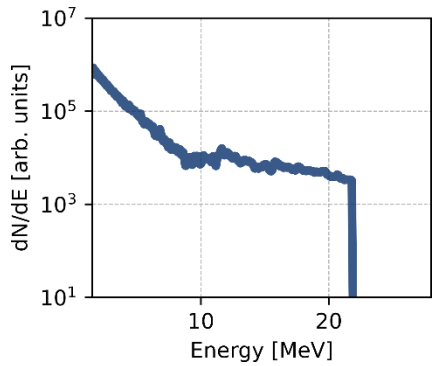


Quantification of elements from X-ray spectrum analysis



with combined **laser-driven PIXE and XRF**





- H^+ and e- emitted in short **bunches**
- H^+ energy ~ **1 - 10s MeV**
- Broad H^+ energy **spectra**
- **X-rays** emitted **from plasma**

M. Barberio, et al. *Scientific reports* 9.1, (2019): 1-9.

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

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

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

M. Salvadori, et al. *Physical Review Applied* 21.6, (2024): 064020.

Goals and setup of the experimental campaign at ELIMAIA

Investigate **quantitative** PIXE-XRF **in-air** on **cultural heritage** materials **with a laser-plasma source**...What objectives need to be achieved?

Laser-plasma radiation source of **non-monoenergetic electrons, ions** and **photons**

Remove laser-plasma **e-** and **heavy ions**

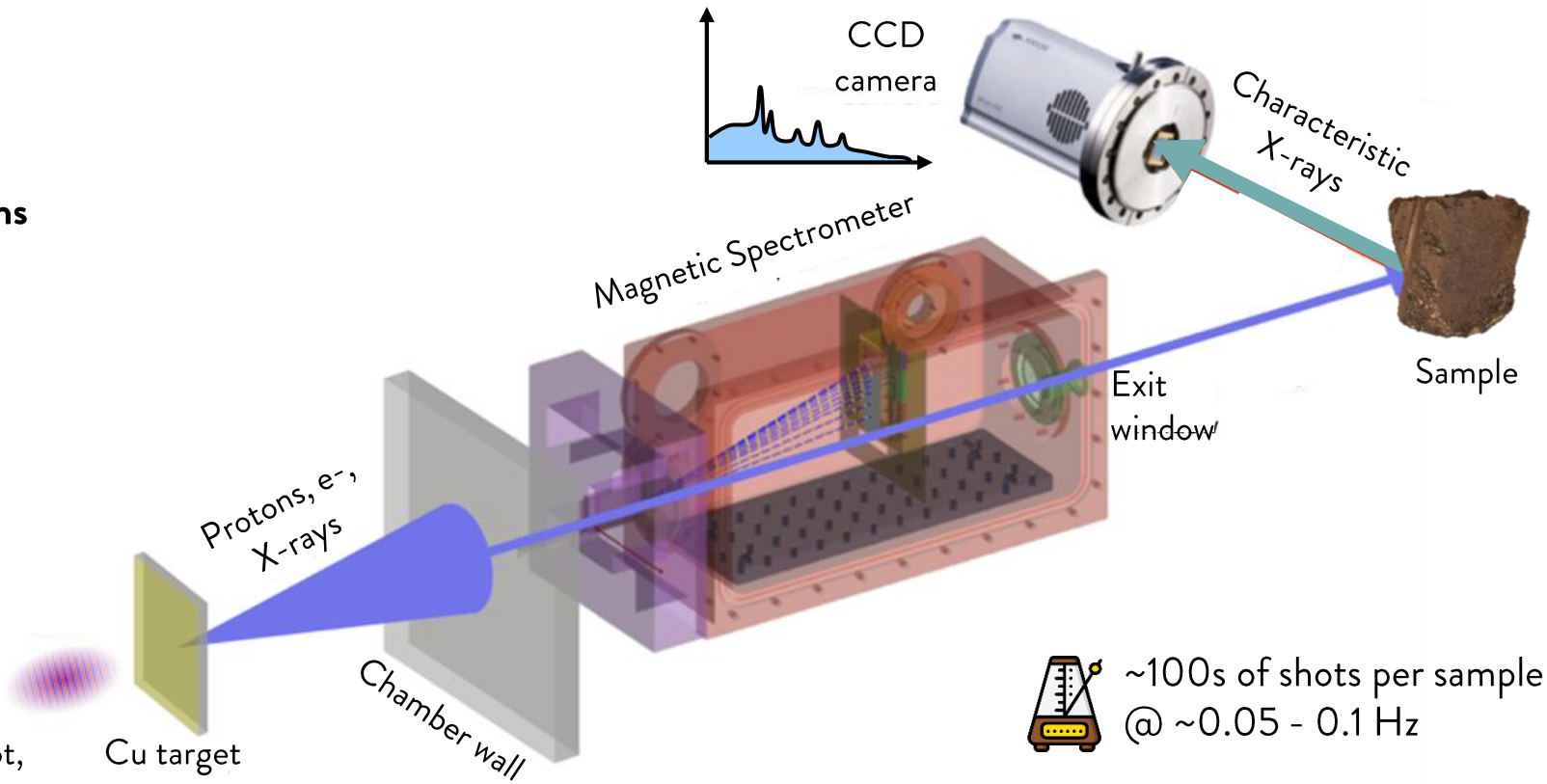
Characterized laser-plasma H^+ and **photons**

Irradiate archeological **samples in-air**

Measure bunches of characteristic **X-rays** through spatial dispersion

Develop a tool for **spectra analysis**

- Access to eli MAIA beamline through 5th User call



eli ELIMAIA

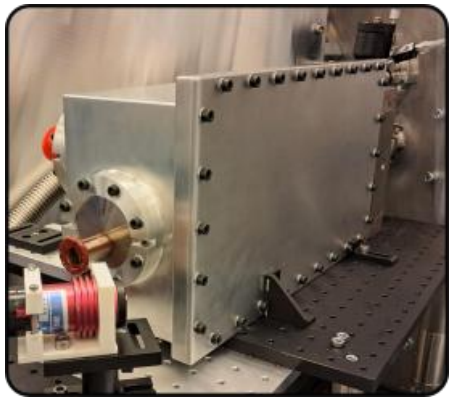
L3-HAPLS laser
(10J, 27 fs, ~1.8 μm spot,
~10^{21} W/cm^2)

~100s of shots per sample
@ ~0.05 - 0.1 Hz

K. Ambrogioni, et al. *Under review @ Science Advances* (2026).

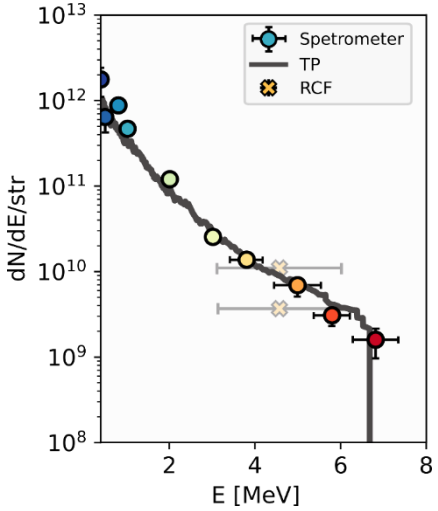
Exploit an application-oriented proton spectrometer developed with RAYLAB DETECTING INNOVATION

Materials analysis requires **precise knowledge** of the source. → Magnetic system for **proton beam** characterization and irradiation.



- Elettropermanent magnet **to tune the B-field** (0 - 0.4 T).

Remove e- and heavy ions



- **Agreement with** the shape of proton spectrum from **Thomson Parabola.**

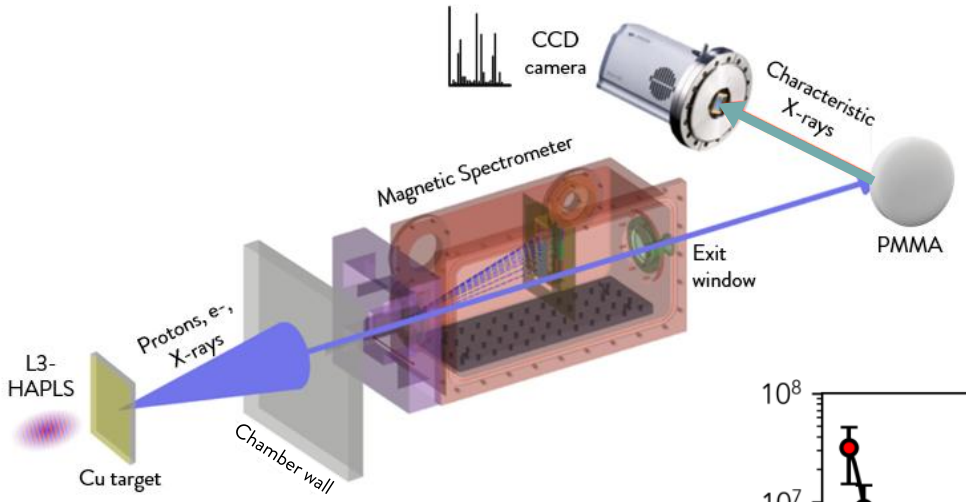
Sample

F. Mirani, et al. *Physical Review Applied* 24.1 (2025): 014017.

F. Gatti, et al. *IEEE Transactions on Instrumentation and Measurement* (2024).

K. Ambrogioni, et al. *Under review @ Science Advances* (2026).

Characterization of protons and X-rays emitted by the laser-plasma source



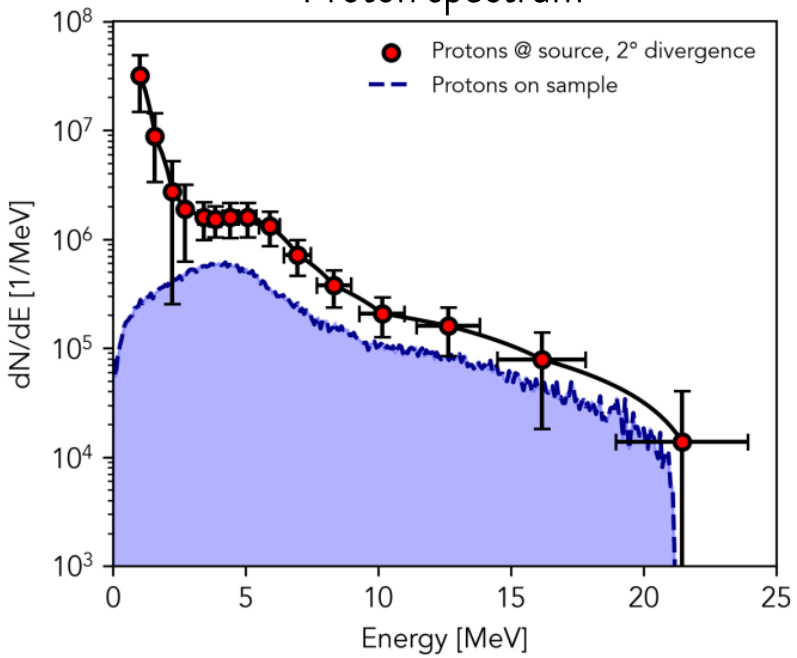
Irradiation of a **PMMA sample** and detection of **backscattered photons.**

GEANT4 simulation to estimate **1.3×10⁵** Cu-**X-rays** per laser shot on sample.

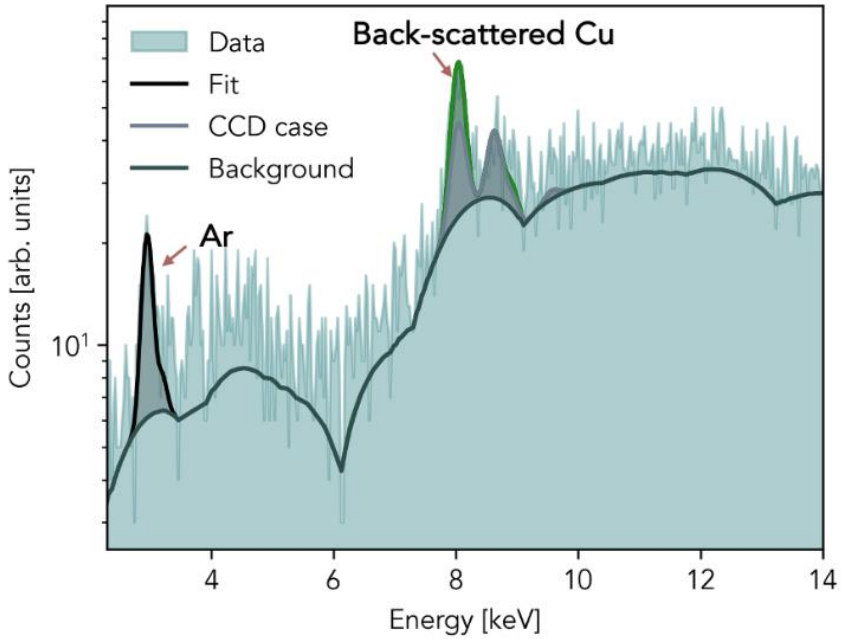
Proton spectrum measured @ source with spectrometer.

GEANT4 simulation to estimate **4×10⁵ protons** per shot on sample.

Proton spectrum

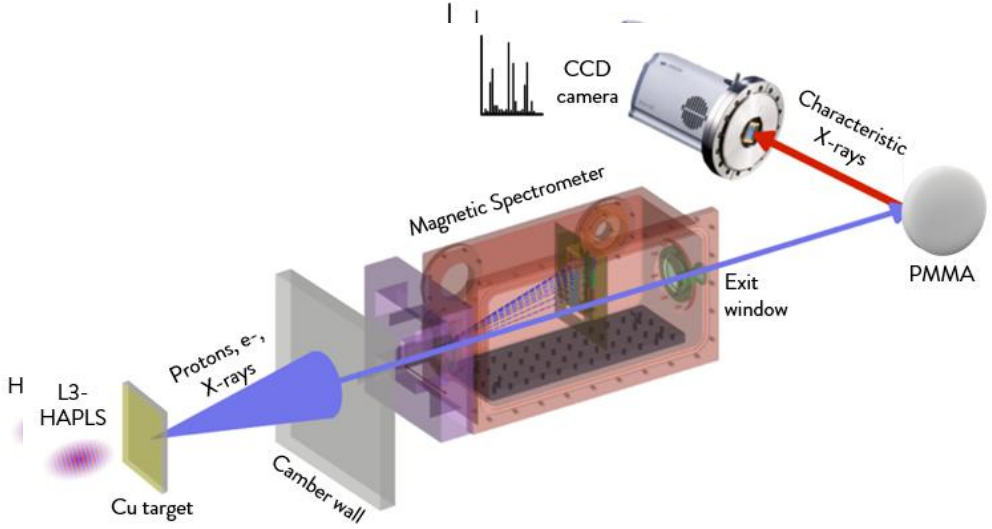


Backscattered X-ray spectrum



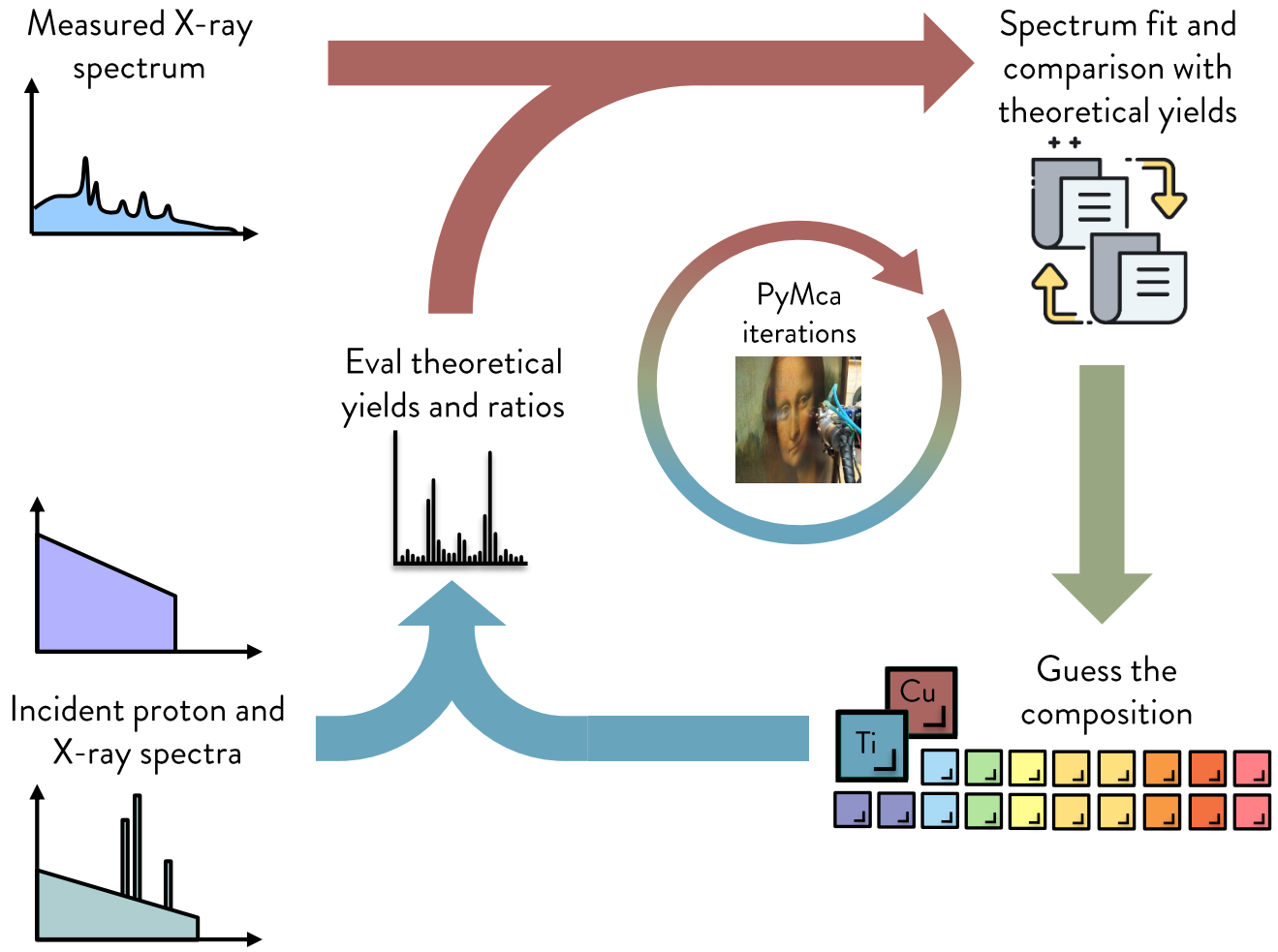
K. Ambrogioni, et al. *Under review @ Science Advances* (2026).

Quantitative laser-driven PIXE-XRF analysis: procedure to get elemental concentrations



Include PIXE theoretical description **in the XRF PyMca** workflow

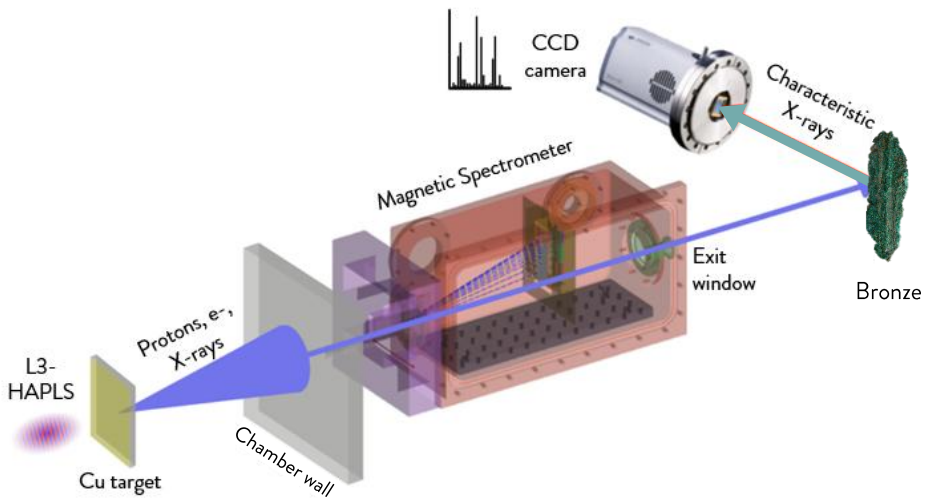
- High accuracy in considering atomic physics and matrix effects.
- Standard in conventional quantitative XRF.



V.A. Solé, et al. *Spectrochimica Acta Part B: Atomic Spectroscopy* 62.1 (2007): 63-68.

K. Ambrogioni, et al. *Under review @ Science Advances* (2026).

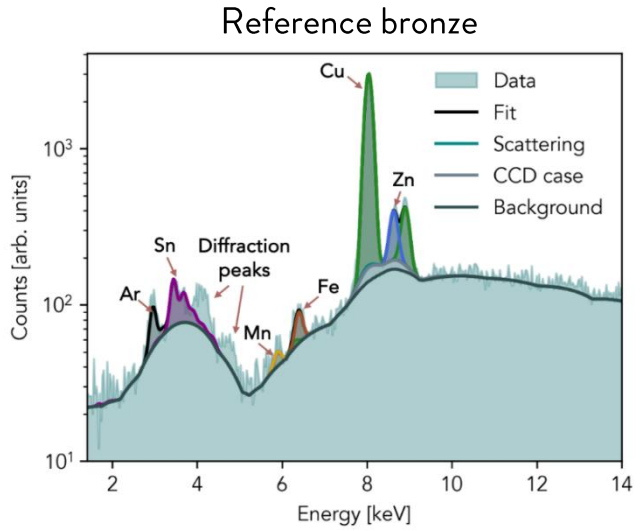
Quantitative laser-driven PIXE-XRF analysis of reference and medieval bronze

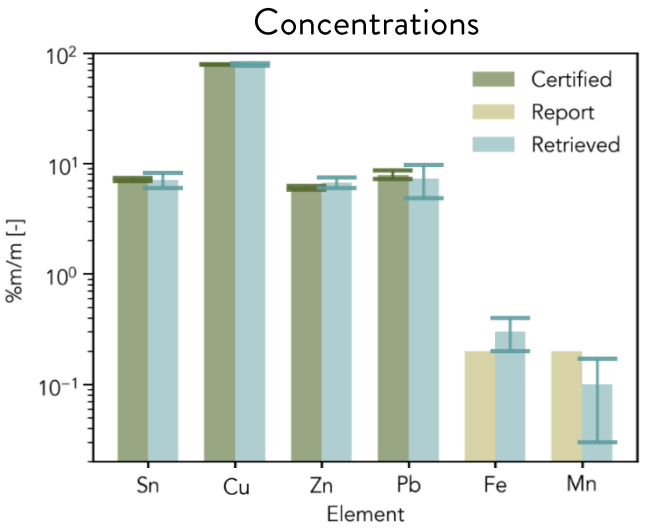


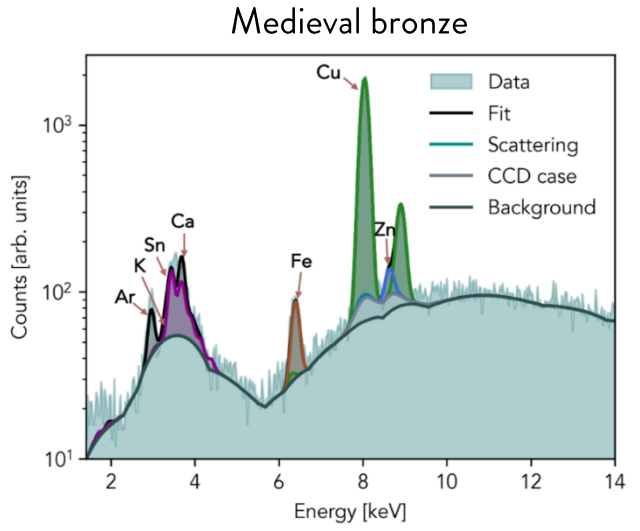
Collect X-ray spectra with CCD from sample irradiation with 100s shots.

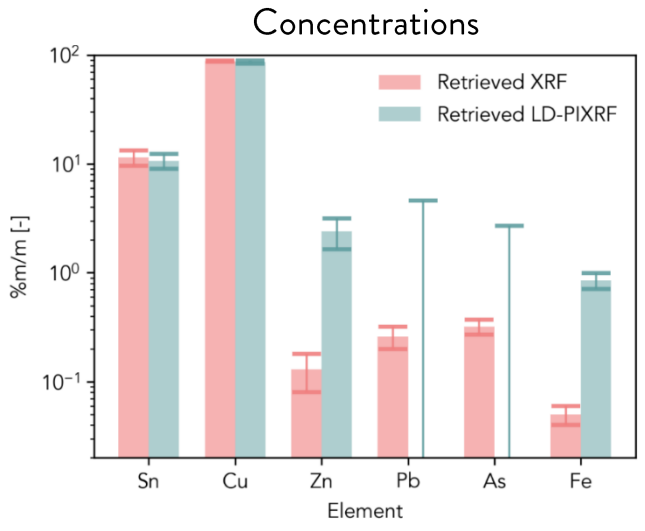
Include PIXE theoretical description **in the XRF PyMca** workflow

- Test with **reference** material
- Analysis of a **medieval** bronze



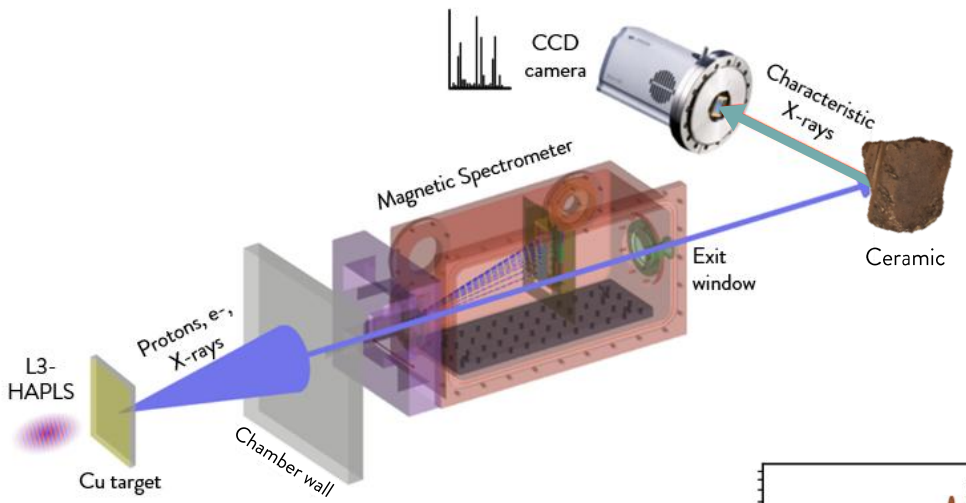






K. Ambrogioni, et al. *Under review @ Science Advances* (2026).

Qualitative analysis of Celtic ceramic with laser-driven PIXE-XRF and conventional XRF

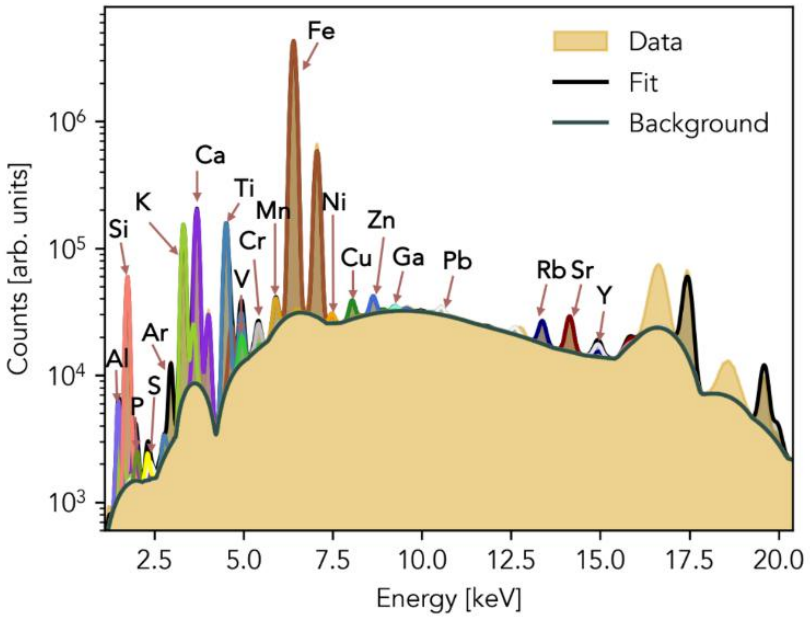


Investigate the **current limits** of the technique through **comparison** with **conventional XRF** on a challenging case study

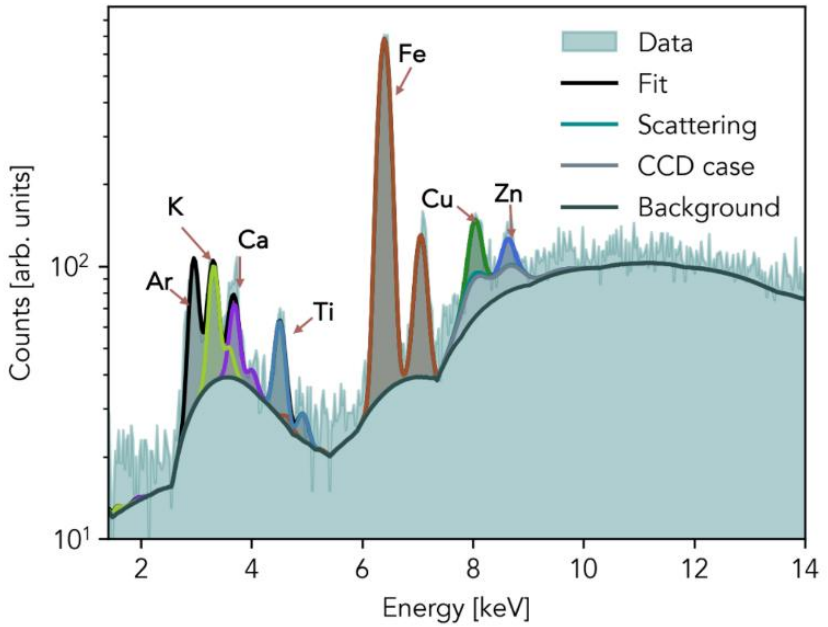
- Main elements (down to ~0.1%) identified with laser-driven PIXE-XRF
- Trace low-Z and high-Z elements not recognized…**improvements** are **needed**

- In collaboration with **XRAYLab** at Consiglio Nazionale delle Ricerche | SPC Istituto di Scienze del Patrimonio Culturale in Catania (Francesco Paolo Romano)

Conventional XRF

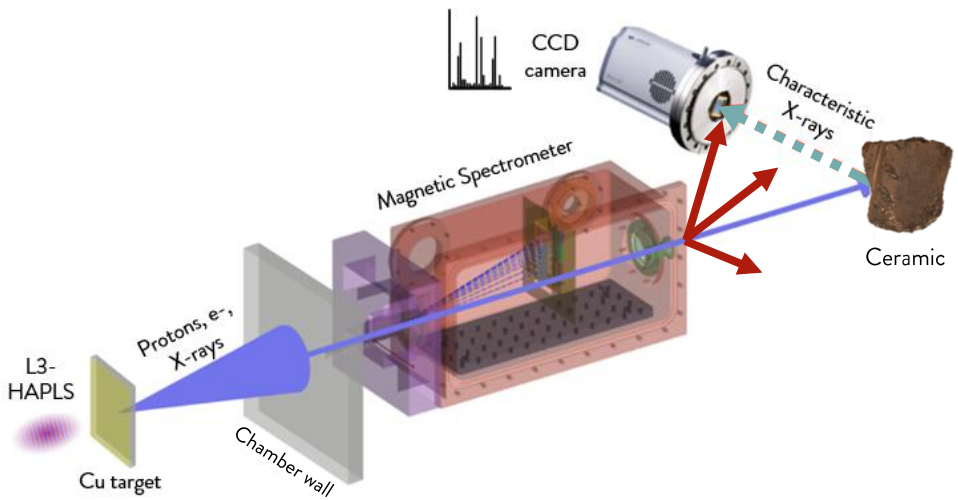


Laser-driven PIXE-XRF



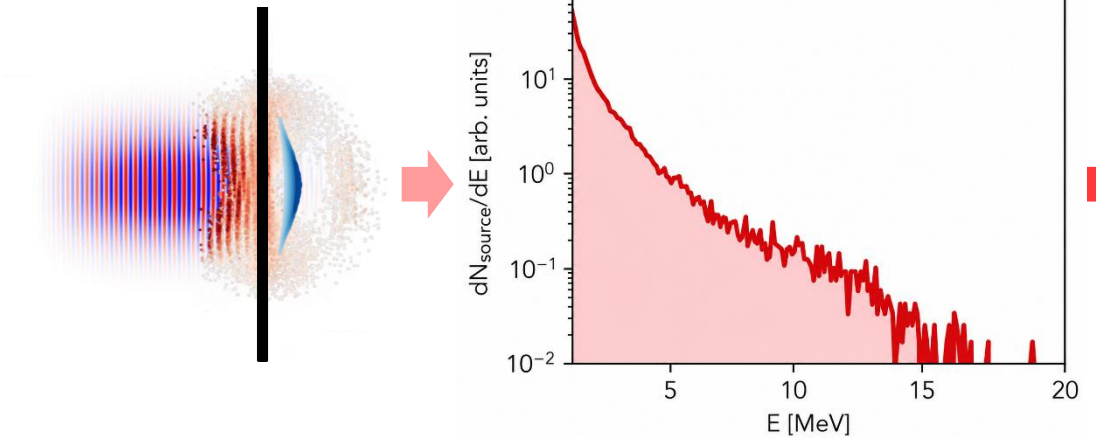
K. Ambrogioni, et al. *Under review @ Science Advances* (2026).

What's next?...Optimization of laser-driven PIXE-XRF setup for cultural heritage analysis

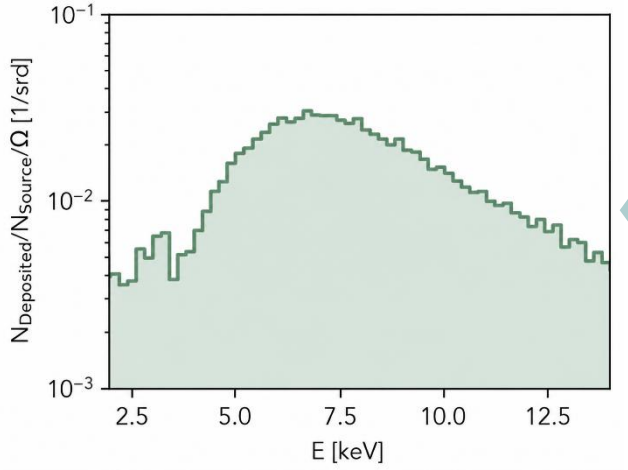


- **Mitigate** low-energy X-ray **attenuation in air** → He flux between sample and CCD camera
- Test alternative CCD cameras with **higher detection efficiency** in the energy region of interest
- A fraction of **high energy electrons** from the laser-plasma source deposit energy **in the CCD** → Shielding improvement

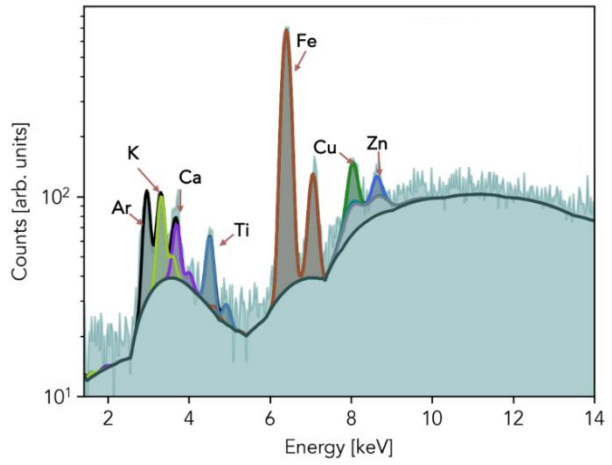
e- spectrum from Smilei PIC



Background in CCD with GEANT4 MC



Comparison with measurement



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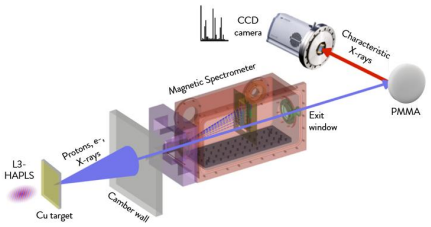
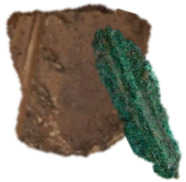
Conclusions...



Development of **compact irradiation** and source **characterisation setup**

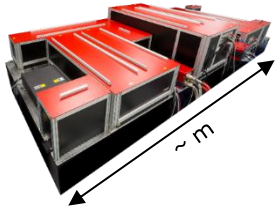
Development of a **robust tool for** reference-free **quantification** based on PyMca



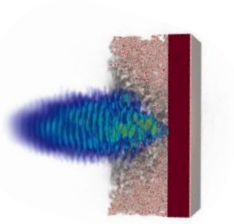
First laser-driven PIXE & XRF on cultural-heritage relevant materials

Assessment of key **steps** for experimental **setup optimization**

...and future developments

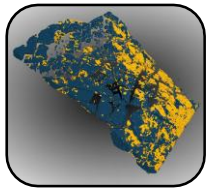


Use of **table-top** 10s of-TW-class lasers working at **high repetition rate** (~1 Hz)



Engineered targets to increase laser-plasma acceleration performance

Reduction of background source through optimisation of the setup



Analysis on the cultural heritage samples **is ongoing** with RBS, Raman, X-ray CT, ...

Thank you for the attention!

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