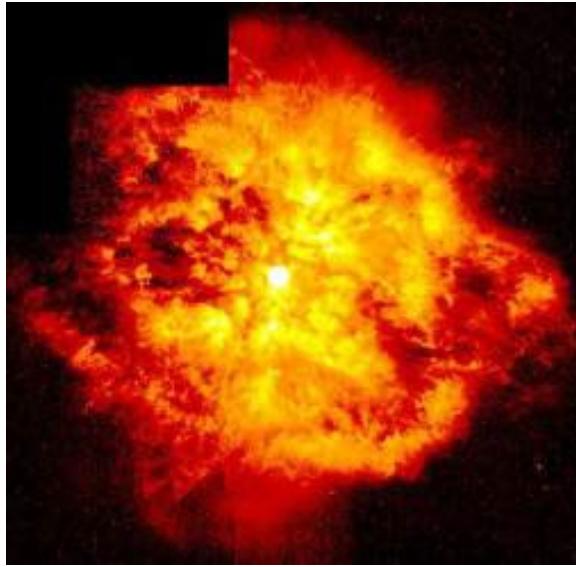


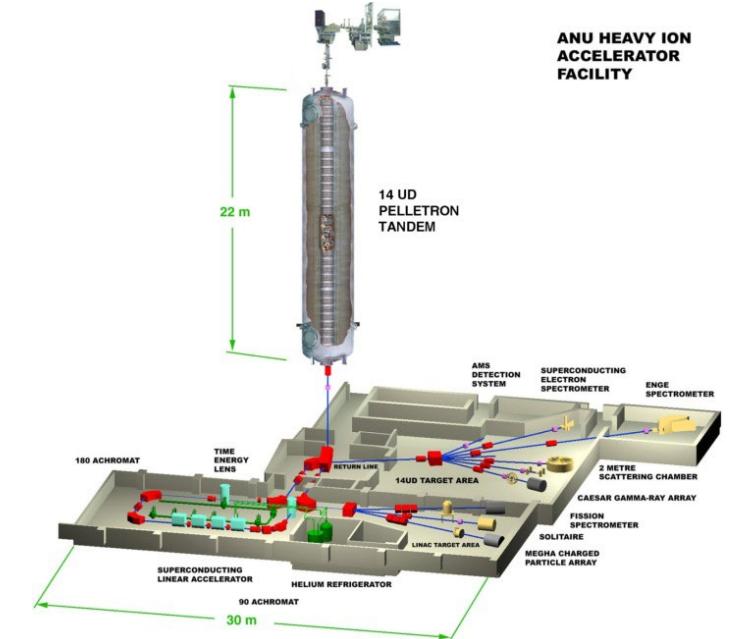
r-process and supernova (SN) deposits in deep-sea archives



A. Wallner

HZDR – Helmholtz Center Dresden,
Germany

The Australian National University
(ANU) Canberra, Australia



r-process and Supernovae (SNe) – the extraordinary development of accelerator mass spectrometry (AMS) for identifying traces of interstellar origin



A. Wallner

HZDR – Helmholtz Center Dresden, Germany

The Australian National University (ANU)
Canberra. Australia

**Norikazu Kinoshita, Dominik Koll, L. Keith Fifield,
Michaela Froehlich, Michael Hotchkis, Michael Paul,
Stefan Pavetich, Stephen Tims**

HZDR (Dresden, GER):

ANU (Canberra, AU):

ANSTO/Sydney (AU):

Univ. of Vienna (AT):

Hebrew Univ. (Israel):

Nagoya/Tokyo/Tsukuba:

TU Munich (Germany):

G. Rugel, S. Merchel, D. Koll, S. Fichter, S. Zwickel

M. Froehlich, S. Pavetich, L.K. Fifield, S. Tims,

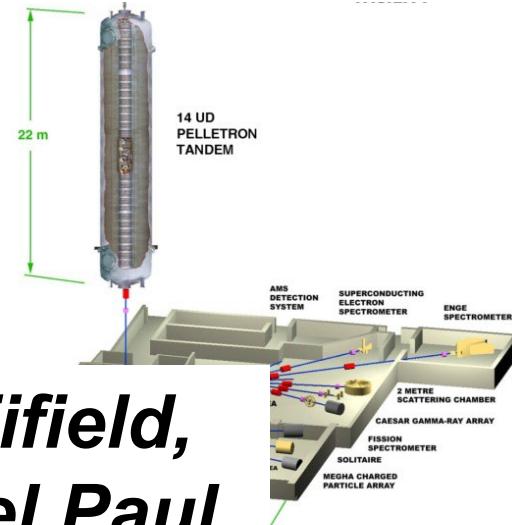
M. Hotchkis, D. Child

J. Feige, R. Golser, W. Kutschera, S. Merchel, A. Priller, P. Steier, S. Winkler

M. Paul

N. Kinoshita, M. Honda, Matsuzaki, Yamagata

G. Korschinek, K. Knie, T. Faestermann



Search for extraterrestrial radionuclides

Isotopic Abundances of Actinide Elements in Lunar Material

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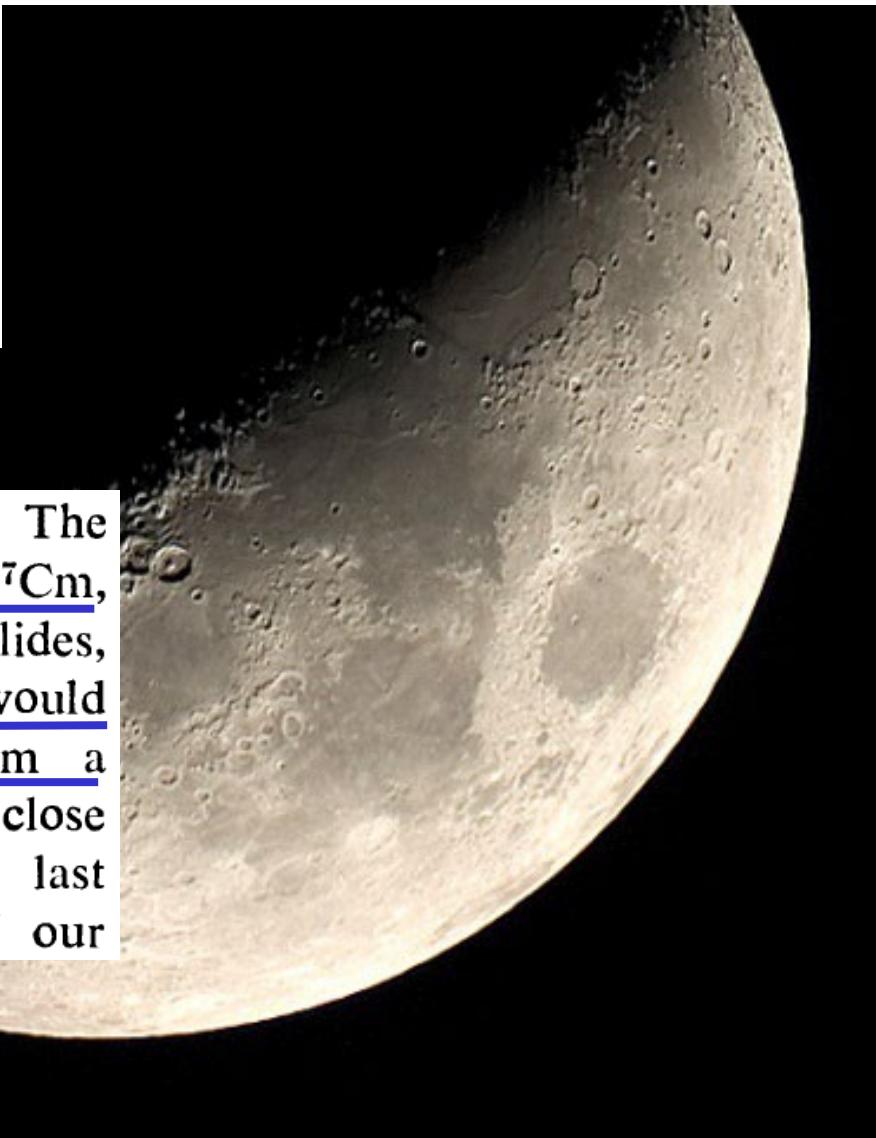
Argonne National Laboratory,

Chemistry Division, Argonne, Illinois

1970

SCIENCE, VOL. 167

heat production on the moon. The possible presence of ^{244}Pu or ^{247}Cm , two extinct or nearly extinct nuclides, was interesting because they would have indicated an infusion from a supernova that occurred quite close to the solar system within the last billion years. Another object of our



Supernova (SN)-rate in our galaxy:

- *2 per century*
- *1 SN per 3 Myr within 100 pc to Earth*

galaxy

Can we find isotopic fingerprints of the ISM (interstellar medium) in terrestrial archives?

Radionuclides contain time information as they can serve as radioactive clocks!

GEOLOGICAL ISOTOPE ANOMALIES AS SIGNATURES OF NEARBY SUPERNOVAE

JOHN ELLIS

Theoretical Physics Division, CERN, Geneva, Switzerland

BRIAN D. FIELDS¹

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AND

DAVID N. SCHRAMM²

University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637

Received 1995 June 15; accepted 1996 May 21

^{60}Fe : $t_{1/2} = 2.6 \text{ Myr}$

Ni 55 209 ms β^+ 7.7... γ (2919; 2976; 3303)	Ni 56 6.075 d ϵ ; no β^+ γ 158; 812; 750; 480; 270...	Ni 57 36.0 h ϵ ; β^+ 0.8... γ 1378; 1920; 127...	Ni 58 68.0769 σ 4.6 $\sigma_{n, \alpha} < 0.00003$	Ni 59 $7.5 \cdot 10^4$ a ϵ ; β^+ ... no γ ; σ 77.7 $\sigma_{n, \alpha}$ 14; $\sigma_{n, p}$ 2 σ_{abs} 92	Ni 60 26.2231 σ 2.9	Ni 61 1.1399 σ 2.5 $\sigma_{n, \alpha} 0.00003$	Ni 62 3.6345 σ 15	Ni 63 100 a β^- 0.07 no γ σ 20
Co 54 1.48 m 193.2 ms β^+ 4.3 γ 411; 1130; 1407	Co 55 17.54 h β^+ 1.5... γ 931; 477; 1409...	Co 56 77.26 d ϵ ; β^+ 1.5... γ 847; 1238; 2598; 1771; 1038...	Co 57 271.79 d ϵ γ 122; 136; 14	Co 58 8.94 h β^+ (25) ϵ σ 140000	Co 59 100 β^+ 0.5; 1.3 γ 811 σ 1900	Co 60 10.5 m 5.272 a β^- 0.3; 1.5... γ 1332; γ (1332...) 1173... σ 58	Co 61 1.65 h β^- 1.2... γ 67; 909...	Co 62 14.0 m 1.5 m β^- 2.9... γ 1173; 1163; 2003... 1129...
Fe 53 2.5 m 8.51 m β^- 701; 1328; 1011; 2340... β^+ 2.8... γ 378; (1620...)	Fe 54 5.845 σ 2.3 $\sigma_{n, \alpha}$ 1E-5	Fe 55 2.73 a ϵ no γ σ 13 $\sigma_{n, \alpha}$ 0.01	Fe 56 91.754 σ 2.8	Fe 57 2.119 σ 1.4	Fe 58 0.282 σ 1.3	Fe 59 44.503 d β^- 0.5; 1.6... γ 1099; 1292... σ 13	Fe 60 2.6 Myr β^- 0.1 m	Fe 61 6.0 m β^- 2.6; 2.8... γ 1205; 1027; 298...
Mn 52 21 m 5.6 d β^+ 2.6... γ 1434... β^- 378	Mn 53 $3.7 \cdot 10^6$ a ϵ no γ	Mn 54 312.2 d ϵ γ 835 σ < 10	Mn 55 100 σ 13.3	Mn 56 2.58 h β^- 2.9... γ 847; 1811; 2113...	Mn 57 1.5 m β^- 2.6... γ 14; 122; 692...	Mn 58 65.3 s 3.0 s β^- 3.9... γ 811; 1323... β^- 6.1... γ 1447; γ 72; σ^- 2433...	Mn 59 4.6 s β^- 4.4; 4.8... γ 726; 473; 571...	Mn 60 1.77 s 0.28 s β^- 5.7... 6.1... γ 823; 1969... β^- 8.2... γ 823; 1150; 1532
Cr 51 27.70 d ϵ γ 320 σ < 10	Cr 52 83.789 σ 0.8	Cr 53 9.501 σ 18	Cr 54 2.365 σ 0.36	Cr 55 3.50 m β^- 2.6 γ (1528...)	Cr 56 5.9 m β^- 1.5 γ 83; 26	Cr 57 21.1 s β^- 5.1... γ 83; 850; 1752; 1535...	Cr 58 7.0 s β^- γ 683; 126; 290; 520... m	Cr 59 1.05 s β^- γ 1238; 1900; 112; 663...

^{60}Fe is rare on Earth ... is produced in massive stars

Actinides – pure r process



80 Myr

152

110

109

108

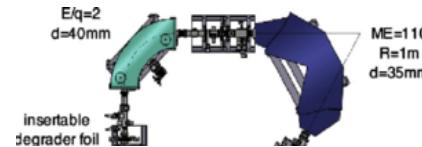
150

148

^{244}Pu is rare on Earth ... is produced in the *r* process

ANU (15 MV) - Canberra

VEGA (1 MV) – ANSTO/Sydney



ANU HEAVY ION
ACCELERATOR
FACILITY

^{60}Fe : **detection efficiency:** $\sim 0.5\%$
abundance sensitivity: $^{60}\text{Fe}/\text{Fe} \sim 2 \times 10^{-17}$



^{244}Pu : **detection efficiency:** $\sim \%$
background-free



sensitivity: few 100 Pu atoms / Myr influx!

→ **sensitivity increase: 100×: 2010 → 2020**

→ e.g. $10^{-21} - 10^{-22} \text{ g } ^{244}\text{Pu} / \text{g crust}$ (100 gram sample)

Archives – de



*direct single atom counting using AMS
- accelerator mass spectrometry -*

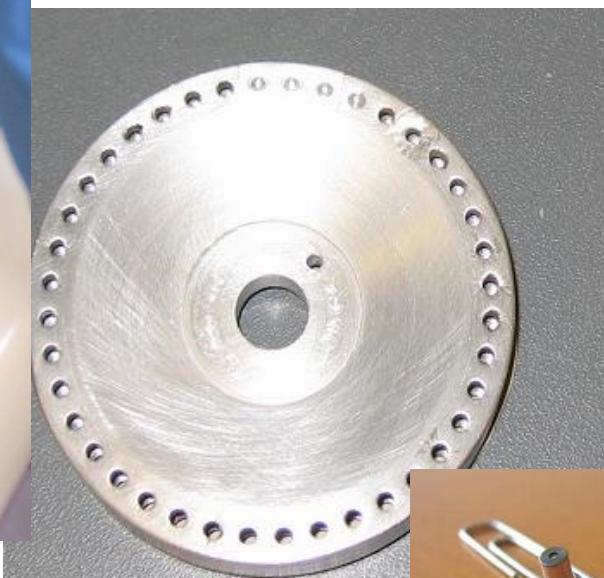
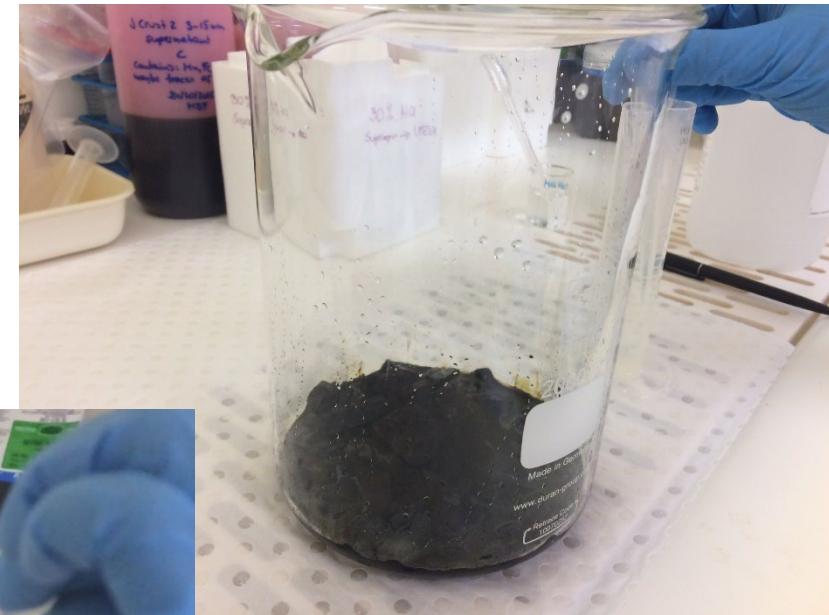
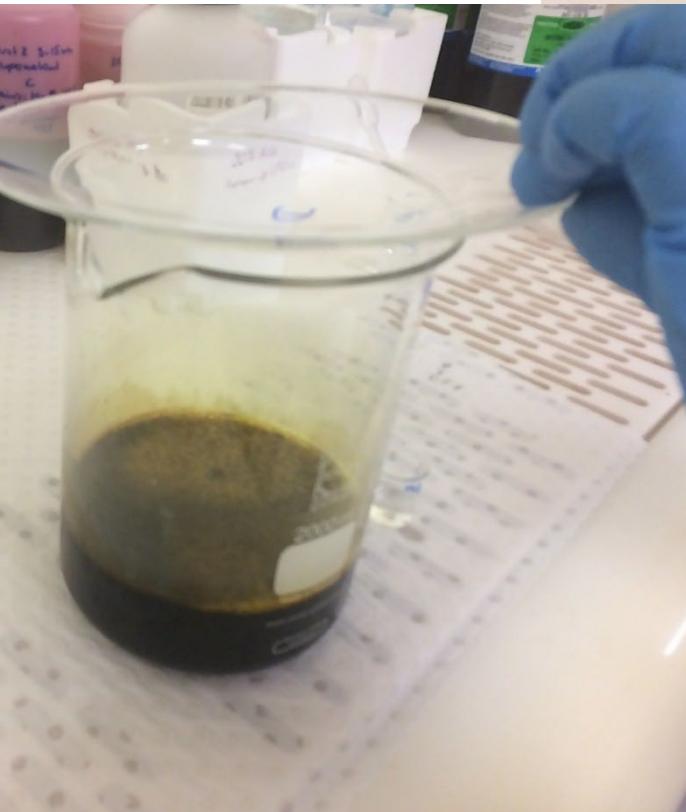
NSTO, Sydney



ary Sciences

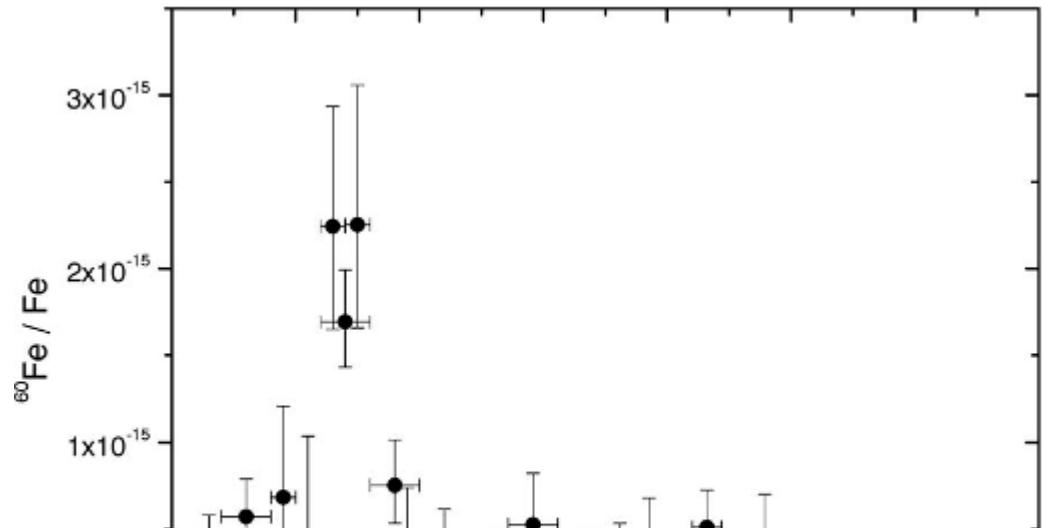
Fe / Pu separation:

M. Froehlich, D. Koll, S. Fichter



^{60}Fe -signal in a deep-sea crust

AMS at Munich



AMS measurement of
 ^{60}Fe content of crust at
TU Munich

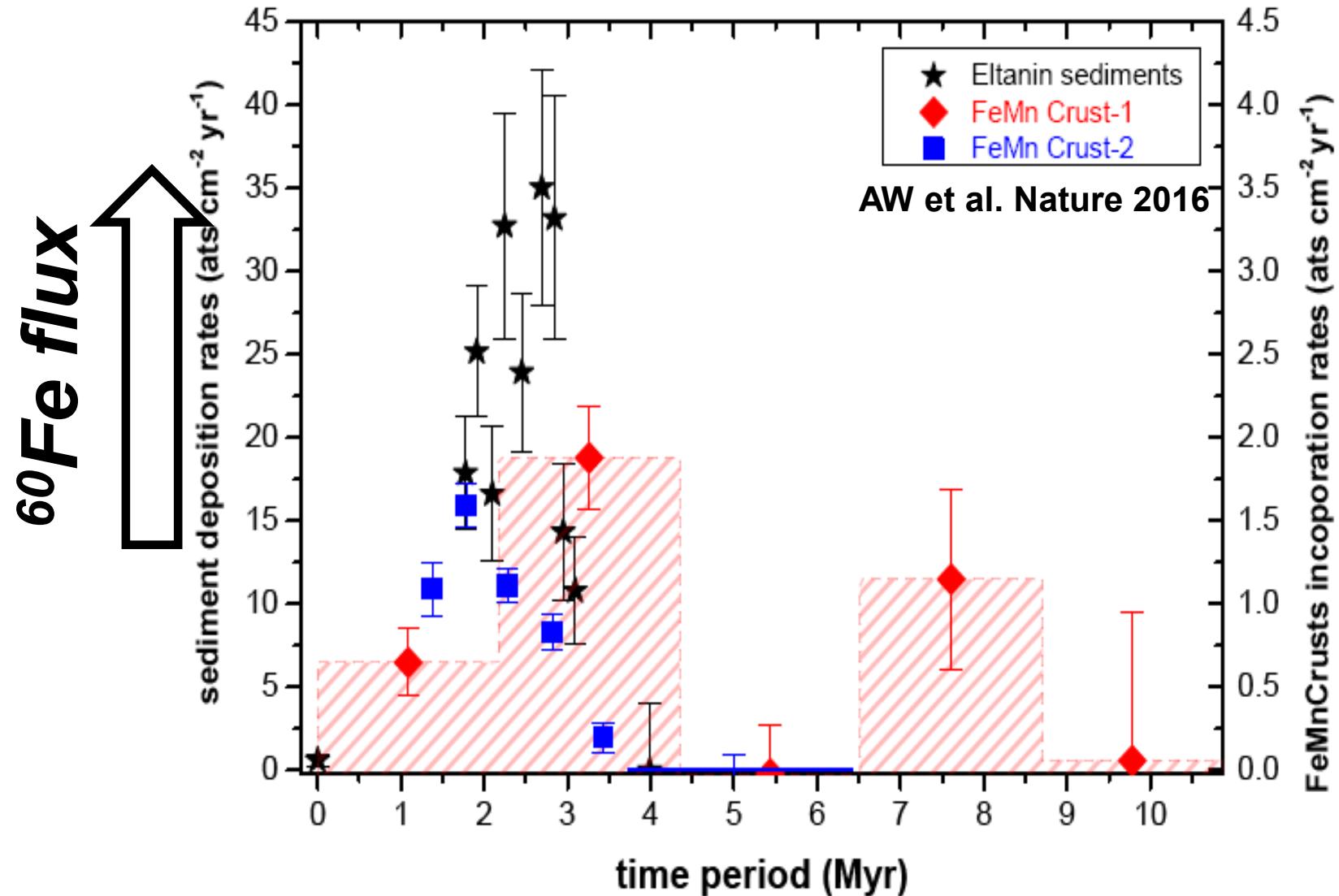
$^{60}\text{Fe}: 2004 \rightarrow 2023$

- **background:** 10x lower (abundance sensitivity)
- **measurement detection efficiency:** 3 x higher

ANU

[note: on average still less than 1 count per hour.]

^{60}Fe from sediments and crusts



Deep-sea:

- Sediments: Ludwig et al. 2016
- Sediments: AW et al. 2016, 2020
- Crust: K. Knie et al. 1999, 2004
- Crust: AW et al. 2016, 2021
- Crust: D Koll et al. 2023
- Nodules: AW et al. 2016

Lunar samples

- Fimiani et al. 2016
- Zwickel et al. 2023

Antarctic snow / ice

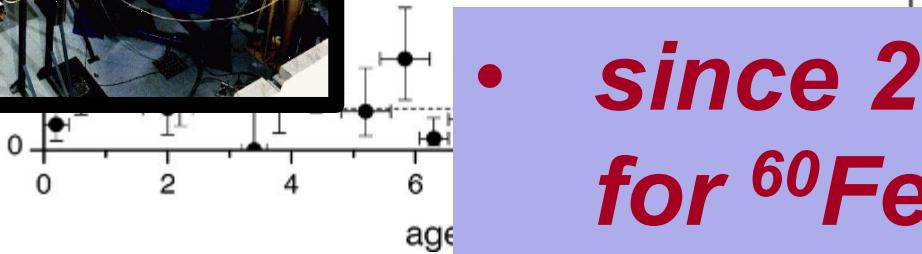
- D. Koll et al. 2020
- D. Koll et al. 2023

^{60}Fe in cosmic rays: Binns et al. 2016

AMS@ANU & TUM: 2016 – ... consistent

^{60}Fe -signal in a deep-sea crust

AMS at Munich



peak at 2-3 Myr!



AMS measurement of
 ^{60}Fe content of crust at

- *since 2021 → ANU the only lab for ^{60}Fe*

VOLUME 93, NUMBER 17

PHYSICAL REVIEW LETTERS

week ending
22 OCTOBER 2004

→ Need for a new state-of-the-art 15MV+ AMS system?

K. Knie,¹ G. Korschinek,^{1,*} T. Faestermann,¹ E. A. Dorfi,² G. Rugel,^{1,3} and A. Wallner^{1,3}

Interstellar ^{60}Fe detected on Earth – is there also some r-process ^{244}Pu ?

Interstellar ^{244}Pu -

- “*How were the heavy elements from iron to uranium synthesized – clues from extraterrestrial ^{244}Pu ?*”
- “*The unknown site of r-process nucleosynthesis – supernovae, massive stars ✓*”
- “ *^{244}Pu - 80 Myr r-process - site unknown
... Supernovae?
... Neutron star merger?*”

Search for extraterrestrial radionuclides

Isotopic Abundances of Actinide Elements in Lunar Material

PAUL R. FIELDS, HERBERT DIAMOND

DONALD N. METTA

CHARLES M. STEVENS

DONALD J. ROKOP, PARKER E. MORELAND

Argonne National Laboratory,

Chemistry Division, Argonne, Illinois

1970

SCIENCE, VOL. 167

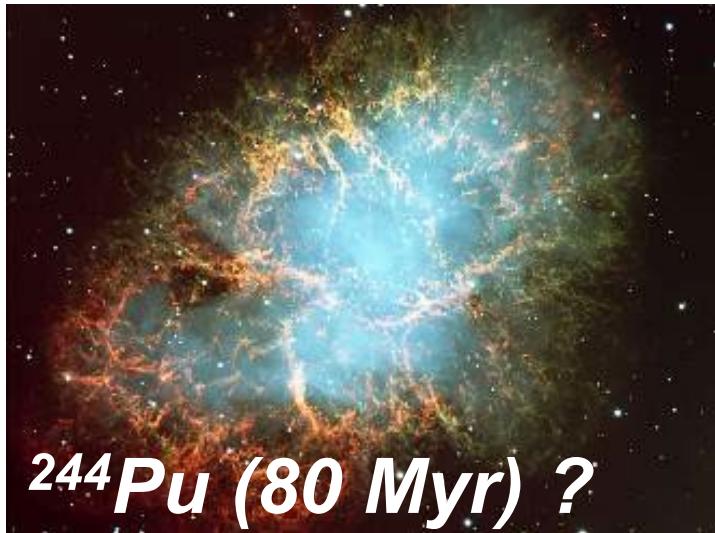


heat production on the moon. The possible presence of ^{244}Pu or ^{247}Cm , two extinct or nearly extinct nuclides, was interesting because they would have indicated an infusion from a supernova that occurred quite close to the solar system within the last billion years. Another object of o

was steady and continuous. The absence of ^{244}Pu and ^{247}Cm in lunar material precludes nearby supernovae explosions within the last eon or two. The precise limits depend strongly on the details of

↔ ↔ **^{60}Fe points to supernovae**

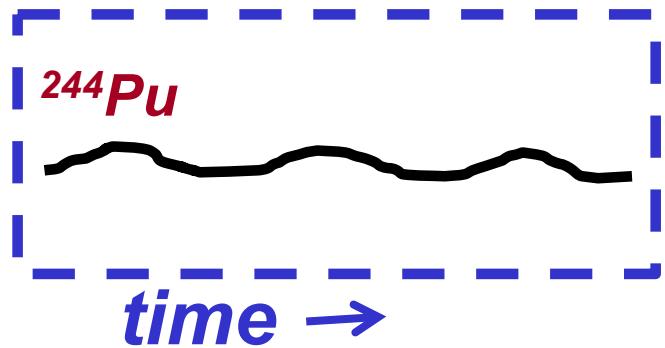
r-process sites?



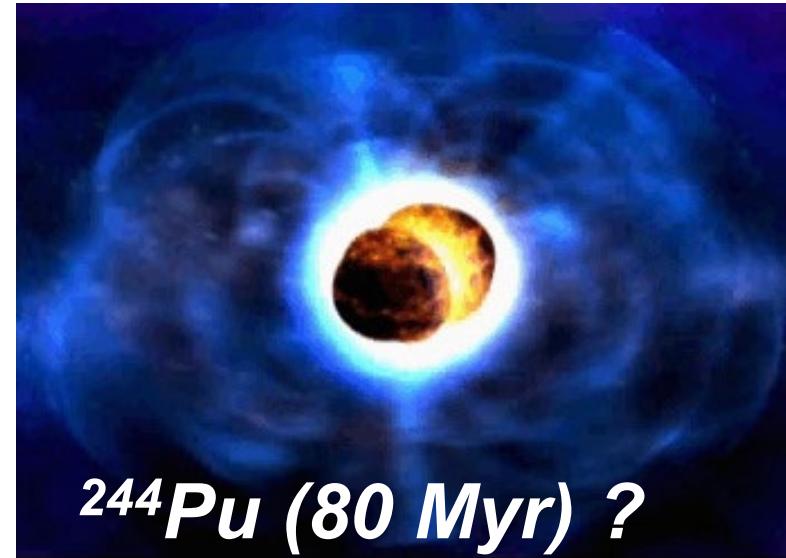
^{244}Pu (80 Myr) ?

Hubble

core collapse supernova



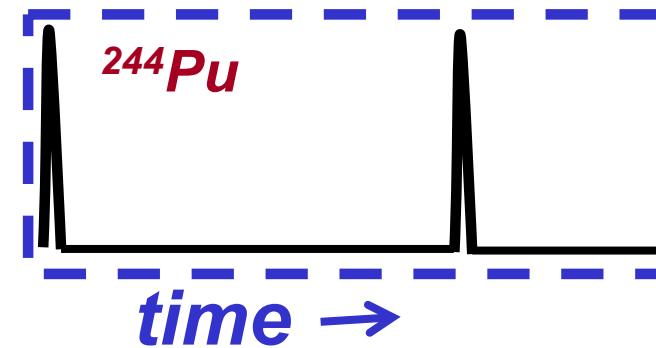
rates:
 $\sim 1000:1$



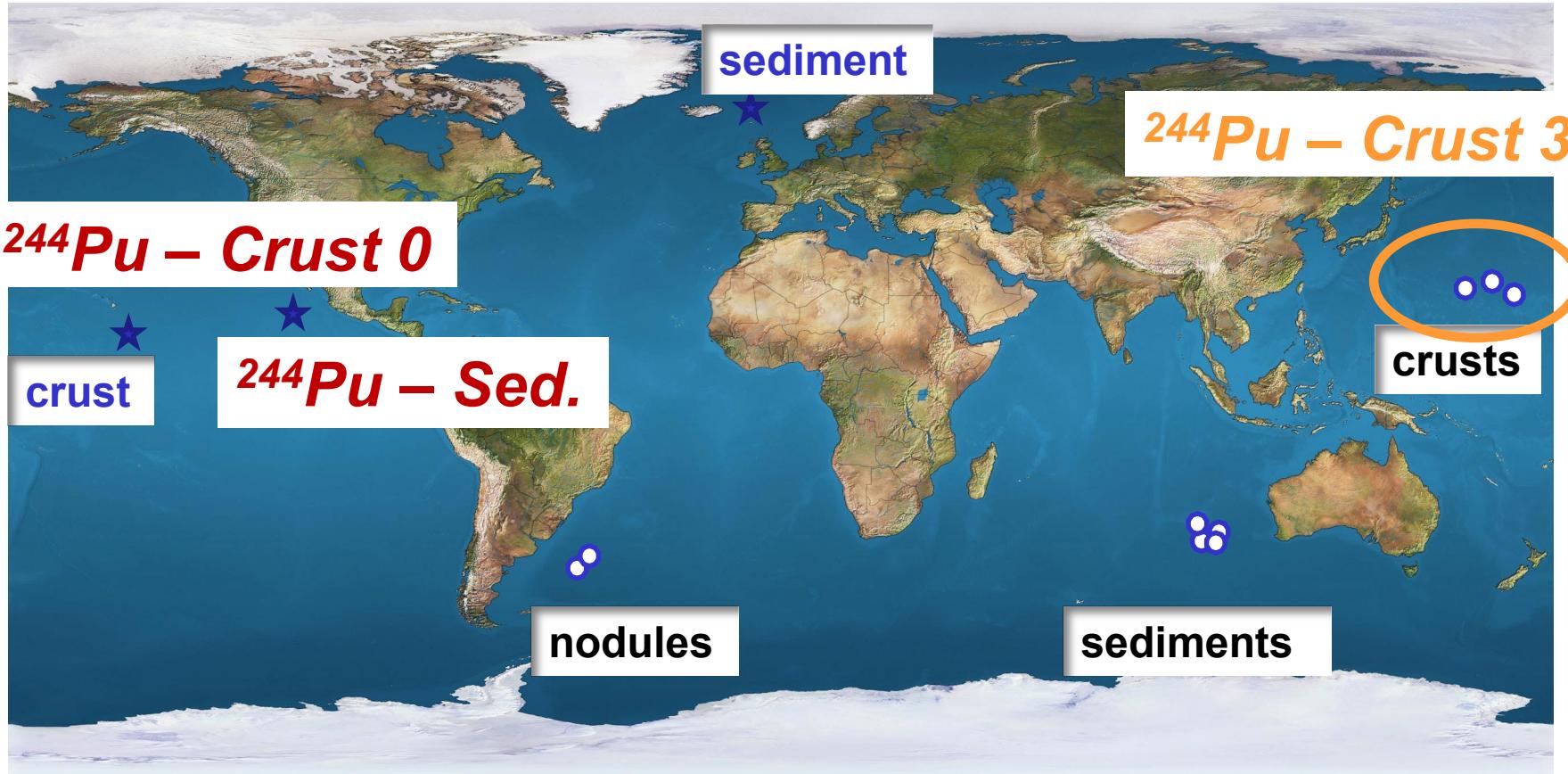
^{244}Pu (80 Myr) ?

© NASA

neutron star mergers



Deep-sea archives for cosmic dust

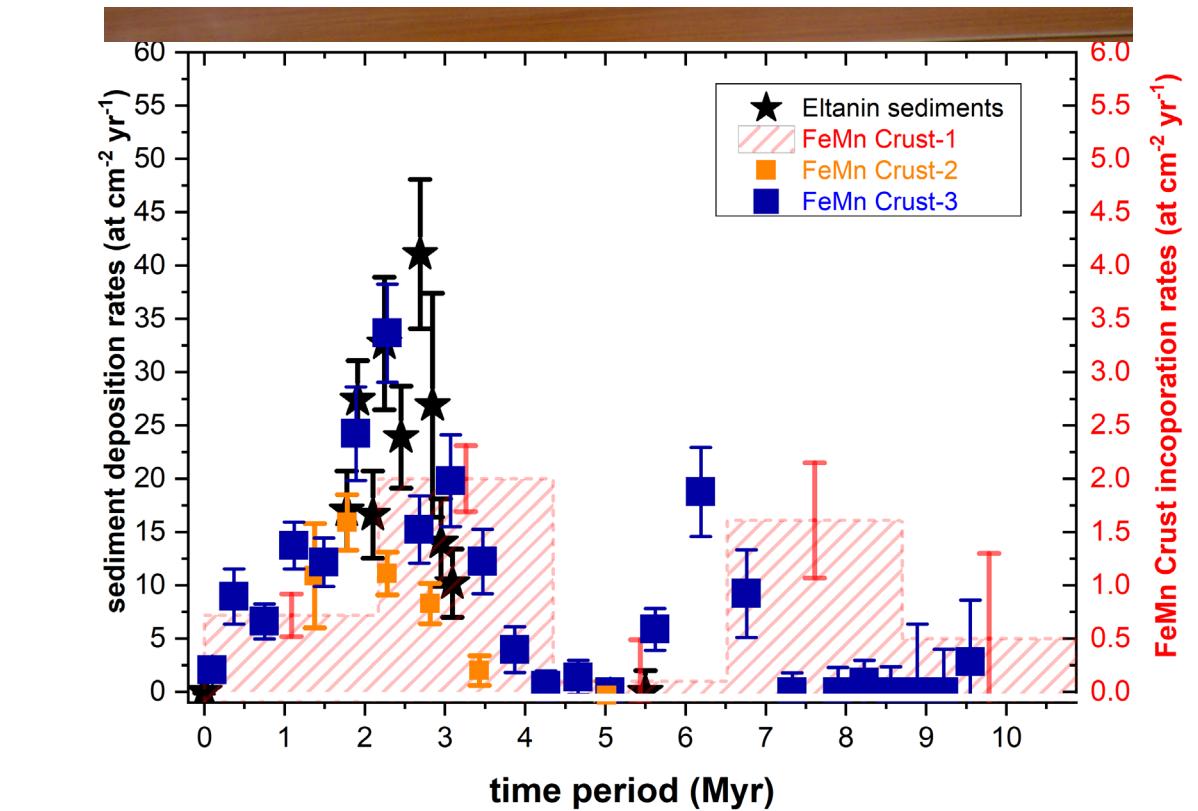


→²⁴⁴Pu / ⁶⁰Fe: Crust-3

→²⁴⁴Pu / ⁶⁰Fe: Crust-0 PhD D. Koll – ongoing

→²⁴⁴Pu / ⁶⁰Fe: lunar soil PhD S. Zwickel - ongoing

Summary – ^{60}Fe & ^{244}Pu in deep-sea archives



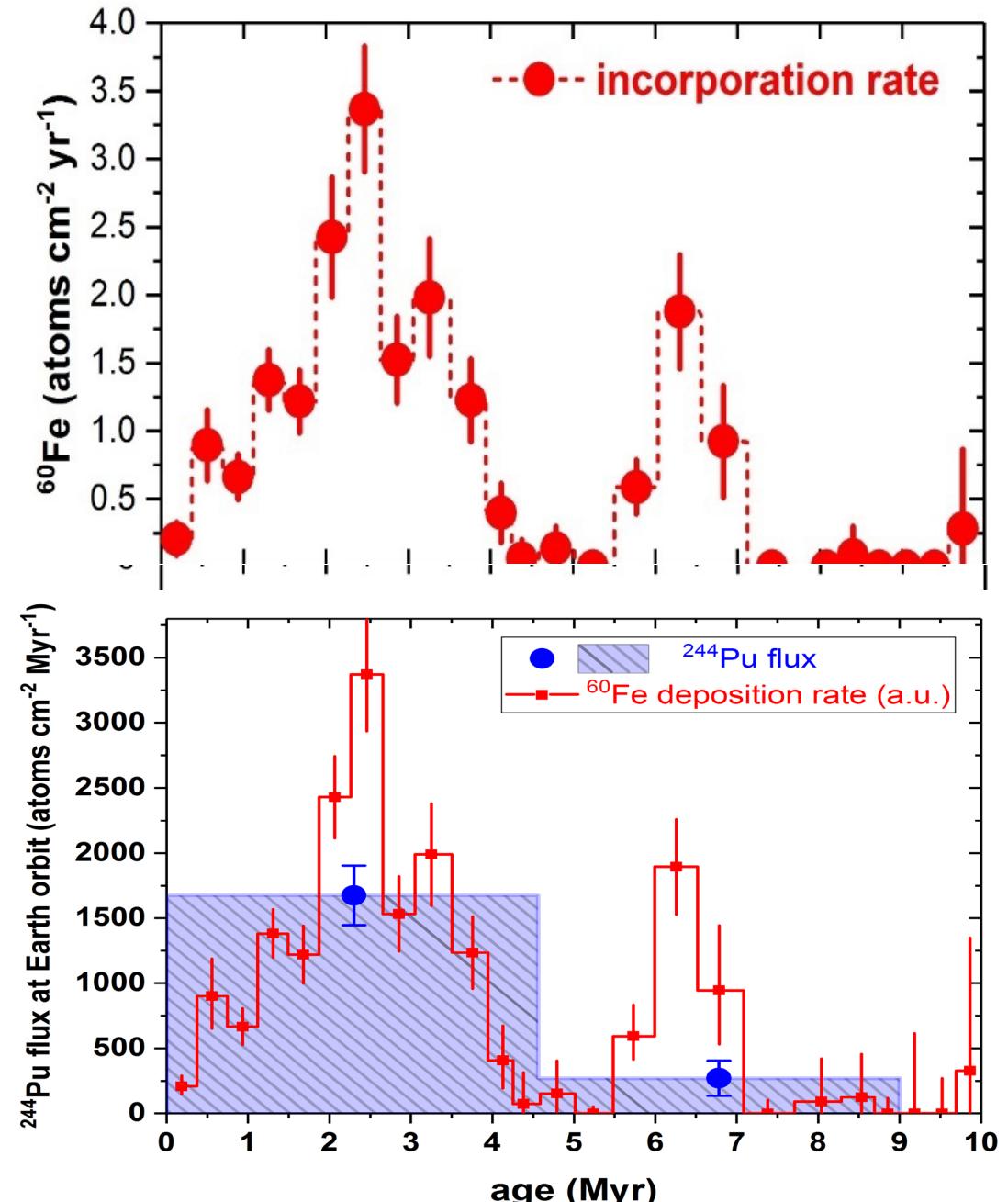
RESEARCH

NUCLEAR ASTROPHYSICS

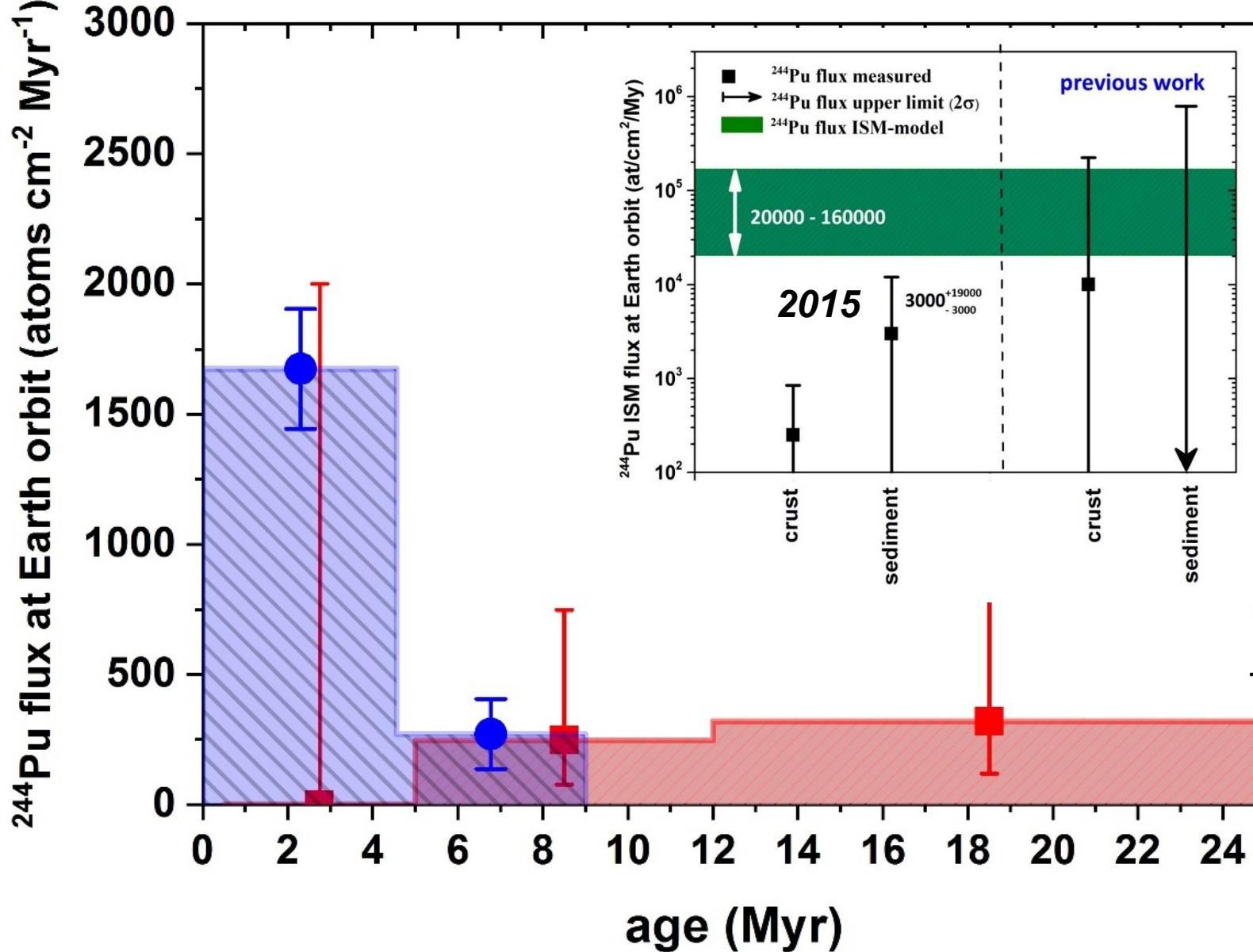
^{60}Fe and ^{244}Pu deposited on Earth constrain the r-process yields of recent nearby supernovae

A. Wallner^{1,2*}, M. B. Froehlich¹, M. A. C. Hotchkis³, N. Kinoshita⁴, M. Paul⁵, M. Martschini^{1†}, S. Pavetich¹, S. G. Tims¹, N. Kivel⁶, D. Schumann⁶, M. Honda^{7‡}, H. Matsuzaki⁸, T. Yamagata⁸

$^{244}\text{Pu}/$



Absolute ^{244}Pu influx – 20 Myr



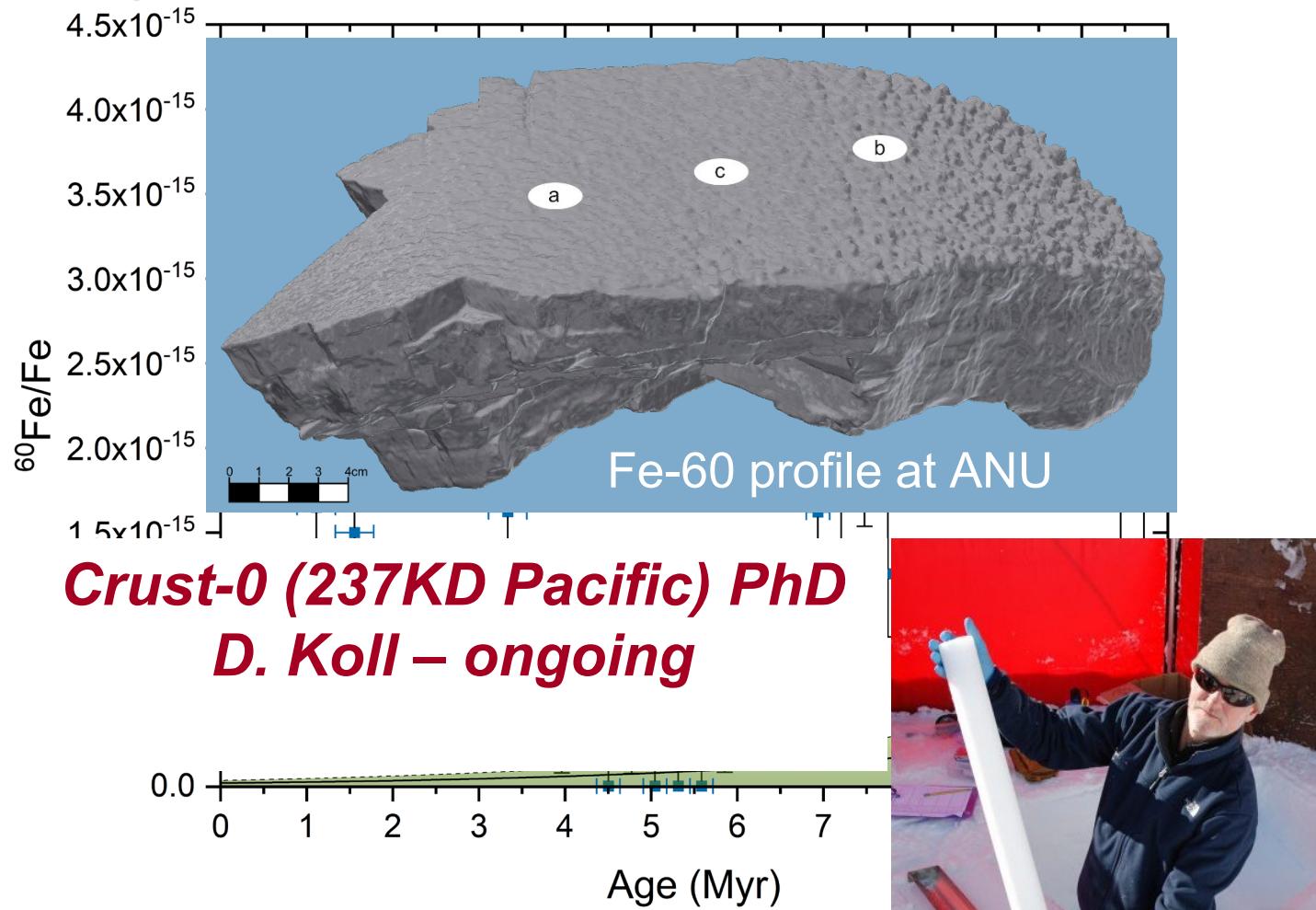
^{244}Pu influx too low for Supernovae as major r process contributor

Previous:

- C. Wallner + 2000, 2004
- M. Paul + 2001, 2007
- G. Raisbeck + 2007
- A. Wallner + 2015

In progress: new crust

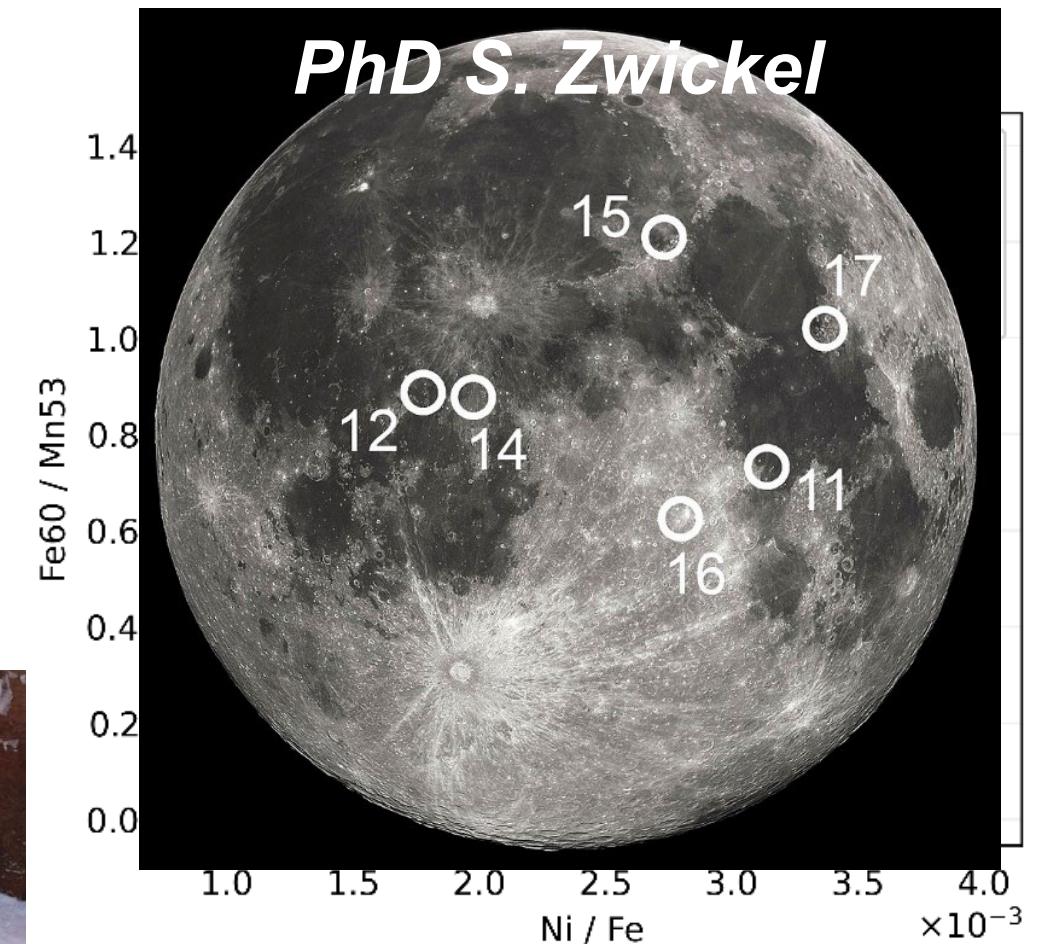
10 Myr time profile of ^{60}Fe & ^{244}Pu



**Crust-0 (237KD Pacific) PhD
D. Koll – ongoing**

**Antarctica – Epica ice core:
D. Koll / A. Rolofs ... - ongoing**

Lunar Soil – ^{60}Fe & ^{244}Pu



Successful – first data

- ^{10}Be , ^{26}Al
- ^{53}Mn , ^{60}Fe
- ^{244}Pu , ...

HAMSTER – a new state-of-the-art AMS system

Helmholtz AMS for Tracing Environmental Radionuclides



HAMSTER



Example: 1-MV facility at ANSTO / Sydney



SCIENCE AND
INNOVATION CAMPUS

^{244}Pu , ^{247}Cm , ^{53}Mn , ^{10}Be , ^{26}Al , ^{182}Hf ... ?

Summary

^{244}Pu

- *small influx of live ^{244}Pu - but significant!*
- *abundance low -> SN production not sufficient*
- *r-element influx correlates with SN- ^{60}Fe*
- *production of ^{244}Pu within the past few 100 Myr*

^{244}Pu (80 Myr) - ^{60}Fe (2.6 Myr)

^{60}Fe

- *clear extraterrestrial influx – points to recent SN activity close-by to Earth*
 - *multiple events? – dynamic interstellar medium*
 - *close-by (≤ 150 pc)*

More ^{60}Fe data 2016 ...

PRL 116, 151104 (2016)

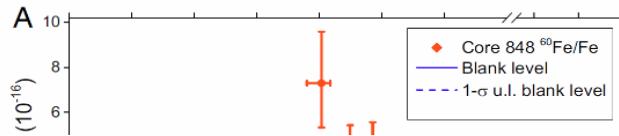
PHYSICAL REVIEW LETTERS

week ending
15 APRIL 2016



Interstellar ^{60}Fe on the Surface of the Moon

L. Fimiani,¹ D. L. Cook,^{2,*} T. Faestermann,¹ J. M. Gómez-Guzmán,¹ K. Hain,¹ G. Korschinek,^{1,†} P. Ludwig,¹ J. Park,² R. C. Reedv,³ and G.

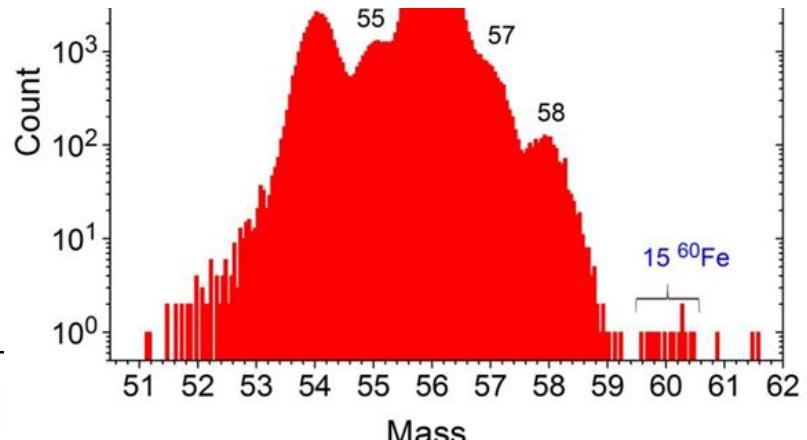


Time-resolved 2-million-year-old supernova discovered in Earth's microfossil record

Peter Ludwig^a, Shawn Bishop^{a,1}, Ramon Egli^b, Valentyna Chernenko^a, Boyana Deneva^c, Nicolai Famulok^a, Leticia Fimiani^a, José Manuel Gómez-Guzmán^a, Karin Hain^a, Gunther Herzer^d, Silke Merchel^d, and Georg Rugel^d

www.pnas.org/cgi/doi/10.1073/pnas.1601040113

**Antarctic snow (TUM) (D. Koll, PRL 2019)
& sediments (ANU) \rightarrow ^{60}Fe influx continues
until present times (PNAS 2020)**



ASTROPARTICLE PHYSICS

Observation of nucleosynthesis in galactic cosmic rays

W. R. Binns,^{1,*} M. H. Israel,¹ K. A. Lave,¹ R. A. Leske,³ R. T. T. von Rosenvinge,² M. E.

PNAS 2020 ^{60}Fe deposition during the late Pleistocene and the Holocene echoes past supernova activity

A. Wallner^{a,b,1}, J. Feige^{c,d}, L. K. Fifield^a, M. B. Froehlich^a, R. Golser^c, M. A. C. Hotchkis^e, D. Koll^a, G. Leckenby^a, M. Martschini^{a,c}, S. Merchel^b, S. Panjkov^a, S. Pavetich^a, G. Rugel^b, and S. G. Tims^a

A. Wallner SCIENCE sciencemag.org

