



# The mission of the INFN-Cultural Heritage Network: the multifaceted example of the Macro-XRF scanner experience

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## Abstract

The mission of the Cultural Heritage Network of the Italian Institute of Nuclear Physics (INFN-CHNet) is presented here through a “virtuous” example: the activity related to the Macro-X-Ray Fluorescence (MA-XRF) scanner. The main focus of INFN-CHNet is the collaboration and sharing of knowledge among the network members, to better address the issues of Cultural Heritage operators, while the fields of activity are research (instrumental development and data management), analysis of cultural objects, education of young scholars and professionals, and dissemination to the general public. In this context, the MA-XRF scanner exemplifies the objectives of INFN-CHNet, being the first instrument developed, tested and optimised jointly by several INFN-CHNet partners. It was designed to be an open (free access to information on processes, components and materials), low-cost system, based on sustainability and interoperability, and modular. All these features allow for easy replication of instruments in any node of the network or reuse of system/subsystem also in different projects. Moreover, for the MA-XRF scanner, the whole path from data acquisition to their storage, management and visualisation/reuse has been addressed. The activities related to the scanner clearly demonstrate the effectiveness of the approach of CHNet in all the issues that arise in conservation and study of CH.

**Keywords** Cultural heritage · CHNet network · Transportable instrumentation · MA-XRF · Imaging analyses · Cloud and web applications · Deep learning

## 1 Introduction

Cultural Heritage (CH) represents the cultural history and identity of humankind. Museums, for example, have the promotion of culture in all its forms as their main purpose. Furthermore, CH has been shown to positively affect the emotional well-being of people (such as for example in Harvard (2017)). In recent years, the definition of CH has undergone changes, moving from an area of study exclusively focussed on the more privileged aspects of human history (works of art, etc.) to a “social heritage”, which encompasses the symbolic character and identity of a community. This includes the set of practices and knowledge of customs, of every human social group or community

(Calligaro 2014). For all these reasons, the study, conservation and restoration of tangible cultural/historical artefacts, and thus their in-depth knowledge, are fundamental to our CH. Indeed, the decision of an appropriate conservation/restoration treatment is connected to the materials, the manufacturing process and the conservation state of the artwork and in-depth knowledge of the object under study allows for choosing the most appropriate products and procedures to be applied by restorers. Knowledge of the material composition is essential to carry out indirect dating, attribution, authentication (or the discovery of forgeries) or obtain historical information to reconstruct the technologies available in the past, the sources of supply of raw materials, or the economic and cultural exchanges between different populations. Considering the artistic and historical value of these objects, diagnostics referred to CH became a fundamental well-established research field to reach a complete knowledge of the object under study (Artioli 2010). For this purpose, a multi-analytical approach providing complementary information is the best choice (Lazic et al. 2018; Holakooei et al. 2017; Clemenza

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et al. 2017; Santos et al. 2016; Robinson et al. 2015; Amat et al. 2013) and non-invasive, non-destructive techniques are obviously preferred.

Within this framework, the exchange of skills between different laboratories working on the study of CH is fundamental; for this reason, in 2017, the Cultural Heritage Network (CHNet) of the National Institute of Nuclear Physics (INFN) was created (<https://chnet.infn.it>). It was born as a network of the INFN laboratories distributed all over Italy that develop and apply innovative setups to investigate the composition of artworks and their structure, or date them and their archaeological contexts.

To better address all the possible aspects playing a role in the CH study, starting from the instrumentation developments, passing through the study of the best approaches and applications, up to the storage, management and reuse of the acquired data, the network opened to external partners, thus bringing together different skills, such as conservation scientists, physicists, chemists, restorers and art historians, both from the national and international scenario. The actual CHNet structure is organised into three level nodes: (1) INFN facilities, (2) Italian institutions with complementary skills to those of INFN, such as restoration centres, University departments and associations, and (3) research centres abroad, where a joint laboratory with shared instrumentation is present (more details about this structure are presented in the Supplementary Information-SI, Figure S1).

The INFN-CHNet mission pays attention to all aspects of CH diagnostics, starting from the instrumentation development, passing through the study of the best approaches and their applications, up to the storage, management and reuse of the acquired data. Therefore, the main activities describing the entire philosophy behind CHNet are briefly summarised (a detailed description can be found in the SI) by

- Analysis

The network nodes combine their expertise to collaborate on analytical studies, in order to better address the needs of Cultural Heritage (CH) operators (Romani et al. 2022; Albertin et al. 2021; Sottili et al. 2020; Clemenza et al. 2021, 2017; Ferrari et al. 2017; Ruberto et al. 2016). The strength of the network approach arises to the accessibility of a large variety of skills and instrumentations, available thanks to the mobile and fixed facilities of each node (Figure S2 in SI).

- Research

The development of instruments and methodologies for CH analysis is one of the main cores of the CHNet activity (Gelli et al. 2023; Taccetti et al. 2023a; Fedi et al. 2020; Giuntini et al. 2021; Mathot et al. 2019; Clemenza et al. 2019; Barile et al. 2019a, b).

The strategy in the development of instrumentation within CHNet is strongly influenced by the philosophy of the network itself. Ideally, all the network activities would be significantly improved if the instrumentation in the network were developed jointly, based on compatible hardware and software, with a modular approach allowing to take into consideration the specific needs of each partner and using low-cost components. User feedback, obtained through the conservation institutes in the network, highlights faults, limitations and alternative uses, and encourages the adoption of new technical solutions. Innovation in response to user needs is important to improve scientific instruments, because scientists have a great deal to gain from involving the user in the design and development process.

Storage, management and digital preservation of the information and knowledge acquired during the diagnostic campaigns is another crucial issue, which is why the network is developing a Digital Heritage Laboratory (DHLab) portal, a powerful tool for data management and analysis.

- Education and third mission activities

Education of students and professionals of the sector and dissemination to the general public, including kids, is another main core of the network mission. For this purpose, a great variety of initiatives was planned during these years, such as the one-week training camps organised in different Italian cultural venues. Dedicated social media accounts have also been created to disseminate the network activities.

This paper aims to highlight and demonstrate the effectiveness of the CHNet network's approach in the CH field, exploiting the example of the CHNet MA-XRF (Macro-X-Ray Fluorescence) unit. The MA-XRF scanner has been actually the first instrument jointly developed, tested and optimised by different CHNet partners. All aspects of the activities have been carried out internally by the network: from the instrumentation development to the acquisition, storage, management and visualisation/reuse of data. In order to point out the mission of CHNet, some novel results, in addition to others extracted from literature, are presented in the following sections.

## 2 CHNet MA-XRF scanners: developments, sharing knowledge and data management

As mentioned in the introduction, the artistic and historical value of the CH objects is typically huge, and for this reason, the analysis has to be preferably carried out respecting the physical integrity of the object under investigation, avoiding damages. Therefore, non-invasive and non-destructive (requiring no sampling or sample preparation) and *in situ* analyses are considered the first and best approach for

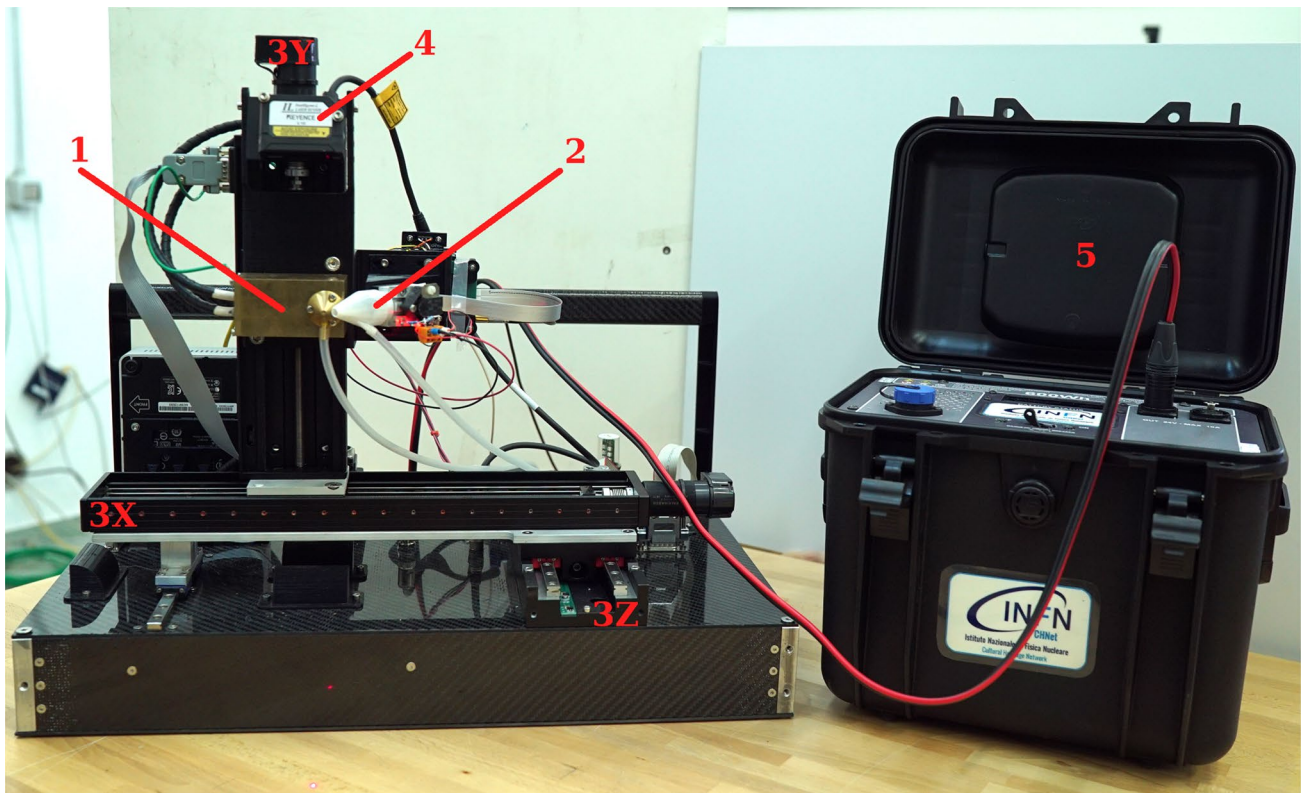
diagnostic campaigns (Dal Bianco and Russo 2012; Van Grieken and Janssens 2004; Janssens and Van Grieken (2004). Being characterised by all these features, among all the techniques available for CH diagnostics, the X-ray fluorescence (XRF) is one of the most used (Charlton 2013; Theden-Ringl and Gadd 2017). In addition, the chance of performing MA-XRF imaging analyses (Alfeld et al. 2013; Alfeld and de Viguierie 2017; Hoffmann et al. 2018; Legrand et al. 2018, 2019; Saverwyns et al. 2018; Van der Snickt et al. 2018), obtaining the distribution of the characteristic elements within the scanned area, makes this technique even more appealing for CH applications. Indeed, the elemental maps undoubtedly provide more significant and reliable results than those produced by multiple “traditional” single-spot analysis, especially when the sample under study has heterogeneous structures, even within apparently uniform areas, as in the case of objects of artistic or historical interest. For all these reasons, a MA-XRF scanner suited for CH diagnostics was developed within the CHNet, by exploiting the high technological level facilities of the network’s laboratories and the significant expertise of its researchers, technologists, restorers, and art historians. The MA-XRF experience is a perfect example to illustrate the mission of the network, as shown in the following. The network approach has been adopted by different nodes in

the development of the scanner, which led to open systems based on compatible hardware and software. The latter is developed in an open Linux environment and using low-cost components, such as Arduino boards. Furthermore, this approach facilitates the replication of instruments, making it easier for CHNet partners to adopt and adapt the same technologies for their own research purposes, as is the case of the “twin” XRF scanners developed in national and international nodes. Furthermore, the large amount of data acquired so far with the MA-XRF scanner are an essential and precious raw material for the DHLab activity, aiming to define strategies and protocols and develop informatic instruments for storage, management and reuse of the CH scientific data.

## 2.1 The first CHNet MA-XRF scanner developments and its employments

The development of this instrument, capable of performing both single spot and imaging, started in 2013; since the first prototype, changes and optimisations have been carried out until 2019 (Ruberto 2017).

Most of the XRF scanner developments have been carried out by the INFN-CHNet Florence node at the LABEC (Laboratory of nuclear techniques for Cultural



**Fig. 1** The most typical setup of the scanner: (1) the 4-mm thick brass case enclosing the Moxtek MAGNUM ® X-ray tube, (2) the white plastic cone surrounding the Amptek XR100 SDD detector, (3)

the 300 mm (3X)×200 mm (3Y)×50 mm (3Z) linear stages adopted in this case, (4) the CMOS laser sensor positioning controller and (5) one example of the batteries available

Heritage and Environmental Applications), with fundamental support by some of the network nodes in the test and optimisation phase (the network was at its infancy); for example, the New York University of Abu Dhabi (NYUAD) developed the dynamic positioning system, while the Opificio delle Pietre Dure (OPD) and the Centro Conservazione e Restauro La Venaria Reale (CCR) provided the first use cases and feedback as final users. Thanks to the numerous and fruitful collaborations, both inside and outside the network, the CHNet XRF scanner has been used in many different applications, ranging from pigments and painting palette characterisation (Sottili et al. 2022a; Mazzinghi et al. 2021a; Ruberto et al. 2016), also in multi-technique diagnostic campaign (Albertin et al. 2021; Dal Fovo et al. 2020, 2023; Bochicchio et al. 2019; Striova et al. 2018), to the evaluation of the restoration procedures (Romani et al. 2022).

The CHNet XRF scanner is compact, lightweight, and easy to handle. The scanner was designed as an open instrument: the control, acquisition, and analysis software were developed using open-source software, making it easy to use and integrate with other software systems. The software and the Graphical Users Interface (GUI) has proved to be robust, fail-safe and “user-friendly” (Taccetti et al. 2019). The scanner is cost-effective, with easily replaceable components, thus accessible to a wider range of users than commercial instruments.

The MA-XRF characteristics of high portability and great versatility, demonstrated by the applications described below, in combination with the feature of the ultra-low radiation dispersion, make it a perfectly suited instrument for education and third mission activities, being safe to use even in public spaces. Actually, it has been widely employed in applications with students and in museums, also when visitors are present. In particular, a MA-XRF laboratory was included in all editions of the CHNet Training Camps (section education and third mission in SI) held in different cultural sites (examples are shown in <https://www.facebook.com/watch/?v=460429622553950> and in [https://www.youtube.com/watch?v=7Rry\\_9ifoGA](https://www.youtube.com/watch?v=7Rry_9ifoGA)). During these camps, analyses have been performed in museums in the presence of the general public, while part of the staff was dedicated to answering their questions.

A detailed description of the optimised version of the scanner and the complete characterisation of its performance were presented in Taccetti et al. (2019). In the following, the main parts of the instrument, shown in Fig. 1, are briefly summarised:

- Source: a small, compact and shielded X-ray tube (1 in Fig. 1), with ultra-low radiation dispersion, which makes the instrument safe to use even in public spaces.

- Detection: low-cost silicon drift detectors SDD (2 in Fig. 1), coupled with a helium flow equipment used to flow gas in the sample-to-detector path, in order to increase the low Z element detection (Taccetti et al. 2019; Migliori et al. 2011); .
- Motion: three linear stages of low weight and high precision (3X, 3Y, 3Z in Fig. 1). Depending on the application, the X and Y motorised axis can be easily changed from 200 mm up to 600 mm.
- Dynamic positioning system: a lightweight laser sensor (4 in Fig. 1), used to keep constant the scanner-to-sample distance. This feature is crucial for non-flat surfaces, in which changes in the irradiation and detection geometries can make analysis difficult or impossible.
- Power supply: mains, as usual, or batteries (5 in Fig. 1) (maximum runtime over 10 h) (Taccetti et al. 2019).

With these characteristics, the CHNet XRF scanner falls in the middle of the international scenario that ranges from massive scanners (Alfeld et al. 2013; Romano et al. 2017; Van der Snickt et al. 2017), which enable the acquisition of large maps in a reasonably short time (Alfeld et al. 2017; Ludwig et al. 2017), to compact and easily transportable instruments, better suited for the analyses of small areas up to a few square centimetres. With the CHNet XRF scanner, it is possible to map relatively large objects in a reasonably



**Fig. 2** The elemental distribution of Bi L $\alpha$  line. The visible image of the painting and the complete characterisation of its palette can be found in Mazzinghi et al. (2022)

short amount of time, maintaining suitable spatial resolution and statistics in each pixel. One example of a large object analysis is the case, conducted in collaboration with OPD, of the painting palette characterisation of Raffaello's Portrait of Leo X, a panel painting with size of about  $155 \times 119$  cm<sup>2</sup>. The detailed description of the obtained results and the setup of the scanner used were reported in Mazzinghi et al. (2022). Here, we simply focus on the reconstruction of the Bismuth (Bi) distribution map over the whole painting, resulting from the stitching of different acquired scans (Fig. 2). This elemental map suggests the use of “bismuth black” (Mazzinghi et al. 2022).

In recent years, the scanners have shown great versatility and extended capabilities, thanks to specific features which are extremely important for CH applications, such as the helium flow equipment and the dynamic positioning system. The latter is particularly relevant in CH applications, where it is extremely hard to find objects with flat/planar surfaces. This characteristic may be due to the manufacturing of the artwork, e.g. in the case of 3D objects or in the presence of three-dimensional decorations, or due to degradation and ageing phenomena, which can deform the surface of the support materials (wood, canvas, paper, parchment, wall, etc.). In addition, large irregularities or deformations may cause the scanner to collide with the sample during scanning. Since artworks are usually fragile and priceless, any damage must be avoided.

In addition, to increase the versatility of the system, different experimental conditions can be easily arranged: the scanners adopt a series of interchangeable collimators, with diameter ranging from 0.1 mm up to 1 mm, which define the beam spot dimension on the sample (Taccetti et al. 2019). This feature, together with the pixel size set by the software, allows to change the spatial resolution according to the specific case. The measuring speed can also be adjusted as required by the specific measurement. The variation of all these parameters allows for the optimisation of the spatial resolution while maintaining a reasonable measuring time.

The studies presented in Mazzinghi et al. (2021b) and in Sottili et al. (2021) are two perfect examples of the versatility of the scanner.

In Mazzinghi et al. (2021b), we report on the study of illuminated manuscripts located in the San Giorgio Maggiore Venetian island (Toniolo and Ponchia 2020), carried out in collaboration with the Fitzwilliam museum (UK). This diagnostic campaign was a challenge for several reasons: first, these artefacts are too fragile and environmentally sensitive to be moved to a scientific laboratory; second, transporting instrumentation to a Venetian island is not a trivial task. Moreover, due to the binding, these objects are highly three dimensional, making it difficult to locate bulky equipment in front of them at the proper distance. A

discussion of the problems arising from this kind of artwork measurements is reported in Ricciardi et al. (2016).

The XRF-CHNet scanner proved to be suitable for this difficult task, being sufficiently compact to be transported to the island and located in front of the manuscripts (see Fig. 3, where the scanner is shown during the acquisition, with the ad hoc designed supports).

The multi-analytical diagnostic campaign allowed us to gain insight into the work of the individual illuminators and provided interesting information about possible methods of production of the manuscripts (Ricciardi et al. 2019). Just to illustrate the quality of results obtained from these challenging samples, four elemental maps of one illuminated initial of the Antiphonary Q are presented in Fig. 3. The Au L $\alpha$  map highlights the use of elemental gold, while the Hg L $\alpha$  map points out the use of Vermilion. The Cu K $\alpha$  map evidences the use of a green copper-based pigment in the leaves, and the Pb L $\alpha$  map indicates the use of lead white in most areas. Further detailed results are available in reference Mazzinghi et al. (2021b).

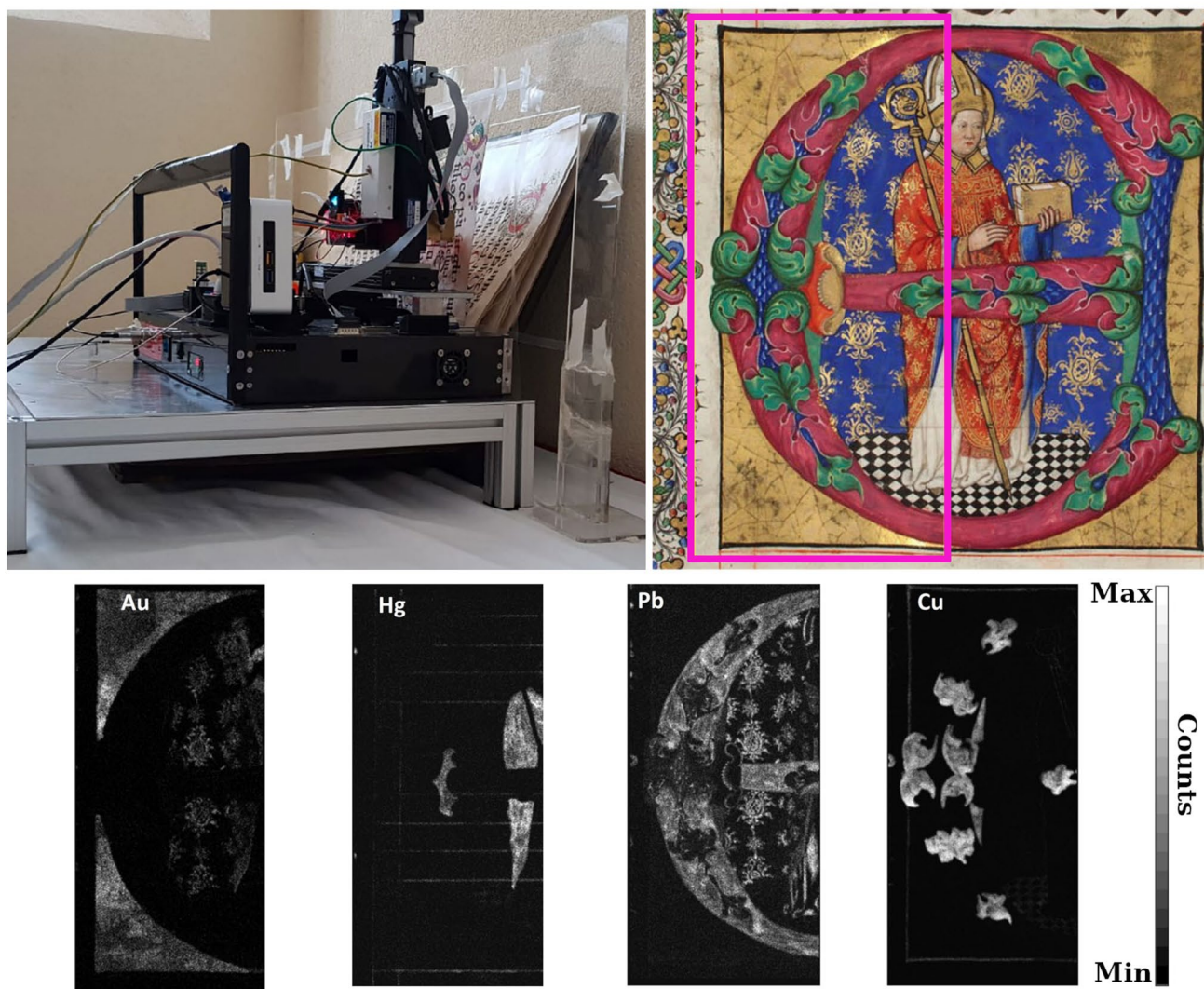
Another example of the scanner potential can be found in Sottili et al. (2021), where the object under study, a desk *Scrivania con scansia* (1701–1777) by Pietro Piffetti (Re et al. 2014; De Blasi et al. 2010), had a complex, three-dimensional structure and thus not easily accessible with bulky instruments. In this case, the compactness and the dynamic positioning system of the CHNet XRF scanner were fundamental to carry out the task. The focus of this study, regarding a quite uncommon object for XRF analysis, was the characterisation of the decorative layers and of the different materials (e.g. polychrome engraved ivories decorations). The work was performed thanks to the collaboration with CCR.

Figure 4 presents a few noteworthy results from the study (Sottili et al. 2021). The Ca map highlights the underlying structure of the ivory decoration's support. The Hg L $\alpha$  map suggests the use of vermilion for shading the red flower, while the Fe map indicates for example the use of an earth pigment in the green area.

## 2.2 The “twin” CHNet MA-XRF scanners: developments and further implementations

In order to lay the basis for a common instrument development among the network nodes, and in view of the national and international scientific results achieved by the first XRF scanner realised in Florence, “twin” XRF scanners have been developed in other network nodes.

MA-XRF scanners are now available in national nodes (such as the section of Turin, National Laboratories of Legnaro (LNL) and Frascati (LNF)) and in international institutions (such as NYUAD and Universidad Nacional de San Martín-UNSAM). The “twin” scanners were jointly



**Fig. 3** Upper left: CHNet MA-XRF scanner during the analysis, the custom-made ‘table’ platform used for positioning the scanner over the open book, where the folio chosen for the analysis was held up vertically thanks to an upside-down U-shape Perspex support. Upper right: in the magenta rectangle is highlighted the analysed detail of

the illuminated initial of the folio 29v of the Antiphonary Q. Bottom: some results from the study, elemental maps of Au ( $L\alpha$ ), Hg ( $L\alpha$ ), Pb ( $L\alpha$ ) and Cu ( $K\alpha$ ) are presented. The working conditions were 500  $\mu\text{m}$  of equivalent pixel size and 800  $\mu\text{m}$  of beam collimator. More details in Mazzinghi et al. (2021b)

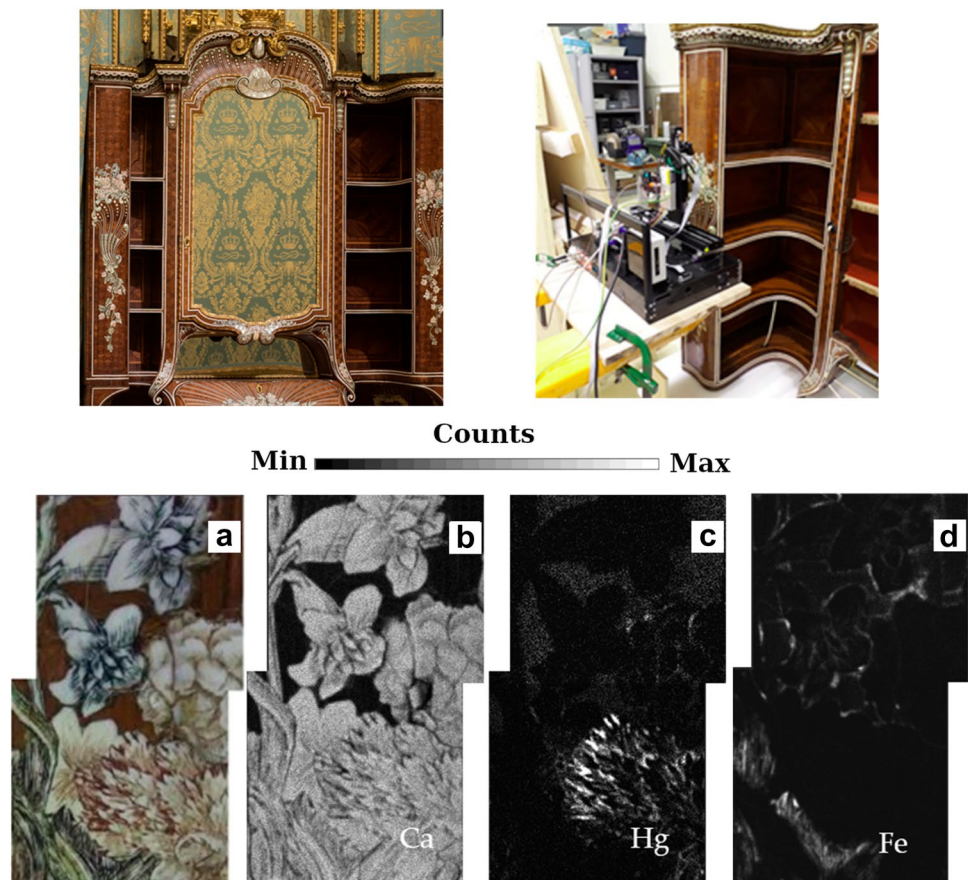
developed, on the basis of the features and capabilities of the system presented in the previous section, and taking into account the needs and expertise of each involved network node.

One example of application carried out with a “twin” scanner is reported in Taccetti et al. (2023b), where the instrument jointly set up, optimised, and applied to CH was presented. This work was carried out with the UNSAM node in Buenos Aires. The XRF scanner development was the starting point, in 2015, for the establishment at Centro de Estudios sobre Patrimonios y Ambiente (CEPyA)-UNSAM, in collaboration with the Restoration Workshop Centro Tarea, of the CHNet laboratory in Argentina, where complementary scientific and humanistic expertise are present.

The XRF scanner, which is the first tangible result of CHNet activity at UNSAM, was optimised for portability and in situ measurements, with particular attention to the incoming possibility of working on batteries, making it an ideal instrument for objects that cannot be moved to the laboratory, such as rock art. This scanner has already been used for diverse applications, as described in Taccetti et al. (2023b), including the experimental study of hidden rock art through laboratory replicas that mimic problems found in archaeological sites, the study and chemical characterisation of archaeological decorated pottery, and the identification of materials and techniques employed in ancient photography.

In this paper, some results of the first test of MA-XRF analyses for the study of rock art are presented (Taccetti et al.

**Fig. 4** Top left: detail of the writing desk “Scrivania con scansia” by Pietro Piffetti. Top right: the CHNet MA-XRF scanner in front of the external side of the scansia during measurements. Bottom: a detail of an ivory decoration and the corresponding Ca ( $K\alpha$ ), Hg ( $L\alpha$ ), and Fe ( $K\alpha$ ) elemental maps. They were acquired with a pixel size of 200  $\mu\text{m}$  and a collimator dimension of 400  $\mu\text{m}$ . Further details about the setup and the obtained results can be found in Sottili et al. (2021)



2023b). As is well known, one of the primary challenges in these studies is the presence of depositions, typically covering the drawings. In order to evaluate the potential of XRF imaging in the lost images recovering, mock-ups simulating rock paintings were created using hematite ( $\text{Fe}_2\text{O}_3$ ), a typical red pigment exploited in rock art (Tascon et al. 2016; Gheco et al. 2019). These samples were analysed using the “twin” XRF scanner, as shown in Fig. 5. The XRF Fe  $K\alpha$  map reveals the full image, in both the uncovered and covered mock-ups, proving the great potential of the MA-XRF imaging approach, particularly in recovering hidden pictures.

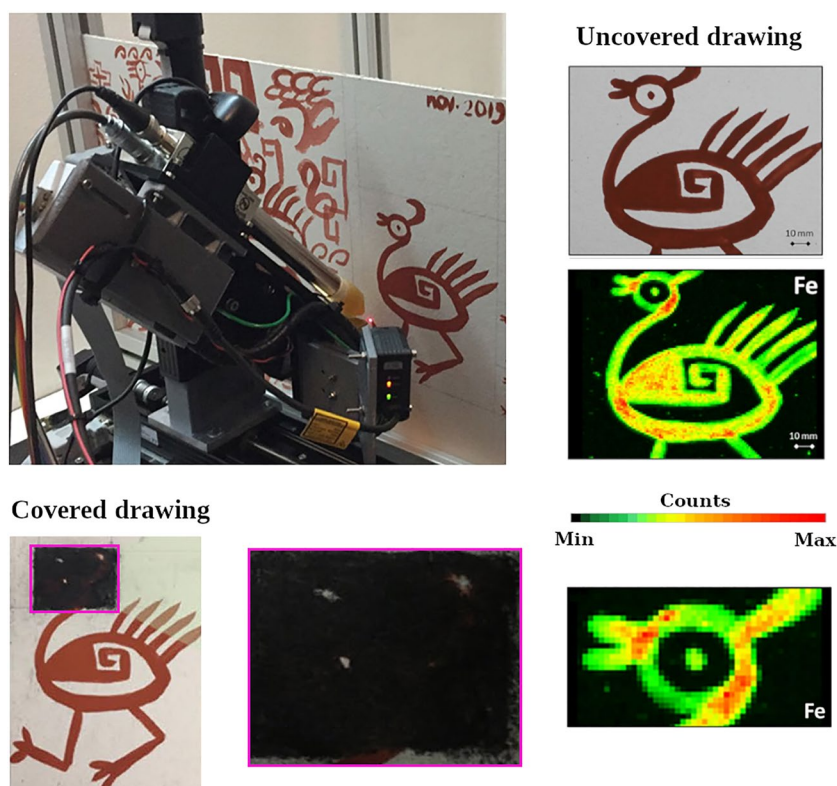
Despite the great analytical capabilities of MA-XRF, it is important to emphasise the value of a full multi-analytical approach for a deeper understanding of the artworks. The ability to use a single apparatus incorporating various analytic techniques (Santos et al. 2019; Mendoza and Gravie 2011; Duran et al. 2014; Bruker 2023)—joining the various specialties inside the network to produce a single multi-technique instrument—can represent an added value for the network.

The integration of MA-XRF, digital radiography (DR), and X-ray Luminescence (XRL) for CH applications is the focus of the ongoing partnership between the Turin node and the CCR. This project is made possible by the combination of skills of the nodes of Florence (MA-XRF) and Turin

(XRL, IL, DR) (Re et al. 2018); Lo Giudice et al. 2017a, b), supported by the CCR knowledge of CH conservation and restoration issues. The benefit of such an instrument is to use a single X-ray tube for a comprehensive examination of the same area.

Digital radiography (DR) was chosen as it is another well-established, non-destructive, non-invasive and transportable X-ray technique whose potential is widely known (Lang and Middleton 2005). It is frequently used in combination with MA-XRF. The first test of the DR and MA-XRF analyses of a detail of the face of the Child of the canvas painting *Madonna ed i Santi Crescentini e Donnino* by Timoteo Viti (Corrada 2013), in collaboration with the CCR expertise, is presented here (Fig. 6). Detailed results can be found in Sottili et al. (2022b)). As expected, the combination of these two techniques gives a more comprehensive information of artworks. Indeed, DR, thanks to its better spatial resolution with respect to MA-XRF, allows us to observe fine details of the support structure, such as the canvas weaves (green square in Fig. 6), but also the conservation state of the pictorial layer. On the other hand, the MA-XRF elemental maps make it possible to identify the materials constituting the painting (red squares in Fig. 6), which create the different radiopacity phenomena in the DR image, for example the effect of gold in the halo is very evident.

**Fig. 5** Top left: the CHNet XRF scanner at CEPyA during a scan. Top right: detail of the mock-up uncovered motif and the corresponding Fe  $K\alpha$  distribution map. Bottom: the same image, after head covering (magenta square) with 50  $\mu\text{m}$  carbon layer: Middle: the covered area. Right: a blow up of the Fe map, showing the ability of image recovery of XRF imaging. More detailed results in Taccetti et al. (2023b)



Overall, the combination of DR and MA-XRF provides a powerful tool for analysing artworks, as it provides more comprehensive information than either technique alone. The findings from the analysis of the *Madonna ed i Santi Crescentini e Donnino* painting demonstrate the usefulness of this approach for art conservation and restoration.

X-ray luminescence (XRL) is a useful technique for Cultural Heritage (CH) applications. XRL exploits X-ray sources to induce visible light emission in luminescent materials, obtaining information on the material composition in a non-destructive and non-invasive manner.

Luminescent properties are used to study artistic and archaeological materials, such as crystals, to gather useful information about the composition and/or structure of the sample under investigation.

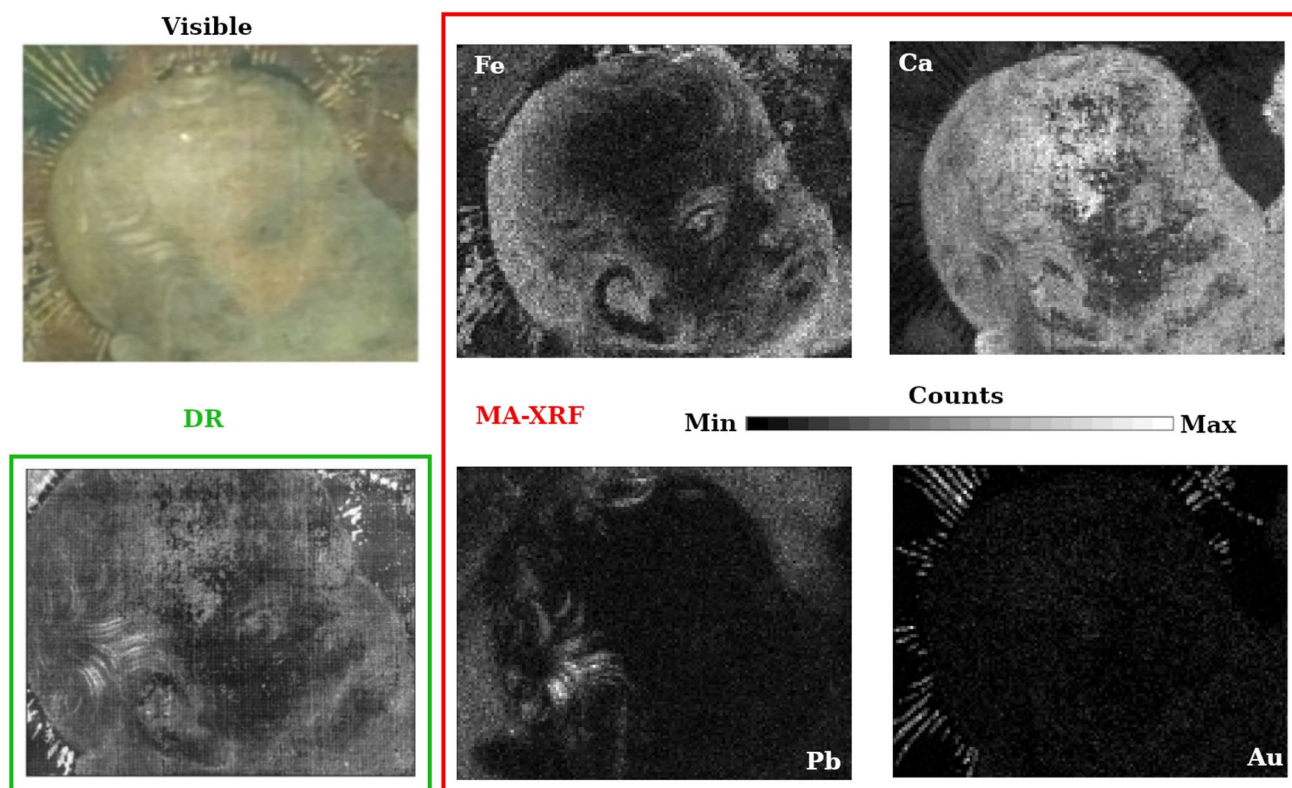
However, XRL has been employed less frequently in the context of CH, in part due to the lack of mobility, which is a crucial requirement for this field. Therefore, to investigate its potential in CH, XRL was tested to examine the provenance of samples from the “Savoy Collection” at the Regional Museum of Natural Sciences-Turin (Re et al. 2018). The outcomes were promising and comparable with those obtained from non-portable instruments. These results may lay the foundation and strengthen collaboration for the development of a multi-technique instrument. XRL’s ability to provide non-destructive and non-invasive analysis of luminescent materials could be particularly

valuable for studying artistic and archaeological materials, as well as for identifying the provenance and authenticity of objects in collections.

As already mentioned in the introduction for the research activity (Section Research in SI), another important aspect of the CHNet approach is the possibility of reusing home-developed solutions in the setting up of new systems. The heart is the modularity, in particular the ability to separate a system into independent components that can be easily combined or replaced. This approach makes all the system and subsystem interoperable among different instruments and also different projects, by easily transferring knowledge and technology from one to another.

In this regard, the MA-XRF scanner acquisition system is a suitable example, as it represented the basis of accelerator-based acquisition systems (such as that in the MACHINA project (Taccetti et al. 2023a; Mathot et al. 2019) and in the TANDEM accelerator of the LABEC laboratory (Giuntini et al. 2015). Finally, the multi-detector acquisition system developed for the accelerators will also be installed on the scanners of our fleet, thus proving the effectiveness of the CHNet synergic approach.





**Fig. 6** In the picture are presented the visible detail of the face of Jesus Christ of the painting *Madonna ed i Santi Crescentini e Donnino* by Timoteo Viti, the elemental distribution maps of Fe ( $K\alpha$ ), Ca

( $K\alpha$ ), Pb ( $L\alpha$ ) and Au ( $L\alpha$ ) in the red squares and the relative DR image in the green square. More results are in Sottili et al. (2022b)

### 2.3 The CHNet MA-XRF data management and storage

As already mentioned, part of CHNet mission is to take care of all aspects of CH diagnostics, starting from the study of the best approaches up to the storage, the management and the reuse of the acquired data.

Over the past 10 years, the development of information and communication technologies (ICTs), especially cloud-related technologies and solutions, has made it possible to define standard methods for finding, accessing, reusing, and integrating community-related data, particularly via web-based platforms. At the same time, a need for standard methods and tools to organise digitised data (including metadata) has emerged, particularly within the scientific community (Bechhofer et al. 2010; Roche et al. 2015). In particular, the FAIR (Findable, Accessible, Interoperable, Reusable) data principles (Wilkinson et al. 2016) were defined and adopted in the European Open Science Cloud initiative (Mons et al. 2017).

For this reason, in recent times, the CHNet network has been working on the developments of its Digital Heritage Laboratories (DHLab). Among all the activities carried

out, one of the most relevant is the design of the CHNet cloud platform THESPIAN (Tools for HERitage Science Processing, Integration, and ANALysis) (Bombini et al. 2022a), an integrated system that provides a set of services for the FAIR storage of acquired data, the standardisation of metadata and their visualisation. In other words, with THESPIAN, researchers can save their raw data, processed data, results, documentation, and article preprints in the cloud, together with a set of standardised metadata. In addition, they can access and (re)use data and metadata through web services provided entirely in the cloud.

One of the first web tools which has been developed is THESPIAN-XRF, entirely devoted to MA-XRF raw data management. THESPIAN-XRF allows the processing of MA-XRF data by both the open-source desktop software and the service embedded in the web application.

The main tasks can be outlined by exploiting the THESPIAN-XRF Visualiser Web App (Fig. 7):

- A raw data pre-processing software tool (red square in Fig. 7), for opening, processing, and interpreting CHNet MA-XRF raw data. The tool saves the data in a common

compressed data format of the ISO standard with an HDF5 extension.

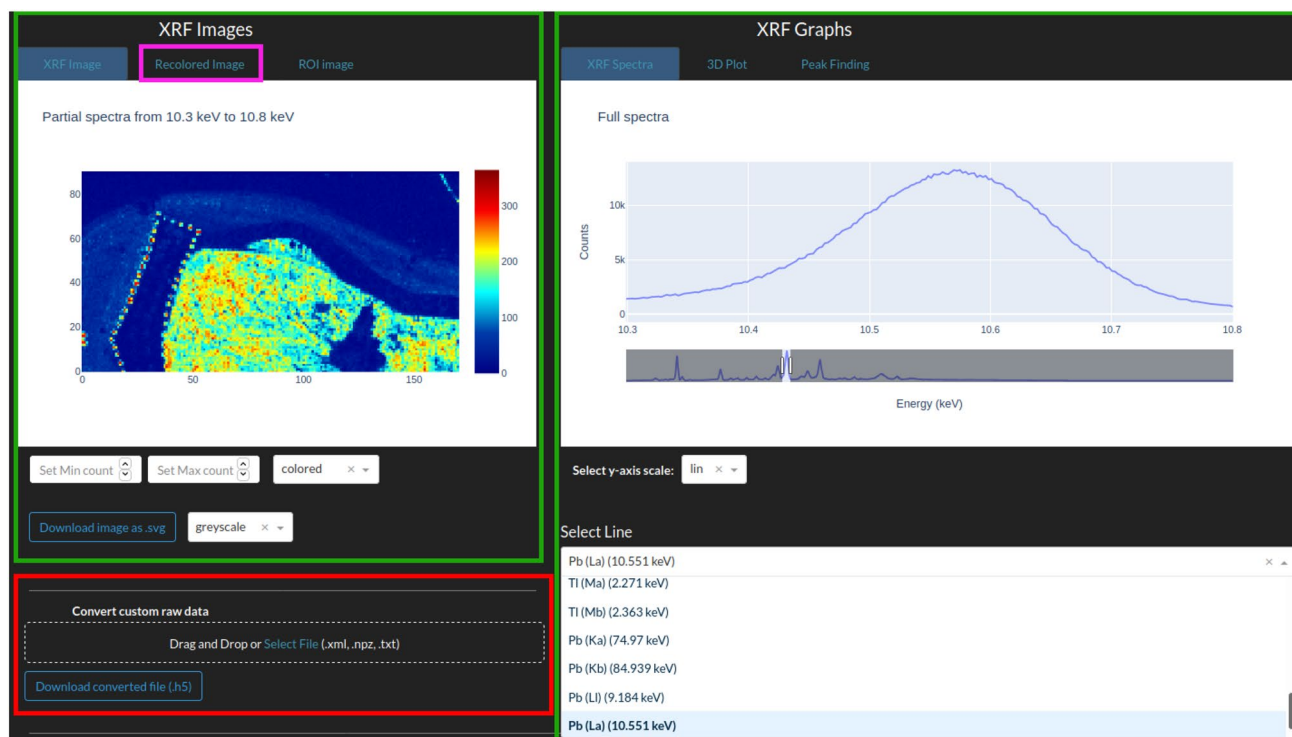
- An interactive tool for analysing and visualising raw MA-XRF data (green square in Fig. 7). This tool can be accessed from anywhere by easily navigating the site with intuitive clicks on the interface. Users can manage data in real time, from the raw data visualisation to the extraction of the processed data, for both spectra (*XRF spectra*) and element distribution maps (*XRF Image*) in single element or tri-element reconstructions. Furthermore, the tool enables three-dimensional visualisation of counts (*3D Plots*).
- Additional microservices, such as the *Recolored Image* (the service tab is highlighted in the magenta square in Fig. 7). This tool, employed within the web-app, allows for the simulation of the RGB image reconstruction starting from the real MA-XRF raw data. Recolored Image is part of the AIRES-CH (Artificial Intelligence for digital REStoration of Cultural Heritages) project (more details below) (Bombini et al. 2022b, c). Indeed, real time recolouring is offered by the AIRES-CH Deep Neural Network (DNN), which infers the RGB images from MA-XRF data cubes. One example of the preliminary results is shown in Fig. 8.

The AIRES-CH project is devoted to the digital restoration of CH and aims to build a web-based application using Computer Vision technologies applied to physical imaging raw data.

It is a very appealing project, as over time artworks can fade, become damaged or be lost altogether, due to degradation phenomena caused by several external agents or to vandalism: from the alteration of the original colour until discolouring of the painting layer, even with the loss of the legibility, depending on the extent of the damages. Moreover, it may happen that an artwork was painted on top of another one, which then can be unveiled by imaging techniques (typically, RX or MA-XRF). Therefore, recovering by digital restoration the information about the lost/hidden colours and virtually recolouring the images can be important to obtain insights into the materials and realisation techniques for CH preservation and restoration.

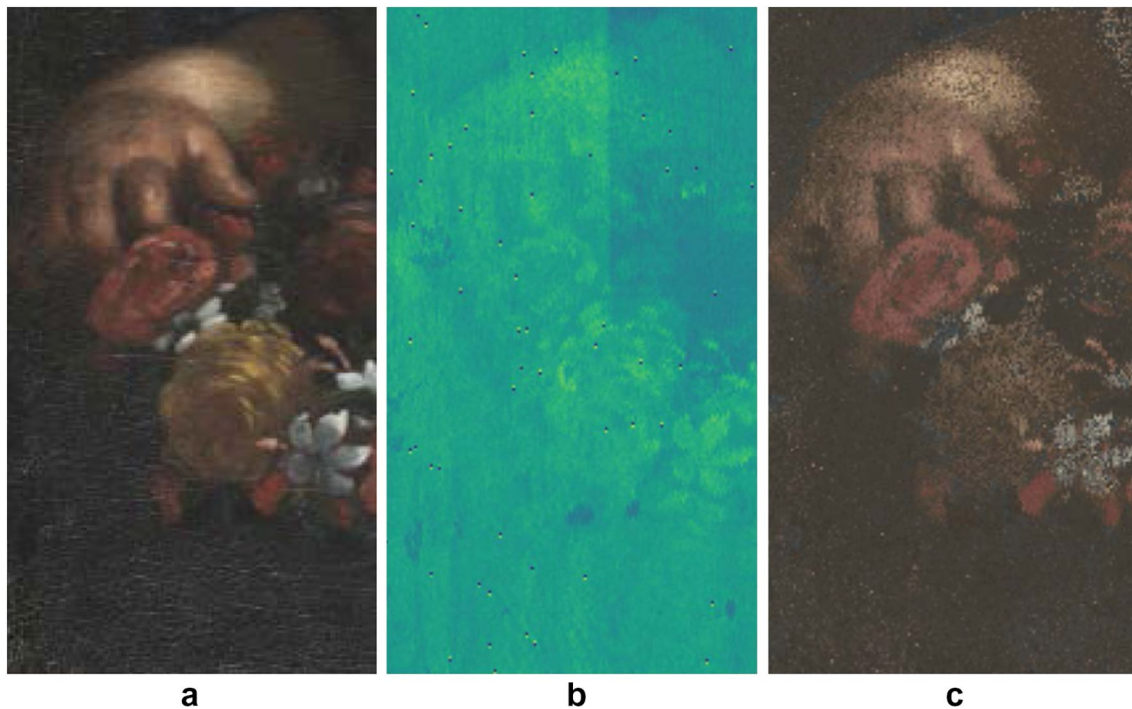
Indeed, the final goal of the digital restoration of artwork, based on the AIRES-CH DNN trained on real MA-XRF data sets, is to provide an effective tool for the reconstruction of an RGB image of the artwork in a pre-alteration phase or when this will no longer be readable.

The AIRES-DNN is currently undergoing development and refinement (more details about the DNN architecture,



**Fig. 7** View of the THESPIAN-XRF web-app, where the main functionalities were highlighted. In red square, the pre-processing data toll for the standardisation of the raw data can be found. In the green squares are presented all the routines for the visualisation, process-

ing and analyses of the raw MA-XRF data. In the yellow square, an example of microservices connected with the web-app, such as the recoloured image to create an RGB image starting from the MA-XRF data. More detail can be found in Bombini et al. (2022b, c)



**Fig. 8** Results of the automatic recolouring tool of the AIRES-CH project on a detail of the “Putto”, painted by an unknown author in the eighteenth century (Ahmetovic 2020): **a** the real RGB image; **b**

the total counts MA-XRF image; **c** the RGB recolored by custom multi-input (1D branch) DNN. Detailed information in Bombini et al. (2022b, c)

set, training and performance are reported in Bombini et al. (2022b, c) after the definition and training phase based on the raw MA-XRF data.

The data used for DNN training was produced by different CHNet instruments and obtained from diverse pictorial artworks (such as illuminated manuscripts, drawings and paintings) dating from different periods of time (such as the Middle Ages, the Renaissance and the modern period) (Bombini et al. 2022b, c).

In the following, one of the results obtained in the alpha phase of the AIRES-DNN architecture is presented and serves as a hint of the effectiveness of the automatic recolouring tool. Indeed, the comparison between the real RGB image and the one recolored by custom multi-input DNN shows no significant differences. This result, illustrating the XRF-to-RGB inference of the deep neural network, underlines the potential of the AI-based techniques for digital restoration.

A further DHLab activity, concerning the evaluation of the enormous possibilities offered by statistical methods, such as manifold learning algorithm applications (Wang et al. 2021), is particularly relevant for CH applications. Within this purpose, some tests were performed for the analyses of residual material on degraded surfaces. This is particularly relevant for example for the frescoes, in

which degradation can be caused by several external agents involving physical, chemical and/or biological factors, such as structure displacements, vibrations, temperature changes, humidity, pollution and mildew (Del Vecovo and Fregolent 2005; Coccato et al. 2017). In particular, chemical and/or biochemical degradation phenomena can lead to the discoloration of the upper painted layer of the fresco and, in the worst cases depending on the extent of the damages, to the loss of legibility of the artwork (Coccato et al. 2017; Fiorillo et al. 2020).

In order to accomplish this task, first, a mock-up was prepared in the laboratory: a *replica* (Fig. 9a) of an Etruscan wall painting from IV century BC from the “Tomba della Quadriga Infernale” (<http://www.museoetruscoarteano.it/pagina4.php>) in Sarteano (Siena, IT) was obtained following the historical buon fresco technique (Cennini 1971; Del Vecovo and Fregolent 2005), consisting in the application of a dry-powder pigment dispersed in water and drawn upon freshly “wet” lime plaster.

Finally, to simulate the loss of pigment, the *strappo* technique was performed (Fig. 9b) (Fiorillo et al. 2020; Mora et al. 1984). This technique historically consists in glueing canvas firmly to the surface of the fresco and then pulling and easing away the *intonachino*, the finishing layer

Painted in *fresco*, from the lime plaster support. After that, the detached layer is re-located on a linen canvas.

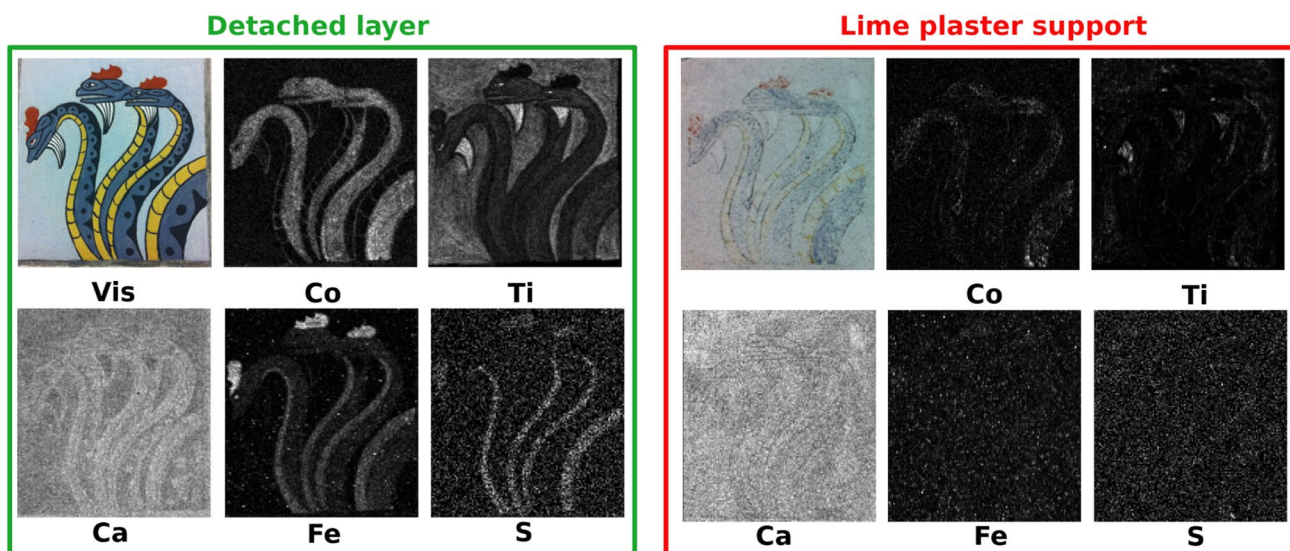
The detached layer (Fig. 9d) and the residual pigment on the plaster background (Fig. 9c) were analysed with the MA-XRF scanner: the results are shown in Fig. 10.

The comparison between the measurements on the detached layer and the lime plaster support highlights that only tiny amounts of the original pigments are transferred to the detached layer. As shown in the maps of Fig. 10, traces of Co and Ti can be noticed in small areas, while the maps of S, Fe and Ca are practically flat, except for the engravings used to make the fresco, visible in the Ca map. The results obtained on the pigment residual on the lime support show that most of the shapes characterising the images of the drawing seem to be lost, indeed only some partial areas

are recognisable. This is partly due to the way in which the data is processed, as demonstrated by the application of the UMAP (Uniform Manifold Approximation and Projection) (McInnes et al. 2018) algorithm for the nonlinear dimensionality reduction. It was applied on both the MA-XRF datacubes of the detached layer and the lime plaster support. The most relevant preliminary results related to the lime plaster support are presented in Fig. 11. The nonlinear dimensionality reduction of the XRF spectra performed with UMAP shows how it is possible to retrieve a relevant amount of statistical information from the XRF raw data, in particular for that related to lime plaster support. UMAP algorithm, in fact, is capable of exploiting the existing statistical relation between the MA-XRF pixels' histogram (spectra), to assign to each one of them a low-dimensional

**Fig. 9** **a** Replica of the “Tomba della Quadriga Infernale” wall painting prepared with the *buon fresco* technique; **b** “detachment” of the *intonachino* layer with the “*strappo*” technique; **c** the residual of the pigment on the lime plaster support; **d** “detached” layer re-located on a linen canvas





**Fig. 10** The visible details and the relative XRF maps of Co, Ti, Ca, Fe and S, of both scanned areas, are presented. In particular, the obtained results are highlighted in the green for the detached layer and in the red for the lime plaster support

representation—in the case at hand, three dimensional—which graphically shows the emergence of clusters of pixels (as visible in Fig. 11).

When the naked eye identification of structures in the elemental maps is hardly feasible (Fig. 10), the application of the UMAP algorithm allows for the recovery of shapes, and therefore, the reading of the image. This is evidenced in the UMAP representations, which are the rearrangement of the pixels and their value along the three reduced space directions (UMAP0, UMAP1, and UMAP2 in Fig. 11).

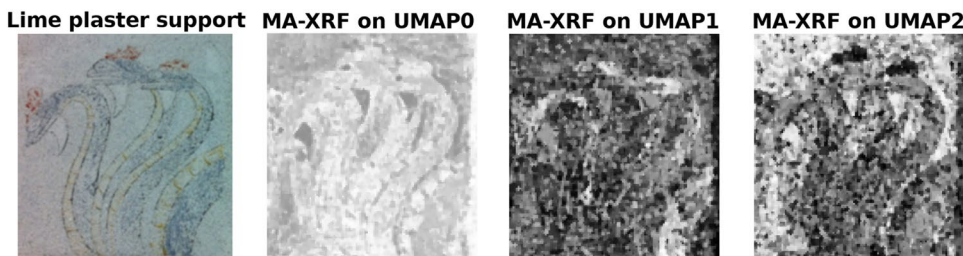
### 3 Conclusions

The CHNet MA-XRF scanner experience represents a perfect example of the mission of the INFN-CHNet network, i.e. taking care of all the aspects of CH diagnostics, from instrument developments up to the study of the best diagnostic approaches and the storage, management and reuse of the acquired data.

The MA-XRF examples reported here demonstrate the effectiveness of the CHNet approach based on exchanging knowledge and technologies in instrument development. The collaboration of the INFN-Section of Florence with the network nodes has produced the CHNet MA-XRF scanner, a compact, lightweight, easy to handle, “user-friendly” instrument, perfectly suited for non-invasive, non-destructive and in situ analyses. The scanner has shown great versatility and capabilities, essential for CH applications. The applications described in the paper demonstrated that the MA-XRF characteristics, in particular the ultra-low radiation dispersion, make the scanner a safe instrument even when used in public spaces. Therefore, it has been possible to widely use it for education and third mission activities, in applications where students were involved and in museums, in particular for example in all editions of the CHNet Training Camps with the MA-XRF laboratory.

CHNet’s approach for instrumentation development, based on sustainability, open/low-cost systems, free access to information on processes, components, and materials, and interoperability, allows for easy replication of instruments in any node of the network. This is well demonstrated by the

**Fig. 11** The detail of the pigments residue on the lime plaster support and the UMAP representations (rearrangement of the pixels and their value along the three directions of the reduced space, respectively UMAP0, UMAP1, and UMAP2) are shown



results obtained with the “twins” CHNet MA-XRF Scanners developed in the national and international nodes. In this paper also the strength of the modularity approach was pointed out, which made all the systems and subsystems interoperable among different instruments and also different projects, as shown in the reported example of the transportable accelerator MACHINA or the TANDEM accelerator in Florence laboratory.

The implementation of the CHNet Digital Heritage Laboratories (DHLab) has yielded important results related to the management and analysis of scientific data. In particular, the CHNet web-based suite, although still under upgrade and improvement, has already produced three interactive, fully operative tools working on MA-XRF data. They consist of a tool for opening, processing, and interpreting the raw data and saving them in a compressed ISO standard format; an interactive tool for analysing and visualising acquired data; a tool for simulating RGB image reconstructions from the elemental maps.

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**Data availability** The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Conflict of interest** The author has no competing interests to declare that are relevant to the content of this article.

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