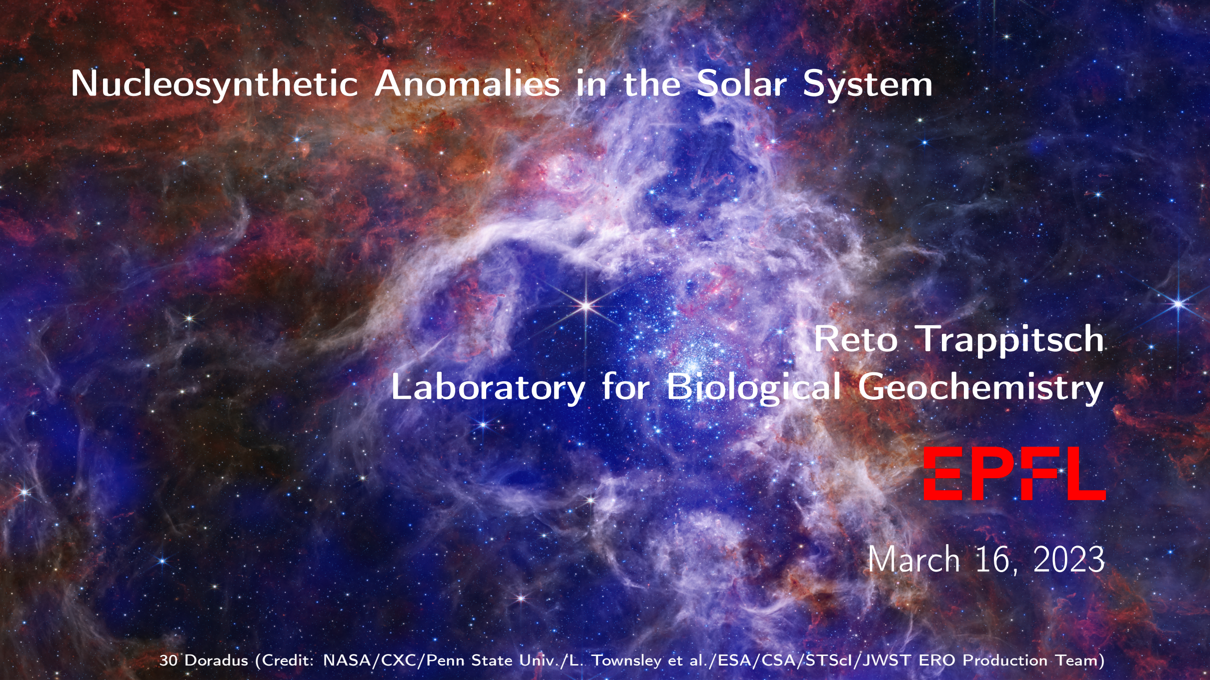


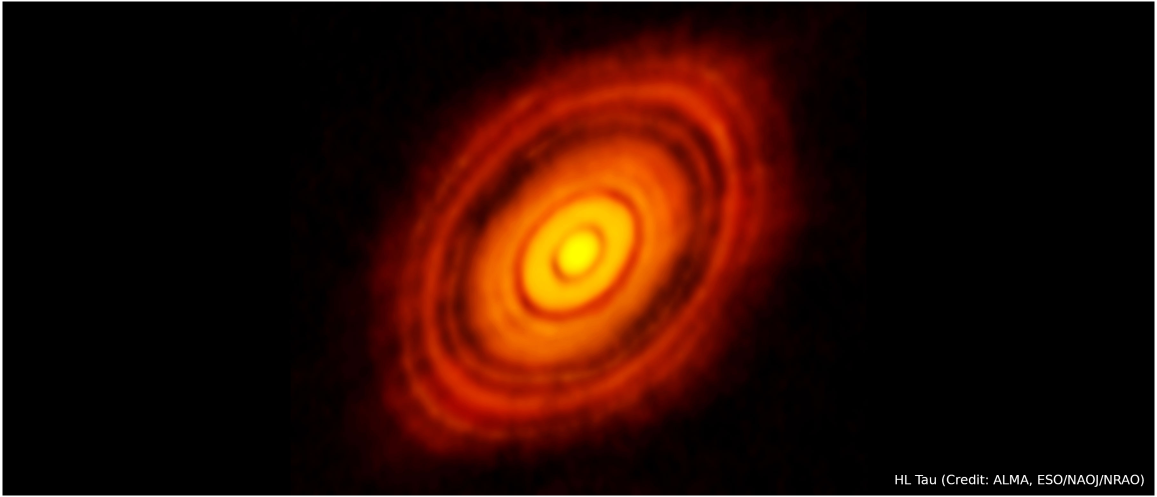
Nucleosynthetic Anomalies in the Solar System

Reto Trappitsch
Laboratory for Biological Geochemistry
EPFL

March 16, 2023

30 Doradus (Credit: NASA/CXC/Penn State Univ./L. Townsley et al./ESA/CSA/STScI/JWST ERO Production Team)

The Solar Nebula: A Turbulent Environment



HL Tau (Credit: ALMA, ESO/NAOJ/NRAO)

Falls and Finds: Where we get Meteorites from

Credit: Navicore, CC BY 3.0

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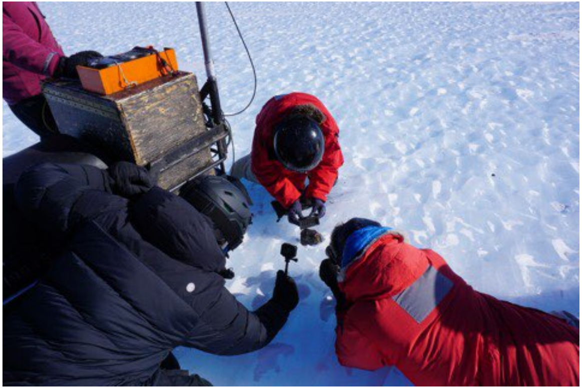
Credit: Navicore, CC BY 3.0

Courtesy: 2019/2020 ANSMET expedition

Falls and Finds: Where we get Meteorites from

Credit: Navicore, CC BY 3.0



Courtesy: 2019/2020 ANSMET expedition

Falls and Finds: Where we get Meteorites from

Credit: Navicore, CC BY 3.0

In Real Life. . .

The Field Museum

1

Meteorite Loan Allocation Request

Please complete the form below. Your request will be reviewed and you will be notified as soon as possible. All allocated specimens are subject to the attached Field Museum loan policy.

Date: August 29, 2018

Name:
Reto Trappitsch

Position:
Postdoctoral Researcher

Students please provide name, e-mail and phone number of supervisor, who will be ultimately responsible for the allocated sample:

Institution:
Lawrence Livermore National Laboratory

Postal Address:
7000 East Ave, L-231
Livermore, CA 94550

Telephone:
925-422-1680

E-mail:
trappitsch1@llnl.gov

Meteorite(s) requested:
List name, ME catalog number, minimum mass required and type for each requested specimen.

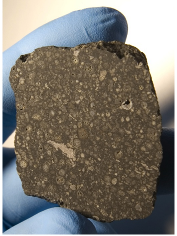
NWA 11115, 10 samples à 10mg each for He, Ne, Ar analyses.

The Field Museum, 1400 South Lake Shore Drive, Chicago, IL 60605-2496, USA
Please return completed form to prheck at fieldmuseum dot org

Credit: Philipp Heck, The Field Museum of Natural History, Chicago

Meteorites: The Poor Scientist's Space Probe

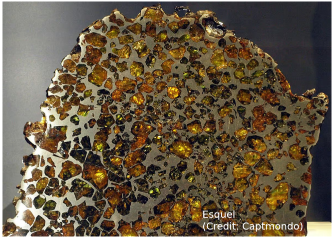
Undifferentiated



Orgeuil
(Credit: MNHN-Paris)

- Silicates and metals are still mixed
- Most primitive meteorites in the Solar System

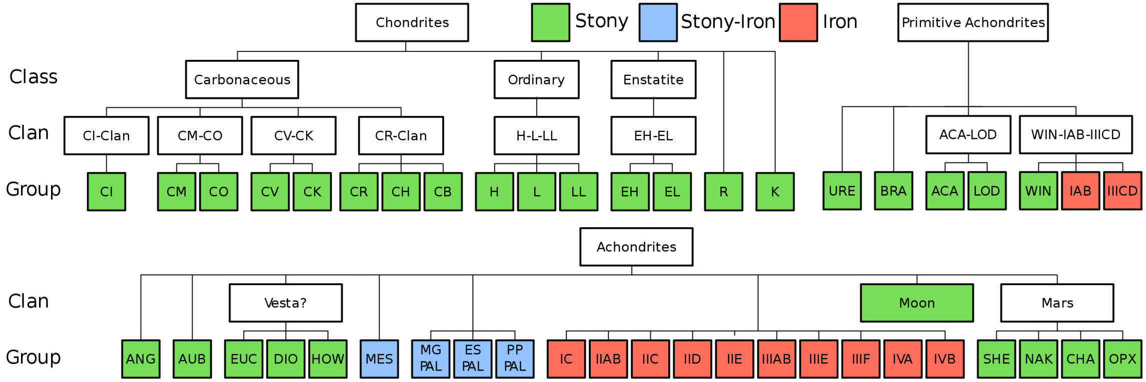
Differentiated



Esquel
(Credit: Captmondo)

- Heated due to radioactivity and/or impacts
- Highly altered: silicates and metals separated

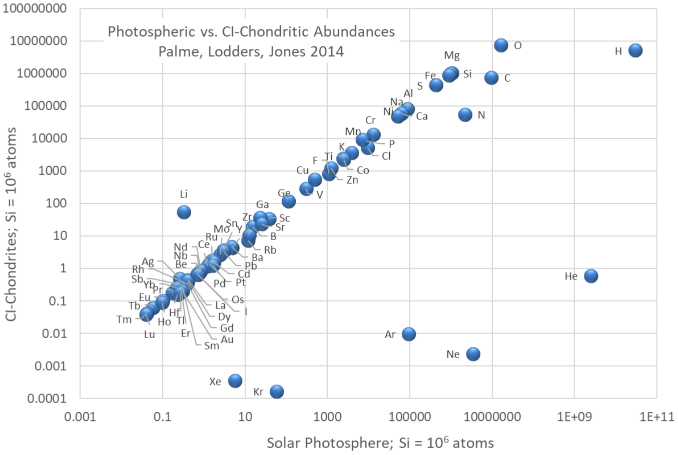
Meteorite Classification after Weisberg et al. (2006)



Credit: Tobias1984 via Wikipedia (CC BY-SA 3.0)

The Solar Composition: Meteorites versus the Sun

- Comparison of elemental abundances in CI chondrites and solar photosphere shows excellent agreement over 10 orders of magnitude
- Noble gases
  - Depleted in meteorites
  - Volatile gases
- H, C, N, O
  - Depleted in meteorites
  - Form highly volatile gases
- Li depleted in Sun
  → Andreas' talk on Tuesday



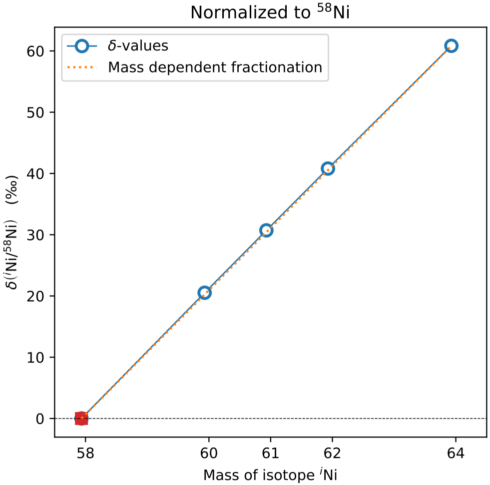
Lodders (2019)

How to Display Isotope Anomalies

- δ-notation $\delta^i X_j$ in ‰:

$$\delta\left(\frac{^i\mathrm{X}}{^j\mathrm{X}}\right) = \left[\frac{(^i\mathrm{X}/^j\mathrm{X})_{\mathrm{smp}}}{(^i\mathrm{X}/^j\mathrm{X})_\odot} - 1\right] \times 1000$$

  - Deviation from solar in ‰
  - Isotope ratio normalized to one isotope (here: ^{58}Ni)
- Mass-dependent fractionation
- Mass-independent fractionation
  - In-situ decay of short-lived radionuclide
  - Nucleosynthetic anomalies
- Internal normalization (Δ-notation)
  → remove mass-dependent fractionation



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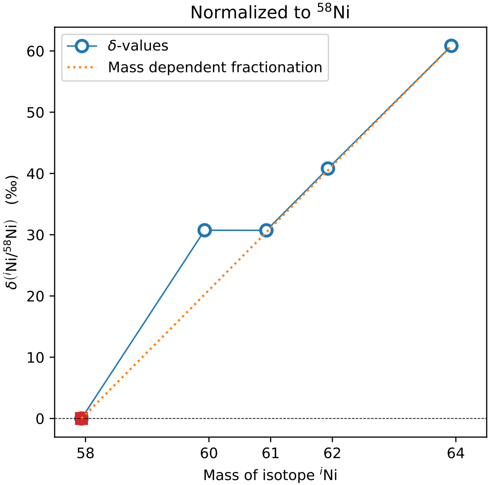

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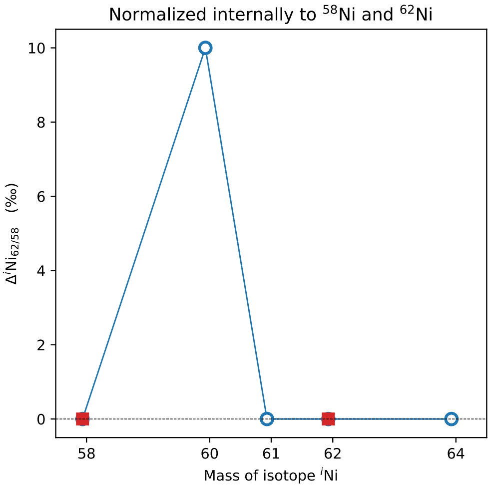
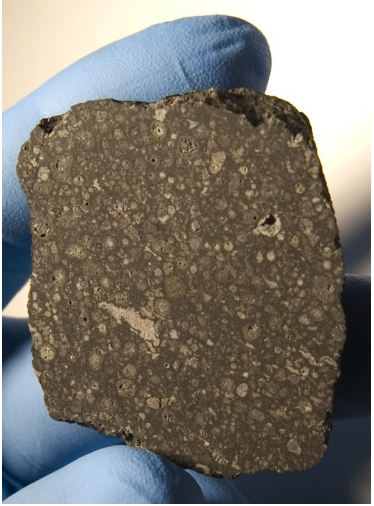


Oxygen Isotopes Reveal that the Solar System is Heterogeneous

- Solar nebula mixing: It was assumed the Solar System is homogeneous
- Mass-dependent fractionation: Evaporation/condensation
- Clayton et al. (1973): Oxygen isotope anomalies
    - Analyzed Allende calcium aluminum-rich refractory inclusions (CAIs)
    - Found enrichments in ^{16}O
    - Nuclear origin?
- Oxygen isotopes heterogeneity likely due to self-shielding of solar nebula
- Determine provenance of objects in Solar System



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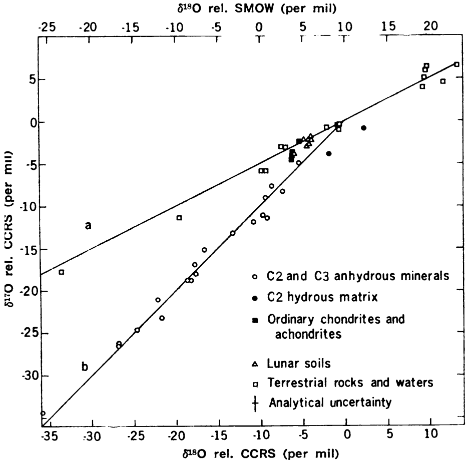

Clayton et al. (1973)

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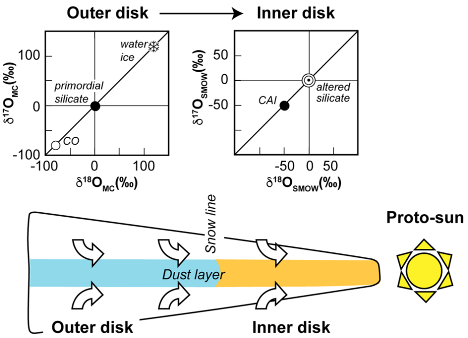

Ireland et al. (2020))

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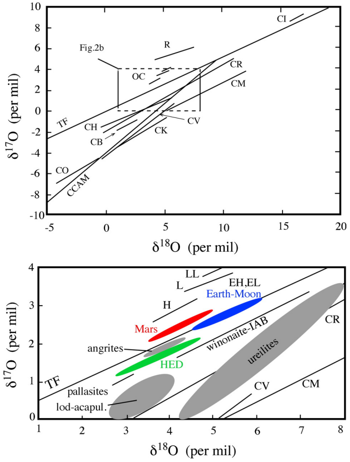
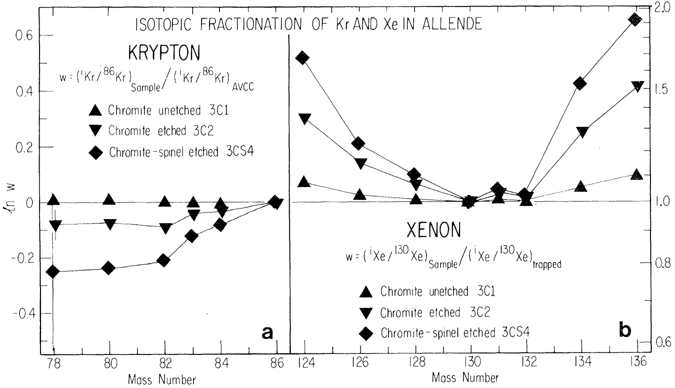


Righter et al. (2011)

The Discovery of Presolar Grains

- Anomalies in noble gases
- Xenon HL could not be explained by any Solar System processes: Enrichment in **H**eavy and **L**ight isotopes
- Isolation of carrier: Presolar nanodiamonds

Presolar nanodiamonds are so small that only one in 10^6 diamonds contains a single Xe atom



Lewis et al. (1975)

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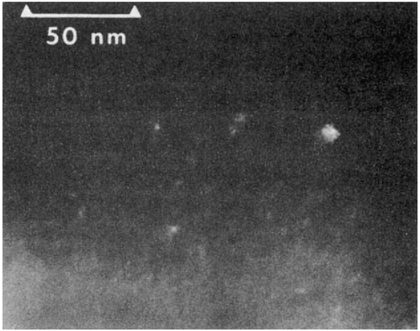
NATURE VOL. 326 12 MARCH 1987

LETTERS TO NATURE

Interstellar diamonds in meteorites

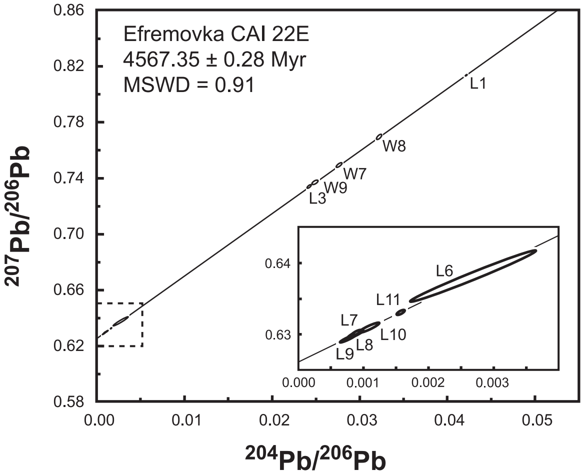
Roy S. Lewis*, Tang Ming*, John F. Wacker*‡, Edward Anders* & Eric Steel†



Pillars of Creation (Credit: NASA, ESA, CSA, STScI)

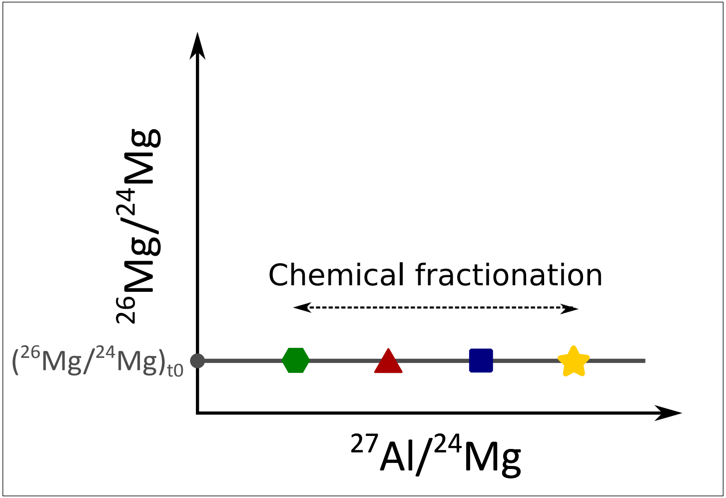
Interlude: The Age of the Solar System

- Two long-lived uranium isotopes:
  - ^{235}U: $T_{1/2} = 7.038 \times 10^8$ a $\rightarrow$ ^{206}Pb
  - ^{238}U: $T_{1/2} = 4.468 \times 10^9$ a $\rightarrow$ ^{207}Pb
- Calcium Aluminum-rich Refractory Inclusions (CAIs) incorporate U but minimal amounts of Pb
- These inclusions are also expected to condense early in Solar System
- Pb-Pb age reveals: **4.567 Ga**
- "Short-lived" radionuclides (SLRs) allow us to date events relative

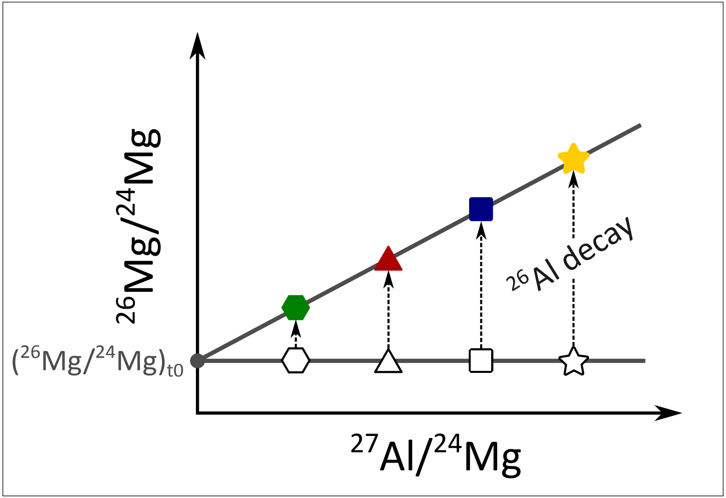


Connelly et al. (2012)

Timing in the Early Solar System: Measuring Isochrons



Timing in the Early Solar System: Measuring Isochrons



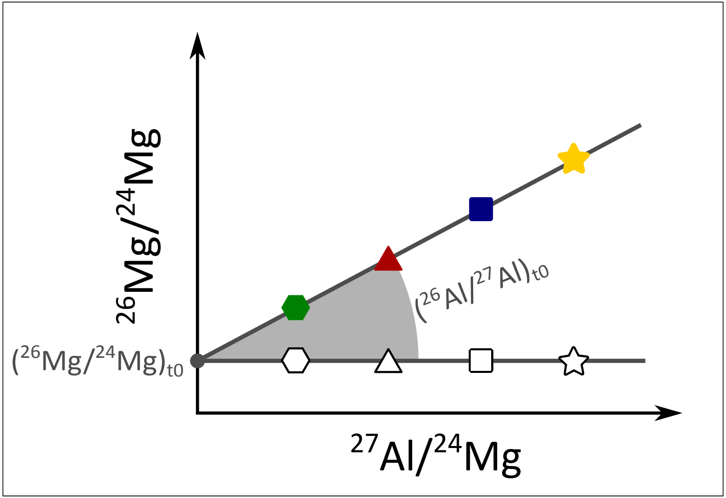
Timing in the Early Solar System: Measuring Isochrons

- A simple, linear regression!

$$\frac{^{26}\mathrm{Mg}}{^{24}\mathrm{Mg}} = \left.\frac{^{26}\mathrm{Al}}{^{27}\mathrm{Al}}\right|_{t_0} \cdot \frac{^{27}\mathrm{Al}}{^{24}\mathrm{Mg}} + \left.\frac{^{26}\mathrm{Mg}}{^{24}\mathrm{Mg}}\right|_{t_0}$$

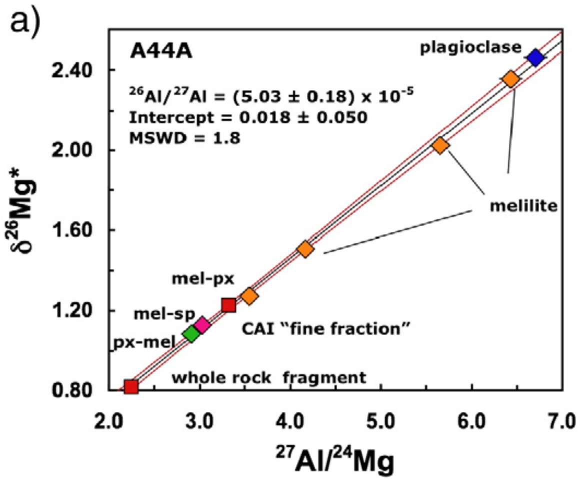
- Intercept: Sample's initial $\left.\frac{^{26}\mathrm{Mg}}{^{24}\mathrm{Mg}}\right|_{t_0}$
- Slope: Sample's initial $\left.\frac{^{26}\mathrm{Al}}{^{27}\mathrm{Al}}\right|_{t_0}$

Timing in the Early Solar System: Measuring Isochrons



Homogeneous Distribution of ^{26}Al in the Solar Nebula

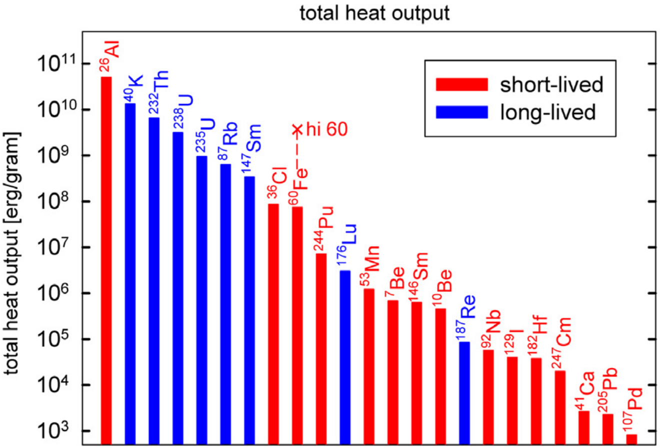
- Early Solar System abundance of ^{26}Al ($T_{1/2} = 717\,\text{ka}$)
  - Anchored by Pb-Pb ages
  - Homogeneous in all analyzed material
  - Initial $^{26}\text{Al}/^{27}\text{Al}$: 5×10^{-5}
- Allows for precise, relative dating of early phases
- But where does it come from?
  - Injection prior to Solar System collapse
  - What is the astrophysical source?
- Weird things: FUN CAIs
  - Fractionated Unknown Nuclear effects
  - $^{26}\text{Al}/^{27}\text{Al}$: $\ll 5 \times 10^{-5}$



Jacobsen et al. (2008)

Radionuclides: An Important Heat Source in the Early Solar System

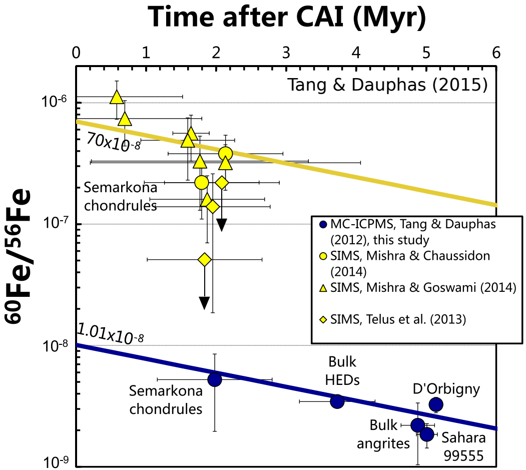
- Decay produces heat in the early solids in the Solar System
- Leads to melting and subsequent differentation of early, large objects
- ^{26}Al is the most important SLR heat source
- The importance of ^{60}Fe depends on its initial abundance



Lugaro et al. (2018)

The ^{60}Fe Controversy (half-life: 2.6 Ma)

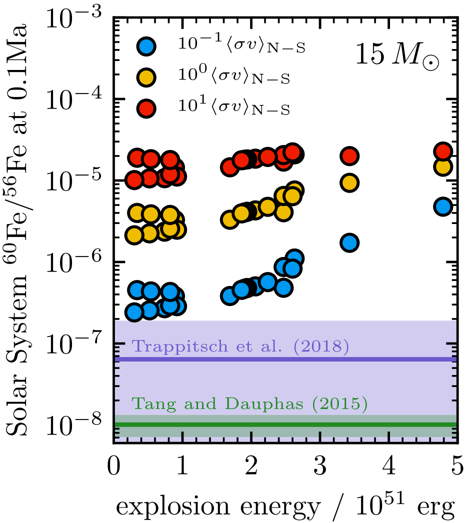
- Initial abundance of $^{60}Fe/^{56}Fe$ dependent on measurement technique
- Bulk studies find Solar System initial $^{60}Fe/^{56}Fe$ of $\sim 10^{-8}$
  (Tang and Dauphas, 2015)
  → "Low" ^{60}Fe
  → Consistent with galactic background
- In-situ studies by secondary ion mass spectrometry (SIMS) show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



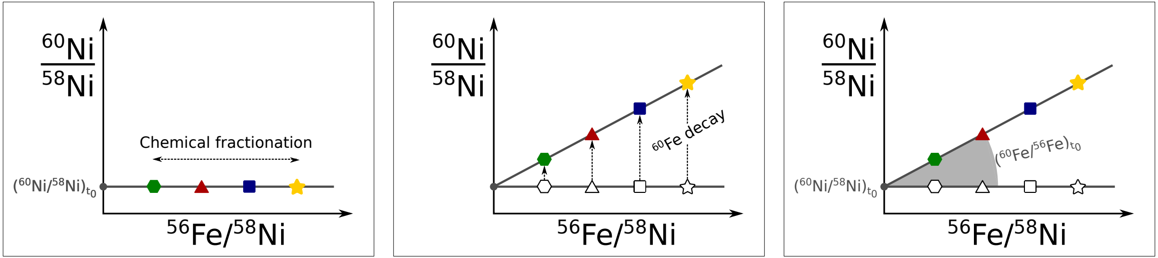
Supernovae Co-Injection of ^{26}Al and ^{60}Fe?

- "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 (except: H-ingestion supernova models – ask Marco!)

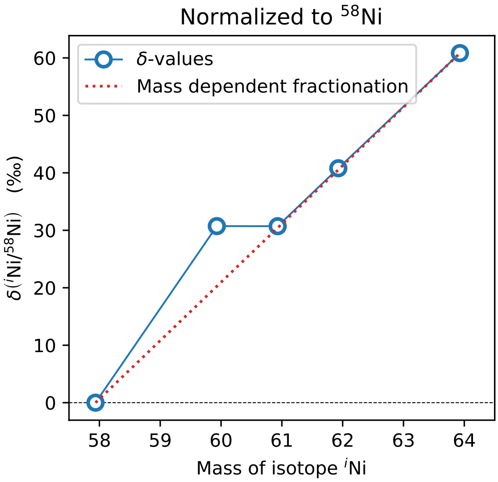


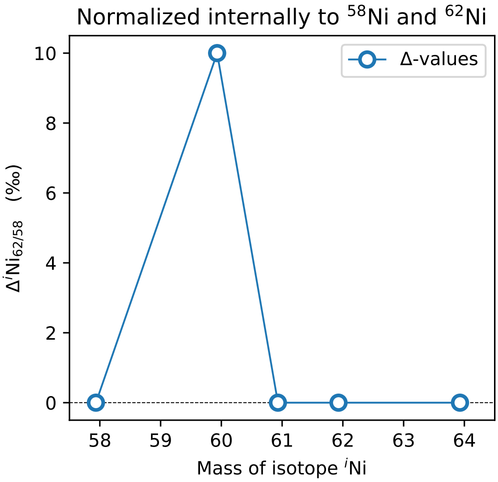
In-situ Measurements of Meteorite Inclusions to Decipher Initial $^{60}Fe/^{56}Fe$



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 \ 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

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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
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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

Remeasuring a Previously Analyzed Sample

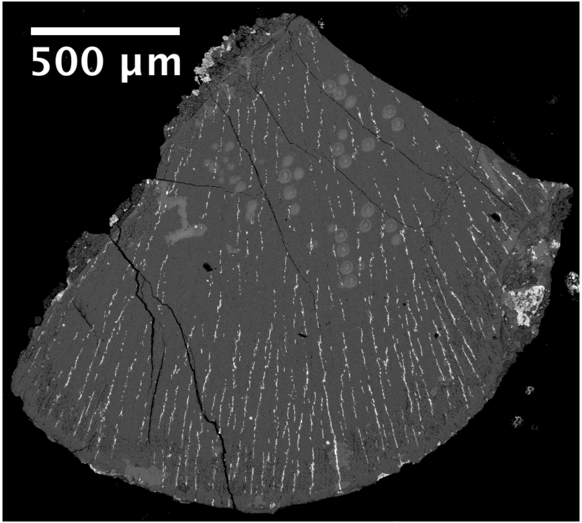
- Semarkona chondrule DAP1:
  A meteorite inclusion, which formed
  $\sim 2\,\mathrm{Myr}$ after Solar System

Previous SIMS measurements

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

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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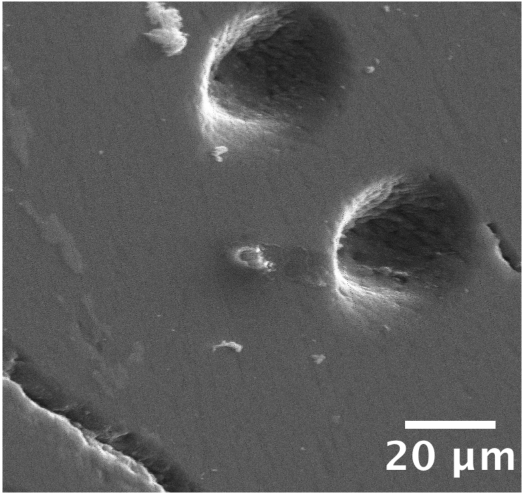
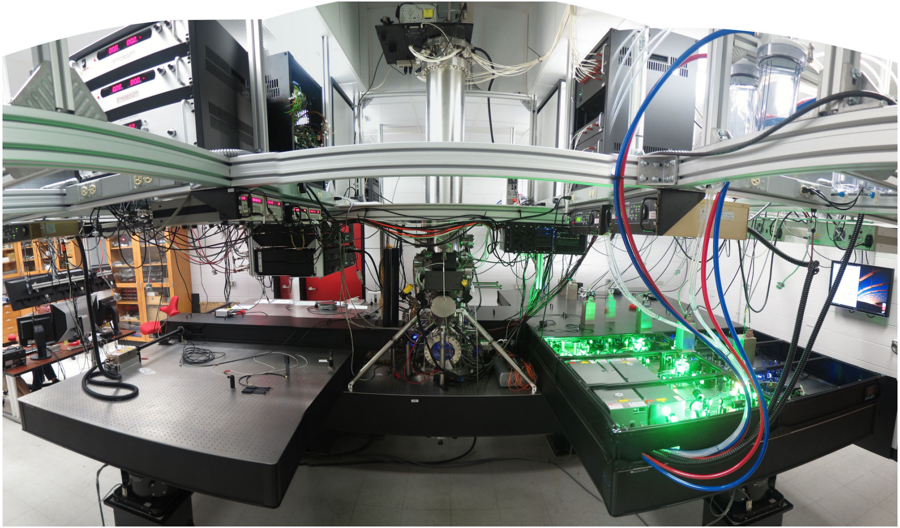


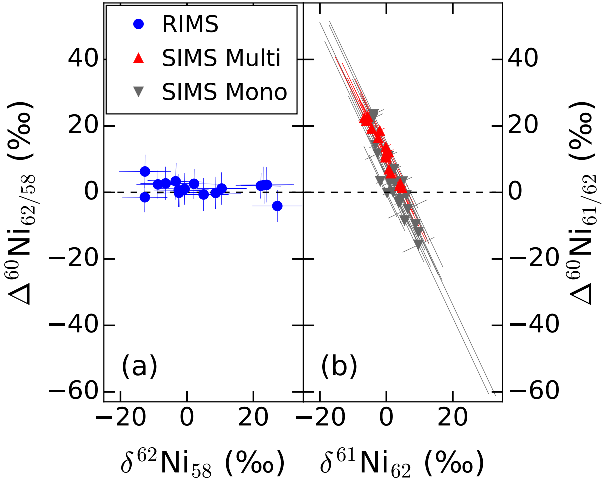
CHILI – A Resonance Ionization Mass Spectrometer for the Task



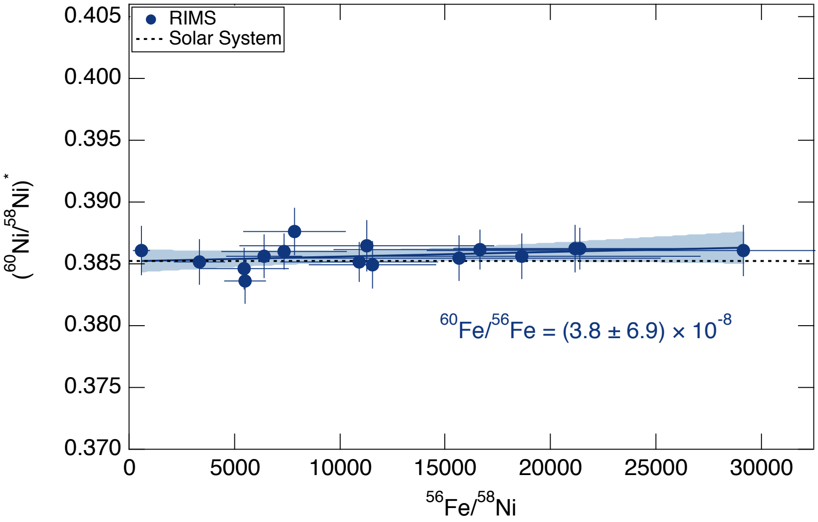
Precision in situ RIMS Analysis of DAP-1 (Trappitsch et al., 2018)

- 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



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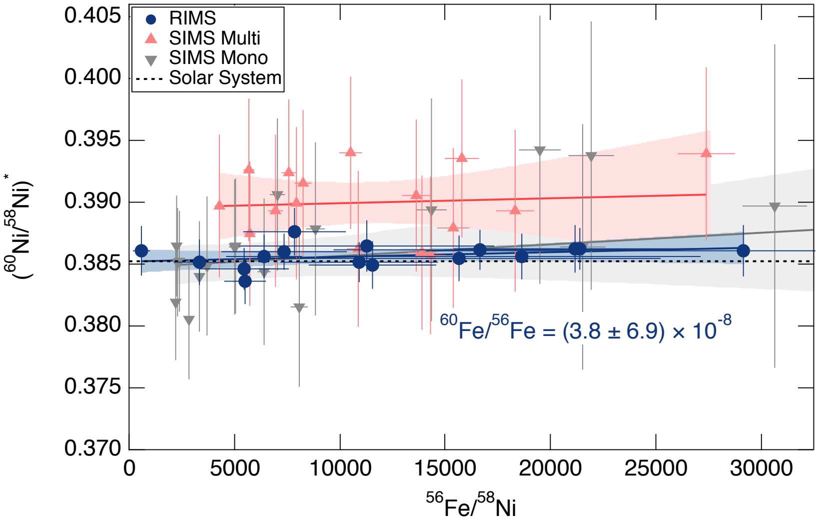
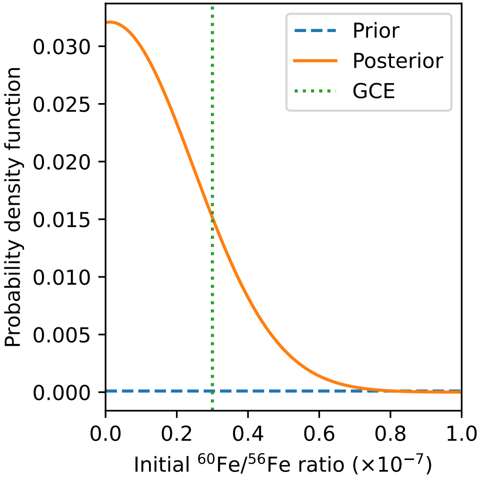


So we Re-evaluated 29 SIMS "Isochrons"

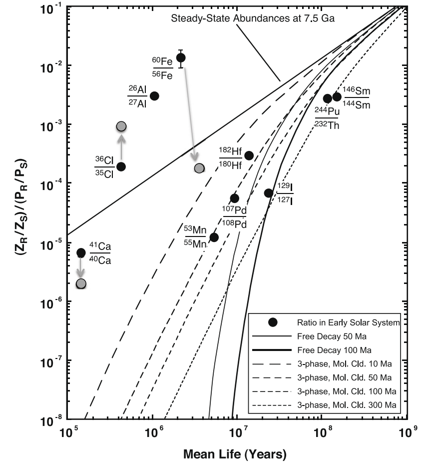
- All data by Hawaii group
- Bayes update starting with uniform prior
  - Gaussian likelihood given by calculated σ
  - Update with all 29 data sets
- Assuming that ^{60}Fe homogeneous in chondrule formation area
- Maximum probability of posterior distribution: $\rightarrow$ $^{60}\text{Fe}/^{56}\text{Fe} = 1.9 \times 10^{-8}$
- Total probability of posterior to be below galactic background: $> 78\%$



Other Radionuclides: A Complex GCE Story

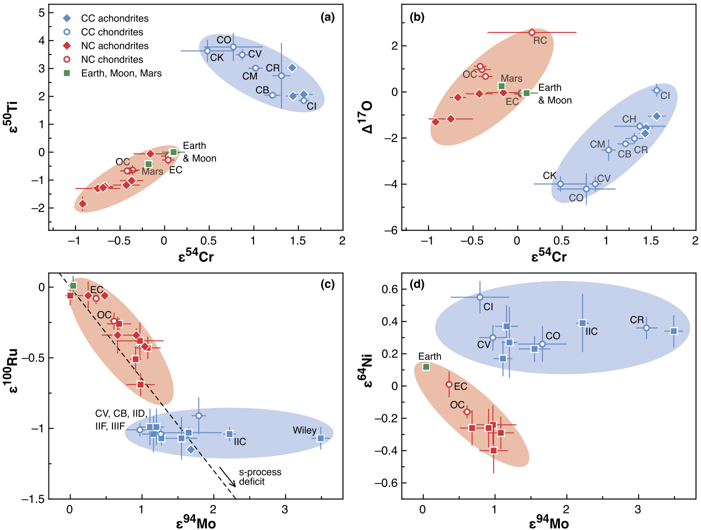
- SLRs trace the contribution of various sources to the early Solar System
- Isolation time scales play an important role
- Some isotopes, e.g., ^{36}Cl produced (partially) in-situ by irradiation with (solar) cosmic rays
- Benjamin's talk on Friday

SLRs help to pin point injection events and associated timings in the solar neighborhood 4.5 Ga ago



Lugaro et al. (2018)

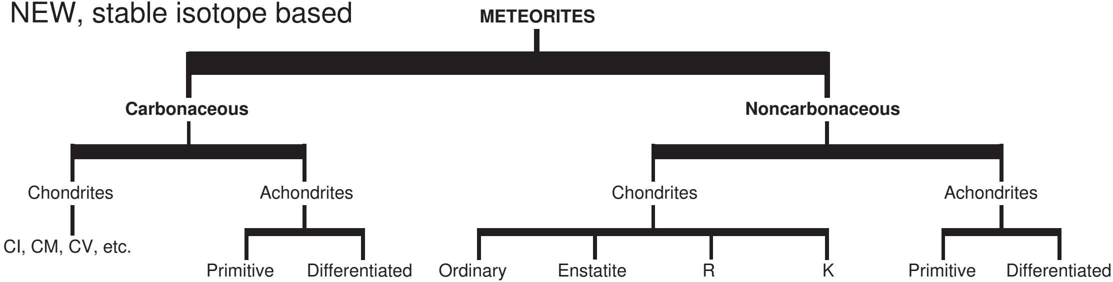
Precision Measurements show Groupings for Solar System Material



Kleine et al. (2020)

A New Classification for Meteorites

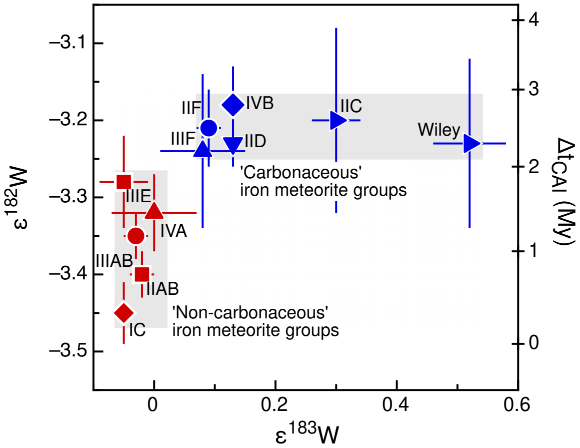
C) NEW, stable isotope based



- Warren (2011): A new classification of meteorites based on stable isotope anomalies
- The difference could be temporal or based on location of precursor formation

Jupiter: The Cause of Two Separated Reservoirs

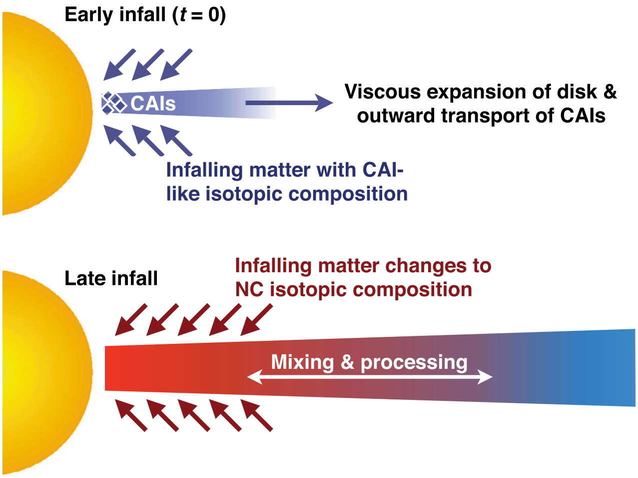
- ^{182}Hf-^{182}W ($T_{1/2} = 8.9 \times 10^6$ a)
  $\rightarrow$ Date timing on core formation
- Dichotomy in in iron meteorites indicate early formation of the two reservoirs
- Most likely scenario: location based separation
- The culprit: Formation of Jupiter
  - Separates the outer from the inner Solar System
  - This dates Jupiter's core formation
- Core of Jupiter ($20\,M_\oplus$): < 1 Ma
- $50\,M_\oplus$ within 4-5 Ma



Kruijer et al. (2017)

The Formation of Jupiter Separated the Reservoirs

- Early infall and formation of CAIs
- Late infall: Separates NC from CC
- Formation of Jupiter's core separates the two reservoirs
- After asteroids formed:
  - Migration of Jupiter, Saturn
  - Mixes material into inner Solar System (Grand Tack model)



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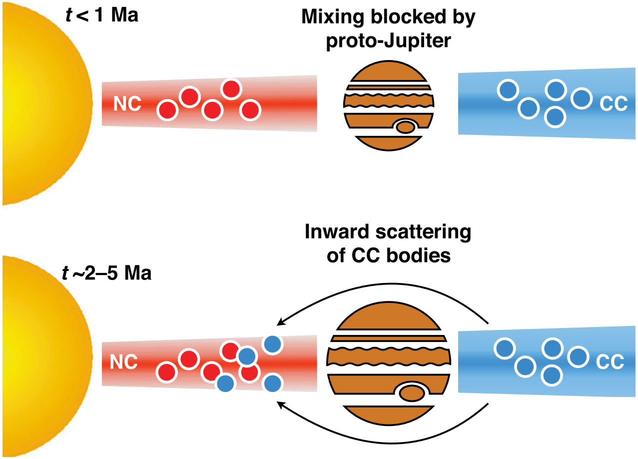
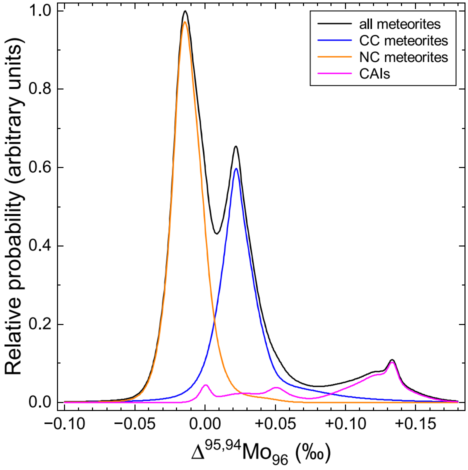


Kleine et al. (2020)

Solar System Started with *s*-Process Anomalies

- Stephan et al. (2019): Determined *s*-, *r*-, and *p*-composition of Solar System by presolar grain analysis
- The *p*/*r* isotope ratio seems constant
- The same is found when re-analyzing all meteorite data
- NC, CC separation indicates variation in the *s*-process component
- Also here: the *p*/*r* composition is constant
    - Are these isotopes created in the same stellar events?
    - Neutrino-driven winds?
- Earth: Between CC and NC composition

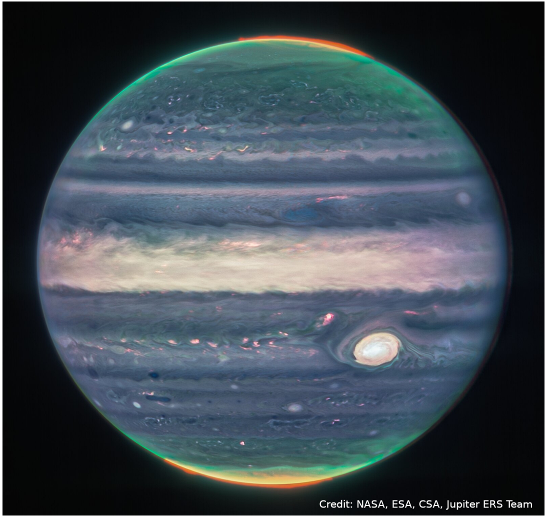


Stephan and Davis (2021)

Exciting Times are Ahead!

- SLRs: Timing of stellar injection / GCE contributions to solar nebula
  - Importance of data evaluation shown in ^{60}Fe story
  - Stochastic GCE important → Talks on Friday!
- Two nucleosynthetic reservoirs NC vs. CC
  - Anomalies due to *s*-process variations
  - Jupiter kept the reservoirs separated
  - Origin of the variation unclear at this point

Many open questions remain, stay tuned!



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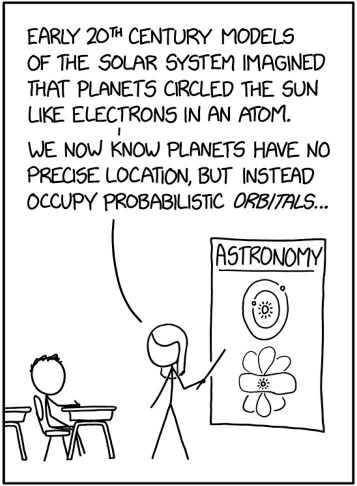

xkcd.com