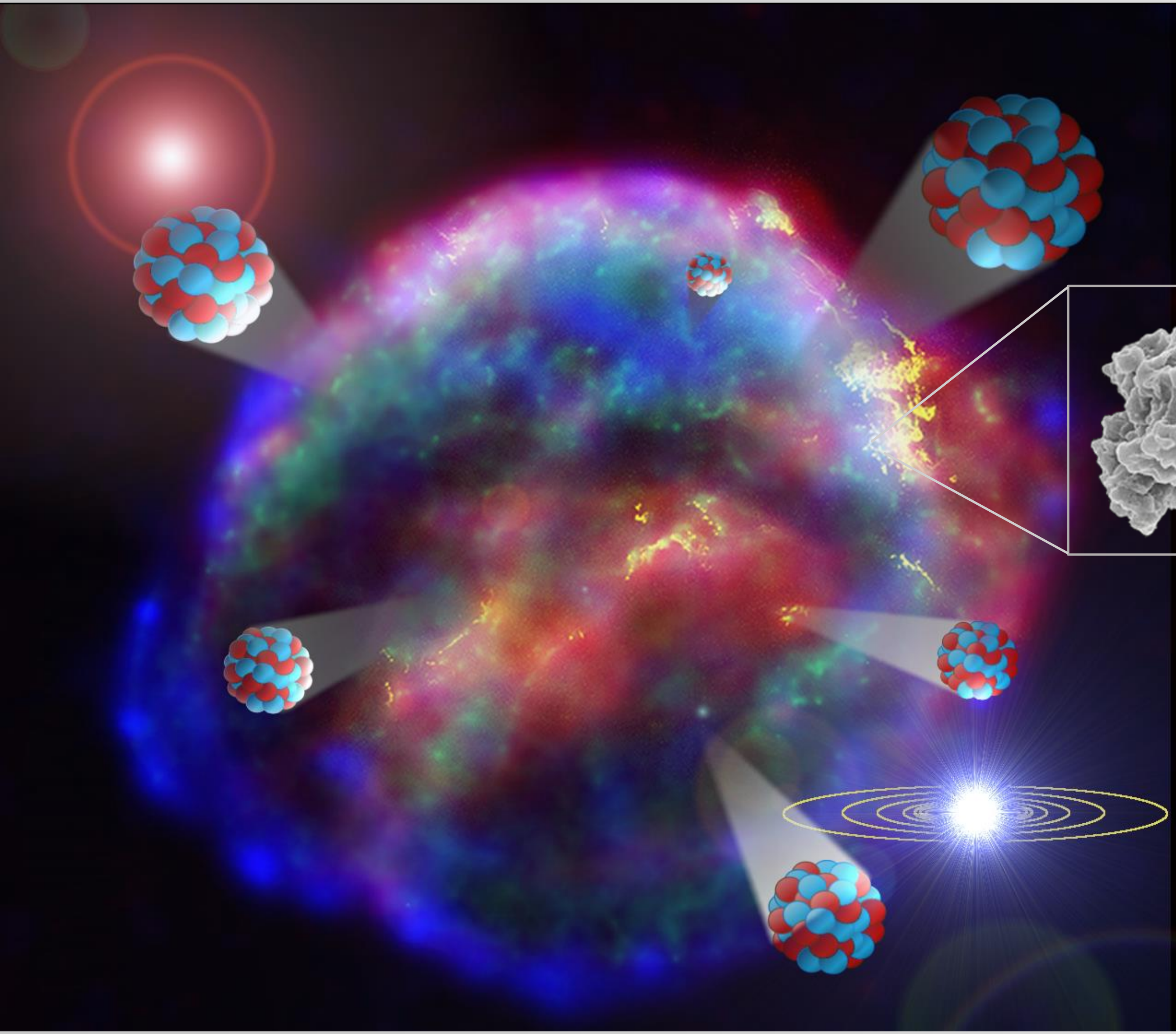
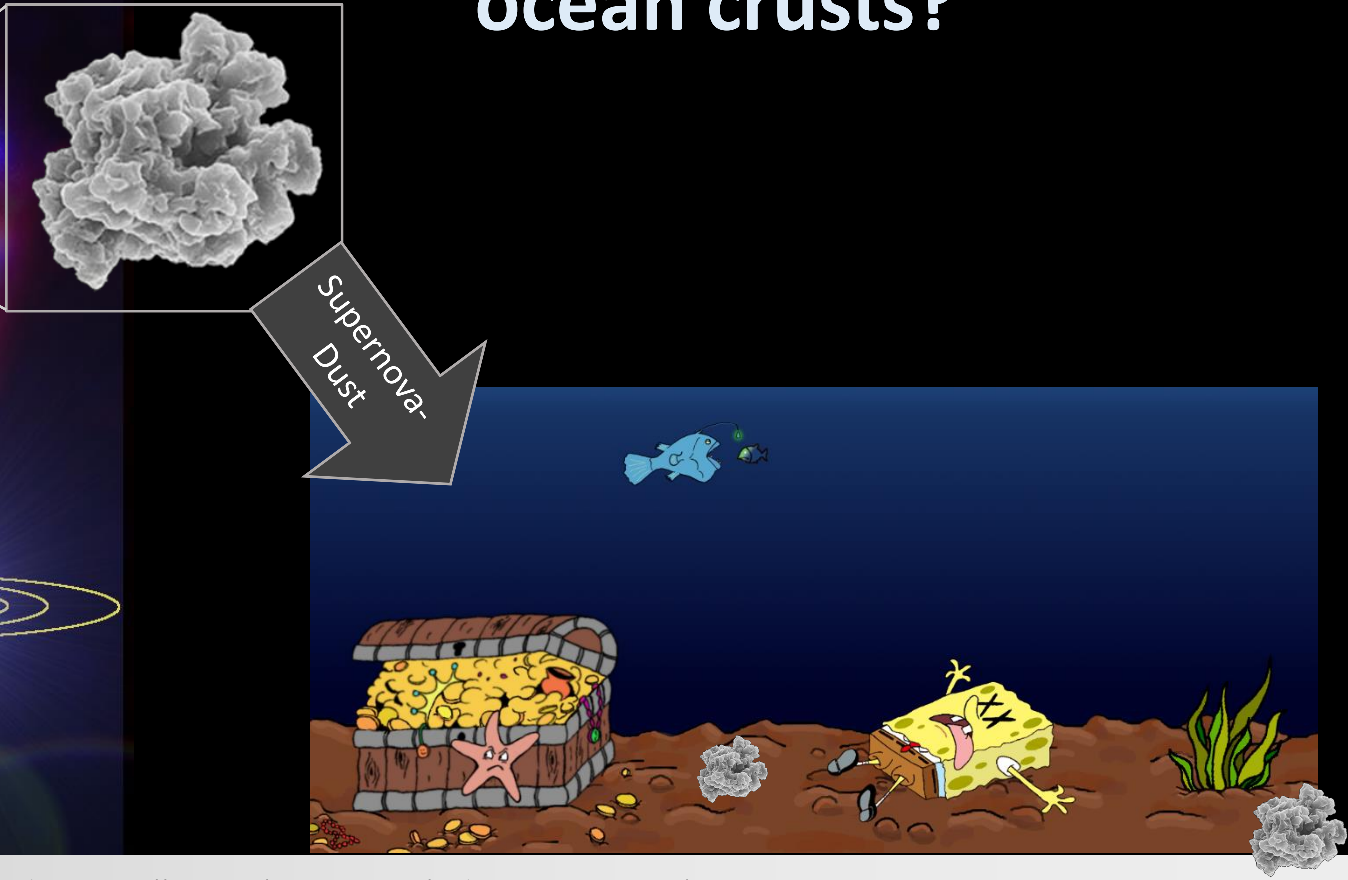
Jenny Feige
Technische Universität Berlin, Germany
13.10.2021

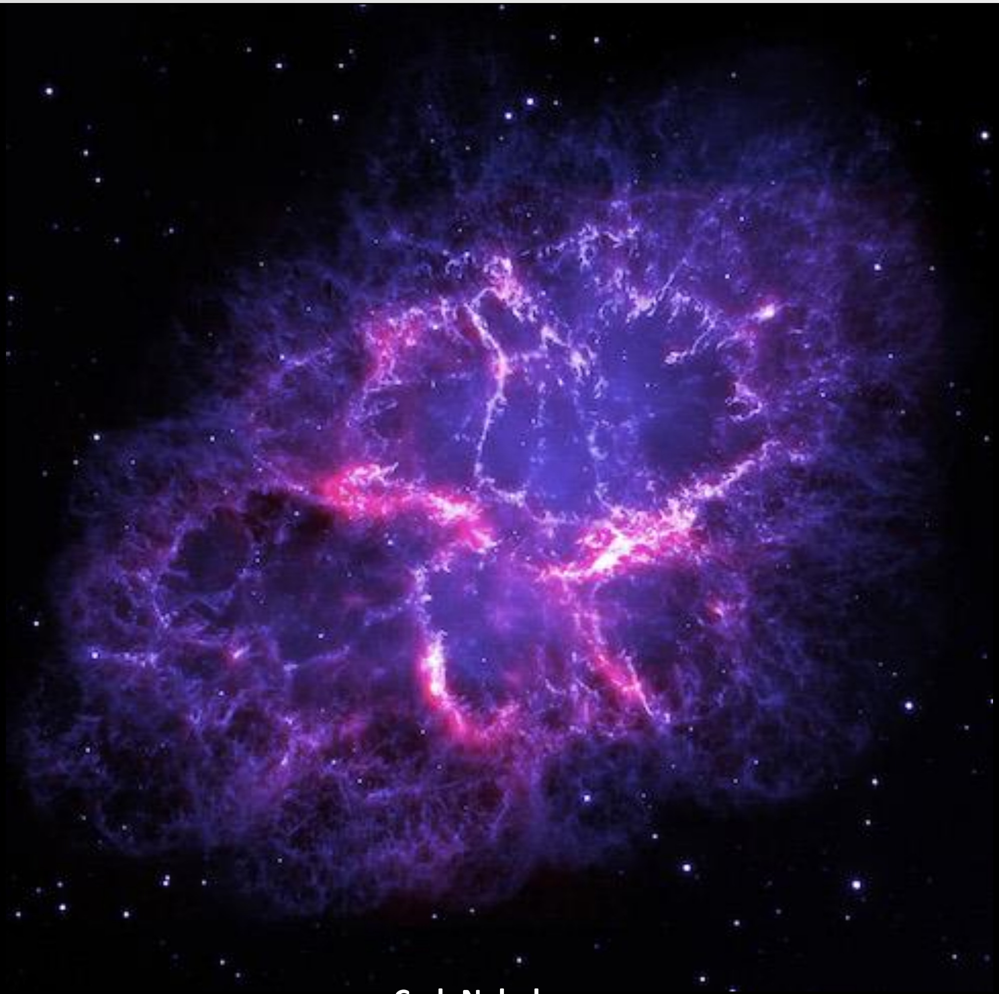


How to study stellar explosions with deep-sea sediments and ocean crusts?



The *Australopithecus afarensis* 2-3 million years ago

Supernova Remnants

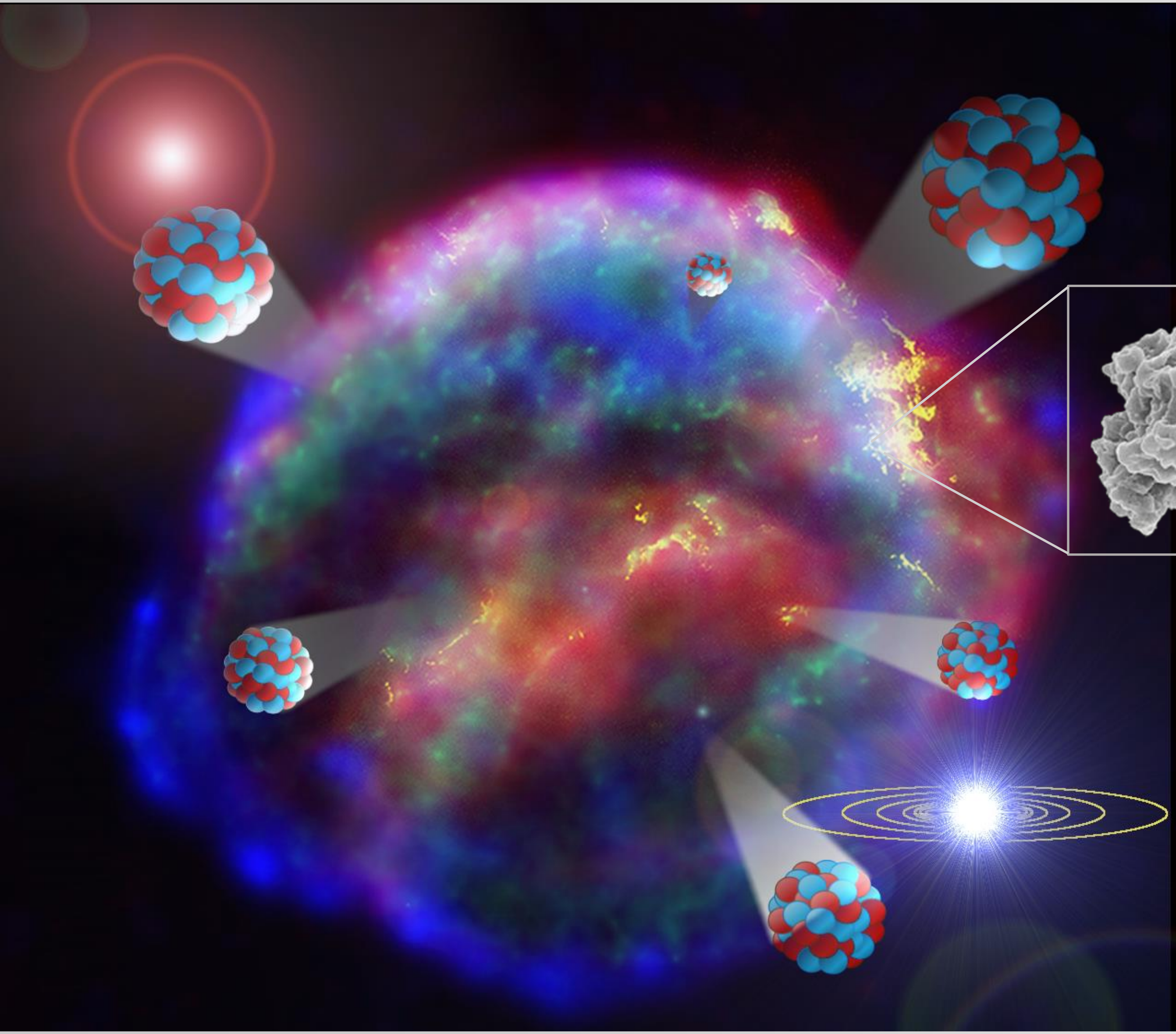


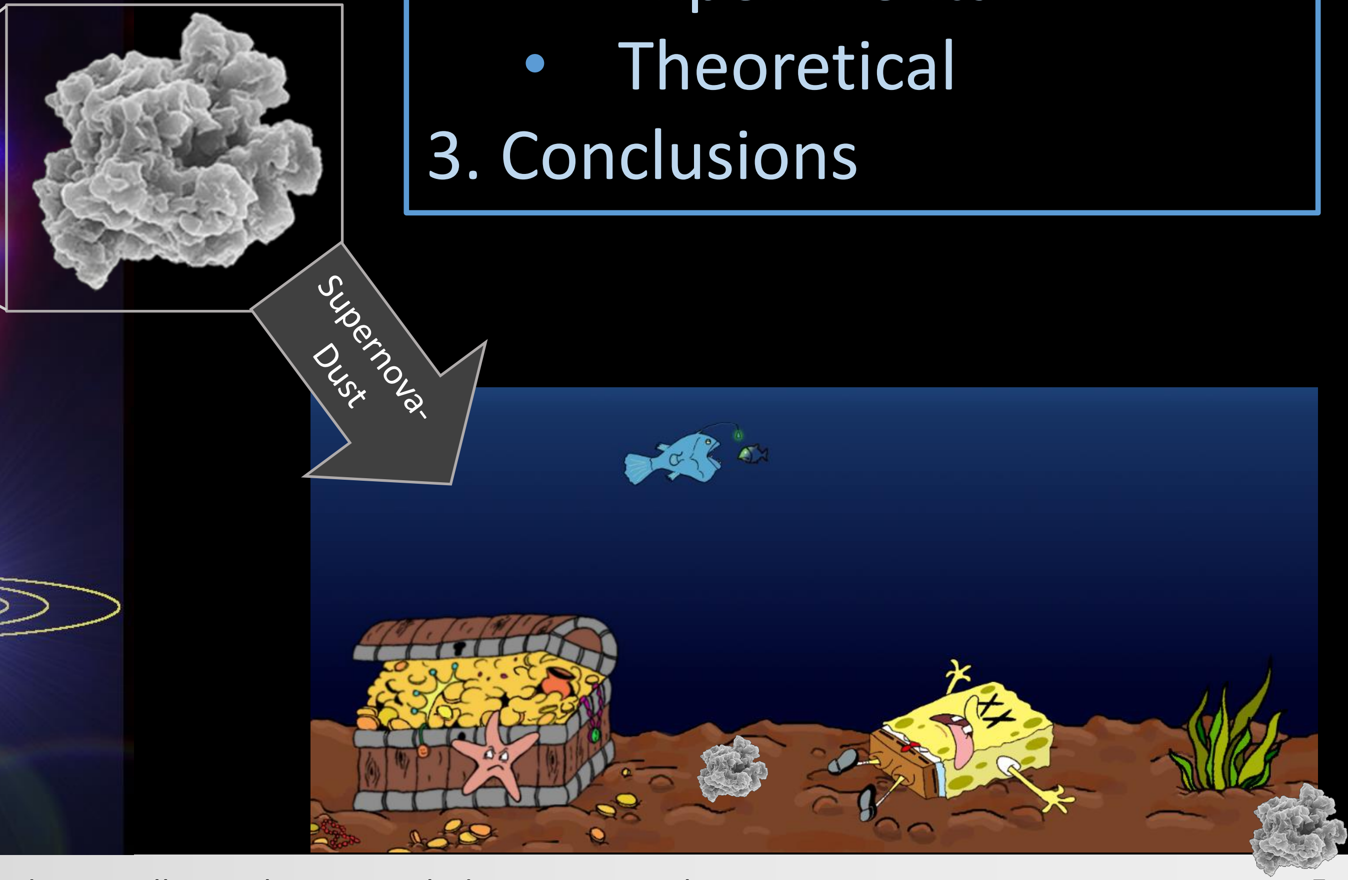
Crab Nebula
Herschel (red) and Hubble (blue) composite

Credit: ESA/Herschel/PACS/MESS Key Programme Supernova Remnant Team; NASA, ESA and Allison Loll/Jeff Hester (Arizona State University).

Observation of Supernova Remnants

Outline





1. Introduction

2. Supernova Dust on Earth
   - Experimental
   - Theoretical

3. Conclusions

The Solar Environment

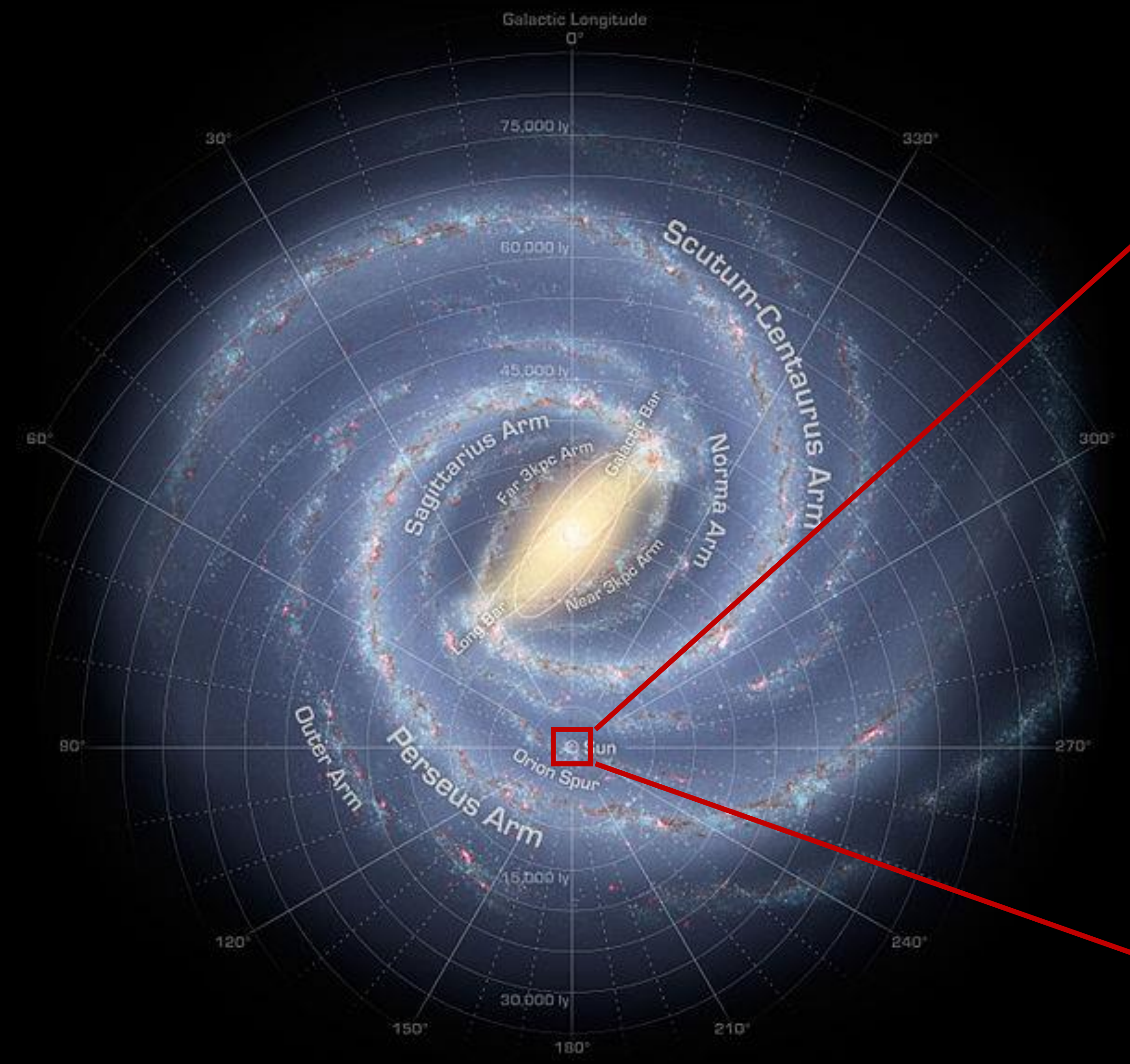
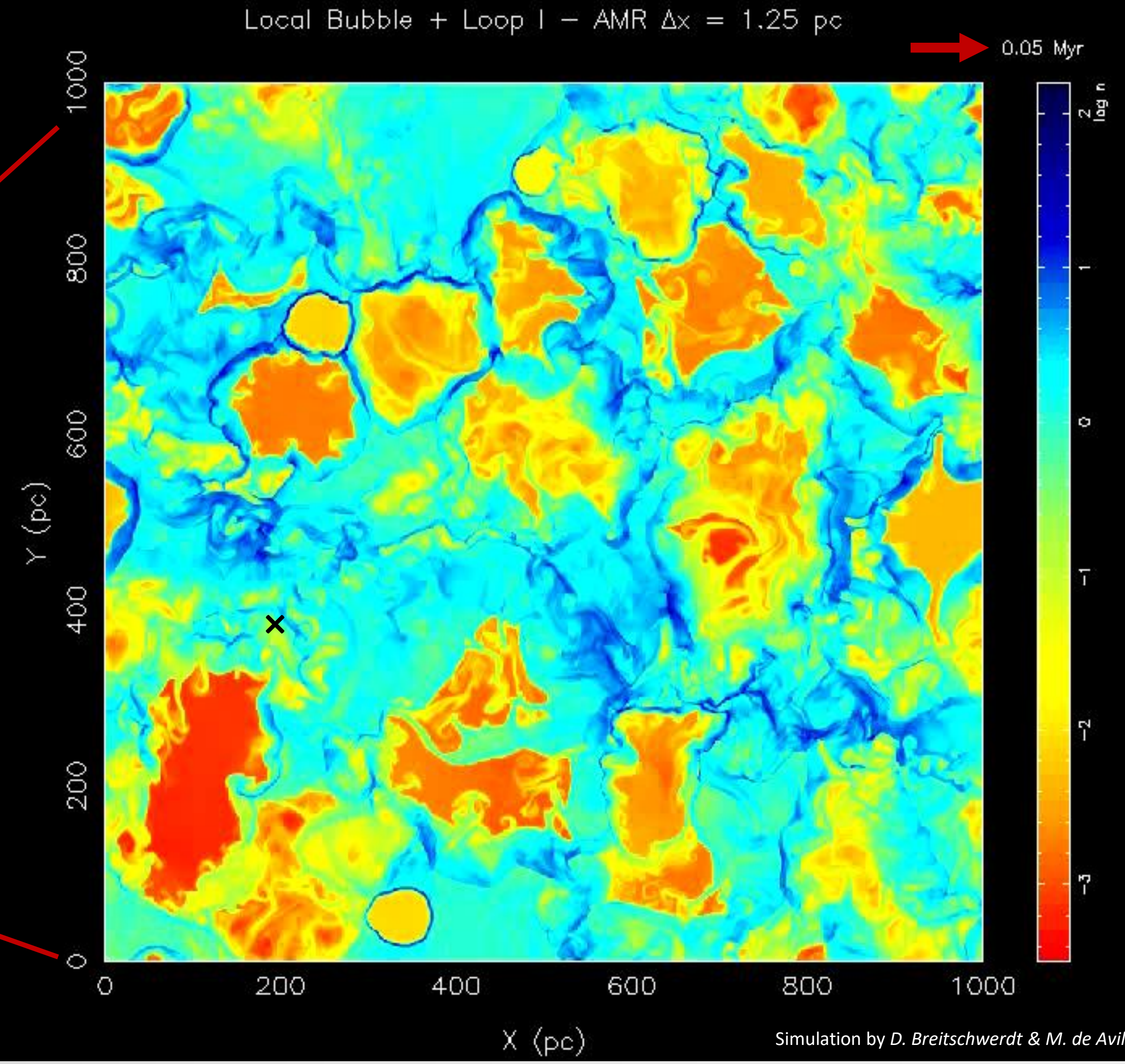
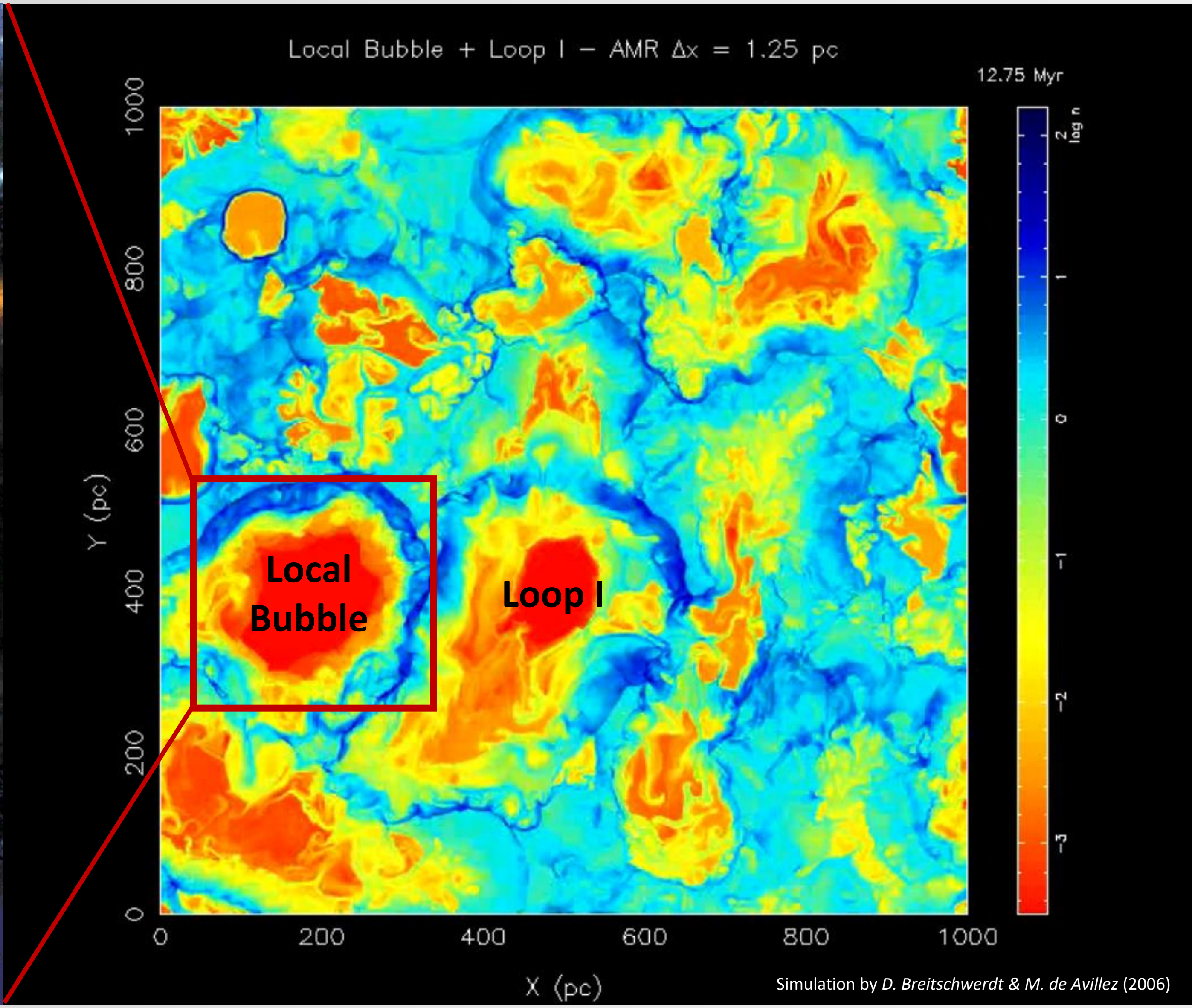


Image credit: NASA/JPL-Caltech/R. Hurt/Wikipedia Commons

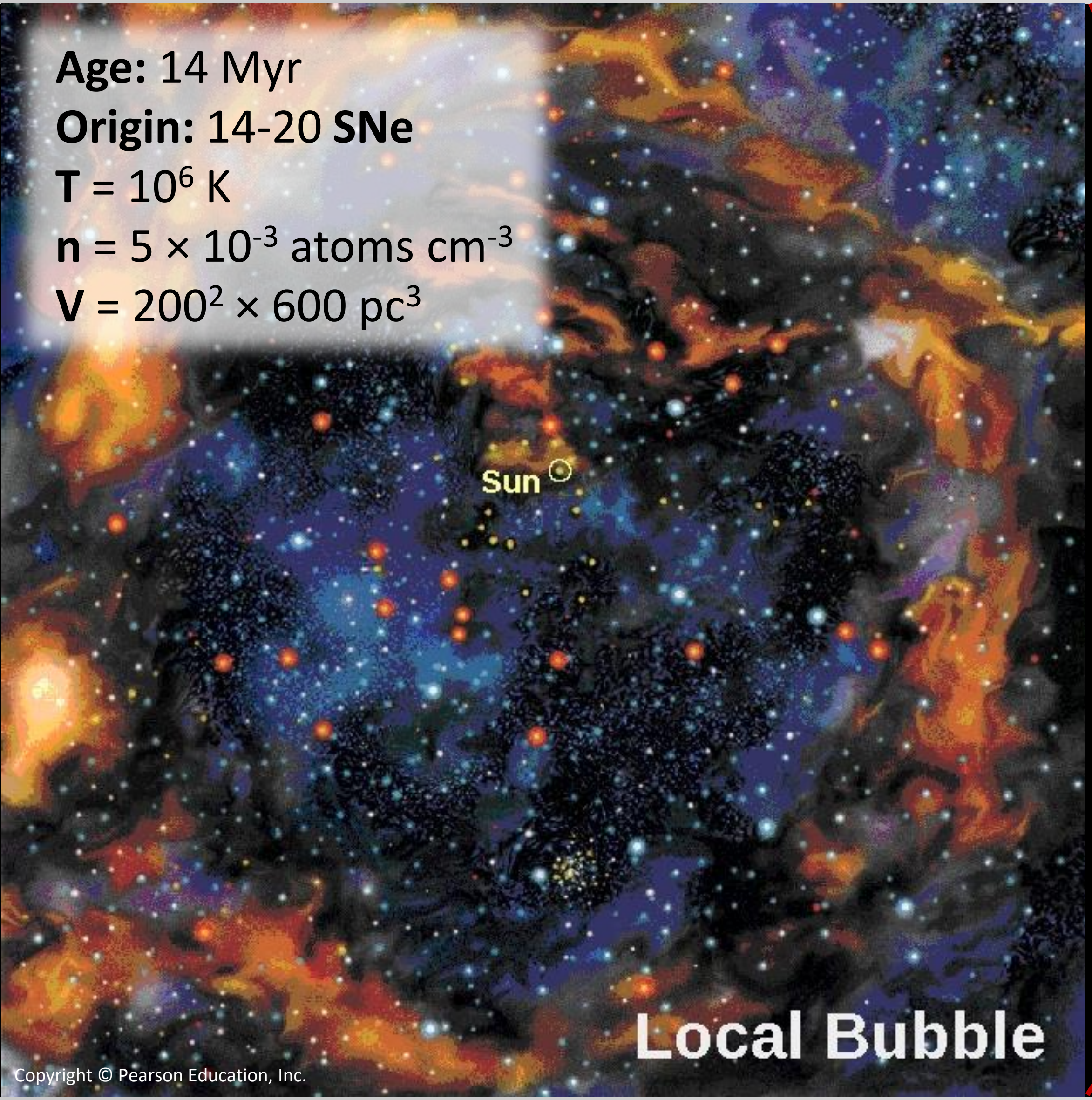


Simulation by *D. Breitschwerdt & M. de Avillez* (2006)

The Solar Environment



The Solar Environment



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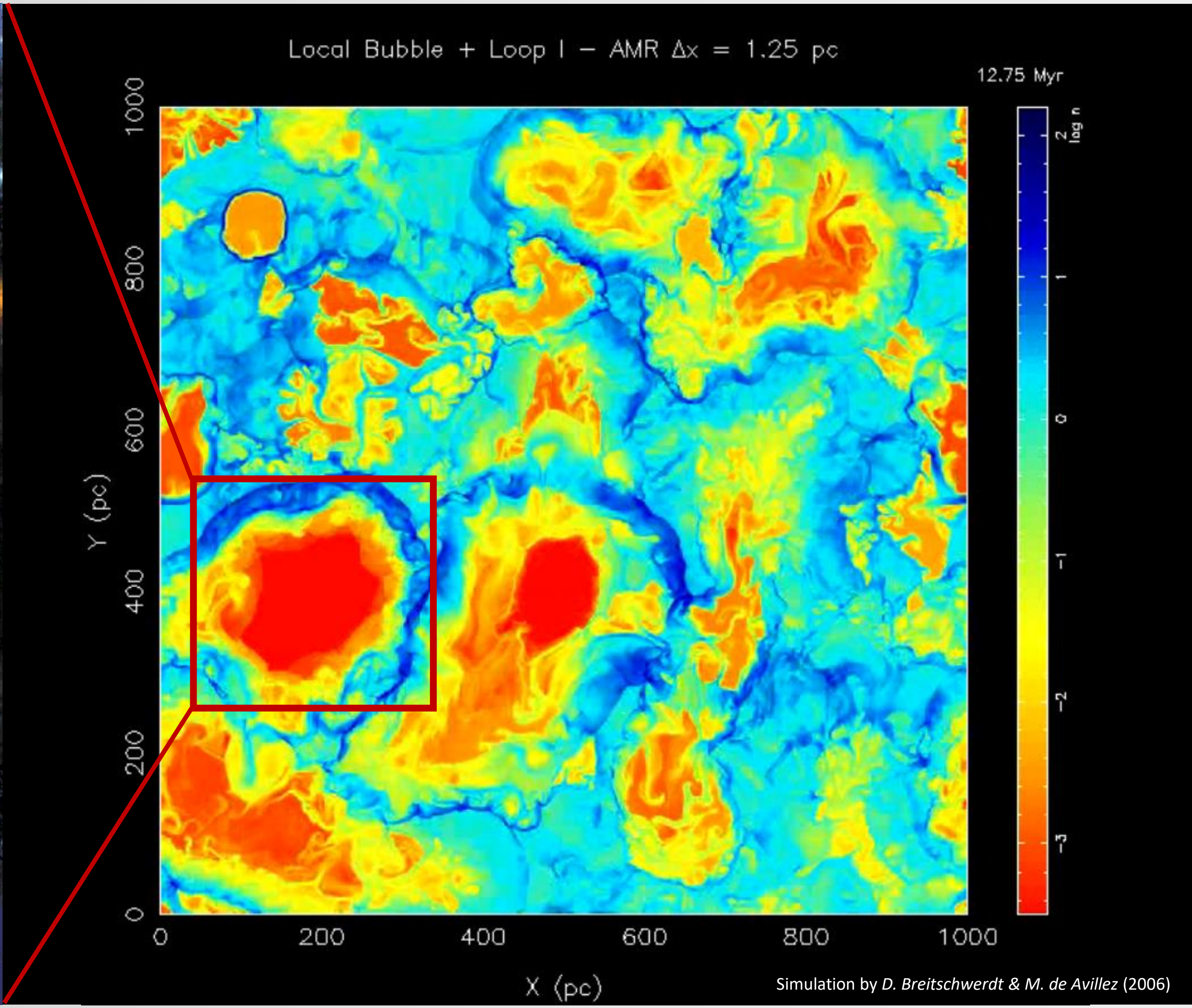

Simulation by *D. Breitschwerdt & M. de Avillez* (2006)

The Solar Environment

T = 7000 K
n = 0.3 atoms cm^{-3}
d = 9.2 pc

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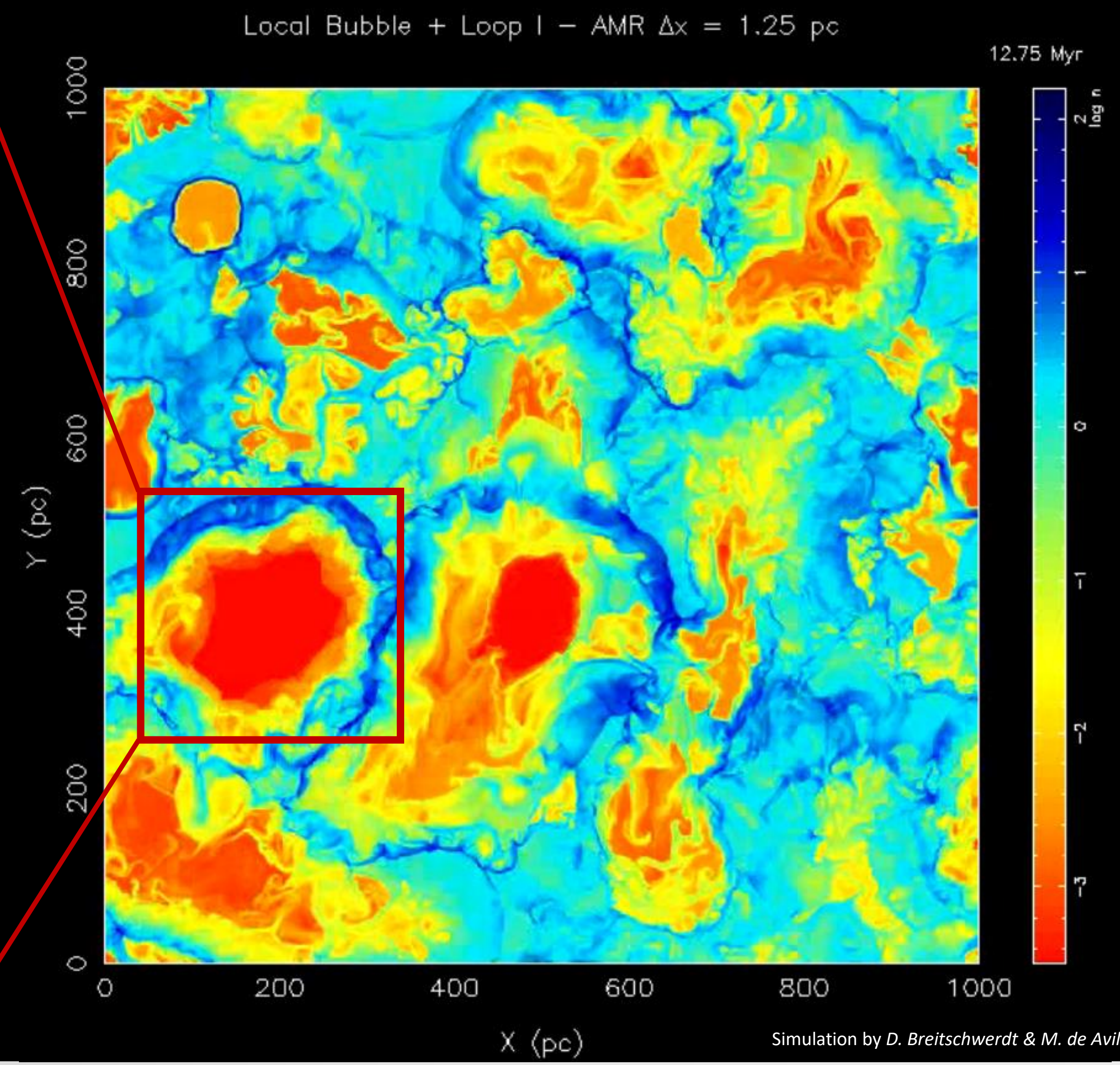

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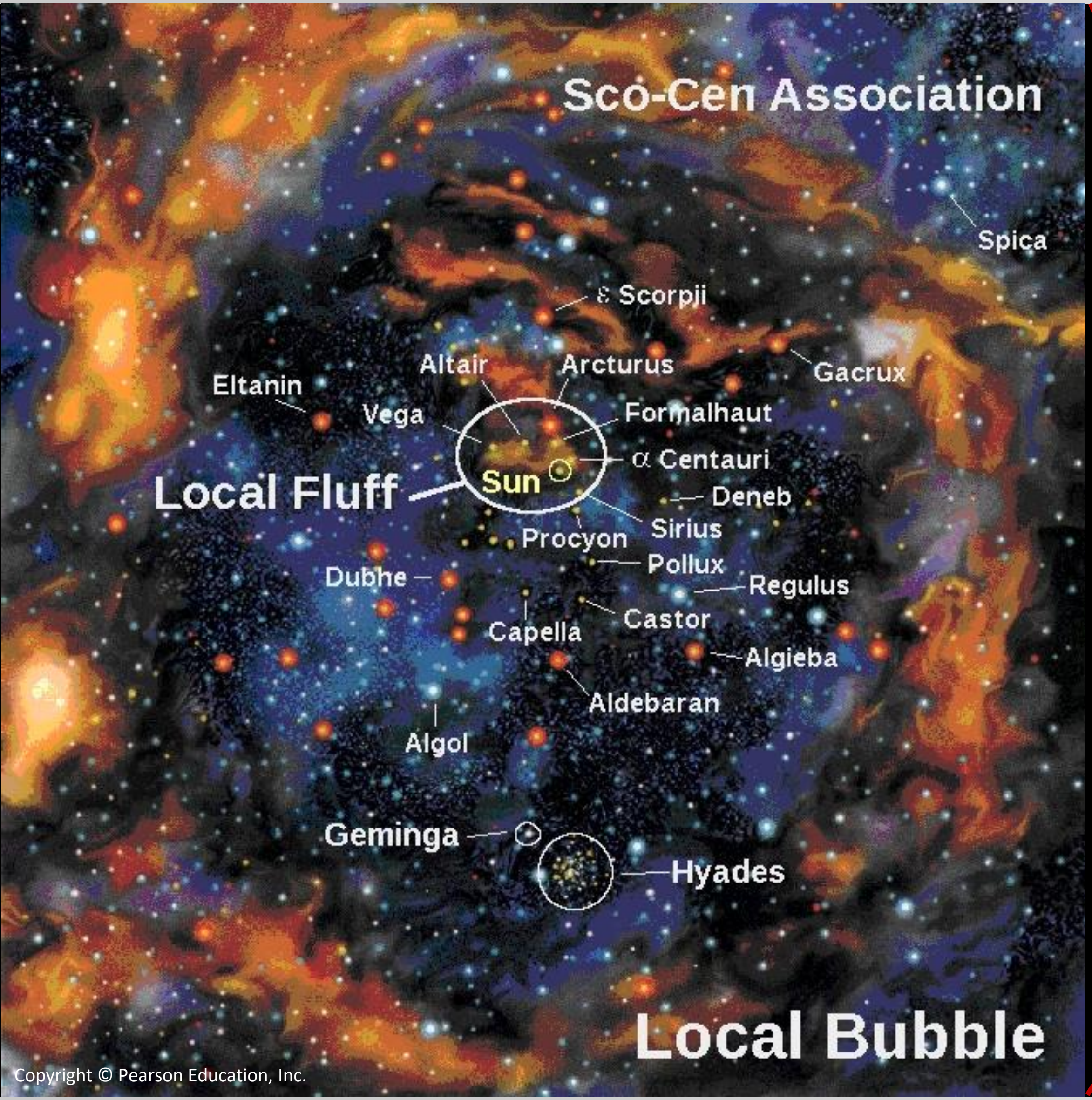

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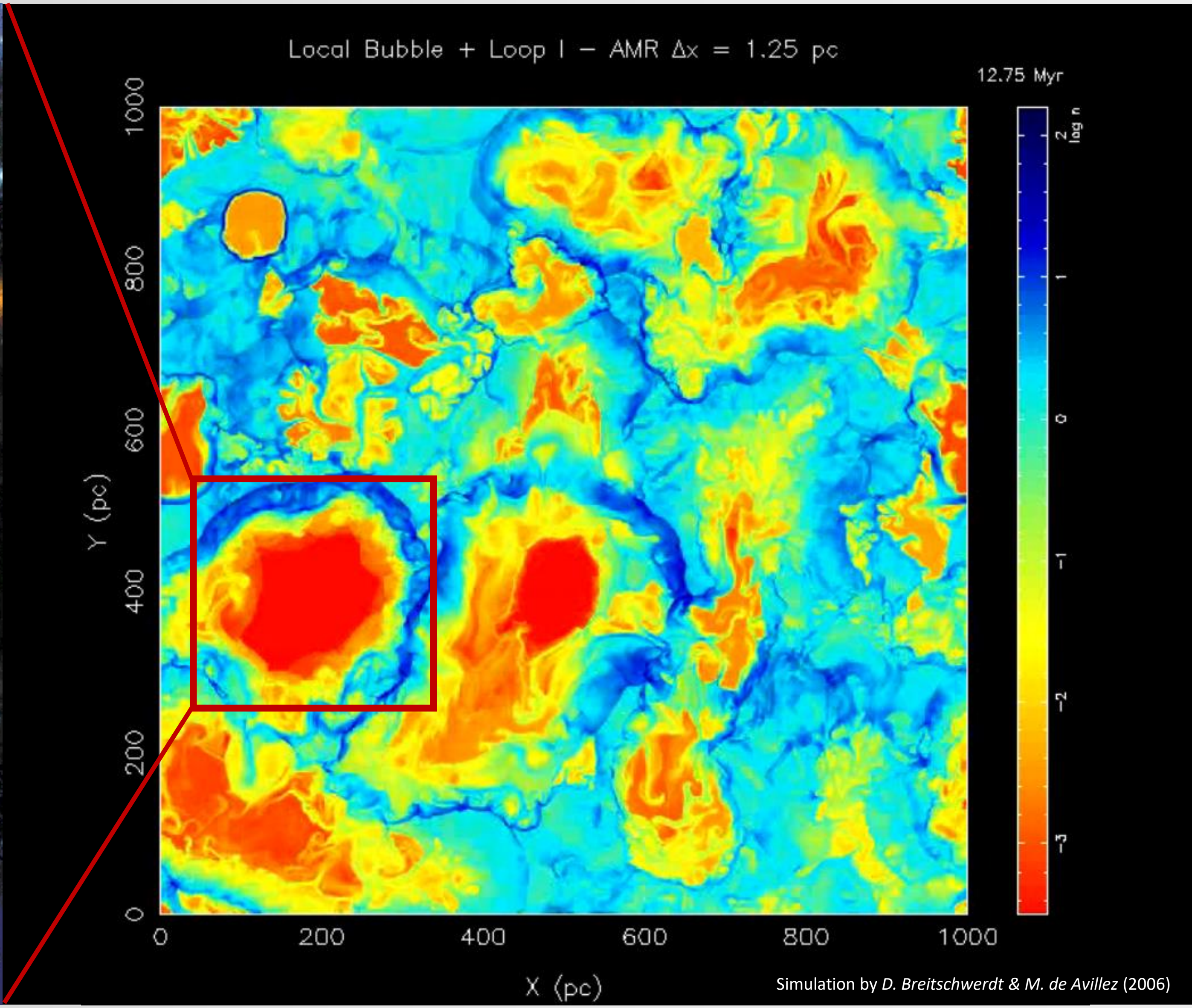

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Supernova Traces on Earth

Radiocarbon 38:68 (1996)

^{60}Fe, A PROMISING AMS ISOTOPE FOR MANY APPLICATIONS

G. KORSCHINEK, T. FAESTERMANN, K. KNIE and C. SCHMIDT

Astrophysics—Type II supernovae are expected to be the main sources for ^{60}Fe distributed in the interstellar medium. By detecting the ^{60}Fe concentration in sediments on Earth, one could get the first positive measurement of ^{60}Fe abundance in the interstellar medium and thus information on the nucleosynthesis in supernovae and the galactic transport of matter released by supernovae.

THE ASTROPHYSICAL JOURNAL, 470:1227–1236, 1996 October 20
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GEOLOGICAL ISOTOPE ANOMALIES AS SIGNATURES OF NEARBY SUPERNOVAE

JOHN ELLIS
Theoretical Physics Division, CERN, Geneva, Switzerland
BRIAN D. FIELDS[1]
Department of Physics, University of Notre Dame, Notre Dame, IN 46556
AND
DAVID N. SCHRAMM[2]
University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637
Received 1995 June 15; accepted 1996 May 21

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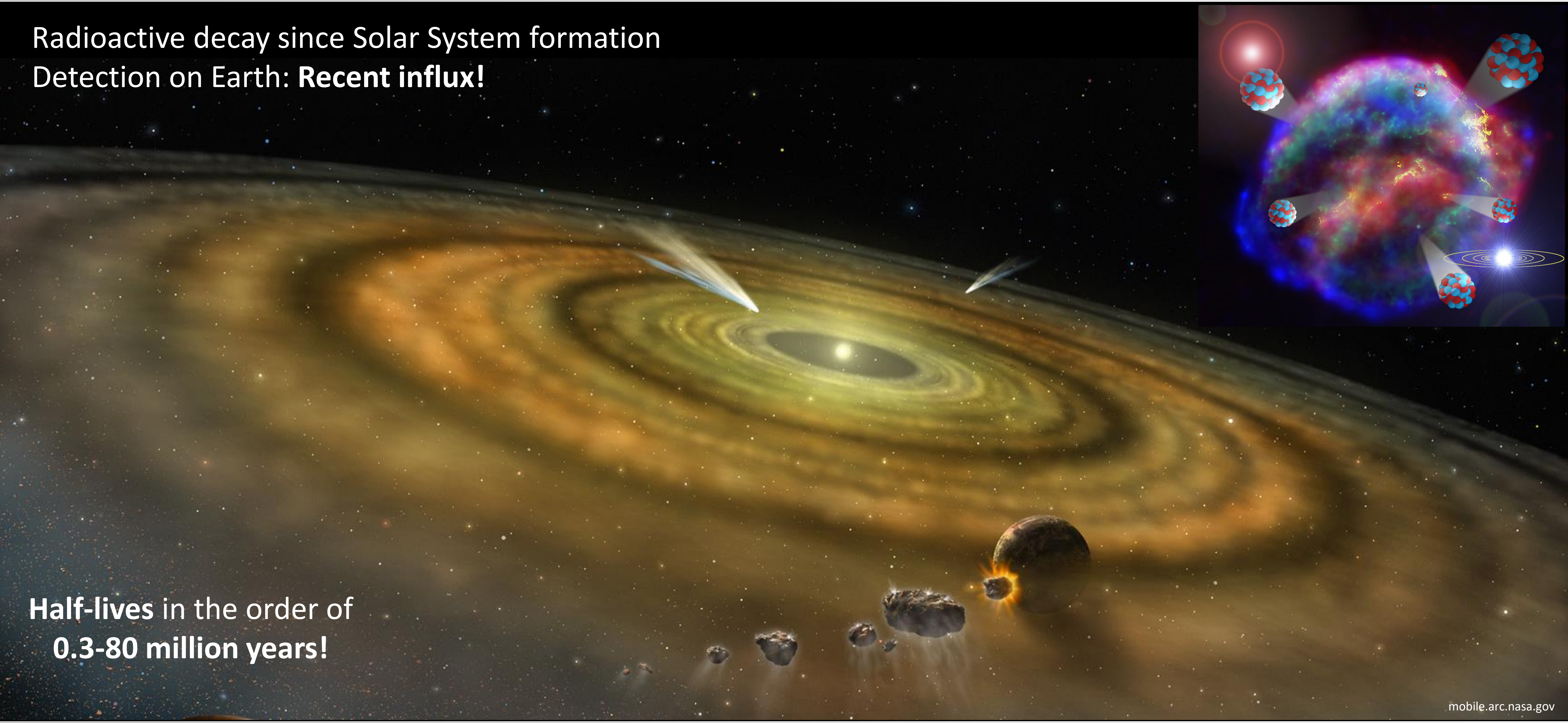
Half-lives in the order of **0.3-80 million years!**

Solar System Formation 4.57 Gyr ago

Radioactive decay since Solar System formation

Detection on Earth: **Recent influx!**



Half-lives in the order of **0.3-80 million years!**

mobile.arc.nasa.gov

Implications for Earth

Radiocarbon 38:68 (1996)

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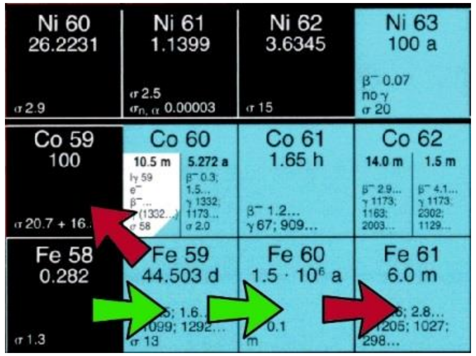
Half-lives in the order of **0.3-80 million years!**

Nucleosynthesis

^{60}Fe, $t_{1/2}$ = 2.6 Myr
(Rugel et al. 2009, Wallner et al. 2015)

- **s- and r-process**
  - (S)AGB stars, Core-collapse supernovae, Electron-capture supernovae



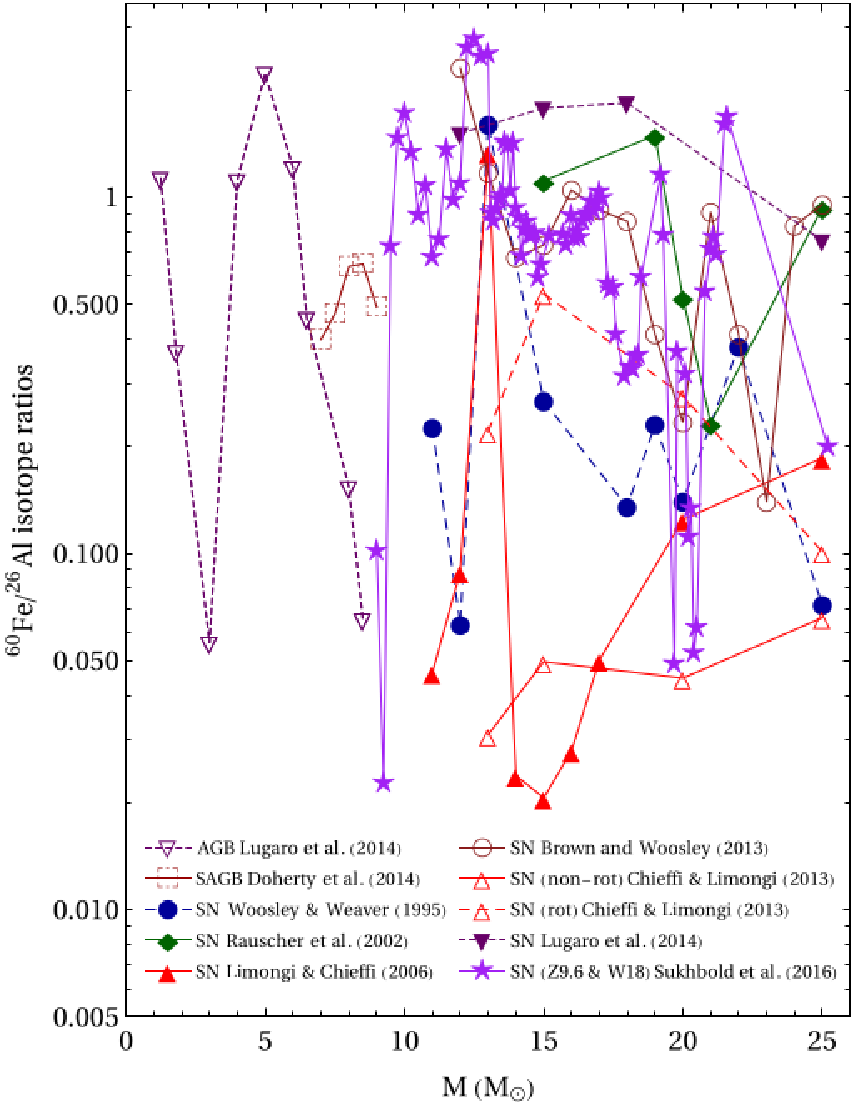
^{26}Al, $t_{1/2}$ = 0.7 Myr

- **^{25}Mg(p,γ) reaction**
  - (S)AGB stars, Core collapse supernovae, Wolf-Rayet stars

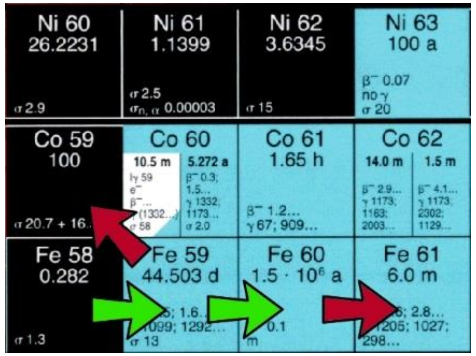
Crab Nebula
Herschel (red) and Hubble (blue) composite

Credit: ESA/Herschel/PACS/MESS Key Programme Supernova Remnant Team; NASA, ESA and Allison Loll/Jeff Hester (Arizona State University).

Nucleosynthesis



Modified from Feige et al., PRL 121, 221103 (2018)



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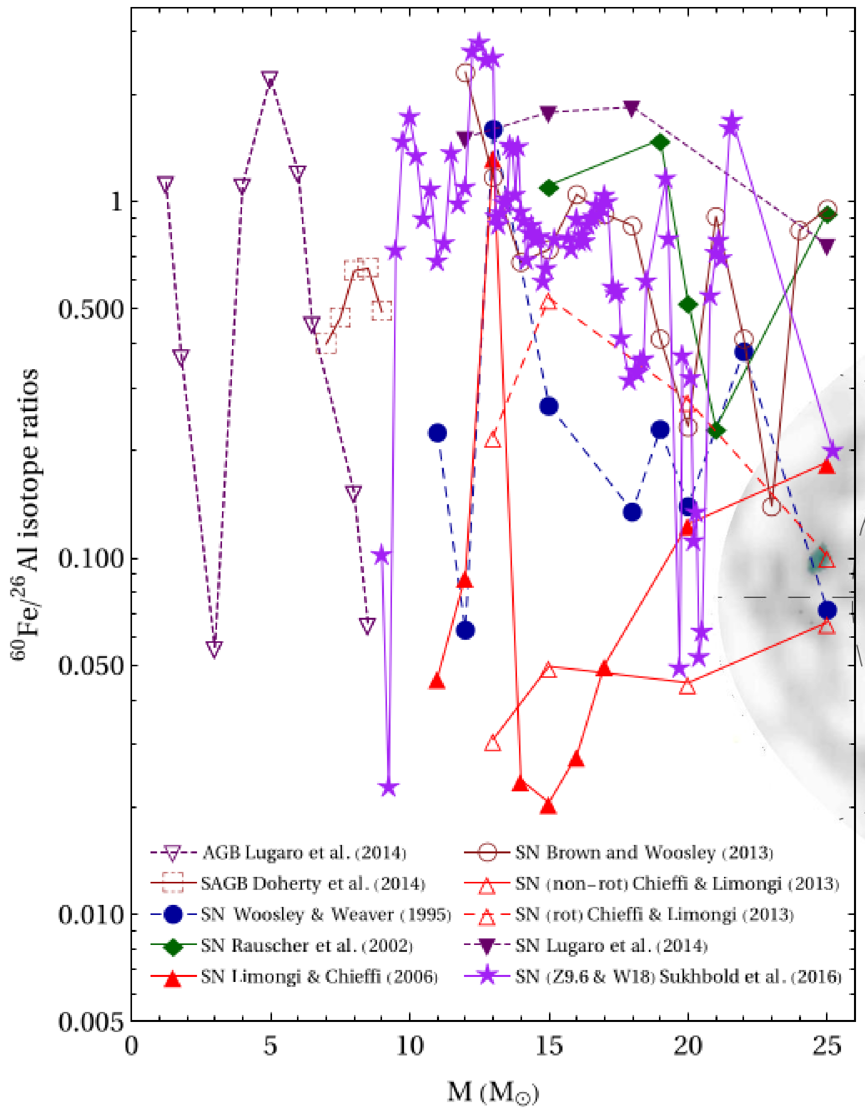
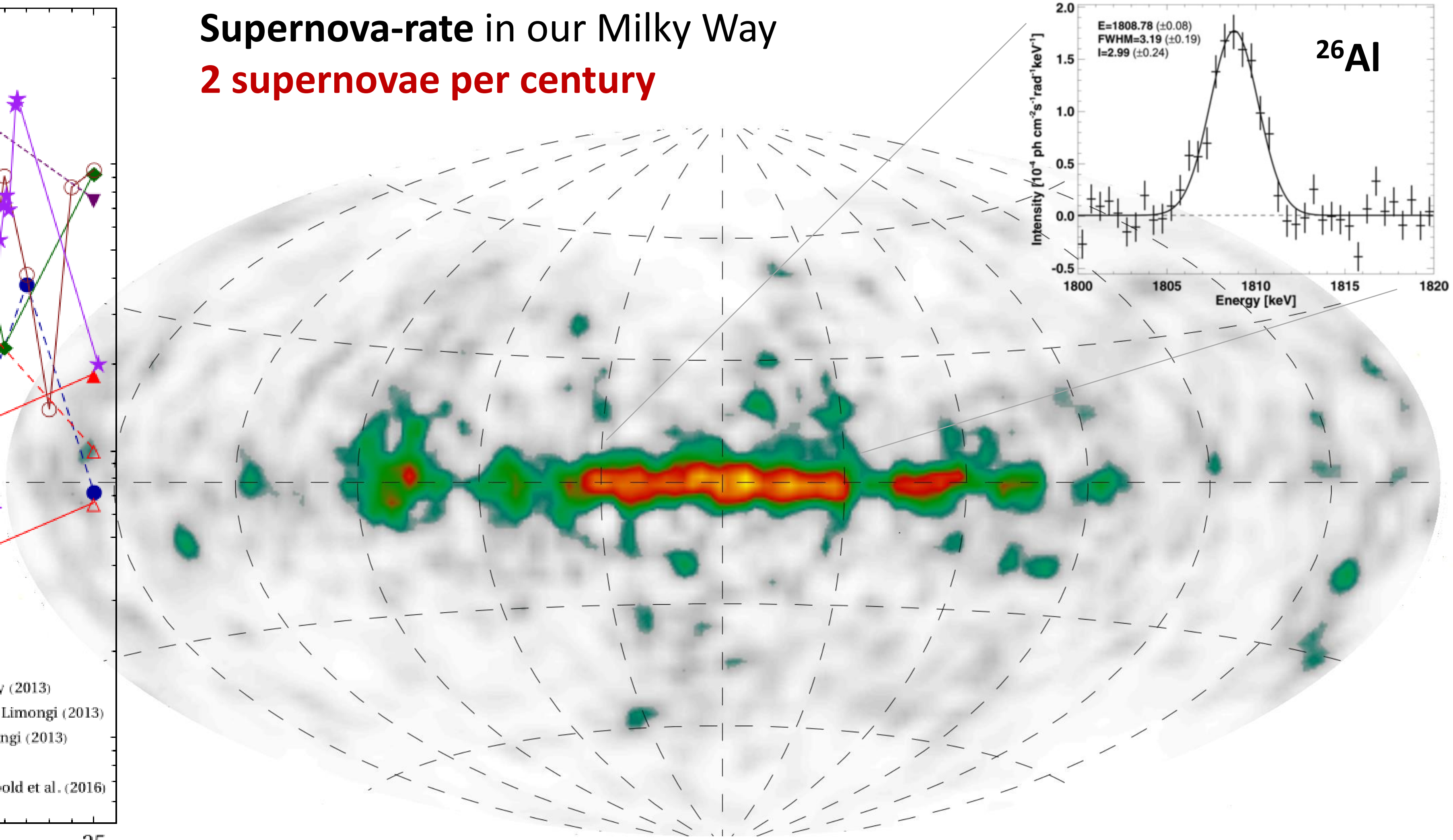
Radioactivity in the Milky Way



Modified from Feige et al., PRL 121, 221103 (2018)

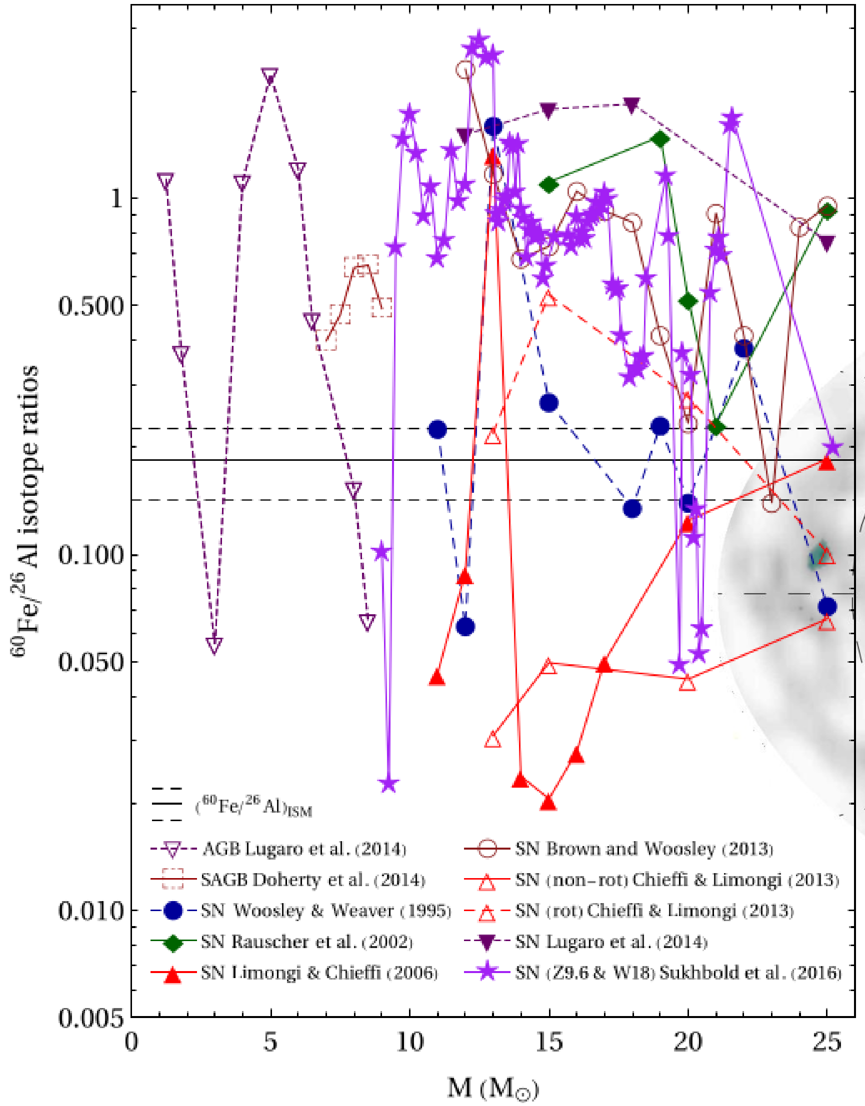
Supernova-rate in our Milky Way

2 supernovae per century



Plüschke et al., ESA Sp. Publ. 459, 55 (2001); Diehl et al., Nature 439, 45 (2006)

Radioactivity in the Milky Way



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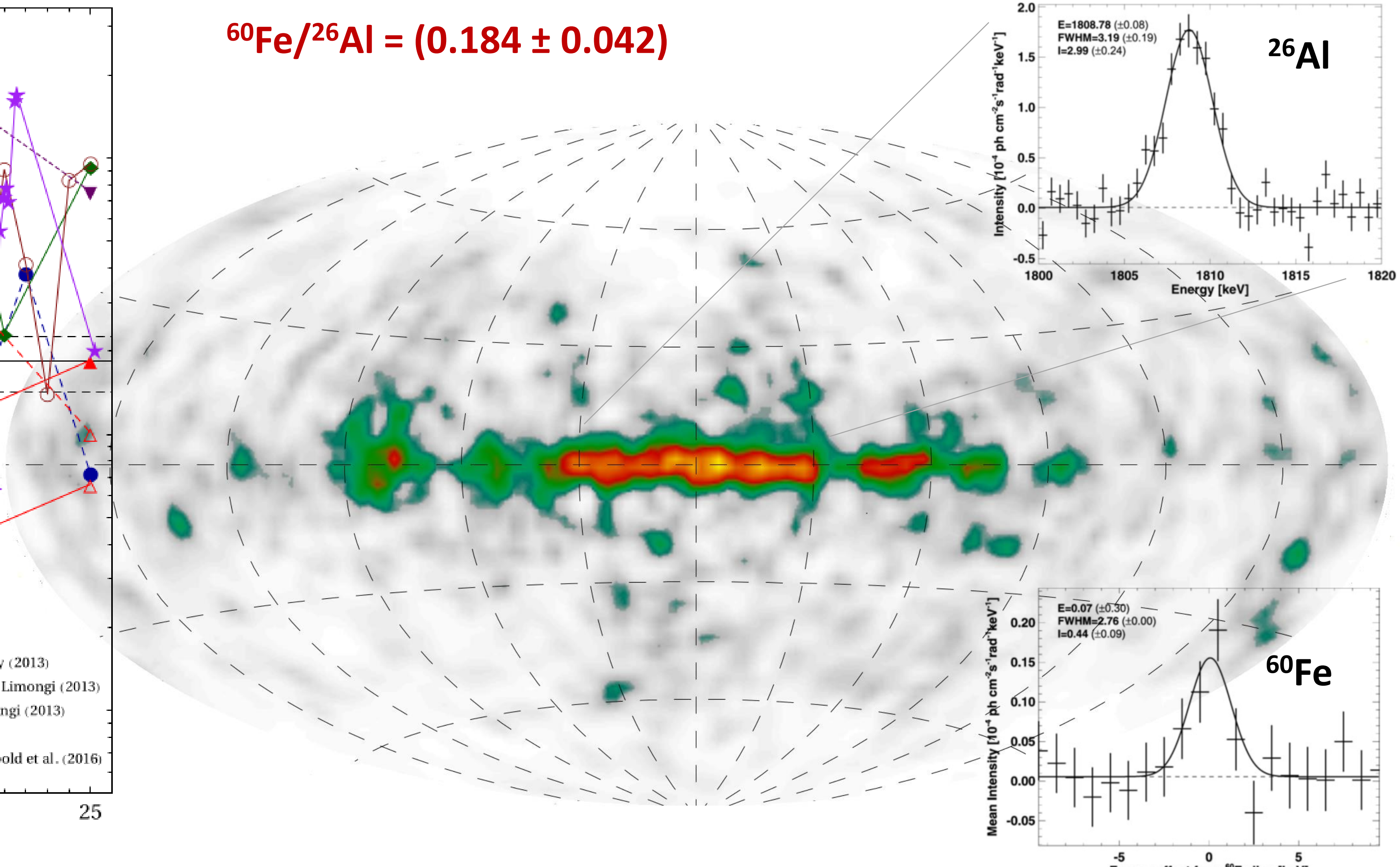
^{60}Fe/^{26}Al = (0.184 ± 0.042)



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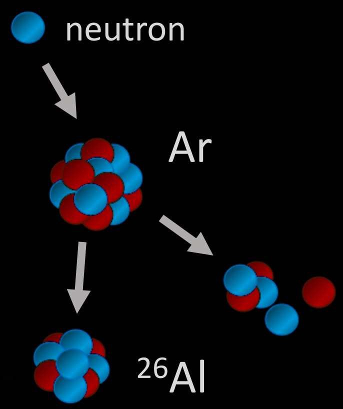
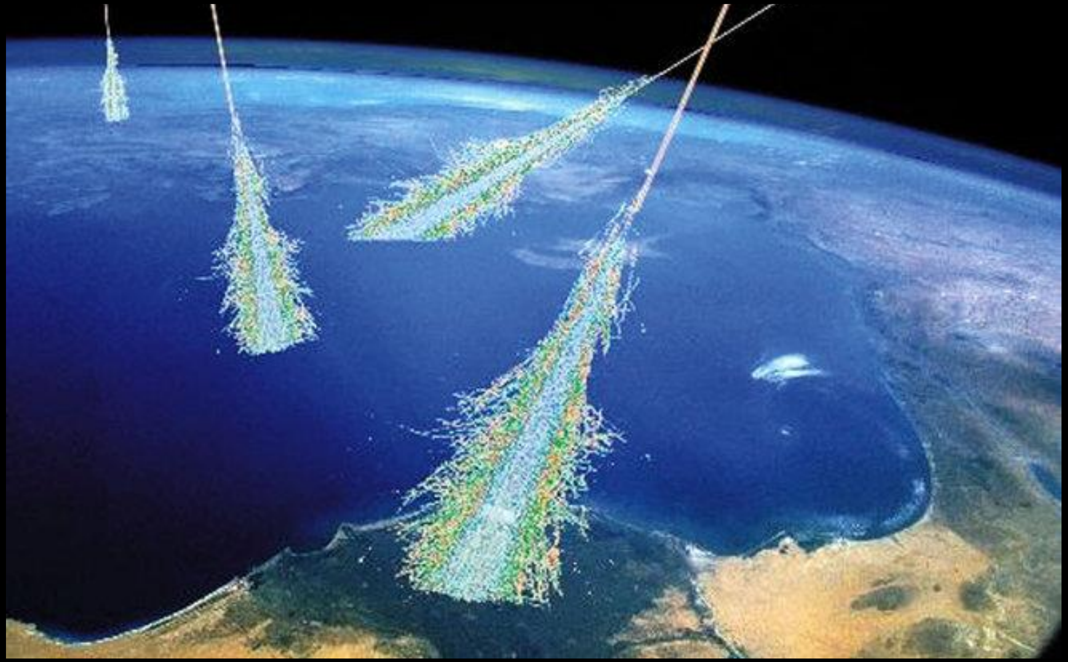
Radioactive Supernova Traces



Other ^{60}Fe sources negligible

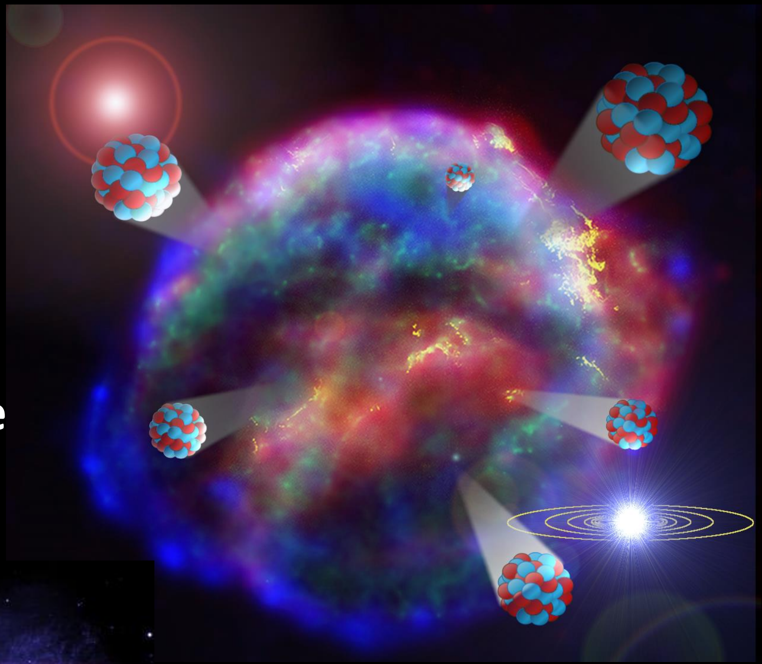
Continuous atmospheric **^{26}Al production:**

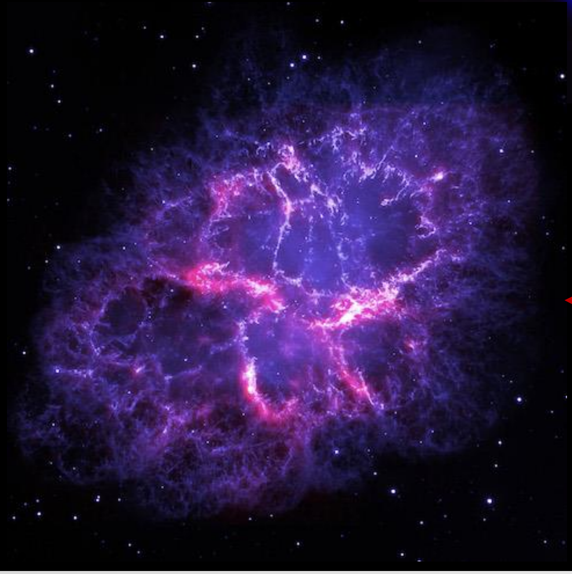
1250 ats cm^{-2} yr^{-1}
(Auer et al., 2009)



Space.com

^{26}Al
^{60}Fe





10 – 150 pc

Supernova Traces on Earth

Radiocarbon 38:68 (1996)

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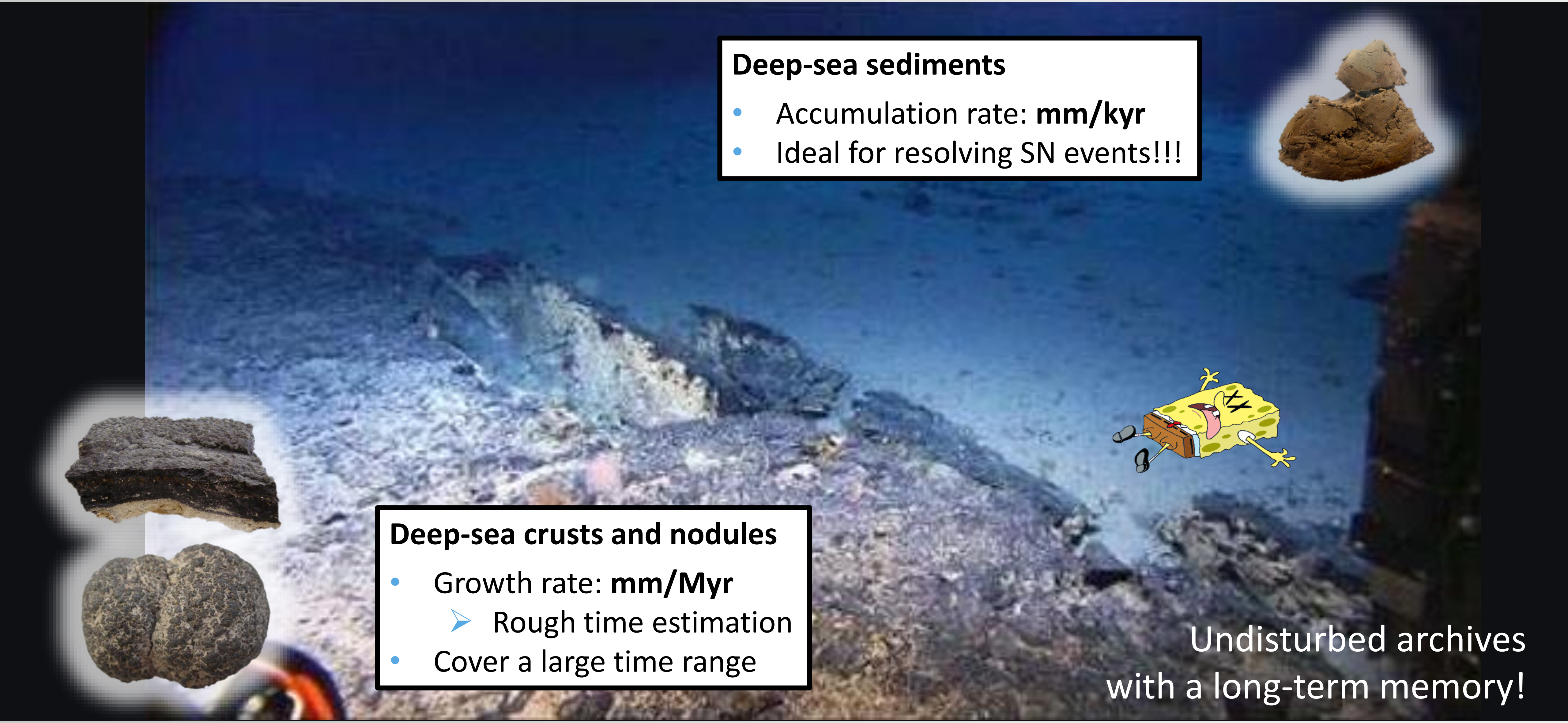
Supernova Traces on Earth

Alessandro Airo demonstrates where not to search for Supernova traces on Earth.

Supernova Traces on Earth



Deep-sea sediments

- Accumulation rate: **mm/kyr**
- Ideal for resolving SN events!!!

Deep-sea crusts and nodules

- Growth rate: **mm/Myr**
  - Rough time estimation
- Cover a large time range

Undisturbed archives
with a long-term memory!

Take-Home Message I

Million-year-old remnants of Supernova can leave traces on Earth if close enough

- Our Sun is located in a region with turbulent history: **The Local Bubble!**
- Suitable geological archives: **Deep-sea records**
- Suitable isotopes: **Long-lived radionuclides**
  - ➢ No leftover from the Solar System formation period
  - ➢ Negligible terrestrial production
  - ➢ **^{60}Fe and ^{26}Al** both have been observed within our Milky Way: Continuous and fresh input from stellar explosions

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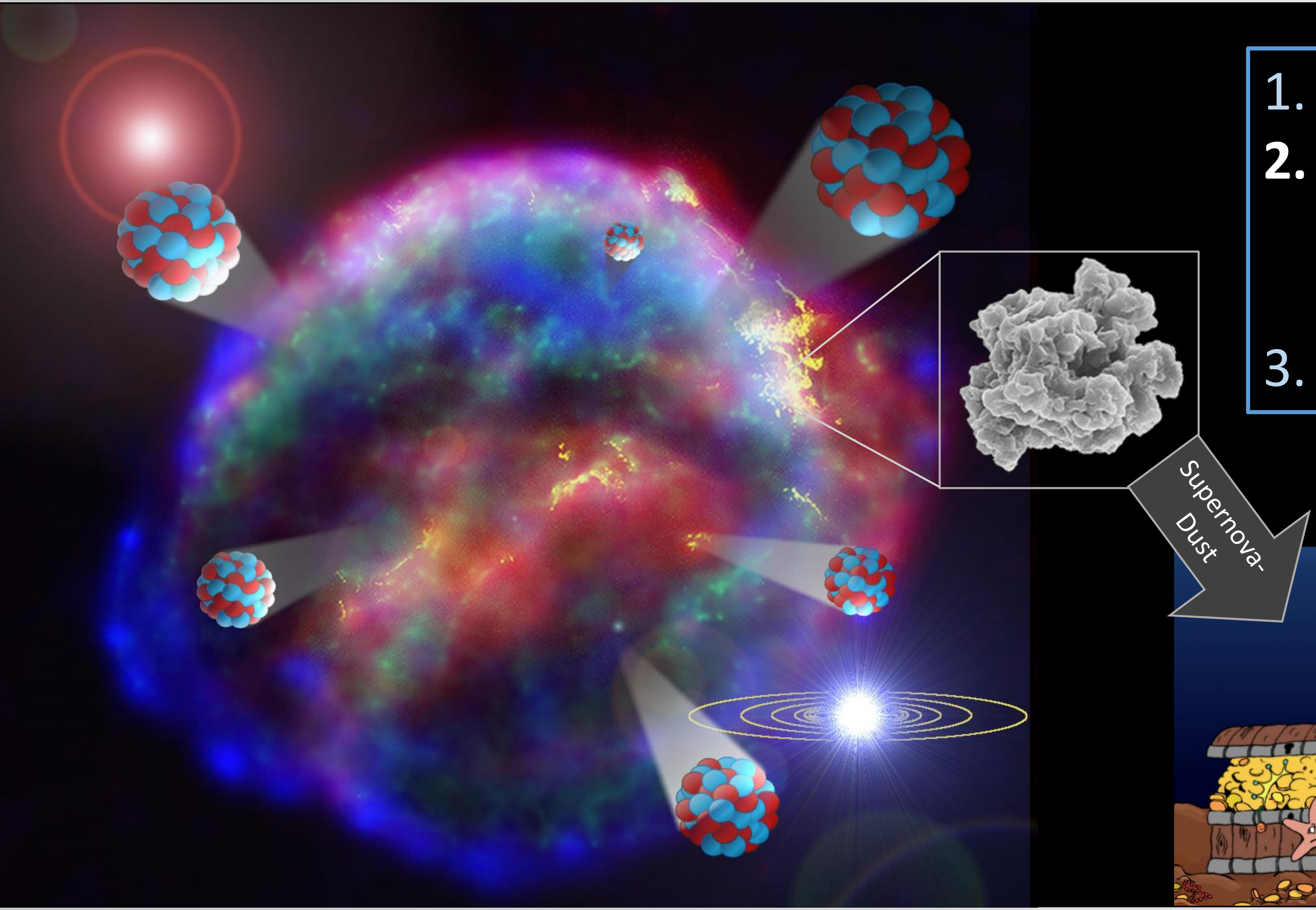
Outline

1. Introduction
2. **Supernova Dust on Earth**
   - **Experimental**
   - Theoretical
3. Conclusions

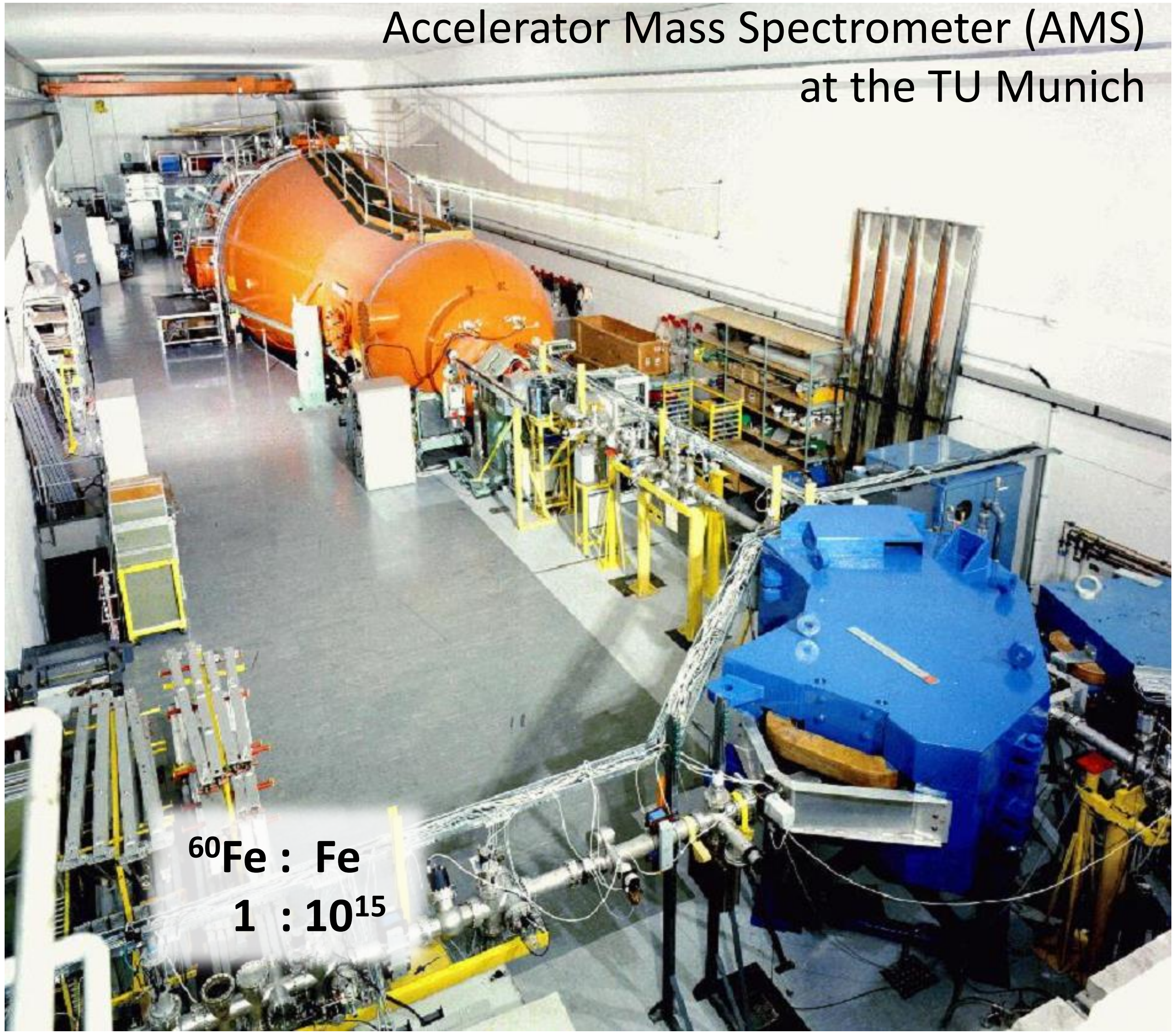


Supernova Traces in a Deep-Sea Crust

Supernova Traces in a Deep-Sea Crust

Klaus Knie cuts the crust into separate layers

Supernova Traces in a Deep-Sea Crust



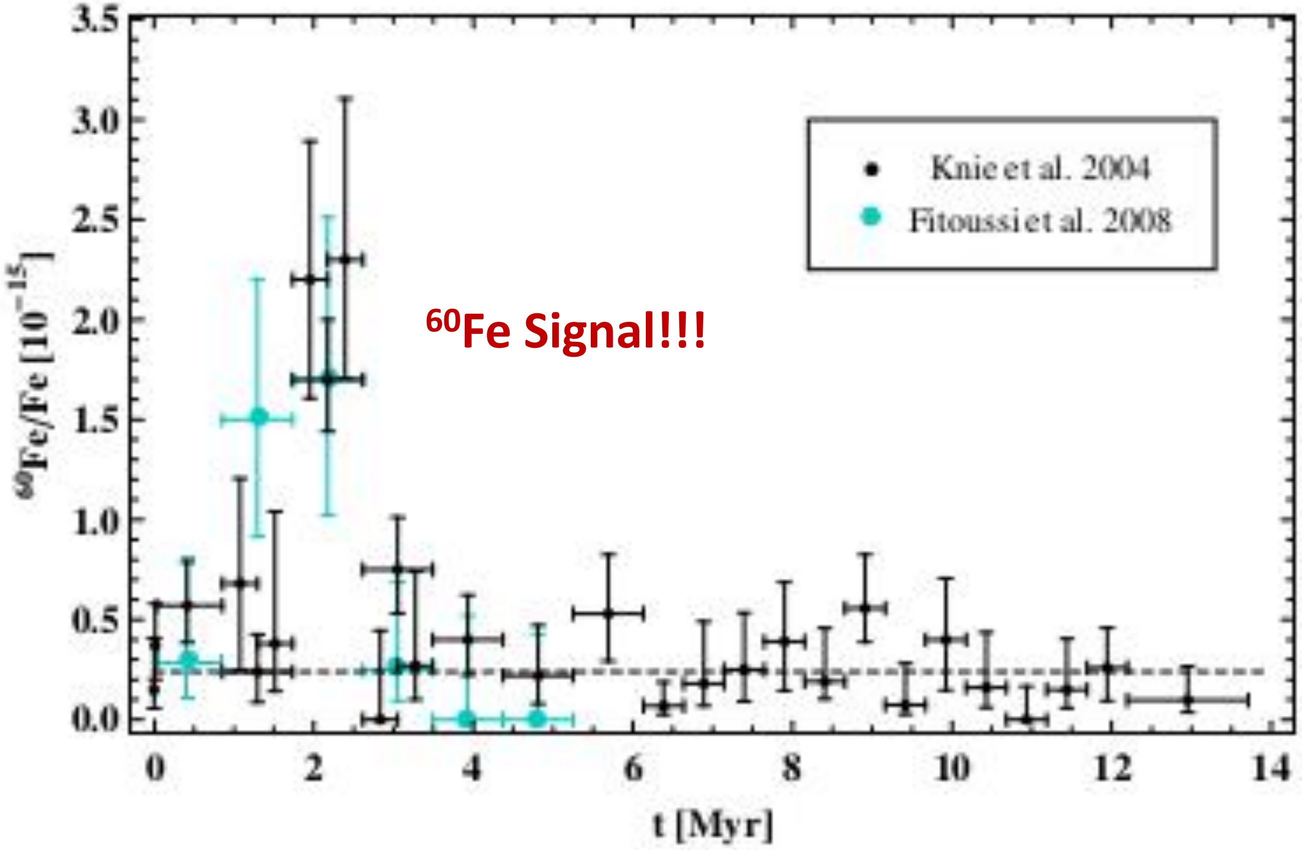
www.mll-muenchen.de/tandem/index.html

Supernova Traces in a Deep-Sea Crust

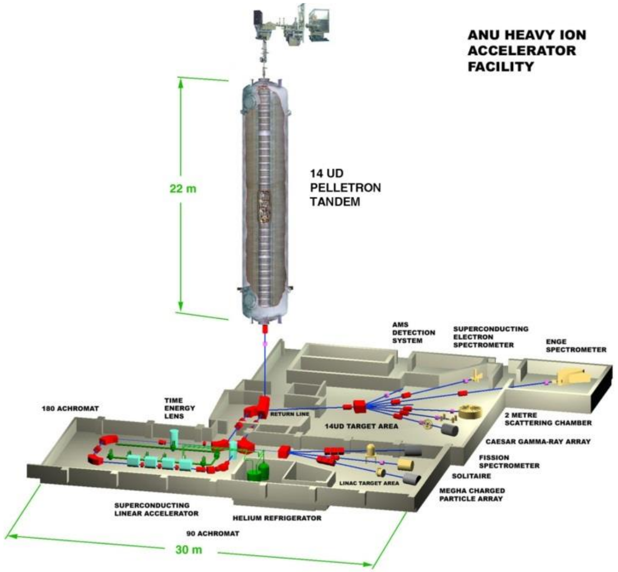
VOLUME 93, NUMBER 17 PHYSICAL REVIEW LETTERS week ending 22 OCTOBER 2004

^{60}Fe Anomaly in a Deep-Sea Manganese Crust and Implications for a Nearby Supernova Source

K. Knie,[1] G. Korschinek,[1,*] T. Faestermann,[1] E. A. Dorfi,[2] G. Rugel,[1,3] and A. Wallner[1,3]



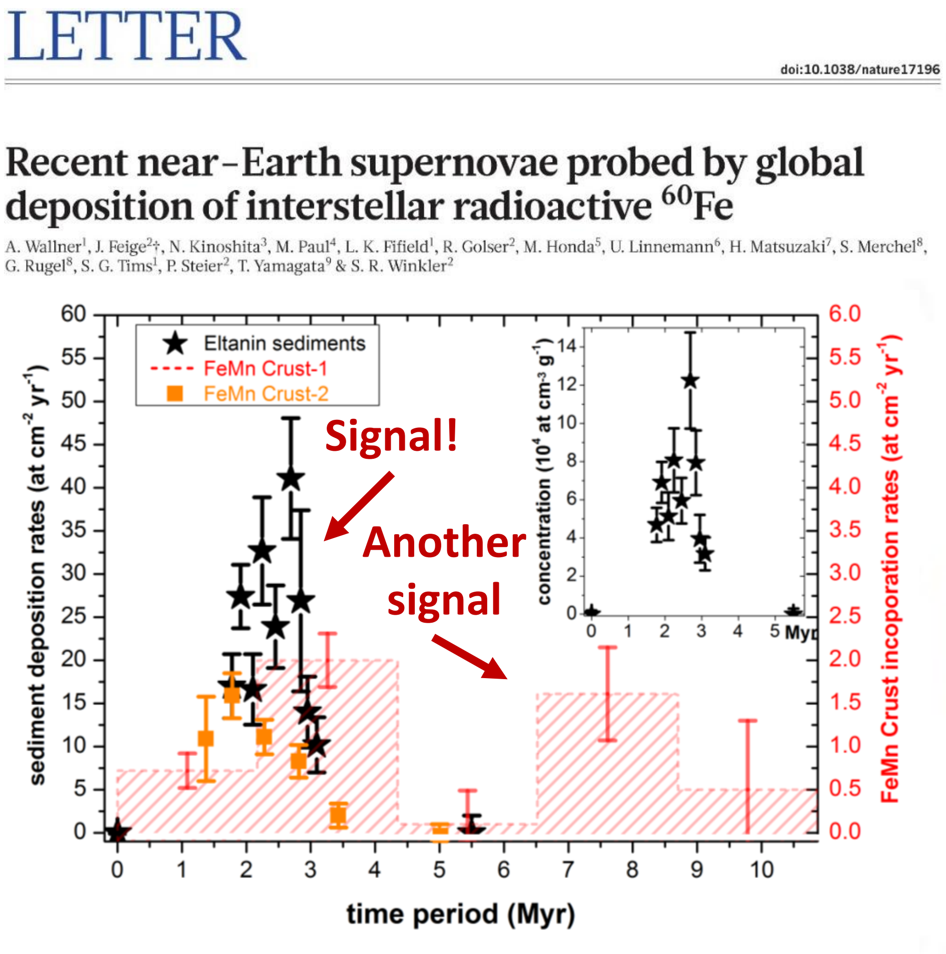
Searching for Global Supernova Traces



ANU
Canberra
Australia

Less than
10 ^{60}Fe atoms
in a 3 g sediment sample!

Global Supernova Traces



LETTER

doi:10.1038/nature17196

Recent near-Earth supernovae probed by global deposition of interstellar radioactive ^{60}Fe

A. Wallner[1], J. Feige[2]†, N. Kinoshita[3], M. Paul[4], L. K. Fifield[1], R. Golser[2], M. Honda[5], U. Linnemann[6], H. Matsuzaki[7], S. Merchel[8], G. Rugel[8], S. G. Tims[1], P. Steier[2], T. Yamagata[9] & S. R. Winkler[2]

Peak-flux: About **30 ats/yr/cm²**

Absolute amount of ^{60}Fe

distributed on Earth: **~20 kg**

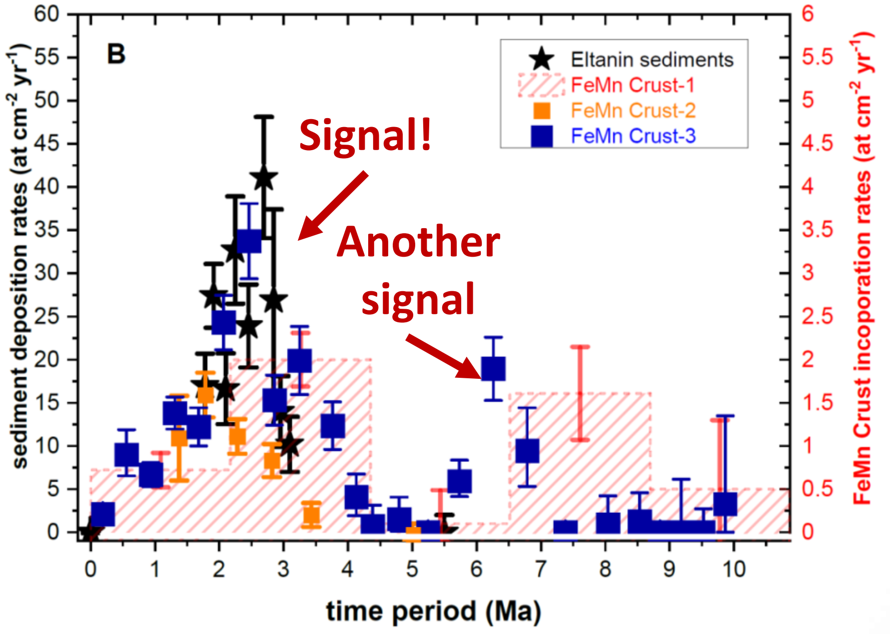
Imagine 20 kg of flour spread over Earth. Can you detect it?

Global Supernova Traces

NUCLEAR ASTROPHYSICS Wallner *et al.*, *Science* **372**, 742–745 (2021)

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

A. Wallner[1,2]*, M. B. Froehlich[1], M. A. C. Hotchkis[3], N. Kinoshita[4], M. Paul[5], M. Martschini[1]†, S. Pavetich[1], S. G. Tims[1], N. Kivel[6], D. Schumann[6], M. Honda[7]‡, H. Matsuzaki[8], T. Yamagata[8]



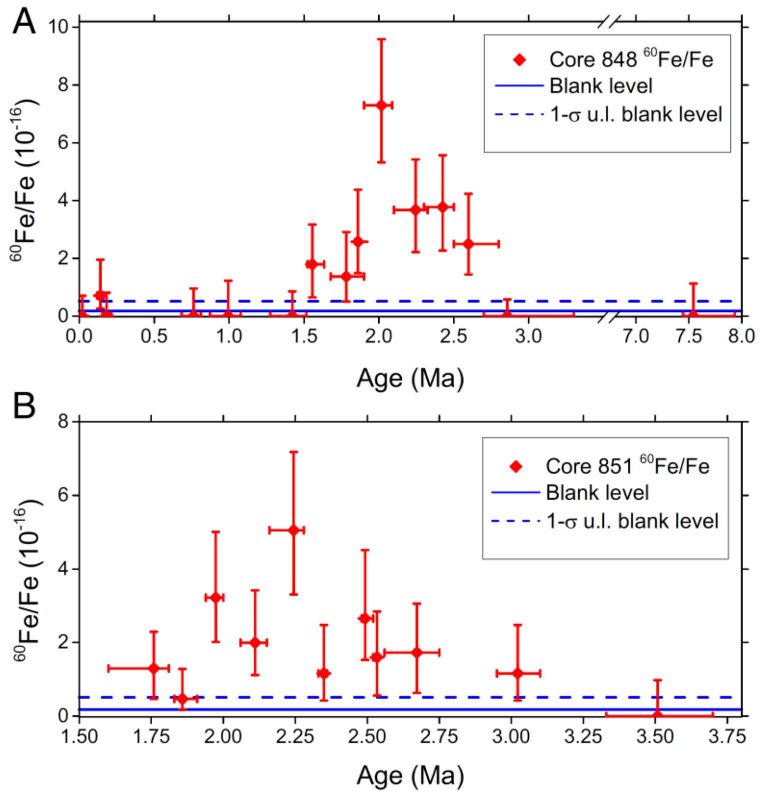
The 2nd signal is real and has been confirmed in another crust!

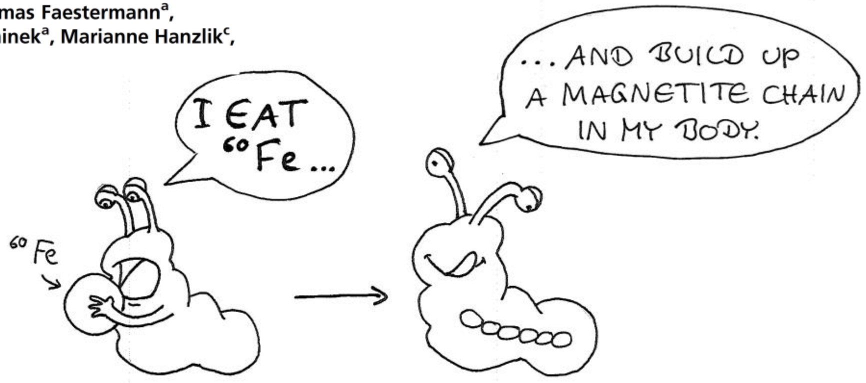
Supernova Traces in Fossil Bacteria

PNAS PNAS PNAS

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

Peter Ludwig[a], Shawn Bishop[a,1], Ramon Egli[b], Valentyna Chernenko[a], Boyana Deneva[a], Thomas Faestermann[a], Nicolai Famulok[a], Leticia Fimiani[a], José Manuel Gómez-Guzmán[a], Karin Hain[a], Gunther Korschinek[a], Marianne Hanzlik[c], Silke Merchel[d], and Georg Rugel[d]





Two sediment cores from equatorial pacific

- Magnetotactic bacteria
- Chemical extraction of magnetofossils
- Time-resolved ^{60}Fe signal in biogenic reservoir

Supernova Traces on the Moon

- No sedimentation
- Gardening effect
- Cosmogenic ^{60}Fe

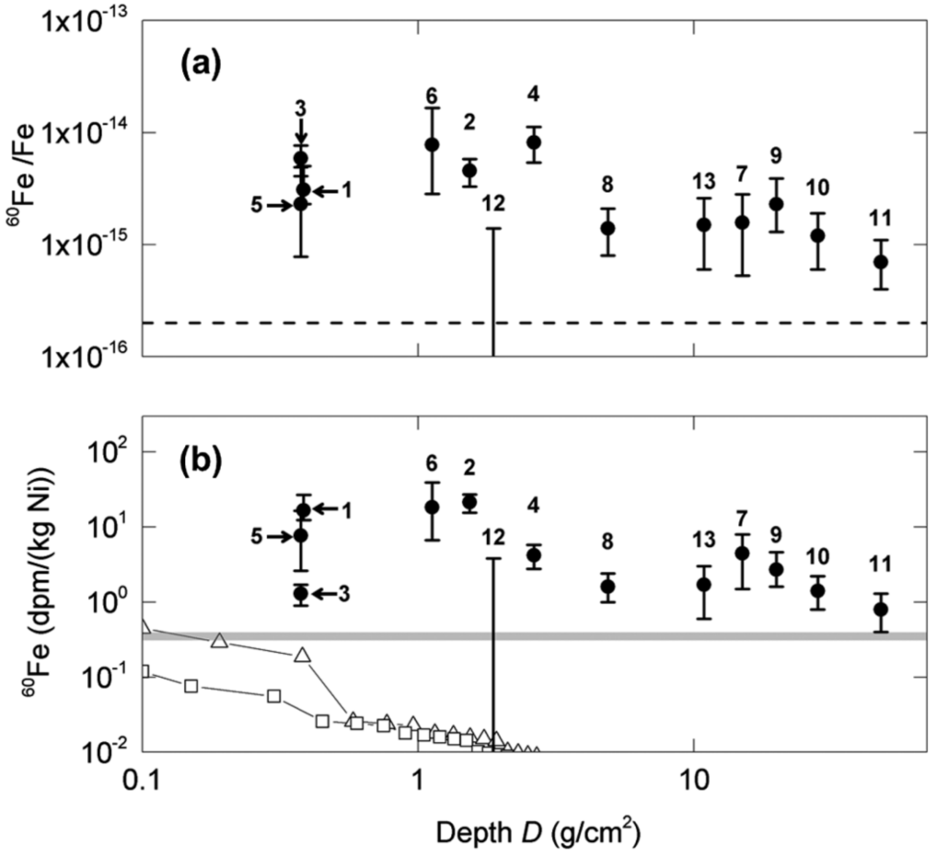
Everything points to one or more supernovae in the past Myr

- ^{60}Fe is everywhere it shouldn' t be!
- We are living in the Local Bubble!

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. Herzog,[2] K. Knie,[1,†] G. Korschinek,[1,‡] P. Ludwig,[1] J. Park,[2] R. C. Reedy,[3] and G. Rugel[1,§]

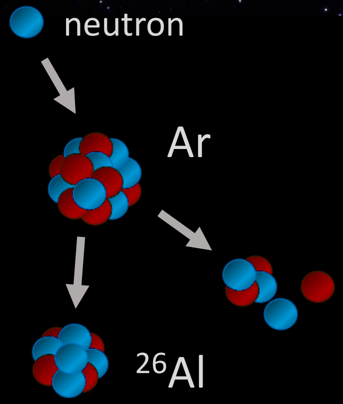


Alan Bean takes **Lunar samples** (Apollo 12, 1969)

^{26}Al in deep-sea sediments

Sources of ^{26}Al

- Supernova
- Atmospheric



^{26}Al in deep-sea sediments

Sources of ^{26}Al

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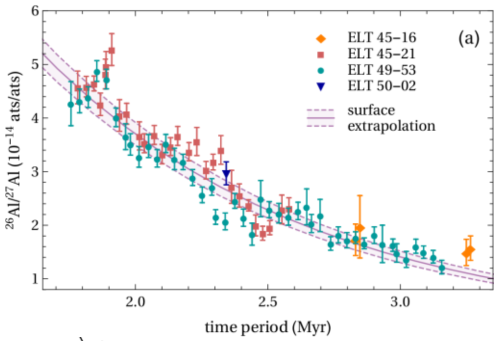
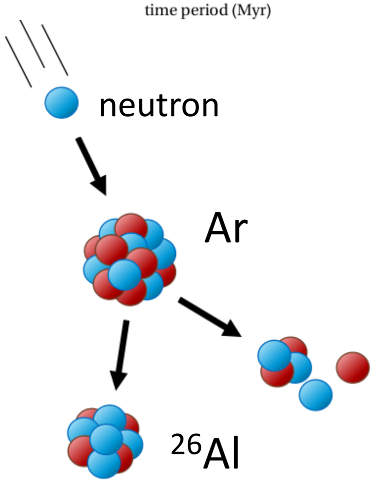


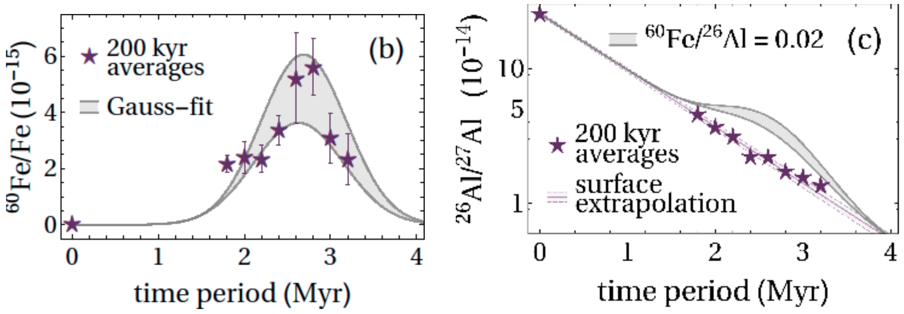


PHYSICAL REVIEW LETTERS **121**, 221103 (2018)

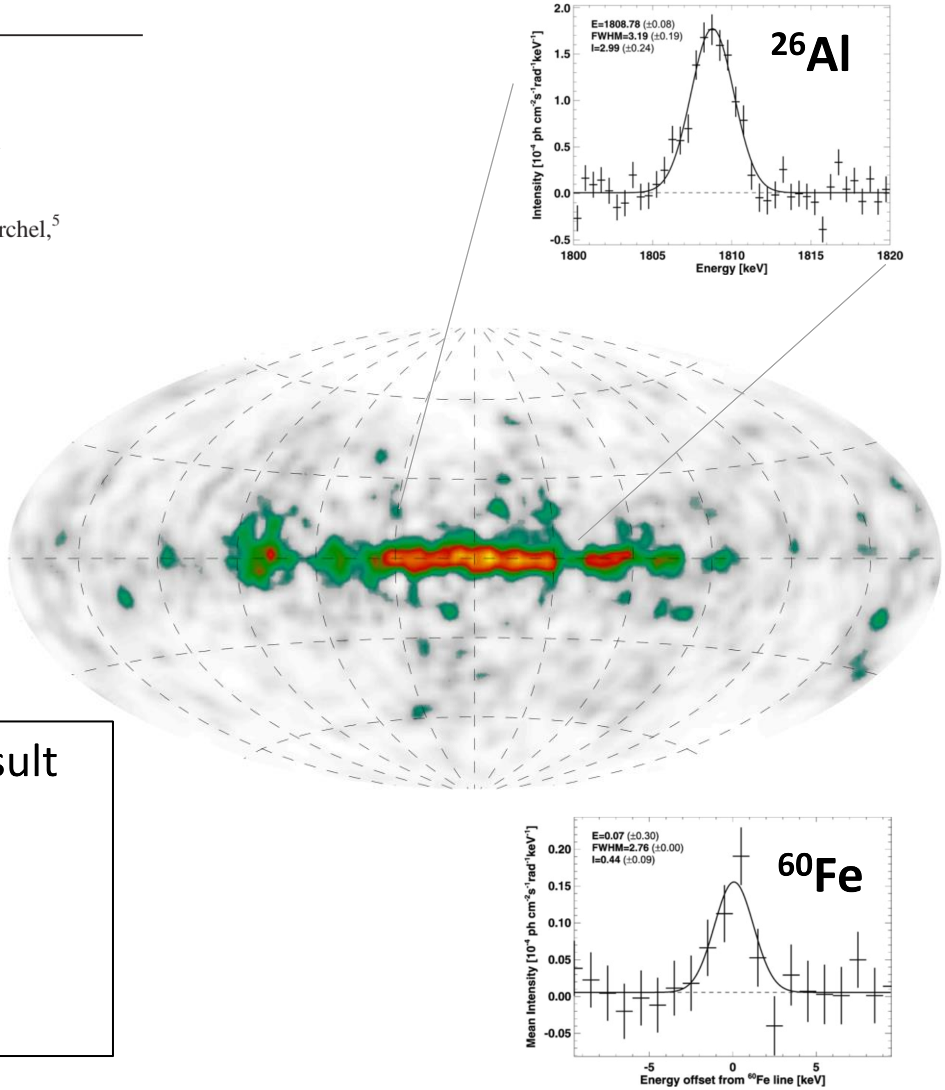
Editors' Suggestion

Limits on Supernova-Associated ^{60}Fe/^{26}Al Nucleosynthesis Ratios from Accelerator Mass Spectrometry Measurements of Deep-Sea Sediments

Jenny Feige,[1,2,*] Anton Wallner,[3] Randolf Altmeyer,[4] L. Keith Fifield,[3] Robin Golser,[2] Silke Merchel,[5] Georg Rugel,[5] Peter Steier,[2] Stephen G. Tims,[3] and Stephan R. Winkler[2,6]



- A low ^{60}Fe/^{26}Al nucleosynthesis ratio should result in a visible ^{26}Al signature.
- The measured data suggests a limit of $0.18^{+0.15}_{-0.08}$.
- Comparable to observations (0.184 ± 0.042) .

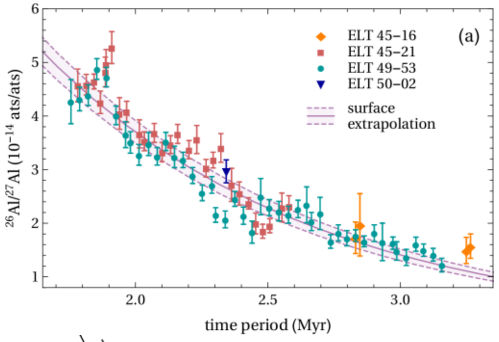


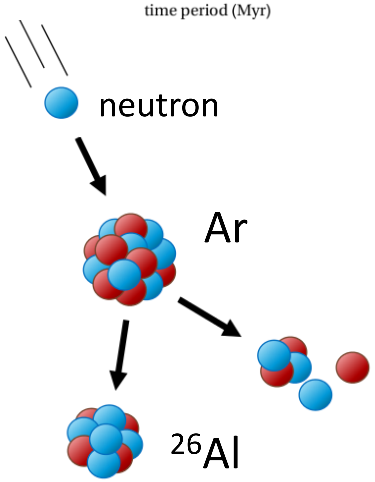
Plüschke et al., ESA Sp. Publ. 459, 55 (2001); Diehl et al., Nature 439, 45 (2006), Wang et al., A&A 469, 1005 (2007); Wang et al., APJ 889, 169 (2020)

^{26}Al in deep-sea sediments

Sources of ^{26}Al

- **Supernova**
- Atmospheric





PHYSICAL REVIEW LETTERS **121,** 221103 (2018)

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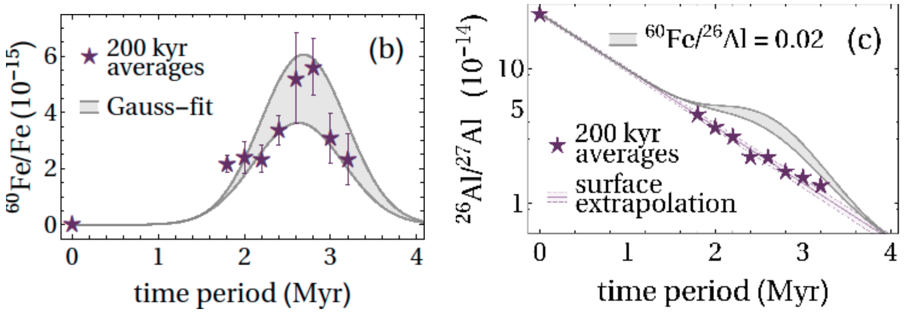

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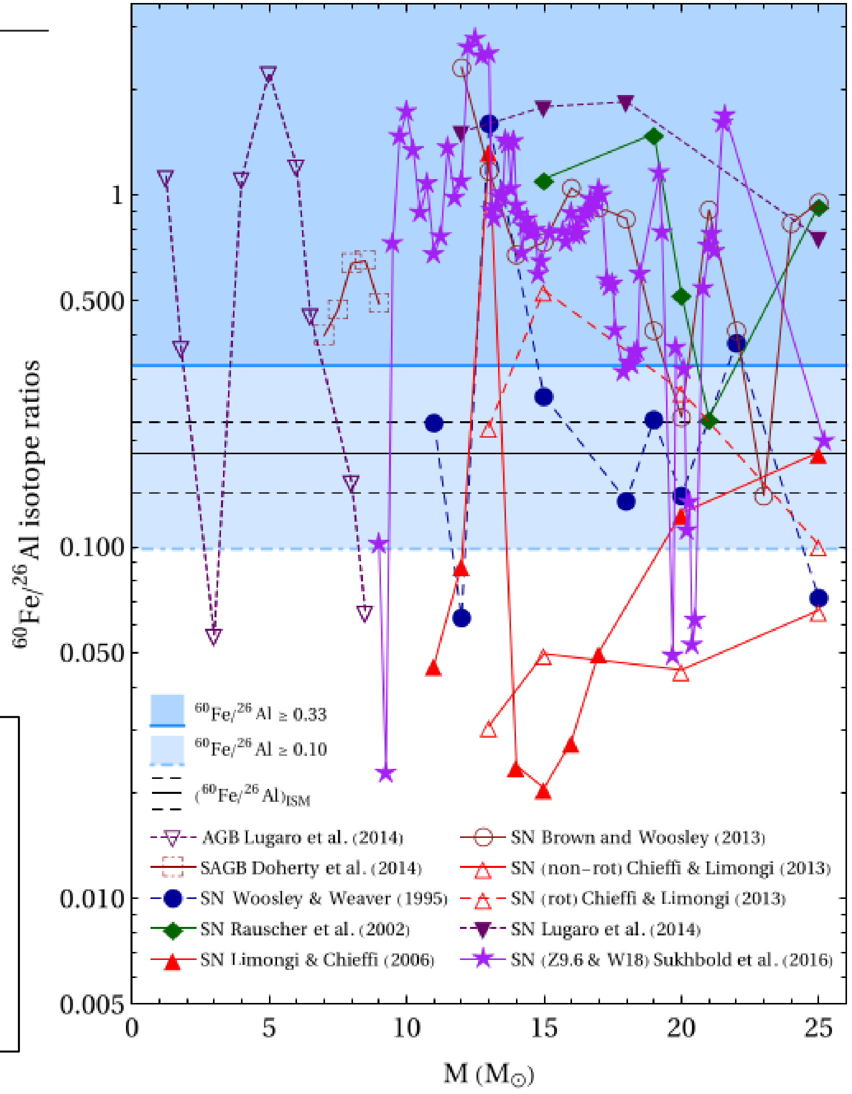
- Comparable to observations (0.184 ± 0.042) .
- Comparable to stellar nucleosynthesis models.



Recent Supernova Influx

PHYSICAL REVIEW LETTERS 123, 072701 (2019)

Editors' Suggestion | Featured in Physics

Interstellar ^{60}Fe in Antarctica

Dominik Koll,[1,*] Gunther Korschinek,[1,2] Thomas Faestermann,[1,2] J. M. Gómez-Guzmán,[1]
Sepp Kipfstuhl,[3] Silke Merchel,[4] and Jan M. Welch[5]

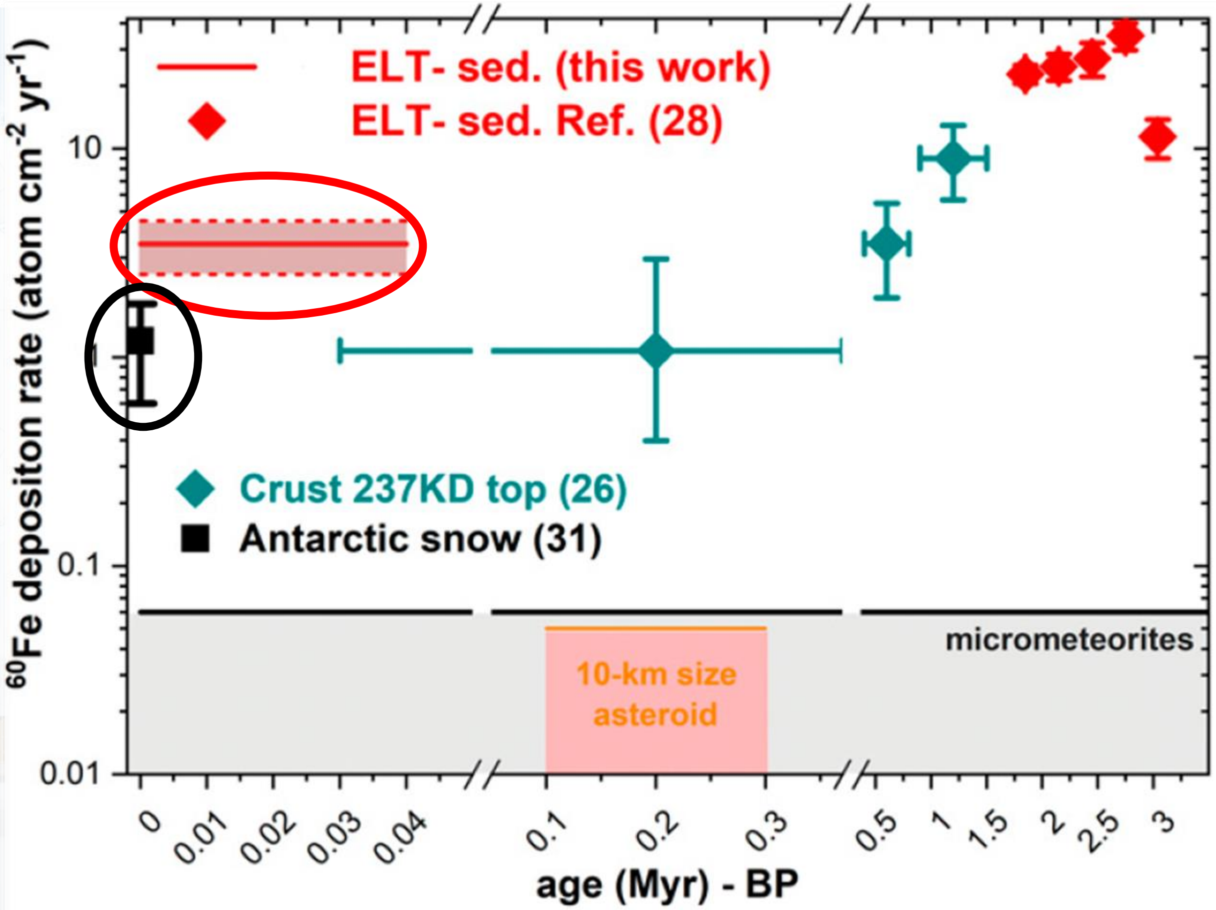
^{60}Fe Flux today

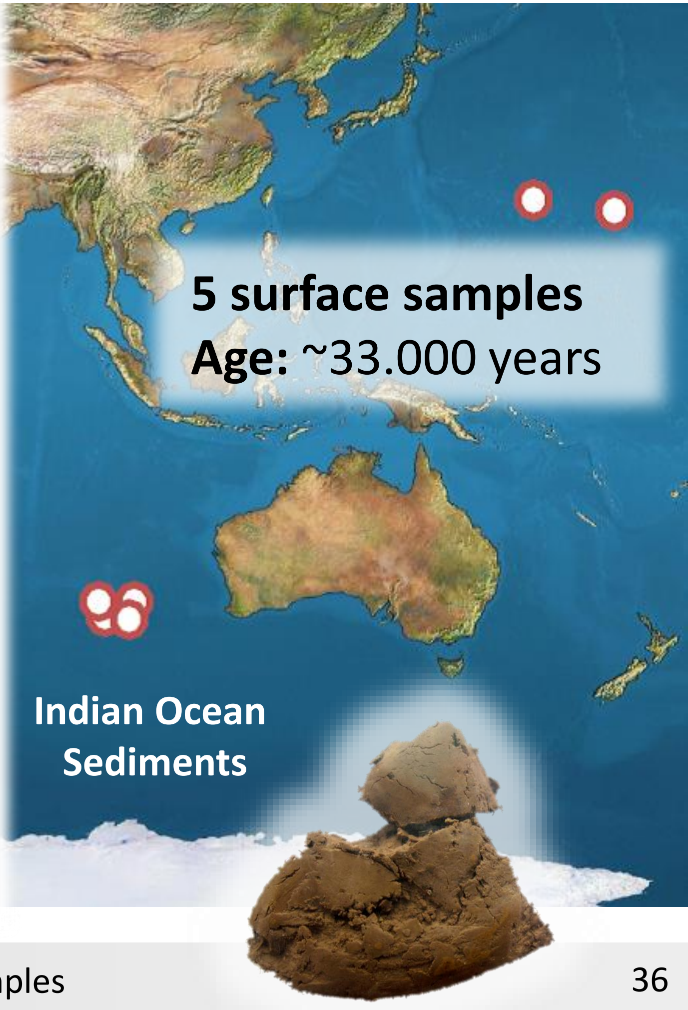
1/10 of peak flux

PNAS

^{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]





Take-Home Message II

Million-year-old Supernova traces have been detected in

- Deep-sea crusts, nodules and sediments all over the world
- Fossil magnetotactic bacteria
- Lunar samples

Two distinct ^{60}Fe signals around 2-3 and 6-7 Myr ago

- SN-derived ^{26}Al is overwhelmed by atmospheric background
  - ➢ Lower ^{60}Fe/^{26}Al limit of ~0.18

Still today ^{60}Fe is reaching our Earth

Further findings

- ^{53}Mn in deep-sea crusts (Korschinek et al., PRL 125, 031101, 2020)
- ^{244}Pu in deep-sea crusts (Wallner et al., Science 372, 742, 2021; D. Koll's talk)

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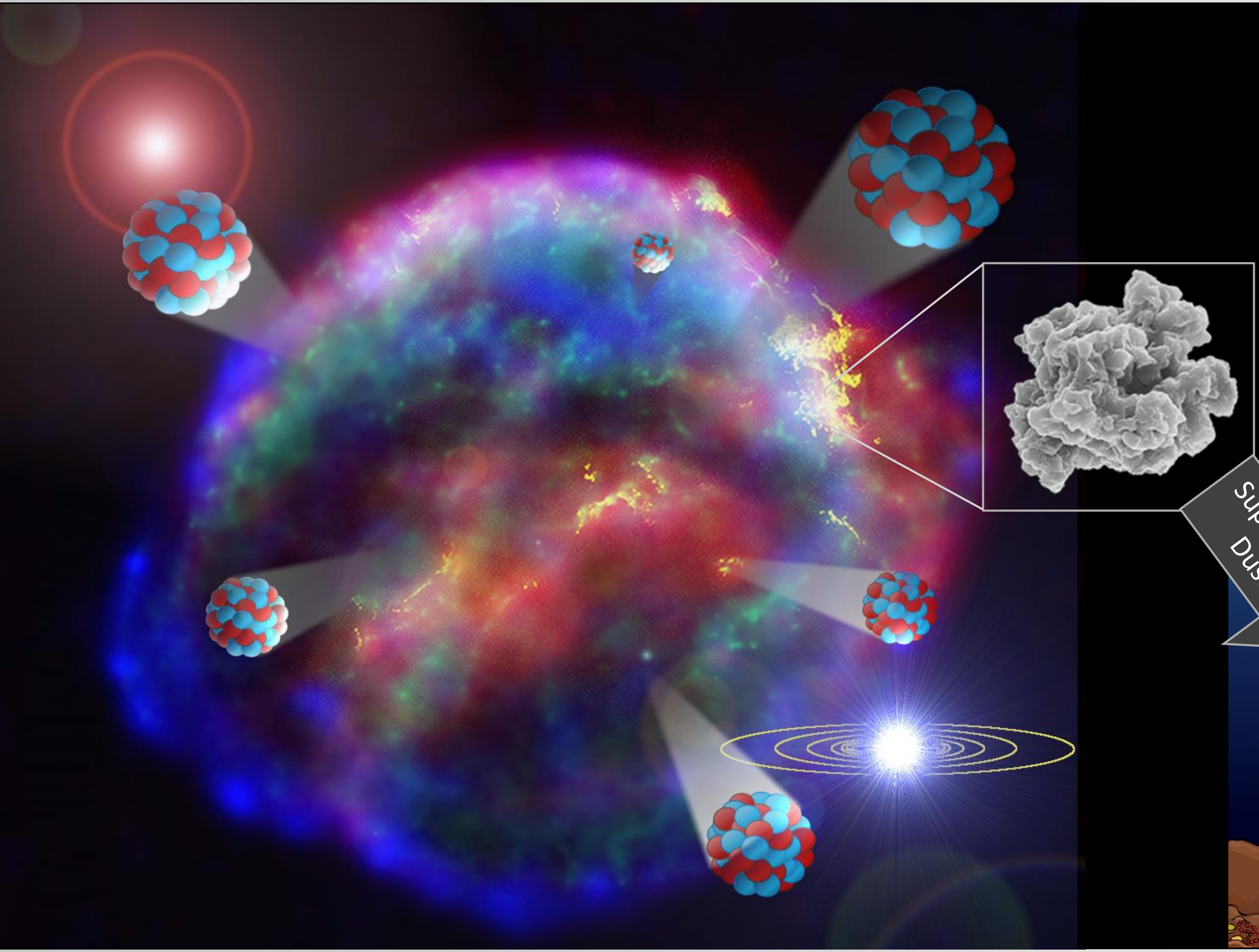
Outline



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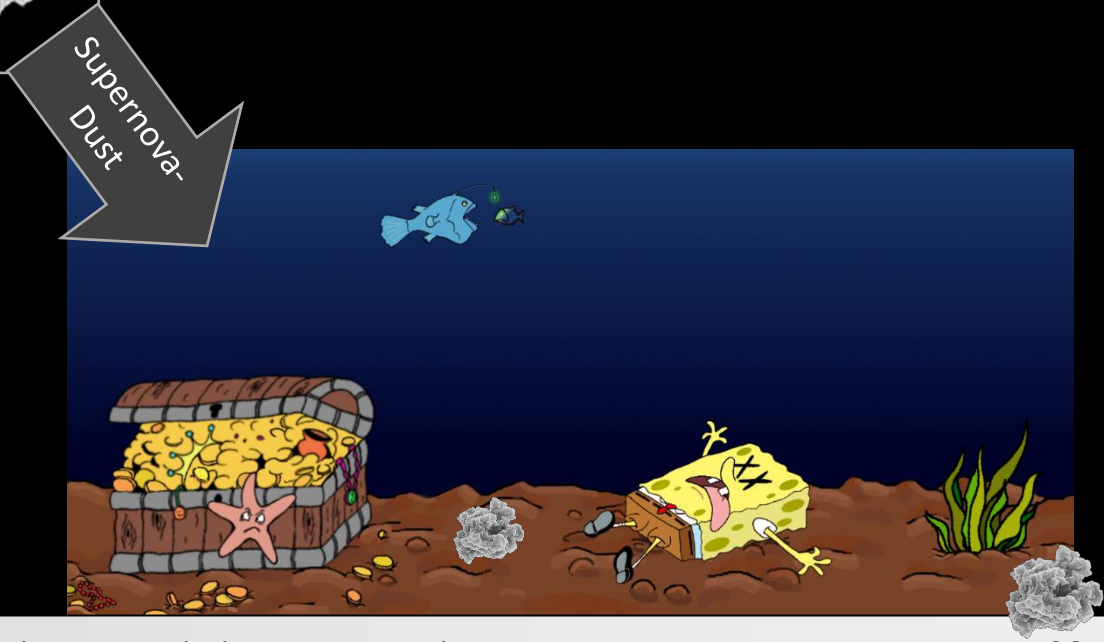
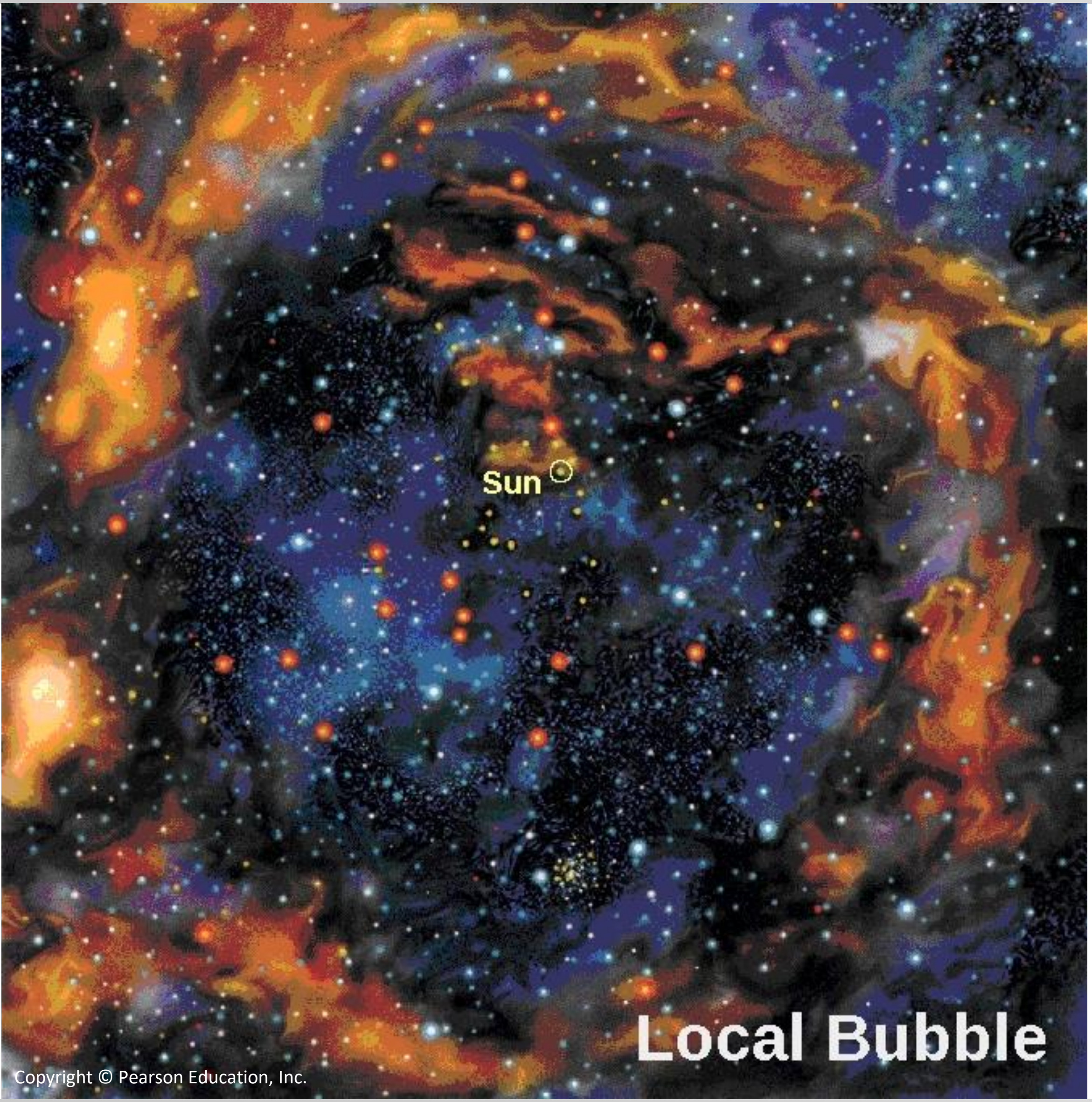
    - Experimental
    - **Theoretical**
3. Conclusions



Supernova Signatures



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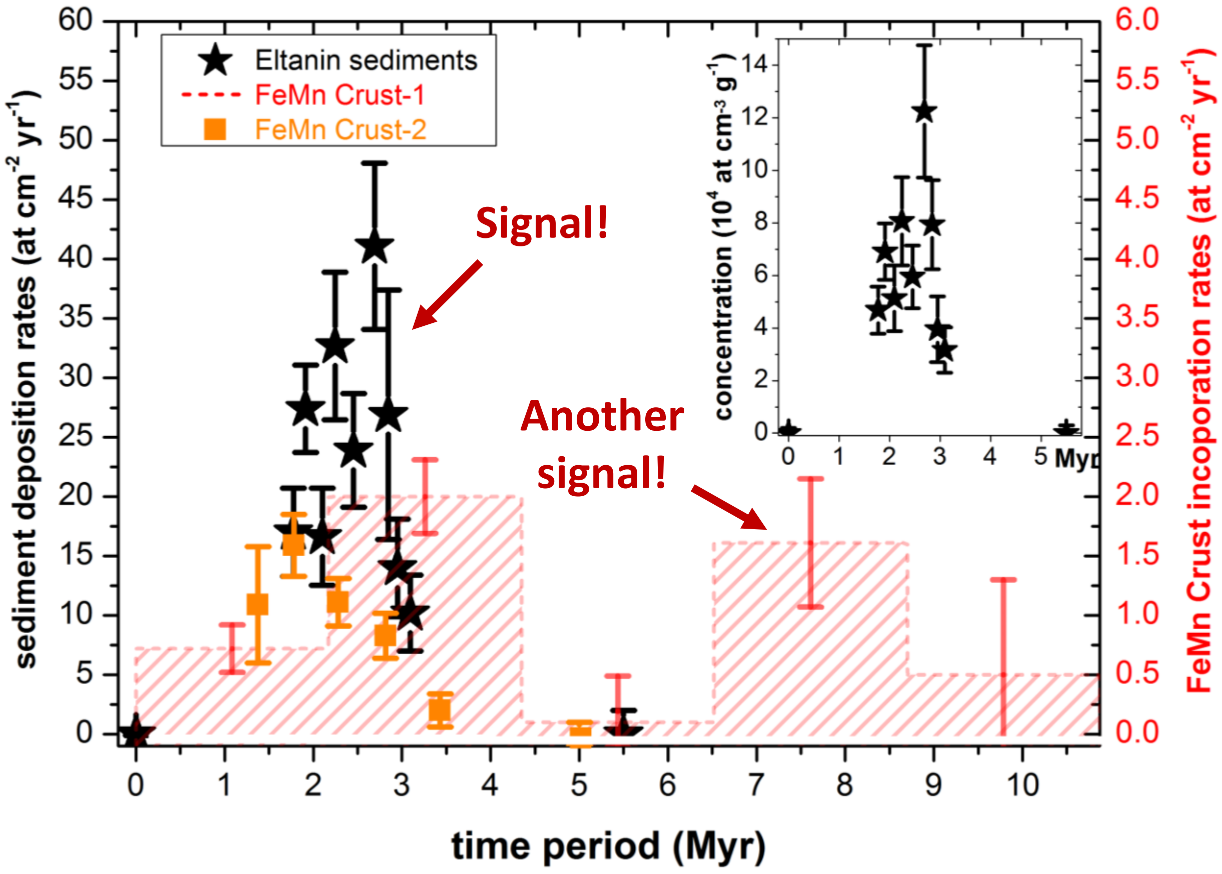
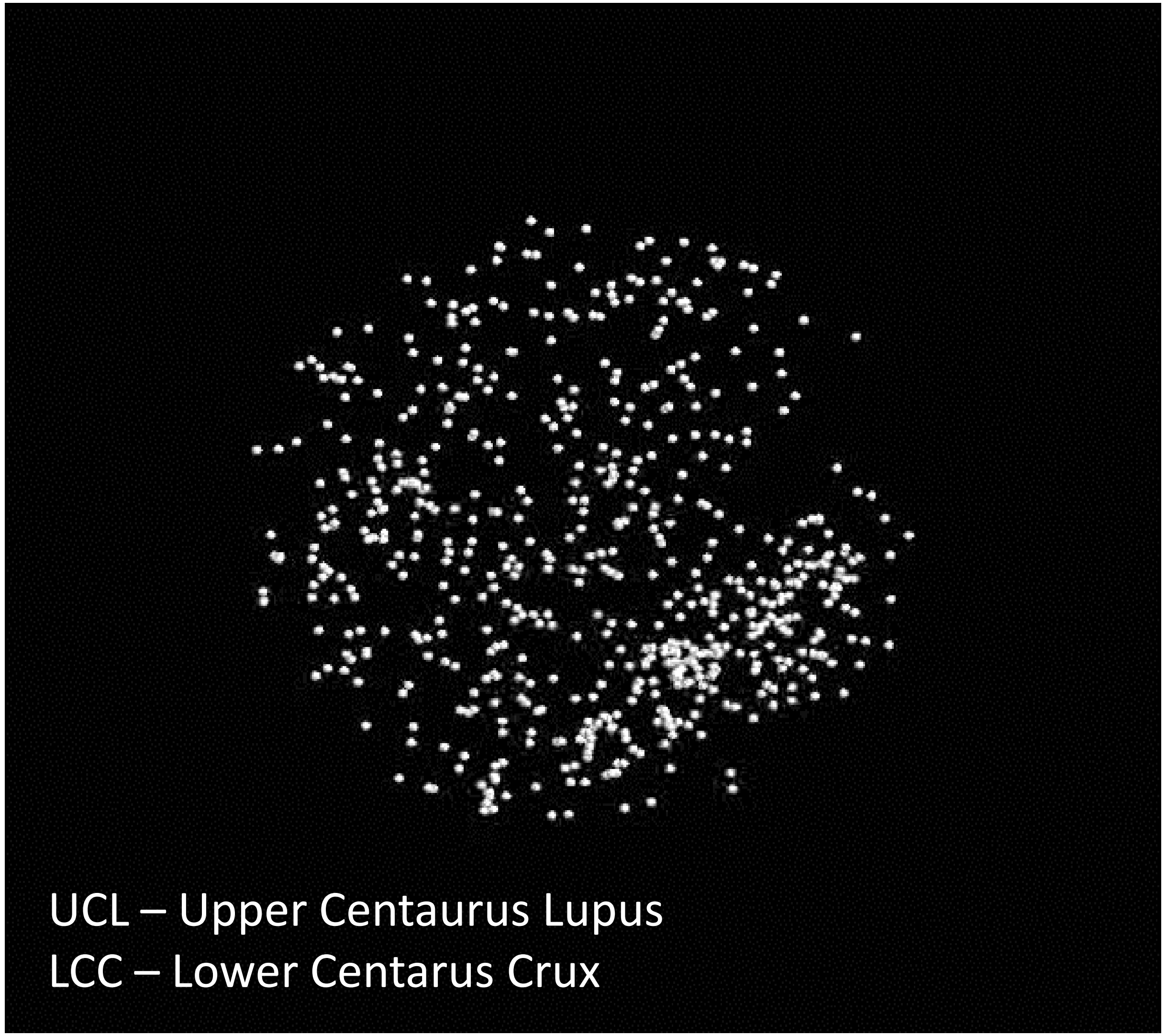
Which stars created the Local Bubble and the ^{60}Fe signals?

Why is ^{60}Fe still arriving on Earth today?



Wallner, Feige et al., Nature 532, 69 (2016)

Nearby Stellar Moving Groups



Mon. Not. R. Astron. Soc. **373,** 993–1003 (2006) doi:10.1111/j.1365-2966.2006.11044.x

The search for the origin of the Local Bubble redivivus

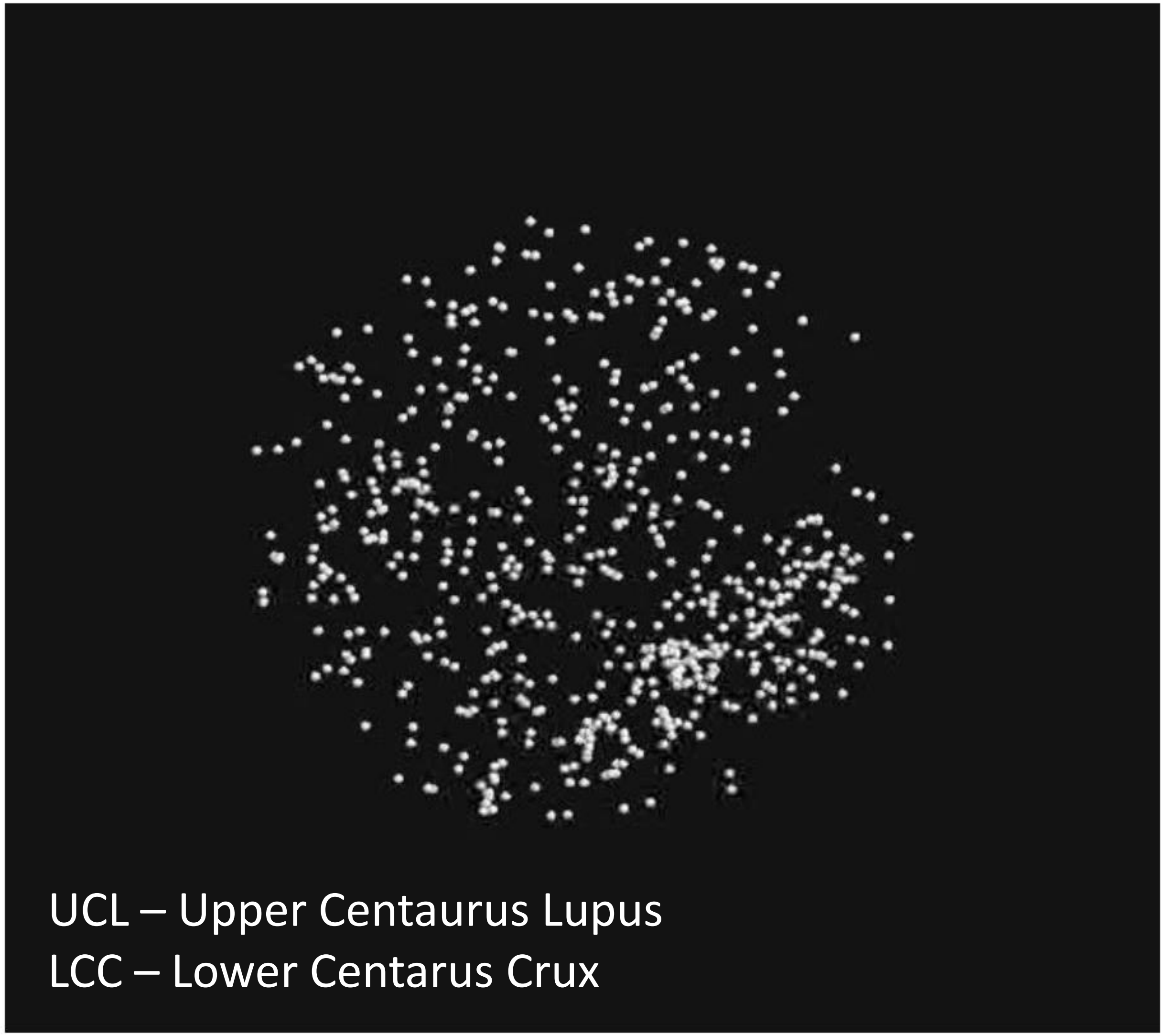
B. Fuchs,[1★] D. Breitschwerdt,[2] M. A. de Avillez,[2,3] C. Dettbarn[1] and C. Flynn[4]

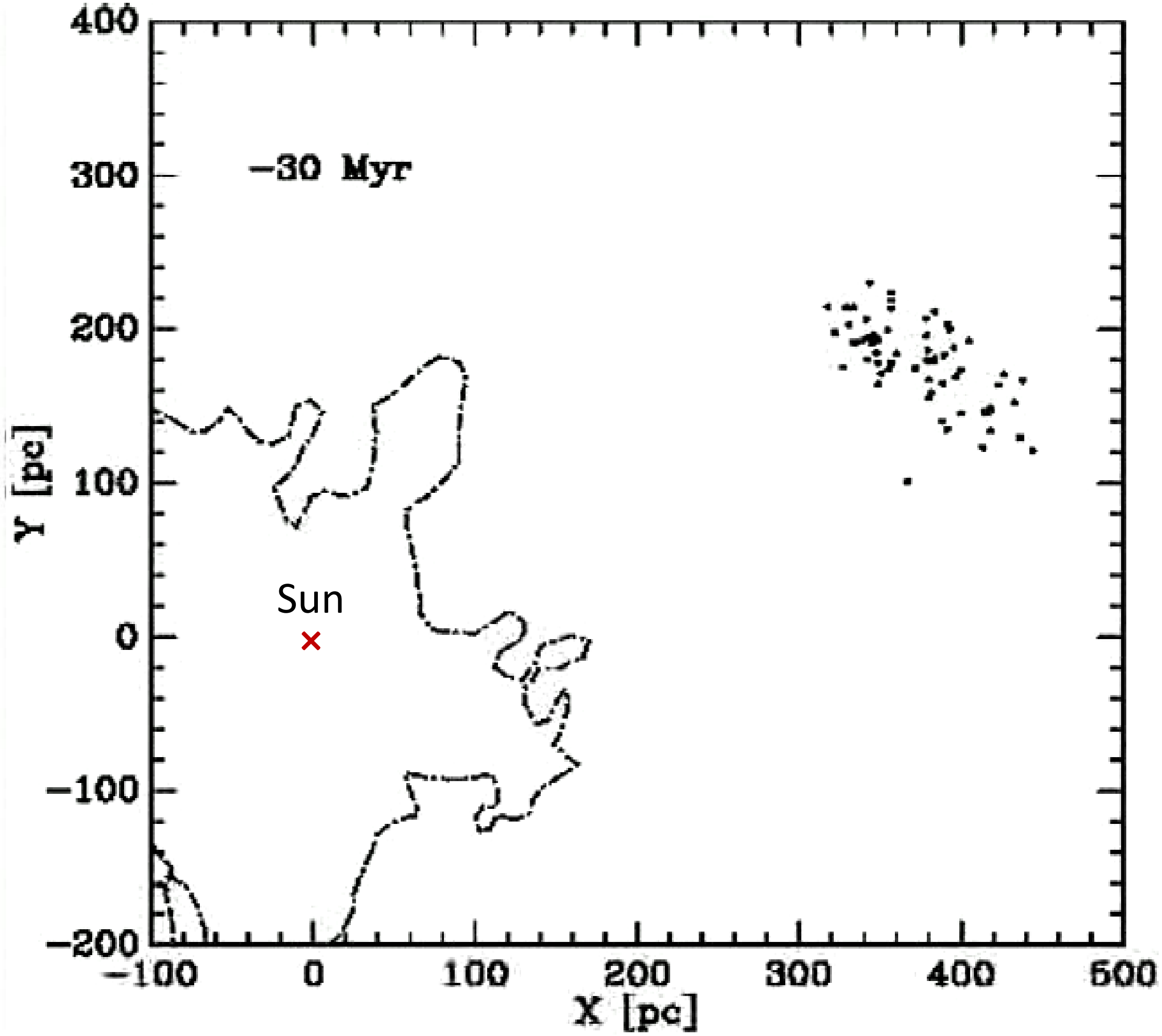
Solar environment (r = 200 pc) was searched for **suspicious stars**.

Subgroups of the **Scorpius-Centaurus association**!

Ages: ~20 Myr

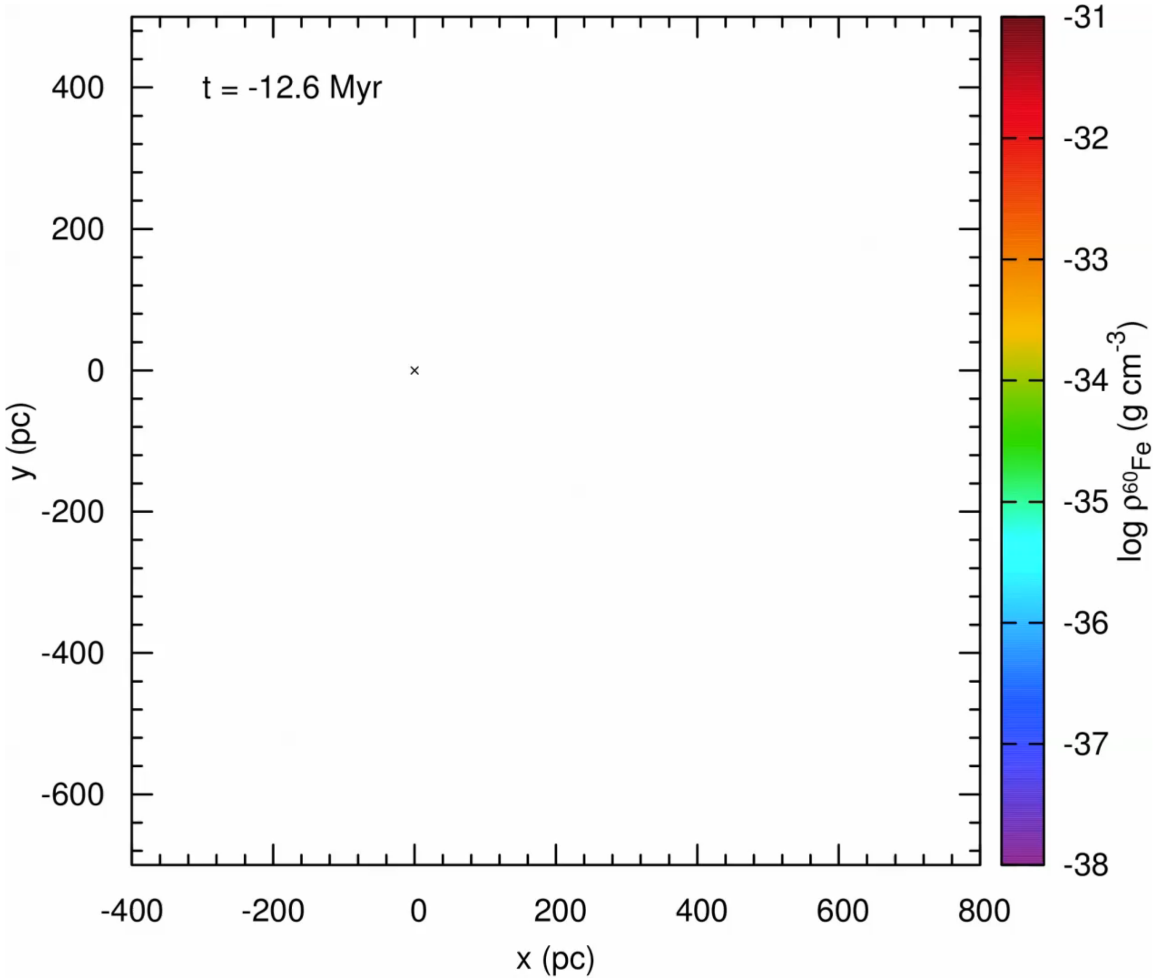
Nearby Stellar Moving Groups





Fuchs et al., MNRAS 373, 993 (2006)

Modelling the ^{60}Fe Signal and the Local Bubble



Homogeneous ambient medium (0.3 ats cm^{-3})

Resolution: 0.7 pc

Number of Supernovae: 16

Local Bubble shell crosses Solar System 2.2 Myr ago!

Fluence:

- Number of atoms that reach the Earth per cm^2

$$F = \frac{U}{4} \frac{M_{ej}}{4\pi r^2 A m_p} e^{-t/\tau}$$

t .... time since explosion
M_{ej} ... ejected ^{60}Fe mass
r .... distance of the explosion site
A ...... mass number
m_p .... proton mass
τ .... ^{60}Fe mean lifetime
U ...... uptake factor

Breitschwerdt, Feige, Schulreich et al., Nature 532, 73 (2016)

Modelling the ^{60}Fe Signal and the Local Bubble

Astronomy & Astrophysics
A&A 604, A81 (2017)
DOI: 10.1051/0004-6361/201629837
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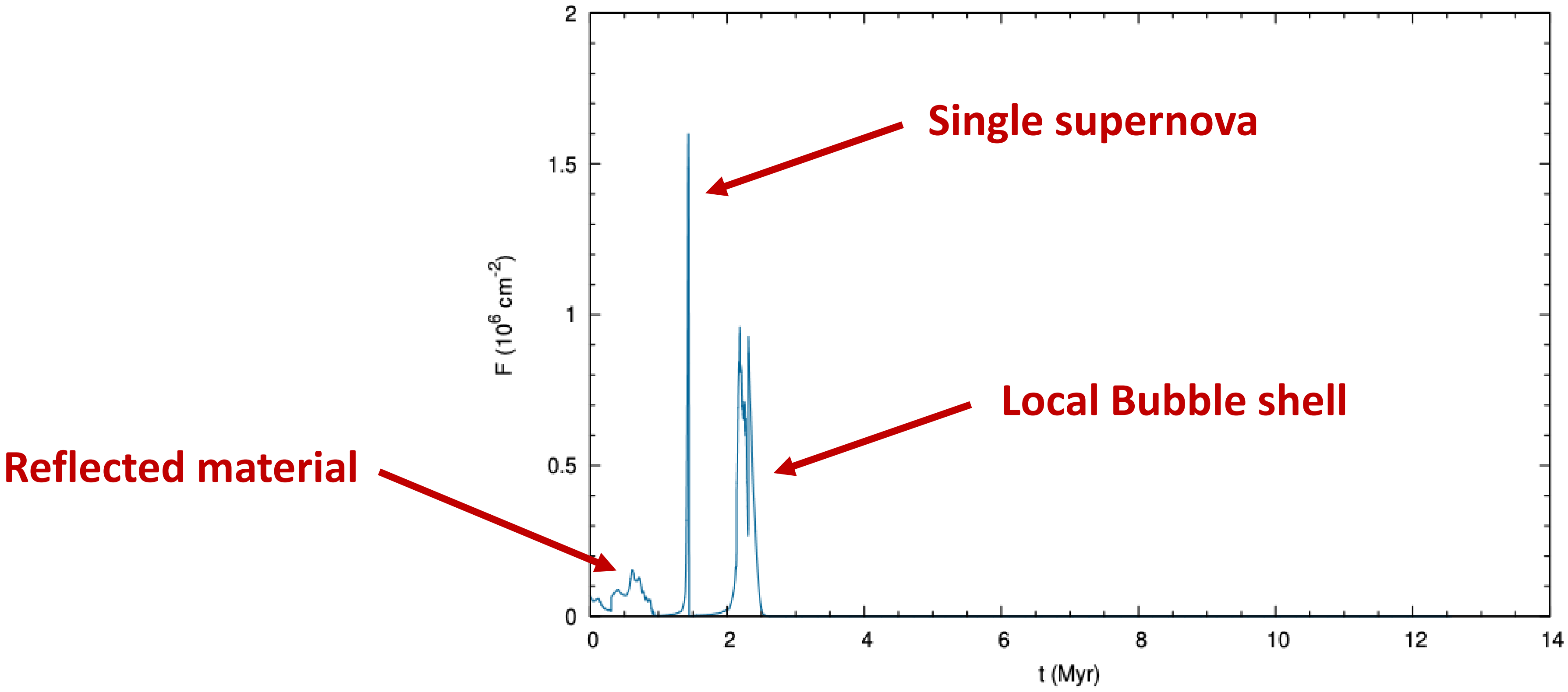
Numerical studies on the link between radioisotopic signatures on Earth and the formation of the Local Bubble

I. ^{60}Fe transport to the solar system by turbulent mixing of ejecta from nearby supernovae into a locally homogeneous interstellar medium

M. M. Schulreich[1], D. Breitschwerdt[1], J. Feige[1], and C. Dettbarn[2]



Modelling the ^{60}Fe Signal and the Local Bubble

LETTER
doi:10.1038/nature17424

The locations of recent supernovae near the Sun from modelling ^{60}Fe transport

D. Breitschwerdt[1], J. Feige[1], M. M. Schulreich[1], M. A. de. Avillez[1,2], C. Dettbarn[3] & B. Fuchs[3]

Astronomy & Astrophysics
A&A 604, A81 (2017)
DOI: 10.1051/0004-6361/201629837
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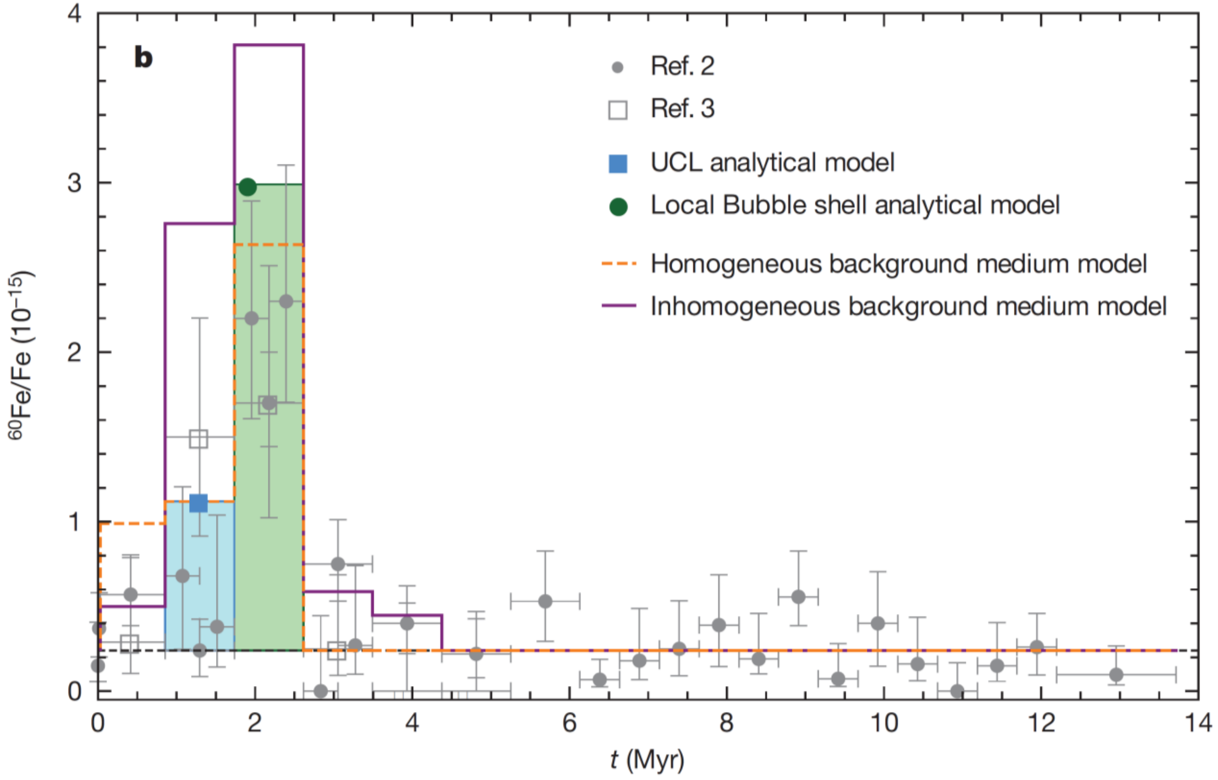
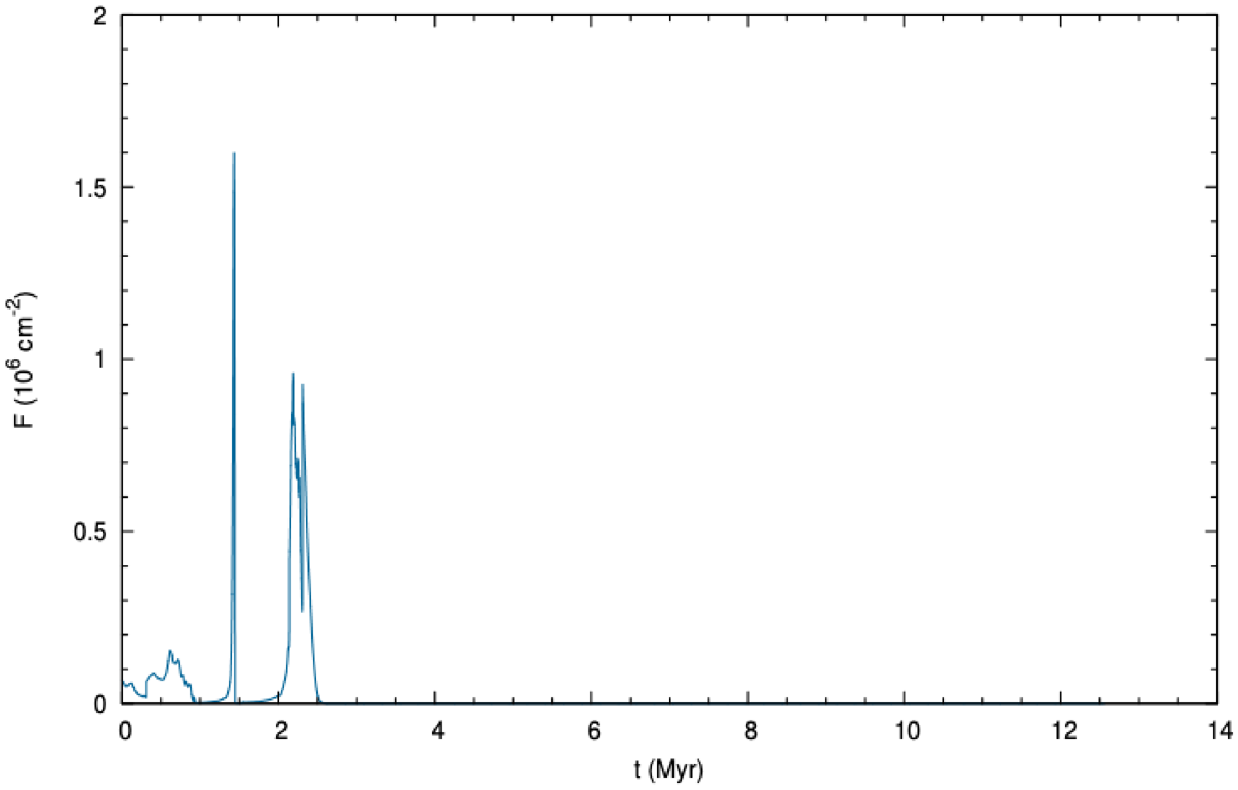




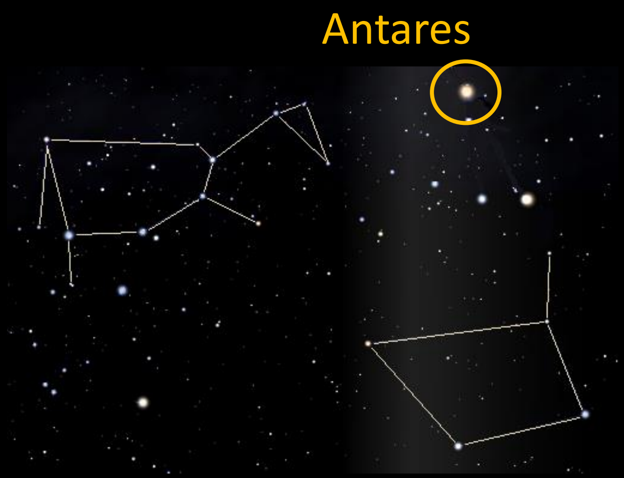
Modelling the ^{60}Fe Signal and the Local Bubble

Most recent supernovae

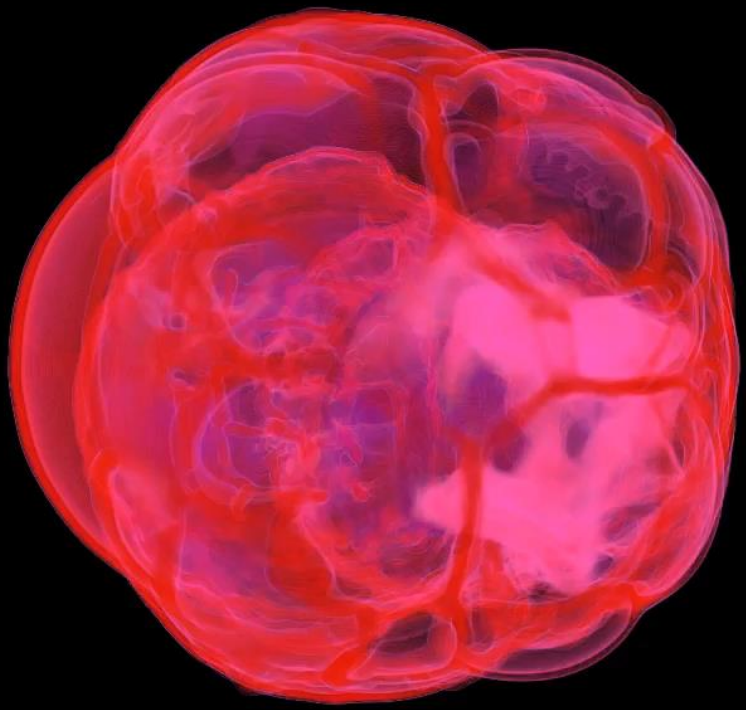
- UCL: 2.6 Myr at 106 pc, 9.4 $M_{\odot}$
- LCC: 2.3 Myr at 91 pc, 9.2 $M_{\odot}$
- UCL: 1.5 Myr at 96 pc, 8.8 $M_{\odot}$

Observable today in

- Libra (UCL)
- Lupus (LCC)



3D simulation of the Local Bubble and the Loop I



Courtesy: Michael M. Schulreich

Recent Supernova Influx

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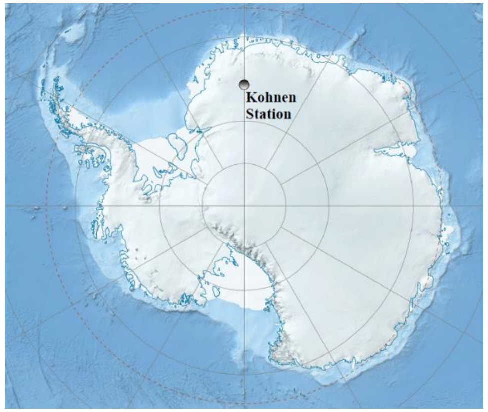
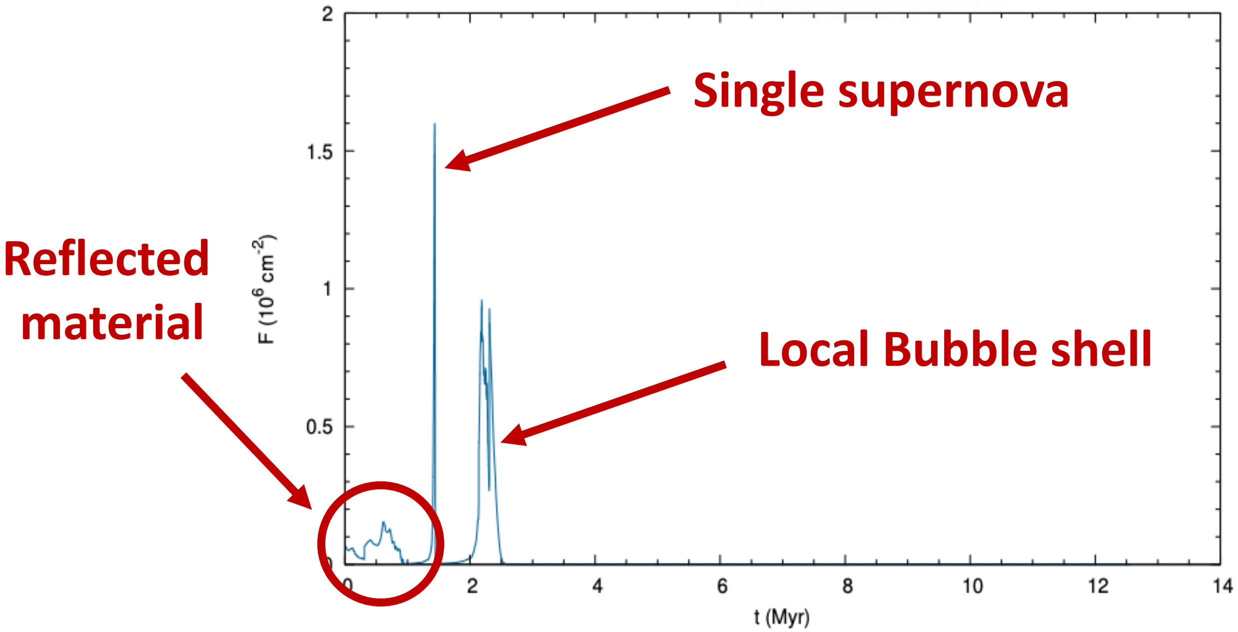
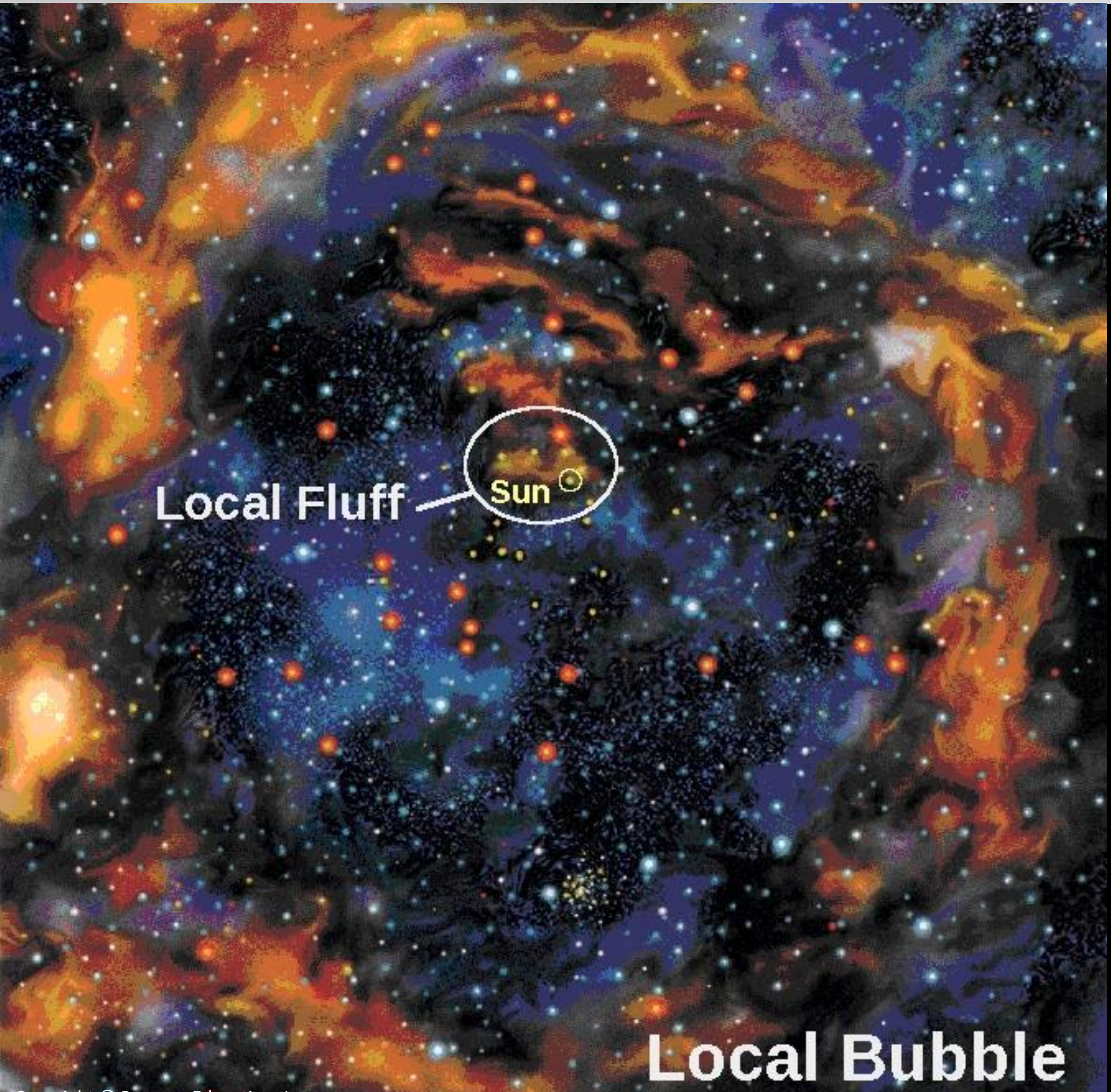
Koll et al., PRL 123, 072701 (2019), Wallner et al., PNAS 117 (36) 21873 (2020)





Schulreich et al., A&A 604, A81 (2017)

Recent Supernova Influx



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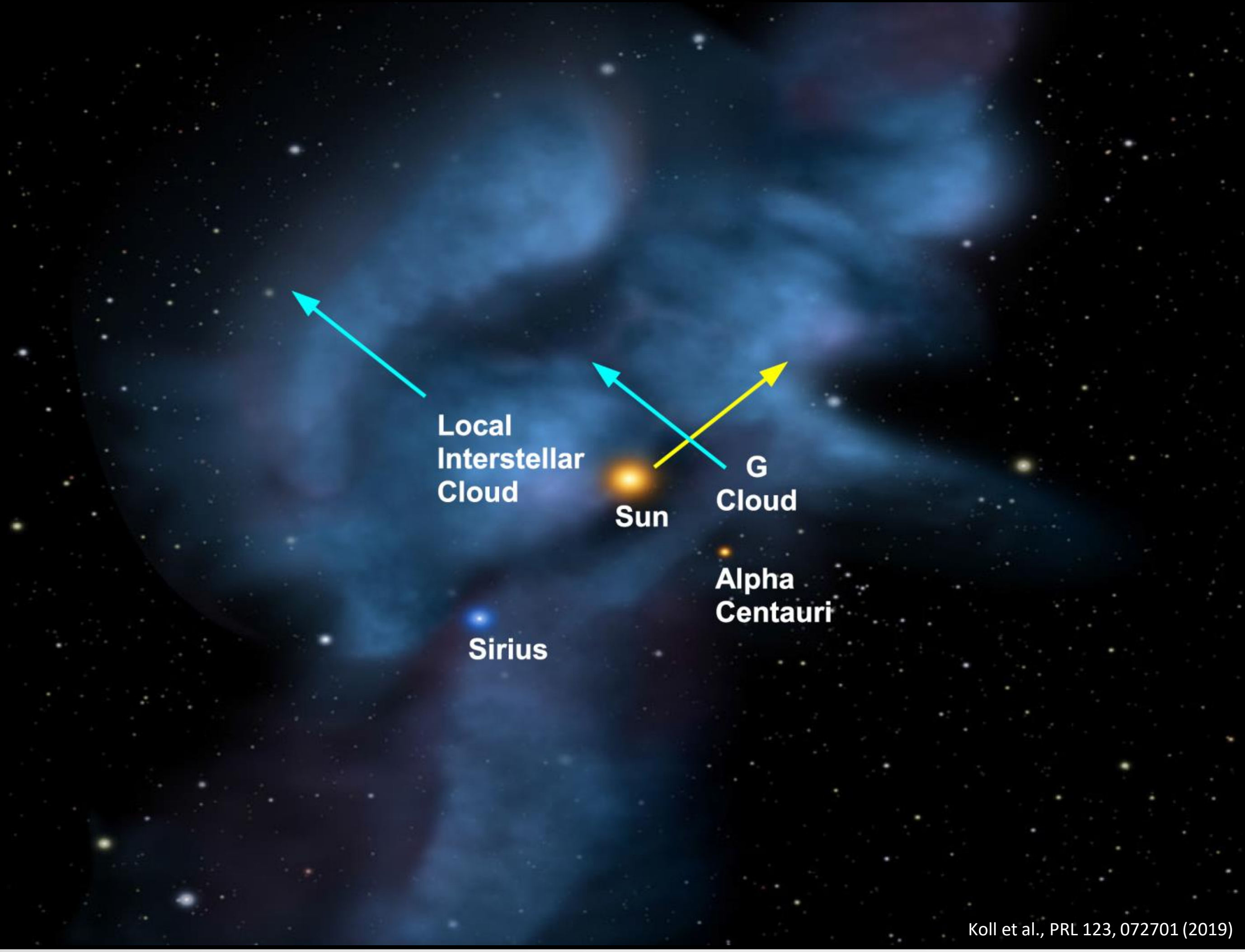
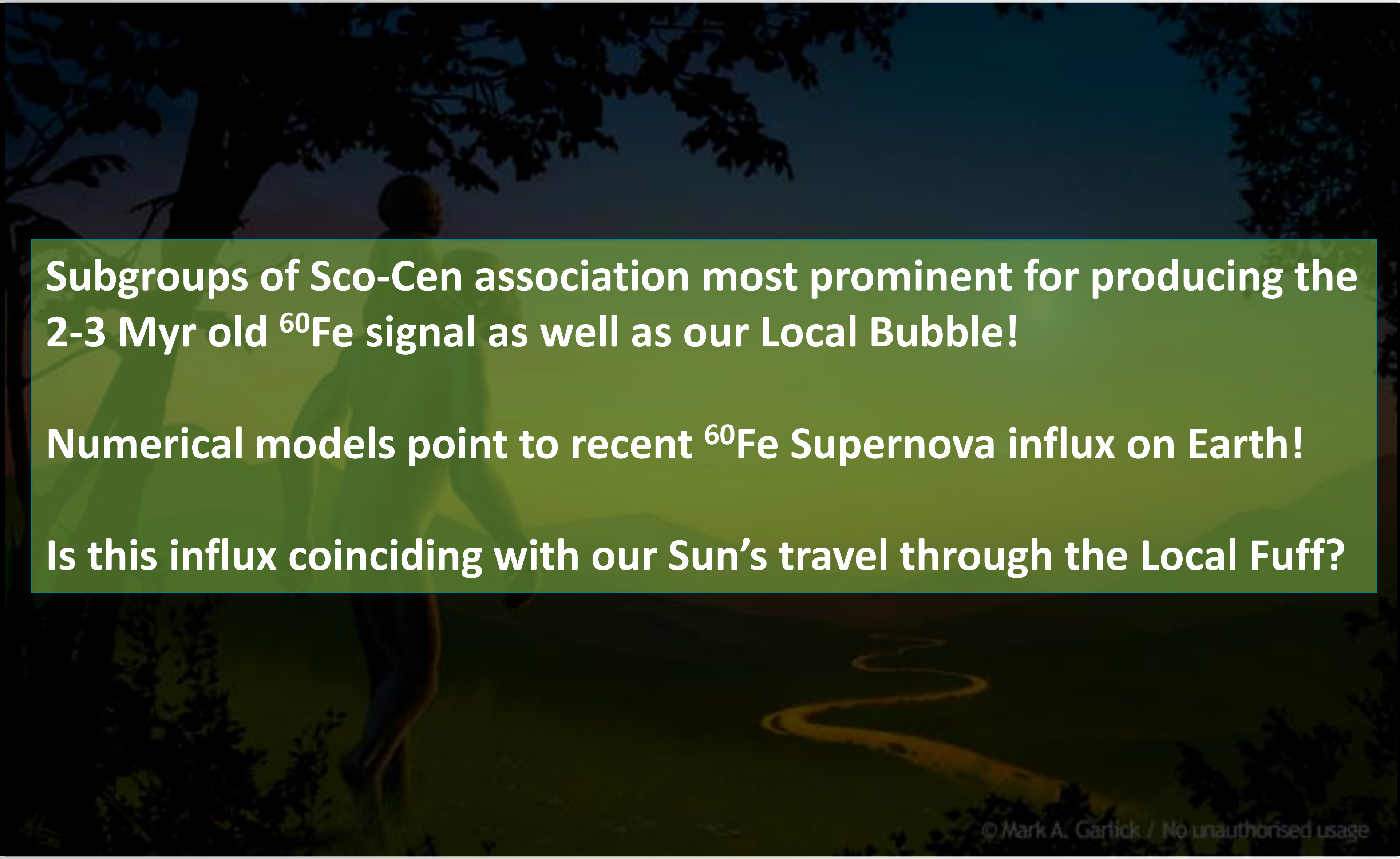
Our Sun is moving through the Local Fluff



Koll et al., PRL 123, 072701 (2019)

Take-Home Message III

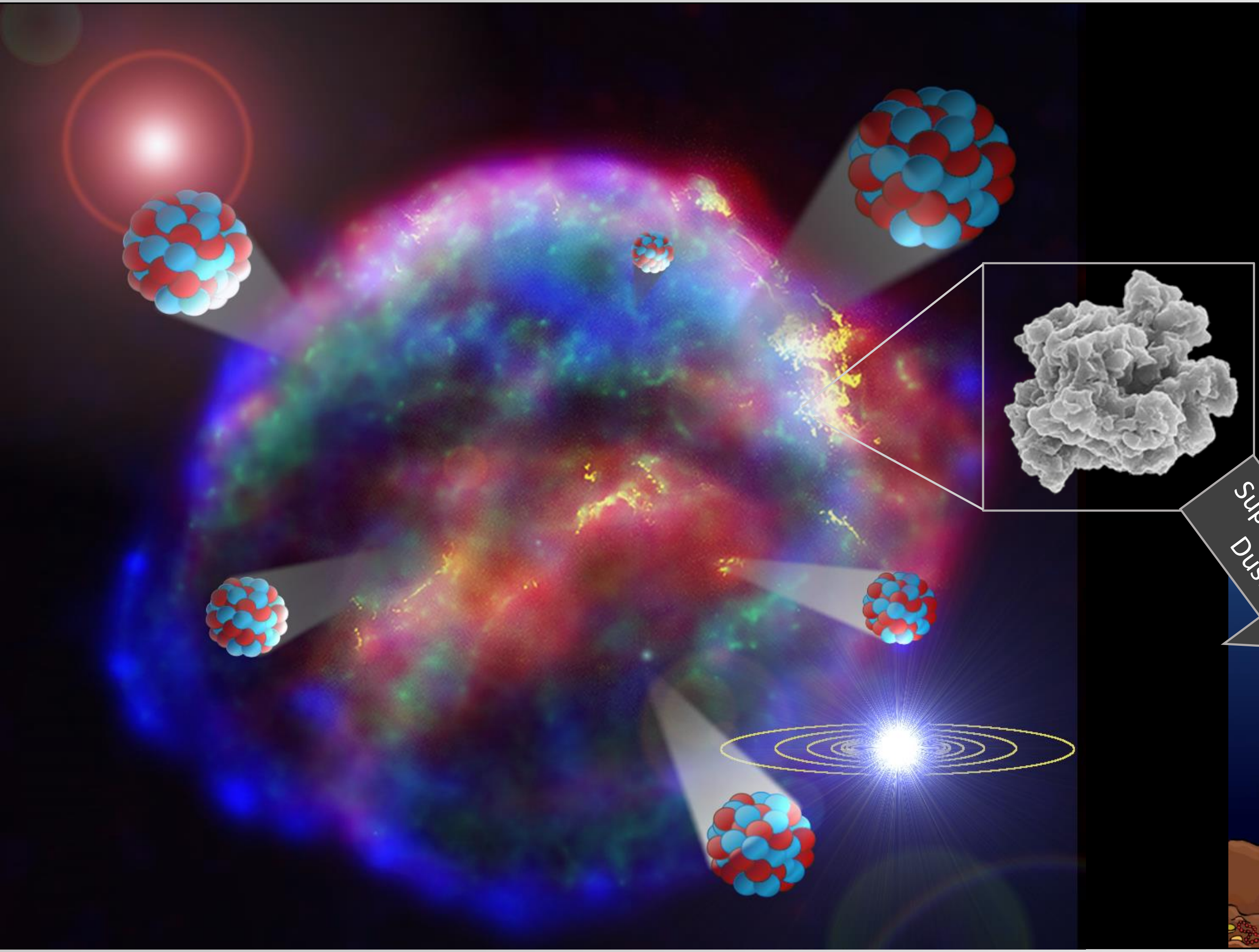


Subgroups of Sco-Cen association most prominent for producing the 2-3 Myr old ^{60}Fe signal as well as our Local Bubble!

Numerical models point to recent ^{60}Fe Supernova influx on Earth!

Is this influx coinciding with our Sun's travel through the Local Fuff?

Outline



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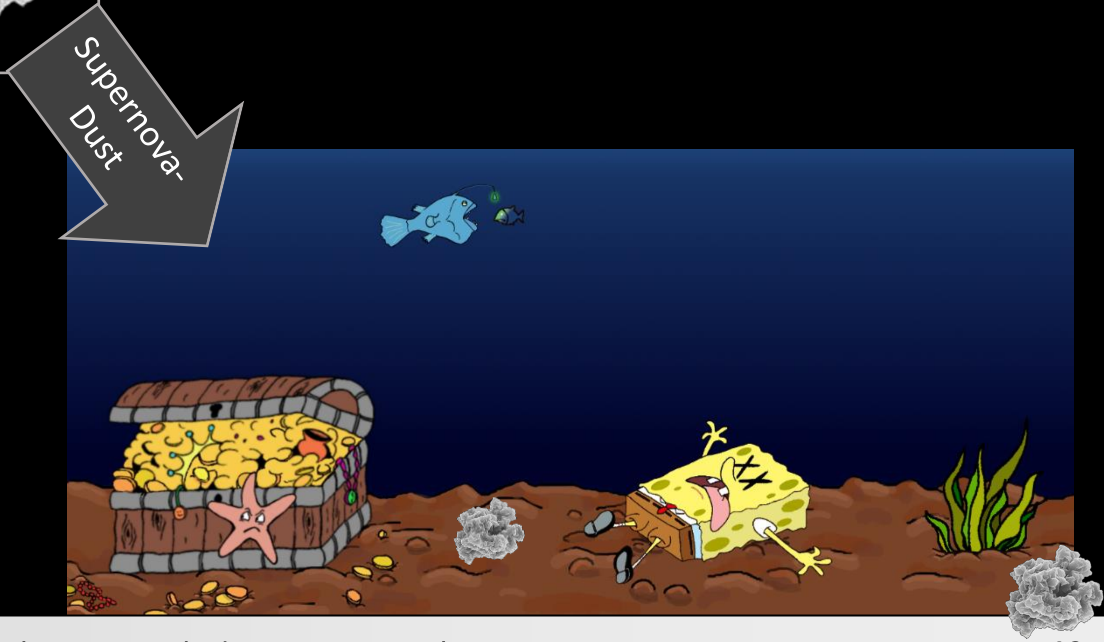
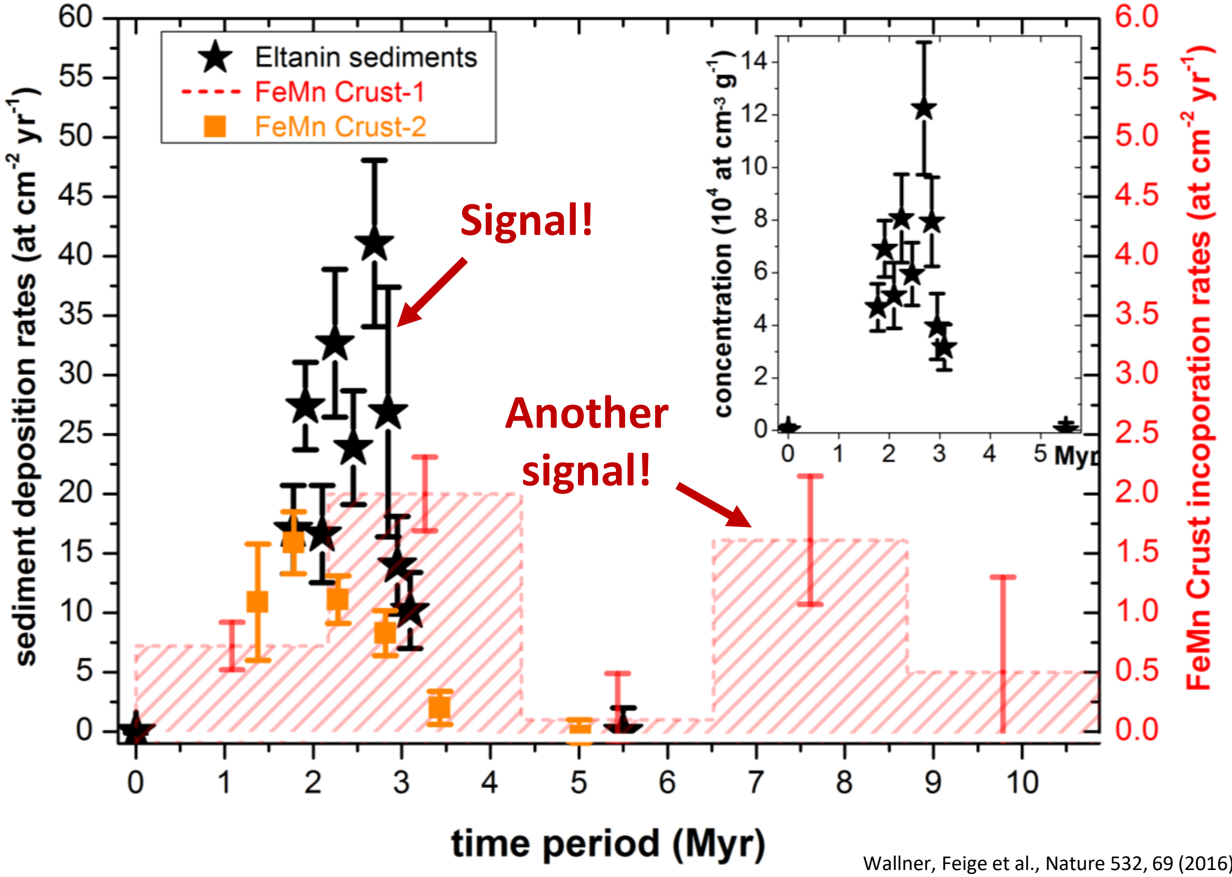


Supernova Signatures

Open questions:

Which stars created the second signal?
Where does the recent influx come from?
What is the $^{60}Fe/^{26}Al$ ratio?



Wallner, Feige et al., Nature 532, 69 (2016)

Related Studies

PRL **115,** 181103 (2015) PHYSICAL REVIEW LETTERS week ending 30 OCTOBER 2015

Signatures of a Two Million Year Old Supernova in the Spectra of Cosmic Ray Protons, Antiprotons, and Positrons

M. Kachelrieß,[1] A. Neronov,[2] and D. V. Semikoz[3]

Related Studies

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Science *RESEARCH ARTICLES*

Cite as: W. R. Binns *et al.*, *Science* 10.1126/science.aad6004 (2016).

Observation of the ^{60}Fe nucleosynthesis-clock isotope in galactic cosmic rays

W. R. Binns,[1*] M. H. Israel,[1*] E. R. Christian,[2] A. C. Cummings,[3] G. A. de Nolfo,[2] K. A. Lave,[1] R. A. Leske,[3] R. A. Mewaldt,[3] E. C. Stone,[3] T. T. von Rosenvinge,[2] M. E. Wiedenbeck[4]

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Science

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galactic c

W. R. Binns,[1*] M
R. A. Mewaldt,[3]

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **498,** 899–917 (2020) doi:10.1093/mnras/stz2629
Advance Access publication 2019 September 23

A nearby recent supernova that ejected the runaway star ζ Oph, the pulsar PSR B1706–16, and ^{60}Fe found on Earth

R. Neuhäuser,[1★] F. Gießler[1] and V. V. Hambaryan[1,2]

Related Studies

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M. Kachelrieß,[1] A. Neronov,[2] and D. V. Semikoz[3]

PHYSICAL REVIEW LETTERS **125,** 031101 (2020)

Supernova-Produced ^{53}Mn on Earth

G. Korschinek,[1,*] T. Faestermann,[1] M. Poutivtsev,[1,†] A. Arazi,[2,3] K. Knie,[1,‡] G. Rugel,[1,4] and A. Wallner[1,4]

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Science

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W. R. Binns,[1*] I
R. A. Mewaldt,

ARTICLE

Received 30 Mar 2014 | Accepted 26 Nov 2014 | Published 20 Jan 2015 DOI: 10.1038/ncomms6956 OPEN

Abundance of live ^{244}Pu in deep-sea reservoirs on Earth points to rarity of actinide nucleosynthesis

A. Wallner[1,2], T. Faestermann[3], J. Feige[2], C. Feldstein[4], K. Knie[3,5], G. Korschinek[3], W. Kutschera[2], A. Ofan[4], M. Paul[4], F. Quinto[2,†], G. Rugel[3,†] & P. Steier[2]

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Science RESEARCH ARTICLES

THE ASTROPHYSICAL JOURNAL, 827:48 (17pp), 2016 August 10 doi:10.3847/0004-637X/827/1/48
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RADIOACTIVE IRON RAIN: TRANSPORTING ^{60}Fe IN SUPERNOVA DUST TO THE OCEAN FLOOR

BRIAN J. FRY[1], BRIAN D. FIELDS[1], AND JOHN R. ELLIS[2]

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **498,** 899–917 (2020) doi:10.1093/mnras/stz2629
Advance Access publication 2019 September 23

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Related Studies

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Science RESEARCH ARTICLES

The Astrophysical Journal, 840:105 (9pp), 2017 May 10 https://doi.org/10.3847/1538-4357/aa6c57

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A Supernova at 50 pc: Effects on the Earth's Atmosphere and Biota

A. L Melott[1], B. C. Thomas[2], M. Kachelrieß[3], D. V. Semikoz[4,5], and A. C. Overholt[6]

Monthly Notices of the Royal Astronomical Society

MNRAS 498, 899–917 (2020) doi:10.1093/mnras/stz2629
Advance Access publication 2019 September 23

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The Astrophysical Journal, 827:48 (17pp), 2016 August 10 doi:10.3847/0004-637X/827/1/48

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RADIOACTIVE IRON RAIN: TRANSPORTING ^{60}Fe IN SUPERNOVA DUST TO THE OCEAN FLOOR

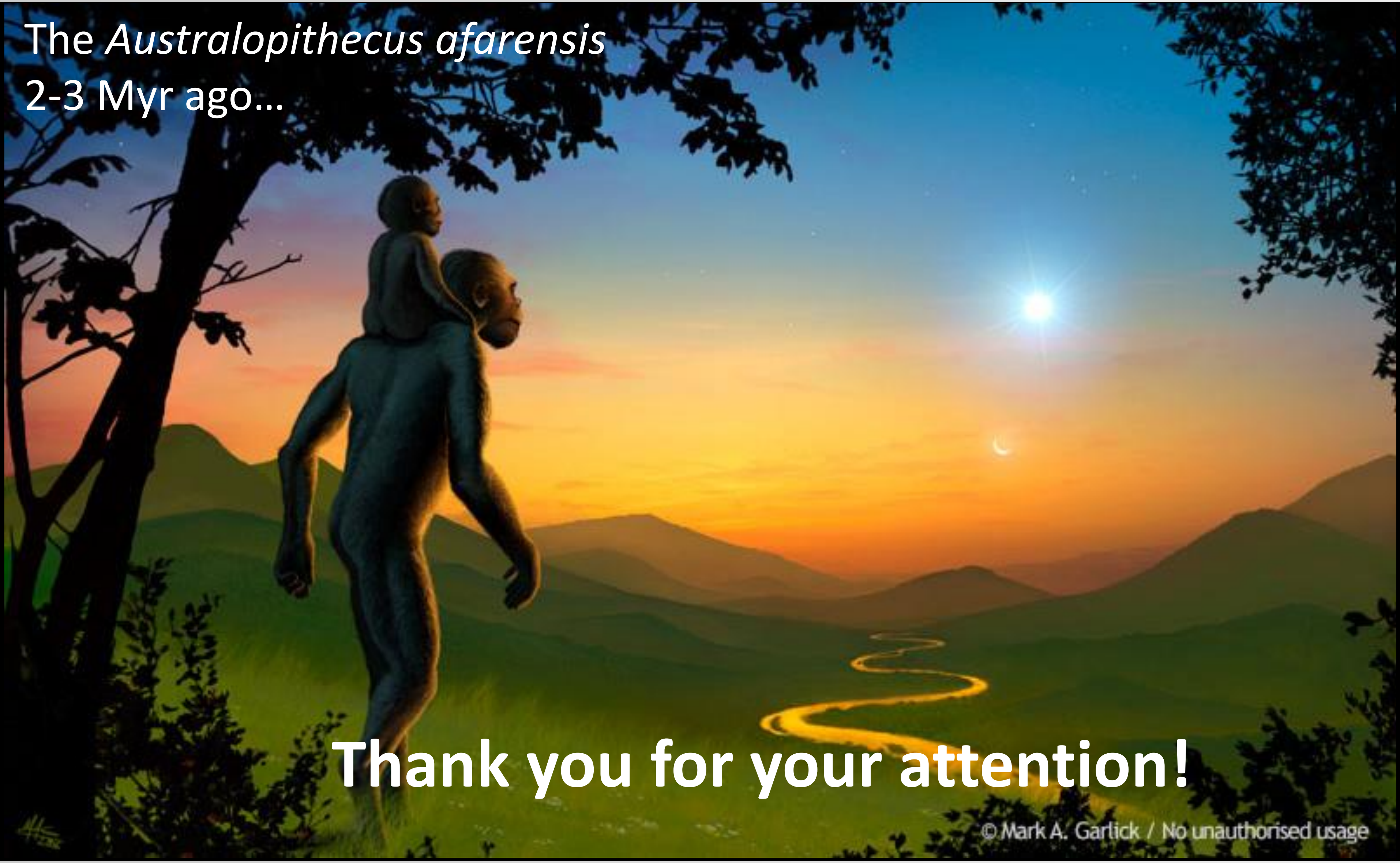
Brian J. Fry[1], Brian D. Fields[1], and John R. Ellis[2]

Conclusions

Daily Journalist/Scientific American

Conclusions

The *Australopithecus afarensis*
2-3 Myr ago…



Thank you for your attention!