

Laser-driven radiation sources for cultural heritage: laser-driven PIXE and XRF on historical and archaeological artifacts

K. Ambrogioni, F. Mirani, F. Gatti, A. Maffini, D. Mazzucconi, A. Pola, C. Conti, E. M. Grassi, E. L. Ravan, F. P. Romano, V. Kantarelou, F. Schillaci, L. Giuffrida, D. Margarone, M. Passoni



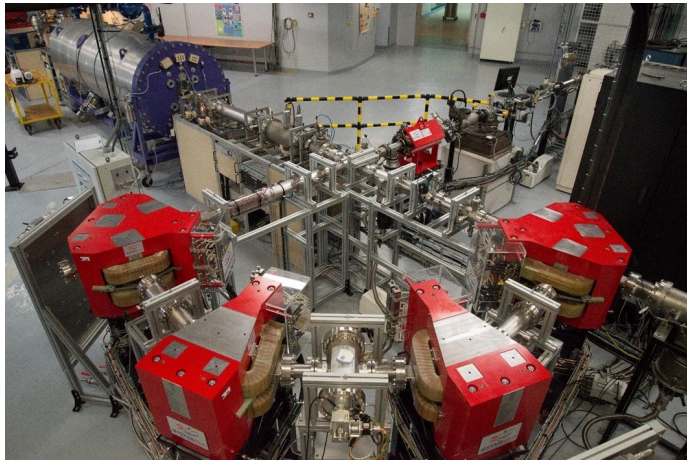
**51st EPS Conference
on Plasma Physics**
Vilnius, 7 – 11 July 2025

Beam Plasmas & Inertial Fusion



Non-destructive material analysis in cultural heritage

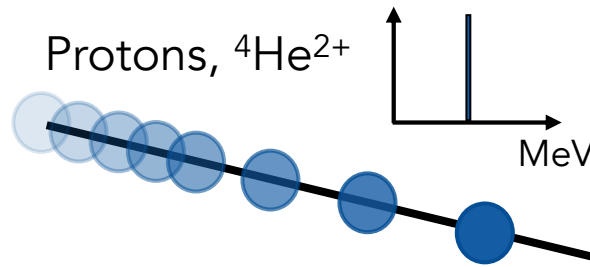
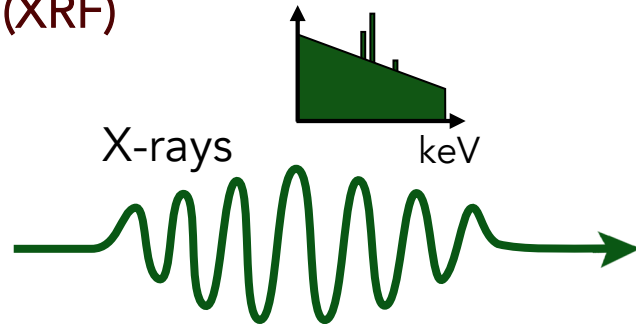
Particle-induced X-ray emission (PIXE)



Electrostatic accelerators

X-ray fluorescence (XRF)

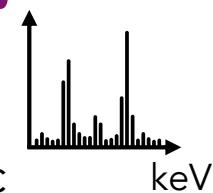
X-ray tubes



X-ray Detector



Characteristic X-rays



- Low background for PIXE
- Portable configurations for XRF
- Quantification of the concentrations



Laser-driven ion sources for material analysis

Thin ($\sim 0.1\text{-}10\ \mu\text{m}$)
solid foil

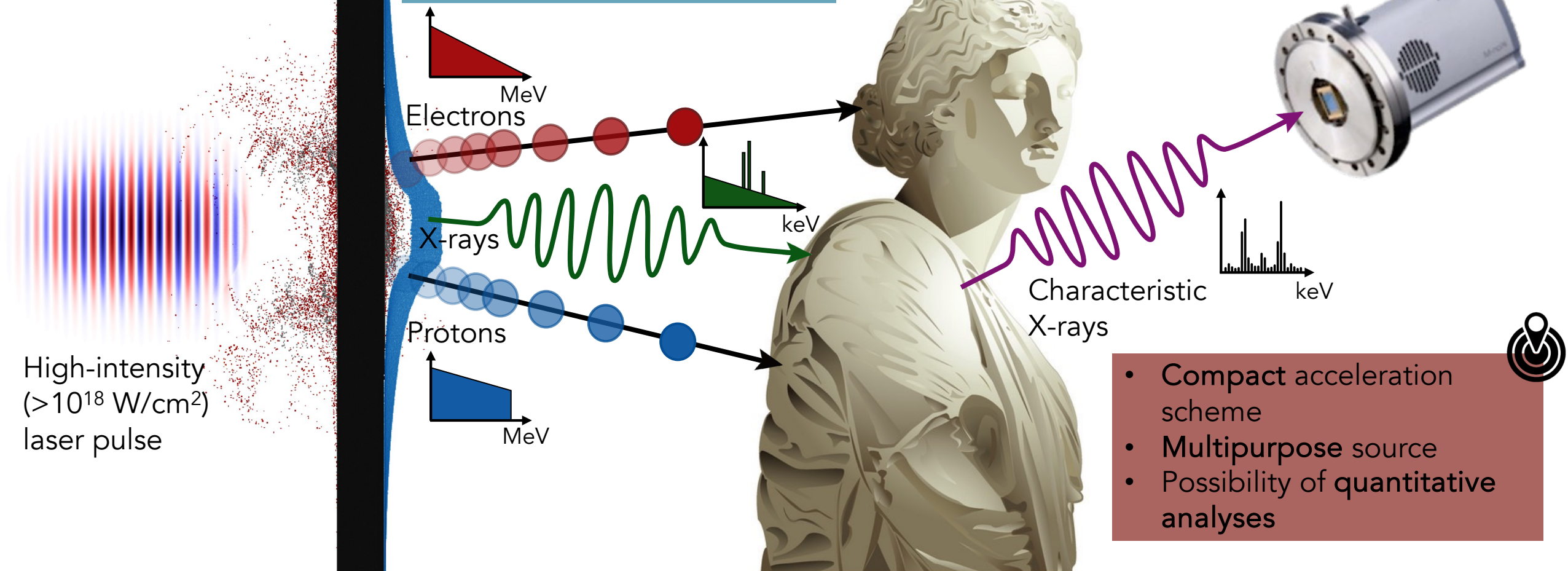
Few proofs of principle: ✓

M. Passoni et al., *Scientific Reports*, 9:9202 (2019)

P. Puyuelo-Valdes et al., *Scientific Reports*, 11:9998 (2021)

F. Mirani et al., *Science Advances*, 7:3 (2021)

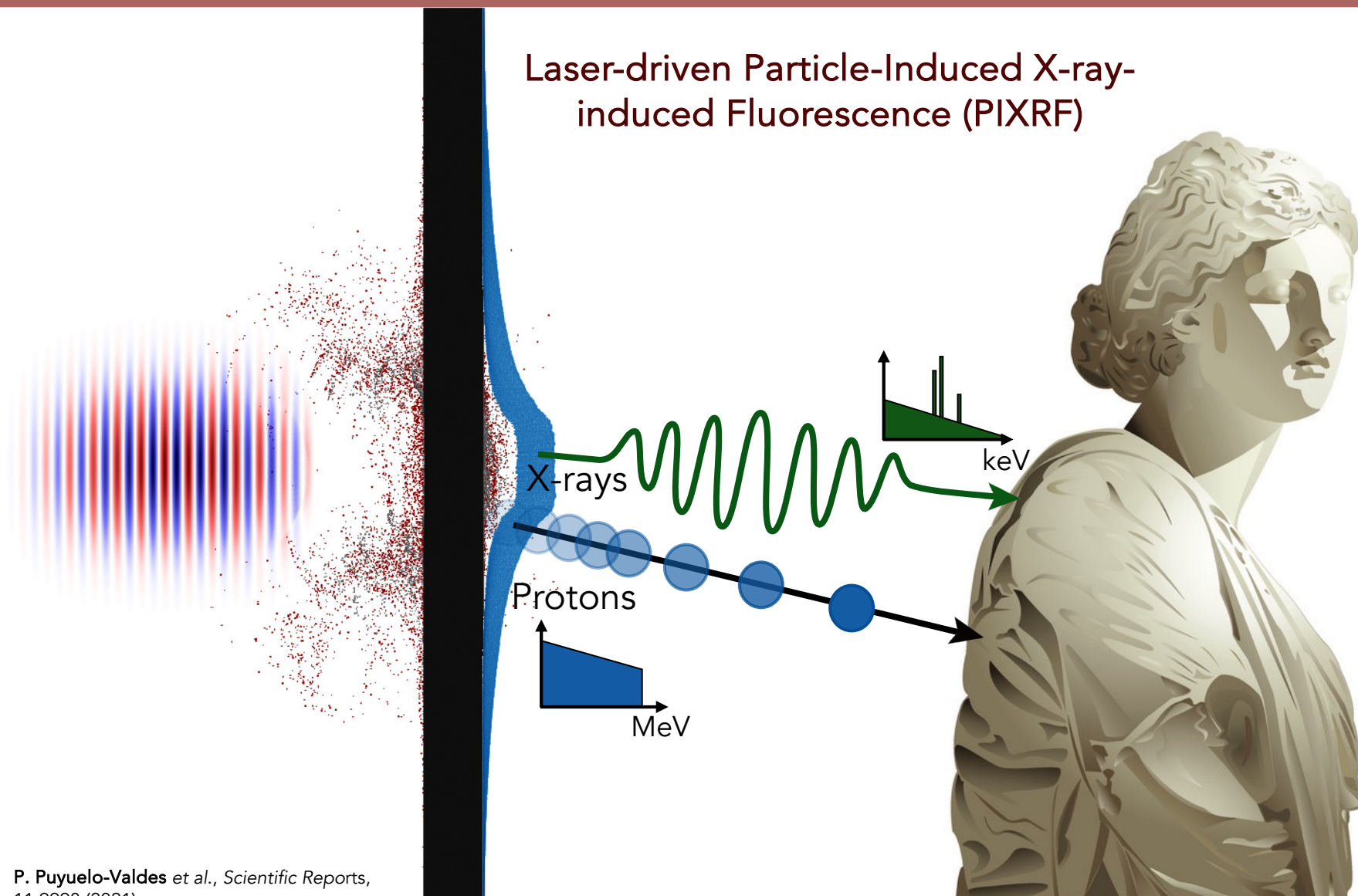
M. Salvadori et al., *Physical Review Applied*, 21: 064020 (2024)



Why laser-driven ion sources for cultural heritage?



Laser-driven Particle-Induced X-ray-induced Fluorescence (PIXRF)



- Potentially transportable
- PIXE, XRF or their combination (PIXRF) with one source
- Possibility of quantitative analyses

What's missing?

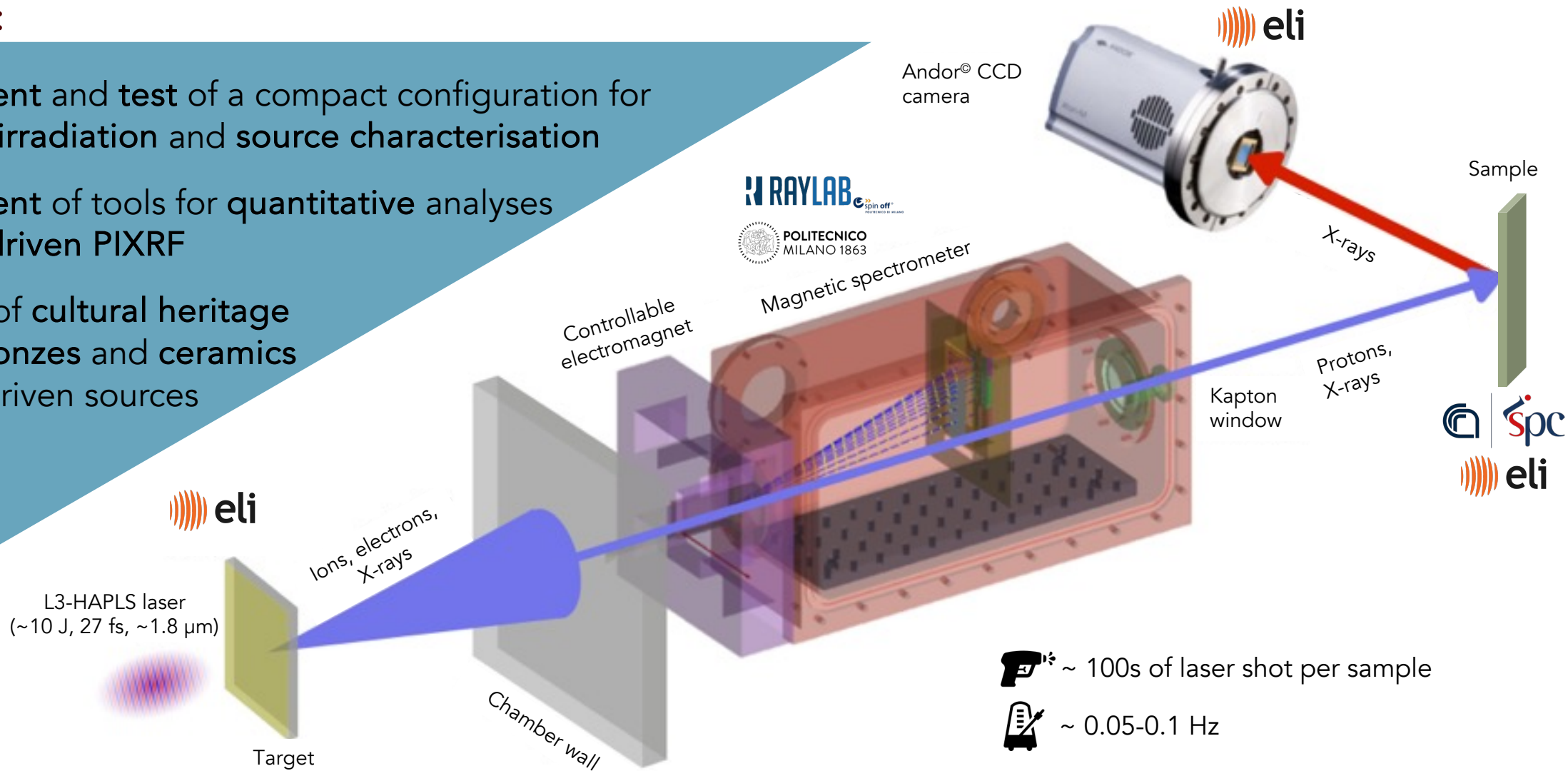
- Test the technique on cultural heritage relevant materials
- Tools for quantitative analysis of PIXRF spectra
- Compact systems for in-air irradiation
- Development of high-repetition-rate for high fluxes

Goals and setup of the experimental campaign at ELIMAIA



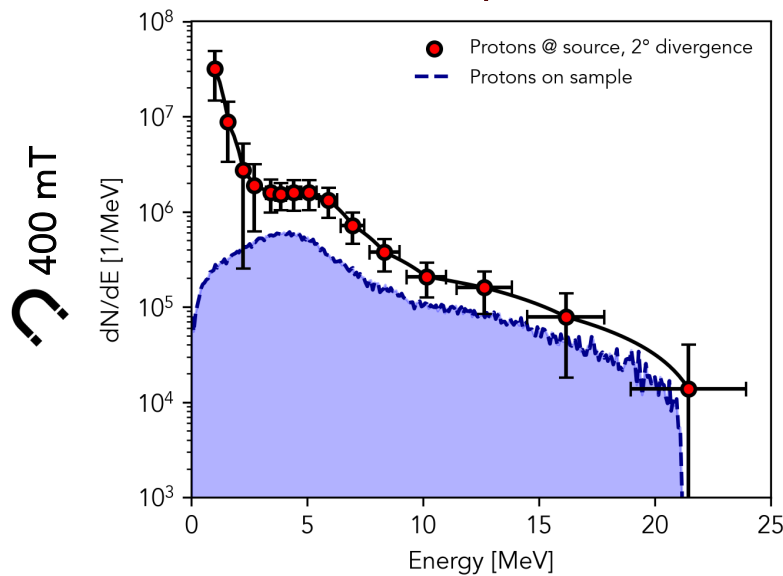
Our goals:

- Development and test of a compact configuration for both in-air irradiation and source characterisation
- Development of tools for quantitative analyses with laser-driven PIXRF
- Irradiation of cultural heritage relevant bronzes and ceramics with laser-driven sources

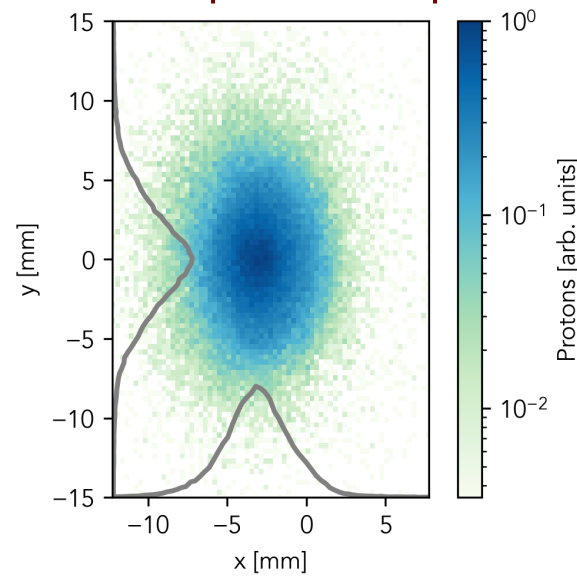


Proton and X-ray emission characterisation

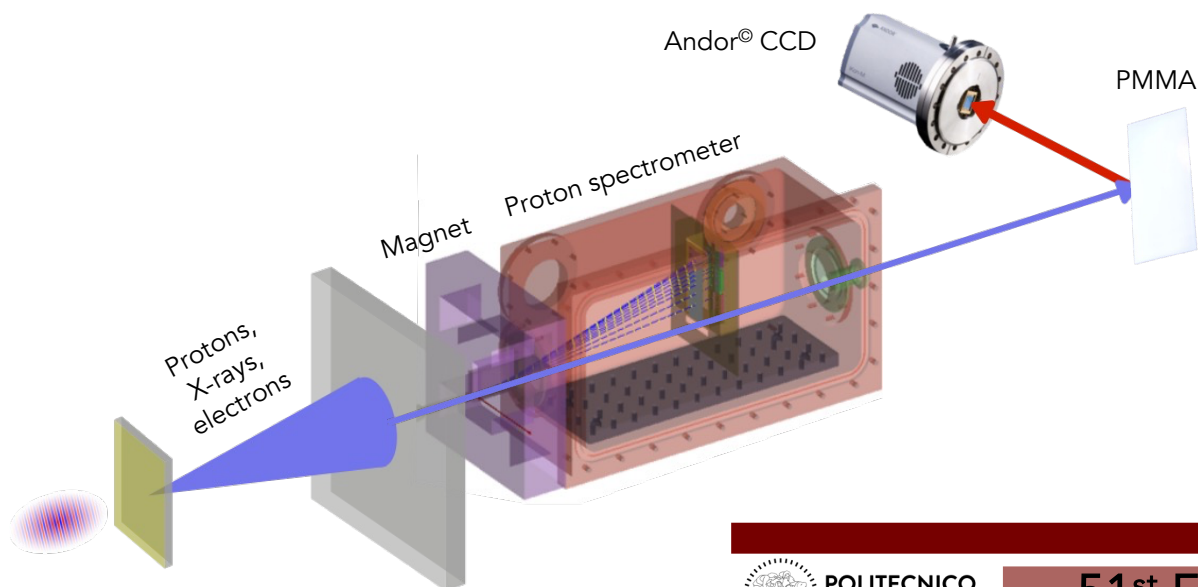
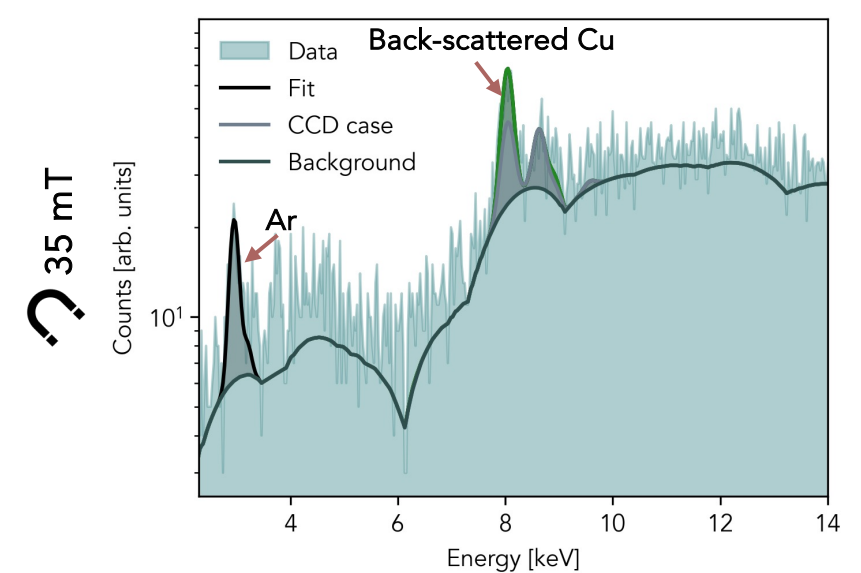
Proton spectrum





Proton spot on sample

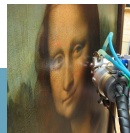


Back-scattering from PMMA



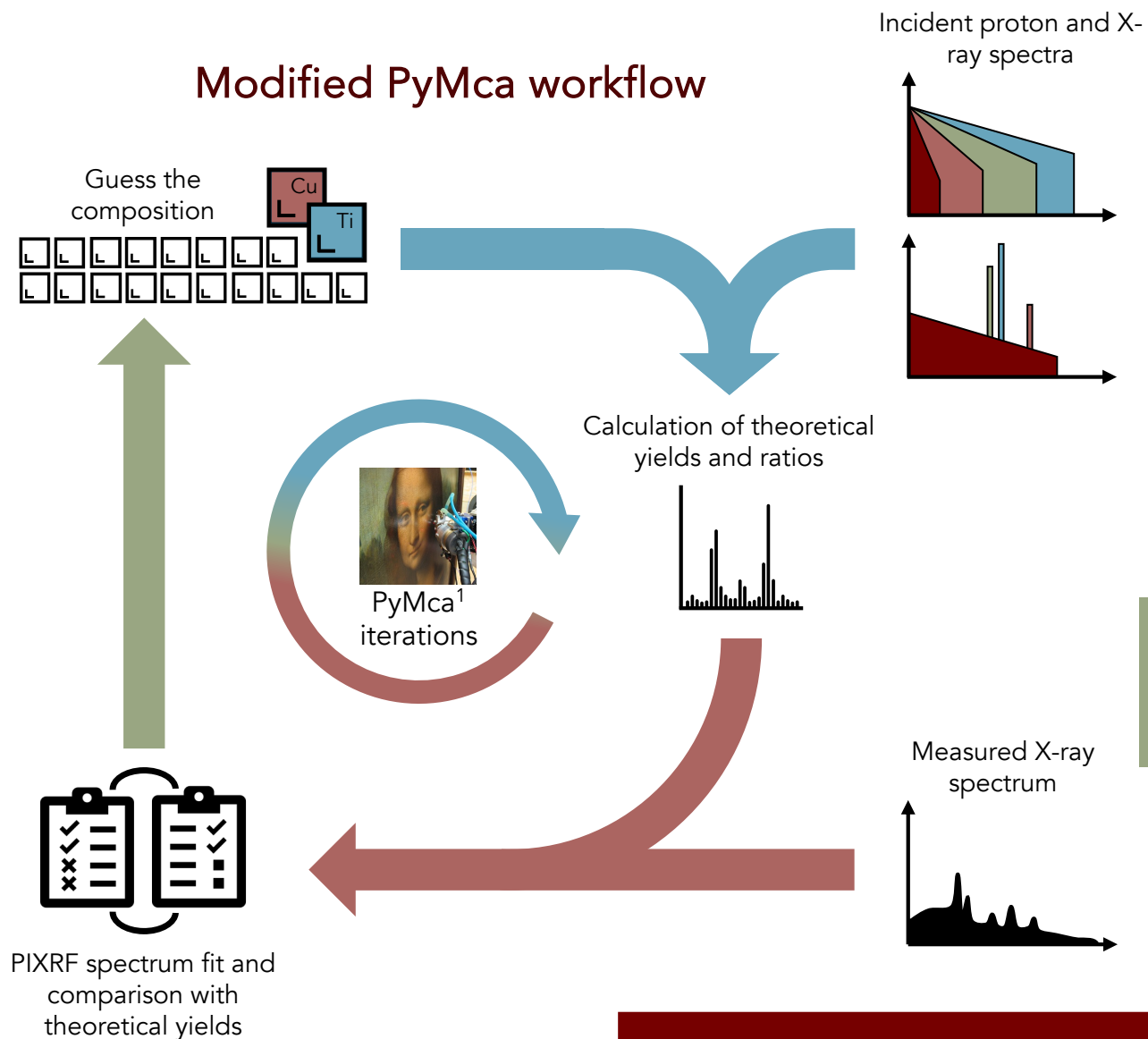
-  **GEANT4** simulation to estimate **protons** on sample
 ✓ 4.0×10^6 protons per laser shot on sample
-  **GEANT4** simulation to estimate **X-ray** back-scattering
 ✓ 1.3×10^5 Cu-X-rays per laser shot on sample

PyMca-based software for elemental concentrations

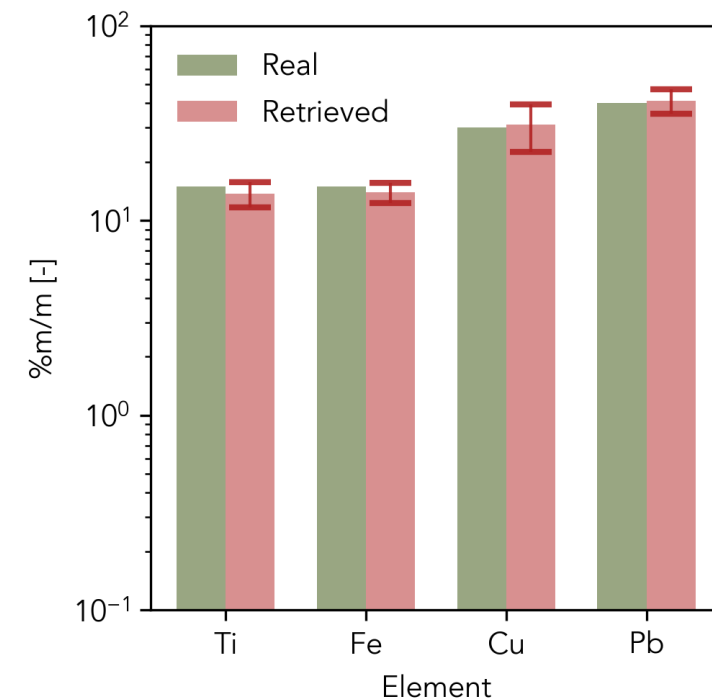


Why PyMca?

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

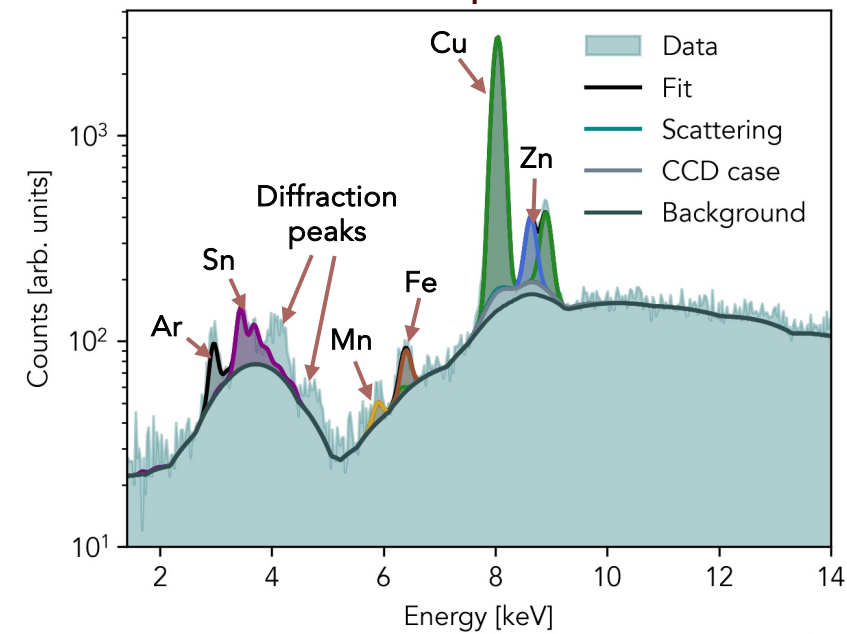


Tested with spectra from **GEANT4** simulations

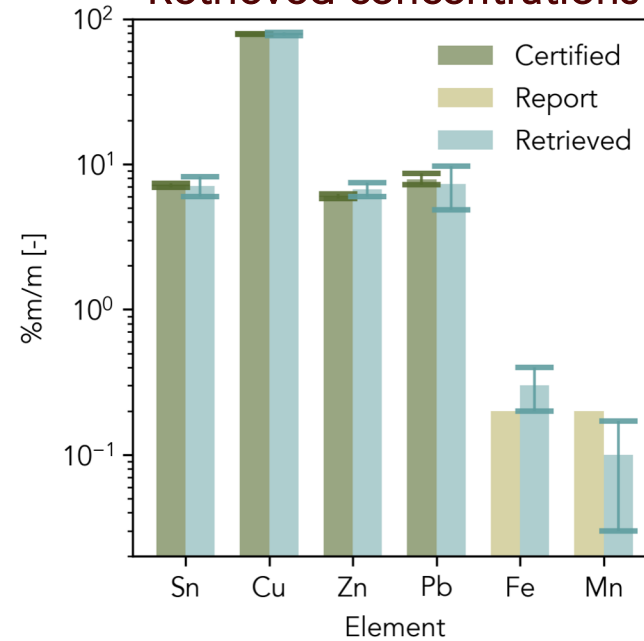


PIXRF on a reference quaternary bronze

PIXRF spectrum



Retrieved concentrations



Test of custom PyMca on experimental data



Calculation of geometrical correction factors

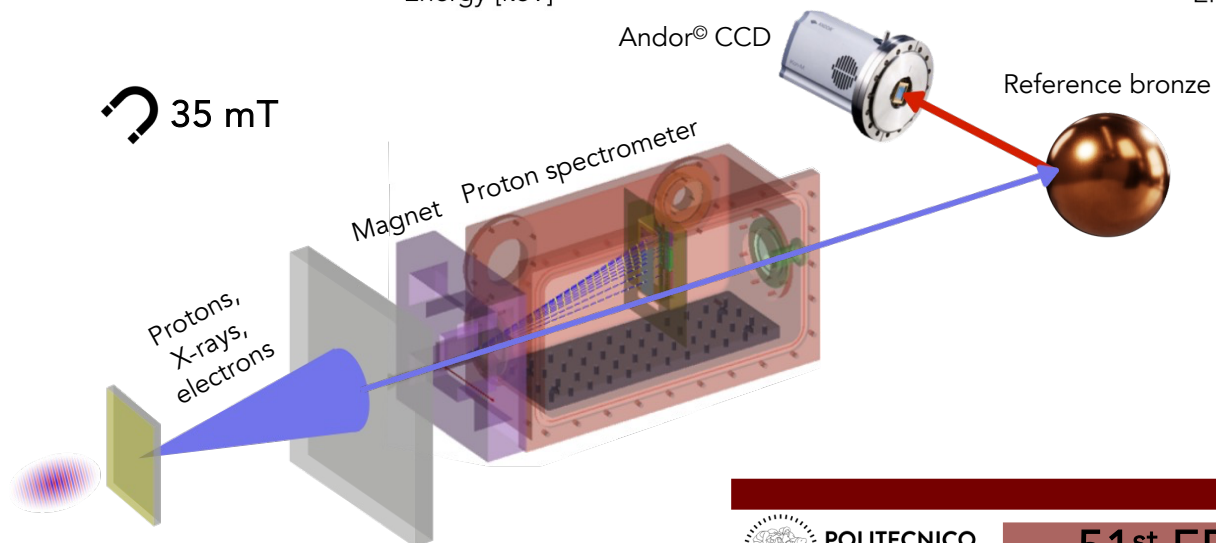


Estimation of detection limits

35 mT

Andor® CCD

Reference bronze



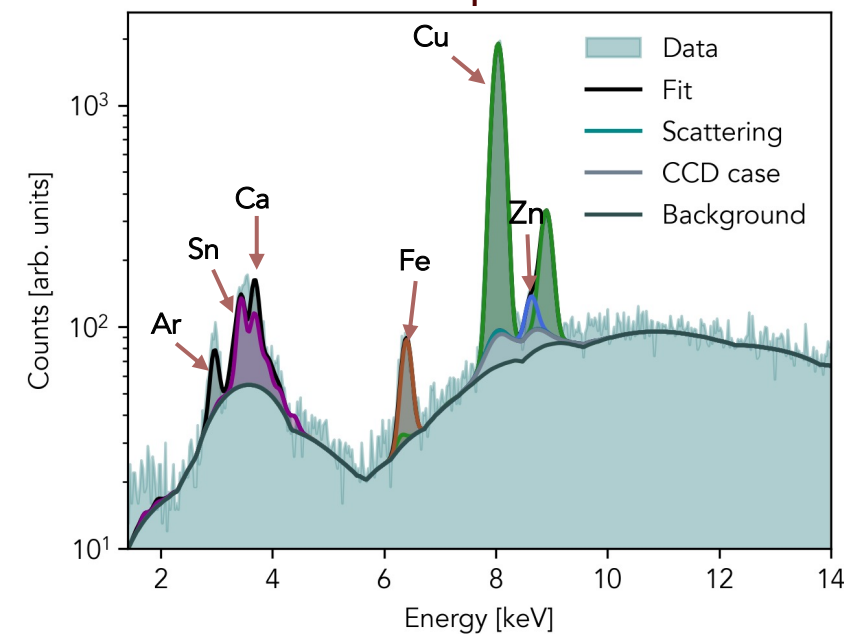
Detection of low concentration elements



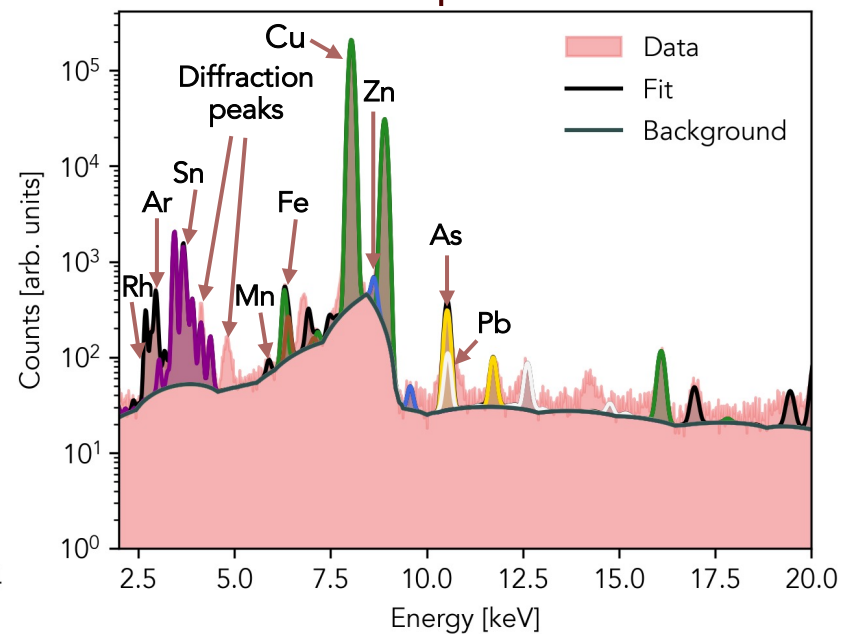
Increase of background below 7 keV

PIXRF on a medieval bronze fragment

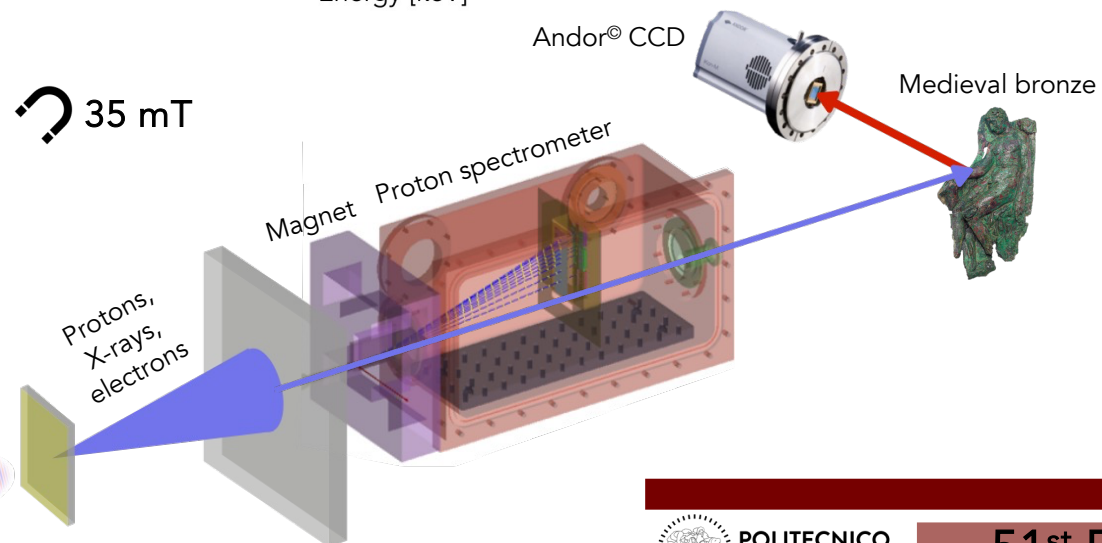
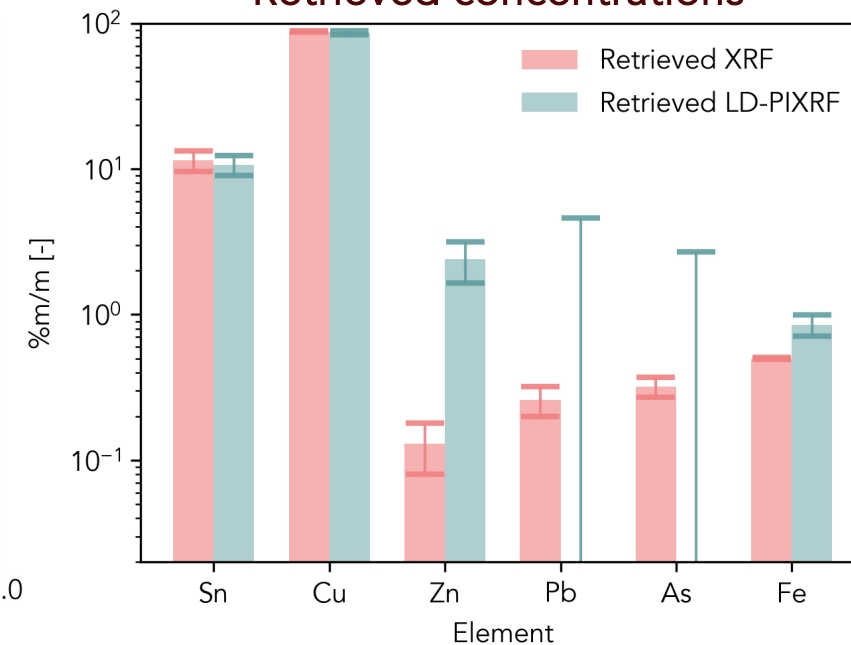
PIXRF spectrum



XRF spectrum



Retrieved concentrations



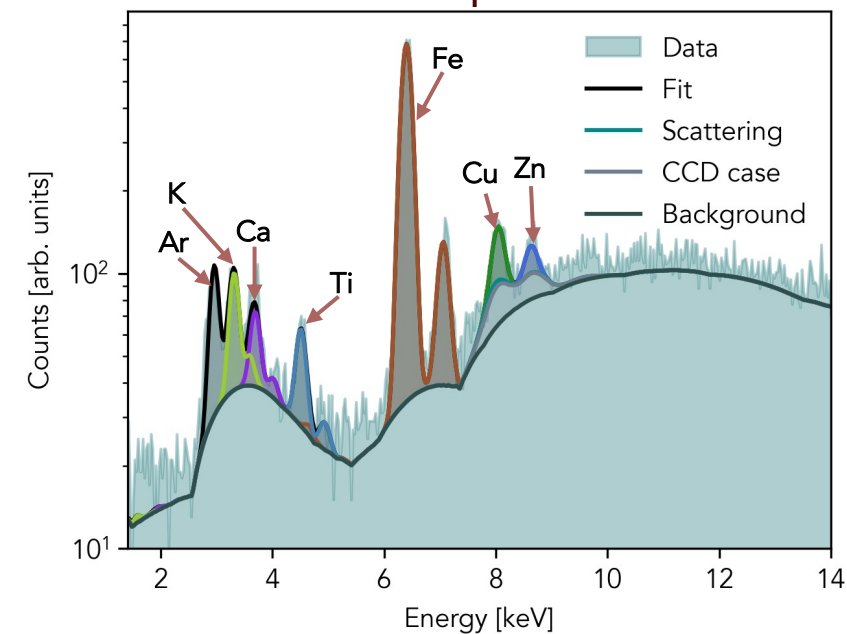
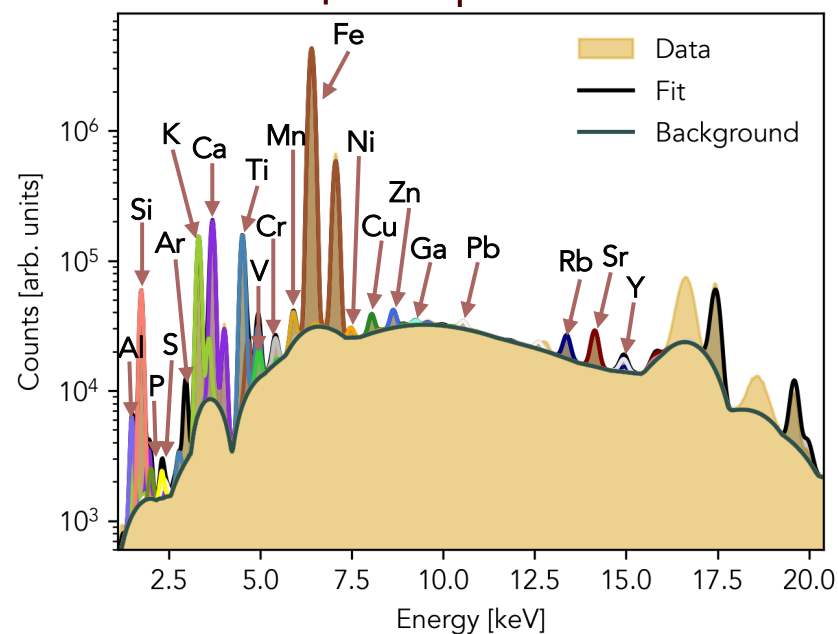
Test of PIXRF
quantification
with unknown
cultural heritage
bronzes



Comparable results
with conventional
quantitative XRF

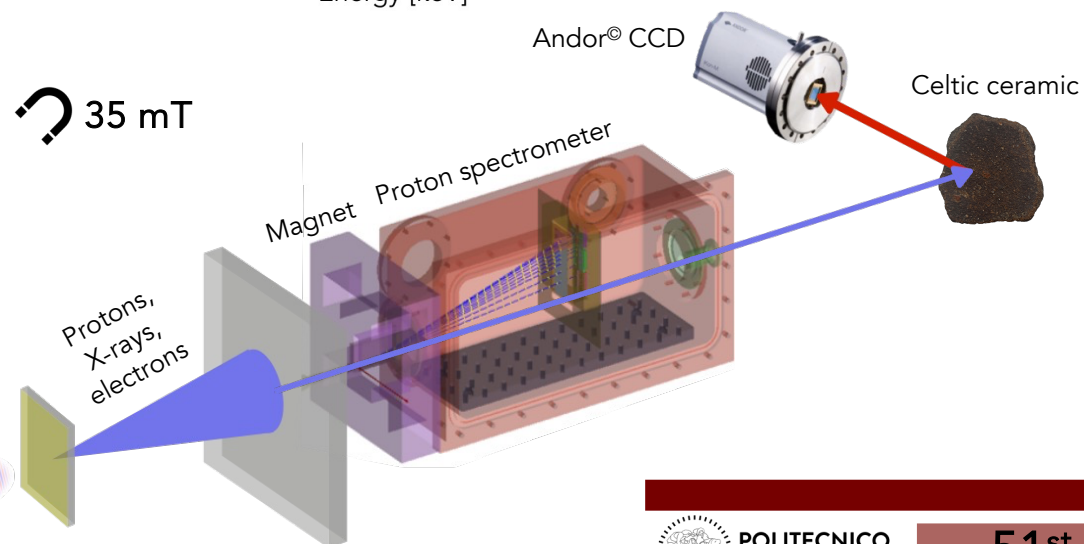
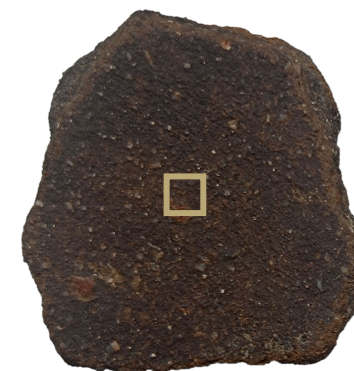
PIXRF on a I-III century ceramic-pot fragment

PIXRF spectrum

 μ XRF spectrum

Ceramic-pot fragment (I-III century)

0 cm 1 2 3



Test of
PIXRF on
ceramic
materials



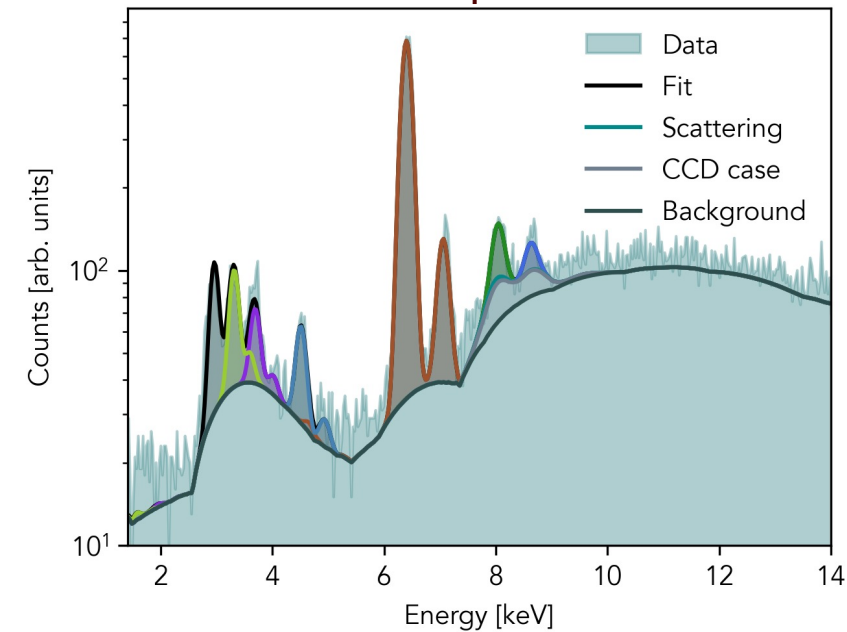
Detection of low
concentration
elements (~0.1%)



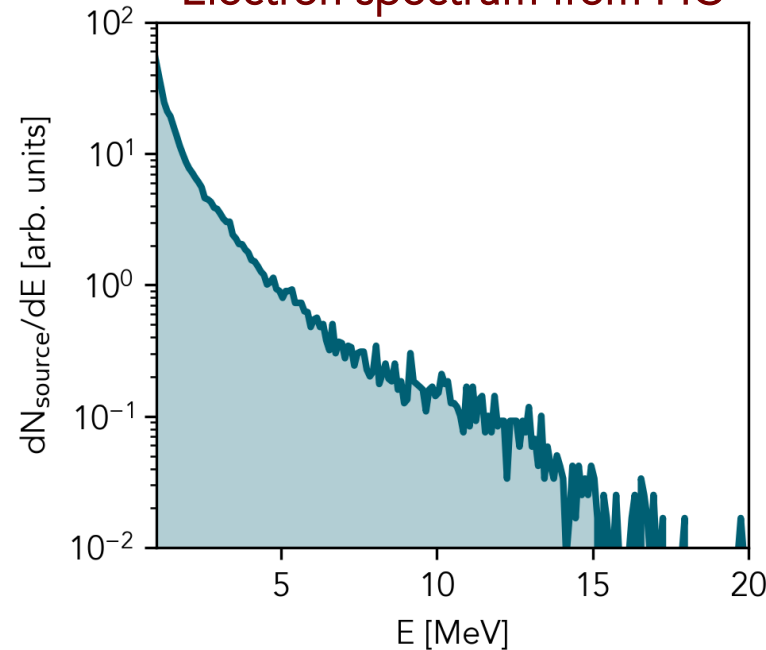
Si and Al matrix,
trace elements
undetected

What about trace elements?

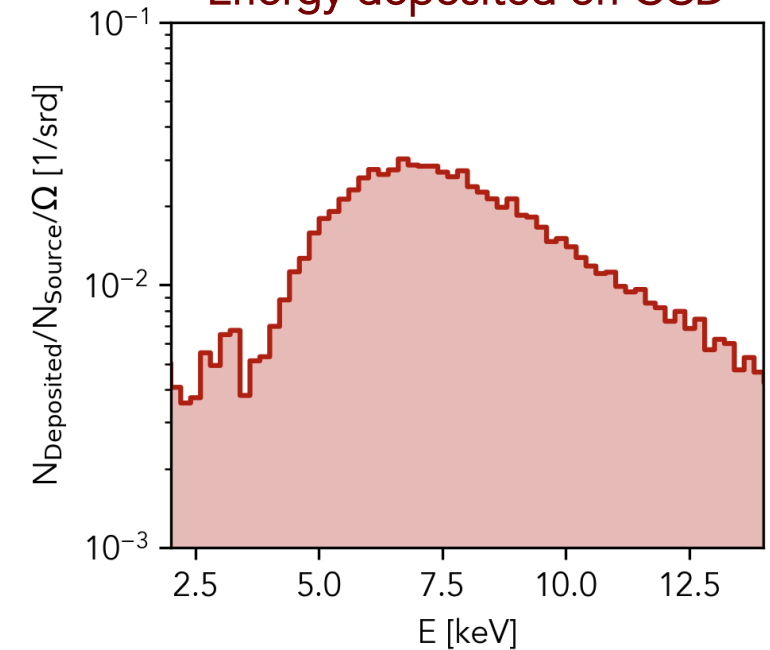
PIXRF spectrum




Electron spectrum from PIC



Energy deposited on CCD



 **GEANT4** and **Smilei**
A SIMULATION TOOLKIT
simulations to
find cause of
background



Electrons impinging
on CCD screen



- Mitigation of background source
- Use of **He** flux to reduce in-air attenuation below 3 keV
- Use of alternative **CCDs** with higher efficiency above 10 keV

Conclusions and future developments

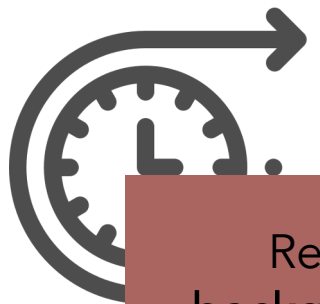


Development of **compact** irradiation and source characterisation setup based on a **magnetic spectrometer**

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

First **laser-driven PIXRF** on **cultural-heritage** relevant materials

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




Reduction of **background source** through **optimisation** of the setup

Work at **higher repetition rate** (~ 1 Hz)

Use of **table-top 10s-of-TW-class lasers**

Engineered targets to increase laser-plasma acceleration **performance**

Acknowledgments

- Our research group @  **POLITECNICO MILANO 1863**
P.I.



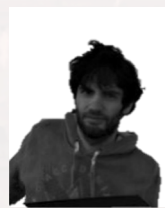
M. Passoni



V. Russo



D. Dellesega



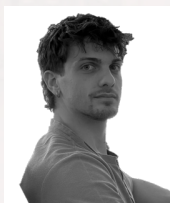
A. Maffini



F. Mirani



D. Orecchia



K. Ambrogioni

M. S. Galli De
Magistris

F. Gatti




A. Pola



D. Mazzucconi




F. Casamichiela


- The collaboration with  **RAYLAB** company



D. Rastelli

- The  **eli** Beamlines facility

- Access to ELIMAIA beamline through 5th User call
- The ELIMAIA internal team: *Vasiliki Kantarelou, Francesco Schillaci, Lorenzo Giuffrida and Daniele Margarone*

- The  **spc** institute of heritage science teams from:

- Milan: Claudia Conti (Raman Lab team leader), Elisa Maria Grassi (Archaeologist)
- Catania: Francesco Paolo Romano (X-Ray Lab team leader), Eva Luna Ravan

Thank you for your attention!



kevin.ambrogioni@polimi.it



www.ensure.polimi.it