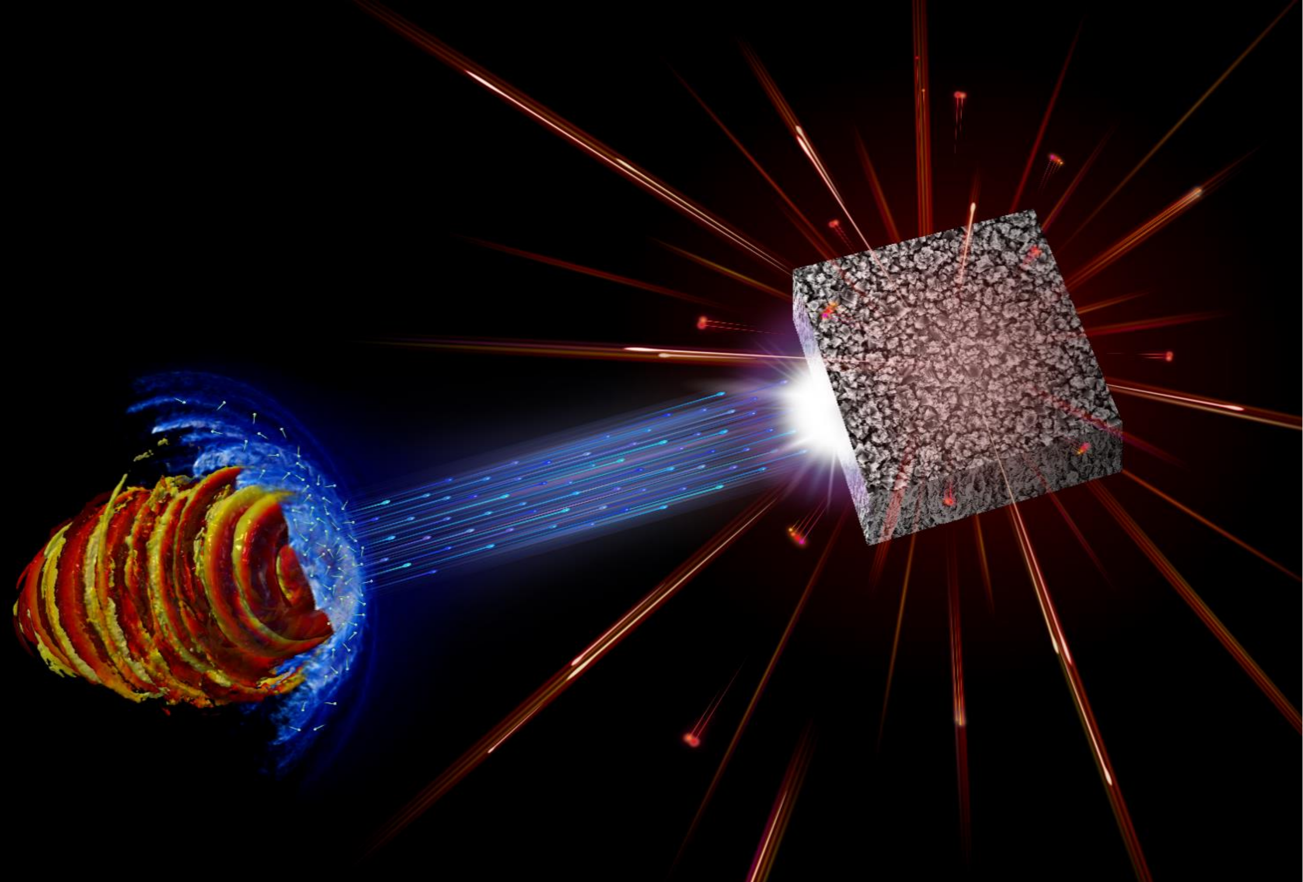
Lasers in the Conservation of Artworks

LACONA XIII

Florence - September 12-16, 2022

Laser-driven particle acceleration for elemental characterization of artworks



Francesco Mirani

ERC-2014-CoG No. 647554
ENSURE

ERC-2016-PoC No. 647554
INTER

ERC-2022-PoC No. 101069171
PANTANI

POLITECNICO MILANO 1863

NanoLab
Department of Energy

- Activities performed within the framework of **ERC consolidator** and **PoC grants** (from 2015 to 2022).

ENSURE erc -2014-CoG No.647554

Exploring the New Science and engineering unveiled by Ultraintense ultrashort Radiation interaction with mattEr

erc ERC- 2016 -PoC No. 647554 **INTER**

erc ERC-2022-PoC No. 101069171 **PANTANI**

POLITECNICO MILANO 1863

DIPARTIMENTO DI ENERGIA

www.ensure.polimi.it

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A. Formenti


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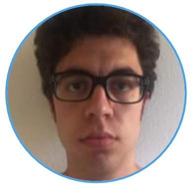
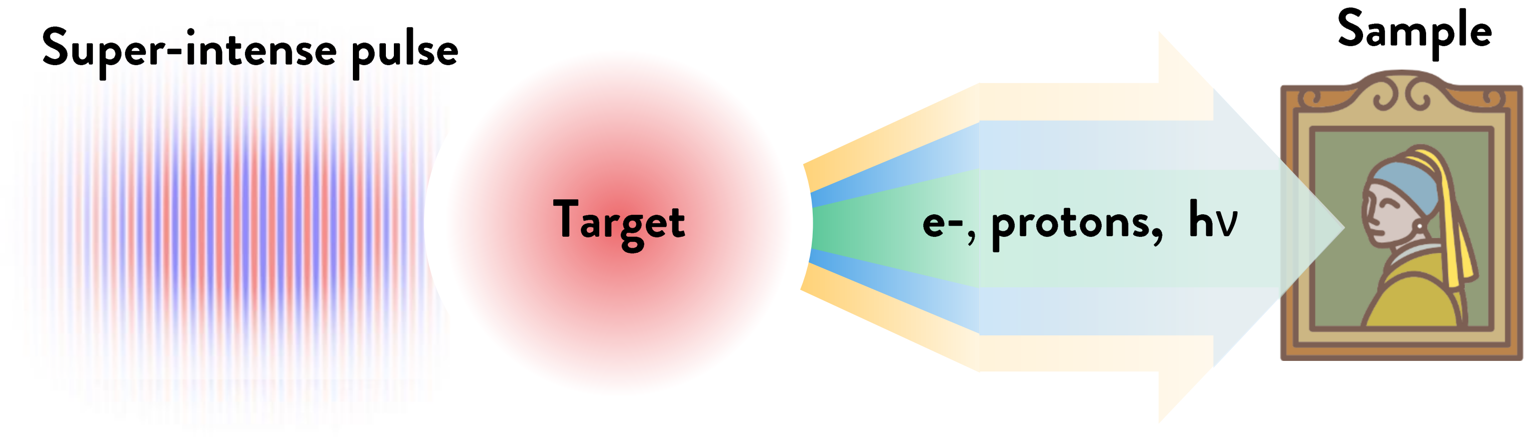

D. Vavassori


M. Galbiati


D. Orecchia


F. Gatti

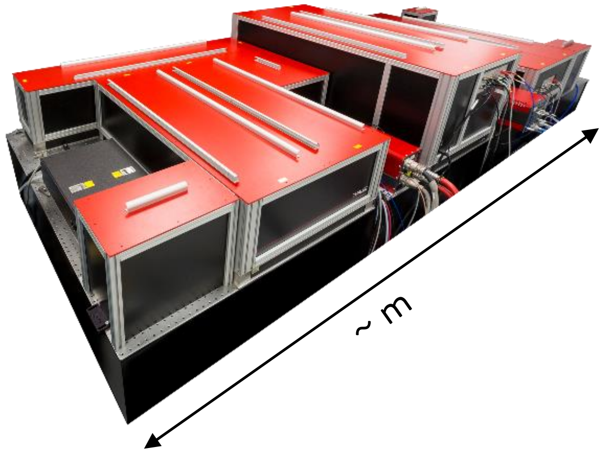
Laser-driven particle sources: an unconventional particle acceleration scheme



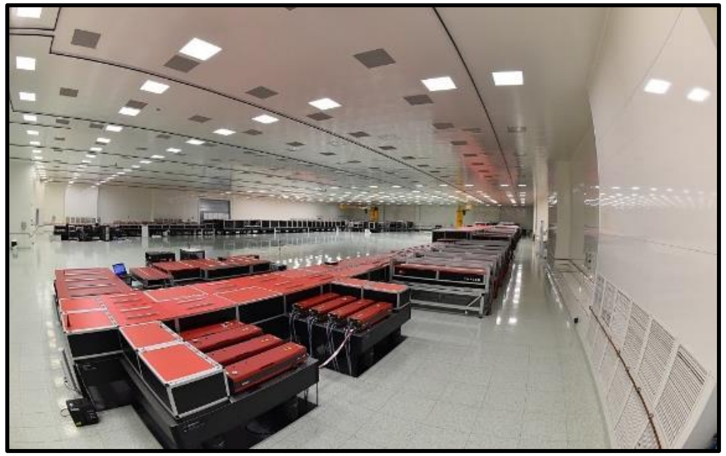
Laser parameters:

- ✓ High powers ~ **10 TW – 10 PW**
- ✓ Ultra-short durations ~ **10 fs**
- ✓ Repetition rate ~ **10^{-3} – 10s Hz**
- ✓ Small areas focal spot ~ **1 – 100 μm^2**
- ✓ Intensity ~ **10^{18} – 10^{23} W/cm^2**

QUARK 30 TW, Thales Group



ELI-NP laser, 10 PW (Romania)

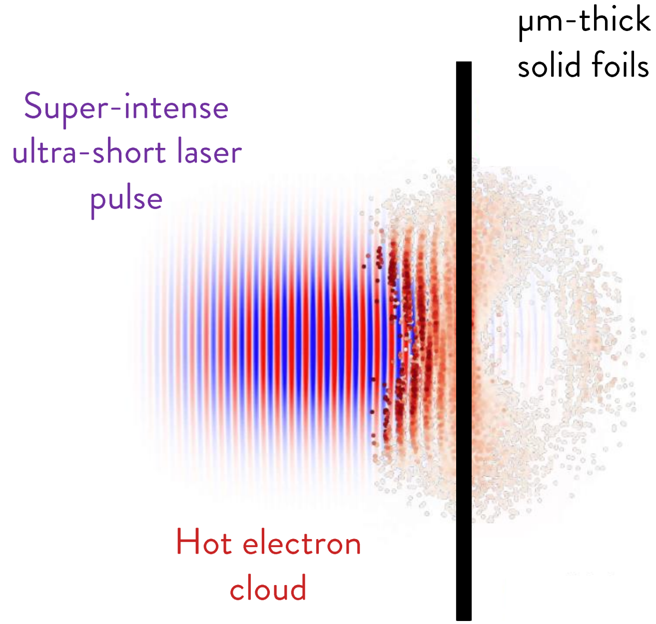


H. Daido, et al. *Rep. Prog. Phys.*, 75(5), (2012): 056401.

A. Macchi, et al. *Rev. Mod. Phys.*, 85(2), (2013): 751.

Laser-driven particle acceleration from solid targets

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



- Formation of **plasma** → **Particle acceleration** driven by **charge separation**.

A. Macchi, et al. *Rev. Mod. Phys.*, 85(2), (2013): 751.
O. N. Rosmej, et al. *PPCF* 62.11 (2020): 115024.
I. Prencipe, et al. *PPCF*, 58(3), (2016): 034019.

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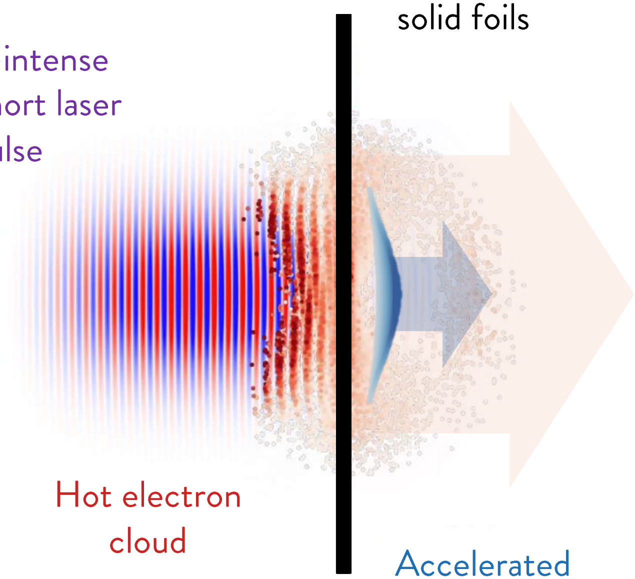
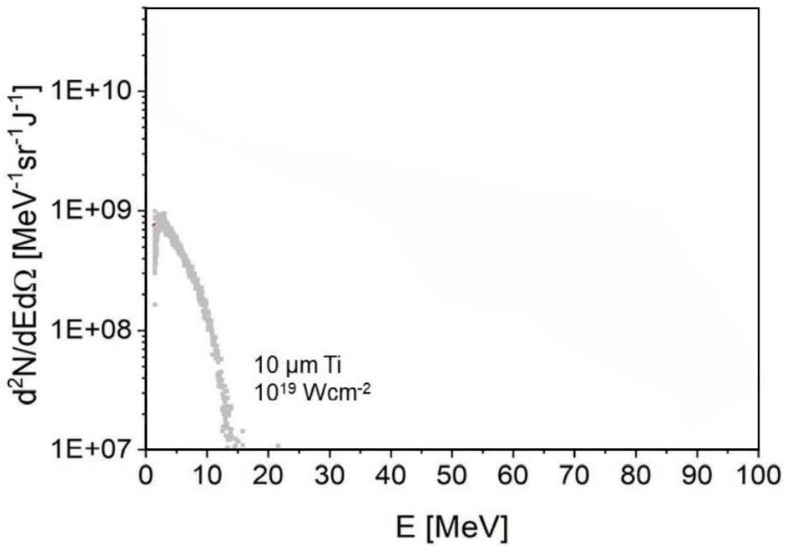
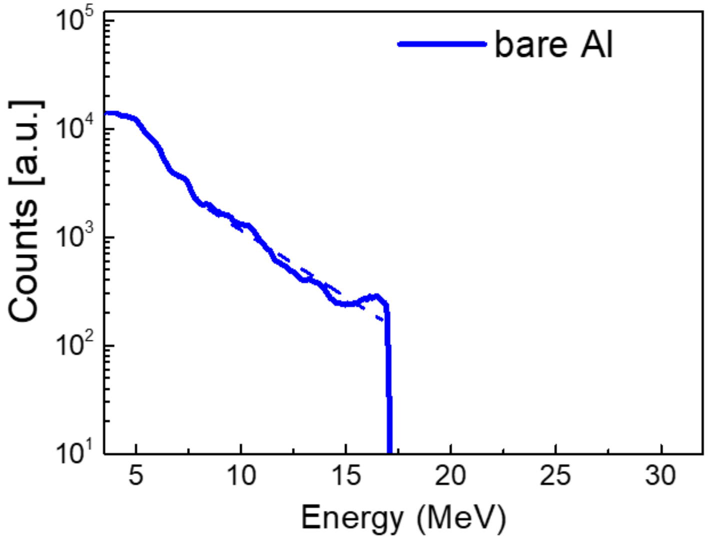


- Particles emitted in short **bunches** (**≤ ns** time duration)
- Huge accelerating field gradients: **MV/µm**
- Broad energy **spectra** (~ **exponential**)
- Maximum energy ~ **1 - 10s MeV**

✓ **Electron** spectrum:



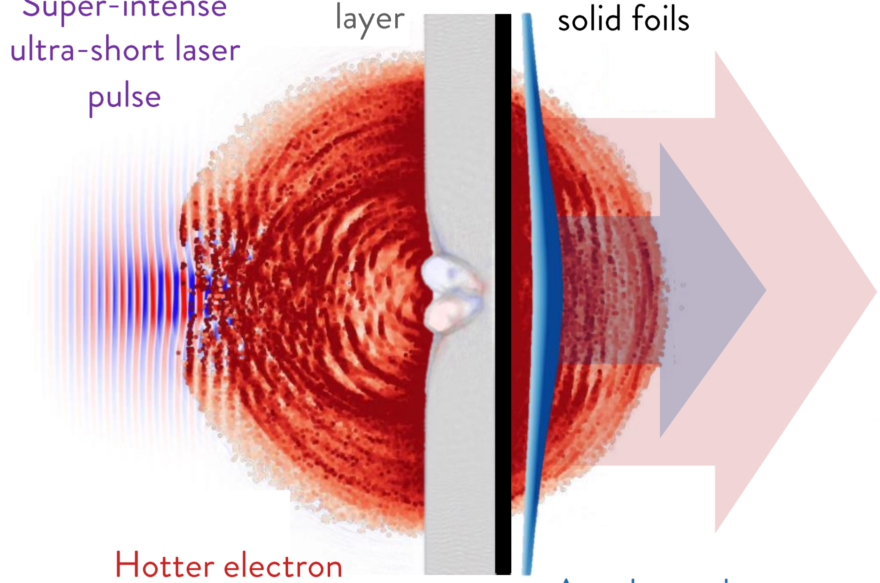
✓ **Proton** spectrum:



A. Macchi, et al. *Rev. Mod. Phys.*, 85(2), (2013): 751.
O. N. Rosmej, et al. *PPCF* 62.11 (2020): 115024.
I. Prencipe, et al. *PPCF*, 58(3), (2016): 034019.

Laser-driven particle acceleration from solid targets

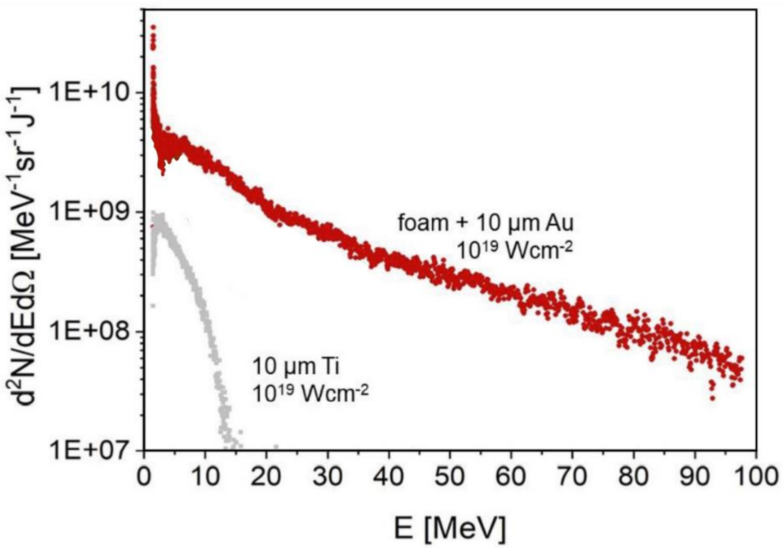
- **Enhanced Target Normal Sheath Acceleration** ⟶ Advanced **near-critical** double-layer **targets** (DLTs)



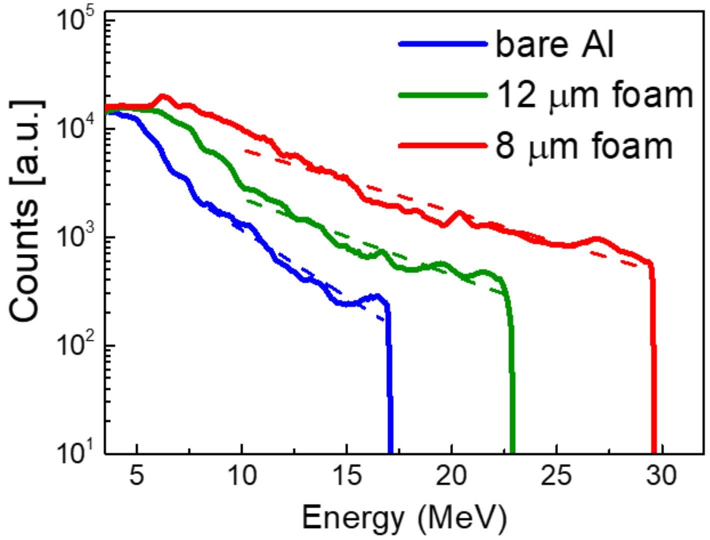
- **Low density** (~ mg/cm^3), **near-critical material** to **enhance laser absorption**

👍 **Increase** the **energy** and **number** of the particles

✓ **Electron** spectrum:

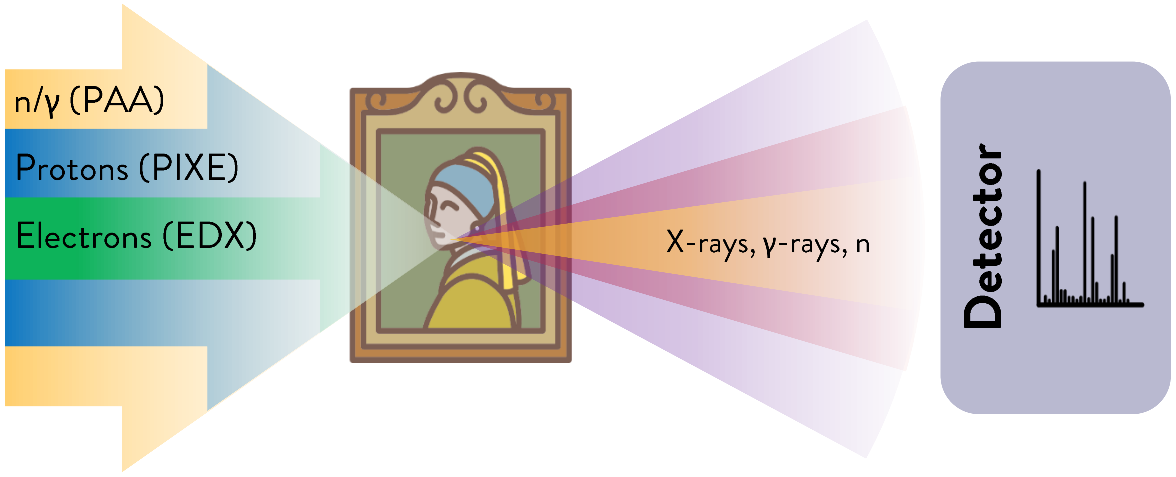


✓ **Proton** spectrum:



A. Macchi, et al. *Rev. Mod. Phys.*, 85(2), (2013): 751.
O. N. Rosmej, et al. *PPCF* 62.11 (2020): 115024.
I. Prencipe, et al. *PPCF*, 58(3), (2016): 034019.

What are the elemental characterization techniques we can carry out with particles?



Particle Induced X-ray Emission (PIXE)

- MeV protons → X-rays
- 0-10s μm, homogeneous and stratigraphic

Energy Dispersive X-ray Spectroscopy (EDX)

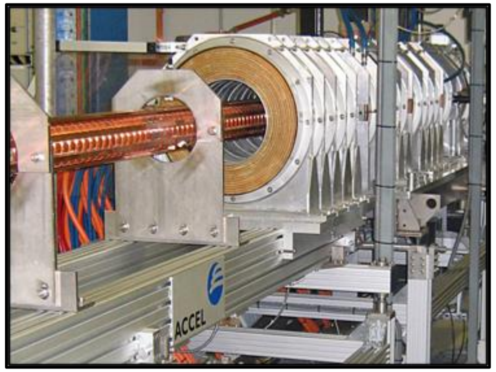
- keV e- → x-rays
- Several μm, homogeneous, small samples

Activation Analysis (PAA, NAA) and Radiography

- Neutrons, MeV photons → γ-rays
- Homogeneous, bulk

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.

What are the particle sources we can exploit?

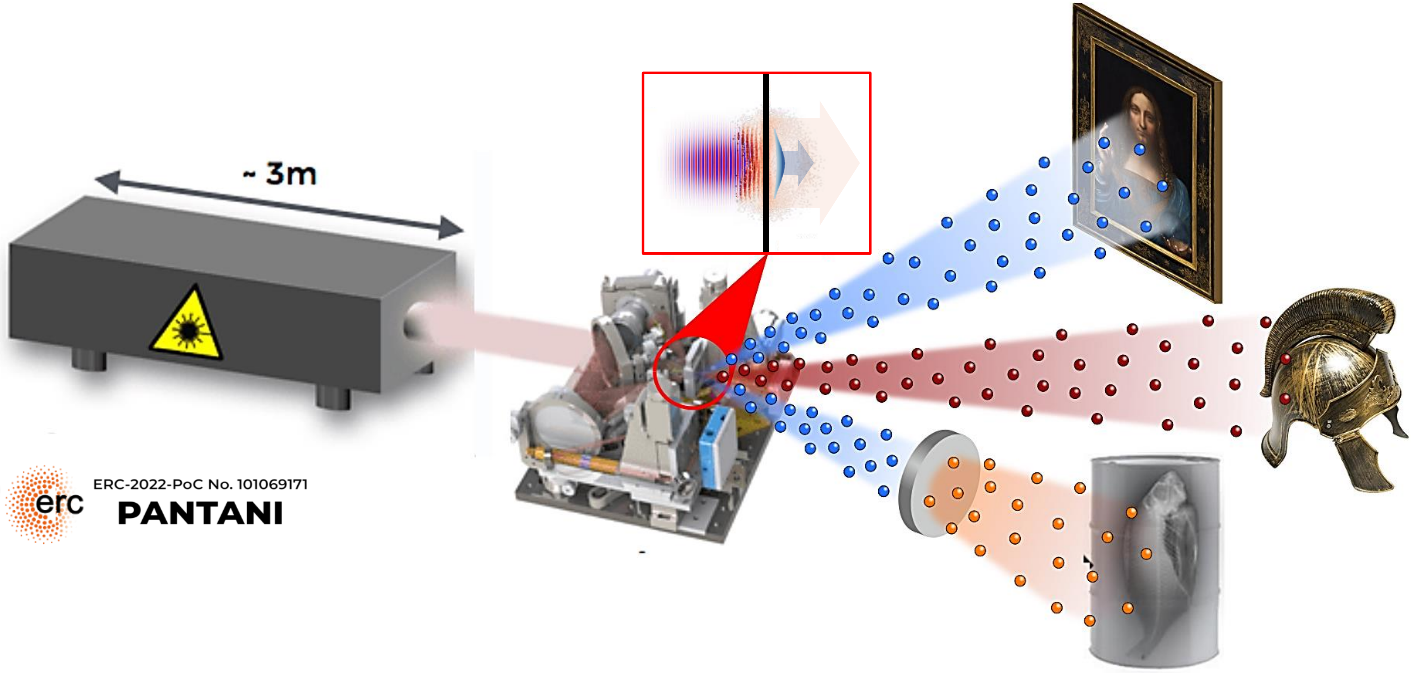


Large and **expensive** particle **accelerators** providing **monoenergetic particles.**

Improvements required in term of:

Compactness **Cheapness** Energy tunability (**flexibility**)

Exploit laser accelerators!
(Compact and multi-purpose)



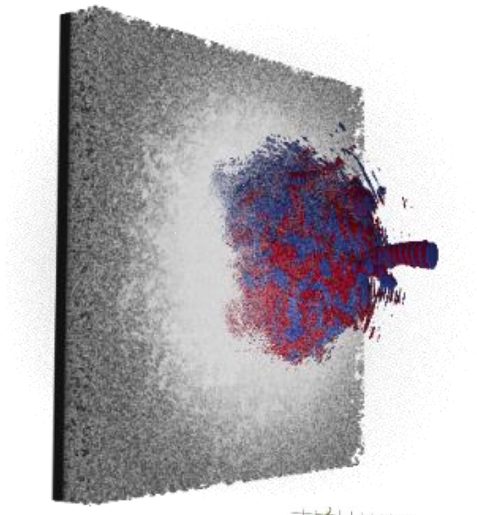
M. Passoni, et al. *PPCF*, 62(1), (2019): 014022.
Verma, Hem Raj. Atomic and nuclear analytical methods. *Springer*, 2007.

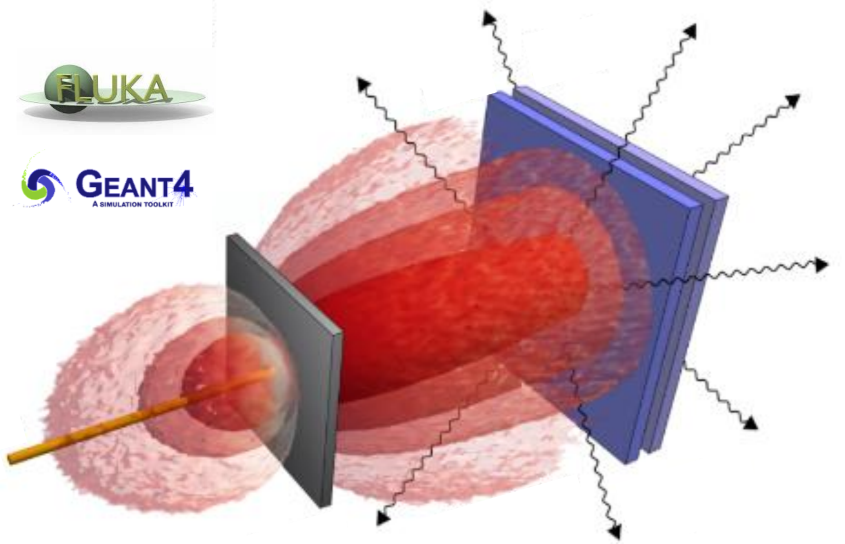
Goal and methods

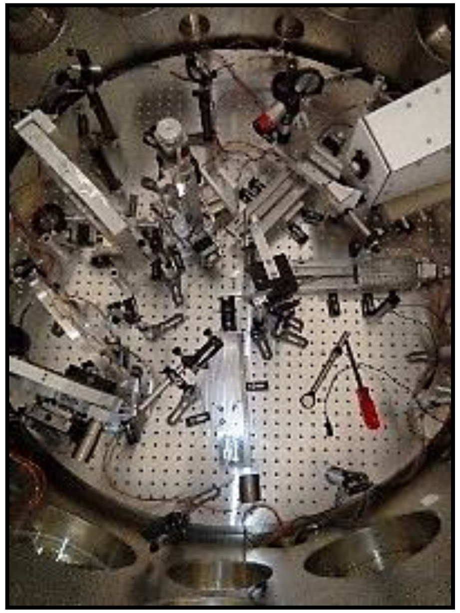
Investigate applicability of **laser-accelerators** to **elemental characterization** for **cultural heritage** (and others).

Exploit through **theoretical** & **experimental** methods:

- ✓ Laser-driven source: **models, Particle-In-Cell**
- ✓ Particle propagation in matter: **Monte Carlo**
- ✓ **Campaigns** in laser facilities

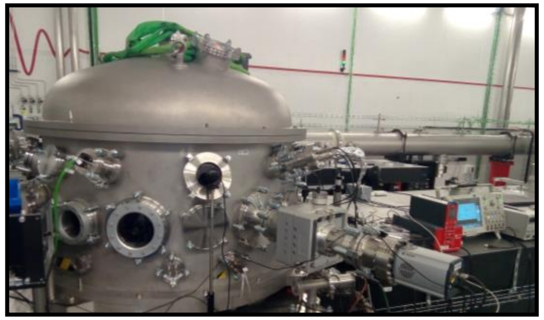


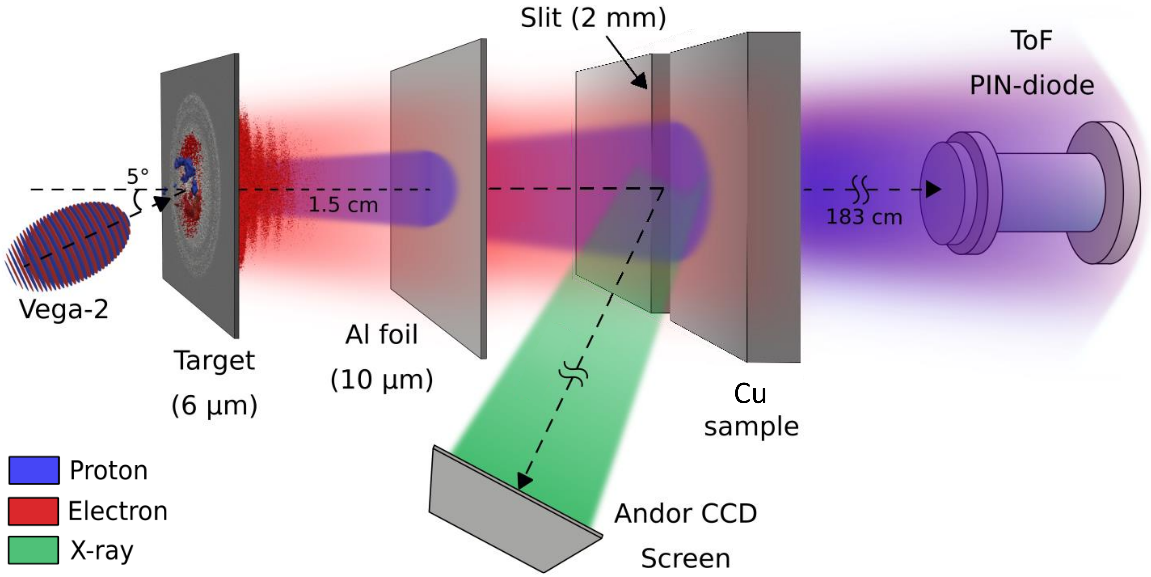




M. Passoni,, et al. *PPCF*, 62(1), (2019): 014022.

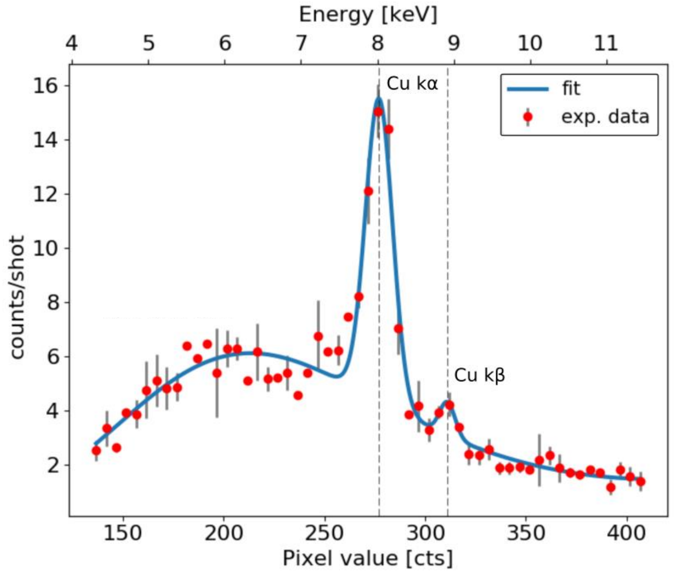
Laser-driven PIXE and EDX proof-of-principle experiment @ CLPU





- **200 TW** laser (2×10^{20} W/cm^2) and single layer target
- Proton energies up to **~ 6 MeV** → Suitable for PIXE

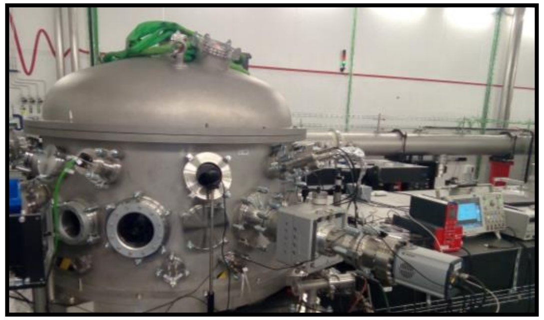
EDX setup → Sample irradiation with both **e-** & **protons**

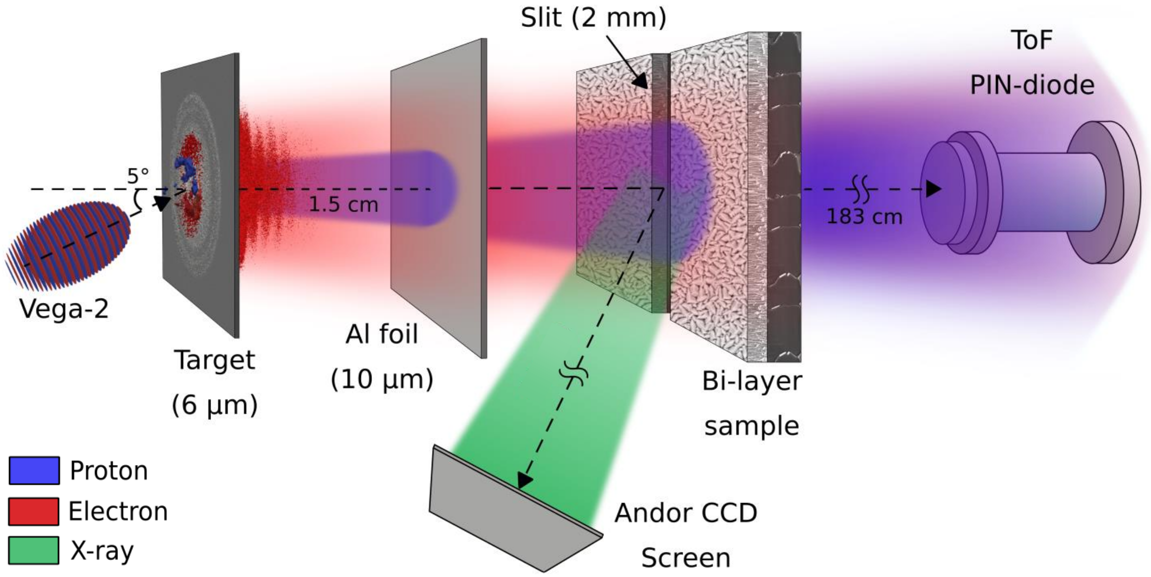


- **First test** with Cu sample and CCD energy calibration

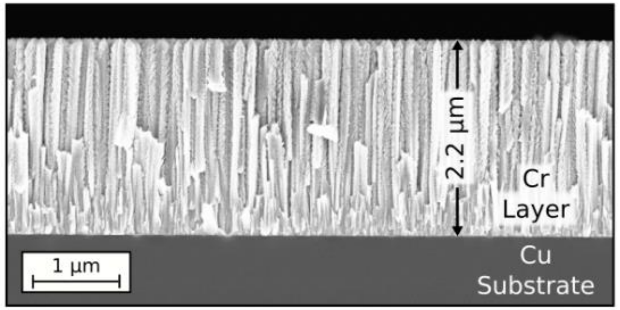
F. Mirani, et al., *Sci. Adv.*, 7.3, (2021): eabc8660.

Laser-driven PIXE and EDX proof-of-principle experiment @ CLPU

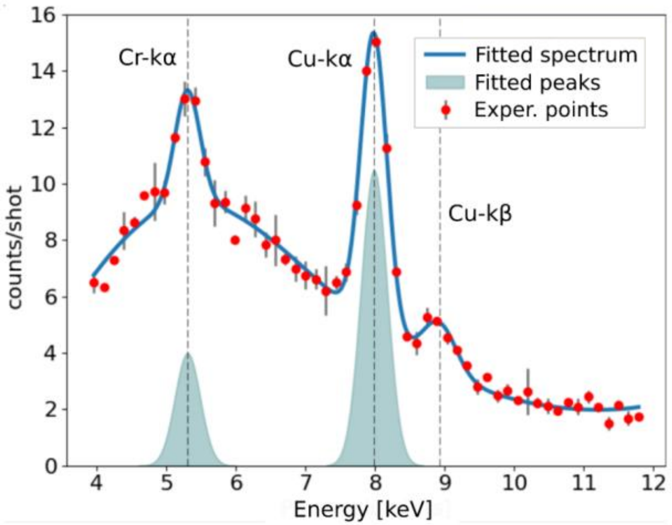




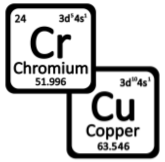
- **Bi-layer sample** (Cr layer + Cu substrate)



Produced with **DCMS** (controlled thickness and composition)



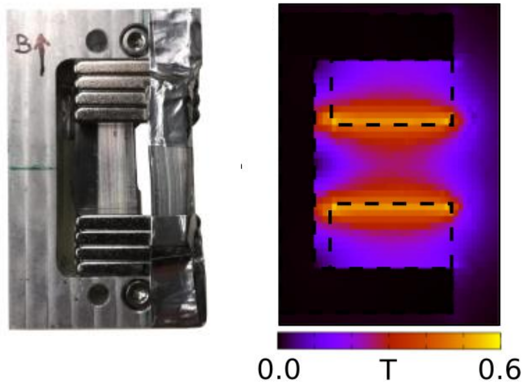
Form the peak energies:



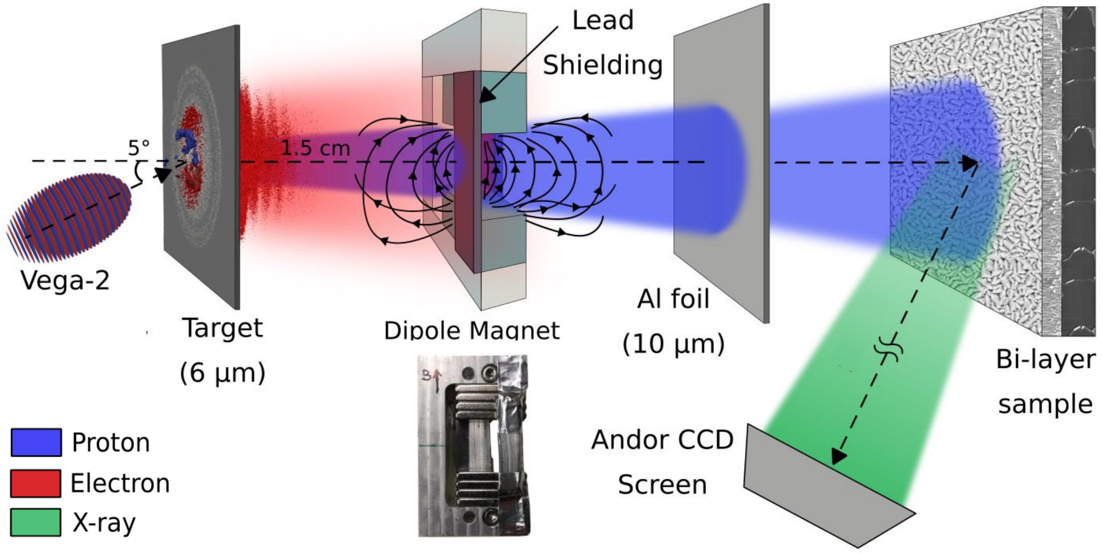
Elements are correctly **recognized**

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

Laser-driven PIXE and EDX proof-of-principle experiment @ CLPU

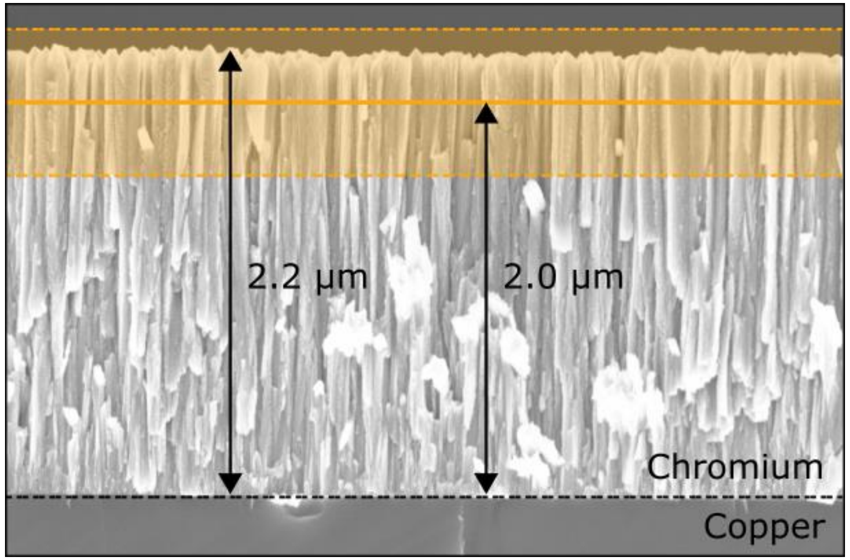


- Removal of the electrons with **dipole magnet**



PIXE setup → Sample irradiation only with **protons**

Cr layer thickness reconstruction → First laser-driven PIXE quantitative analysis measurement



(Dedicated software to process laser-driven PIXE spectra)

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

Numerical study of laser-driven PIXE feasibility for the analysis of artworks

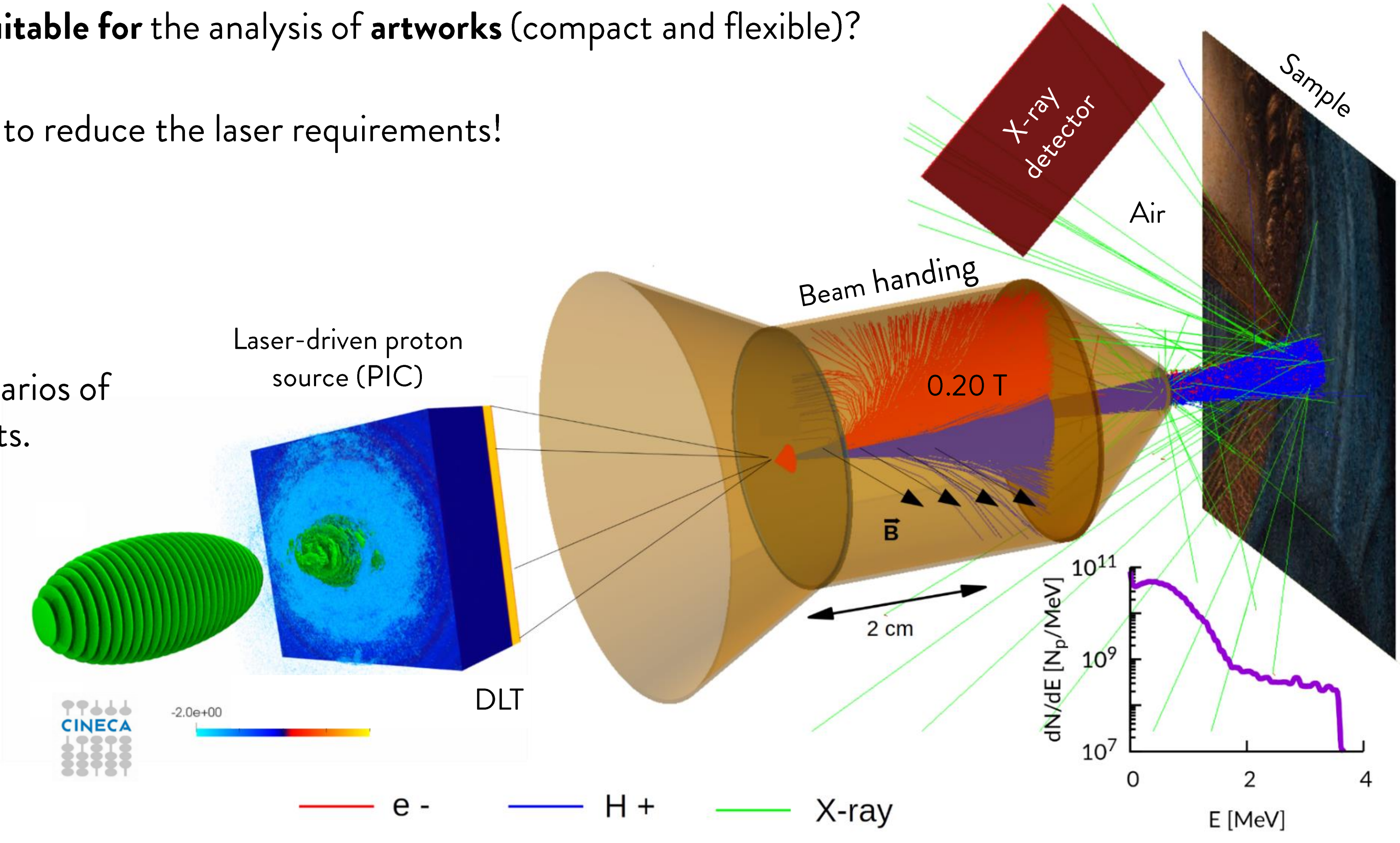
? How do we make the **PIXE suitable for** the analysis of **artworks** (compact and flexible)?

Exploit **Double Layer Targets** to reduce the laser requirements!

- **20 TW** laser;
- **DLT** target;

Simulations of real-case scenarios of **laser-driven PIXE** experiments.

- piccante: 3D Particle-In-Cell
- GEANT4: Monte Carlo

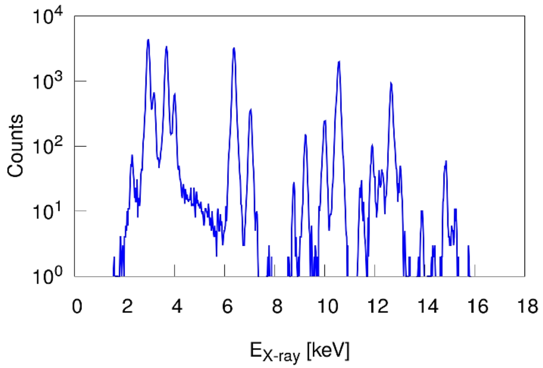


M. Passoni, et al. *Sci. Rep.* 9.1, (2019): 9202.

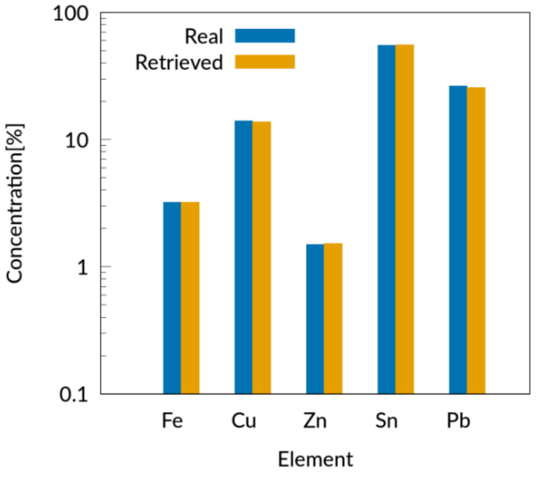
Numerical study of laser-driven PIXE feasibility for the analysis of artworks

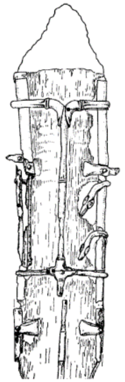
Dedicated software to process X-ray spectra and retrieve the **sample composition**.

Applied to the **“synthetic” X-ray spectra** from the Monte Carlo.

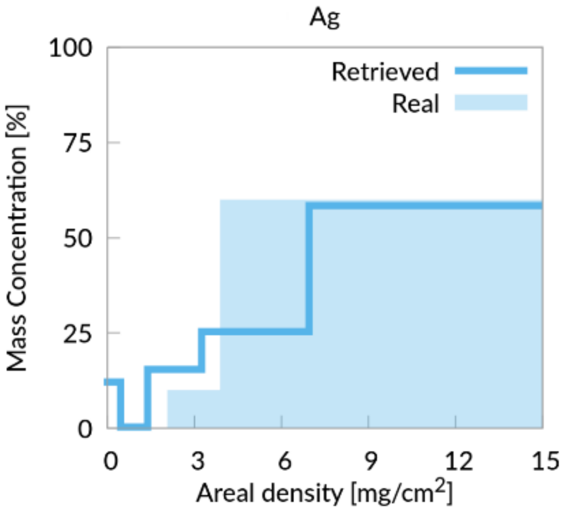


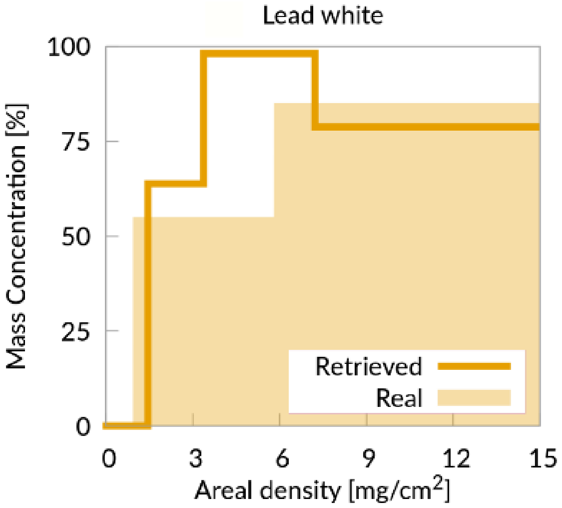
- **Homogeneous** sample (Roman sword-scabbard):





- **Complex structured** samples (Medieval brooch and Renaissance painting) :





Ž. Šmit, et al. Nucl. Instrum. Methods Phys. Res. B: Beam Interact. Mater. At. 239.1-2, (2005): 27-34.
Ž. Šmit, et al. Nucl. Instrum. Methods Phys. Res. B: Beam Interact. Mater. At. 266.10, (2008): 2329-2333.
L. De Viguerie, et al. Analytical chemistry 81.19, (2009): 7960-7966.
M. Passoni, et al. *Sci. Rep.* 9.1, (2019): 9202.

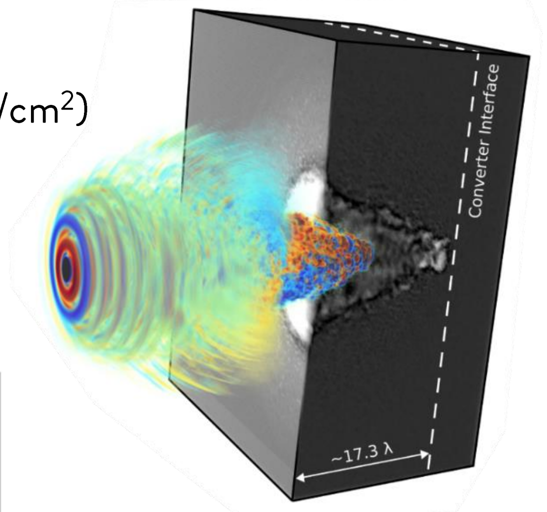
Numerical study of laser-driven PAA feasibility

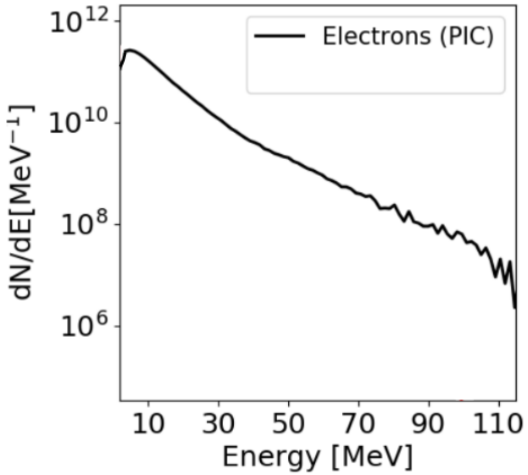
Development of a **scheme** to perform laser-driven Photon Activation Analysis

1. Super-intense **laser** interacting with **near-critical** material (**3D PIC**)

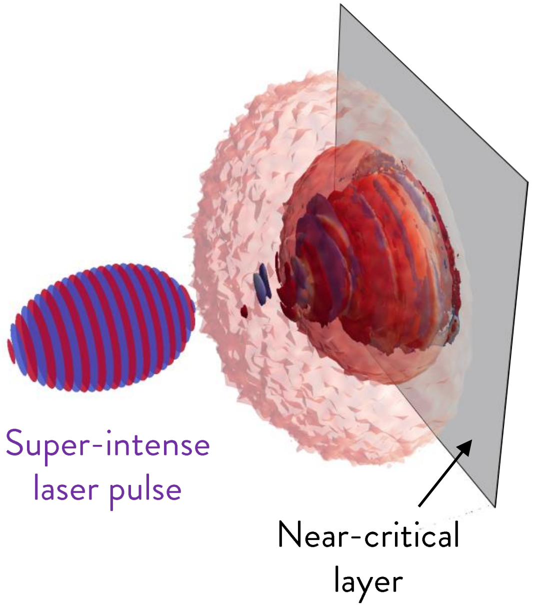
200 TW laser (8×10^{20} W/cm^2)

Near-critical layer





✓ **Hot e-** generation with $E_{max} \approx 110$ MeV



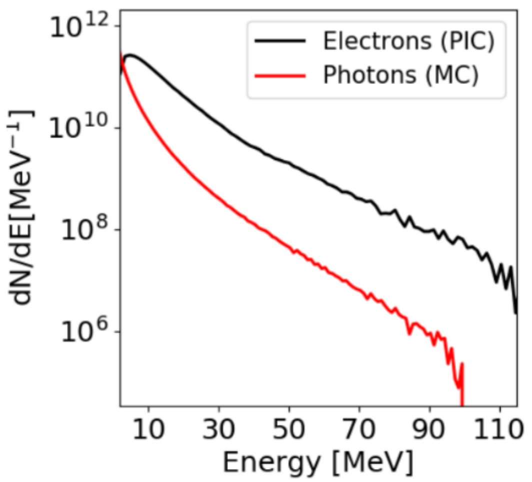
F. Mirani, et al. *Commun Phys* 4.1, (2021): 1-13

Numerical study of laser-driven PAA feasibility

Development of a **scheme** to perform laser-driven Photon Activation Analysis

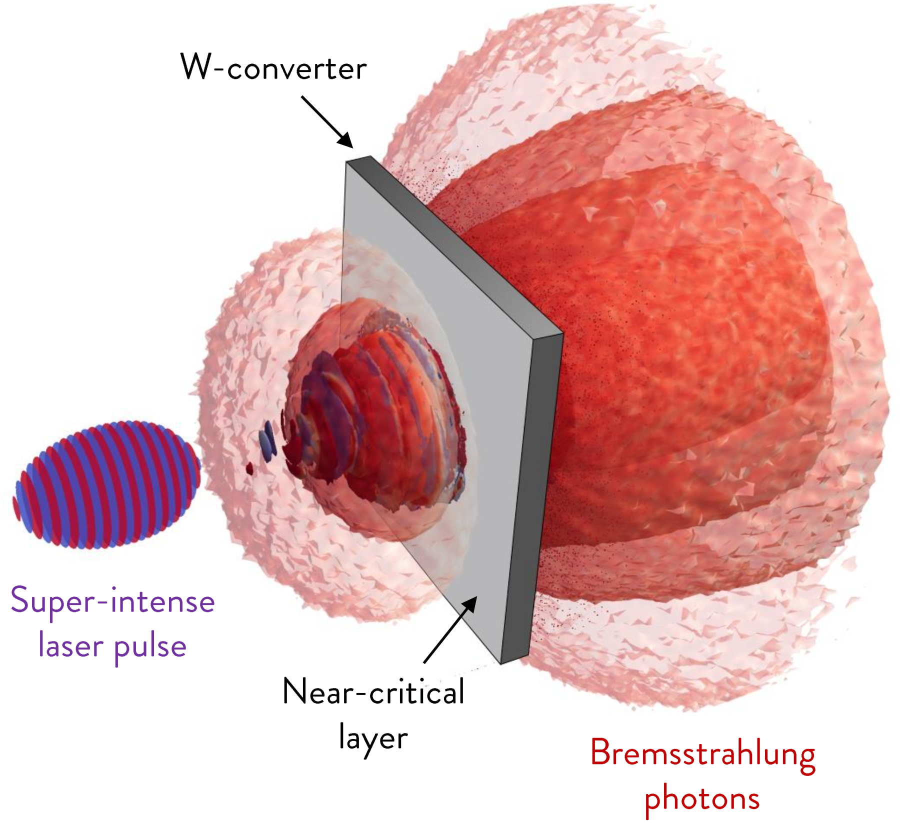
2. **Hot e-** interaction with mm-thick **W converter** → **Bremsstrahlung photons** generation (**Monte Carlo** FLUKA)

- W-converter thickness = **2.6 mm**



✓ Broad angular distribution

✓ Energy up to 100 MeV



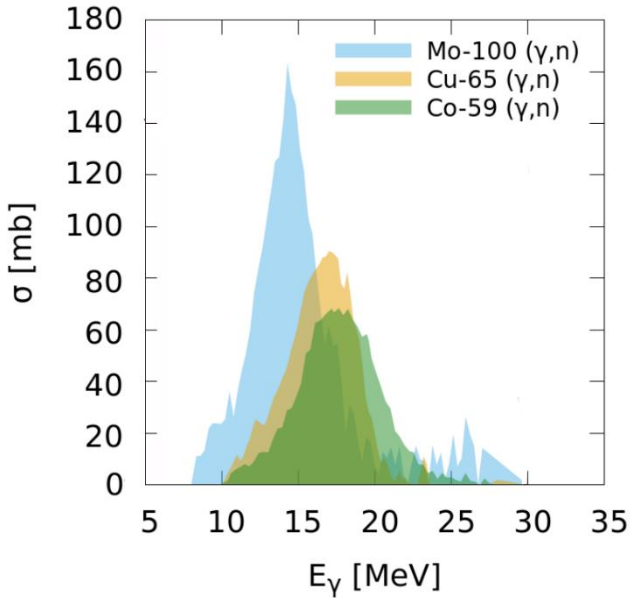
F. Mirani, et al. *Commun Phys* 4.1, (2021): 1-13

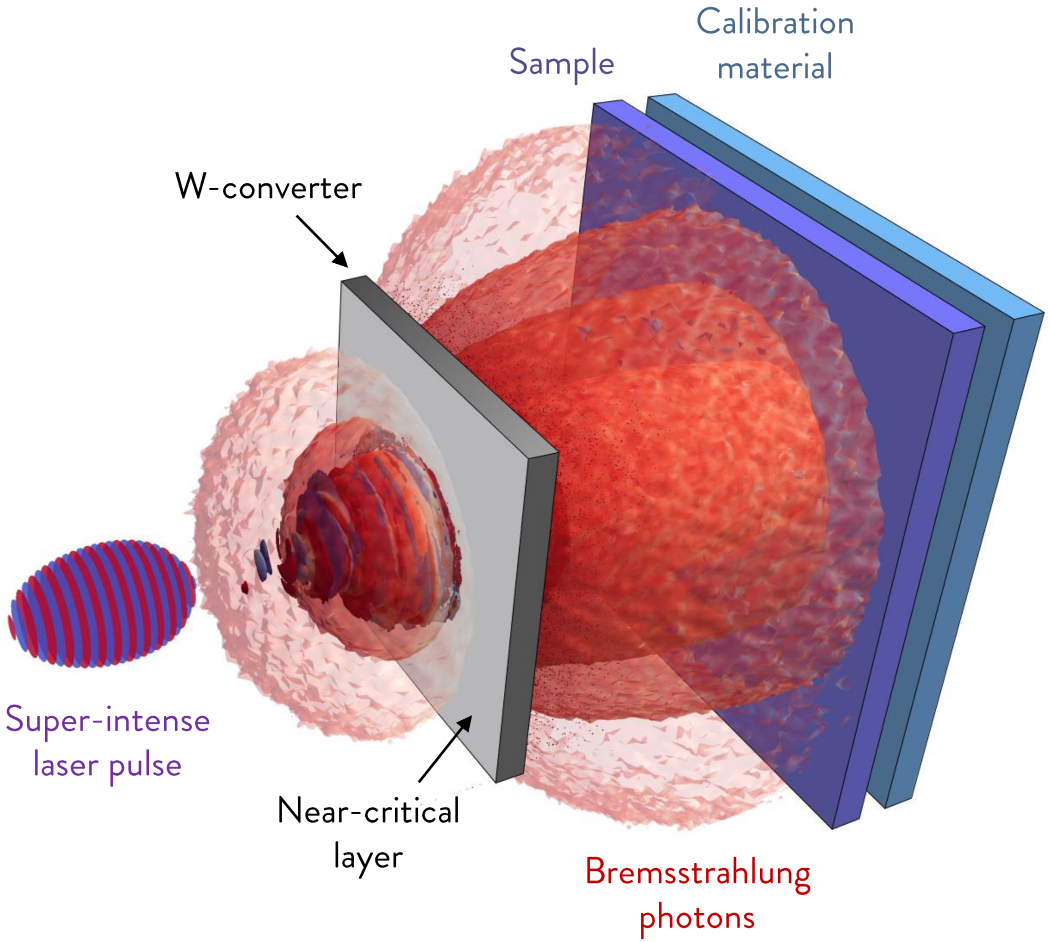
Numerical study of laser-driven PAA feasibility

Exploit **laser-driven photon source** for the PAA and **comparison** with conventional electron **accelerators**

3. Sample and comparative **material irradiation** (**Monte Carlo** FLUKA)

- Photonuclear reaction cross sections:



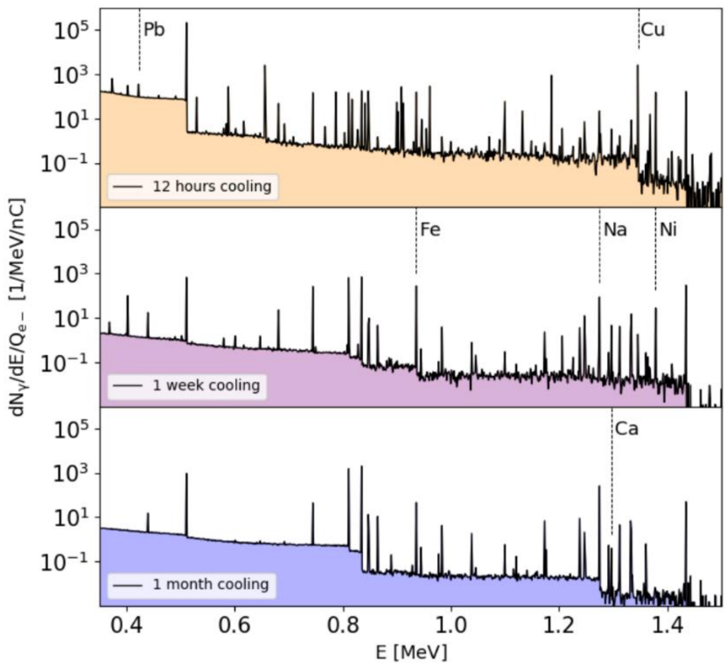


F. Mirani, et al. *Commun Phys* 4.1, (2021): 1-13

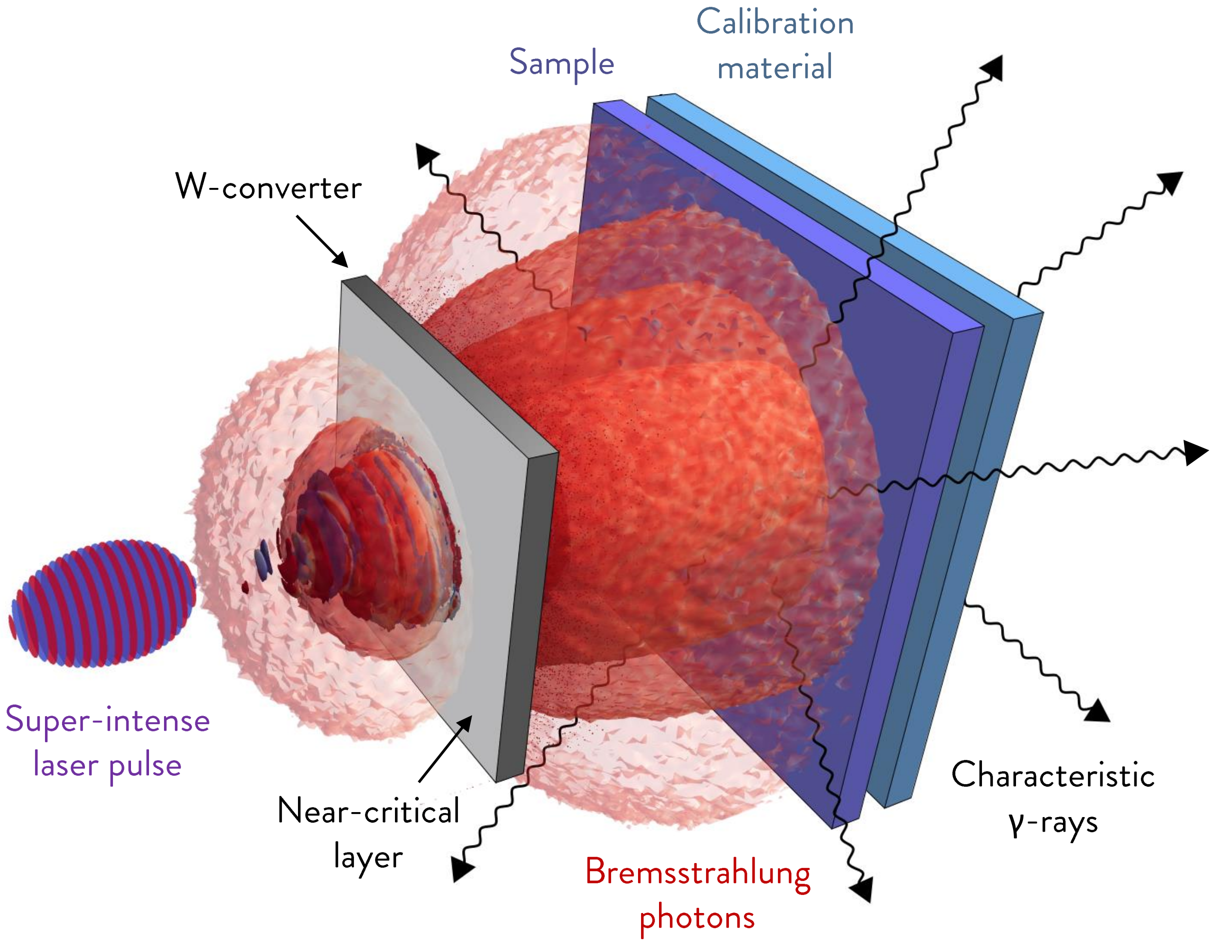
Numerical study of laser-driven PAA feasibility

Exploit **laser-driven photon source** for the PAA and **comparison** with conventional electron **accelerators**

3. Sample and comparative **material irradiation** → **Delayed** emission of characteristic **γ-rays** (**Monte Carlo** FLUKA)



→ **Peak intensities**



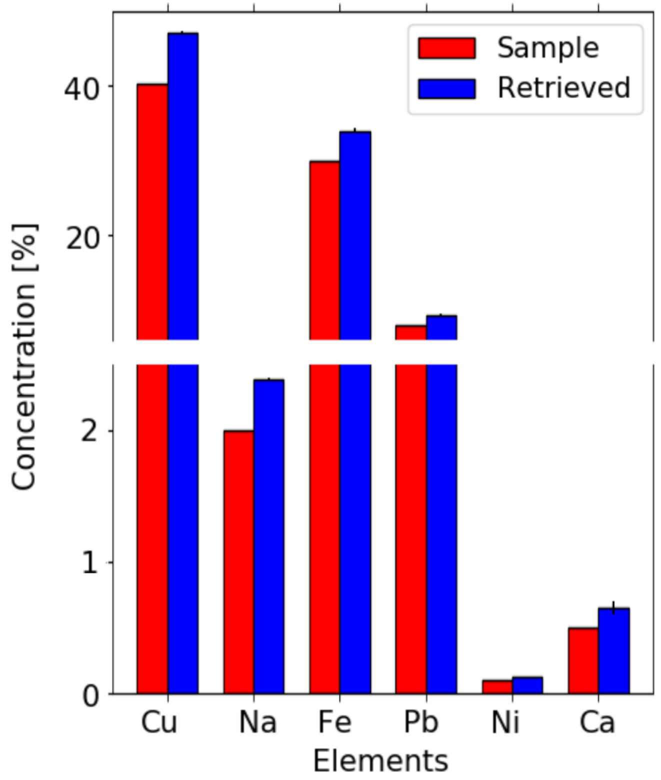
F. Mirani, et al. *Commun Phys* 4.1, (2021): 1-13

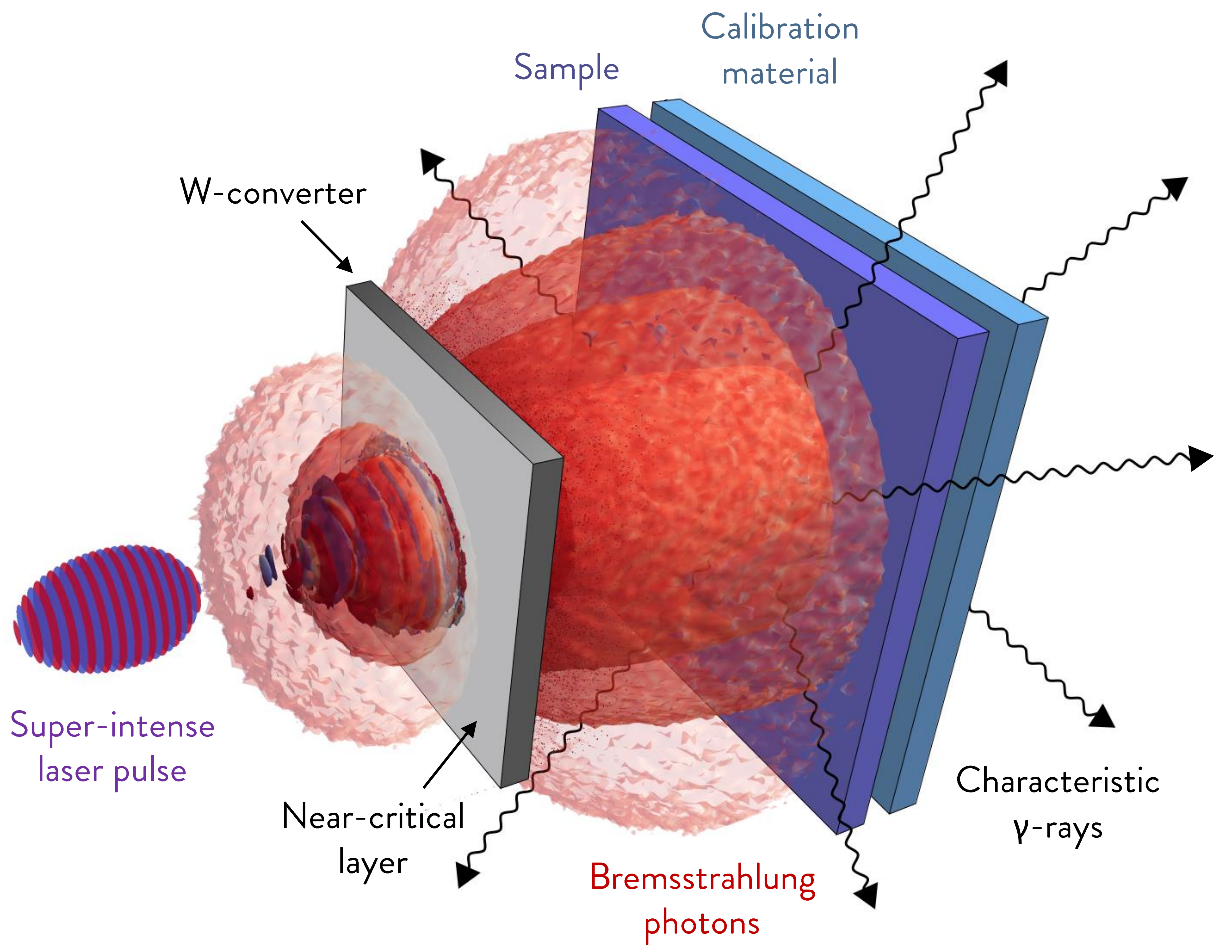
Numerical study of laser-driven PAA feasibility

Exploit **laser-driven photon source** for the PAA and **comparison** with conventional electron **accelerators**

3. Retrieve the **elemental composition** of a cm-thick homogeneous sample (South-Levantine bronze sculpture).

Comparison with the calibration →





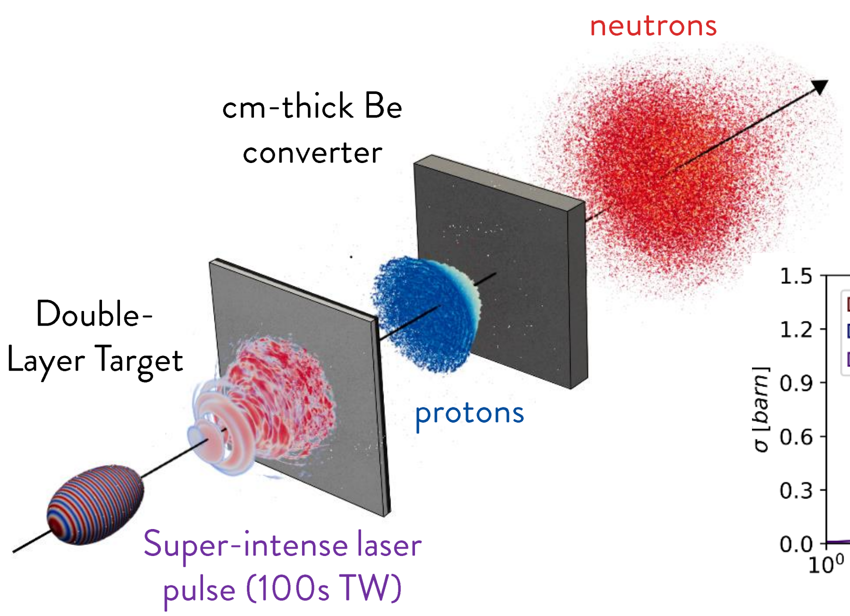
B. Maróti, et al. J. Radioanal. Nucl. Chem. 312.2 (2017): 367-375.

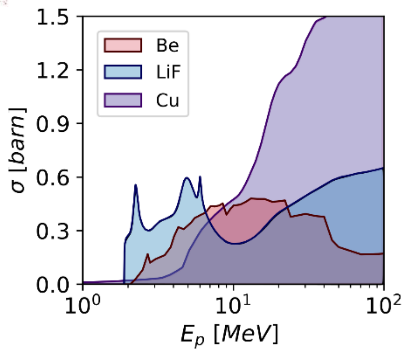
F. Mirani, et al. *Commun Phys* 4.1, (2021): 1-13

Numerical study of laser-driven FNRR feasibility

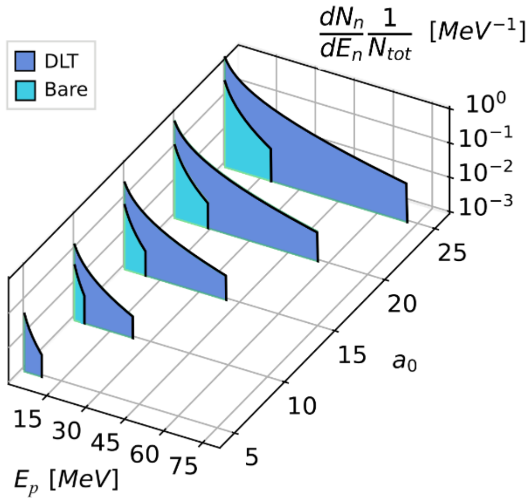
Exploit **laser-driven neutron source** to perform radiography of large samples.

1. Super-intense **laser** interacting with **Double-Layer Target** (model from literature).
2. Accelerated **protons** interaction with cm-thick **converter** → (p, n) reactions → **fast neutron** generation.

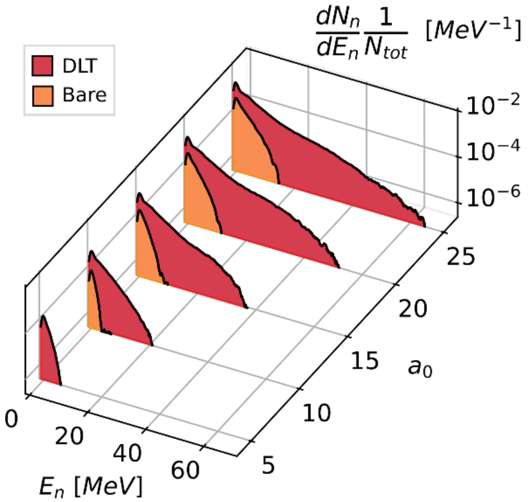




- Monte Carlo GEANT4 results:
  - ✓ **Proton** spectra:



  - ✓ **Neutron** spectra:



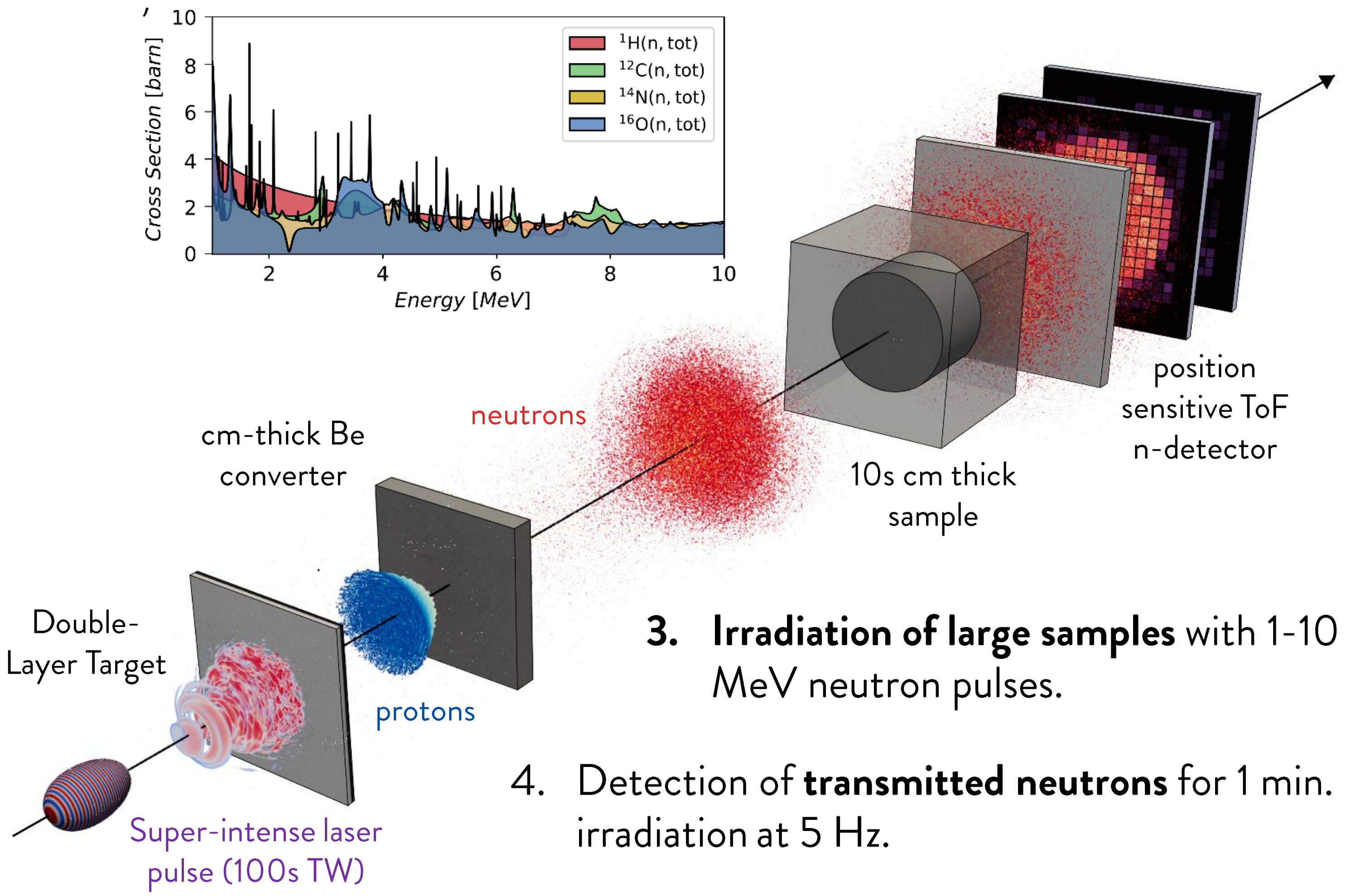
✓ Broad spectrum up to 10s MeV.

✓ $\geq 10^4$ n/cm^2/s at $\geq$ 3 m distance for $a_0 > 15$ (≈ 250 TW).

Mirani, F., et al. Under review at *Phys. Rev. Appl.*
A. Pazzaglia, et al. *Commun Phys* 3.1, (2020): 1-13.

Numerical study of laser-driven FNRR feasibility

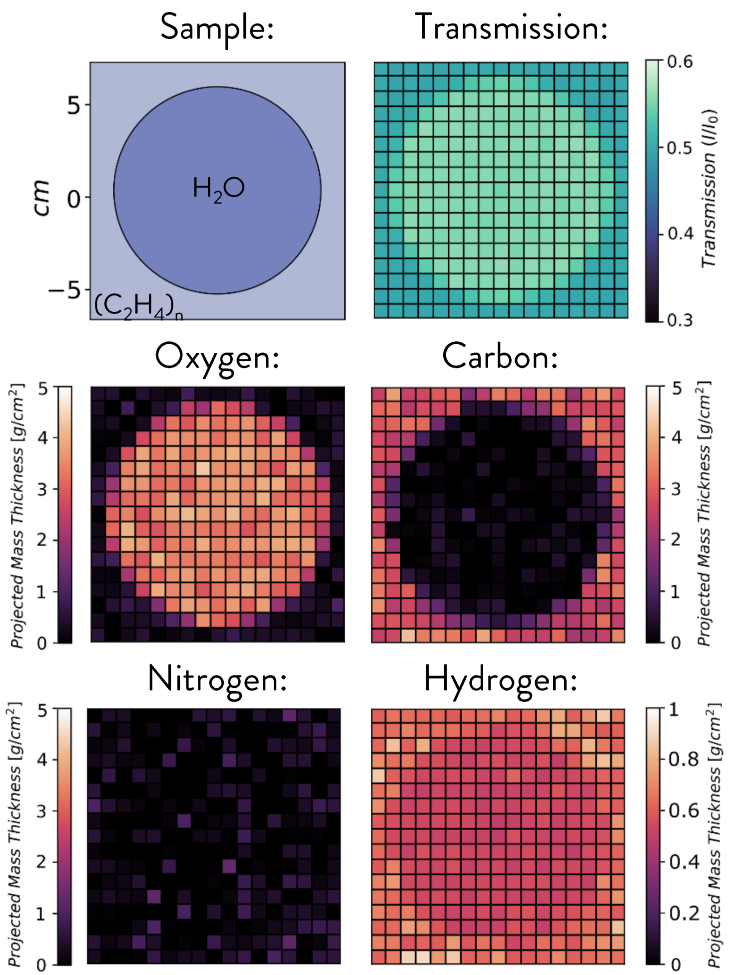
Exploit **laser-driven neutron source** to perform radiography of large samples.



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

4. Detection of **transmitted neutrons** for 1 min. irradiation at 5 Hz.

Elemental imaging of O, C, N and H.



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

Conclusions and perspectives

Laser accelerators are promising sources for the **characterization** of **artworks**.

Compact lasers and **advanced targets** to achieve the requirements for materials characterization techniques.

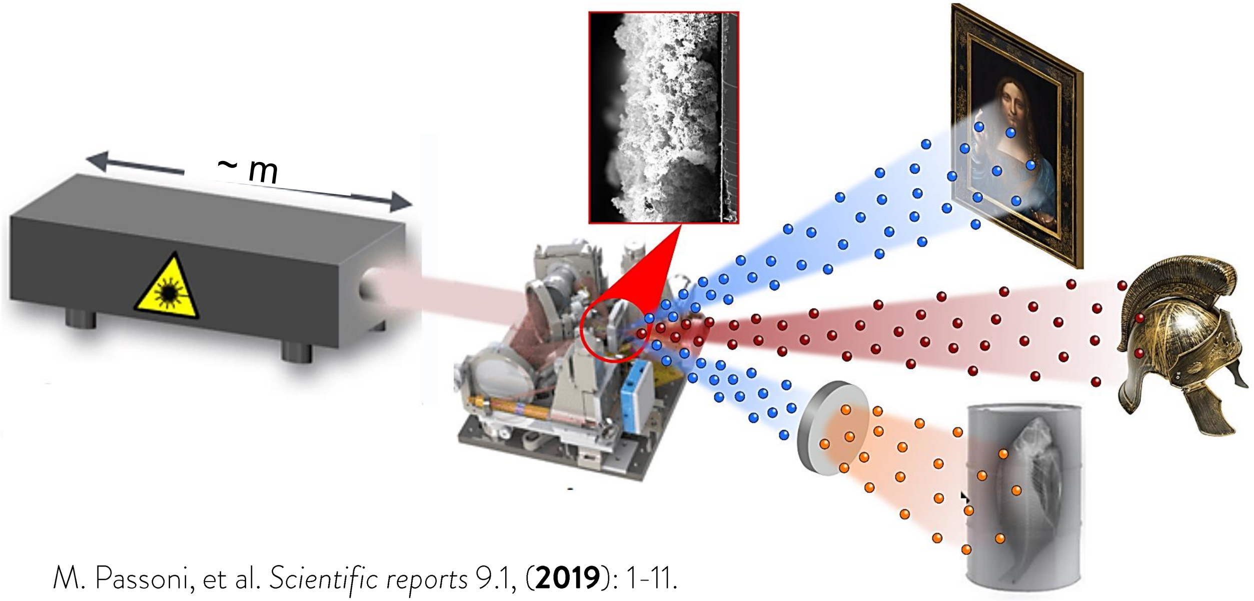
Feasibility of a **multi-purpose acceleration system** for cultural heritage studies.

What next?

Optimization of the proof-of-principle **setups.**

New experiments of **laser-driven particle acceleration, PIXE, EDX, PAA** and **FNRR** also with **samples relevant** for **cultural heritage**.

RAYLAB, SourceLAB, CLPU



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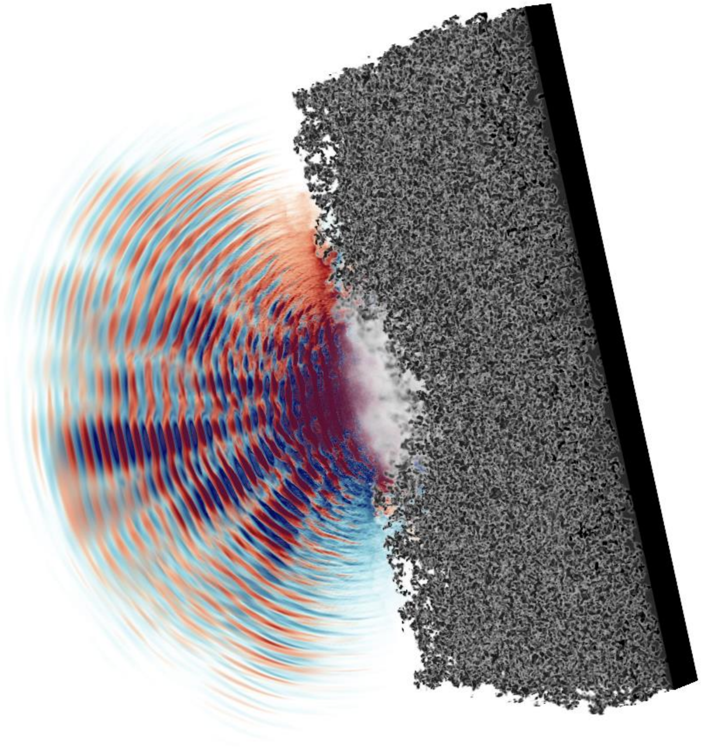

Thank you for the attention!

Lasers in the Conservation of Artworks
LACONA XIII
Florence - September 12-16, 2022

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