The Need for Compact Coherent Light Sources - An Example - X-ray Phase Contrast Tomography Reveals the Secrets of Herculaneum Papyri

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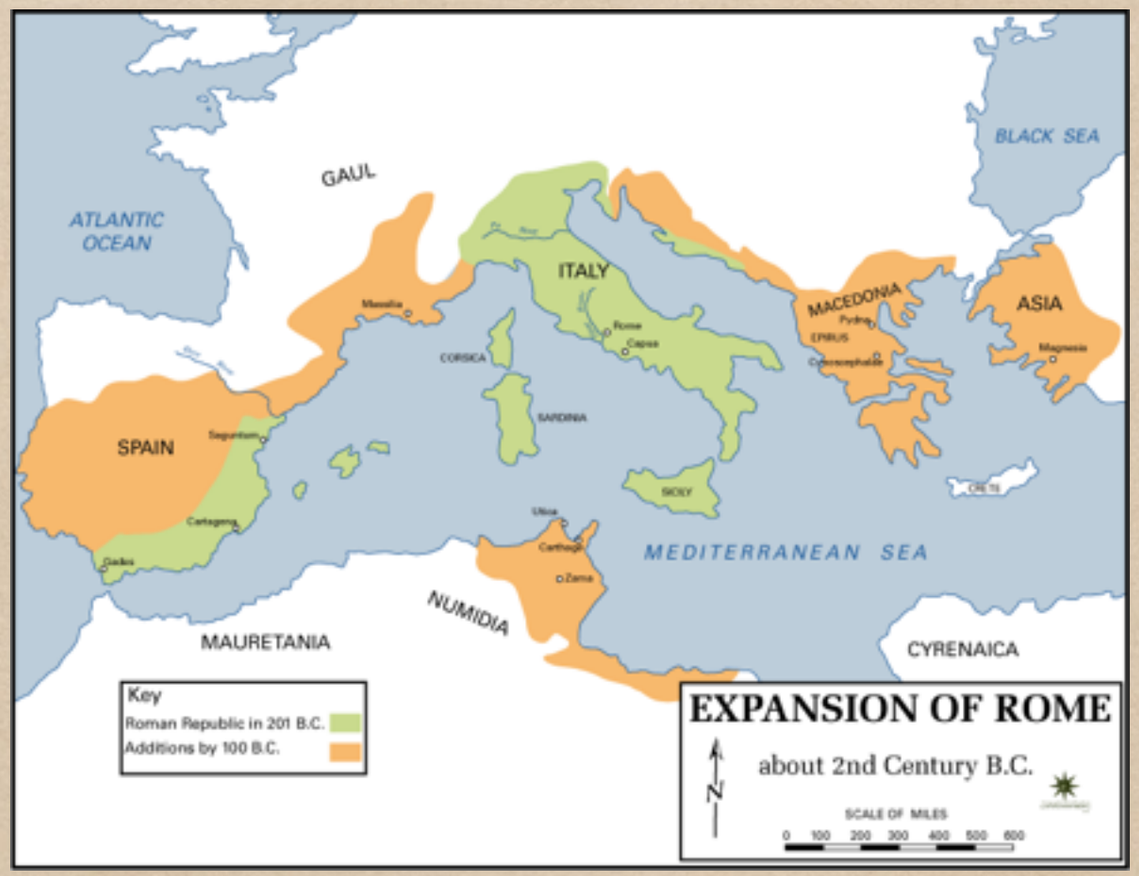
SLAC - Chicago October 14, 2016

Once upon a time..

Roman Republic 1st Cent. BC



Greece is attached to the Roman Republic

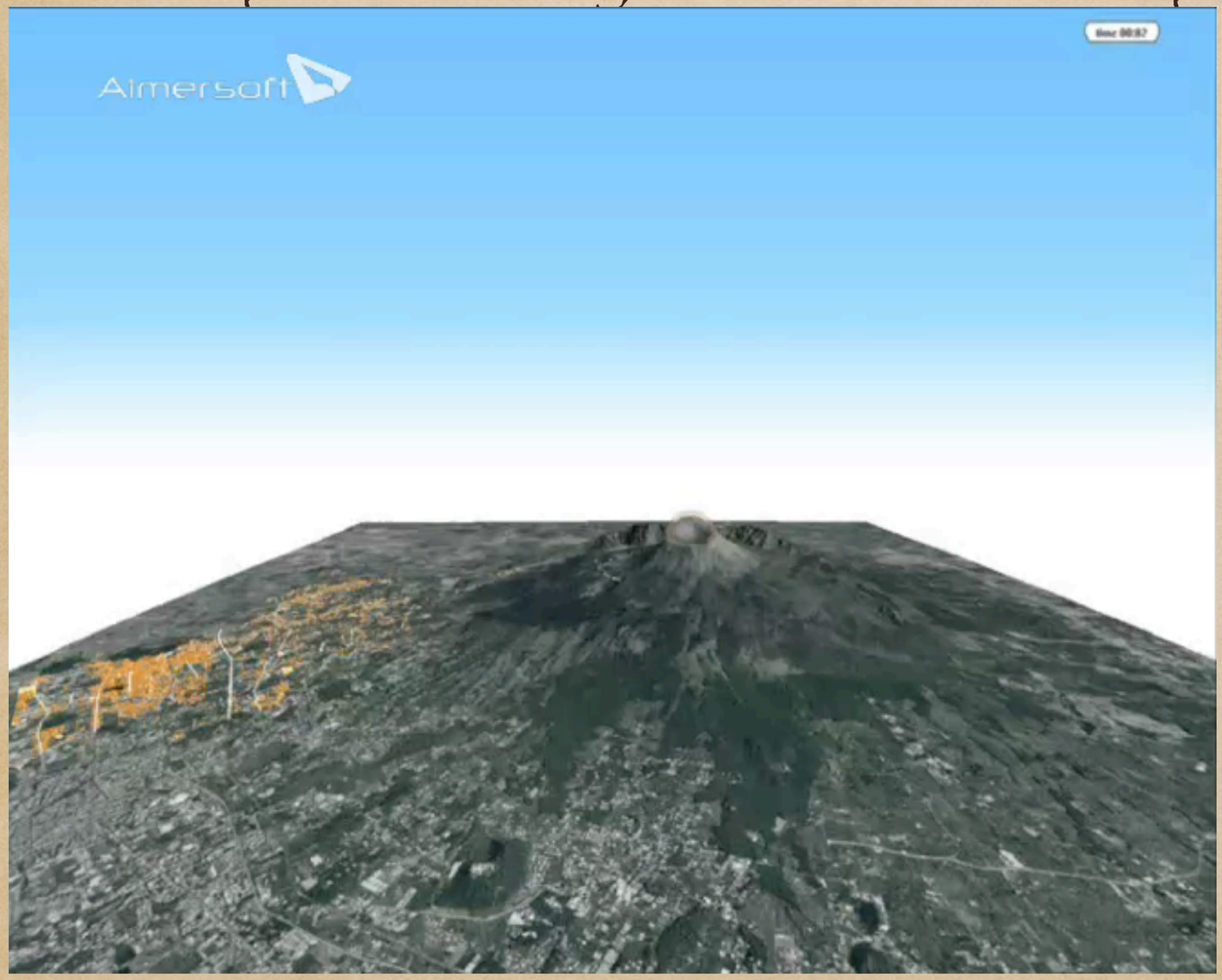
The republic is transformed into Empire and ...

In a small town, Herculaneum …

.. is founded an Epicurean school under the guidance of Philodemus of Gadara and the patronage of Lucius Calpurnius Piso

79 AD...

an eruption destroy Herculaneum,Pompeii, Stabiae...

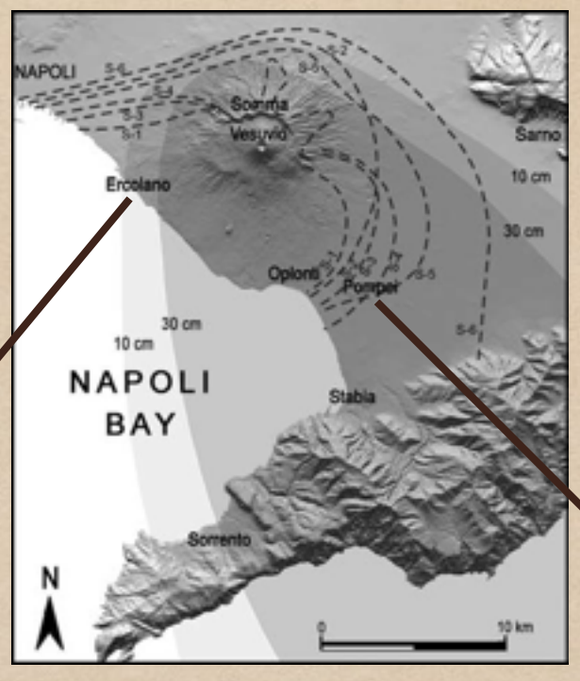


Neri, et al.
Journal of Geophysical Research
2003

Simulation of collapsing volcanic columns and pyroclastic flow - Sub-Plinian eruption

Herculaneum vs Pompeii

Herculaneum, only 7 km west of the crater of Vesuvius, was buried under 20 m. of pyroclastic deposits during the eruption



Only <u>one</u> pyroclastic flow was deposited in Pompeii. The pyroclastic flow deposits at Pompeii is regarded as lateral equivalents of the lower deposits at Herculaneum.

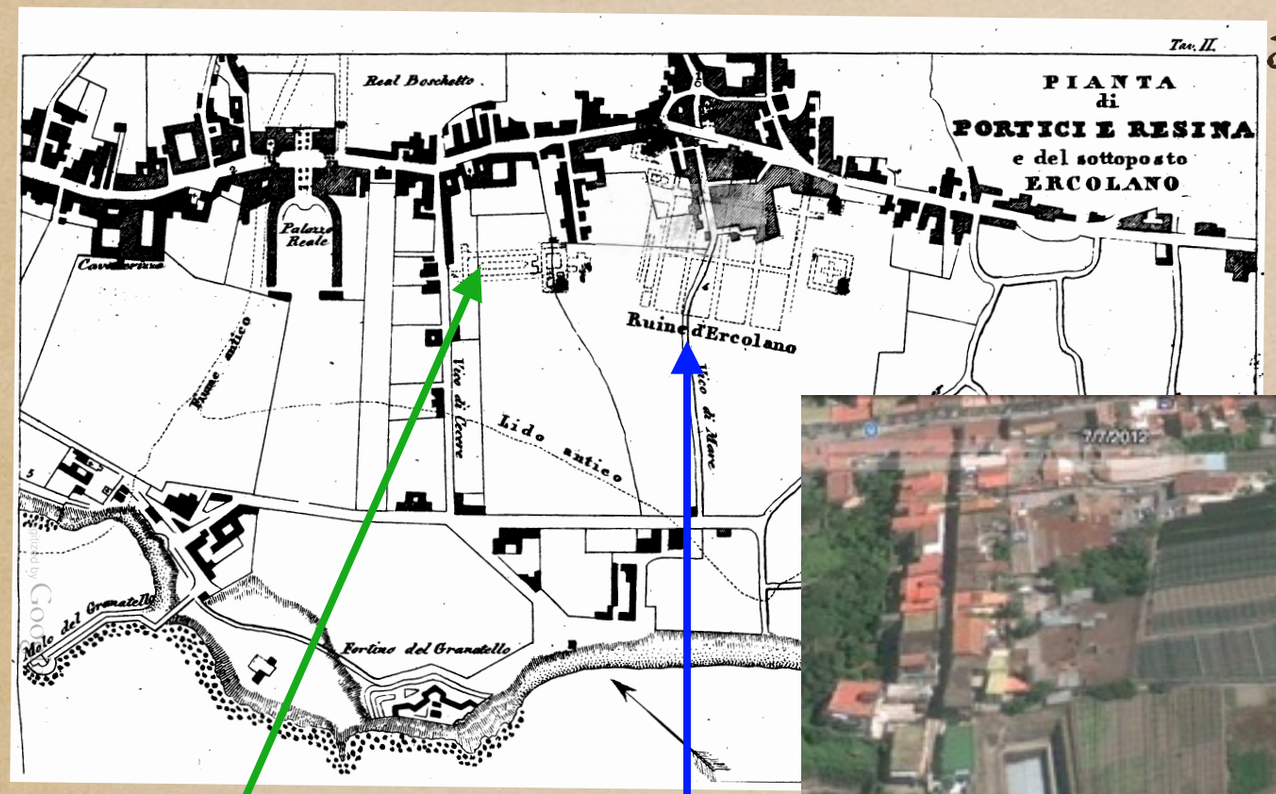
Herculaneum

sealed by pyroclastic deposits

Pompeii

Location of the villa compared to the excavations

around 1820



Satellite

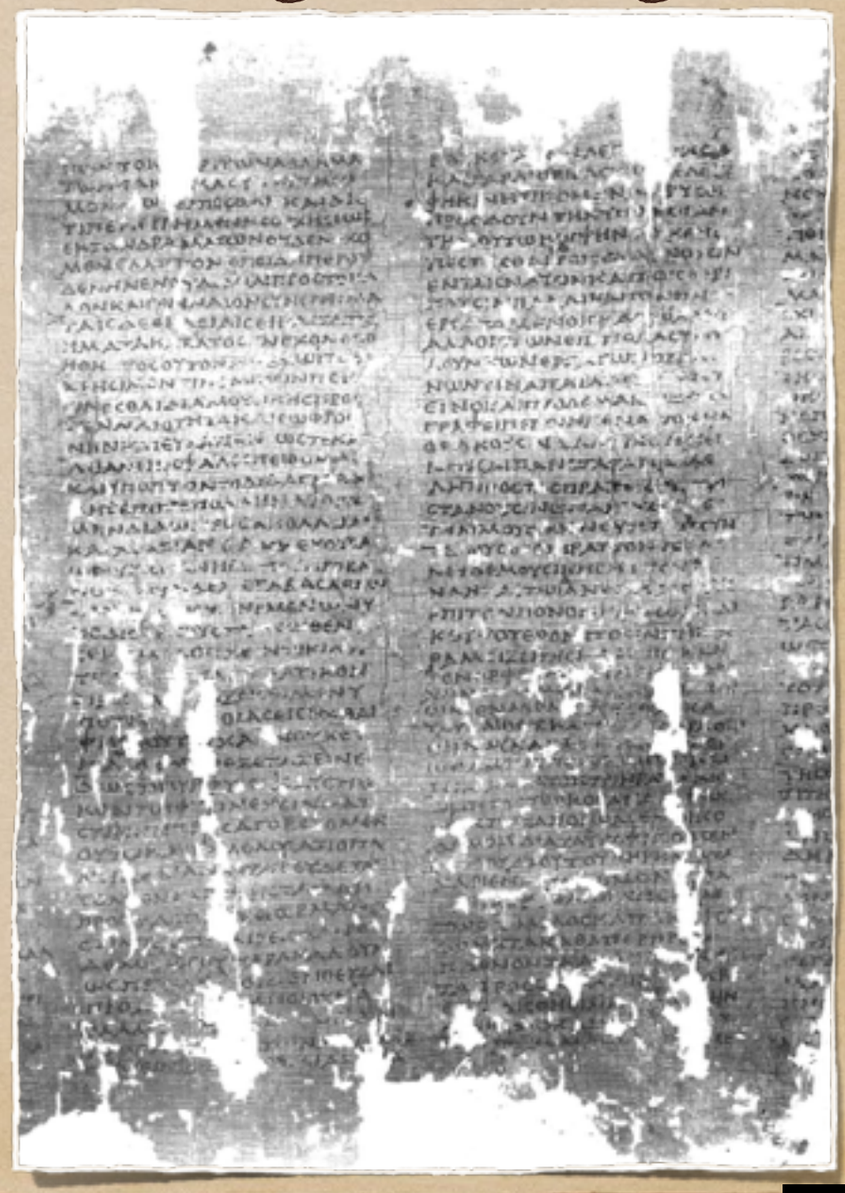
Villa

Herculaneum excavation

What does Herculanean papyri look like?

The pyroclastic flow at around 320 °C carbonized papyri

preserving the writing inside



PHerc. 1497
col. 121-122
(IR image)
24 cm height,
columns width 5,5 cm approx.

A Treasure for Humanity

- This is the only Ancient Library to survive together with its books.

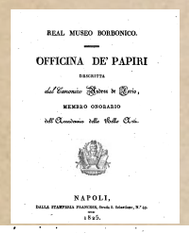
- This rich book collection, consisting principally of Epicurean philosophical texts, is a unique cultural treasure: the texts preserved in these papyri had been unknown to scholars since they had not been copied and recopied in late Antiquity, the Middle Ages and Renaissance.

Opening methods

First attempt

Immediately after discovery until 1848

Destructive method



REAL MUSEO BORBONICO.

OFFICINA DE' PAPIRI

DIRETTA

dal Cavaliere Padre D. Piero,

MEMBRO ONORARIO

dell'Accademia delle Belle Arti.

NAPOLI,

DALLA STAMPERIA REALE, Strada S. Sebastiano, N.° 39.

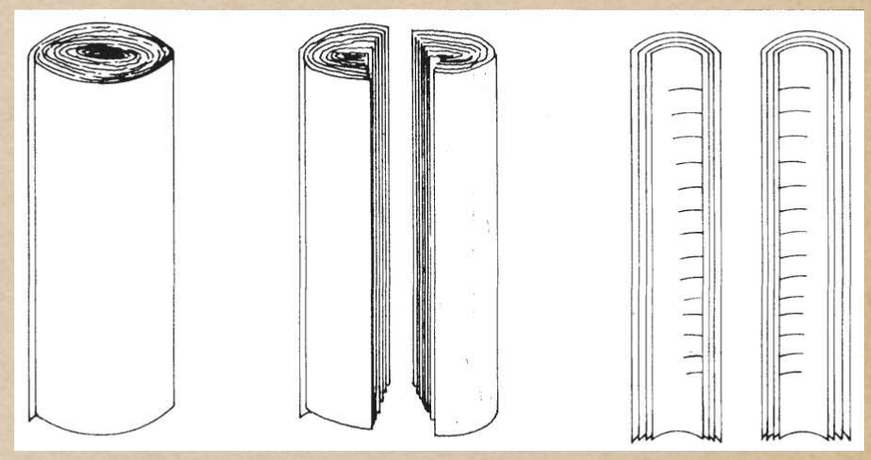
1825.

Sistema attuale per lo svolgimento, e per la pubblicazione de' papiri.

Prescelti che sono i rotoli, o le scorze o frammenti, che a giudizio degl'impiegati nell'officina, sembrano esternamente più atti allo svolgimento, si espongono ad un saggio. Se le prime pagine si rinvengono o senza caratteri, o con l'apparenza sola di esservi un tempo esistiti (a), o se il rotolo atto non sia a svolgersi per altra circostanza (b), si ripongono nell'armadio per conservarsi come semplici monumenti di antichità. Que' pochi che s'incontrano atti allo sviluppo ed alla lettura, rimangono nelle mani degl'incaricati di questa lunga e penosa operazione. Svolte che sono tre o quattro pagine, si troncano dal resto del papiro, e si fissano su di una tavoletta (a).

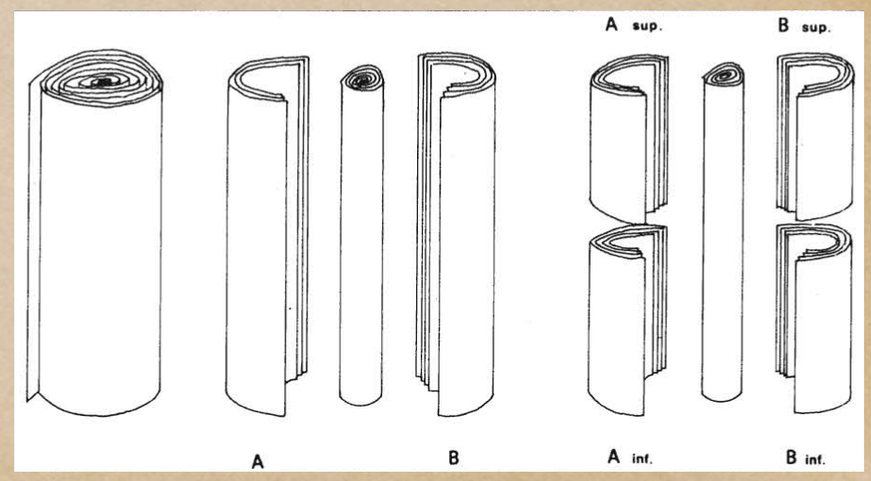
Total Scorzatura

Scratching the papyrus layer by layer



Partial Scorzatura

A variant,
considering negligible the middle part



Piaggio's Machine

From 1753 until the 1900

Partly destructive method

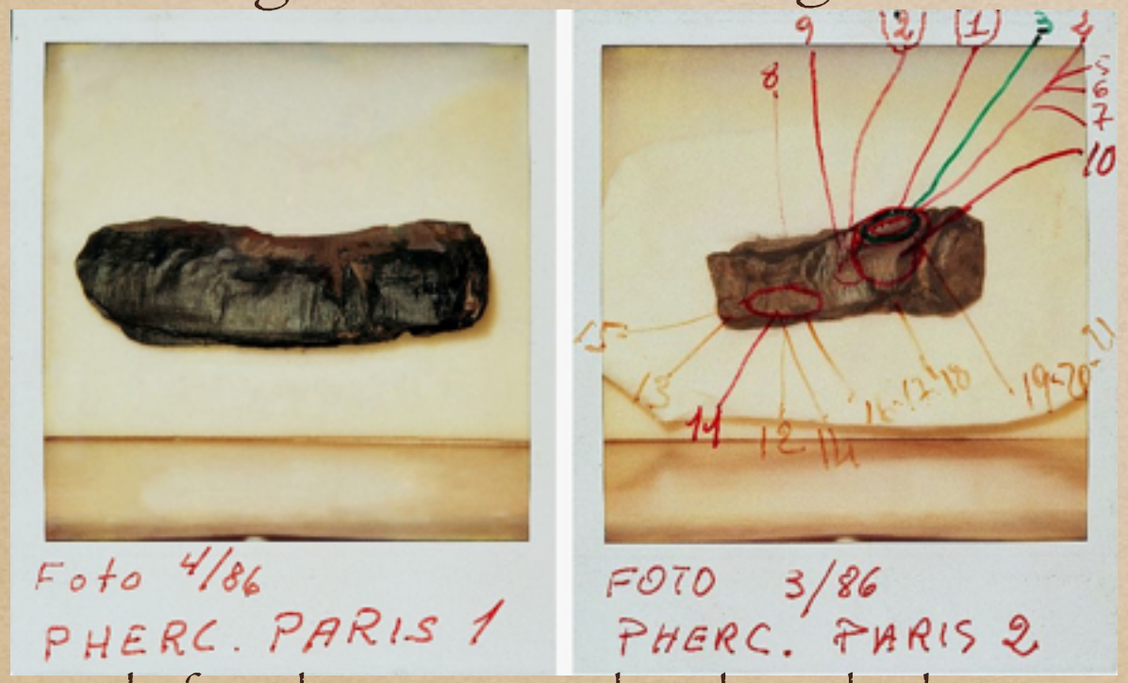
Technological opening : the Oslo Method

Fosse-Kleve-Stormer 1983-1993

A biochemical method continues the method of Piaggio, since in both there is the use of a type of glue that for its organic components does not damage the papyrus; but if in the first case the detachment occurred for mechanical traction, in accordance with the same glue, once dried, causes detachment of the sheet from the underlying layers of papyrus

broken in 380 fragments

broken in 283 fragments



Papyri before the opening with Oslo method opening in 1986-87

Problematic Results

After

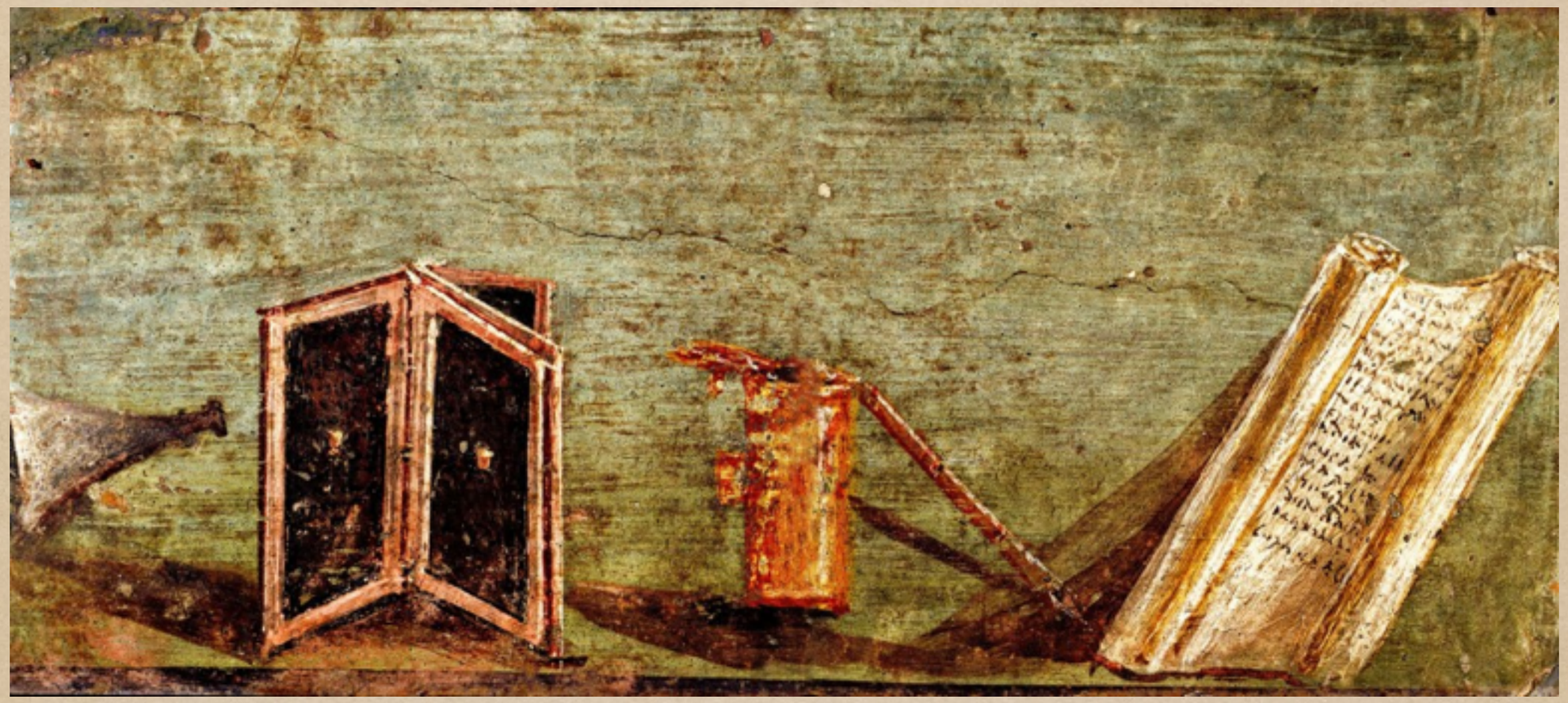
Present situation

Hundreds papyri ....

sometimes still kept in the position they were placed on the shelves of the library

All further attempts to unroll the papyri or to separate their layers mechanically had been abandoned until now to preserve their physical integrity and the possibility of reading them as continuous texts one day, because an excessive percentage of these ancient texts was irretrievably lost by the application of different methods

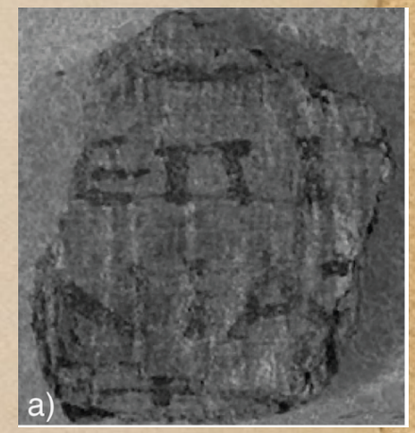
Something about writing in Antiquity…

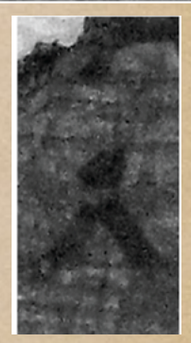


Writing on paper is essential to civilization, as Pliny the Elder remarks in his Natural History1, when he describes the different types of papyri, the method of manufacturing them and all what concerns writing materials in the mid-1st century AD

Material and Methods

2 fragments were used for the analysis





- X- Fluorescence (ID21)

  Spectroscopic technique that allows elemental analysis

- Xray Diffraction (ID11)

  Analysis of the structural atomic arrangement (cristalline structure)

- X-Ray Absorption Near Edge Structure (Xanes - Dubble)

  Allows studying the chemical bounds, which compound of Pb

- InfraRed Microscopy (Det lab)

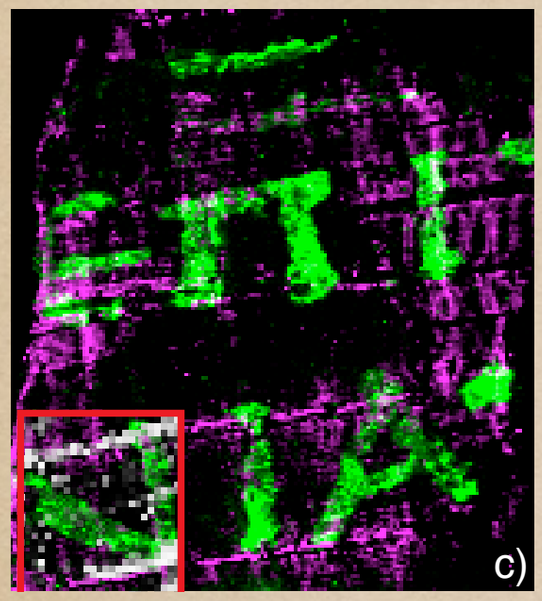
  Qualitative technique for a better visualization

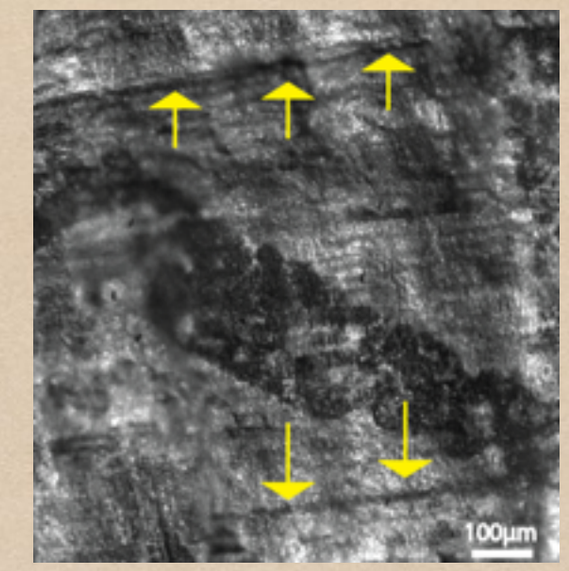
Ruled lines

ABC

Si Pb Cristobalite

XR + XR



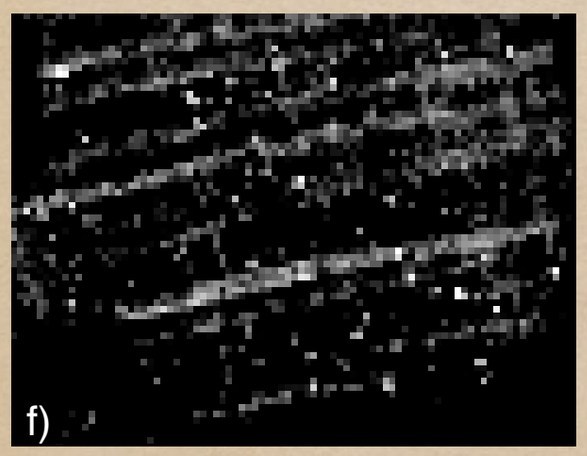


Quartz stylus or
Natural Ruled Lines?

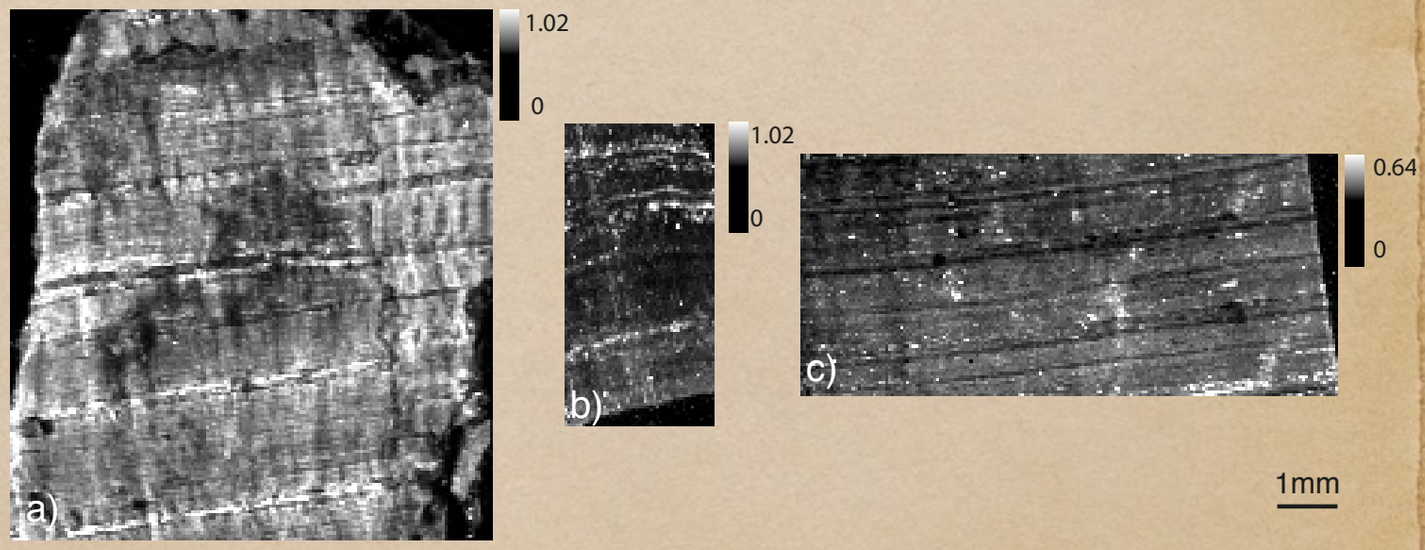
Cristobalite has the same chemical formula as quartz, SiO2, but a distinct crystal structure

Cristobalite

XRD

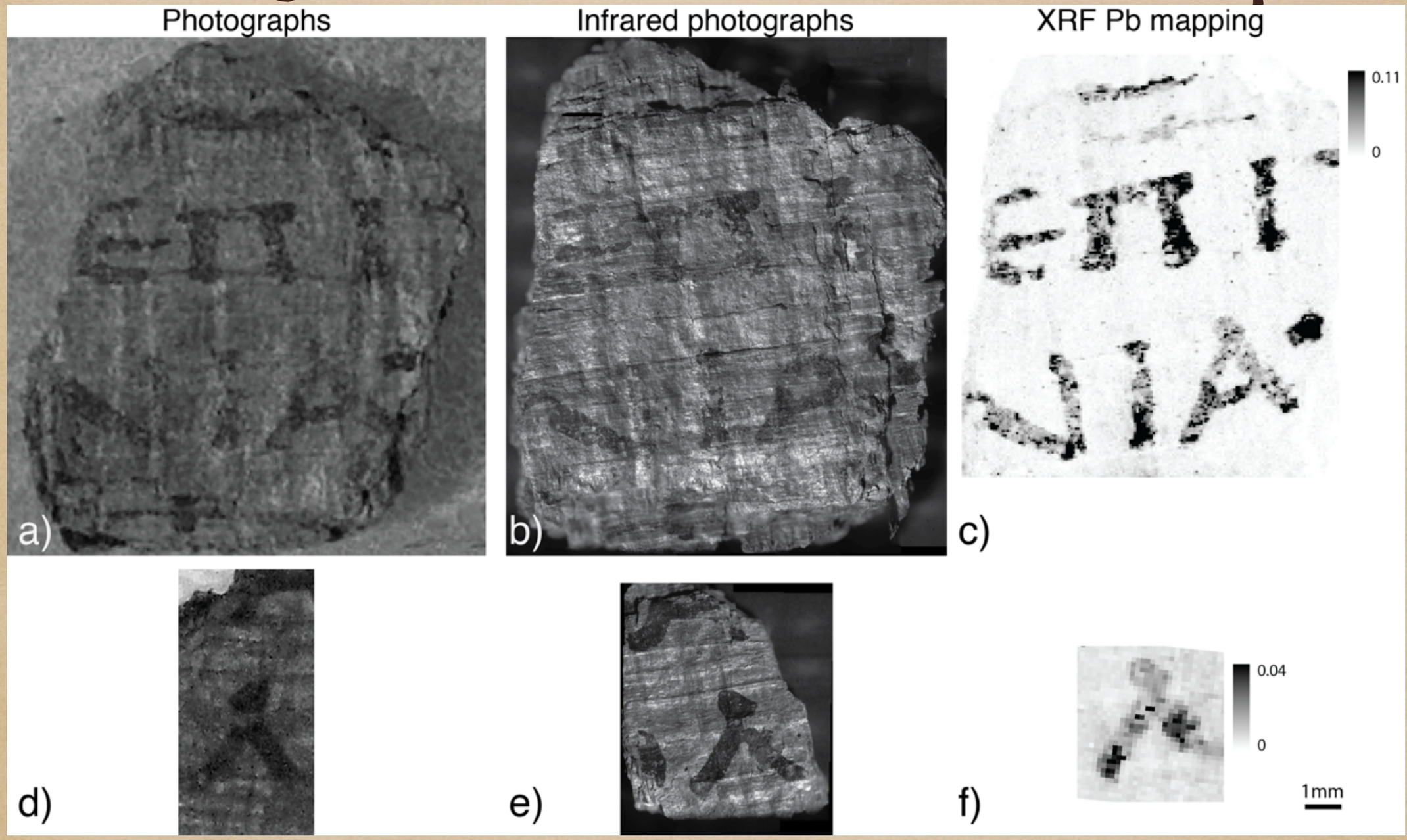


Herculaneum 200C Fresh



Scribes used straight and thick horizontal papyrus fibers to guide the writing of letters in straight lines

X-ray Fluorescence Maps

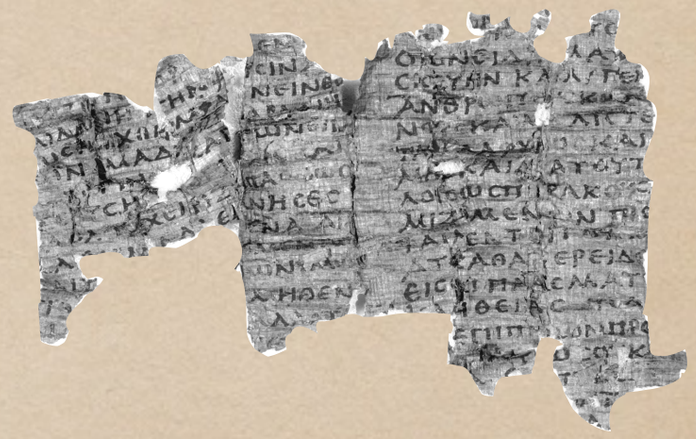


E. Brun, ..& V.Mocella., "Revealing metallic ink in Herculaneum papyri", Proc. Natl. Acad. Sci. USA, 113 (14) 3751-3754 (2016).
P. Tack, et al Tracking ink composition on Herculaneum papyrus scrolls: quantification and speciation of lead by X-ray based techniques and Monte Carlo simulations. Scientific Reports 6, 20763 (2016)

Non invasive reading :principal difficulties

- Ink chemical contrast

In Antiquity, papyri were written using a black carbon-based ink obtained from smoke residues, the density of which is almost the same as that of the carbonized papyrus.



- Conventional approaches

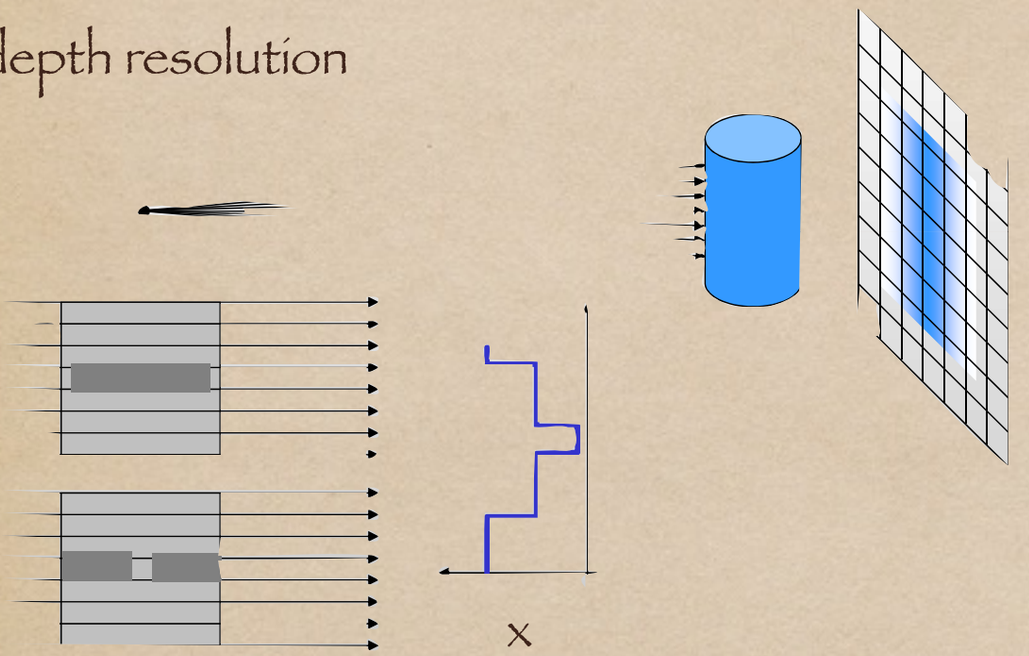
Until now, therefore, it has appeared impossible to distinguish ink from papyrus inside a papyrus roll using the penetrating radiation of a conventional X-ray source and technique, where the X-ray image contrast is based exclusively on the X-ray-absorption patterns of different materials

Absorption Radiography & Tomography

Radiography : Sum of the attenuation along a ray

Good lateral resolution

No depth resolution

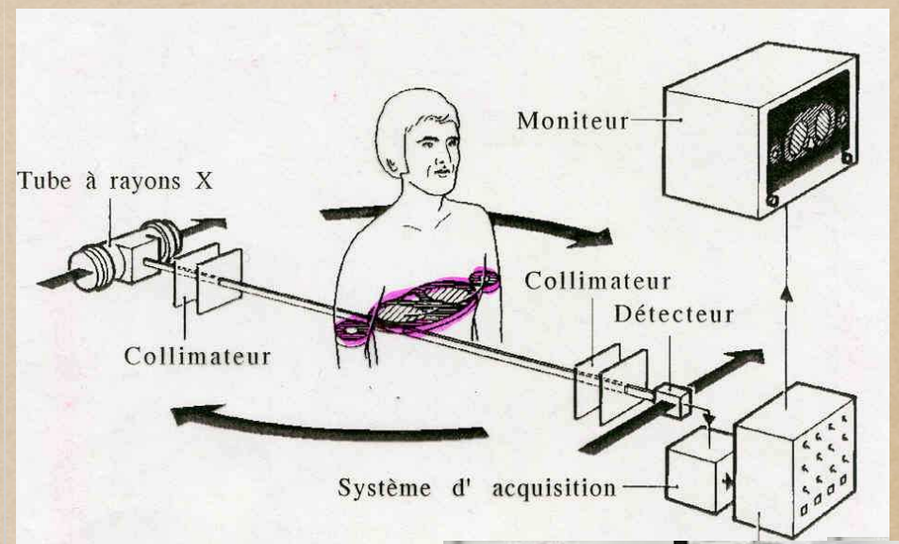


$$\frac{I}{I_0} = \exp \int -\mu \, dx$$

First public radiography (1895)

Tomography

3 Dimension in medicine and industry

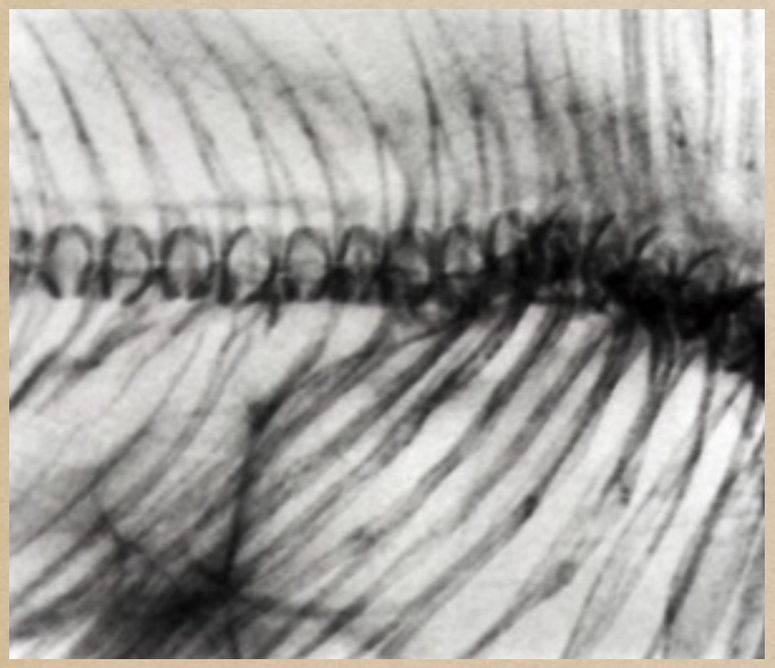


Nobel Prize 1979 (medicine) to G.N. Hounsfield, « for the development of computer assisted tomography »

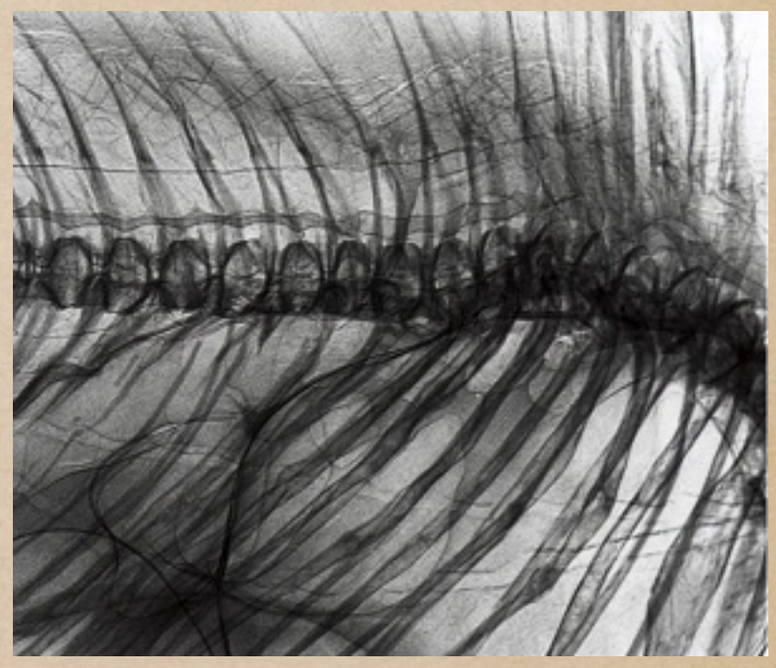
Absorption vs Phase Contrast Radiography

Davis, T. J. et al, Nature 373 (1995)

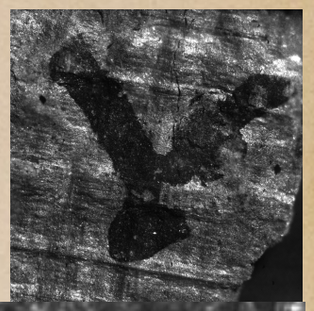
Absorption



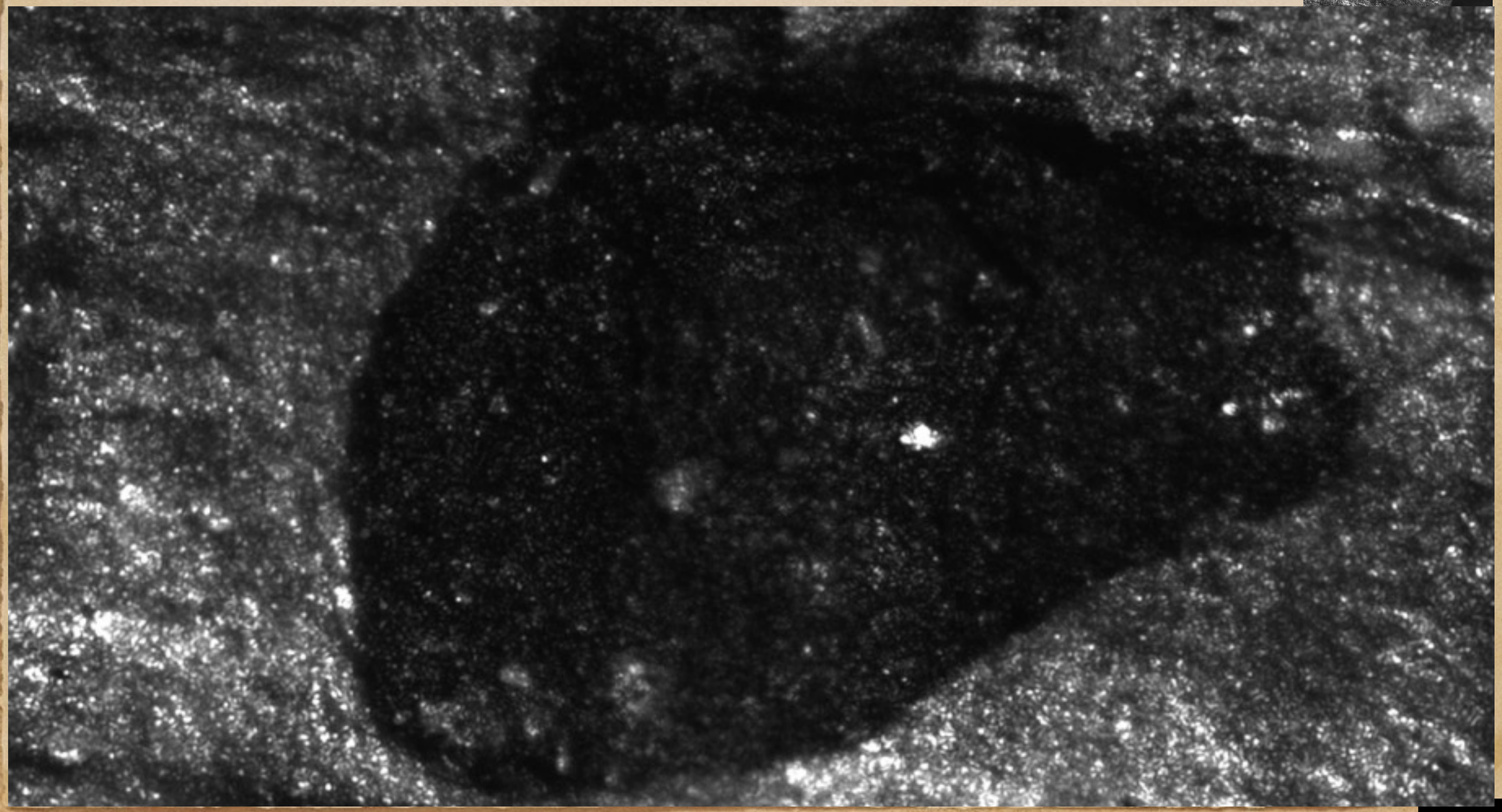
Phase Contrast



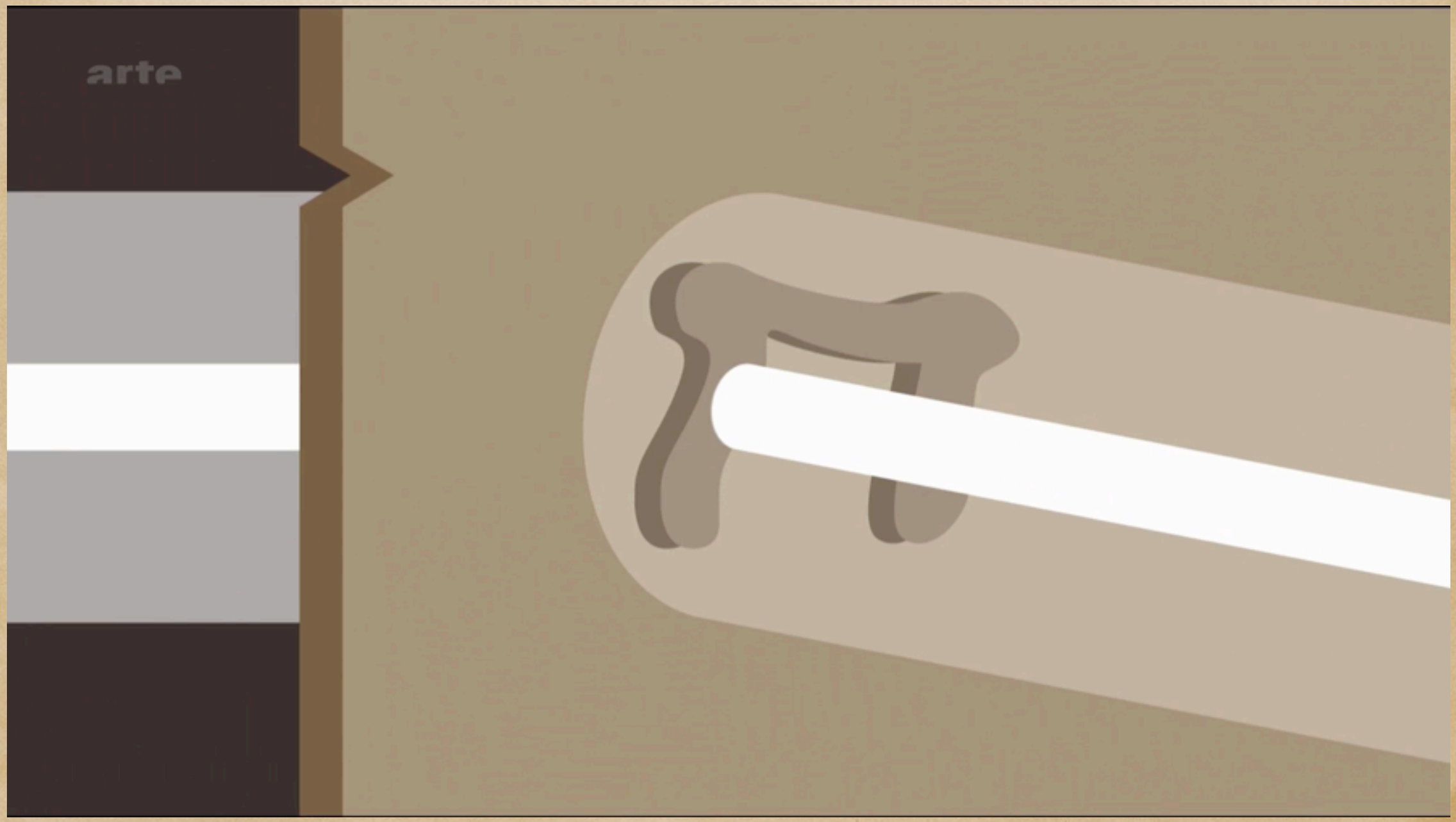
Revealing writing : our approach (1)



Ink is slightly in relief



How letters are detected?



Phase vs Absorption

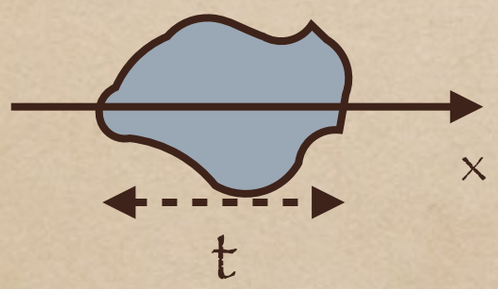
Complex refractive Index

$$n = 1 - \delta + i\beta$$

$$\beta = \frac{\lambda\mu}{4\pi} \qquad \mu \quad \text{linear absorption}$$

$$\delta = \frac{N r_c \lambda^2}{2\pi} \qquad N \quad \text{electron density}$$

$$\frac{I}{I_0} \sim \left| \int \exp\left(-\frac{2\pi}{\lambda} n x \right) dx \right|^2$$

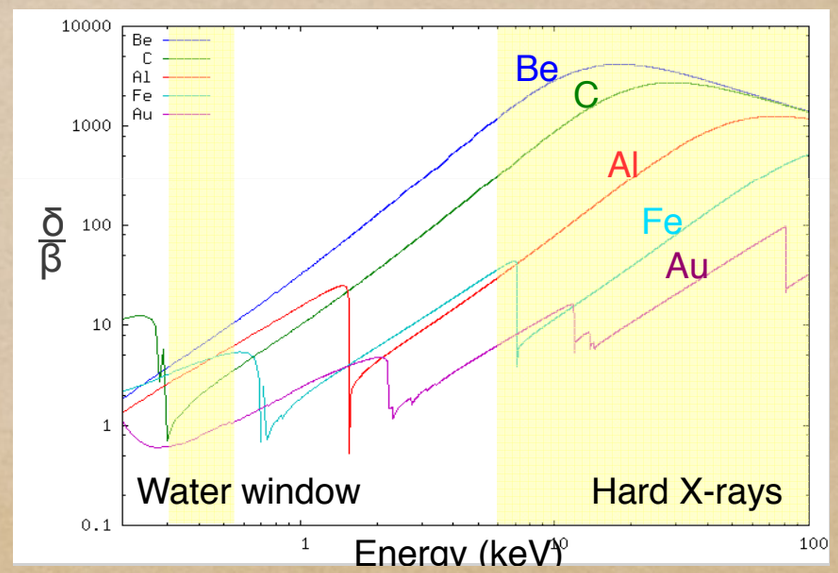


$$\Delta\phi = \frac{2\pi\delta t}{\lambda}$$

phase difference

Ratio between Phase and Absorption effect

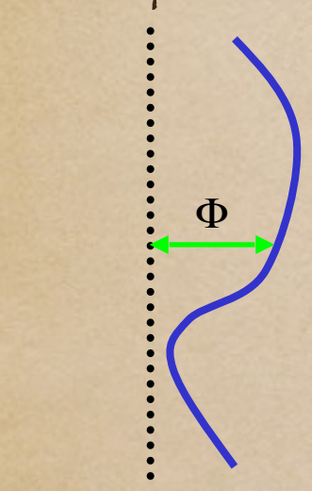
$$\frac{\delta}{\beta} \sim 10,1000 \quad \text{in hard X-ray}$$

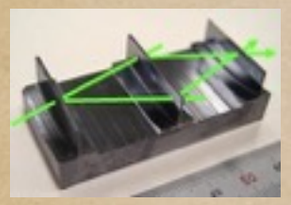


Seeing the Phase

Phase sensitive images are obtained:

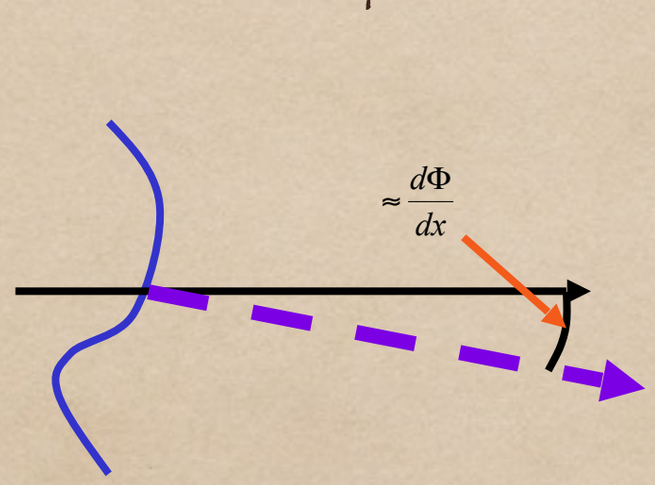
Direct phase shift

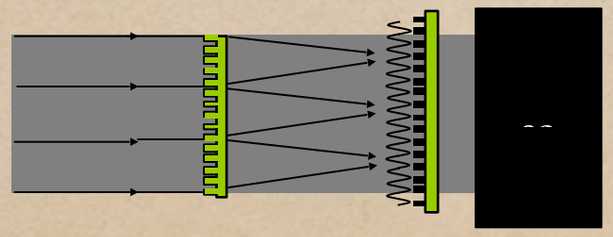




Interferometer

Differential phase shift

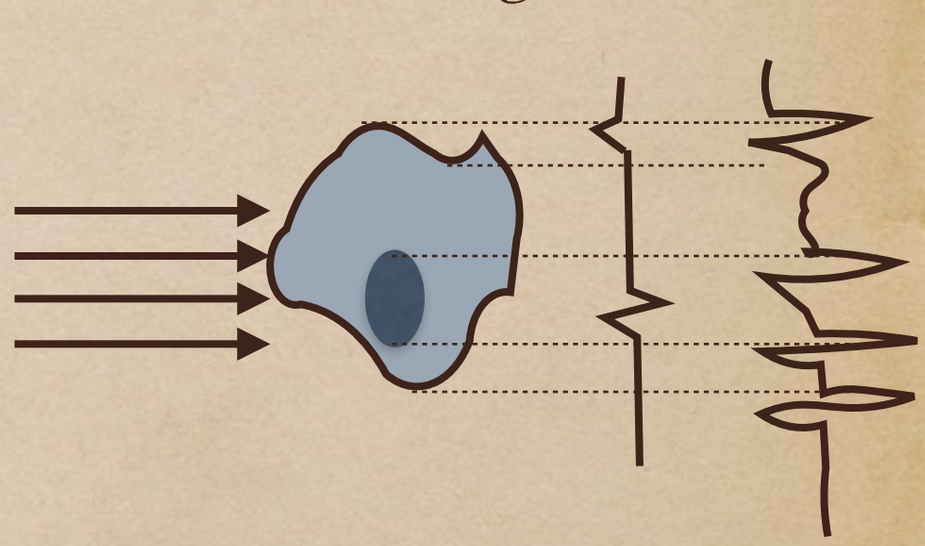




Crystal analyser

Grating interferometry

Edge detection



Propagation Based – edge contrast

Coherent illumination

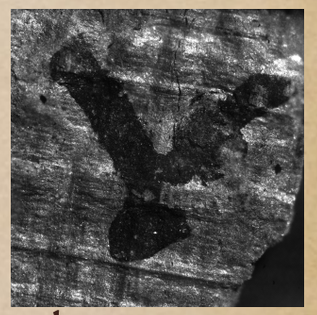
Coherent x-ray source : synchrotron light

Grenoble..

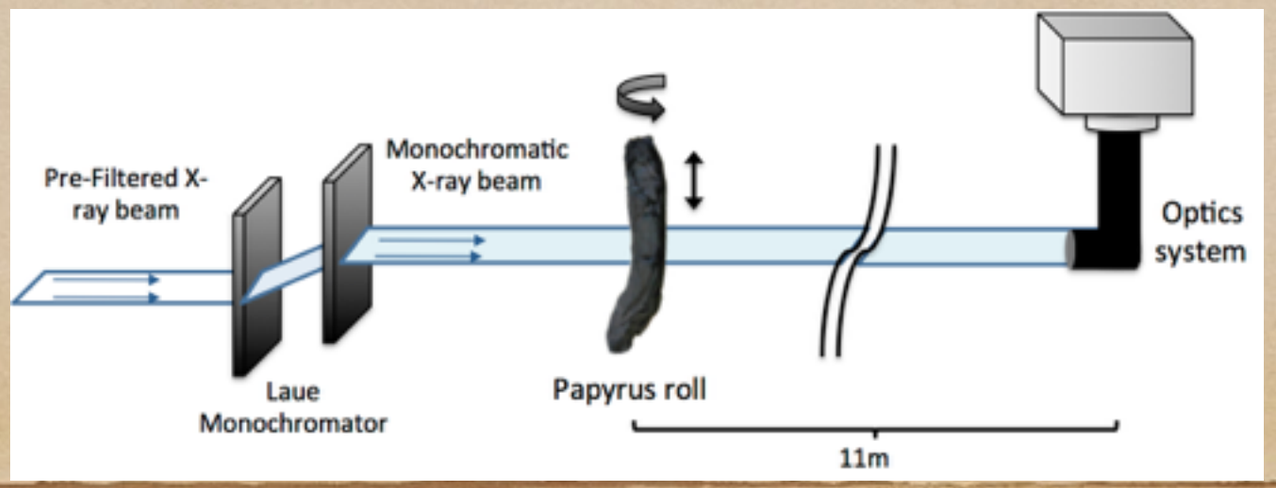
.. at the end of every road, a mountain

Our approach (2)

- We radically changed the paradigm of the technique:
  - The morphological information as the internal deformation or the length of the papyrus, the arrangement and the characteristics of the fibers which make up the structure of the support is only the starting point
  - Our attempt is to retrieve a special kind of information, the text, identified with the weak relief of ink deposited on the papyrus surface.



- Letters can be read using Phase contrast - edge detection
- Even if Papyrus and Ink absorb quite uniformly a significantly enhancing the image-contrast effect is obtained exploiting X-ray phase-contrast tomography (XPCT)



Analysed Papyri

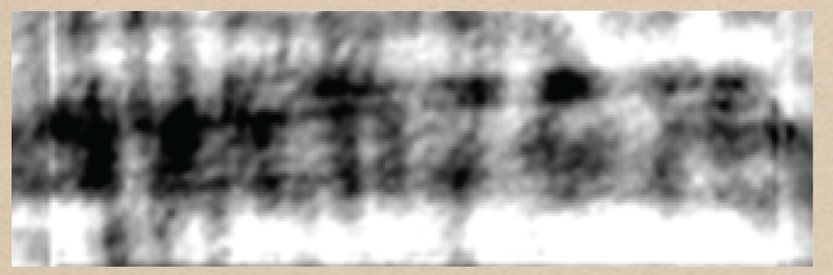
PHerc.Paris.4

PHerc.Paris.1
fragment

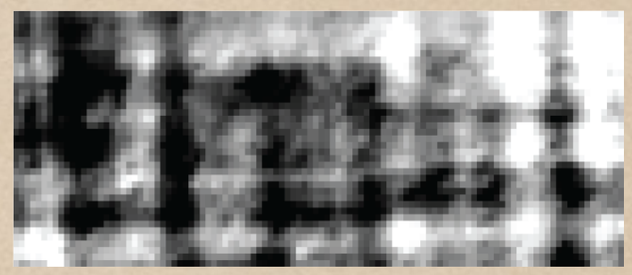
Words from fragment

Phase contrast edge detection + Absorption is enough to distinguish letters

1 mm



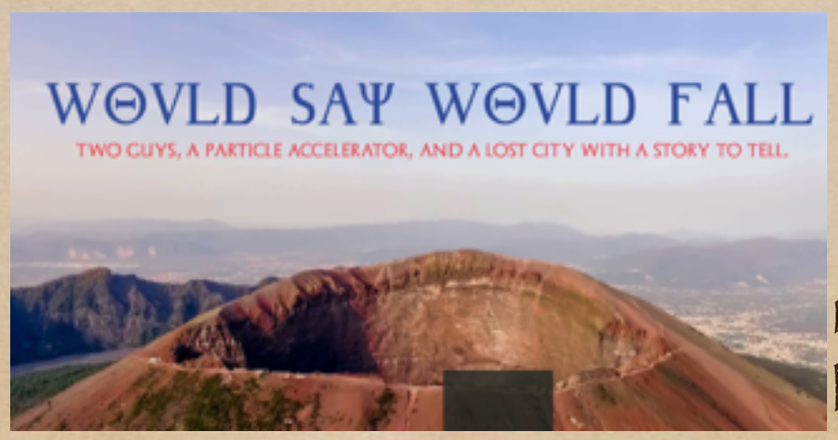
Π Ι Π Τ Ο Ι Ε



Ε Ι Π Ο Ι

"would fall"

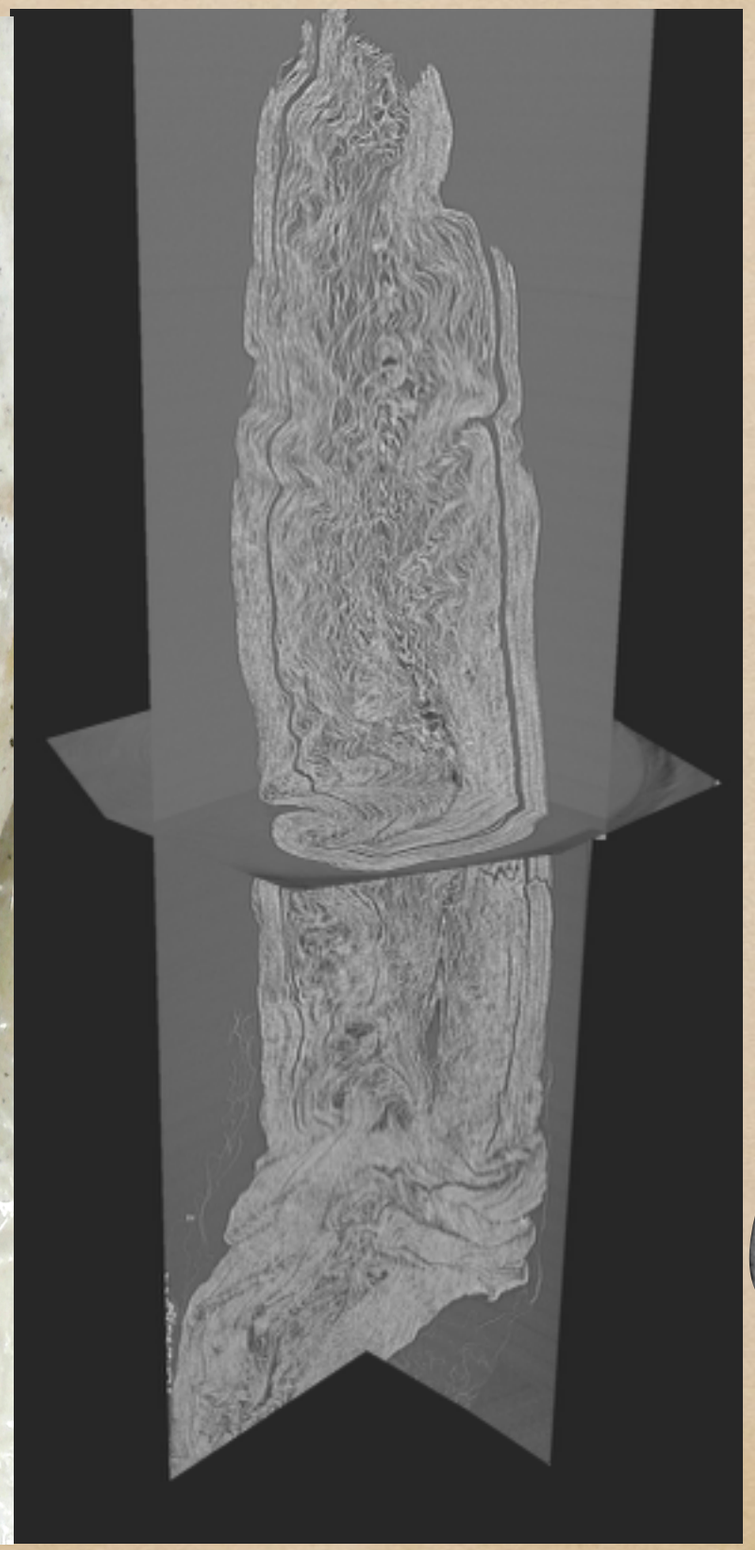
"would say"



MEL films

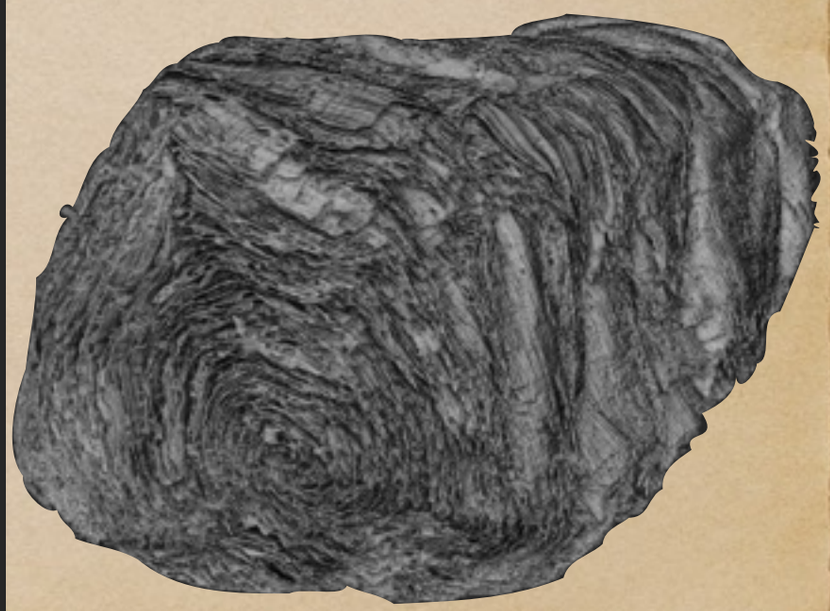
https://vimeo.com/171348361

Complex Internal Structure of PHerc . Paris. 4



Sections

3D Volume



Animated rendering of the Data Analysis

PHerc.Paris.4 - 1: Phase Contrast Tomographic Reconstruction

Mocella, V. et al. Revealing letters in rolled Herculaneum papyri by X-ray phase-contrast imaging. Nat. Commun. 6:5895 (2015).

Letters sequences

inside the scroll

The script here is noticeably different from that of fragment from PHerc.Paris. 1

1 mm

APN

can be a single word like
αρν-εισθαι … 'to deny'

HEY

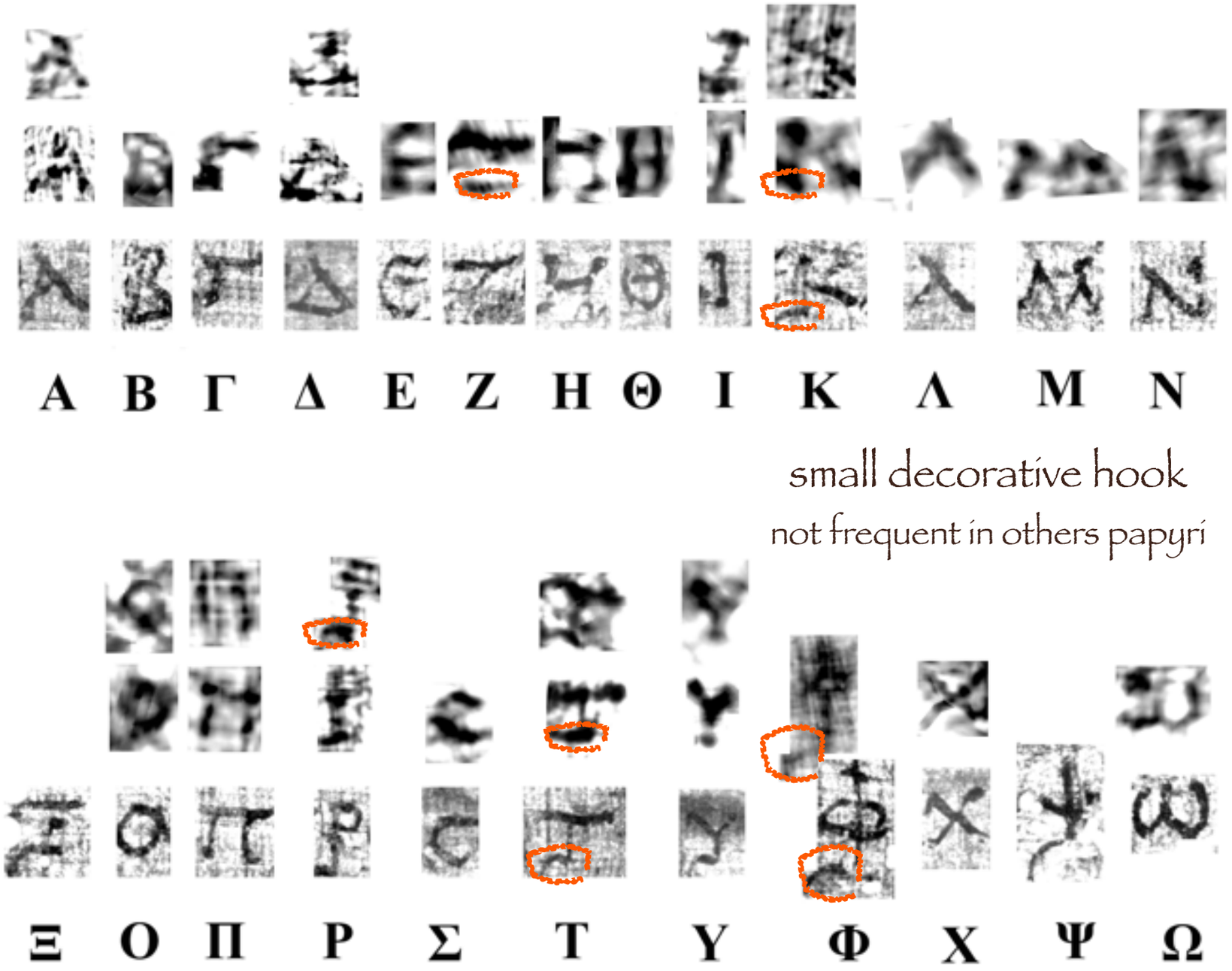
feminine definite
article "The"

"Eu.."
first syllable of a nominal
cf. for example, in English
euphonia, euphonic,..

K I

for example, a word of the
verb family κινεῖν 'to move'

A reconstructed alphabet



Recovered letters

PHerc.1471

Recovered letters

PHerc.1471

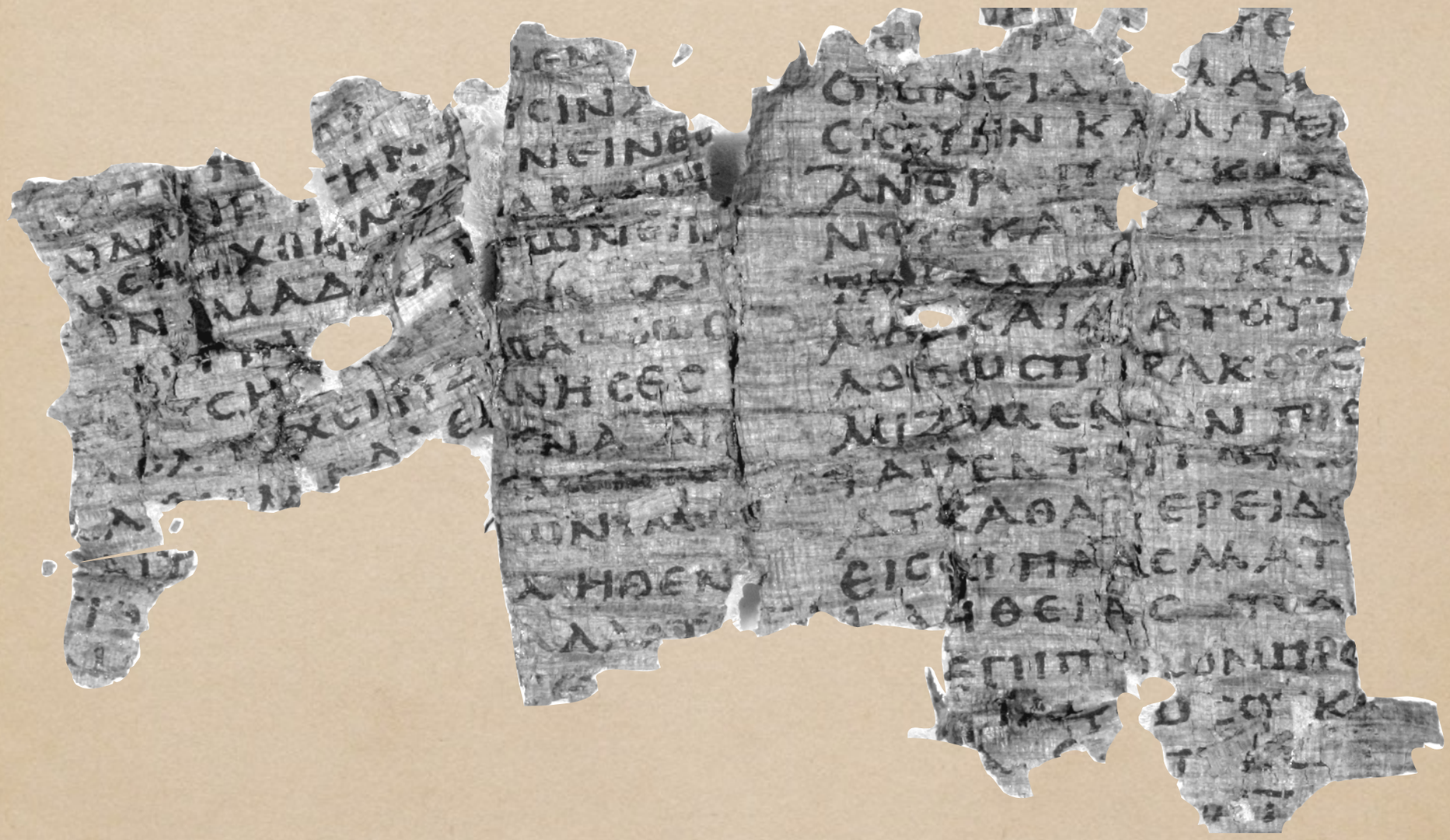
A possible attribution

The overall close similarity of the two hands could lead us to date PHerc.Paris. 4 to the same period as PHerc. 1471, that is, the second quarter of the first century BC, according to the dating proposed by G. Cavallo

The papyrus is quite likely to contain a text by Philodemus.

From ink...

...to the text



Future Prospects (1)

Data analysis:

Improve algorithms for segmentation applied to very complex surface

many collaborations are starting right now

Develop totally new approaches

Experimental techniques

Improvement of technique: new experiments are scheduled

Development of new techniques → New detectors

New compact coherent sources

Experimental Techniques

New techniques (Most promising is):

Fluorescence based Tomography

combined with the

Phase Contrast Tomography

Can add chemical sensitivity exploiting our knowledge about ink composition.

Requires the development of new efficient detectors.

New coherent compact sources

If Papyri can't go to the mountain-synchrotron,
the mountain-synchrotron must come to papyri.

In perspective :

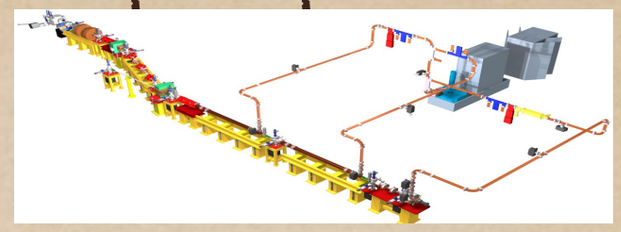
- We cannot bring hundreds papyri to Grenoble or elsewhere
- We expect to find new burn papyri in Herculaneum

We need Coherent Compact sources

Ideally combining new efficient and coherent compact source with new experimental techniques.

Many coherent compact source proposals

Thomson backscattering (TS) such as



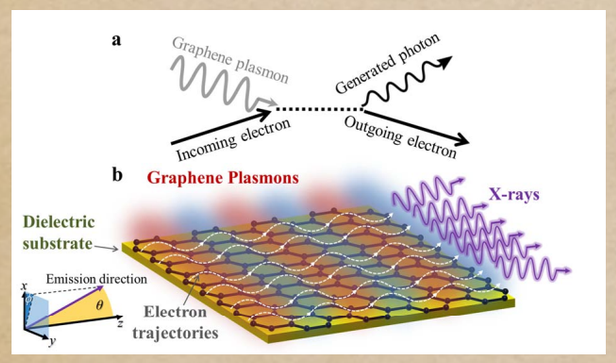
SPARC_LAB at at LNF

STAR project (Southern european Thomson source for Applied Research)

Inverse Compton scattering compact x-ray light source with flux and brilliance orders of magnitude beyond existing laboratory scale sources are proposed

High-peak power laser (PW) Biedron et al. Proc. SPIE 996406 (2016)

Graphene -plasmons based free-electron



electron-plasmon scattering is distinct from the electron-photon scattering of the standard Thomson/Compton effect, opening up many possibilities not achievable with regular photons

Nature Photonics 10, 46–52 (2016)

Plasma wakefield effect (Nature Physics 6, (2010)

What about unexcavated levels

Partial excavation ('80 e '90)

Wall painting

Virtual reconstruction

Future Prospects (2)

A promise that many text from the library of the 'Villa dei Papiri',

the contents of which have so far remained unknown,
may in future be deciphered without damaging the papyrus in any way.

New prospects not only for the many papyri still unopened,

but also for others that have not yet been discovered, perhaps including a second library of Latin papyri at a lower, as yet unexcavated level of the Villa

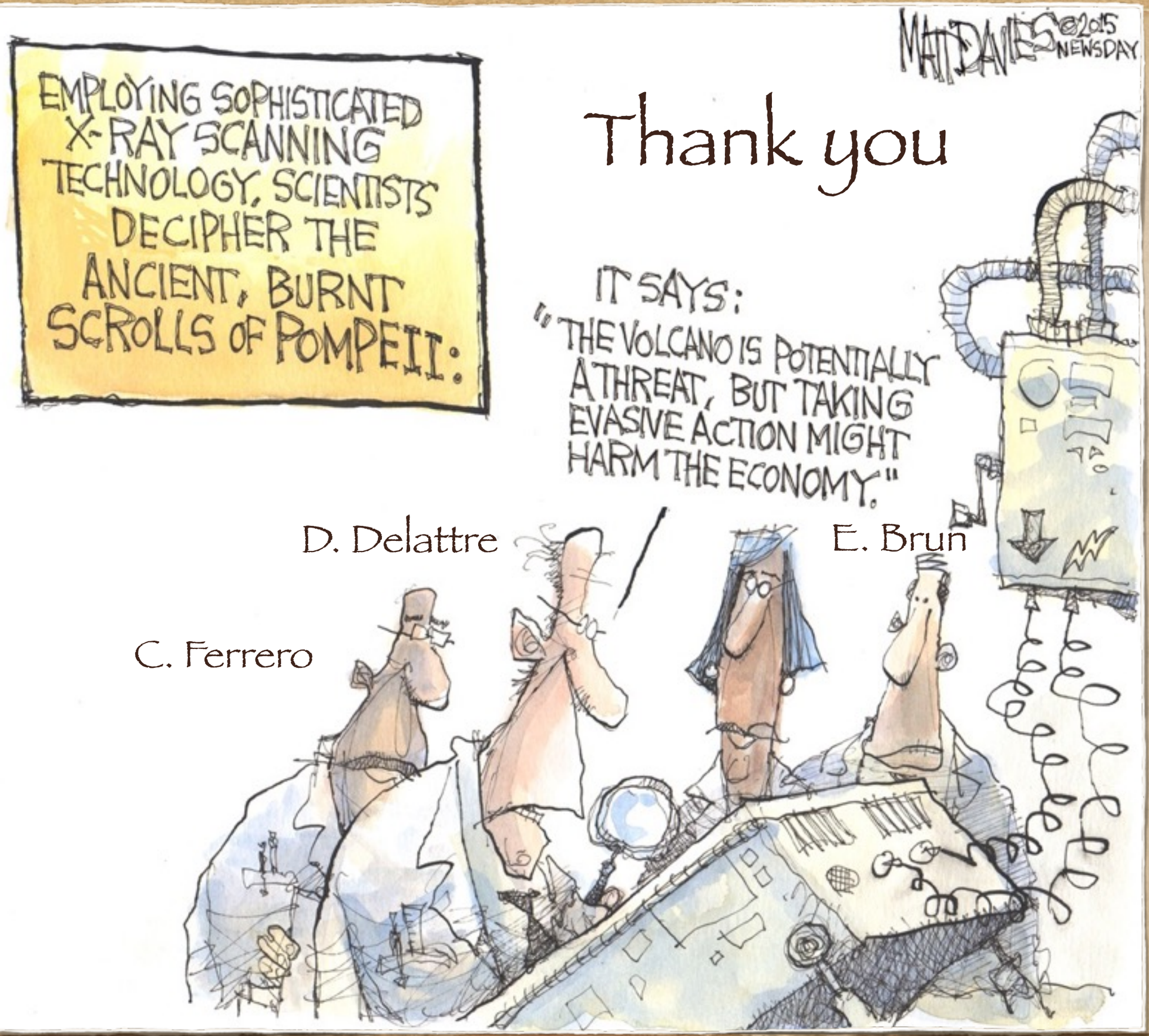
Need efficient coherent compact source

New excavations cannot be postponed indefinitely

The eruption of 1944 of Mount Vesuvius

Vesuvius is one of the most dangerous volcanoes in the world

Nature 473, 140-141 (2011)


EMPLOYING SOPHISTICATED X-RAY SCANNING TECHNOLOGY, SCIENTISTS DECIPHER THE ANCIENT, BURNT SCROLLS OF POMPEII:
MATT DAVIES ©2015 NEWSDAY
Thank you
IT SAYS:
"THE VOLCANO IS POTENTIALLY A THREAT, BUT TAKING EVASIVE ACTION MIGHT HARM THE ECONOMY."
D. Delattre
E. Brun
C. Ferrero