Presolar Grains
Odd Ones Out in the Solar System

Reto Trappitsch
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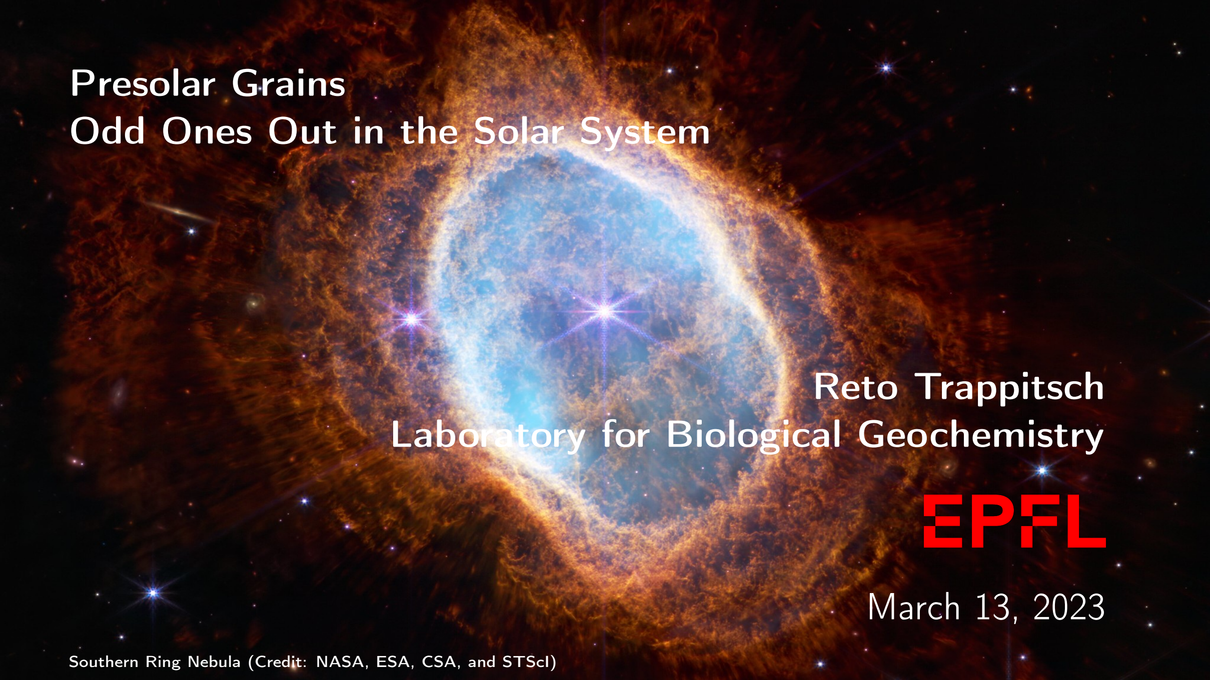
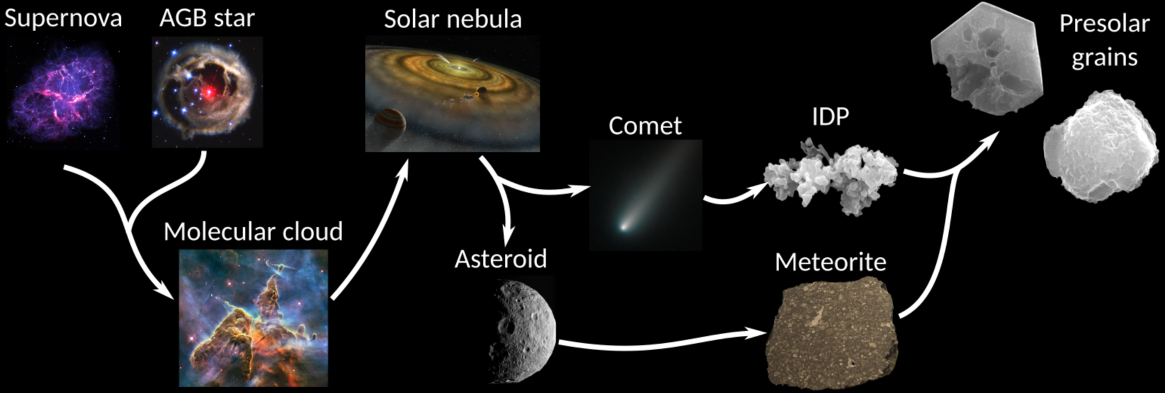
March 13, 2023



Southern Ring Nebula (Credit: NASA, ESA, CSA, and STScI)


Supernova
AGB star
Solar nebula
Presolar
grains
Comet
IDP
Molecular cloud
Asteroid
Meteorite

Various Phases of Presolar Grains Are Known Today

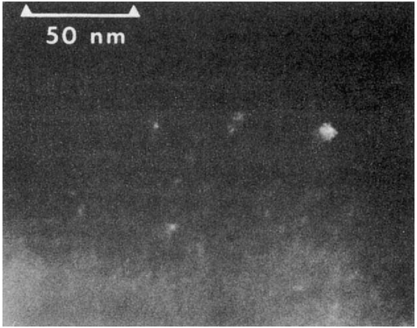
- Nanodiamonds: Only a few million atoms
- Silicon Carbide (SiC)
  - Best studied phase
  - Extracted
- Graphites
  - Large as well
  - Tend to contain significant contamination
- Silicates, oxides, etc.
  - $< 1\,\mu m$ in diameter
  - Must be found in-situ

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†



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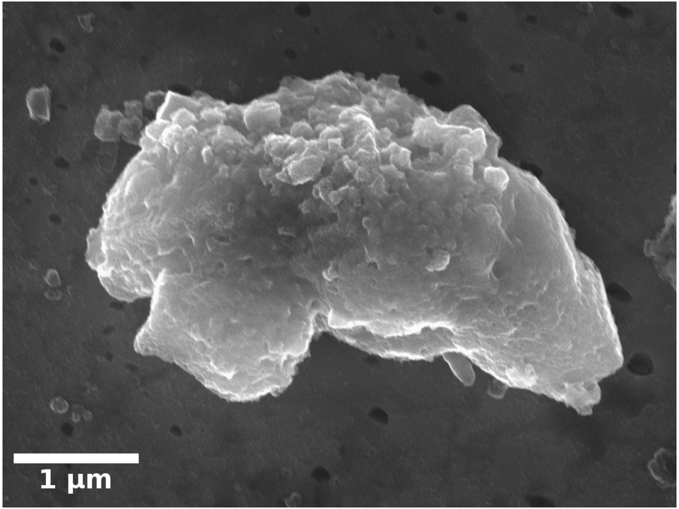

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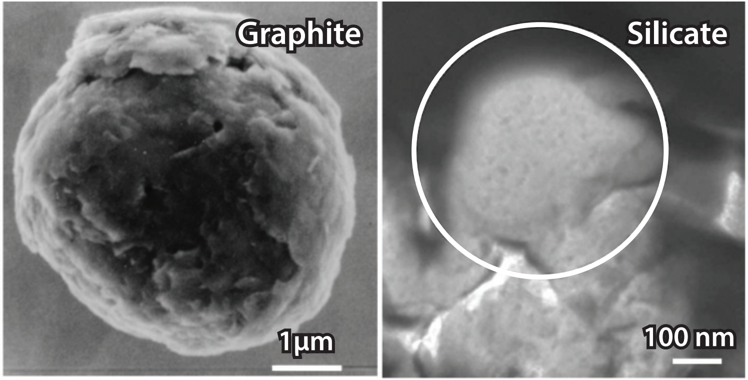

Nittler and Ciesla (2016)

The Best Studied Presolar Phase: Silicon Carbide (SiC)

- δ-units: Deviation from solar (‰)
- Presolar grains identified by their extreme isotopic composition
- Classified by analyzing their Si, C, and N isotopic composition
- Carry their parent stars isotopic composition
- Hands-on astrophysics samples
    - Galactic chemical evolution
    - Stellar nucleosynthesis
    - Transport processes in the interstellar medium
- **Are you convinced that these grains come from other stars?**

Definition:

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

- smp: Sample measured
- $\odot$: Solar composition

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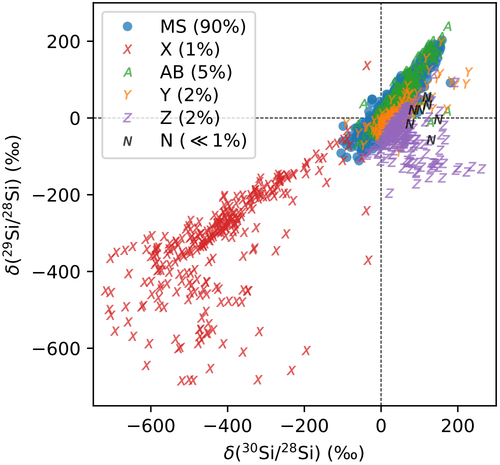

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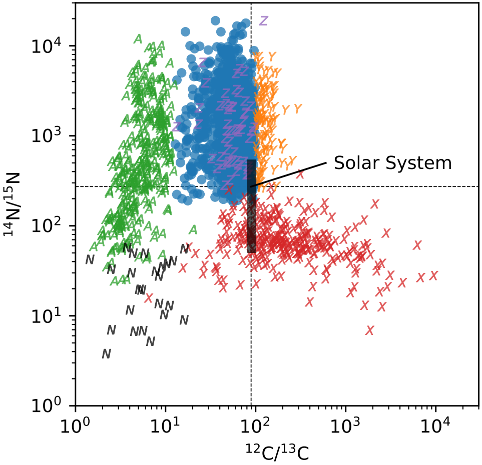
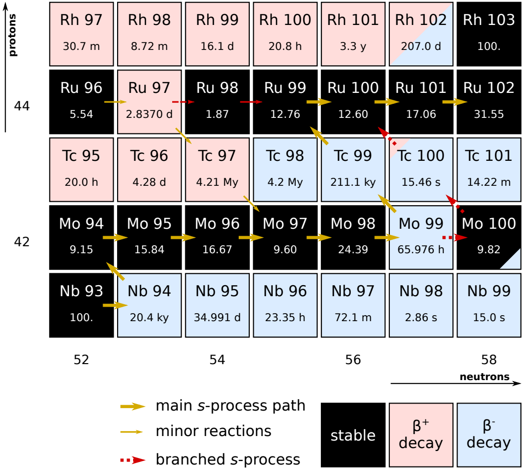
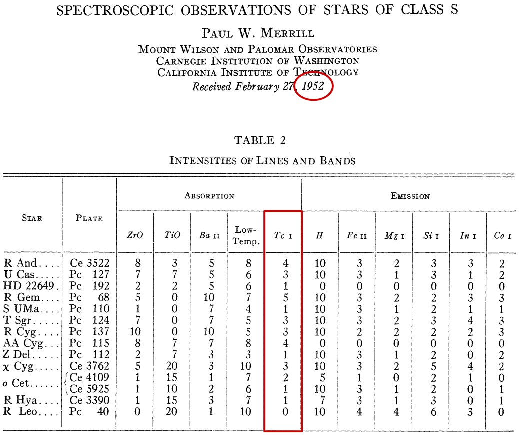


Observations of Live ^{99}Tc in AGB Stars





SPECTROSCOPIC OBSERVATIONS OF STARS OF CLASS S

PAUL W. MERRILL

MOUNT WILSON AND PALOMAR OBSERVATORIES
CARNEGIE INSTITUTION OF WASHINGTON
CALIFORNIA INSTITUTE OF TECHNOLOGY

Received February 27, 1952

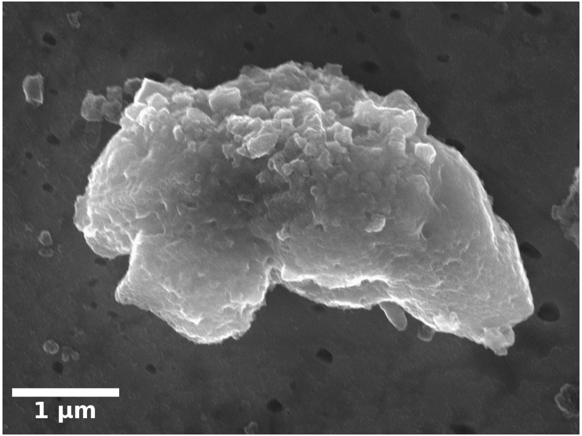
TABLE 2

INTENSITIES OF LINES AND BANDS

Star	Plate	Absorption					Emission					
		ZrO	*TiO*	*Ba* II	Low-Temp.	*Tc* I	*H*	*Fe* II	*Mg* I	*Si* I	*In* I	*Co* I
R And....	Ce 3522	8	3	5	8	4	10	3	2	3	3	2
U Cas.....	Pc 127	7	7	5	6	3	10	3	1	3	1	2
HD 22649.	Pc 192	2	2	5	6	1	0	0	0	0	0	0
R Gem....	Pc 68	5	0	10	7	5	10	3	2	2	3	3
S UMa....	Pc 110	1	0	7	4	1	10	3	1	2	1	1
T Sgr.....	Pc 124	7	0	7	5	3	10	3	2	3	4	3
R Cyg....	Pc 137	10	0	10	5	3	10	2	2	2	2	3
AA Cyg...	Pc 115	8	7	7	8	4	0	0	0	0	0	0
Z Del.....	Pc 112	2	7	3	3	1	10	3	1	2	0	2
χ Cyg.....	Ce 3762	5	20	3	10	3	10	3	2	5	4	2
o Cet......	Ce 4109	1	15	1	7	2	5	1	0	2	1	0
	Ce 5925	1	10	2	6	1	10	3	1	2	0	1
R Hya....	Ce 3390	1	15	3	7	1	7	3	1	3	0	1
R Leo....	Pc 40	0	20	1	10	0	10	4	4	6	3	0

Enhancements in ^{99}Ru in Presolar Stardust (Savina+, 2004)

- Ruthenium isotopic composition measured in µm-sized SiC grains by RIMS
- Comparison with slow neutron capture process models
  - ^{101}Ru/^{100}Ru agrees with models
  - ^{99}Ru/^{100}Ru elevated due to in-situ decay of ^{99}Tc
- Measurements require in-situ decay of ^{99}Tc
- Proof that these grains come from AGB stars (stars of class S)
- Many further measurements since



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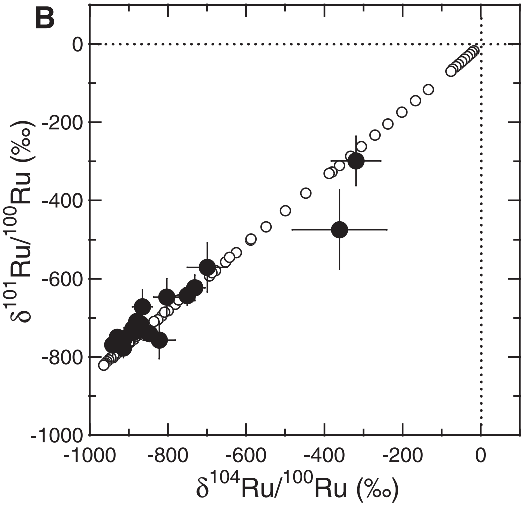

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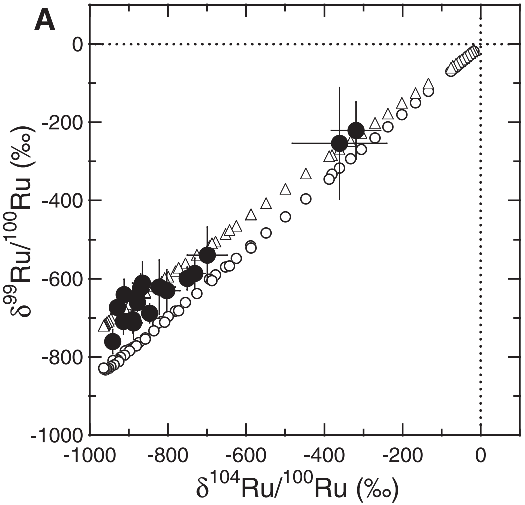
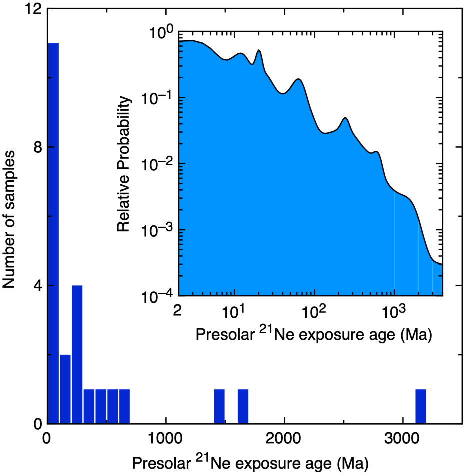


How Old are Presolar Grains? At Least 4.5 Billion Years!

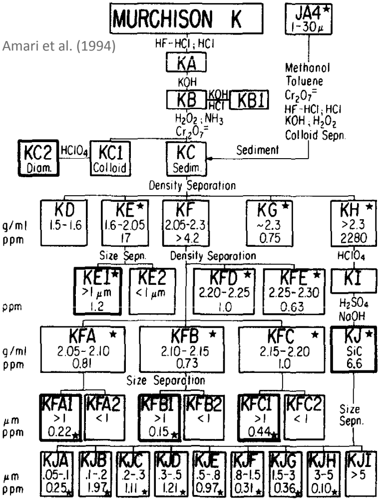
- Cosmic-rays in ISM irradiate presolar grain
- Production of cosmogenic ^{21}Ne
  - Not expected to condense into grain
  - Concentration c can be measured
  - Production rate p can be calculated
  - Exposure time $t = c/p$
- Heck et al. (2020): Measured cosmic ray exposure ages for 40 SiC grains
- Most grains formed < 1 Ga prior to solar system
- Some are several billion years old
- Ages likely dominated by destruction of grains in ISM



Extracting Presolar Grains in the Laboratory

- Silicon Carbide:
  - Hardness: 9/10
  - Density: $3.2\,\mathrm{g\,cm^{-2}}$
  - Very acid resistant
- Crush and freeze-thaw separation
- Remove Solar System phases by acid treatment
- Density separation in heavy-liquids to isolate SiC

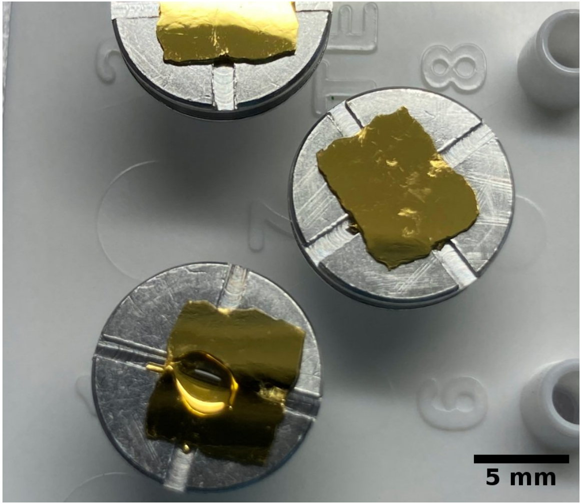
Finding the Needle in the Haystack by Burning Down the Hay



Amari et al. (1994)

Sample mounting and mapping

- Samples are drop-deposited on ultra-clean gold foil
- Solution evaporates and SiC stays behind
- Imaging by secondary electron microscopy
- Phase detection by energy dispersive X-rays
  $\rightarrow$ Find the SiC grains
- Create an overview map for navigation on the sample



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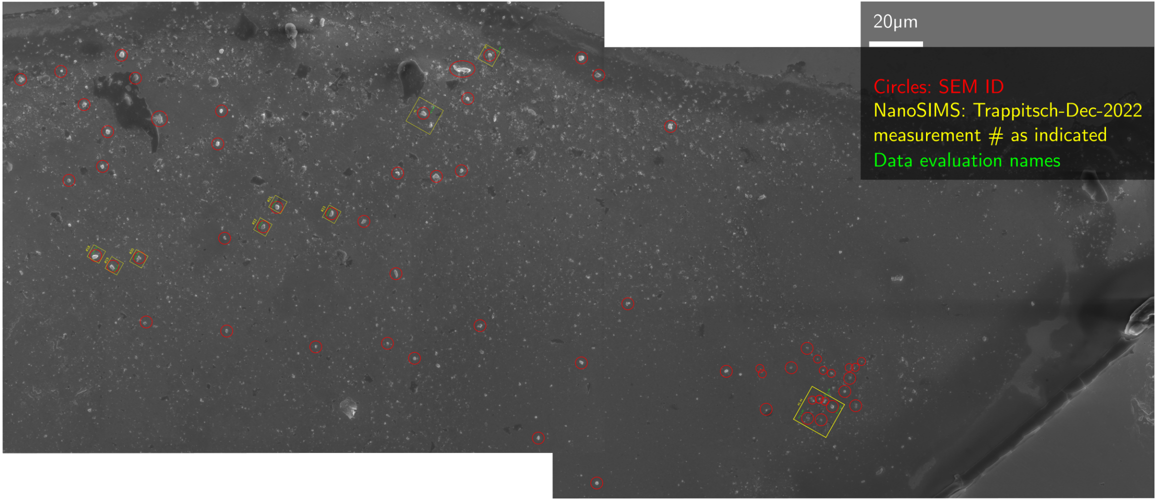
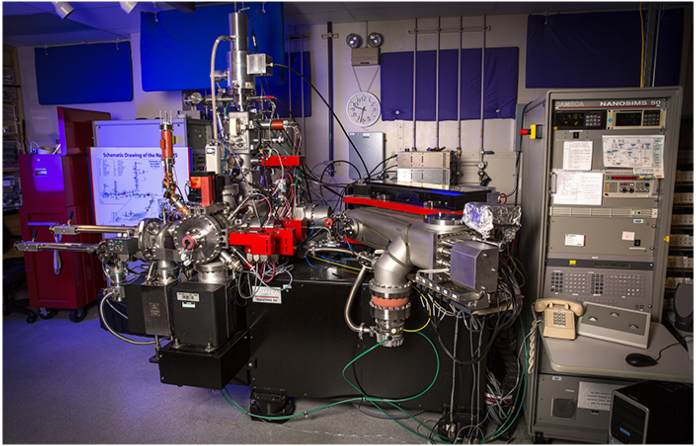
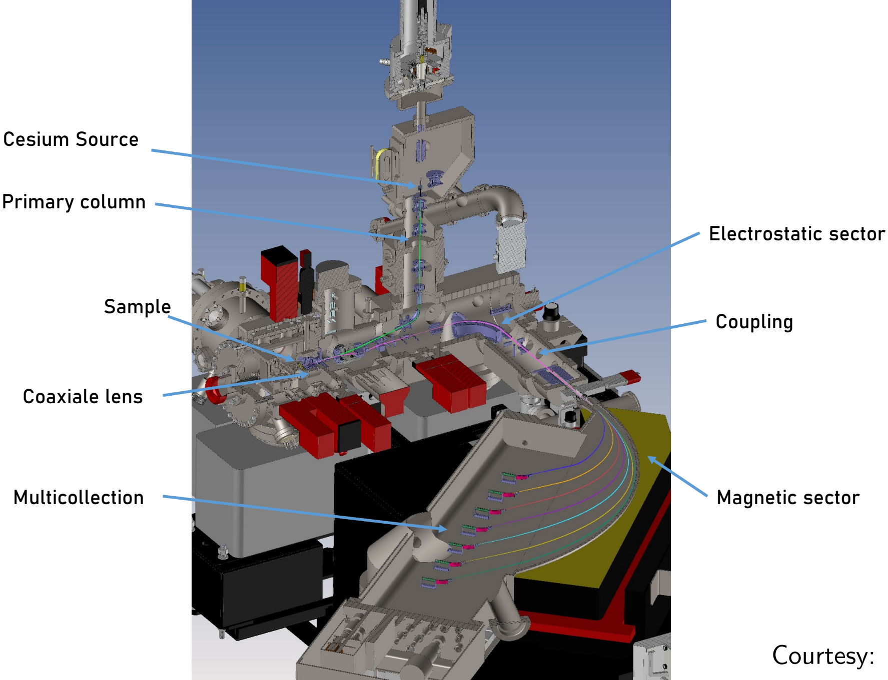
Detection of SiC



Nanoscale Secondary Ion Mass Spectrometry (NanoSIMS)

- Analyze the isotopic composition of Si, C, N in SiC grains (requires 7 detectors)
- Secondary ions analyzed
  $\rightarrow$ prone to isobaric interferences
- Ideal instrument to measure major isotopic composition



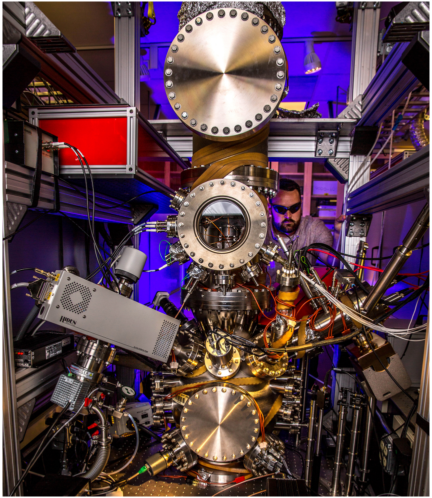


Courtesy: Florent Plane


NanoSIMS 50L
CAMECA
AMETEK

Trace element isotopic analyses

- Resonance Ionization Mass Spectrometry (RIMS)
- Most sensitive technique available for atom-limited samples
- Up to $\sim 40\%$ useful yield
- Only two instruments worldwide that analyze presolar grains
  - LION at Lawrence Livermore National Laboratory
  - CHILI at the University of Chicago



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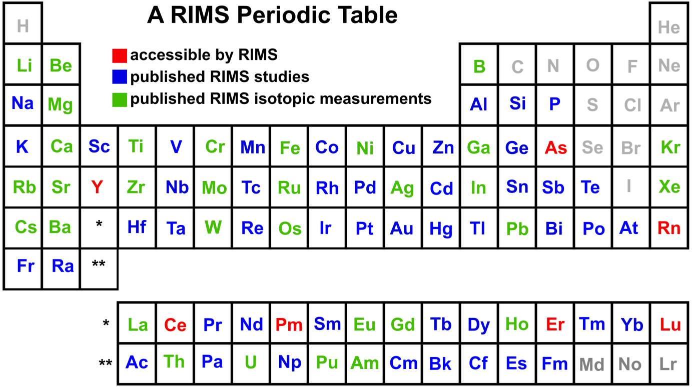
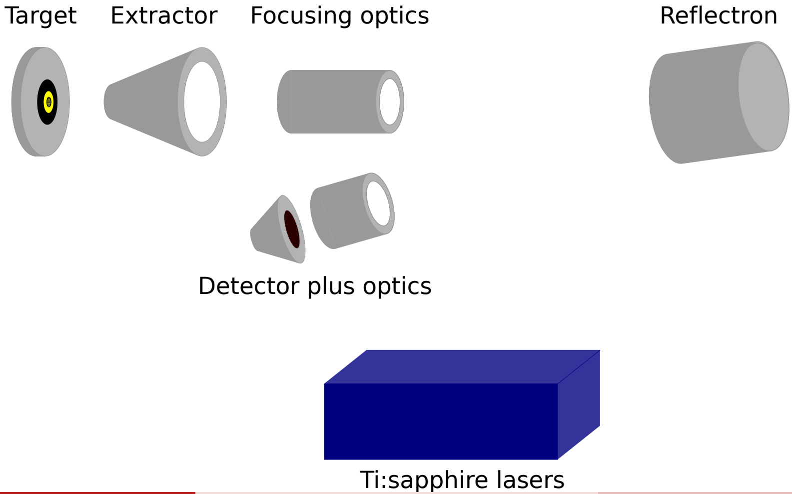


after Savina and Trappitsch (2019)

An overview of Resonance Ionization Mass Spectrometry (RIMS)



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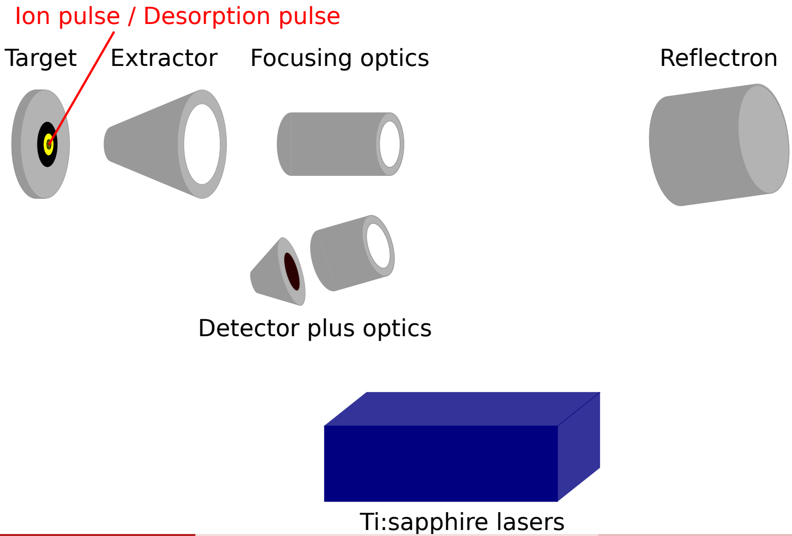

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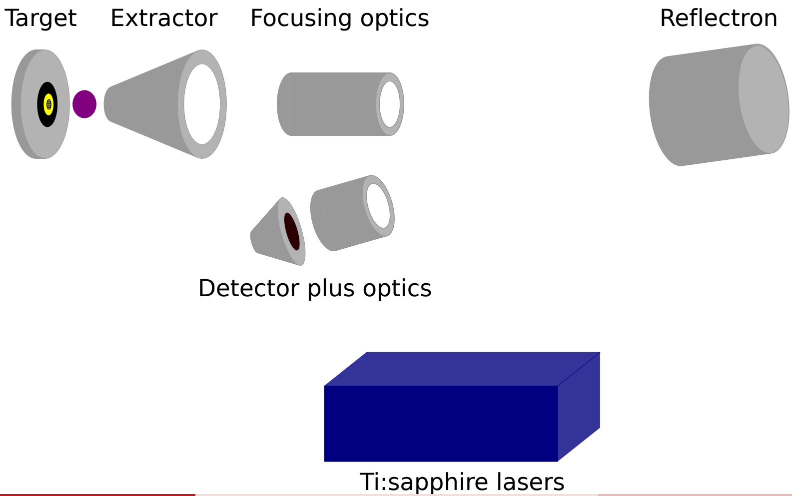

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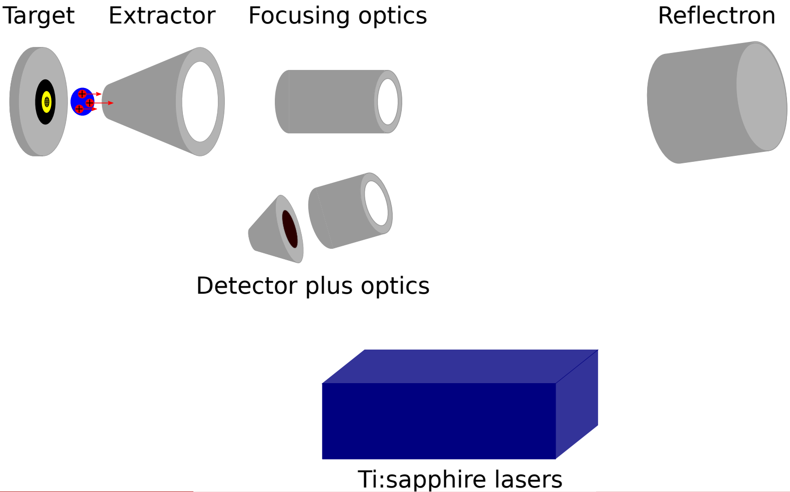

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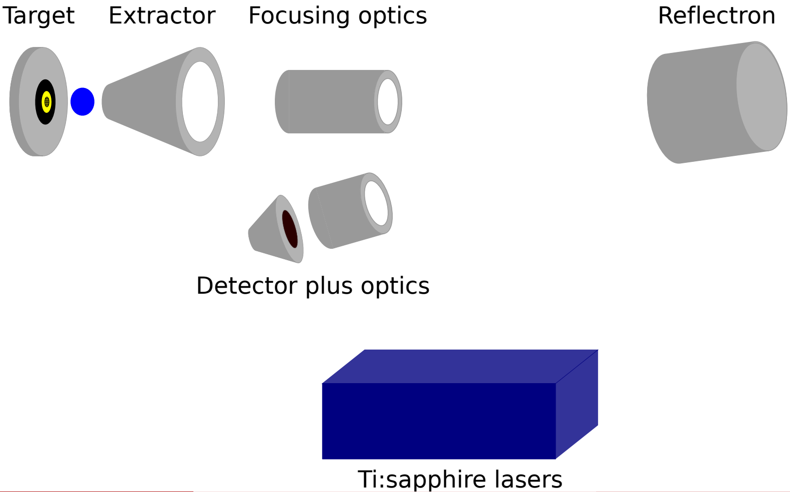

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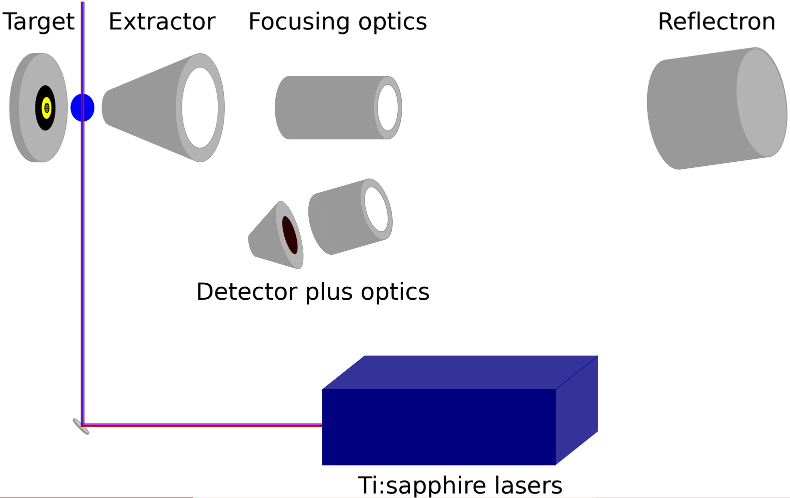

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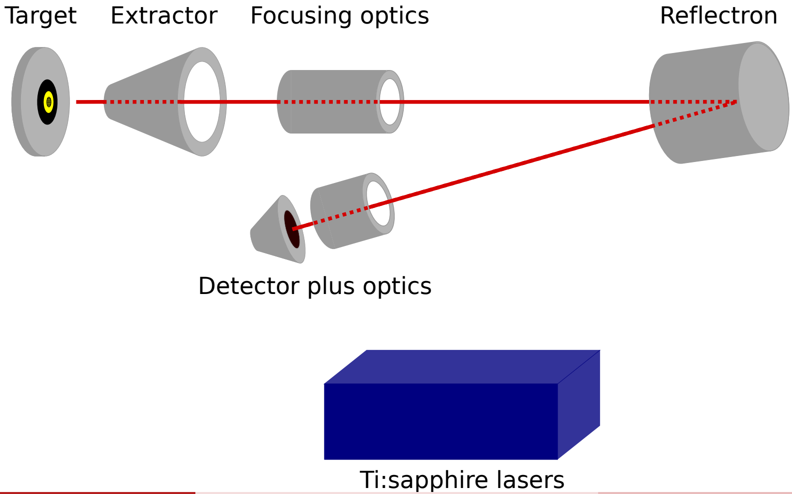
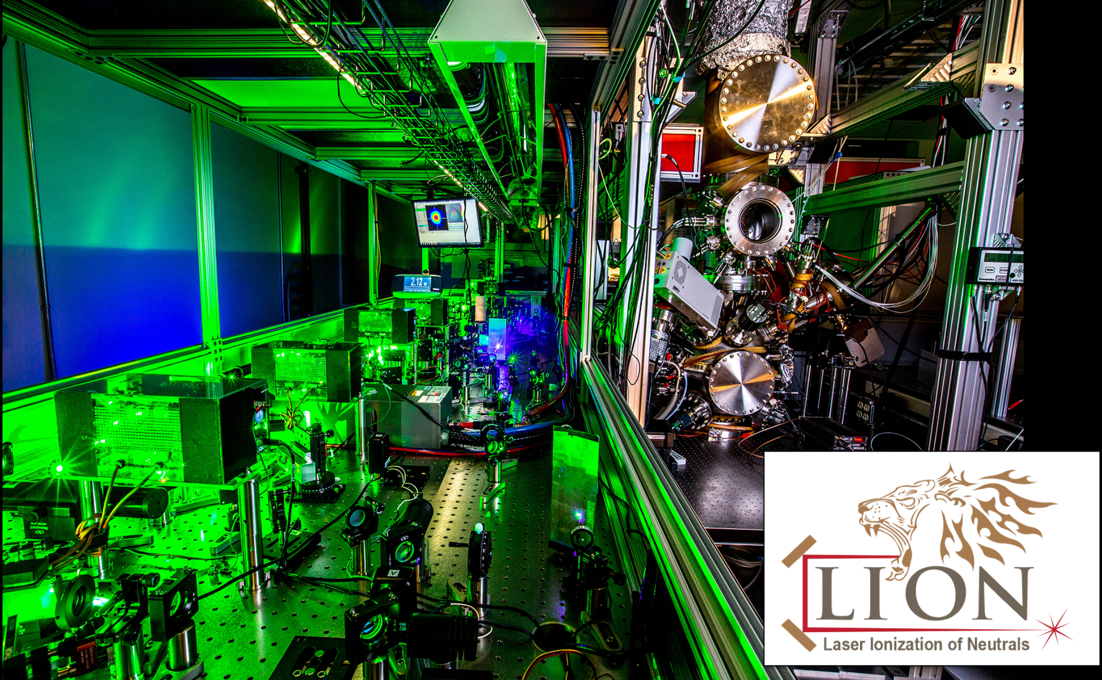
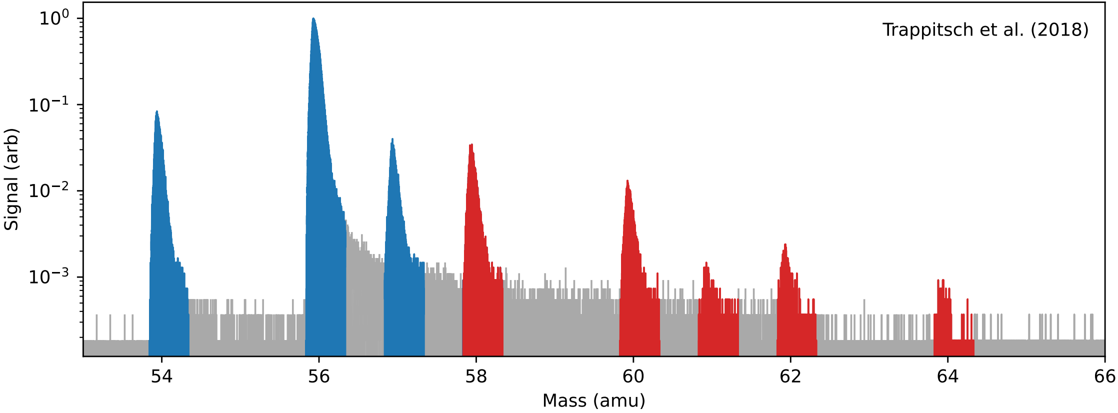



2.12 W
LION
Laser Ionization of Neutrals

Simultaneous Measurements of Iron and Nickel



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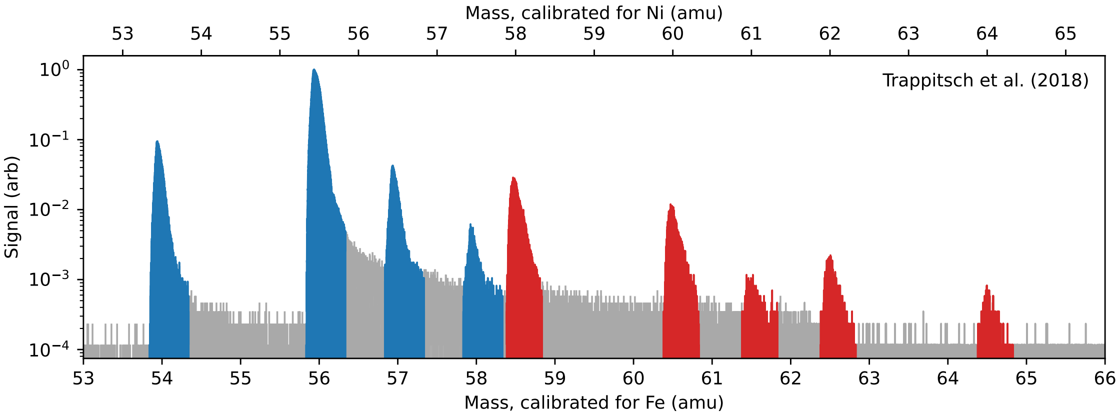
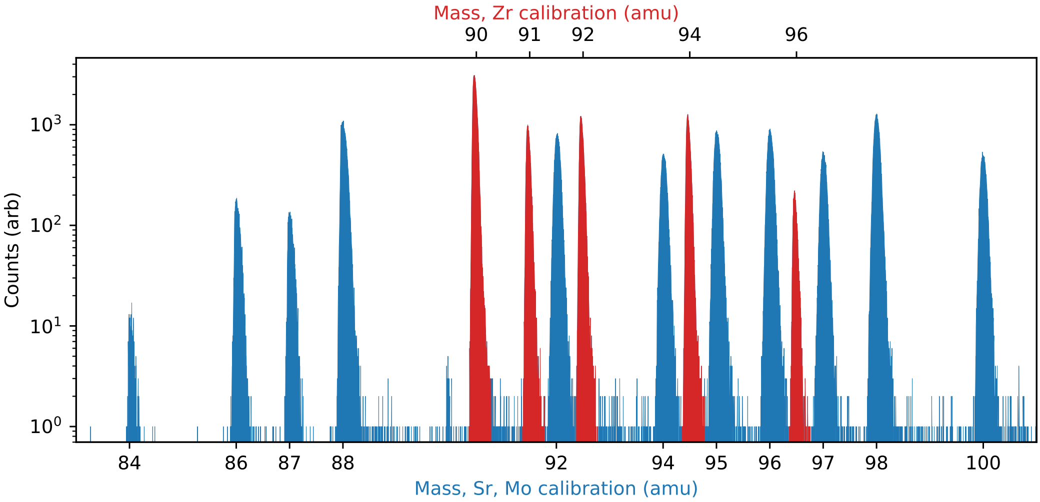
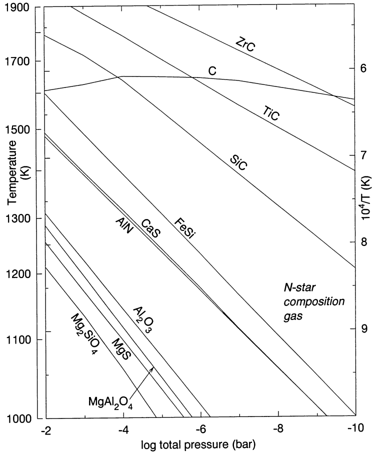


Simultaneous Sr, Zr, and Mo analysis (Shulaker+, 2022)



Limitations of Presolar Grain Measurements

- Elemental Ratios: Highly dependent on condensation environment
- Elements of interest must condense into presolar grain
  - Condensation temperature?
  - Refractory elements are more likely to condense than volatile ones
- We must have a reasonable number of atoms in the sample to analyze them



C-star condensation (Lodders and Fegley, 1999)

The Number of Atoms in a SiC Grain

- Mass m of a grain with density ρ and radius r

$$m = V\rho = \frac{4}{3}\pi r^3 \rho$$

- Most of mass is SiC with a molar mass of $M_{\mathrm{SiC}} = 40\,\mathrm{g/mol}$
- Number of SiC atoms in grain (N_A: Avogadro's number)

$$n_{\mathrm{SiC}} = \frac{m}{M_{\mathrm{SiC}}} N_A = \frac{4\pi r^3 \rho N_A}{3 M_{\mathrm{SiC}}}$$

- For a trace element with concentration c_x (wt/wt) and molar mass M_x

$$m_x = c_x m \quad \rightarrow \quad n_x = N_A \frac{m_x}{M_x}$$

Example:

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Example:
SiC grain with $r = 1\,\mu\mathrm{m}$ radius:

$$n_{\mathrm{SiC}} = 2 \times 10^{11}$$

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Assume 10 ppm (wt/wt) Fe:

$$n_{\mathrm{Fe}} = 1.4 \times 10^{6}$$

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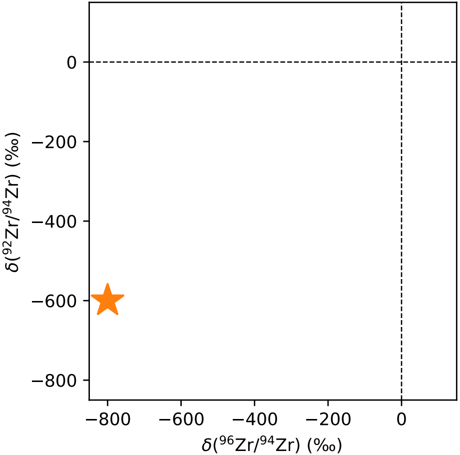
Solar abundance of ^{58}Fe: 0.282%

$$n_{^{58}\mathrm{Fe}} = 4014$$

Beware of Contamination

- Presolar Grains spent 4.5 Ga in meteorite
- Extraction with harsh acids of "solar" composition
- Isotopes ratios of the same element
  - Simple mixing
  - Contamination with Solar on straight line
- Isotopes ratios of different elements
  - Potential mixing region
  - Contamination curve depends on elemental composition of sample
  - A more complicated case!
- For SiC: Most contamination results from handling the samples in lab!



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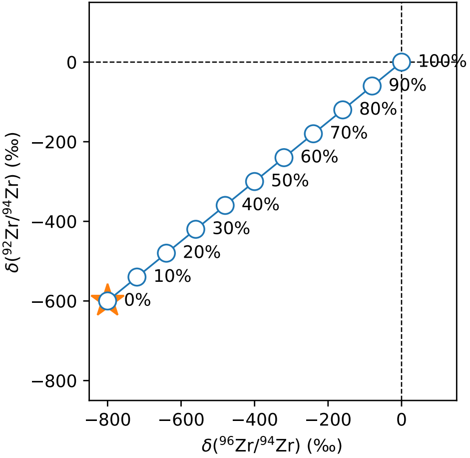

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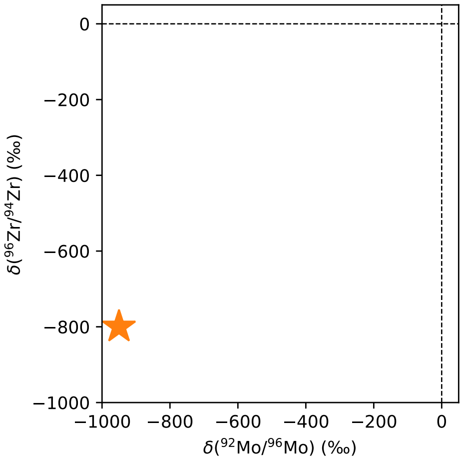

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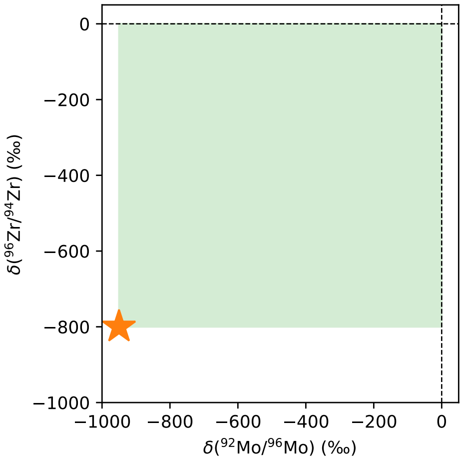

Beware of Contamination

- Presolar Grains spent 4.5 Ga in meteorite
- Extraction with harsh acids of "solar" composition
- Isotopes ratios of the same element
  - Simple mixing
  - Contamination with Solar on straight line
- Isotopes ratios of different elements
  - Potential mixing region
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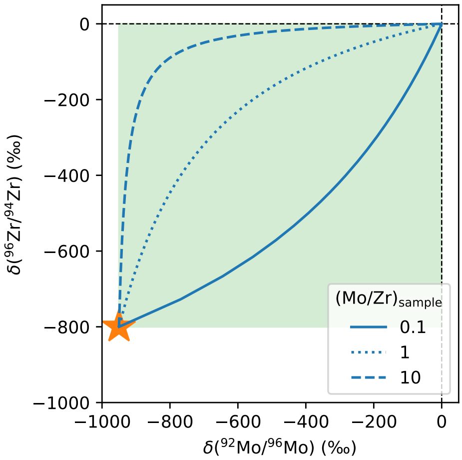

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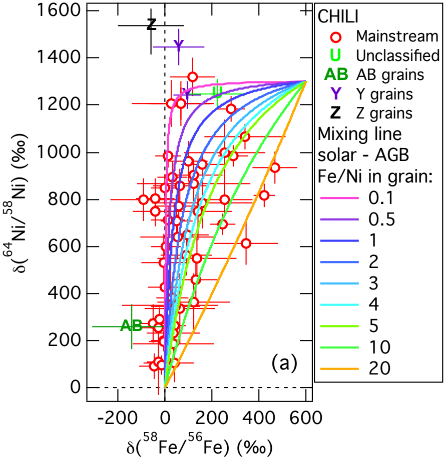
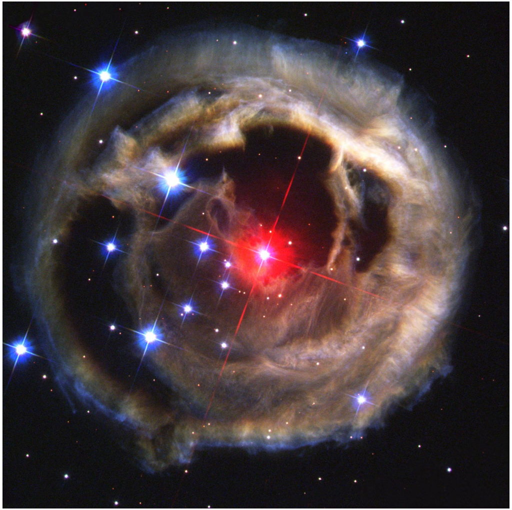


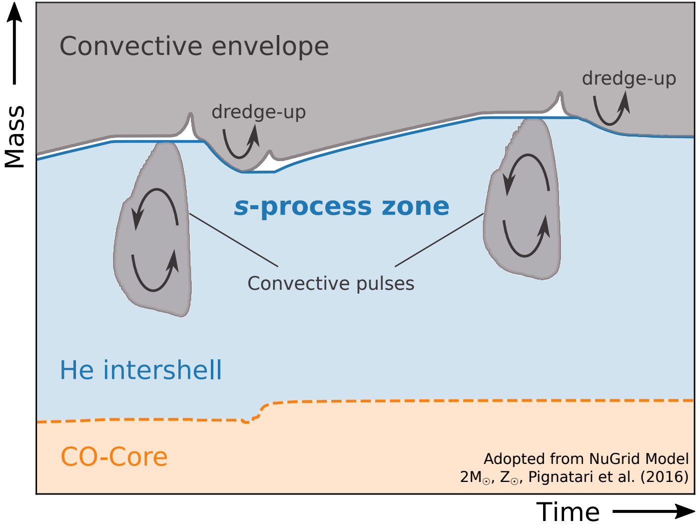
Trappitsch et al. (2018)

Asymptotic Giant Branch (AGB) Stars

- Star expands rapidly, and cools
- Cycles between H and He burning
  $\rightarrow$ Thermally pulsing AGB star
- AGB stars are copious dust producers
- Slow neutron capture (*s*-) process forms elements along the valley of stability
- Two important neutron sources:
  - $^{13}C(\alpha, n)^{16}O$
  - $^{22}Ne(\alpha, n)^{25}Mg$



Two Neutron Sources are at Work



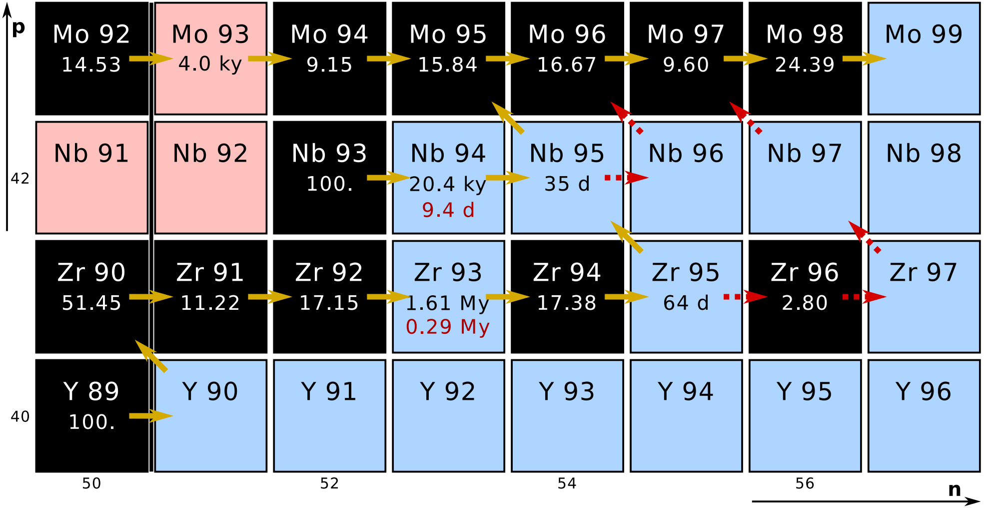
^{13}C(α, n)^{16}O

- Main s-process neutron source
- Max $< 10^7\ n\,\mathrm{cm}^{-3}$
- 1000s of years

^{22}Ne(α, n)^{25}Mg

- Bottom of He intershell
- Max $5 \times 10^9\ n\,\mathrm{cm}^{-3}$
- A few years

Where to Look in Presolar Grains



Who wins: Neutron Capture or β^--Decay

- Branching ratio f_n

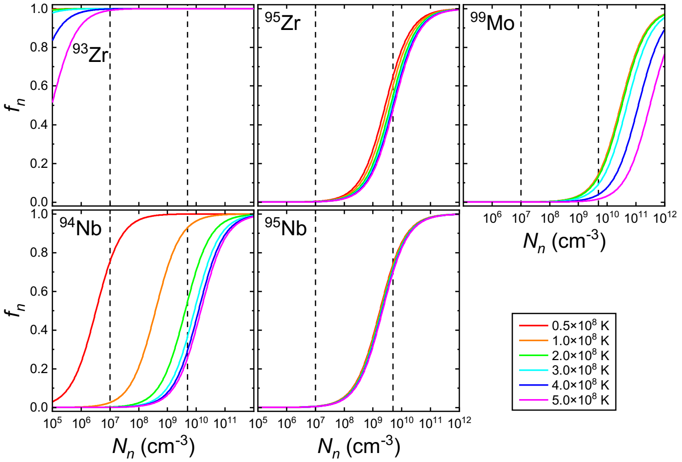
$$f_n = \frac{\lambda_n}{\lambda_n + \lambda_\beta}$$

- Neutron capture rate

$$\lambda_n = N_n v_T \langle\sigma\rangle$$

- β^--decay rate

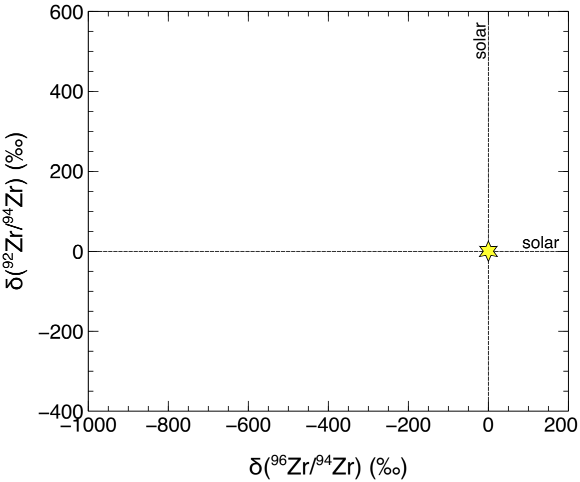
$$\lambda_\beta = \frac{\ln(2)}{T_{1/2}}$$



Stephan et al. (2019)

Deciphering the Parent Star Conditions with Stardust Measurements

- SiC grains can only condense in carbon-rich areas, with C>O
- Heavier-mass stars get hotter
  $\rightarrow$ Activate ^{22}Ne neutron source more
  $\rightarrow$ Activate ^{96}Zr production more
- Additional complication: Nuclear physics input uncertainties, e.g., ^{95}Zr(n, γ) cross section
- Comparison of isotope with stardust measurements allows determination of parent stars



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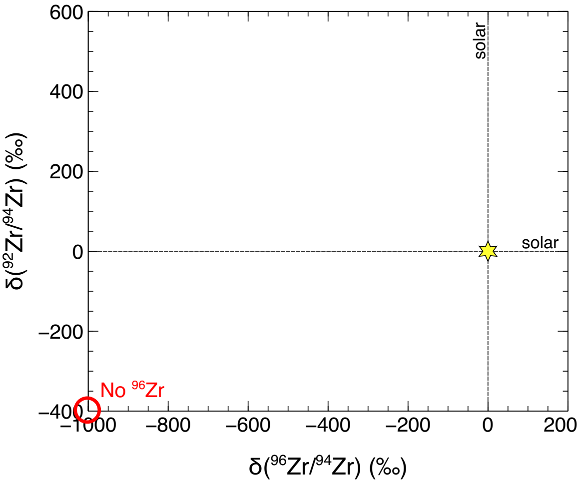

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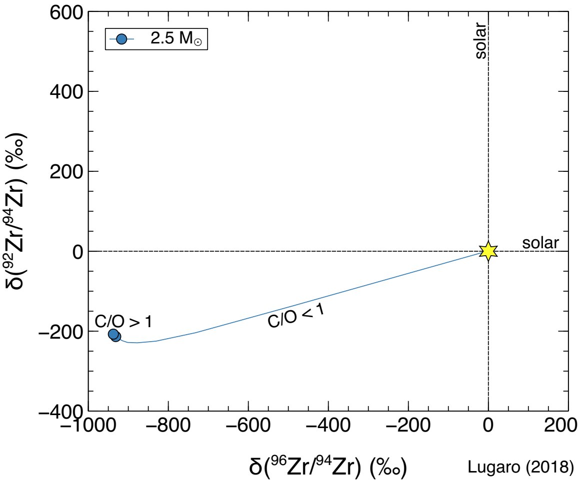

Lugaro (2018)

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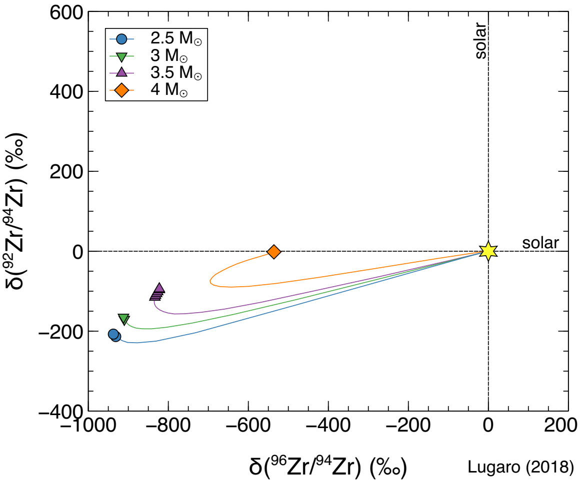

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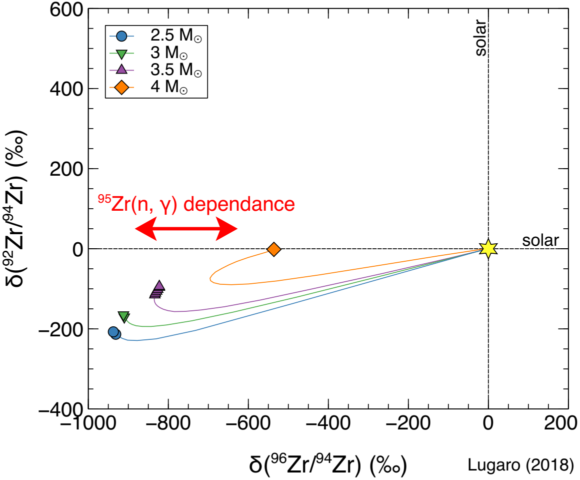

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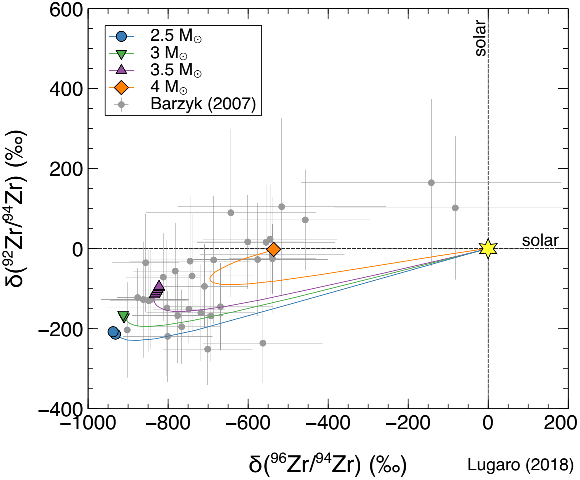
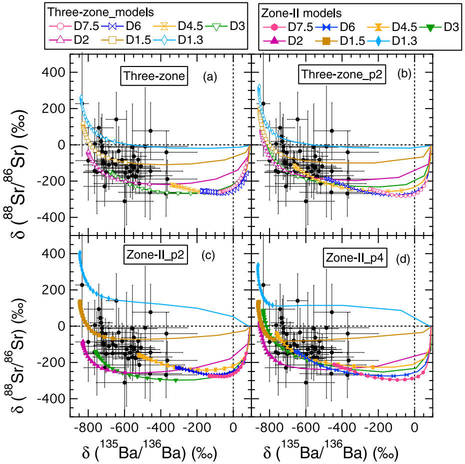


Lugaro (2018)

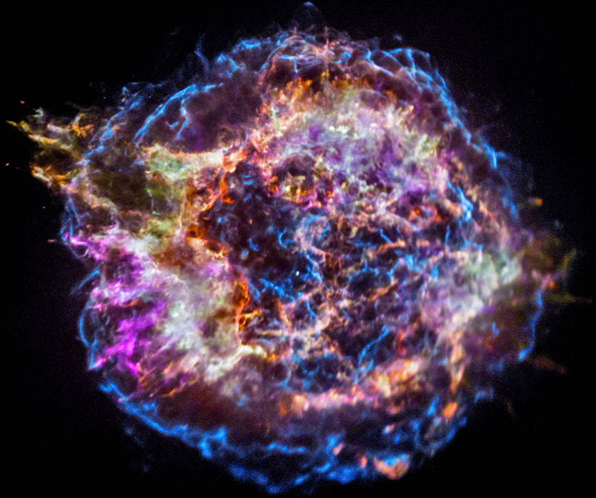
Multi-Element Measurements to Constrain the ^{13}C-Pocket

- Presolar grains allow us to probe the formation, size, and mass of the ^{13}C-pocket
- Multi-element isotopic measurements in individual grains can help to decipher the physics
- Many possible ^{13}C-pocket configurations can explain the measurements
- One set of model must fulfill all measurements constraints simultaneously

See Nan Liu et al. (20xx)

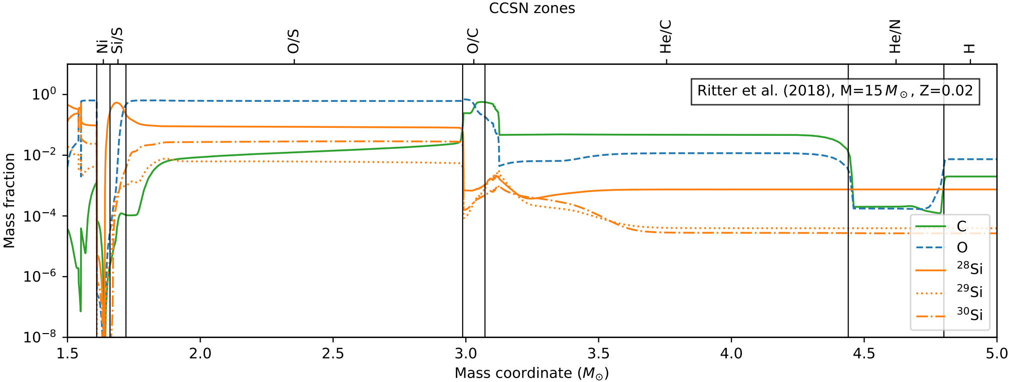


Liu et al. (2015)



Cassiopeia A: Si, S, Ca, Fe, X-rays (NASA/CXC/SAO)

Supernova Ejecta Mixing: What Regions do we Probe with Presolar Grains?

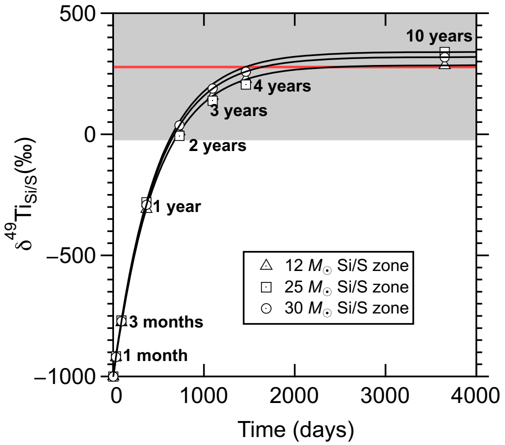


- How does material mix in the supernova ejecta? It's already complicated in 1D!

Short-Lived Radionuclides: Timing Grain Condensation

- Short-lived radionuclides allow to determine the speed of condensation
  - ^{49}V–^{49}Ti: > 2 a (Liu et al., 2018)
  - ^{137}Cs–^{137}Ba: ~ 20 a (Ott et al., 2019)
- Of course, these results are model-dependant!
- Multiple stable isotope ratios have been determined as well
- Presolar grains from supernovae are very rare

Supernova grains are currently vastly understudied!

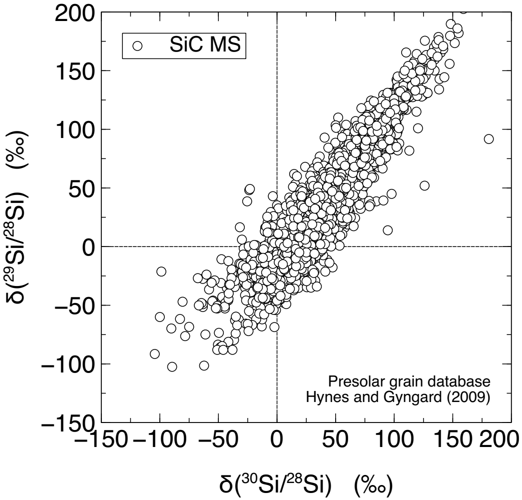


Liu et al. (2018)

The Curious Case of GCE Dominated Isotopes in Presolar Grains

- Mainstream SiC grains: from low-mass stars
- Star does not contribute to Si isotopic composition
- Certain isotopes are thus great proxies for GCE
- GCE predicts enrichment of ^{29}Si and ^{30}Si over time in galaxy
  Age-metallicity relation
- Presolar grains however are enriched in ^{29}Si and ^{30}Si compared to Solar System

Presolar grain measurements require heterogeneous GCE



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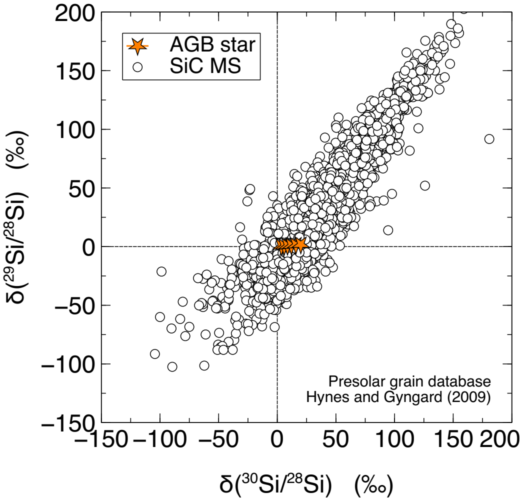

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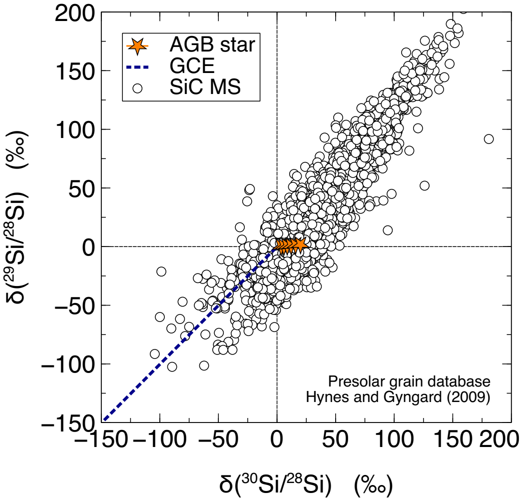
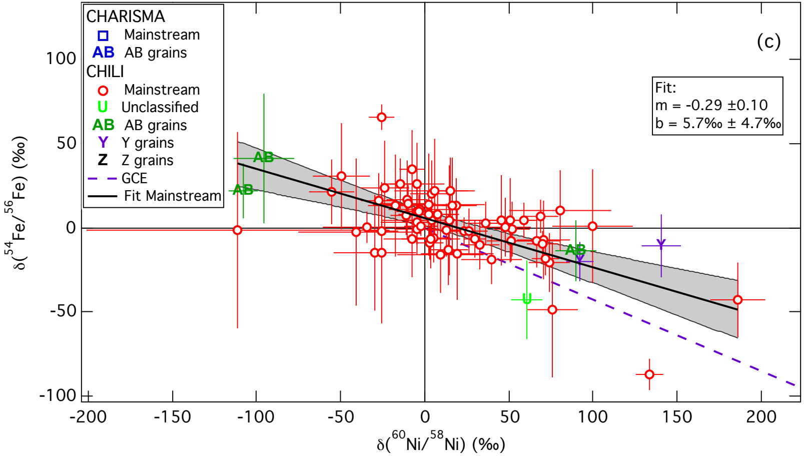


Other Isotopes show the Same Behavior compared to the Solar System

- ^{54}Fe and ^{60}Ni correlate with ^{29}Si
- Enrichments in ^{54}Fe and ^{60}Ni found as well
- Age-metallicity relation cannot explain these observations



Trappitsch et al. (2018)

Many Explanation Attempts Over the Years

- The problem is twofold:
  - Slope of Si correlation > 1
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- Stellar migration (Clayton, 1997)
  → Range too small
- Presolar galactic merger (Clayton, 2003)
- Stochastic/heterogeneous GCE (Lugaro et al., 1999, Nittler, 2005)
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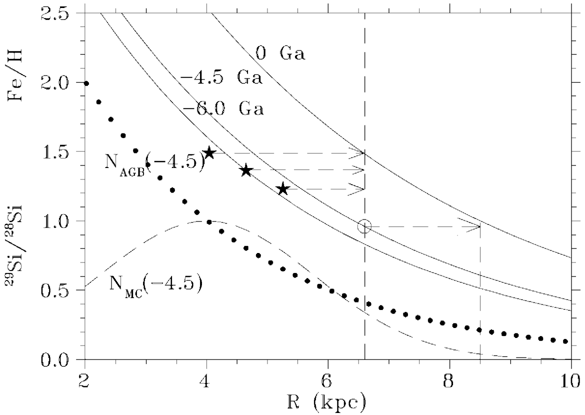

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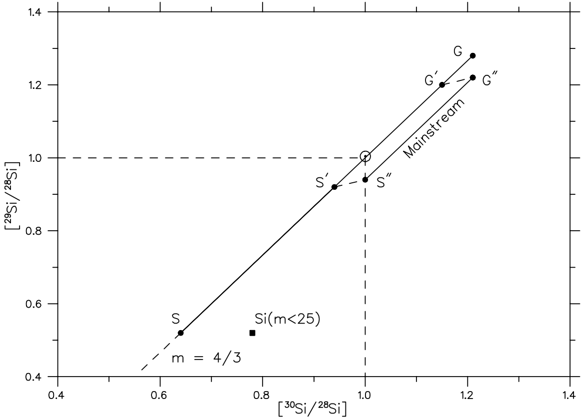

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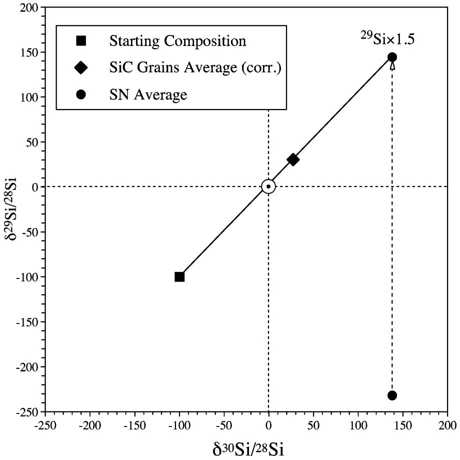

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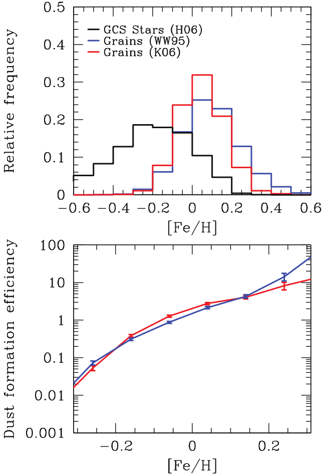

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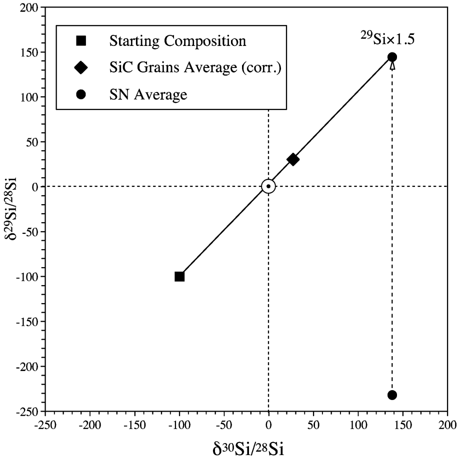
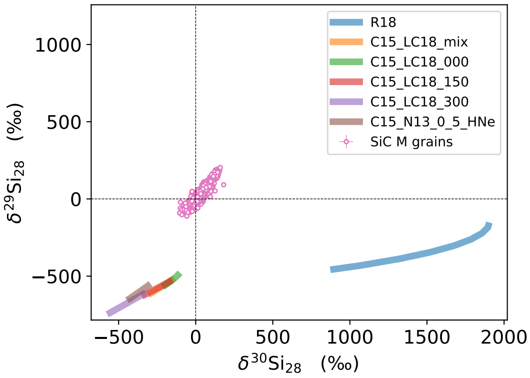
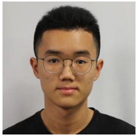


Lugaro et al. (1999)

Influence of Nuclear Reaction Rates for Si Production/Destruction





- HungKwan Fok (Brandeis University)
- NuPyCEE GCE simulations show differences between yield sets

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- Example of $^{26}Mg(\alpha, n) \times 3$ shows enhancement in ^{29}Si and ^{30}Si

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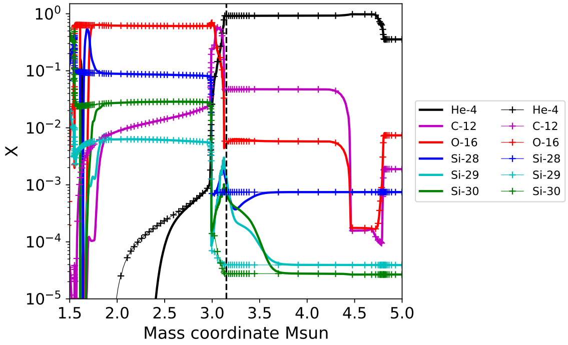

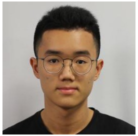

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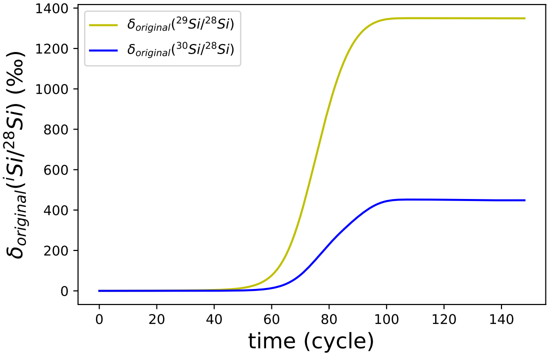

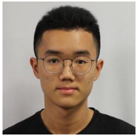

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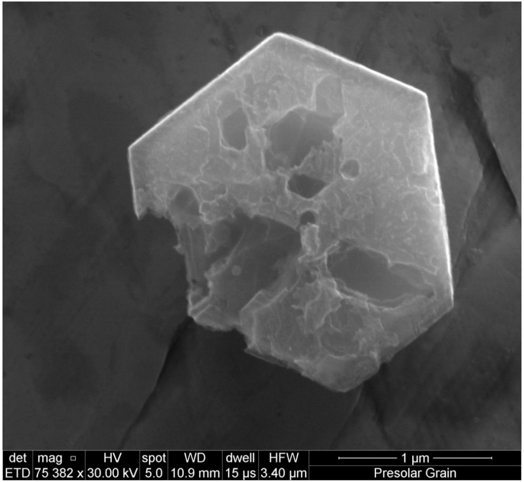
Where to Go From Here?

- Presolar grains allow us to directly probe stellar nucleosynthesis in the laboratory
- Allows us to study
  - Nucleosynthesis
  - Galactic Chemical Evolution
  - Interstellar Medium
- Isotopic information is unique

Another Messenger to Elucidate our Understanding of Nuclear Astrophysics!



Thank You! Questions?

Brandeis University: HungKwan Fok

EPFL / UniL: Stéphane Escrig, Cristina Martin Olmos, Anders Meibom, Florent Plane

Lawrence Livermore National Laboratory: Barbara Allen (Wang), Jutta Escher, Jason Harke, Richard Hughes, Brett Isselhardt, Wei Jia Ong, Mike Savina, Ziva Shulaker, Peter Weber

The University of Chicago / The Field Museum for Natural History: Andy Davis, Philipp Heck, Mike Pellin, Thomas Stephan

Konkoly Observatory Marco Pignatari