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

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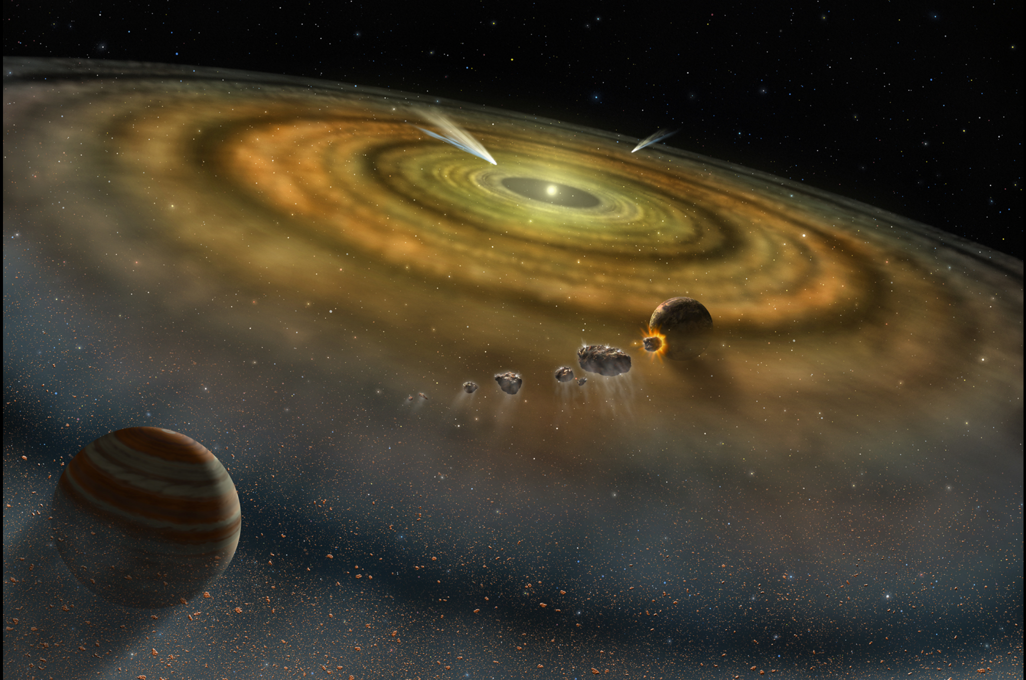
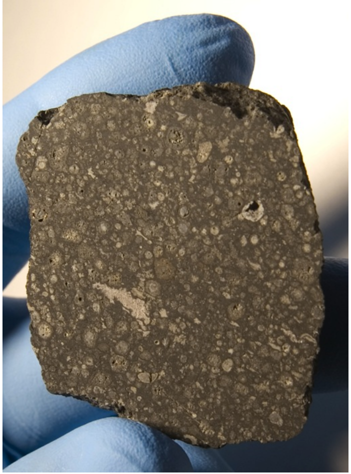
Hubble's Diamond in the Dust (Credit: ESA/Hubble & NASA)



Short-lived radionuclides were present in the solar nebula

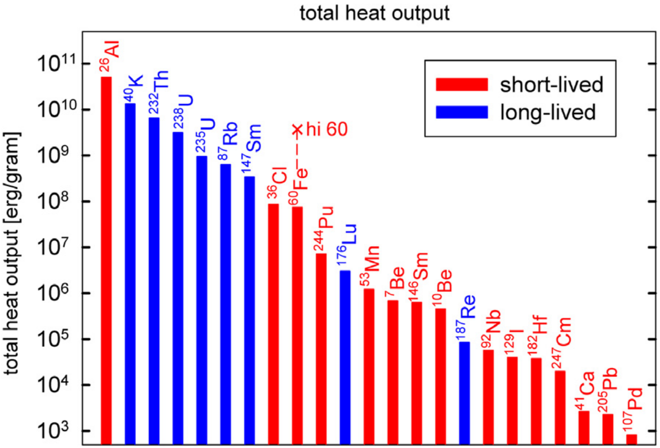
- Unaltered meteorites preserved the solar nebula composition
- The decay products of short-lived radionuclides (SLRs) can be found in meteorites and their inclusions, e.g., in chondrules
- Various SLRs were present in solar nebula
- Presence of some SLRs is consistent with galactic background
- Other SLRs, e.g., ^{26}Al, require injection event prior to Solar System formation
- Local production of some SLRs, e.g., ^{10}Be

SLRs help deciphering composition and timing of Solar System formation



SLRs are an important heat source in the early Solar System

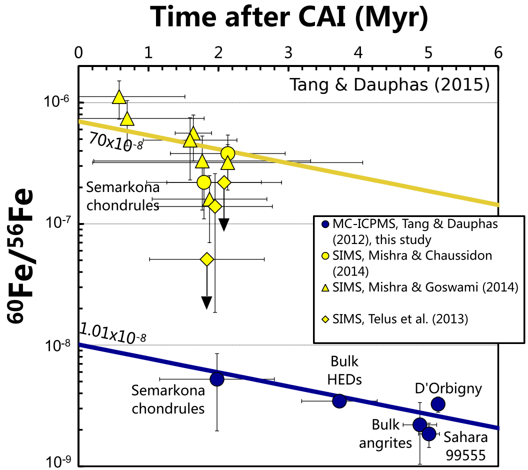
- SLR decay produces heat in the early solids in the Solar System
- Leads to melting and subsequent differentation of early, large objects
- ^{26}Al is the most important SLR heat source
  $\rightarrow$ Homogenous in solar nebula
- The importance of ^{60}Fe depends on its initial abundance



Lugaro et al. (2018)

The so-far unsolved ^{60}Fe controversy (half-life: 2.6 Ma)

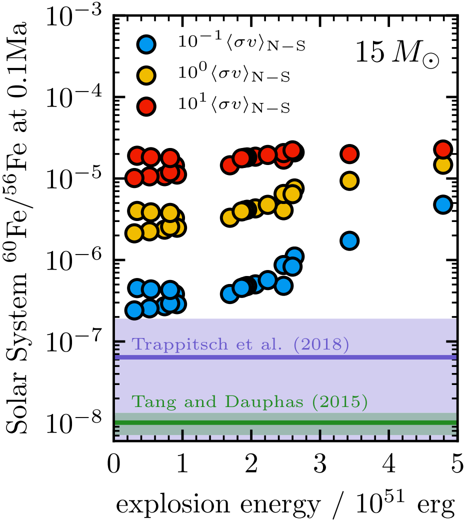
- Initial abundance of $^{60}Fe/^{56}Fe$ dependent on measurement technique
- Bulk studies find Solar System initial $^{60}Fe/^{56}Fe$ of $\sim 10^{-8}$ (Tang and Dauphas, 2015)
  $\rightarrow$ "Low" ^{60}Fe
  $\rightarrow$ Consistent with galactic background
- In-situ studies by secondary ion mass spectrometry (SIMS) show initial $^{60}Fe/^{56}Fe$ of up to $\sim 10^{-6}$ (Telus et al., 2018, Mishra and Chaussidon, 2014)
  $\rightarrow$ "High" ^{60}Fe
  $\rightarrow$ Co-injected with ^{26}Al by supernova



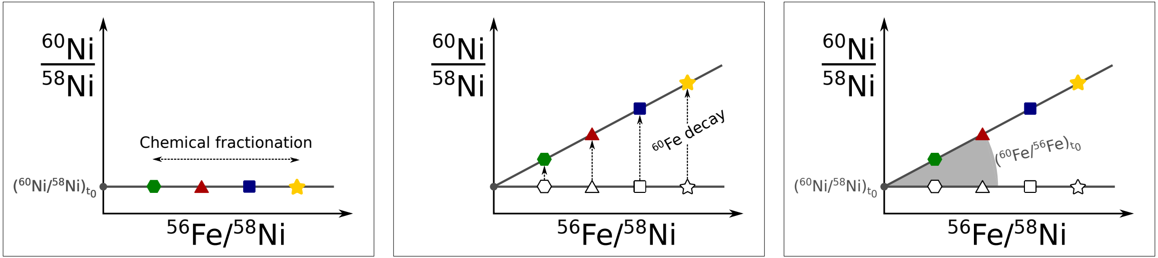
Supernovae co-injection of ^{26}Al and ^{60}Fe?

- "High" ^{60}Fe: Requires an additional source
- Co-injection of ^{26}Al and ^{60}Fe only consistent with high ^{60}Fe value
- "Low" ^{60}Fe: Consistent with galactic background
- Supernovae models by Jones et al. (2019)
  - Vary ^{59}Fe$(n,\gamma)^{60}$Fe reaction rate by factor of 10
  - Free decay-time from production to injection: 10^5 a
  - Injection of ^{26}Al fixed to solar nebula value

Supernova cannot be responsible for ^{26}Al injection if "low" ^{60}Fe value holds true

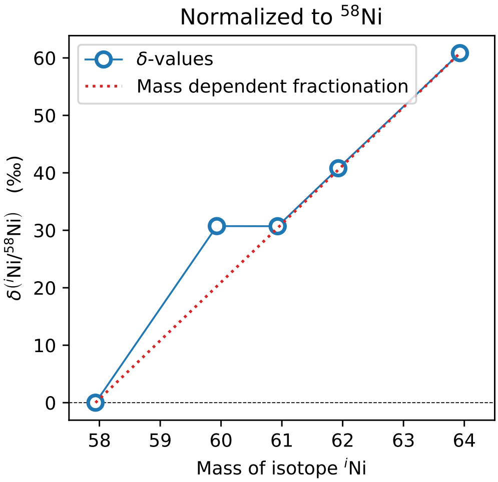


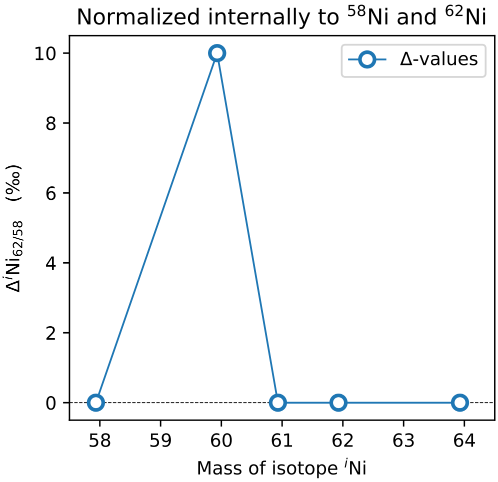
In-situ measurements of meteorite inclusions to decipher initial $^{60}Fe/^{56}Fe$



1. Different phases incorporate different amounts of iron and nickel during condensation
2. Any life ^{60}Fe decays over lifetime of the Solar System to ^{60}Ni
3. Slope in such an isochron diagram shows the initial $^{60}Fe/^{56}Fe$ ratio

Determining a sample's $^{60}Ni/^{58}Ni$ ratio is difficult





SIMS can effectively only measure three nickel isotopes

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
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Remeasuring a previously analyzed sample

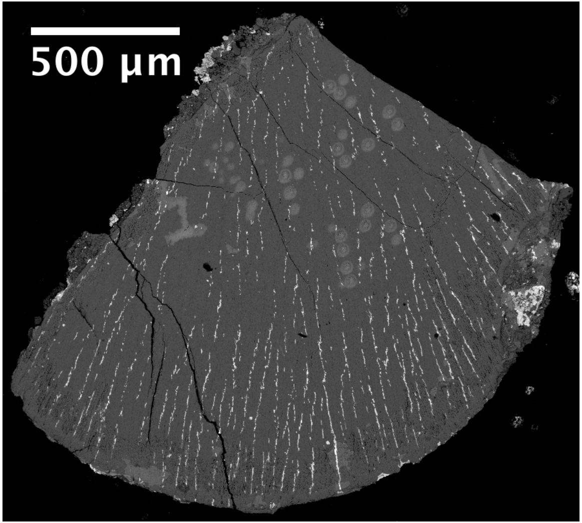
- Semarkona chondrule DAP1:
  A meteorite inclusion, which formed
  $\sim 2\,$Myr after Solar System

Previous SIMS measurements

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

RIMS study by Trappitsch et al. (2018)

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



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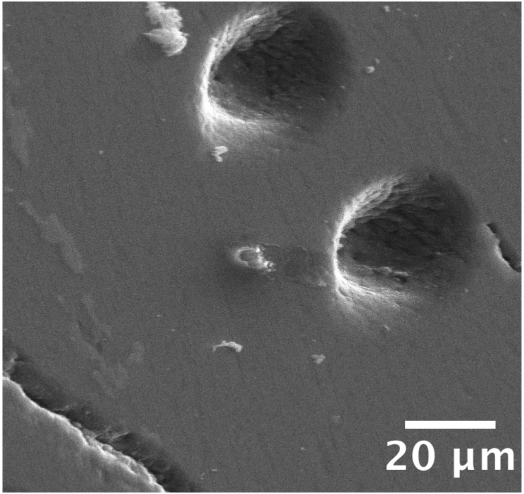
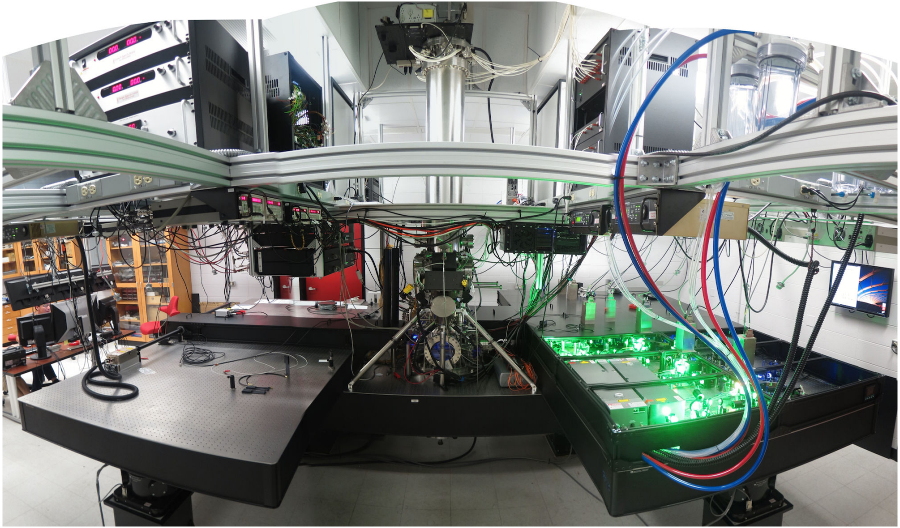


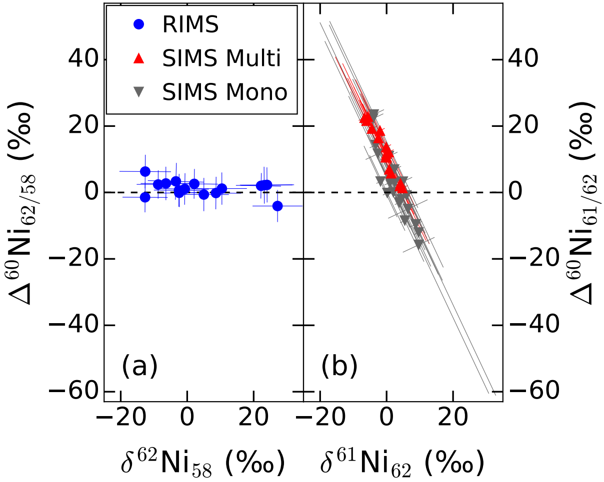
CHILI – A resonance ionization mass spectrometer for the task



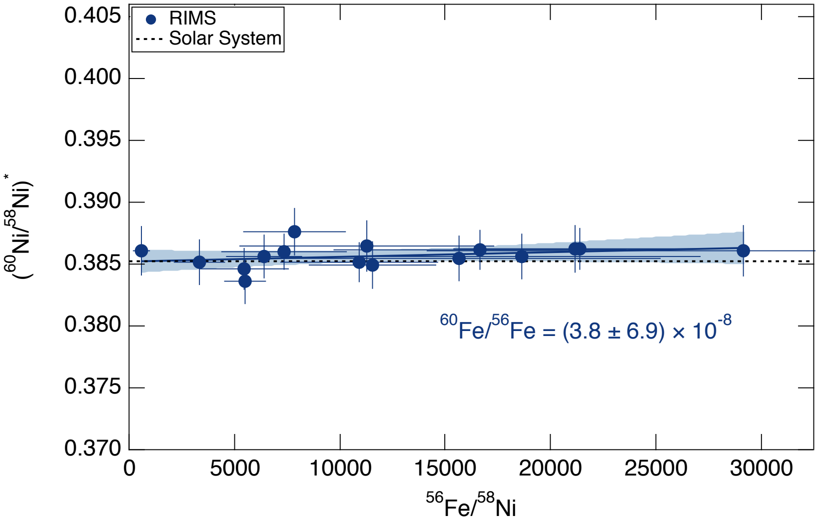
Precision in situ RIMS analysis of DAP-1 (Trappitsch et al., 2018)

- 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!



Re-analysis by RIMS showed no evidence for live ^{60}Fe in DAP-1 sample



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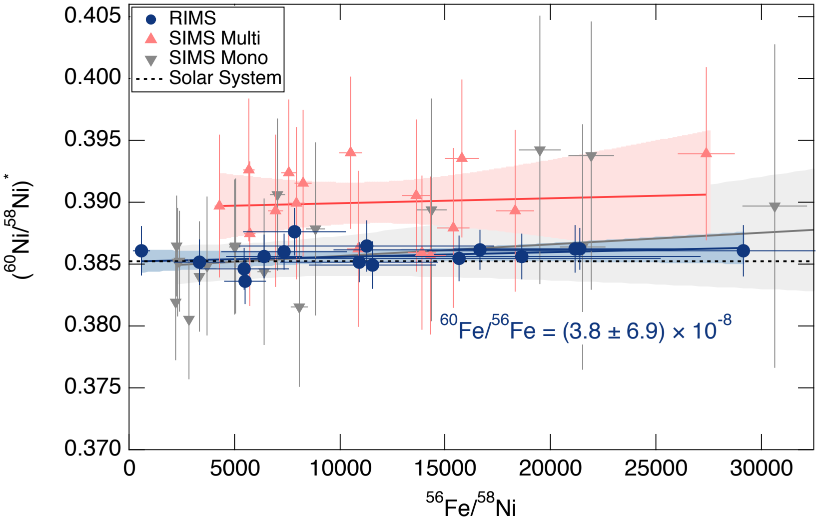
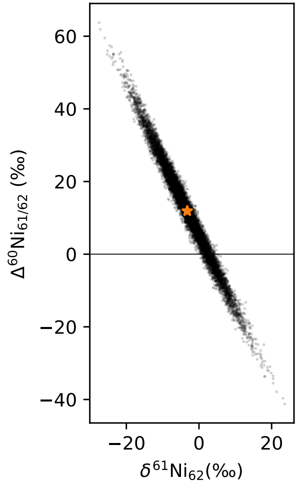


Re-evaluate all SIMS measurements by Telus et al. (2018)

- Telus et al. (2018) published raw data
- Go back to raw count rates and process evaluation using Monte Carlo error propagation
- Here: chondrule from the Krymka meteorite
- $\Delta^{60}Ni_{61/62}$ versus $\delta^{61}Ni_{62}$: Uncertainties strongly correlated
    - ^{61}Ni in nominator of both axes
    - Dashed line: ^{61}Ni variability
- Strong dependency on ^{61}Ni since it is the least abundant isotope
- Consideration of these correlations is crucial for evaluating the initial $^{60}Fe/^{56}Ni$



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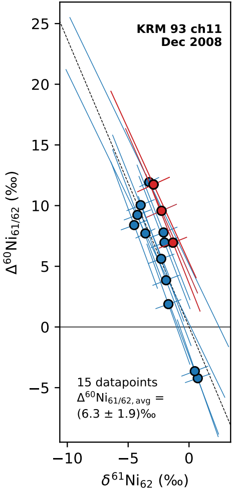
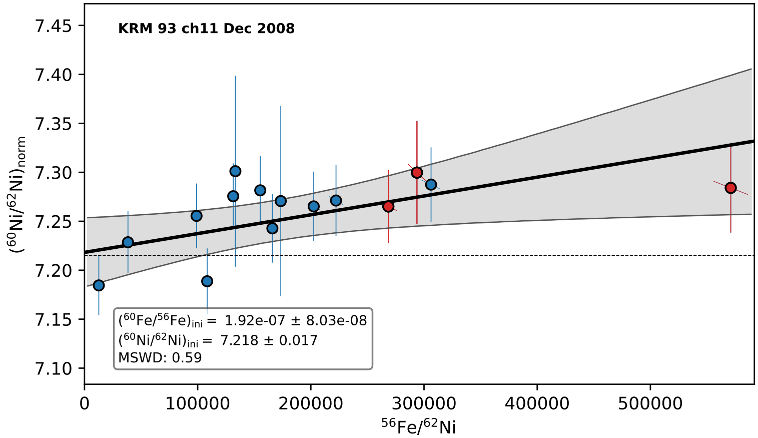


Re-evaluation shows no unambiguous proof of high ^{60}Fe

- Two out of 29 samples show an an initial $^{60}Fe/^{56}Fe > 2\sigma$ different from zero
- Both samples from Krymka
- Initial $^{60}Fe/^{56}Fe$:
  - Positive: 2.4σ
  - Negative: 2.1σ
- We need a statistically sound approach



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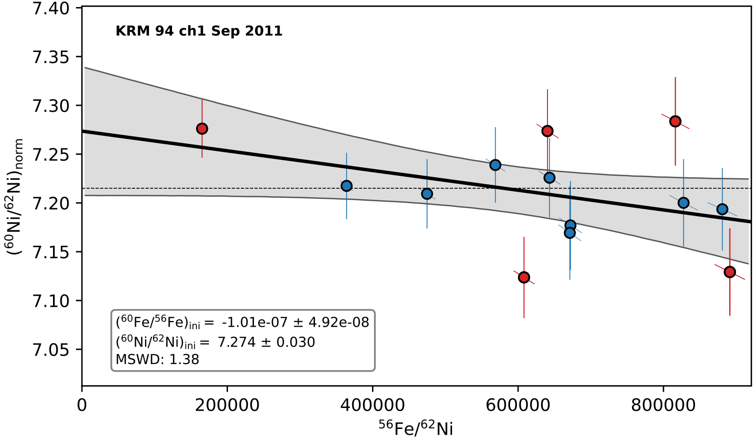
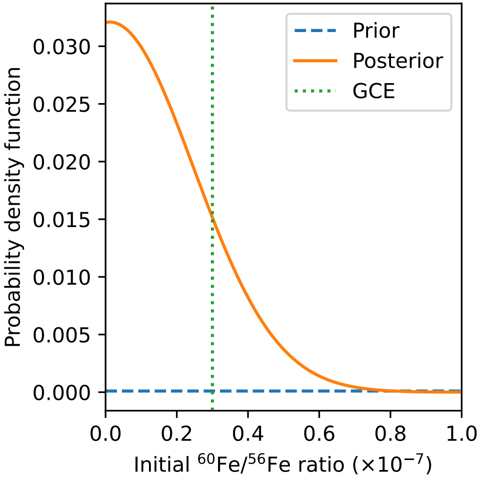


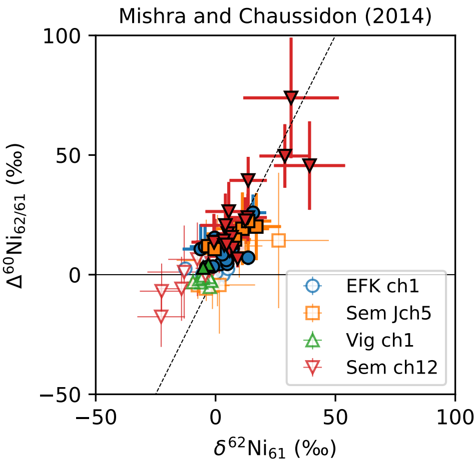
Bayes update for uniform prior using all SIMS measurements

- Assume uniform prior for initial ^{60}Fe/^{56}Fe between 0 and 10^{-5}
- Update with SIMS measurements
    - Gaussian likelihood given by calculated σ
    - Update with all 29 measurements
- Assuming that ^{60}Fe homogeneous in chondrule formation area
- Maximum probability of posterior distribution: $\rightarrow$ $^{60}\text{Fe}/^{56}\text{Fe} = 1.9 \times 10^{-8}$
- Total probability of posterior to be below galactic background: $> 78\%$



Data by Mishra et al.: Hint at the same ^{61}Ni variability effects

- Mishra et al.: No re-evaluation, raw data is lost (Mishra, pers. comm.)
- All measurements plot closely to the dashed ^{61}Ni variability line
- Remember: These plots should show random enhancements in $\Delta^{60}Ni_{61/62}$ since figures contain no information on Fe/Ni elemental ratio
- Mishra et al. (2016) uses unexplained "correction" for measurements
- Data likely suffer from the same effects as in Telus et al. (2018)



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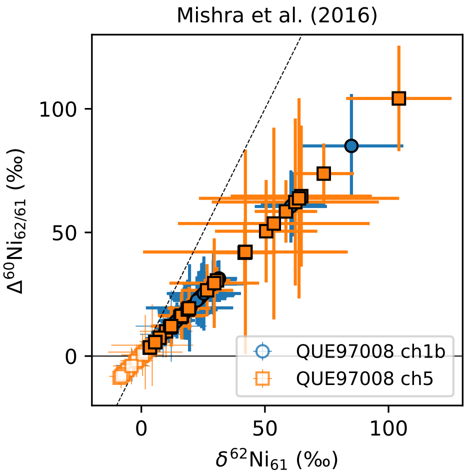

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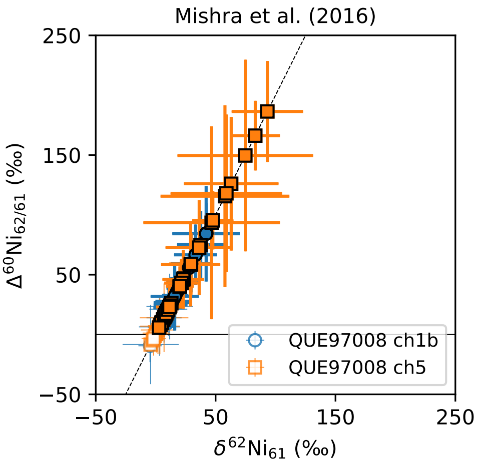
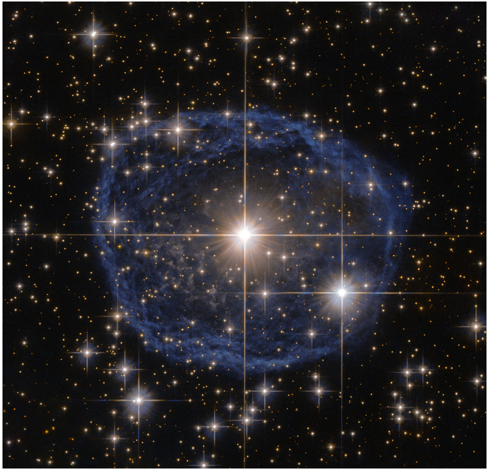


In-situ measurements show no clear proof of high ^{60}Fe in early Solar System

- In-situ meausrements by SIMS must accurately measure the minor isotope ^{61}Ni
- Re-evaluation of all data by Telus et al. (2018) shows no clear proof of high ^{60}Fe
- Previous claims of high ^{60}Fe based on erroneous uncertainty propagation
- ^{60}Fe cannot have been co-injected with ^{26}Al by supernova
- Alternative scenario:
  - ^{60}Fe agrees with galactic background
  - ^{26}Al originated in Wolf Rayet star (e.g., Dwarkadas et al., 2017)



Wolf Rayet star WR 31a, Credit: ESA/Hubble & NASA

Workshop on the Origin of the Isotopes

Astronomical Observations, Presolar Grains, and Nucleosynthetic Modeling

Sponsored by IReNA

Next week Tuesday and Thursday (asynchronous possible)

Discussion in dedicated Slack Workspace

With contributions by:

- Maria Bergemann
- Benoit Cote
- Camilla Hansen
- Erika Holmbeck
- Amanda Karakas
- Larry Nittler
- Marco Pignatari
- Thomas Stephan
- Francois Tissot

More information and registration at
`https://indico.frib.msu.edu/event/49/`

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