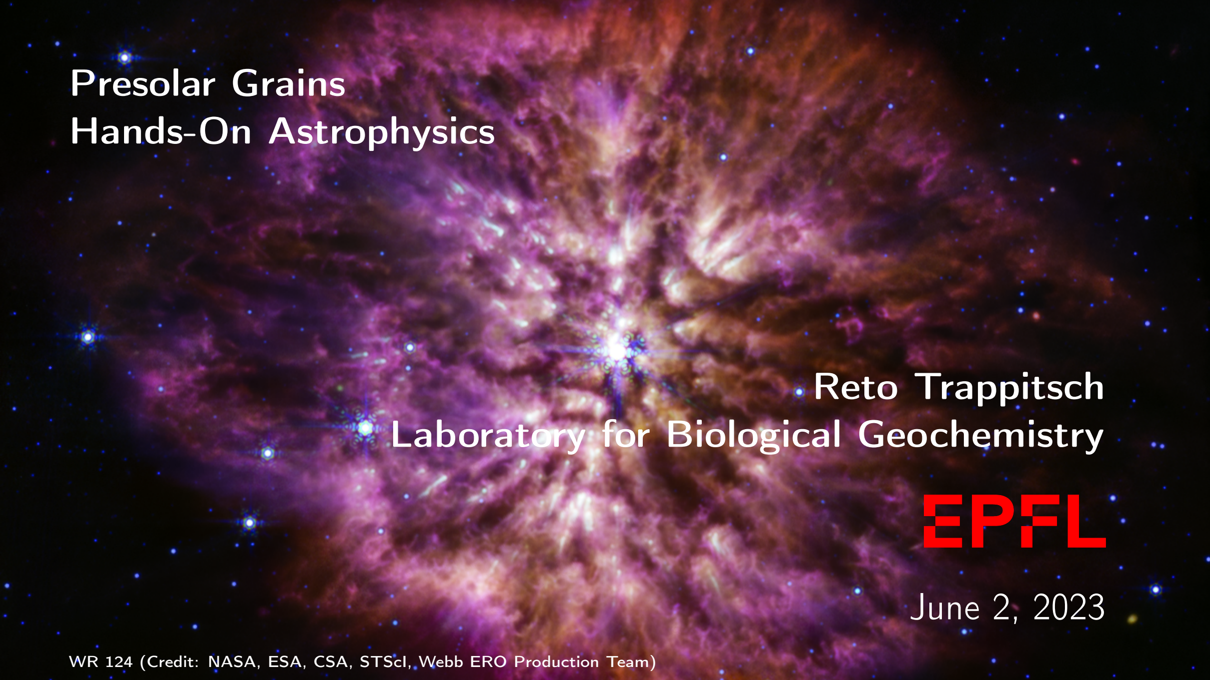
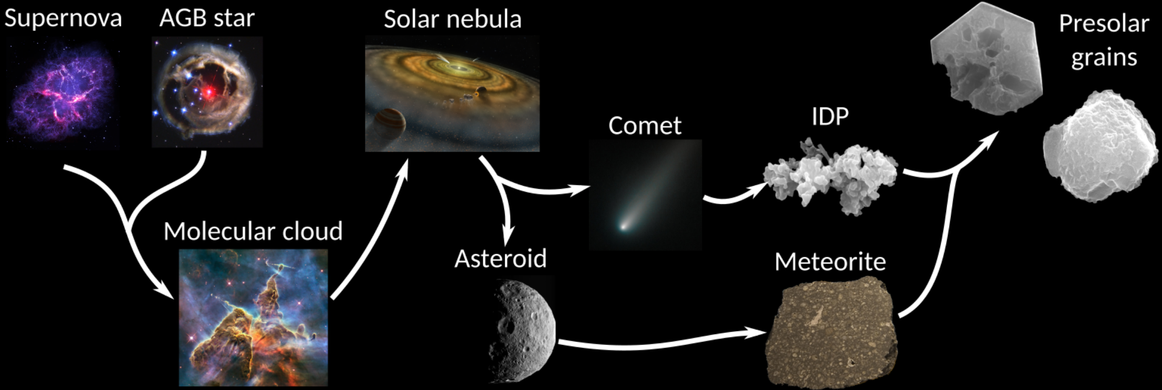
Presolar Grains
Hands-On Astrophysics



Reto Trappitsch
Laboratory for Biological Geochemistry
EPFL

June 2, 2023

WR 124 (Credit: NASA, ESA, CSA, STScI, Webb ERO Production Team)



Supernova

AGB star

Molecular cloud

Solar nebula

Comet

Asteroid

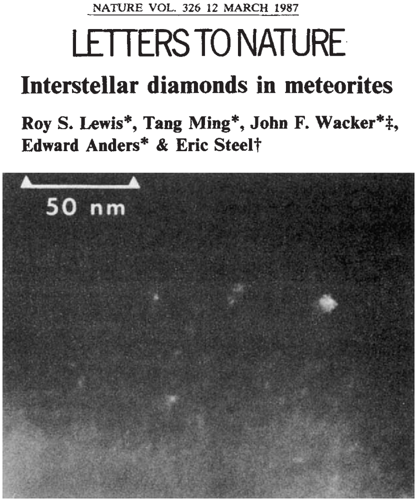
IDP

Meteorite

Presolar grains

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.
    - $< 1\,\mu\text{m}$ 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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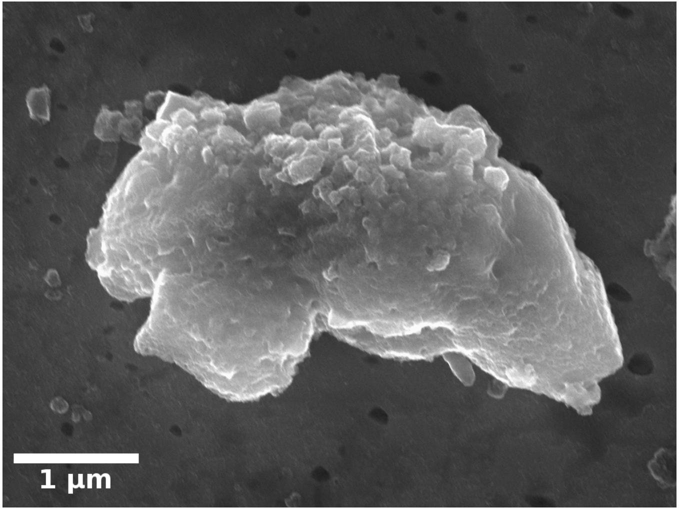

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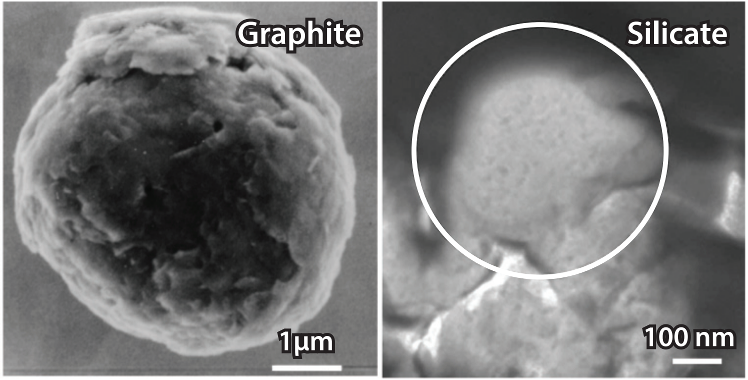

Nittler and Ciesla (2016)

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

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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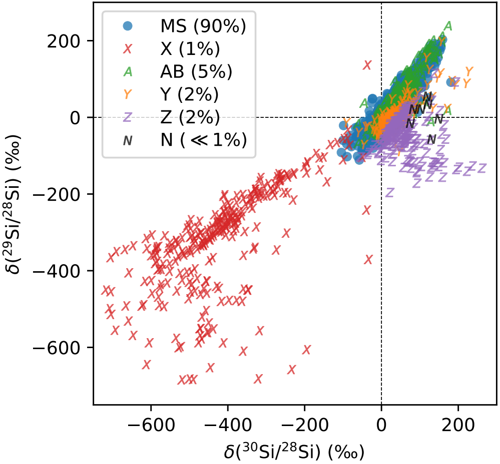

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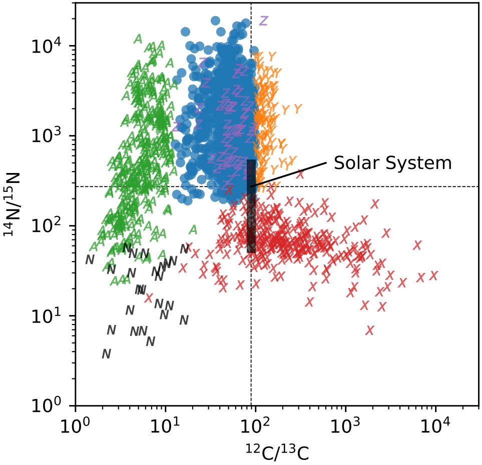
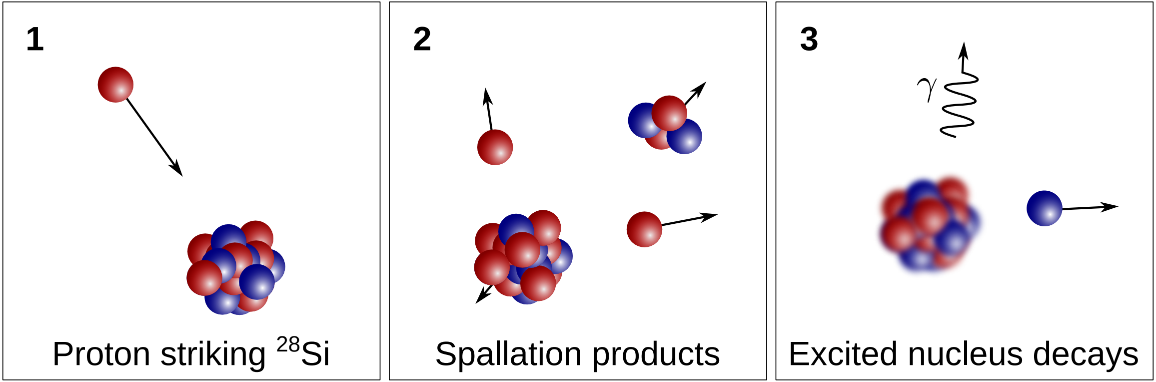
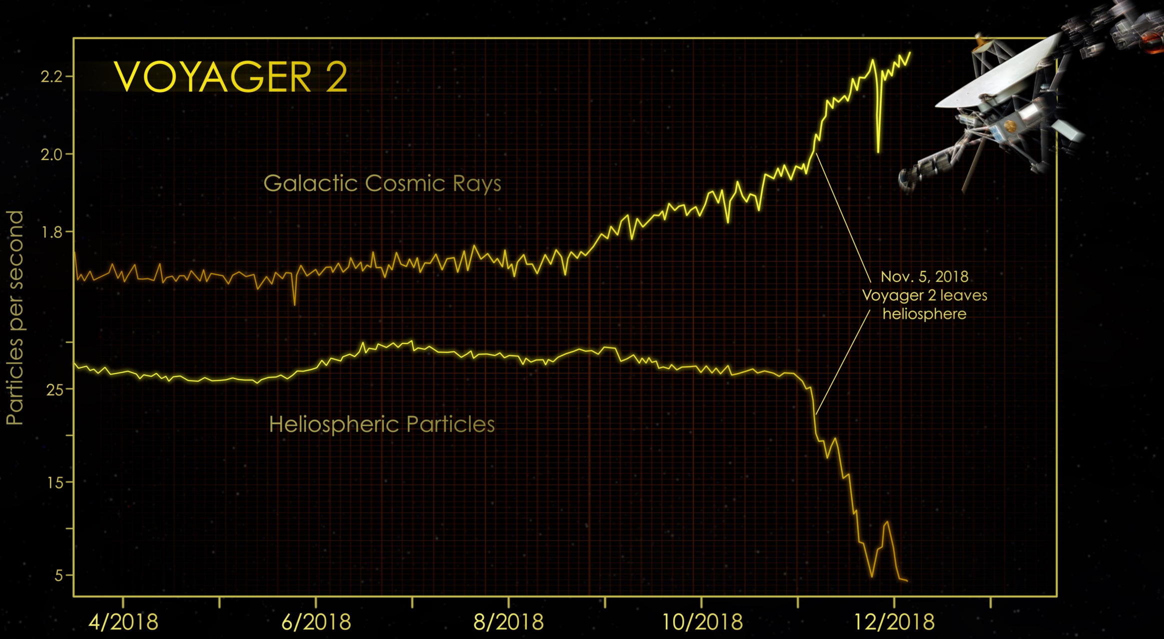


Comsmic ray induced spallation



- Cosmogenic nuclide production rates based on galactic cosmic ray spectrum in interstellar medium (Trappitsch and Leya, 2016)

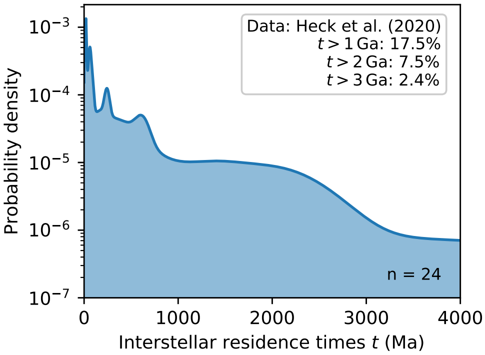
VOYAGER 2



Nov. 5, 2018
Voyager 2 leaves
heliosphere

How old are presolar grains? At least 4.5 billion years!

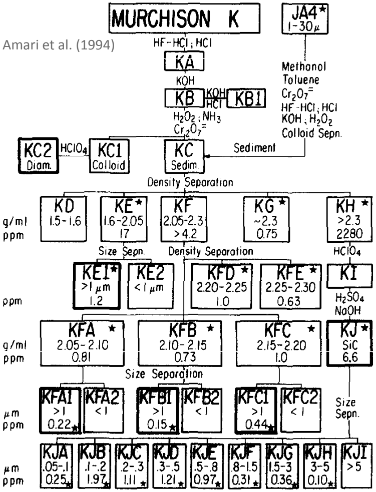
- Cosmic-rays in ISM irradiate presolar grain
- Production of cosmogenic ^{21}Ne
  - Not expected to condense into grain
  - Concentration c can be measured
  - Production rate p can be calculated
  - Exposure time $t = c/p$
- Heck et al. (2020): Measured cosmic ray exposure ages for 40 SiC grains
-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



Data from Heck et al. (2020)

Preparing samples for analysis

- Chemical separation to remove Solar System phases
- Density separation in heavy-liquids to isolate SiC
- Drop-deposition on ultra-clean gold foil
- Imaging by secondary electron microscopy
  - Phase detection by energy dispersive X-rays
  - Mapping of sample mount for navigation


Amari et al. (1994)

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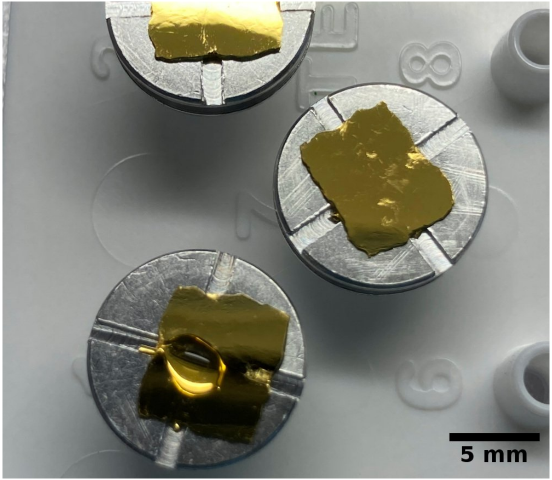

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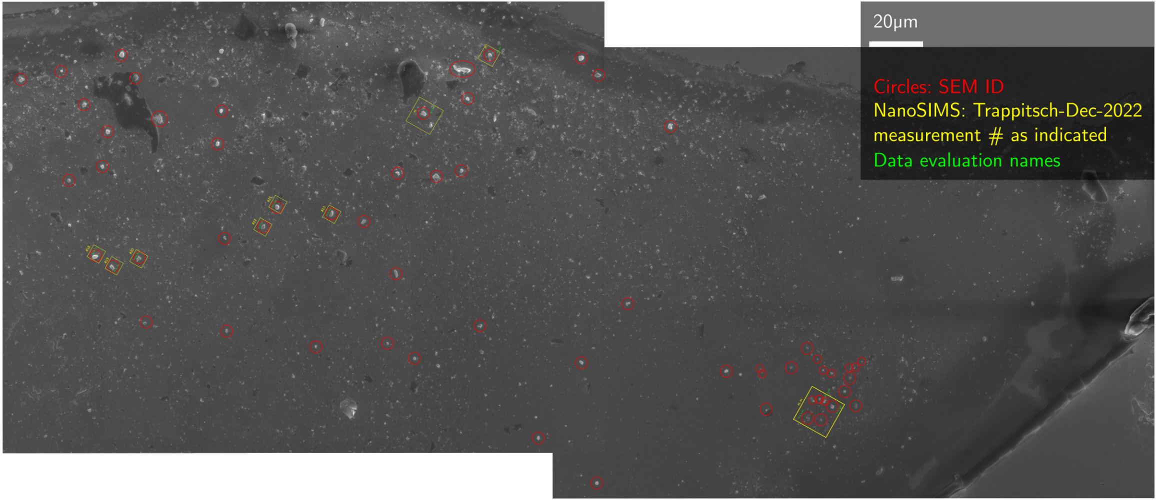
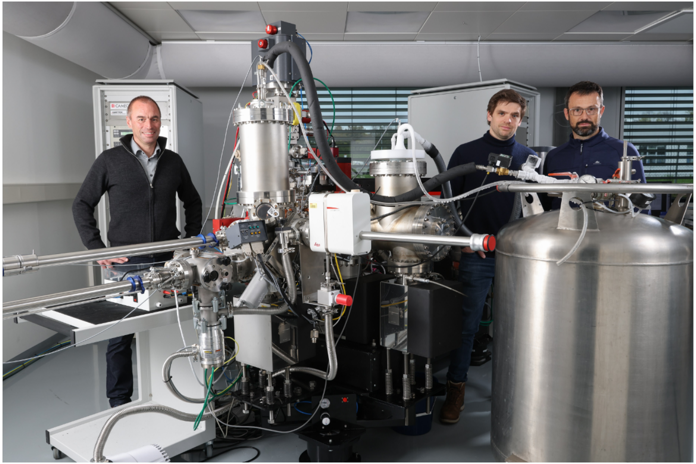
Detection of SiC

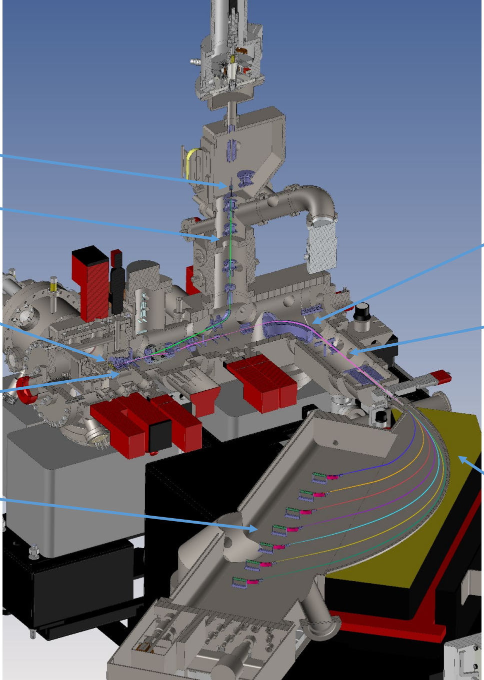


Nanoscale Secondary Ion Mass Spectrometry (NanoSIMS)

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



CryoNanoSIMS at EPFL/UNIL



Cesium Source

Primary column

Sample

Coaxiale lens

Multicollection

Electrostatic sector

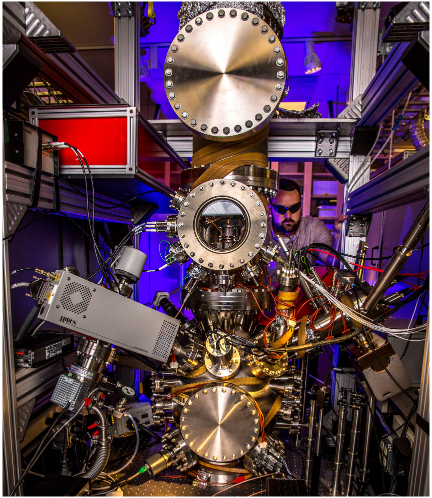
Coupling

Magnetic sector

Courtesy: Florent Plane

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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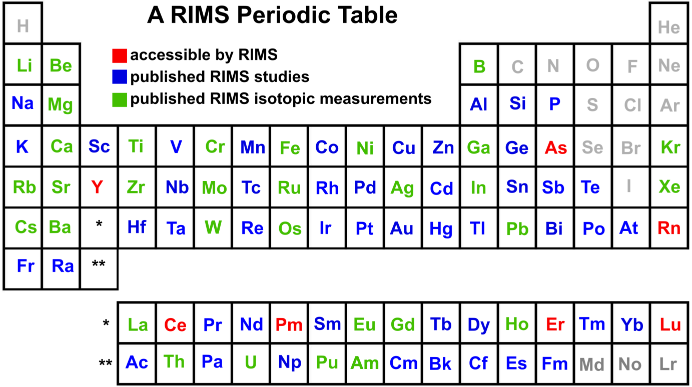


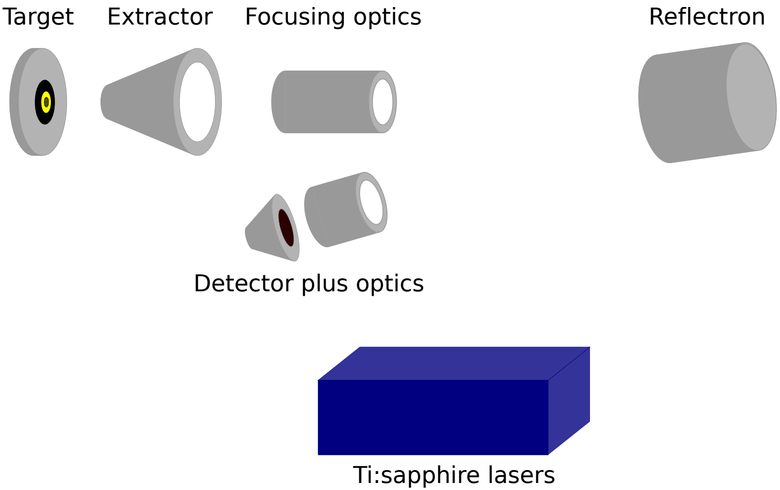
A RIMS Periodic Table

🟥 accessible by RIMS
🟦 published RIMS studies
🟩 published RIMS isotopic measurements

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	*	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	**															
		*	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
		**	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

after Savina and Trappitsch (2019)

An overview of Resonance Ionization Mass Spectrometry (RIMS)



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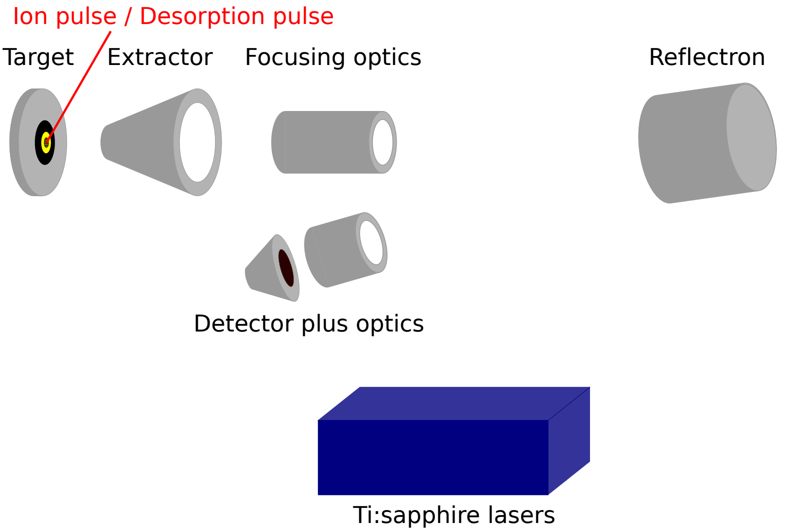

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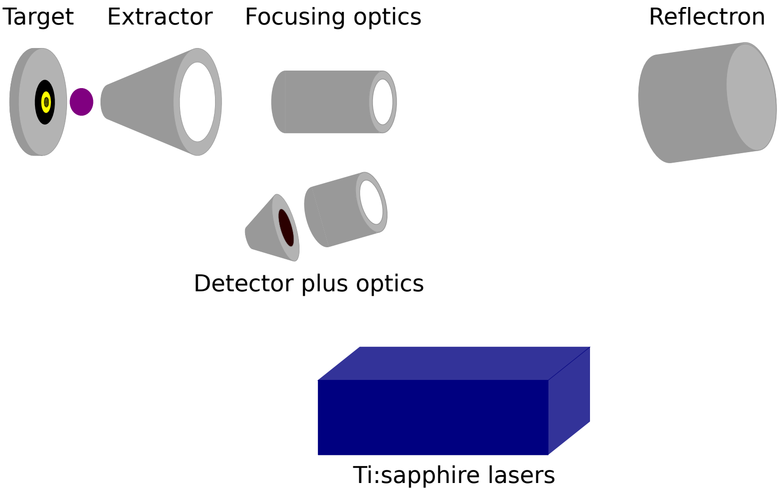

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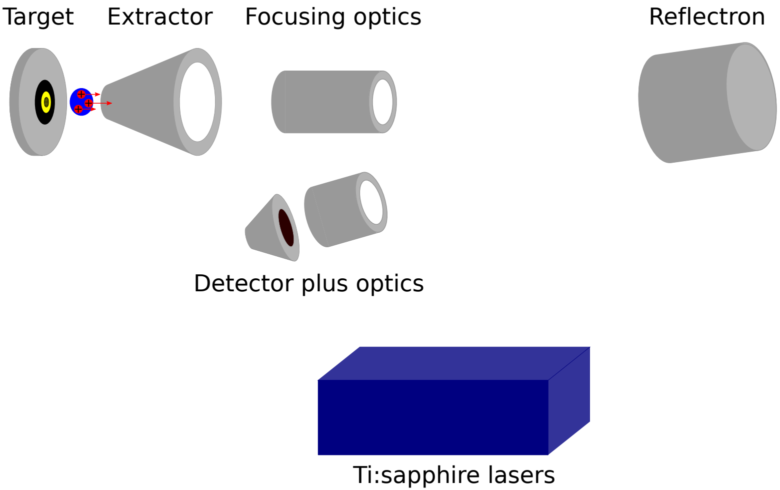

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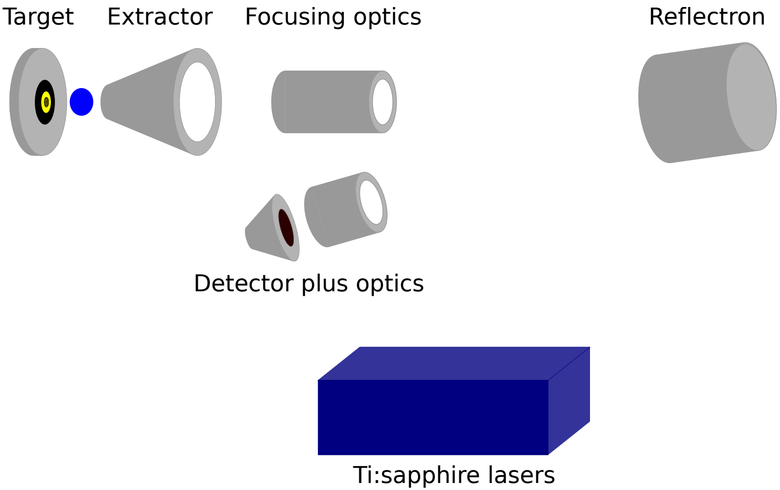

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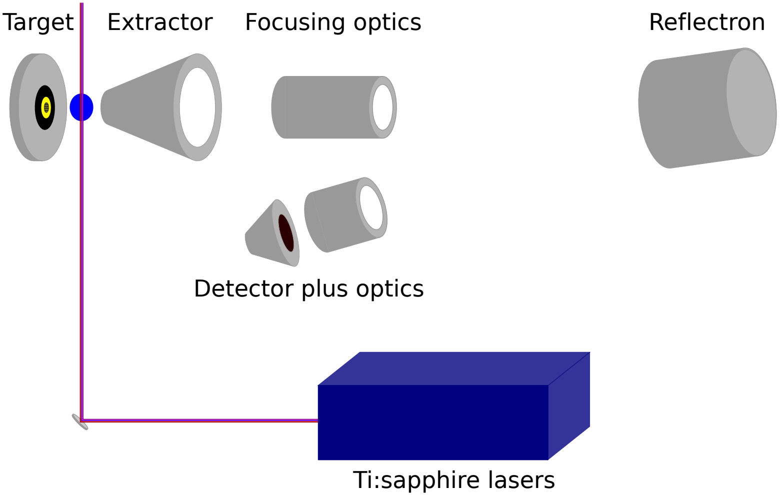

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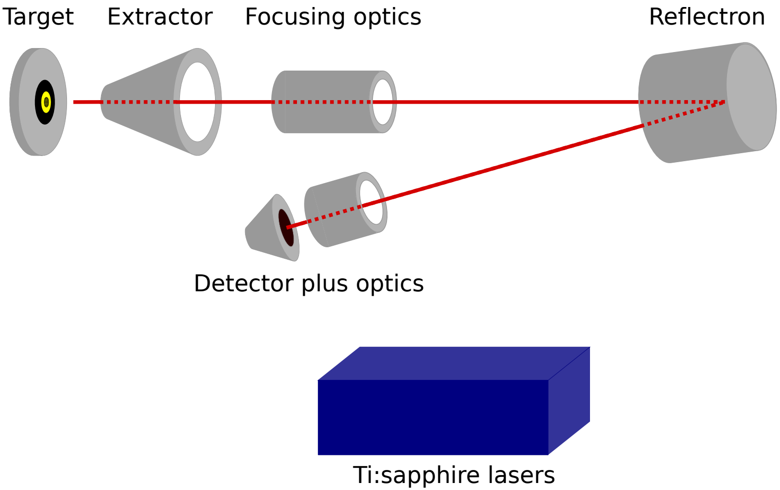
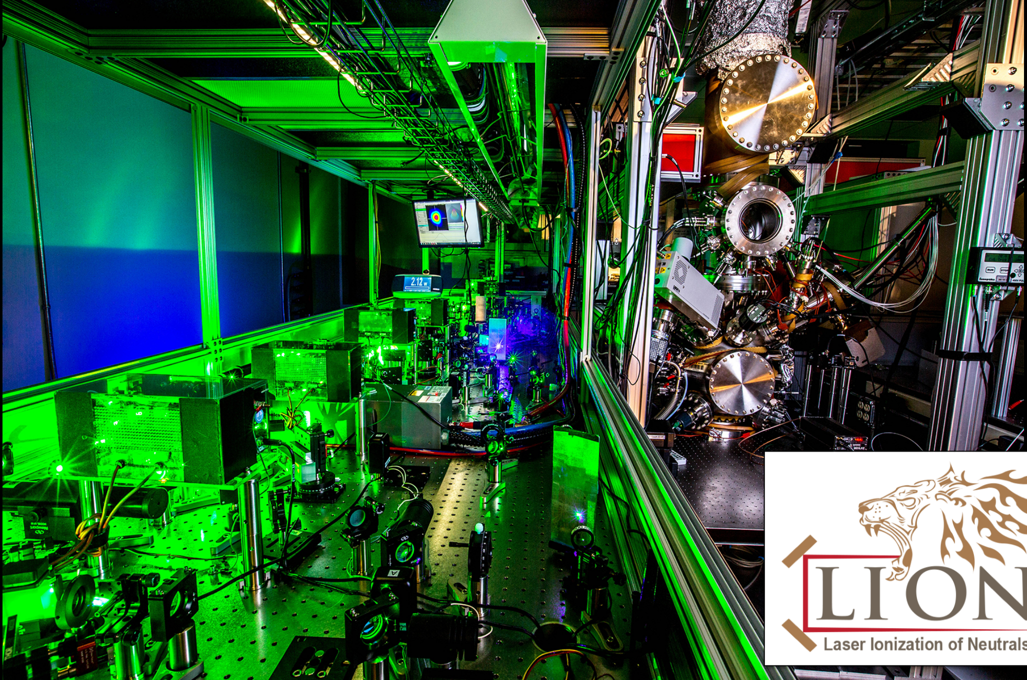
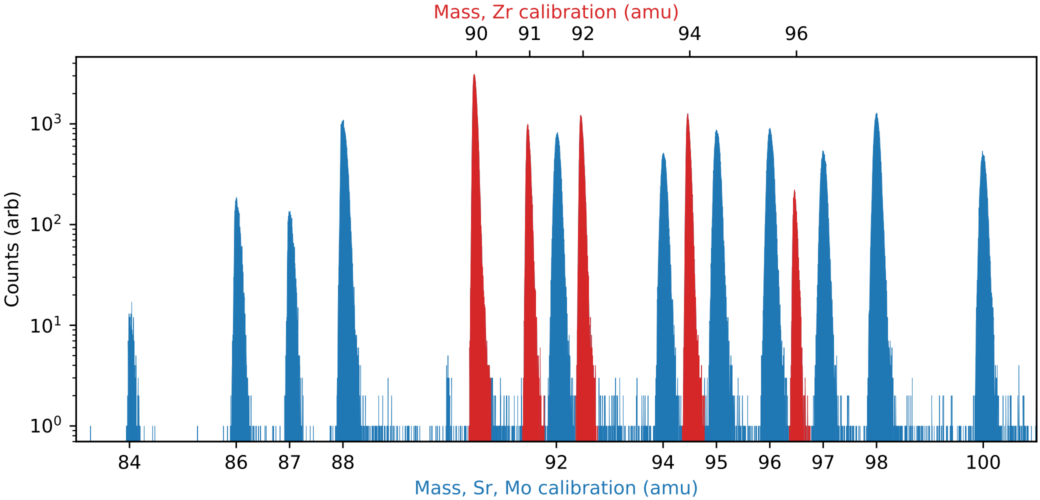




LION

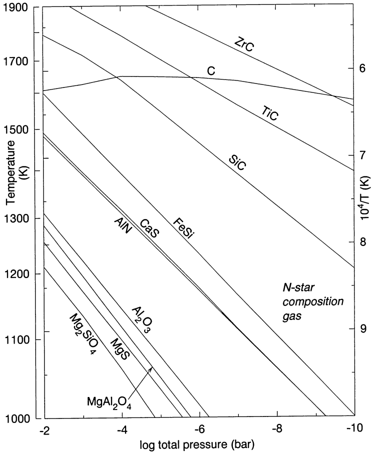
Laser Ionization of Neutrals

Simultaneous Sr, Zr, and Mo analysis (Shulaker et al., 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
- Micrometer-sized grains must be free of solar contamination



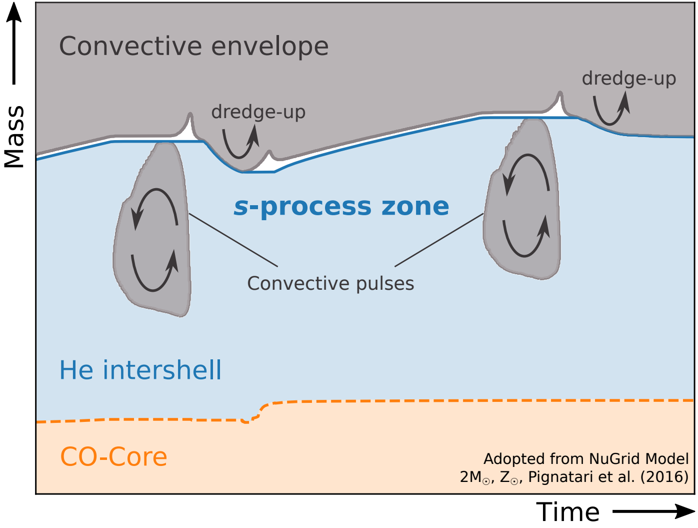
C-star condensation (Lodders and Fegley, 1999)

Asymptotic Giant Branch (AGB) stars

- Star expands rapidly, and cools
- Cycles between H and He burning
  → 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(α, n)^{16}O
  - ^{22}Ne(α, n)^{25}Mg

V838 Monocerotis (Credit: NASA/ESA)

Two neutron sources are at work



Adopted from NuGrid Model
$2M_{\odot}$, $Z_{\odot}$, Pignatari et al. (2016)

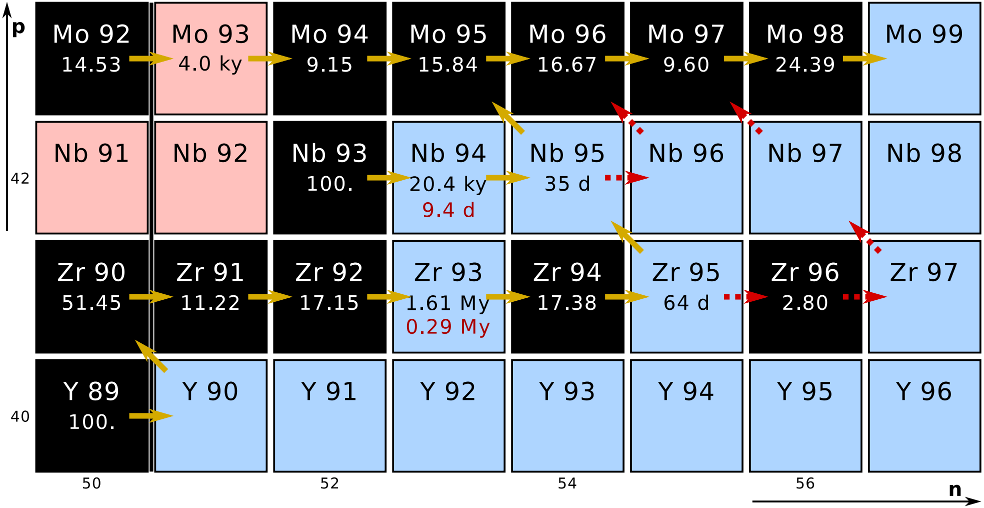
$^{13}C(\alpha, n)^{16}O$

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

$^{22}Ne(\alpha, n)^{25}Mg$

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

Where to look in presolar grains



Mo 92 14.53	Mo 93 4.0 ky	Mo 94 9.15	Mo 95 15.84	Mo 96 16.67	Mo 97 9.60	Mo 98 24.39	Mo 99
Nb 91	Nb 92	Nb 93 100.	Nb 94 20.4 ky 9.4 d	Nb 95 35 d	Nb 96	Nb 97	Nb 98
Zr 90 51.45	Zr 91 11.22	Zr 92 17.15	Zr 93 1.61 My 0.29 My	Zr 94 17.38	Zr 95 64 d	Zr 96 2.80	Zr 97
Y 89 100.	Y 90	Y 91	Y 92	Y 93	Y 94	Y 95	Y 96

Who wins: Neutron capture or β^--decay

- Branching ratio f_n

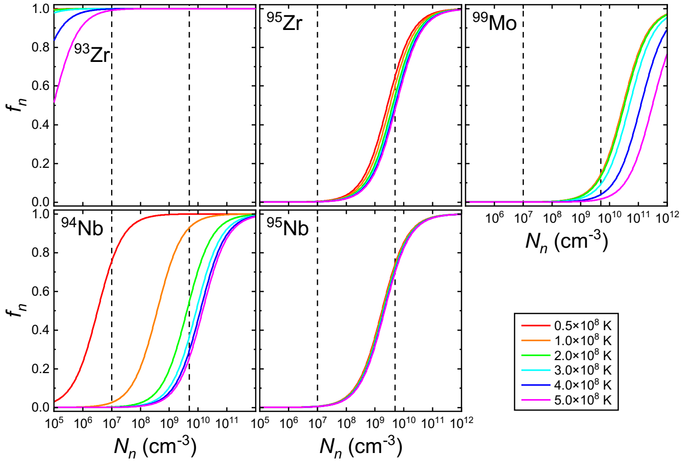
$$f_n = \frac{\lambda_n}{\lambda_n + \lambda_\beta}$$

- Neutron capture rate

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

- β^--decay rate

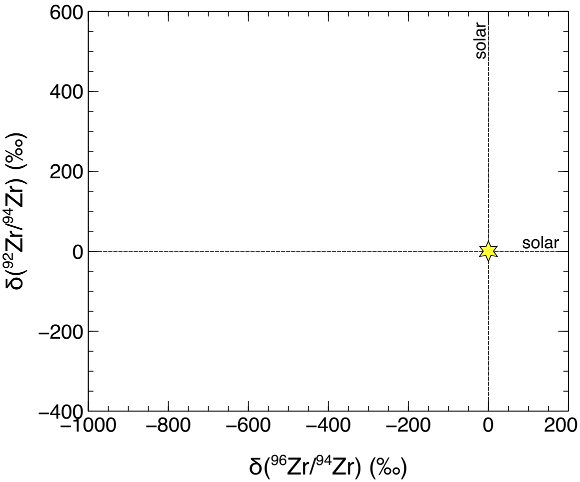
$$\lambda_\beta = \frac{\ln(2)}{T_{1/2}}$$



Stephan et al. (2019)

Deciphering the parent star conditions with presolar grain measurements

- SiC grains can only condense in carbon-rich areas, with C>O
- Heavier-mass stars get hotter
  → Activate ^{22}Ne neutron source more
  → 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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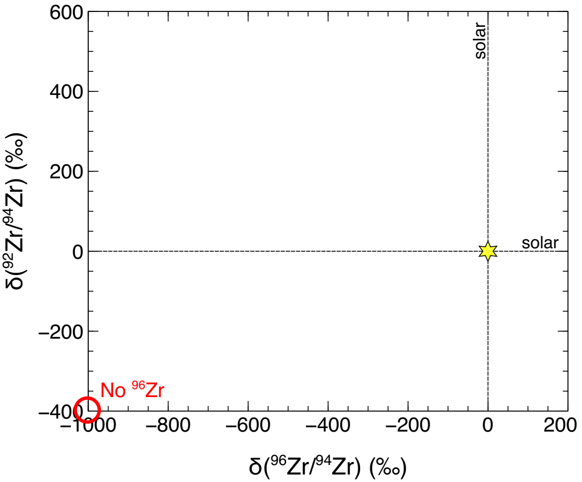

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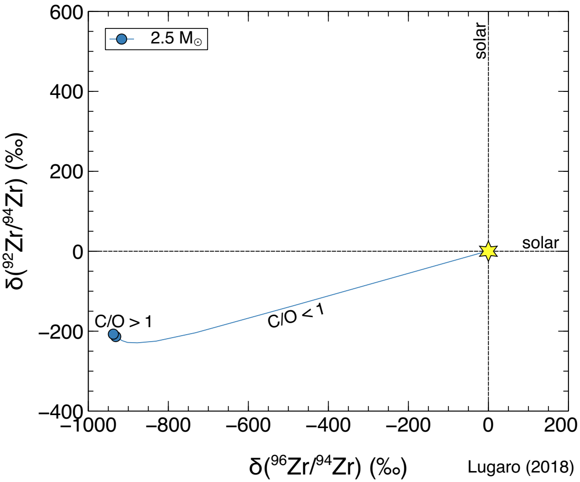

Lugaro (2018)

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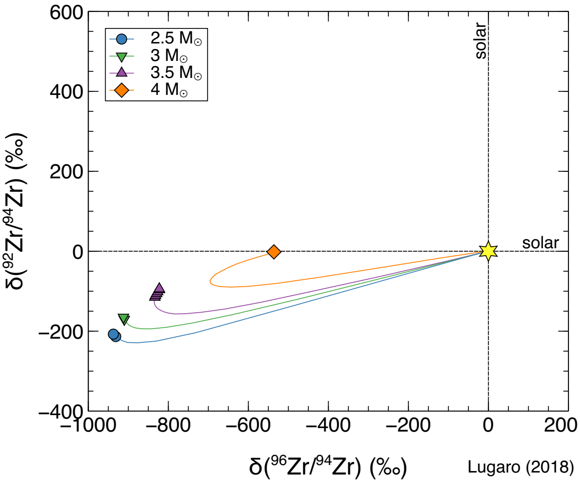

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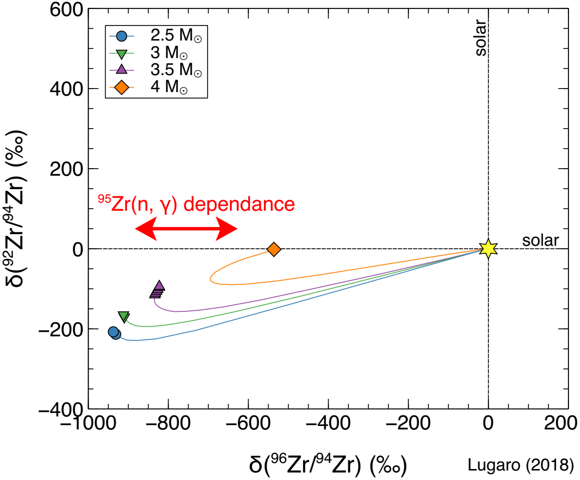

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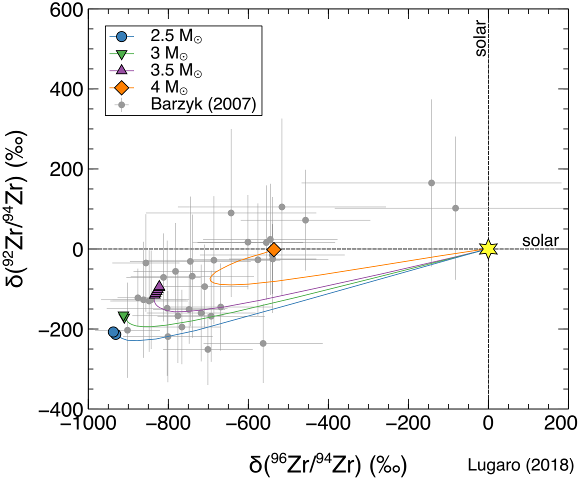
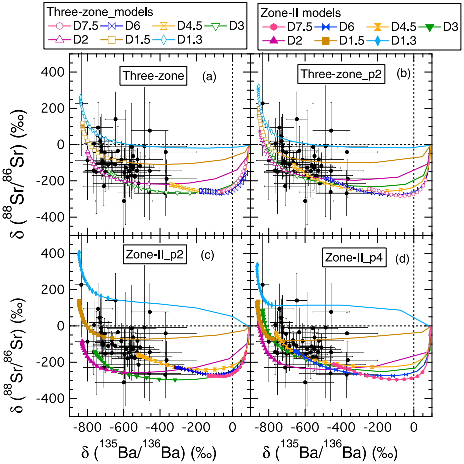


Lugaro (2018)

Multi-element measurements to constrain the ^{13}C-pocket

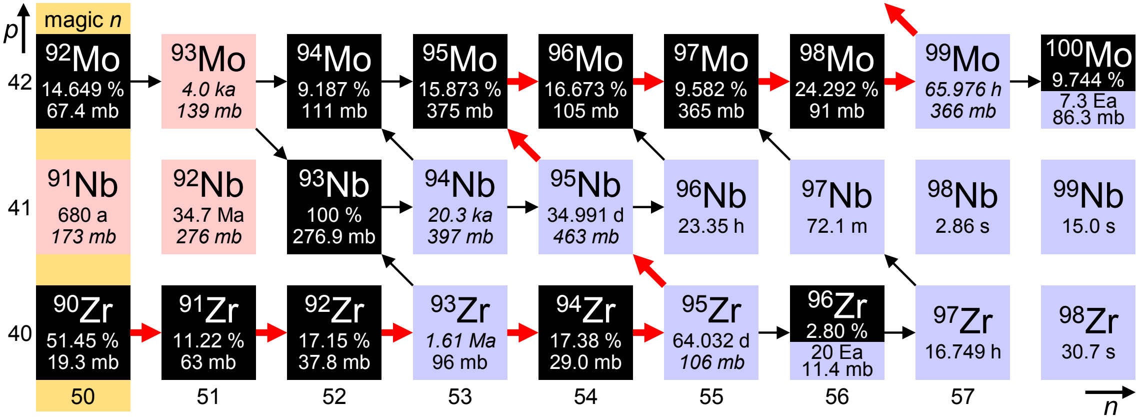
- Presolar grains allow us to probe the formation, size, and mass of the ^{13}C-pocket
- Multi-element isotopic measurements in individual grains can help to decipher the physics
- Many possible ^{13}C-pocket configurations can explain the measurements
- One set of model must fulfill all measurements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

See Nan Liu et al. (20xx)



Liu et al. (2015)

Mo: An ideal element to study *s*-process nucleosynthesis

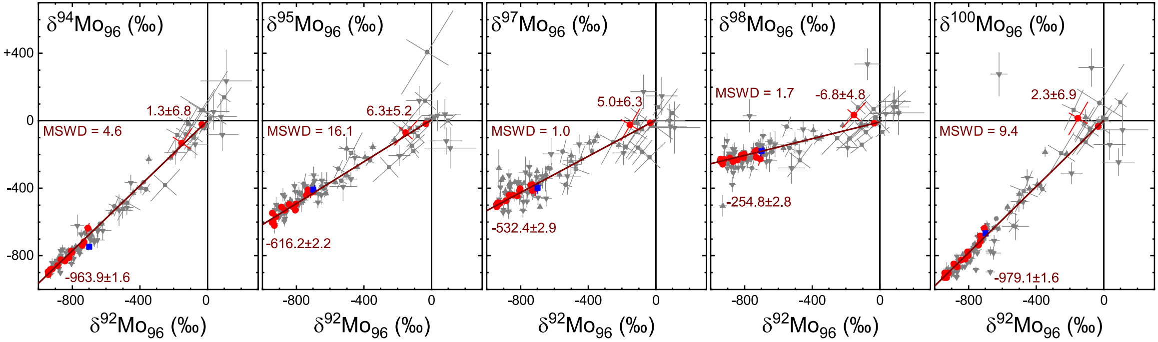


magic *n*

p	50	51	52	53	54	55	56	57	*n*
42	^{92}Mo 14.649 % 67.4 mb	^{93}Mo *4.0 ka* *139 mb*	^{94}Mo 9.187 % 111 mb	^{95}Mo 15.873 % 375 mb	^{96}Mo 16.673 % 105 mb	^{97}Mo 9.582 % 365 mb	^{98}Mo 24.292 % 91 mb	^{99}Mo *65.976 h* *366 mb*	^{100}Mo 9.744 % 7.3 Ea 86.3 mb
41	^{91}Nb 680 a *173 mb*	^{92}Nb 34.7 Ma *276 mb*	^{93}Nb 100 % 276.9 mb	^{94}Nb *20.3 ka* *397 mb*	^{95}Nb 34.991 d *463 mb*	^{96}Nb 23.35 h	^{97}Nb 72.1 m	^{98}Nb 2.86 s	^{99}Nb 15.0 s
40	^{90}Zr 51.45 % 19.3 mb	^{91}Zr 11.22 % 63 mb	^{92}Zr 17.15 % 37.8 mb	^{93}Zr *1.61 Ma* 96 mb	^{94}Zr 17.38 % 29.0 mb	^{95}Zr 64.032 d *106 mb*	^{96}Zr 2.80 % 20 Ea 11.4 mb	^{97}Zr 16.749 h	^{98}Zr 30.7 s

Stephan et al. (2019)

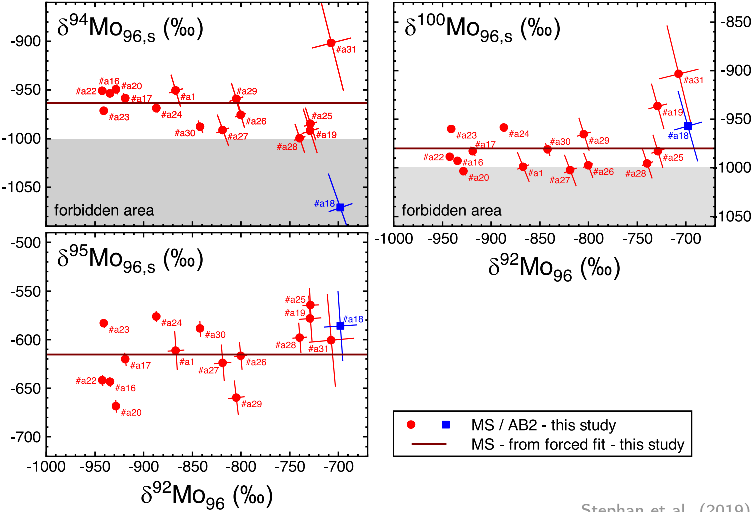
Deriving the *s*-process composition of Mo (Stephan et al., 2019)



- ^{92}Mo cannot be made by *s*-process and inherited amount is consumed
- Linear regressions through stardust data yields the pure *s*-process Mo composition

Variations in ^{94}Mo, ^{95}Mo, and ^{100}Mo isotopic composition

- Mo *s*-process trend constant among different grain types
- ^{97}Mo and ^{98}Mo constant
- Variations in ^{94}Mo, ^{95}Mo, and ^{100}Mo likely due to different stellar conditions
- Variations of temperature / neutron density around branch points
- **Mo p/r-ratio constant among this grain populations!**

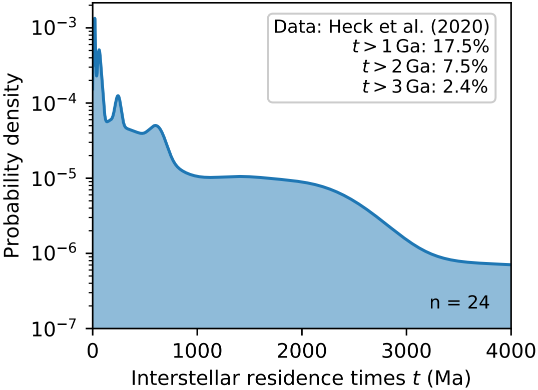


Stephan et al. (2019)

What does the constant Mo *p*/*r*-ratio tell us?

- 17 grains analyzed by Stephan et al.
  - Giant molecular clouds (GMC): Live for tens of Ma
  - Unlikely that all grains have parent stars from within this GMC
- Constant *p*/*r*-ratio
  - Constant throughout GCE
  - Co-production in the same astrophysical sites?
- What could account for co-production?
  - Neutrino-driven winds: stops around Ag
  - νr-process

Presolar grains: Isotopic observations to test these scenarios!



Data from Heck et al. (2020)

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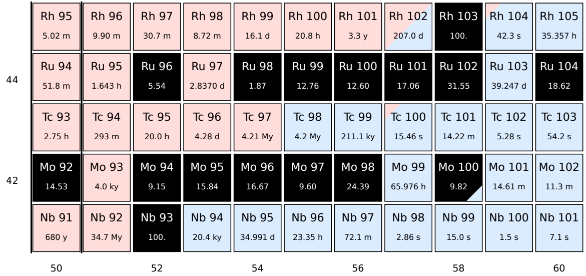


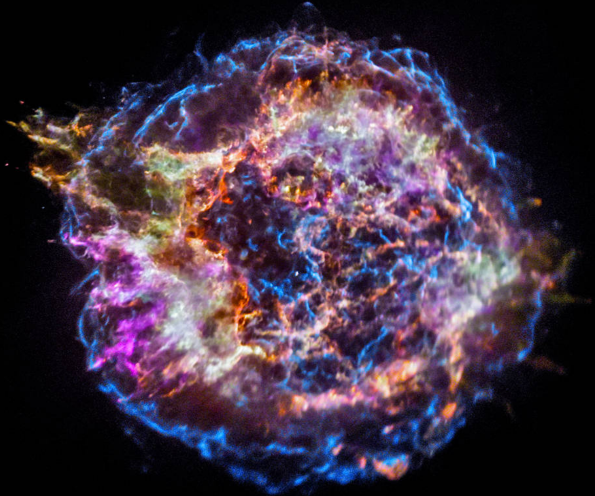
	Rh 95 5.02 m	Rh 96 9.90 m	Rh 97 30.7 m	Rh 98 8.72 m	Rh 99 16.1 d	Rh 100 20.8 h	Rh 101 3.3 y	Rh 102 207.0 d	Rh 103 100.	Rh 104 42.3 s	Rh 105 35.357 h
44	Ru 94 51.8 m	Ru 95 1.643 h	Ru 96 5.54	Ru 97 2.8370 d	Ru 98 1.87	Ru 99 12.76	Ru 100 12.60	Ru 101 17.06	Ru 102 31.55	Ru 103 39.247 d	Ru 104 18.62
	Tc 93 2.75 h	Tc 94 293 m	Tc 95 20.0 h	Tc 96 4.28 d	Tc 97 4.21 My	Tc 98 4.2 My	Tc 99 211.1 ky	Tc 100 15.46 s	Tc 101 14.22 m	Tc 102 5.28 s	Tc 103 54.2 s
42	Mo 92 14.53	Mo 93 4.0 ky	Mo 94 9.15	Mo 95 15.84	Mo 96 16.67	Mo 97 9.60	Mo 98 24.39	Mo 99 65.976 h	Mo 100 9.82	Mo 101 14.61 m	Mo 102 11.3 m
	Nb 91 680 y	Nb 92 34.7 My	Nb 93 100.	Nb 94 20.4 ky	Nb 95 34.991 d	Nb 96 23.35 h	Nb 97 72.1 m	Nb 98 2.86 s	Nb 99 15.0 s	Nb 100 1.5 s	Nb 101 7.1 s
	50		52		54		56		58		60

Further elements of interest, measurable in presolar grains

62	Sm 136 47 s	Sm 137 45 s	Sm 138 3.1 m	Sm 139 2.57 m	Sm 140 14.82 m	Sm 141 10.2 m	Sm 142 72.49 m	Sm 143 8.75 m	Sm 144 3.07	Sm 145 340 d	Sm 146 68 My	Sm 147 14.99	Sm 148 11.24	Sm 149 13.82	Sm 150 7.38	Sm 151 90 y	Sm 152 26.75	Sm 153 46.284 h	Sm 154 22.75
	Pm 135 49 s	Pm 136 107 s	Pm 137	Pm 138 10 s	Pm 139 4.15 m	Pm 140 9.2 s	Pm 141 20.90 m	Pm 142 40.5 s	Pm 143 265 d	Pm 144 363 d	Pm 145 17.7 y	Pm 146 5.53 y	Pm 147 2.6234 y	Pm 148 5.368 d	Pm 149 53.08 h	Pm 150 2.698 h	Pm 151 28.40 h	Pm 152 4.12 m	Pm 153 5.25 m
60	Nd 134 8.5 m	Nd 135 12.4 m	Nd 136 50.7 m	Nd 137 38.5 m	Nd 138 5.04 h	Nd 139 29.7 m	Nd 140 3.37 d	Nd 141 2.49 h	Nd 142 27.152	Nd 143 12.174	Nd 144 23.798	Nd 145 8.293	Nd 146 17.189	Nd 147 10.98 d	Nd 148 5.756	Nd 149 1.728 h	Nd 150 5.638	Nd 151 12.44 m	Nd 152 11.4 m
	Pr 133 6.5 m	Pr 134 17 m	Pr 135 24 m	Pr 136 13.1 m	Pr 137 1.28 h	Pr 138 1.45 m	Pr 139 4.41 h	Pr 140 3.39 m	Pr 141 100.	Pr 142 19.12 h	Pr 143 13.57 d	Pr 144 17.28 m	Pr 145 5.984 h	Pr 146 24.15 m	Pr 147 13.4 m	Pr 148 2.29 m	Pr 149 2.26 m	Pr 150 6.19 s	Pr 151 18.90 s
58	Ce 132 3.51 h	Ce 133 97 m	Ce 134 3.16 d	Ce 135 17.7 h	Ce 136 0.185	Ce 137 9.0 h	Ce 138 0.251	Ce 139 137.641 d	Ce 140 88.450	Ce 141 32.511 d	Ce 142 11.114	Ce 143 33.039 h	Ce 144 284.91 d	Ce 145 3.01 m	Ce 146 13.52 m	Ce 147 56.4 s	Ce 148 56.8 s	Ce 149 4.94 s	Ce 150 6.05 s
	La 131 59 m	La 132 4.8 h	La 133 3.912 h	La 134 6.45 m	La 135 19.5 h	La 136 9.87 m	La 137 60 ky	La 138 0.08881	La 139 99.91119	La 140 40.285 h	La 141 3.92 h	La 142 91.1 m	La 143 14.2 m	La 144 40.8 s	La 145 24.8 s	La 146 6.27 s	La 147 4.06 s	La 148 1.35 s	La 149 1.07 s
56	Ba 130 0.106	Ba 131 11.52 d	Ba 132 0.101	Ba 133 10.551 y	Ba 134 2.417	Ba 135 6.592	Ba 136 7.854	Ba 137 11.232	Ba 138 71.698	Ba 139 83.13 m	Ba 140 12.7527 d	Ba 141 18.27 m	Ba 142 10.6 m	Ba 143 14.5 s	Ba 144 11.5 s	Ba 145 4.31 s	Ba 146 2.22 s	Ba 147 894 ms	Ba 148 620 ms
	74		76		78		80		82		84		86		88		90		92

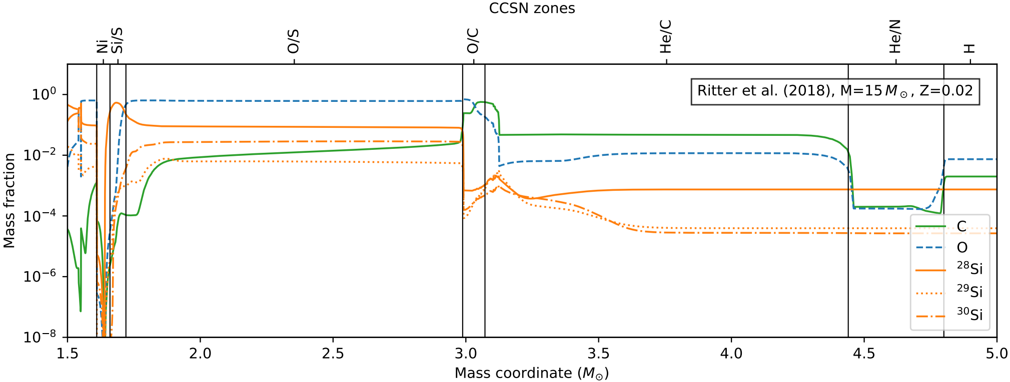
Further elements of interest, measurable in presolar grains

78	Pt 184 17.3 m	Pt 185 70.9 m	Pt 186 2.08 h	Pt 187 2.35 h	Pt 188 10.2 d	Pt 189 10.87 h	Pt 190 0.012	Pt 191 2.83 d	Pt 192 0.782	Pt 193 50 y	Pt 194 32.86	Pt 195 33.78	Pt 196 25.21	Pt 197 19.8915 h	Pt 198 7.36
	Ir 183 58 m	Ir 184 3.09 h	Ir 185 14.4 h	Ir 186 16.64 h	Ir 187 10.5 h	Ir 188 41.5 h	Ir 189 13.2 d	Ir 190 11.78 d	Ir 191 37.3	Ir 192 73.830 d	Ir 193 62.7	Ir 194 19.28 h	Ir 195 2.29 h	Ir 196 52 s	Ir 197 5.8 m
76	Os 182 21.84 h	Os 183 13.0 h	Os 184 0.02	Os 185 92.95 d	Os 186 1.59	Os 187 1.96	Os 188 13.24	Os 189 16.15	Os 190 26.26	Os 191 14.99 d	Os 192 40.78	Os 193 29.830 h	Os 194 6.0 y	Os 195 6.5 m	Os 196 34.9 m
	Re 181 19.9 h	Re 182 64.2 h	Re 183 70.0 d	Re 184 35.4 d	Re 185 37.40	Re 186 3.7183 d	Re 187 62.60	Re 188 17.0040 h	Re 189 24.3 h	Re 190 3.1 m	Re 191 9.8 m	Re 192 16.0 s	Re 193	Re 194 5 s	Re 195 6 s
74	W 180 0.12	W 181 121.2 d	W 182 26.50	W 183 14.31	W 184 30.64	W 185 75.1 d	W 186 28.43	W 187 24.000 h	W 188 69.78 d	W 189 10.7 m	W 190 30.0 m	W 191	W 192	W 193	W 194
	106		108		110		112		114		116		118		120



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

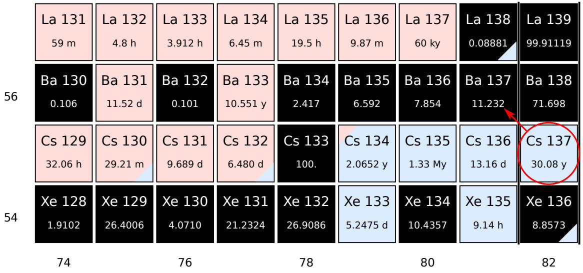
Supernova ejecta mixing: What regions do we probe with presolar grains?



- How does material mix in the supernova ejecta? It's already complicated in 1D!
- Can we follow dust formation in these ejecta?

Presolar grains from supernovae directly probe the ejecta

- Short-lived radionuclides allow to determine the speed of condensation
    - ^{137}Cs–^{137}Ba: $\sim 20\,\mathrm{a}$ (Ott et al., 2019)
- 1D dust condensation models:
    - Dependent on explosion energy
    - Only a small fraction forms SiC
    - Dust formation allows insight into supernova physics
    - Critical to understand observations
- Future: 3D dust formation models
    - How does mixing affect dust formation?
    - Benchmark with observations and presolar grain data
- **We need more grain measurements!**



	La 131 59 m	La 132 4.8 h	La 133 3.912 h	La 134 6.45 m	La 135 19.5 h	La 136 9.87 m	La 137 60 ky	La 138 0.08881	La 139 99.91119
56	Ba 130 0.106	Ba 131 11.52 d	Ba 132 0.101	Ba 133 10.551 y	Ba 134 2.417	Ba 135 6.592	Ba 136 7.854	Ba 137 11.232	Ba 138 71.698
	Cs 129 32.06 h	Cs 130 29.21 m	Cs 131 9.689 d	Cs 132 6.480 d	Cs 133 100.	Cs 134 2.0652 y	Cs 135 1.33 My	Cs 136 13.16 d	Cs 137 30.08 y
54	Xe 128 1.9102	Xe 129 26.4006	Xe 130 4.0710	Xe 131 21.2324	Xe 132 26.9086	Xe 133 5.2475 d	Xe 134 10.4357	Xe 135 9.14 h	Xe 136 8.8573
	74		76		78		80		82

- Live ^{137}Cs condenses into SiC grain
- Decays to ^{137}Ba
- ^{137}Ba isotope anomaly reveales condensation time

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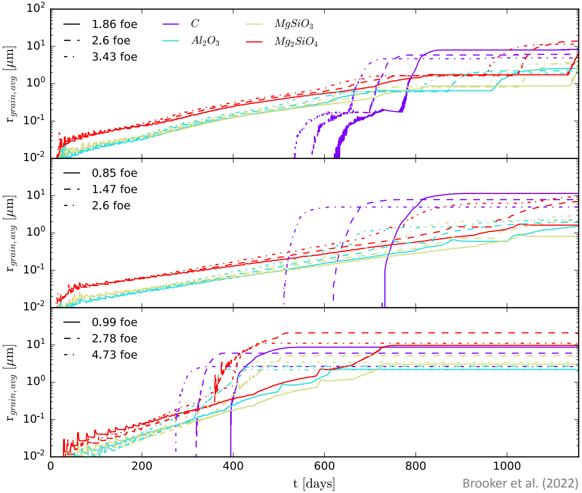
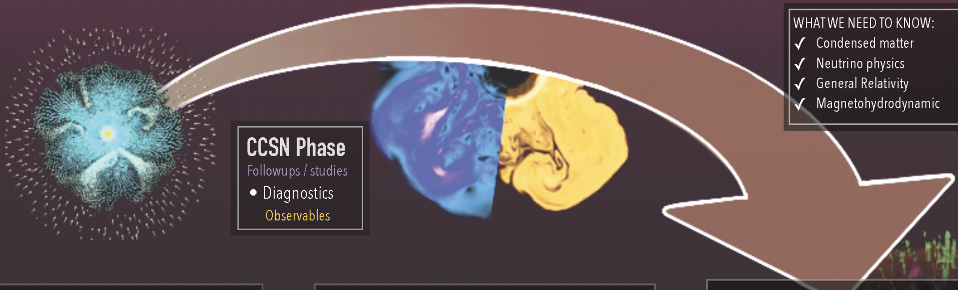


Brooker et al. (2022)

Understanding Core-Collapse Supernovae



CCSN Phase
Followups / studies
- Diagnostics
  Observables

WHAT WE NEED TO KNOW:
- ✓ Condensed matter
- ✓ Neutrino physics
- ✓ General Relativity
- ✓ Magnetohydrodynamic
- ✓ Plasma Turbulence
- ✓ Nuclear physics
- ✓ Cosmic-ray acceleration
- ✓ Radiation transport
- ✓ Chemistry of Galactic dust

Phase I – Core collapse

Radio followup (pulsars)
X-ray followup (binaries)
Multimessenger detections

- Prompt emission
  Gravitational waves
  MeV Neutrinos
- Compact remnants
  Mass and spin (through GW, radio and X-ray observations)

Phase II – Propagation of the blastwave through the star

EM followup for stellar abundance patterns
Dust study (in lab and with SN observations)

- Shock breakout
  UVOIR and X-ray light curves, spectra
- Nucleosynthetic yields
  Galactic dust composition
  Galactic chemical evolution

Phase III –Propagation of the blastwave through the circumstellar medium

Broad band followup (Radio – gamma-ray)

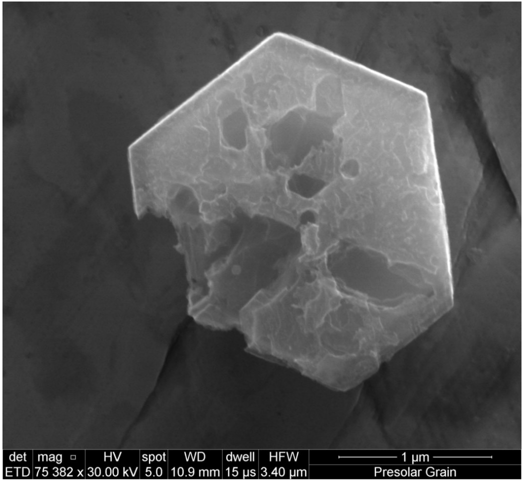
- Temporal evolution of emitted radiation
  Light curves and spectra
- Supernova remnant
  Light curves, spectra (lines)
  Imaging of morphology (asymmetric explosions)
  Polarimetry (magnetic fields structure)

Fryer et al. (2023)

Presolar grain measurements allow hands-on astrophysics

- Presolar grains allow us to directly probe stellar nucleosynthesis in the laboratory
- AGB star grains
    - Understanding the *s*-process
    - Galactic chemical evolution
- Supernova grains
    - Timing of dust condensation
    - Probe nucleosynthesis
    - Only few measurements beyond the iron peak available so far

Another Messenger to Elucidate our Understanding of Nuclear Astrophysics!



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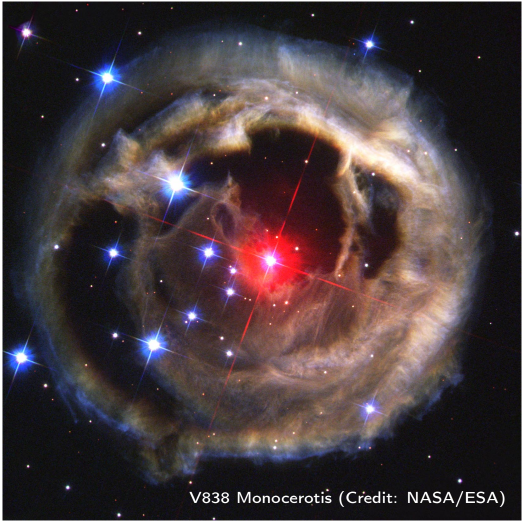

V838 Monocerotis (Credit: NASA/ESA)

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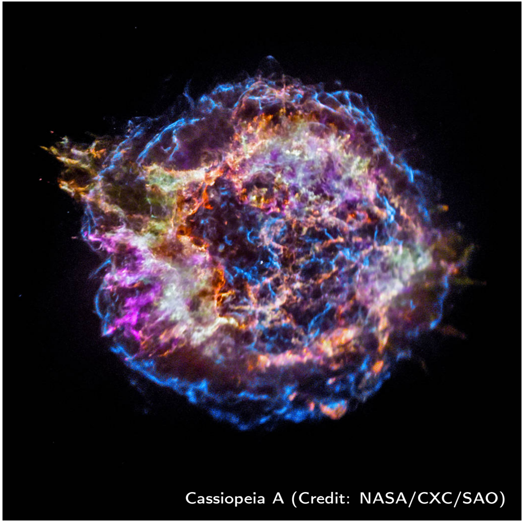


Cassiopeia A (Credit: NASA/CXC/SAO)

Where to go from here?

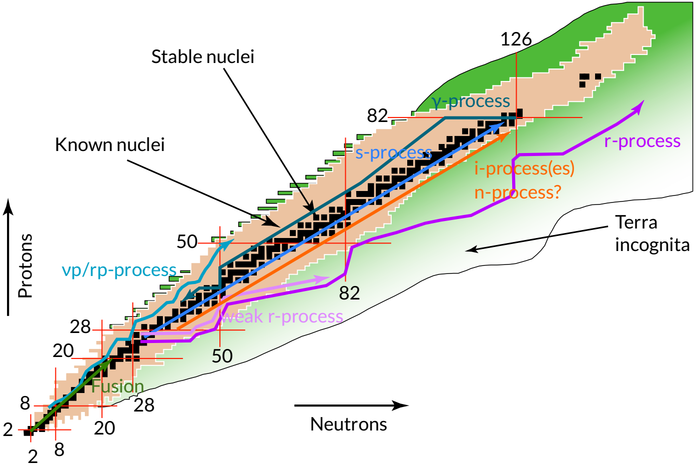
Galactic chemical evolution of the solar neighborhood

- For which elements are p/r-ratios constant?

Core-collapse supernovae

- Where do presolar grains condense?
- What nucleosynthesis processes are recorded?
- Can we track the nuclear enginge?

Stay tuned!



Adopted after figure by Frank Timmes, ASU

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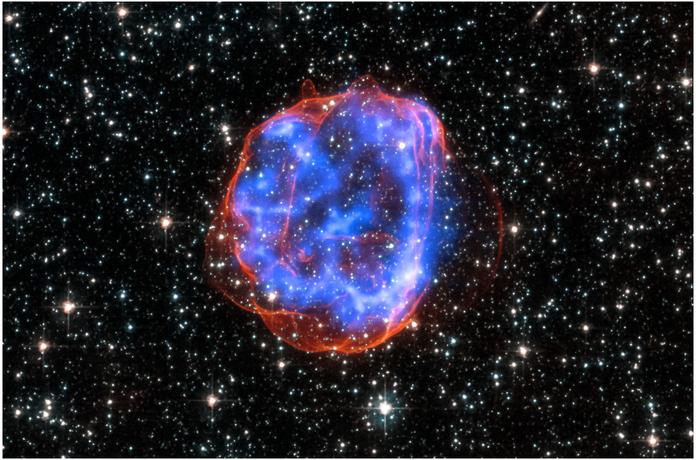

SNR E0519-69.0 (Credit: X-ray: NASA/CXC/Rutgers/J.Hughes; Optical: NASA/STSc)

Thank you! Questions?

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

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Los Alamos National Laboratory: Chris Fryer, Chris Mauney

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

Konkoly Observatory Marco Pignatari