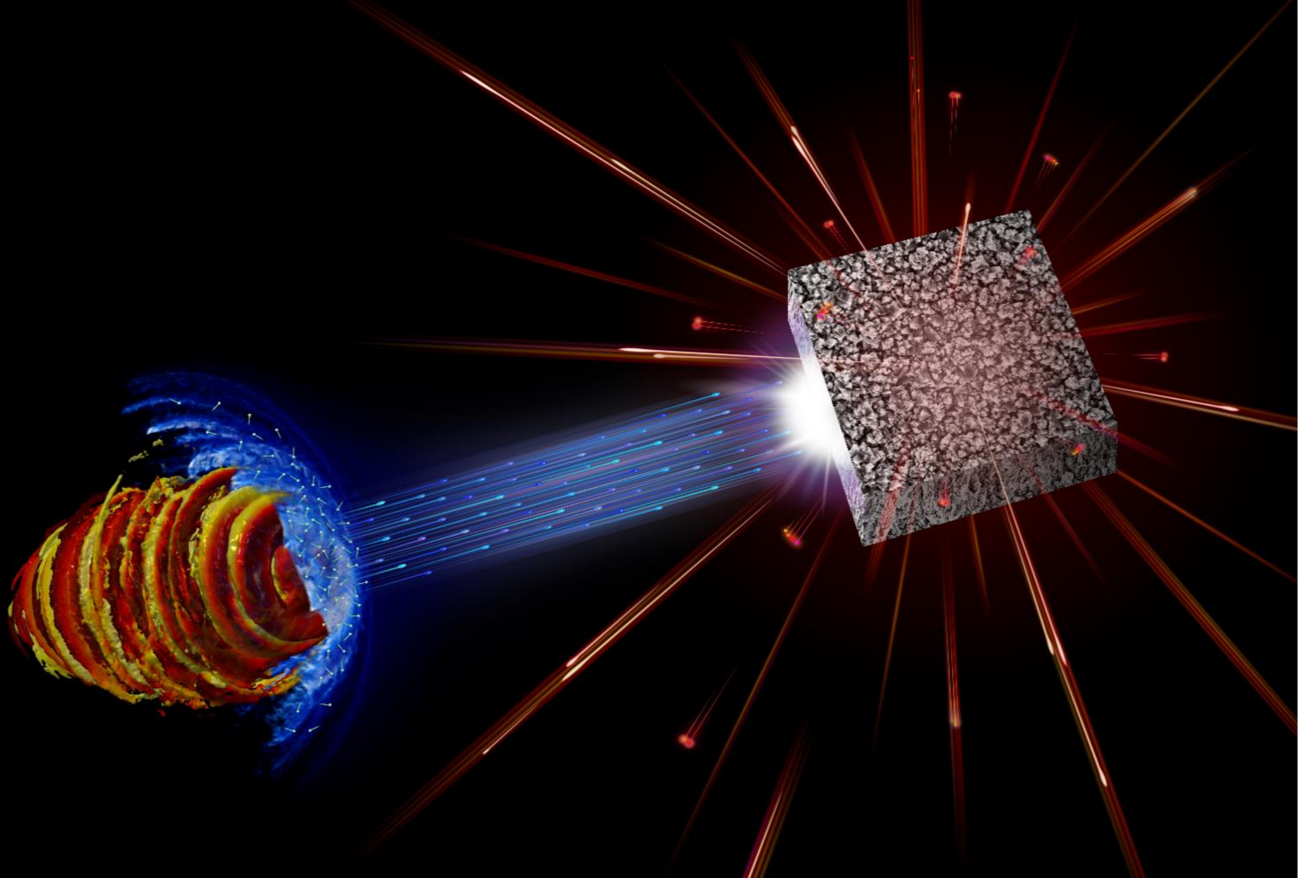
Joint ELI User Workshop on Advanced Technologies

Laser driven ion sources and applications

Laser-driven radiation sources with foam targets and applications in cultural heritage



Francesco Mirani

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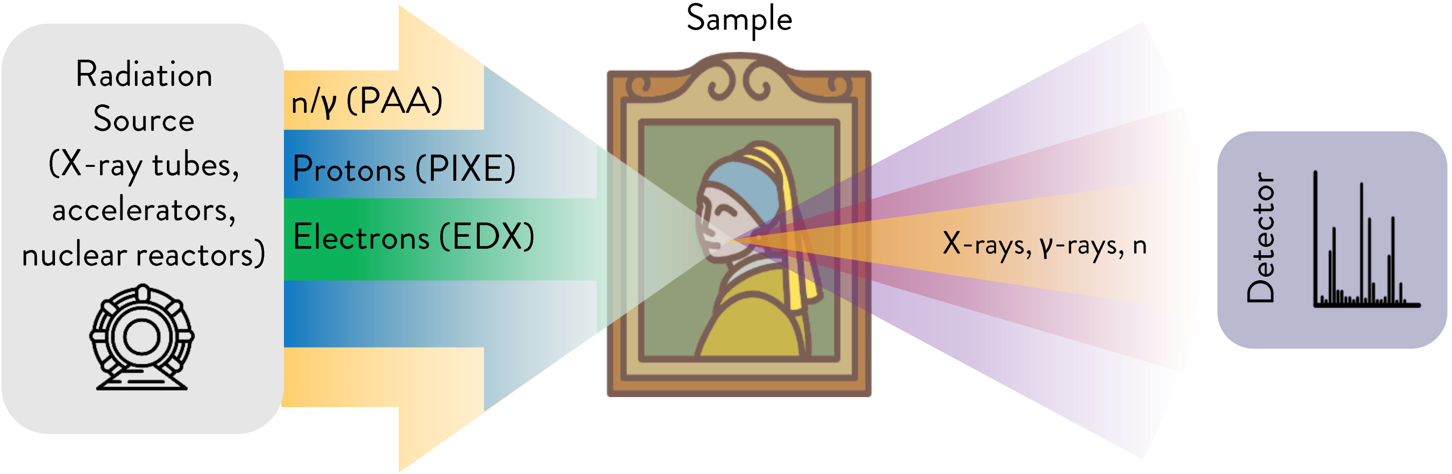
- **Collaboration** with industrial companies: RAYLAB DETECTING INNOVATION spin off POLITECNICO DI MILANO, SourceLAB

www.ensure.polimi.it

Artworks characterization with conventional particle and radiation sources



Particle Induced X-ray Emission (PIXE)

- MeV protons → X-rays
- ~10 μm range, homogeneous and stratigraphic

Energy Dispersive X-ray Spectroscopy (EDX)

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

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.

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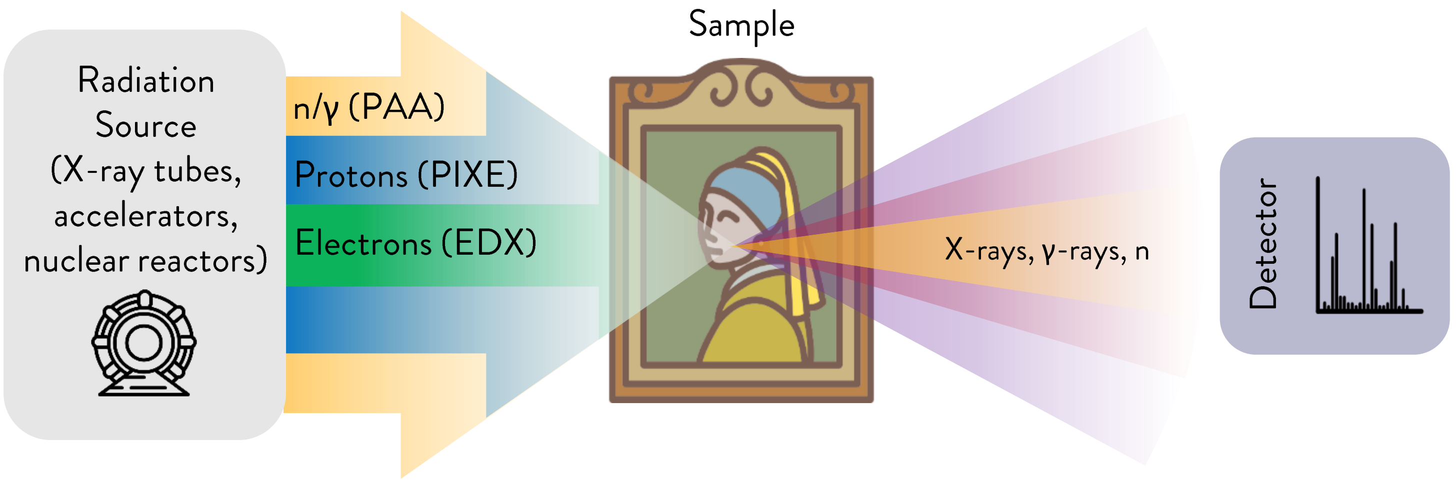
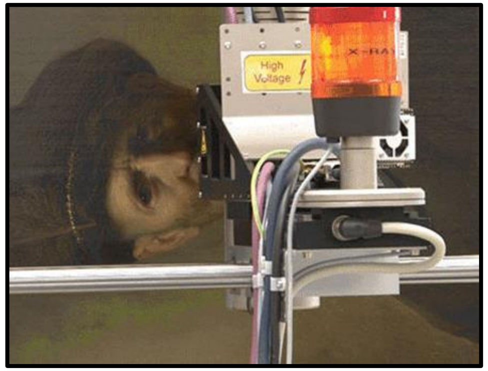


X-ray Ray Fluorescence Spectroscopy (XRF)

- keV photons → X-rays
- ~10s μm, homogeneous and large samples in-air



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.
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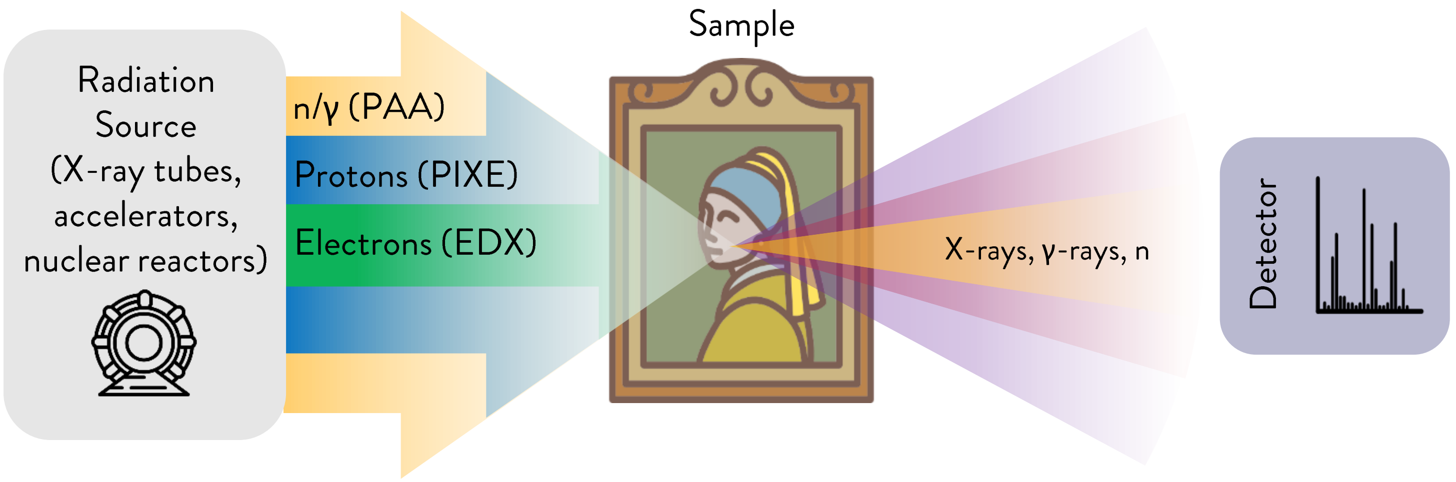
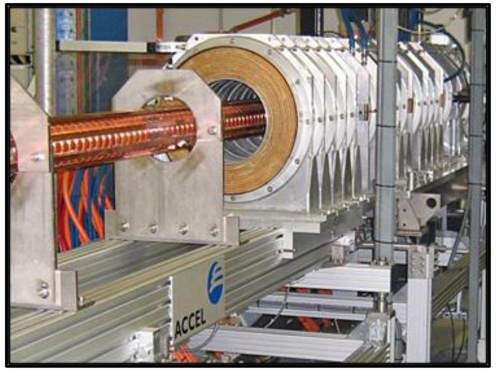




Large and **expensive** particle **accelerators** providing **monoenergetic particles.**

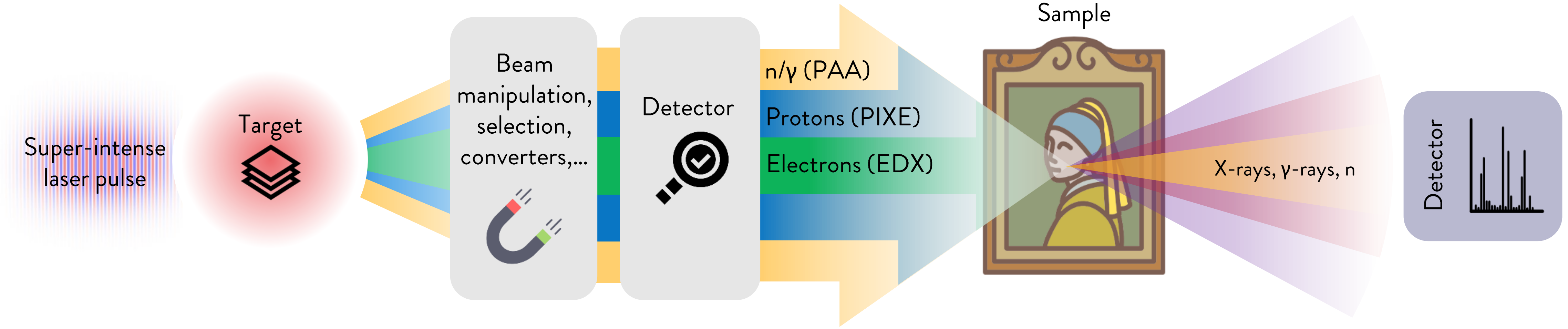
Improvements required in term of:

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

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.

Artworks characterization with laser-driven particle and radiation sources



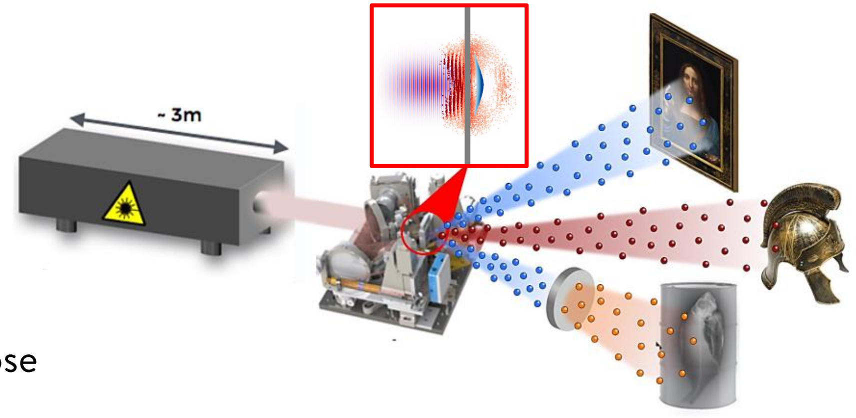
...many potential appealing features!

Compactness

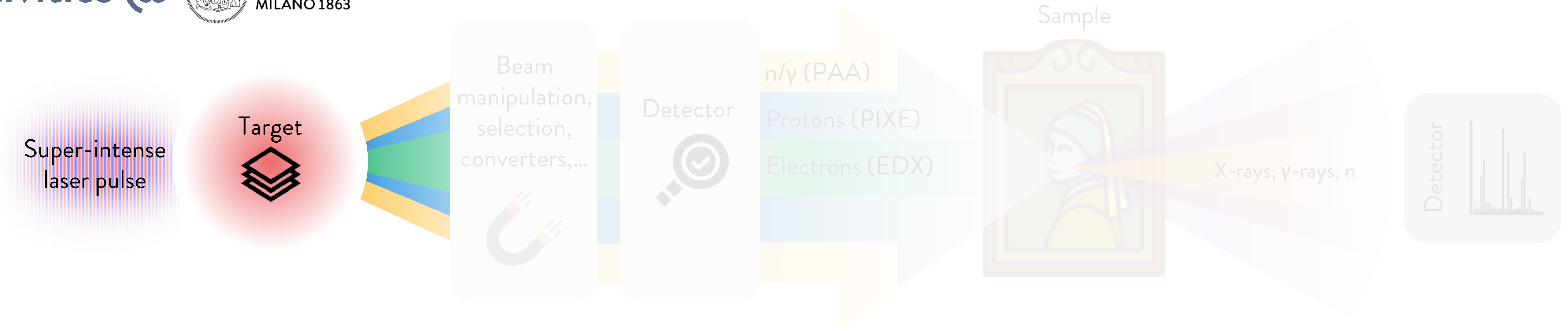
Cheapness

Energy tunability (**flexibility**)

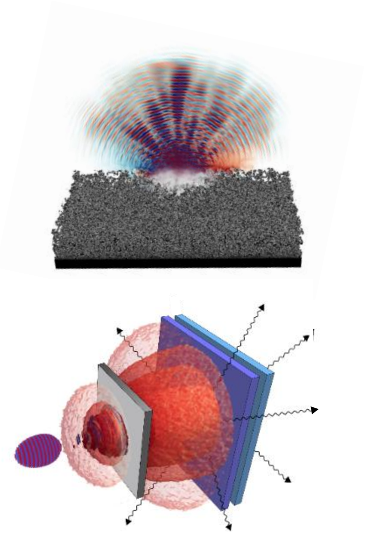
Multiple radiation **fields** → multi-purpose



Artworks characterization with laser-driven particle and radiation sources: activities @ POLITECNICO MILANO 1863



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

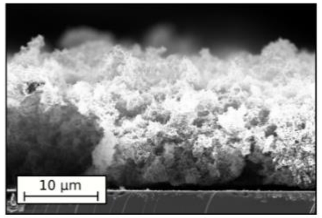


M. Galbiati, et al. *Front. Phys.* 11 (2023): 1117543.

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.



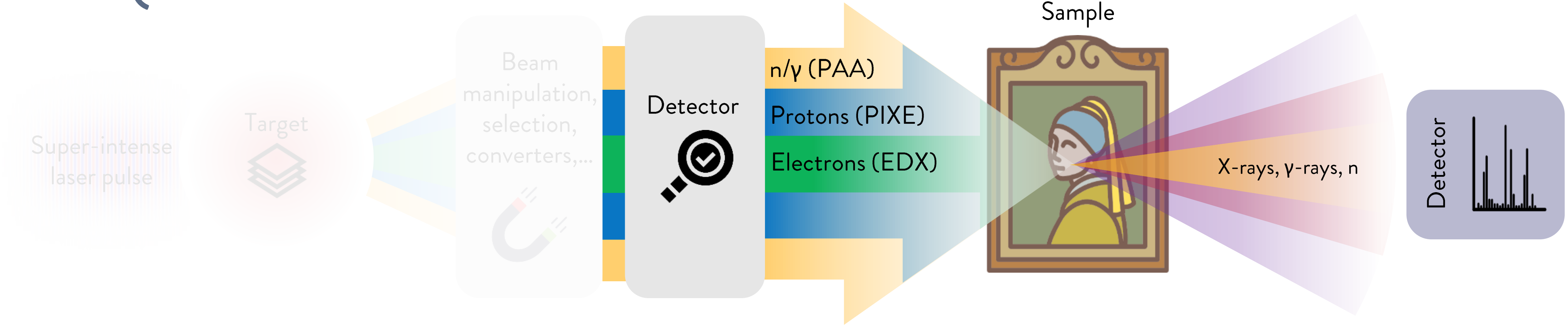
Pulsed-Laser Deposition (**PLD**) and **Magnetron Sputtering** to produce advanced materials (e.g. **Double-Layer Targets**).

A. Maffini, et al. *Phys. Rev. Mater.* 3.8 (2019): 083404.

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

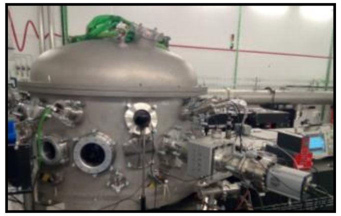
A. Maffini, et al. *Appl. Surf. Sci.* (2022): 153859.

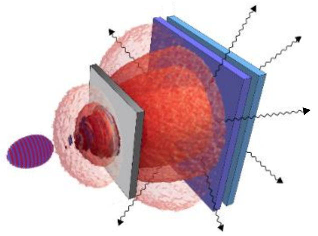
Artworks characterization with laser-driven particle and radiation sources: activities @

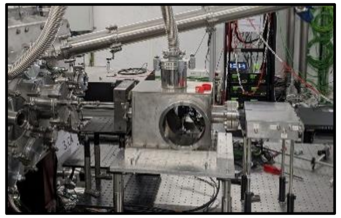


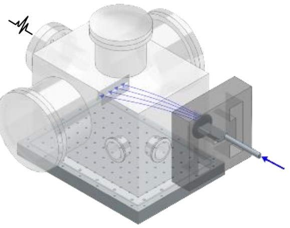
Study **applications** of laser-driven particle sources in **materials characterization.**

A. Maffini, et al. *Front. Phys.* 11 (2023): 1223023.
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. *Phys. Rev. Appl.* 19.4 (2023): 044020.







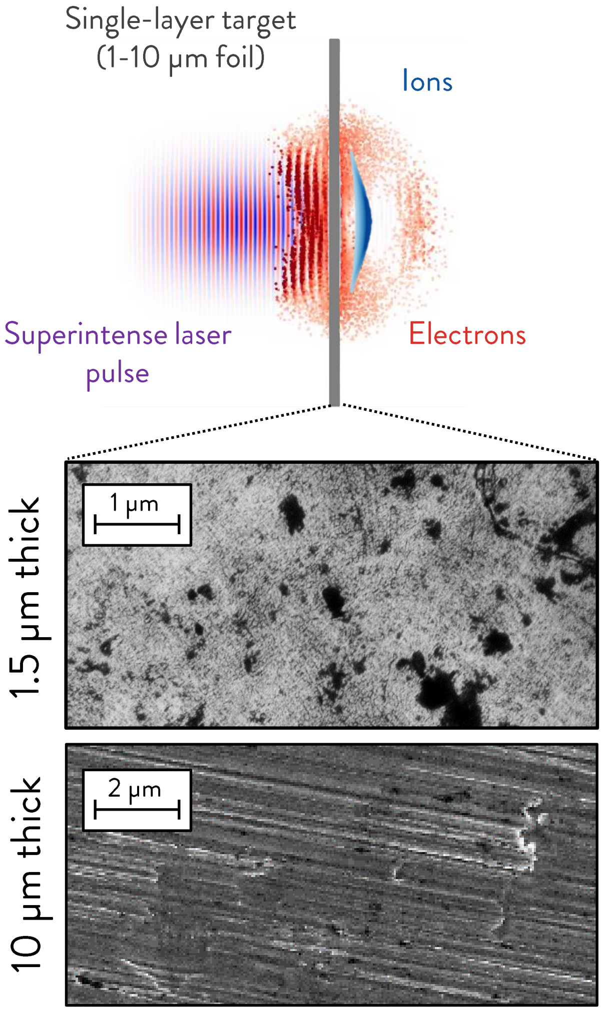


Development of a commercial, **application-oriented proton spectrometer** in collaboration with RAYLAB

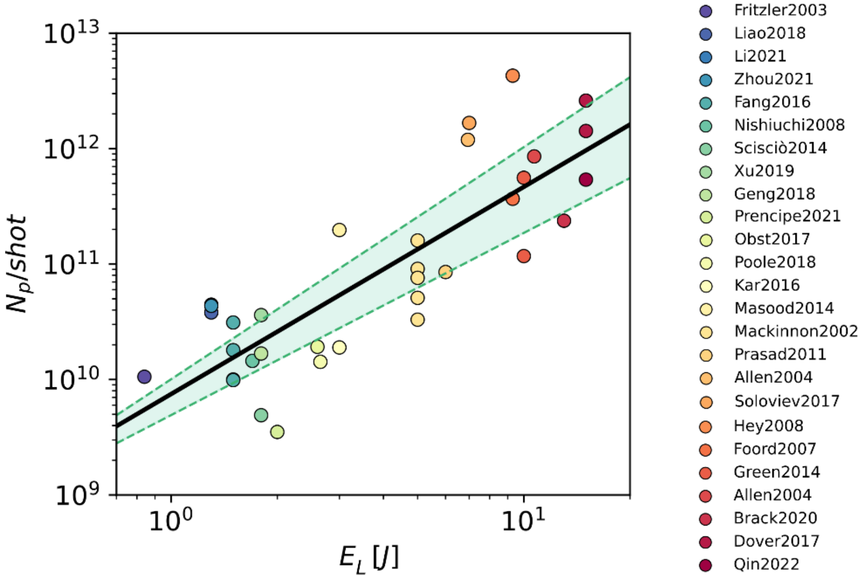
F. Casamichiela. "Study of a novel technique for laser-driven proton beam diagnostics." *MS Thesis* (2019).

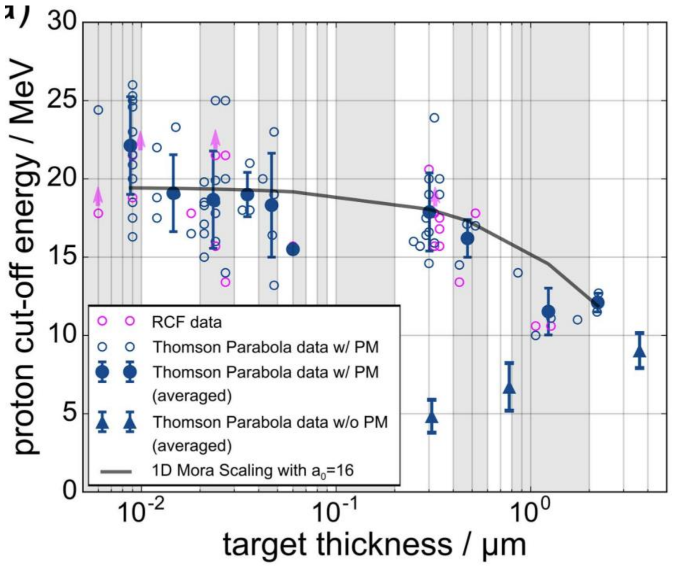
F. Gatti, et al. *in preparation*.

Laser-driven particle acceleration with solid targets



- Emission of **electrons** and **ions.**
- **10^9 - 10^{12} protons/shot** accelerated (depending on laser and target properties).
- **Broad** energy **spectra** (max ~ 1 - 10s MeV).
- **Control target properties (e.g. thickness)** → tune the energy.

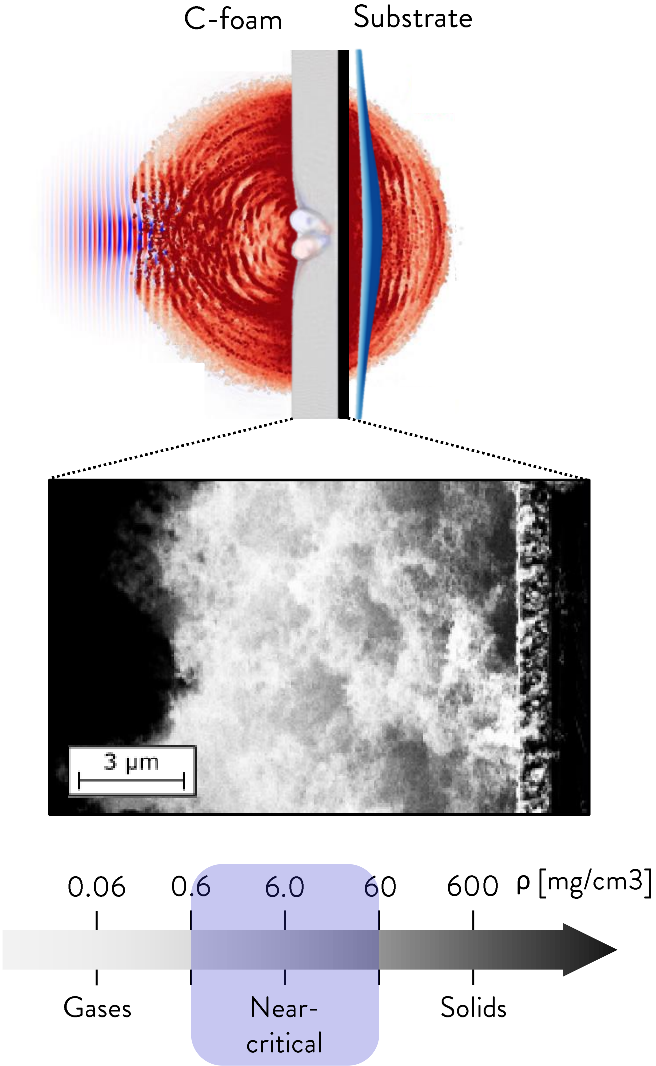




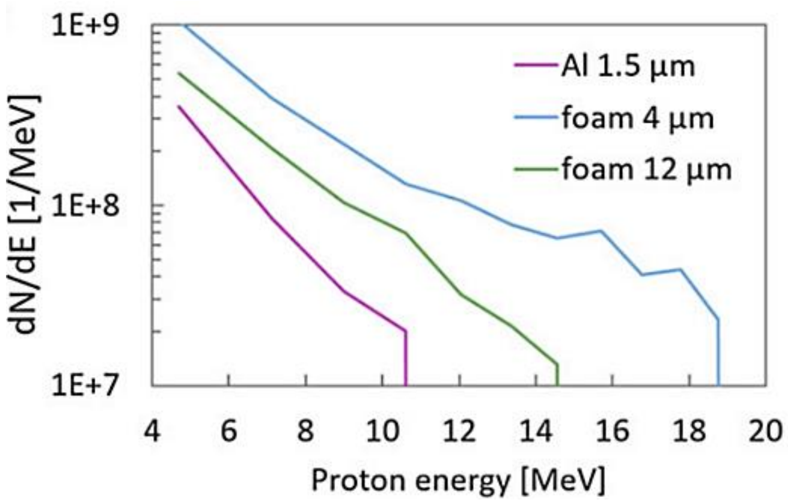
F. Mirani, et al. *Phys. Rev. Appl.* 19.4 (2023): 044020.
P. L. Poole, et al. *New J. Phys.* 20.1 (2018): 013019.

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

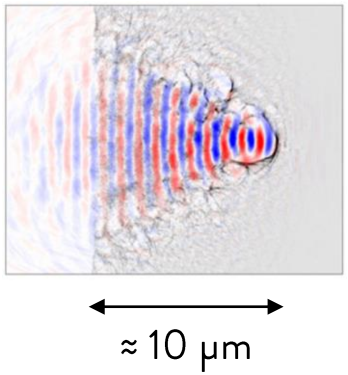
Double-Layer Targets for enhanced particle acceleration



Carbon foam-based **DLT** allows a **higher laser absorption** → **Increase the energy and number** of accelerated particles. → **Meet** requirements of demanding **applications!**



- **Laser self-focusing** process:



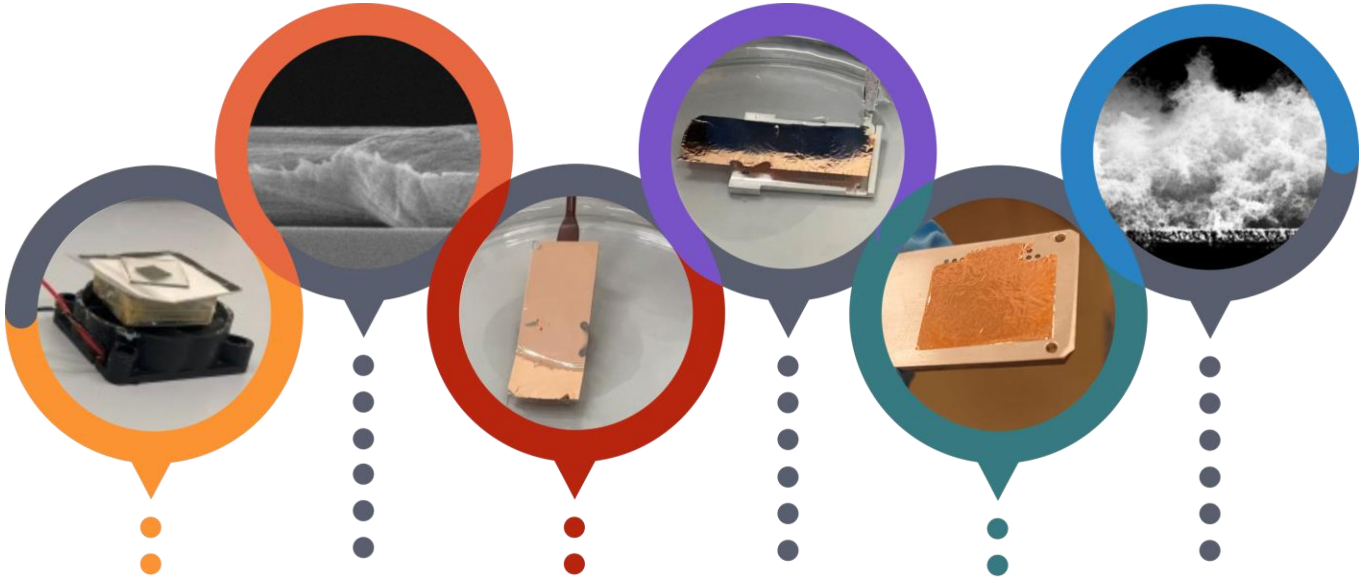
Control of all target properties to tune the energy and increase the shot-to-shot reproducibility → **Strategy to entirely produce the DLT**.

A. Maffini, et al. *Appl. Surf. Sci.* (2022): 153859.

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

Fully-optimized target production procedure for the experimental campaign

- **Deposition** of both the Aluminium **substrate (50 nm – 6 μm) and carbon-foam** to properly control thickness and density.

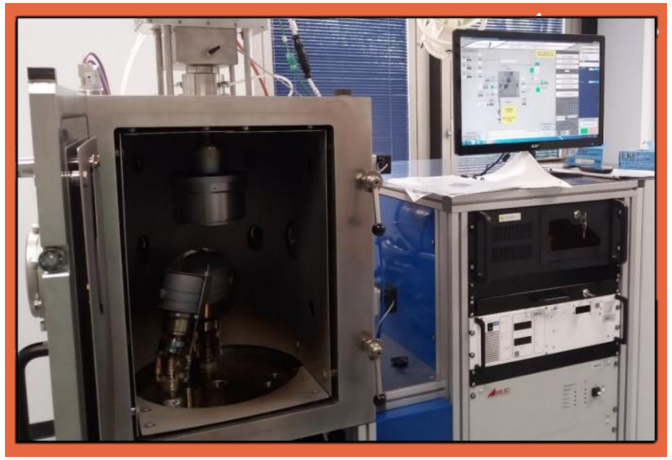


Spin coated soap layer on wafer → HiPIMS **substrate deposition** → **Dissolution** in water → **Fishing** of the film → Free-standing **substrate** → PLD **C-foam deposition** →

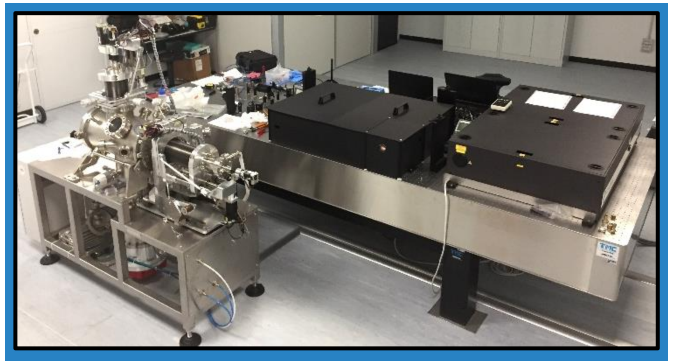
- **Tested** in November 2023 @ CLPU (Centro de Láseres Pulsados) with 1 PW Vega-3 laser!

A. Maffini, et al. *EPJ Techniques and Instrumentation* 10.1 (2023): 15.

Facilities @ PoliMi



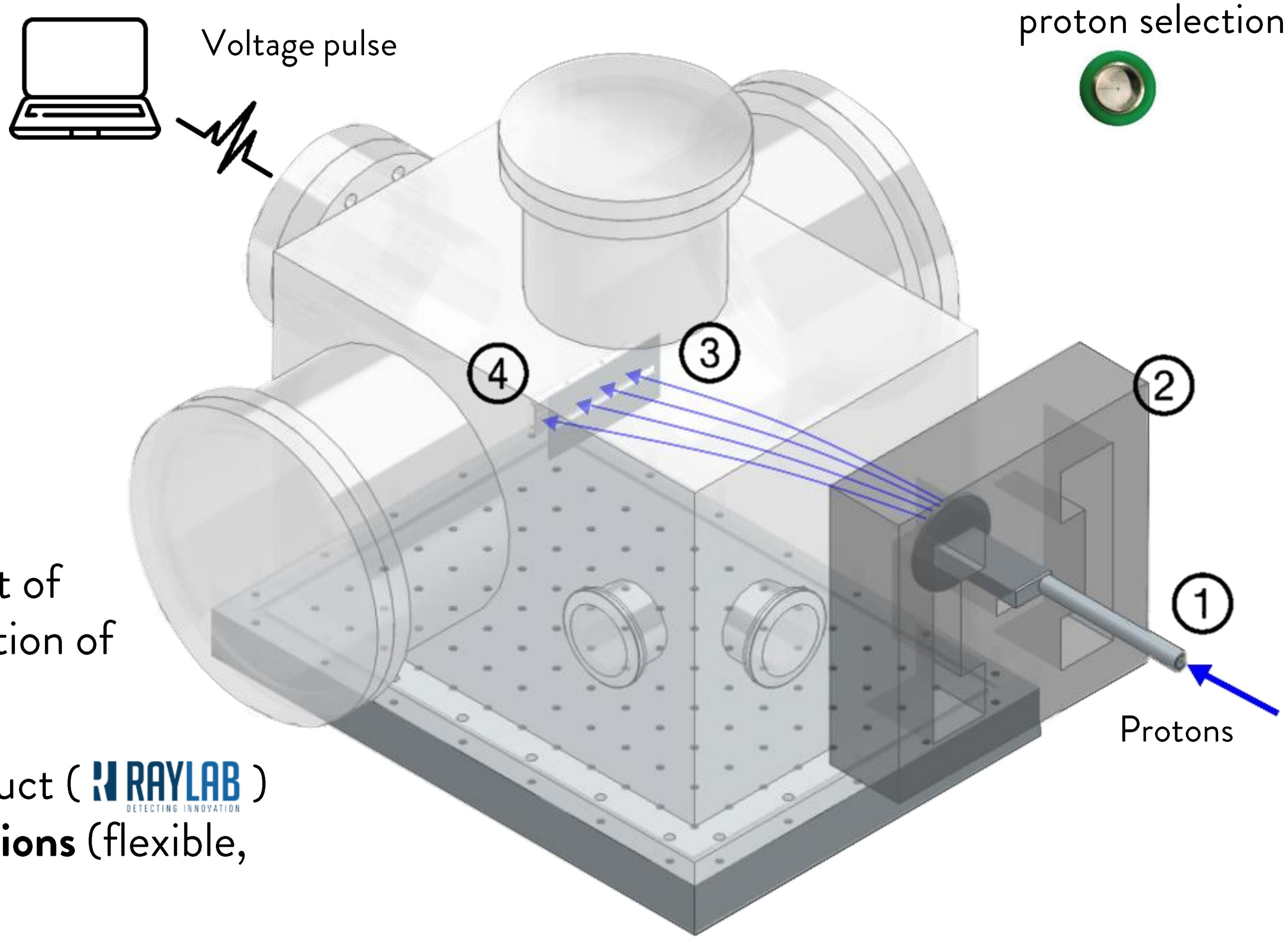
High-Power Impulse Magnetron Sputtering



Pulsed-Laser Deposition

Development of a spectrometer for proton characterization and applications

- Provide the **proton spectra online** (0.4 – 20 MeV).
- Absolute calibration → **Number of accelerated particle.**
- **High resolution at low-medium energy** → Most of protons for characterization of artworks.
- Future commercial product (RAYLAB) **oriented toward applications** (flexible, compact and reliable)
- **Tested** in November 2023 @ CLPU with 1 PW Vega-3 laser!

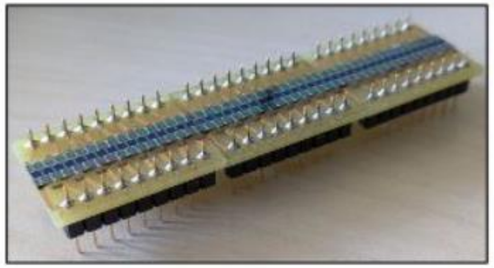


① **Pin-hole** for proton selection

② **Magnet** to deflect protons

③ **Multilayer stopper** to remove C-ions

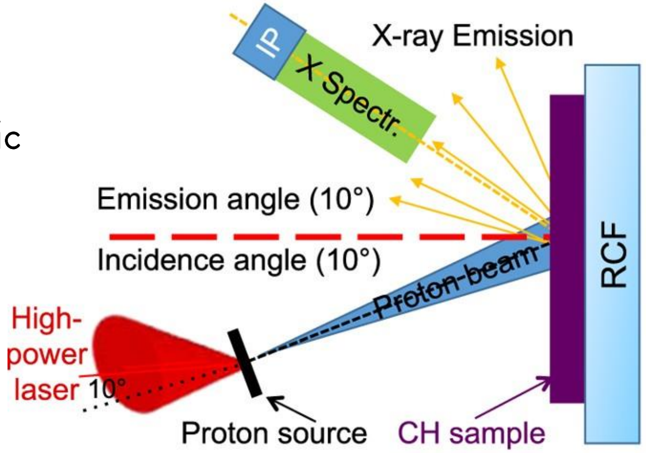
④ **Silicon photodiode array** for proton detection

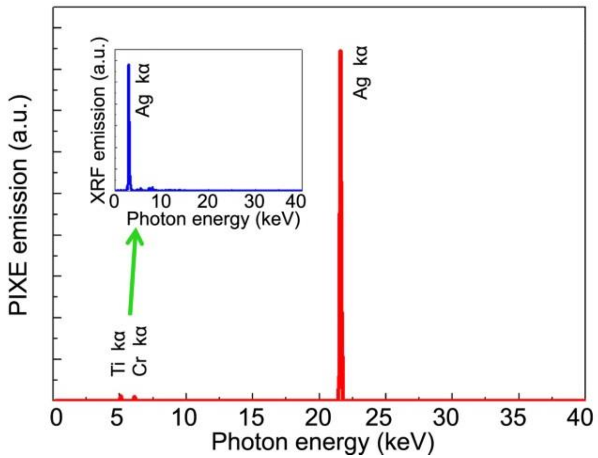


Overview of laser-driven PIXE experiments

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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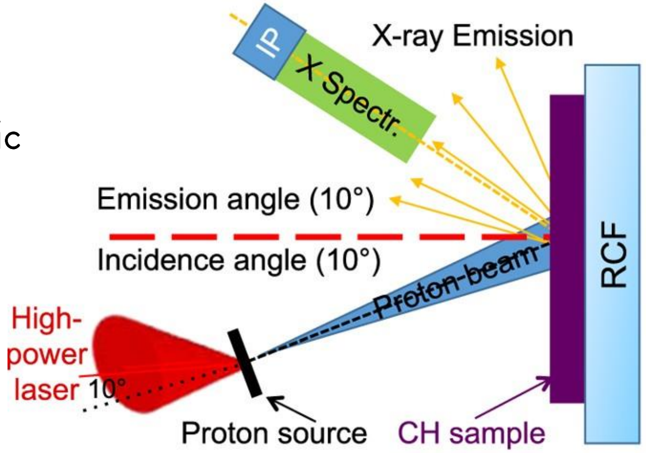

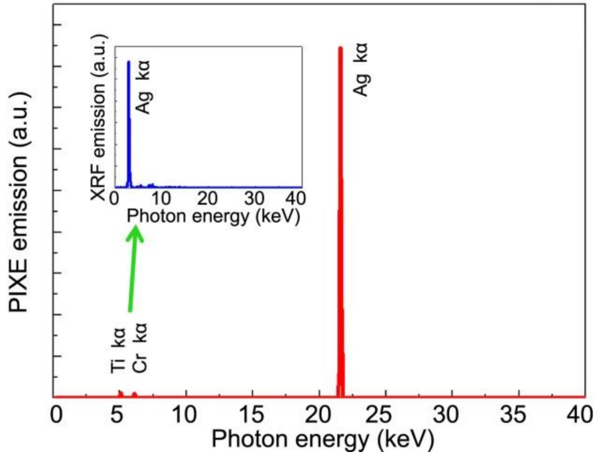

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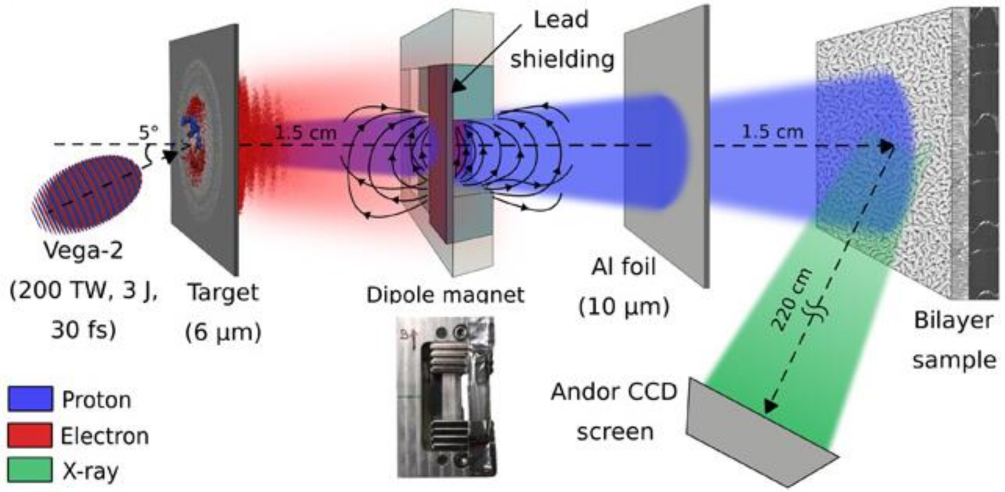
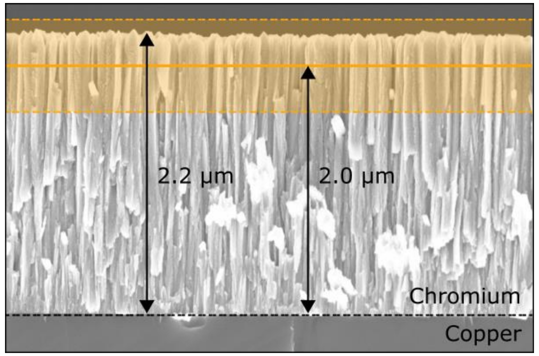
Experiment of combined laser-driven **PIXE quantitative analysis** & **EDXS.**



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

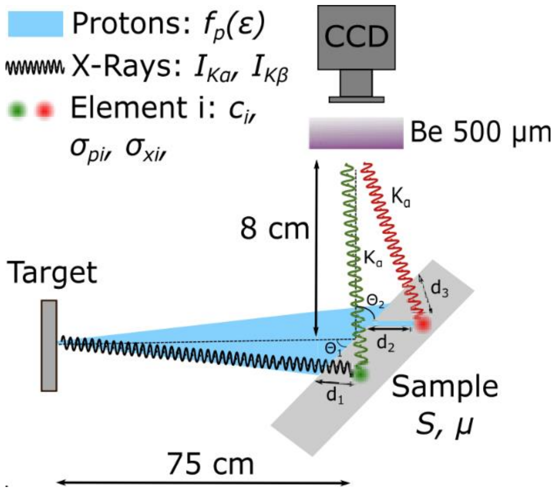


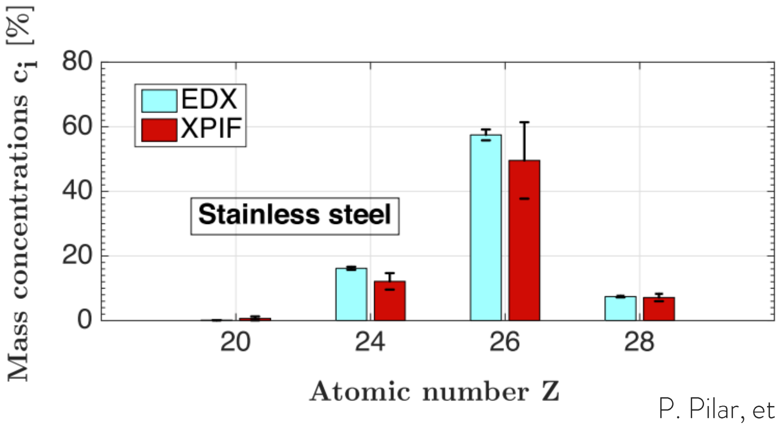
F. Mirani, et al. *Sci. Adv.* 7.3 (2021): eabc8660.

Overview of laser-driven PIXE experiments

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.

Overview of laser-driven PIXE experiments

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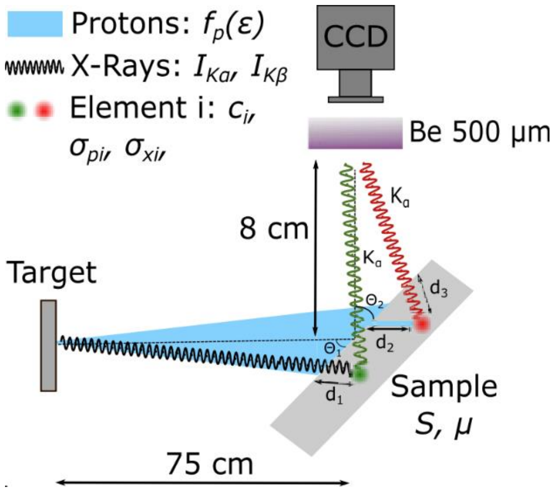
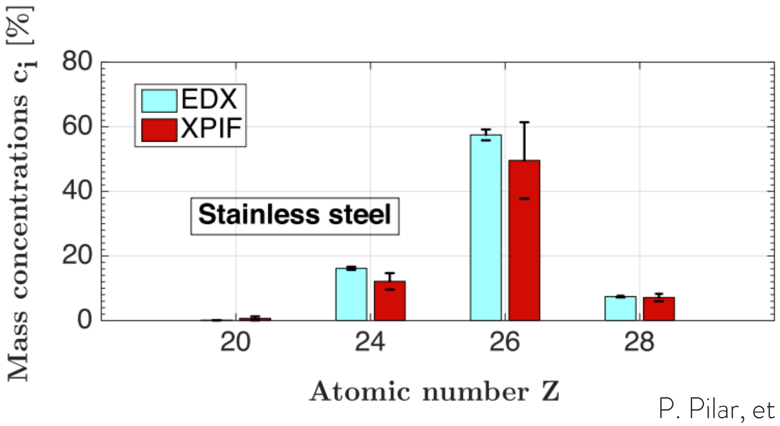
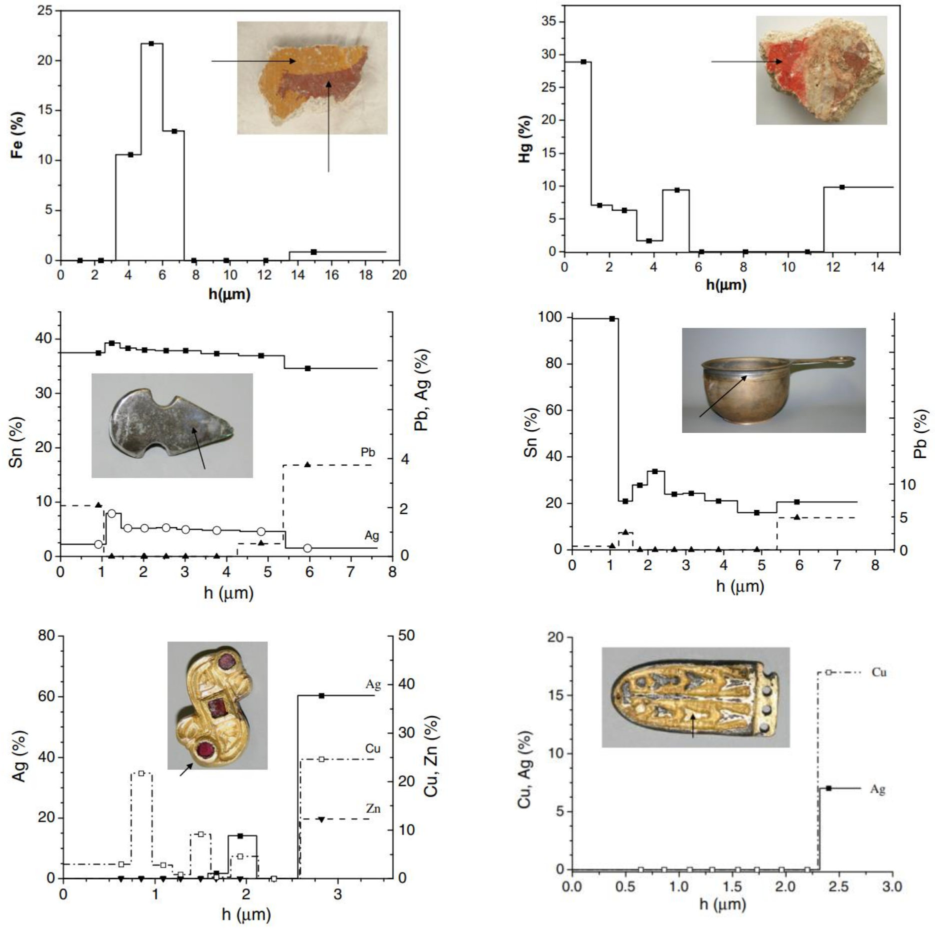




P. Pilar, et al. *Sci. Rep.* 11.1 (2021): 1-10.

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

In the framework of cultural heritage studies, differential PIXE is of particular interest...



Ž. Šmit, et al. *Nucl Instrum Methods Phys Res B* 266.10 (2008): 2329-2333.

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

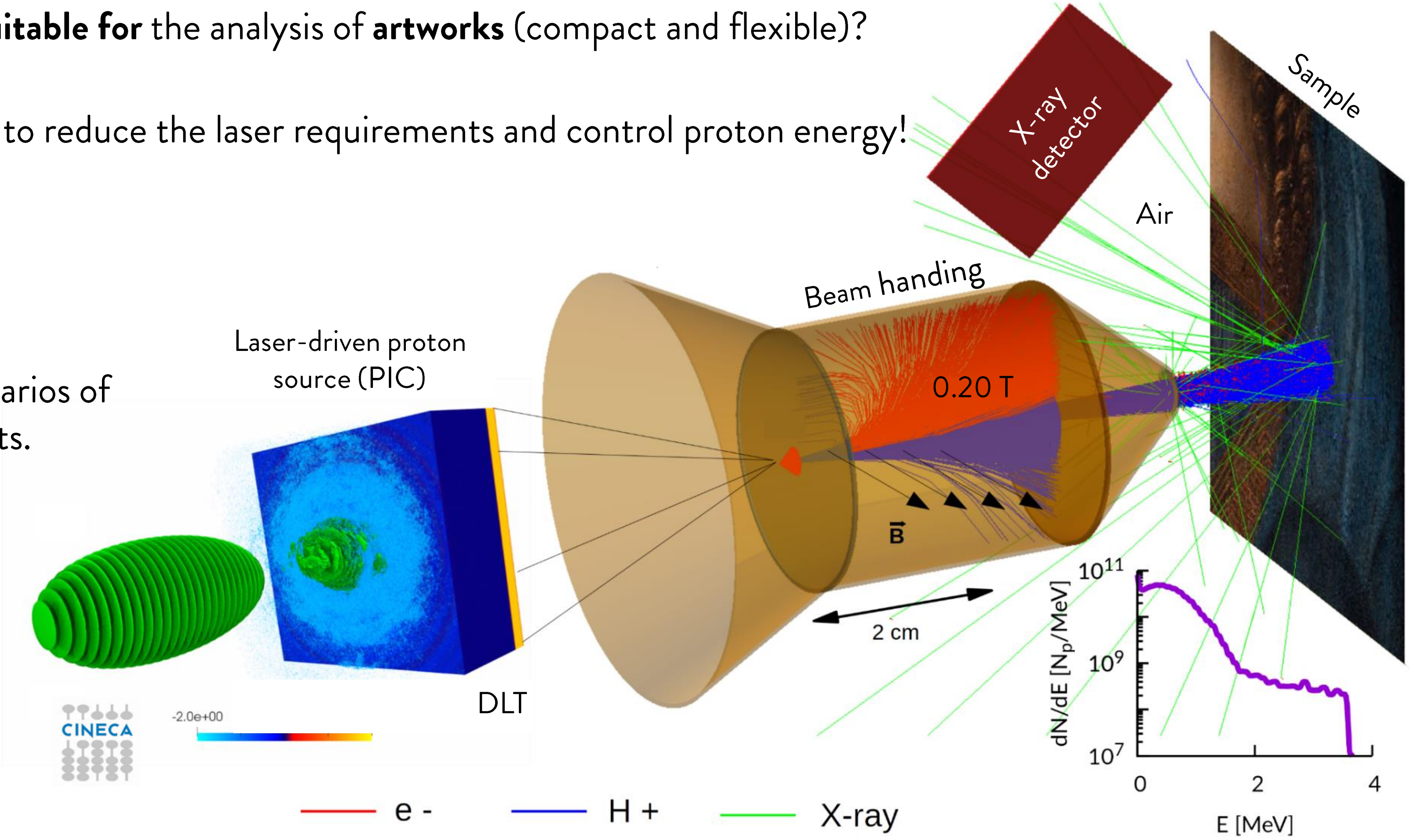
How do we make the **PIXE suitable for** the analysis of **artworks** (compact and flexible)?

Exploit **Double Layer Targets** to reduce the laser requirements and control proton energy!

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

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

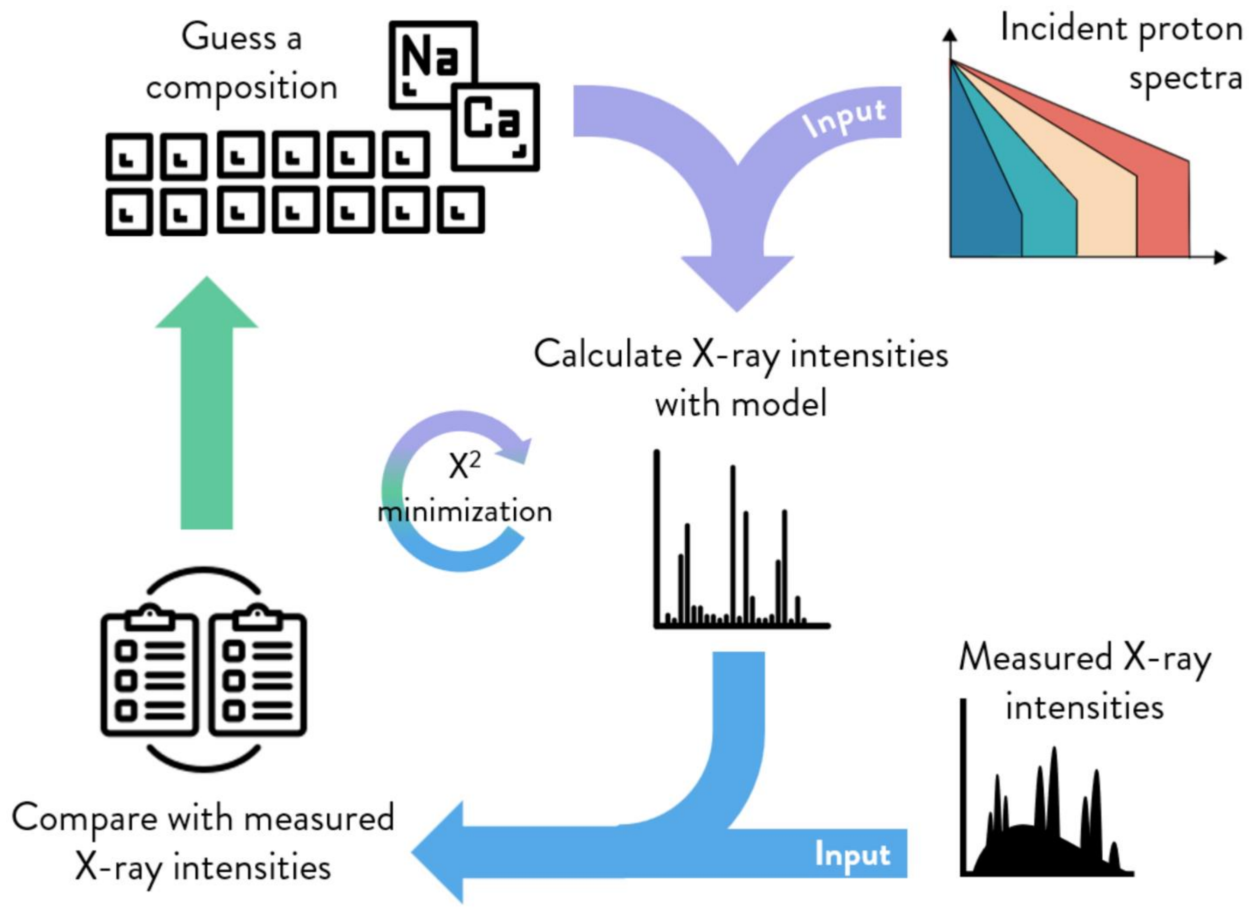
- piccante — 3D Particle-In-Cell
- GEANT4 — Monte Carlo



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**.



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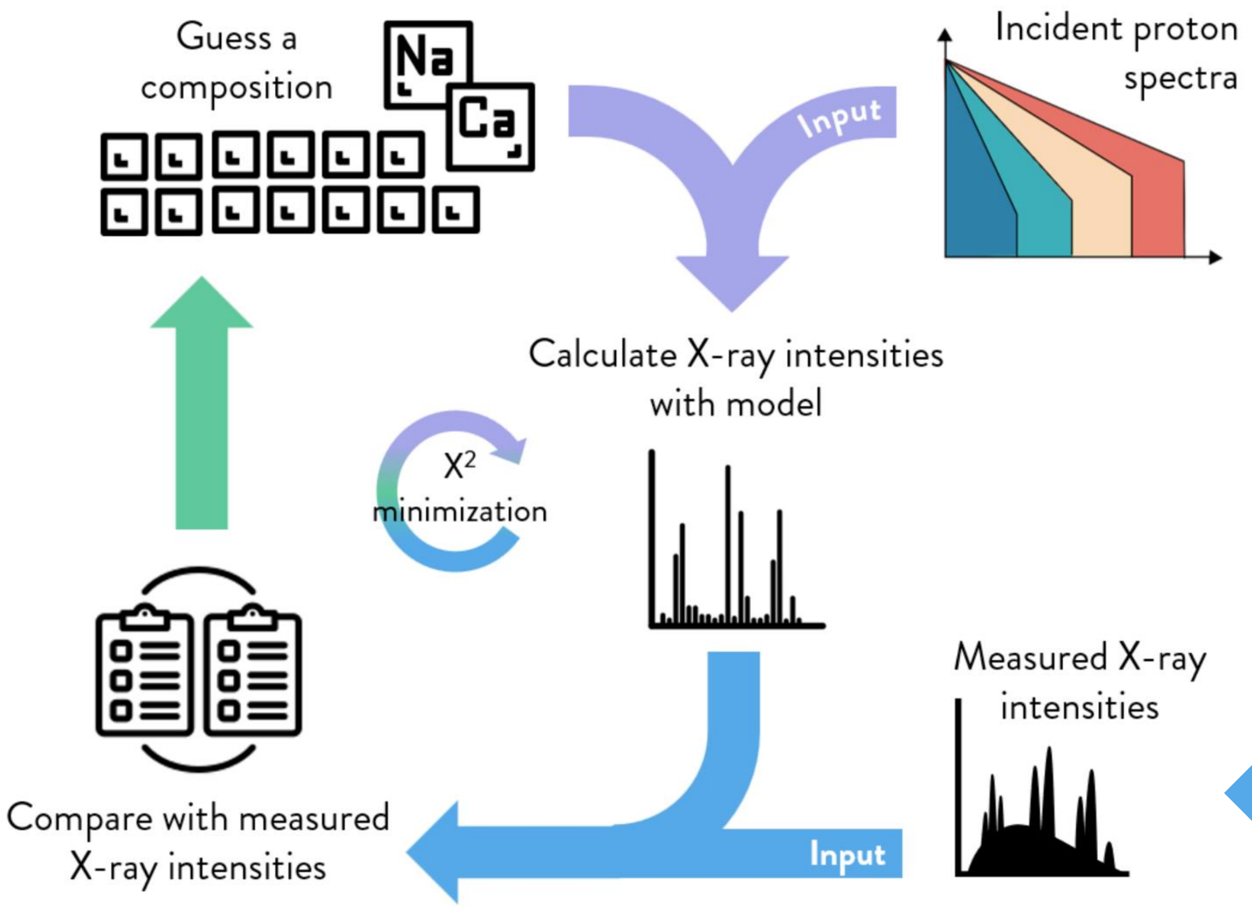
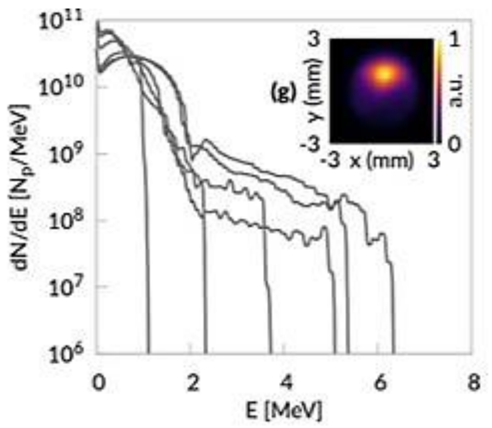
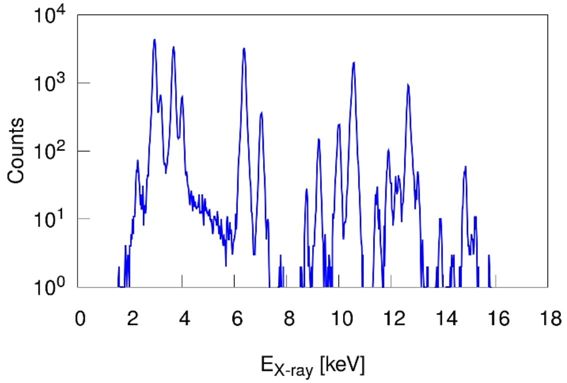






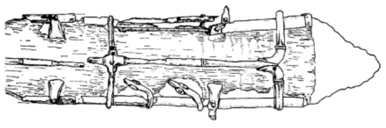
Tested with PIC proton spectra and “synthetic” X-ray spectra from the Monte Carlo.

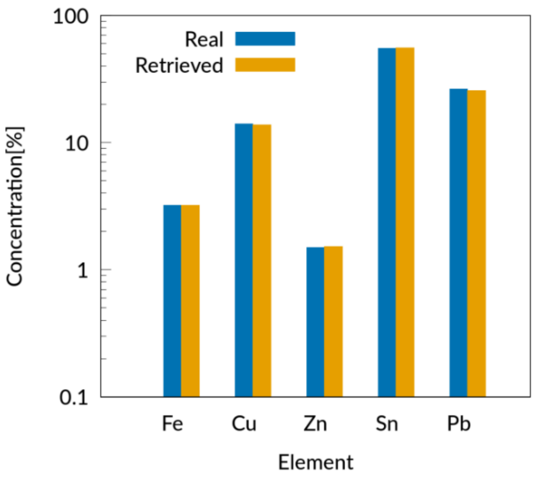
M. Passoni, et al. *Sci. Rep.* 9.1, (2019): 9202.

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

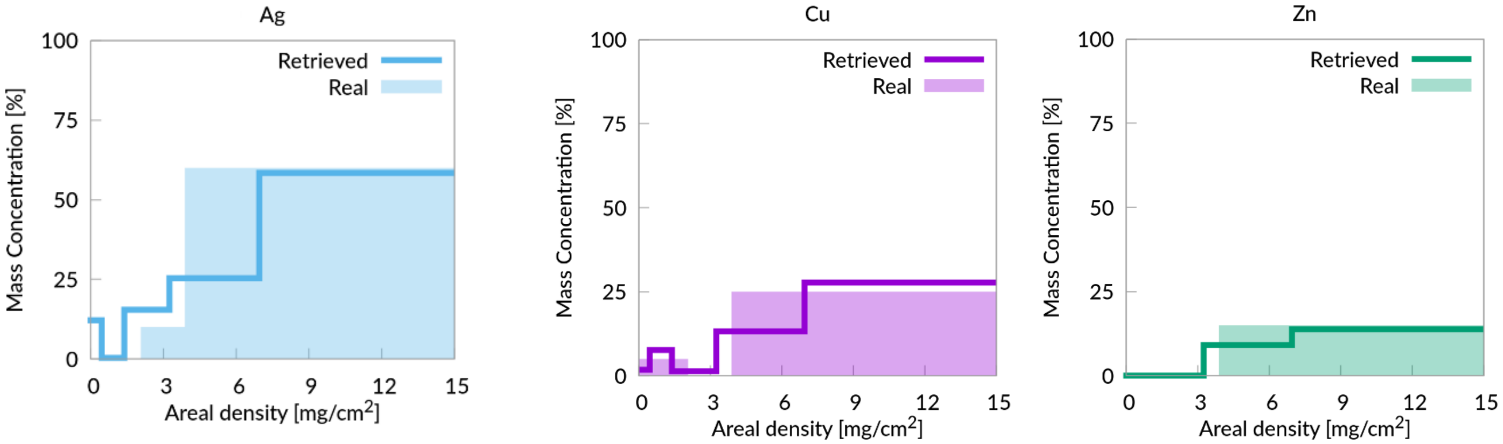
Dedicated software to process X-ray spectra and retrieve the **sample composition**.

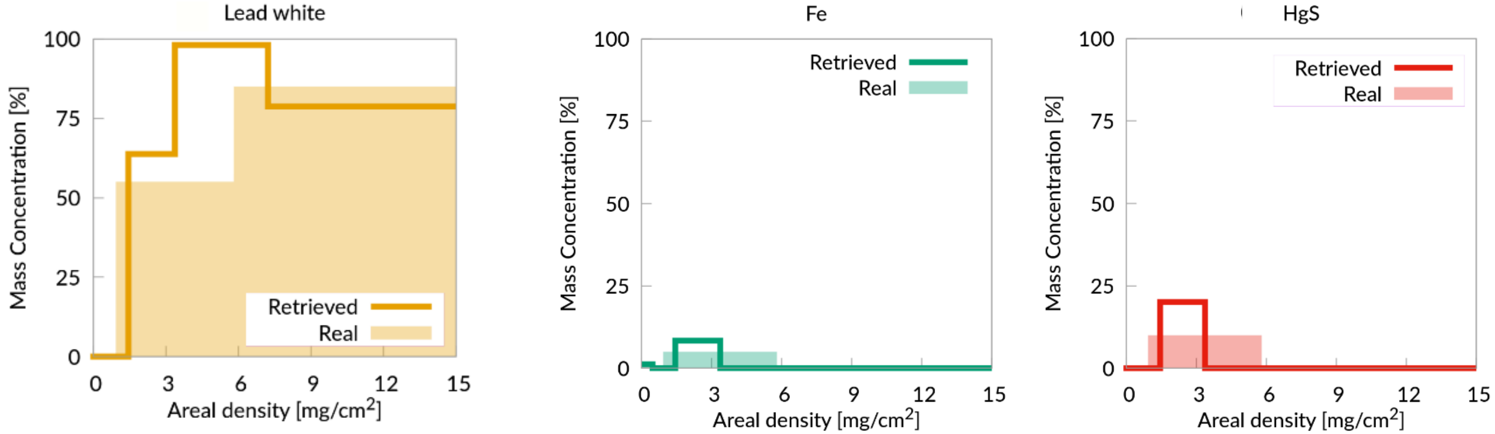
- **Homogeneous** sample (Roman sword-scabbard):





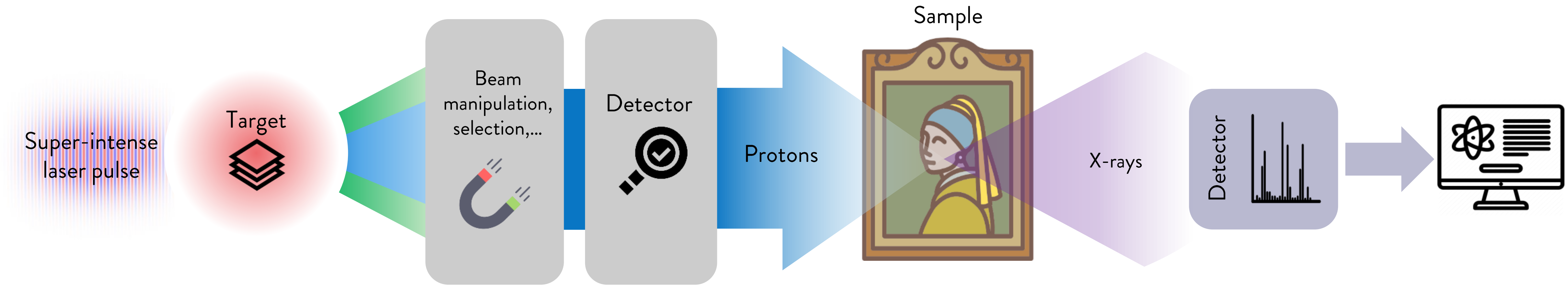
- **Complex structured** samples (Medieval brooch and Renaissance painting) :



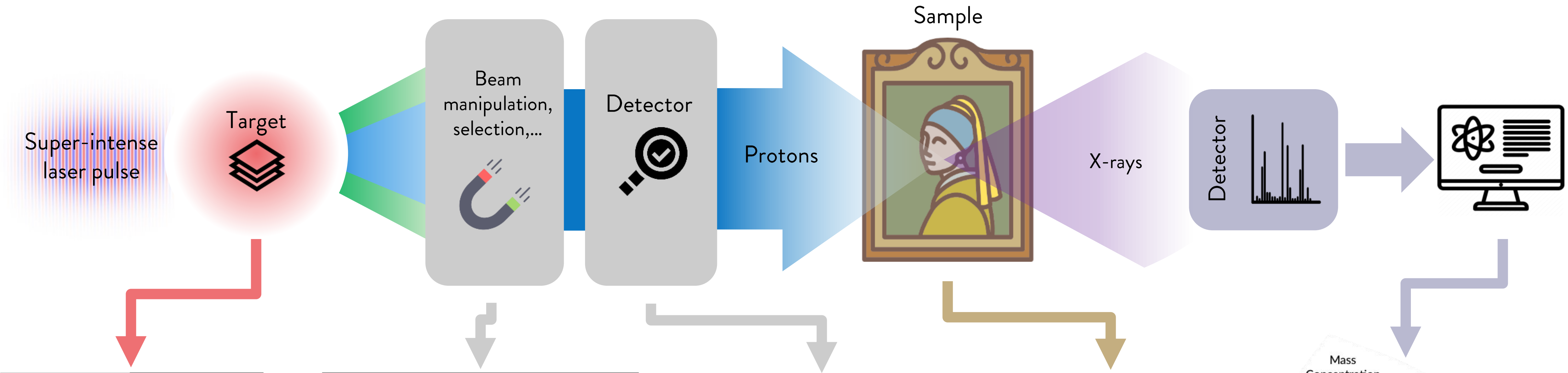


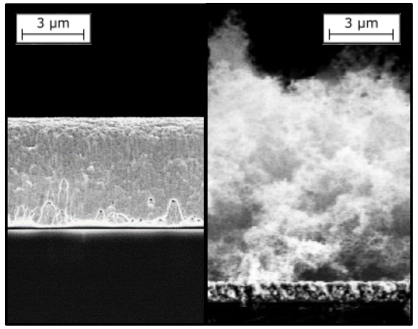
M. Passoni, et al. *Sci. Rep.* 9.1, (2019): 9202.
L. De Viguerie, et al. Analytical chemistry 81.19, (2009): 7960-7966.

Proposed differential laser-driven PIXE experiment @ eli Beamlines

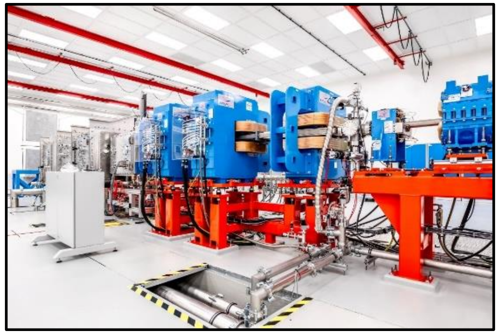


Proposed differential laser-driven PIXE experiment @ eli Beamlines

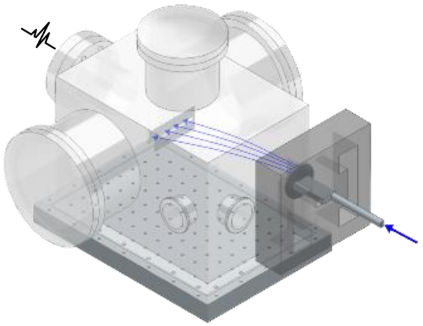




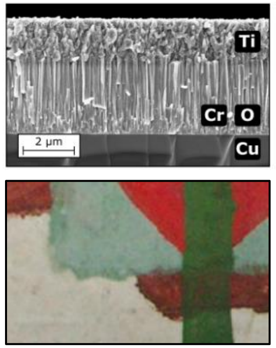
Advanced targets and **DLTs** to **enhance proton number and energy**



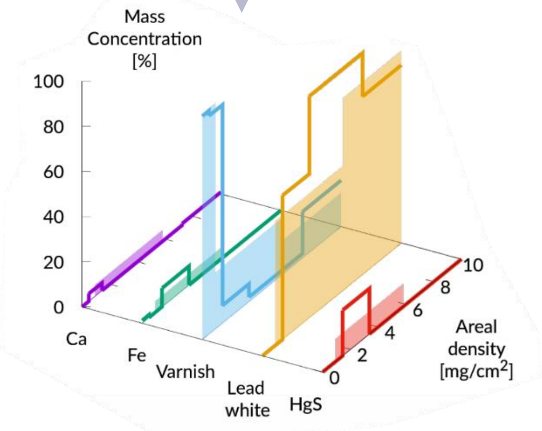
ELIMAIA **Beamline to tune proton** energy



Spectrometer to support proton characterization



Self-produce **multilayer samples** and **cultural heritage** objects

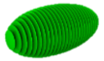


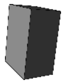
Code for **differential PIXE** stratigraphic analysis

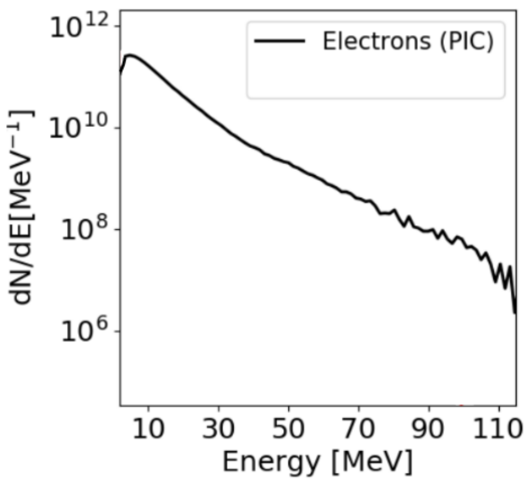
Numerical study of laser-driven PAA feasibility

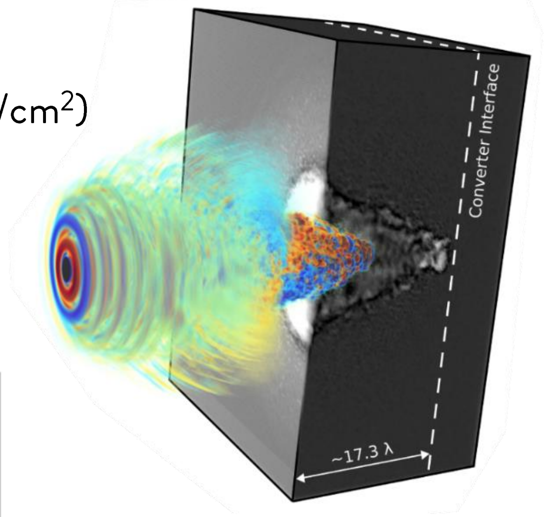
Development of a **scheme** to perform laser-driven Photon Activation Analysis

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

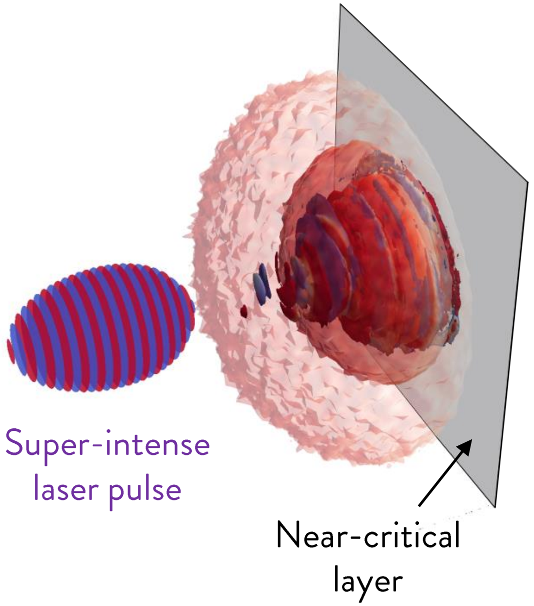

200 TW laser (8×10^{20} W/cm^2)


Near-critical layer





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



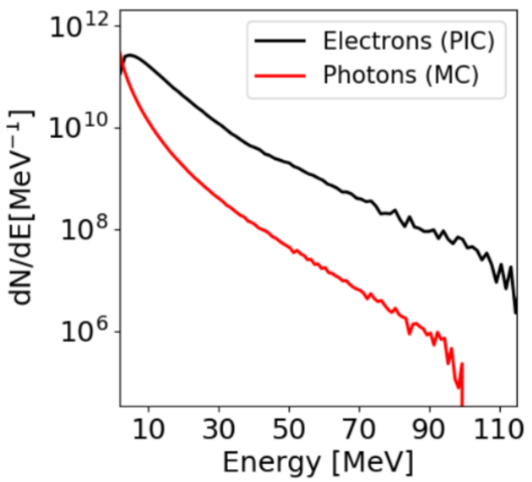
F. Mirani, et al. *Commun Phys* 4.1, (2021): 1-13

Numerical study of laser-driven PAA feasibility

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

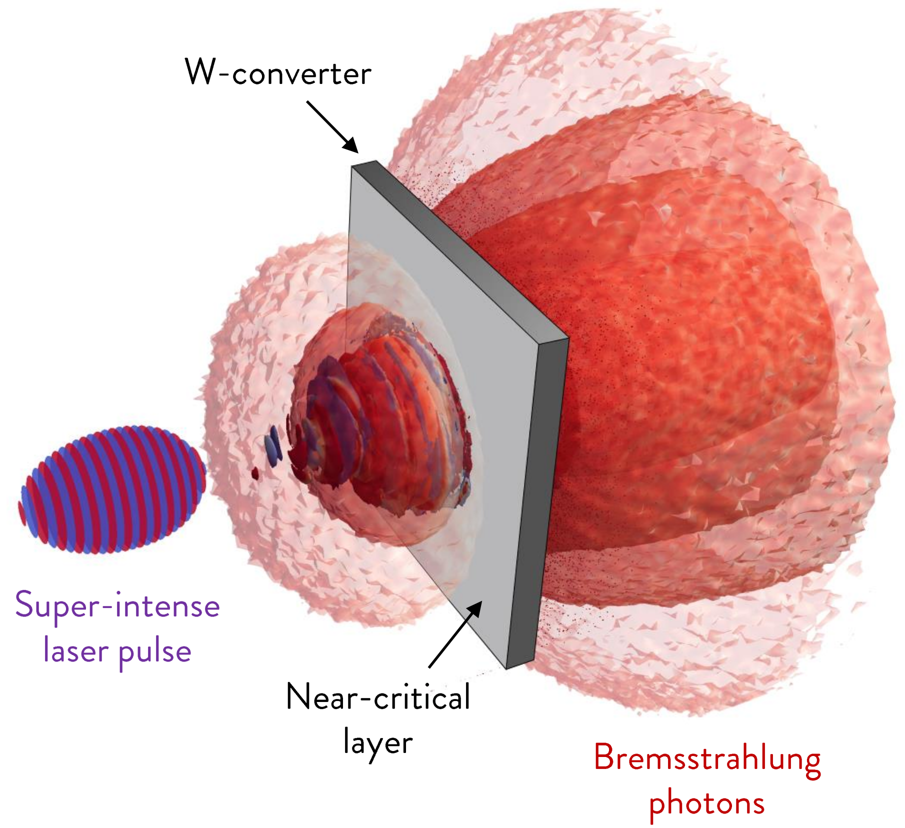
2. **Hot e-** interaction with mm-thick **W converter** → **Bremsstrahlung photons** generation (**Monte Carlo** FLUKA)

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



✓ Broad angular distribution

✓ Energy up to 100 MeV



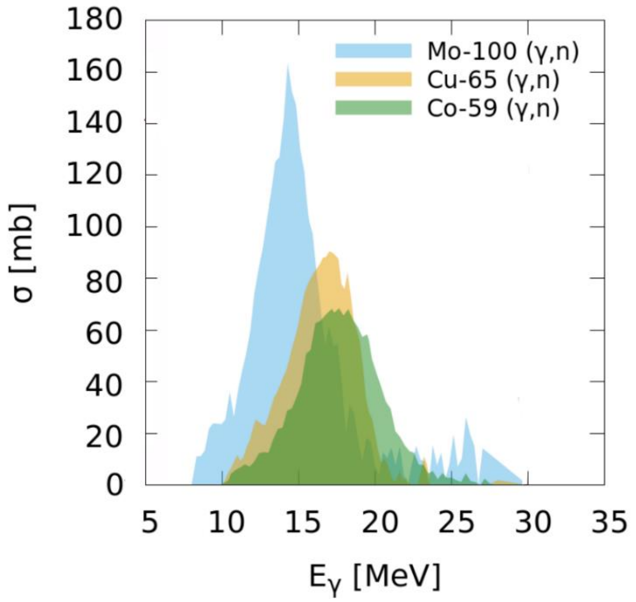
F. Mirani, et al. *Commun Phys* 4.1, (2021): 1-13

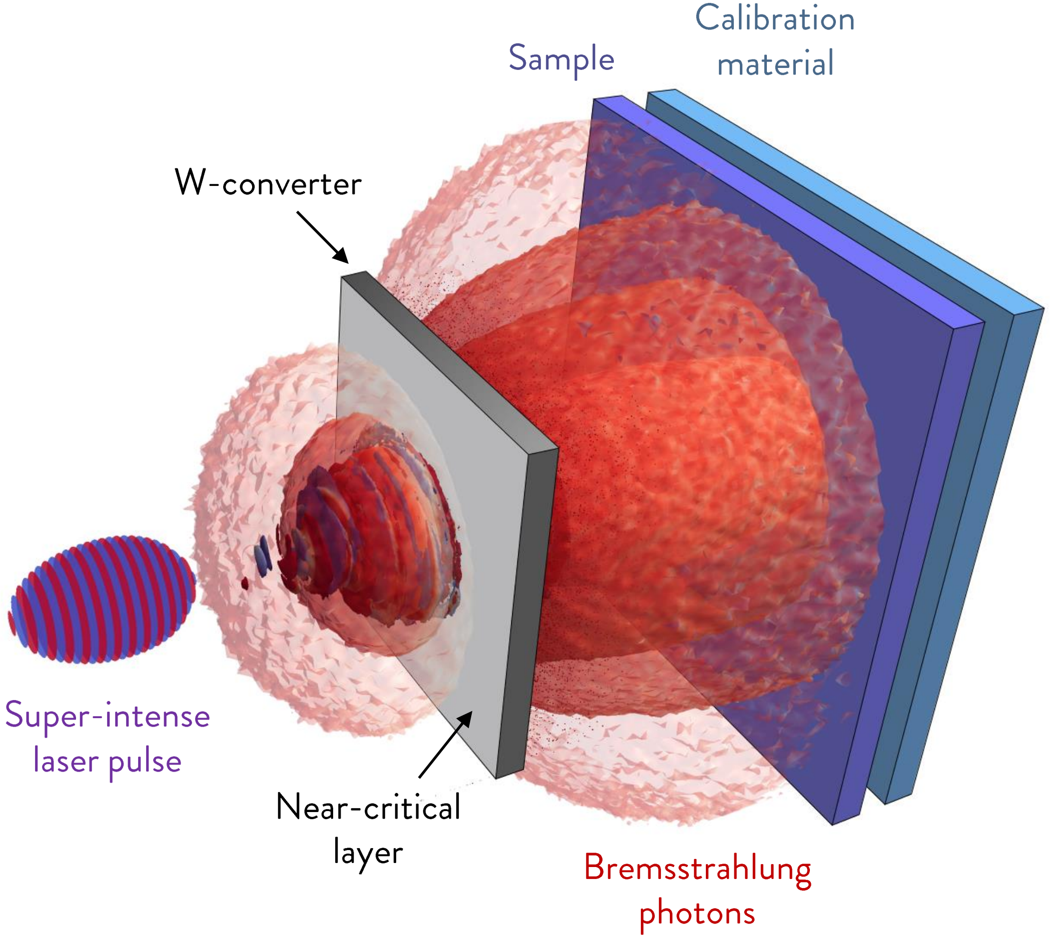
Numerical study of laser-driven PAA feasibility

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:



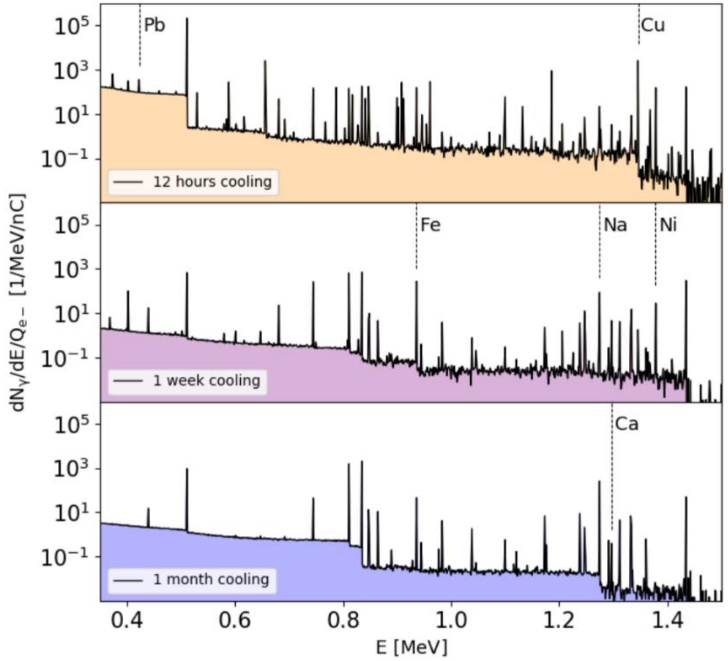


F. Mirani, et al. *Commun Phys* 4.1, (2021): 1-13

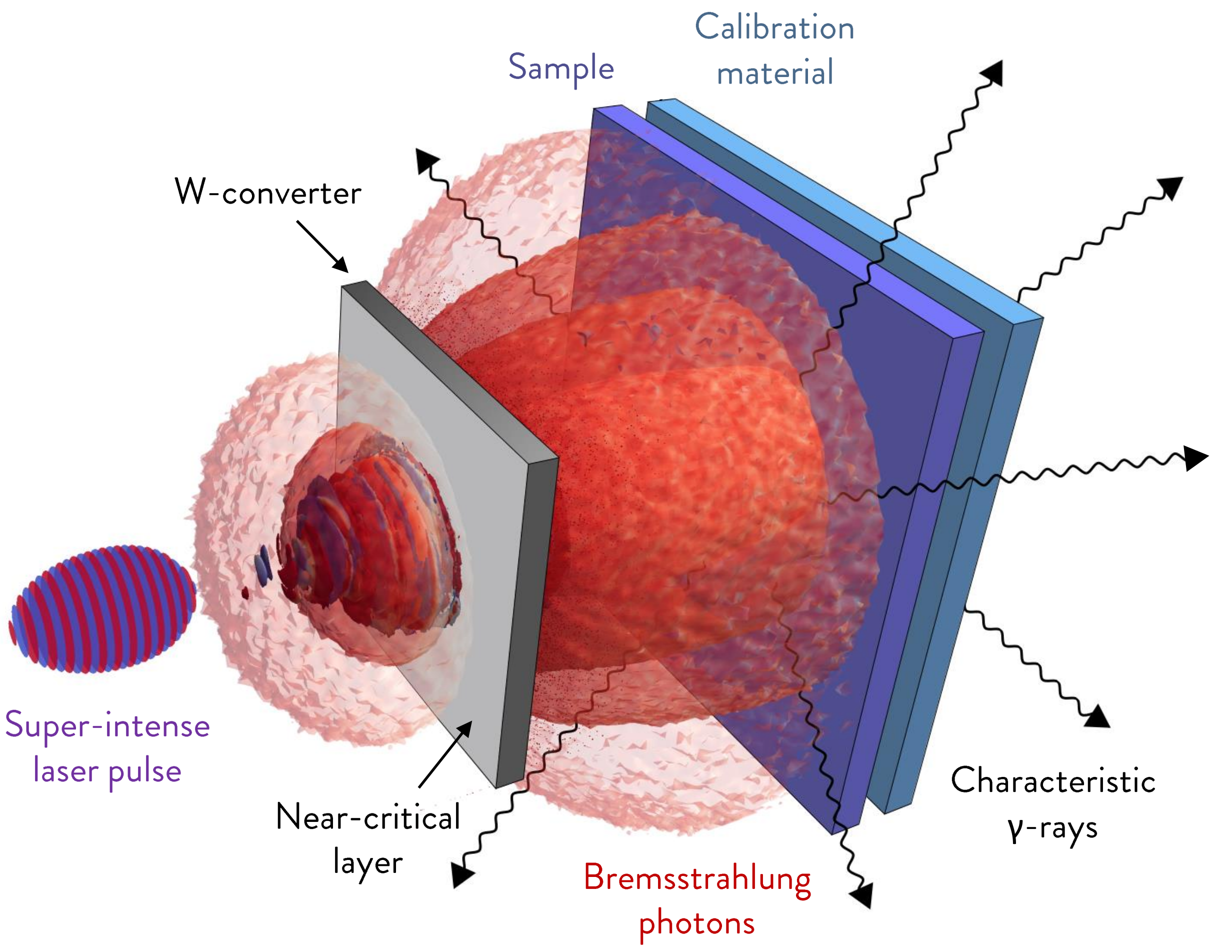
Numerical study of laser-driven PAA feasibility

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**



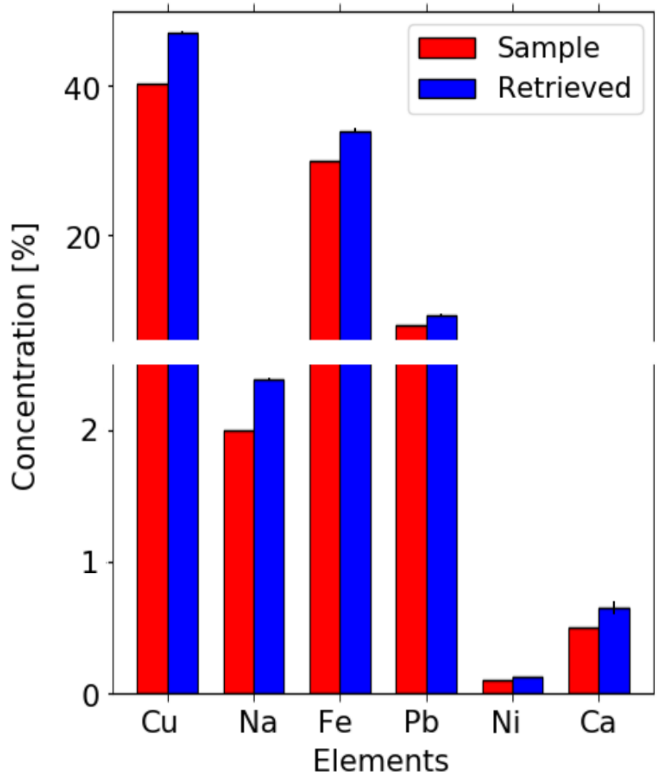
F. Mirani, et al. *Commun Phys* 4.1, (2021): 1-13

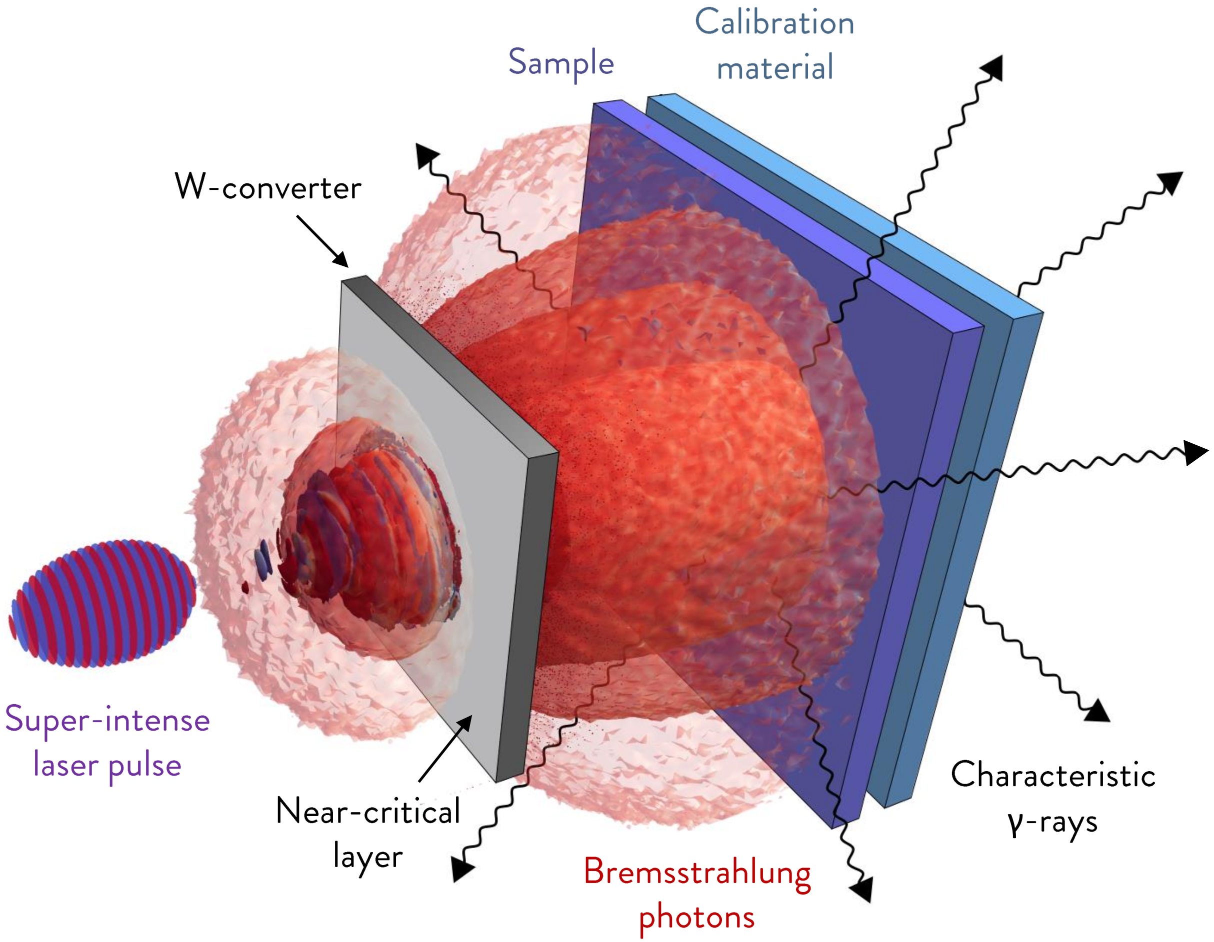
Numerical study of laser-driven PAA feasibility

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





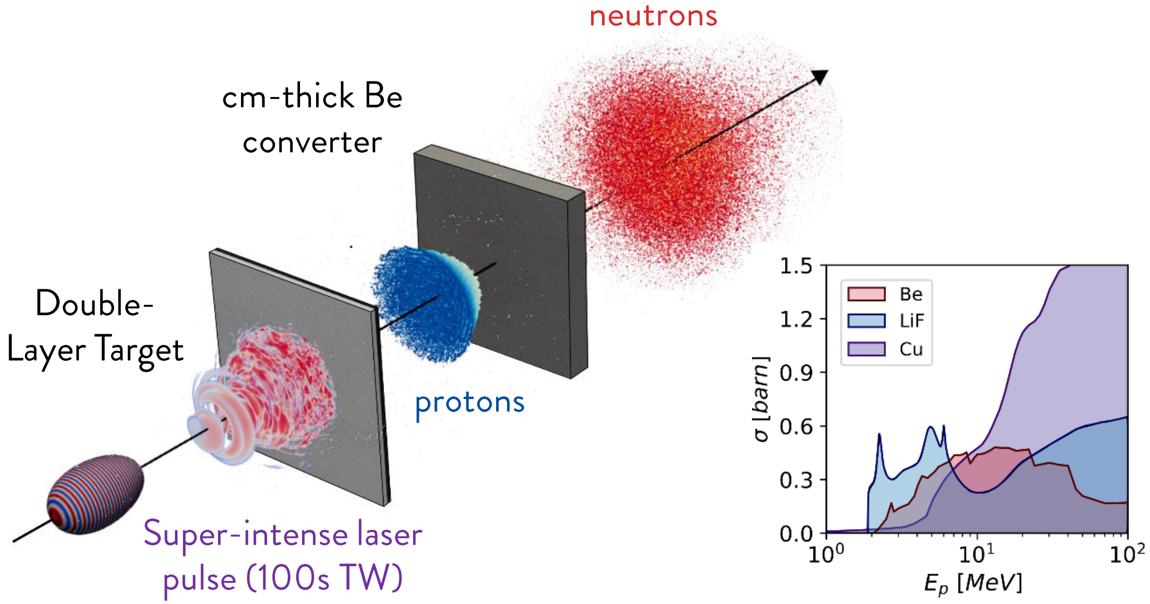
B. Maróti, et al. J. Radioanal. Nucl. Chem. 312.2 (2017): 367-375.

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

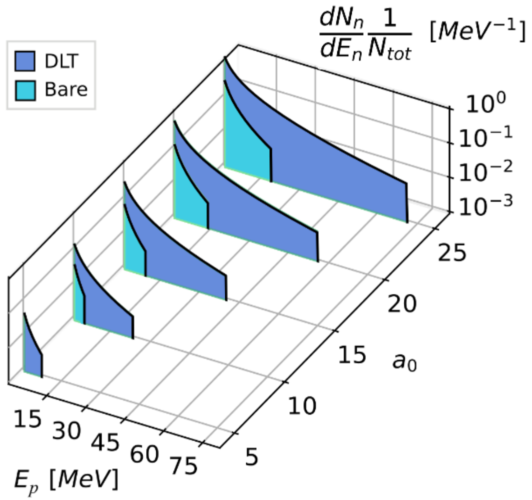
Numerical study of laser-driven FNRR feasibility

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

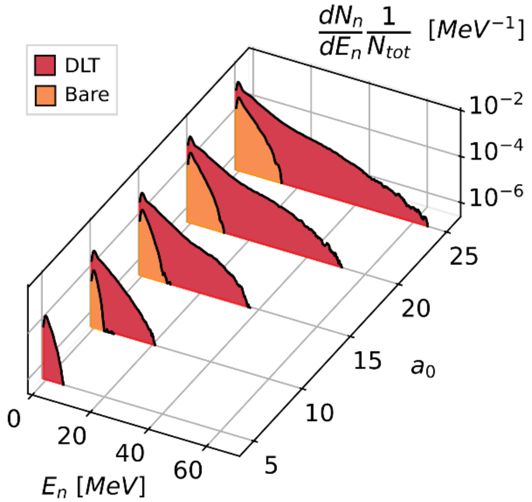
1. Super-intense **laser** interacting with **Double-Layer Target** (model from literature).
2. Accelerated **protons** interaction with cm-thick **converter** → (p, n) reactions → **fast neutron** generation.



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



  - ✓ **Neutron** spectra:



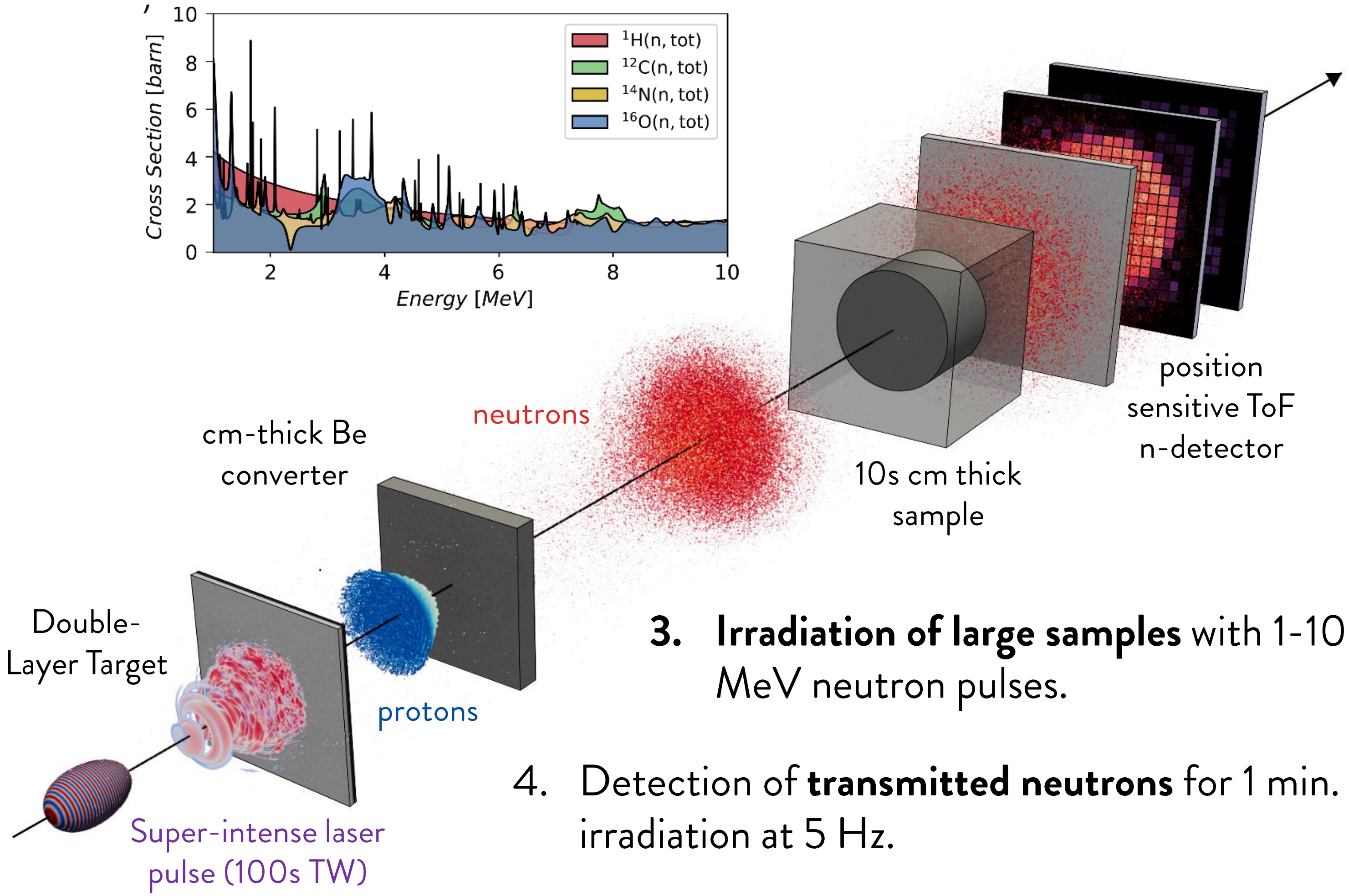
✓ Broad spectrum up to 10s MeV.

✓ $\geq 10^4$ n/cm^2/s at ≥ 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

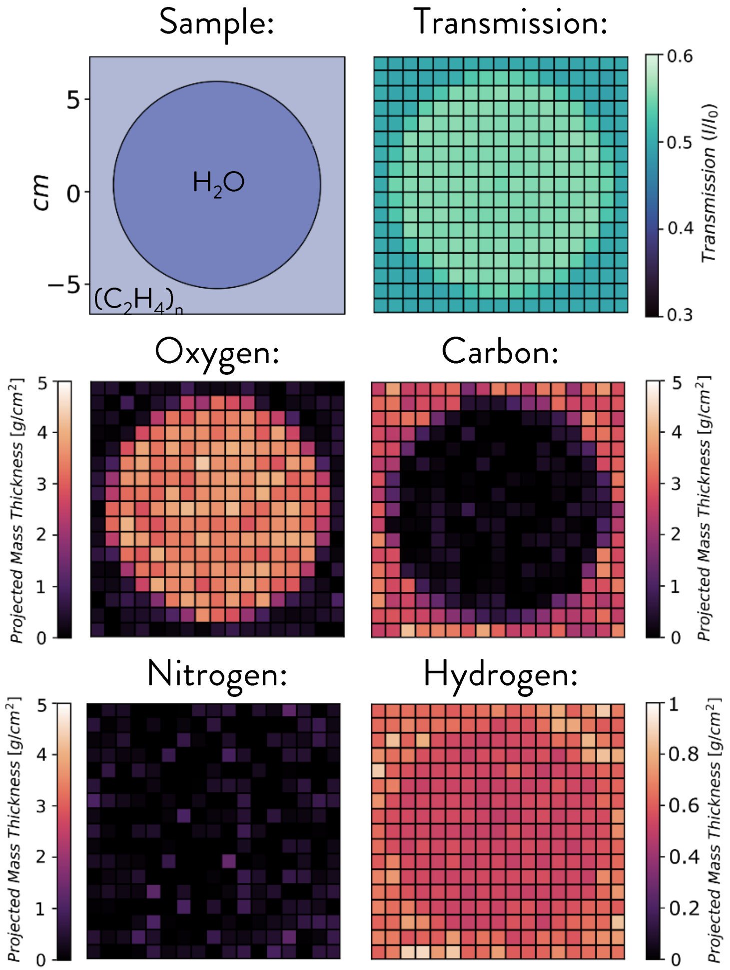
Exploit **laser-driven neutron source** to perform radiography of large samples.



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.*

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).
- **Near-critical Double-Layer Targets are worth of consideration.**
  - ➢ **Enhancement** of the number and energy of **accelerated particle**.
  - ➢ Energy tunability and selection.
- **Laser-driven differential PIXE (most powerful and ambitious), PAA and FNRR** still need an experimental demonstration!

List of relevant publications…

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

M. Passoni, et al. *Plasma Physics and Controlled Fusion* 62.1, (**2019**): 014022.

F. Mirani, et al. *Communications Physics* 4, 185 (**2021**).

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

M. Barberio, et al. *Scientific reports* 7.1, (**2017**): 1-8.

M. Barberio, et al. *Science advances* 5.6, (**2019**): eaar6228.

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

A. Morabito, et al. *Laser and Particle Beams* 37.4, (**2019**): 354-363.

M. Zimmer, et al. *In EPJ Web of Conferences* (Vol. 231, p. 01006). (**2020**). EDP Sciences.

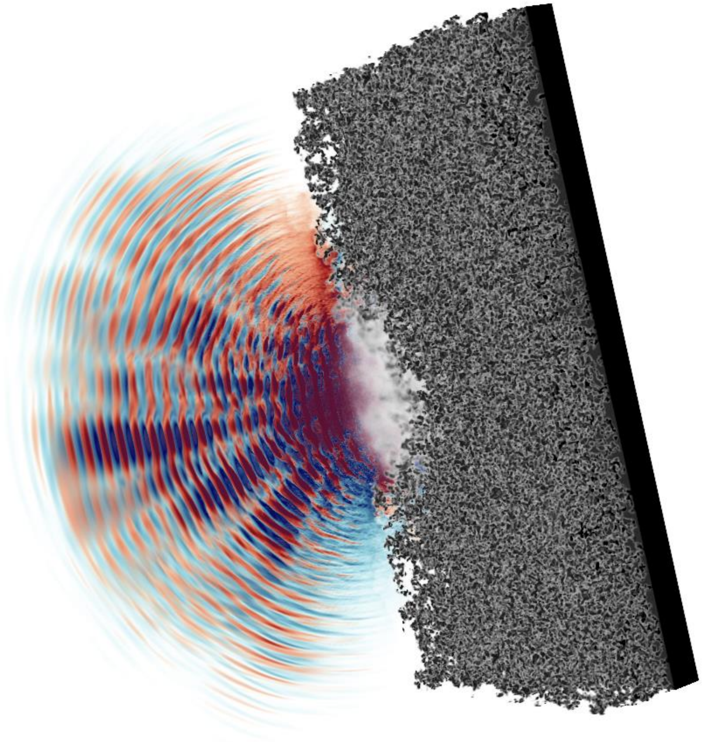
P. Puyuelo-Valdes, et al. *Scientific reports* 11.1, (**2021**): 1-10.

F. Brandi, et al. *Applied Sciences*, 11(14), (**2021**): 6358.

F. Boivin, et al. *New Journal of Physics* 24.5, (**2022**): 053018.

A. Maffini, et al. *EPJ tech. instrumm.* 10.1 (**2023**): 15

F. Mirani, et al. *Phys Rev. Appl.* 19.4 (**2023**): 044020



Thank you for the attention!

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