DUST-BUSTER: a high-sensitivity wide-range mass spectrometer for isotopic study of star-dust from comet Wild-2 and primitive meteorites

NTHU Physics Colloquium by Typhoon Lee, 4/20/05

Chun-Yen Chen[1] , Jason J-S Shen[1]
Wally F. Calaway[2] Jerry E. Moore[2]
Mike J. Pellin[2], Igor V Veryovkin[2]

[1]: Institute of Earth Sciences, Academia Sinica, TAIPEI
[2]: Material Science Division, Argonne National Lab. USA

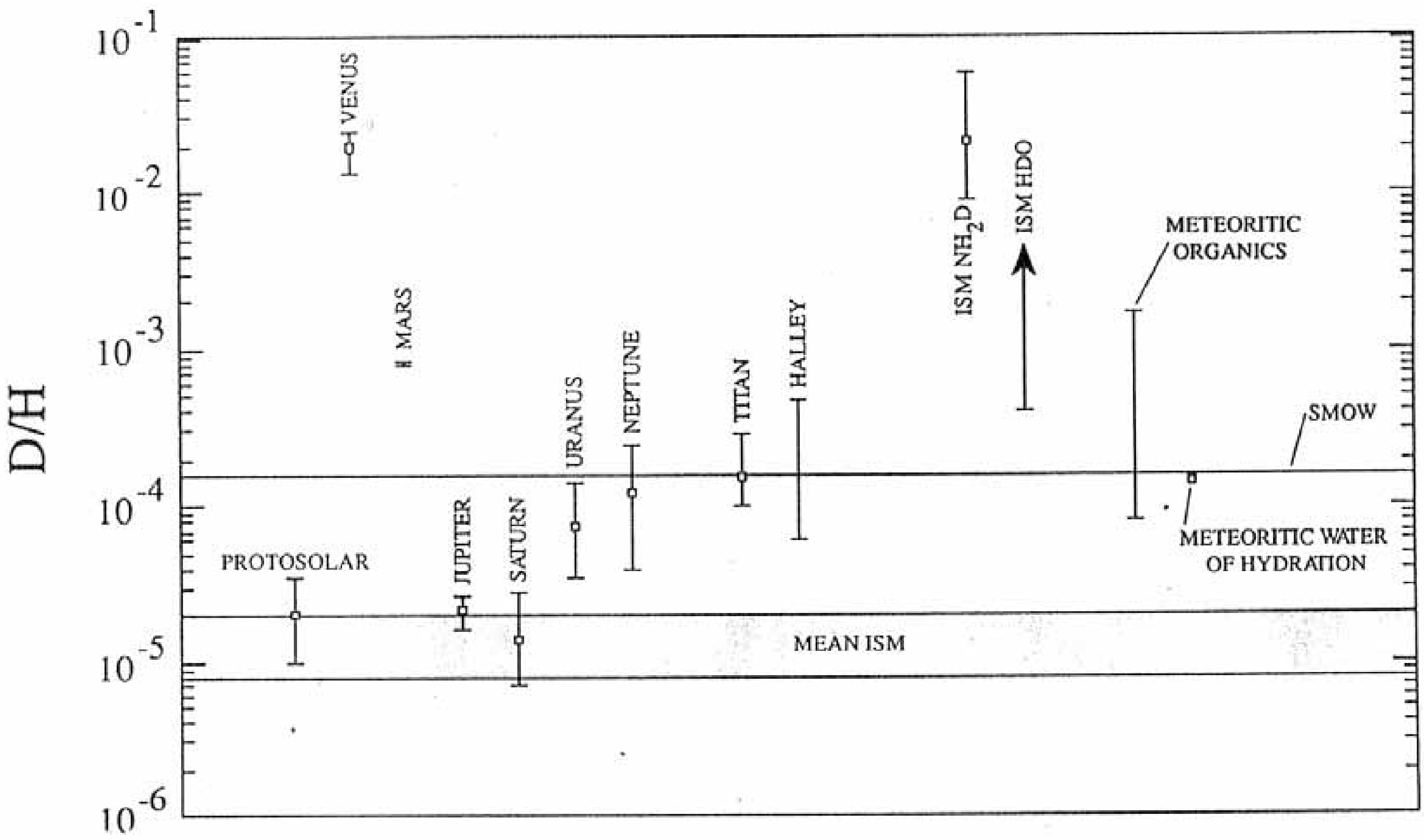
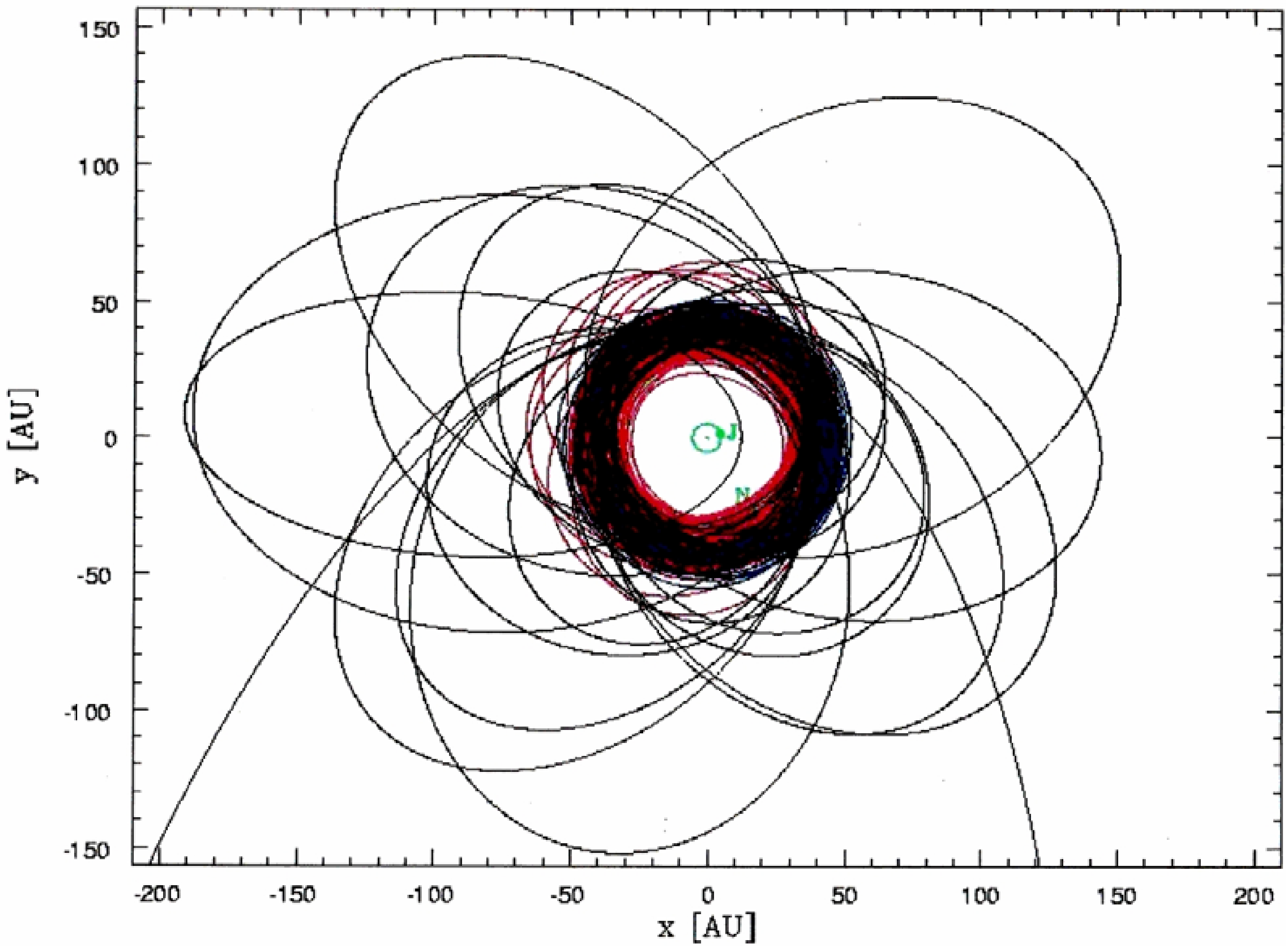
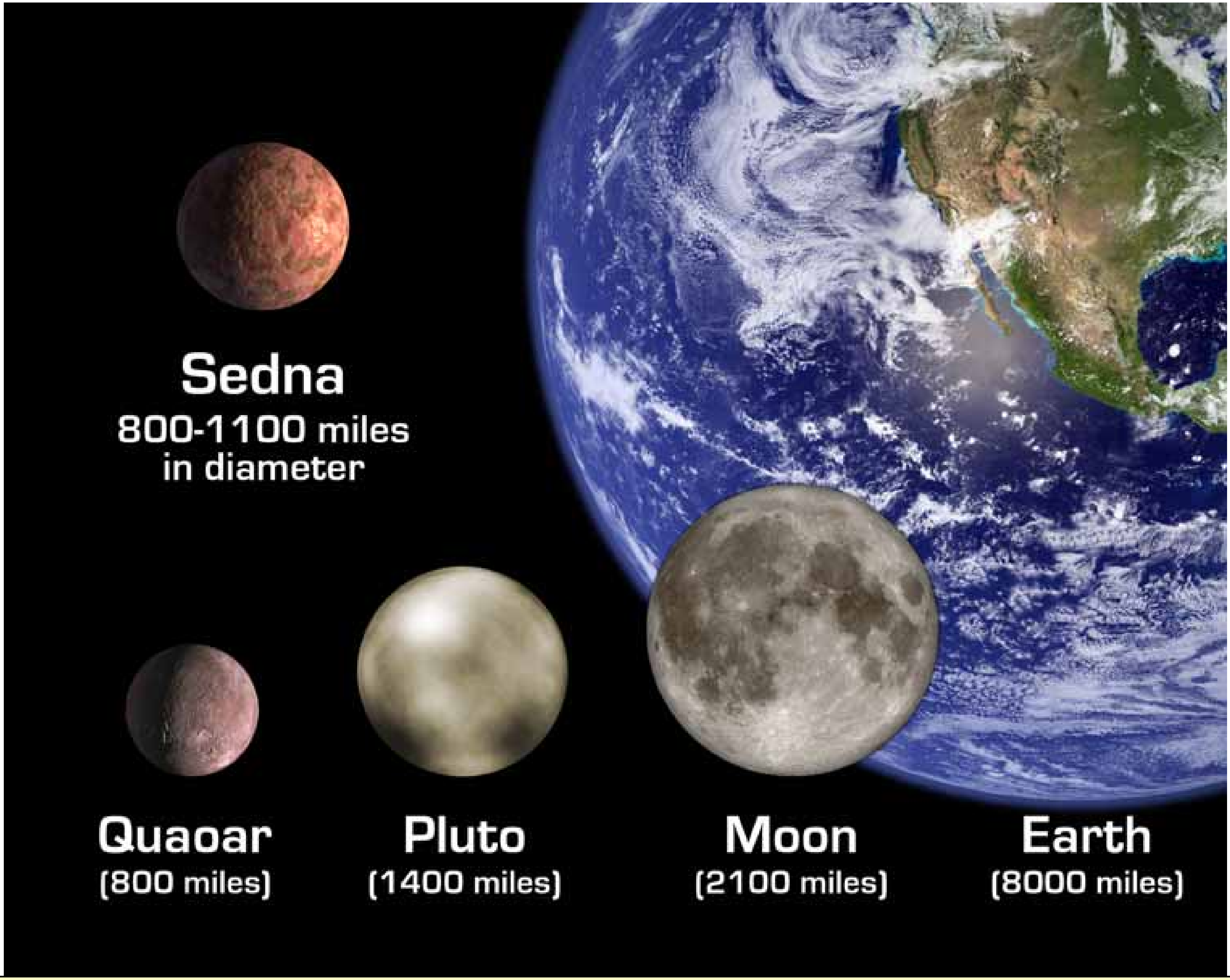


Figure 4.16 D/H ratios in the solar system and interstellar molecular clouds. The uncertainties in the measurement are enclosed by vertical bar. SMOW = standard mean ocean water, ISM= interstellar medium

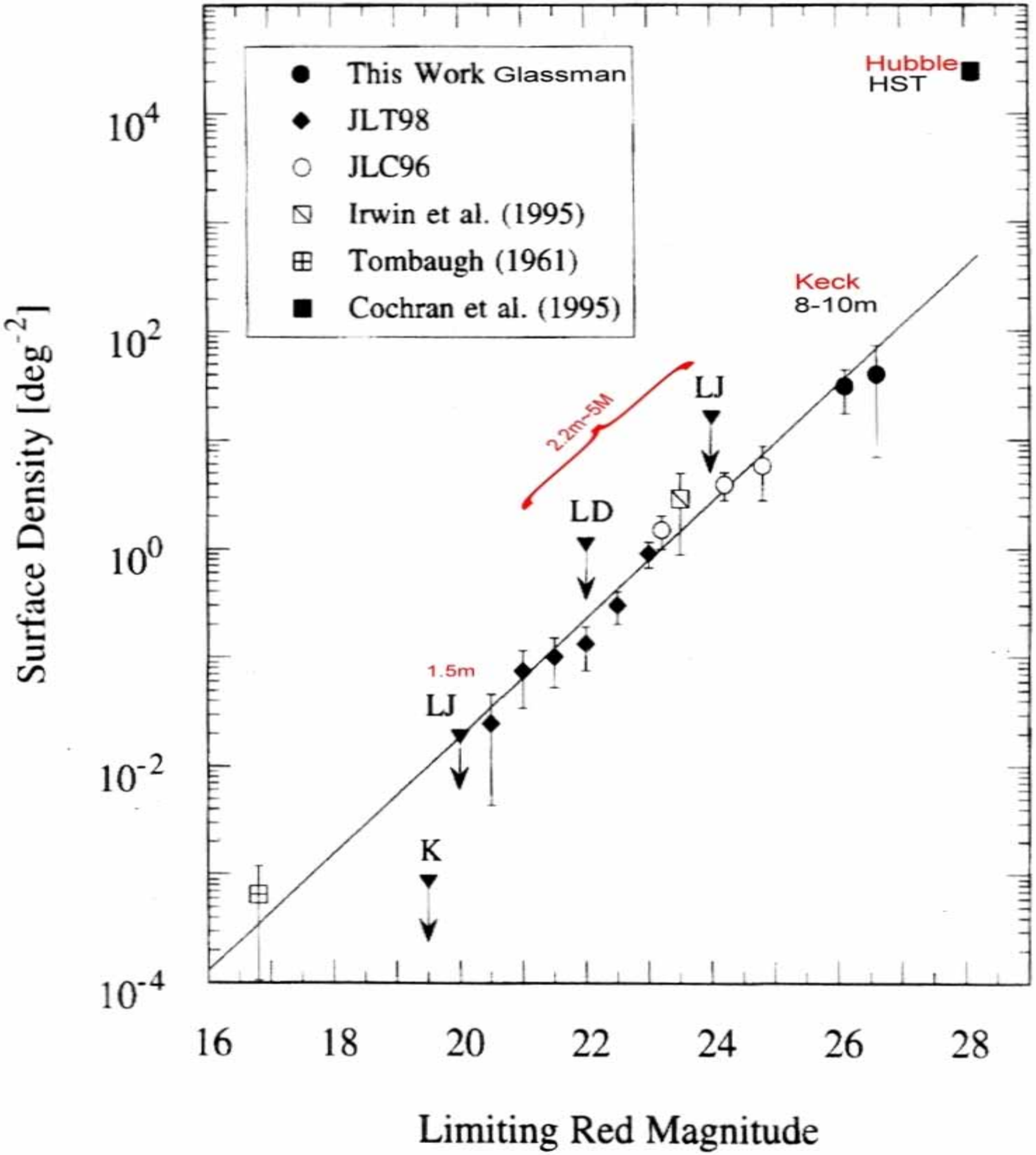


Plutino, Classical, scattered March, 2003, 700+ KBOs?



Sedna Size Comparison

The artist's rendition shows the newly discovered planet-like object, dubbed 'Sedna,' in relation to other bodies in the Solar System, including Earth and its Moon; Pluto; and Quaoar, a planetoid beyond Pluto that was until now the largest known object beyond Pluto.



$N(S) \propto S^{-q}$

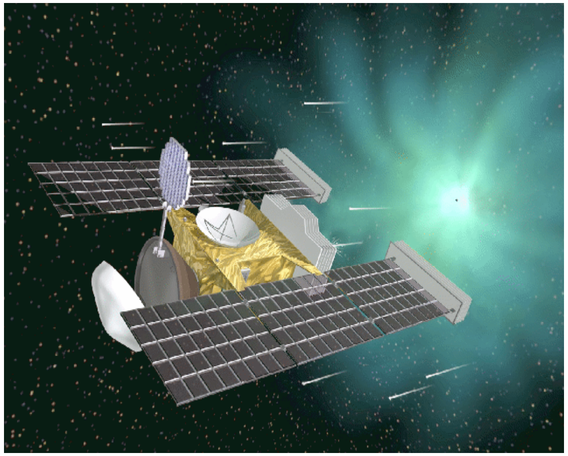
S= diameter

q= 3.5±0.5

STARDUST: space mission for comet sample return.

Dusts carried in the jets from comet Wild-2 were collected at a distance of 200+ km from its nucleus during the 1/2004 fly-by.

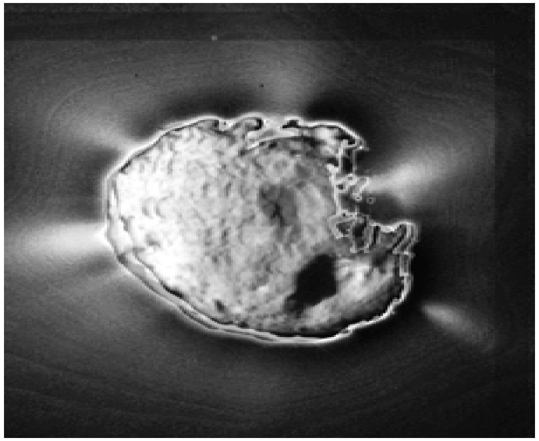
The sample module will be dropped to Utah on 1/14/2006.



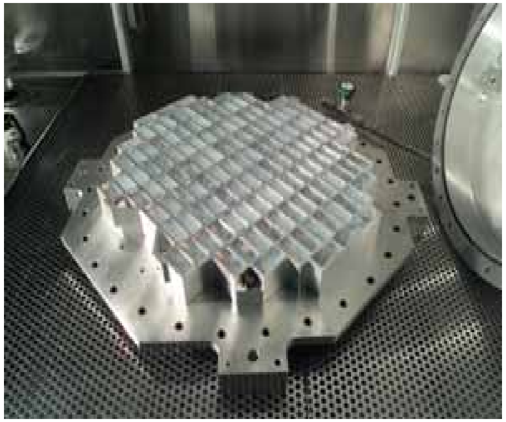
Fly-by results summarized in *Science*, *304*, 1764, (2004).

official web site:

'stardust. jpl. nasa. gov'



Wild-2 nucleus was small (5km) & dark (reflectivity < 5%).



How to extract dust from aerogel?

DESIGN REQUIREMENTS

I. Wide mass range up to Fe-Ni <=> temp. 10-4,000 mega-k <=> H-burning shell to Si-burning (iron core) inside stars.

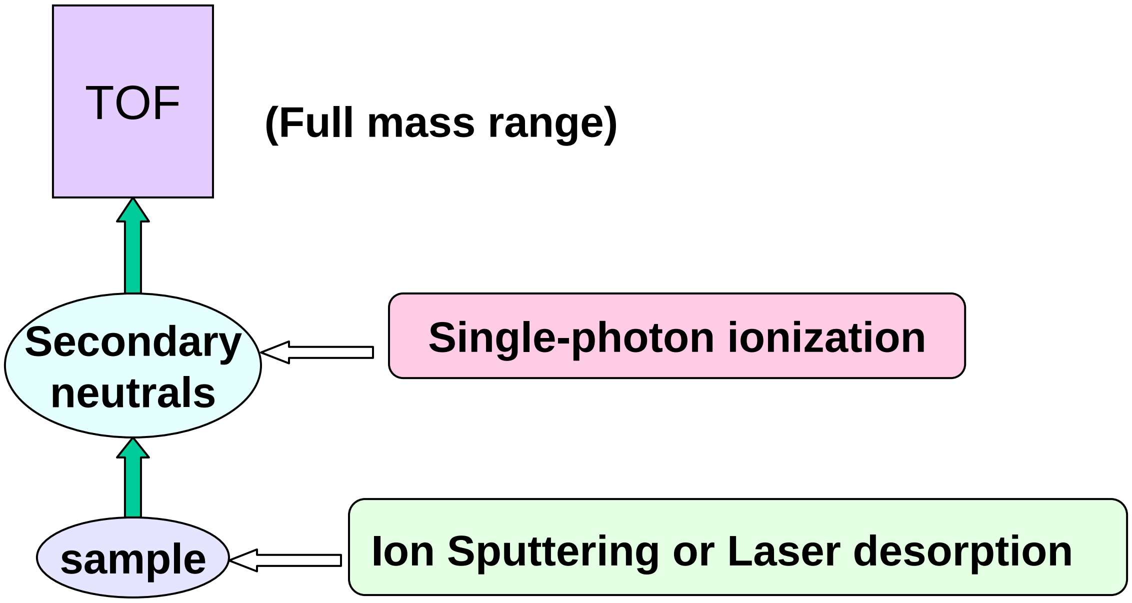
II. High sensitivity => ability to measure dust from comet & ISM ($1\,\mu^3$= 1 pg = 1E10 atoms)

Goal: look for large isotope effect in small grains

Dust size ~ 1 μm, ~10^{-12} gram, ~ 10^{10} atoms

3σ ~ 10% effect

Cover as many as isotope ratios over large mass range in order to examine the structure of individual source star of solar system nuclides

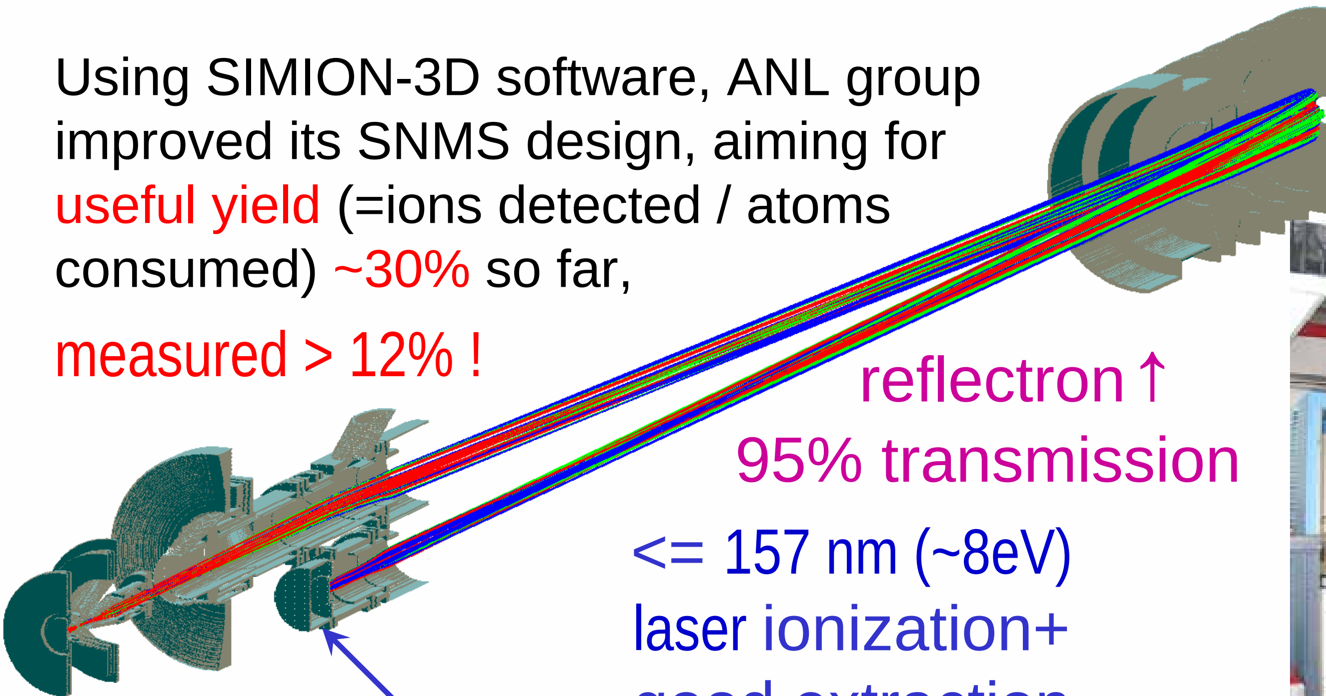


Secondary-Neutral Mass-Spectrometry

(Time-Of-Flight) (Non-Resonant Single-Photon Post-Ionization)

Using SIMION-3D software, ANL group improved its SNMS design, aiming for useful yield (=ions detected / atoms consumed) ~30% so far,

measured > 12% !



reflectron↑
95% transmission

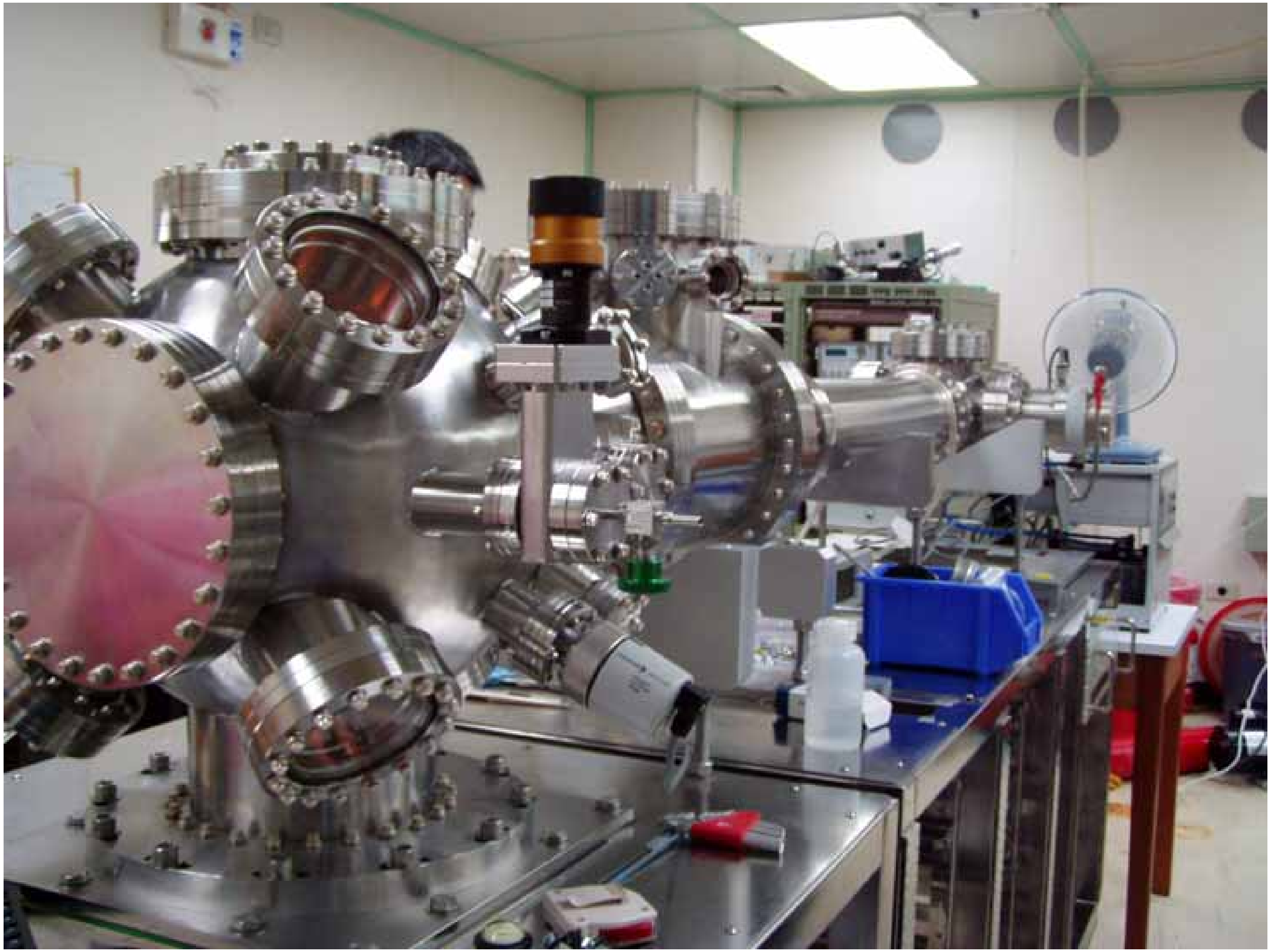
<= 157 nm (~8eV)
laser ionization+
good extraction
in 4x4x3 mm^3

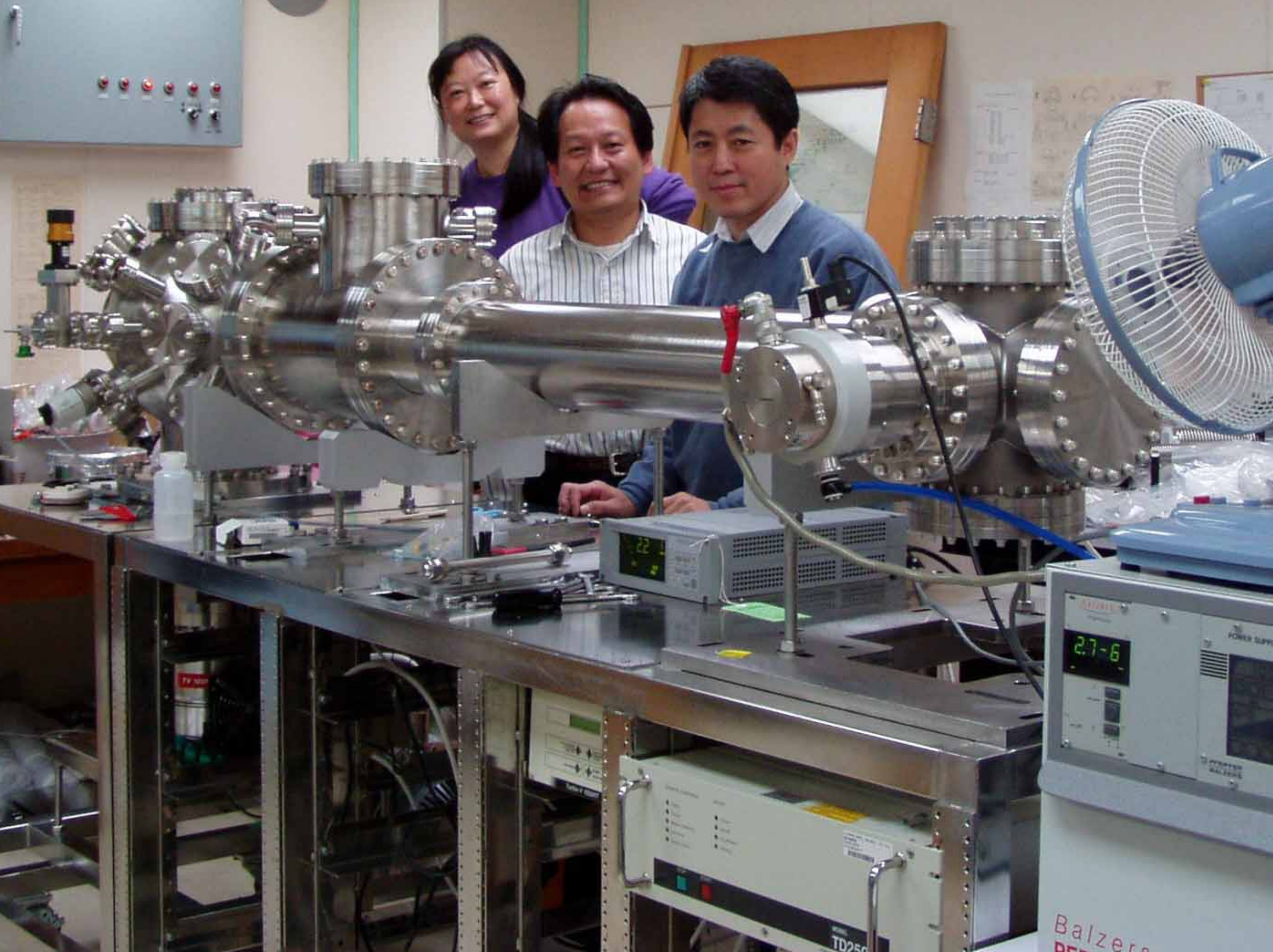
In matter sputtered or ablated off the sample surface: neutral >> ion, => SNMS >> SIMS in sensitivity.

We are using SPIRIT↗one of the three new SNMS built by ANL to develop NR-SNMS methodology. AS is building DUST BUSTER based on ANL design. Together, we study dust and further improve the instrument.

DUST-BUSTER: Secondary-Neutral Mass-Spec Time-Of-Flight.

(157 nm~8eV) Single-Photon Post-Ionization (Non-Resonant)




Balzers

Alignment test of the chamber ports

Sections of ion optics

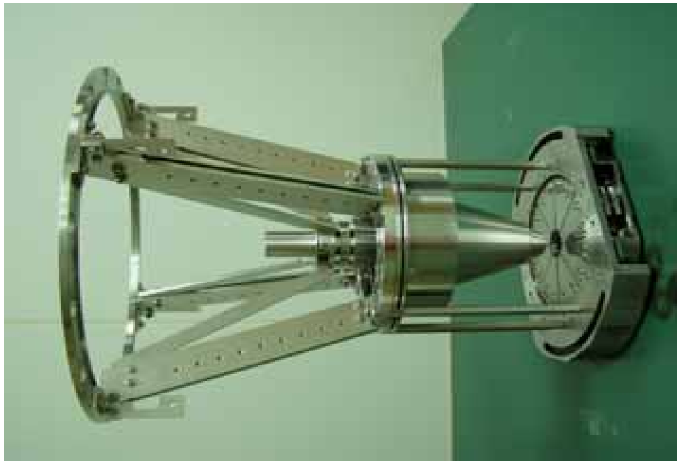
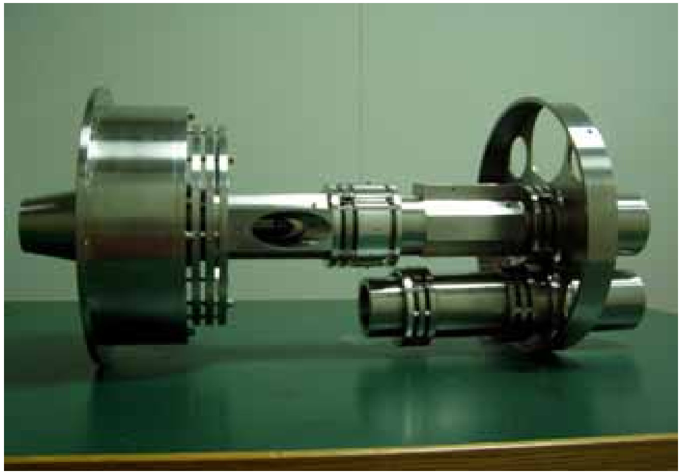
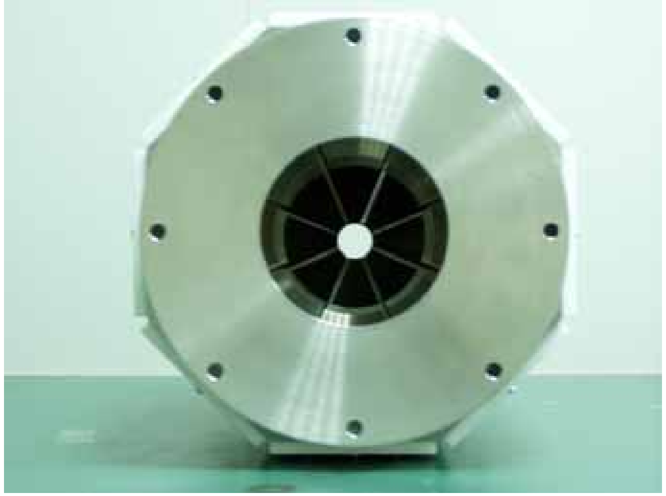


Photo-ion extraction section



Ion beam bending &
detector housing section

Reflectron section (side view)

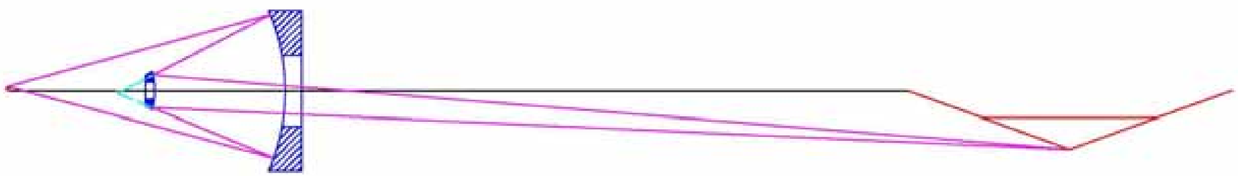


Reflectron (front view)

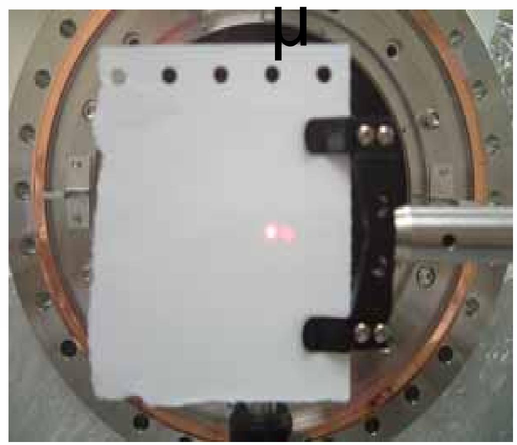
Ion optics mounted in vacuum chamber

Schwarzschild microscope
(cousin of Cassegrain telescope)

A reflecting microscope with long working distance and high magnification for illuminating, viewing, and photo-desorbing μm samples.

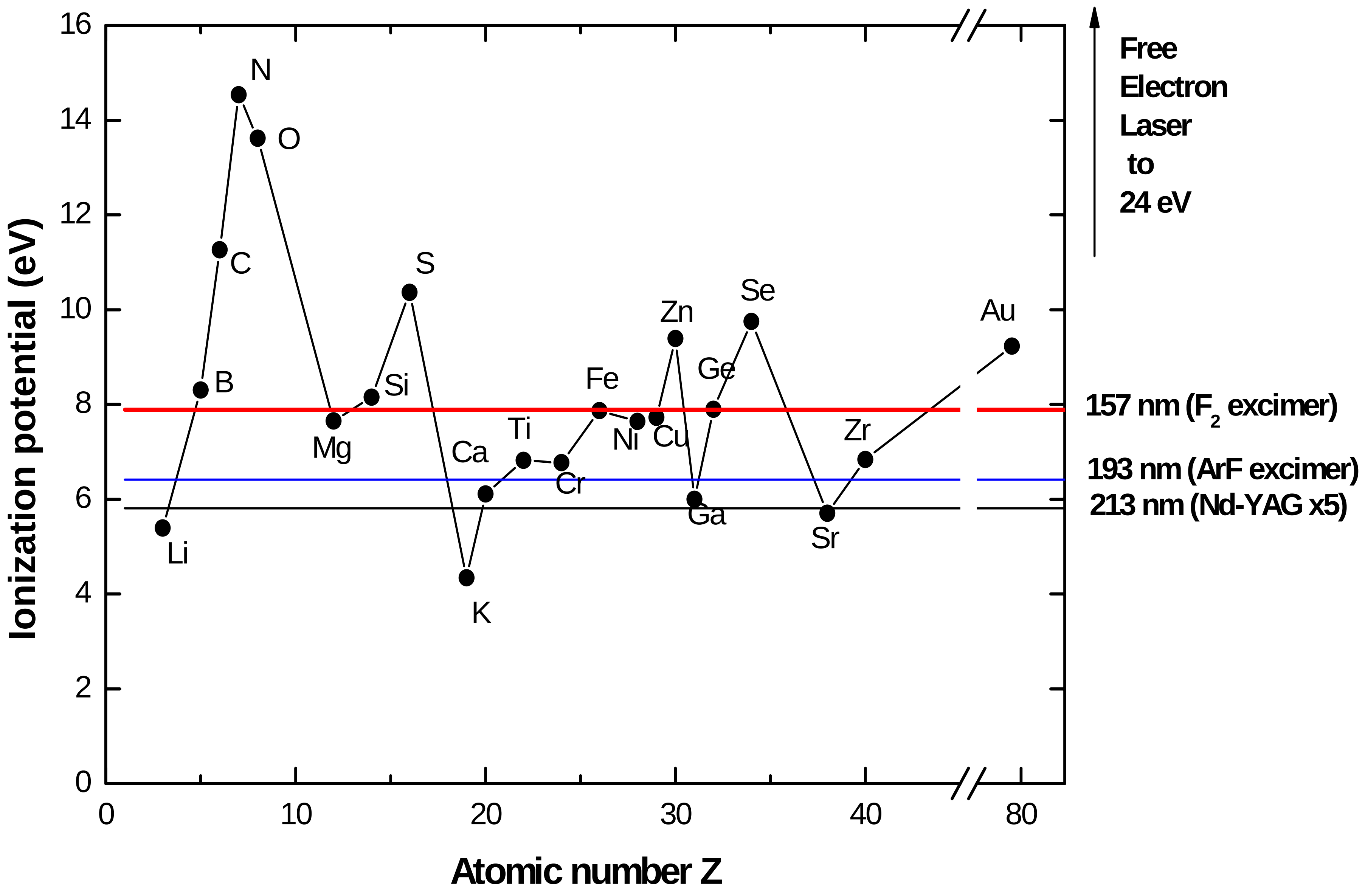


μ

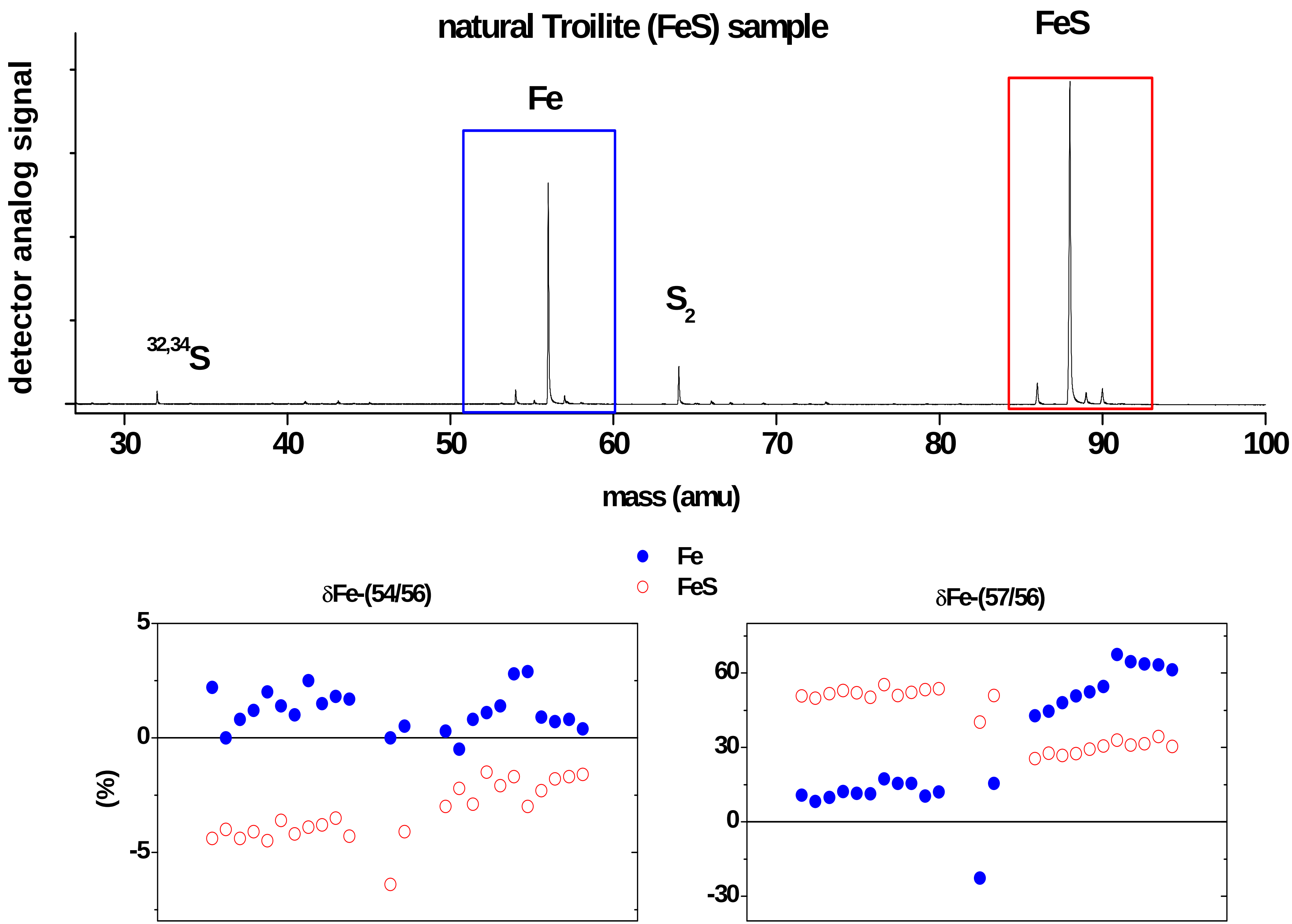


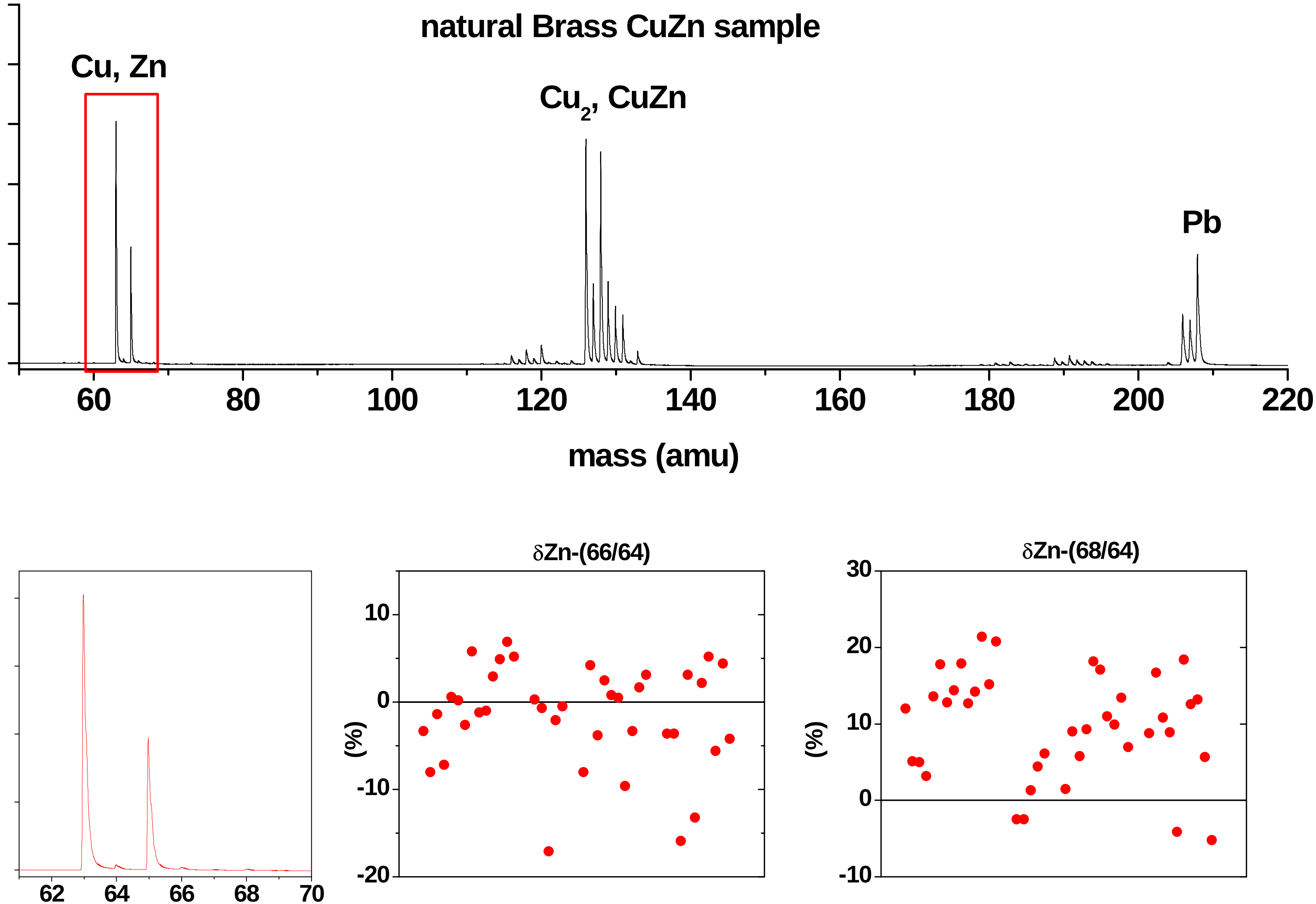
2.2 μm wide bars on the air force test pattern (right photo) were resolved.

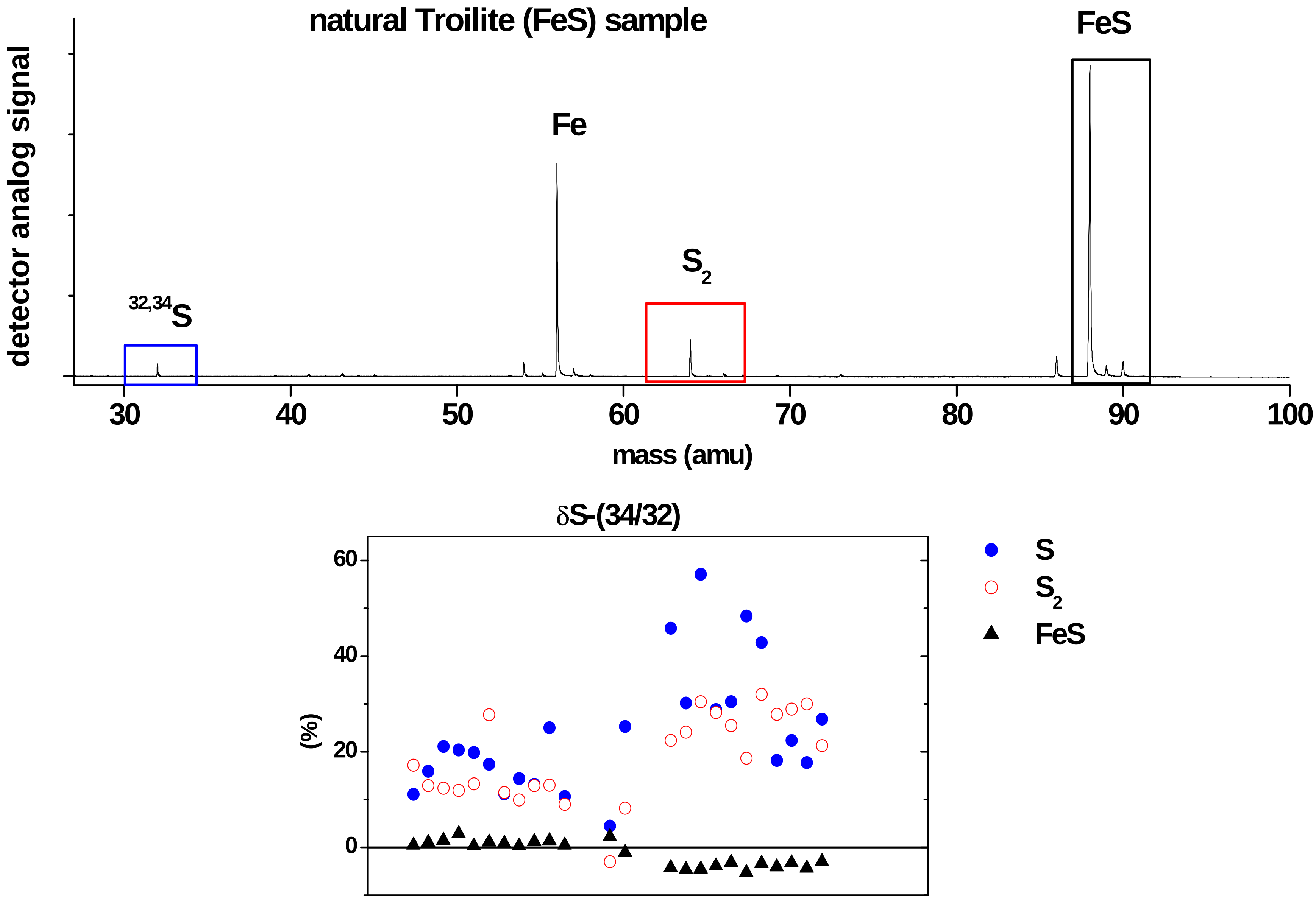
Ionization potentials of atomic elements vs. laser wavelength

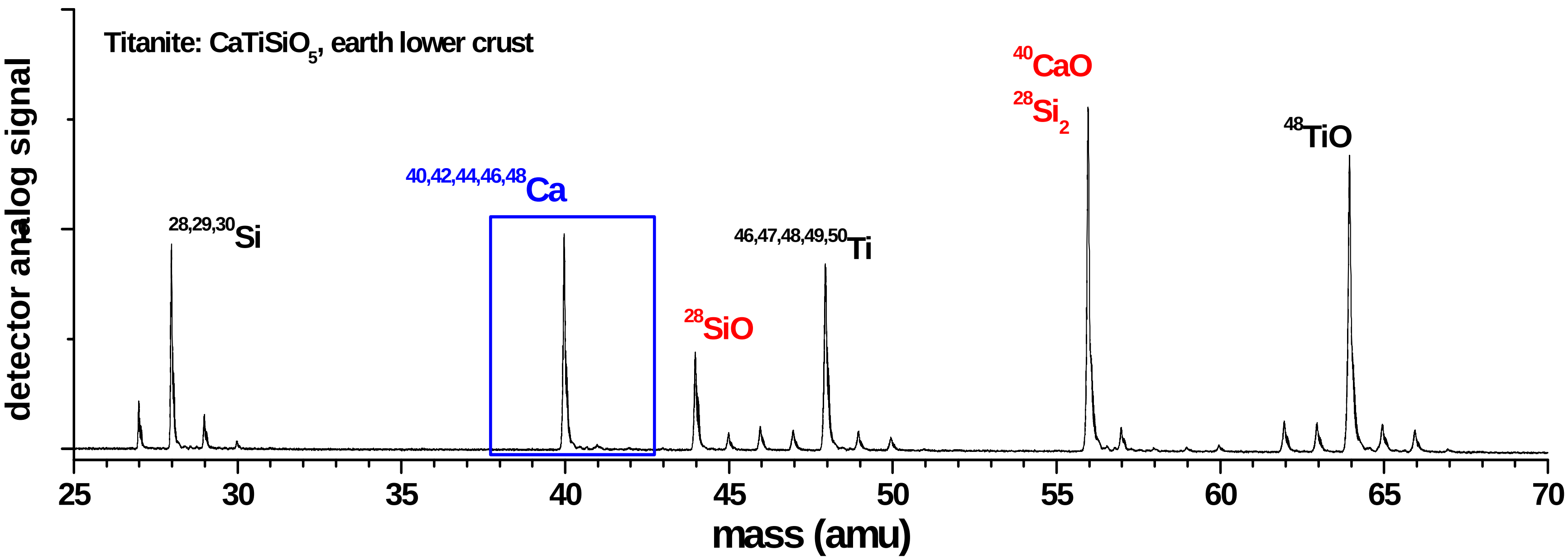


Element	Isotope	Ion	Sample
Mg	24, 25, 26	Mg^+	Ruby Spinel ($MgAl_2O_4$)
			Synthetic MgO
			Rutile (TiO_2) (N. Carolina NMNH120812)
			Diopside ($MgCaSi_2O_6$) (Mantle xenolith (San Carlos))
Si	28, 29, 30	Si	Sphene ($CaTiSiO_5$) (Brazil NMNHR17030)
S	32, 34	S^+, S_2^+, FeS^+	Troilite (FeS) (california NMNH94472-2)
Ca	40, 42	Ca^+	Sphene
Ti	46, 47, 48, 49, 50	Ti^+, TiO^+	Sphene
			Rutile
Fe	54, 56, 57	Fe^+, FeS^+	Troilite
		Fe^+, $FeOH^+$	Iron meteorite (cape york)
Ni	58, 60, 61, 62, 64	Ni^+	Iron meteorite

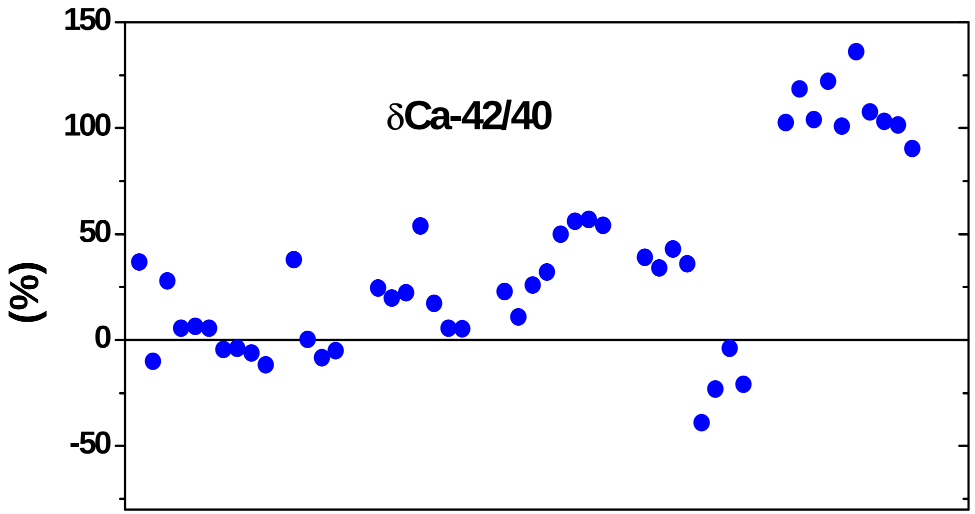

natural Troilite (FeS) sample
FeS
Fe
S_2
$^{32,34}S$
detector analog signal
30
40
50
60
70
80
90
100
mass (amu)
Fe
FeS
δFe-(54/56)
δFe-(57/56)
5
0
-5
(%)
60
30
0
-30


natural Brass CuZn sample
Cu, Zn
Cu2, CuZn
Pb
60
80
100
120
140
160
180
200
220
mass (amu)
62
64
66
68
70
δZn-(66/64)
(‰)
10
0
-10
-20
δZn-(68/64)
(‰)
30
20
10
0
-10

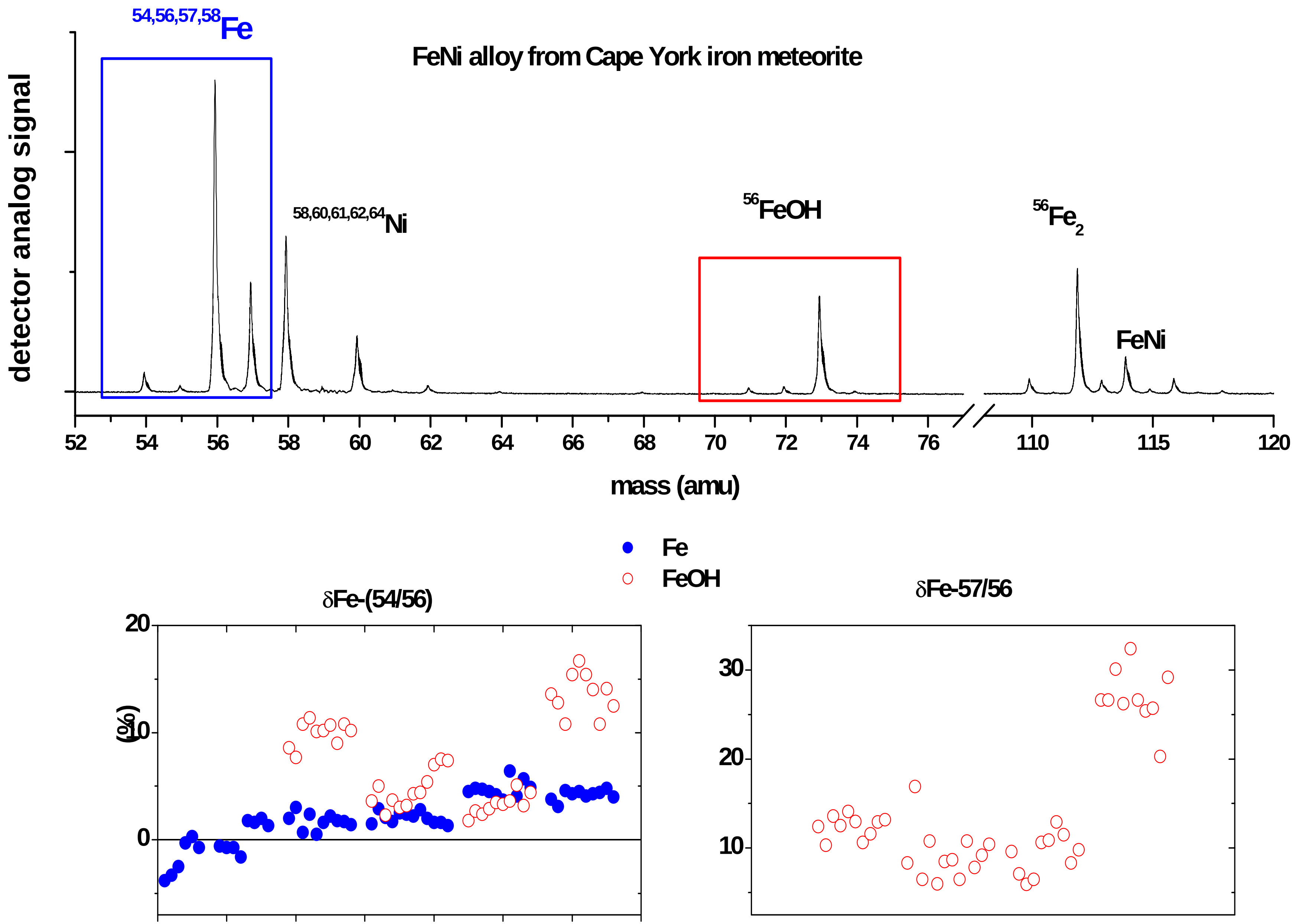

natural Troilite (FeS) sample
detector analog signal
32,34S
Fe
S2
FeS
30
40
50
60
70
80
90
100
mass (amu)
δS-(34/32)
60
40
20
0
(%)
S
S2
FeS



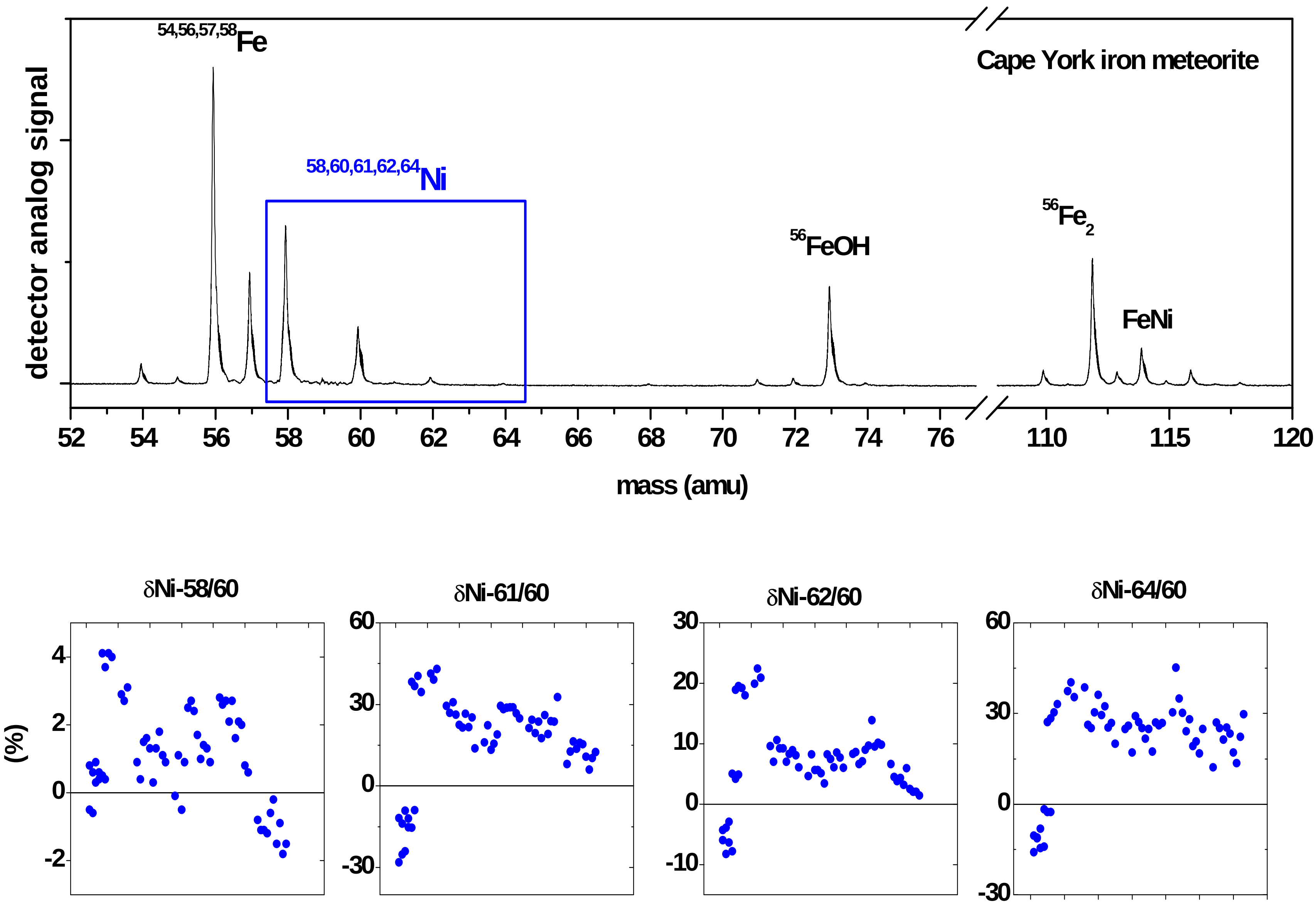
Titanite: CaTiSiO5, earth lower crust
detector analog signal
28,29,30Si
40,42,44,46,48Ca
28SiO
46,47,48,49,50Ti
40CaO
28Si2
48TiO
25
30
35
40
45
50
55
60
65
70
mass (amu)



δCa-42/40
(%)
150
100
50
0
-50



54,56,57,58Fe
FeNi alloy from Cape York iron meteorite
detector analog signal
58,60,61,62,64Ni
56FeOH
56Fe2
FeNi
52 54 56 58 60 62 64 66 68 70 72 74 76 110 115 120
mass (amu)
Fe
FeOH
δFe-(54/56)
(‰)
20
10
0
δFe-57/56
30
20
10



54,56,57,58Fe
Cape York iron meteorite
58,60,61,62,64Ni
56FeOH
56Fe2
FeNi
detector analog signal
52 54 56 58 60 62 64 66 68 70 72 74 76 110 115 120
mass (amu)
δNi-58/60
δNi-61/60
δNi-62/60
δNi-64/60
(%)
4
2
0
-2
60
30
0
-30
30
20
10
0
-10
60
30
0
-30

sample	element	Isotope ratio	Deviation and reproducibility (%)	Photoion species
Natural Troilite (FeS)	S	34/32	16.4 +/- 4.8	S
			13.8 +/- 5.1	S_2
			1.0 +/- 0.7	FeS
	Fe	54/56	1.5 +/- 0.7	Fe
			-4.1 +/- 0.3	FeS
		57/56	12.2 +/- 2.8	Fe
			52.1 +/- 1.6	FeS
Iron meteorite (FeNi alloy)	Fe	54/56	4.2 +/- 0.5	Fe
			13.6 +/- 1.9	FeOH
		57/56	1013.8 +/- 125	Fe
			26.9 +/- 3.2	FeOH
	Ni	58/60	-1.1 +/- 0.5	Ni
		61/60	12.1 +/- 3.4	
		62/60	3.6 +/- 1.7	
		64/60	21.7 +/- 5.8	

CHALLENGES

The dynamic range of the detector is being improved to get higher S/N simultaenously for both major and minor isotopes.

Pulsing MCP HV, gain switching multiplier

Hydride Interference is significant especially for the peaks one amu above major isotopes (such as Mg 24+H at Mg-25).

Higher resolving power, reduce H-source.

STATUS (4/2005)

Methodology development using the SPIRIT at ANL are well underway. A number of key elements (Mg, Si, S, Ca, TI, Fe, Ni, Cu, Zn, Sn, Zr, Mo, and Pb so far) are being explored in a variety of terrestrial, meteoritic, and man-made host material. We found :

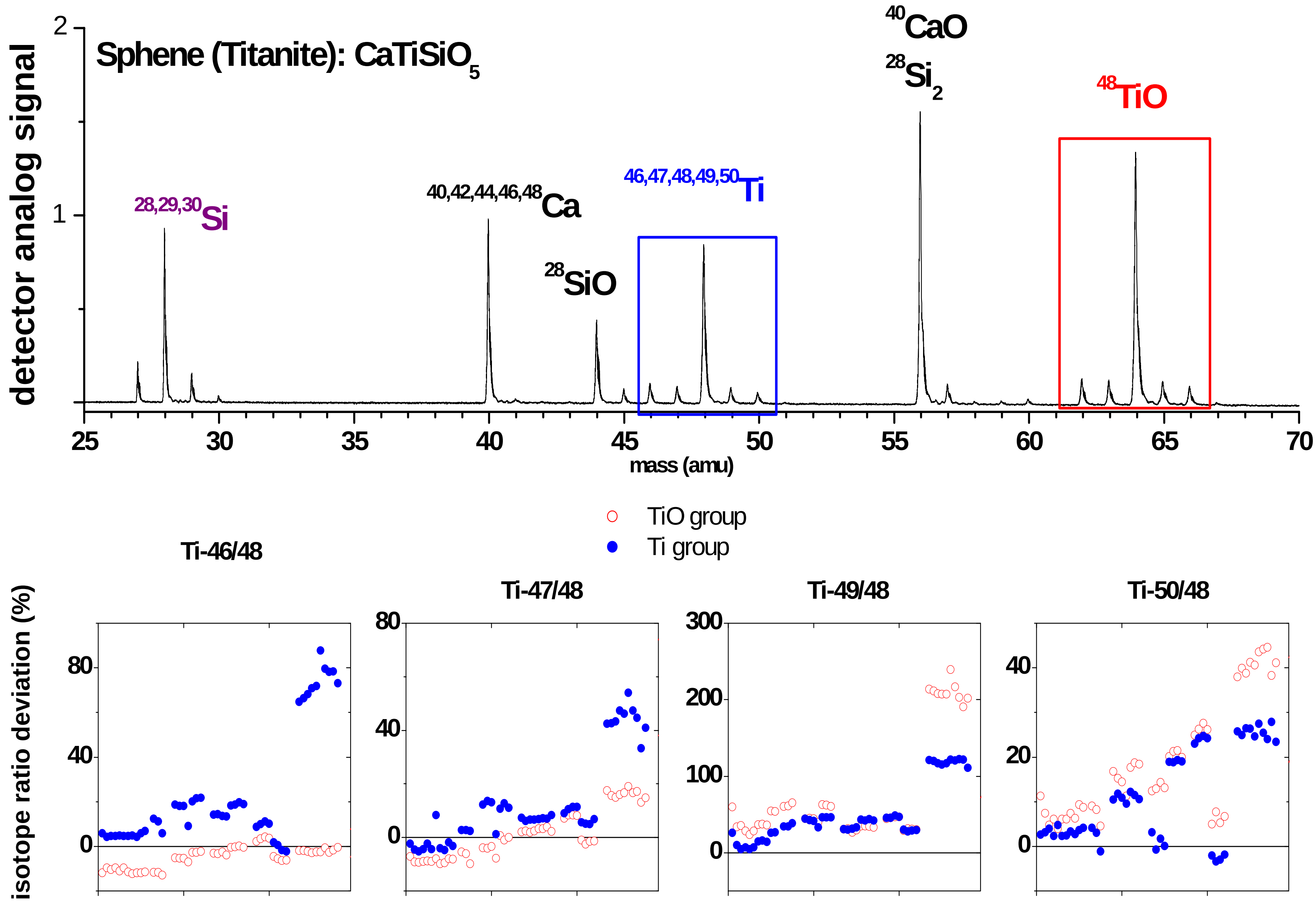
High S/N isotope ratios can be measured with good precision (s<2%)

Same isotope ratios measured on different species in the same mass spectrum provide internal checks against false alarms (e.g. due to interference). Ti, TiO, Fe, FeS, FeNi.

High ionization potential elements sometimes can be analyzed as molecules. (S-FeS)

The construction of DUST BUSTER will be completed by this summer. It will go through extensive testing including the analysis using star dust samples from meteorites before comet samples returned by the STAR DUST are ready for distribution by mid-2006.

Vibration problem and solution.

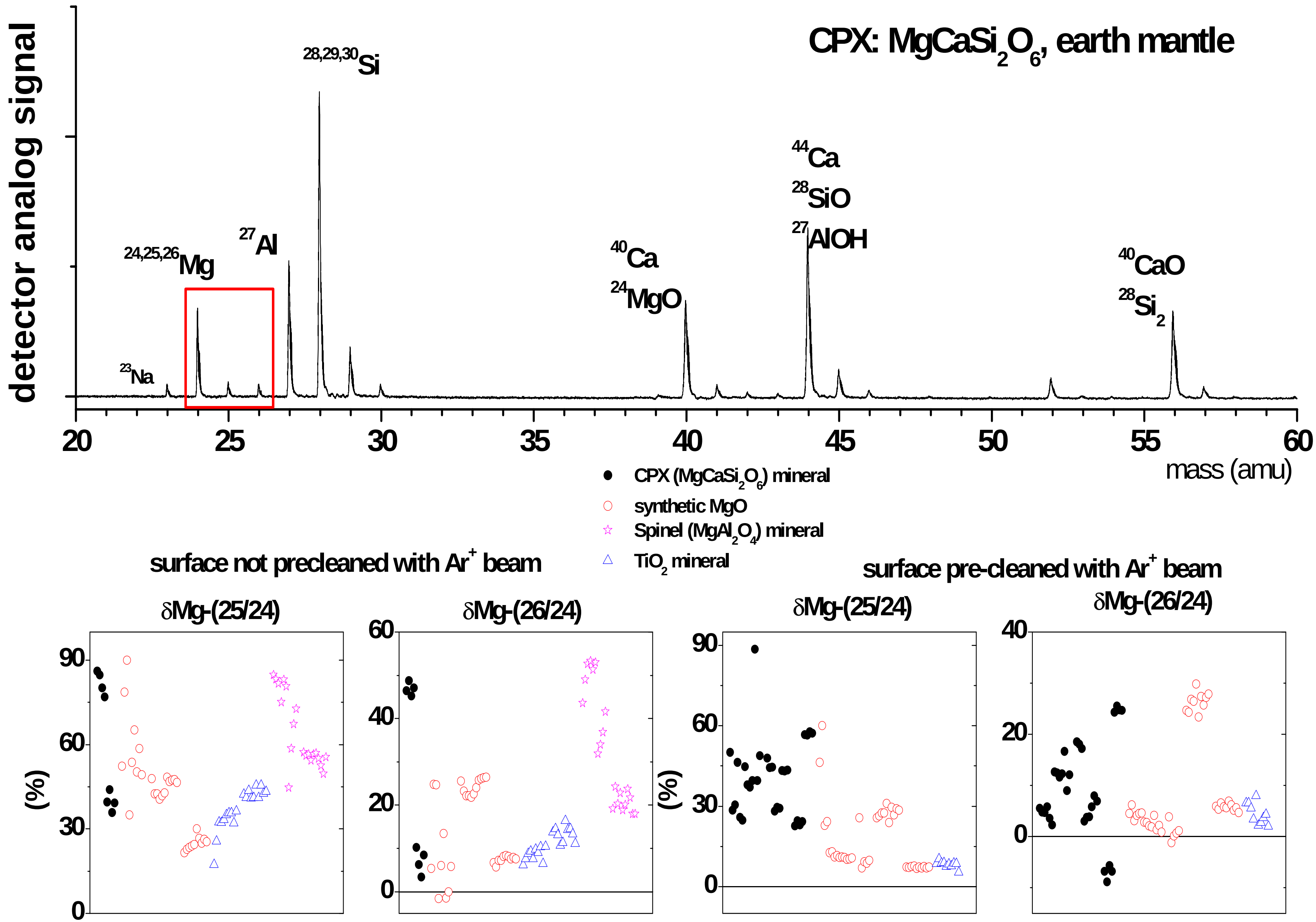


Sphene (Titanite): CaTiSiO5
detector analog signal
28,29,30Si
40,42,44,46,48Ca
28SiO
46,47,48,49,50Ti
40CaO
28Si2
48TiO
mass (amu)
TiO group
Ti group
Ti-46/48
Ti-47/48
Ti-49/48
Ti-50/48
isotope ratio deviation (%)

Difference of measured isotopic ratio to that in solar material and the experiment reproducibility at 1σ level (the deviation are calculated only from those data which are taken under the same experimental parameters)

sample	element	Isotope ratio	Deviation and reproducibility (%)
Titanite ($CaTiSiO_5$)	Si	29/28	250.8 +/- 6.8
		30/28	54.4 +/- 3.3
	Ca	42/40	54.3 +/- 3.1
	Ti	46/48	19.0 +/- 0.6
			-0.2 +/- 0.3
		47/48	7.3 +/- 0.7
			3.2 +/- 0.7
		49/48	42.3 +/- 0.9
			34.3 +/- 0.6
		50/48	19.0 +/- 0.2
			20.8 +/- 0.8

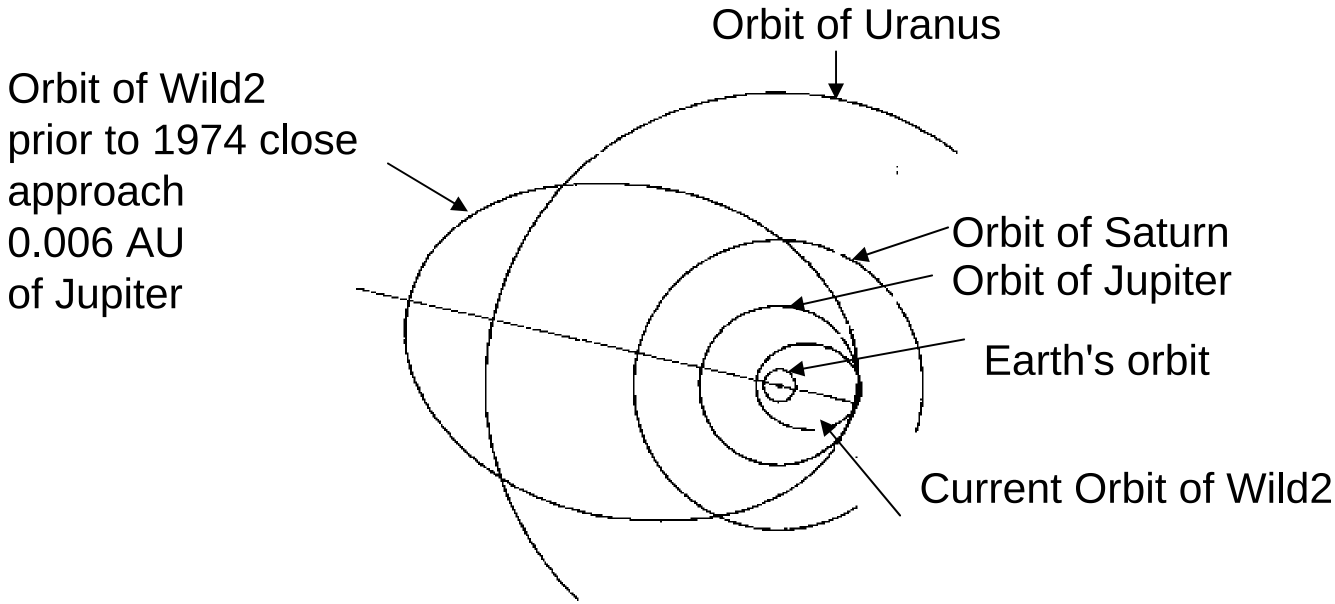
The ratios of Si, Ca, and Ti shown in this table are all extracted from the same mass spectra


CPX: MgCaSi2O6, earth mantle
detector analog signal
23Na
24,25,26Mg
27Al
28,29,30Si
40Ca
24MgO
44Ca
28SiO
27AlOH
40CaO
28Si2
20
25
30
35
40
45
50
55
60
mass (amu)
CPX (MgCaSi2O6) mineral
synthetic MgO
Spinel (MgAl2O4) mineral
TiO2 mineral
surface not precleaned with Ar+ beam
surface pre-cleaned with Ar+ beam
δMg-(25/24)
δMg-(26/24)
δMg-(25/24)
δMg-(26/24)
(%)
90
60
30
0
60
40
20
0
(%)
90
60
30
0
40
20
0

Comet Wild-2

(discovered by Paul Wild on January 6, 1978)

Jupiter family comet.
perihelion : near Mars;
aphelion: near Jupiter



http://stardust.jpl.nasa.gov

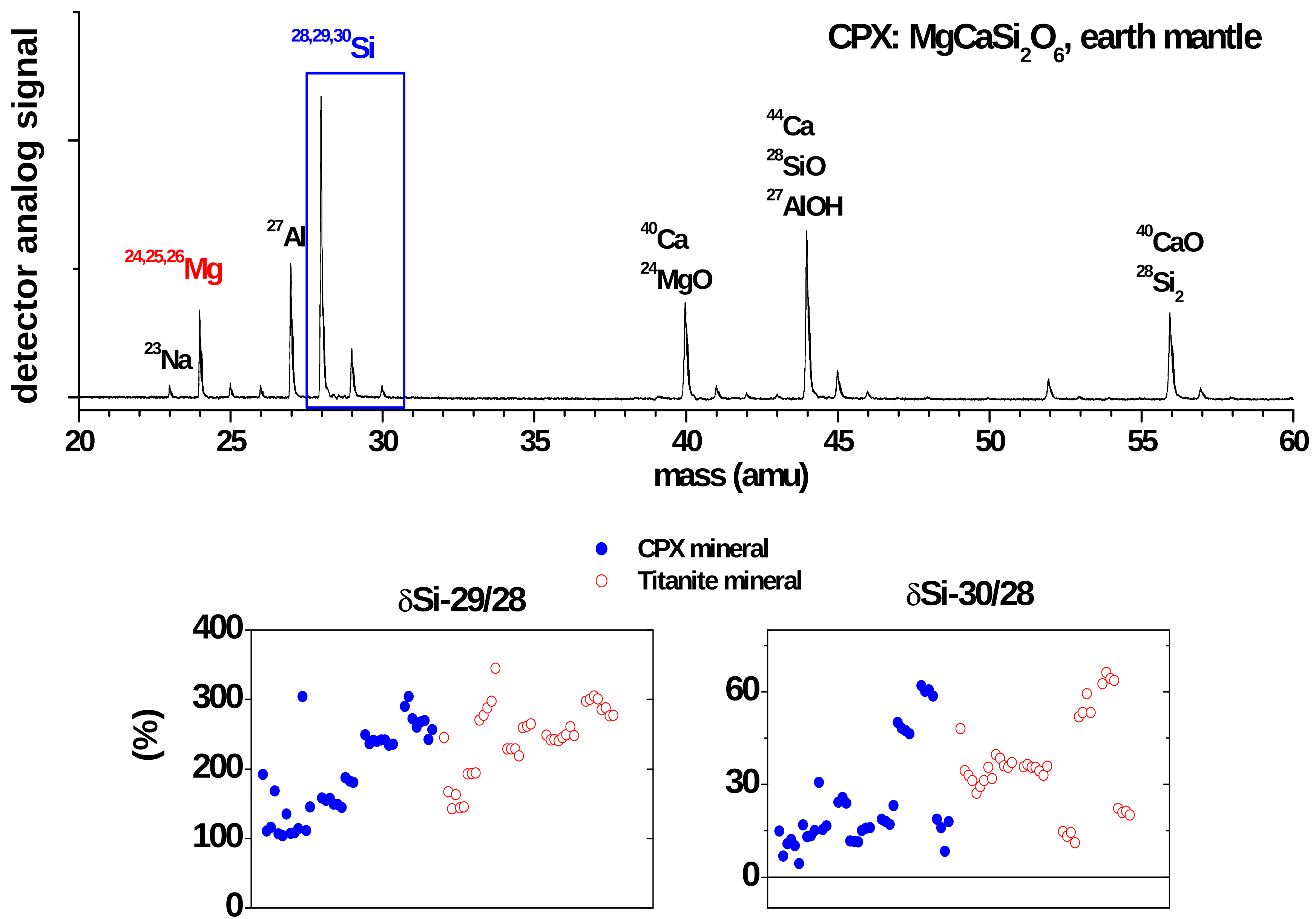
Hope for :

1: cometary dusts collected from Wild-2 will have a safe journey
return to earth.

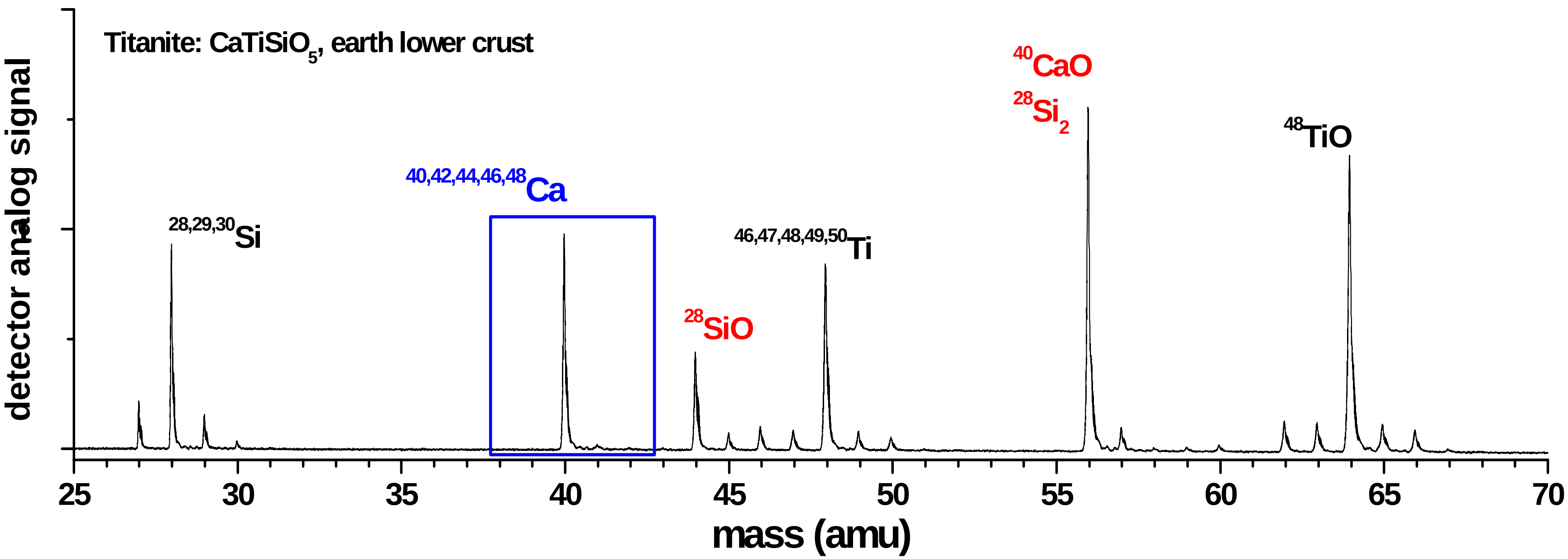
2: collected dust grain is pristine, has not been mixed and homogenized,
its characteristic isotopic composition from the source star is still preserved.

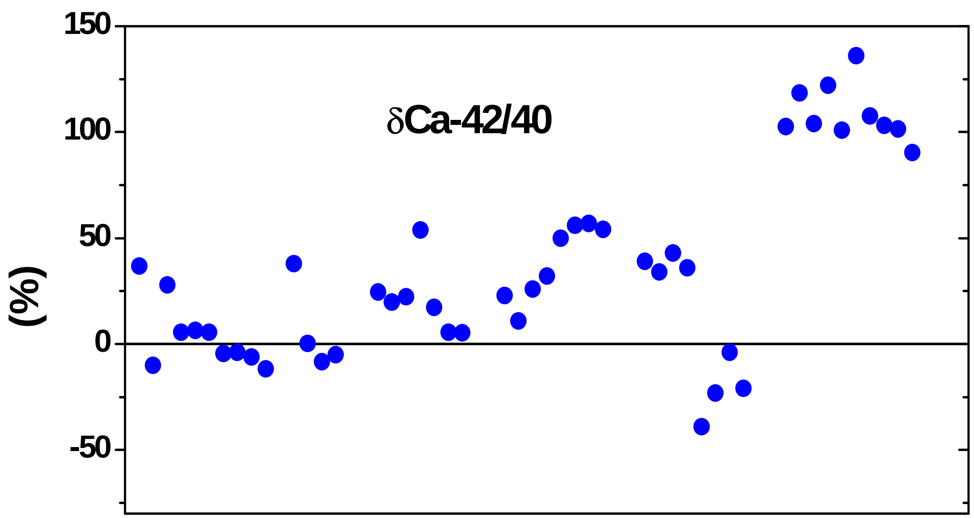
Science goal:

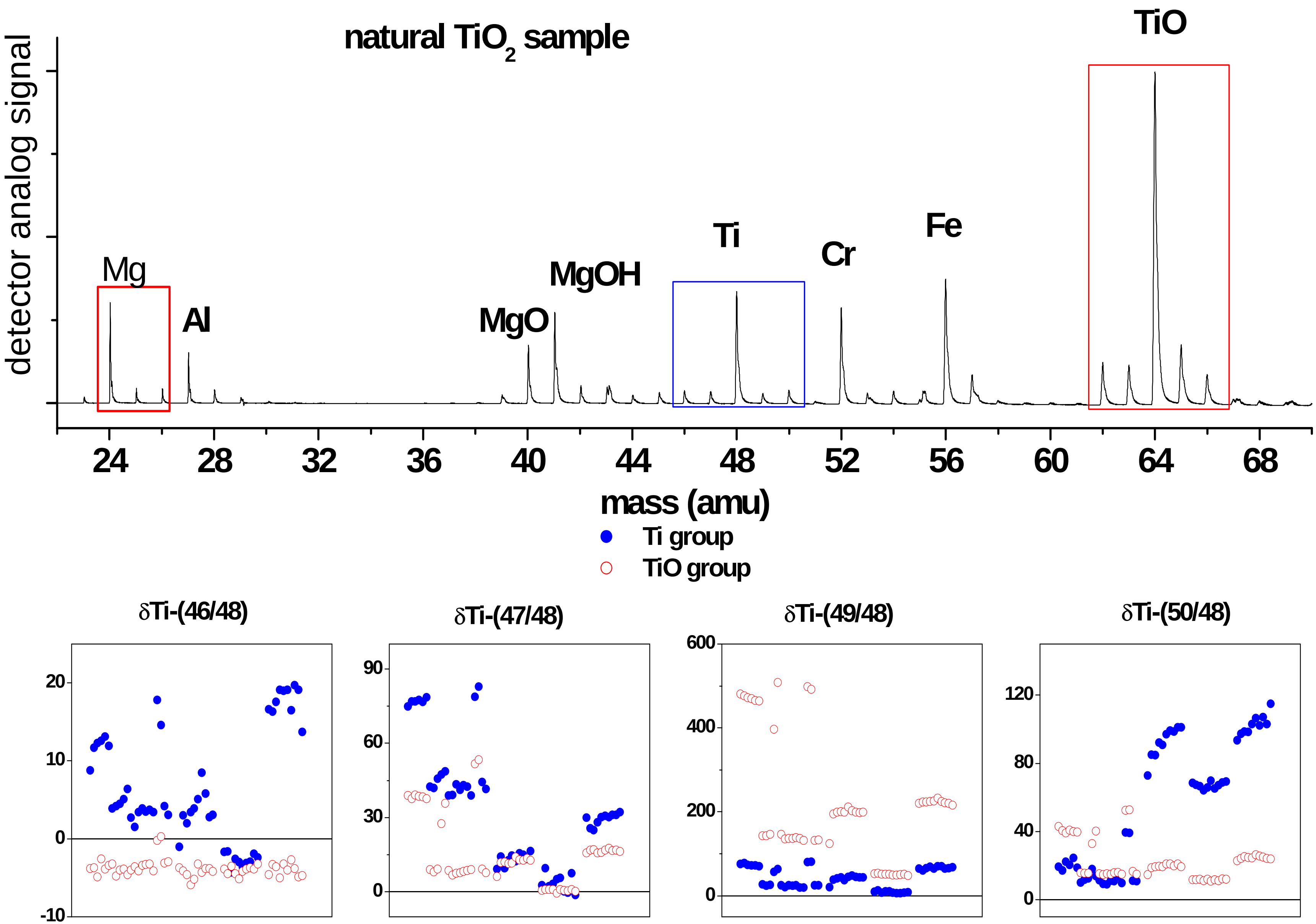
Get to know our cosmic origin:;
identify source stars of our solar system nuclides by comparing the isotopic signature of different nucleosynthetic processes with the measured isotopic compositions.

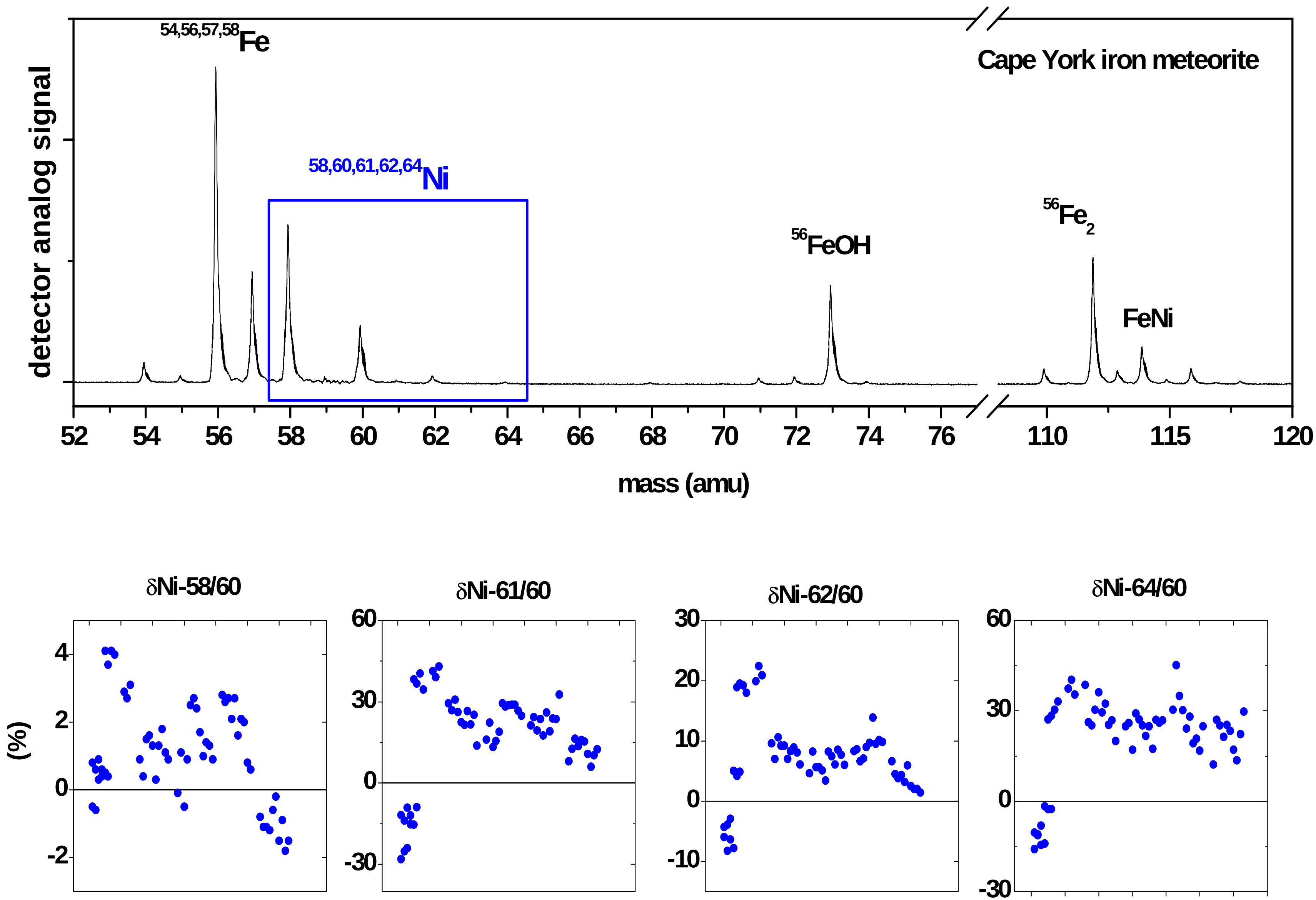


detector analog signal
CPX: MgCaSi2O6, earth mantle
28,29,30Si
24,25,26Mg
23Na
27Al
40Ca
24MgO
44Ca
28SiO
27AlOH
40CaO
28Si2
20
25
30
35
40
45
50
55
60
mass (amu)
CPX mineral
Titanite mineral
δSi-29/28
δSi-30/28
(%)
400
300
200
100
0
60
30
0

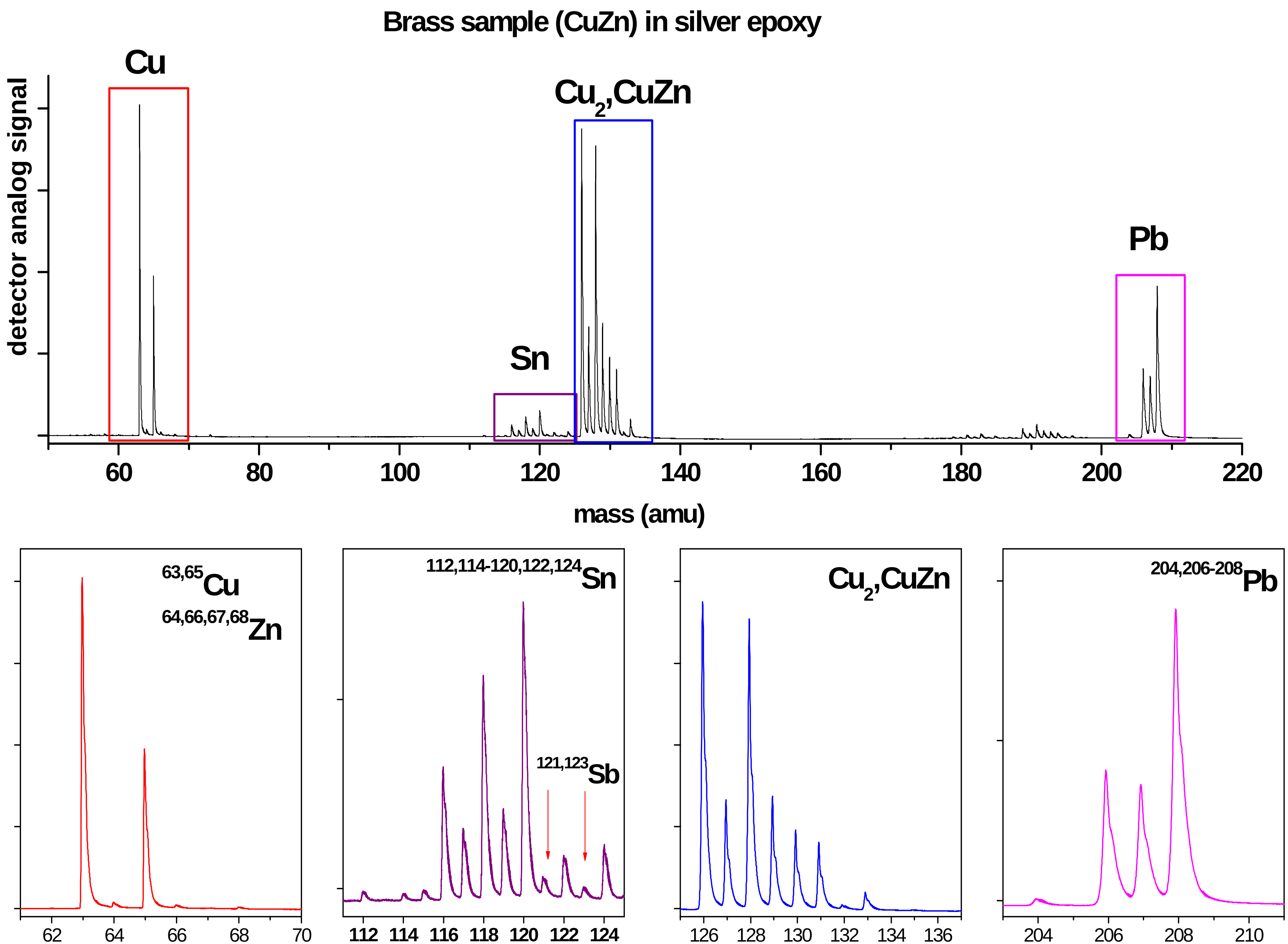

Titanite: CaTiSiO5, earth lower crust
detector analog signal
mass (amu)
28,29,30Si
40,42,44,46,48Ca
28SiO
46,47,48,49,50Ti
40CaO
28Si2
48TiO
25
30
35
40
45
50
55
60
65
70


δCa-42/40
(%)
150
100
50
0
-50

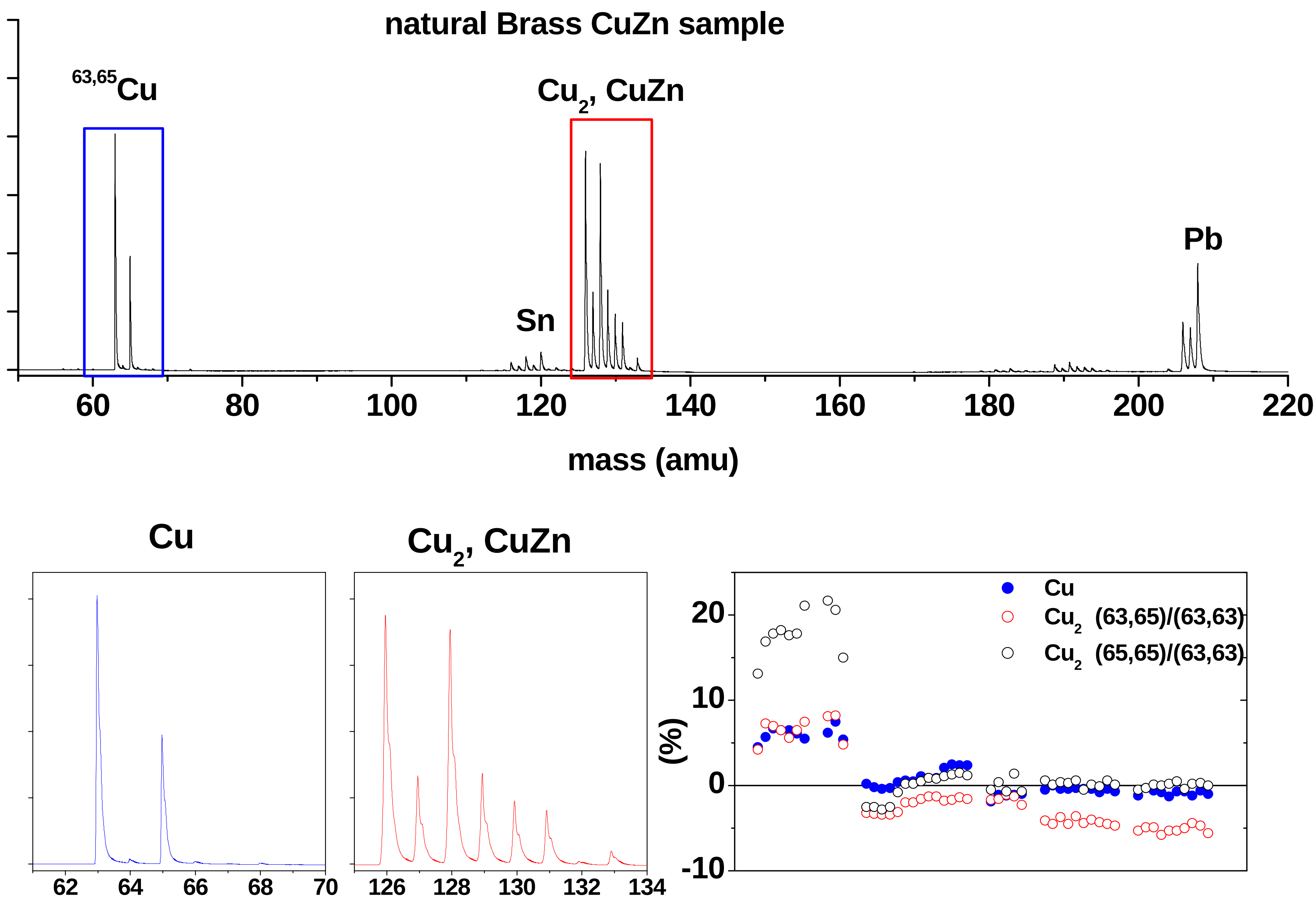

natural TiO_2 sample
detector analog signal
Mg
Al
MgO
MgOH
Ti
Cr
Fe
TiO
24
28
32
36
40
44
48
52
56
60
64
68
mass (amu)
Ti group
TiO group
δTi-(46/48)
δTi-(47/48)
δTi-(49/48)
δTi-(50/48)
20
10
0
-10
90
60
30
0
600
400
200
0
120
80
40
0



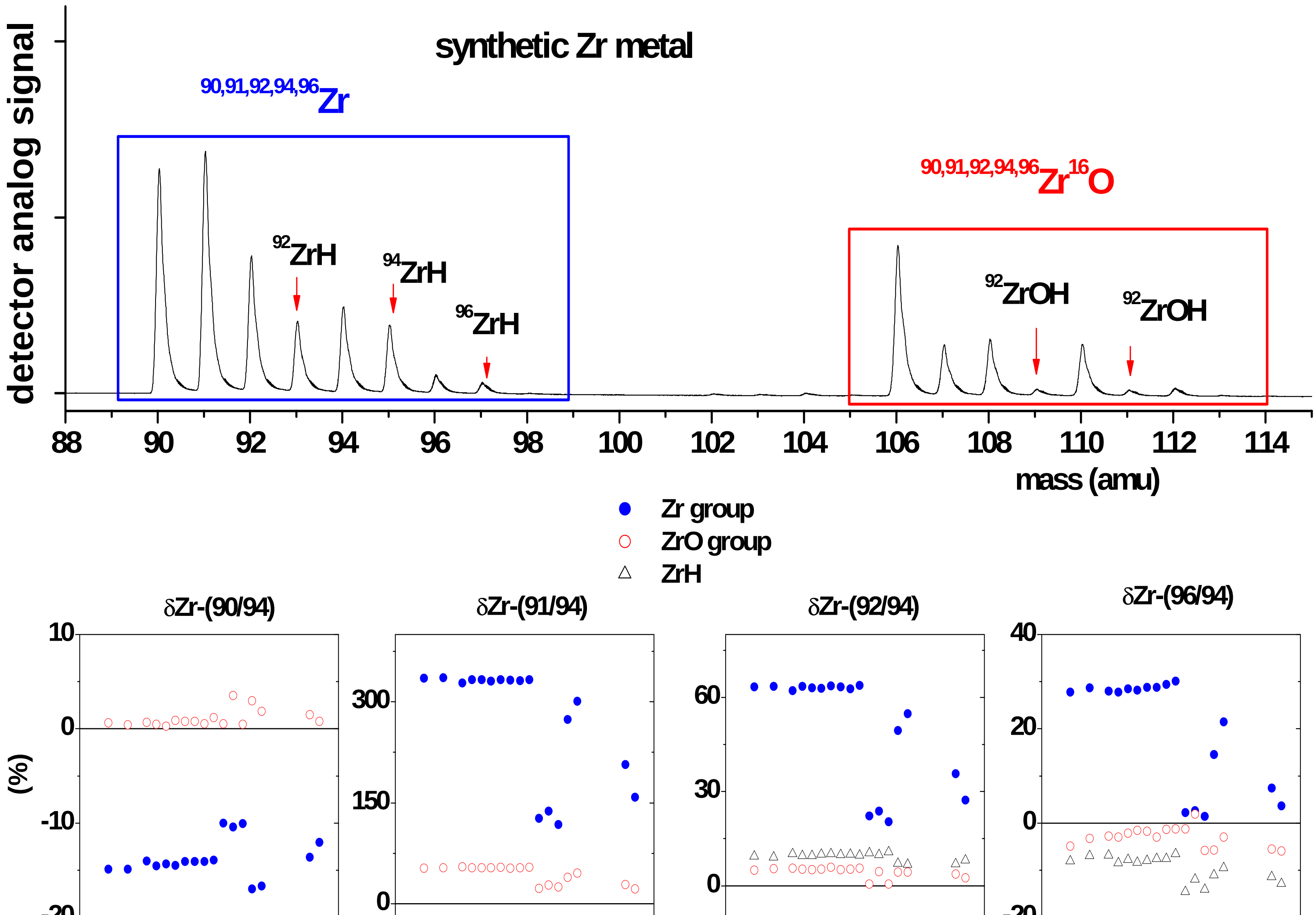
Cape York iron meteorite
^{54,56,57,58}Fe
^{58,60,61,62,64}Ni
^{56}FeOH
^{56}Fe$_2$
FeNi
detector analog signal
mass (amu)
52
54
56
58
60
62
64
66
68
70
72
74
76
110
115
120
δNi-58/60
δNi-61/60
δNi-62/60
δNi-64/60
(%)
4
2
0
-2
60
30
0
-30
30
20
10
0
-10
60
30
0
-30

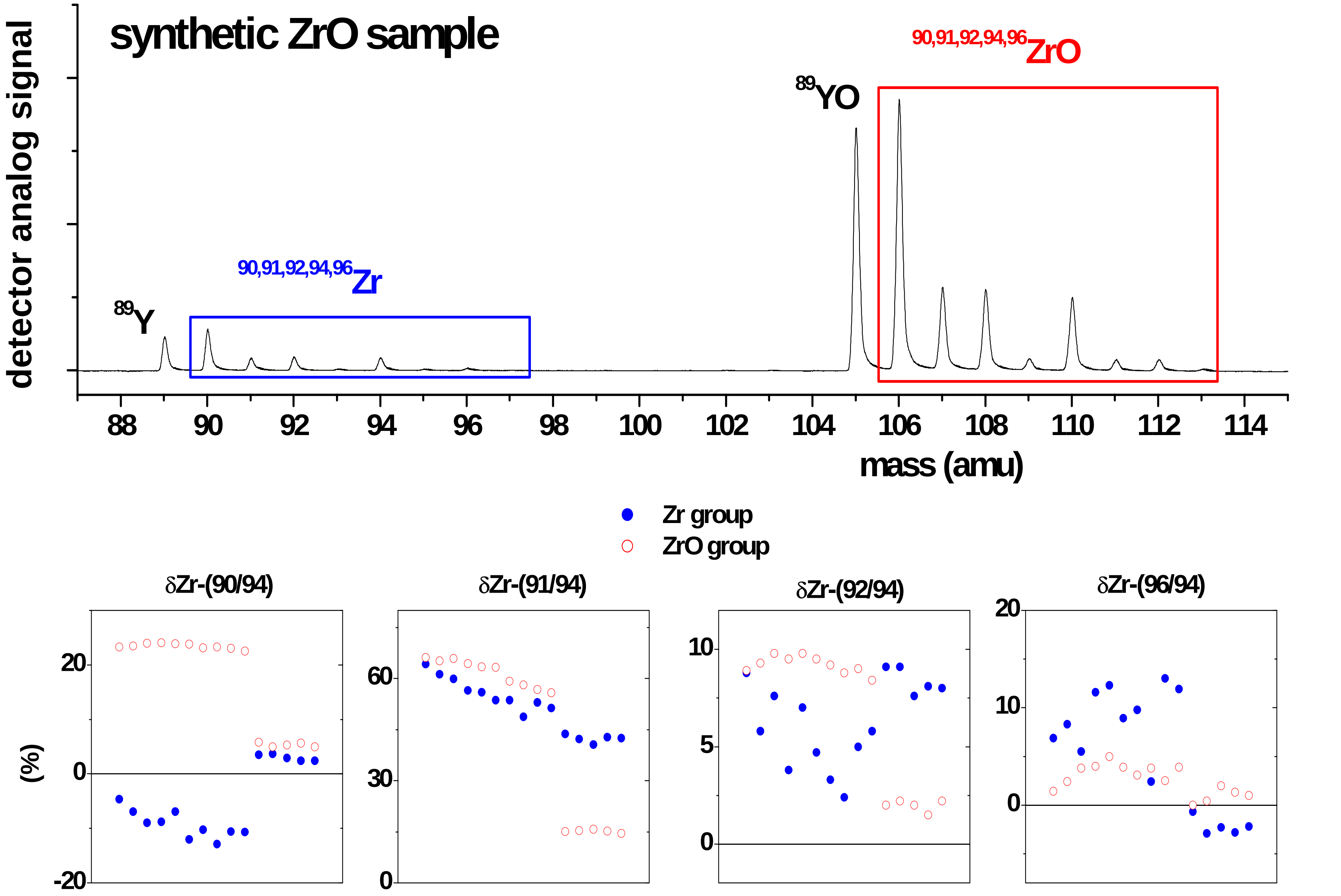


Brass sample (CuZn) in silver epoxy
Cu
Cu2,CuZn
Sn
Pb
detector analog signal
mass (amu)
60 80 100 120 140 160 180 200 220
63,65Cu
64,66,67,68Zn
62 64 66 68 70
112,114-120,122,124Sn
121,123Sb
112 114 116 118 120 122 124
Cu2,CuZn
126 128 130 132 134 136
204,206-208Pb
204 206 208 210



natural Brass CuZn sample
63,65Cu
Cu2, CuZn
Sn
Pb
60
80
100
120
140
160
180
200
220
mass (amu)
Cu
Cu2, CuZn
62
64
66
68
70
126
128
130
132
134
20
10
0
-10
(%)
Cu
Cu2 (63,65)/(63,63)
Cu2 (65,65)/(63,63)


synthetic Zr metal
90,91,92,94,96Zr
90,91,92,94,96Zr16O
92ZrH
94ZrH
96ZrH
92ZrOH
92ZrOH
detector analog signal
mass (amu)
88
90
92
94
96
98
100
102
104
106
108
110
112
114
Zr group
ZrO group
ZrH
δZr-(90/94)
δZr-(91/94)
δZr-(92/94)
δZr-(96/94)
(%)
10
0
-10
-20
300
150
0
60
30
0
40
20
0
-20


synthetic ZrO sample
detector analog signal
mass (amu)
89Y
90,91,92,94,96Zr
89YO
90,91,92,94,96ZrO
88
90
92
94
96
98
100
102
104
106
108
110
112
114
Zr group
ZrO group
δZr-(90/94)
δZr-(91/94)
δZr-(92/94)
δZr-(96/94)
(%)
20
0
-20
60
30
0
10
5
0
20
10
0

sample	element	Isotope ratio	Deviation and reproducibility (%)		Photoion species	Possible interference species
Rutile (TiO_2)	Ti	46/48	17.7 +/- 1.9	No pre-clean	Ti	
			-4.0 +/- 0.8		TiO	
		47/48	29.4 +/- 2.4		Ti	^{46}TiH
			16.6 +/- 0.6		TiO	^{46}TiOH
		49/48	66.4 +/- 3.2		Ti	^{48}TiH
			223.5 +/- 4.2		TiO	^{48}TiOH
		50/48	102.5 +/- 6.1		Ti	^{50}Cr, ^{49}TiH
			24.7 +/- 0.9		TiO	^{49}TiOH
		46/48	-2.7 +/- 0.9	With preclean	Ti	
			-4.0 +/- 0.5		TiO	
		47/48	3.5 +/- 3.5		Ti	^{46}TiH
			0.7 +/- 0.5		TiO	^{46}TiOH
		49/48	8.6 +/- 2.2		Ti	^{48}TiH
			50.9 +/- 1.6		TiO	^{48}TiOH
		50/48	67.3 +/- 1.9		Ti	^{50}Cr, ^{49}TiH
			11.7 +/- 0.5		TiO	^{49}TiOH

The isotopic ratios of Mg and Ti from sample Rutile as shown in this and the next pages are all extracted from the same mass spectra

sample	element	Isotope ratio	Deviation and reproducibility (%)		Photoion species	Possible interference species
Spinel ($MgAl_2O_4$)	Mg	25/24	55.0 +/- 2.4	(no pre-clean)	Mg	^{24}MgH
		26/24	20.7 +/- 2.3			^{25}MgH
Synthetic MgO	Mg	25/24	25.0 +/- 2.4	(no pre-clean)	Mg	^{24}MgH
		26/24	7.5 +/- 0.8			^{25}MgH
		25/24	7.2 +/- 0.3	With preclean	Mg	^{24}MgH
		26/24	5.8 +/- 0.7			^{25}MgH
CPX ($MgCaTiSi_2O_6$)	Mg	25/24	40.0 +/- 3.3	(no pre-clean)	Mg	^{24}MgH
		26/24	7.1 +/- 2.3			^{25}MgH
		25/24	57.0 +/- 0.6	With preclean	Mg	^{24}MgH
		26/24	24.8 +/- 0.5			^{25}MgH
Rutile (TiO2)	Mg	25/24	42.7 +/- 1.8	(no pre-clean)	Mg	^{24}MgH
		26/24	13.3 +/- 1.8			^{25}MgH
		25/24	8.3 +/- 1.3	With preclean	Mg	^{24}MgH
		26/24	4.5 +/- 2.1			^{25}MgH

sample	element	Isotope ratio	Deviation and reproducibility (%)	Photoion species	Possible interference
Brass (CuZn alloy)	Cu	65/63	-0.8 +/- 0.3	Cu	
			-5.1 +/- 0.4	$^{63,65}Cu_2$ / $^{63,63}Cu_2$	
			0.01 +/- 0.3	$^{65,65}Cu_2$ / $^{63,63}Cu_2$	
	Zn	66/64	-3.1 +/- 7.2	Zn	
		68/64	8.6 +/- 7.9		
Synthetic Zr metal	Zr	90/94	-14.3 +/- 0.4	Zr	
			0.7 +/- 0.3	ZrO	
		91/94	332.4 +/- 2.3	Zr	
			53.5 +/- 0.8	ZrO	
		92/94	63.2 +/- 0.5	Zr	
			5.4 +/- 0.3	ZrO	
			9.8 +/- 0.3	ZrH	
		96/94	28.6 +/- 0.8	Zr	
			-2.5 +/- 1.1	ZrO	
			-7.6 +/- 0.7	ZrH	
Synthetic ZrO	Zr	90/94	-9.3 +/- 2.6	Zr	
			23.5 +/- 0.5	ZrO	^{89}YO
		91/94	55.8 +/- 4.8	Zr	
			61.8 +/- 3.9	ZrO	
		92/94	5.4 +/- 2.0	Zr	
			9.2 +/- 0.5	ZrO	
		96/94	9.1 +/- 3.4	Zr	
			3.4 +/- 1.0	ZrO	

Difference of measured isotopic ratio to that in solar material and the experiment reproducibility at 1σ level (the deviation are calculated only from those data which are taken under the same experimental parameters)

sample	element	Isotope ratio	Deviation and reproducibility (%)	Photoion species	Possible interference species
Titanite ($CaTiSiO_5$)	Si	29/28	250.8 +/- 6.8	Si	^{28}SiH
		30/28	54.4 +/- 3.3	Si	^{29}SiH
	Ca	42/40	54.3 +/- 3.1	Ca	
	Ti	46/48	19.0 +/- 0.6	Ti	^{47}TiH
			-0.2 +/- 0.3	TiO	$^{47}TiOH$
		47/48	7.3 +/- 0.7	Ti	^{46}TiH, ^{47}TiH
			3.2 +/- 0.7	TiO	$^{46}TiOH$. $^{47}TiOH$
		49/48	42.3 +/- 0.9	Ti	$^{48}TiH^+$, $^{47}TiH^+$
			34.3 +/- 0.6	TiO	$^{48}TiOH$, $^{47}TiOH$
		50/48	19.0 +/- 0.2	Ti	^{49}TiH, ^{47}TiH
			20.8 +/- 0.8	TiO	$^{49}TiOH$, $^{47}TiOH$

The ratios of Si, Ca, and Ti shown in this table are all extracted from the same mass spectra