Reconstructing the Past, Understanding the Present and Predicting the Future based on Isotopic Analysis via Multi-Collector ICP - Mass Spectrometry

Frank Vanhaecke

Ghent University, Belgium

UNIVERSITAS MASARYKIANA BRUNENSIS

MASARYK UNIVERSITY
Czech Republic

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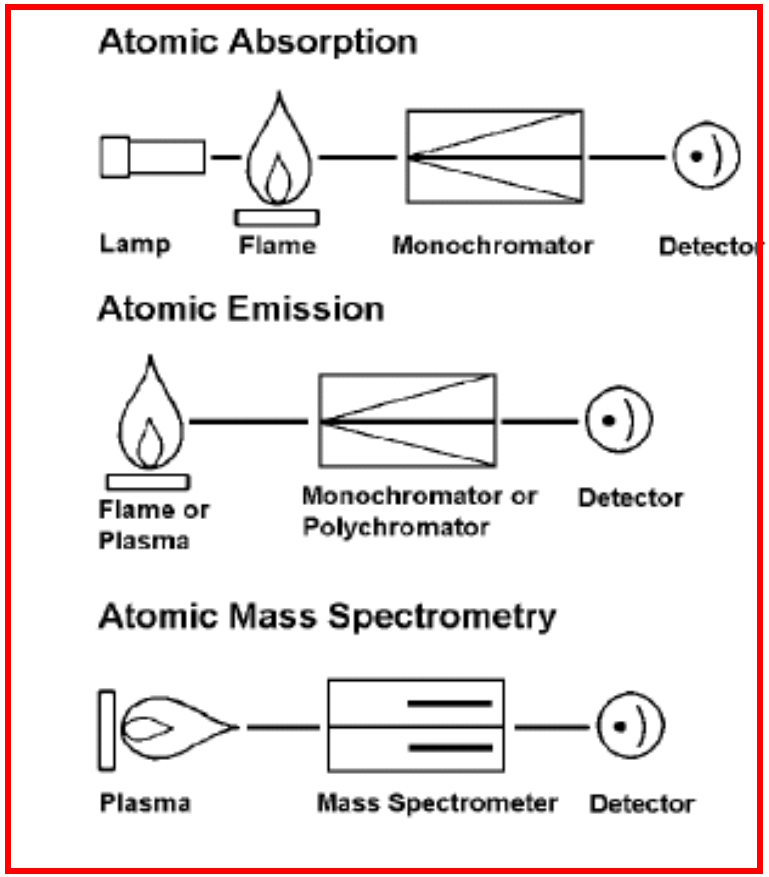
ICP – MASS SPECTROMETRY

- ***Analytical technique for (ultra)trace element analysis***
  - ***° 1983***
- ***Compared to AAS***
  - ***Even lower LODs***
  - ***Multi-element capabilities***
- ***Compared to ICP-OES***
  - ***Lower LODs***



ICP – MASS SPECTROMETRY

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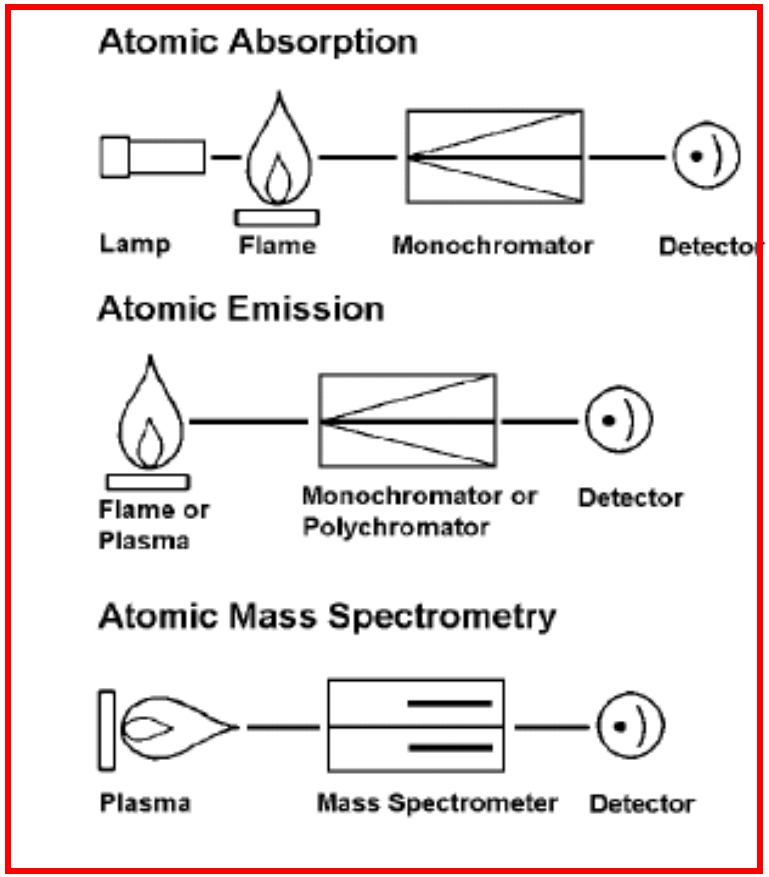
  - ***° 1983***
- ***Compared to AAS***
  - ***Even lower LODs***
  - ***Multi-element capabilities***
- ***Compared to ICP-OES***
  - ***Lower LODs***
- ***Compared to AAS & ICPOES***
  - ***Isotopic information !!***



ISOTOPES ?

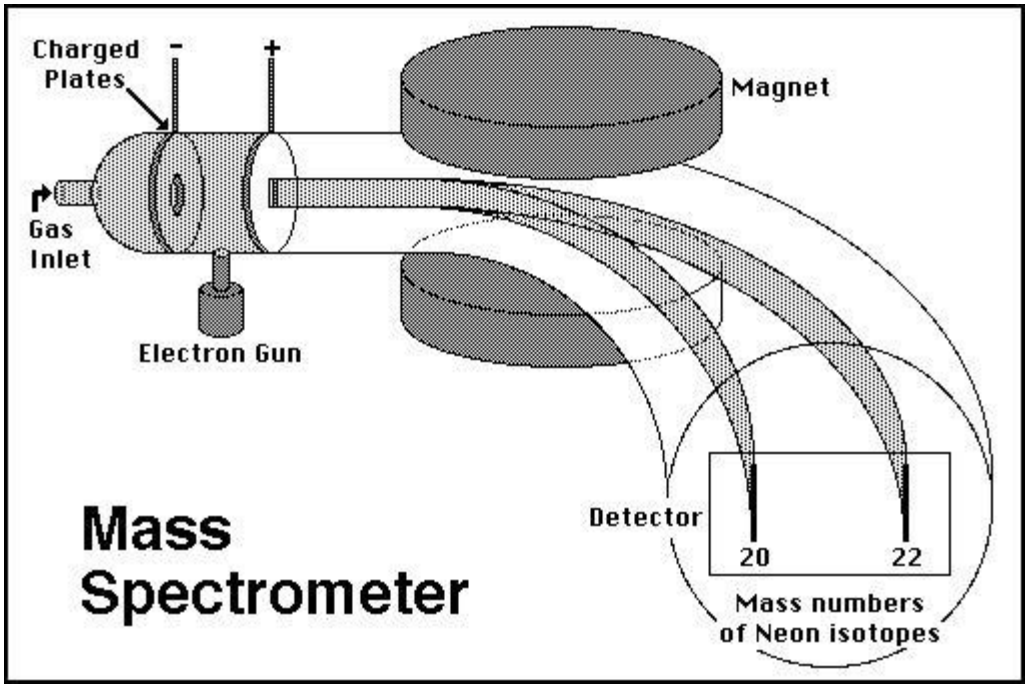
- ***Isotopes of an element M:***
  - ***same atomic number A***
    - ***Same number of protons in their nuclei***
    - ***Same number of electrons in their shells***
  - ⇒ ***Identical chemical behaviour***
    - ***First approximation – statement will be refined later on***
  - ***Different mass number Z***
    - ***Different number of neutrons in their nuclei***
  - ⇒ ***Different masses***
- ***Notation***

$${}^{A}_{Z}X \quad \textit{or} \quad {}^{A}X$$

- ***Terminology?***
  - ***Isotope: same place in PSE***
  - ***Todd & Soddy (early 20th century)***

DISCOVERY OF ISOTOPES

- ***Separation of isotopes according to their mass in MS***
  - ***Thomson: separation of Ne^+ isotopes in magnetic field***



  - ***Later on: Aston → isotopes for a suite of elements***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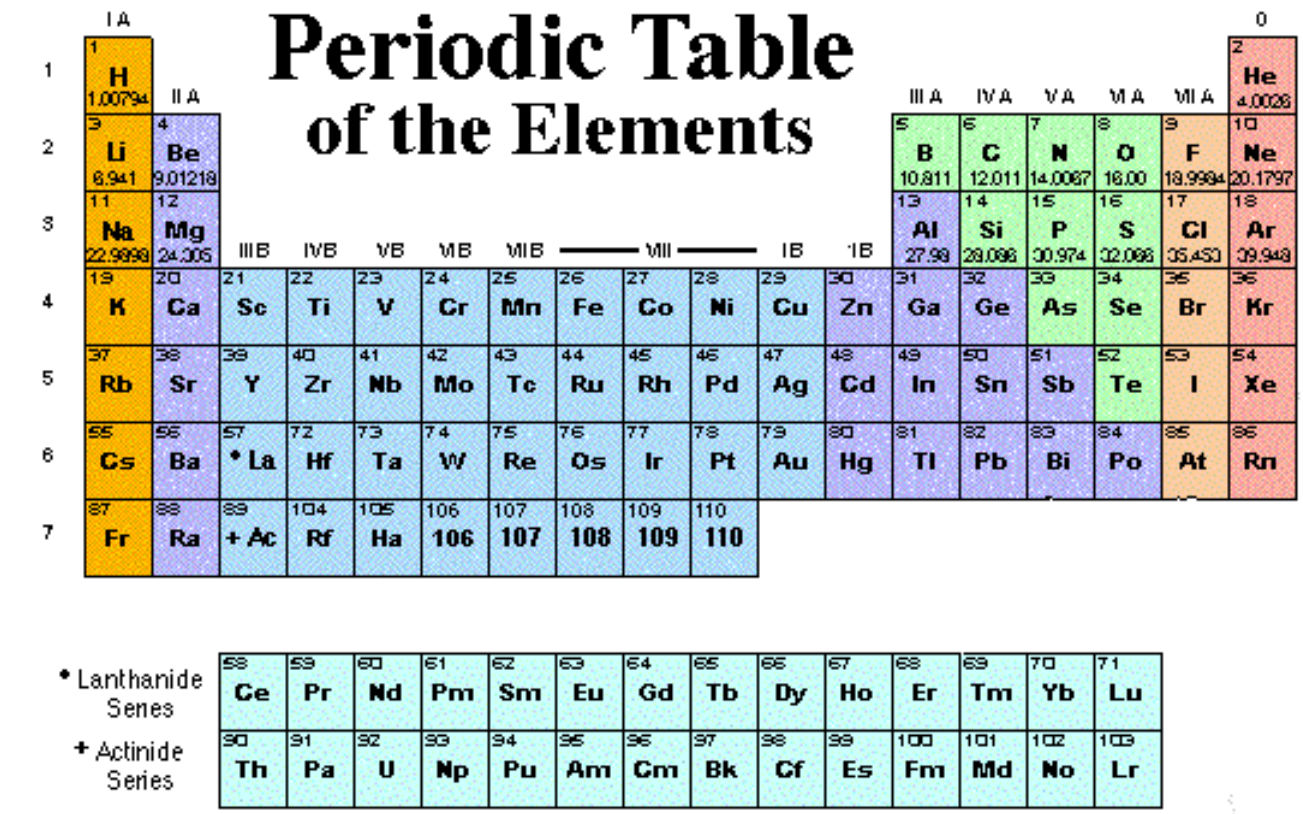
http://www.hibbing.edu/chem/abomb/page_id_64208.html

ISOTOPES ?



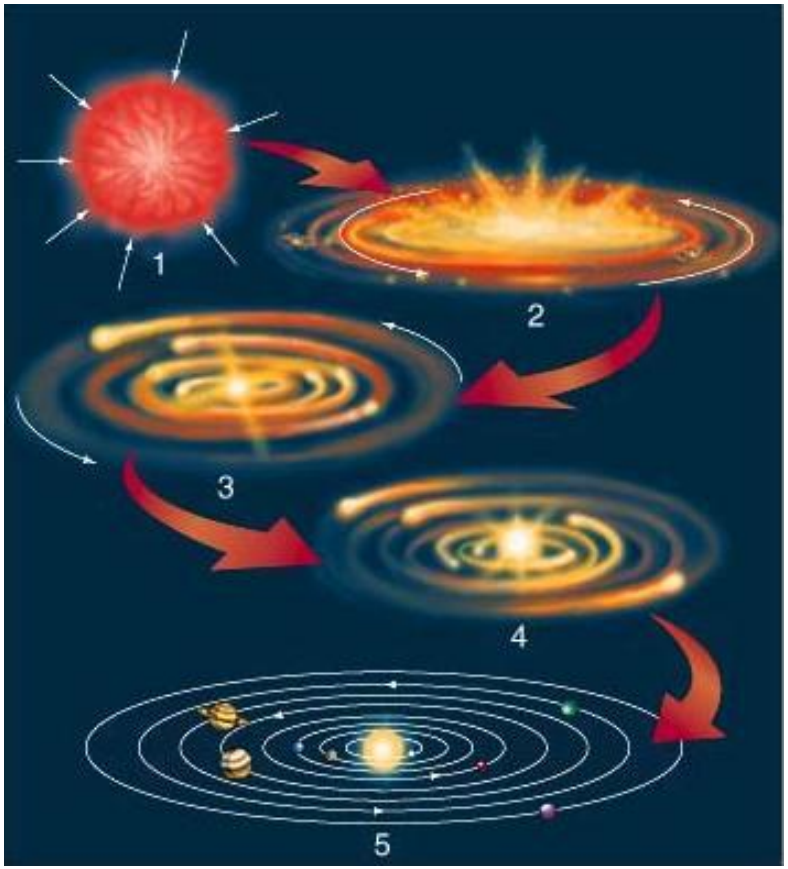
- ***Mono-isotopic elements?***
  - ***^{9}Be, ^{19}F, ^{23}Na, ^{27}Al, ^{31}P, ^{45}Sc, ^{55}Mn, ^{59}Co, ^{75}As, ^{89}Y, ^{93}Nb, ^{103}Rh, ^{127}I, ^{133}Cs, ^{141}Pr, ^{159}Tb, ^{165}Ho, ^{169}Tm, ^{197}Au, ^{209}Bi, ^{231}Pa, ^{232}Th***
- ***Other elements?***
  - ***2 – 10 isotopes***

THE ISOTOPIC COMPOSITION OF THE ELEMENTS

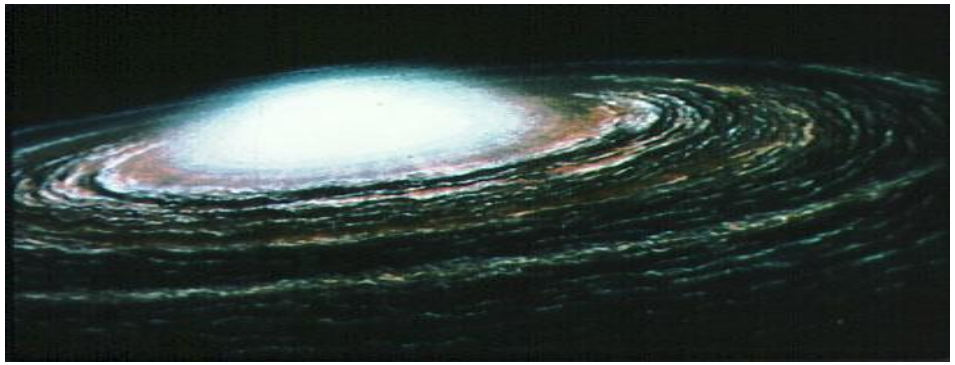
- ***First approximation:***

  all elements show an isotopic composition that is stable in nature

- ***Why ?***
  - ***Thorough mixing during formation of our solar system (4.6 . 10^9 years BP)***



The solar system was formed approximately 4.5 billion years ago. The material making up the solar system all came from a single, mostly homogeneous cloud of material (solar nebula). The matter rotated in a flattened plane, splayed out in a disk due to the angular momentum. With time, material not falling to the central sun, would either be thrown out of the system or begin to collect and build up planetesimals. At safe relative distances, planetesimals built up to form the planets.



THE ISOTOPIC COMPOSITION OF THE ELEMENTS

1. *Decay of naturally occurring, long-lived radionuclides*
2. *Natural isotope fractionation effects*
3. *Man-made variations*
4. *Interaction of cosmic rays with terrestrial matter*
5. *Variations observed in extra-terrestrial materials*

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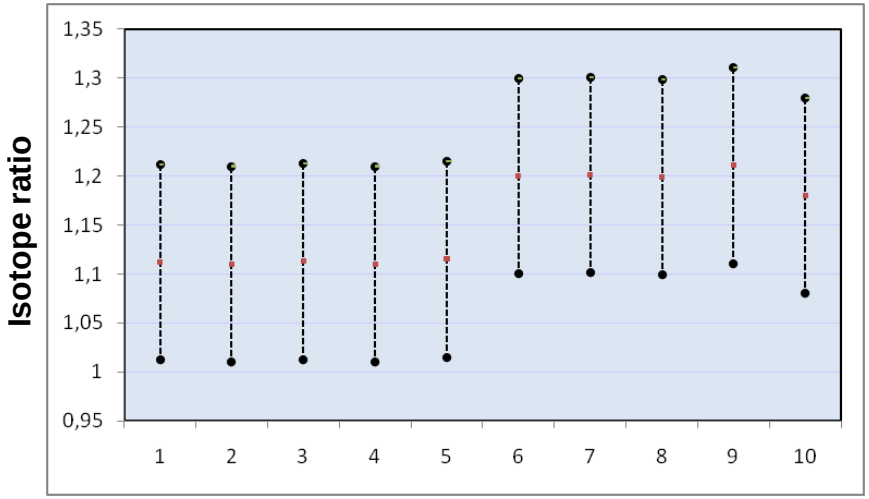
- ***Importance of isotope ratio precision?***



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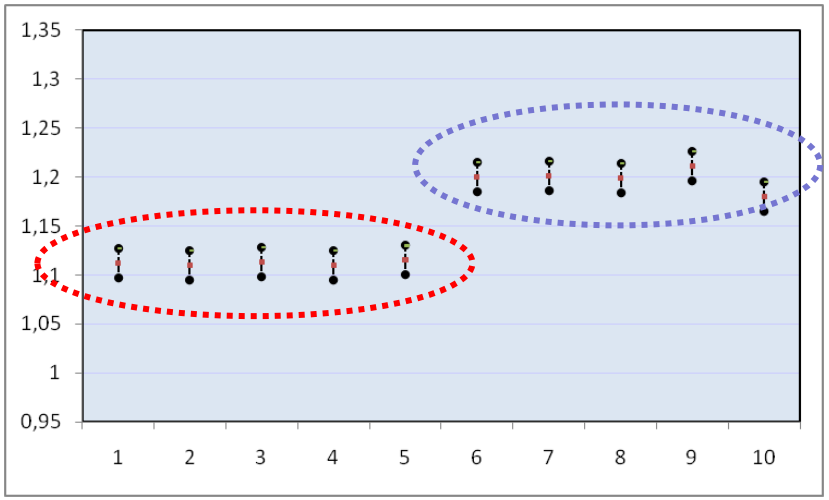
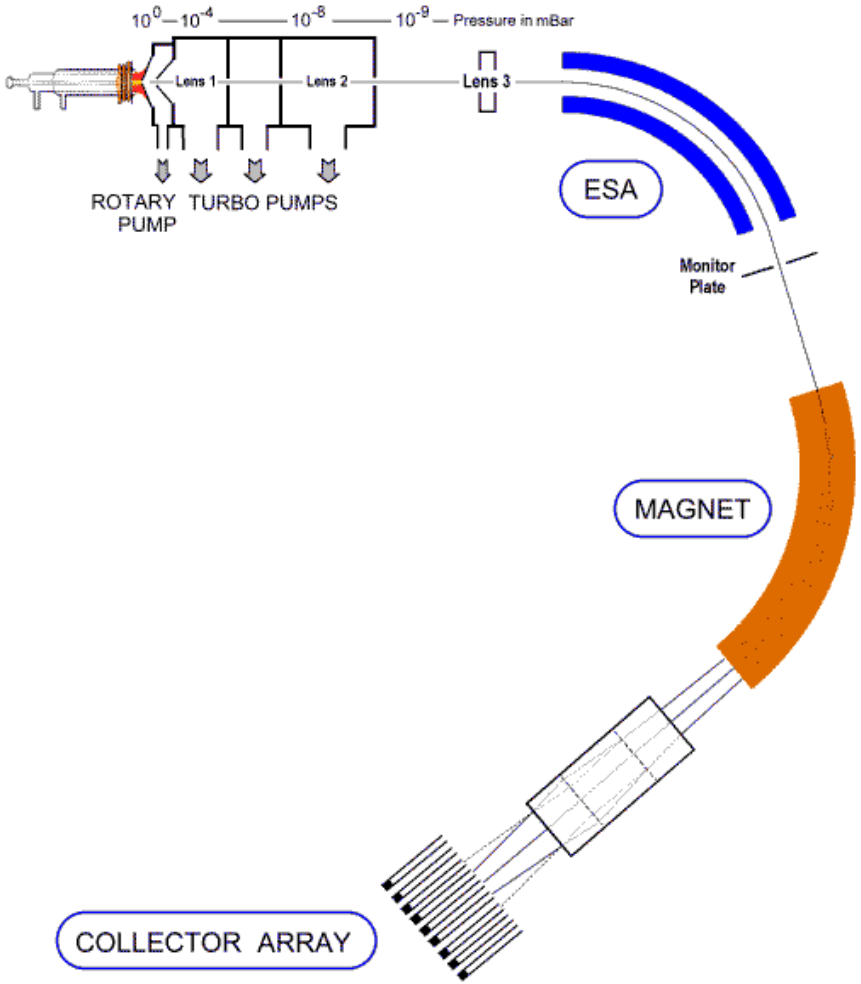
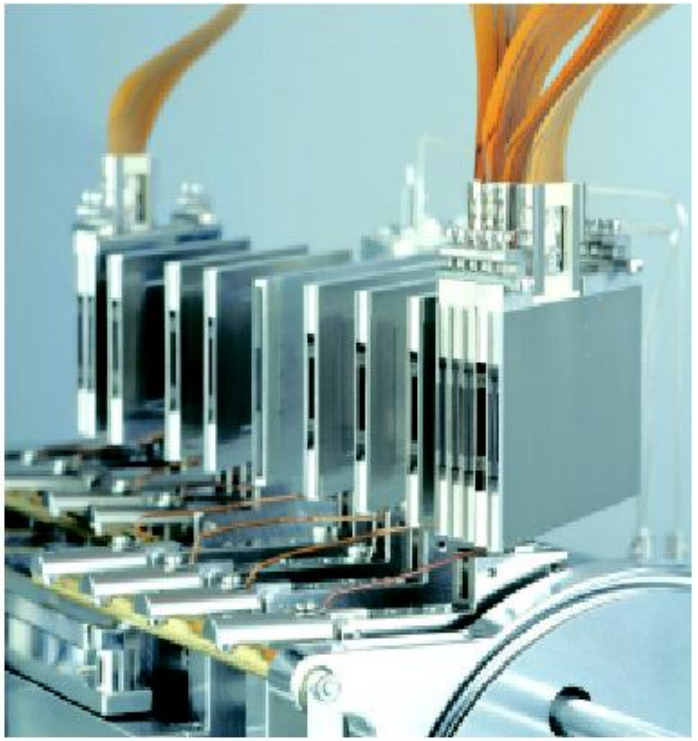


2 different populations ⇒ *conclusions*!

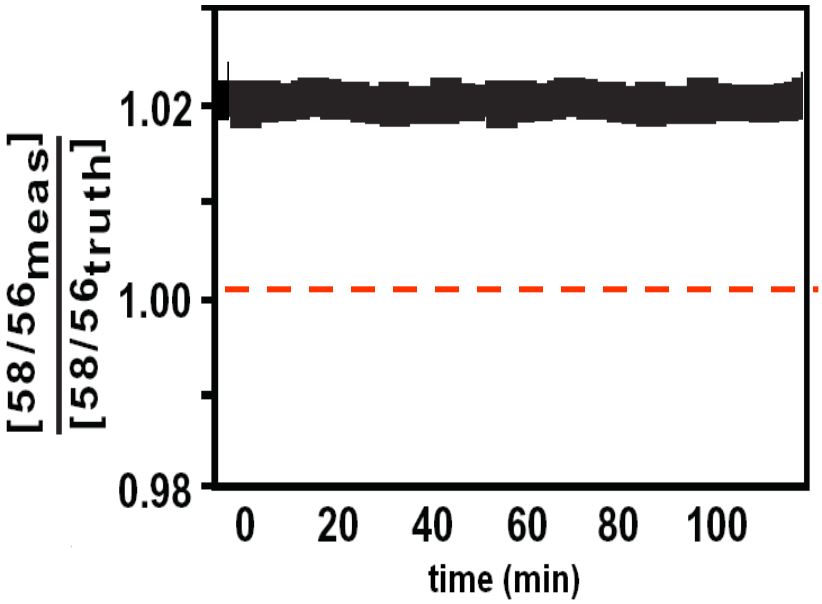
MULTI-COLLECTOR ICP – MASS SPECTROMETRY



Isotope ratio precision: down to 0,002 % RSD !



MULTI-COLLECTOR ICP – MASS SPECTROMETRY
INSTRUMENTAL MASS DISCRIMINATION



- Mass discrimination
  - Measured ratio ≠ true value
  - Order of magnitude
    - ca. 1% per mass unit @ mid-mass
    - Considerably larger @ low masses
  - Not a systematic f(time)

- ***Caused by space-charge effects***
- ***Preferential transmission of the heavier isotope***
- ***Afftected by***
  - ***Matrix composition***
  - ***Target element concentration***

Isolation of target element required

CHROMATOGRAPHIC ISOLATION OF TARGET ELEMENT

- ***Class-10 clean lab facilities***

< 10 particles / ft^3 @ 0.5 µm vs. millions particles / ft^3

Ultrapure water & acids

Discipline!

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LECTURE CONTENT ?

- ***Real-life applications***
  - ***Ghent University & international literature***

MEASURING NATURAL VARIATION
ELEMENTS WITH RADIOGENIC ISOTOPES

The Classics

$^{238}U \rightarrow {}^{206}Pb$, $^{235}U \rightarrow {}^{207}Pb$, $^{232}Th \rightarrow {}^{208}Pb$

Pb isotope	Natural range of relative isotopic abundance
^{204}Pb	1.04 – 1.65 %
^{206}Pb	20.84 – 27.48 %
^{207}Pb	17.62 – 23.65 %
^{208}Pb	51.28 – 56.21 %
IUPAC, 1997	

$^{87}Rb \rightarrow {}^{87}Sr + \beta^{-} + \nu$

Sr isotope	Natural range of relative isotopic abundance
^{84}Sr	0.55 – 0.58 %
^{86}Sr	9.75 – 9.99 %
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IUPAC, 1997	

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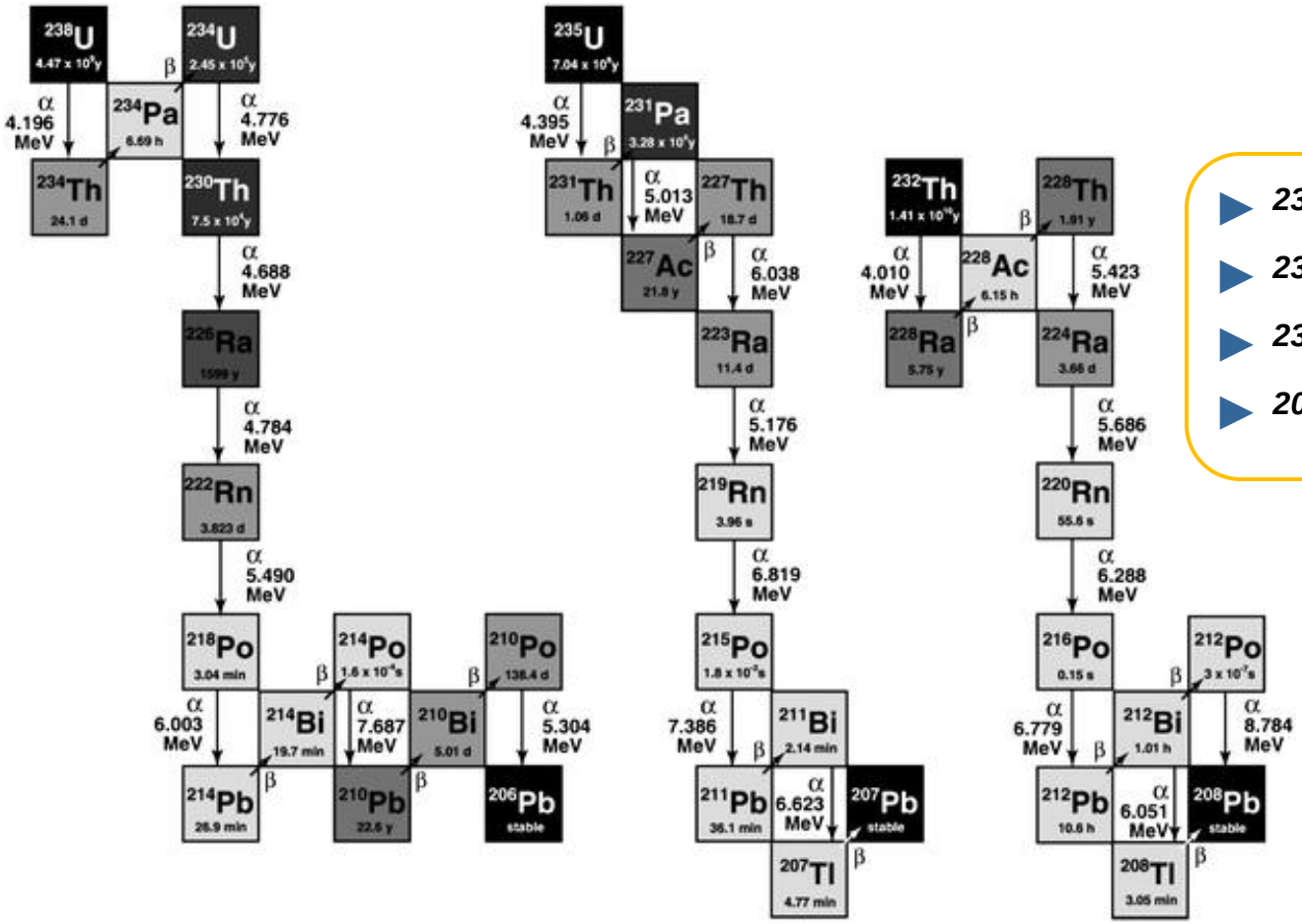
NATURAL VARIATIONS IN THE ISOTOPIC COMPOSITION OF PB



- $^{238}U \rightarrow {}^{206}Pb$
- $^{235}U \rightarrow {}^{207}Pb$
- $^{232}Th \rightarrow {}^{208}Pb$
- ^{204}Pb: not radiogenic

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NATURAL VARIATIONS IN THE ISOTOPIC COMPOSITION OF PB

- *Pronounced variation*

Pb isotope	Natural range of relative isotopic abundance
^{204}Pb	1.04 – 1.65 %
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Böhlke et al., J. Phys. Ref. Data, 2005

- *Pb in the earth's crust*
  - *Shows isotopic variation, but ^{206}Pb/^{207}Pb ~ 1.20*
- *Pb in ores*
  - *Shows isotopic variation, but << 1.20*
    - *Separated from Th & U @ time of ore formation*

PbS ore – galena

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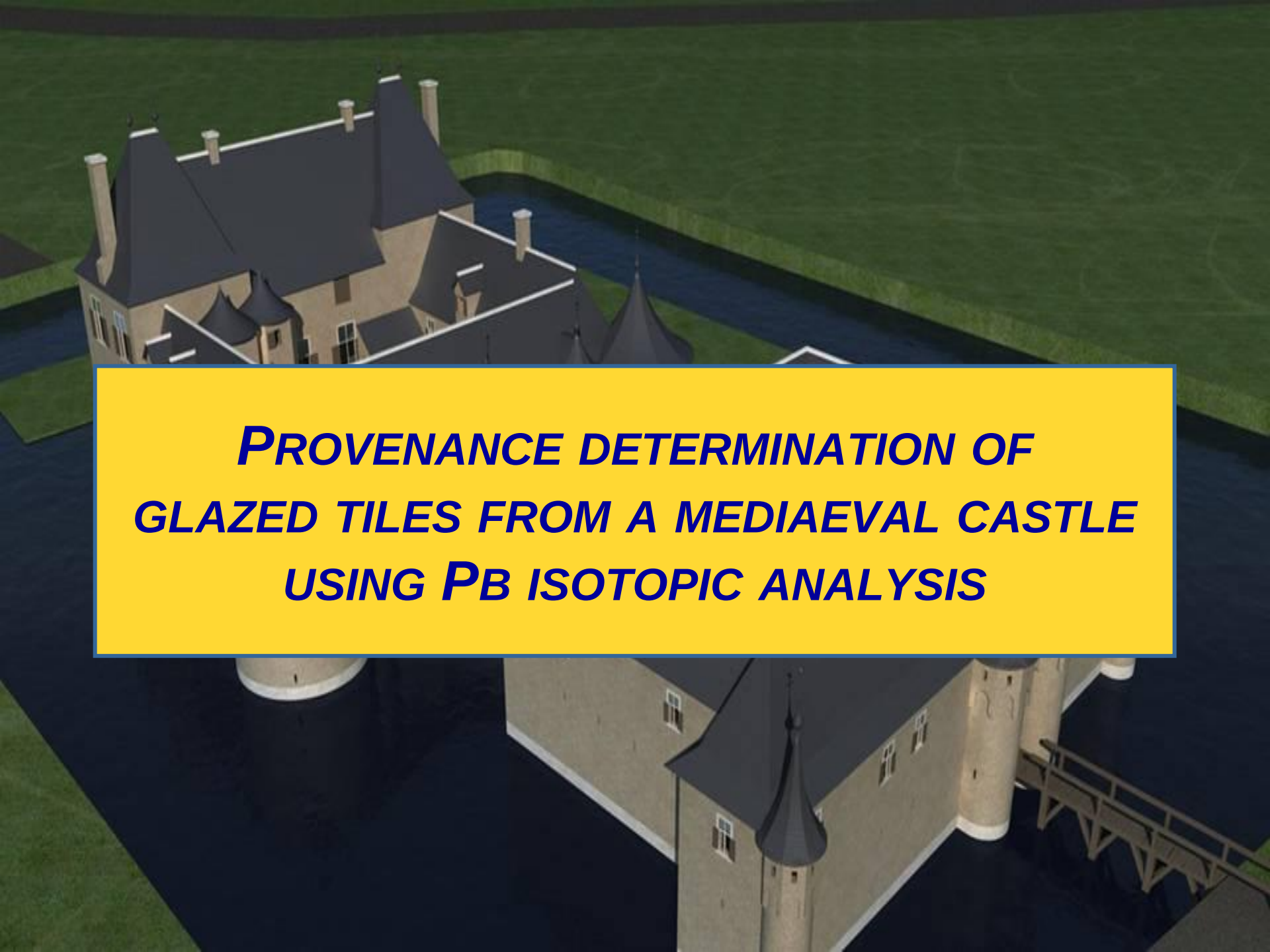


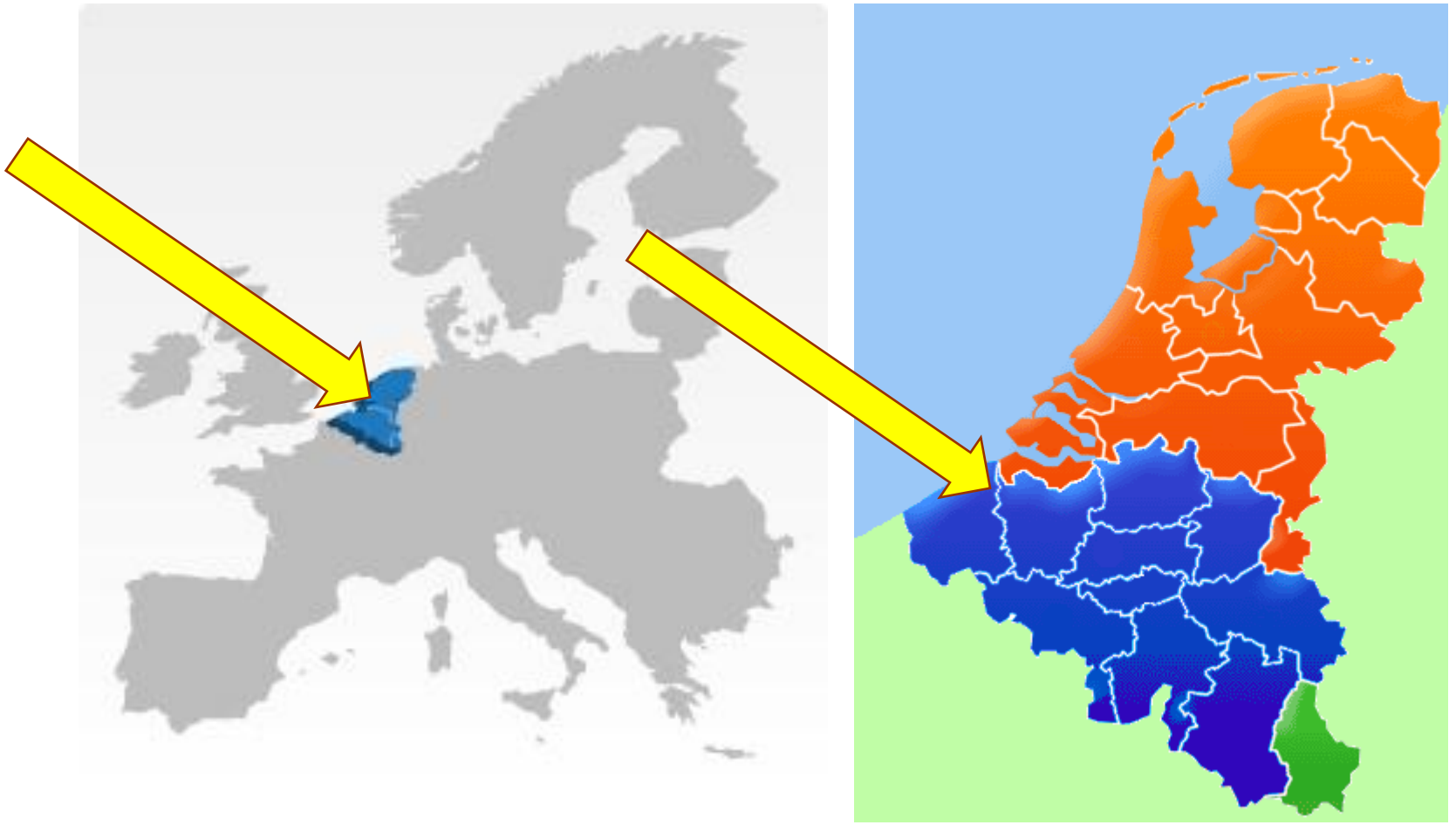
PROVENANCE DETERMINATION OF GLAZED TILES FROM A MEDIAEVAL CASTLE USING PB ISOTOPIC ANALYSIS

PIETER BLADELIN

- ***Pieter Bladelin***
  - ***Governor general of all finances of Philip the Good***
    - ***Duke of Burgundy & Count of Flanders***
  - ***Built a castle in 1448***

Painting by Rogier van der Weyden

CASTLE OF MIDDELBURG
NEAR TO BRUGES (BELGIUM)



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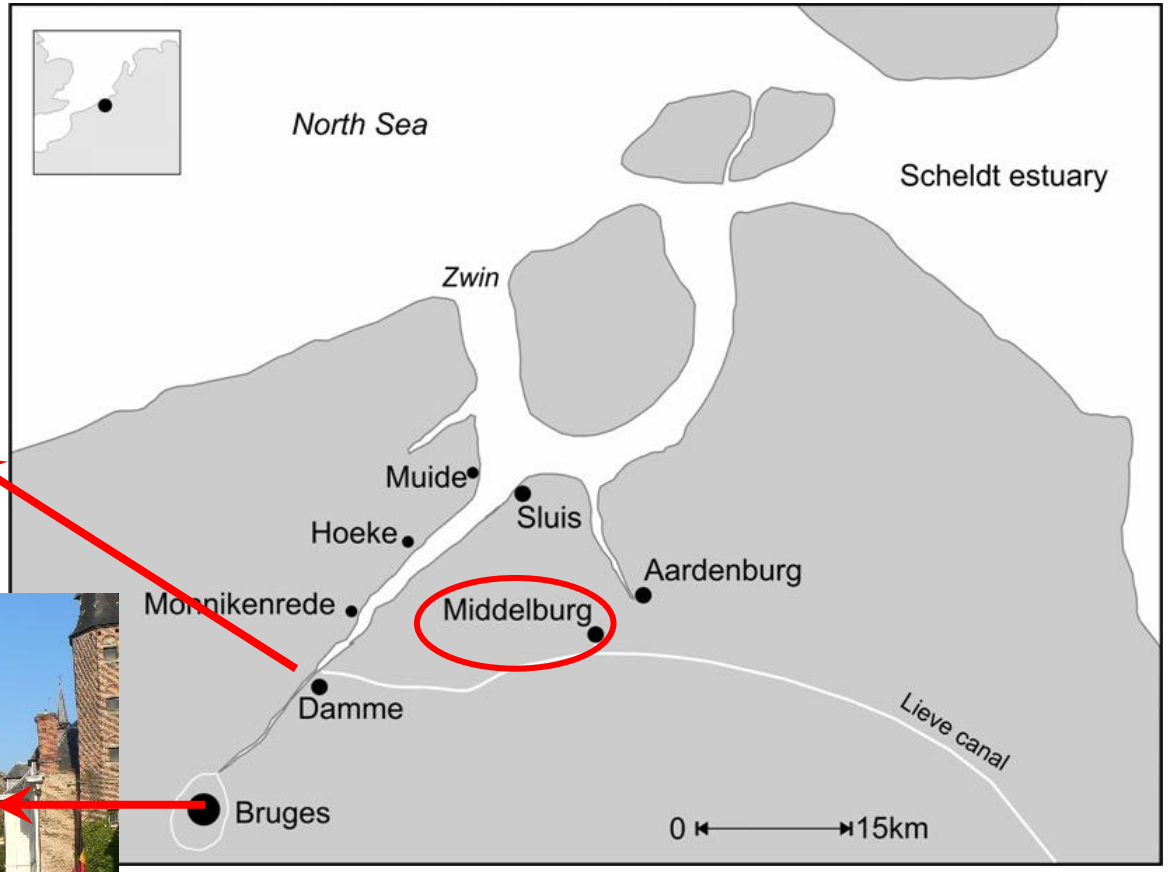


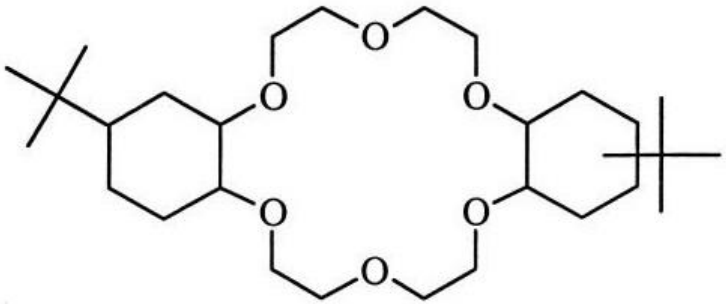
CASTLE OF MIDDELBURG
NEAR TO BRUGES (BELGIUM)

TILES FROM CASTLE OF MIDDELBURG NEAR TO BRUGES (BELGIUM)

- ***Sn-glazed tiles***
  - ***PB → Pieter Bladelin***
  - ***Completely different from 15th century local & regional tiles***
    - ***Calcareous instead of siliceous & iron-rich***
    - ***Tin/lead glaze instead of salt or copper glaze***
    - ***Diring technology***
  - ***Resemblance to Valencian (Spain) tiles?***
    - ***Floral & islamic designs***

ISOTOPIC ANALYSIS OF PB IN GLAZE

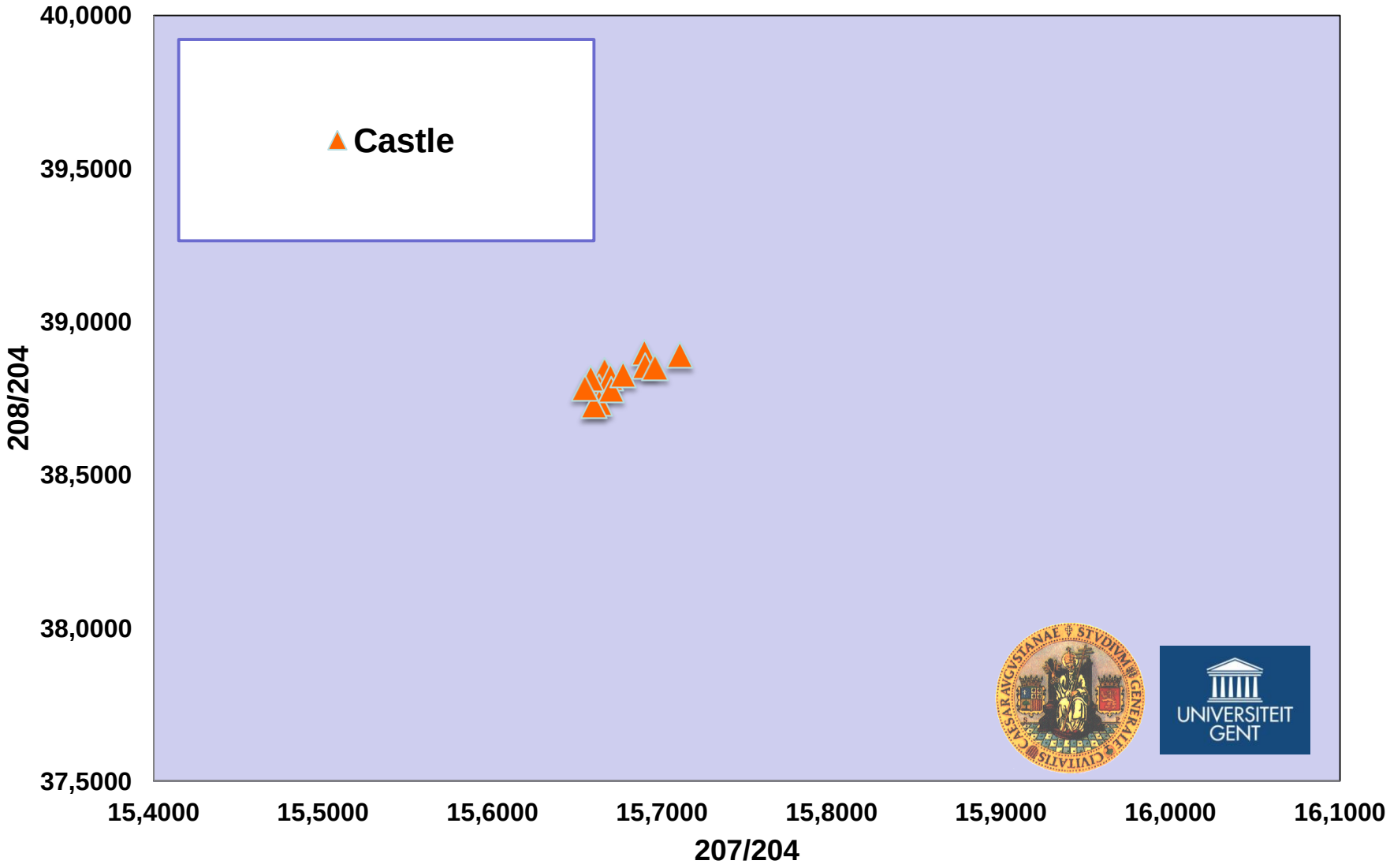
- ***Sample preparation***
  - ***Extraction of Pb out of glaze using acetic acid***
  - ***Isolation of Pb using extraction chromatography***



PbSPEC™
(Eichrom Technologies)

  - ***Apporpriate dilution & addition of Tl***
    - ***Internal standard for correction for mass discrimination***
- ***Isotopic analysis***
  - ***Neptune MC-ICP-MS unit***
- ***Data handling***
  - ***Correction for mass discrimination via Tl***
  - ***Exponential law***

3-ISOTOPE PLOT FOR LEAD



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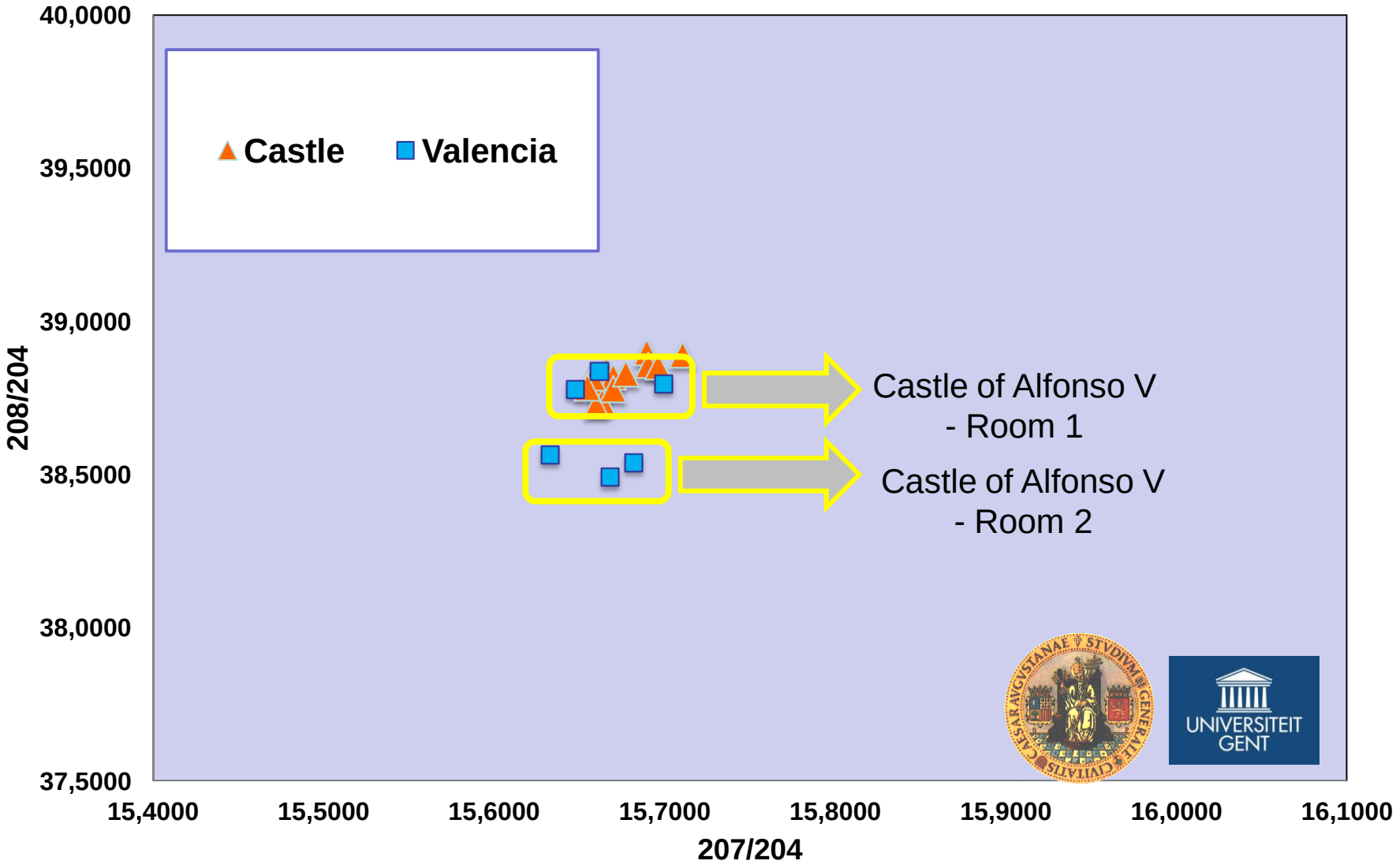

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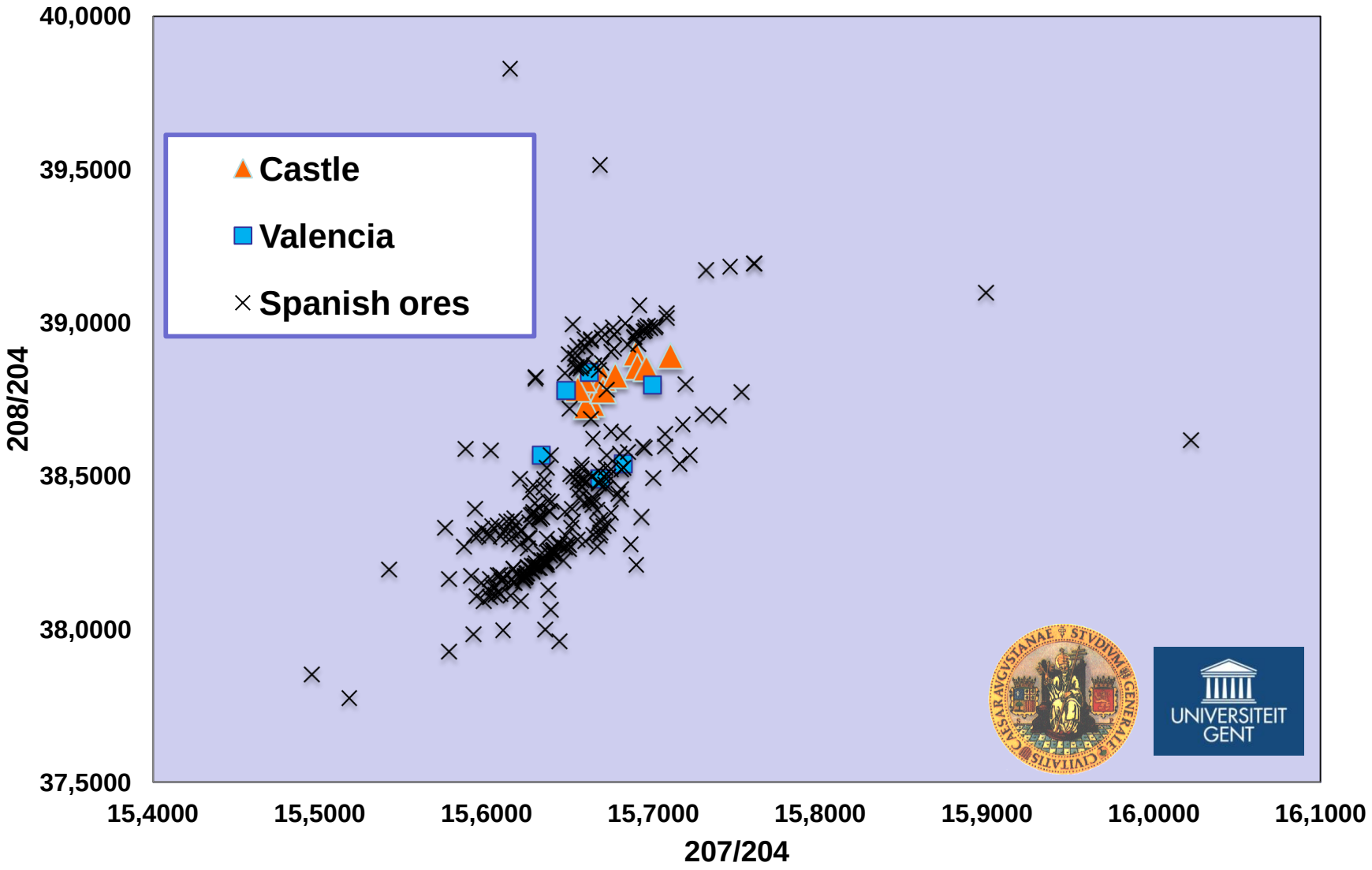
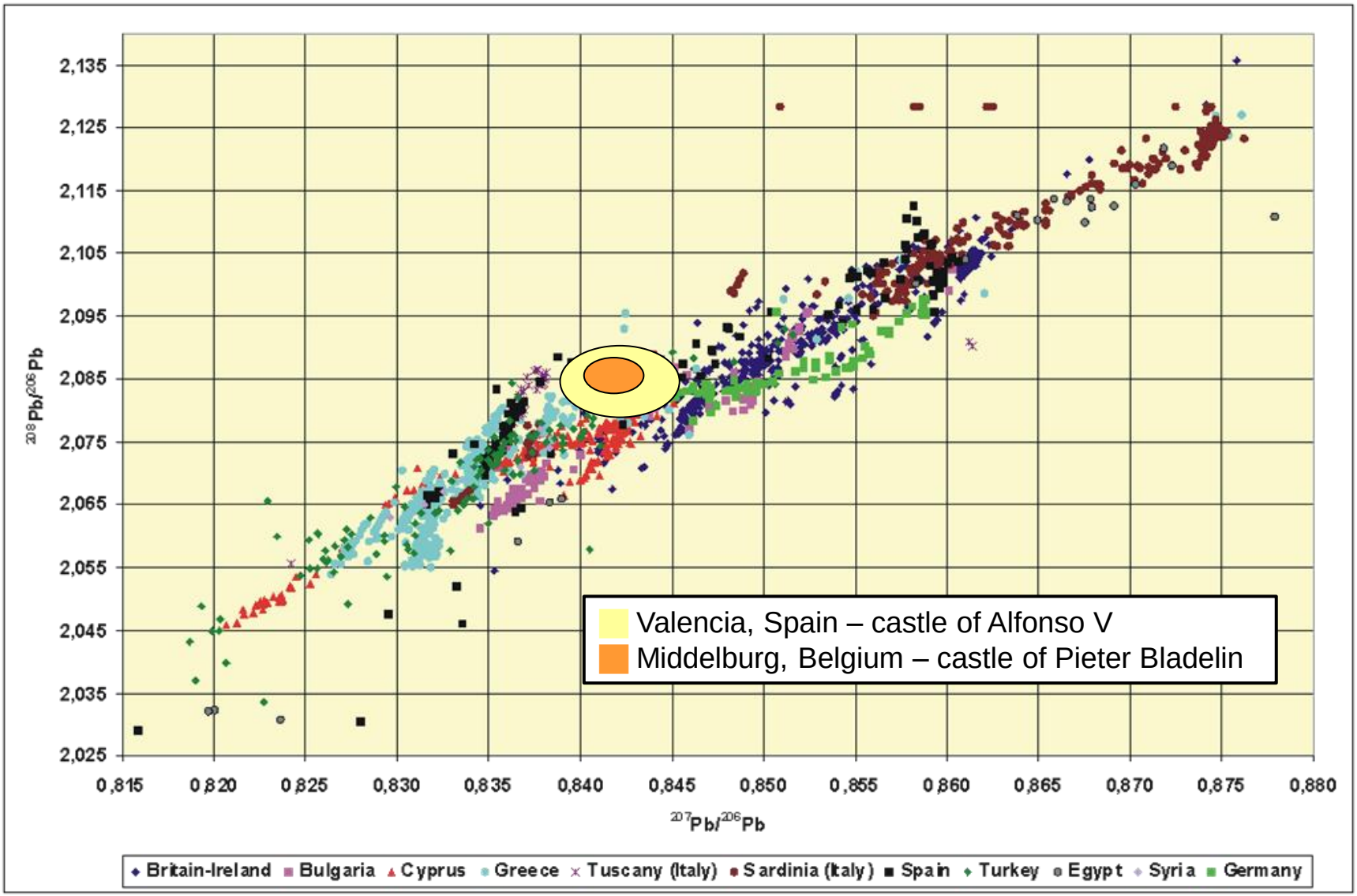


3-ISOTOPE PLOT FOR LEAD
$^{208}Pb/^{206}Pb$ VS. $^{207}Pb/^{206}Pb$



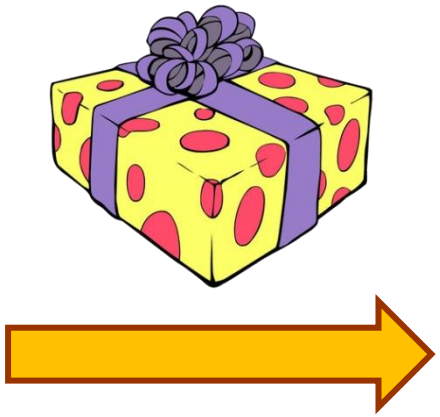
TILES FROM MIDDELBURG CASTLE
ARCHAEOMETRIC INVESTIGATION – CONCLUSIONS

- ***Next to Pb isotopic analysis:***
  - ***LA-ICP-MS***
  - ***XRF***
  - ***Raman spectroscopy***
  - ***Thin sections for petrographical assessment***

- ***All results: tiles from***
  - ***Middelburg castle***
  - ***Castle of Alfonso V (Valencia)***

} common technological context & common origin

TILES FROM MIDDELBURG CASTLE
ARCHAEOLOGICAL CONCLUSION



- ***Historic sources***
  - ***Strong socio-economical and cultural contacts between Philip the Good and Alfonso V between 1444 and 1451***
  - ***"Presents" were a well-known practice in the context of 15th century European elites***

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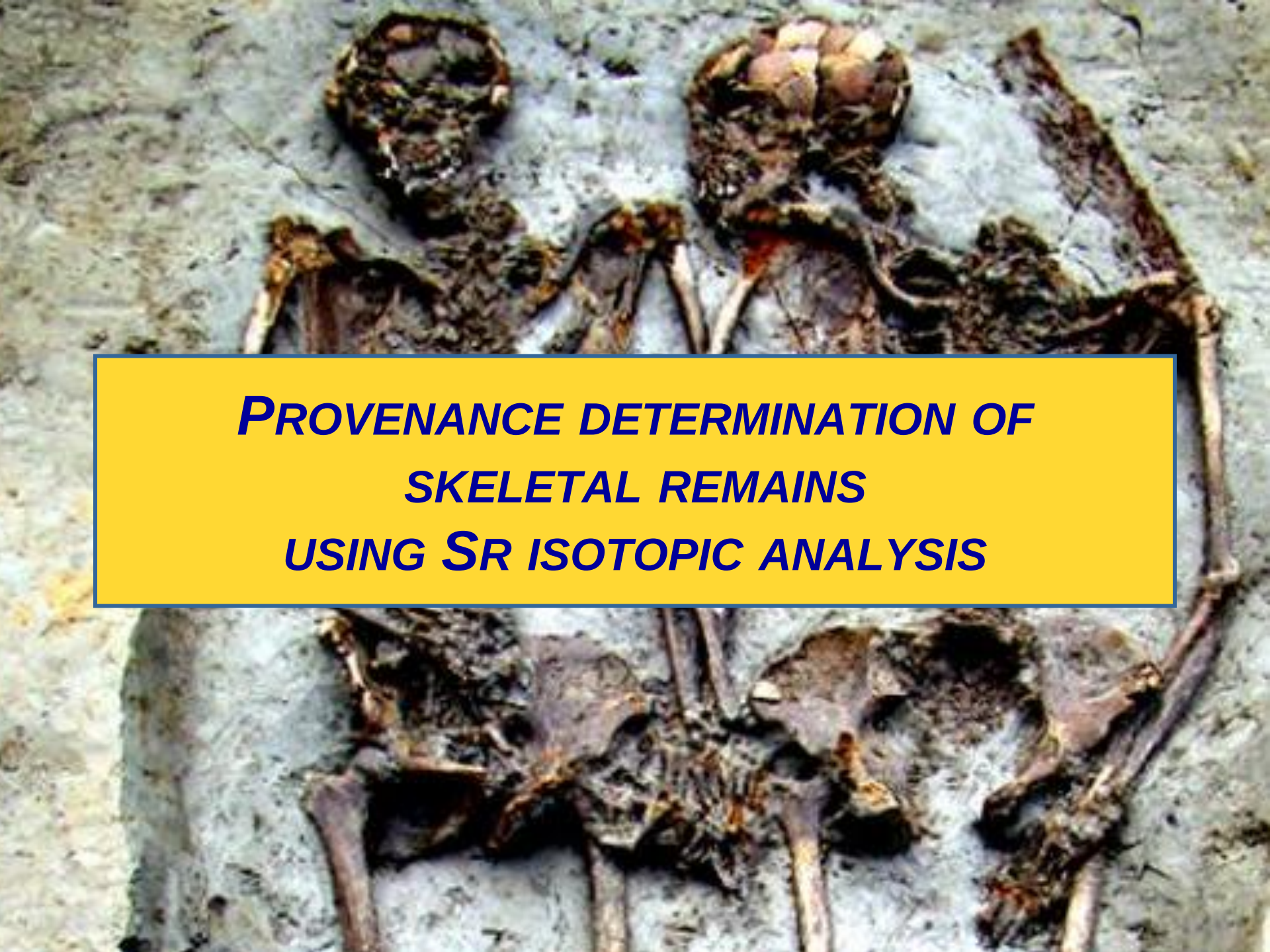


PROVENANCE DETERMINATION OF SKELETAL REMAINS USING SR ISOTOPIC ANALYSIS

VARIATIONS IN THE ISOTOPIC COMPOSITION OF SR

- ***Variations in Sr isotopic composition due to:***

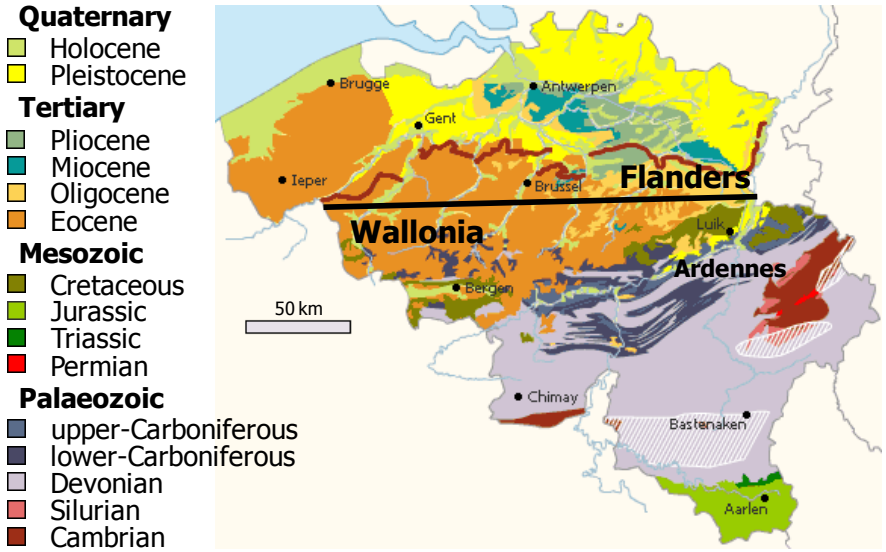
$$^{87}\mathrm{Rb} \rightarrow {}^{87}\mathrm{Sr} + \beta^{-} + \bar{\nu}$$

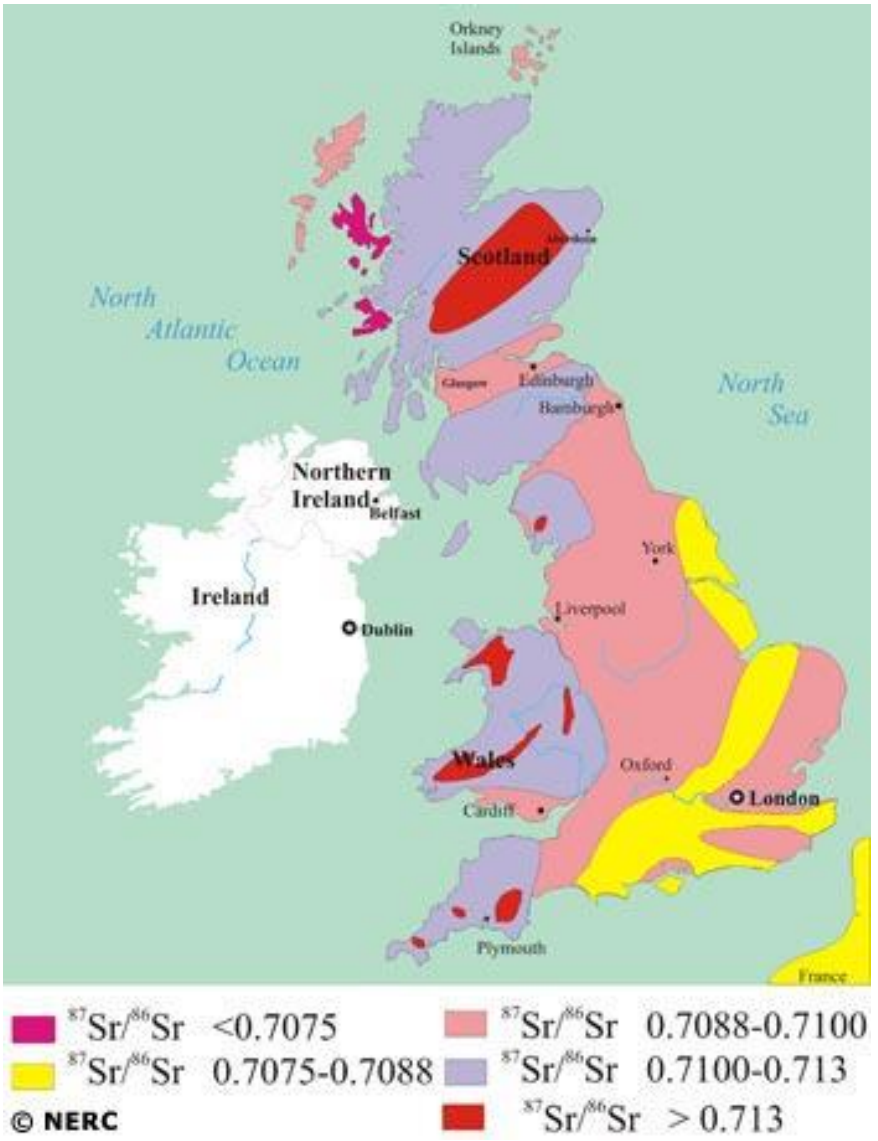
  - ***^{87}Rb = naturally occurring, long-lived radionuclide***
    - ***$T_{1/2}$ = 48.8 x 10^9 y***
    - ***Isotopic composition of Rb has changed through time***
    - ***Isotopic composition of Rb presently equal for all terrestrial materials***
  - ***Isotopic composition of Sr: variable!***
    - ***E.g., rocks: dependent on elemental Rb/Sr ratio + age***

Sr isotope	Natural range of relative isotopic abundances
^{84}Sr	0.55 – 0.58%
^{86}Sr	9.75 – 9.99%
^{87}Sr	6.94 – 7.14%
^{88}Sr	82.29 – 82.75%
Böhlke et al., J. Phys. Ref. Data, 2005	

PROVENANCE DETERMINATION VIA SR ISOTOPIC ANALYSIS

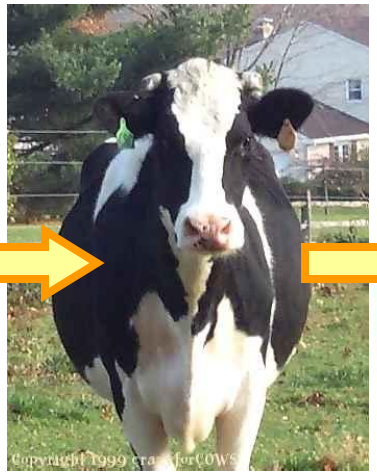
- *Varying geology*
- *Varying Sr isotopic composition*

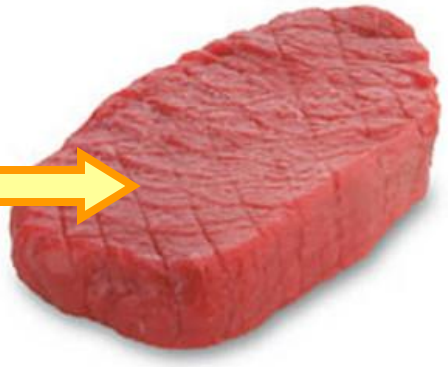




NATURAL VARIATIONS IN THE ISOTOPIC COMPOSITION OF SR – PROVENANCE DETERMINATION OF AGRICULTURAL PRODUCTS

Transfer of Sr without measurable isotopic fractionation





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NATURAL VARIATIONS IN THE ISOTOPIC COMPOSITION OF SR – PROVENANCE DETERMINATION OF AGRICULTURAL PRODUCTS

- ***Provenancing agricultural products ?***
  - ***To detect incorrect indication of geographical origin (fraud)***
- ***Which products?***
  - ***Of plant origin:***
    - ***Wine:*** *Almeida & Vasconselos, JAAS, 2001, Barbaste et al., JAAS, 2002*
    - ***Cider:*** *Garcia-Ruiz et al., ACA, 2007*
    - ***Rice:*** *Kawasaki et al., Soil Sci Plant Nutr, 2002*
    - ***Ginseng:*** *Choi et al., Food Chem, 2008*
    - ***Asparagus:*** *Swoboda et al.,ABC, 2008*
    - ***…***
  - ***Of animal origin:***
    - ***Cheese:*** *Fortunato et al., JAAS, 2004*
    - ***Caviar:*** *Rodushkin et al., ACA, 2008*
    - ***…***

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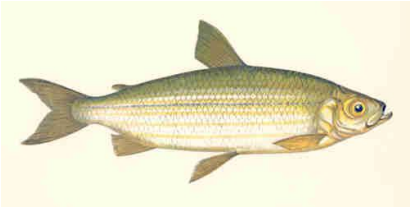
AUTHENTICATION OF KALIX (NE SWEDEN) VENDACE CAVIAR

RODUSHKIN ET AL., ACA, 583, 310, 2007



$^{87}Sr/^{86}Sr$:

seasonal variation Kalix
< geographical variation
complemented with:
trace element fingerprint
Os isotopic analysis

	$^{87}Sr/^{86}Sr$			
	ICP-SFMS			MC-ICP-MS
	Day 1 ($n=3$)	Day 2 ($n=3$)	Both days	($n=2$)
Kalix, (2005)	0.7102 (17)	0.7102 (14)	0.71017 (4)	0.710646 (6)
Kalix (2004)	0.7106 (10)	0.7102 (10)	0.71040 (48)	0.710700 (12)
Kalix (2003)	0.7110 (10)	0.7108 (12)	0.71087 (29)	0.710990 (18)
Kalix (2003–2005)	0.7106 (8)	0.7104 (6)	0.7105 (8)	0.7108 (4)
Finland	0.7217 (6)	0.7212 (6)	0.72141 (69)	0.721315 (3)
Vänern	0.7224 (14)	0.7222 (22)	0.72231 (19)	0.722270 (10)
USA	0.7185 (10)	0.7181 (12)	0.71834 (54)	0.718257 (36)
Salt	0.7109 (4)	0.7102 (8)	0.71057 (96)	0.710611 (40)
Standard	0.7079 (9)	0.7074 (14)	0.70766 (67)	0.707793 (40)

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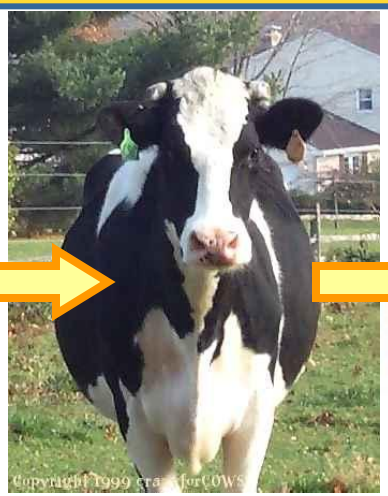
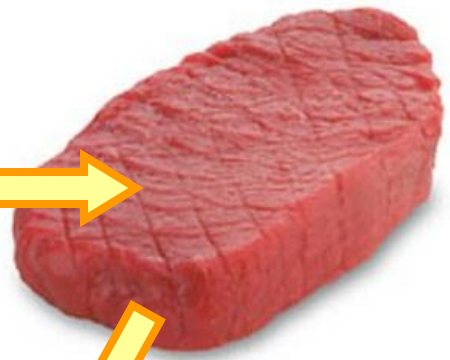
SR ISOTOPIC ANALYSIS FOR PROVENANCE DETERMINATION

Transfer of Sr without measurable isotopic fractionation





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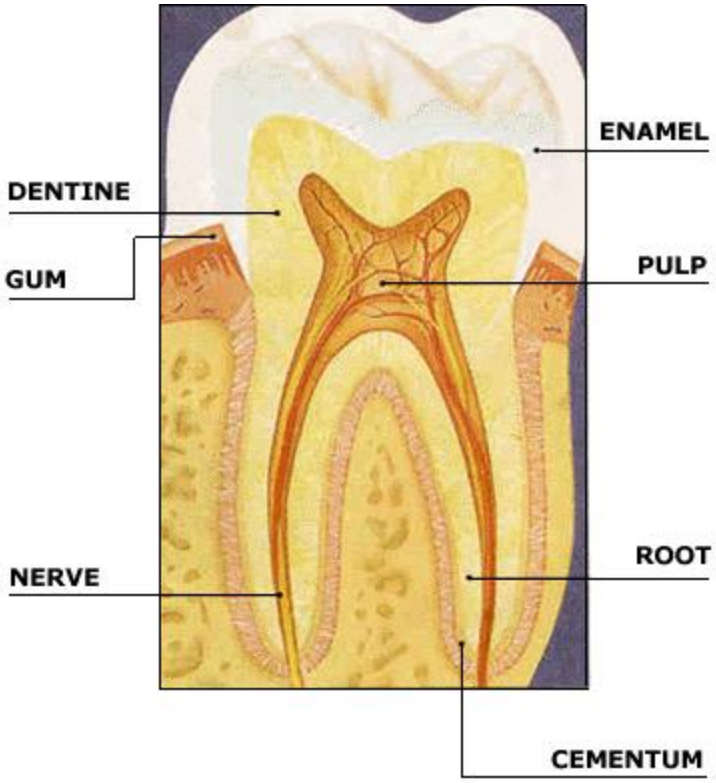
Sr isotopic analysis for provenance determination of human remains



- ***Enamel***
  - ***Formed during early childhood***
  - ***$^{87}Sr/^{86}Sr$ ~ food age 1 – 7***
- ***Dentine***
  - ***Continuously renewed***
  - ***Faster Sr turnover rate***
  - ***$^{87}Sr/^{86}Sr$ ~ food last years***
- ***Useful info***
  - ***Archaeology***

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Sr isotopic analysis for provenance determination of human remains

- *St-Servatius basilica*
  - *Maastricht, Netherlands*
  - *1600 years of history*
  - *Early christianity in the Maas valley*
  - *Important archaeological excavations*
  - *Analysis of the grave-field population*
    - *Locals and/or immigrants?*

- *Sr isotopic analysis of tooth tissue & soil (UGent & ETH)*
  - *Acid digestion of samples (open beaker – HNO3 & HCl)*
  - *Isolation of Sr using Sr-spec (Eichrom Technologies)*
  - *Sr isotopic analysis using multi-collector ICP-MS*
    - *Internal correction, based on constant $^{86}Sr/^{88}Sr$*
    - *Russell's equation*

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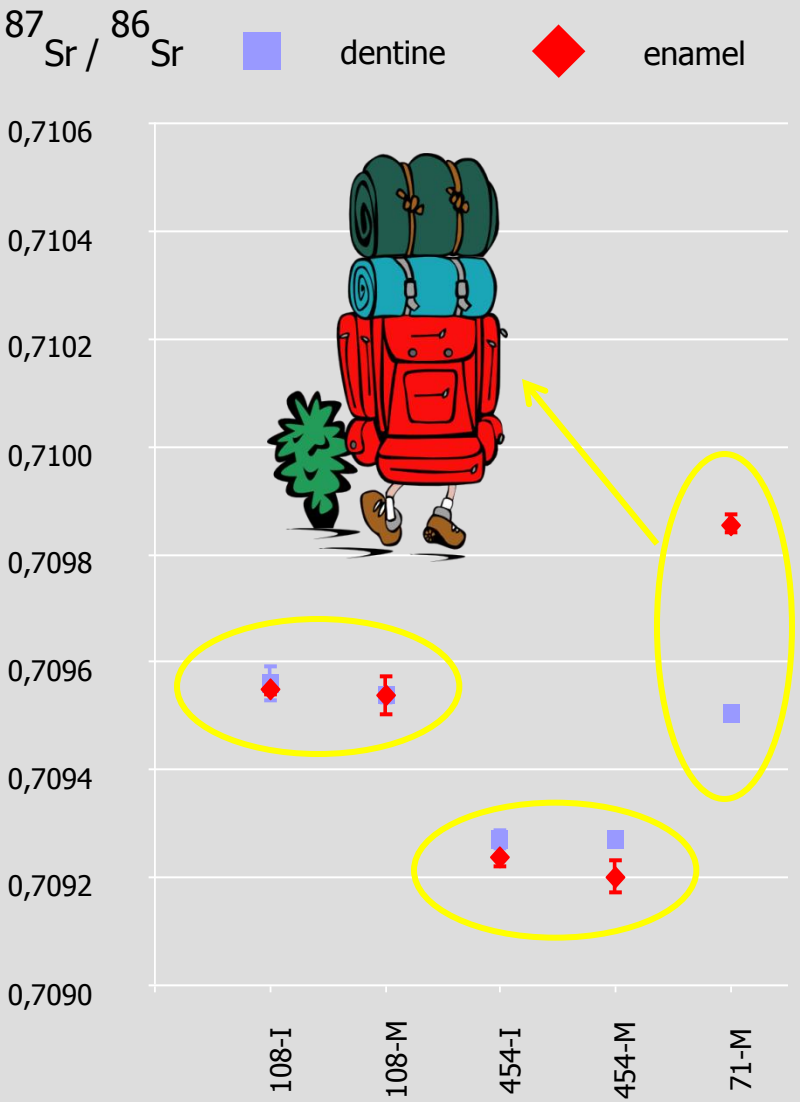
Sr isotopic analysis for provenance determination of human remains



←*Pandhof population*

I: incisor, M: molar

STILL VALID IN A GLOBAL WORLD ?

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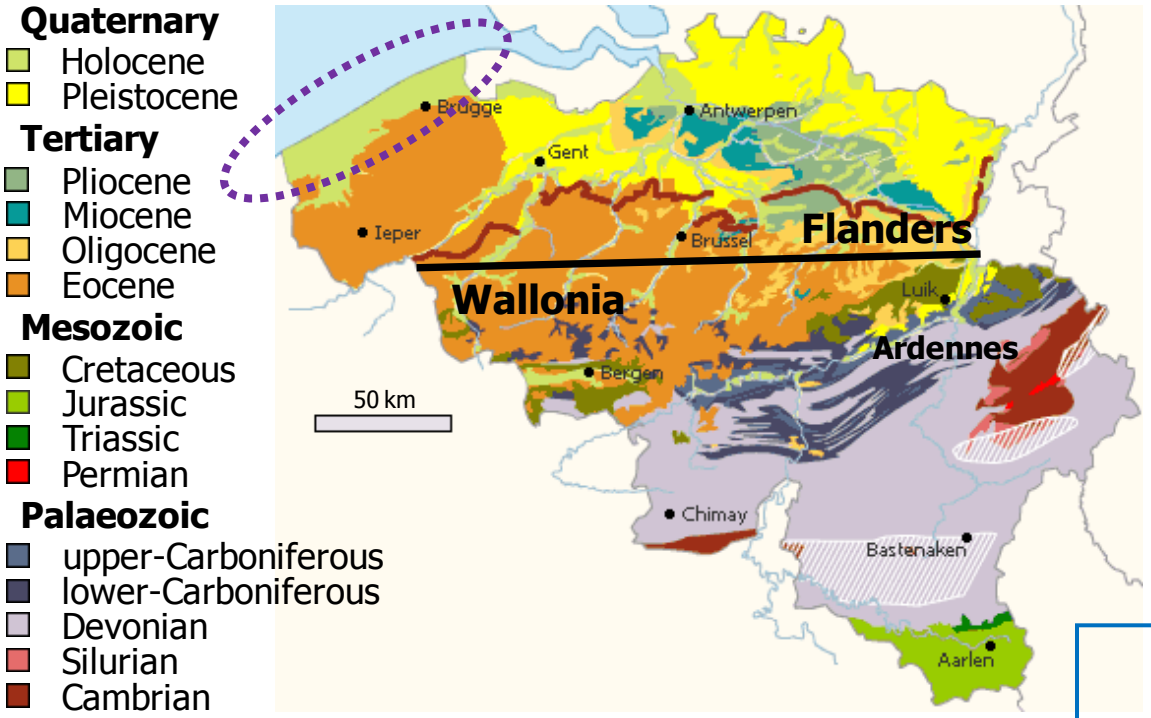
FROM A GAME TO A REAL-LIFE APPLICATION: FORENSICS

- ***Case A: infant killed a few days after birth***
  - ***$^{87}Sr/^{86}Sr$: if Belgium ⇒ coastal region***



Degryse et al;, Anal Meth, 4, 2674-2679, 2012

  - ***Police enquiry***
    - ***⇒ mother not natively living in that region?***
    - ***Lived mostly in that region during pregnancy***

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FROM A GAME TO A REAL-LIFE APPLICATION: FORENSICS

- **Case B**
  - $^{87}Sr/^{86}Sr$: if Belgium ⇒ coastal region
  - No match with missing person from that area
  - Search in other European areas with similar $^{87}Sr/^{86}Sr$
  - Possible match found ⇒ assumed origin confirmed later
- **Case C**
  - $^{87}Sr/^{86}Sr$: difference between bone & teeth (enamel)
    - Bone: $^{87}Sr/^{86}Sr$; if in Belgium ⇒ central Flanders
    - Enamel $^{87}Sr/^{86}Sr$: outside Benelux
  - Police enquiry
    - Victim came from outside Europe & lived for > 10 years in central Flanders

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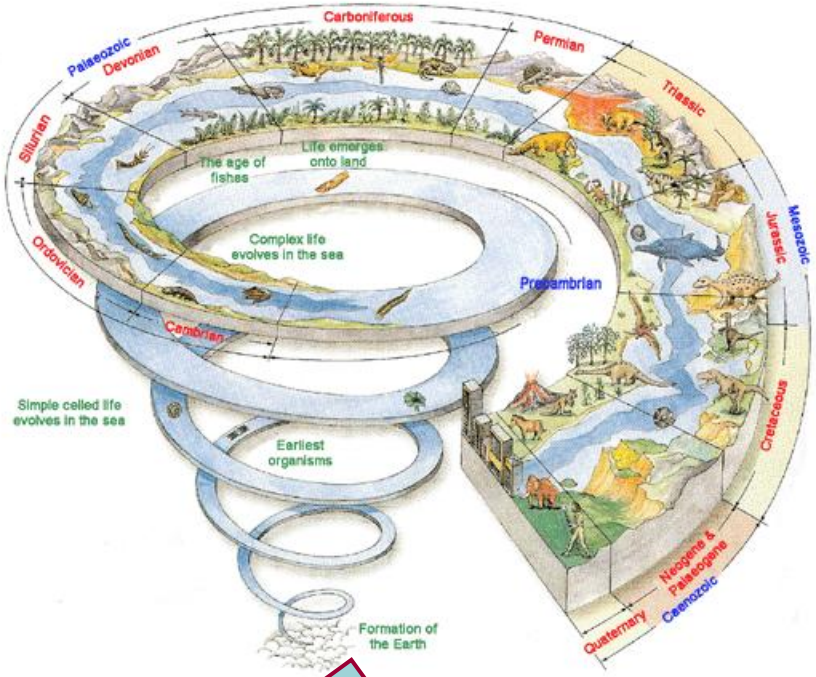
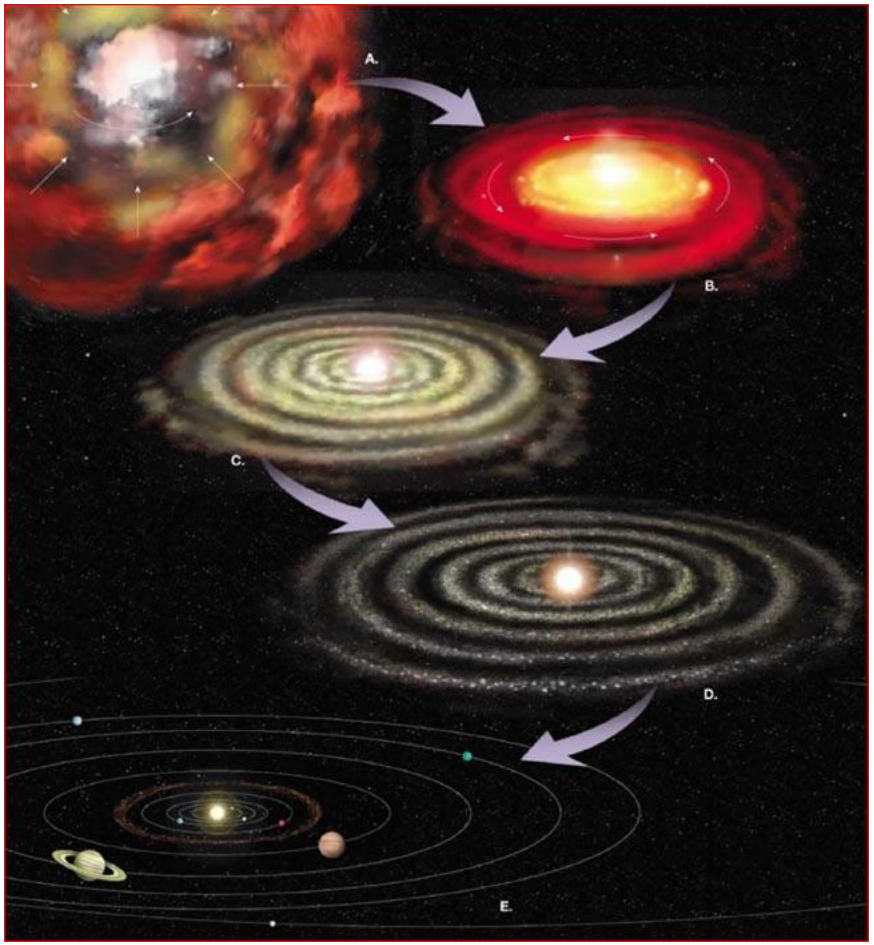
Degryse et al;, Anal Meth, 4, 2674-2679, 2012

GOING BACK FURTHER IN TIME …



Formation of
(our) solar system



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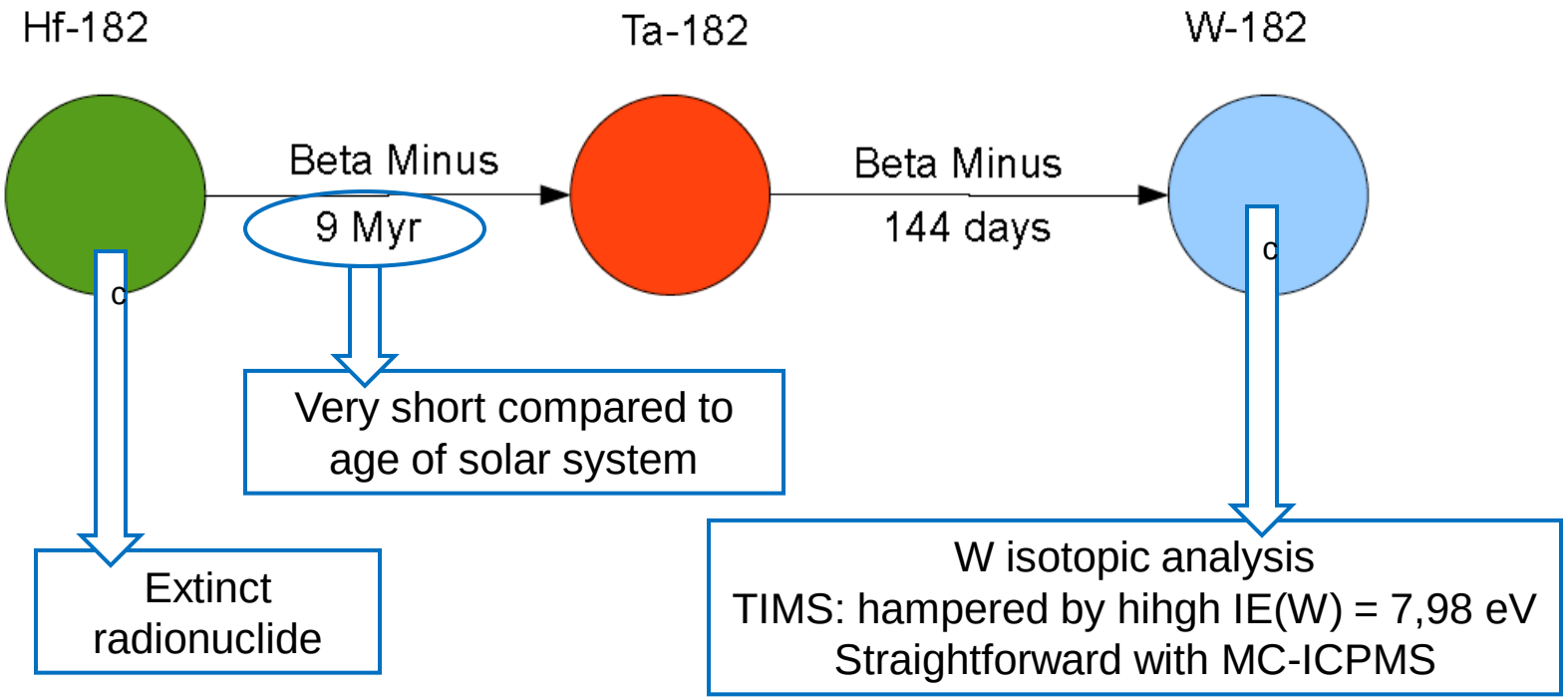
THE ^{182}HF-^{182}W CHRONOMETER

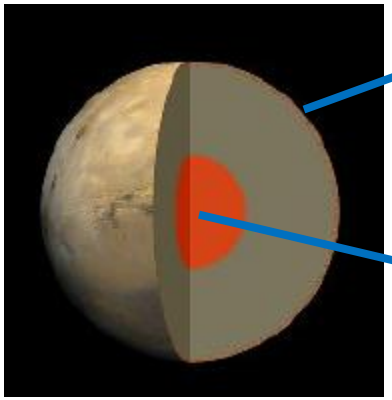
S.B. JACOBSEN, EPSL, 33, 531, 2005



THE ^{182}HF-^{182}W CHRONOMETER

S.B. JACOBSEN, EPSL, 33, 531, 2005

- ***Formation of a planet ?***
  - ***Accretion***
    - ***Growth of an object by attracting more matter (gravity)***
  - ***Differentiation***
    - ***Core formation***



Crust (light)

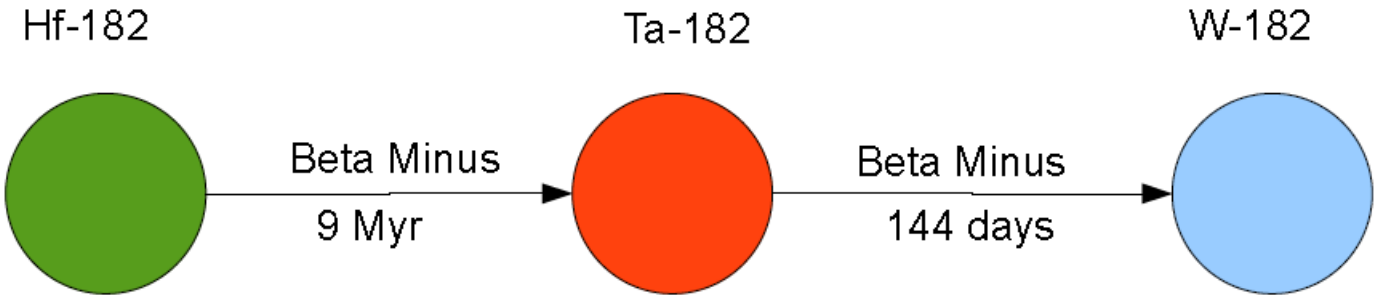
Iron core (heavy)

Hf = lithophile
⇒
prefers crust

W = siderophile
⇒
prefers core

THE ^{182}HF-^{182}W CHRONOMETER

S.B. JACOBSEN, EPSL, 33, 531, 2005

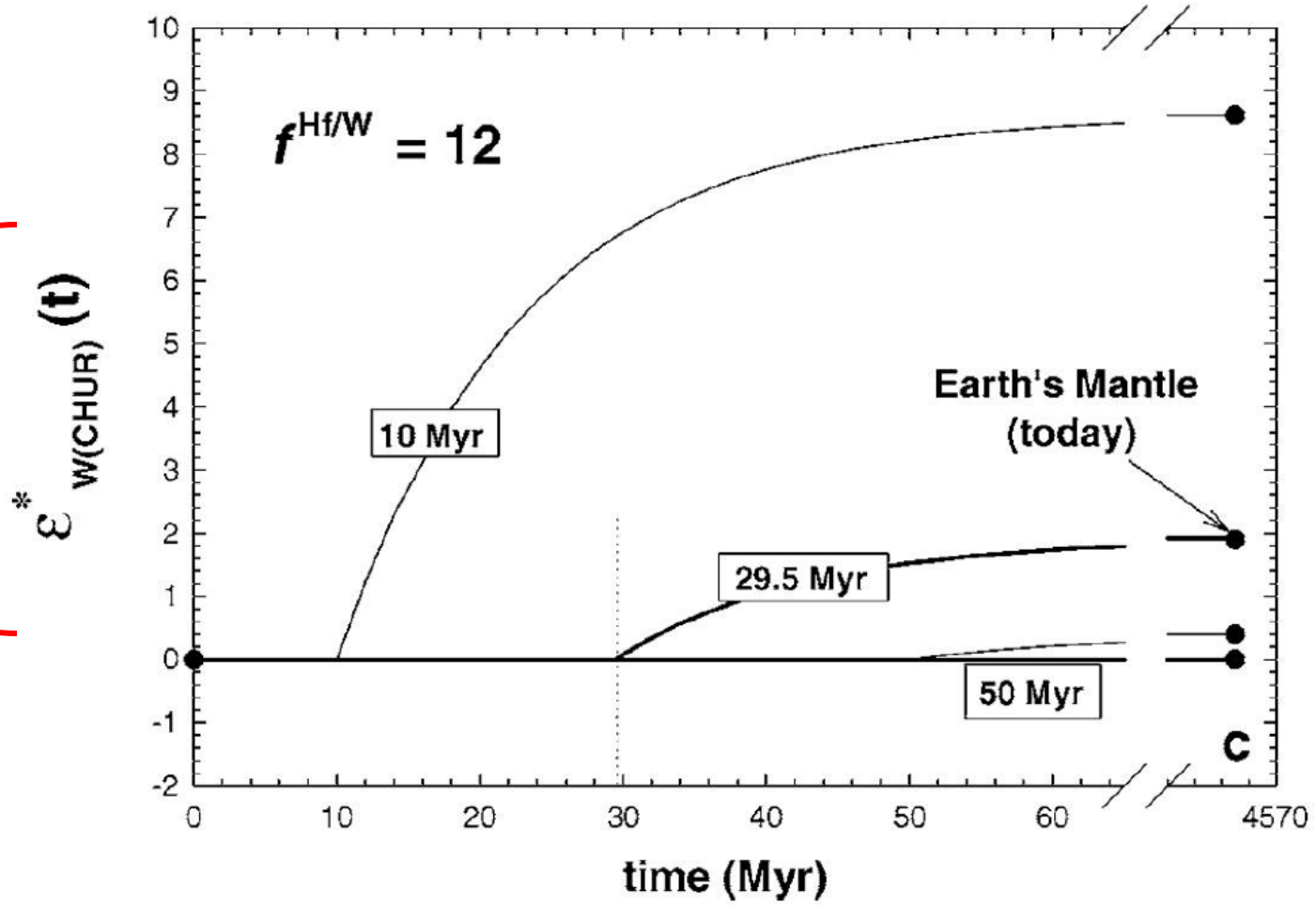


- ***Effect of planetary differentiation?***
  - ***Situation 1: Hf & W only separated after extinction of ^{182}Hf***
    - ***Hf/W ratio ~ chondritic meteorites (unfractionated reservoir)***
  - ***Situation 2: Hf & W were separated while ^{182}Hf was still around***
    - ***High Hf/W ratio in crust $\Rightarrow$ higher enrichment in ^{182}W***
- ***^{182}Hf-^{182}W chronometer***
  - ***Timing of planetary differentiation***

THE ^{182}HF-^{182}W CHRONOMETER

S.B. JACOBSEN, EPSL, 33, 531, 2005

Increase in
^{182}W/^{183}W
In silicate fraction



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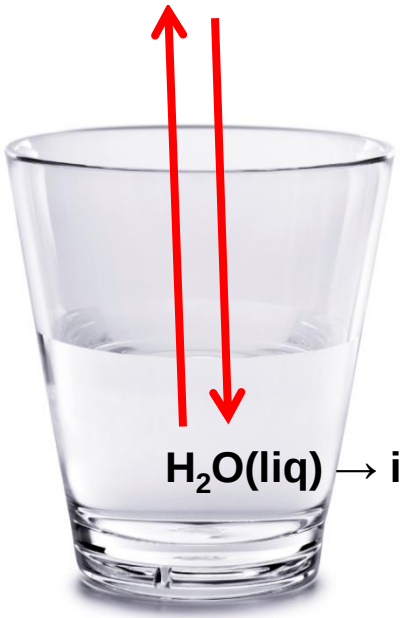
MEASURING NATURAL VARIATION
ISOTOPE FRACTIONATION EFFECTS

- *Different isotopes of an element*
  - *Chemically identical*
    - *Determined by number of electrons / protons*
  - *Different mass*
    - *Different efficiency in participation to*
      - *Chemical reactions*
      - *Physical processes*
- *Magnitude of isotope fractionation?*
  - *Degree of participation to processes & reactions*
  - *Relative mass difference between isotopes*
    - *More pronounced for lighter elements*
      - *H, C, N, O, S ⇒ IRMS*
      - *Li, B*
      - *All elements !*
  - *Thermodynamics & kinetics*

VARIATIONS IN ISOTOPIC COMPOSITION
NATURAL FRACTIONATION EFFECTS

$H_2O(gas) \rightarrow$ isotopically lighter



$H_2O(liq) \rightarrow$ isotopically heavier

$$\delta^{18}O\left(‰\right) = \frac{\left(\frac{^{18}O}{^{16}O}\right)_{sample} - \left(\frac{^{18}O}{^{16}O}\right)_{standard}}{\left(\frac{^{18}O}{^{16}O}\right)_{standard}} \cdot 1{,}000$$

- *Very small effects*
  - *Special notation introduced*

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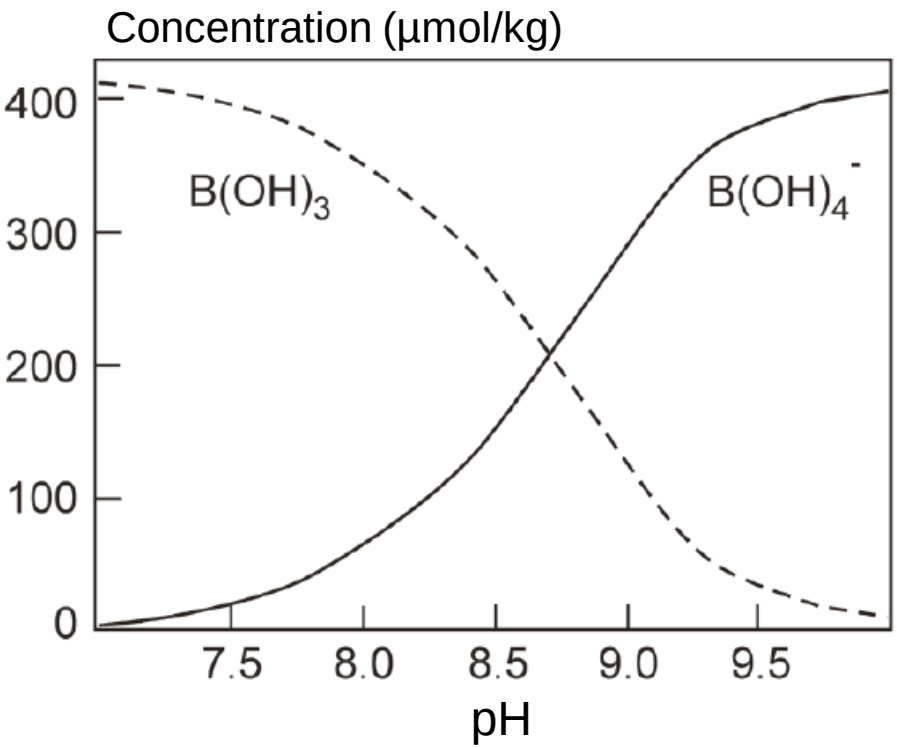
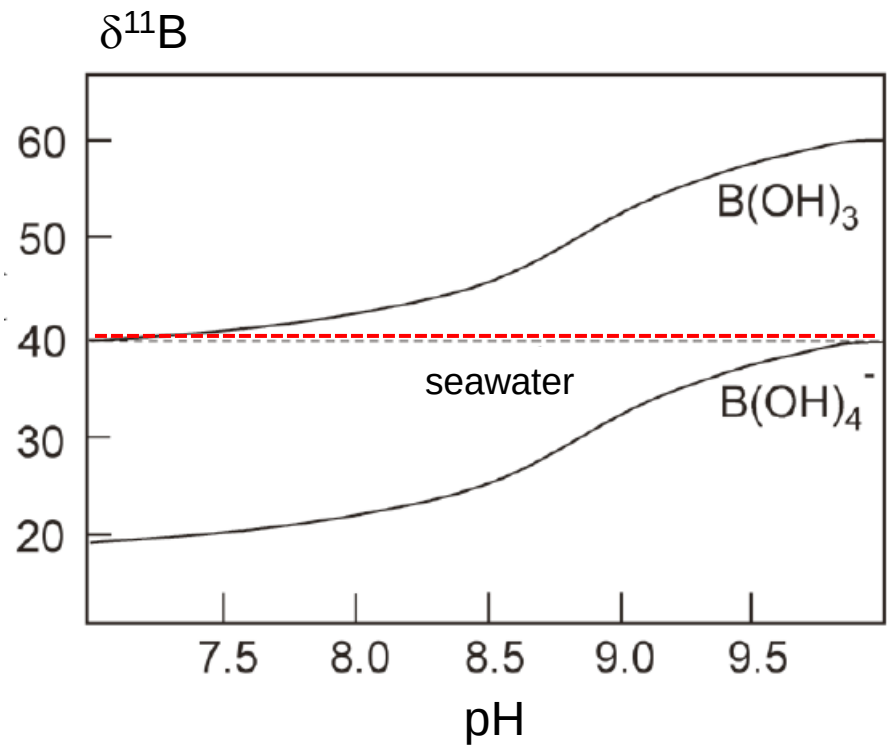
$^{11}B/^{10}B$ AS A PALEO pH SEAWATER PROXY

- ***B in seawater:***
  - ***Present as $B(OH)_3$ & $B(OH)_4^-$ / distribution dependent on pH***





  - ***$^{11}B/^{10}B$ isotope ratio in the past? ⇒ foraminifera & corals***

$^{11}B/^{10}B$ AS A PALEO pH SEAWATER PROXY

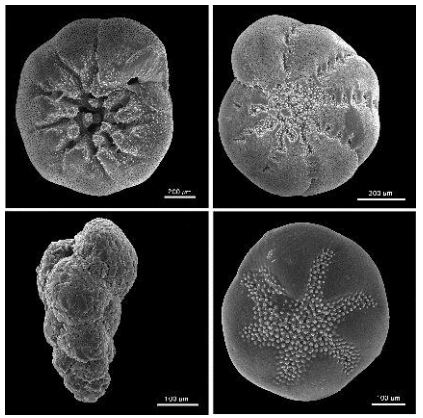
- ***In seawater:***

$$B(OH)_3 + H_2O \leftrightarrows B(OH)_4^- + H^+$$

isotopically heavier

isotopically lighter

$B(OH)_4^-$ taken up **without** isotopic fractionation in corals & foraminifera



Foraminifera
living or fossil
eukaryotic monocellular
organisms with $CaCO_3$ skeleton

pH of seawater as a function(time)

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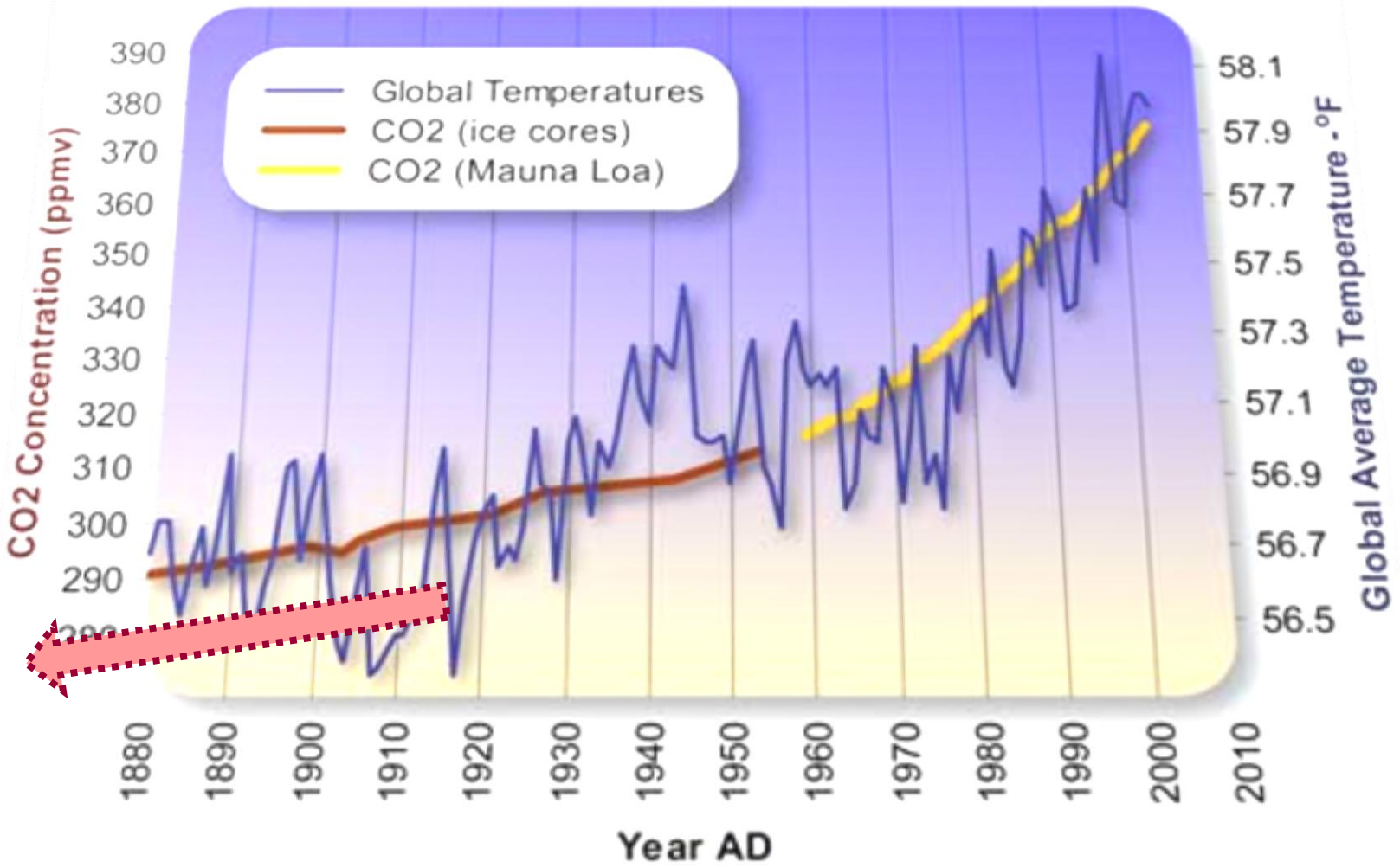
RELEVANCE OF pH OF SEAWATER ?

- ***Determined by CO_2 concentration in the atmosphere***

  - ***Information on CO_2 level over geological times***
  - ***Is the current increase in CO_2 level exceptional ?***

RELEVANCE OF pH OF SEAWATER ?



OTHER ISOTOPE RATIOS AS PALEOPROXIES ?

- ***Paleoredox proxies: oxic/anoxic conditions in seawater***
  - ***Mo***
  - ***U***

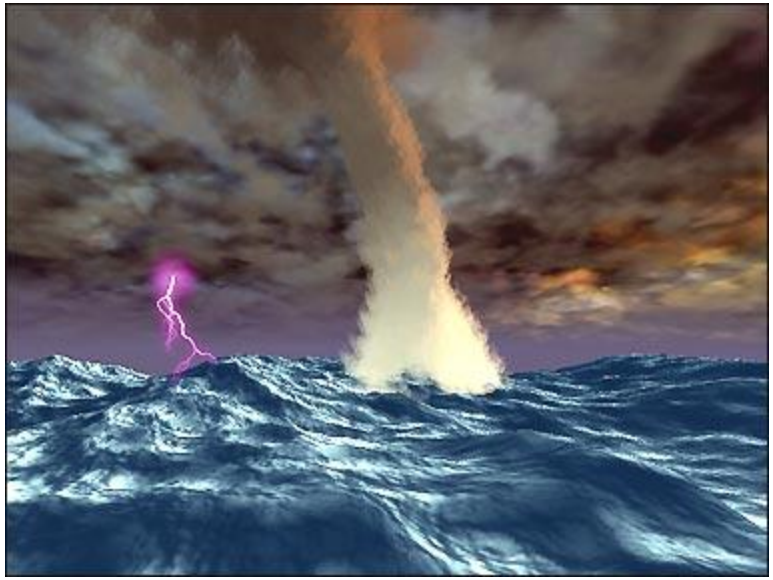
  e.g., marine sediments

- ***Paleotemperature proxy: seawater***
  - ***Ca***

  e.g., bivalves

- ***Paleoproxy for $p(CO_2)$***
  - ***Si***

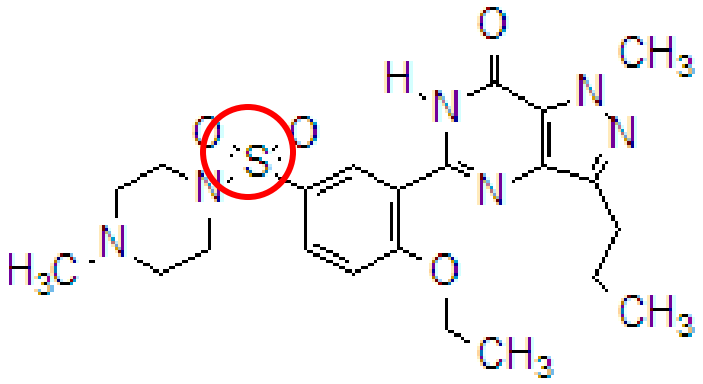
  e.g., diatoms



S ISOTOPIC ANALYSIS FOR TRACING DOWN COUNTERFEIT DRUGS

R. CLOUGH ET AL., ANAL. CHEM., 78, 6126, 2006.

- *Counterfeit drugs*
  - *violation of intellectual property laws*
  - *inappropriate quantities of active ingredients*
  - *may contain ingredients that are not on the label (purity)*
  - *often inaccurate, incorrect or fake packaging & labeling*
- *"Money making" drugs*



Sildenafil, VIAGRA*

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S ISOTOPIC ANALYSIS FOR TRACING DOWN COUNTERFEIT DRUGS

R. CLOUGH ET AL., ANAL. CHEM., 78, 6126, 2006.

- ***S isotopic analysis in viagra using MC-ICP-MS***

	$\delta^{34}S$ relative to Pfizer Viagra	
	bulk tablet by laser ablation (‰)	sildenafil citrate by HPLC (‰)
counterfeit Viagra 1	-8.0 ± 0.36	-3.0 ± 0.9
counterfeit Viagra 2	$+10.5 \pm 0.39$	$+5.0 \pm 1.1$

WHAT ABOUT THE FUTURE?

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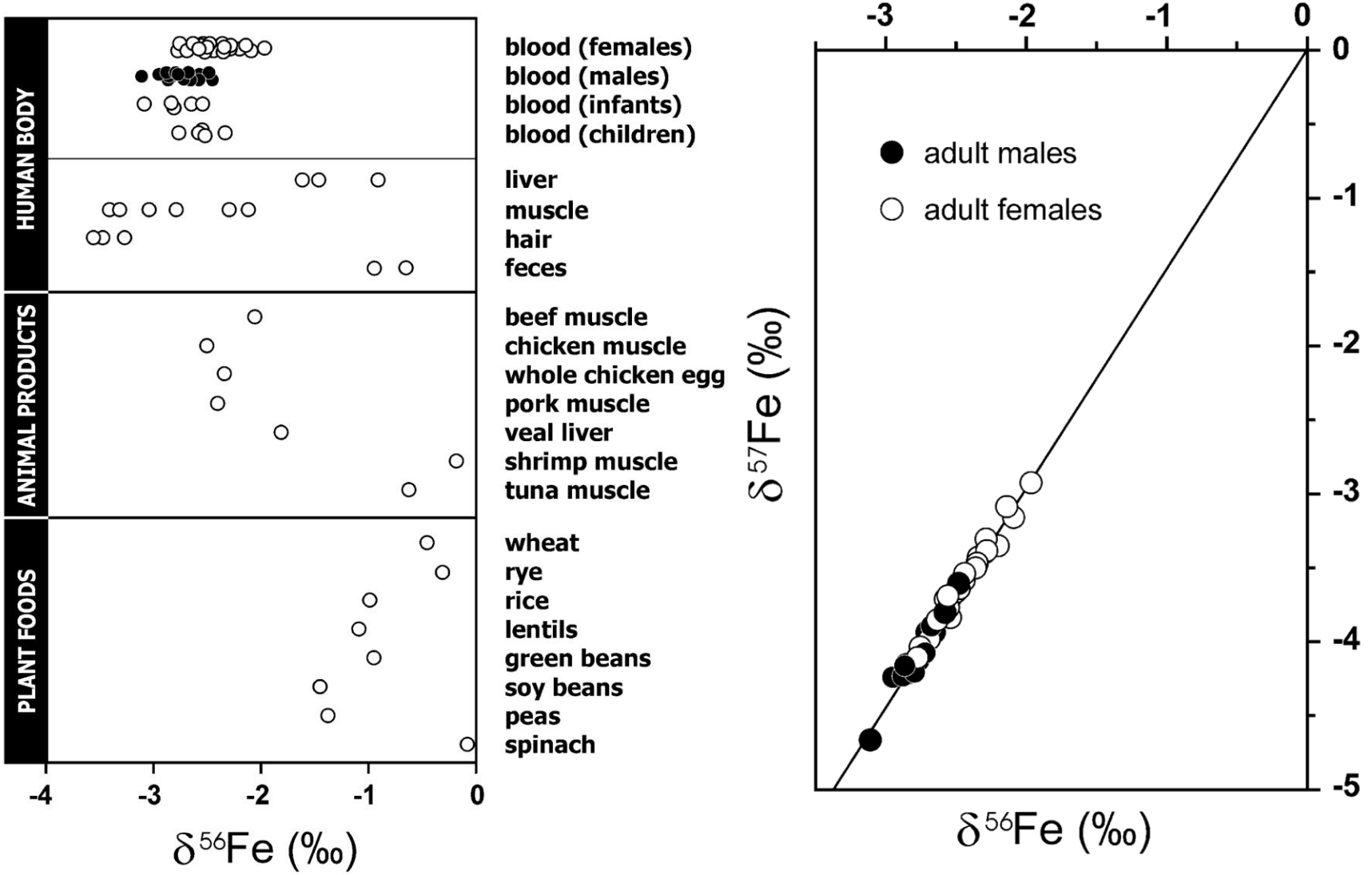
NATURAL ISOTOPE RATIO VARIATIONS IN A BIOMEDICAL CONTEXT
PIONEERING WORK – VON BLANCKENBURG & WALCZYK



Walczyk and von Blanckenburg, Science, 295, 2065 (2002)

NATURAL ISOTOPE RATIO VARIATIONS IN A BIOMEDICAL CONTEXT
PIONEERING WORK – VON BLANCKENBURG & WALCZYK

blood

2005 105: 3812-3816
Prepublished online Jan 21, 2005;
doi:10.1182/blood-2004-07-2807

Hereditary hemochromatosis is reflected in the iron isotope composition of blood

Pierre-Alexandre Krayenbuehl, Thomas Walczyk, Ronny Schoenberg, Friedhelm von Blanckenburg and Georg Schulthess

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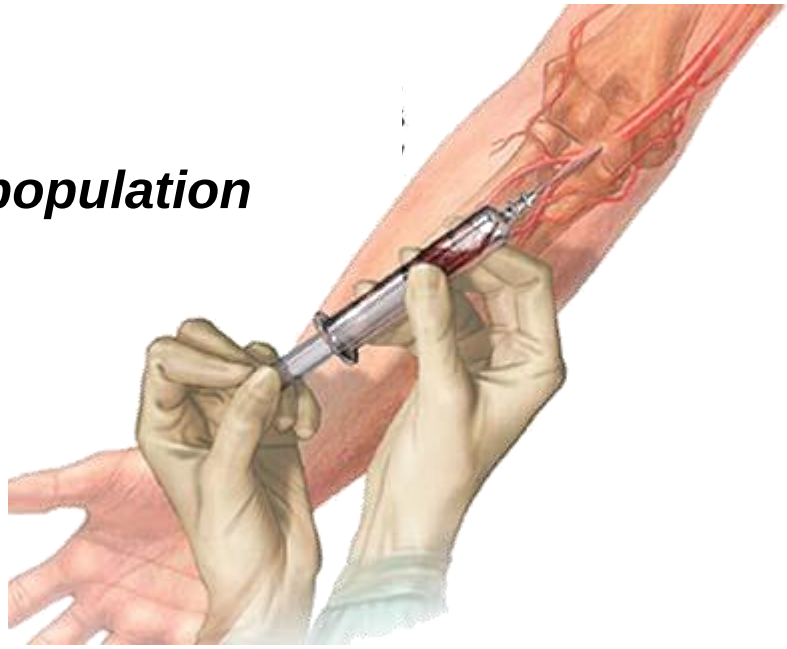
NATURAL ISOTOPE RATIO VARIATIONS IN A BIOMEDICAL CONTEXT RESEARCH PROJECT @ GHENT UNIVERSITY

- *Other diseases affecting the metabolism of essential elements*

  ⇒ change in isotopic composition in blood ?

- *Our study*
  - *Fe, Cu & Zn*
  - *Step 1: spread in the reference population*
    - *Determining factors ?*



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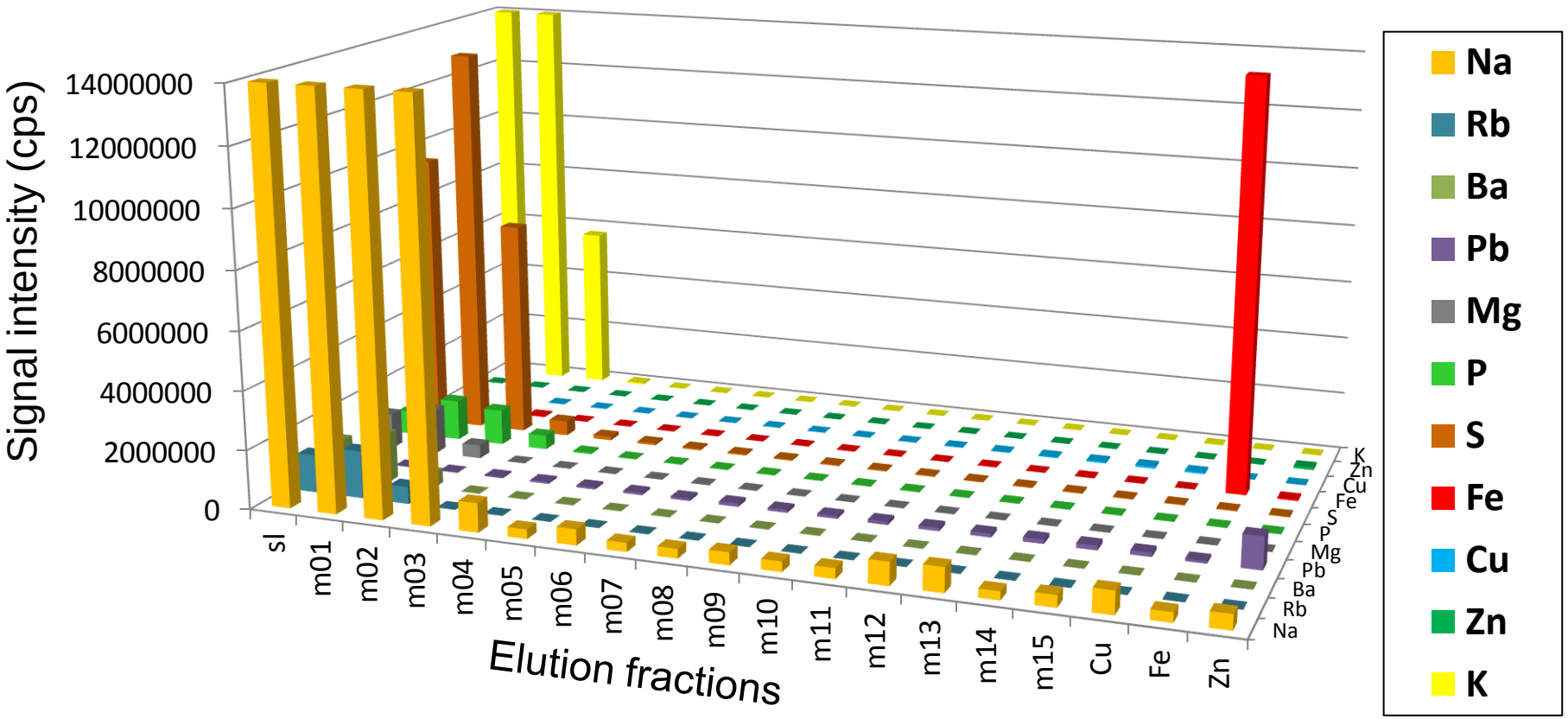
REMOVAL OF MATRIX ELEMENTS SERONORM TRACE ELEMENTS WHOLE BLOOD



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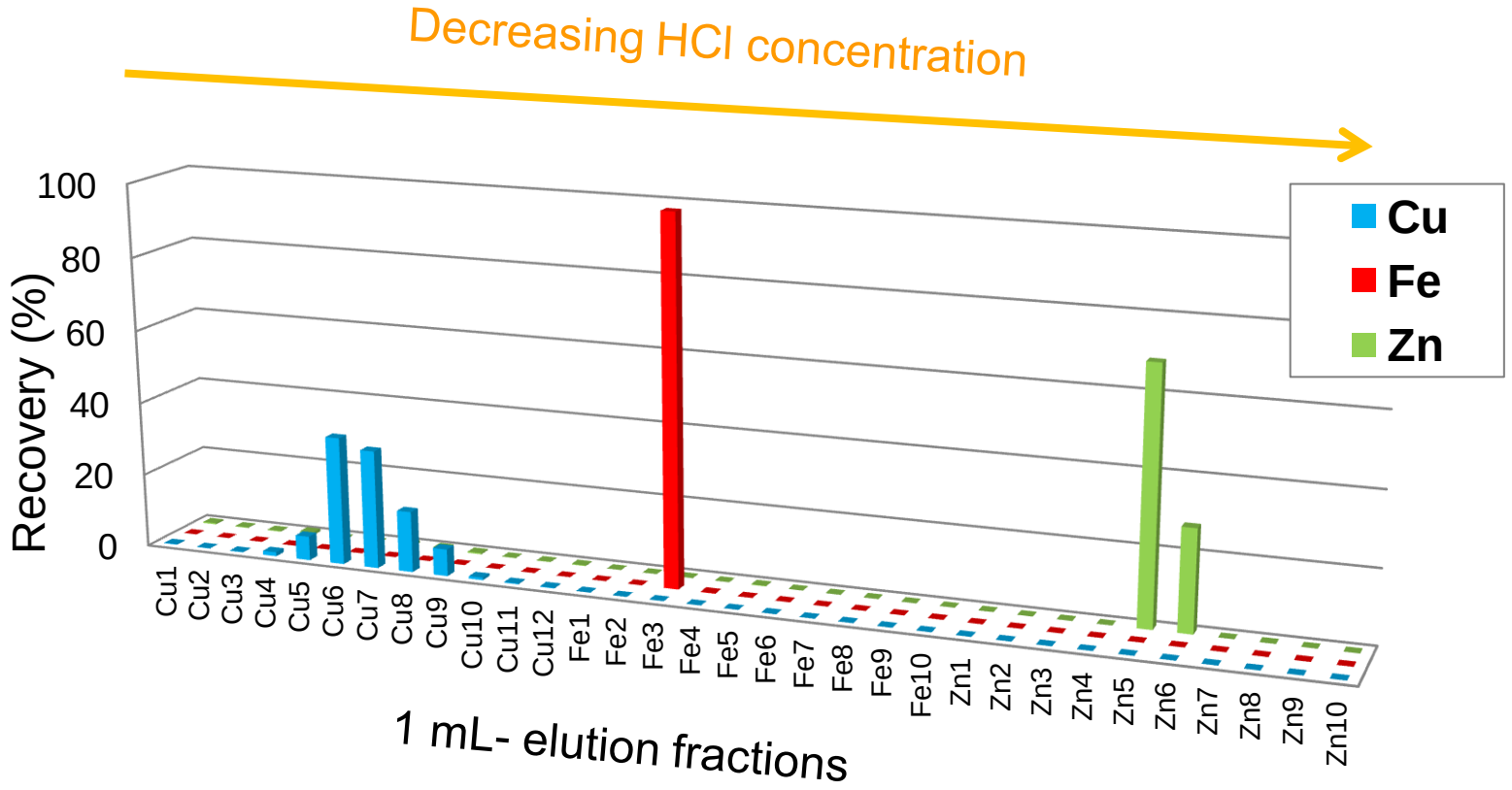
Van Heghe et al., JAAS, 27, 1327-1334, 2012

ISOLATION OF CU, FE & ZN SERONORM TRACE ELEMENTS WHOLE BLOOD



100 % target element recovery ⇒ no effect of potential on-column fractionation

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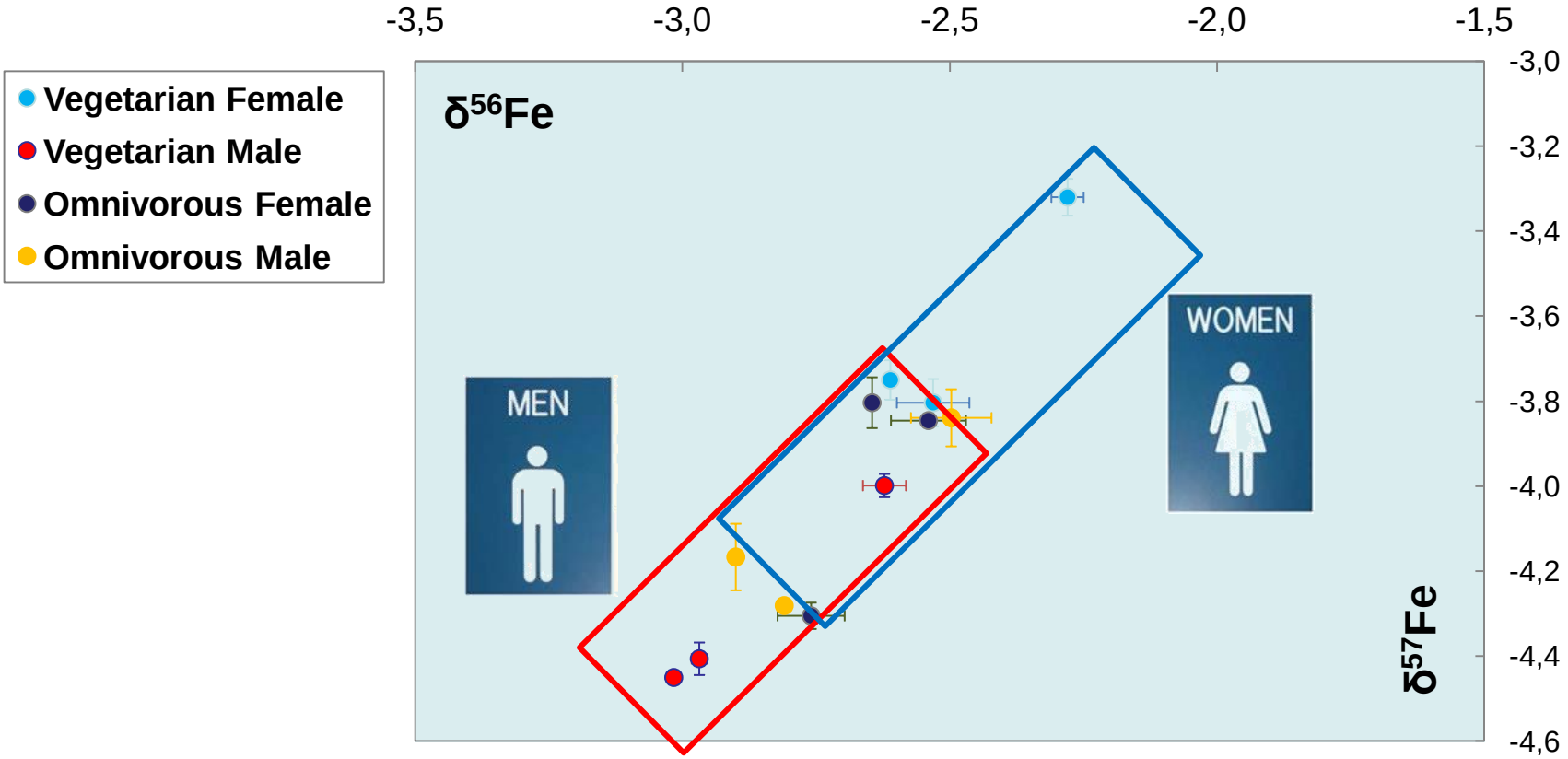
Van Heghe et al., JAAS, 27, 1327-1334, 2012

RESULTS FE ISOTOPIC ANALYSIS
HUMAN BLOOD / REFERENCE POPULATION



MD correction based on Ni as int. std.

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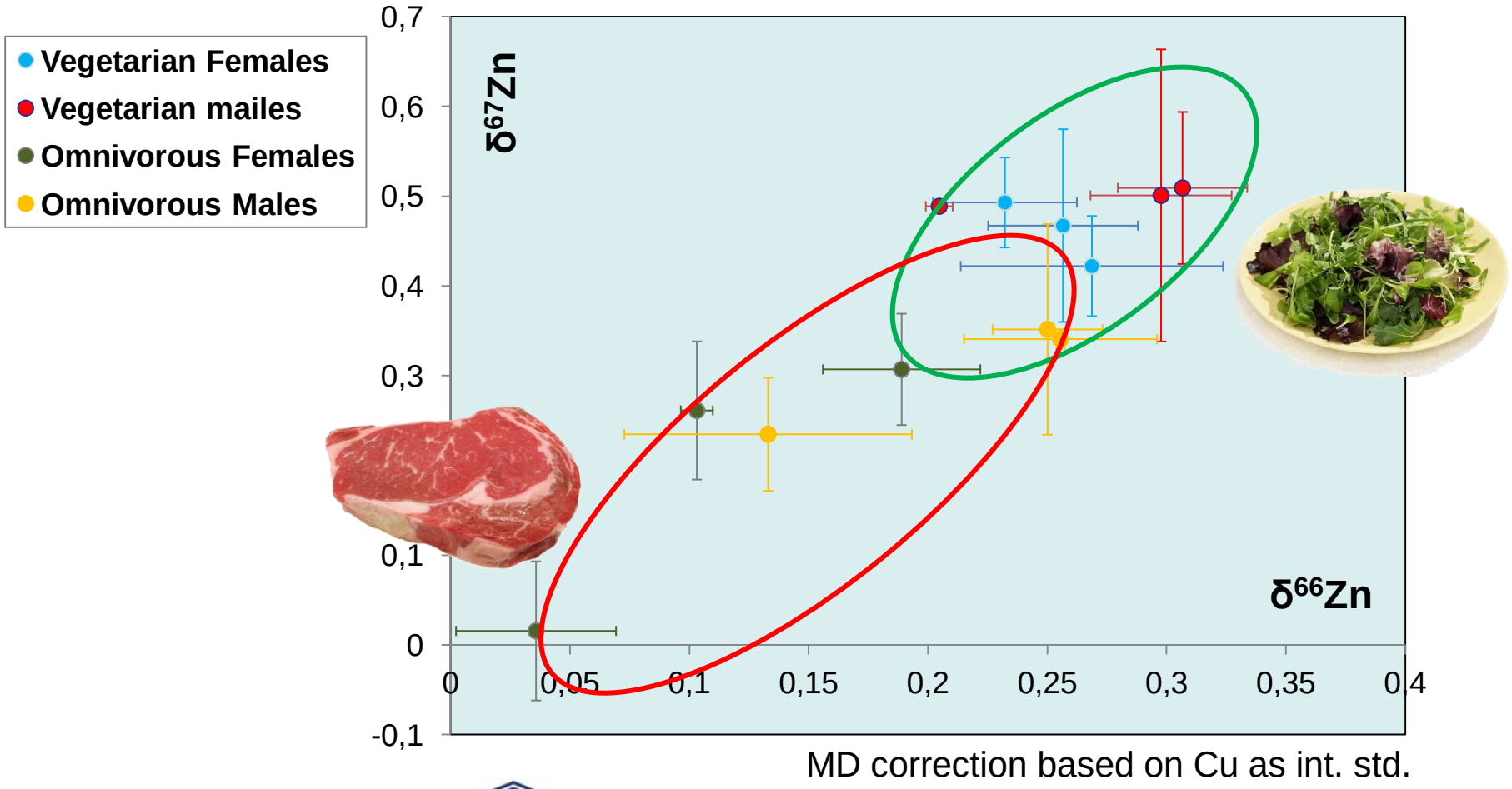
Van Heghe et al., JAAS, 27, 1327-1334, 2012

RESULTS ZN ISOTOPIC ANALYSIS
HUMAN BLOOD / REFERENCE POPULATION



MD correction based on Cu as int. std.

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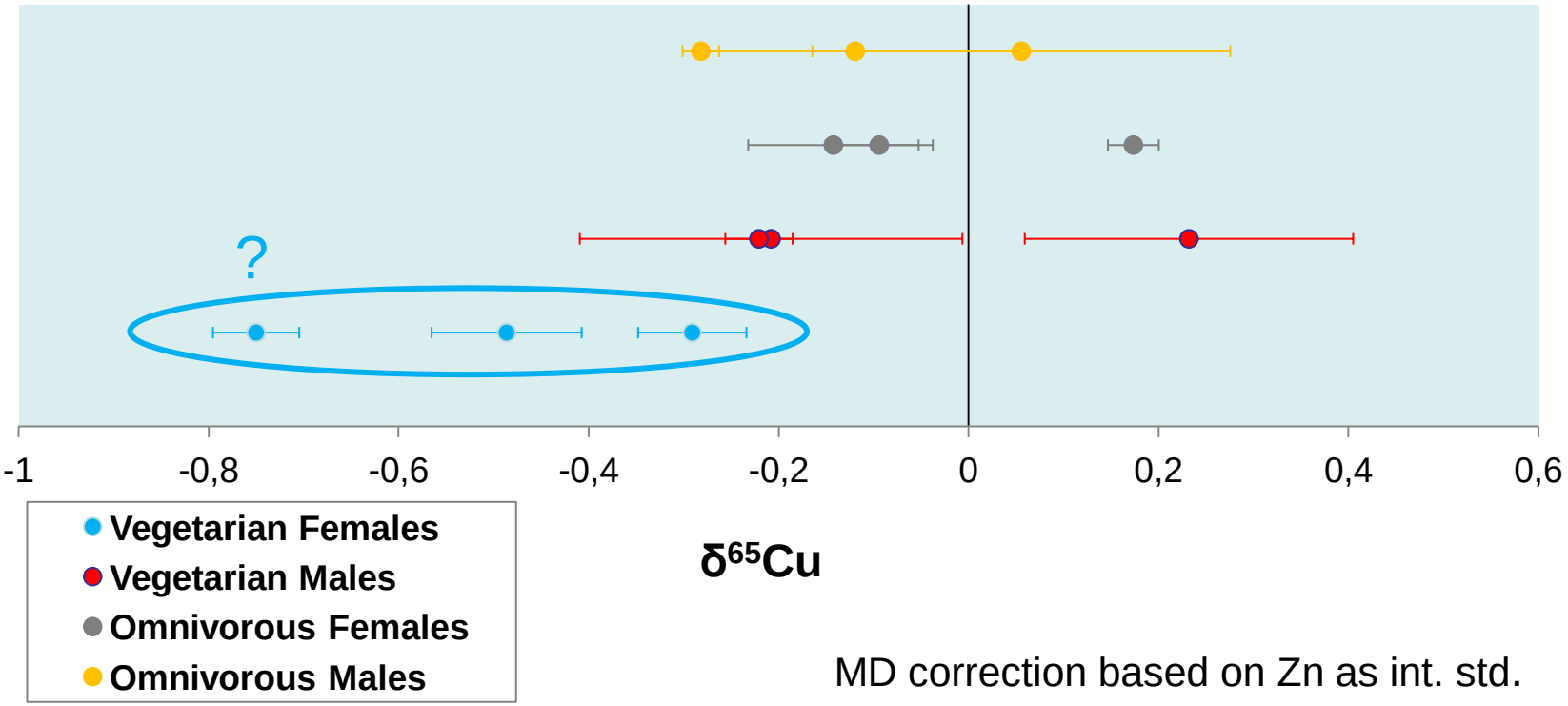
Van Heghe et al., JAAS, 27, 1327-1334, 2012

RESULTS CU ISOTOPIC ANALYSIS
HUMAN BLOOD / REFERENCE POPULATION



MD correction based on Zn as int. std.

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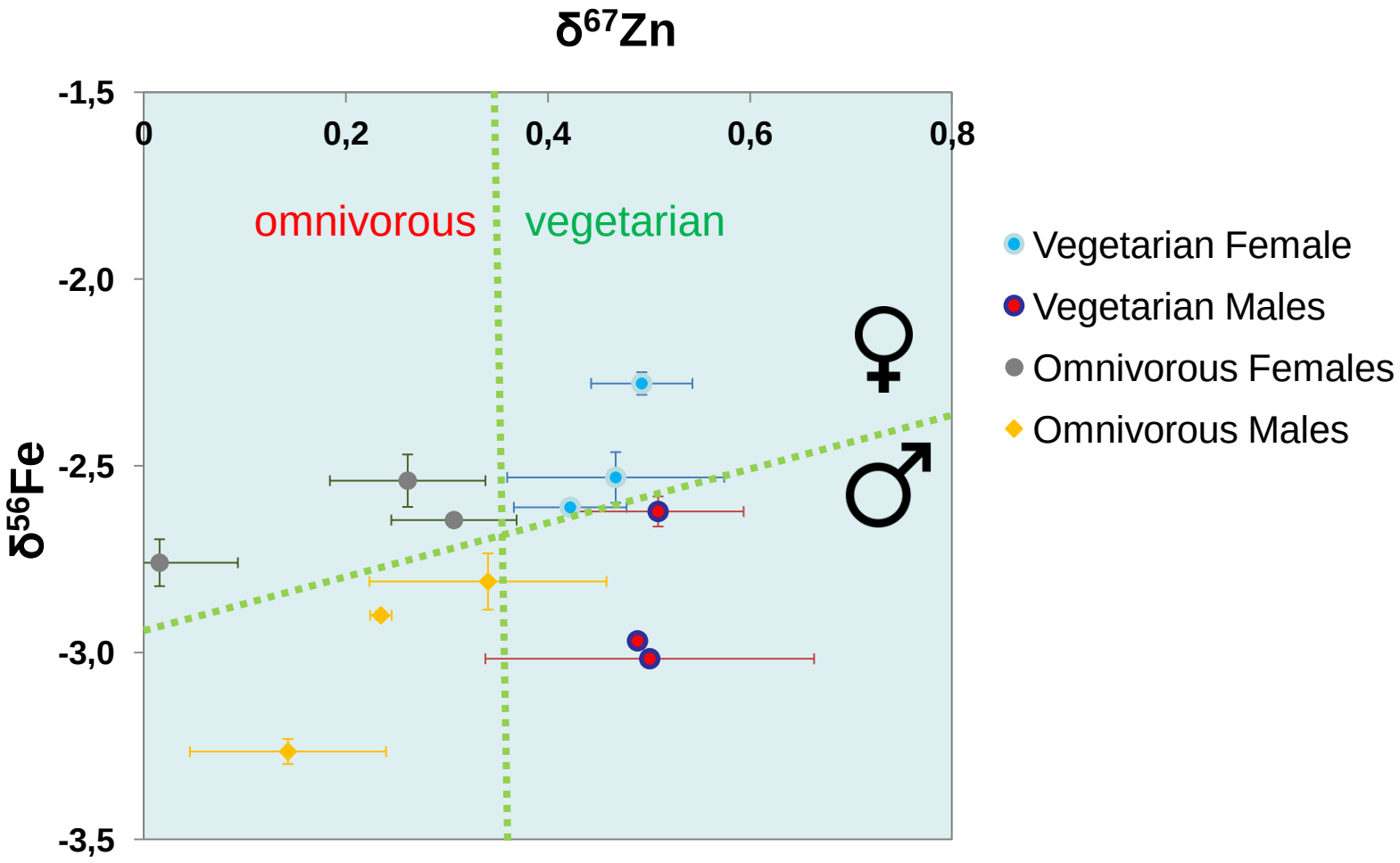
Van Heghe et al., JAAS, 27, 1327-1334, 2012

RESULTS FE + ZN ISOTOPIC ANALYSIS
HUMAN BLOOD / REFERENCE POPULATION



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Van Heghe et al., JAAS, 27, 1327-1334, 2012

Fe, Cu, Zn isotopic analysis in human blood

- ***Factors affecting isotope ratios in reference population***
  - ***Gender***
  - ***Feeding habits***
  - ***…***

- ***Comparison Reference population vs. patient groups***
  - ***Diseases affecting Fe, Cu and/or Zn metabolism***
  - ***Diagnostic means?***
    - ***Less invasive***
    - ***Earlier stage of disease ⇒ prediction***

- ***Use in archaeology?***

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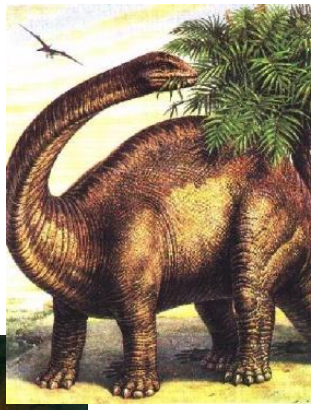
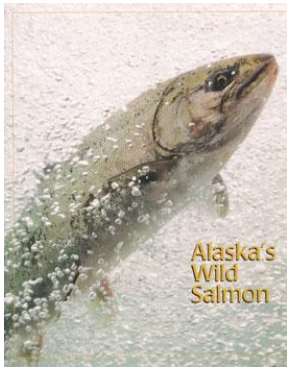
Isotopic Analysis using MC-ICP-MS
Conclusions

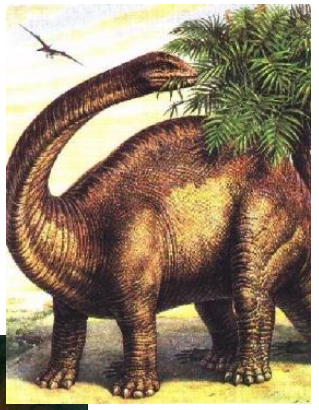
- *Determining (geographical) provenance*
- *Unraveling history*
- *Solving crimes*
- *Diagnosing diseases*

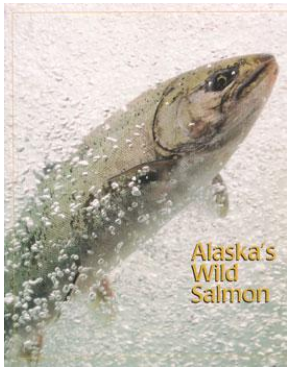




ISOTOPIC ANALYSIS USING MC-ICP-MS
CONCLUSIONS

- *Determining (geographical) provenance*
- *Unraveling history*
- *Solving crimes*
- *Diagnosing diseases*
- ***But be careful !***





ISOTOPIC ANALYSIS USING MC-ICP-MS
CONCLUSIONS

- ***Determining (geographical) provenance***
- ***Unraveling history***
- ***Solving crimes***
- ***Diagnosing diseases***
- ***But be careful !***