Interstellar and Cosmogenic Fingerprints in Lunar Soil

S. Zwickel[1,2], S. Fichter[1], M. Hotchkis[3], D. Koll[1,2], J. Lachner[1], M. Norman[4], S. Pavetich[4], G. Rugel[1], K. Stuebner[1], S. Tims[4], A. Wallner[1,2,4]

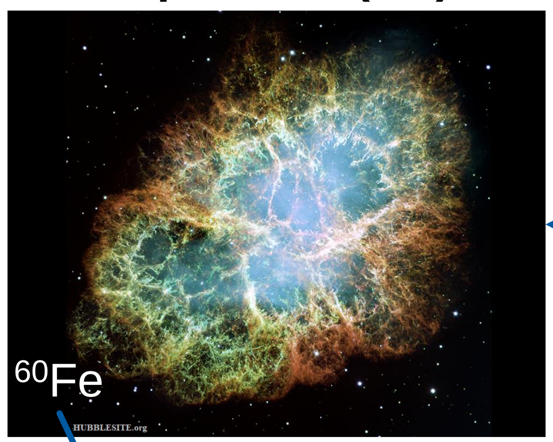
[1]Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Dresden, Germany, [2]TUD Dresden University of Technology, Dresden, Germany, [3]Australian Nuclear Science and Technology Organisation (ANSTO), Sydney, Australia, [4]Australian National University (ANU), Canberra, Australia

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

TECHNISCHE UNIVERSITÄT DRESDEN

Astrophysical Motivation

Core collapse supernova (SN)

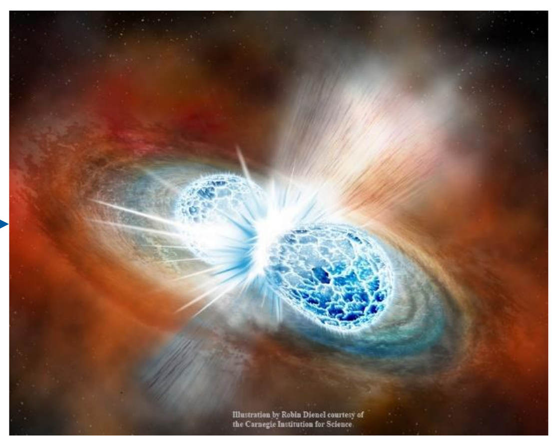


Astrophysical site of the ***r*-process**?

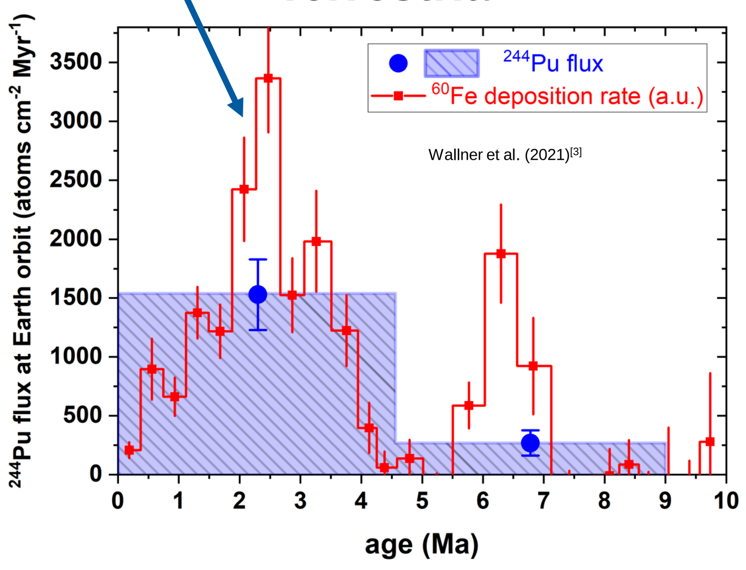
Rates ~1000:1

Pure *r*-process tracer[1]: ^{244}Pu $_{(t_{1/2}=81\,Myr)}$ & ^{247}Cm $_{(t_{1/2}=16\,Myr)}$

Neutron star merger and rare subset of SN

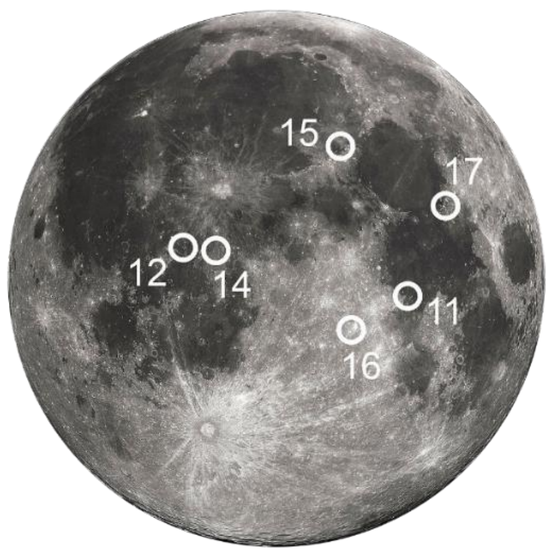


Terrestrial



Interstellar ^{60}Fe and ^{244}Pu in deep-sea ferro-manganese crust[3]

Lunar



Samples from all six Apollo missions integrating from ~1 Myr to ~200 Myr

Interstellar Radionuclides in the Solar System

Terrestrial:

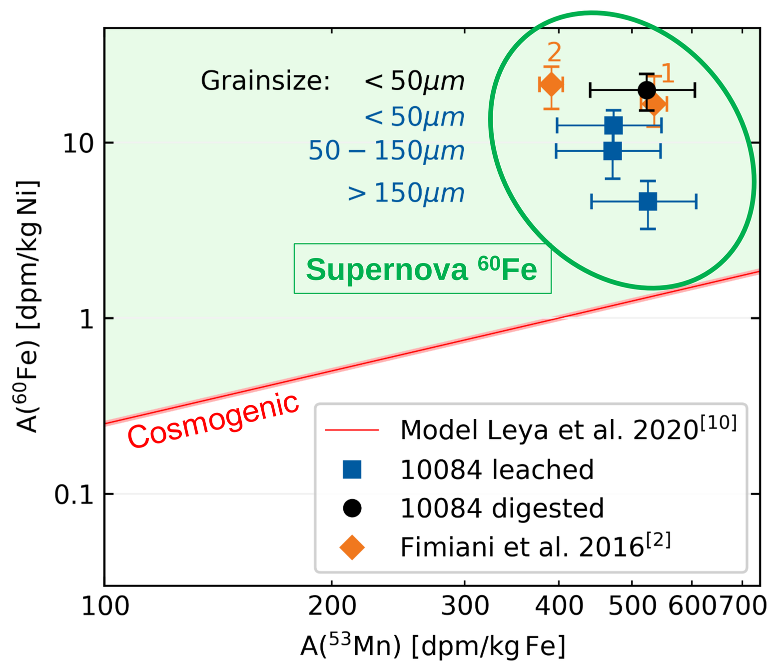
- Time resolution ☺
- Look back ~20 Myr ☹
- Large samples (~kg) ☺
- ^{60}Fe[3], ^{244}Pu[3], ^{247}Cm ✓ ✓ ?

Lunar:

- No time resolution ☹
- Integrating up to 400 Myr ☺
- Small samples (~g) ☹
- ^{60}Fe[2], ^{244}Pu, ^{247}Cm ✓ ? ?

- **Focus of this work: Lunar soil**
  - Technique to extract simultaneously up to 9 elements from a single Lunar soil sample (Be, Al, Ca, Mn, Fe, Ni, Hf, Pu, Cm)
  - Cosmogenic radionuclides for exposure time (^{10}Be, ^{26}Al, ^{41}Ca and ^{53}Mn)
  - Confirm interstellar ^{60}Fe in Lunar soil

Interstellar Radionuclides



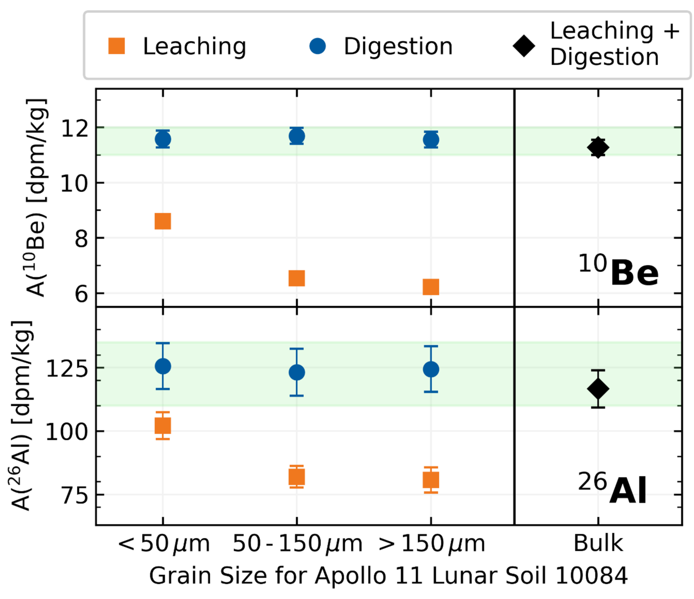
- Excess ^{60}Fe above cosmogenic production → **interstellar ^{60}Fe!**
- In agreement with literature and terrestrial data[2,3]
- More interstellar ^{60}Fe in smaller grains

Actinides

- Tests at ANSTO on ^{242}Pu-spike measurements in lunar simulants yielded total efficiencies ≥3‰ → ready for real samples

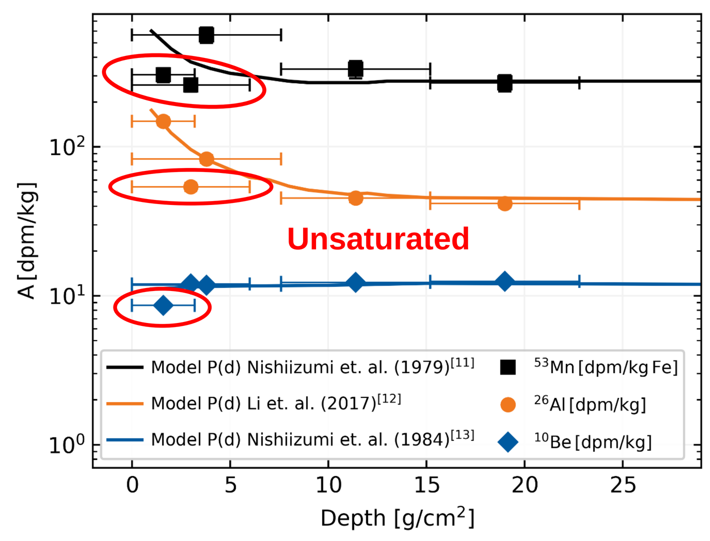
Cosmogenic Radionuclides

Is leaching already enough? → No!



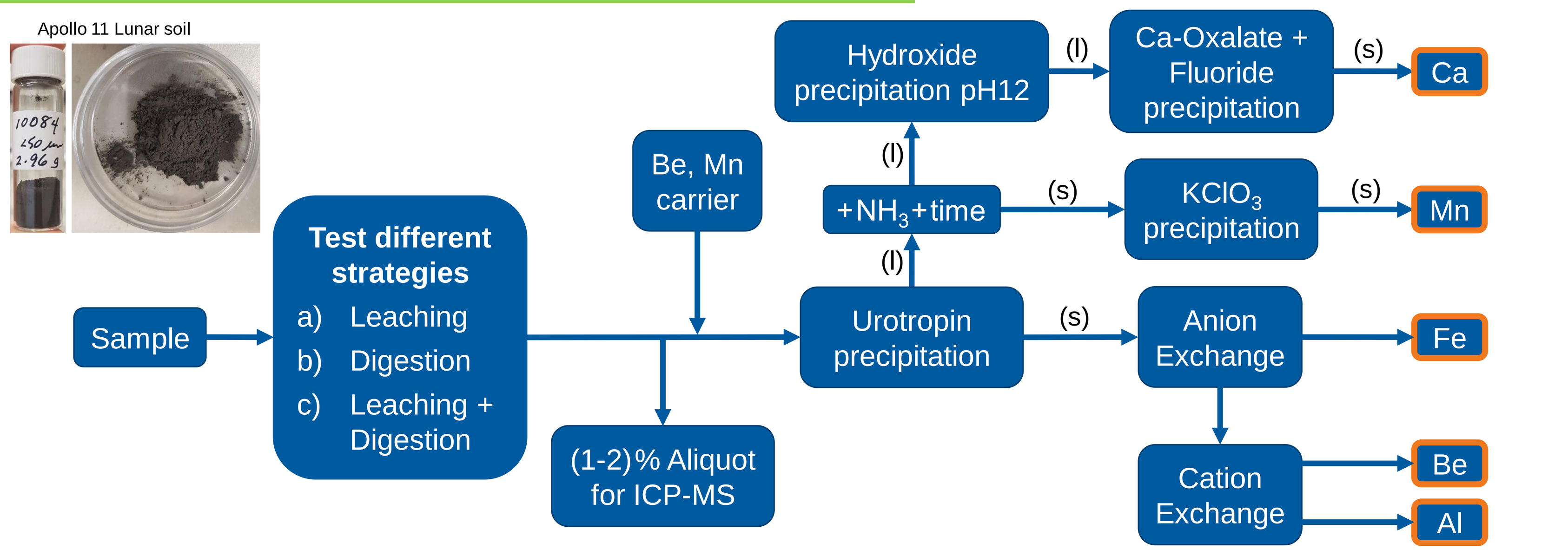
- Leaching not sufficient for complete radionuclide extraction

Exposure age on the Moon?



- Activity grows over time with A(t) = P(d)*(1-e$^{-\lambda t}$)
- ^{41}Ca (0.1 Myr) always saturated → exposure time >0.5 Myr

Sample Preparation

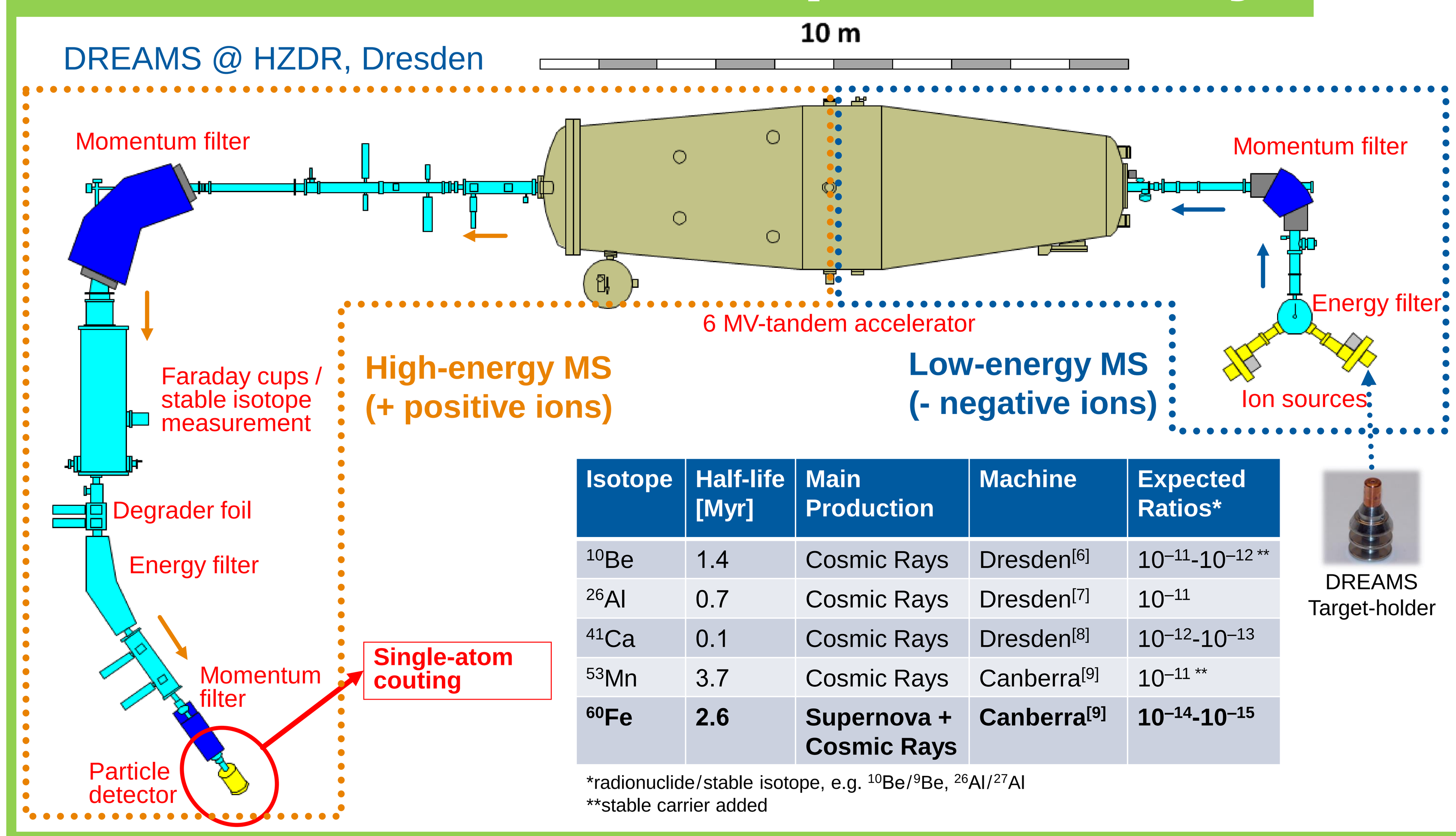


AMS-Sample (~mg)

- Test different leaching/digestion procedures[4, 5]
- Chemical yields typically >75%
- ~mg to ~50 mg sample necessary for all light elements
- Gram sized samples needed for ^{244}Pu ((^{244}Pu/^{60}Fe)$_{terr}$=10^{-5})[3]

Accelerator Mass Spectrometry

DREAMS @ HZDR, Dresden



Isotope	Half-life [Myr]	Main Production	Machine	Expected Ratios*
^{10}Be	1.4	Cosmic Rays	Dresden[6]	10^{-11}-10^{-12} **
^{26}Al	0.7	Cosmic Rays	Dresden[7]	10^{-11}
^{41}Ca	0.1	Cosmic Rays	Dresden[8]	10^{-12}-10^{-13}
^{53}Mn	3.7	Cosmic Rays	Canberra[9]	10^{-11} **
^{60}Fe	**2.6**	**Supernova + Cosmic Rays**	**Canberra[9]**	**10^{-14}-10^{-15}**

*radionuclide/stable isotope, e.g. ^{10}Be/^{9}Be, ^{26}Al/^{27}Al
**stable carrier added

DREAMS Target-holder

Summary and Outlook

- AMS as sensitive and efficient tool to provide new data → e.g. only few 100 ^{244}Pu-atoms in sample needed for one significant detector event!
- Technique established for **simultaneous extraction of multiple elements**
- Some samples not yet saturated in ^{10}Be, ^{26}Al, and/or ^{53}Mn → **exposure time** to cosmic rays
- **Interstellar ^{60}Fe** found in agreement with literature and terrestrial data
- Total AMS detection efficiencies between 0.2 and 8‰

Work in progress

- More ^{60}Fe measurements at HIAF, ANU
- ^{244}Pu & ^{247}Cm measurements at VEGA, ANSTO and HAMSTER, HZDR → interstellar *r*-process signatures in Lunar soil?

Acknowledgement: We thank the NASA/JSC Apollo Sample Curation Team for providing the samples. We acknowledge the support of ANSTO via the proposal AP16204. Thanks to S. Beutner (ICP-MS, HZDR) and S. Linke, E. Stoll (Lunar simulant TUBS-M, TU Berlin).

References: [1] Fields, B. D. and Wallner A. (2023) Annu. Rev. Nucl. Sci. 73, 365-395. [2] Fimiani, L. et al. (2016) PRL 116, 151104. [3] Wallner, A., et al. (2021) Science, 372(6543), 742-745. [4] Merchel, S. and U. Herpers (1999) Radiochim. Acta 84, 215. [5] Koll, D. et al. (2022) NIMB 530, 53-58. [6] Lachner et al. (2023) NIMB 535, 29-33. [7] Rugel et al. (2016) NIMB 370, 94-100. [8] Vivo-Vilches et al. (2023) NIMB 540, 188-193. [9] Wallner et al. (2023) NIMB 534, 48-53. [10] Leya, I., et al. (2020) Meteorit. & Planet. Sci., 55(4), 818-831. [11] Nishiizumi, K., et al. (1979) EPSL 44(3), 409-419. [12] Li, Y., et al. (2017) J. Geophys. Res. Space Phys. 122(2), 1473-1486. [13] Welten, K. C., et al. (2023) LPSC 54, #2921

www.hzdr.de/ams

Institute of Ion Beam Physics and Materials Research · Accelerator Mass Spectrometry and Isotope Research

Sebastian Zwickel · s.zwickel@hzdr.de · www.hzdr.de/ams

ANSTO · Australian National University · DRESDEN concept SCIENCE AND INNOVATION CAMPUS