The Abundance of ^{60}Fe in the Early Solar System

Reto Trappitsch

Patrick Boehnke, Thomas Stephan, Myriam Telus, Michael R. Savina, Olivia Pardo, Andrew M. Davis, Nicolas Dauphas, Gary R. Huss, and Michael J. Pellin

Lawrence Livermore National Laboratory

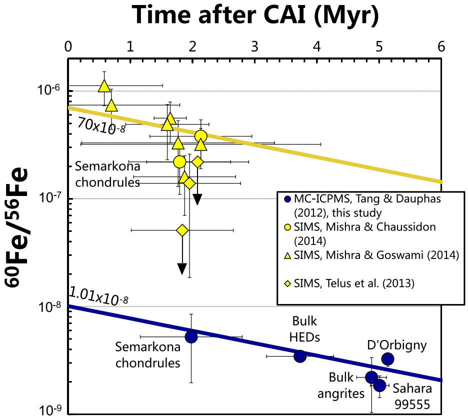
June 28, 2018

LLNL-PRES-753264

^{60}Fe abundance in the early Solar System ($T_{1/2} = 2.6$ Myr)

- ^{60}Fe/^{56}Fe initial abundance varies depending on measurement technique
- Bulk measurements:
  "Low" value of $\sim 10^{-8}$
- In situ secondary ion mass spectrometry (SIMS):
  "High" value, up to $\sim 10^{-6}$
- High $\rightarrow$ "Smoking gun" for supernova injection
- Low $\rightarrow$ Galactic background
  - Require an independent ^{26}Al source to explain its early Solar System abundance

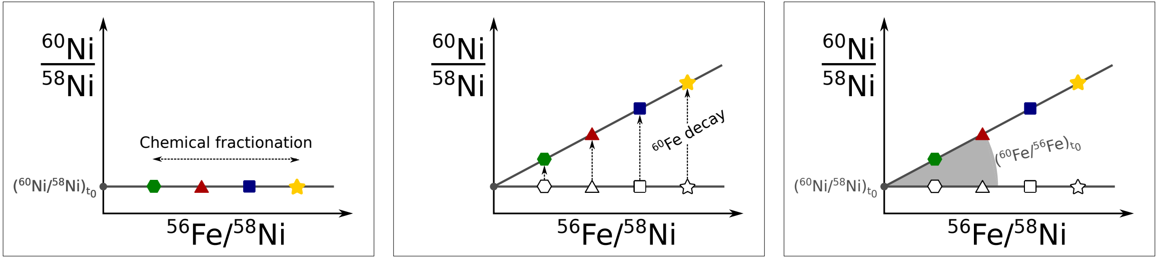
Did a supernova contribute the short-lived radionuclides to the early Solar System?



Analyses of various early Solar System samples

Tang and Dauphas (2015)

Isochron diagrams to determine the initial ^{60}Fe abundance



- Life ^{60}Fe gets incorporated into condensed early Solar System phases
- Today: All ^{60}Fe has decayed and is measured as excess ^{60}Ni
- ^{60}Ni excess depends on materials Fe/Ni elemental ratio
- Measure slope of isochron's linear correlation:

$$\frac{^{60}\mathrm{Ni}}{^{58}\mathrm{Ni}} = \frac{\mathbf{^{60}Fe}}{\mathbf{^{56}Fe}} \cdot \frac{^{56}\mathrm{Fe}}{^{58}\mathrm{Ni}} + \left(\frac{^{60}\mathrm{Ni}}{^{58}\mathrm{Ni}}\right)_0$$

The SIMS problem: Isobaric interferences & low abundance

p										
30	^{58}Zn 84 ms	^{59}Zn 182 ms	^{60}Zn 2.38 min	^{61}Zn 89.1 s	^{62}Zn 9.193 h	^{63}Zn 38.1 min	^{64}Zn 49.17% 59±5mb	^{65}Zn 243.93 d *162±27 mb*	^{66}Zn 27.73% 34±3mb	^{67}Zn 4.04% 153±15mb
29	^{57}Cu 196.3 ms	^{58}Cu 3.204 s	^{59}Cu 81.5 s	^{60}Cu 23.7 min	^{61}Cu 3.339 h	^{62}Cu 9.67 min	^{63}Cu 69.174% 60.1±6.2mb	^{64}Cu 12.701 h *262±66mb*	^{65}Cu 30.826% 31.2±1.7mb	^{66}Cu 5.120 min
28	^{56}Ni 6.075 d *8±2mb*	^{57}Ni 35.60 h *71±18mb*	^{58}Ni 68.0769% 34.1±1.5mb	^{59}Ni 76 ky *58±12mb*	^{60}Ni 26.2231% 26.8±1.6mb	^{61}Ni 1.1399% 95.1±9.5mb	^{62}Ni 3.6345% 22.2±1.3mb	^{63}Ni 73.2 y 62.7±7.7mb	^{64}Ni 0.9256% 7.7±0.3mb	^{65}Ni 2.5175 h
27	^{55}Co 17.53 h	^{56}Co 77.236 d *145±36mb*	^{57}Co 271.74 d *180±45mb*	^{58}Co 70.86 d *285±71mb*	^{59}Co 100% 43.2±1.9mb	^{60}Co 5.271 y *253±63mb*	^{61}Co 10.50 min	^{62}Co 1.649 h	^{63}Co 1.54 min	^{64}Co 193.28 ms
26	^{54}Fe 5.845% 28.4±1.2mb	^{55}Fe 2.744 y *91±24mb*	^{56}Fe 91.754% 11.7±1.2mb	^{57}Fe 2.1191% 26.8±4.4mb	^{58}Fe 0.2819% 14.3±0.9mb	^{59}Fe 44.495 d 23.6±5.2mb	^{60}Fe 2.62 My 5.6±0.8mb	^{61}Fe 5.98 min	^{62}Fe 68 s	^{63}Fe 8.51 min
25	^{53}Mn 3.74 My *132±33mb*	^{54}Mn 312.20 d *244±61mb*	^{55}Mn 100% 32.7±3.1mb	^{56}Mn 2.5789 h	^{57}Mn 85.4 s	^{58}Mn 3.0 s	^{59}Mn 4.59 s	^{60}Mn 0.28 s	^{61}Mn 0.709 s	^{62}Mn 92 ms
n	28	29	30	31	32	33	34	35	36	37

The SIMS problem: Isobaric interferences & low abundance

p \ n	28	29	30	31	32	33	34	35	36	37
30	^{58}Zn 84 ms	^{59}Zn 182 ms	^{60}Zn 2.38 min	^{61}Zn 89.1 s	^{62}Zn 9.193 h	^{63}Zn 38.1 min	^{64}Zn 49.17% 59±5mb	^{65}Zn 243.93 d *162±27 mb*	^{66}Zn 27.73% 34±3mb	^{67}Zn 4.04% 153±15mb
29	^{57}Cu 196.3 ms	^{58}Cu 3.204 s	^{59}Cu 81.5 s	^{60}Cu 23.7 min	^{61}Cu 3.339 h	^{62}Cu 9.67 min	^{63}Cu 69.174% 60.1±6.2mb	^{64}Cu 12.701 h *262±66mb*	^{65}Cu 30.826% 31.2±1.7mb	^{66}Cu 5.120 min
28	^{56}Ni 6.075 d *8±2mb*	^{57}Ni 35.60 h *71±18mb*	^{58}Ni 68.0769% 34.1±1.5mb	^{59}Ni *76 ky* *58±12mb*	^{60}Ni 26.2231% 26.8±1.6mb	^{61}Ni 1.1399% 95.1±9.5mb	^{62}Ni 3.6345% 22.2±1.3mb	^{63}Ni 73.2 y 62.7±7.7mb	^{64}Ni 0.9256% 7.7±0.3mb	^{65}Ni 2.5175 h
27	^{55}Co 17.53 h	^{56}Co 77.236 d *145±36mb*	^{57}Co 271.74 d *180±45mb*	^{58}Co 70.86 d *285±71mb*	^{59}Co 100% 43.2±1.9mb	^{60}Co 5.271 y *253±63mb*	^{61}Co 10.50 min	^{62}Co 1.649 h	^{63}Co 1.54 min	^{64}Co 193.28 ms
26	^{54}Fe 5.845% 28.4±1.2mb	^{55}Fe 2.744 y *91±24mb*	^{56}Fe 91.754% 11.7±1.2mb	^{57}Fe 2.1191% 26.8±4.4mb	^{58}Fe 0.2819% 14.3±0.9mb	^{59}Fe 44.495 d 23.6±5.2mb	^{60}Fe 2.62 My 5.6±0.8mb	^{61}Fe 5.98 min	^{62}Fe 68 s	^{63}Fe 8.51 min
25	^{53}Mn 3.74 My *132±33mb*	^{54}Mn 312.20 d *244±61mb*	^{55}Mn 100% 32.7±3.1mb	^{56}Mn 2.5789 h	^{57}Mn 85.4 s	^{58}Mn 3.0 s	^{59}Mn 4.59 s	^{60}Mn 0.28 s	^{61}Mn 0.709 s	^{62}Mn 92 ms

The SIMS problem: Isobaric interferences & low abundance

p \ n	28	29	30	31	32	33	34	35	36	37
30	^{58}Zn 84 ms	^{59}Zn 182 ms	^{60}Zn 2.38 min	^{61}Zn 89.1 s	^{62}Zn 9.193 h	^{63}Zn 38.1 min	^{64}Zn 49.17% 59±5mb	^{65}Zn 243.93 d *162±27 mb*	^{66}Zn 27.73% 34±3mb	^{67}Zn 4.04% 153±15mb
29	^{57}Cu 196.3 ms	^{58}Cu 3.204 s	^{59}Cu 81.5 s	^{60}Cu 23.7 min	^{61}Cu 3.339 h	^{62}Cu 9.67 min	^{63}Cu 69.174% 60.1±6.2mb	^{64}Cu 12.701 h *262±66mb*	^{65}Cu 30.826% 31.2±1.7mb	^{66}Cu 5.120 min
28	^{56}Ni 6.075 d *8±2mb*	^{57}Ni 35.60 h *71±18mb*	^{58}Ni 68.0769% 34.1±1.5mb	^{59}Ni 76 ky *58±12mb*	^{60}Ni 26.2231% 26.8±1.6mb	^{61}Ni 1.1399% 95.1±9.5mb	^{62}Ni 3.6345% 22.2±1.3mb	^{63}Ni 73.2 y 62.7±7.7mb	^{64}Ni 0.9256% 7.7±0.3mb	^{65}Ni 2.5175 h
27	^{55}Co 17.53 h	^{56}Co 77.236 d *145±36mb*	^{57}Co 271.74 d *180±45mb*	^{58}Co 70.86 d *285±71mb*	^{59}Co 100% 43.2±1.9mb	^{60}Co 5.271 y *253±63mb*	^{61}Co 10.50 min	^{62}Co 1.649 h	^{63}Co 1.54 min	^{64}Co 193.28 ms
26	^{54}Fe 5.845% 28.4±1.2mb	^{55}Fe 2.744 y *91±24mb*	^{56}Fe 91.754% 11.7±1.2mb	^{57}Fe 2.1191% 26.8±4.4mb	^{58}Fe 0.2819% 14.3±0.9mb	^{59}Fe 44.495 d 23.6±5.2mb	^{60}Fe 2.62 My 5.6±0.8mb	^{61}Fe 5.98 min	^{62}Fe 68 s	^{63}Fe 8.51 min
25	^{53}Mn 3.74 My *132±33mb*	^{54}Mn 312.20 d *244±61mb*	^{55}Mn 100% 32.7±3.1mb	^{56}Mn 2.5789 h	^{57}Mn 85.4 s	^{58}Mn 3.0 s	^{59}Mn 4.59 s	^{60}Mn 0.28 s	^{61}Mn 0.709 s	^{62}Mn 92 ms

Remeasure a previously analyzed sample

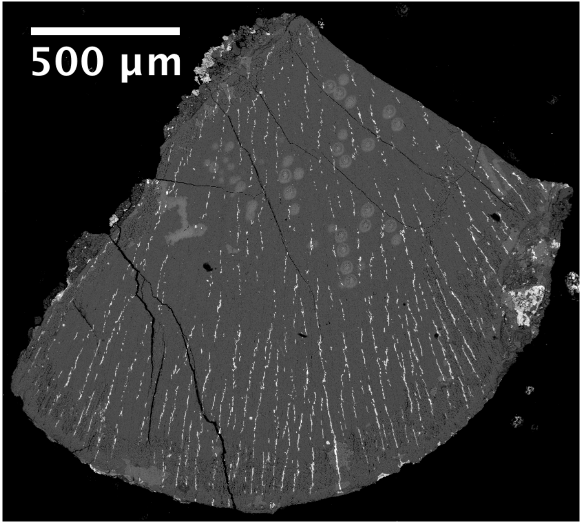
- Semarkona chondrule DAP1:
  A meteorite inclusion, which formed
  $\sim 2\,\mathrm{Myr}$ after Solar System

Previous SIMS measurements

- Can only measure $^{60,61,62}Ni$
- Evaluation revised multiple times

Our new in situ study

- New analyses by resonance ionization mass spectrometry (RIMS)
- Much smaller spot size
- No isobaric interferences
  →measure all Ni isotopes



Remeasure a previously analyzed sample

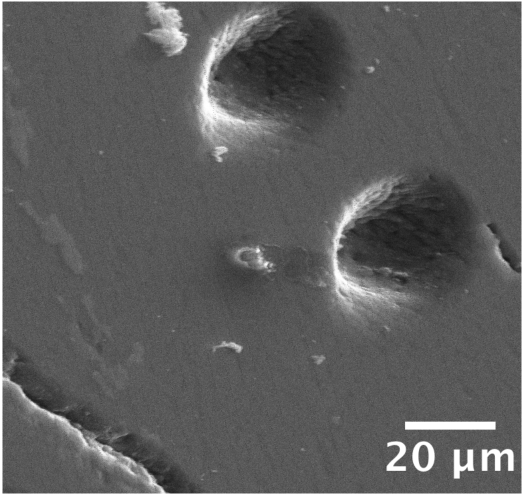
- Semarkona chondrule DAP1:
  A meteorite inclusion, which formed
  ~ 2 Myr after Solar System

Previous SIMS measurements

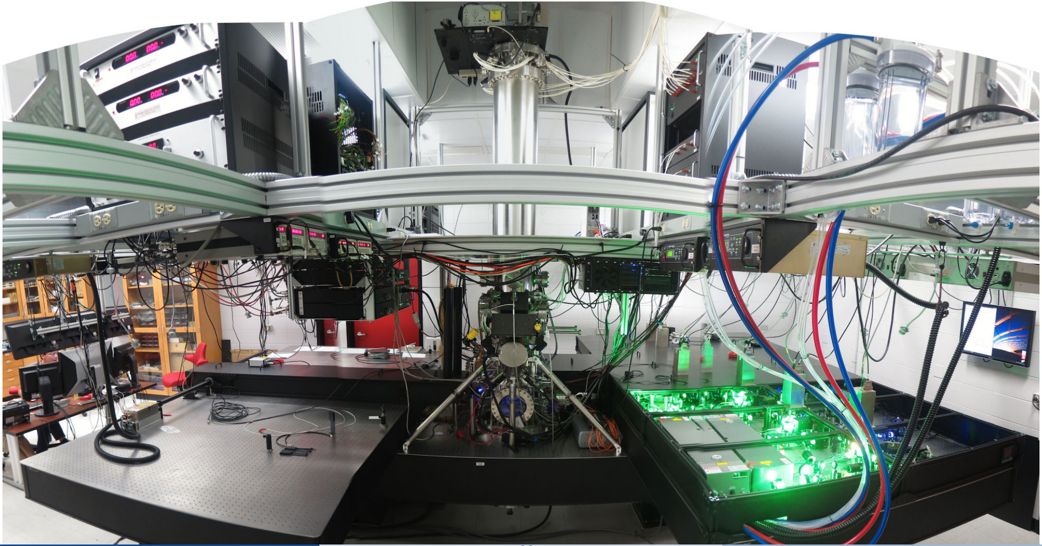
- Can only measure ^{60,61,62}Ni
- Evaluation revised multiple times

Our new in situ study

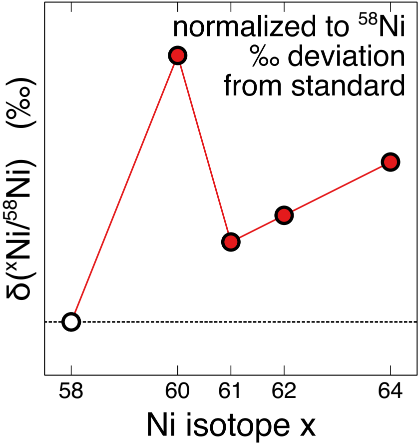
- New analyses by resonance ionization mass spectrometry (RIMS)
- Much smaller spot size
- No isobaric interferences
  $\rightarrow$measure all Ni isotopes

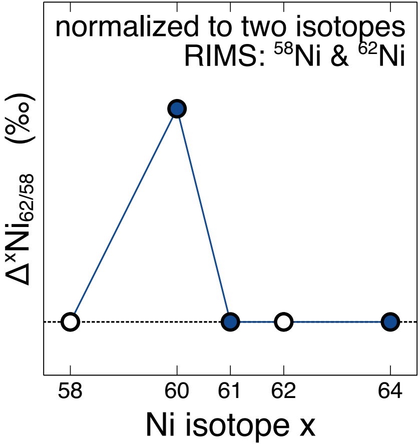


CHILI – A RIMS instrument up for the task



Dealing with mass-dependent fractionation



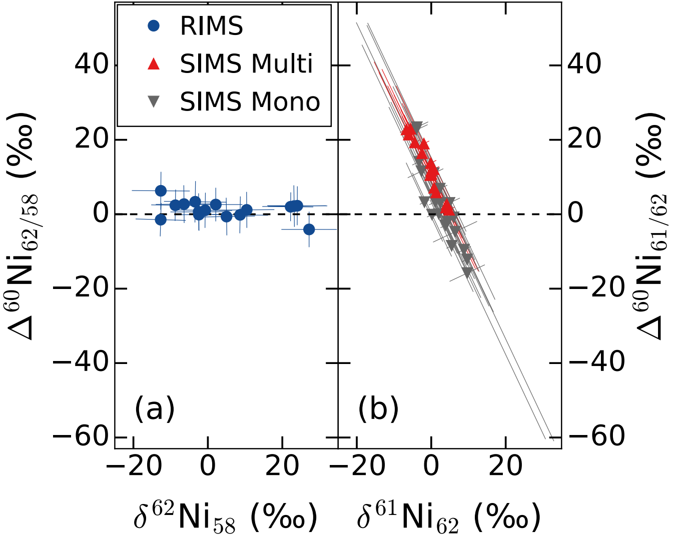


- Internal normalization removes mass-dependent fractionation
- Necessary to evaluate ^{60}Ni excess due to in situ ^{60}Fe decay

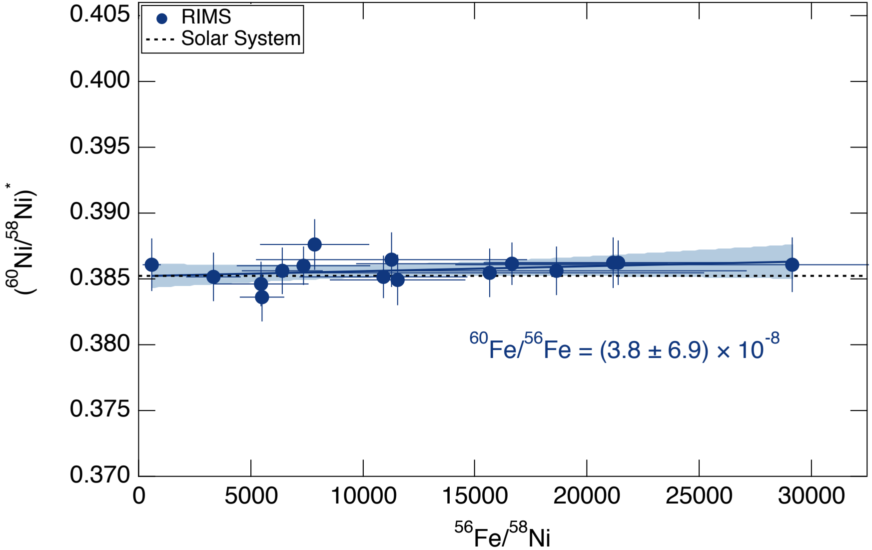
Precision in situ RIMS analysis of DAP1

- RIMS measurements:
  - Uncorrelated since normalized to abundant ^{58}Ni
  - No significant excesses in ^{60}Ni
- Re-evaluation of SIMS measurements:
  - Highly correlated since normalized to ^{61}Ni
  - No excesses in ^{60}Ni found
- Improper uncertainty treatment of SIMS data can result in isochron

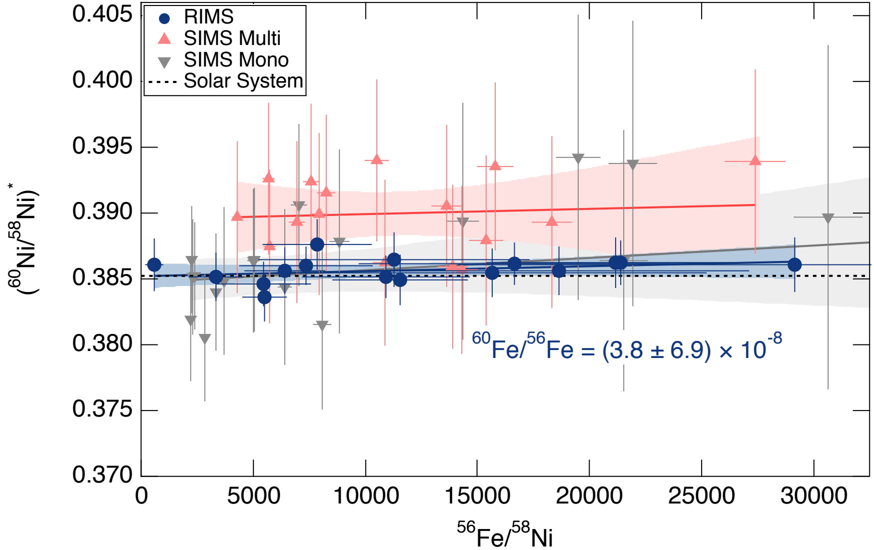
This Figure contains no information of elemental Fe/Ni ratio!



Isochron diagram shows no significant ^{60}Fe abundance



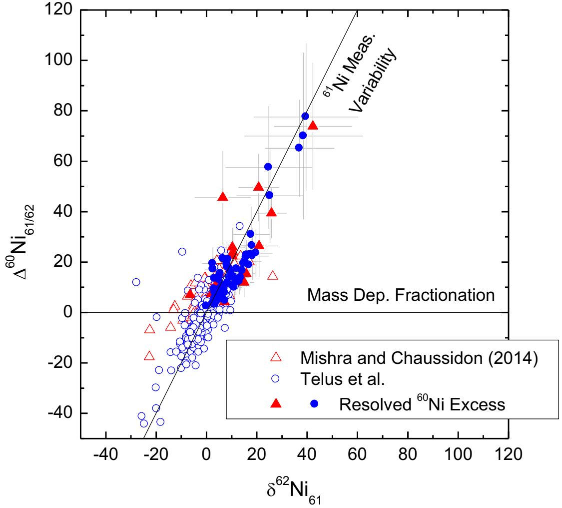
Isochron diagram shows no significant ^{60}Fe abundance



Re-evaluation of all Telus et al. (2018) measurements

- All SIMS measurements seem to be highly correlated with ^{61}Ni measurement variability
- ^{61}Ni is difficult to measure to its low abundance of only 1.1%
- Re-evaluate data from Telus et al. (2018):
  - Enough detail for re-evaluation
  - Reported uncertainties are too low
- Monte Carlo evaluation shows measurements are highly correlated
- 5.4% of measurements with excess ^{60}Ni

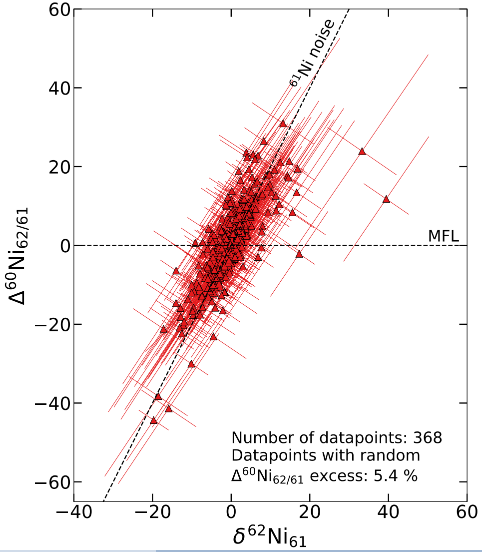
Discovered ^{60}Fe excesses are consistent with statistical noise



Re-evaluation of all Telus et al. (2018) measurements

- All SIMS measurements seem to be highly correlated with ^{61}Ni measurement variability
- ^{61}Ni is difficult to measure to its low abundance of only 1.1%
- Re-evaluate data from Telus et al. (2018):
  - Enough detail for re-evaluation
  - Reported uncertainties are too low
- Monte Carlo evaluation shows measurements are highly correlated
- 5.4% of measurements with excess ^{60}Ni

Discovered ^{60}Fe excesses are consistent with statistical noise

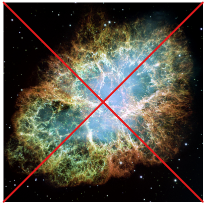


Low $^{60}Fe/^{56}Fe$ in early Solar System excludes SN origin

- ^{60}Fe abundance consistent with galactic background & bulk measurements (Tang and Dauphas, 2015)
- RIMS measurements can avoid measurement issues by analyzing ^{58}Ni
- ^{60}Ni excesses in **all** measurements by Telus et al. (2018) are consistent with statistical noise
- Contribution of ^{26}Al could be made by Wolf-Rayet star (e.g., Dwarkadas et al., 2017; Young 2014; Gounelle & Meynet 2012; Gaidos et al. 2009)

Wolf-Rayet star WR124

There is currently no proof that the $^{60}Fe/^{56}Fe$ in the early Solar System requires the injection of material from a core-collapse supernova.



No supernova injection required!

Lawrence Livermore National Laboratory