Nearly pure AGB He-shell material in in presolar graphite

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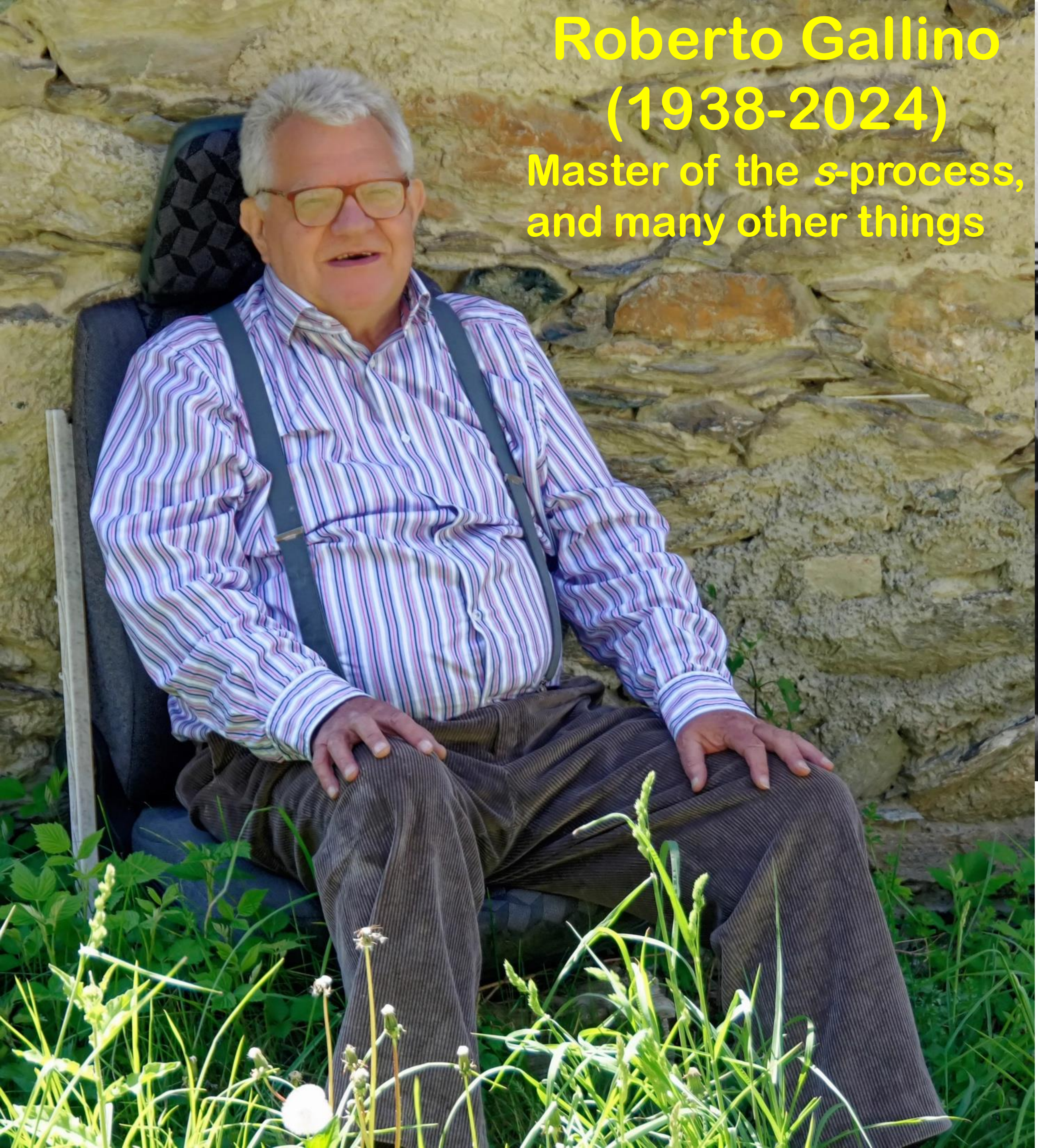


Edward Anders (1926-2025)

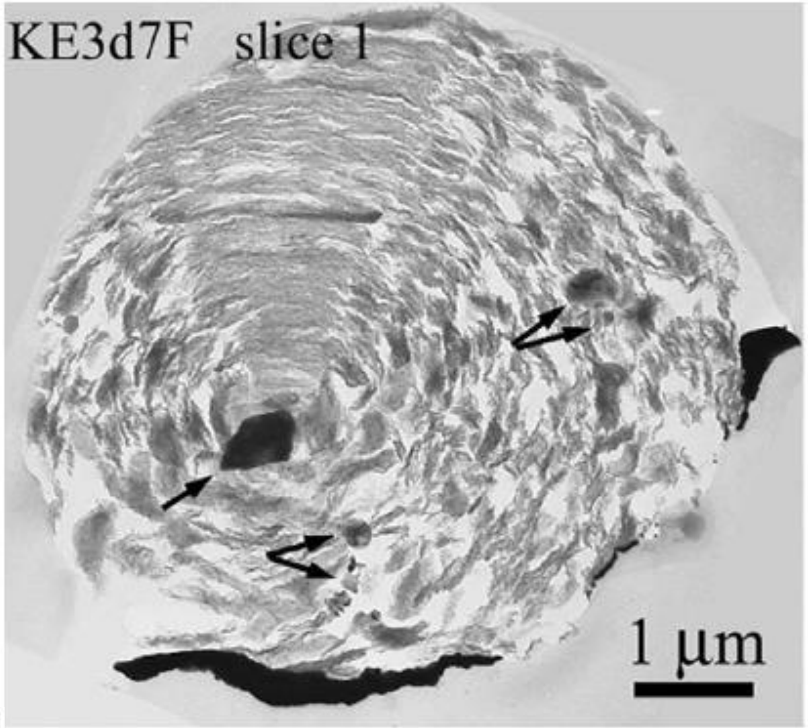
Shown with Roy Lewis. Ed and Roy were the codiscoverers of presolar grains in meteorites in 1987, the culmination of a 20-year search for the carriers of noble gases in meteorites.

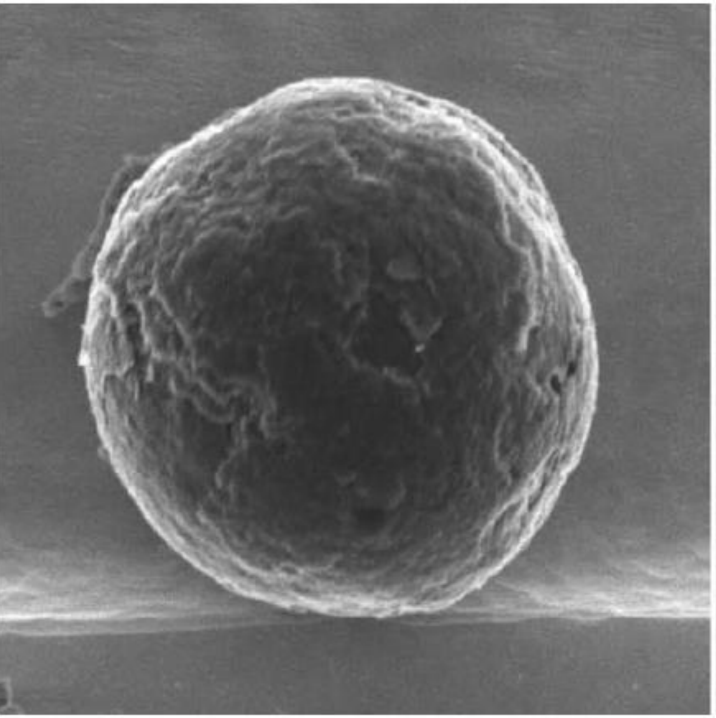
Summary on multi-isotope analyses of presolar grains

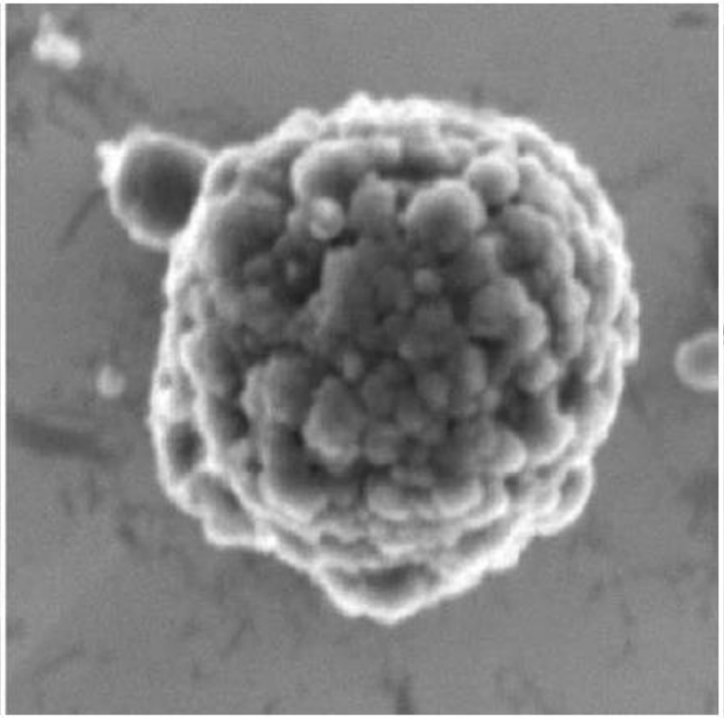
- Mo, Ru, and Ba isotopes in most presolar SiC and graphite grains are dominated by *s*-process nucleosynthesis
- Mo appears to be more susceptible to surface contamination than Ru and Ba; furthermore, graphite is more severely affected by surface contamination than SiC
- Careful chemical separation and mounting of SiC minimizes the effect of surface contamination
- The AGB stars that made presolar SiC and graphite had near-solar initial proportions of *r*-, *p*-, and *s*-process isotopes
- For more, see
  - Stephan T et al. (2025, ApJ 981: 201)
  - Stephan T et al. (2019, ApJ 877:101)
  - Barzyk J et al. (2007, MAPS 42:1103)

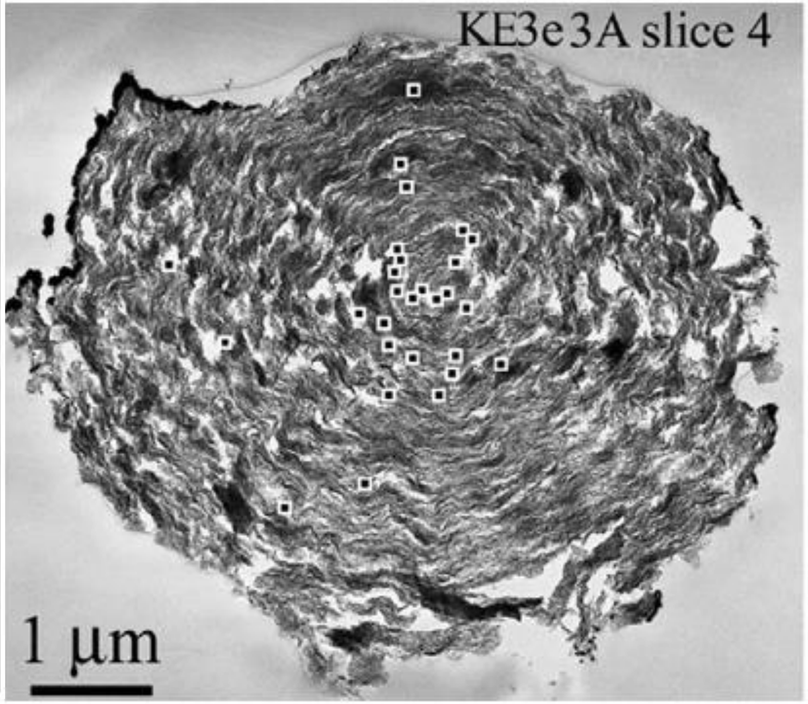
Graphite

- Little rocks, with inclusions of Ti, Mo, Zr, and Ru carbides and metallic Fe
- From supernovae (~60%) and AGB stars (~30%)





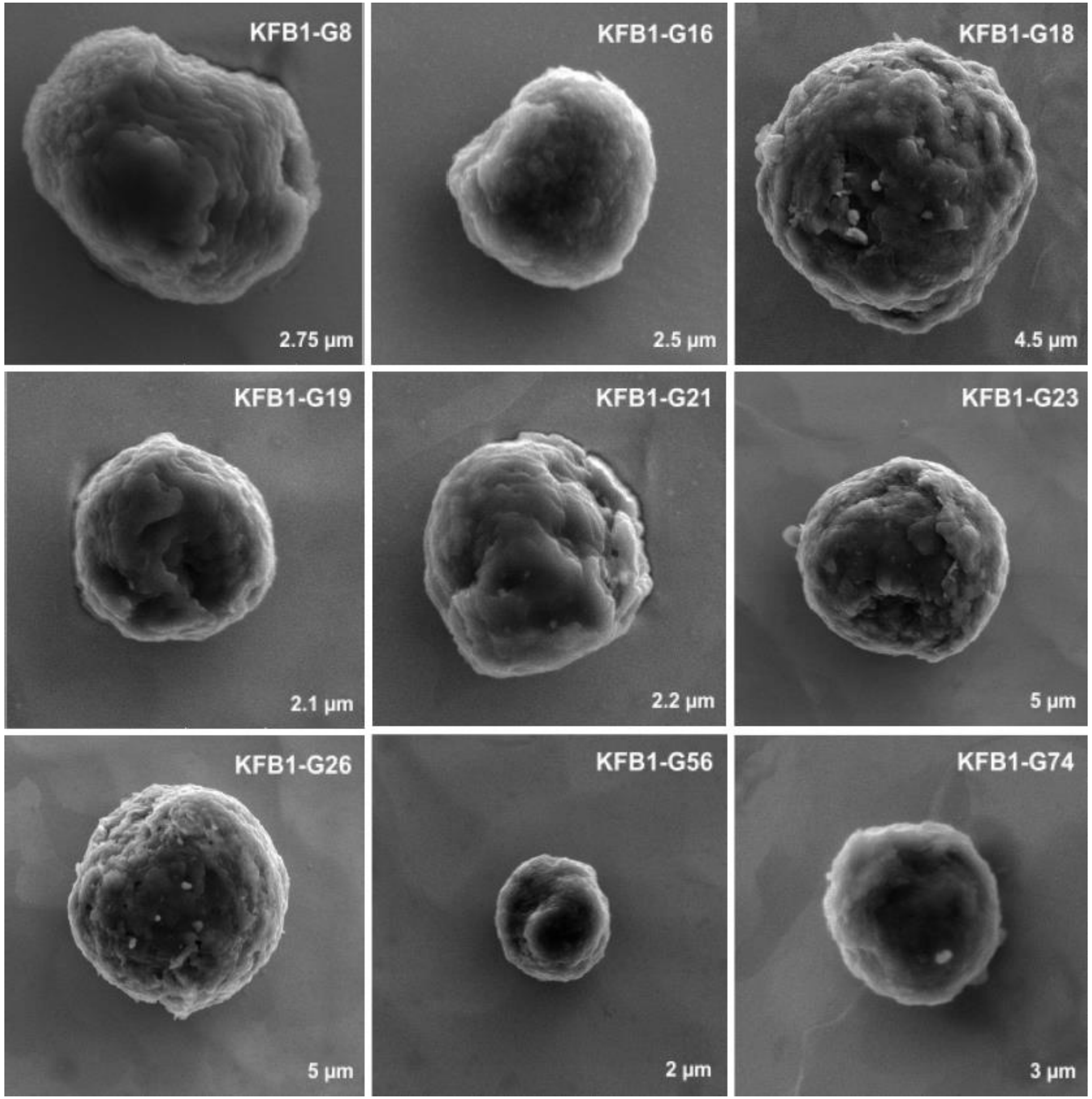


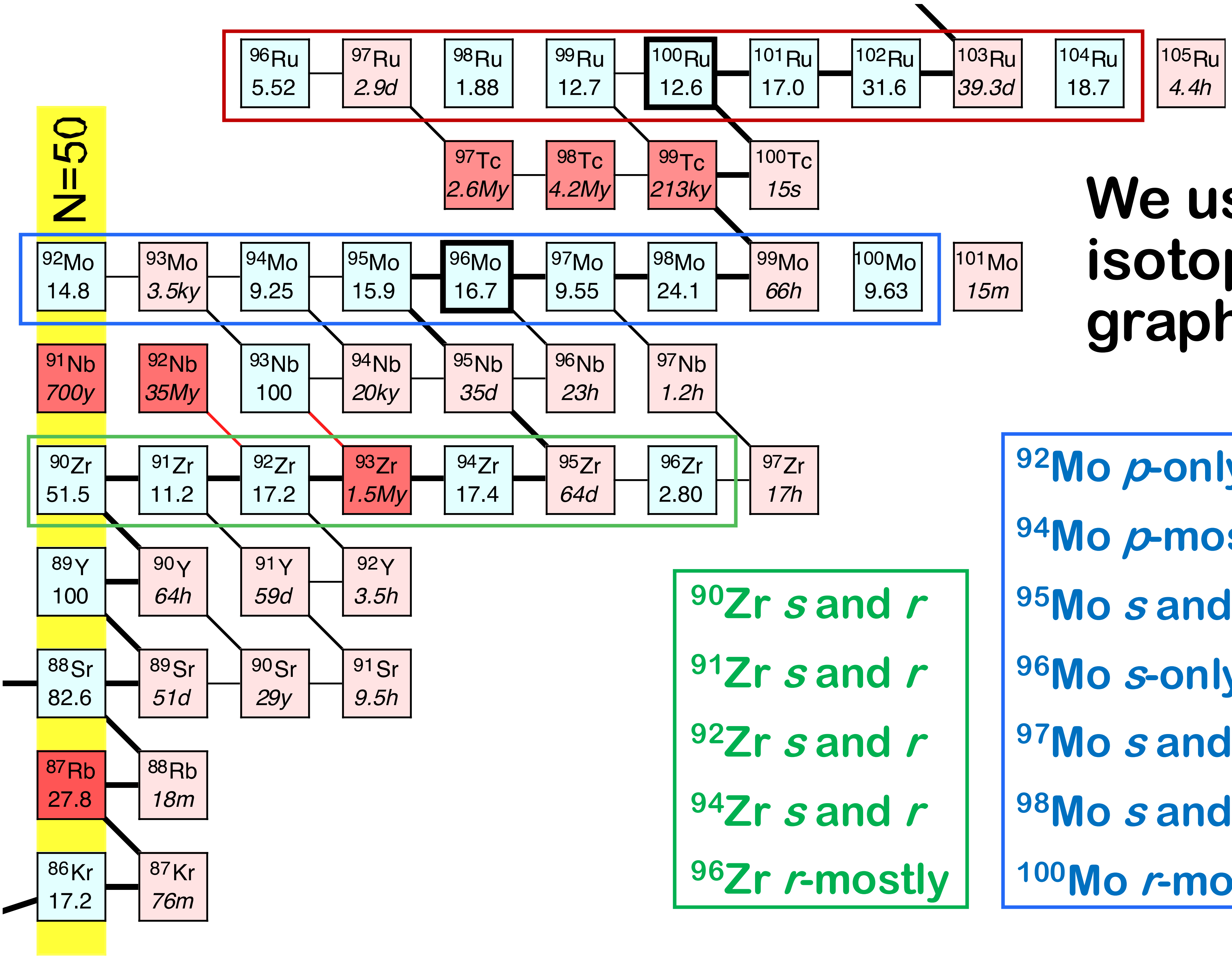


An old AGB graphite puzzle

Models of AGB stars don't have high enough concentrations of C, Zr, Mo, and Ru to condense carbide inclusions or even large graphite grains (Bernatowicz et al., 1996, ApJ 472: 760)

We are now coming back to graphite after first analyzing Mo and Zr in them in the late 1990s





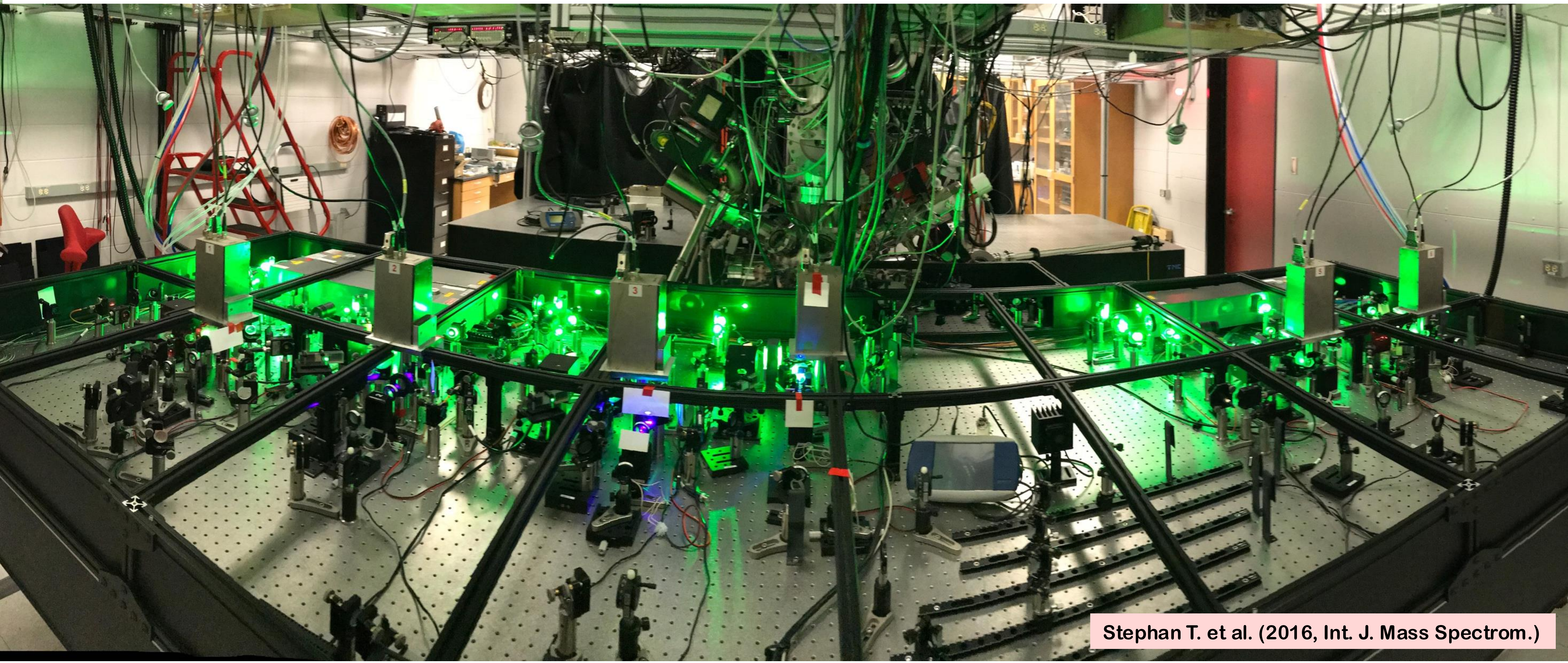
We use Zr, Mo, and Ru isotopes to study graphite grains

- ^{90}Zr *s* and *r*
- ^{91}Zr *s* and *r*
- ^{92}Zr *s* and *r*
- ^{94}Zr *s* and *r*
- ^{96}Zr *r*-mostly

- ^{92}Mo *p*-only
- ^{94}Mo *p*-mostly
- ^{95}Mo *s* and *r*
- ^{96}Mo *s*-only
- ^{97}Mo *s* and *r*
- ^{98}Mo *s* and *r*
- ^{100}Mo *r*-mostly

- ^{96}Ru *p*-only
- ^{98}Ru *p*-only
- ^{99}Ru *s* and *r*
- ^{100}Ru *s*-only
- ^{101}Ru *s* and *r*
- ^{102}Ru *s* and *r*
- ^{104}Ru *r*-mostly

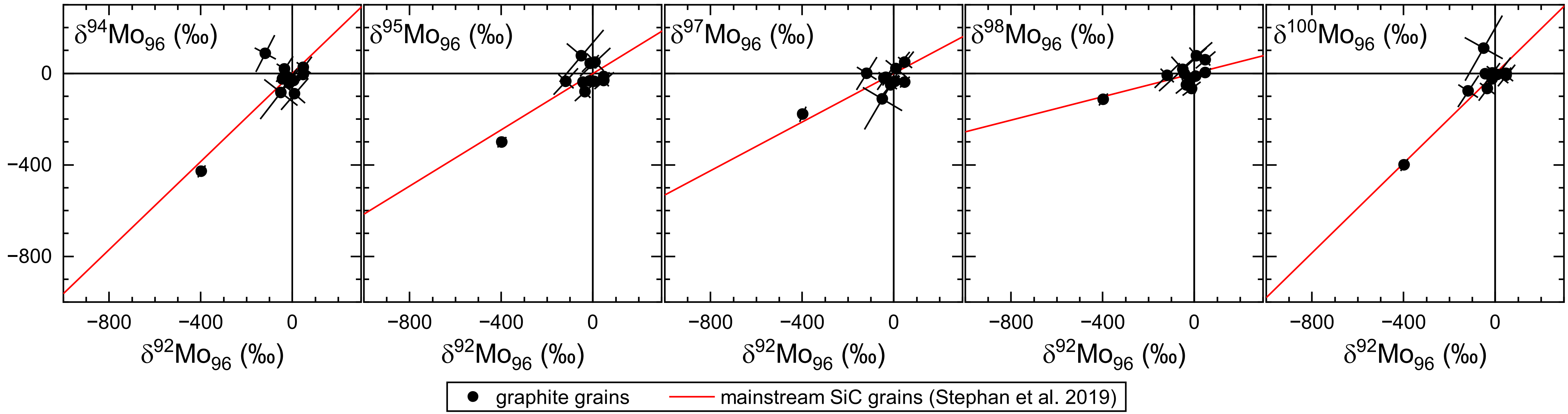
CHicago Instrument for Laser Ionization



Stephan T. et al. (2016, Int. J. Mass Spectrom.)

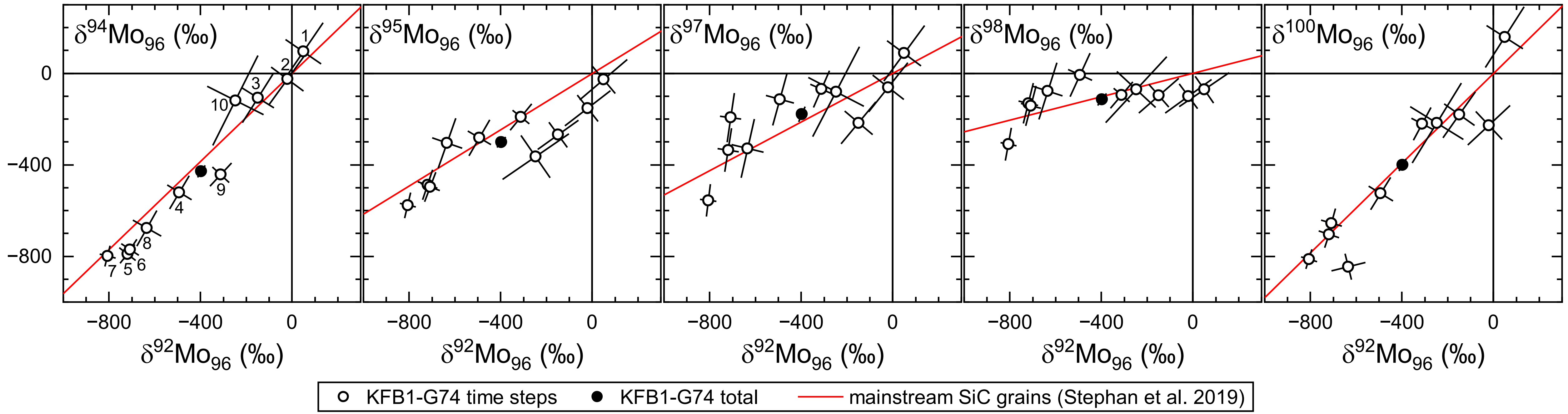
CHILI is a resonance ionization mass spectrometer, capable of high sensitivity, high spatial resolution (<1 μm), and exquisite control of interferences

Mo in separated graphite grains



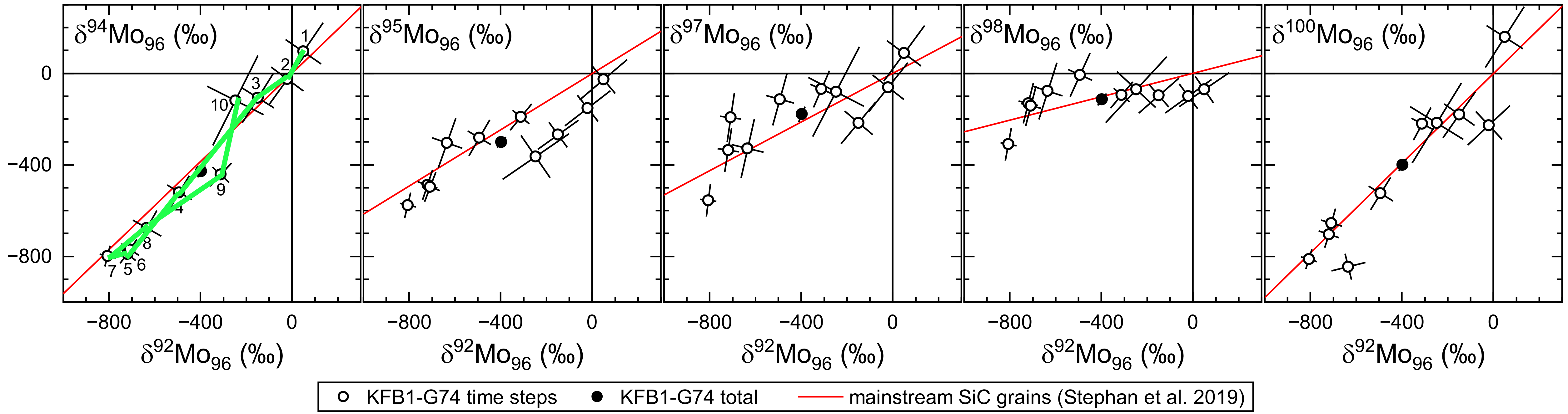
- **Most graphite grains plot on SiC regression line, but near terrestrial composition**
- **They appear to be contaminated with Mo, either on the meteorite parent body or during chemical separation from meteorite**

Mo in KFB1-74 graphite grain



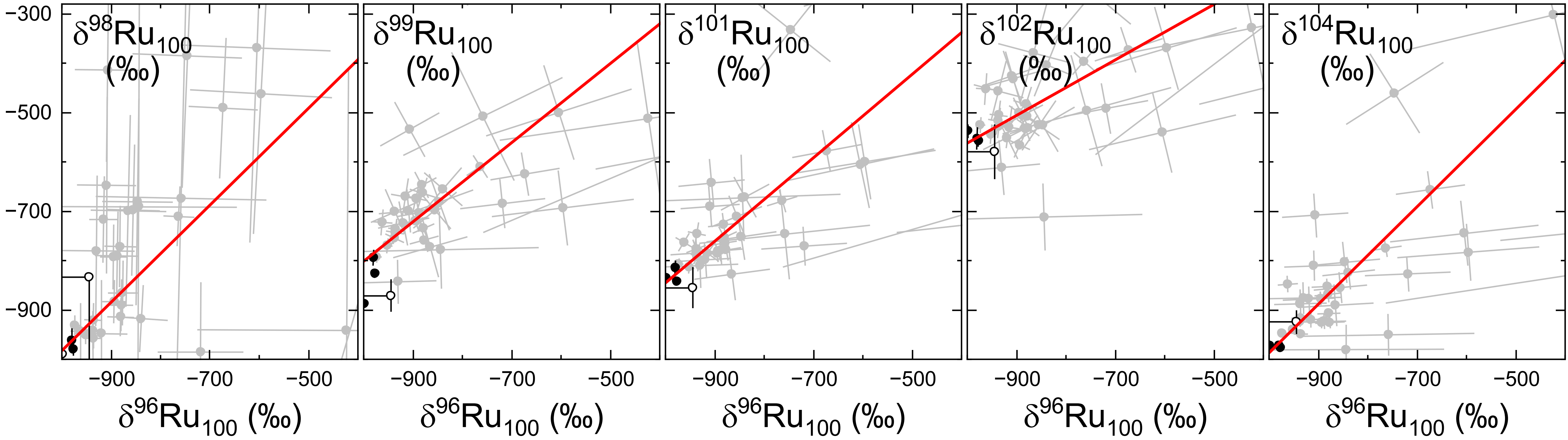
- **One graphite grain showed dramatic changes as we ablated into it**

Mo in KFB1-74 graphite grain

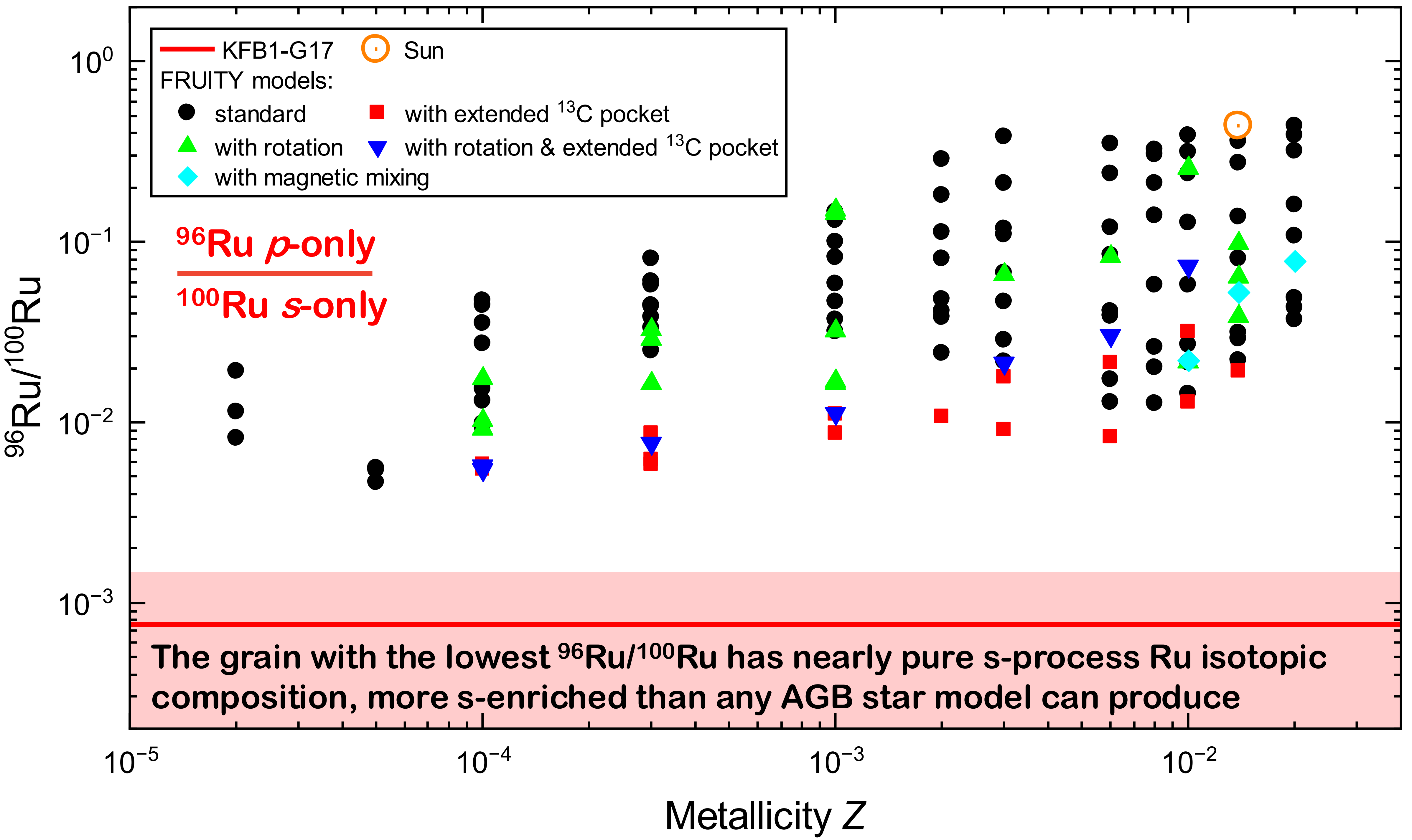


- The grain was normal at the surface, *s*-process-enriched at the center, and normal at the end

Ru in separated graphite grains

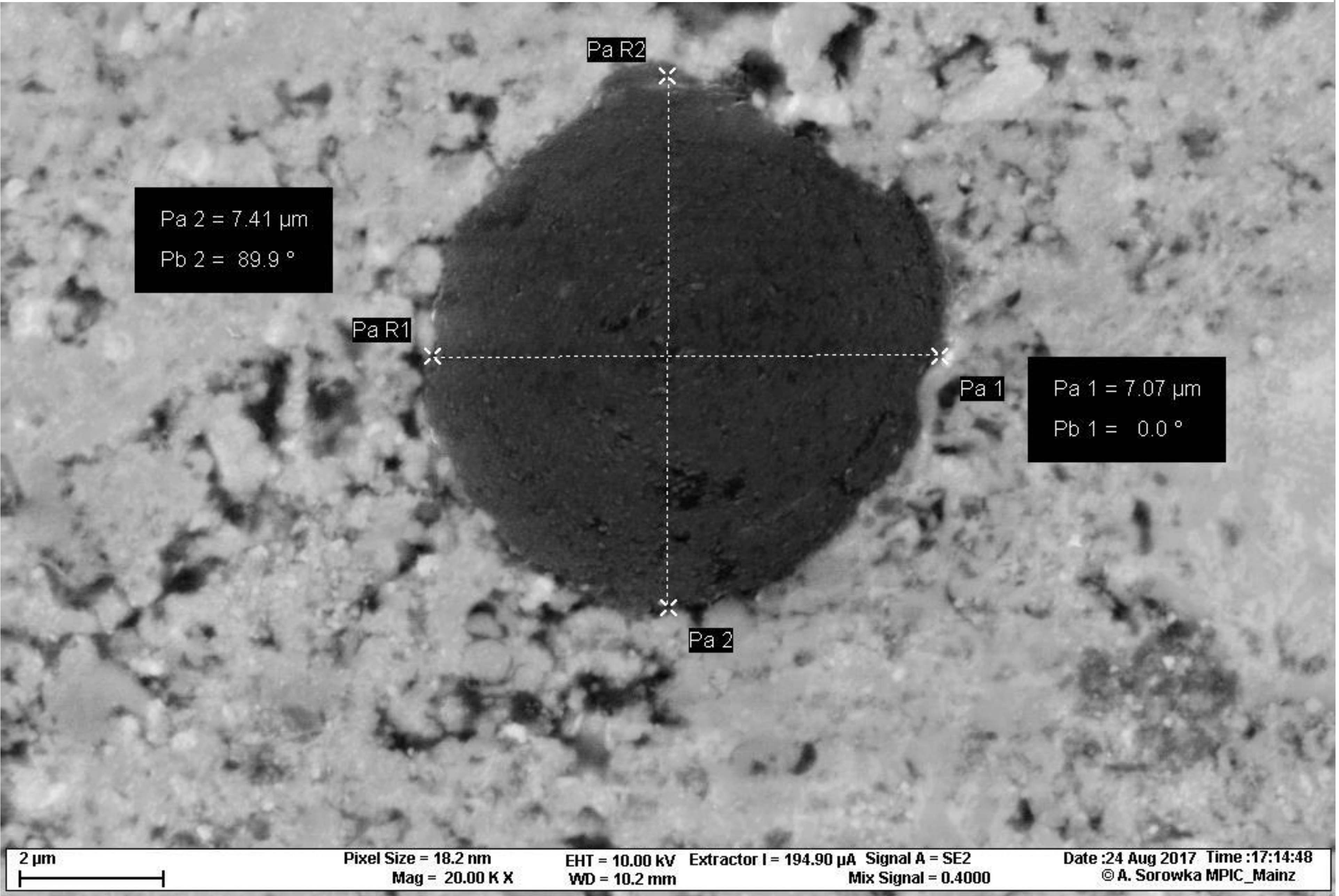


- Only the four graphite grains have detectable Ru, almost pure Ru_s
- There is no surface Ru contamination
- Gray points are SiC, shown for comparison



KFB1-G17
Sun
FRUITY models:
standard
with extended ^{13}C pocket
with rotation
with rotation & extended ^{13}C pocket
with magnetic mixing
^{96}Ru p-only
^{100}Ru s-only
^{96}Ru/^{100}Ru
10^{0}
10^{-1}
10^{-2}
10^{-3}
The grain with the lowest ^{96}Ru/^{100}Ru has nearly pure s-process Ru isotopic composition, more s-enriched than any AGB star model can produce
10^{-5}
10^{-4}
10^{-3}
10^{-2}
Metallicity Z

Mo & Zr in *in situ* graphite grains



Maribo:
MAR_C_B_001

$^{12}C/^{13}C$ = 313±1

$^{14}N/^{15}N$ = 272±2

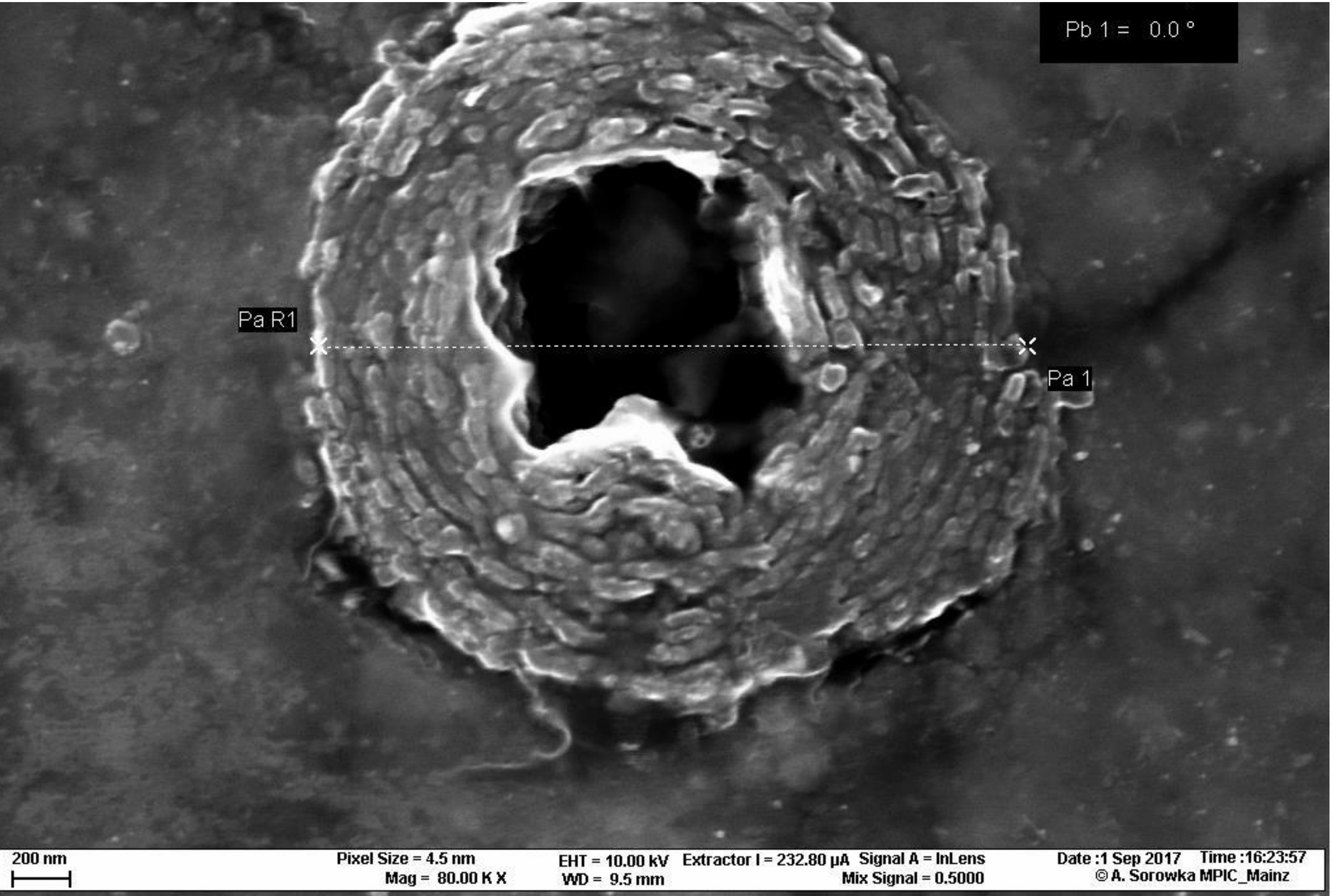
d ~7 µm

„HD"-like characteristics (likely AGB star origin)

Jan Leitner, MPI Mainz, has found graphite grains in situ in polished sections of CM chondrites

He sent us two to analyze

Mo & Zr in *in situ* graphite grains



Murchison:
MUR_C_002

$^{12}C/^{13}C$ = 271±2

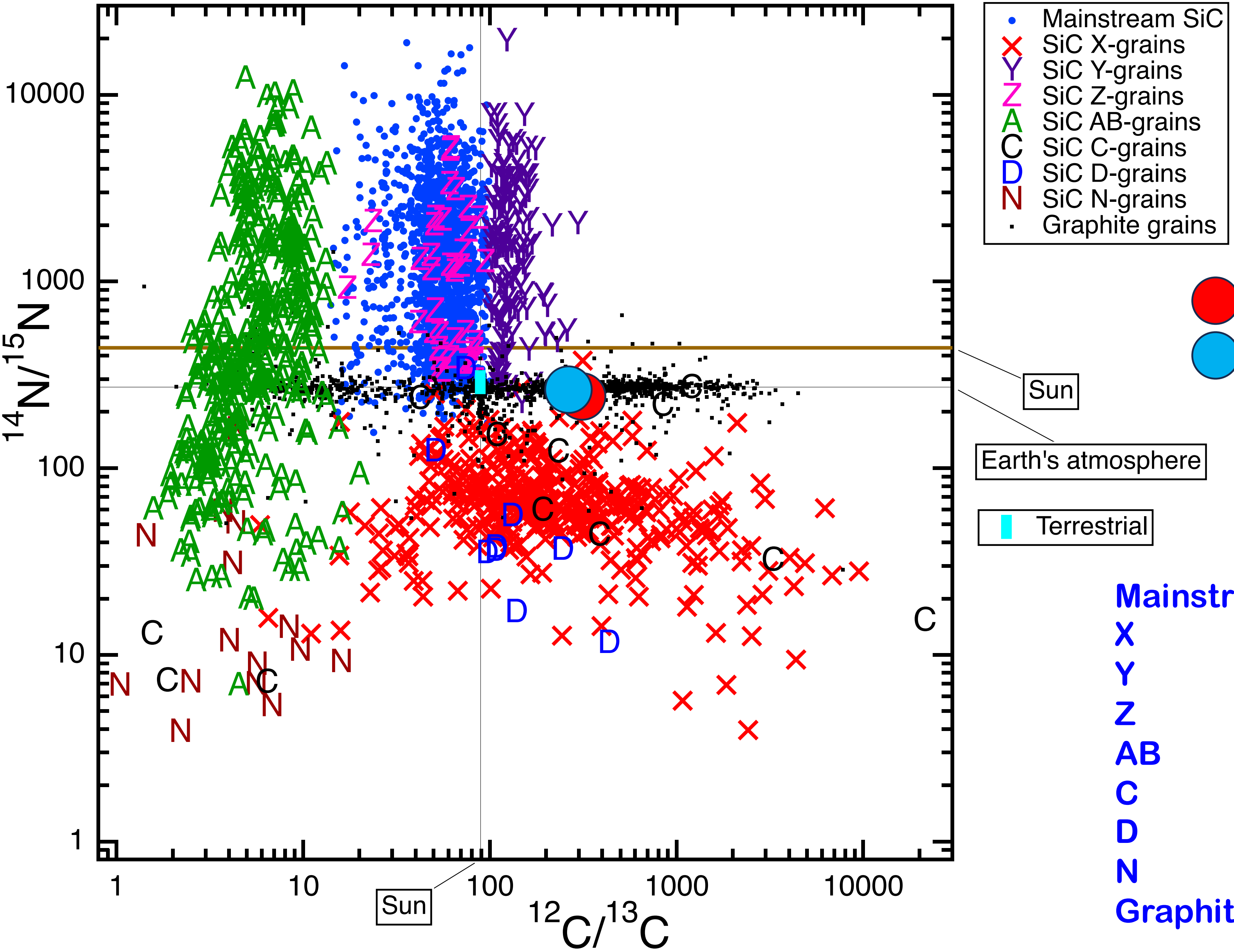
$^{14}N/^{15}N$ = 292±7

d ~2.5 µm

„HD"-like characteristics (likely AGB star origin)

Here's the other one

Data from Presolar Grains Database May 2025 (Stephan et al., ApJS, 2024)



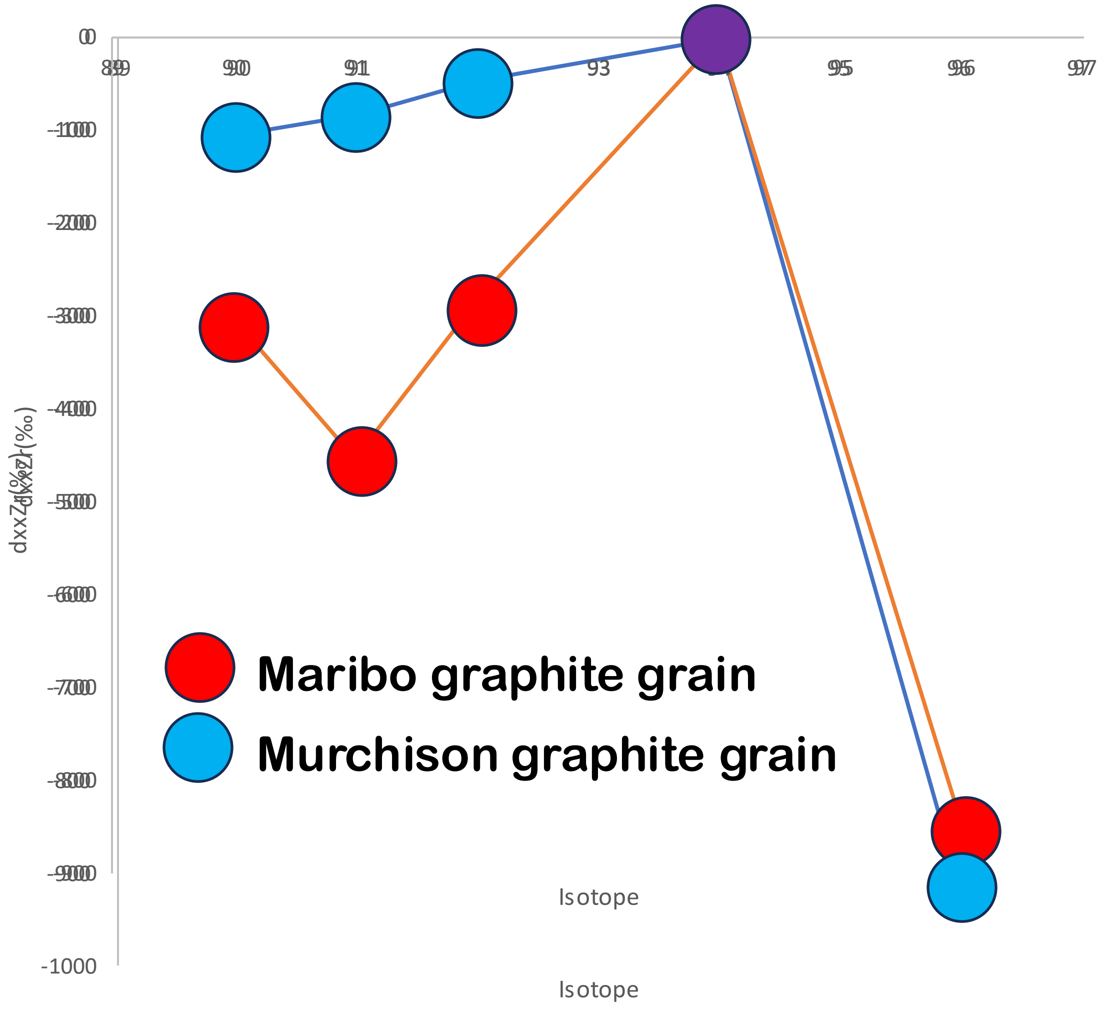
Maribo graphite grain

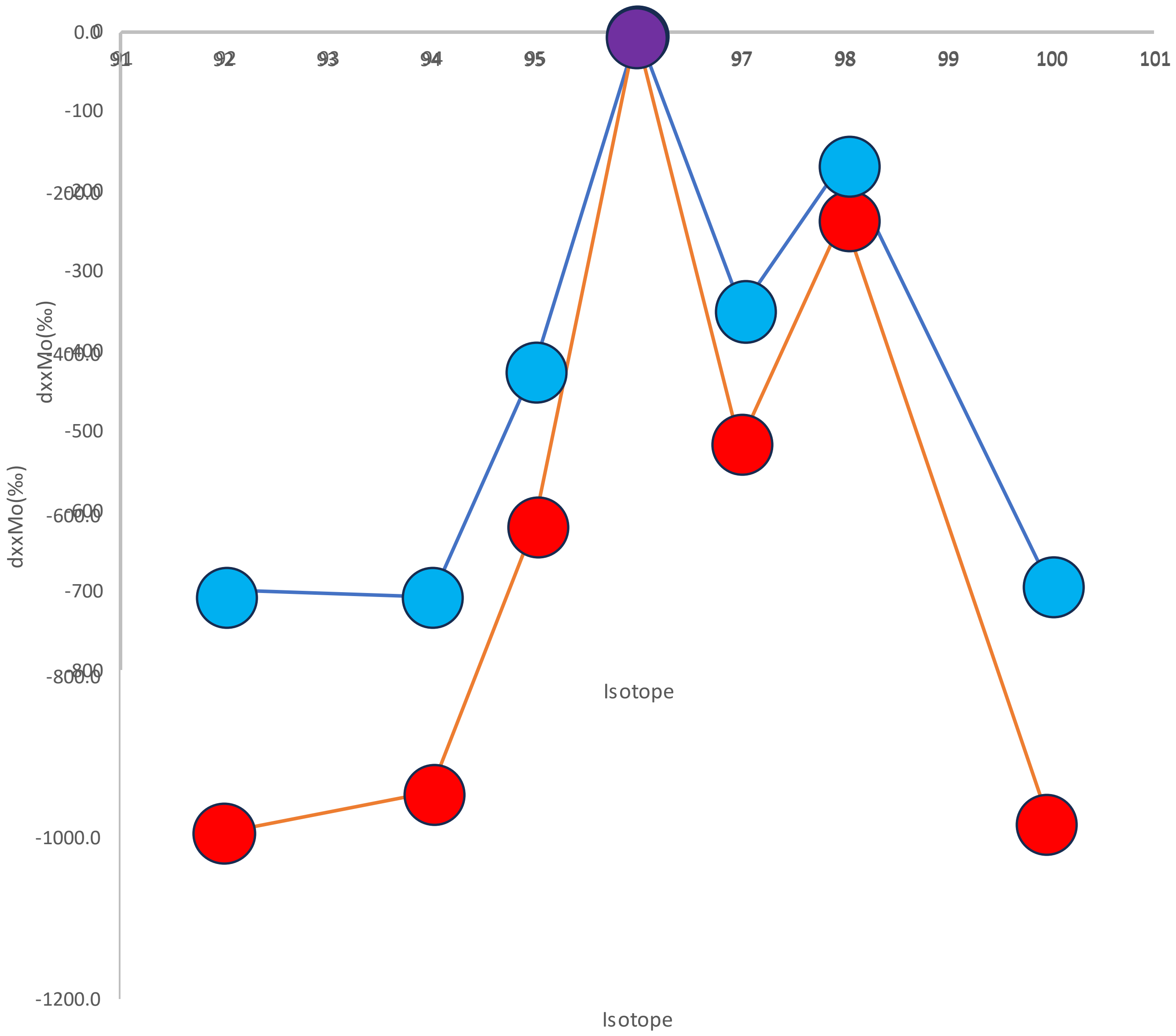
Murchison graphite grain

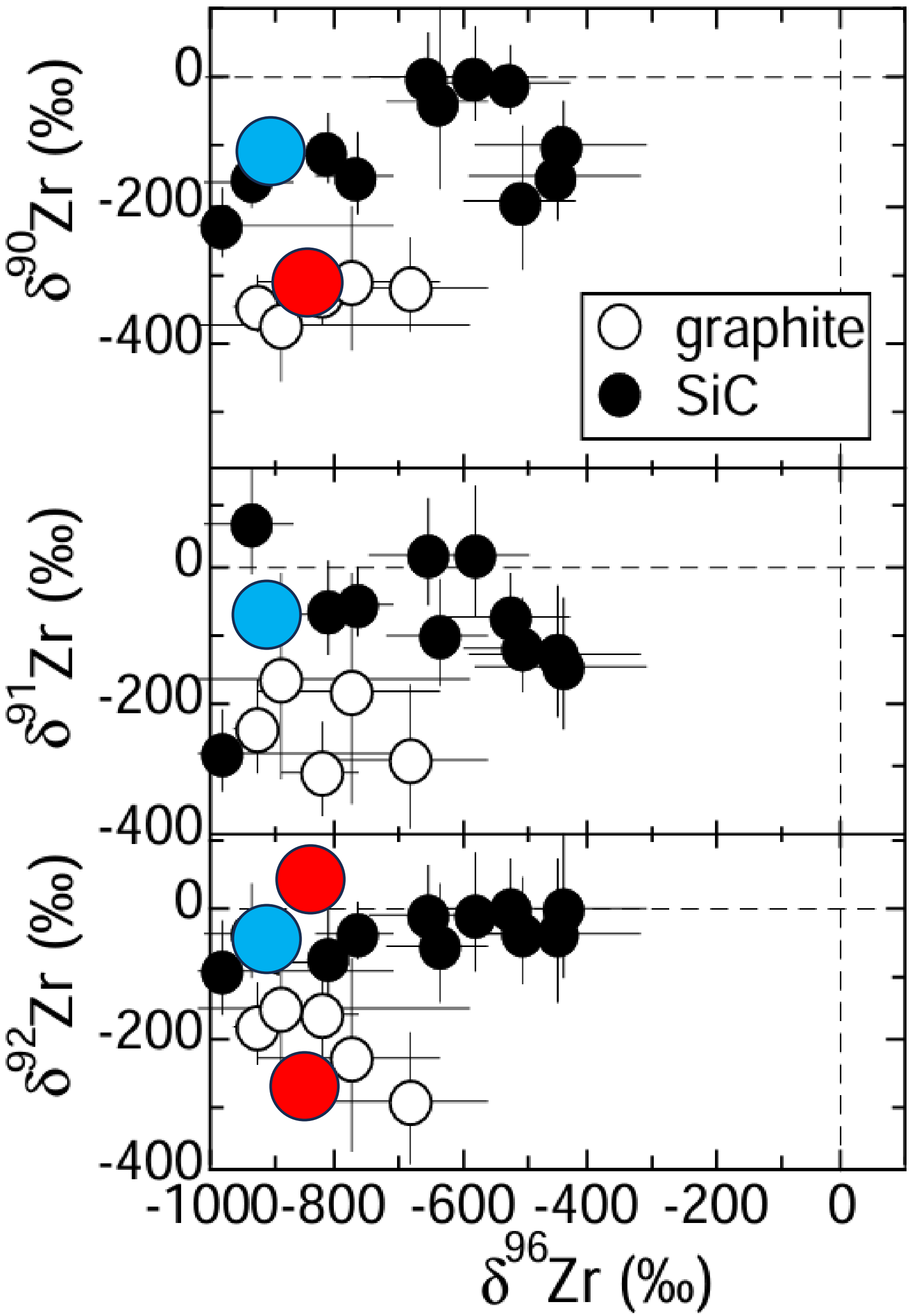
Mainstream	88.4%	AGB stars
X	1.3%	SNII
Y	3.9%	low Z AGB?
Z	1.4%	lower Z AGB?
AB	4.8%	SNII; J-stars
C	0.10%	SNII
D	0.02%	SNII
N	0.07%	Novae
Graphite		AGB, SNII

Here are the Zr and Mo isotope patterns, typical of the *s*-process

(sorry about the poor plots: that's what Excel on an iPad is capable of)

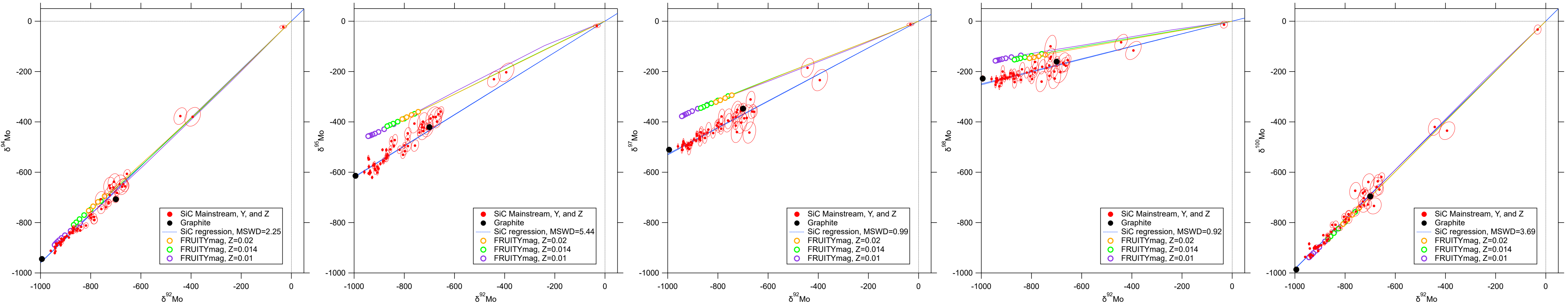




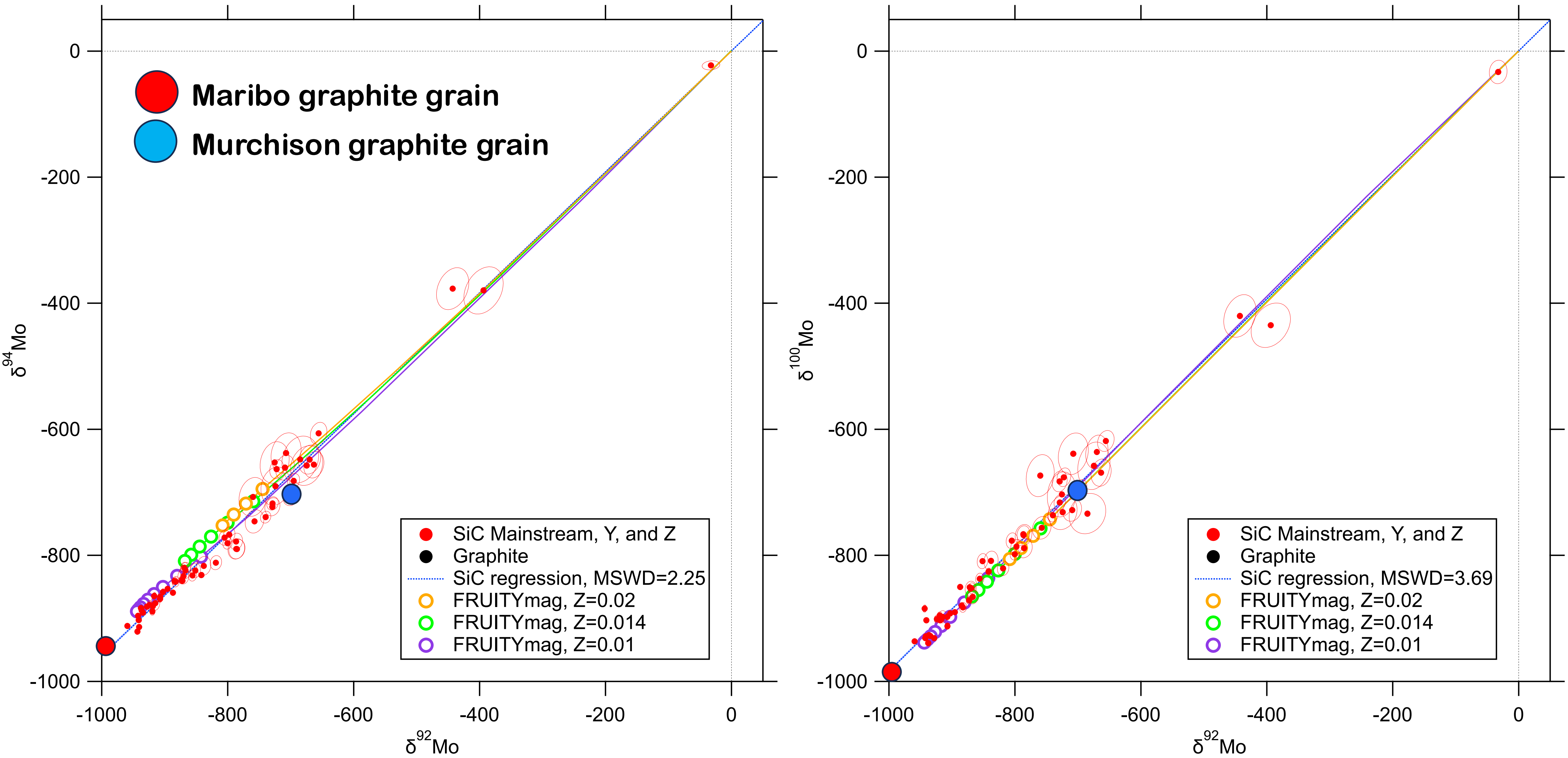


Both grains are depleted in ^{96}Zr and one is depleted in ^{90}Zr, ^{91}Zr, and ^{92}Zr, like other graphites; the other is more like what we see in SiC

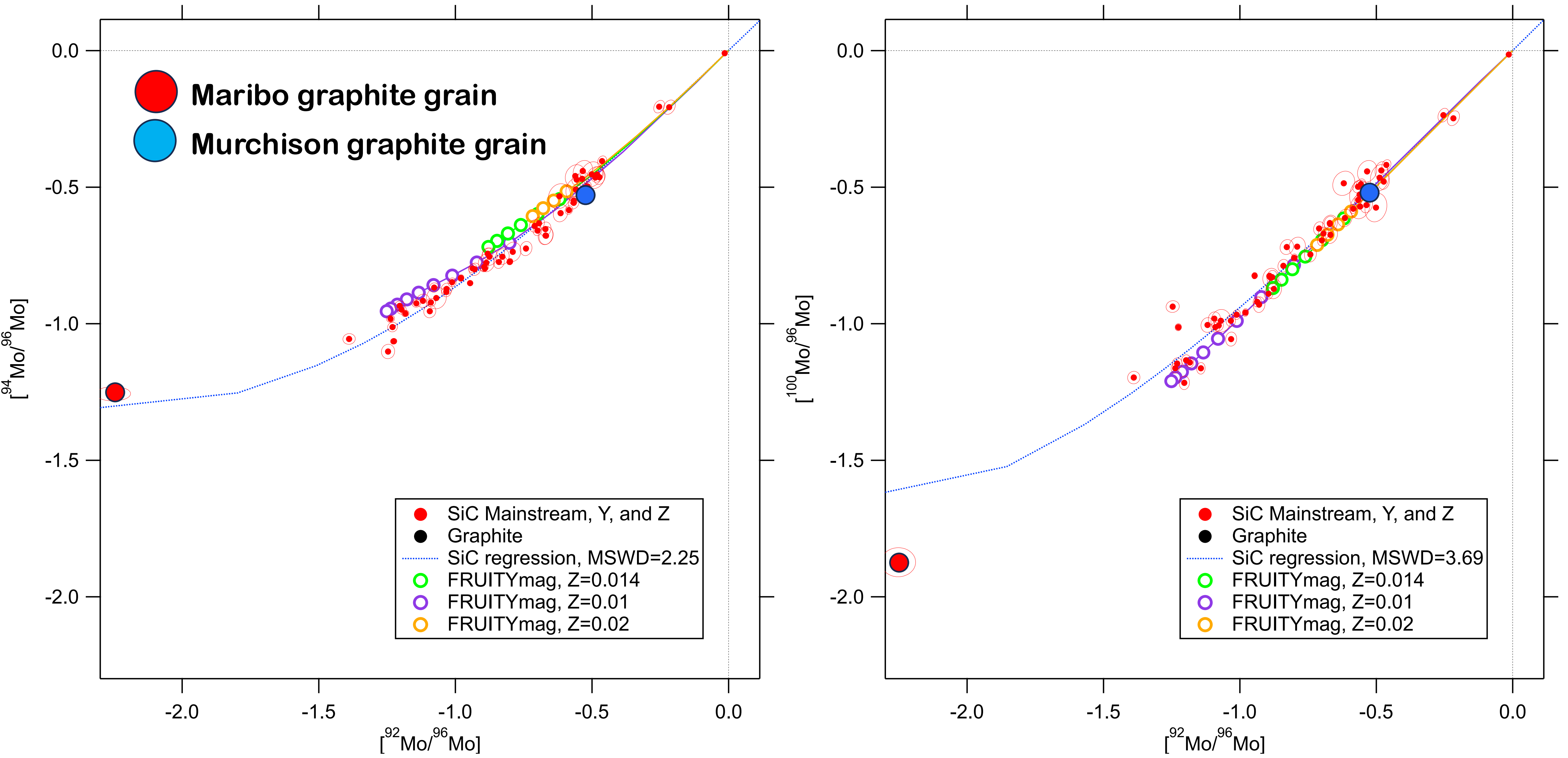
- Maribo graphite grain
- Murchison graphite grain



- **Both grains have near normal Mo at their surface, but highly *s*-process-enriched Mo as we ablated into them**
- **The black points are the interiors of the two grains**



- **Here are two three-isotope plots, showing that the graphite cores lie along the same regression line as SiC grains from AGB stars**



- **Log-log plots show how dramatically enriched in *s*-process Mo one of the grains is, ~10X more than models can produce in AGB envelopes**

Graphite summary

- The sizes of graphite grains from AGB stars, as well as the presence of Zr, Mo, and Ru carbide inclusions have long been hard to explain with traditional AGB star models, which assume that the outer part of the star is well mixed
- New CHILI data on Mo and Ru show the purest *s*-process signatures ever seen in presolar grains, up to 99.5% pure *s*-process
- This represents a ~200× enrichment relative to terrestrial isotopic composition, whereas AGB star models cannot produce enrichments above ~20×
- What's going on?
  - Are these due to a very late thermal pulse (VLTP) on a post-AGB star?
  - Can AGB stars dredge up He-shell material without it thoroughly mixing in the convective envelope?