Hands-on Astrophysics

Analysis of Presolar Stardust Grains to Decipher Stellar Nucleosynthesis

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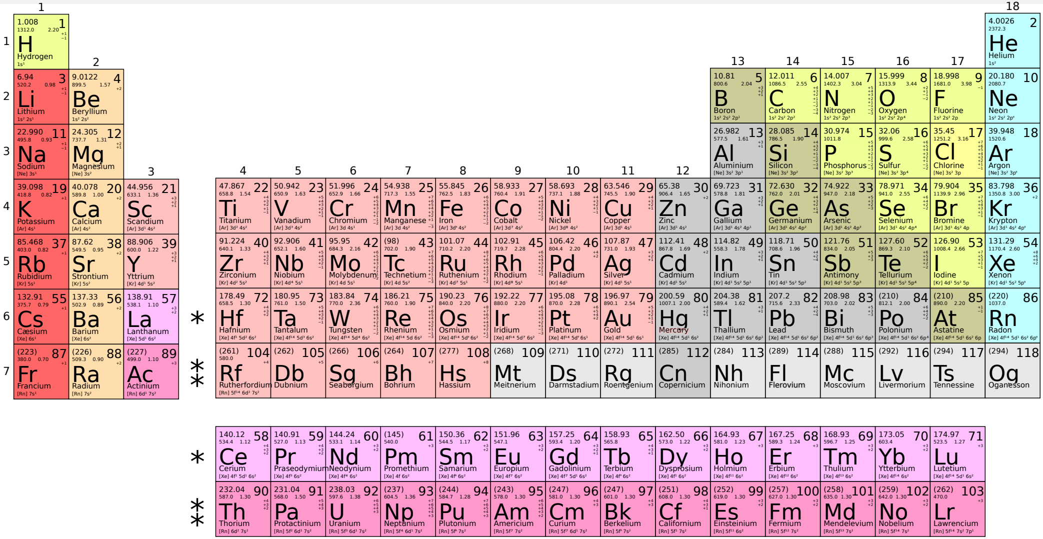
Illuminated Dust Around Supergiant Star V838 Monocerotis (Credit: NASA, AURA/STScI)

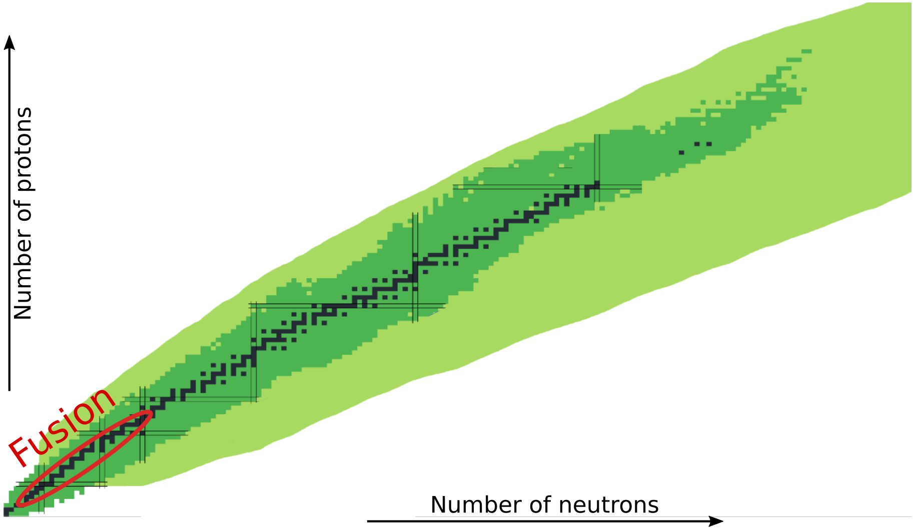
Elements that formed during Big Bang nucleosynthesis

	1	18
1	1.008 1 1312.0 2.20 +1 −1 **H** Hydrogen $1s^1$	4.0026 2 2372.3 **He** Helium $1s^2$
2	6.94 3 520.2 0.98 +1 −1 **Li** Lithium $1s^2\ 2s^1$	

The rest of the elements – what's left to explain



Stellar nucleosynthesis – the three main processes (Burbidge et al., 1957)



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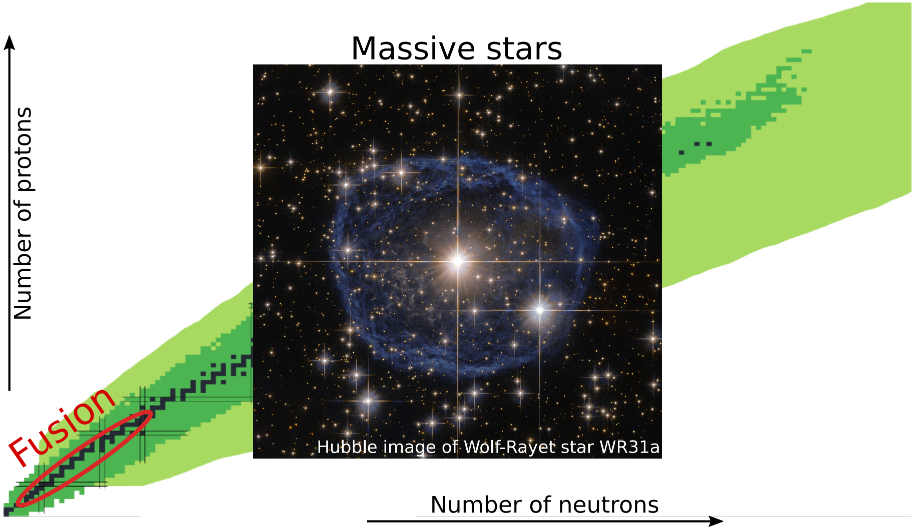

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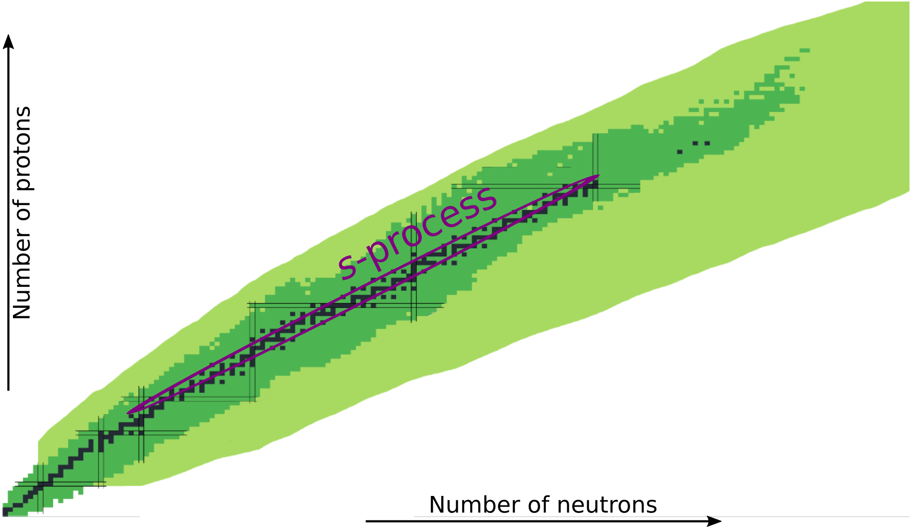

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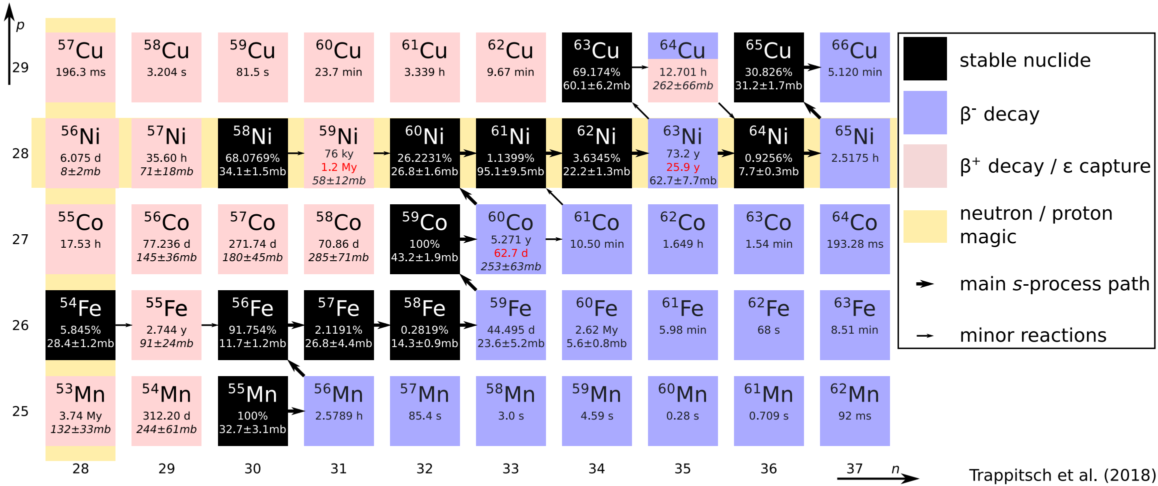

Trappitsch et al. (2018)

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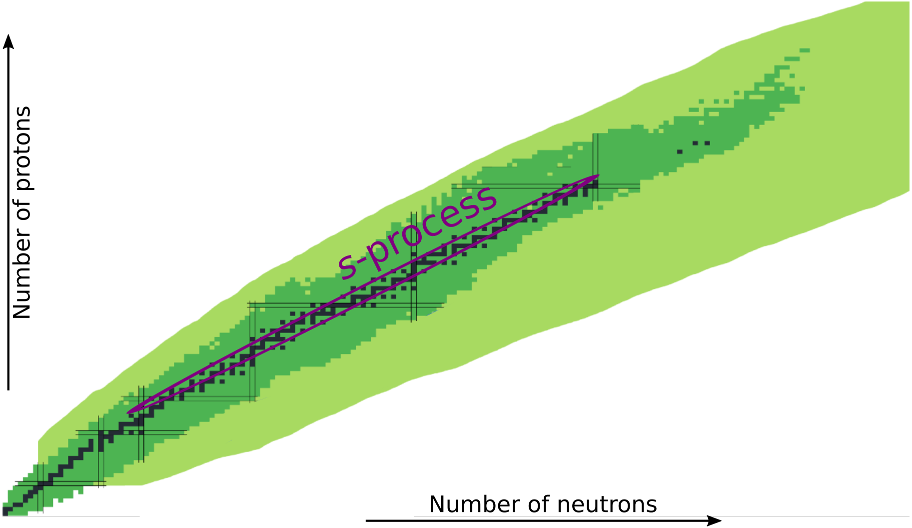

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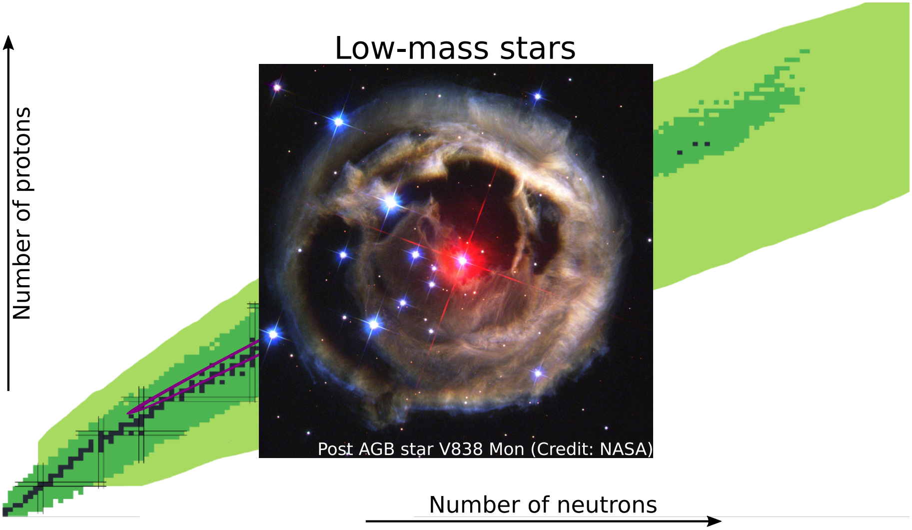

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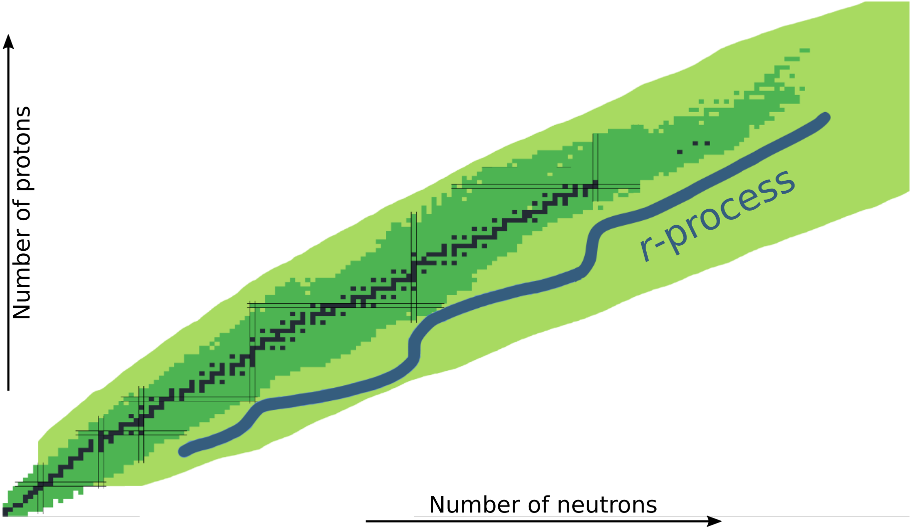

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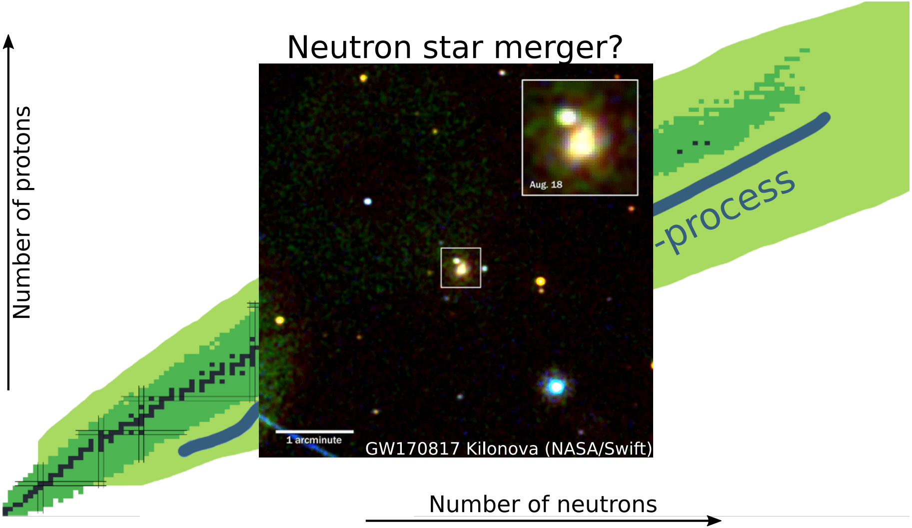
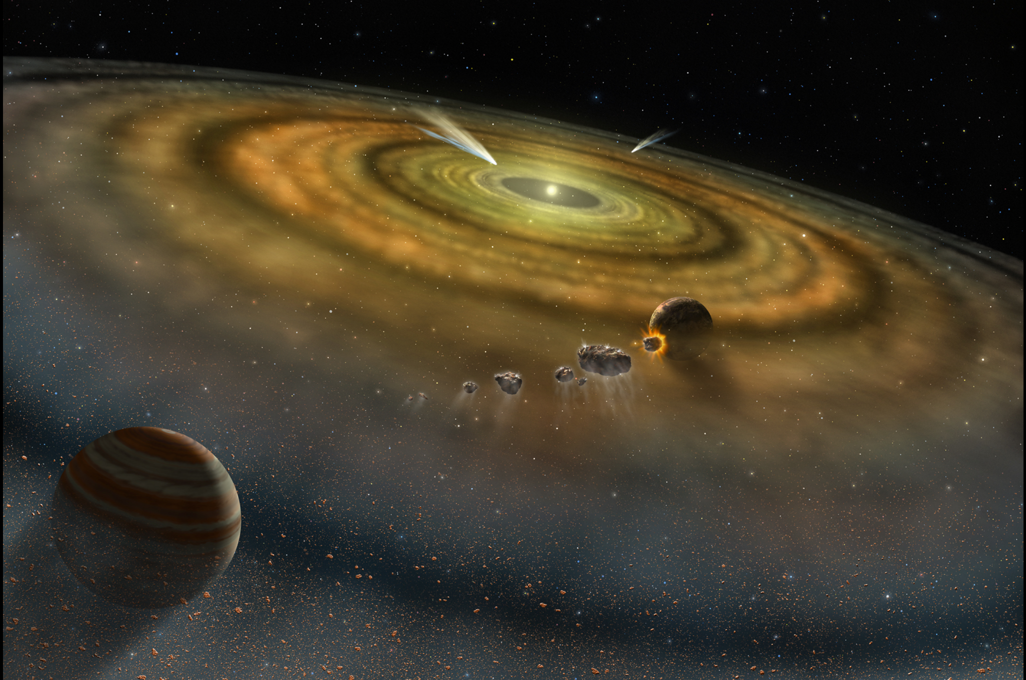


Neutron star merger?

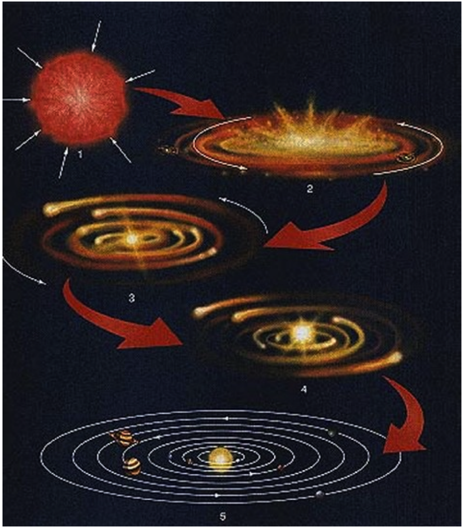
GW170817 Kilonova (NASA/Swift)



Solar System formation from average material in Milky Way

- Formation of the first Solar System solids: 4.567 Ga ago
- Composition of the solar nebula defined by galactic chemical evolution (GCE)
- GCE of Milky Way prior to Solar System formation: ~ 9 Ga

Understanding the origin of the Solar System requires knowledge on how the formation took place and where its material originated



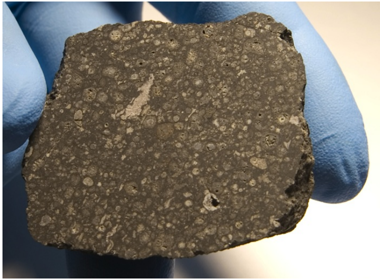
The witnesses of the early Solar System

Meteorites

- Unaltered, primitive meteorites
- Analyze solar nebula composition
- Short-lived radionuclides to inform early Solar System timing

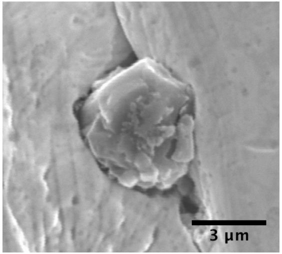
Presolar grains

- Incorporated into meteorite parent bodies
- Bona fide stardust
- Recorded the composition of their parent star

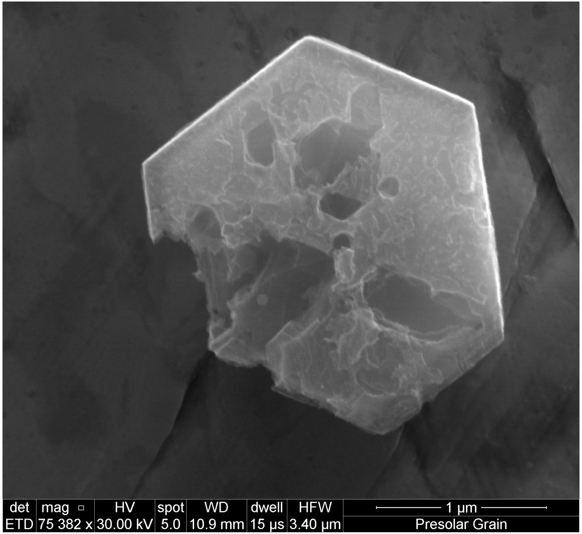


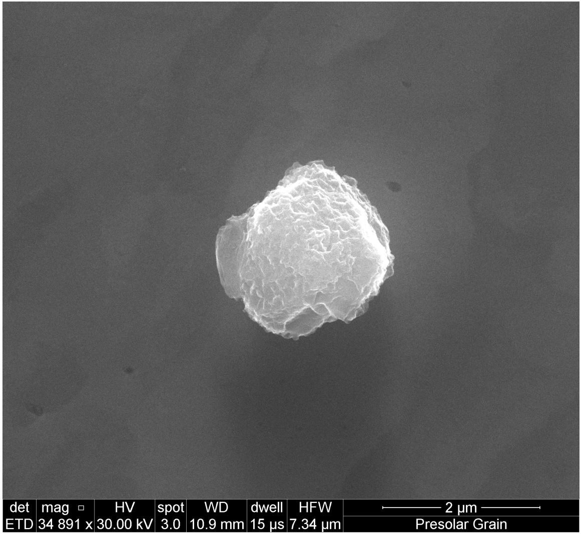
Allende CV3 chondrite

Presolar SiC grain from Murchison CM2 chondrite



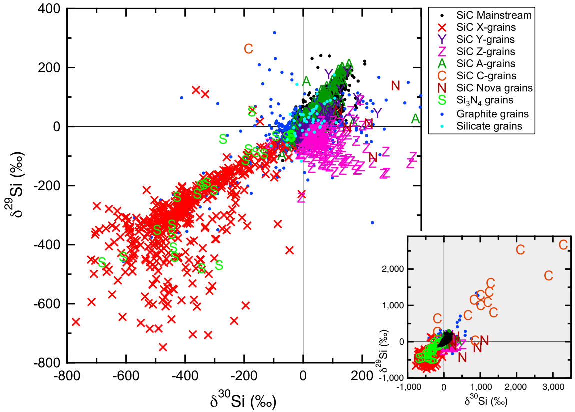
Presolar grains: stellar remnants





Presolar stardust and their parent stars

- δ-units: Deviation from solar (‰)
- Presolar grains identified by their extreme isotopic composition
- SiC grains: best studied samples
- 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



Davis (2011)

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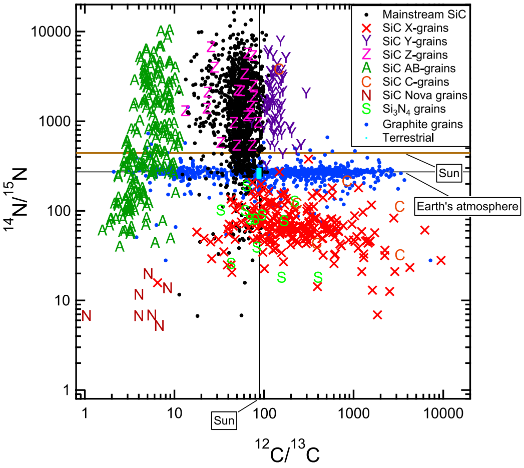
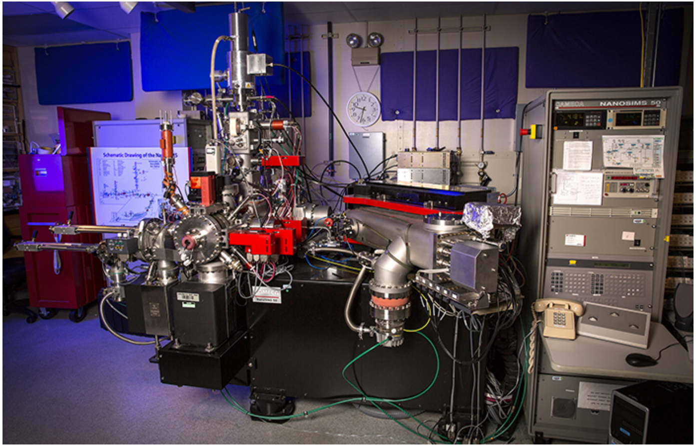


Davis (2011)

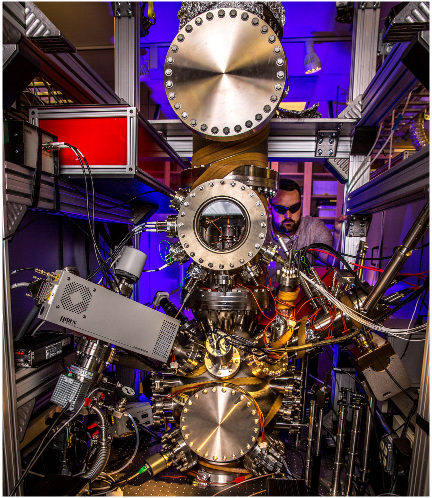
Classification: Analyzing the grain's C, Si isotopic compositions

- Analyze the isotopic composition of Si, C, (N) in SiC grains
- NanoSIMS: Nanoscale Secondary Ion Mass Spectrometer
- Secondary ions analyzed
  $\rightarrow$ prone to isobaric interferences
- Ideal instrument to measure major isotopic composition



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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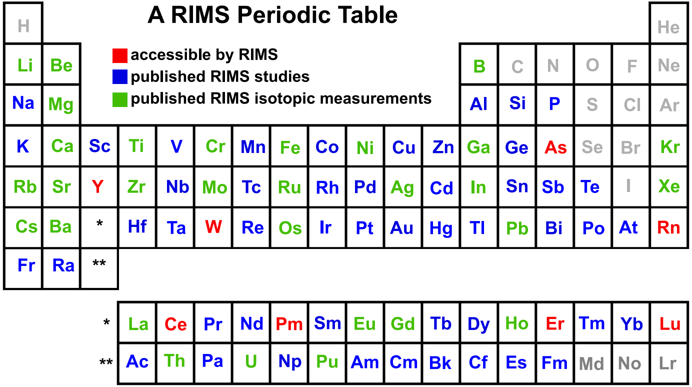
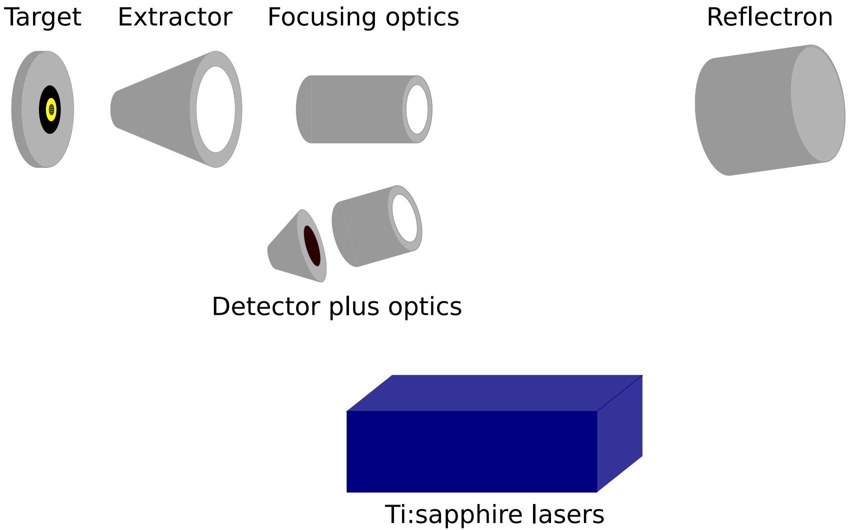
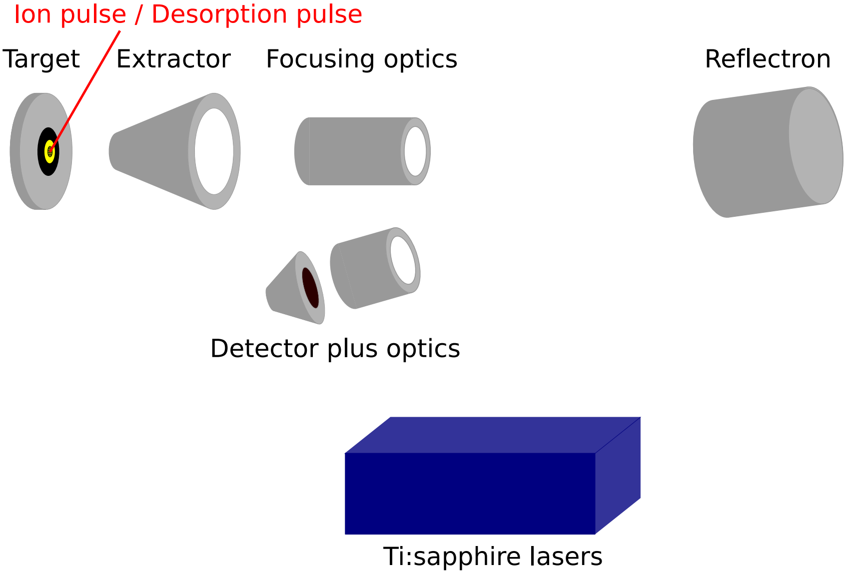


Savina and Trappitsch (2019)


Target
Extractor
Focusing optics
Reflectron
Detector plus optics
Ti:sapphire lasers


Ion pulse / Desorption pulse
Target
Extractor
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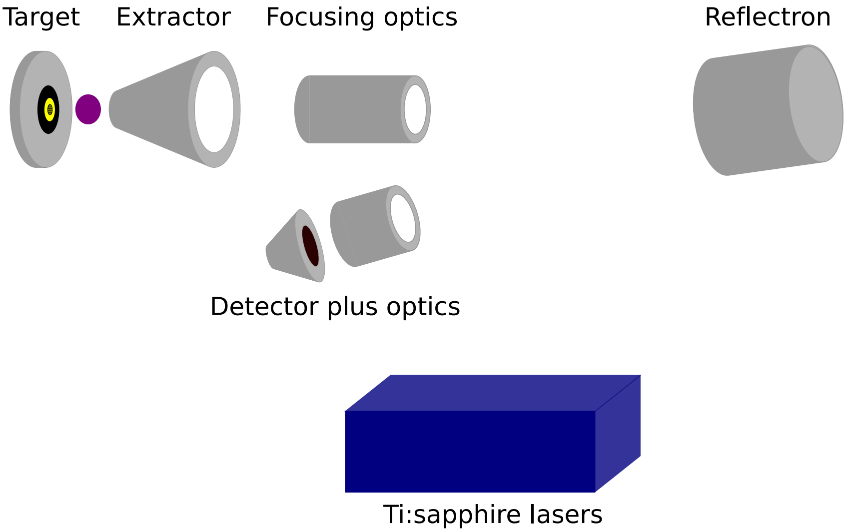
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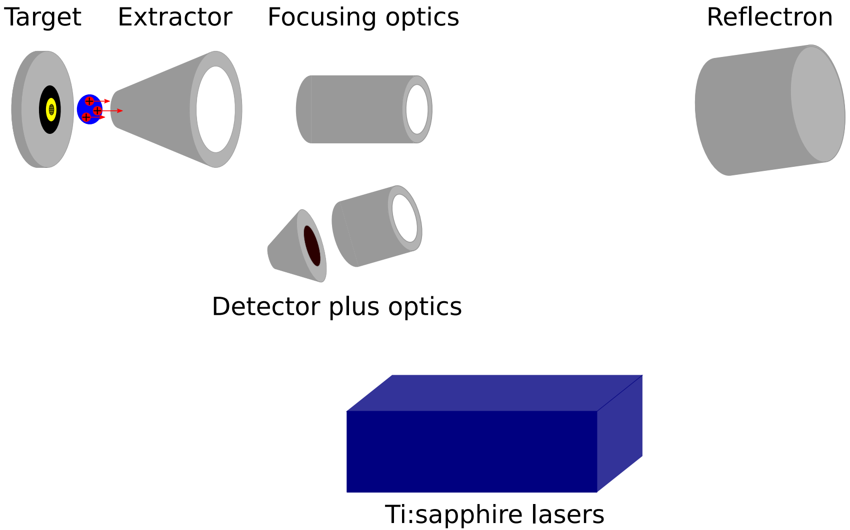
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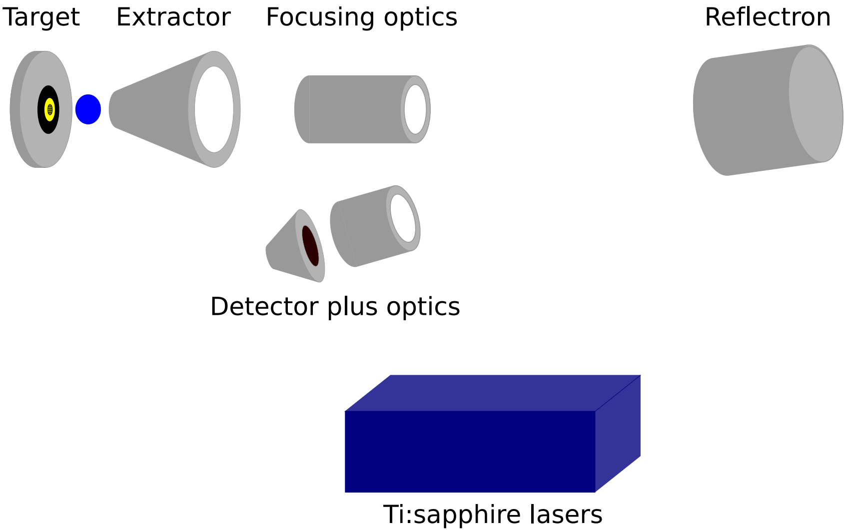
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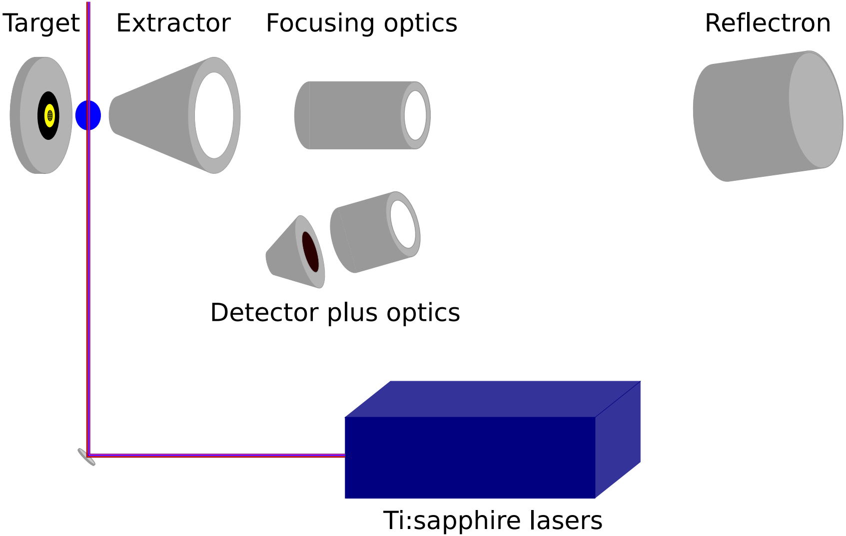
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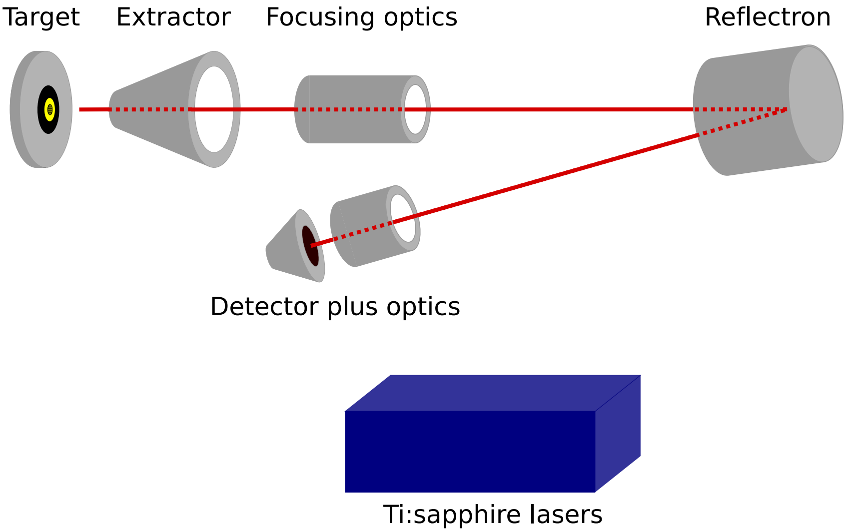
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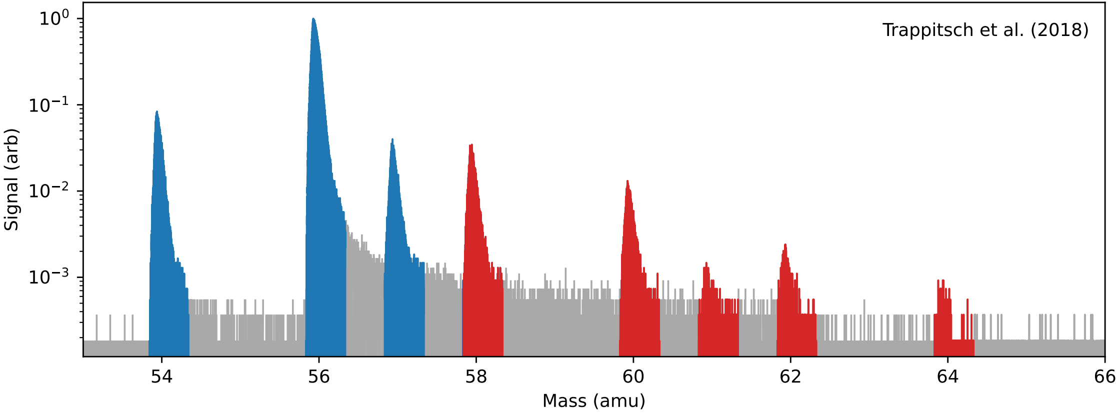
Simultaneous analysis of Fe and Ni by RIMS



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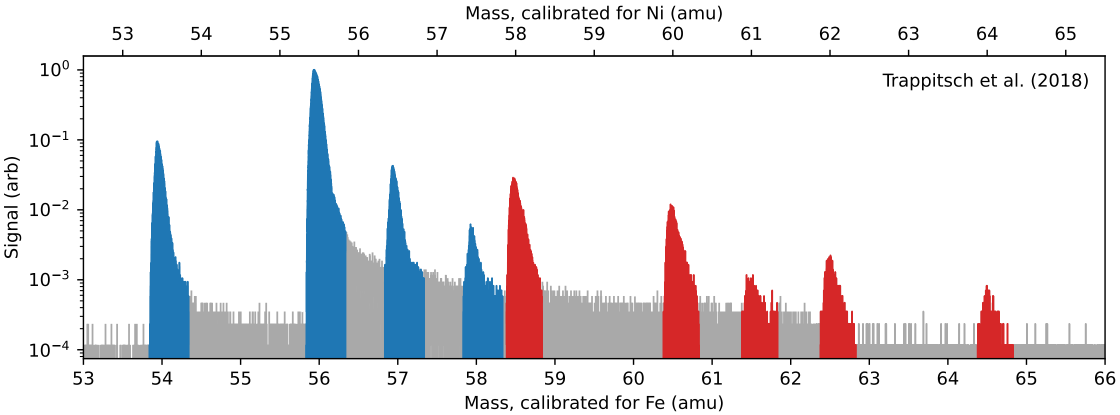
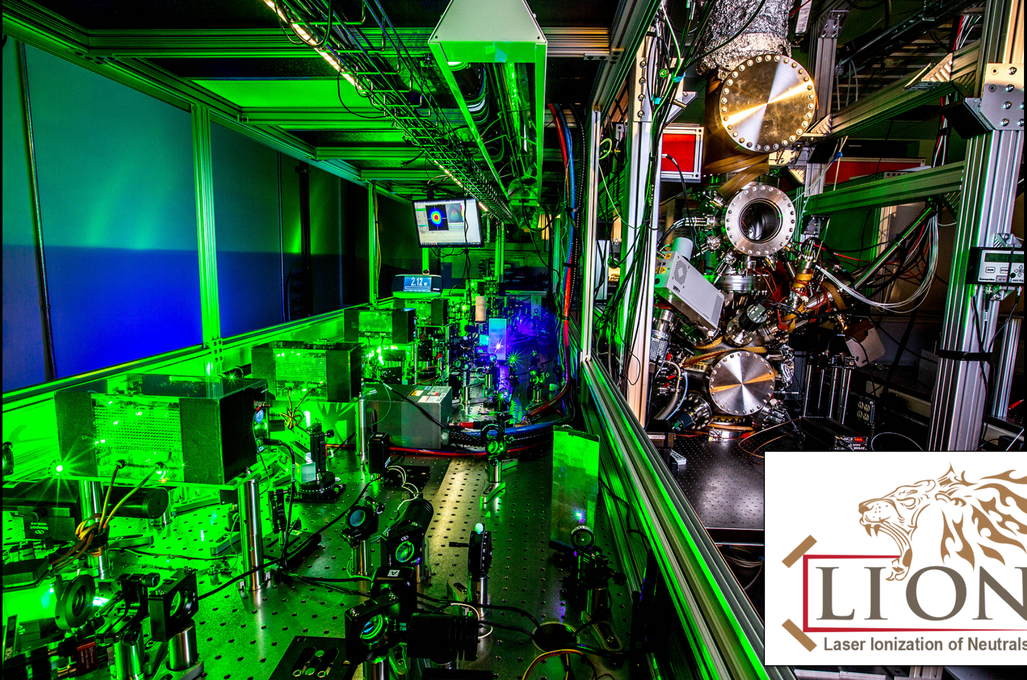
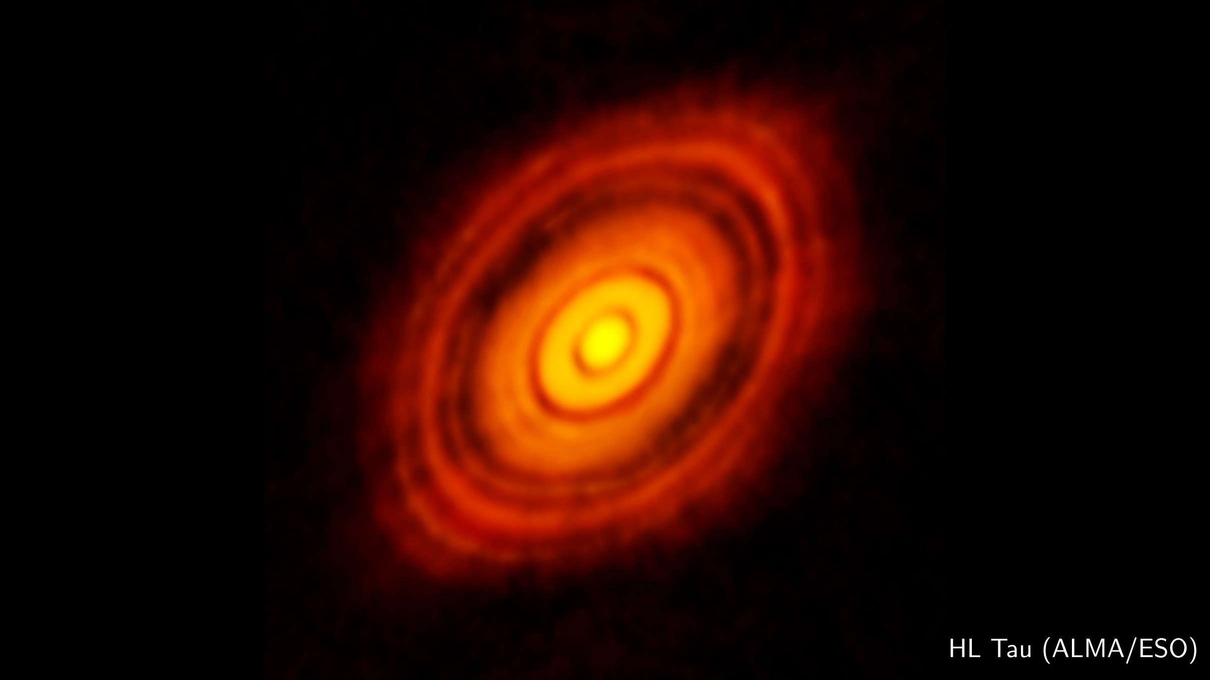




LION
Laser Ionization of Neutrals

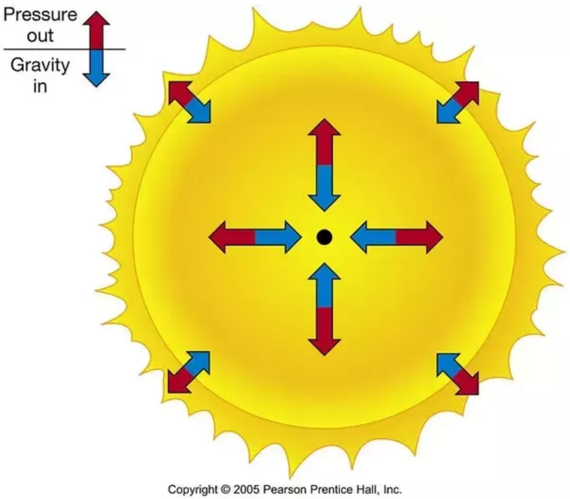
Carina Nebula (NASA/ESA/STScI)

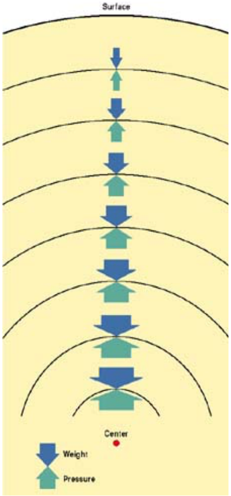


HL Tau (ALMA/ESO)

Pleiades (NASA/ESA/AURA/Caltech)

Hydrostatic equilibrium – Gravity vs. nuclear burning





Stellar lifetimes – the James Dean syndrome

- Mass luminosity relationship

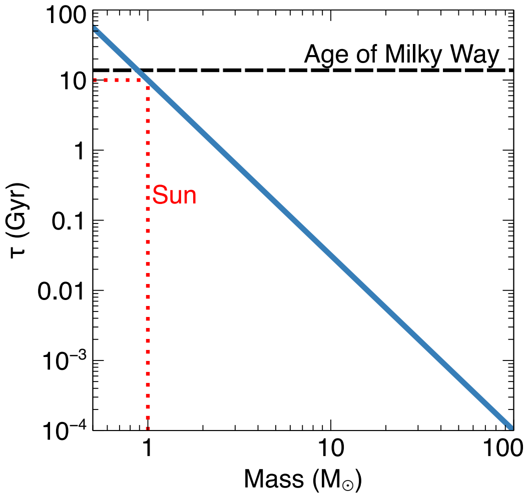
$$L \propto M^{3.5}$$

- Stellar lifetimes τ depends on fuel availability

$$\begin{aligned} \tau &\propto M \\ \tau &\propto L^{-1} \end{aligned}$$

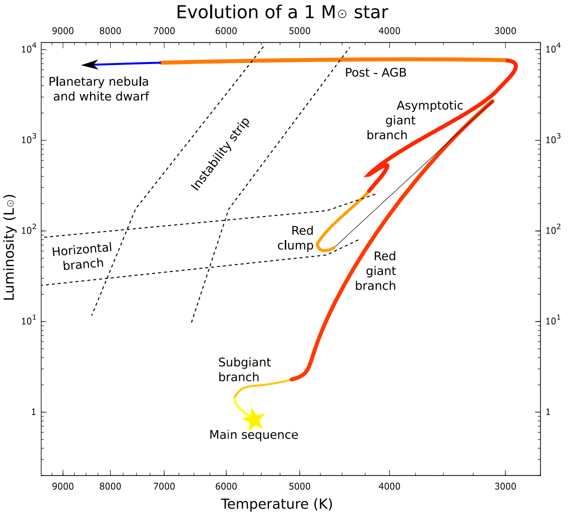
- Sun can burn $\sim$ 10% of its H
- $\tau \approx 10\,\mathrm{Gyr}$

$$\tau = 10\,\mathrm{Gyr}\left(\frac{M}{M_\odot}\right)^{-2.5}$$



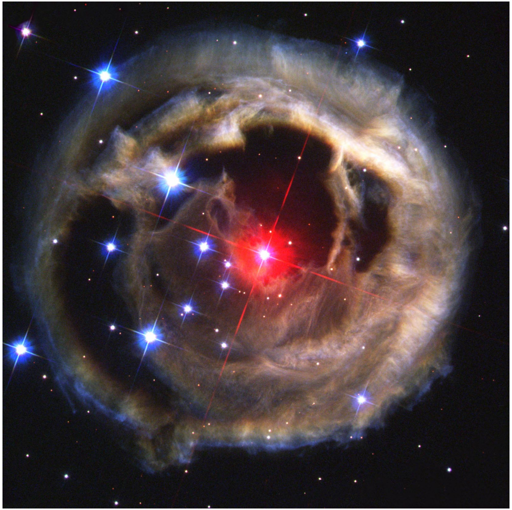
Life and death of a low-mass star ($0.4\,M_\odot \lesssim M \lesssim 4\,M_\odot$)

- Solar core now: $T_9 \approx 15$, $\rho \approx 150\,\mathrm{g\,cm^{-3}}$
- H runs out: core contracts, H-shell burning
- Envelope becomes convective
- Meanwhile, the core keeps contracting until degenerate
- He is added and temperature rises
- He ignites – He-flash: a thermonuclear runaway (for $M \lesssim 2\,M_\odot$)
  $\rightarrow$ Energy goes into lifting degeneracy
- Quiet He burning to CO core
- CO core w/ He, H burning shells
- H burning adds He until ignition

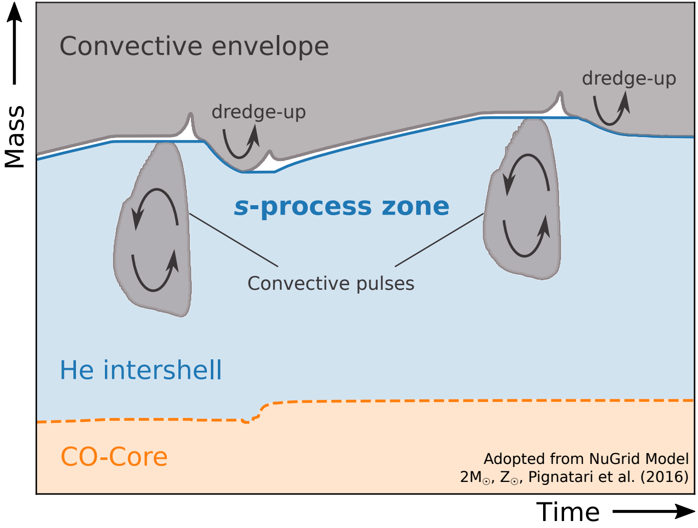


Asymptotic giant branch (AGB) stars

- 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(α, n)^{16}O
  - ^{22}Ne(α, n)^{25}Mg



Two neutron sources are at work



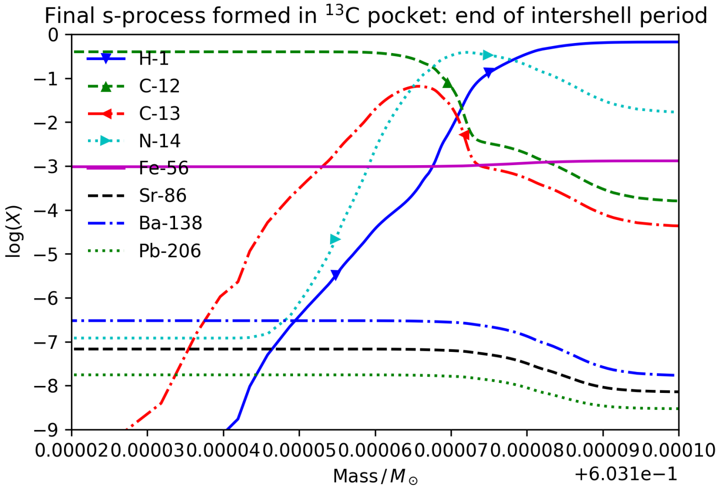
$^{13}C(\alpha, n)^{16}O$

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

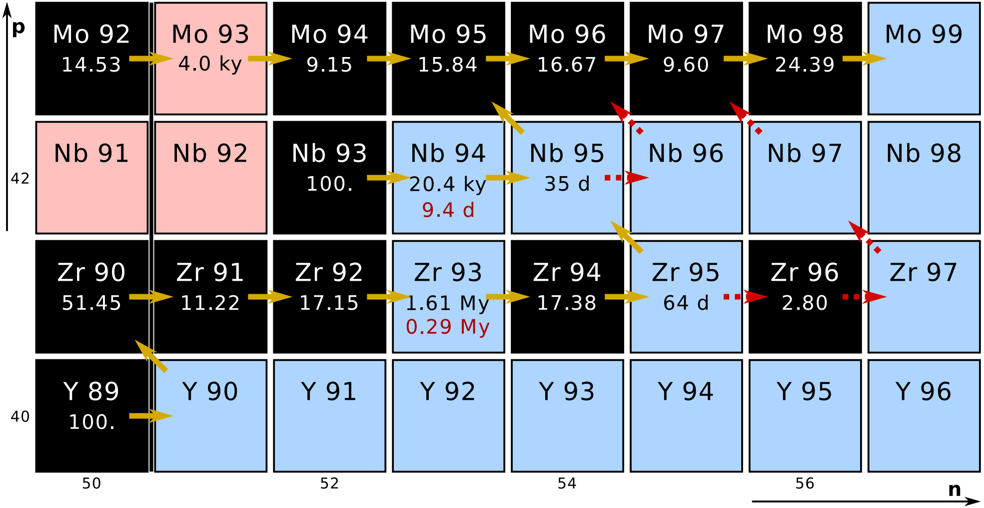
$^{22}Ne(\alpha, n)^{25}Mg$

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

A more detailed look into the ^{13}C pocket



What to look in stardust grains



Who wins: Neutron capture or β^--decay

- Branching ratio f_n

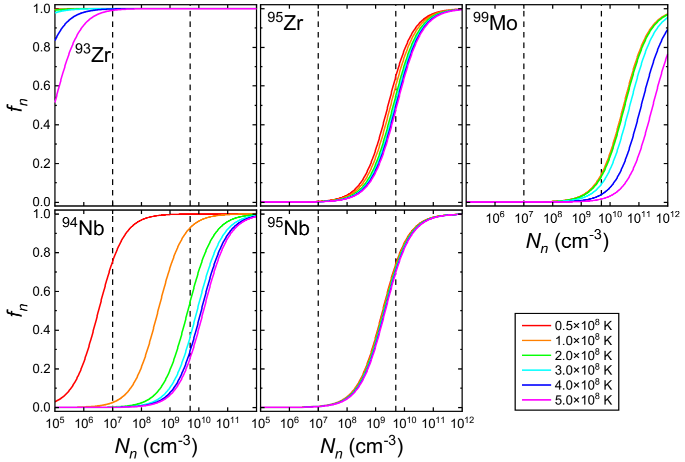
$$f_n = \frac{\lambda_n}{\lambda_n + \lambda_\beta}$$

- Neutron capture rate

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

- β^--decay rate

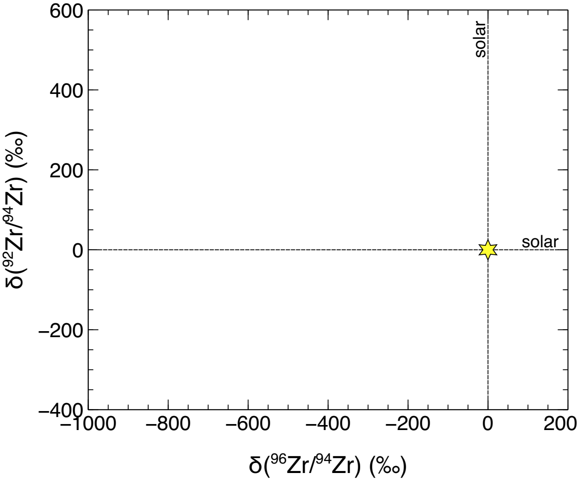
$$\lambda_\beta = \frac{\ln(2)}{T_{1/2}}$$



Stephan et al. (2019)

Deciphering the parent star conditions with stardust measurements

- δ-units: deviation of isotope ratio from solar system average value (usually in ‰)
- 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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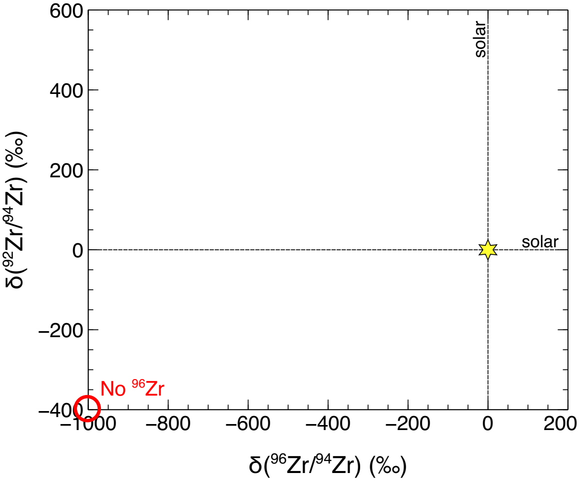

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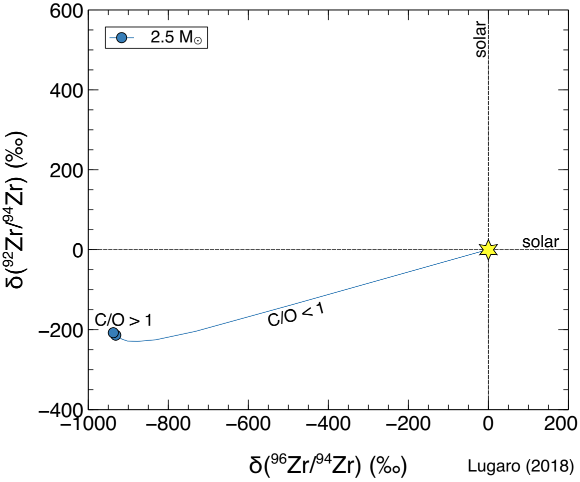

Lugaro (2018)

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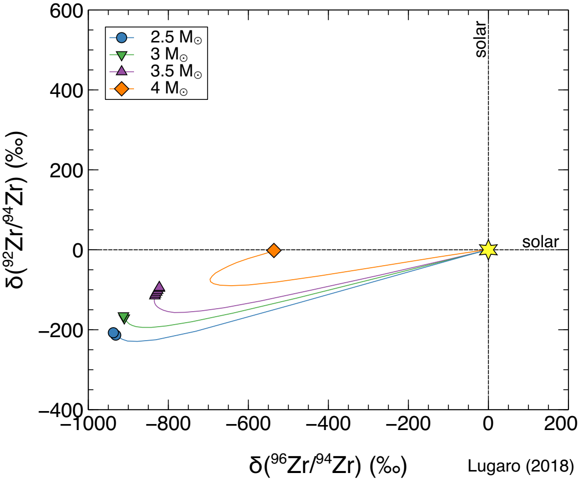

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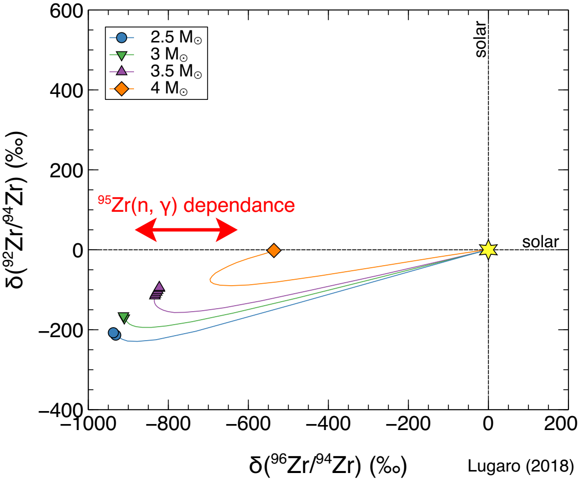

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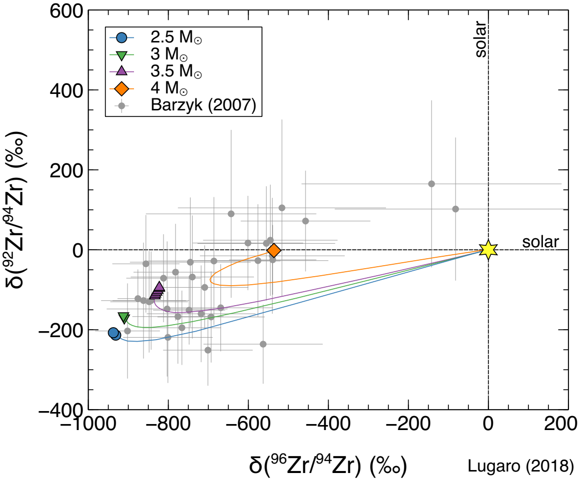
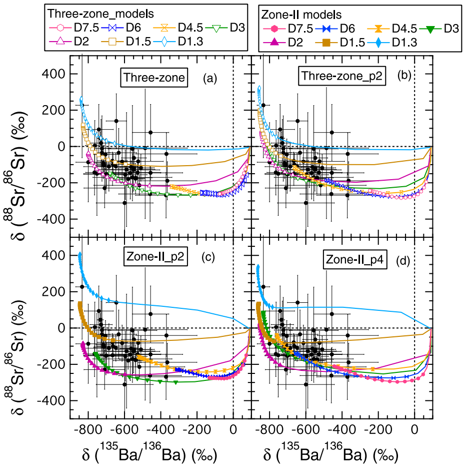


Lugaro (2018)

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

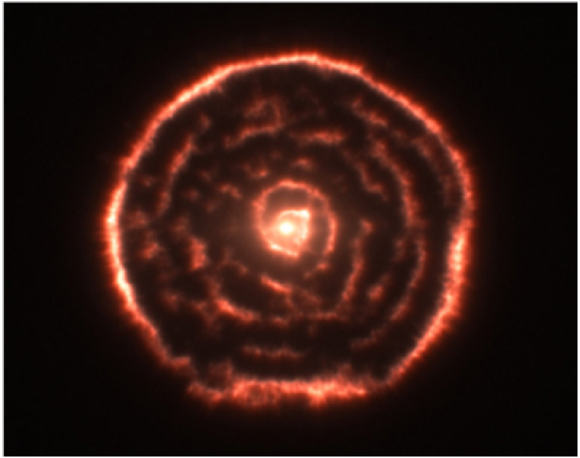
- Formation, size, mass of ^{13}C-pocket remain poorly understood
- Multi-element isotopic measurements in individual grains can help to decipher the physics
- Study by Liu et al. (2015) for Sr, Ba $\rightarrow$
- Many possible ^{13}C-pocket configurations can explain the measurements
- One set of model must fulfill all measurements constraints simultaneously



Liu et al. (2015)

Stardust analyses from AGB stars enable tight constraints on *s*-process

- Existing multi-element measurements constrain the *s*-process
- Large uncertainties of existing measurements
- New RIMS techniques allow simultaneous, precision measurements of Zr, Ba, and W
- ^{138}Ba: Neutron magic
  $\rightarrow$ Bottle neck for neutron flux
- Zr and W isotopes
  - On either side of Ba
  - Branch points to constrain activation of ^{22}Ne neutron source



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  $\rightarrow$ Bottle neck for neutron flux
- Zr and W isotopes
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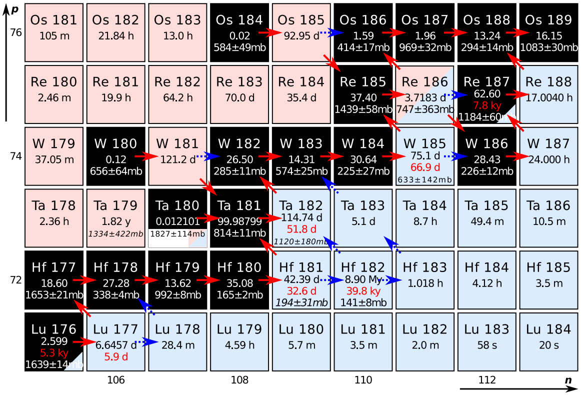

Stardust analyses from AGB stars enable tight constraints on *s*-process

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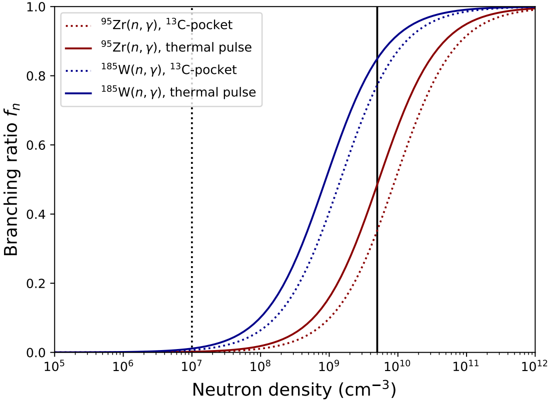

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