^{60}Fe supernova-searches with AMS

Peter Ludwig[1]

Russbach School
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Shawn Bishop[1], Ramon Egli[2], Valentyna Chernenko[1],
Thomas Faestermann[1], Leticia Fimiani[1], Jose Gomez[1], Karin Hain[1], Gunther Korschinek[1]
Nicolai Famulok[1], Thomas Frederichs[3], Marianne Hanzlik[4], Silke Merchel[5], Georg Rugel[5]

[1] Physik Department, Technische Universität München
[2] Zentralanstalt für Meteorologie und Geodynamik, Wien
[3] Fachbereich Geowissenschaften, Universität Bremen
[4] Fakultät für Chemie, Technische Universität München
[5] Helmholtz Zentrum Dresden Rossendorf

Outline

- Accelerator Mass Spectrometry (AMS)
  - → Basics
  - → AMS isotopes
  - → Applications
- AMS Setups at MLL in Garching
- Recent example: Search for supernova 60Fe
  - → in ferromanganese crusts
  - → in microfossils
  - → on the moon
- Summary and outlook

AMS Basics

Accelerator Mass Spectrometry (AMS) is a high-sensitivity ion counting technique, primarily used for determination of isotopic ratios involving long-lived radionuclides

- I will not be talking about ^{14}C table top machines !
- Tandem-accelerator based systems → complete suppression of molecular background
- High energies (100-200 MeV) → nuclear physics particle identification techniques
- Sensitivity can reach down to isotopic ratios of 10^{-16}

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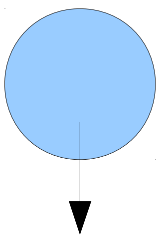
- High energies (100-200 MeV) → nuclear physics particle identification techniques
- Sensitivity can reach down to isotopic ratios of 10^{-16}
- Only few milligrams of sample material required (however: destructive!)
- Isotopic ratios measured → systematic errors (ion source efficiency, …) cancelled
- Challenge: Suppression of isobaric background, e.g. ^{60}Ni, ^{60}Fe or ^{53}Cr, ^{53}Mn, …
- AMS Facility used for all measurements in this study: Maier-Leibnitz-Laboratory Garching

AMS Basics

Sample (Element X)



Radioisotope ^{n}X
Tiny fraction: $^{n}X/X = 10^{-12}...10^{-17}$

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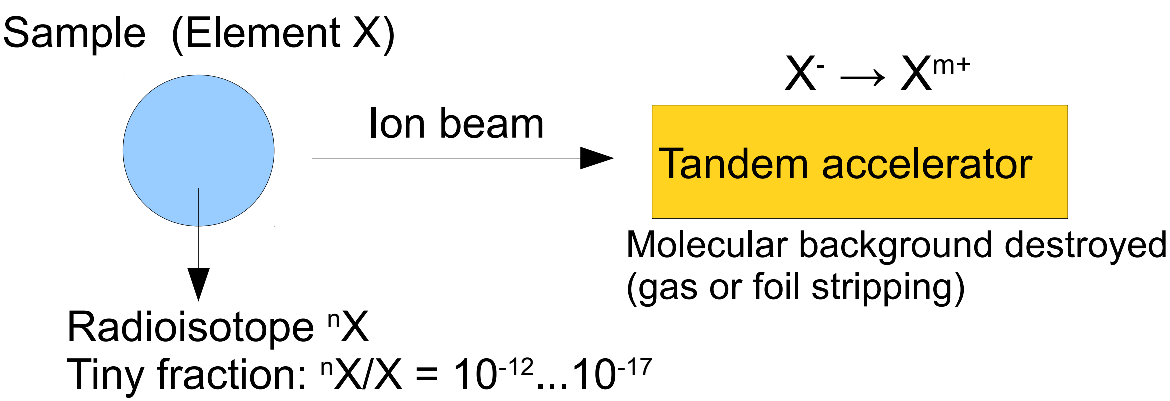
Sample (Element X)
$X^- \rightarrow X^{m+}$
Ion beam
Tandem accelerator
Molecular background destroyed
(gas or foil stripping)
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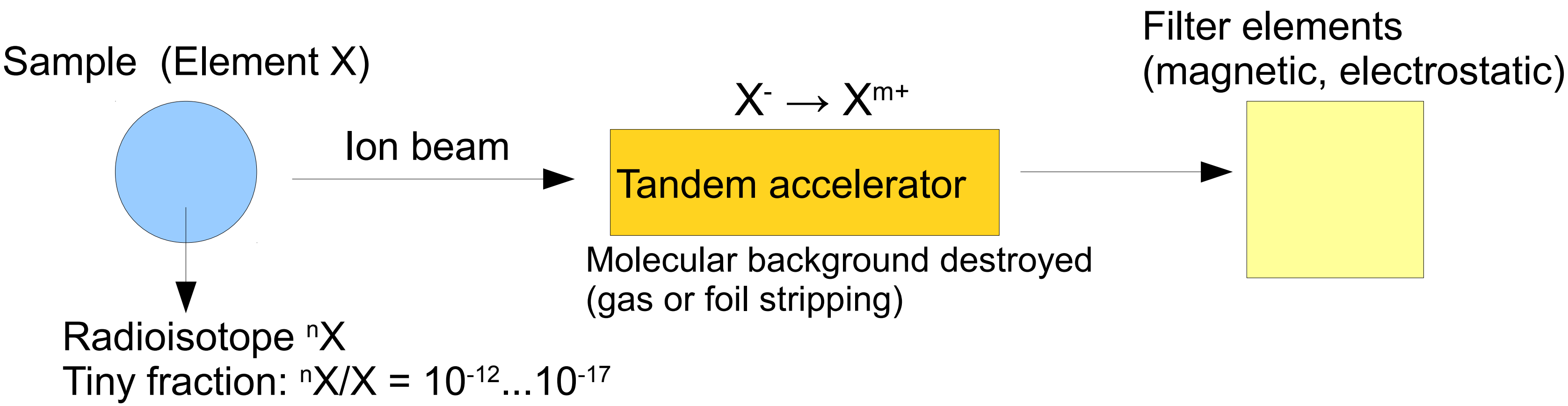
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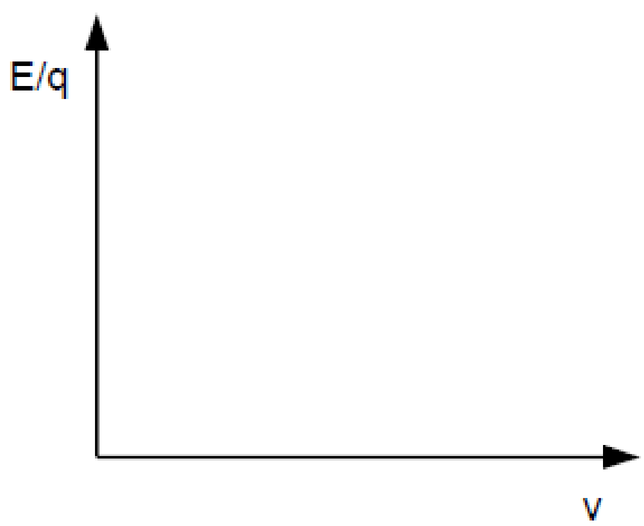

1.) Magnetic analyzer
(typically 90 degree dipole magnet)

$$E(v)=\frac{1}{2} q\, r\, B\cdot v \sim v$$

2.) Electrostatic analyzer (ESA)

$$\frac{E}{q}=\frac{1}{2}\frac{r\,U}{d} \sim const$$

3.) Wien-Filter

$$v=\frac{U}{B\,d} \sim const$$

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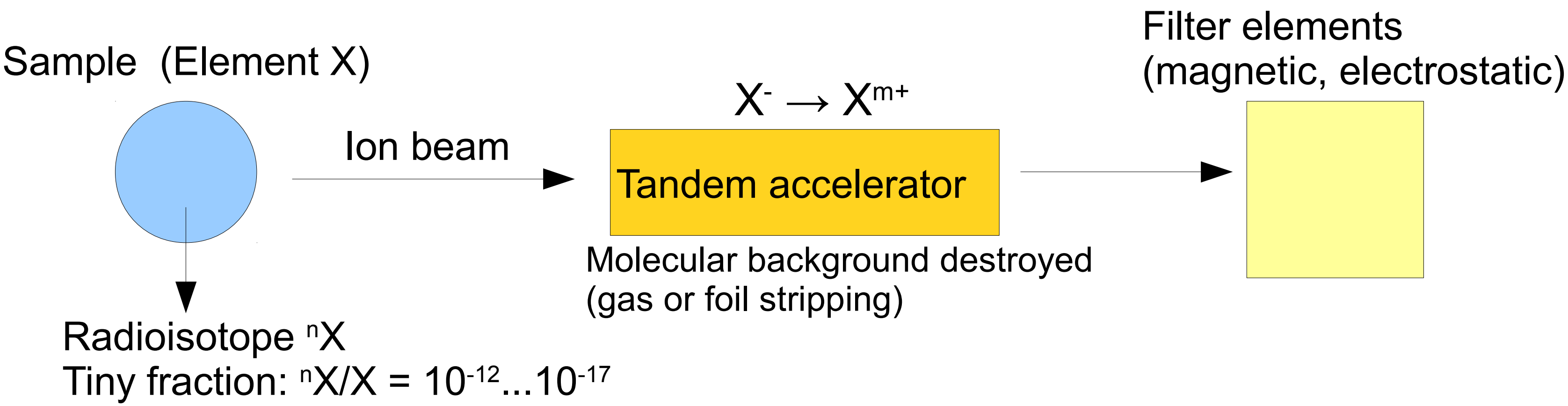

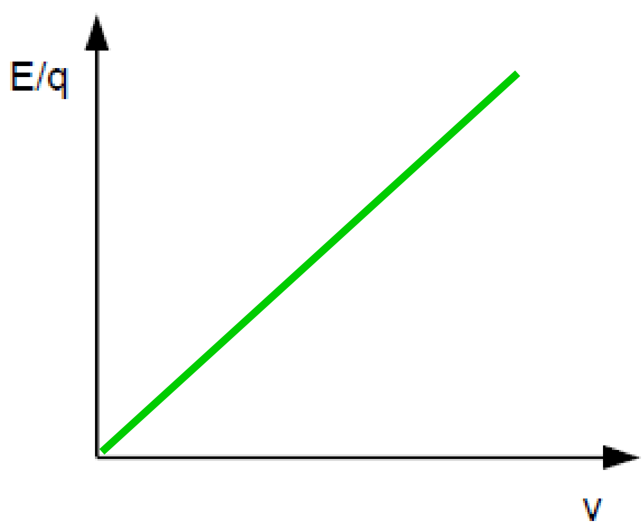

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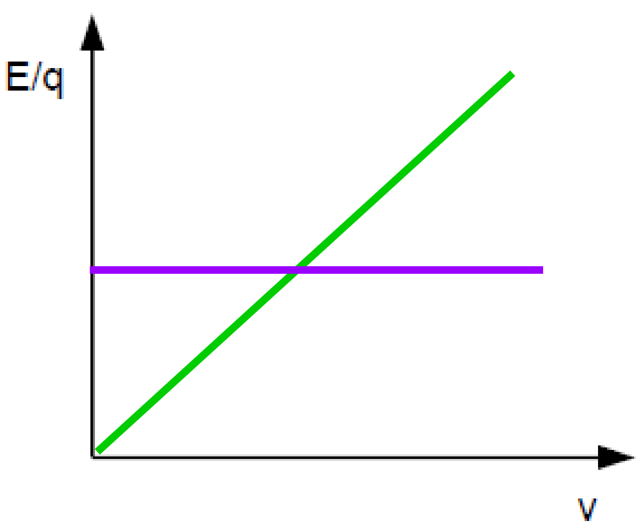

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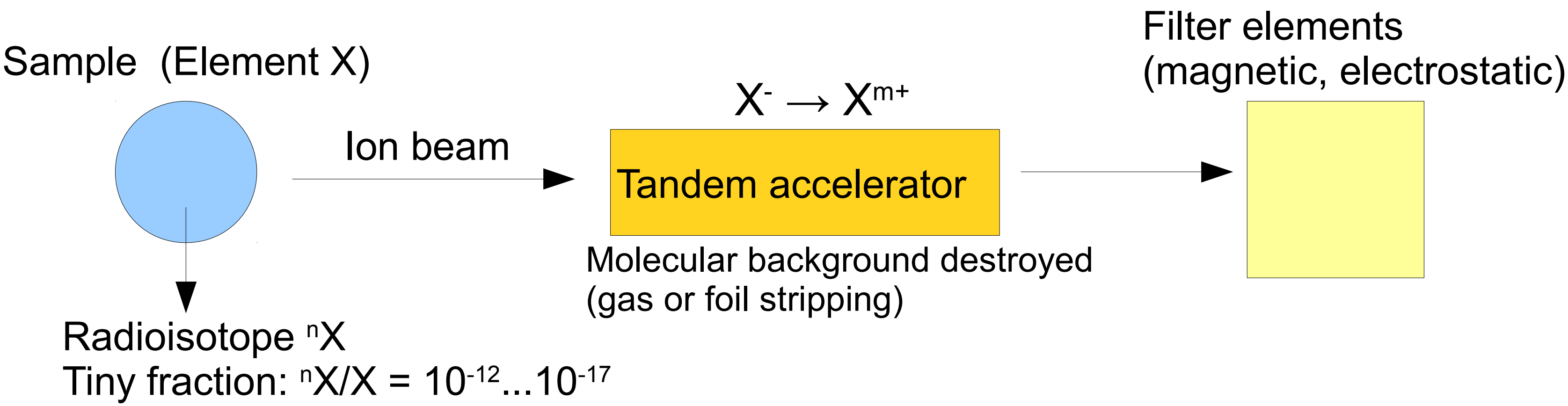

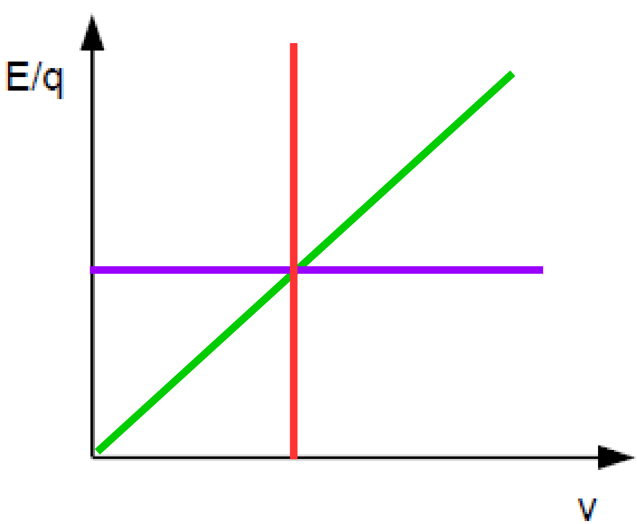

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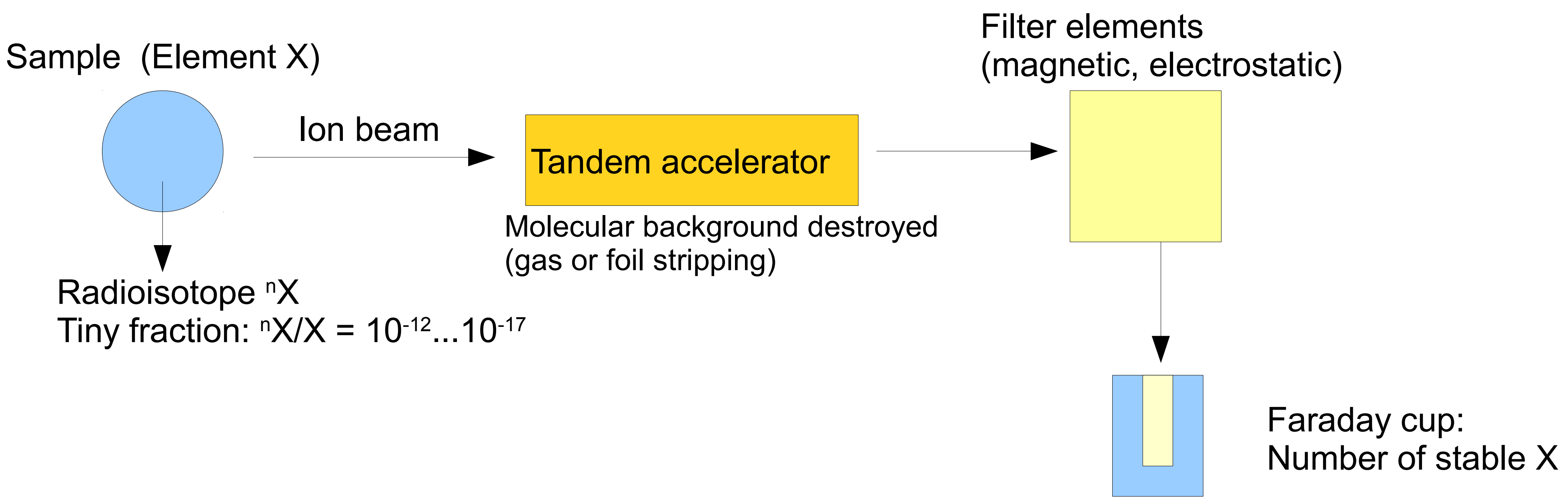
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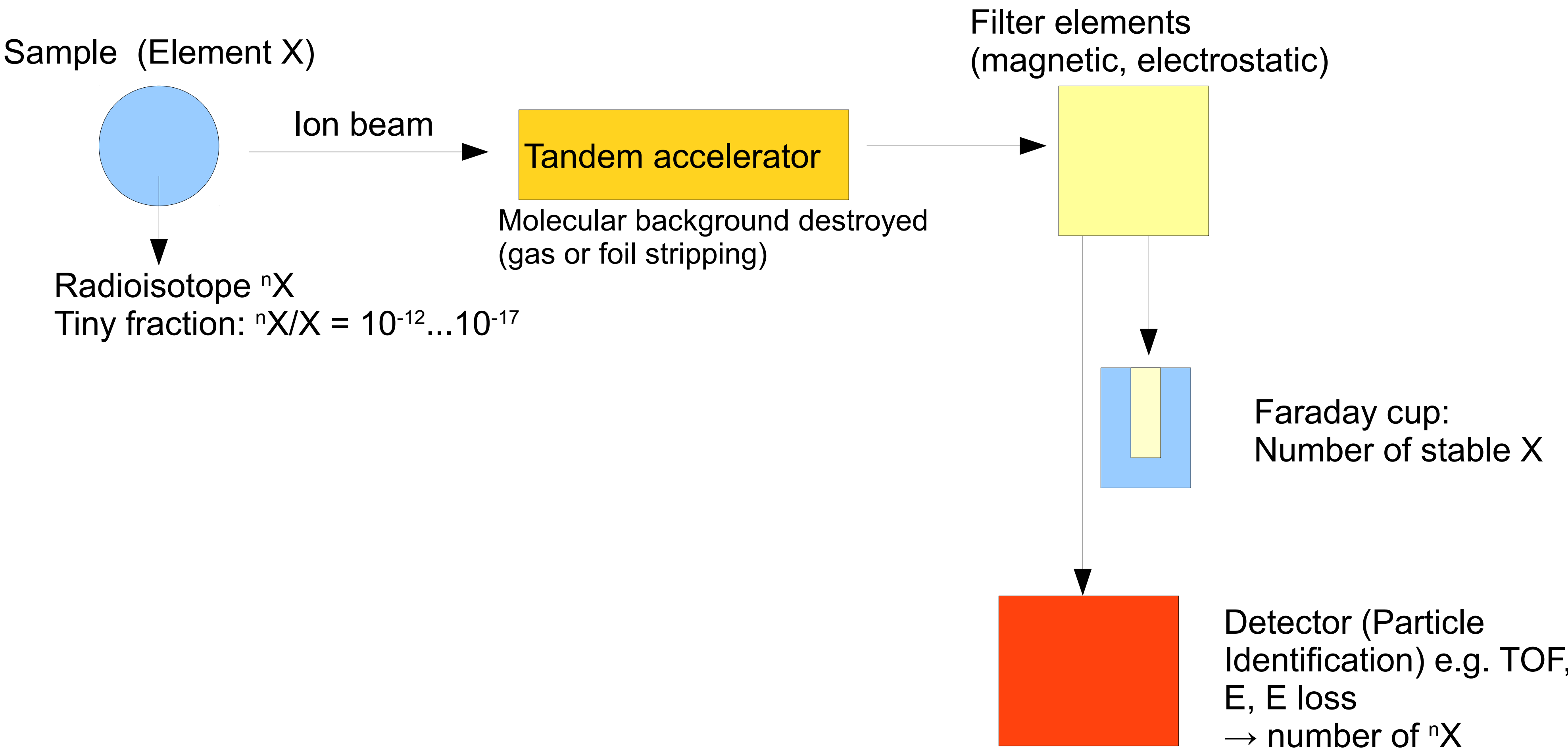

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Faraday cup:
Number of stable X
Detector (Particle Identification) e.g. TOF, E, E loss
→ number of ^{n}X

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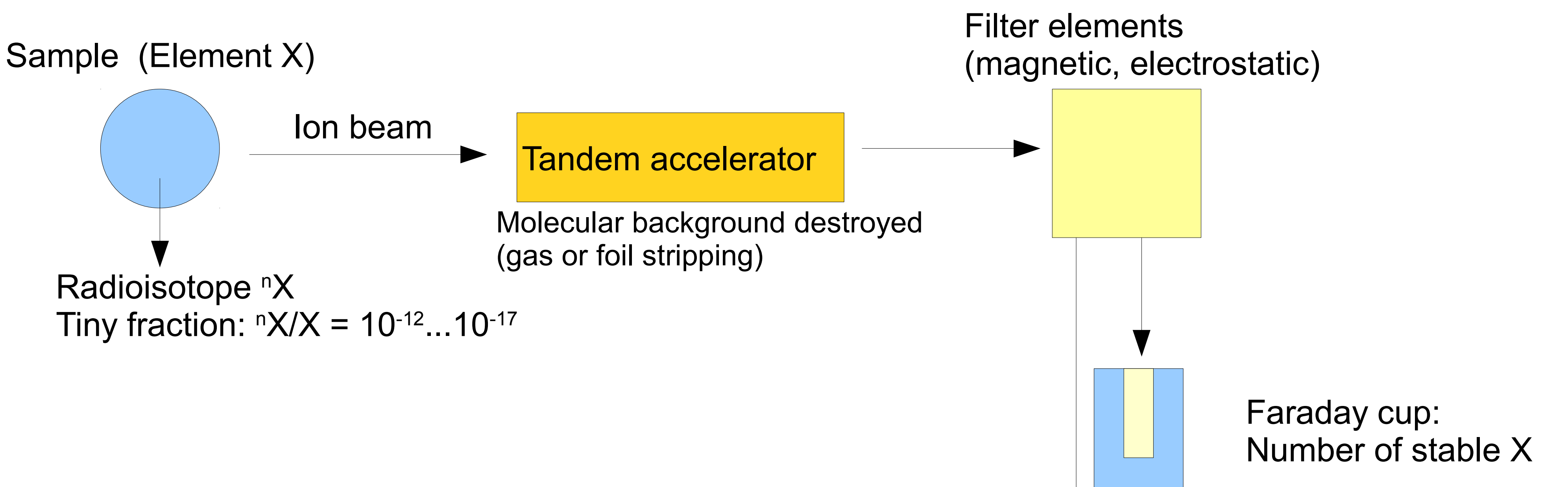
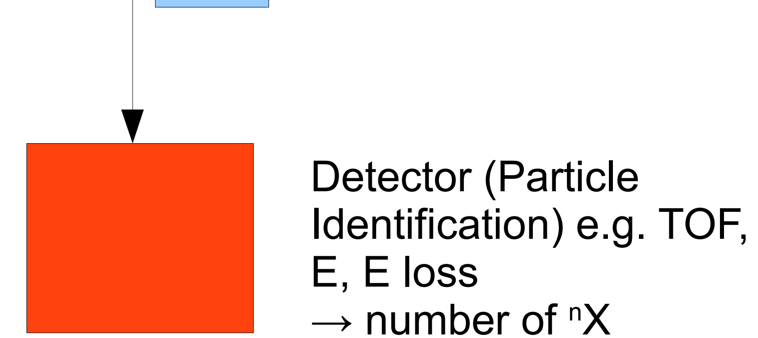


Problem: Transmission from Faraday cup to detector

→ Normally, AMS does **not** measure **absolute** !

→ compare number of counts to a standard sample

→ Give concentration **relative to standard sample**



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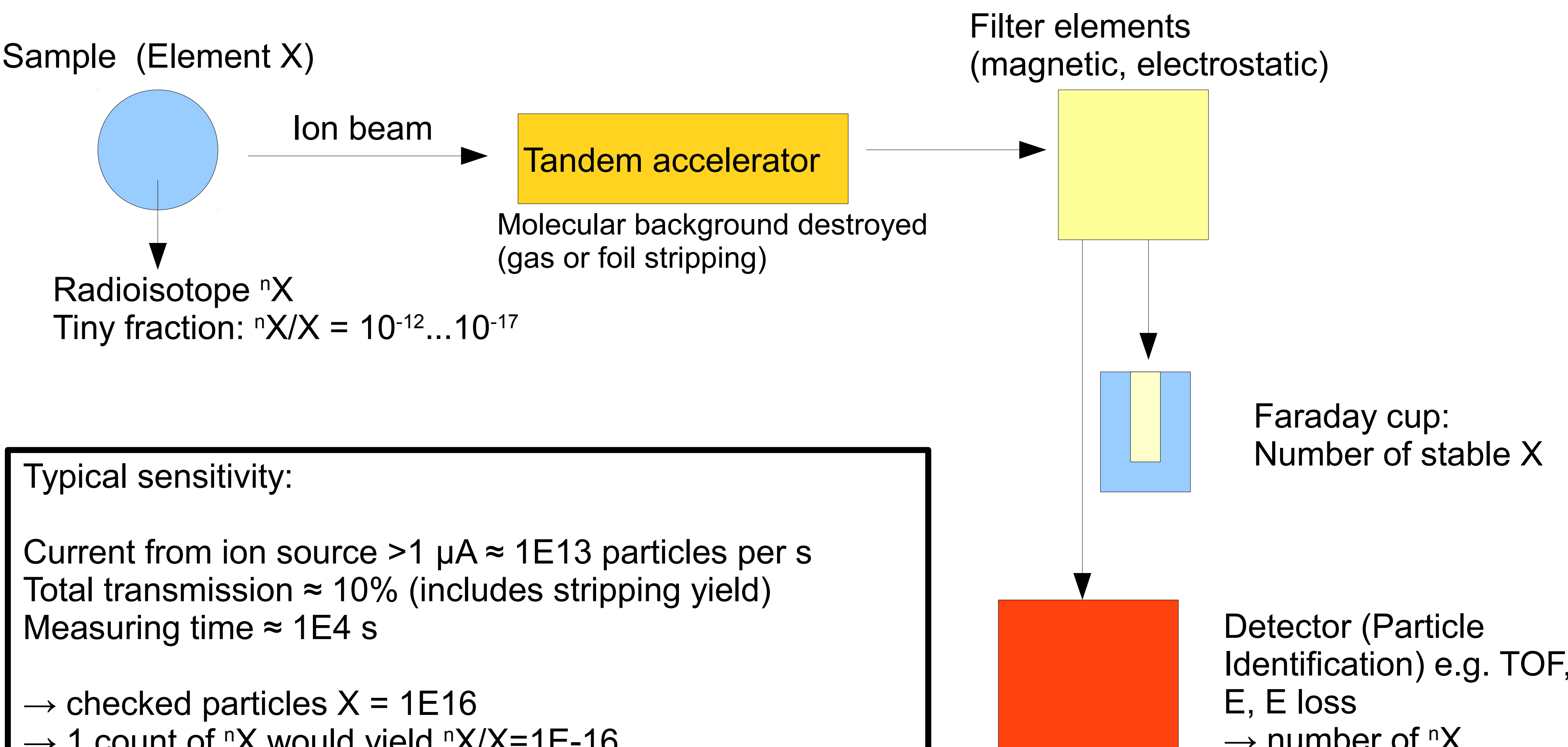

Typical sensitivity:

Current from ion source >1 μA ≈ 1E13 particles per s
Total transmission ≈ 10% (includes stripping yield)
Measuring time ≈ 1E4 s

→ checked particles X = 1E16
→ 1 count of ^{n}X would yield $^{n}X/X$=1E-16

This is a pretty hard limitation, because of limited beamtime

AMS requirements

Can I measure my favourite isotope with AMS?

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Half-life:
$T_{1/2}$ > 100 Ma → primordial background
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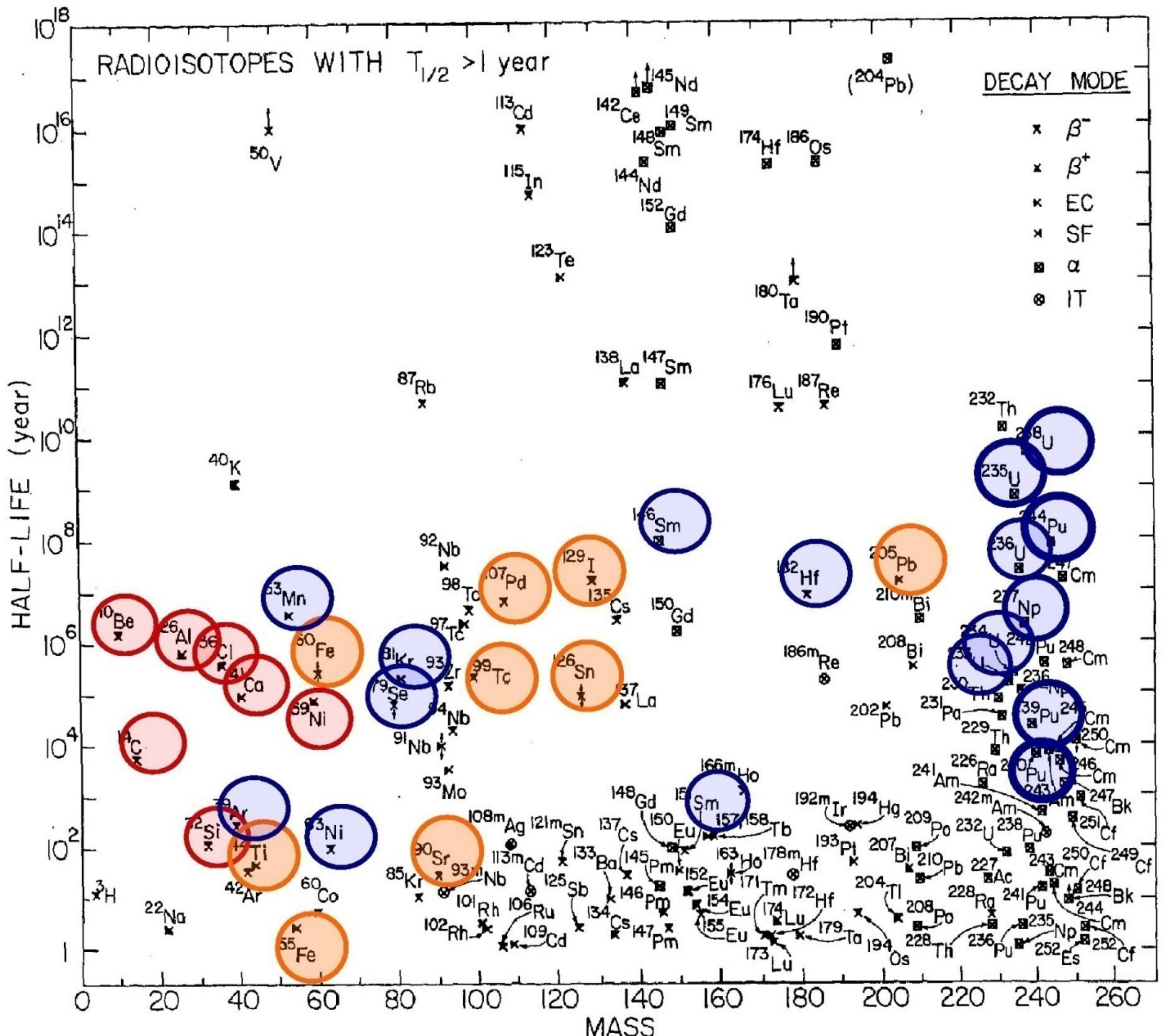
Standard material available?
Since AMS measures relative, standard
Necessary to obtain concentrations

AMS isotopes



1981
AMS-2

^{10}Be, ^{14}C, ^{26}Al, ^{32}Si, ^{36}Cl, ^{41}Ca, ^{59}Ni

1996
AMS 3 —7
+9 new isotopes

2008
AMS 8 - 11

+17 more new isotopes

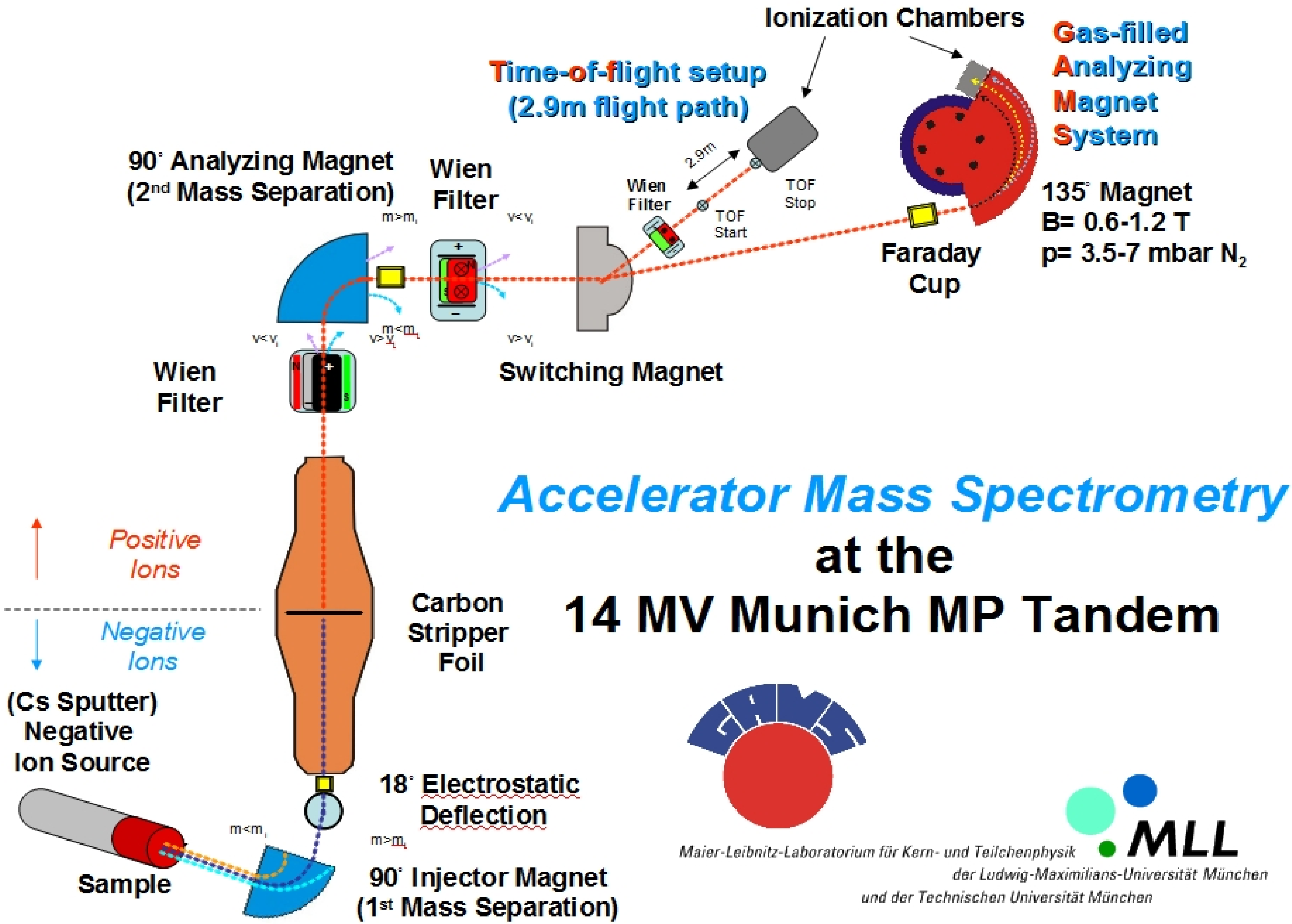
Fig. 4 from D.Fink, NIM B 268, 2010
modified/updated from W. Kutschera 1981

AMS is multidisciplinary

- Environmental and Geo-science	● atmosphere, oceanography, glacier, **climate**, groundwater, erosion, dating paleooceanography, …
- Material science	fusion research, active waist management
- human metabolism and medical application	● **dosimetry**, pharmacology, ...
- Chemistry	tracing molecules and elements, …
- Extraterrestrial	meteorites (e.g. Lunar and Martian origin) ● **interplanetary dust, SN,** related cross sections, …
- Physics	● **nuclear astrophysics**, super- asymmetric fission, …

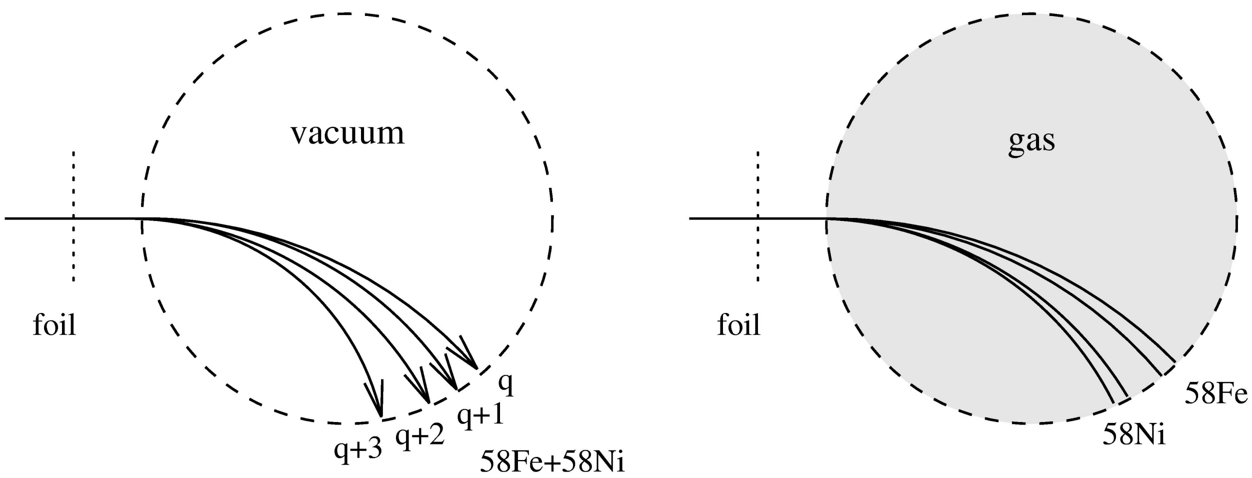
Maier-Leibnitz Laboratory (MLL) Garching

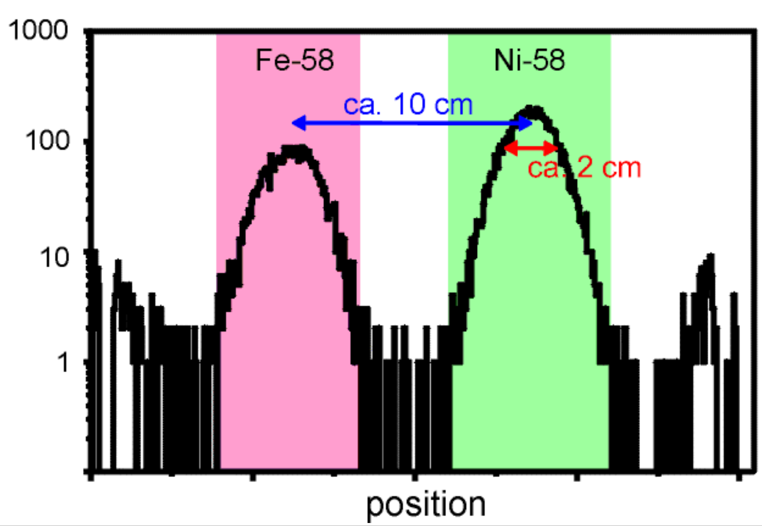
AMS in Garching

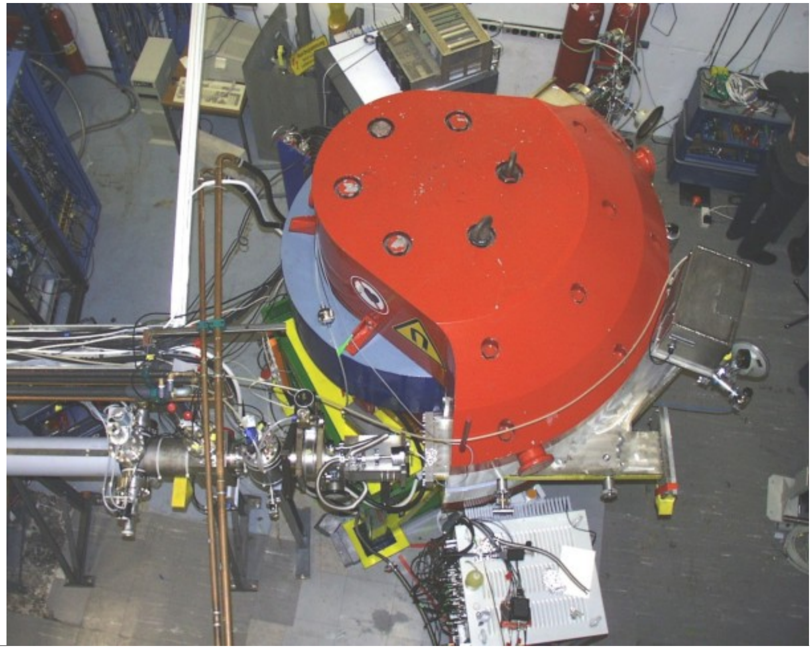


Isobar suppression: GAMS

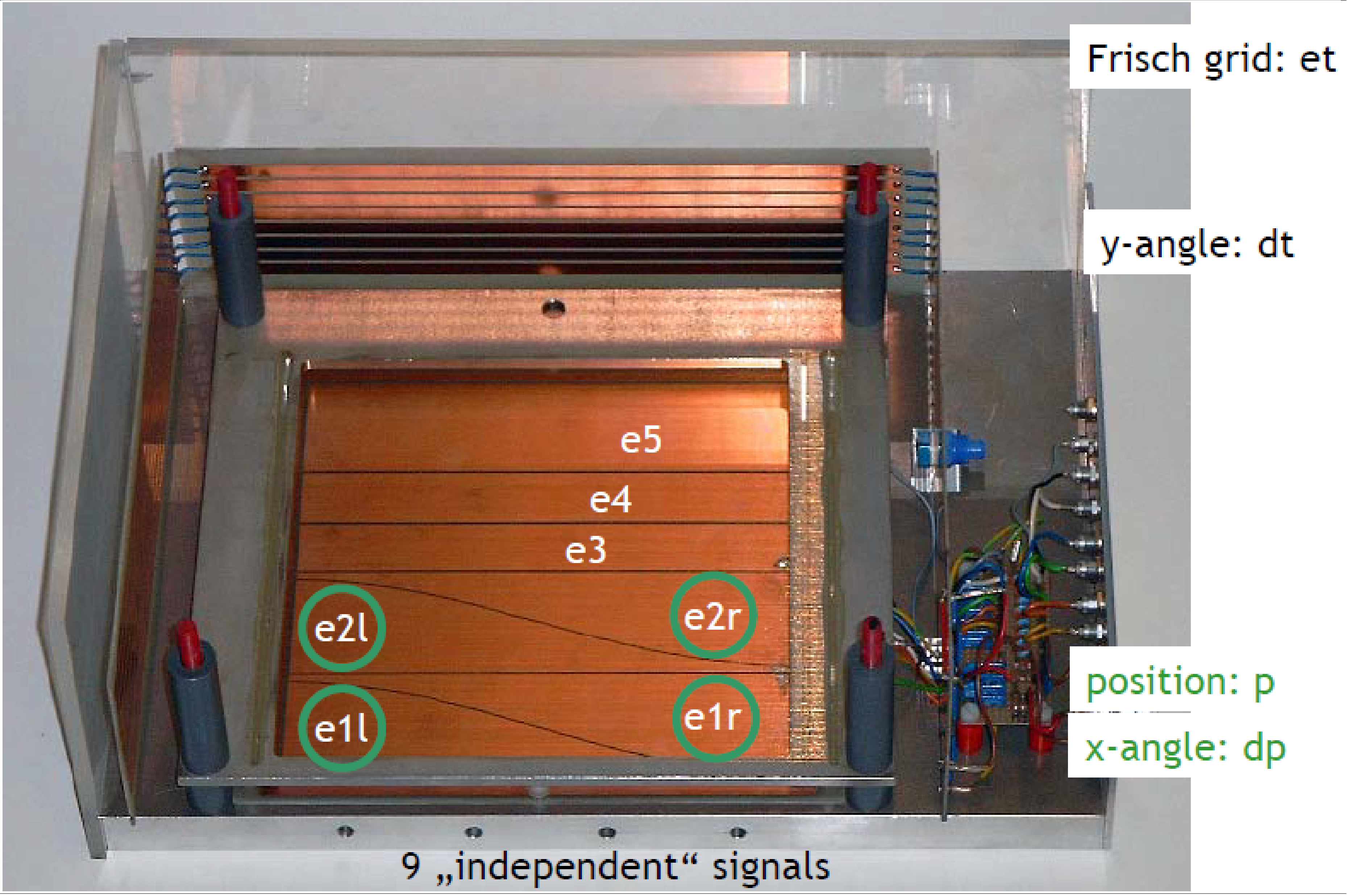
Challenge: Isobar separation of ^{60}Ni → use of the Gas-filled-Analyzing-Magnet-System (GAMS)







Ionization chamber



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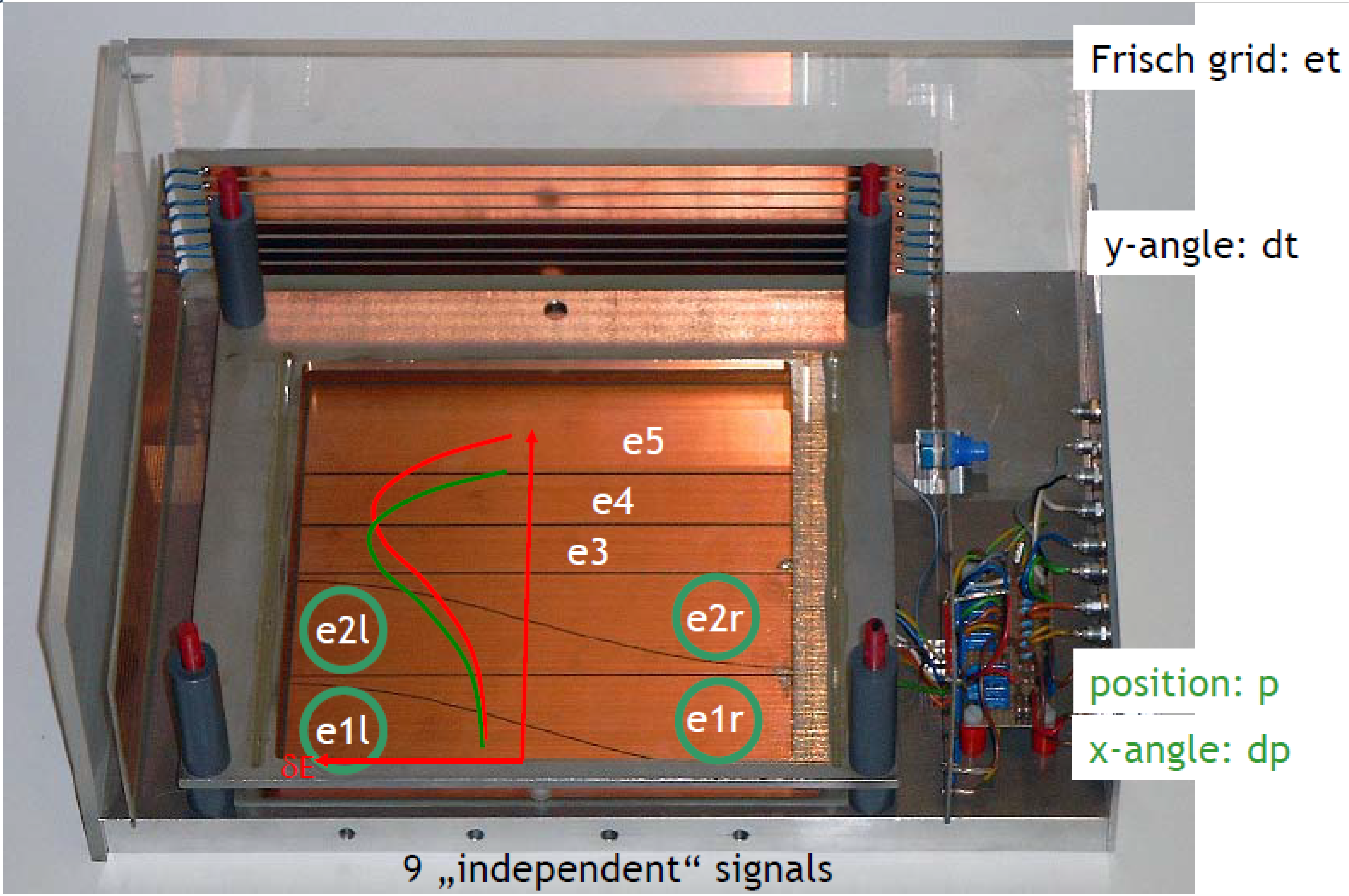
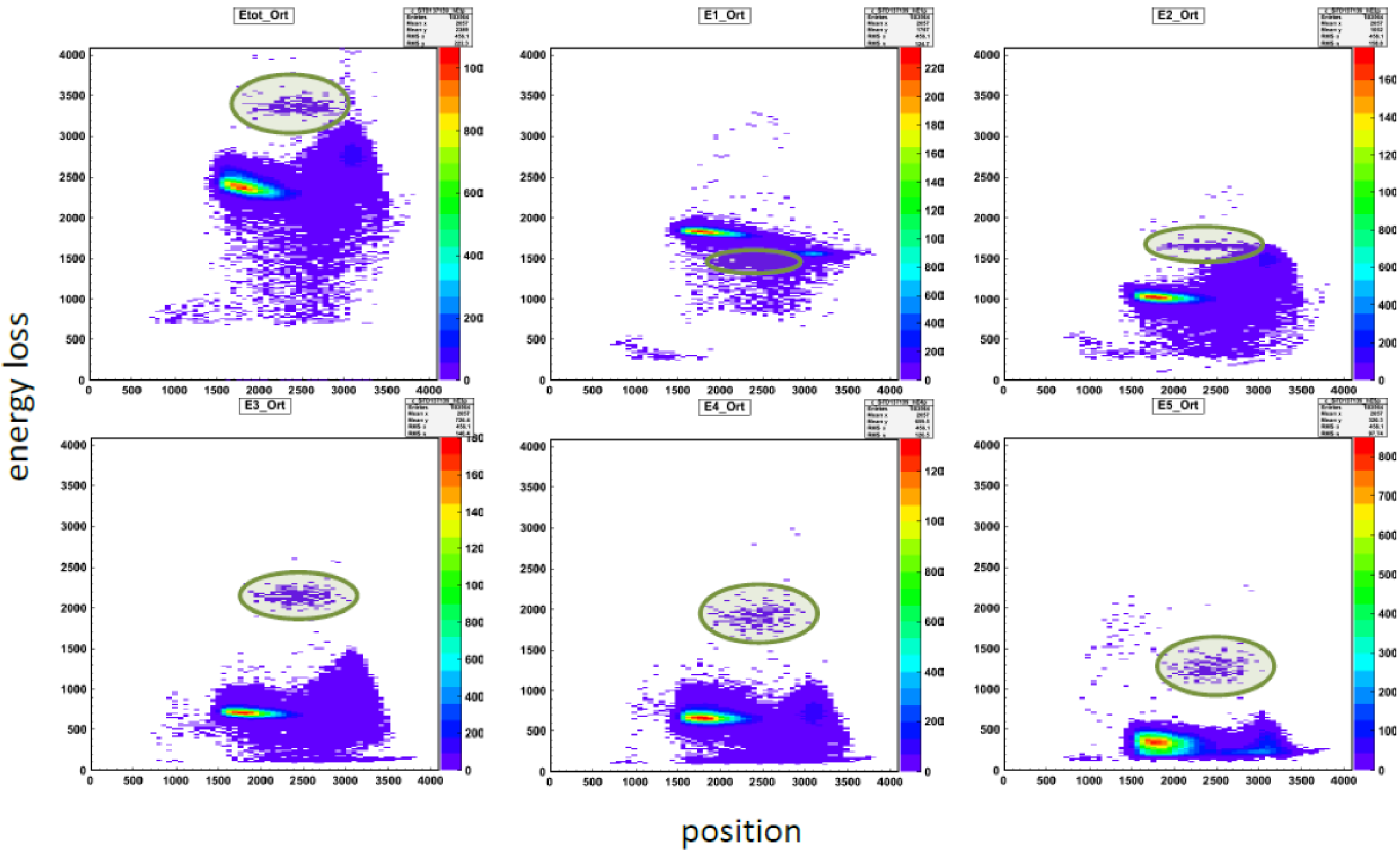


60Fe standard sample 60Fe/Fe~1E-12



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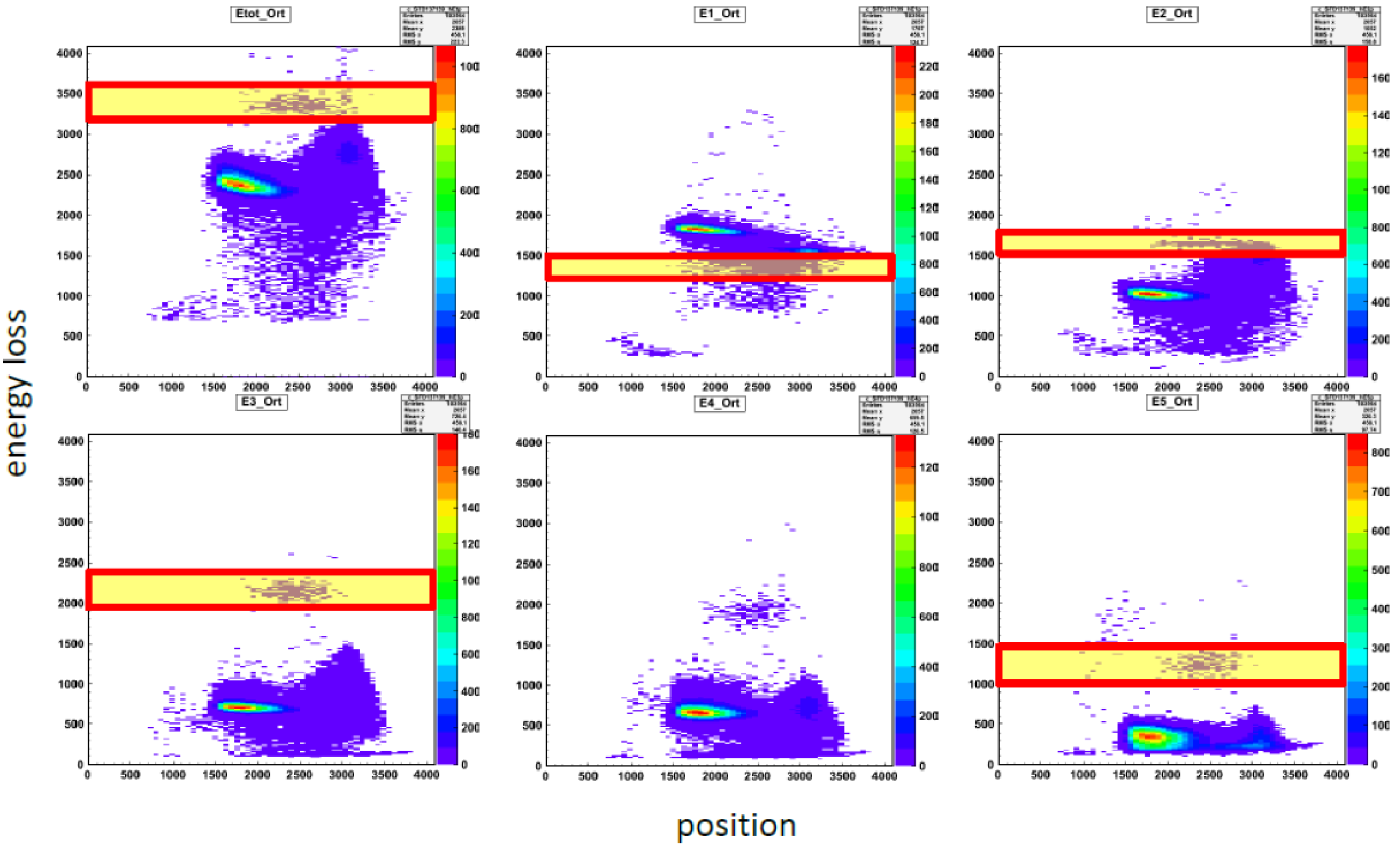
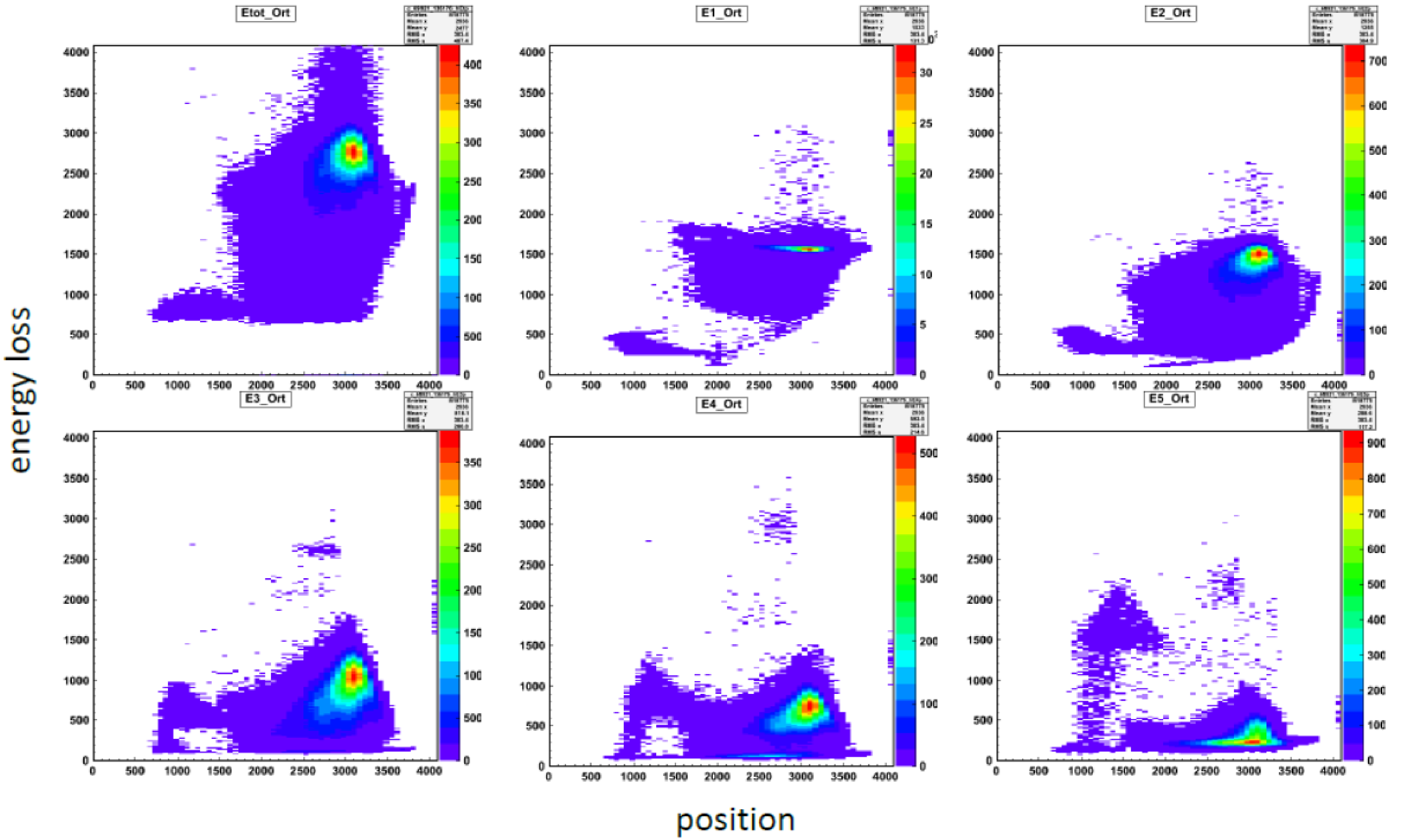


Real sample 60Fe/Fe=?



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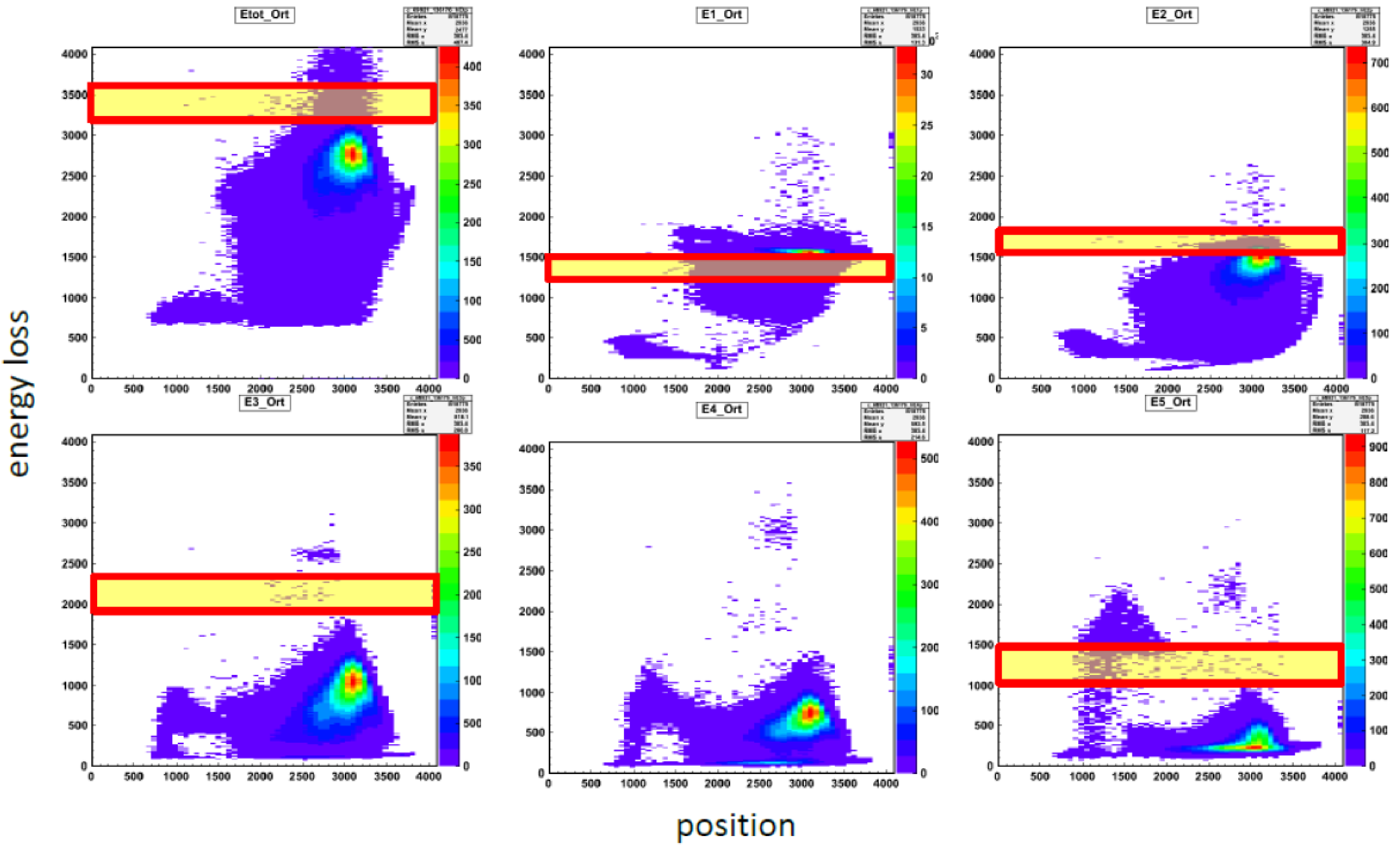

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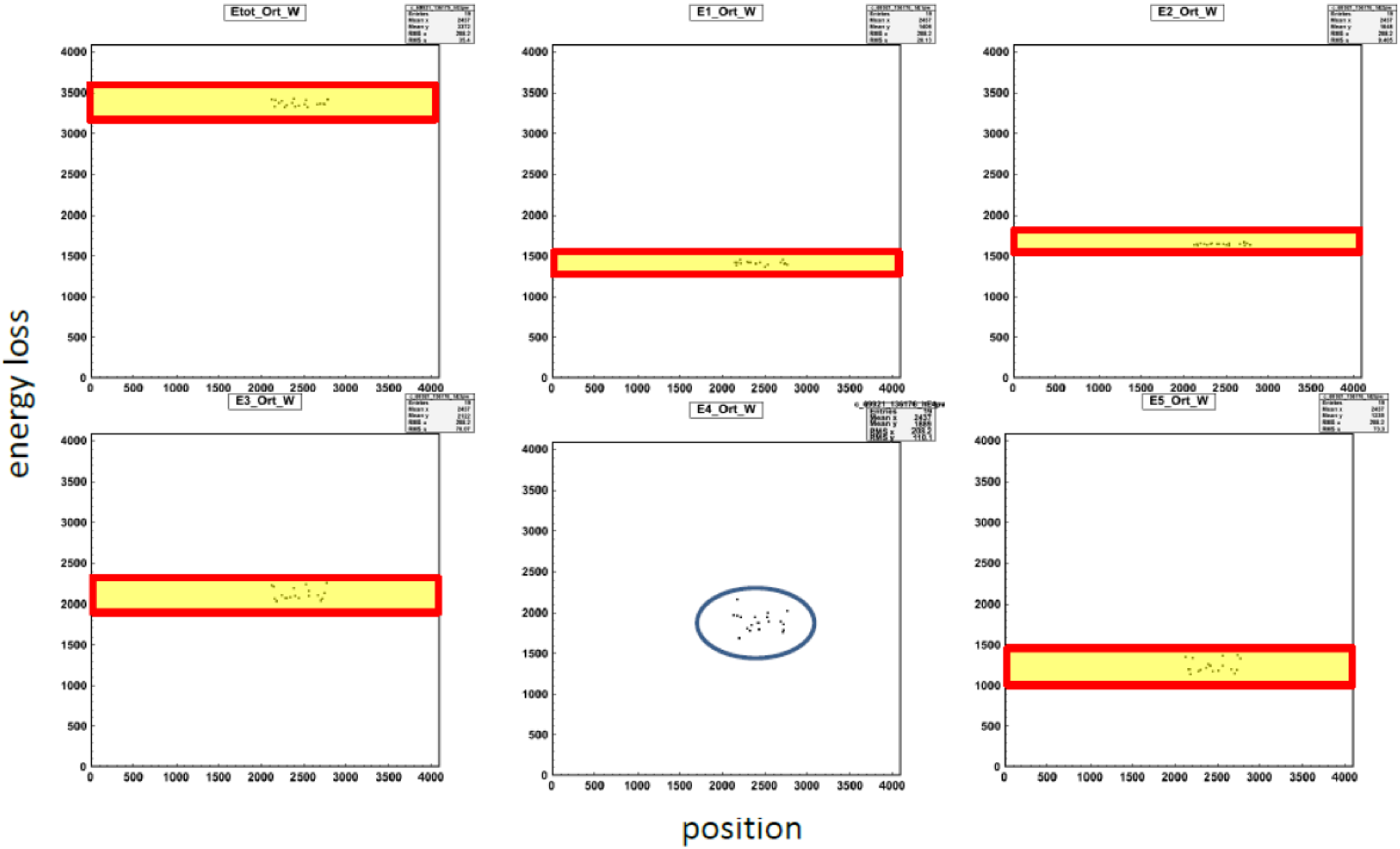


AMS measurements with GAMS

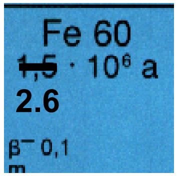
isotope	application	ion in ion out	isobar	isobar Supp.	sensitivity
^{26}Al	astroph. x-section manganese crusts	AlO^- Al^{7+}	^{26}Mg	10^9	few 10^{-15}
^{36}Cl	groundwater, meteorites	Cl^- Cl^{10+}	^{36}S	10^9 – 10^{10}	< 10^{-15}
^{41}Ca	Hiroshima teeth, meteorites	CaH_3^-, CaF_3^- Ca^{9+}	^{41}K	10^9 – 10^{10}	< 10^{-15} 10^{-14} CaF
^{44}Ti	astroph. x-section	TiO^- Ti^{9+}	^{44}Ca	10^9 – 10^{10}	few 10^{-15}
^{53}Mn	crusts, in-situ, meteorites, sediments, moon rocks	$^{53}MnO^-$, $^{53}MnF^-$ $^{53}Mn^{11+}$	^{53}Cr	10^9	few 10^{-15}
^{59}Ni	nuclear waste, meteorites, astroph. x-section	$^{59}Ni^-$ $^{59}Ni^{12+}$	^{59}Co	10^9	few 10^{-14}
^{60}Fe	crusts, meteorites, moon rock, nuclear waste	$^{60}FeO^-$ $^{60}Fe^{11+}$	^{60}Ni	>10^{11}	few 10^{-16}
^{63}Ni	Hiroshima copper, neutron dosimetry astroph. x-section	$^{63}Ni^-$ $^{63}Ni^{12+}$	^{63}Cu	10^8 – 10^9	few 10^{-14}
^{79}Se, ^{93}Mo, ^{93}Zr, ^{107}Pd	astroph. x-section, half-life, nuclear waste	various	^{79}Br, ^{93}Nb, ^{107}Ag	10^6	few 10^{-12} ? few 10^{-10} ? ?

TECHNISCHE UNIVERSITÄT MÜNCHEN

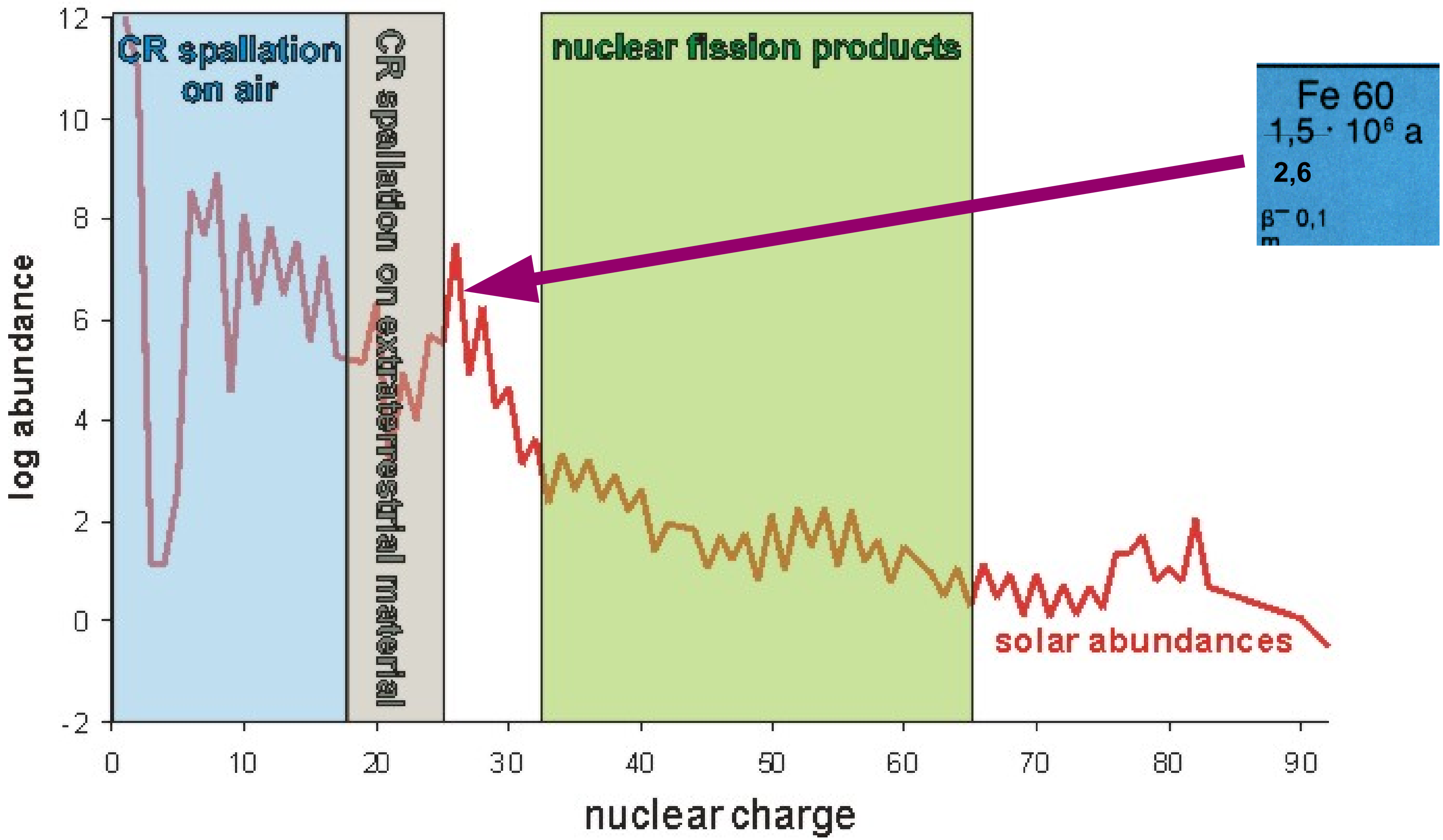
Chosing an isotope

Lehrstuhl E12

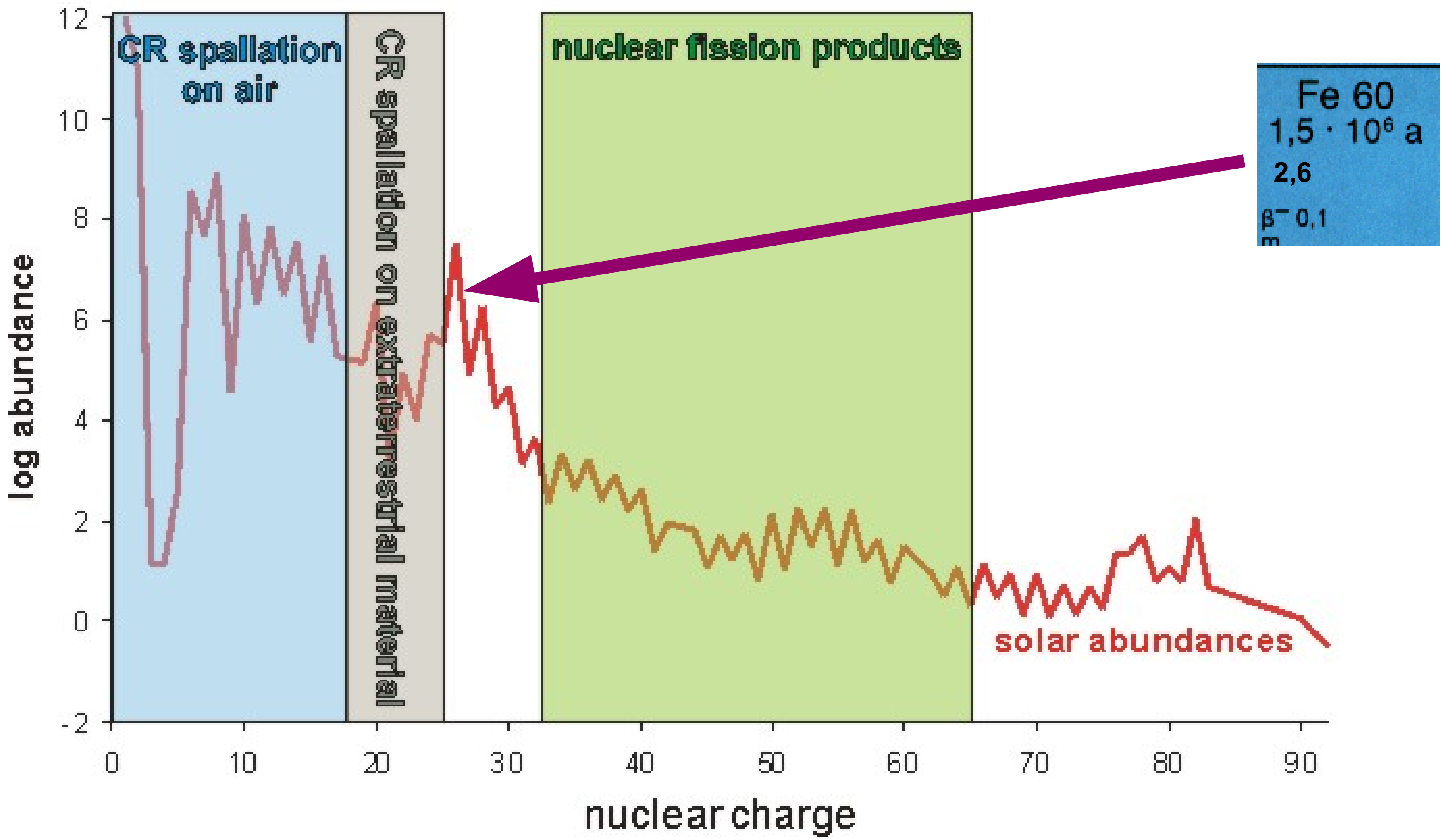
However, I can only talk about ONE of those isotopes today:



Why ^{60}Fe?

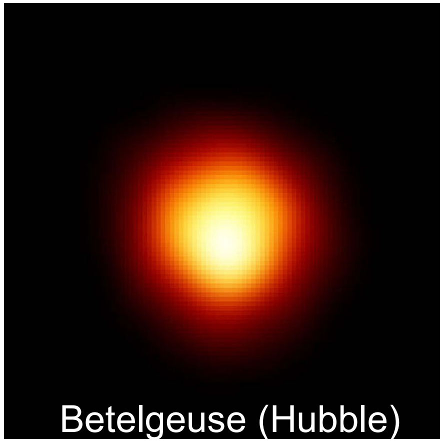

CR spallation on air
CR spallation on extraterrestrial material
nuclear fission products
solar abundances
log abundance
nuclear charge
12
10
8
6
4
2
0
-2
0
10
20
30
40
50
60
70
80
90
Fe 60
1,5 · 10⁶ a
2,6
β⁻ 0,1

Why ^{60}Fe?



→ Unique situation: 1) Isobar ^{60}Ni has ΔZ = 2 (good for AMS!)
2) Expected background in terrestrial samples ^{60}Fe/Fe < 10^{-16}
3) Half-life on the order of Myr (interesting SN ages)

Motivation

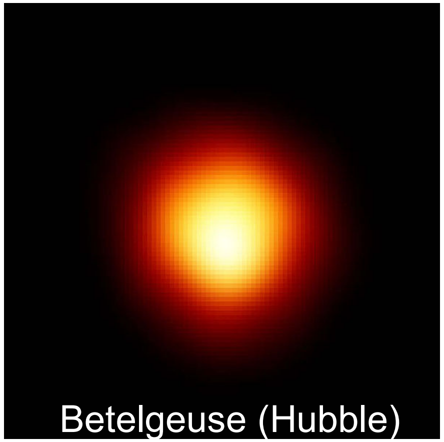


Massive star forming ^{60}Fe

Motivation

Supernova explosion

^{60}Fe



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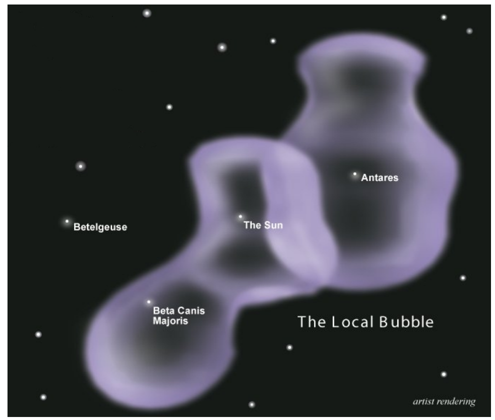
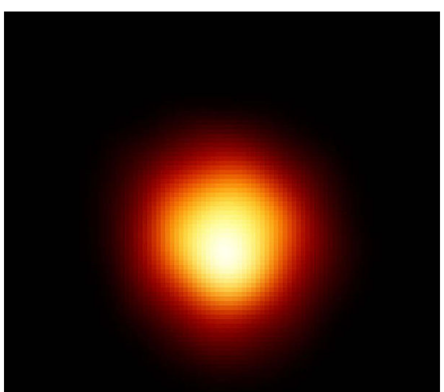
Interstellar medium near Earth:
Local Bubble



^{60}Fe



Betelgeuse (Hubble)

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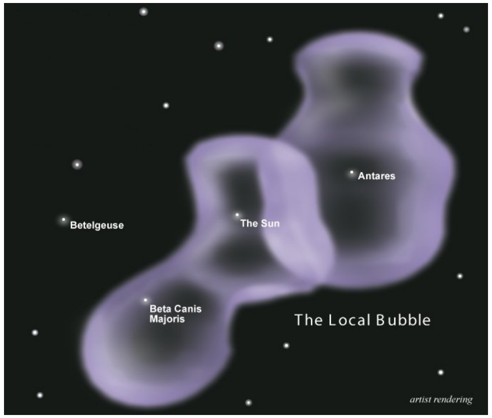

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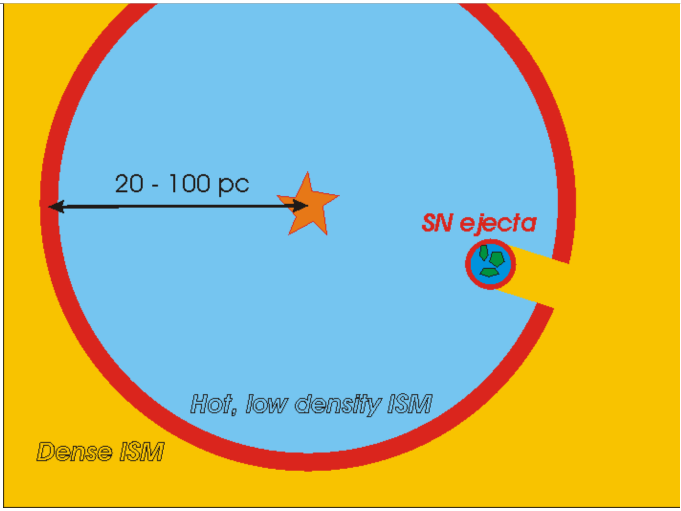
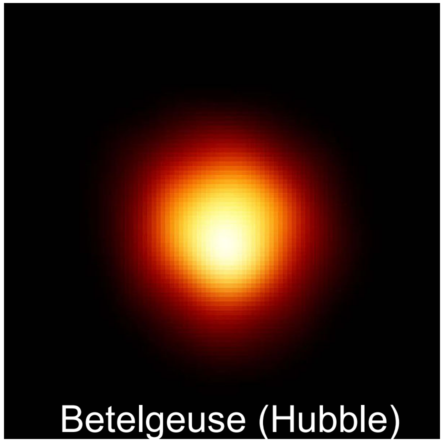


Solar system can „pick up“ supernova debris

^{60}Fe



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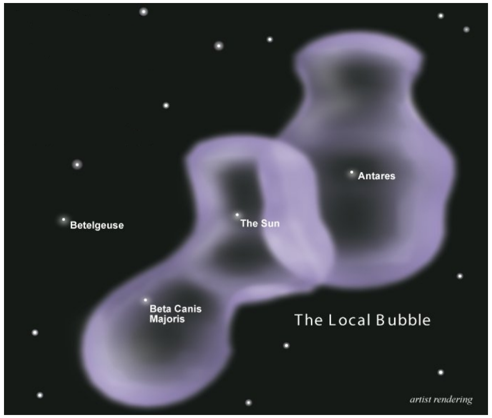

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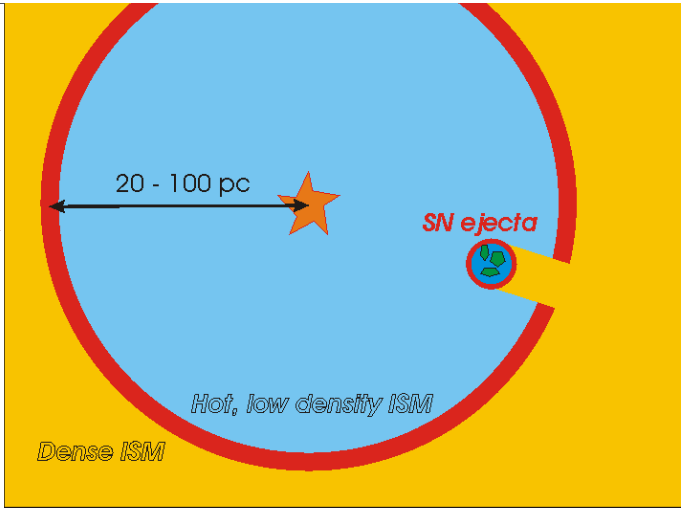


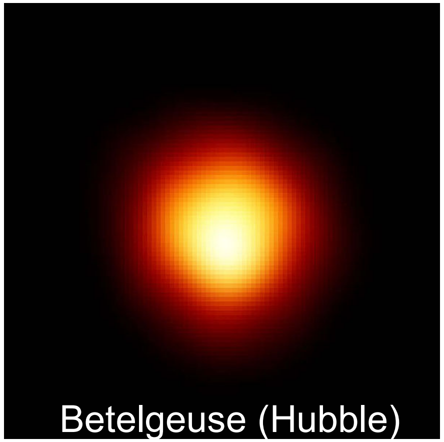
Solar system can „pick up" supernova debris

Ferromanganese Crust

Marine Sediment

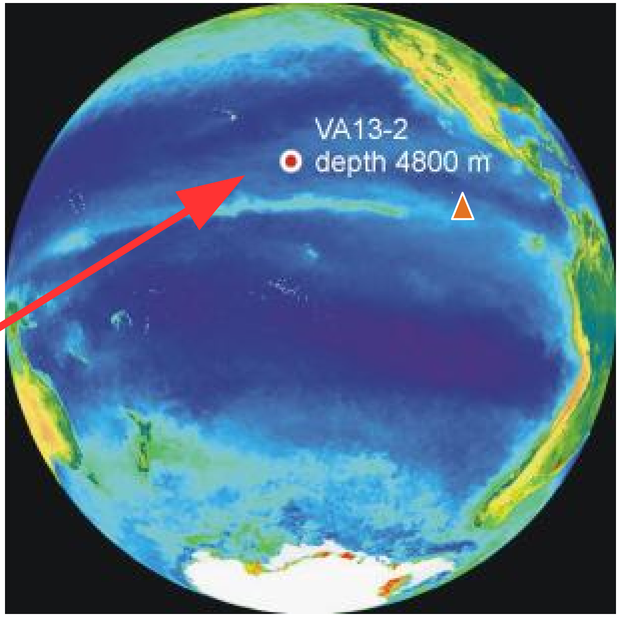
Lunar samples

^{60}Fe



Massive star forming ^{60}Fe

Earlier measurement: Ferromanganese Crust



Ferromanganese crust from equatorial pacific (9°18´N, 146°03´W), depth 4830 m

– Slow growing (few mm per Ma)
– Can be dated by 10Be measurements

Earlier measurement: Ferromanganese Crust

Ferromanganese crust from
equatorial pacific
(9°18´N, 146°03´W), depth 4830 m

Earlier measurement: Ferromanganese Crust

- Indication for a supernova signal already found using the GAMS setup
- Possible SN event 2-3 Ma ago at a distance ~40 pc
- Goal: Confirmation of this finding in slow growing sediment

Ferromanganese crust from equatorial pacific
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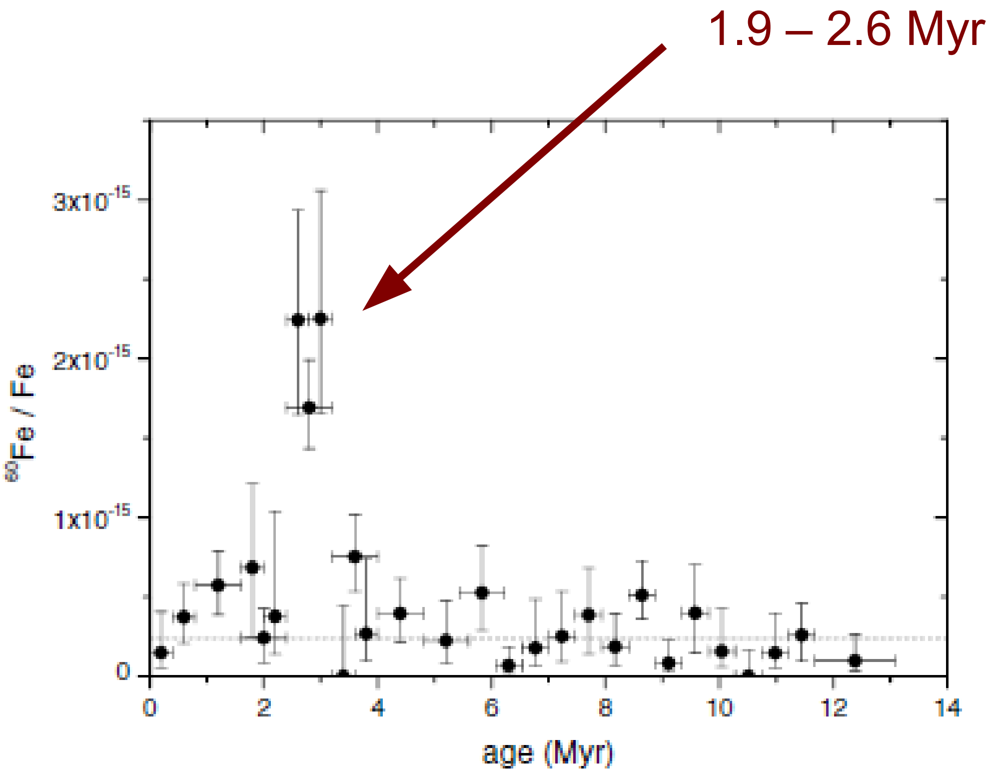

Knie et. al., PRL **93**, 171103 (2004)

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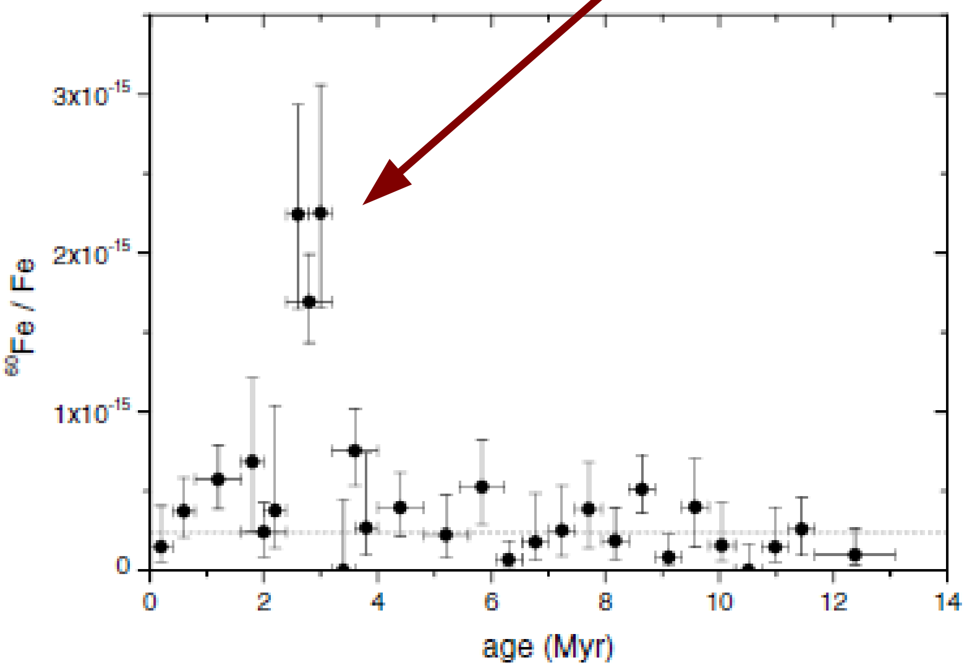
(9°18´N, 146°03´W), depth 4830 m

1.9 – 2.6 Myr

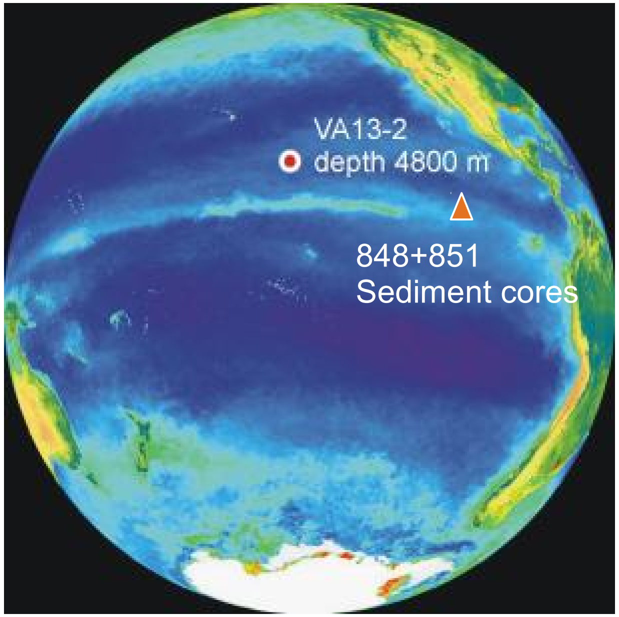


Knie et. al., PRL **93**, 171103 (2004)

Search in Pacific Ocean sediment

Search for ^{60}Fe in ocean sediment:

- Samples from two drill cores from ODP (Ocean Drilling Program) were obtained, 8 kg of material total – leg 138 – Cores 848 + 851
- Goal: measure depth profile of $^{60}Fe/Fe$ with resolution ~30.000 years in the age range 1.8 – 3.8 Myr
- Dating available from magnetic field reversal (among others), however, independent dating currently underway using 10Be and 26Al at DREAMS in Dresden



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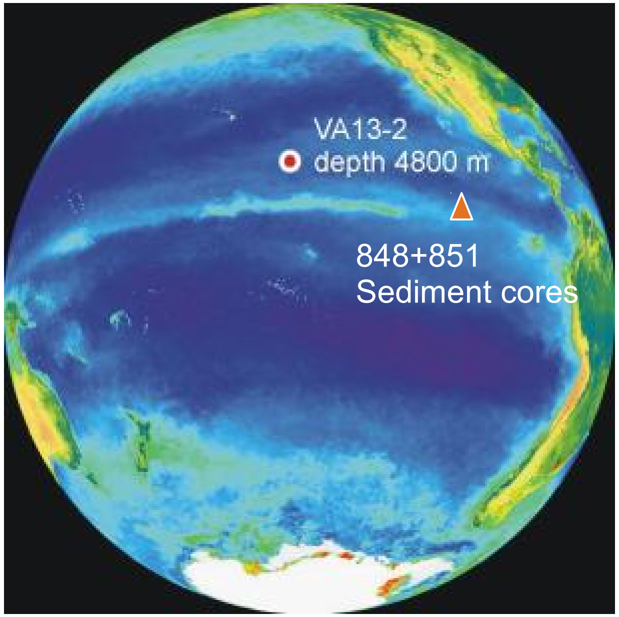
- Dating available from magnetic field reversal (among others), however, independent dating currently underway using 10Be and 26Al at DREAMS in Dresden
- Problems:
  - Which Fe-bearing minerals could contain the ^{60}Fe signal?
  - How to prevent dilution of signal?

Primary
Transported in by wind/water
Large grains (µm)
^{60}Fe only on surface

^{60}Fe

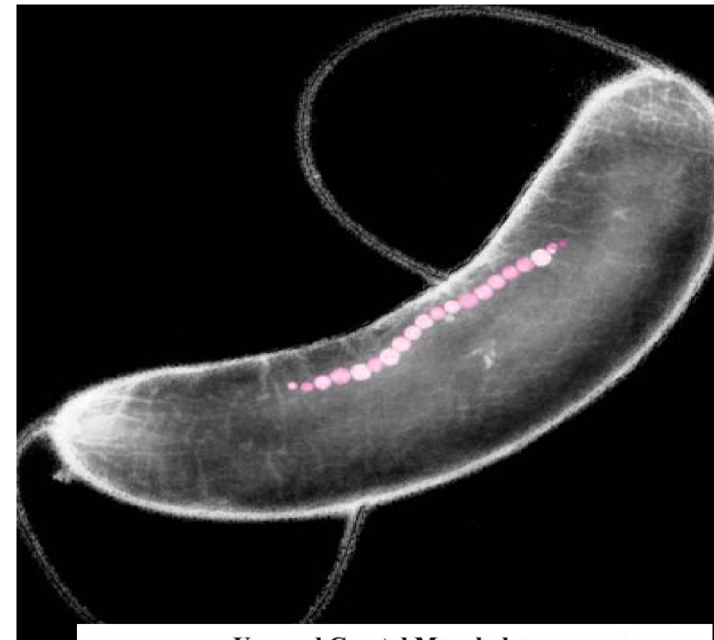
Secondary
Formed in situ
Small grains (20-200 nm)
e.g. magnetite crystals
(Fe_3O_4)

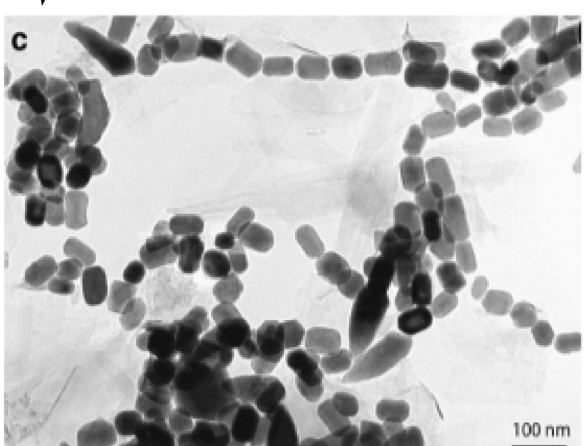


Magnetotactic bacteria

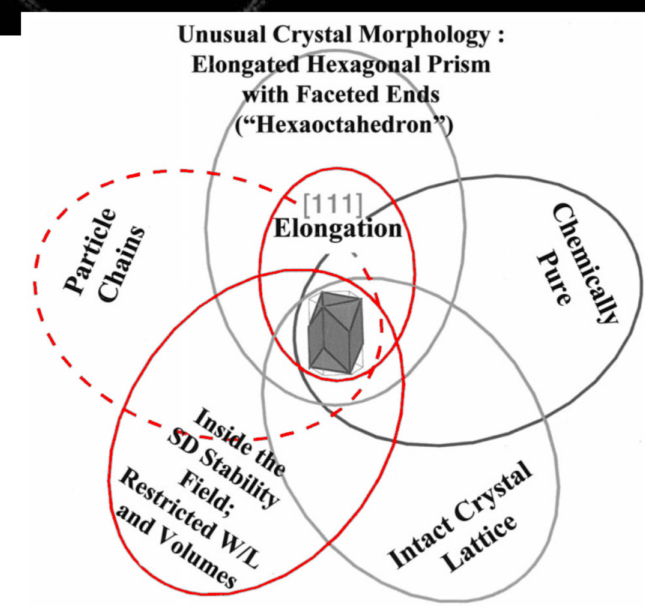
Intracellular formation of biogenic magnetite crystals:

- Magnetotactic bacteria live in sediment just below the surface-water interface
- Bacteria build up chains of magnetite grains (20-80 nm) for orientation in earth's magnetic field (magnetotaxis) → secondary !
- In ^{60}Fe-enriched ocean water, bacteria are forced to build magnetosomes with ^{60}Fe-rich iron
- Magnetic signature can be preserved over geologically significant timescales if the magnetosome chains survive sedimentation.
- Magnetic signature resembles non-interacting single domain (SD) particles → characterization using magnetic measurements is possible because of their unique properties





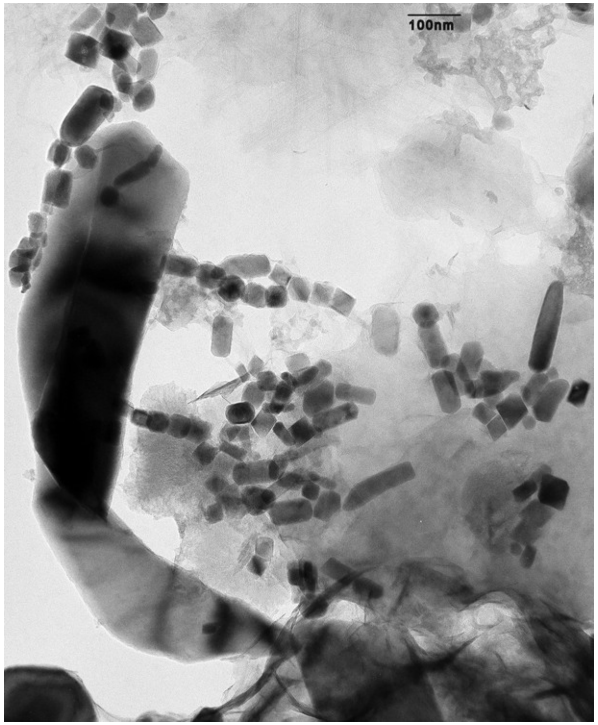
Sediment sample – 150 Myr after sedimentation → chain structure still visible

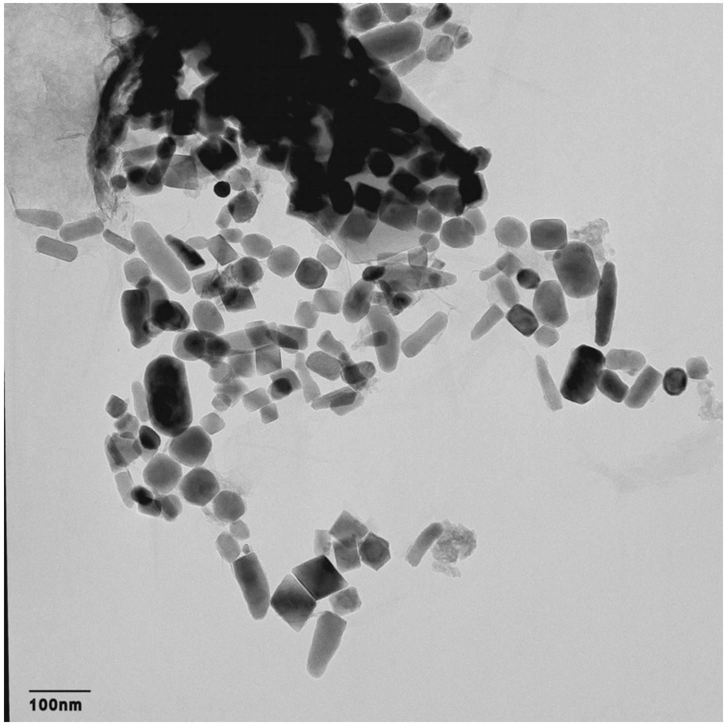


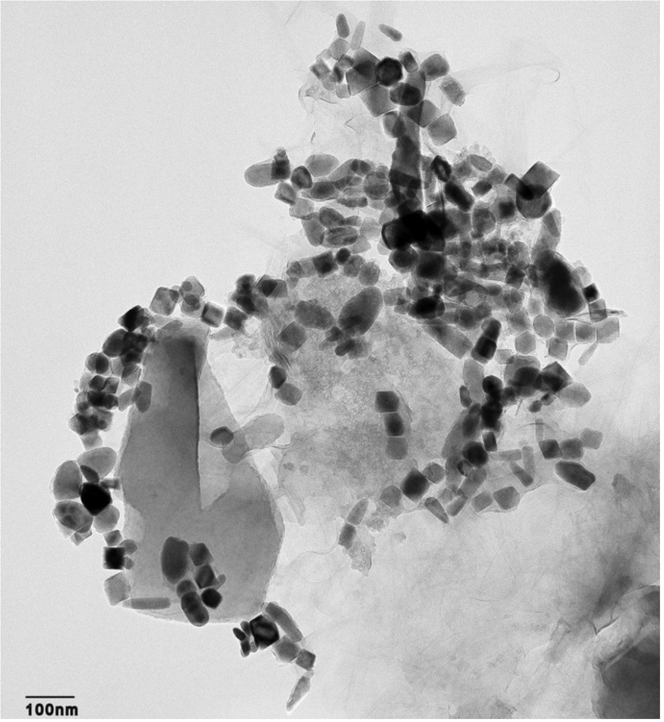
TEM on Sediment

Transmission electron microscopy (TEM):

- After rmagnetic extraction on one of our sediment samples
- High abundance of small magnetite grains as chain fragments and clusters





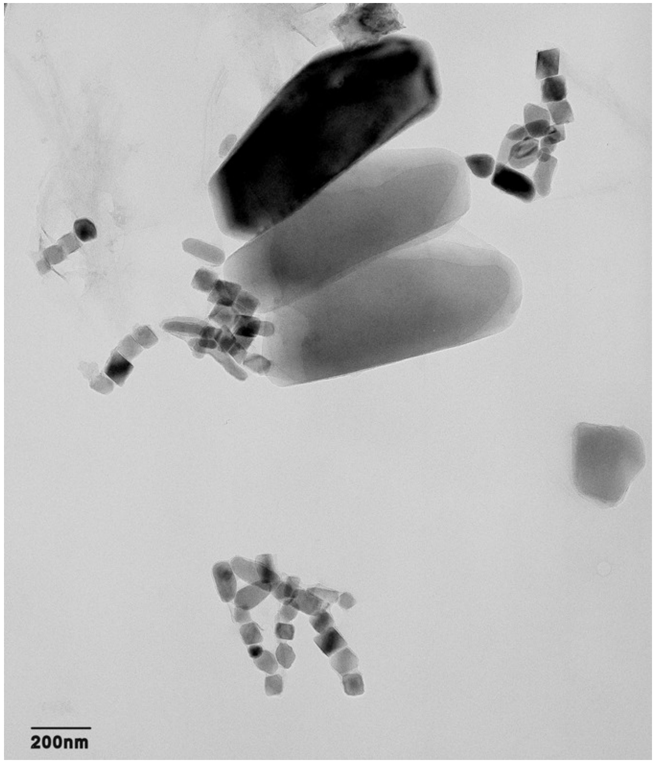


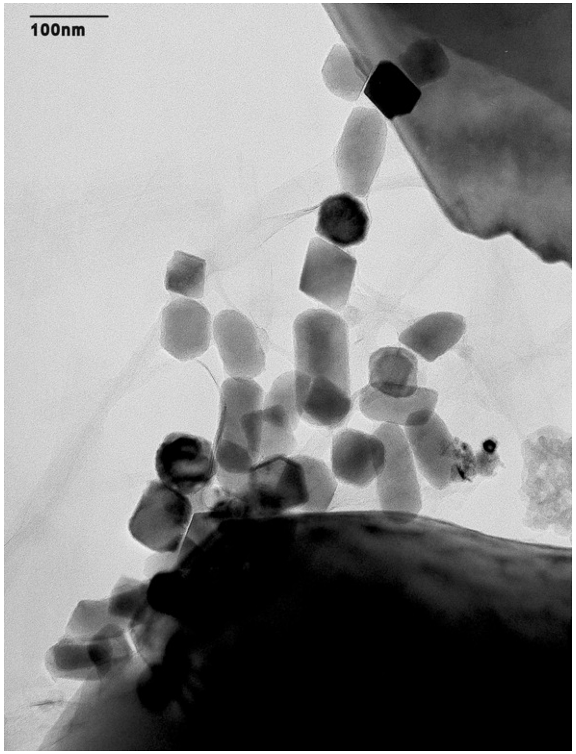
Interpretation:

- Is this magnetite? → zoom in → diffraction analysis OR perform EDX, both say: YES

- It it biogenic? Both shape and size say YES

- How much is it? → roughly 10% (mass) of the magnetic extract
  → fits very well with estimate from preliminary ARM/IRM magnetic measurements

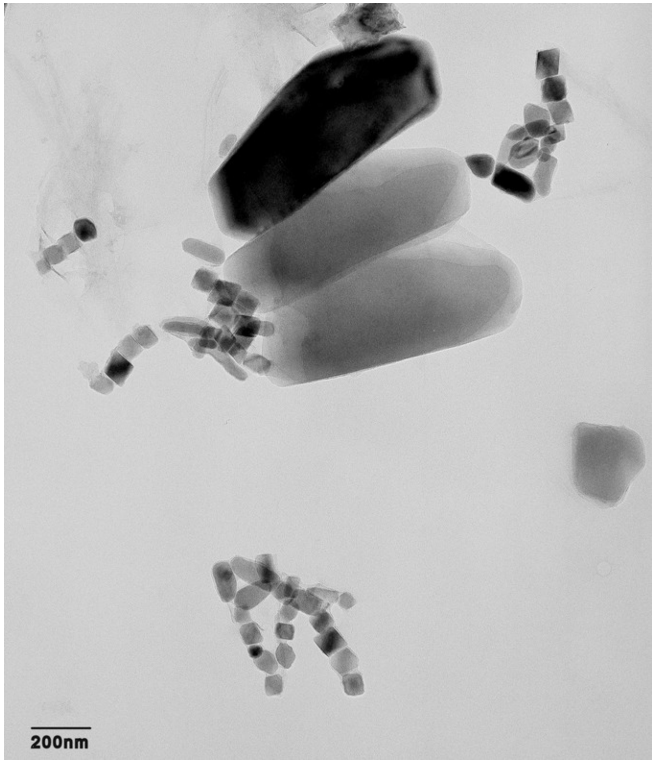


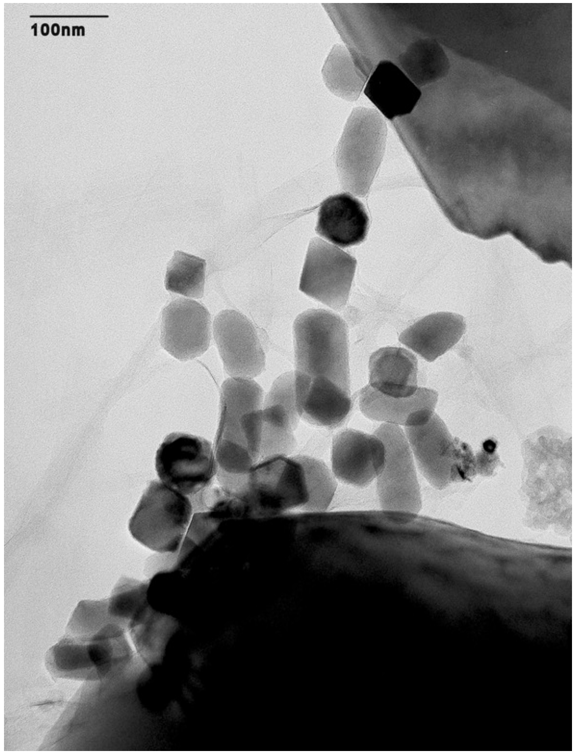


TEM on Sediment

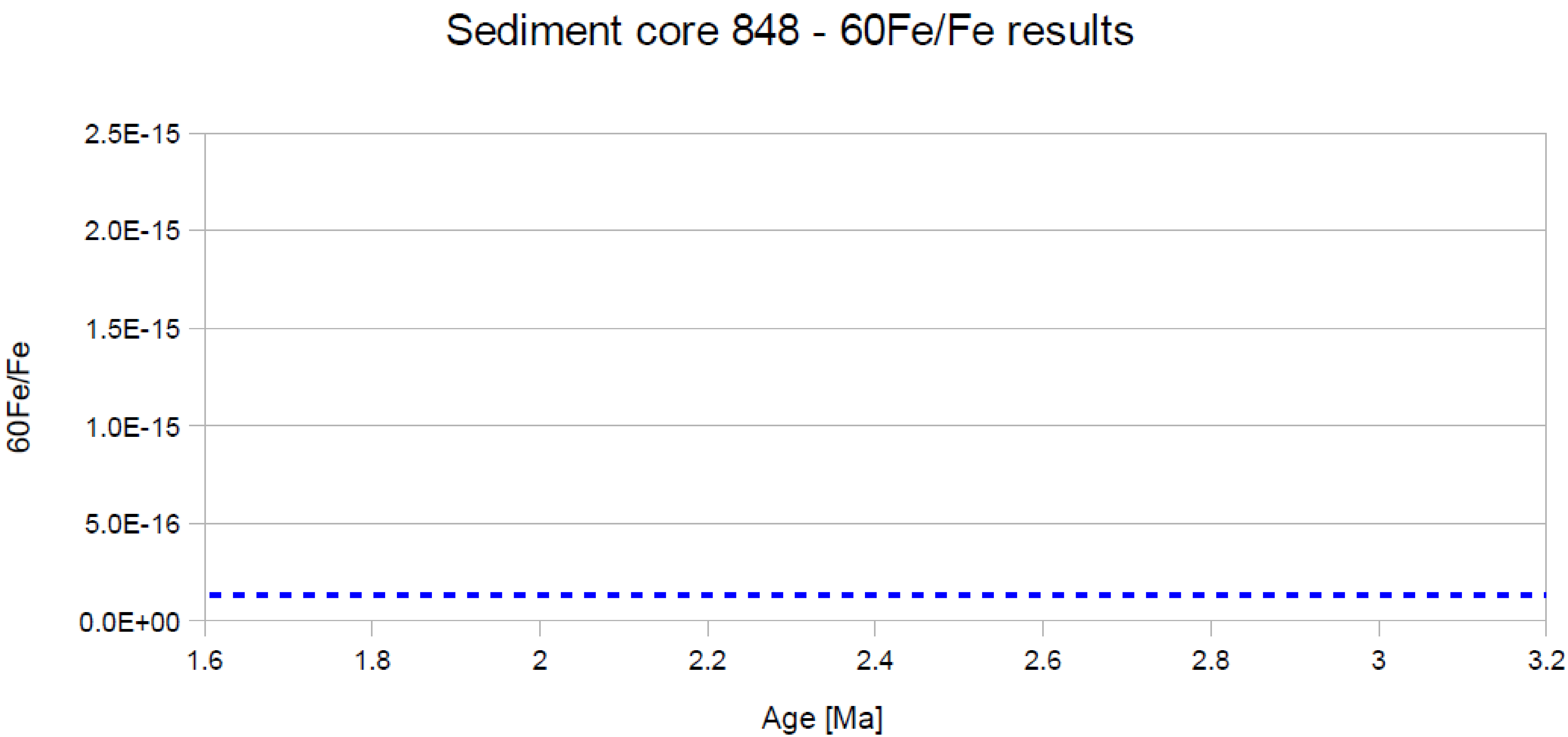
How to get small grained magnetite out to make AMS samples?

→ Citrate Bicarbonate Dithionite technique (CBD)
- very mild leaching (dissolves only < 200 nm)
- 30 g of sediment yield about 5 mg of Fe_2O_3 AMS sample
- about 1 week of chemistry needed (not shown here, just to mention...)





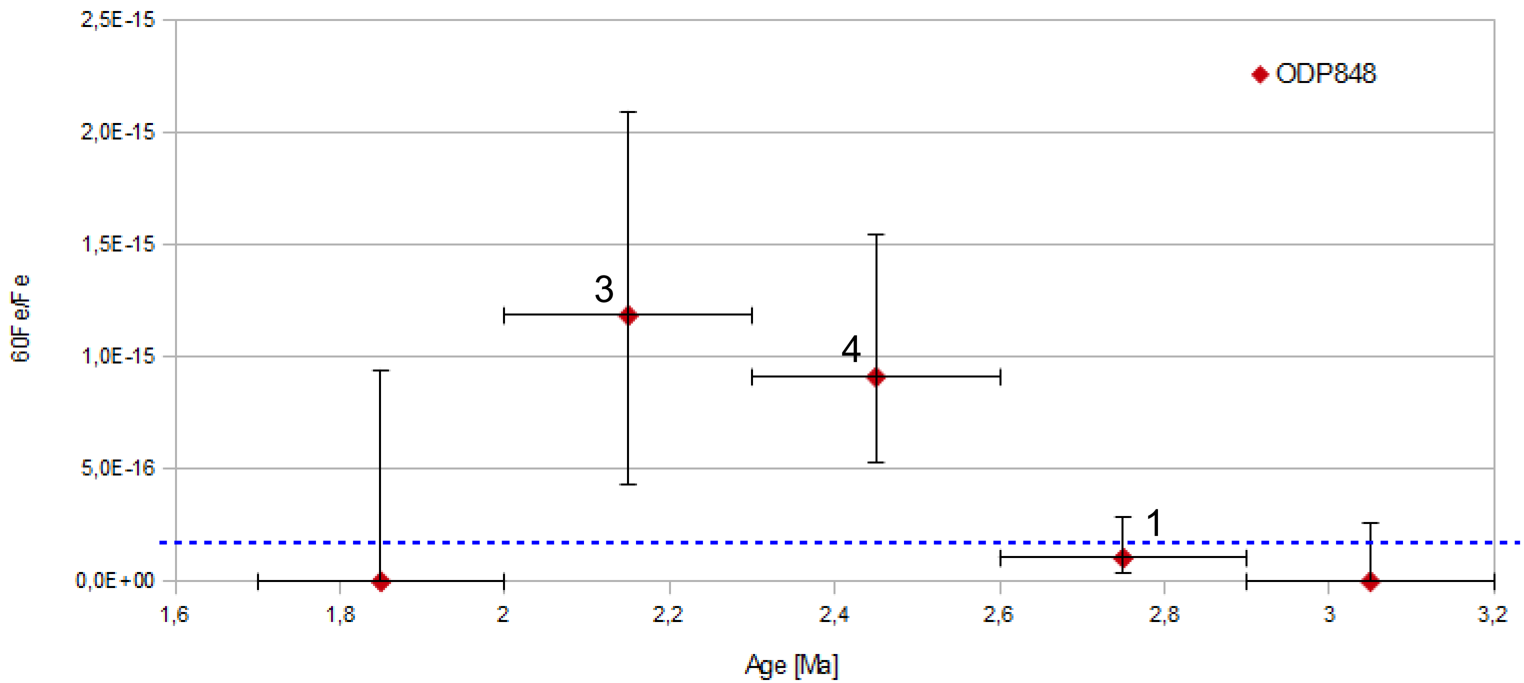
AMS results core 848



- - - - Blank level (1-σ): $^{60}Fe/Fe = 1.7e-16$
From chemistry blank (0 counts)

AMS results core 848

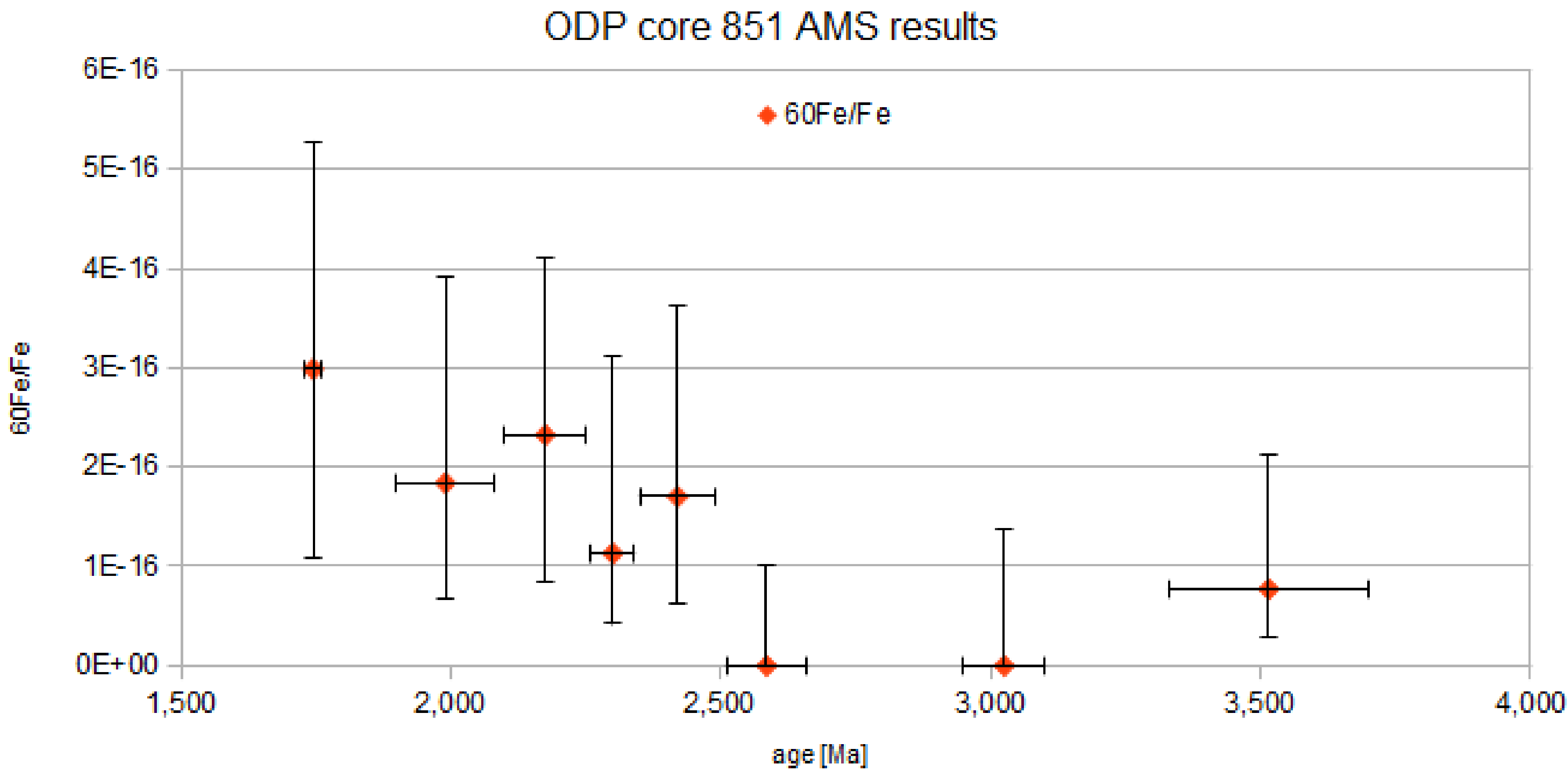
Sediment core 848 – 3 samples grouped each – 8 counts total



-------- Blank level (1-σ): $^{60}Fe/Fe$ = 1.7e-16
From chemistry blank (0 counts)

Core 851 preliminary results

- Data analysis still ongoing, better statistics will be available soon
- The signal is not yet significant enough → more beamtimes necessary
- 12 counts total detected so far



Preliminary results from sediment cores

CORE 848

- Core sediment used up except for aliquots
- 90% of AMS samples already measured
- 8 counts of 60Fe detected in the range 1.9 – 2.7 Ma
- Average concentration over 1.9 – 2.6 Ma:
  $^{60}Fe/Fe \sim 1\times10^{-15}$
- Rough estimation of total number of incident 60Fe atoms can be made
  → local interstellar fluence
  $\Phi_{LIF} \sim$ few 10^{7} $^{60}Fe\ cm^{-2}$

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Preliminary results from sediment cores

Lehrstuhl E12

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CORE 851

- Only ~30% of core measured yet
- 13 counts of ^{60}Fe detected, among those 12 in the range 1.7-2.5 Ma
- Average concentration in that range only 2-3 x 10^{-16}
- This is very low → better blank level needed and of course, more counts ^{60}Fe
- Idea: try magnetic extraction instead of chemical to reduce dilution → currently being set up

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Preliminary results from sediment cores

Lehrstuhl E12

CORE 848

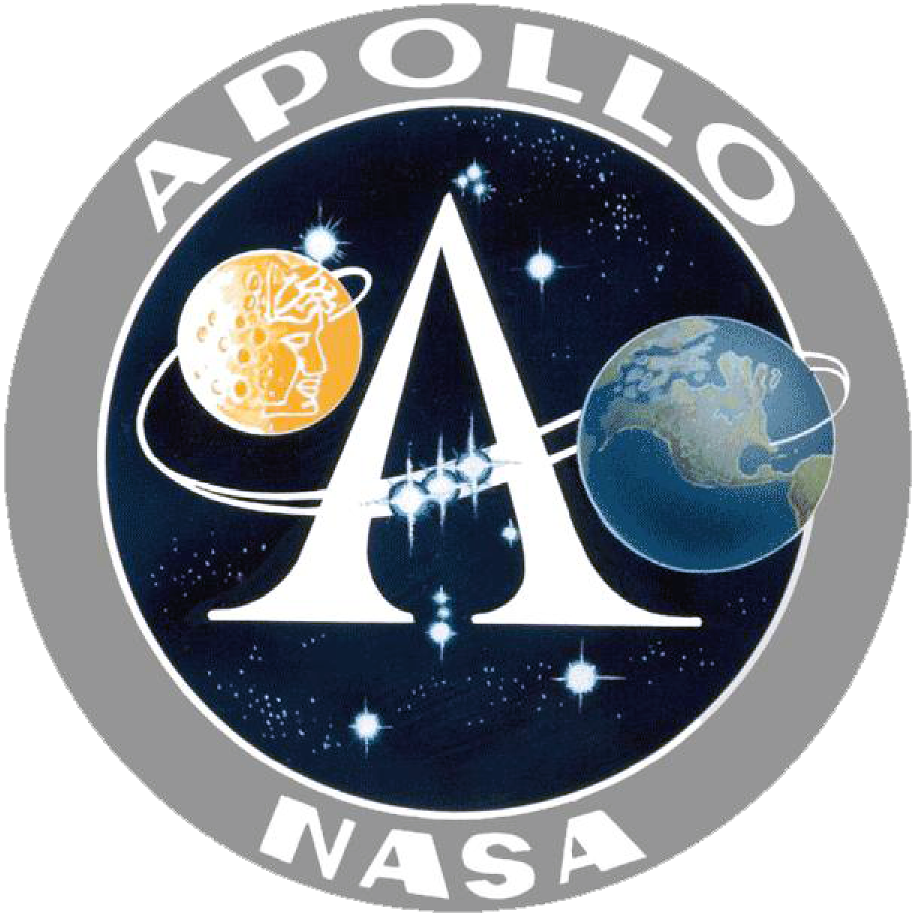
- Core sediment used up except for aliquots
- 90% of AMS samples already measured
- 7 counts of 60Fe detected in the range 1.9 – 2.7 Ma
- Average concentration over 1.9 – 2.6 Ma:
  $^{60}Fe/Fe \sim 1 \times 10^{-15}$
- Rough estimation of total number of incident 60Fe atoms can be made
  → local interstellar fluence
  $\Phi_{LIF} \sim$ few 10^{7} ^{60}Fe cm^{-2}

CORE 851

- Only ~30% of core measured yet
- 13 counts of ^{60}Fe detected, among those 12 in the range 1.7-2.5 Ma
- Average concentration in that range only 2-3 x 10^{-16}
- This is very low → better blank level needed and of course, more counts ^{60}Fe
- Idea: try magnetic extraction instead of chemical to reduce dilution → currently being set up

Most important result so far: **60Fe input** seems to have been **rather long (> 500 kyr)**. This Was previously unknown from crust measurements becaue of low time resolution

^{60}Fe (and ^{53}Mn) in lunar samples



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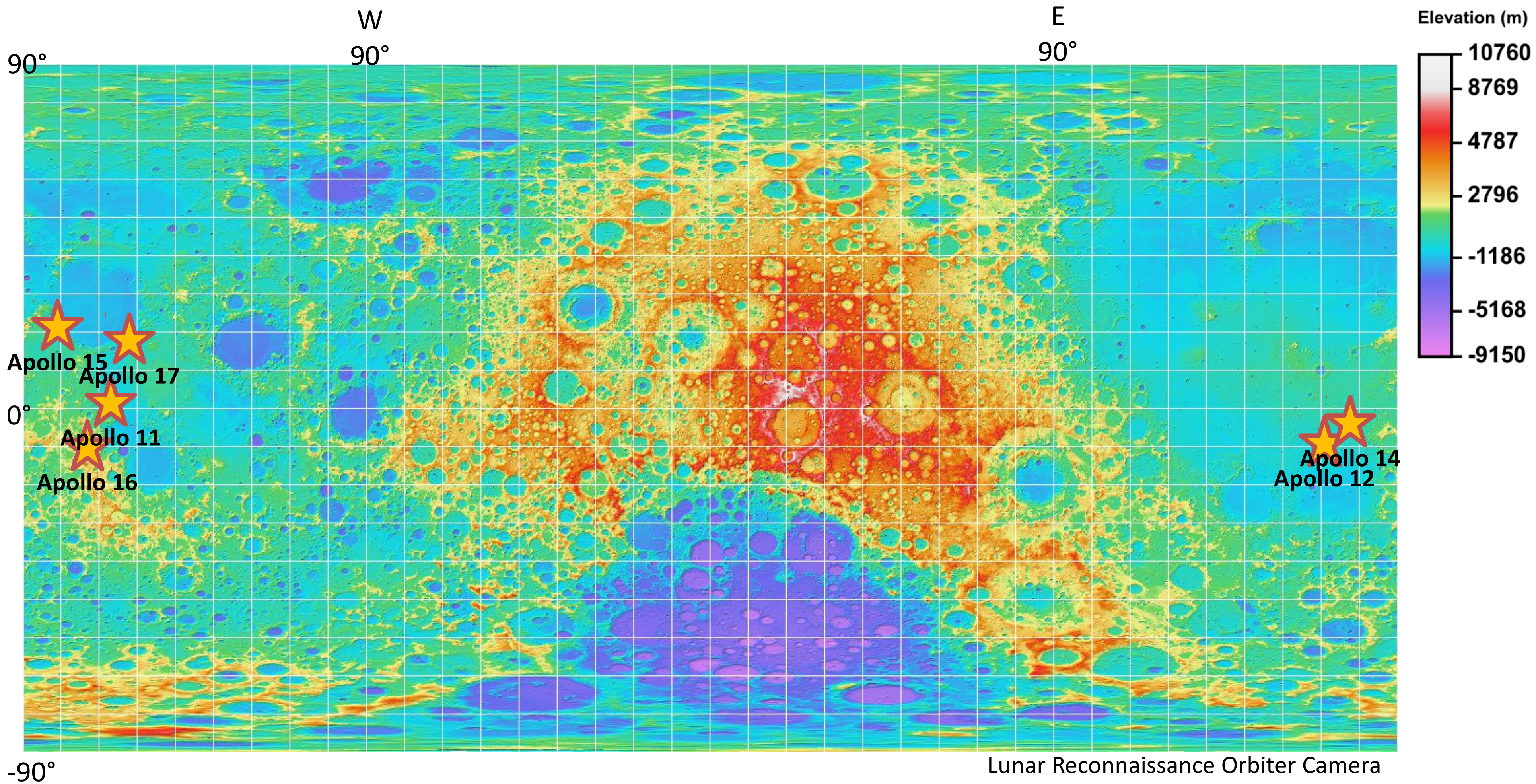
Lehrstuhl E12

Apollo Landing Sites

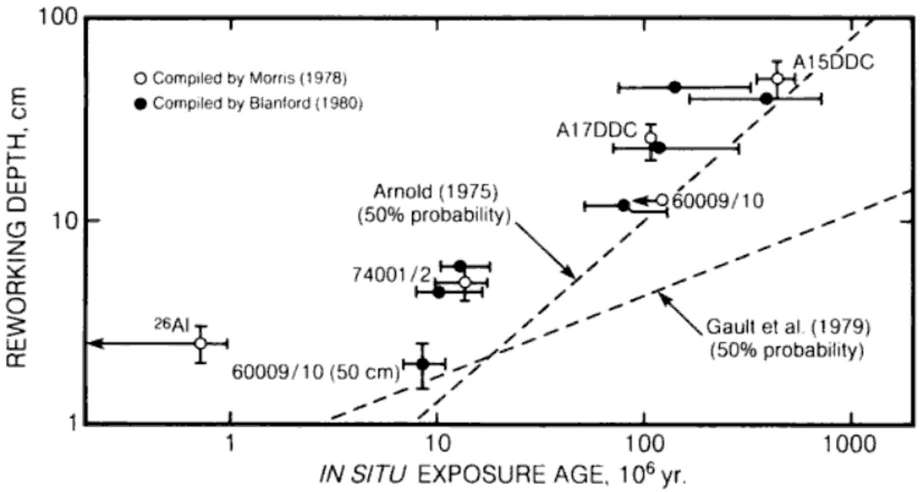
- 60Fe and 53Mn Samples from Apollo 12,15, and 16 obtained



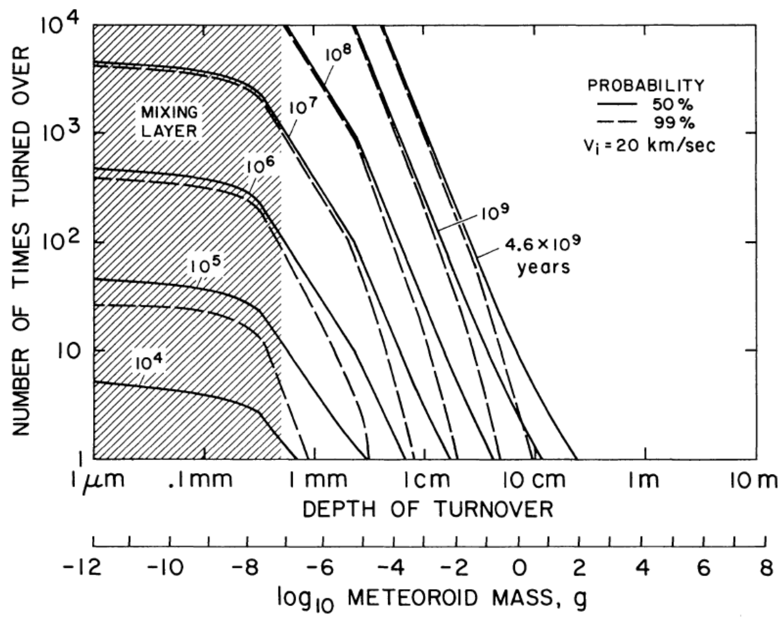
Lunar Reconnaissance Orbiter Camera
Arizona State University, November 2011

On the moon...

- ✓ Net sedimentation rates are small: U60Fe~100%
- ✓ Ni concentrations are in general low: low in-situ production of 60Fe
- ✗ Gardening of the lunar surface: ~2-3 cm reworking depth in 10Myr
- ✗ Hard to reach

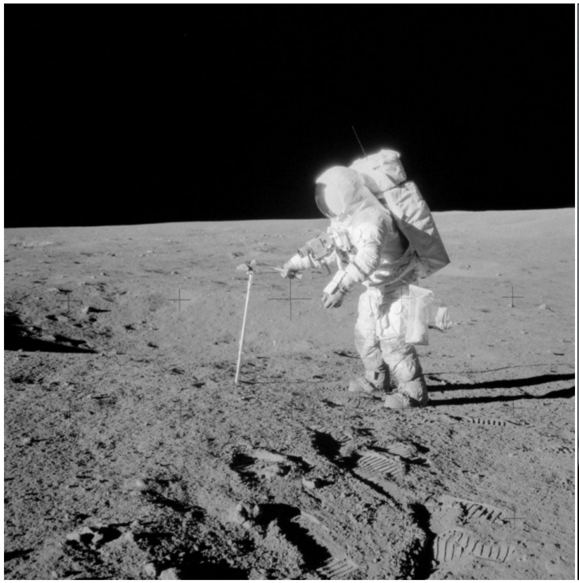


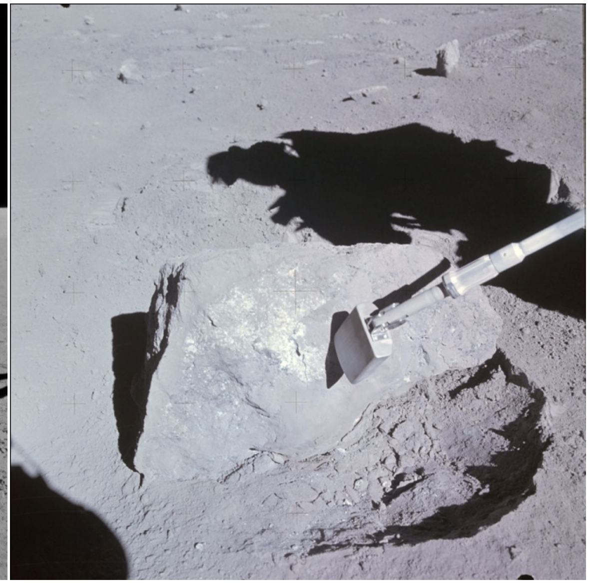
McKay et al. Lunar Sourcebook, Cambridge University Press, pp. 285-356



Gault et al., Proceedings of the 5th Lunar Conference (1974)

Sample history and production of 60Fe





Potential origins:

- ✓ Galactic Cosmic Rays
- ✓ Solar Cosmic Rays
- ✓ Deposition of SN debris.

P60Fe-GCR = (0.88±0.44) dpm/kg Ni

Knie et al, Planet.ary Science Letters **34**, 729 (1999)

P60Fe-SCR = 0.07– 0.45 dpm/kg Ni on the surface

Cook et al, LPSC XXXIX (2009)

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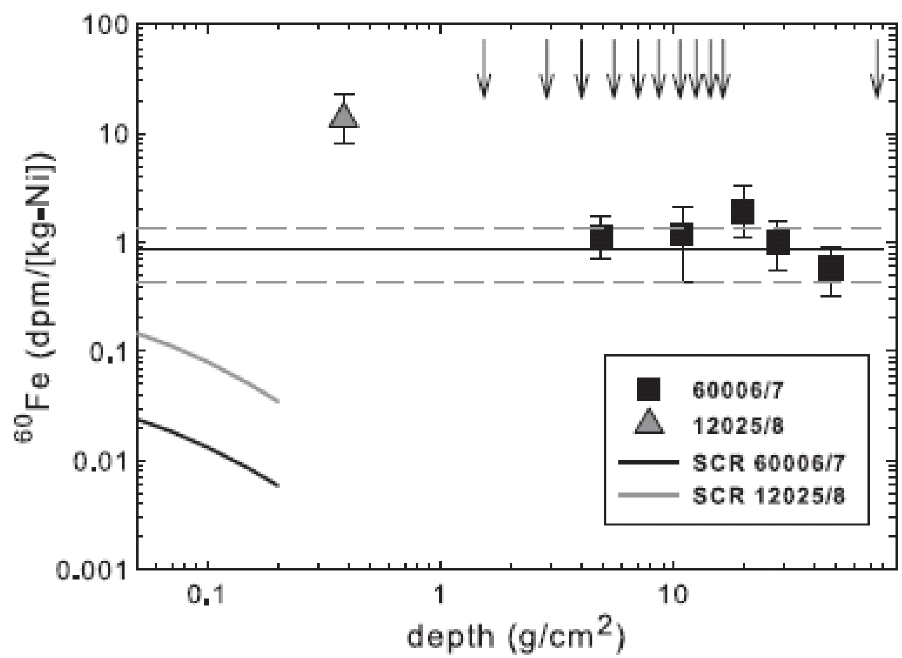
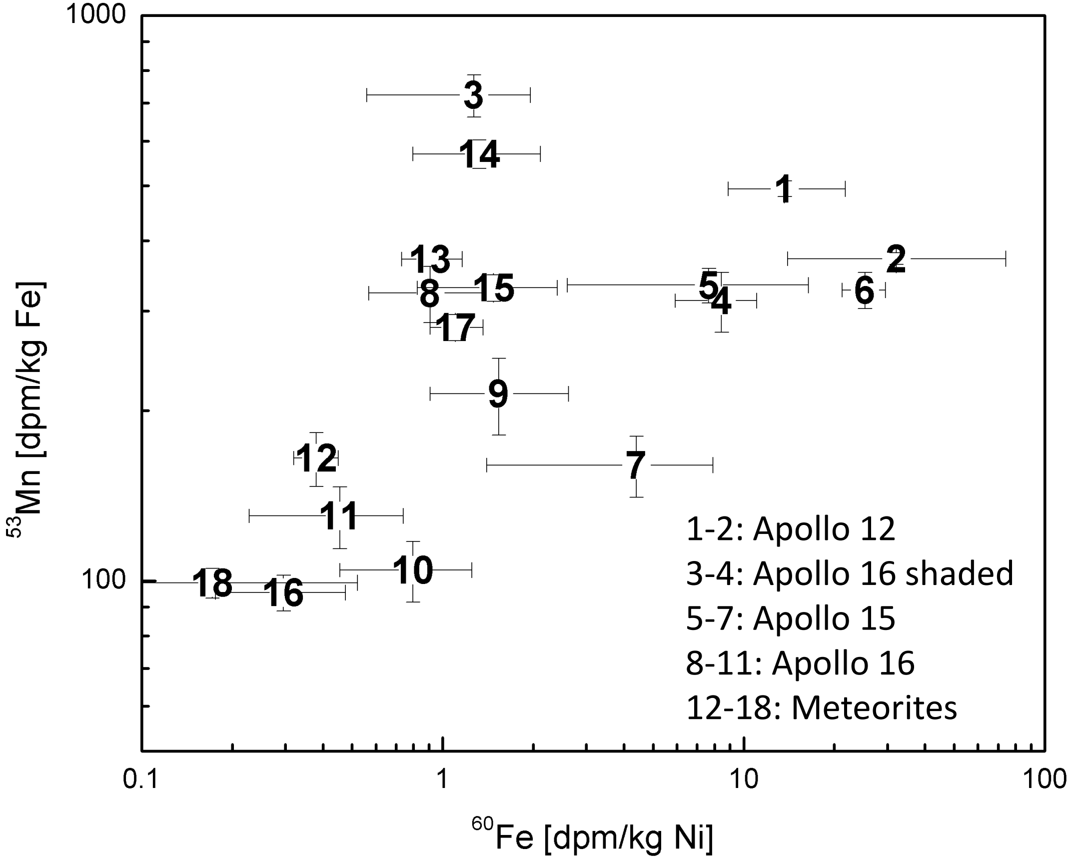


60Fe and 53Mn measurements

- Plot shows both radioisotopes, 53Mn and 60Fe divided by mass of their respective most likely source element under irradiation from cosmic rays

- Enhancement in both isotopes for some samples visible



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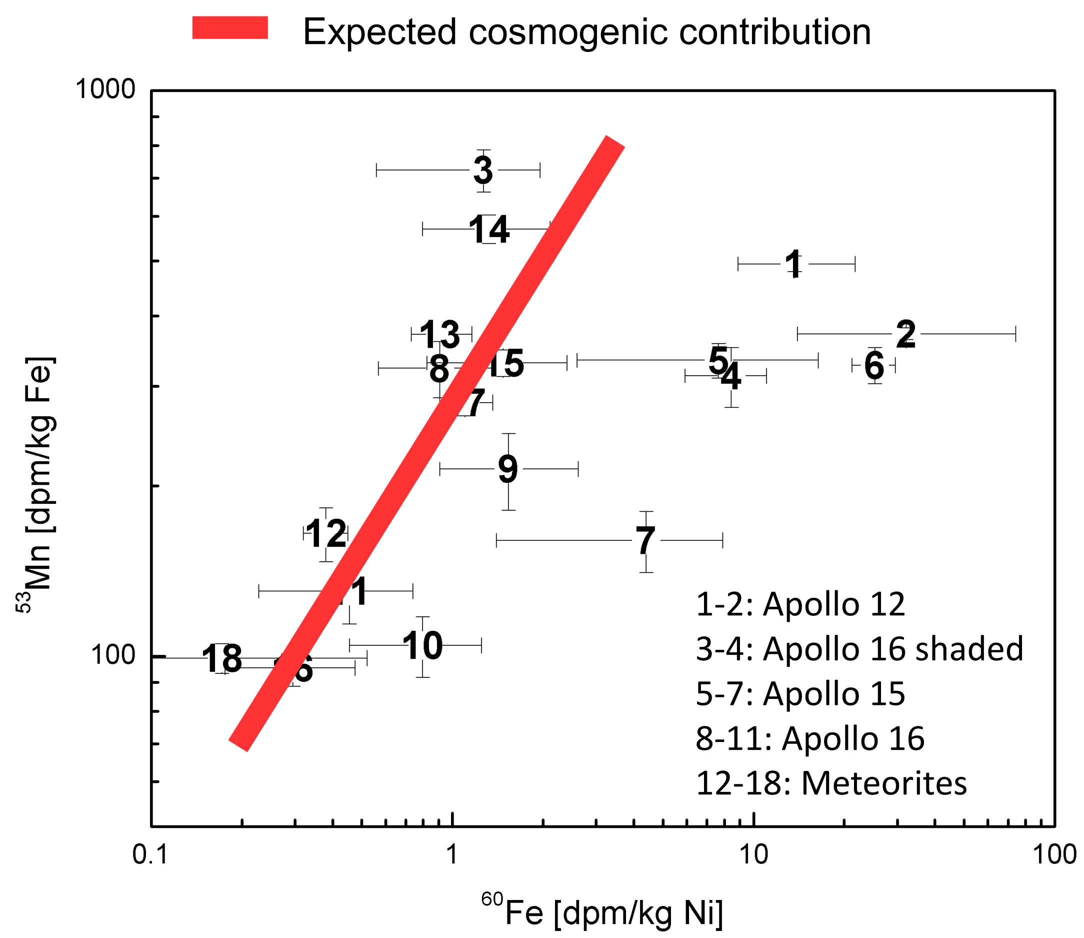

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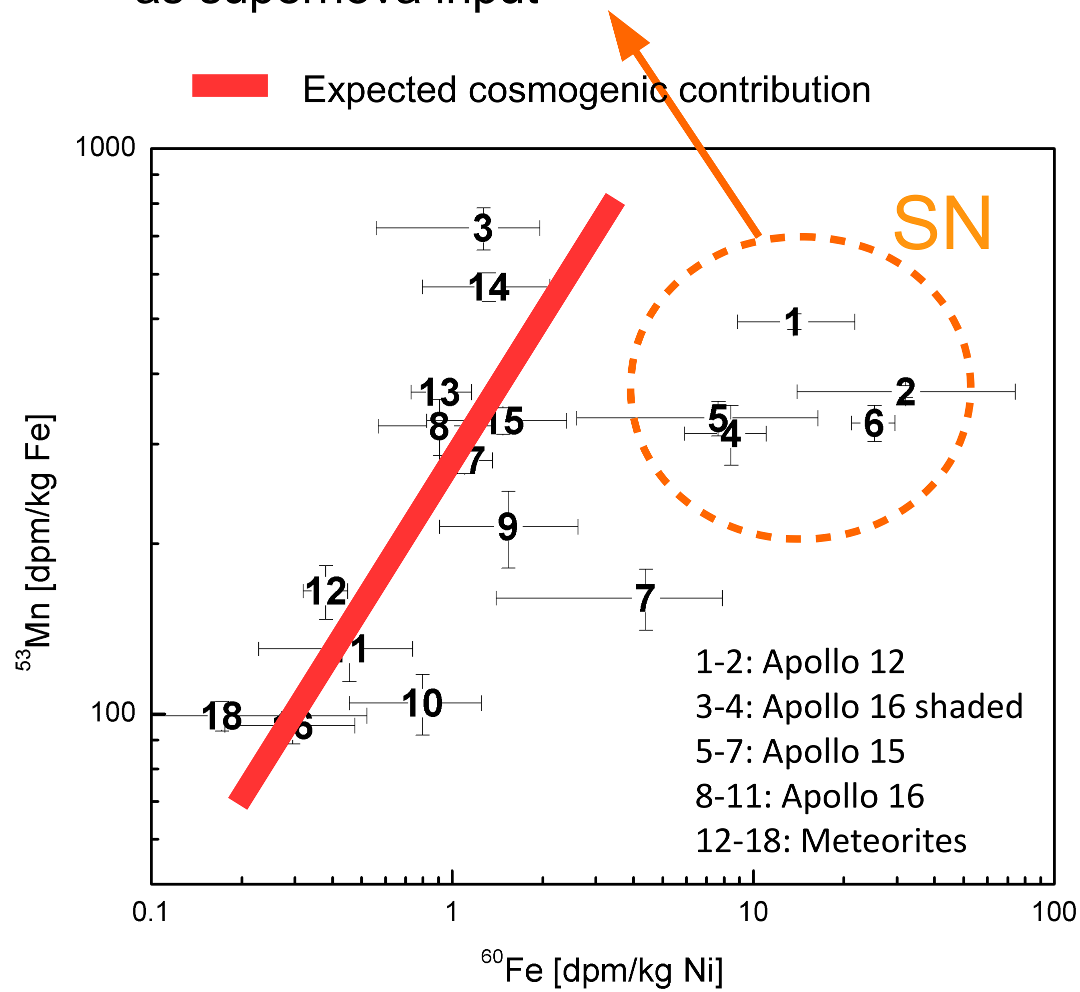
Excess in 60Fe in 5 samples interpreted as supernova input



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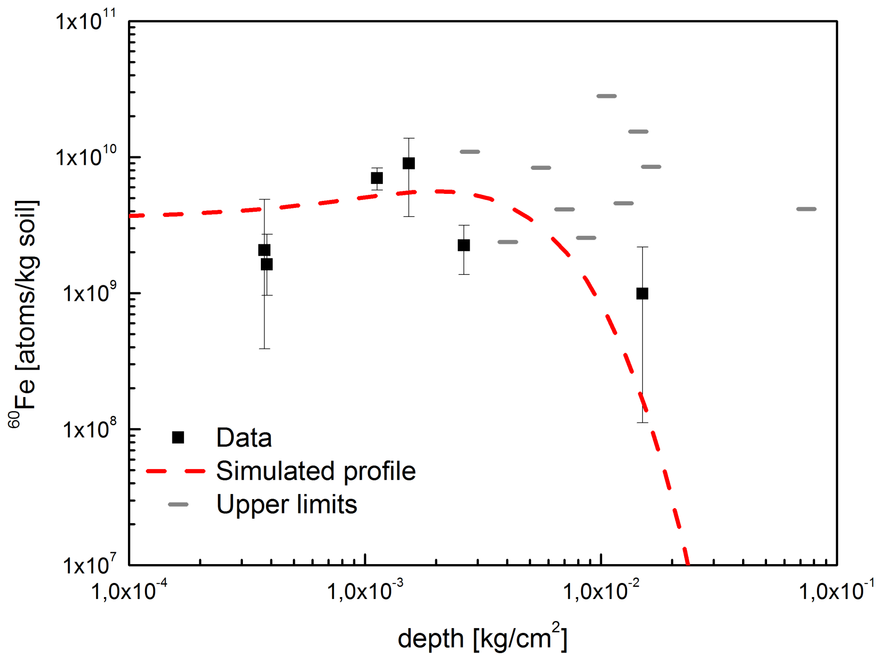

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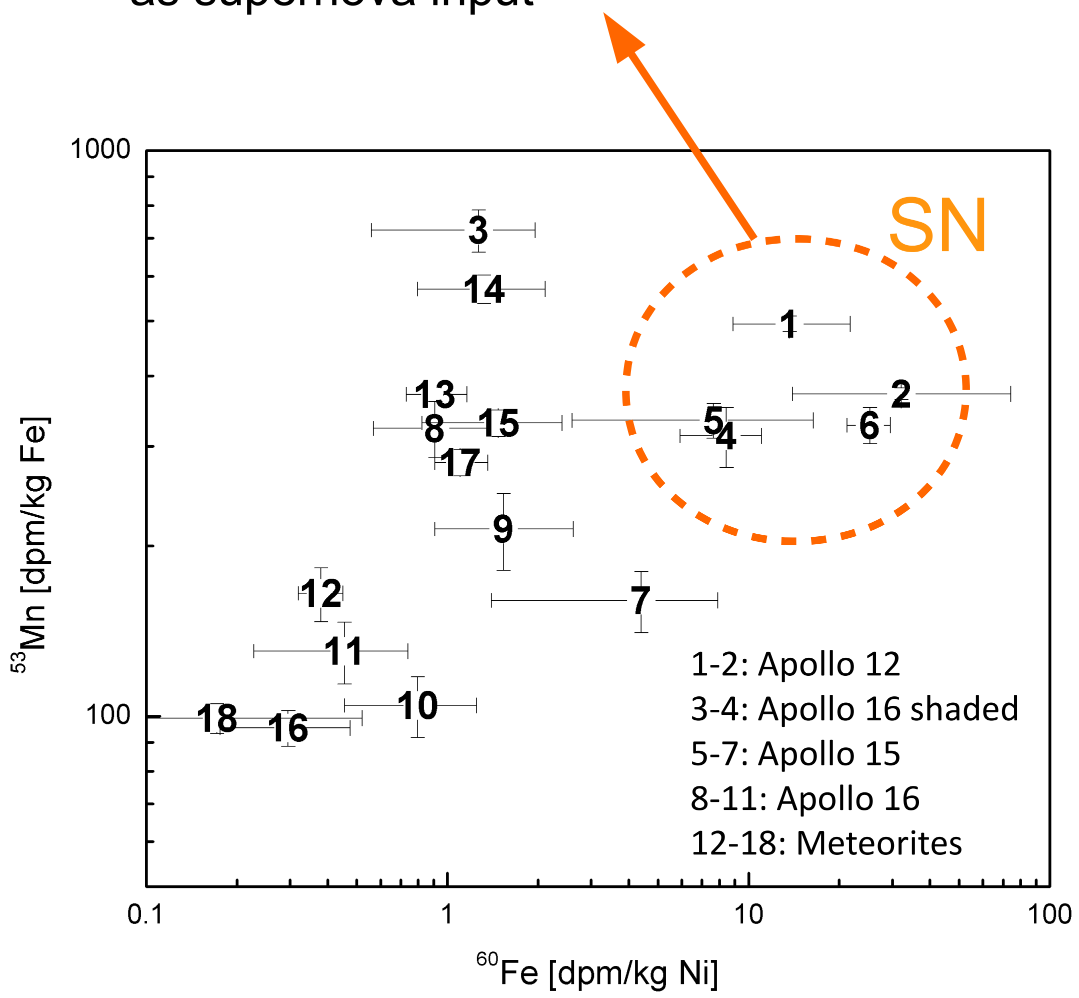

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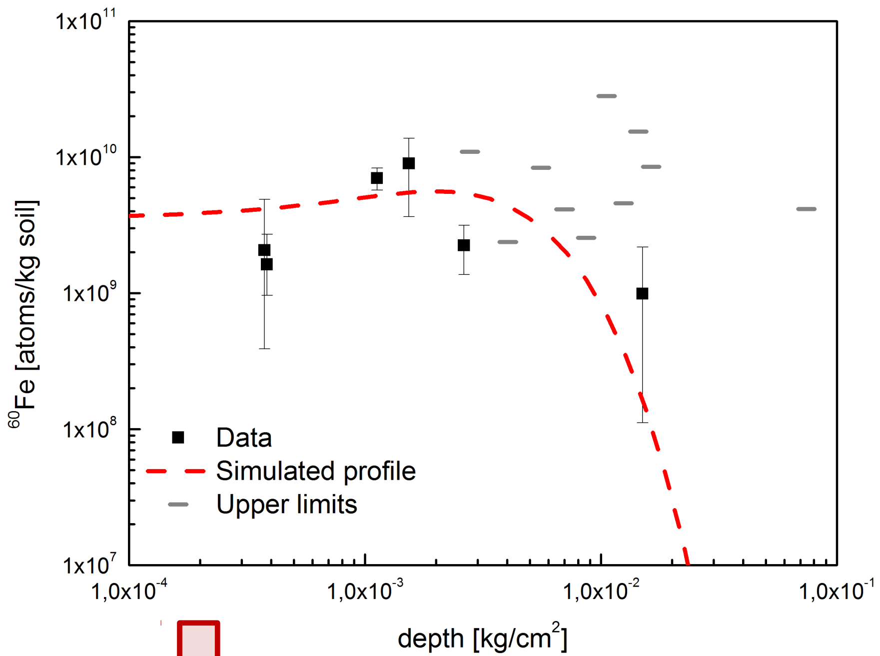

Ingetrate to obtain
Local interstellar fluence:

$$\Phi_{^{60}Fe,LIS} \approx 3.5 \times 10^7 \frac{at}{cm^2}$$

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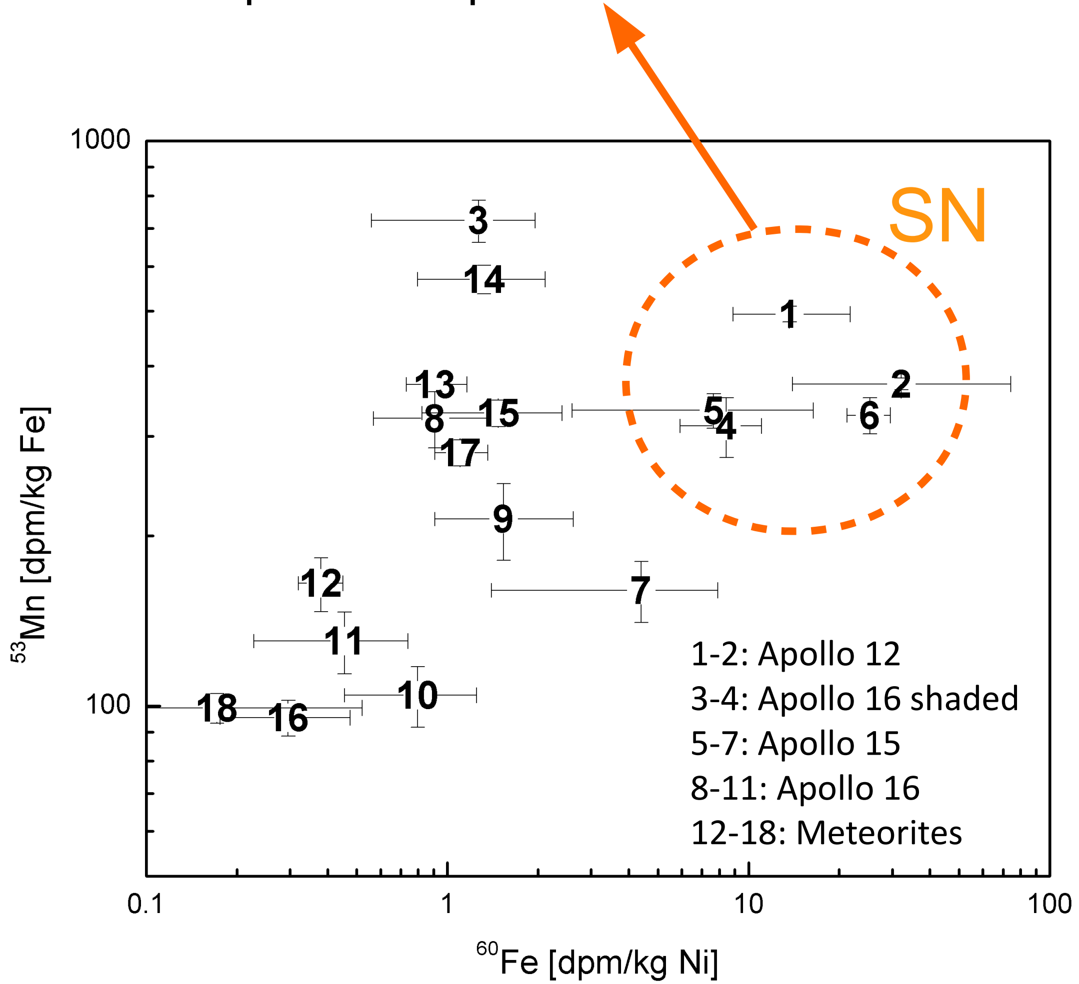


Summary

- AMS is an ultrasensitive technique for isotope ratio measurement
- Sensitivities reaching down to and below 1E-16
- Applications in nuclear astrophysics
- Setup at MLL in Garching with 2 AMS beamlines
- GAMS beamline for isobar suppression (intermediate A)
- New results: 60Fe signature found in sediment (~20 counts so far but: more statistics required –> further beamtimes
  → favors long input time (~500 kyr)
- Lunar samples scanned for 53Mn and 60Fe
- Enhancement of 60Fe found in 5 samples → SN input

→ ϕ_{LIS}~3.5 x 10^7 at/cm^2 (not decay-corrected)

Thank you for your attention

Citrate-Bicarbonate-Dithionite (CBD) Extraction

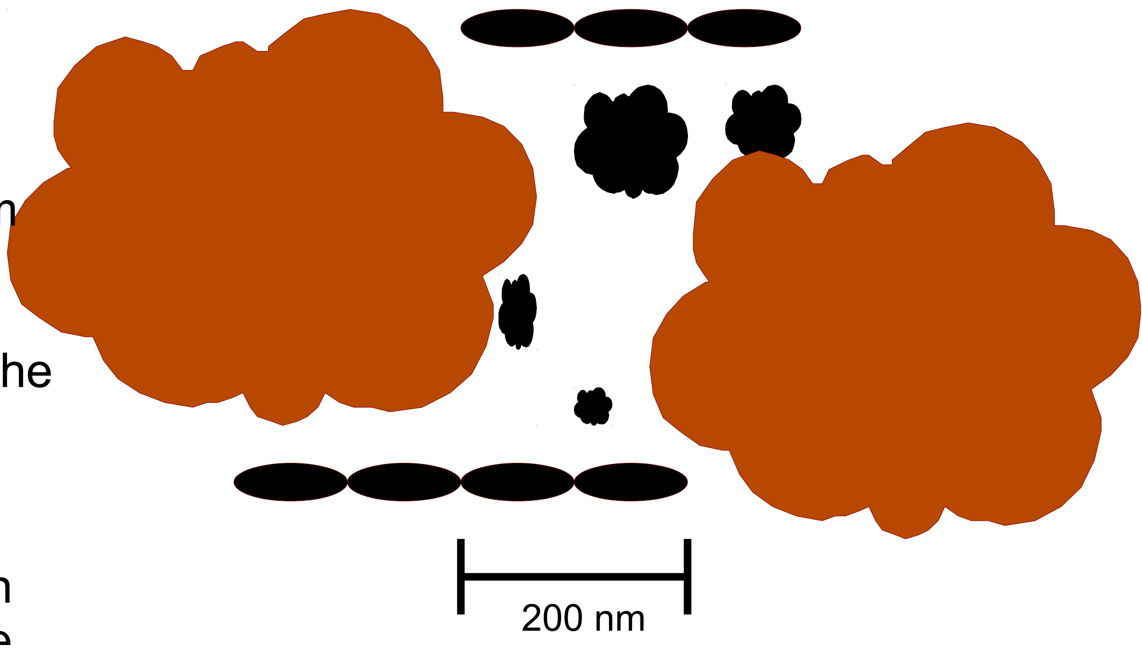
- Fe content of drill core material ~1-2%

- ^{60}Fe expected in small iron oxide (e.g. magnetite) grains: size << 1µm in the form of bacteria fossils and others

- Primary iron oxide (brown) would dilute the signal contained in secondary minerals (black)

- Chemical extraction of small grained iron oxides using Citrate-bicarbonate-dithionite (CBD) extraction method: Dissolves mainly small grained material

    → Dithionite: Strong reducing agent (Fe III+ → Fe II+)
    → Citrate: extracts and chelates Fe II+
    → Sodium-Bicarbonate: pH buffer



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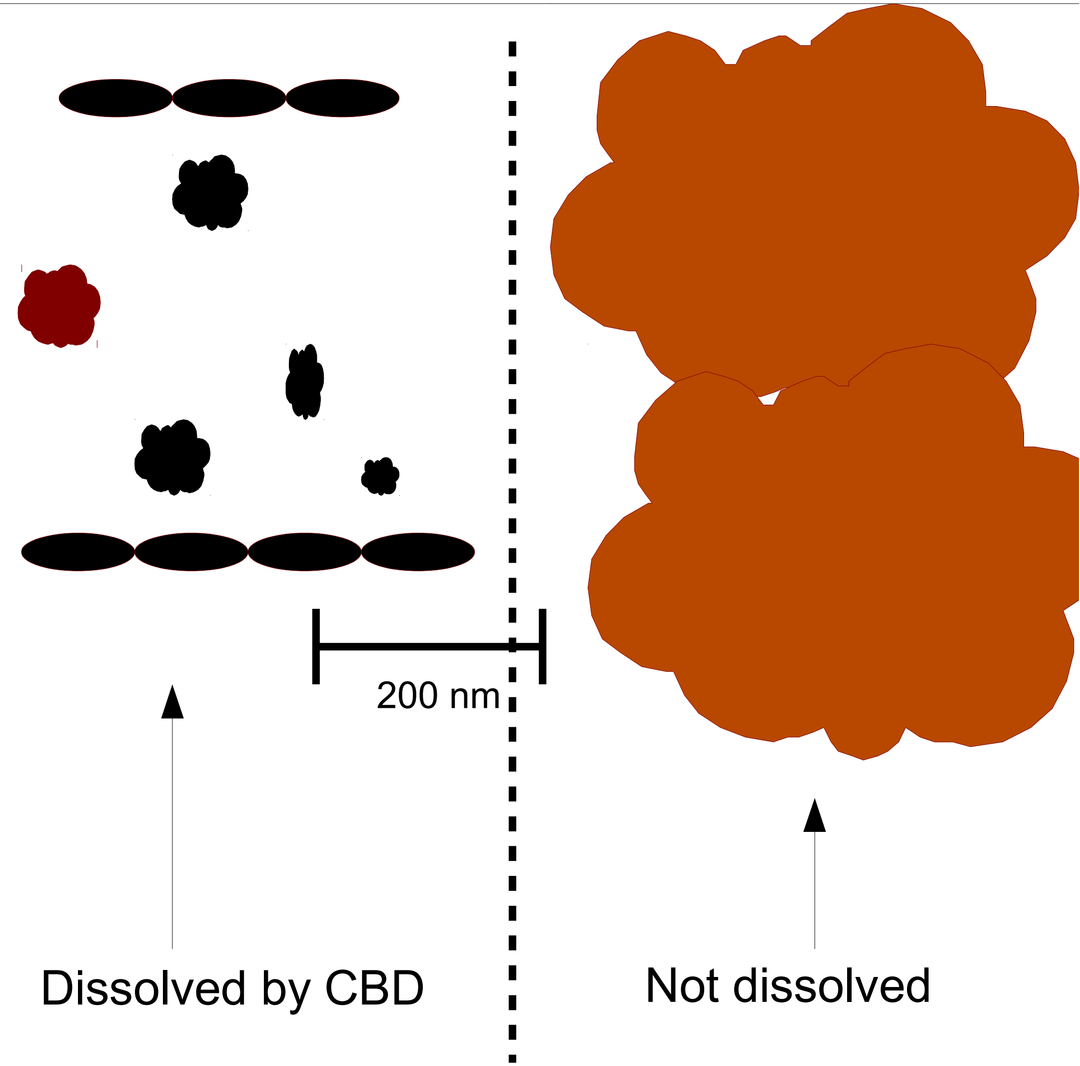

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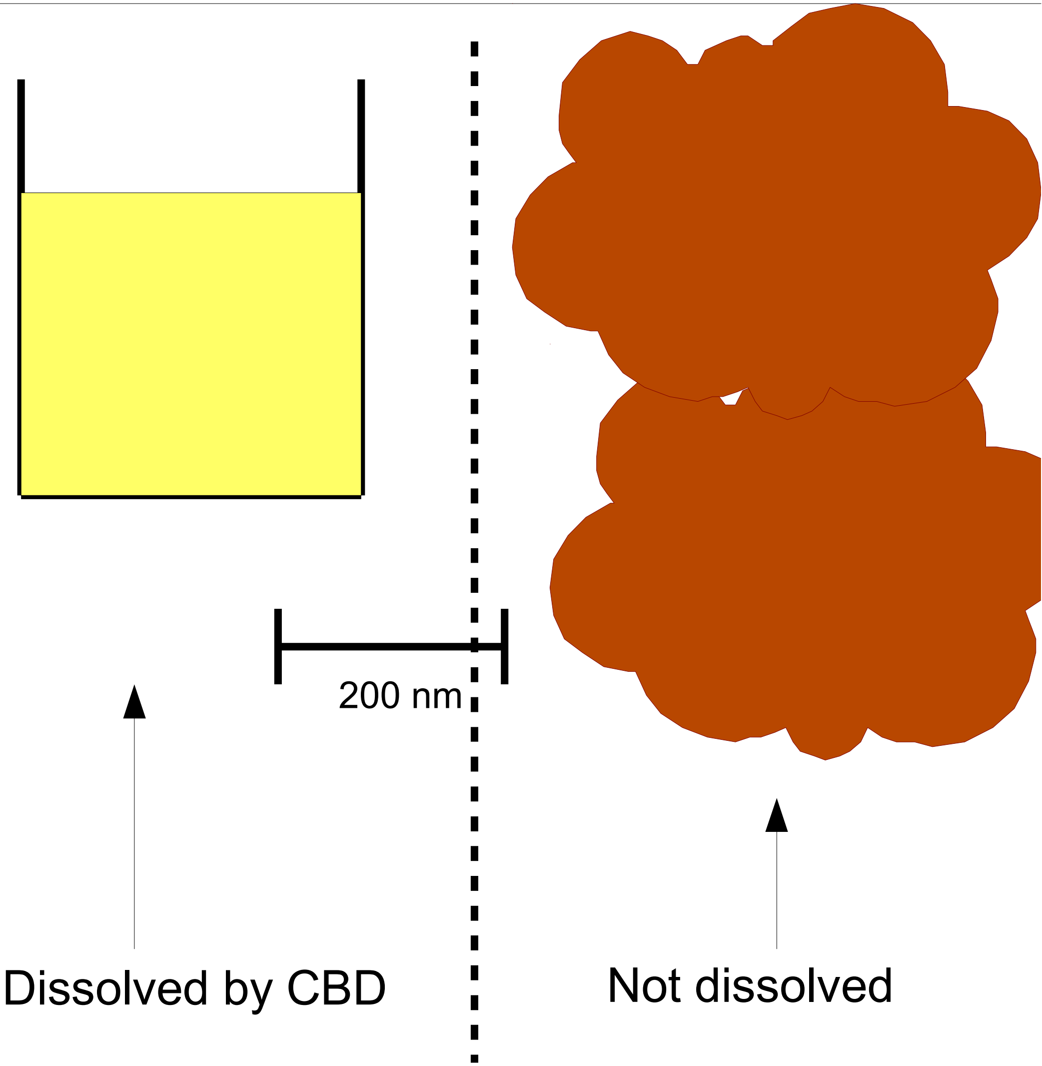

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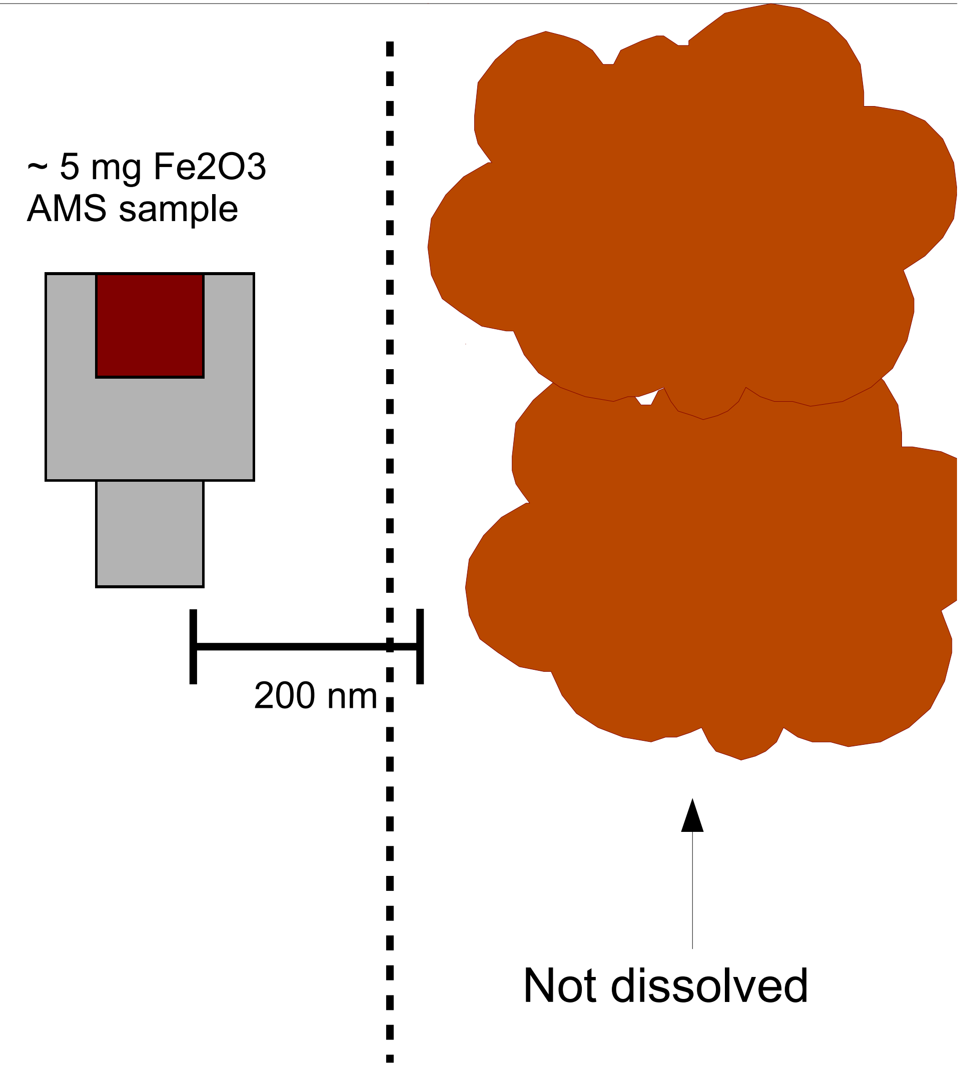
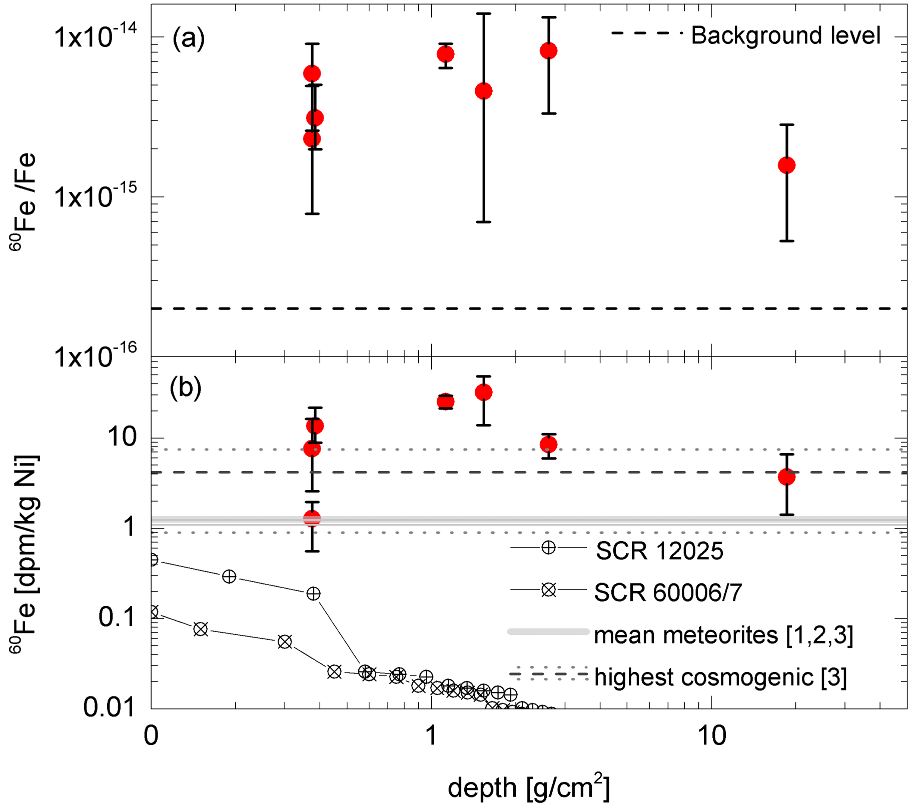


New 60Fe measurements

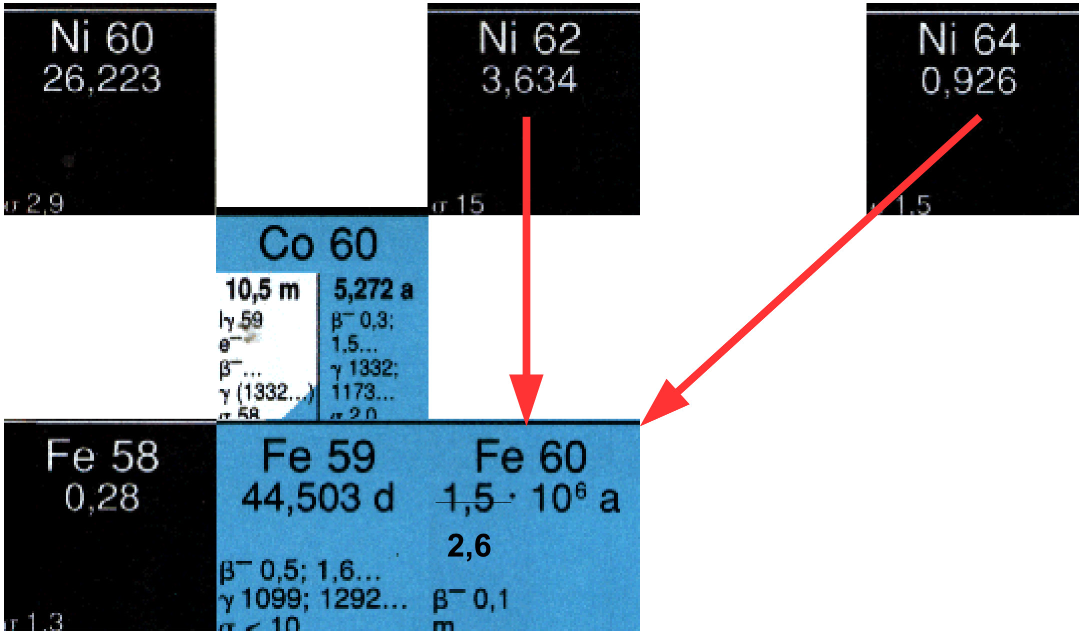


- New 60Fe measurements show 60Fe counts in 7 samples
- To distinguish from cosmic ray production look at 60Fe/kg(Ni)

→ 3 samples show significantly higher values than highes cosmogenic production observed in meteorites

→ indentification as SN input possible

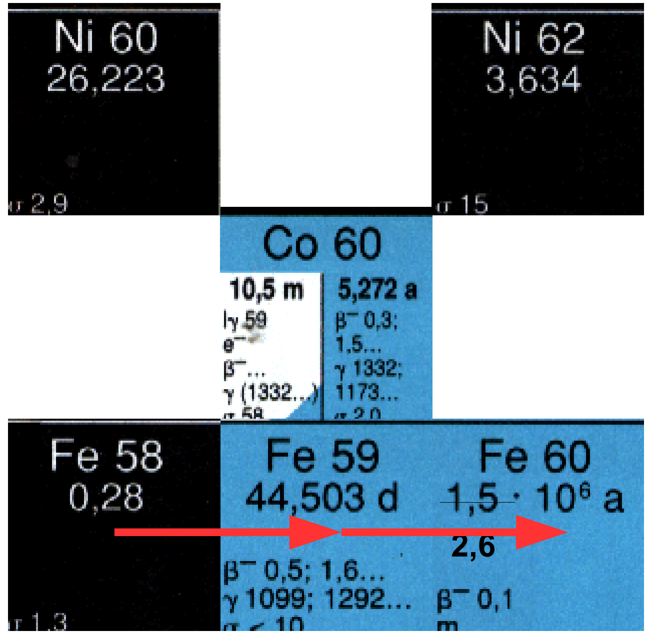
^{60}Fe production: Spallation



<u>Cosmic ray spallation:</u>

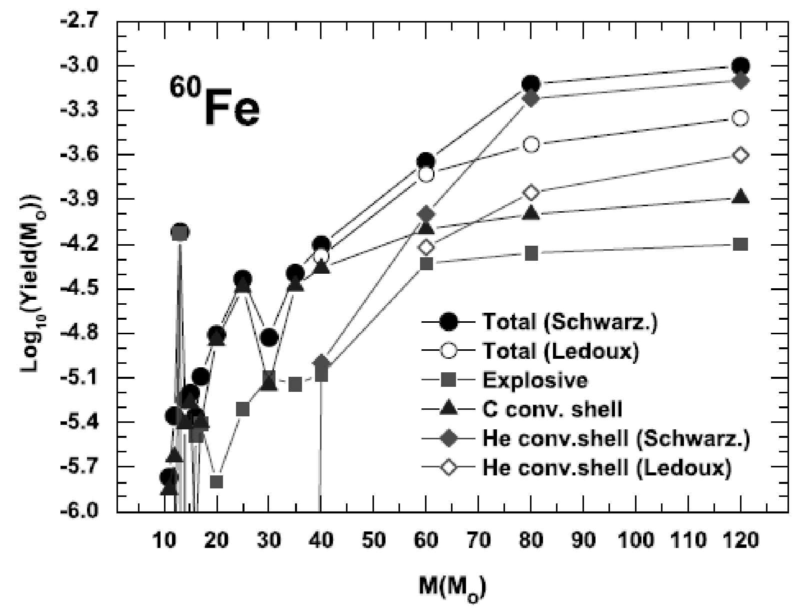
- ^{60}Fe production in cosmic ray spallation mostly on Ni targets
- On Earth, atmosphere prevents large build-up - background ^{60}Fe/Fe < 10^{-16}
- In meteorites and lunar samples, this is not given

^{60}Fe production: Stellar



Production in stars:

- 2 Neutron captures (s-process) on ^{58}Fe
- Shell He burning in massive stars ($M > 40\ M_{sun}$)
- Shell C burning in massive stars ($M < 40\ M_{sun}$)
- Explosive synthesis in SN when shockwave passes through shells → small contribution

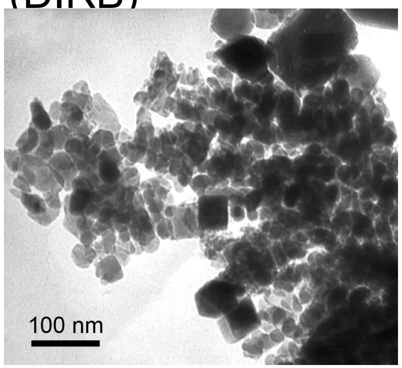


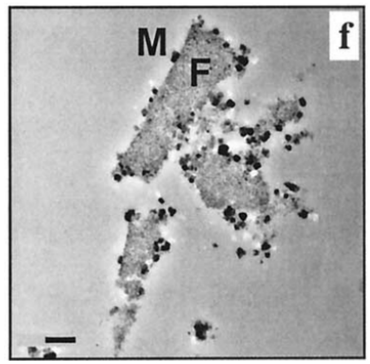
Limongi, M., & Chieffi, A. 2006, ApJ, 647, 483

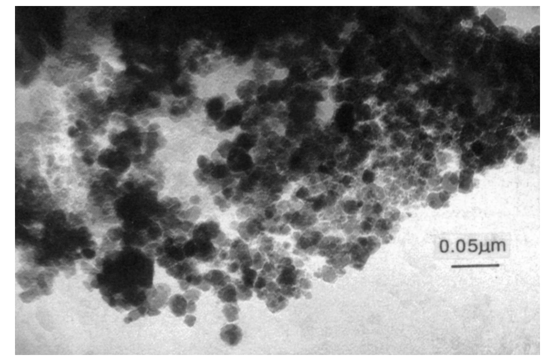
Magnetite in sediment

“Extracellular magnetite”

Secondary magnetite precipitated from redox reactions, either *inorganically*, or by mediation of *dissimilatory metal reducing bacteria* (DIRB)

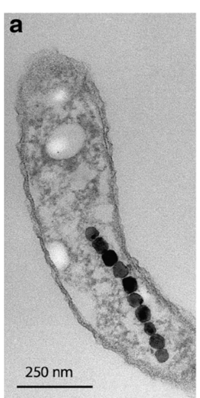


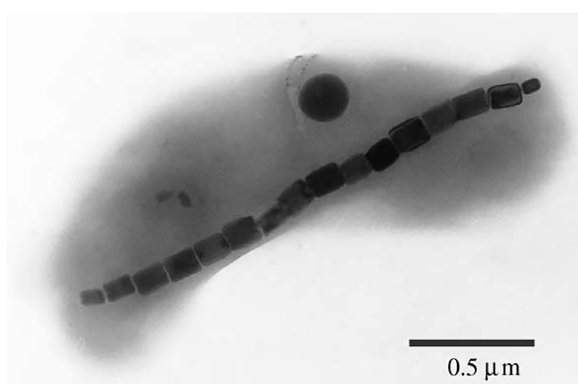


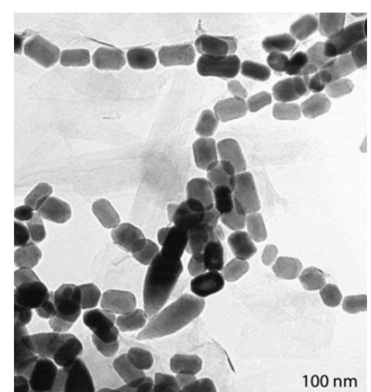


“Biogenic magnetite”

Magnetosomes and magnetosome chains produced by *magnetotactic bacteria* (MB)



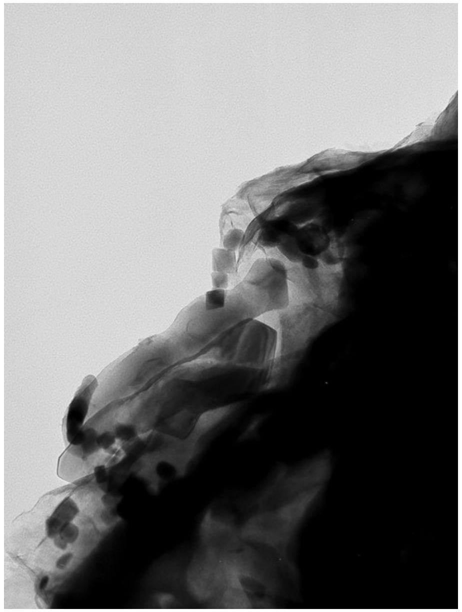


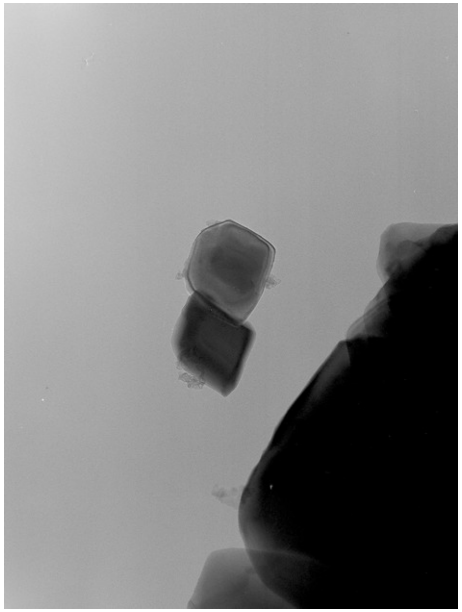


Do we have biogenic magnetite in our sediment?

Transmission electron microscopy (TEM):

- Setup at TUM Chemistry (Marianne Hanzlik)
- First try: TEM on untreated sediment
  → extremely difficult and time consuming
- Results show at lease some biogenically-looking magnetite particles
  (magnetite identified by diffraction analysis)

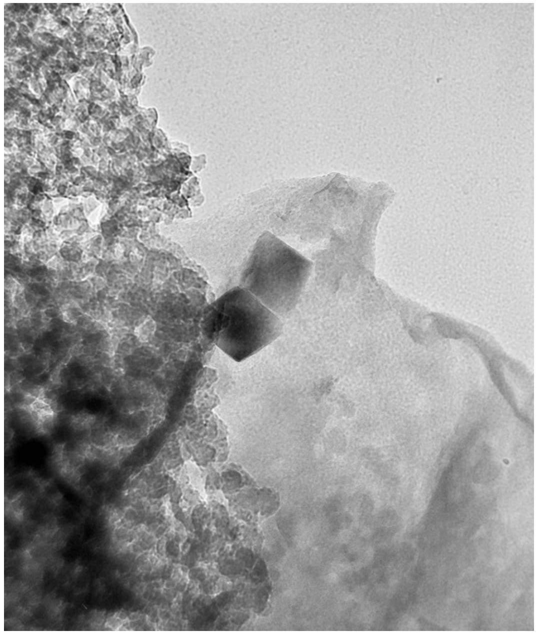


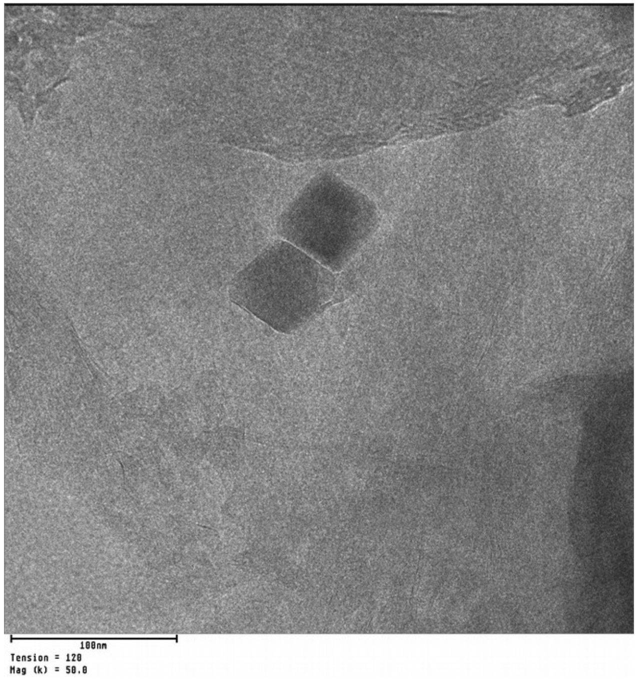


TEM on Sediment

Transmission electron microscopy (TEM):

- Second try: pre-treatment of sediment with AcOH (20%) for 1 hour
  → reduction of sample mass by 80% → calcite matrix dissolved
- Still extremely time-consuming and difficult

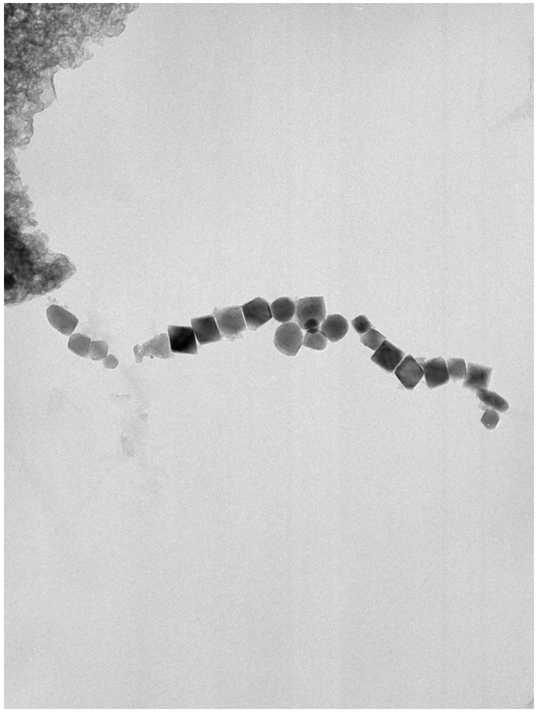
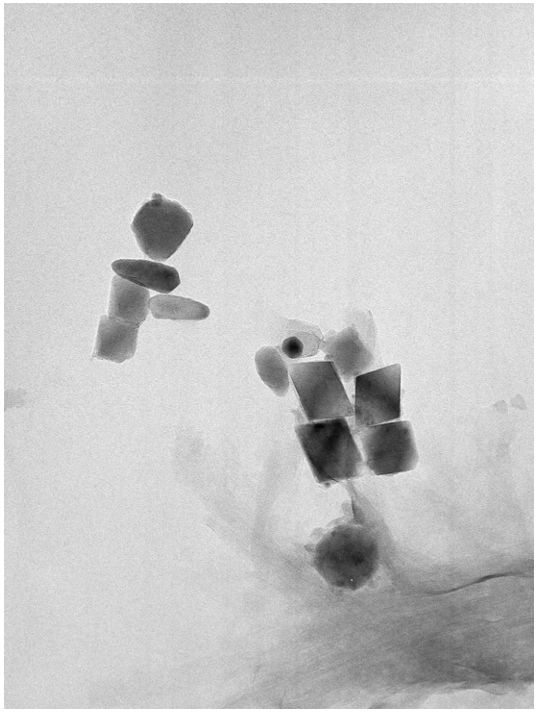
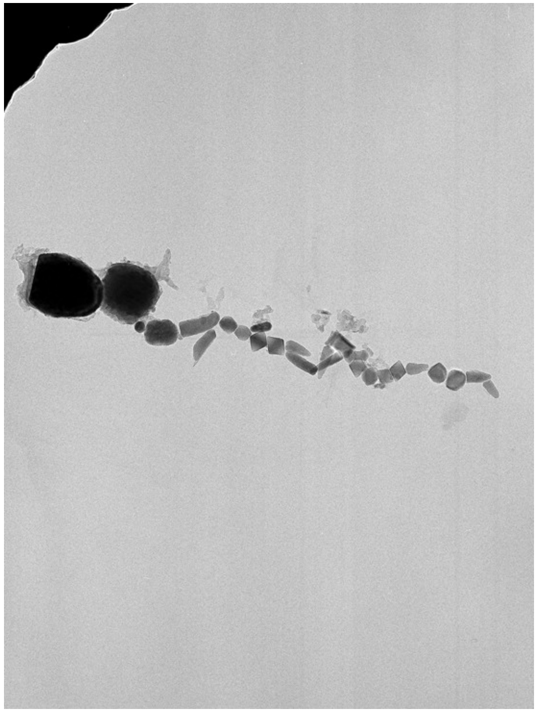




TEM on Sediment

Transmission electron microscopy (TEM):

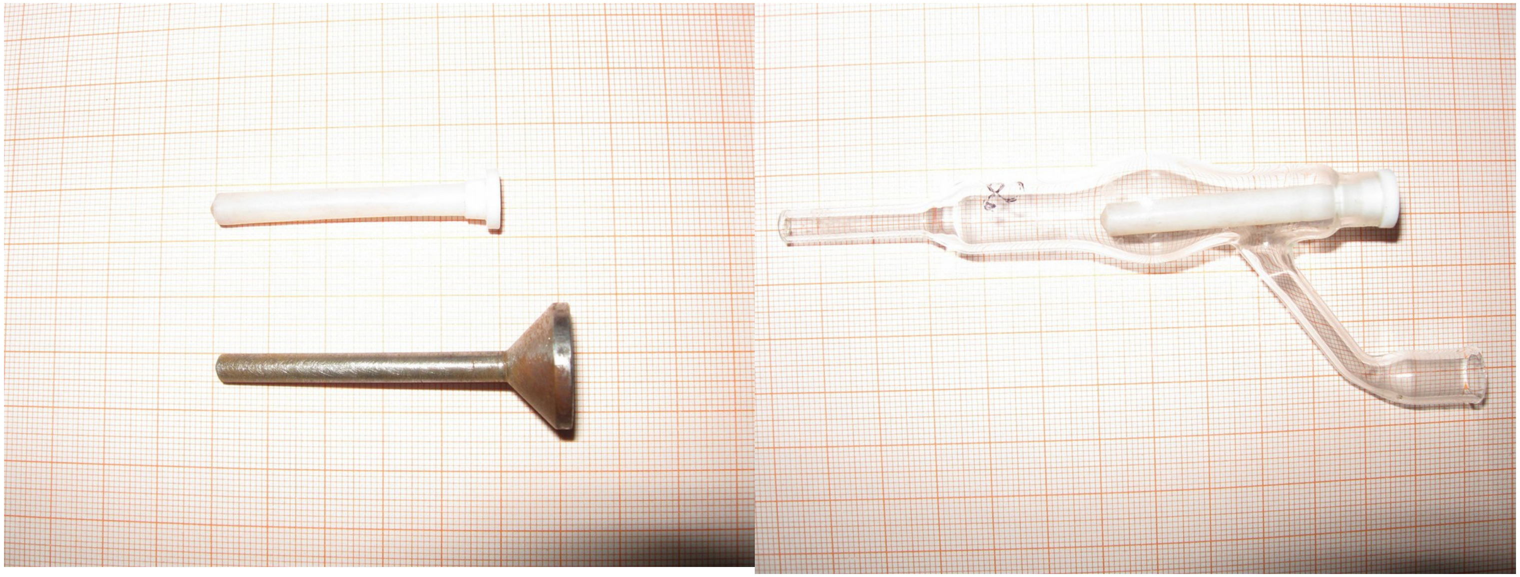
- Third try: Insert magnetic finger into sample from try #2
- Much easier to find magnetite formations: chains and clusters can be seen
- HOWEVER: Are these originally present in the sediment? Or just formed during magnetic extraction? → impossible to interpret

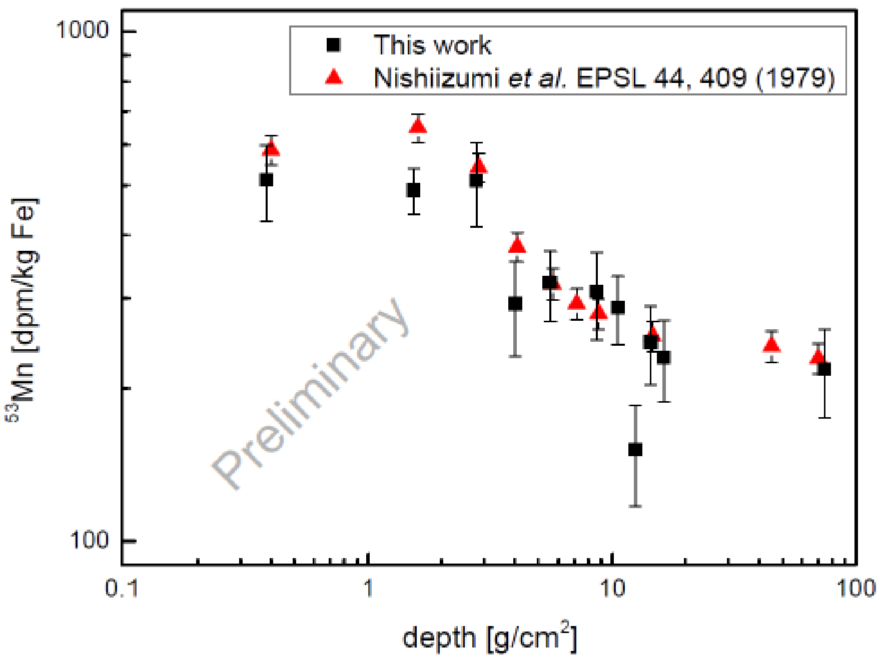
Future Plans for Sediment samples

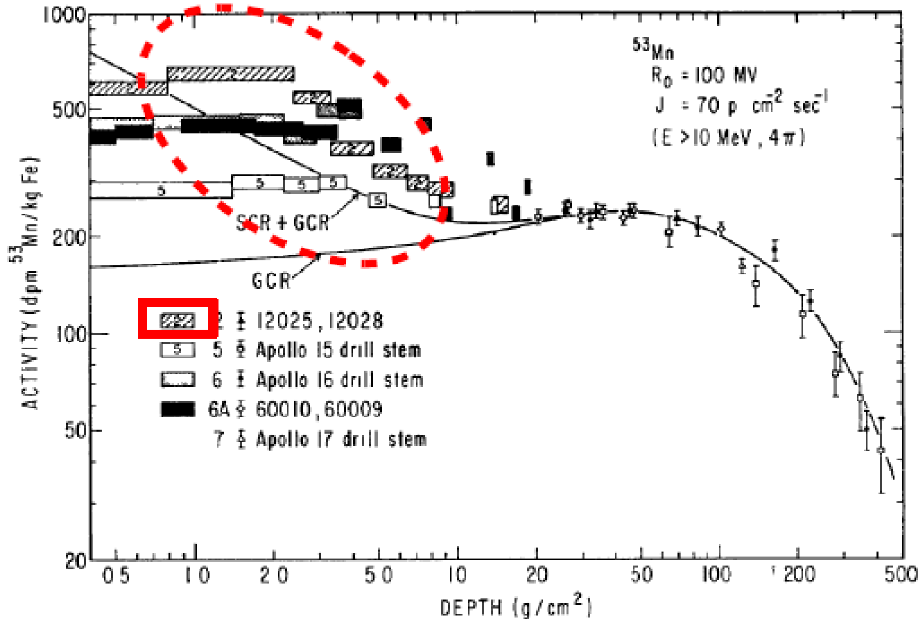
- Attempt to obtain more sediment of core 848 in SN region
  → Currently being discussed, samples may be available

- Try alternative extraction method:
  → Dissolve calcite matrix with AcOH (20%)
  → Perform magnetic extraction
  → Optionally then CBD extraction
  → AMS
  The magnetic extraction is currently being set up in Garching as a Bachelor's Thesis



53Mn in lunar samples





Excess of ^{53}Mn? →

? Mixing of the regolith

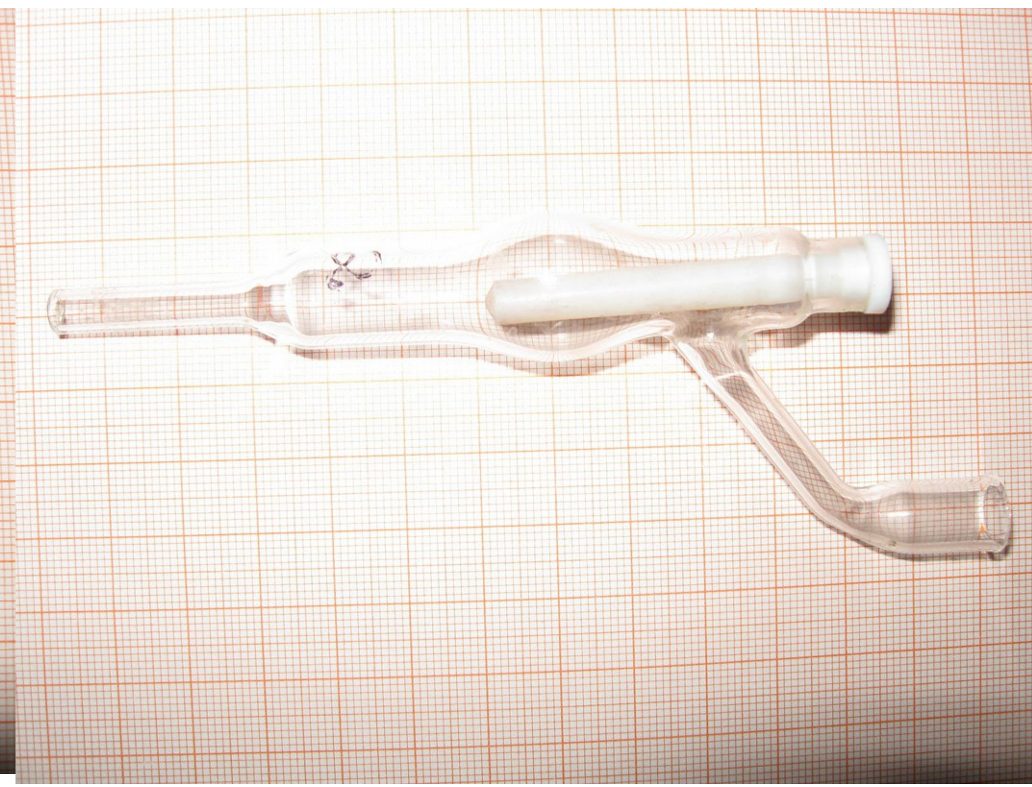
? Addition of irradiated material

? Deposition of SN debris

? …

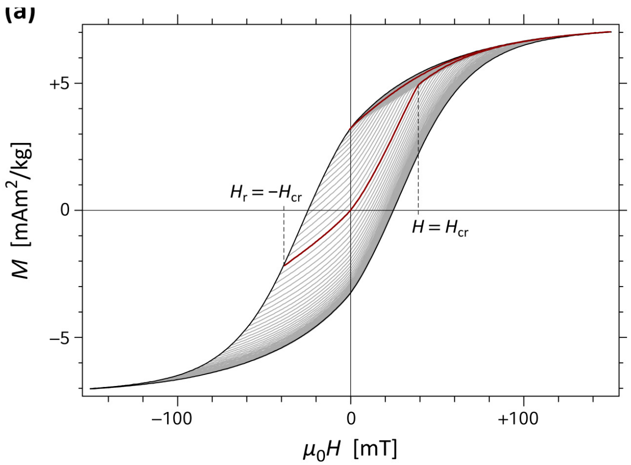
Transmission electron microscopy (TEM):

- Fourth try: Perform magnetic extraction directly on sediment
- V I D E O



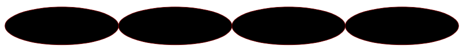
FORC measurements

Use an Alternate Gradient Field Magnetometer (in Bremen) to record a set of 450 first-order reversal curves (FORCs), 4-5 times → total time ~1 day per sample



Chemical isolation of iron

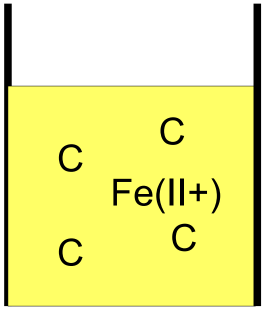
Procedure for ~30g sediment



Magnetosomes in Sediment:
Fe_3O_4 = Fe(II+) + Fe(III+)

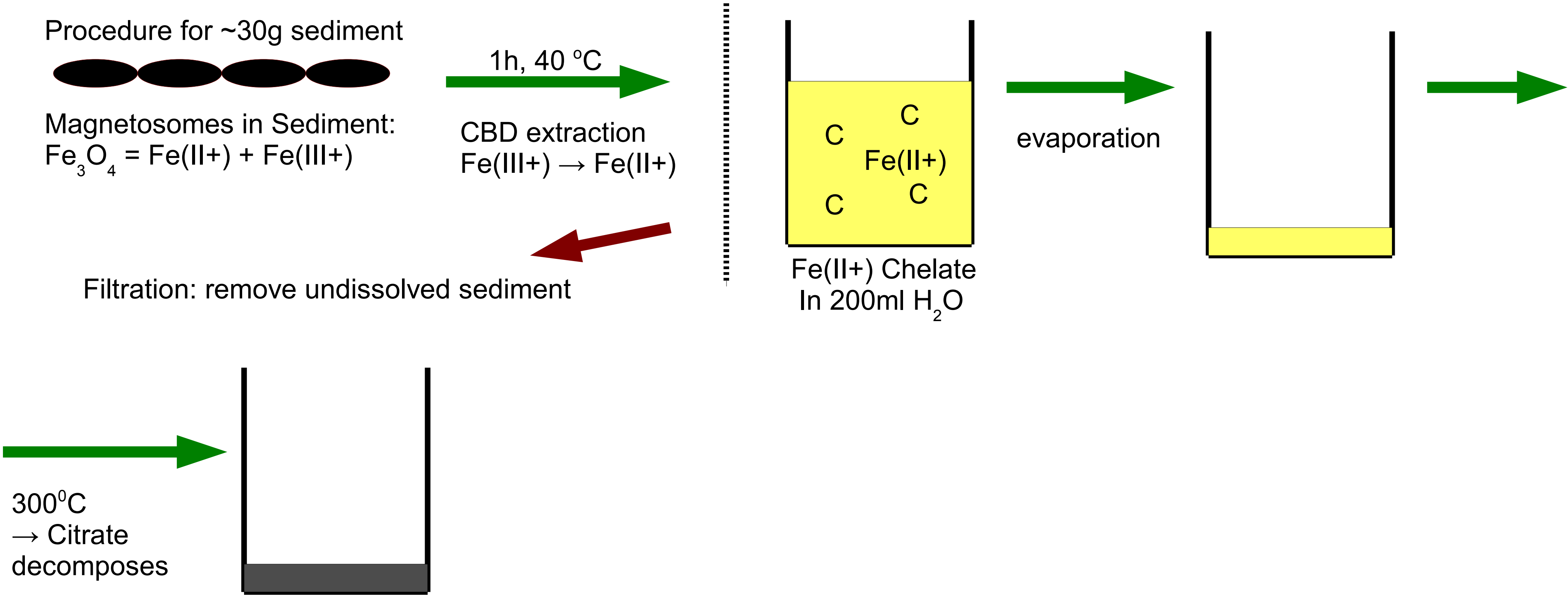
1h, 40 °C

CBD extraction
Fe(III+) → Fe(II+)

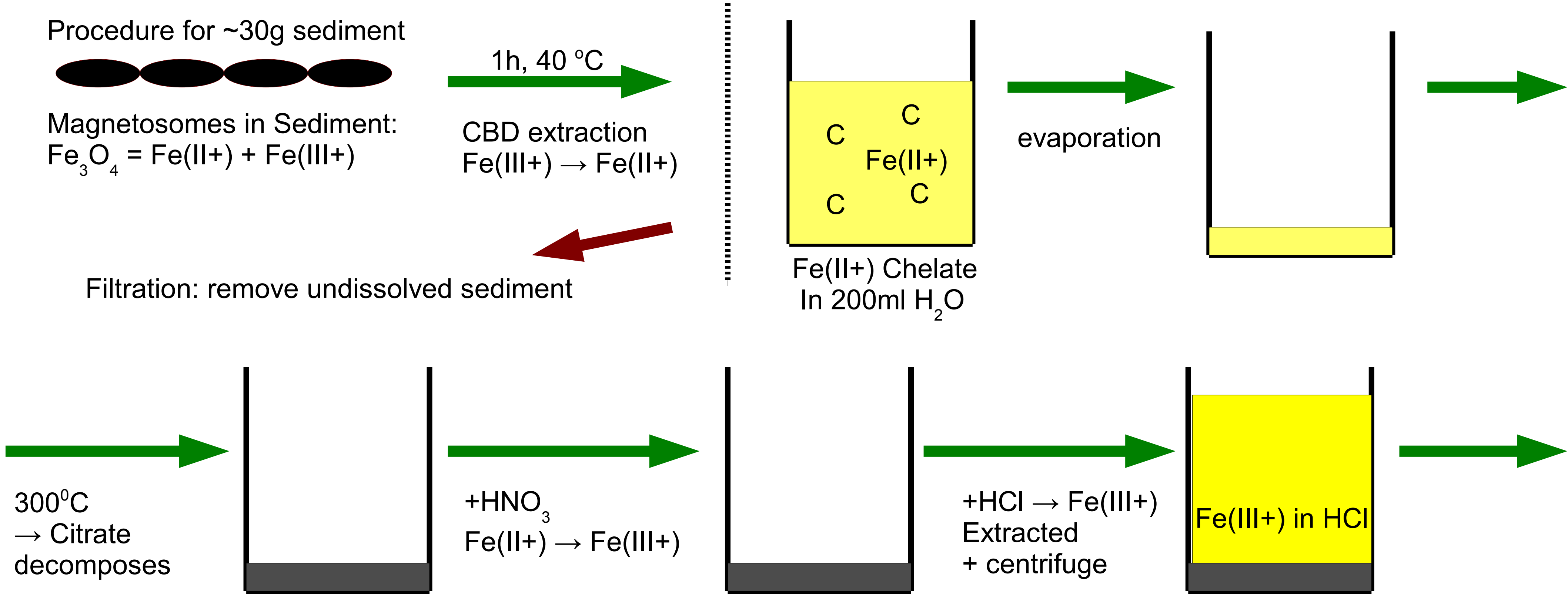


Filtration: remove undissolved sediment

Chemical isolation of iron



Chemical isolation of iron



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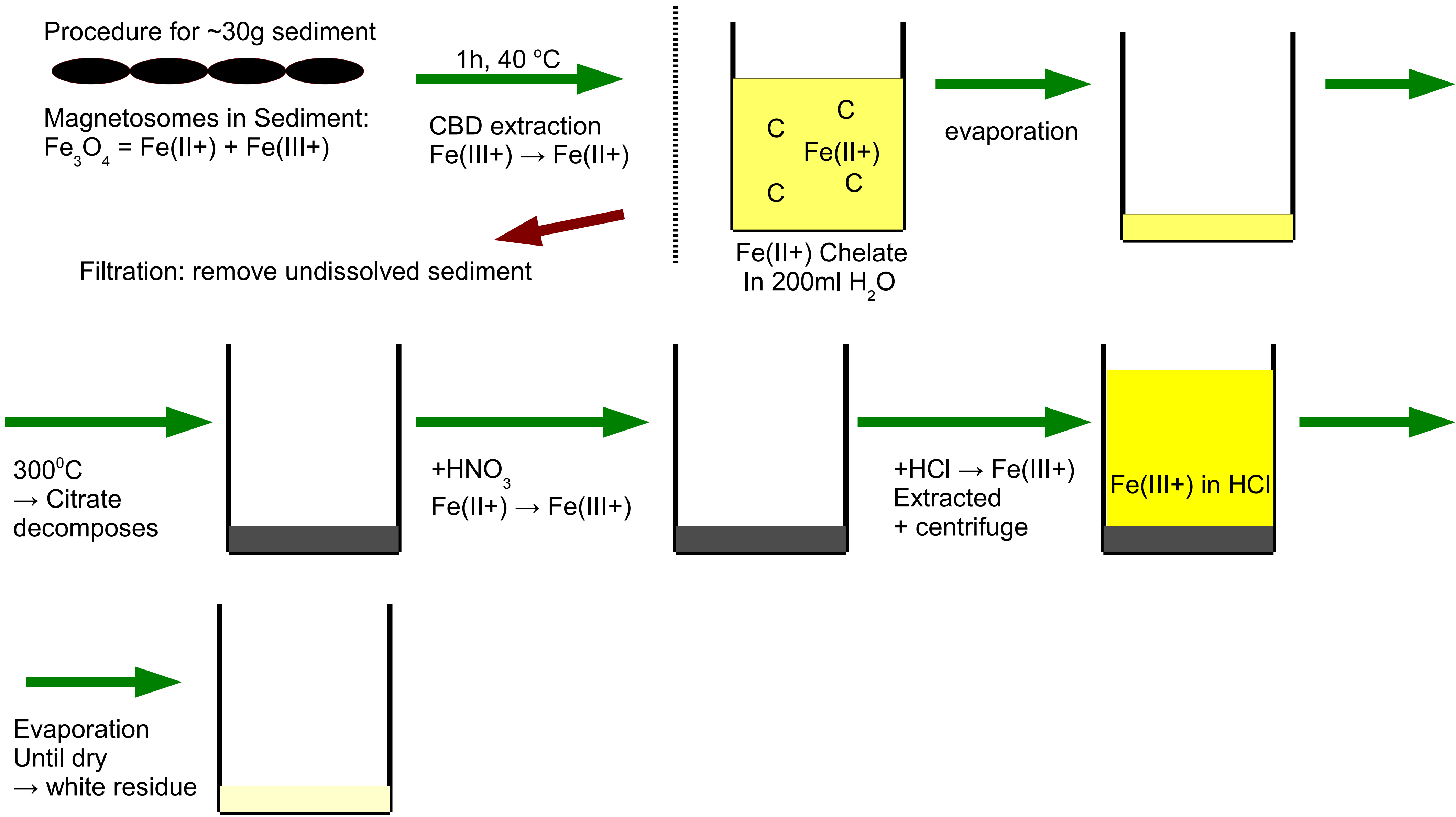
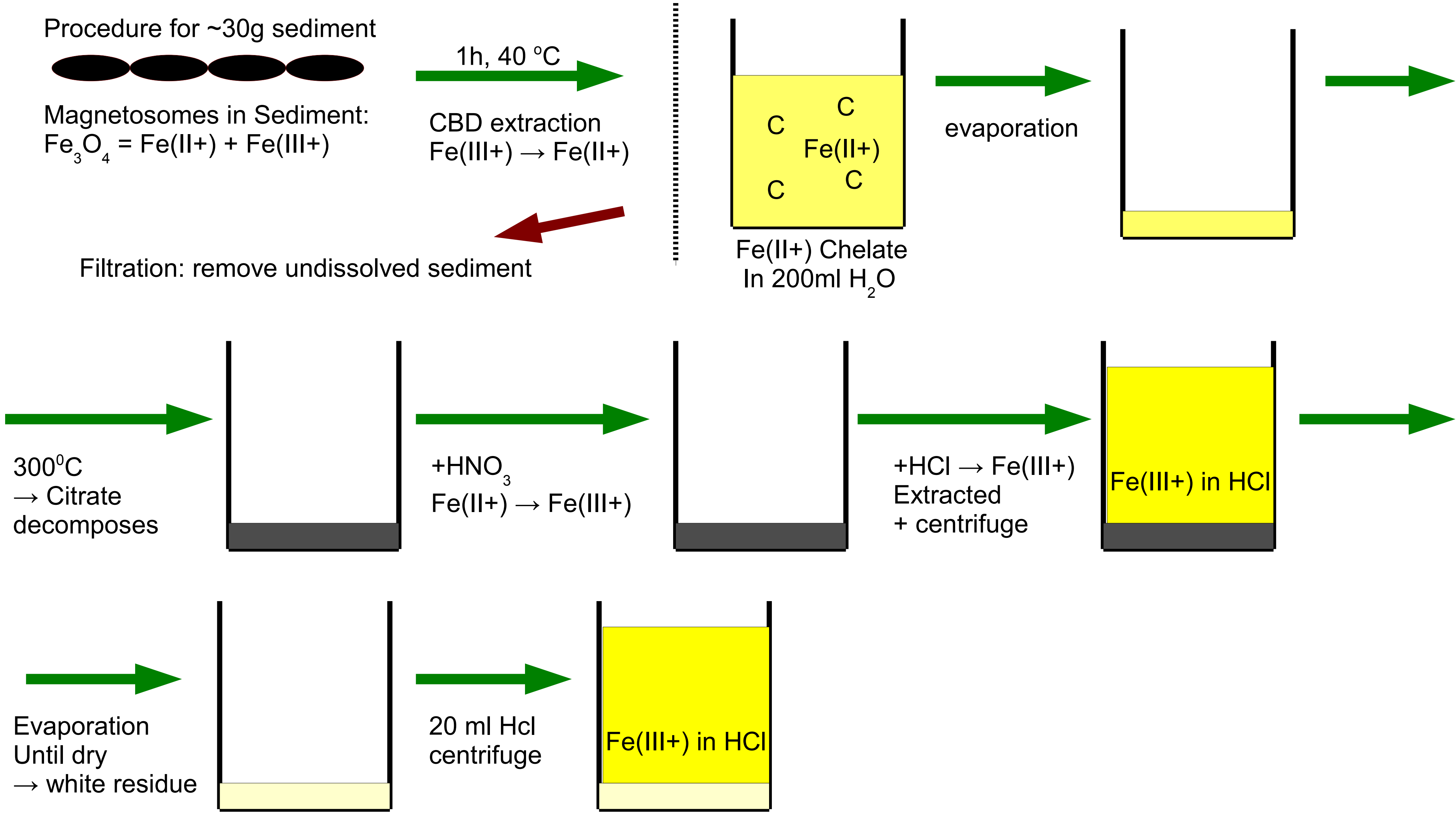
Chemical isolation of iron

Lehrstuhl E12



Chemical isolation of iron



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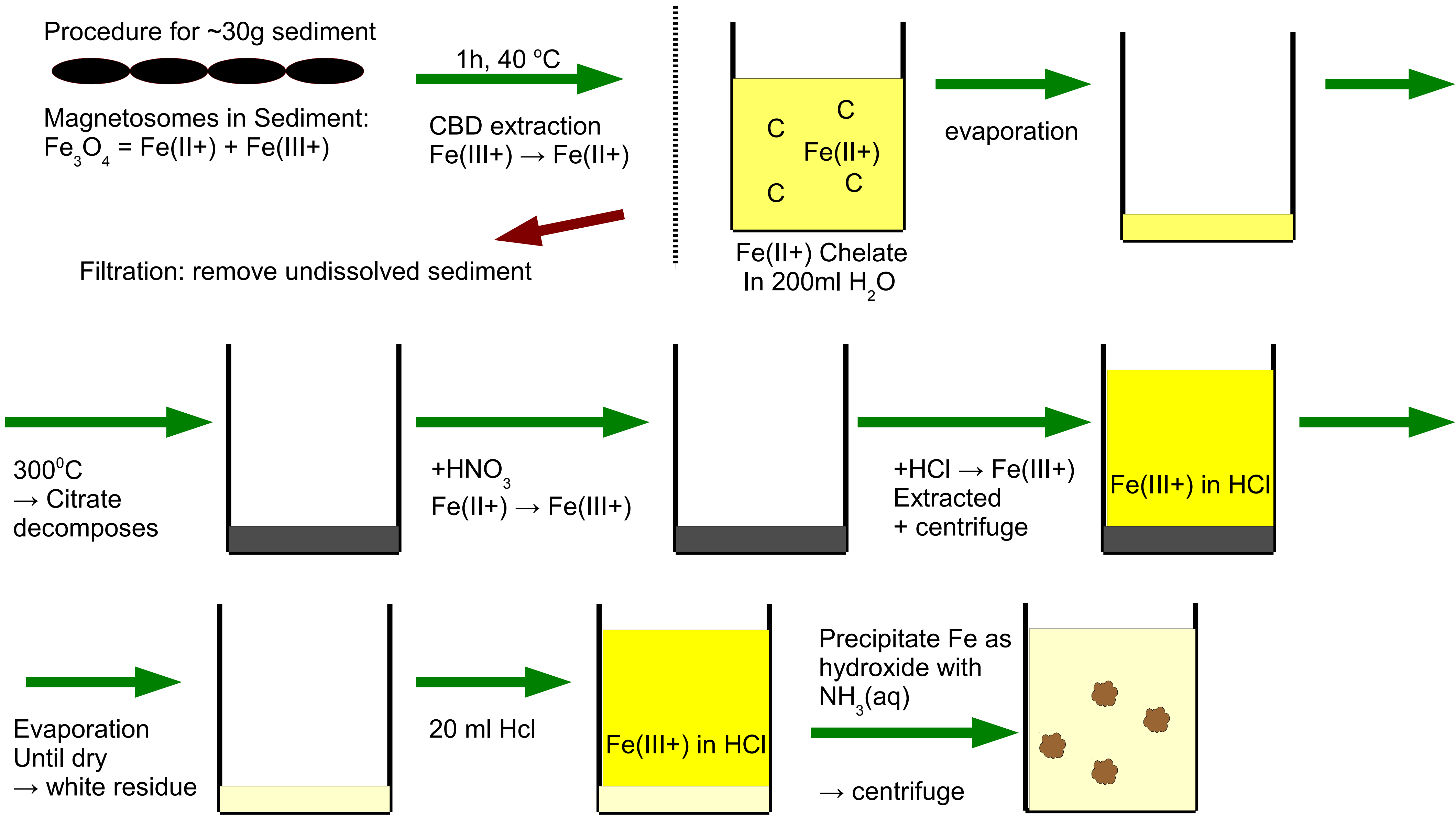

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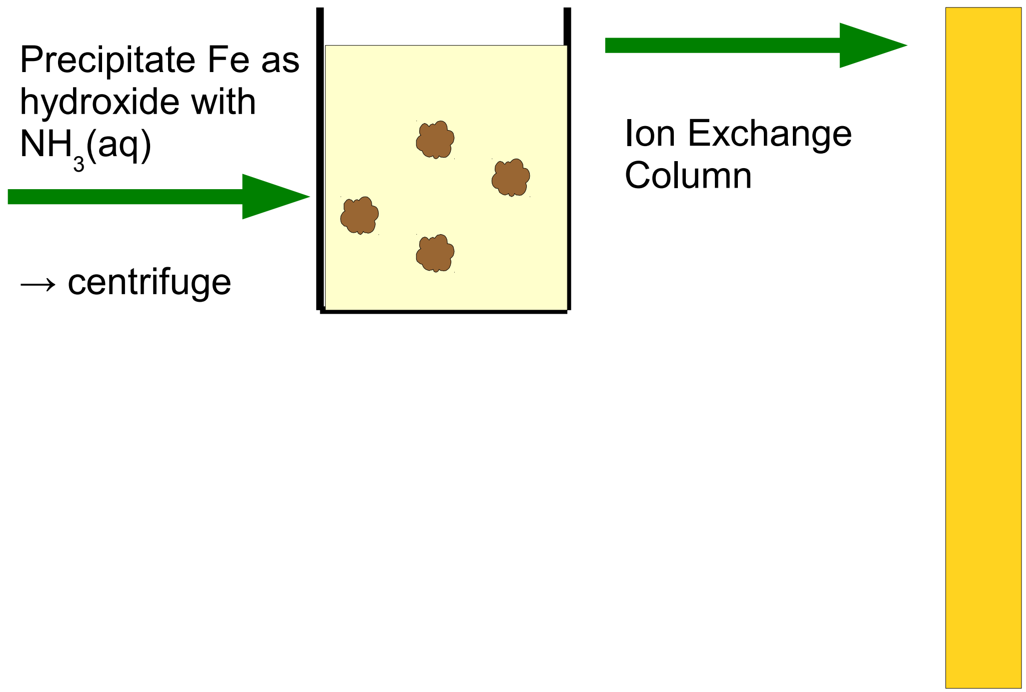

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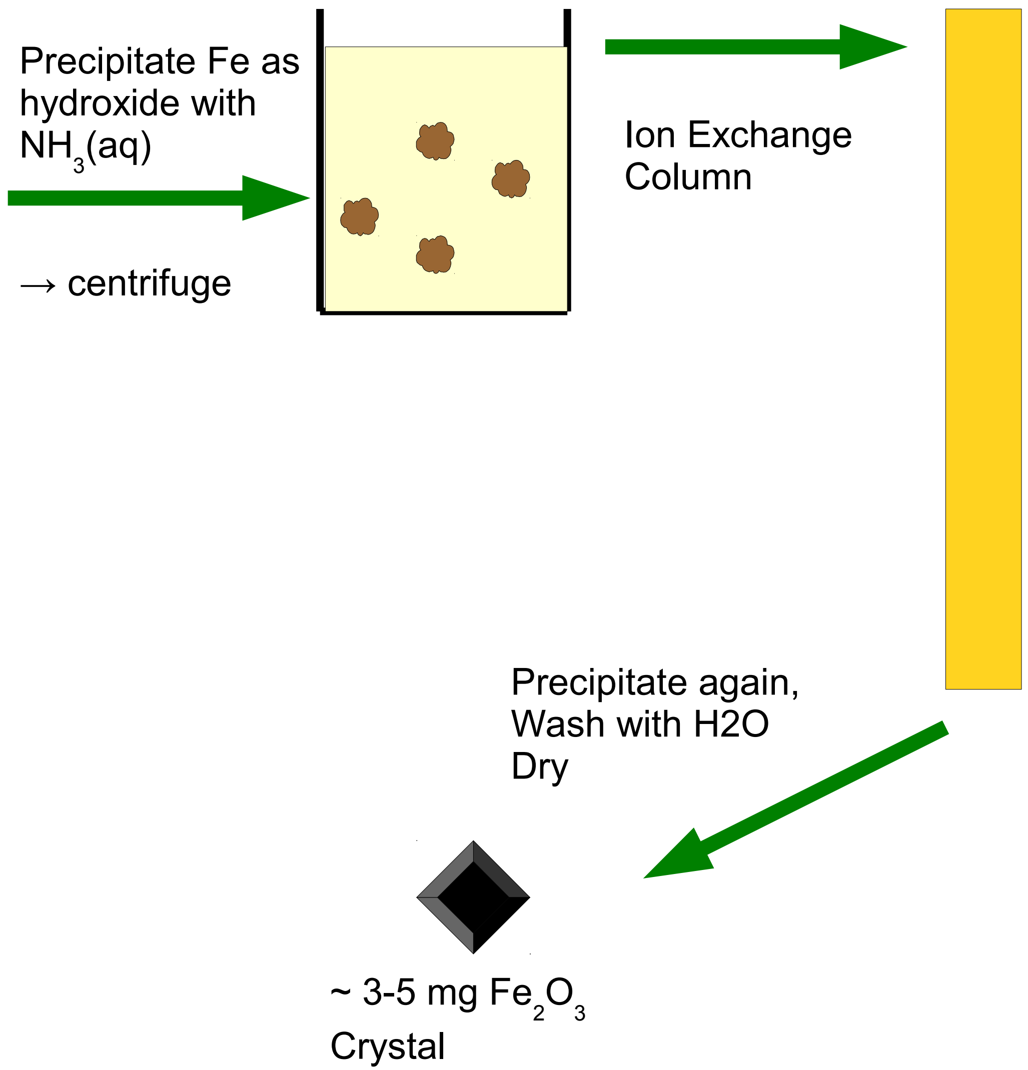

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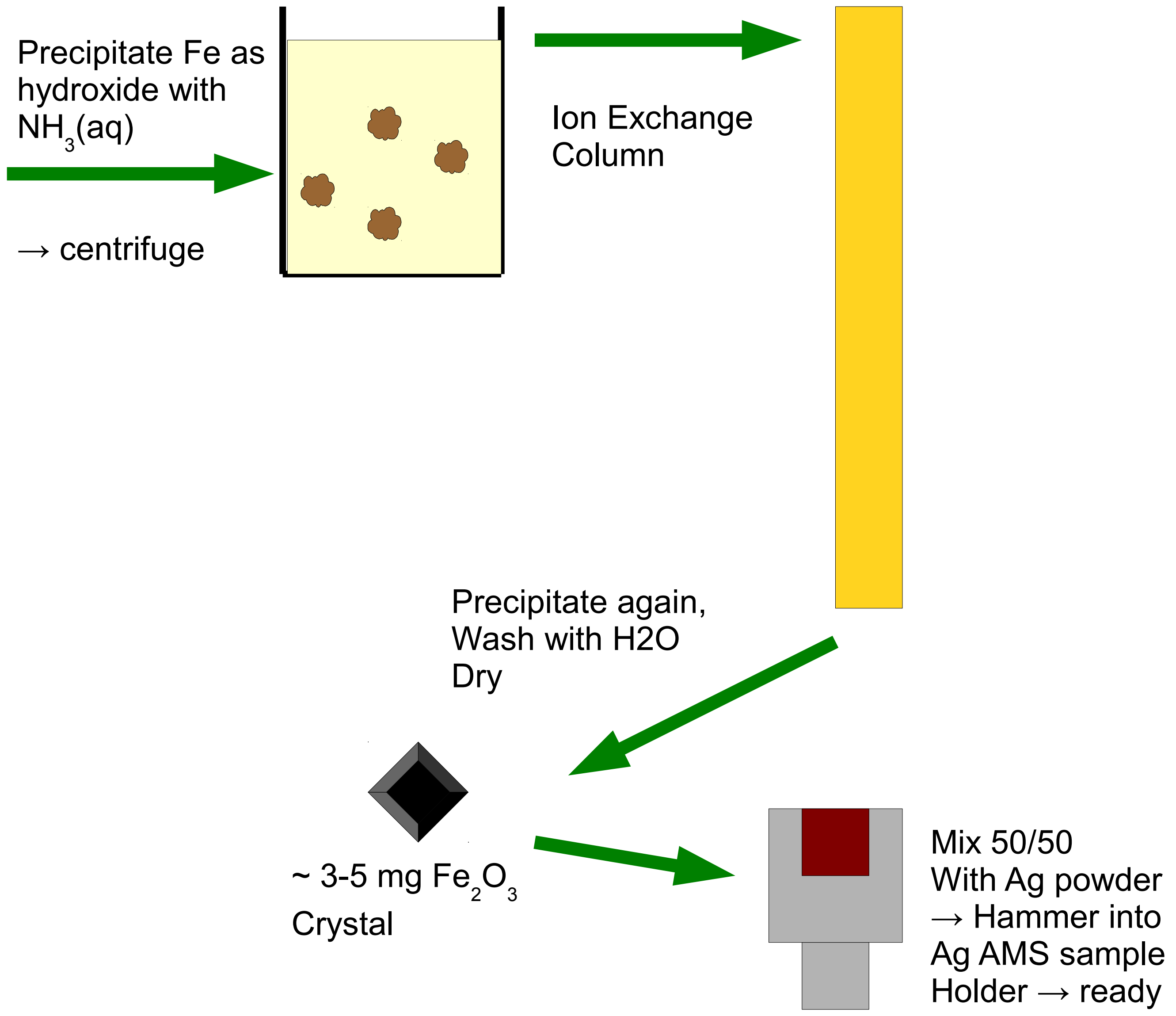
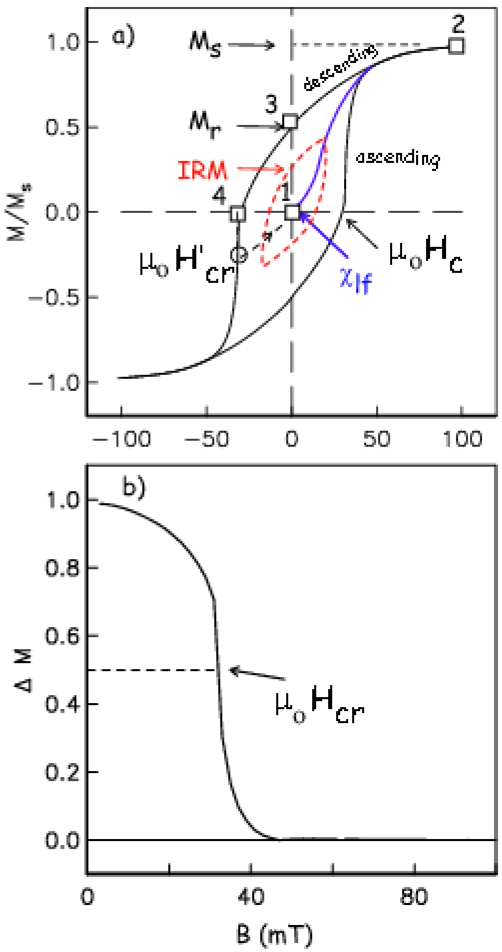
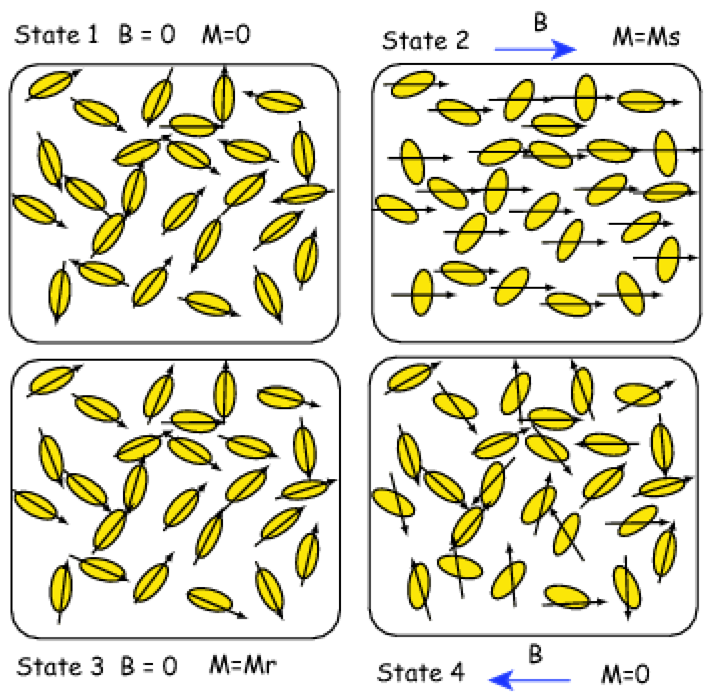


Hysteresis measurements





B (H) – External mag. Field [mT]

M – Magnetization

M_s – saturation magnetization

M_r (M_{rs}) – remanence magnetization

H_c – Coercivity

H_{cr} – Coercivity of remanence

χ_{lf} – low-field susceptibility

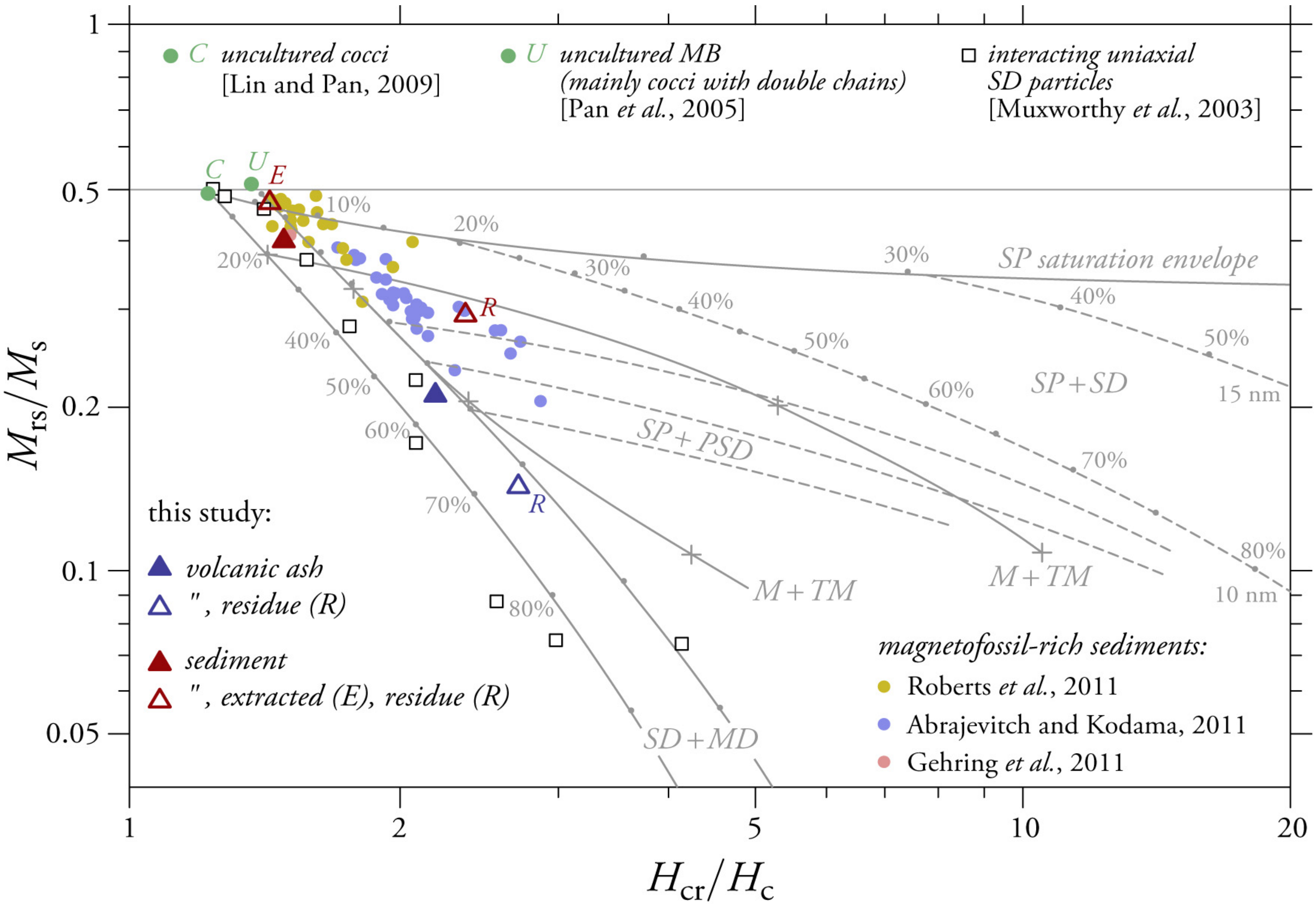
IRM – Isothermal remnant mag.

(a) Hysteresis loop of ferromagnetic material

(b) Difference between descending and ascending curve of (a), giving another measure for H_{cr}

Tauxe, L., Essentials of Paleomagnetism, University of California Press, 2010

Day plot



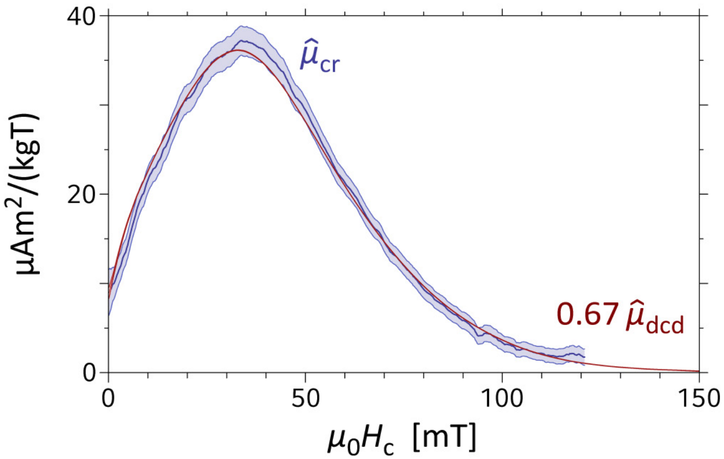
Day plot:

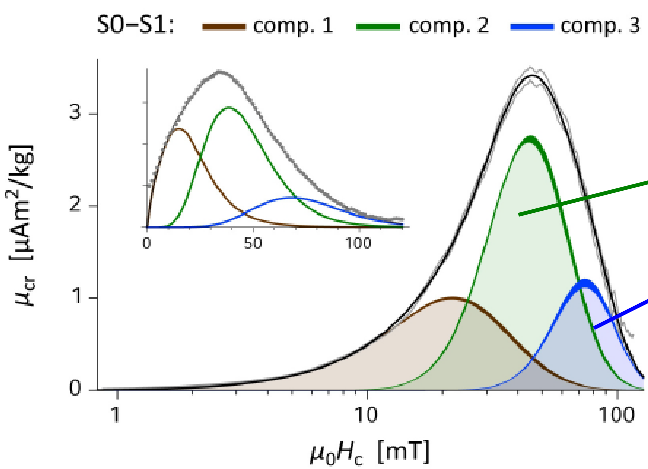
- Domain-state sensitive
- Generated from bulk mag. Properties
- Problem: Non-unique interpretations
- Hints to high abundance of magnetofossils in our sediment, BUT:
- For quantitative analysis, this is not enough!

Legend:

- SD – single domain
- MD – multi domain
- SP – super paramagnetic
- PSD – pseudo SD
- M – magnetite
- TM – Titanomagnetite

AMS sample coercivity distribution





Magnetofossils !!!

Untreated sediment:

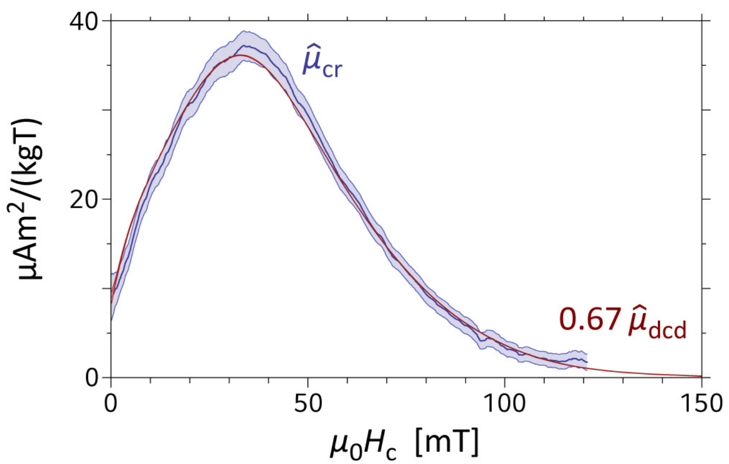
- ≈ 2% total Fe
- 60 ppm SD iron
- ≈ 3% Fe in mag. minerals

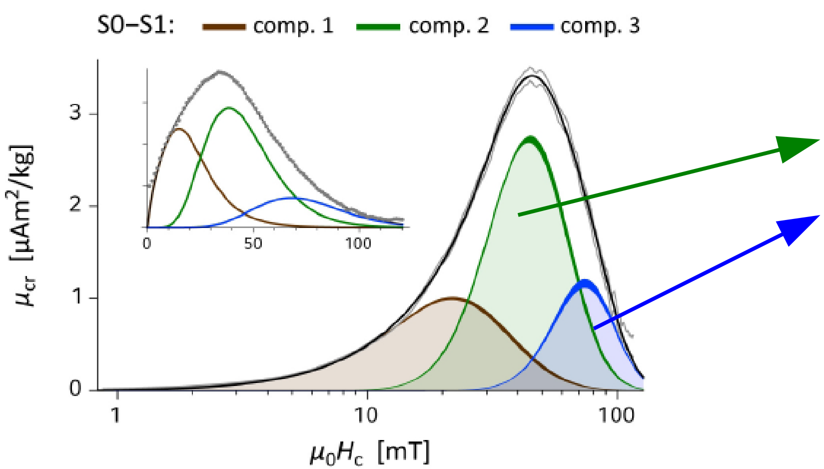
CBD extraction

Sample for AMS:

- 60% from magnetic minerals
- 40% from non-mag. minerals
- < 6% from primary mag. minerals
- >27% from mag. Bacteria

Summary magnetic characterization core 848





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Assuming ^{60}Fe only in secondary magnetic minerals (lower limit)
$^{60}Fe/Fe$ is enhanced by a factor of ≈ 250 relative to complete dissolution of Fe.

Dilution compared to original ^{60}Fe concentration in secondary minerals < 1.9

→ core 848 suited for CBD extraction, assuming roughly constant composition across the core

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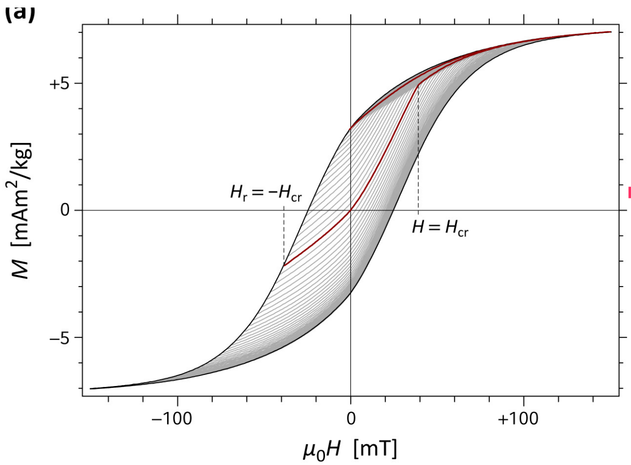


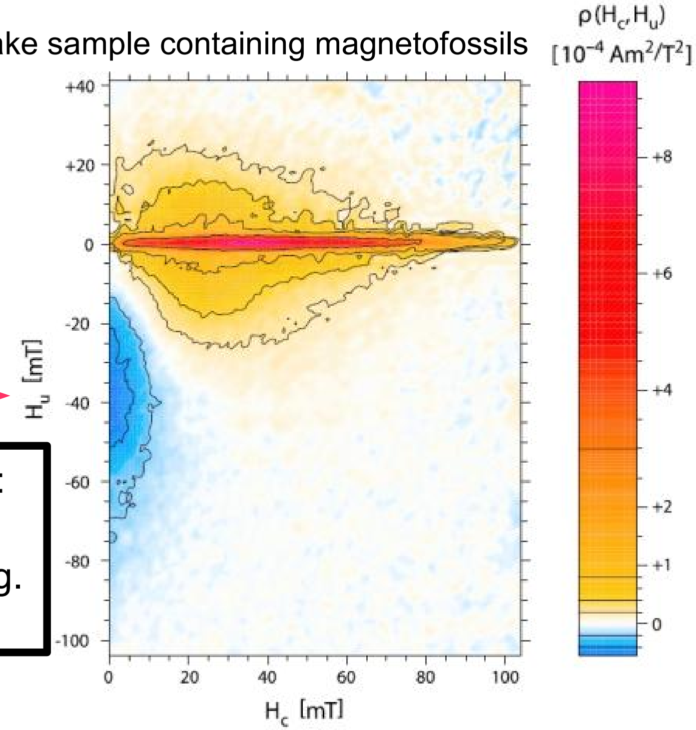
Mathematical transformation: H-M → H_u-H_c

where H_u : bias field (from other particles)

H_c : coercivity (mag. hardness)

Feature of FORC diagram of SD particles:
Central ridge: Delta function along H_u=0
to identify non-interacting SD particles, e.g. magnetofossils

Lake sample containing magnetofossils



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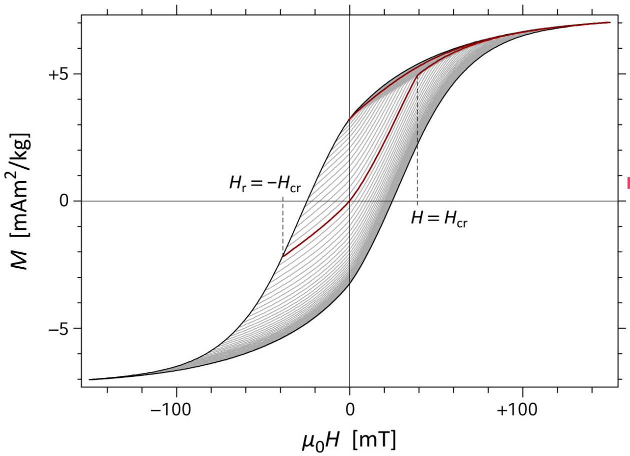

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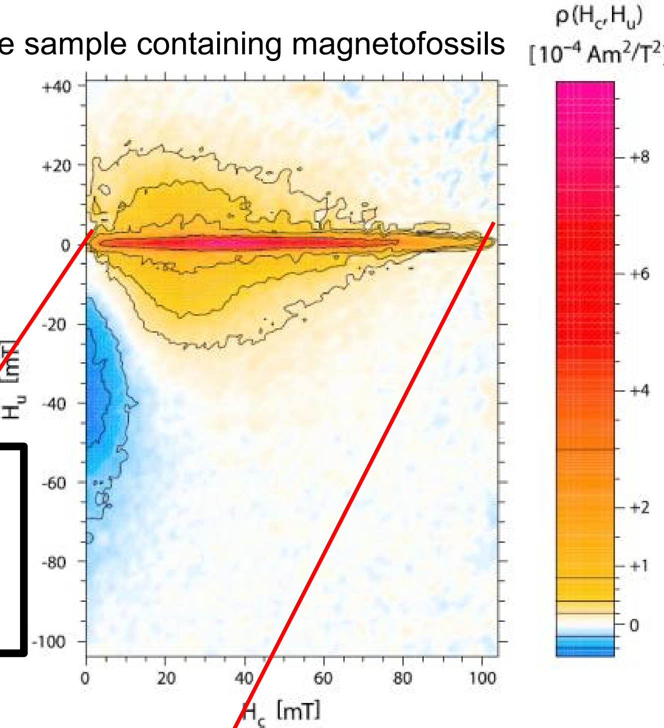
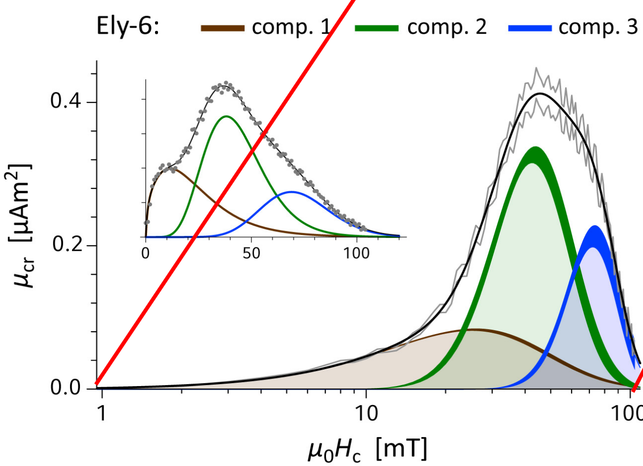
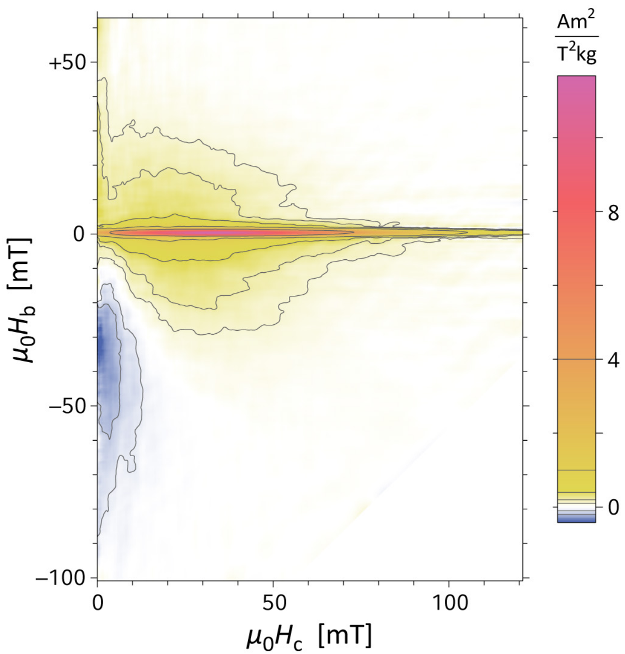




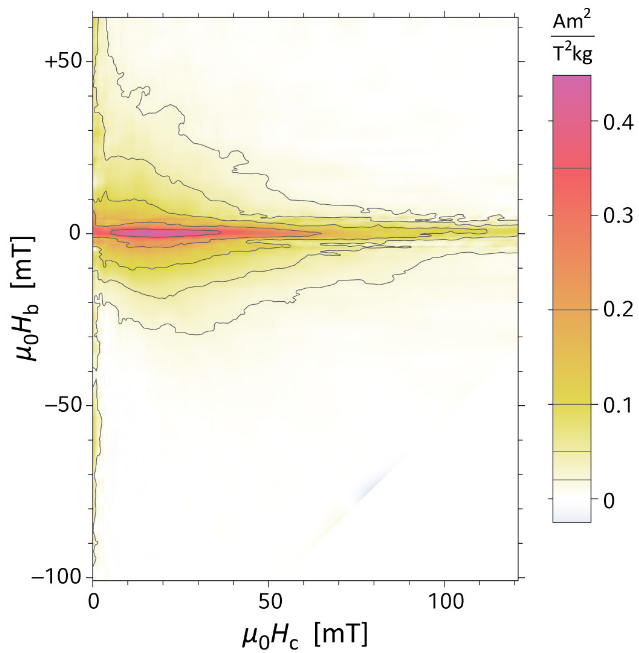
Integrate and fit coercivity distribution:
For the lake sample – 3 components
(1) Extracellular (low coercivity)
(2) Biogenic soft
(3) Biogenic hard

FORC analysis of sediment

Sediment 848 – 3.2-3.3 Myr
untreated



Sediment 848 – 3.2-3.3 Myr
after CBD extraction



AMS sample

?

Central ridge almost disappears (~5% left) after 1 CBD extraction

BUT: What's the magnetic signature of the AMS sample?

FORC analysis of sediment

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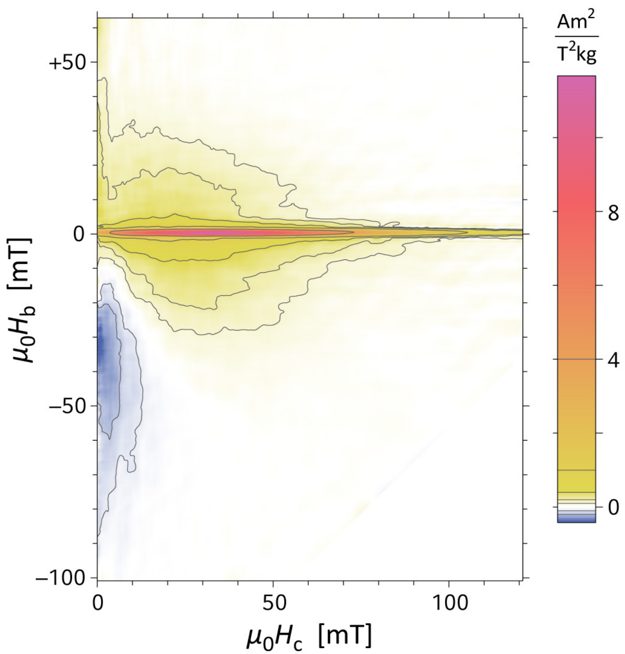

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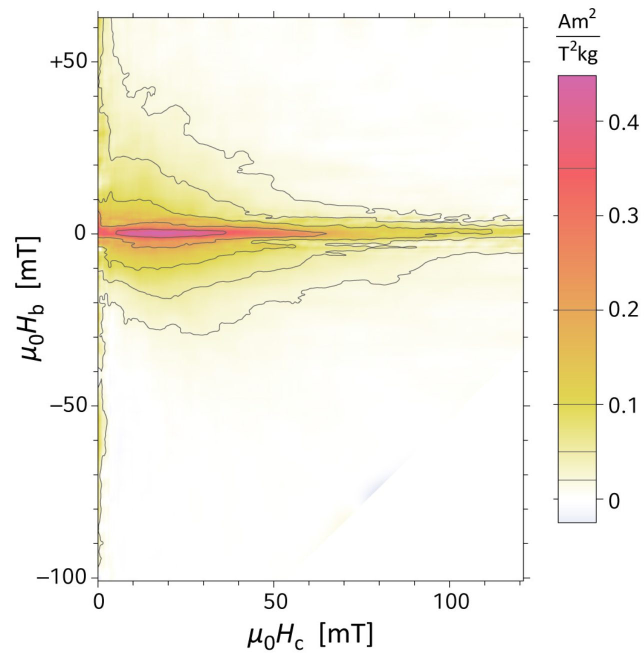

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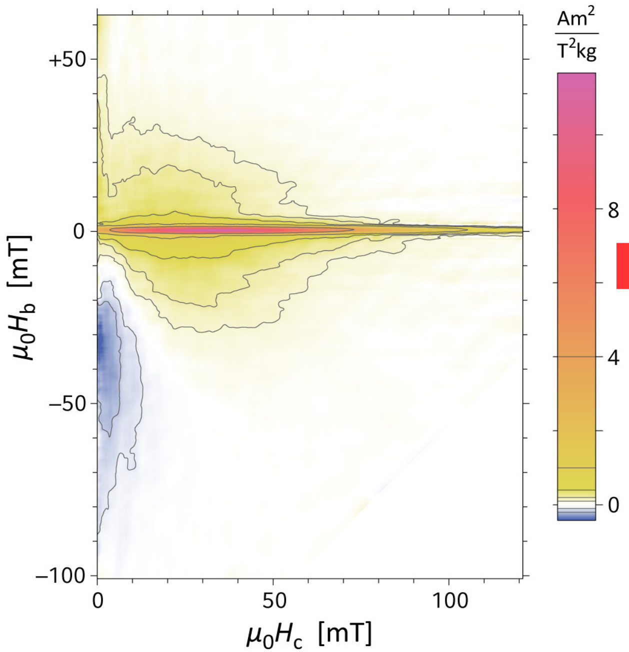

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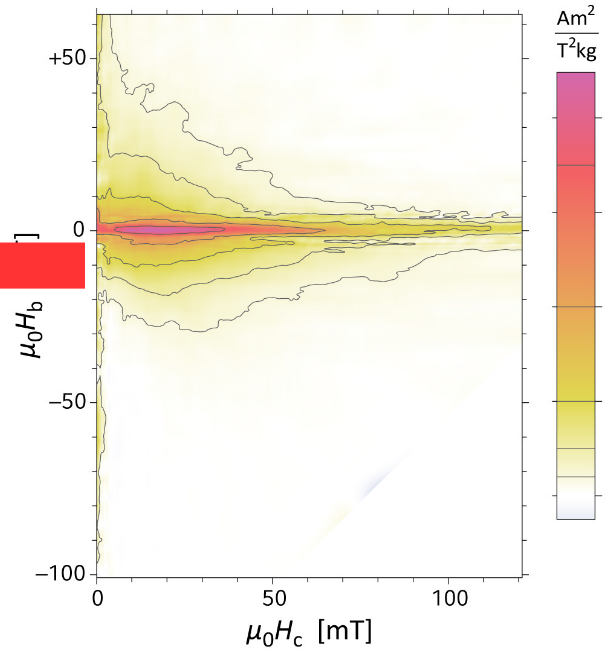
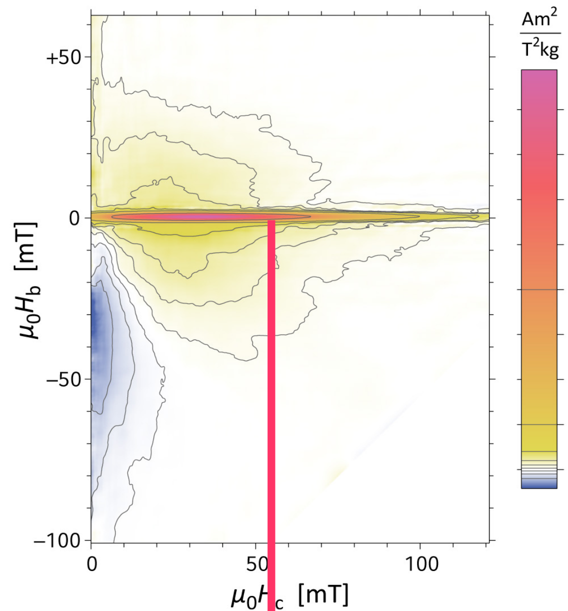
After CBD extraction



AMS sample
calculated as difference



Integrate to obtain coercivity distribution