Nuclei in the Cosmos School
2025

COSMOCHEMISTRY

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GUF Frankfurt, Germany

NASA/Space Telescope Science Institute

Cosmochemistry: Presolar Grains/Stardust

Part 1: Introduction

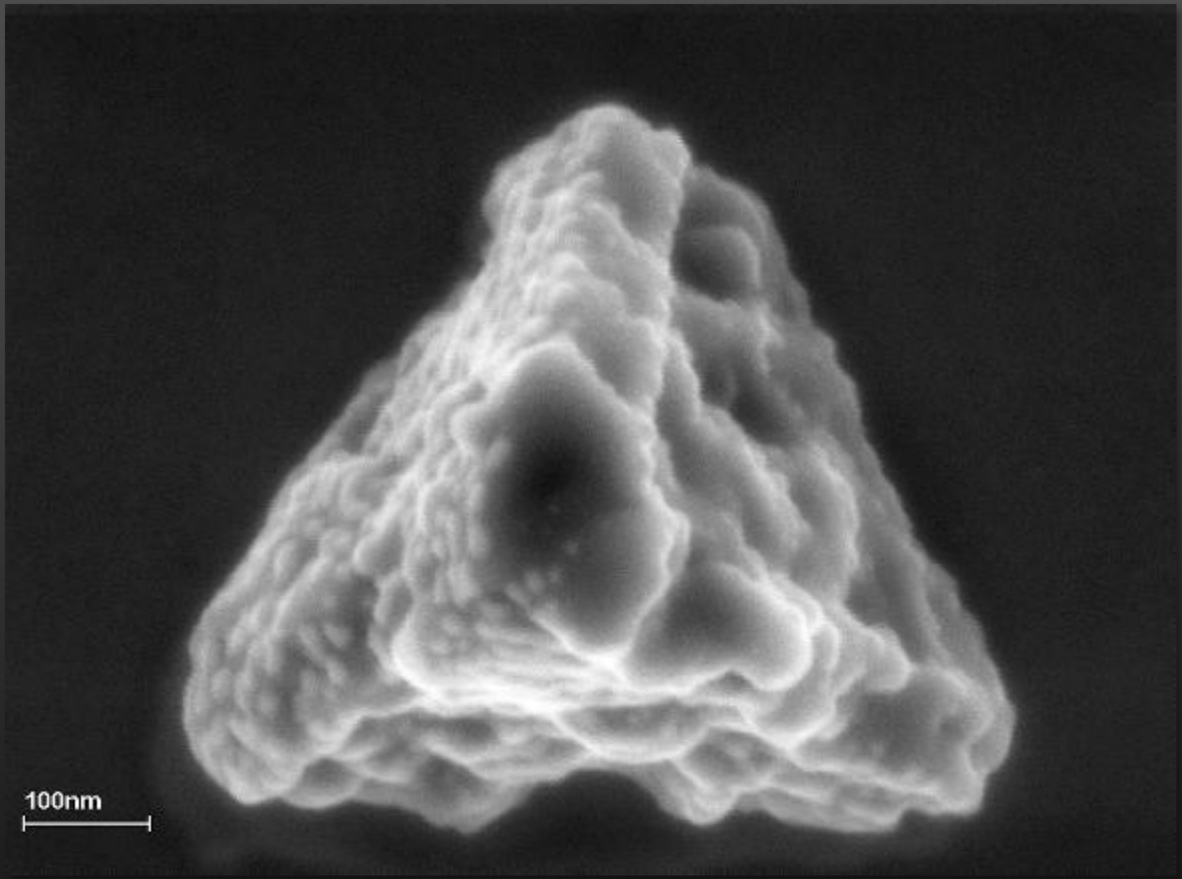
Dr. Sheri Singerling

NIC School 2025

Day 1

The Discovery of Presolar Grains

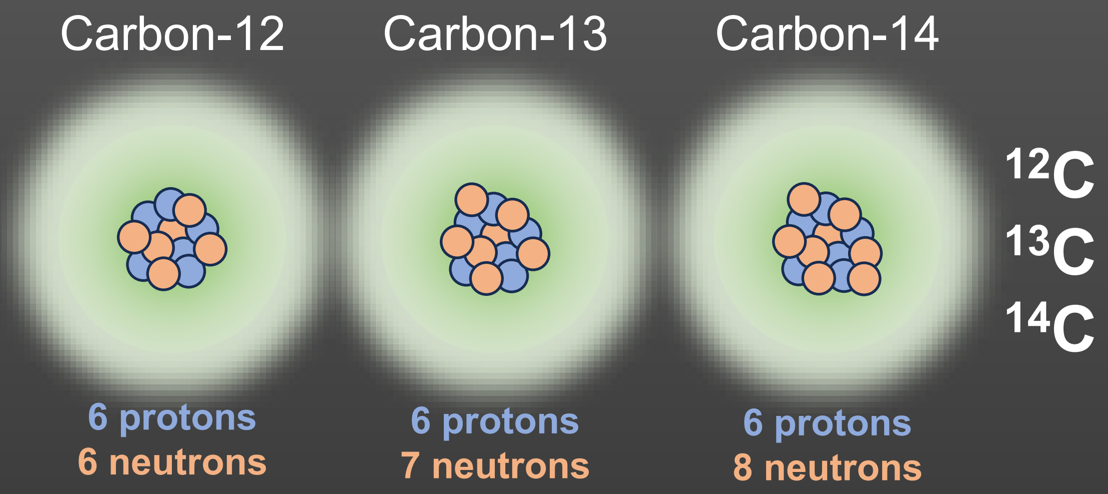
Like many great discoveries, it started with data that did not make sense. But first, some background…



Hoppe (1999)

Isotopes

- Definitions
  - Isotope
    - Same atomic number (Z)
    - Different atomic mass (A = Z + N)
  - Nuclides = isotopes of more than one element (^{12}C, ^{16}O)



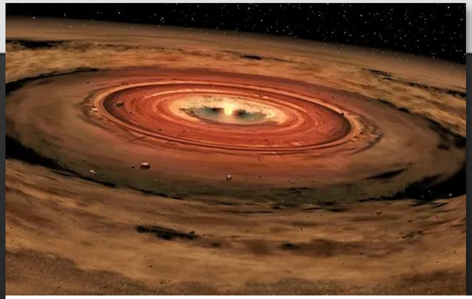
- Measurements
  - Delta notation
    - Makes small differences more apparent
    - Ratios are heavy isotope/light isotope

$$\delta^{18}O = \left(\frac{\left(\frac{^{18}O}{^{16}O}\right)_{sample}}{\left(\frac{^{18}O}{^{16}O}\right)_{standard}} - 1 \right) \times 1000‰$$

The Discovery of Presolar Grains

1962

- Solar System passed through high-T stage that vaporized all solids → no isotopic anomalies



The Formation of the Sun and Planets

A. G. W. CAMERON

Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, and Atomic Energy of Canada Limited, Chalk River, Ontario, Canada, and NASA Institute for Space Studies, New York, N. Y.

1964

- Identified Xe isotopic anomalies in a chondrite

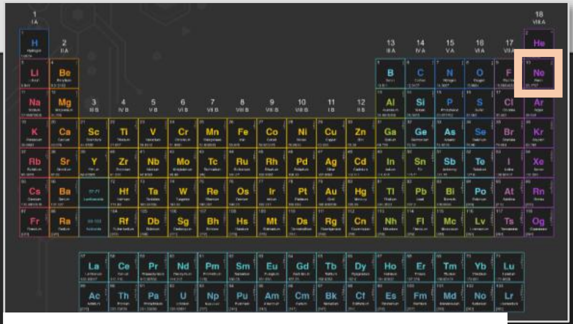
Rare gases in the chondrite Renazzo

J. H. Reynolds, G. Turner

First published: 1 August 1964 | https://doi.org/10.1029/JZ069i015p03263 | Citations: 245

1969

- Identified Ne isotopic anomalies in a chondrite



TRAPPED NEON IN METEORITES – II

D.C.BLACK and R.O.PEPIN

School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA

Received 11 July 1969

1973

- Identified O isotopic anomalies in early Solar System condensates (CAIs)

A Component of Primitive Nuclear Composition in Carbonaceous Meteorites

ROBERT N. CLAYTON
LAWRENCE GROSSMAN
TOSHIKO K. MAYEDA

The Discovery of Presolar Grains

1975

- Isolated carrier of Xe anomaly in a chondrite using acid digestion but could not identify the phase

Host Phase of a Strange Xenon Component in Allende

Most of the noble gases reside in three rare minerals comprising less than 0.5 percent of the meteorite.

Roy S. Lewis, B. Srinivasan, Edward Anders

Noble Gases in the Murchison Meteorite: Possible Relics of *s*-Process Nucleosynthesis

B. Srinivasan*, Edward Anders
Enrico Fermi Institute and Department of Chemistry, University of Chicago, Chicago, Illinois 60637

1978

- Extrapolated acid residue Xe back to pure-end member → matched s-process nucleosynthesis (only happens in stars)

More and more anomalies detected: Sr, Nd, Ti, Ca, etc.

Interstellar diamonds in meteorites

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

* Enrico Fermi Institute and Department of Chemistry, University of Chicago, Chicago, Illinois 60637, USA
† Center for Analytical Chemistry, National Bureau of Standards, Gaithersburg, Maryland 20899, USA

1987

- Determined that Xe carrier was pure C (nanodiamonds) by using very harsh acid (perchloric)

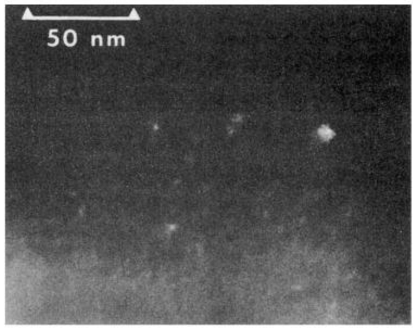


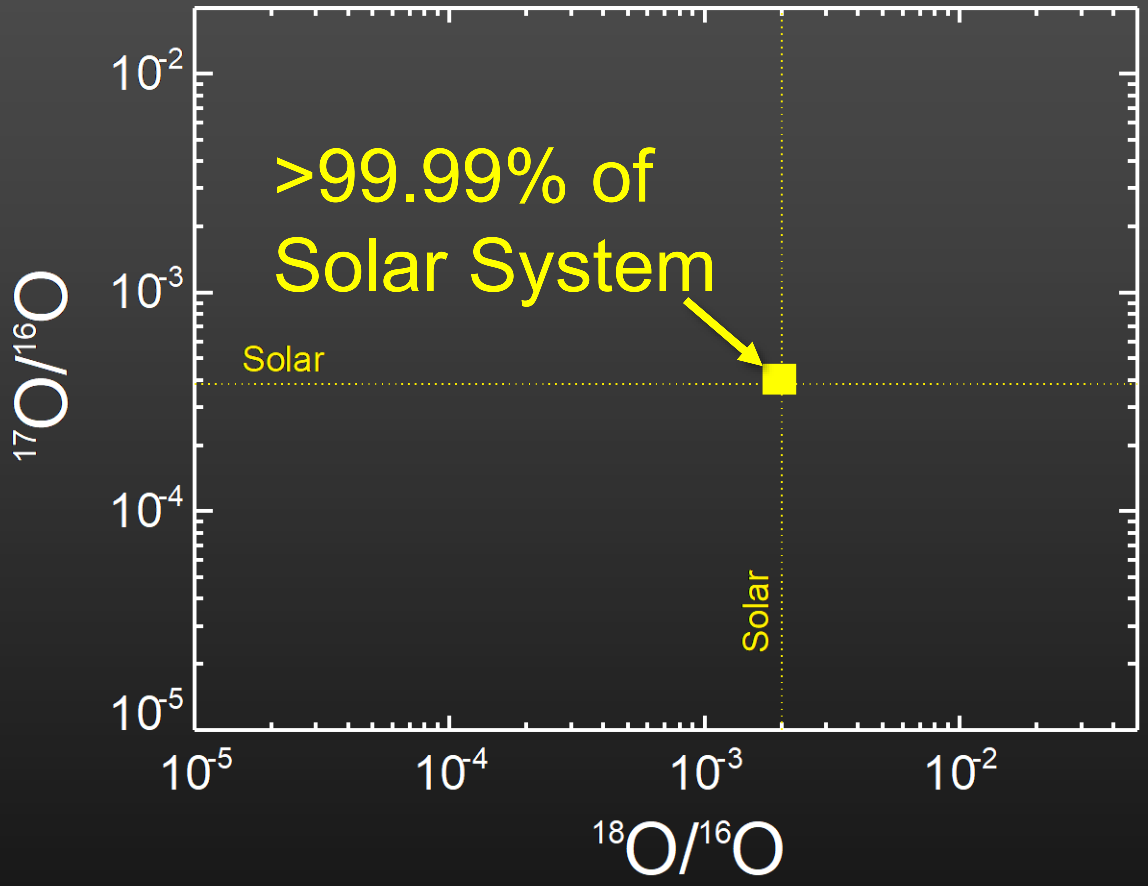
Fig. 1 Dark-field transmission electron micrograph of Allende CJ, in which bright areas are diamond grains diffracting electrons into one part of the innermost ring of the diffraction pattern shown in Fig. 2. As most grains do not have the proper orientation, the true abundance of diamond is perhaps five times higher than indicated by the bright areas in the picture.

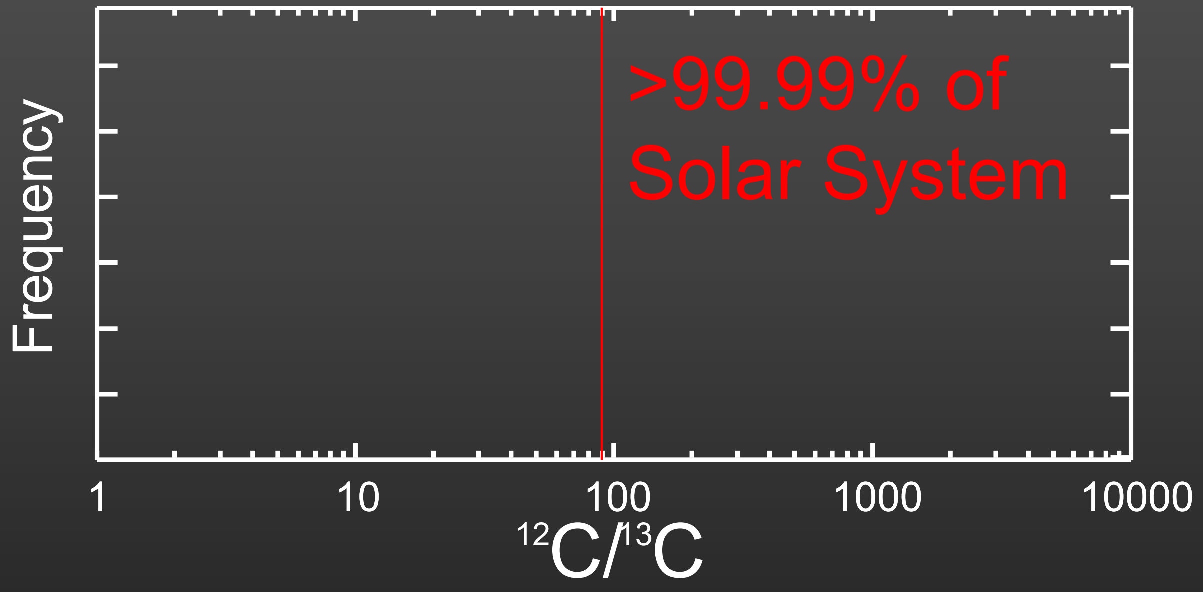
Other carriers of isotopic anomalies identified:

SiC = Ne, Xe
Graphite = Ne

Isotopic Anomalies

- How anomalous is anomalous?





Isotopic Anomalies

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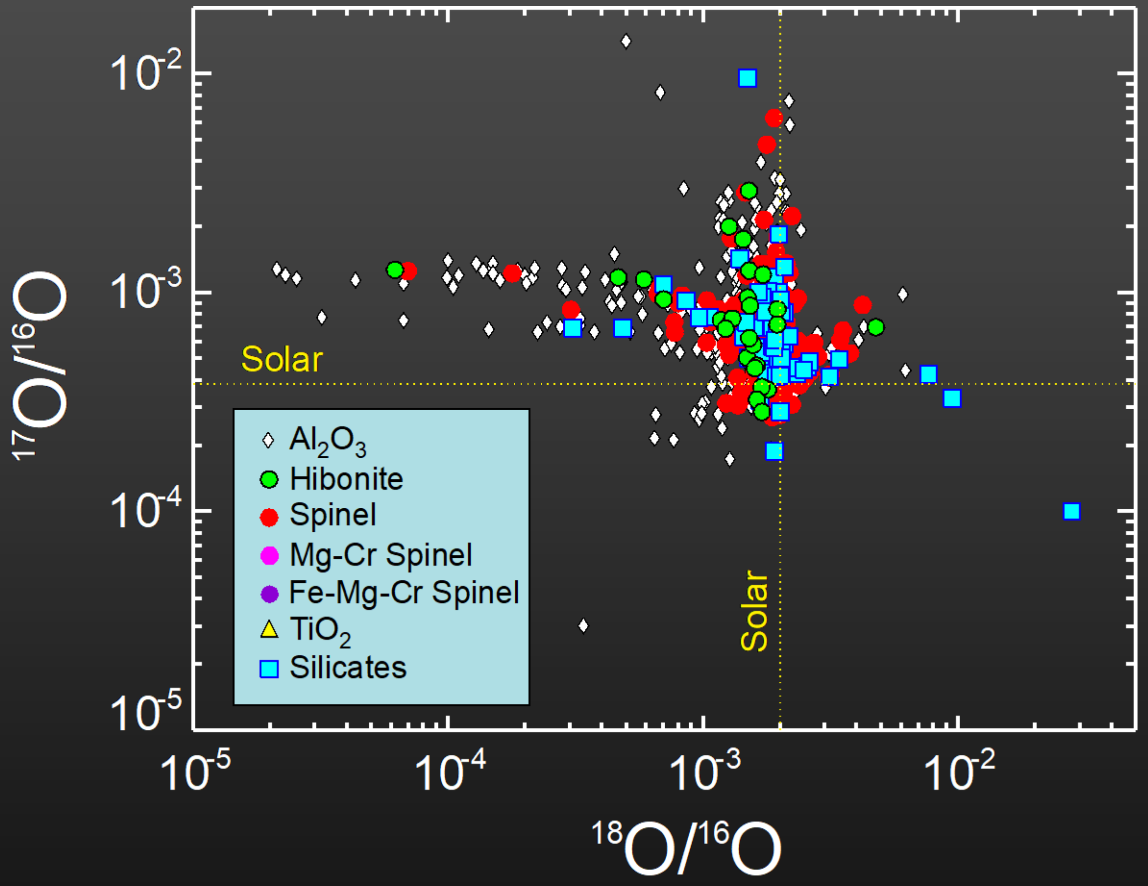
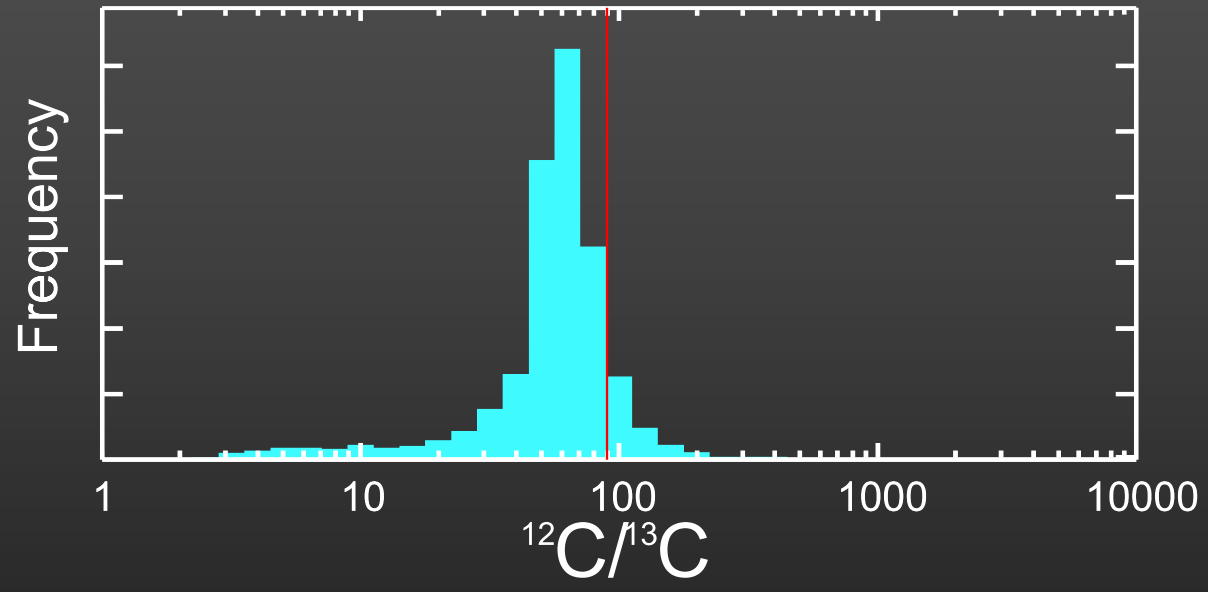
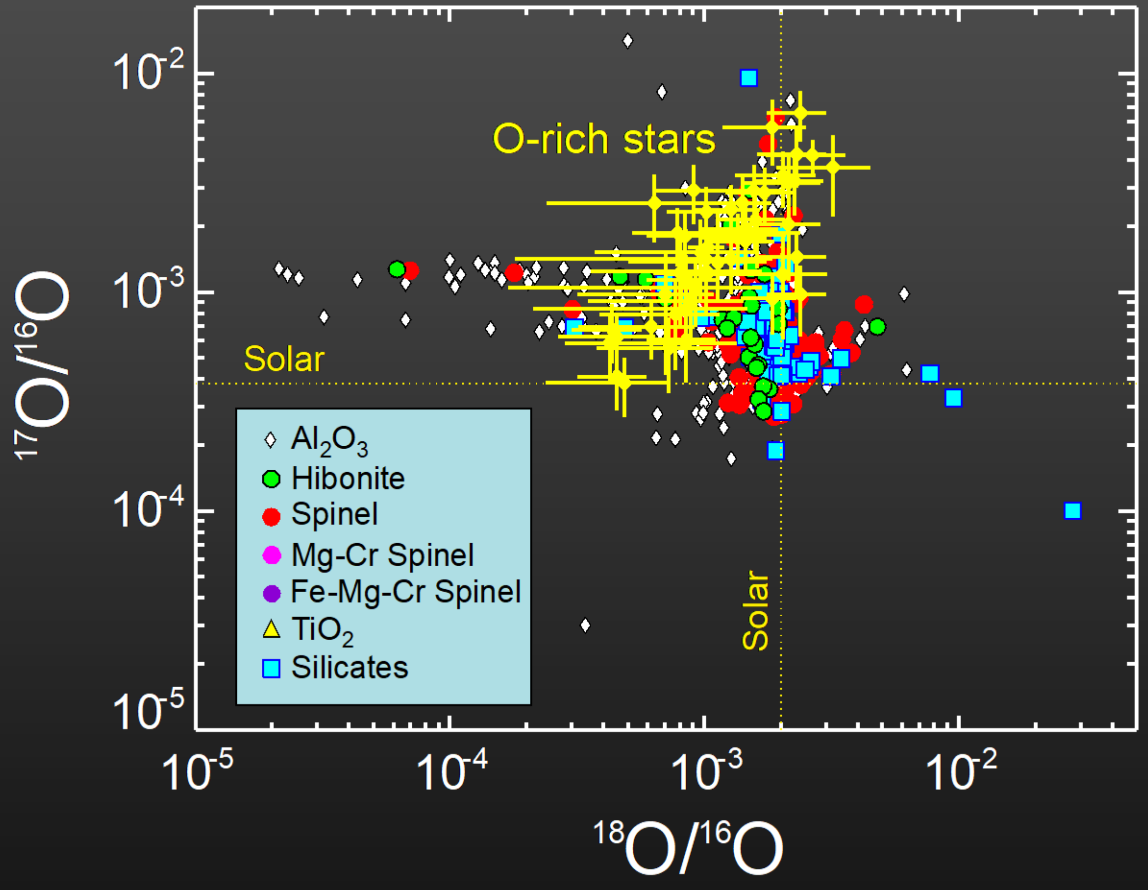
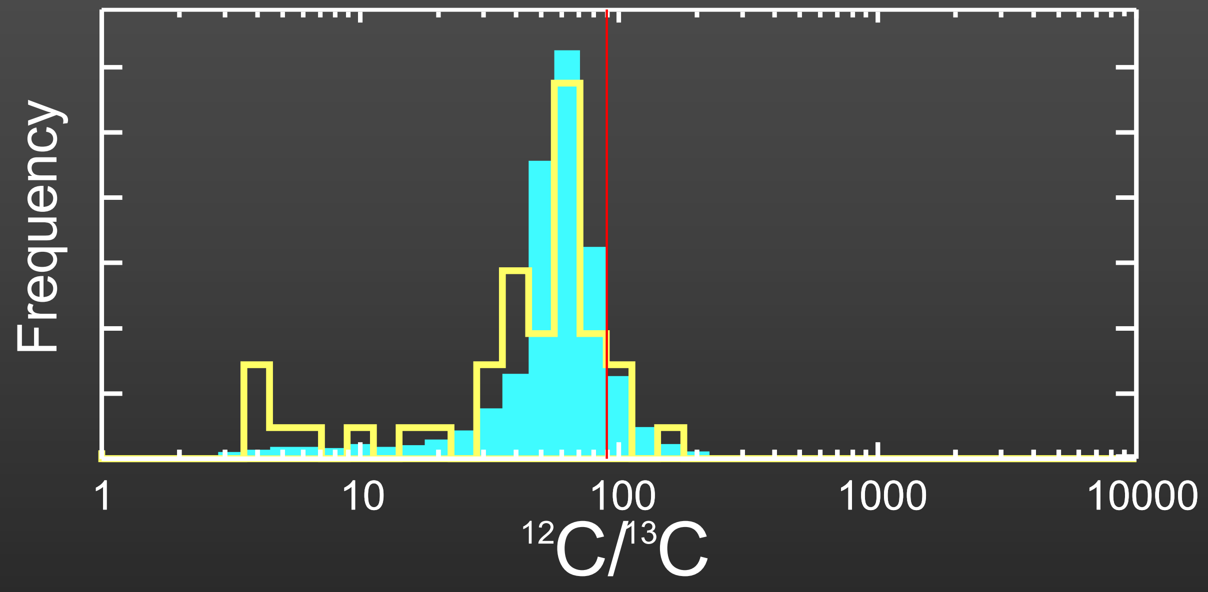




Isotopic Anomalies

- How anomalous is anomalous?





How Old are Presolar Grains?

Presolar means before the Solar System…

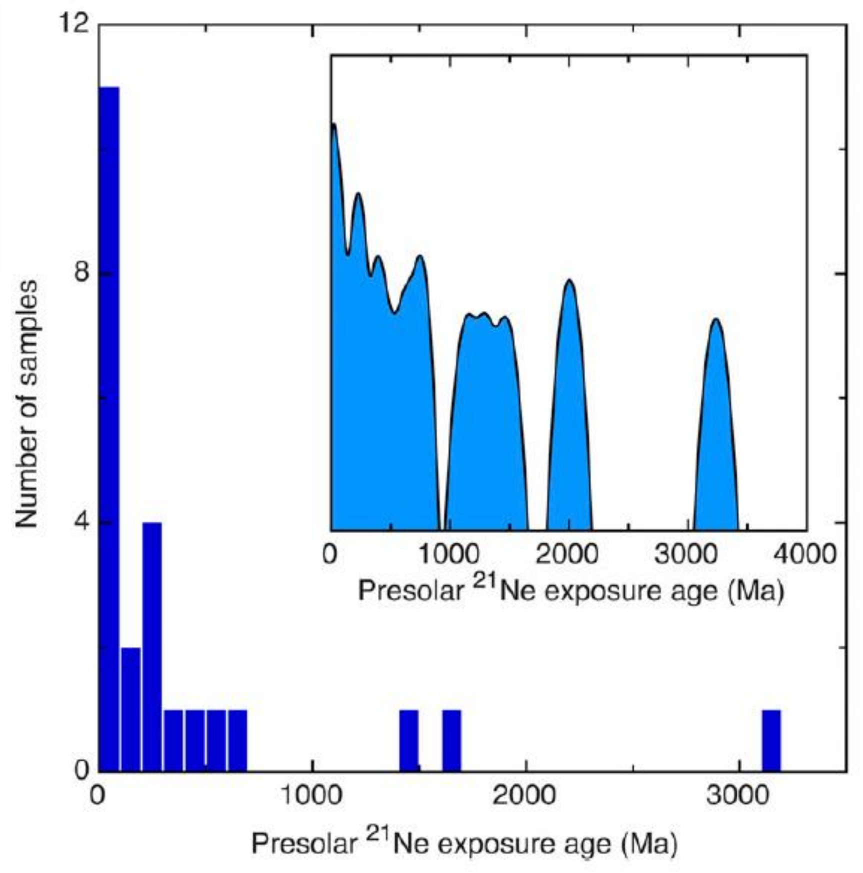
…but how long before?

Lifetimes of interstellar dust from cosmic ray exposure ages of presolar silicon carbide

2020 PNAS paper

Philipp R. Heck[a,b,c,1], Jennika Greer[a,b,c], Levke Kööp[a,b,c], Reto Trappitsch[d], Frank Gyngard[e,f], Henner Busemann[g], Colin Maden[g], Janaína N. Ávila[h], Andrew M. Davis[a,b,c,i], and Rainer Wieler[g]

- Performed age-dating using exposure ages instead of long-lived radionuclides (e.g., U-Pb)
    - Exposure ages = spallation reactions from cosmic rays in the interstellar medium (produce cosmogenic Ne)
    - Long-lived radionuclide analyses require more sample material and known initial isotopic compositions

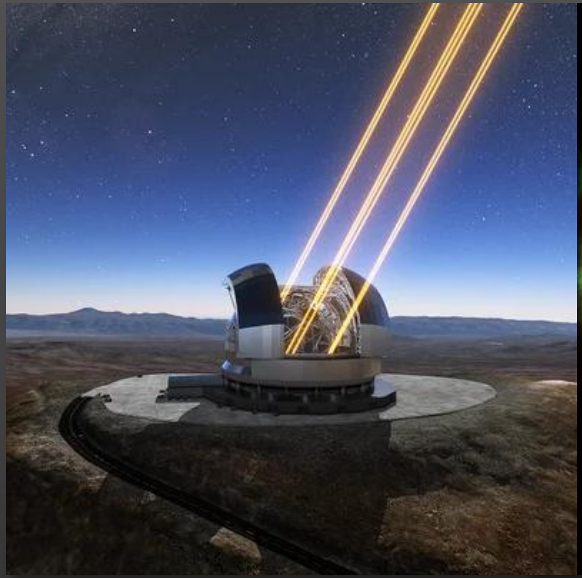


40 large SiC grains from AGB stars

- **3.9** ± 1.6 **Ma** to **~3** ± 2 **Ga** before the start of the Solar System (~4.6 Ga)
- One grain as old as **7.6 Ga**!

Significance of Presolar Grains

- Presolar grains are our only samples from stars and so act as ground-truth for astrophysical studies
  - Theoretical work
  - Observational work
  - Lab-based work



- Presolar grains have experienced many different processes over their long "lives"
  - Formation around stars
  - Transit through the space between stars
  - Residence in the solar nebula
  - Residence on small bodies

Presolar grains can teach us about **galactic chemical evolution**, **stellar evolution**, **nucleosynthesis**, and **the early Solar System**

Cosmochemistry:
Presolar Grains/Stardust

Part 2:
Nucleosynthesis

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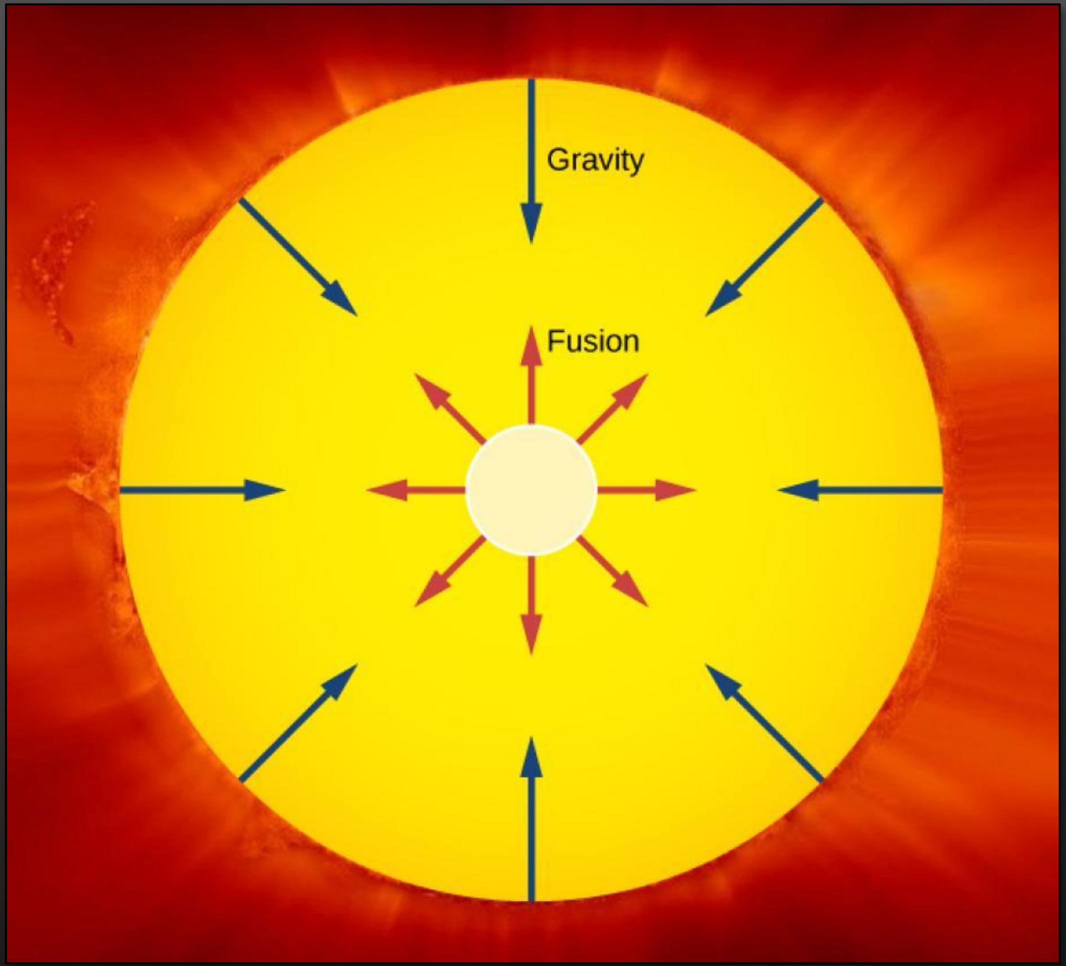
NIC School 2025

Day 1

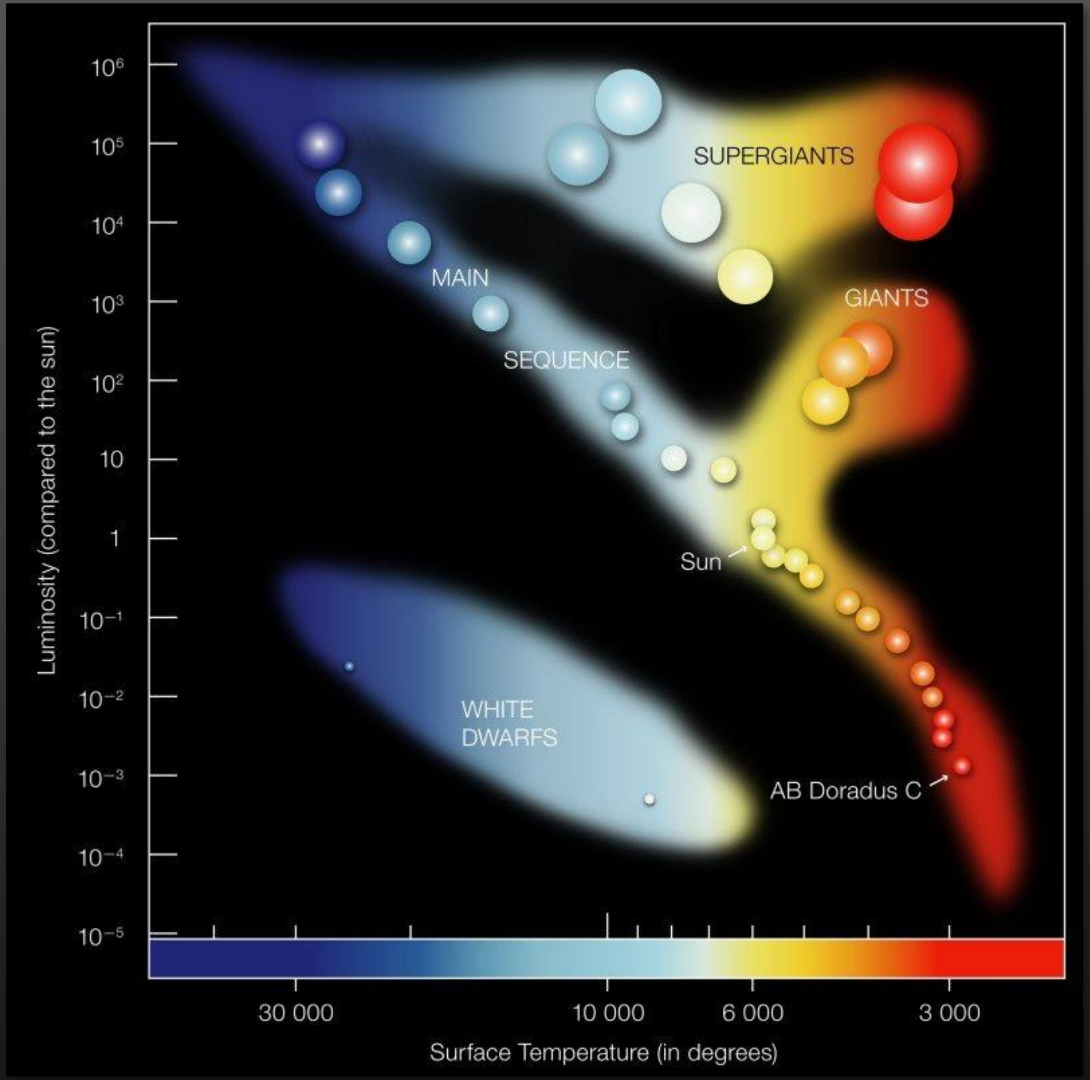
Stellar Life Cycles

- Stars are the product of two fundamental forces battling one another
  - Outward push of energy from thermonuclear fusion vs inward pull of gravity



Stellar Life Cycles

- Stars are the product of two fundamental forces battling one another
  - Outward push of energy from thermonuclear fusion vs inward pull of gravity
- Stars go through a series of stages from birth to death
  - The stages are marked by a change in the delicate balance of fusion vs gravity
- Mass determines what stages a star goes through and its ultimate fate



Brief Summary

Birth

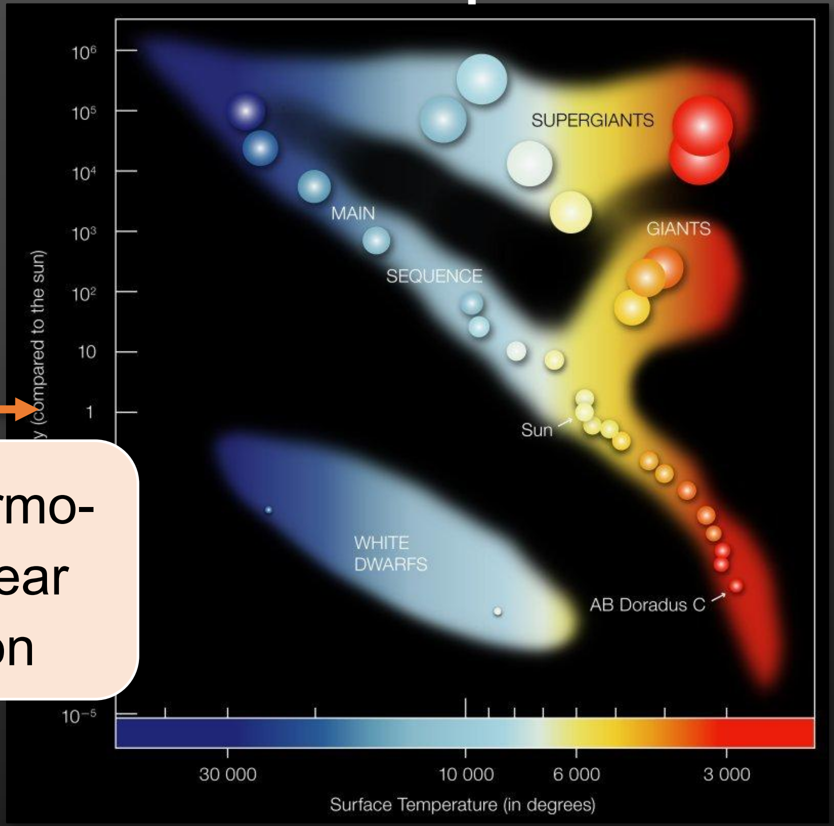
Stellar Nurseries
(molecular clouds)

Pre-Main Sequence

Protostars

Thermo-
nuclear
fusion

Main Sequence



Main Sequence Star

H-core burning

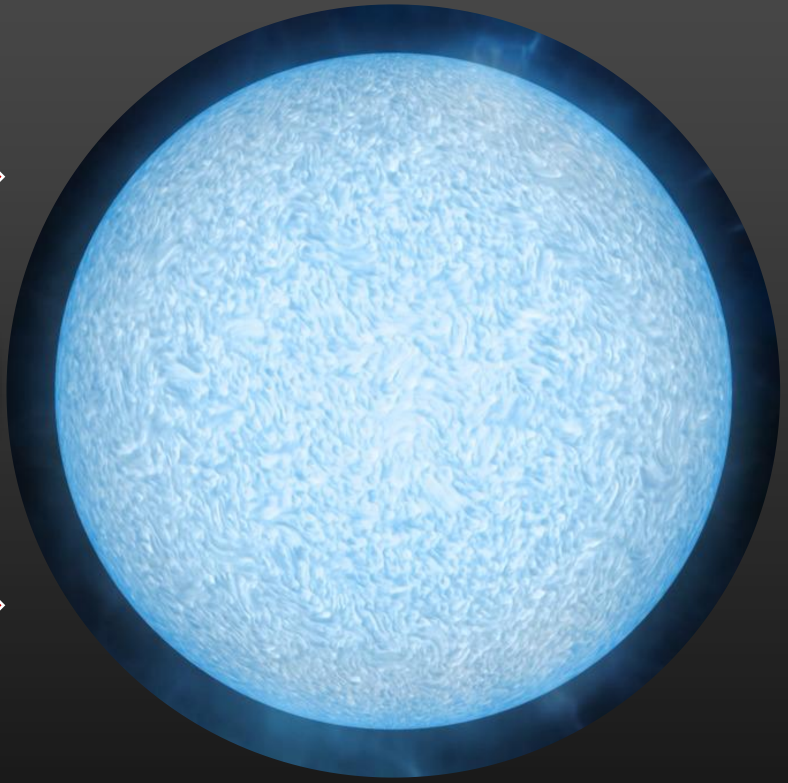
Brief Summary

Post-Main Sequence

Depends on the mass of the star

Low mass

(<0.4 $M_\odot$)

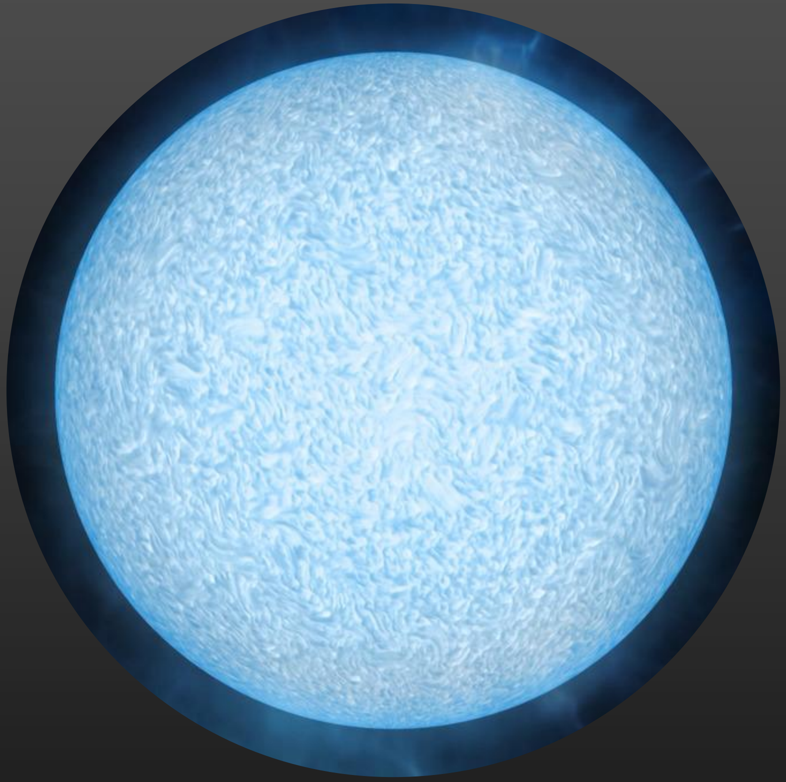


Intermediate/high mass

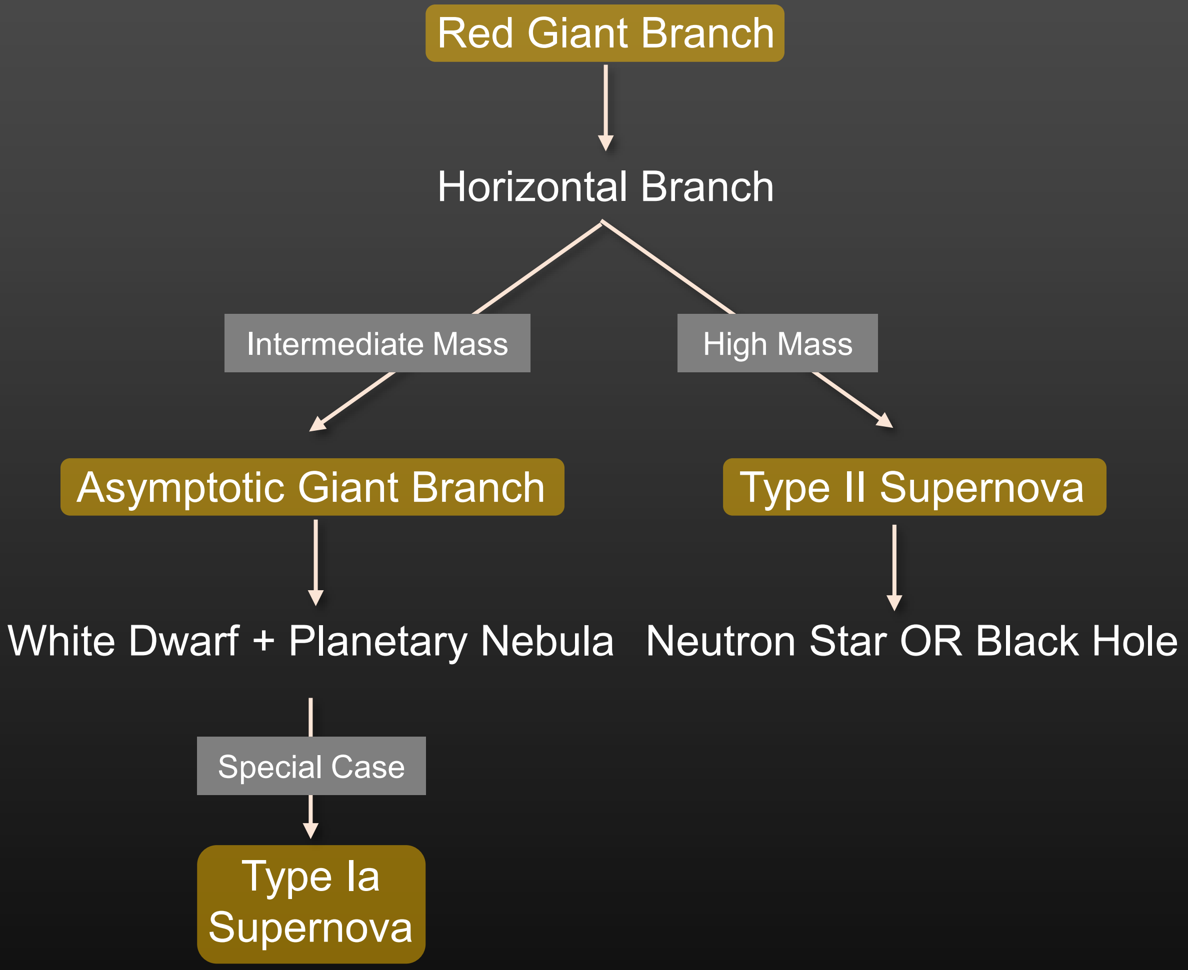
(≥0.4 $M_\odot$)

Brief Summary

Post-Main Sequence

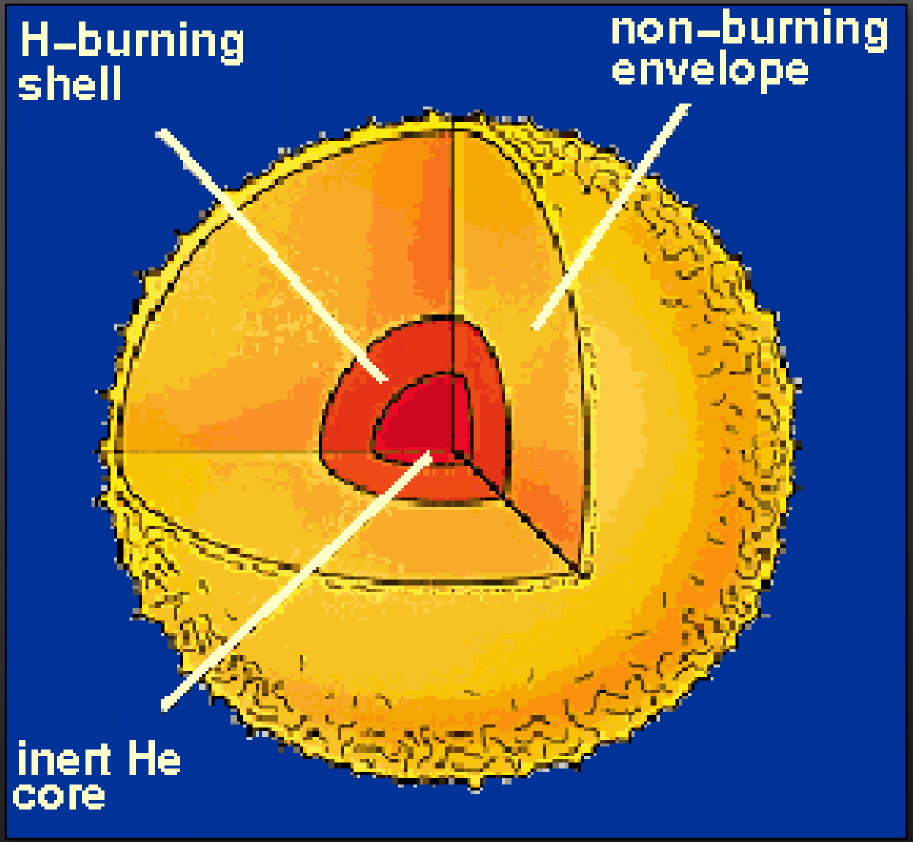


Intermediate/high mass
(≥0.4 $M_\odot$)



Stages That Produce Presolar Grains

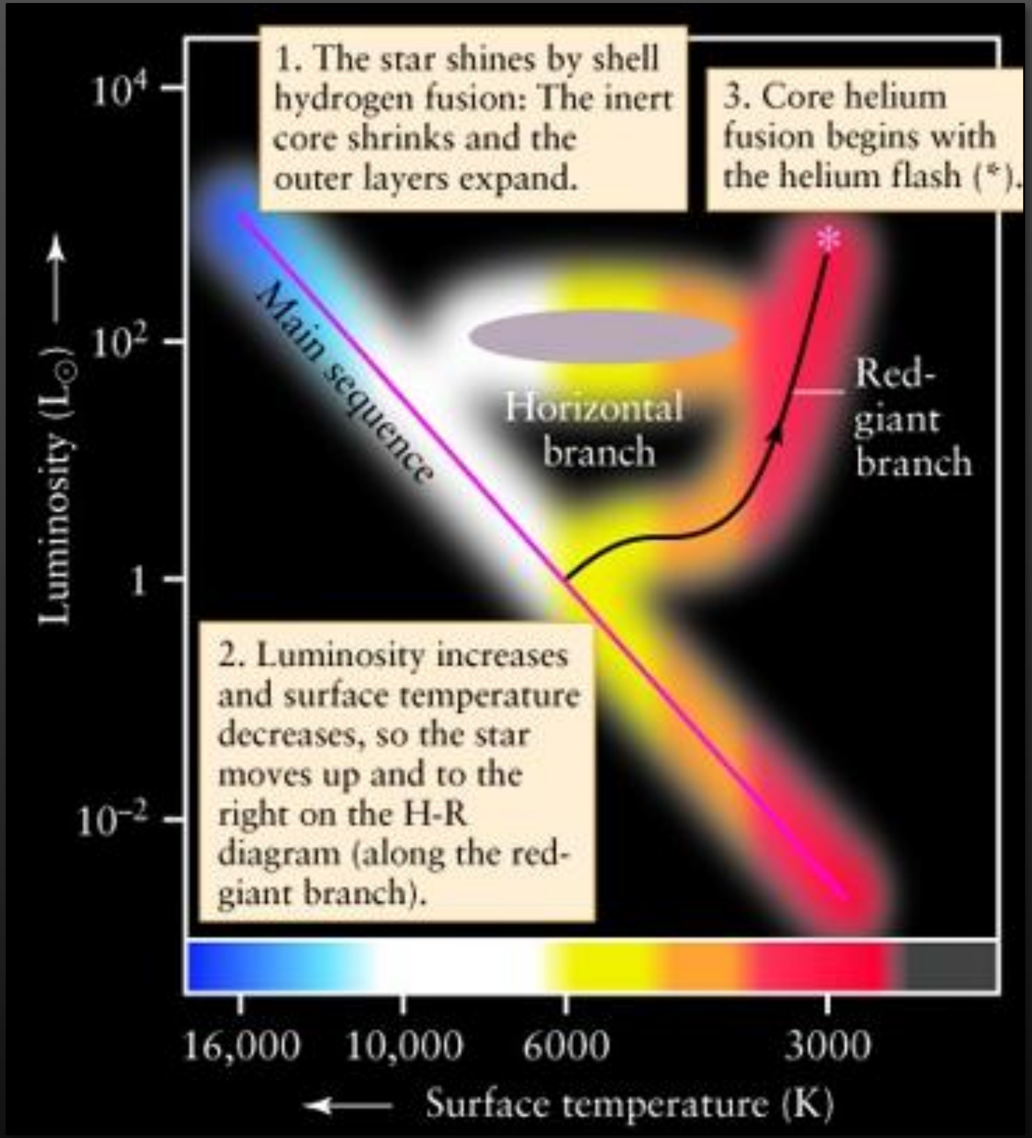
RGB stars



H-shell burning

↓

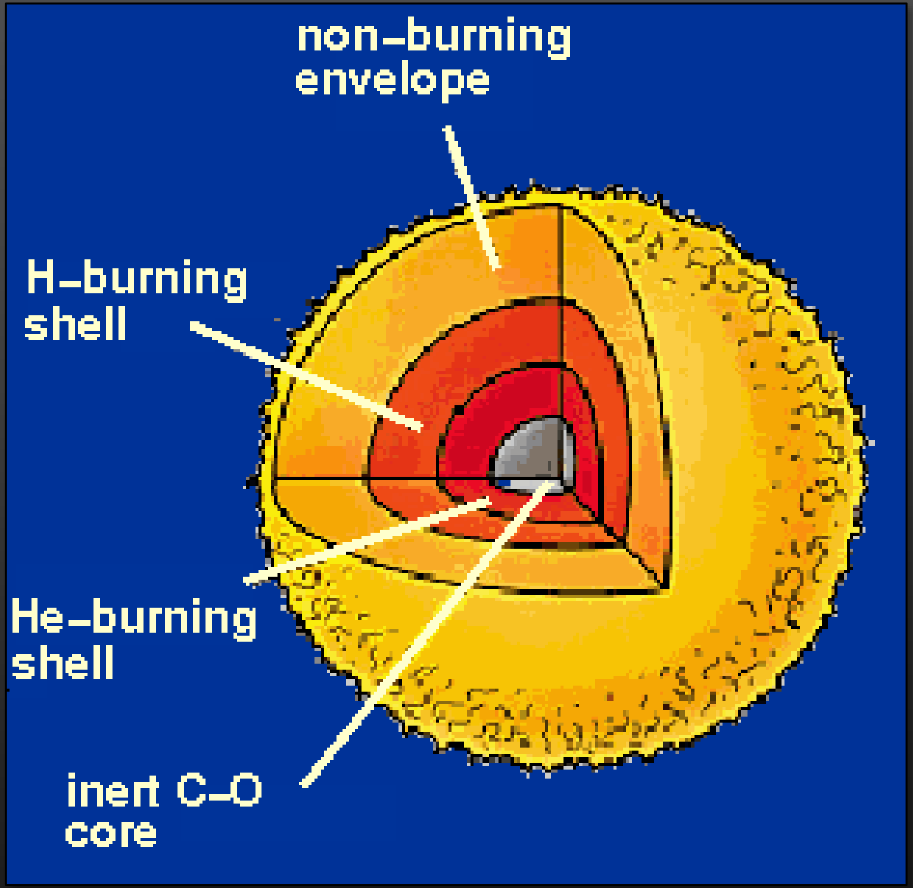
He-core burning



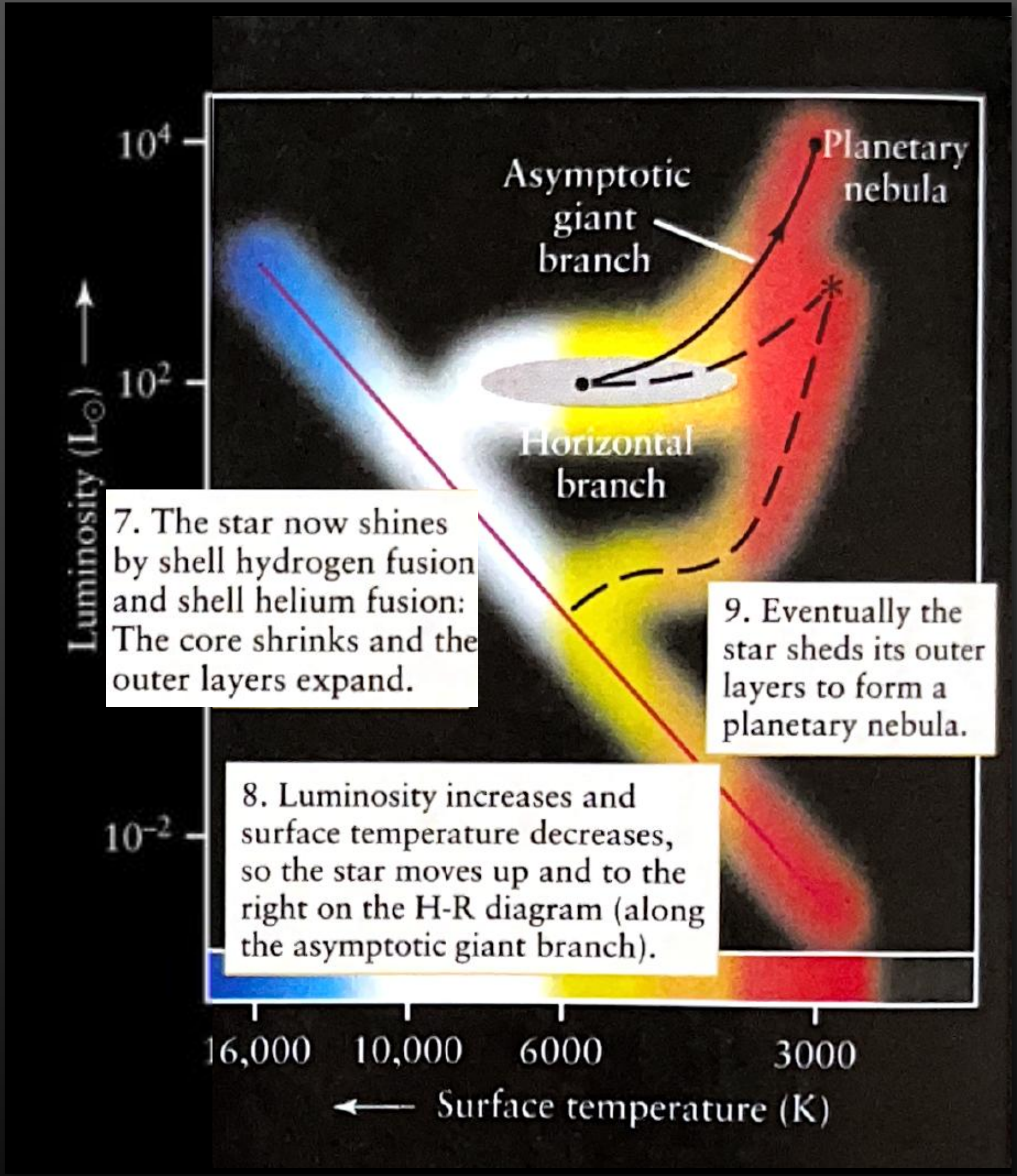
- Larger radius of red giants means gravity is weaker near the surface → results in mass loss → *PRESOLAR GRAINS!*

Stages That Produce Presolar Grains

AGB stars



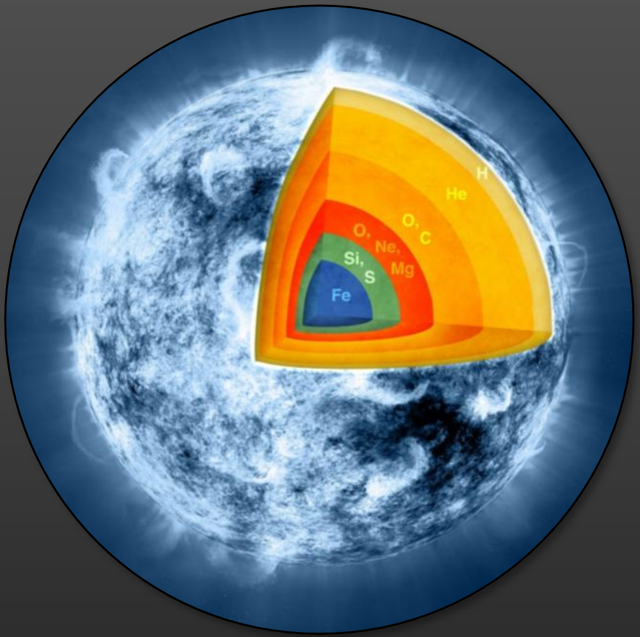
He-shell burning



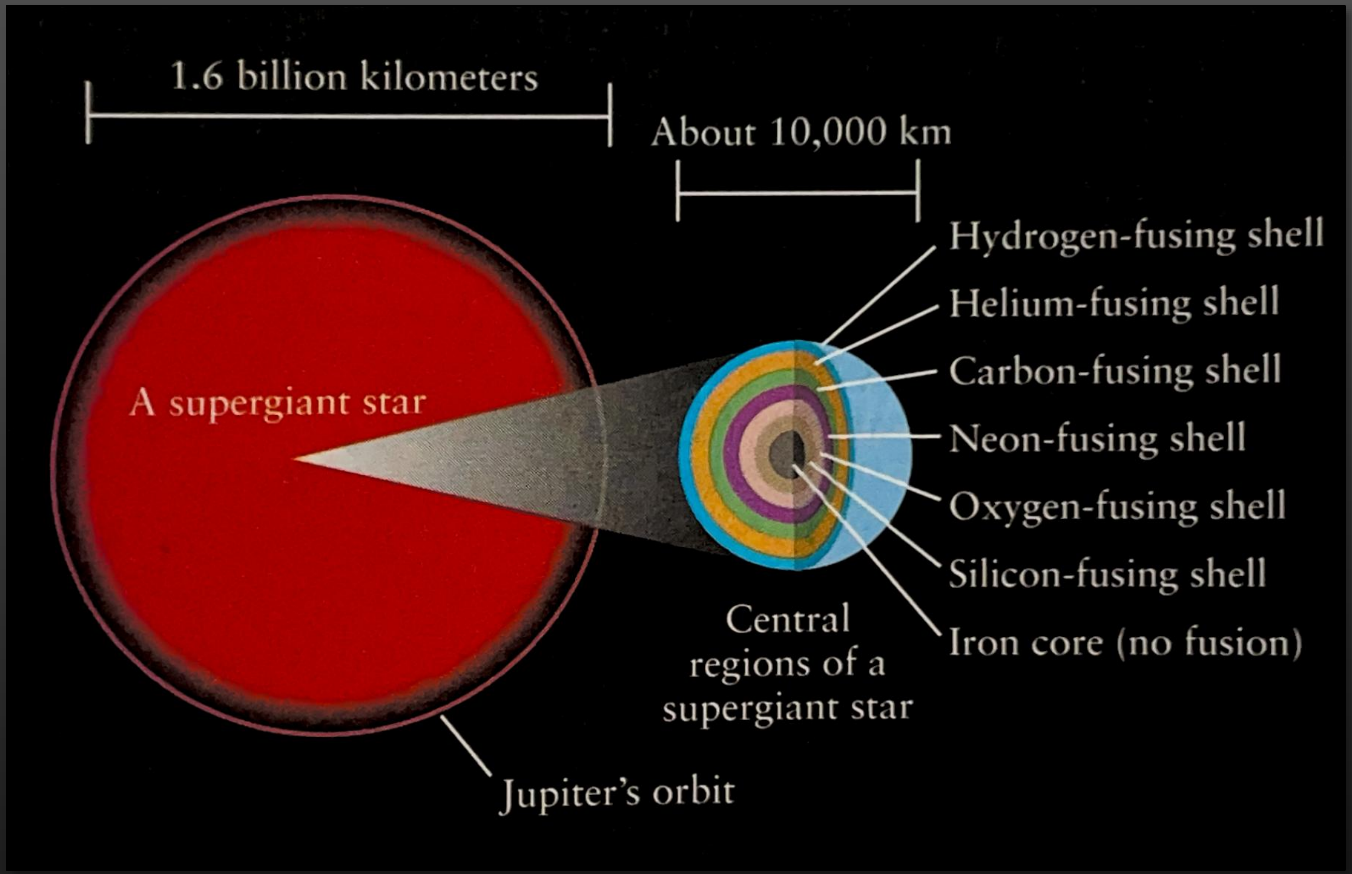
- Thermal pulses eject material → results in mass loss → *PRESOLAR GRAINS!*

Stages That Produce Presolar Grains

Type II SNe



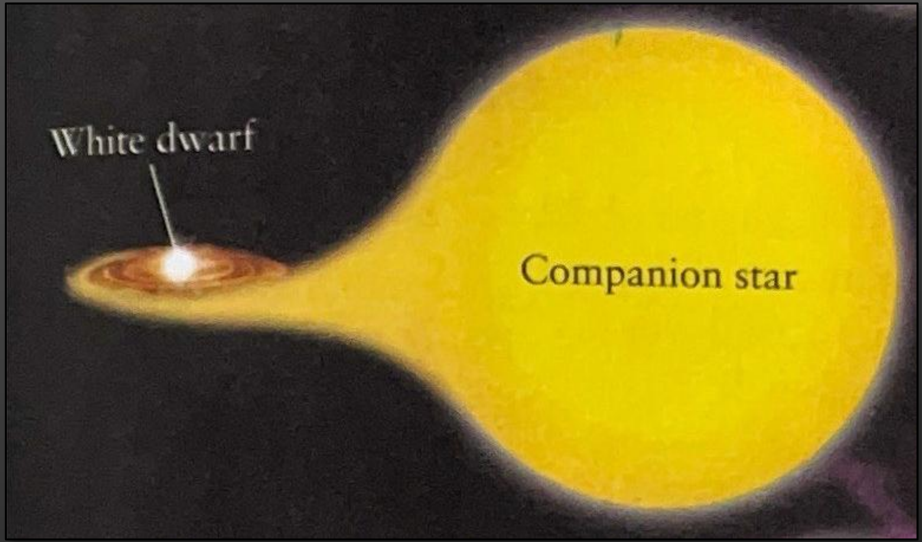
C-fusion
↓
Ne-fusion
↓
O-fusion
↓
Si-fusion

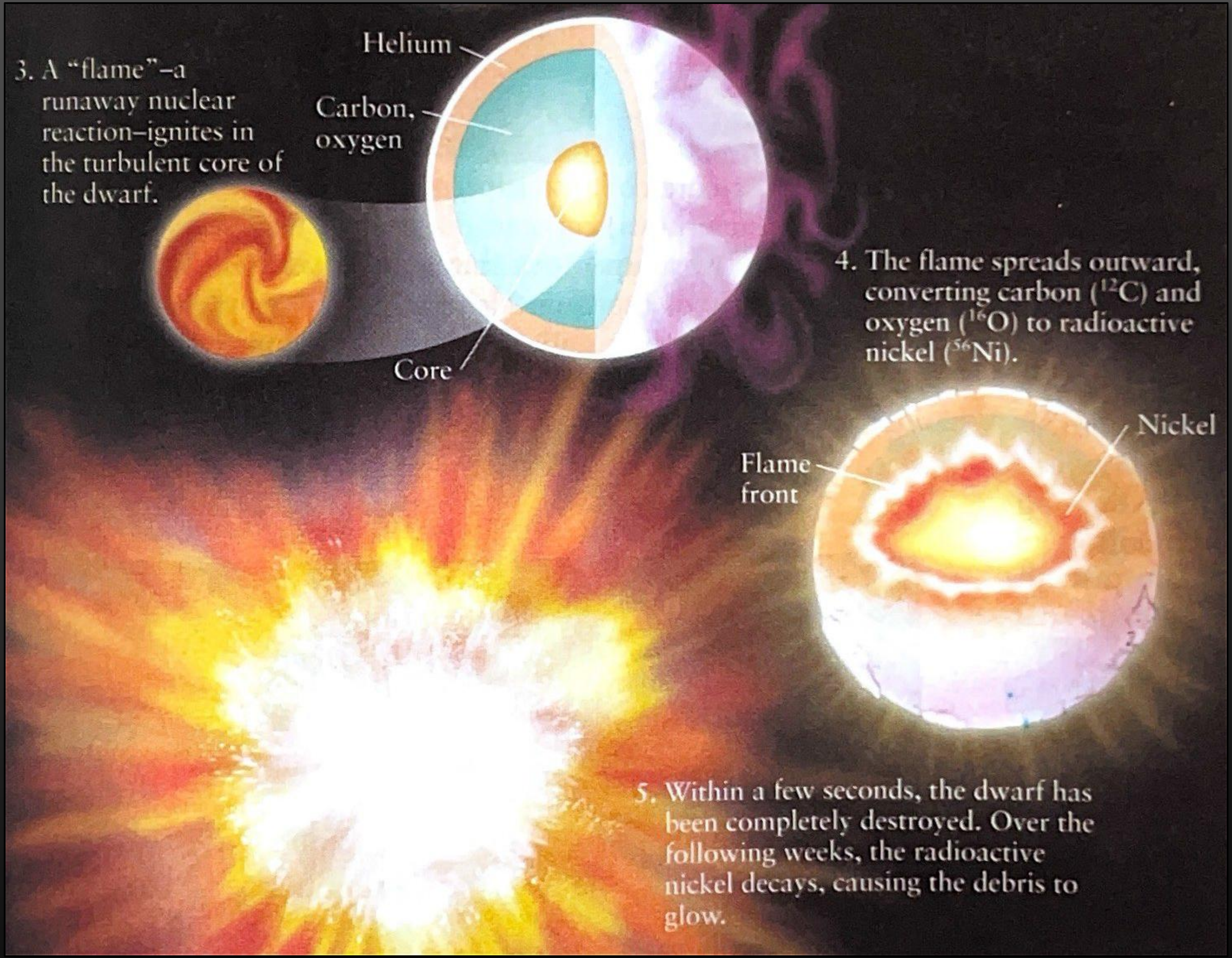


- Fe cannot undergo fusion
- All material in the star rushes into the core
- The core bounces back and produces a powerful shockwave → *PRESOLAR GRAINS!*

Stages That Produce Presolar Grains

Type Ia SNe

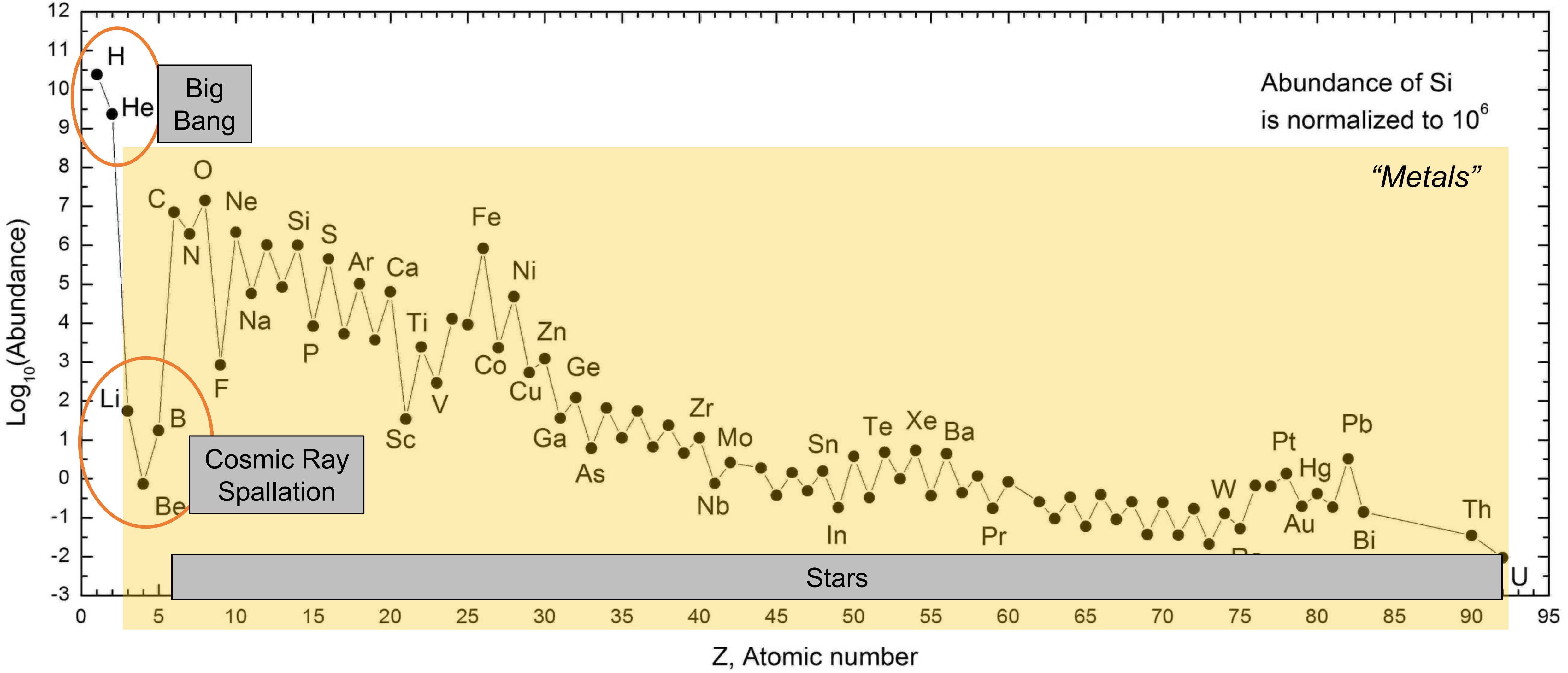




C-core burning from companion star

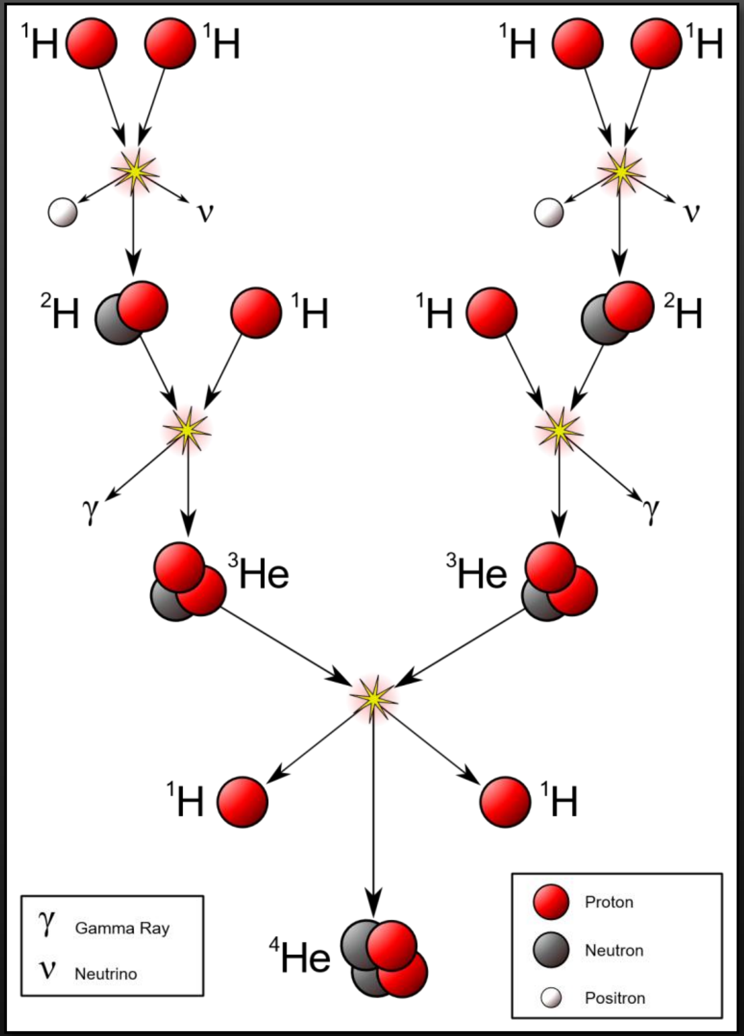
- High T and P leads to explosion → *PRESOLAR GRAINS!*

Element Formation

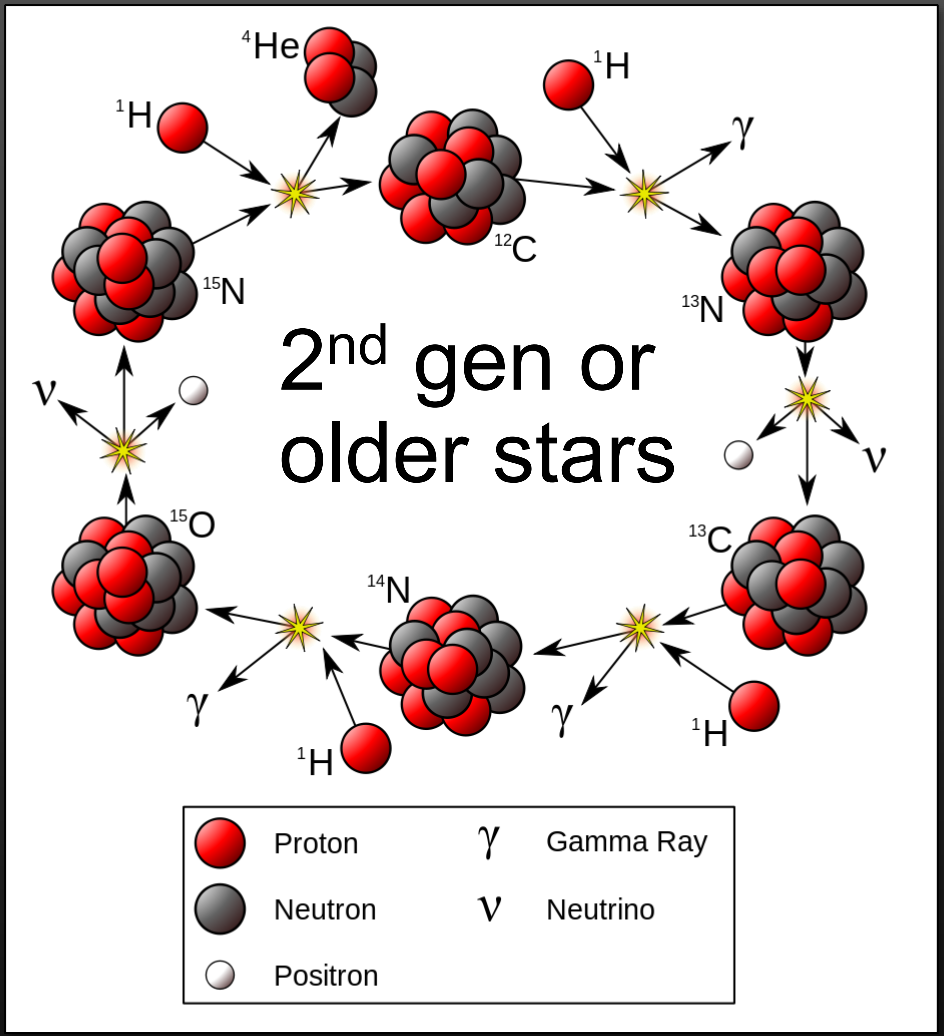


Nucleosynthesis in Stellar Cores

H → He



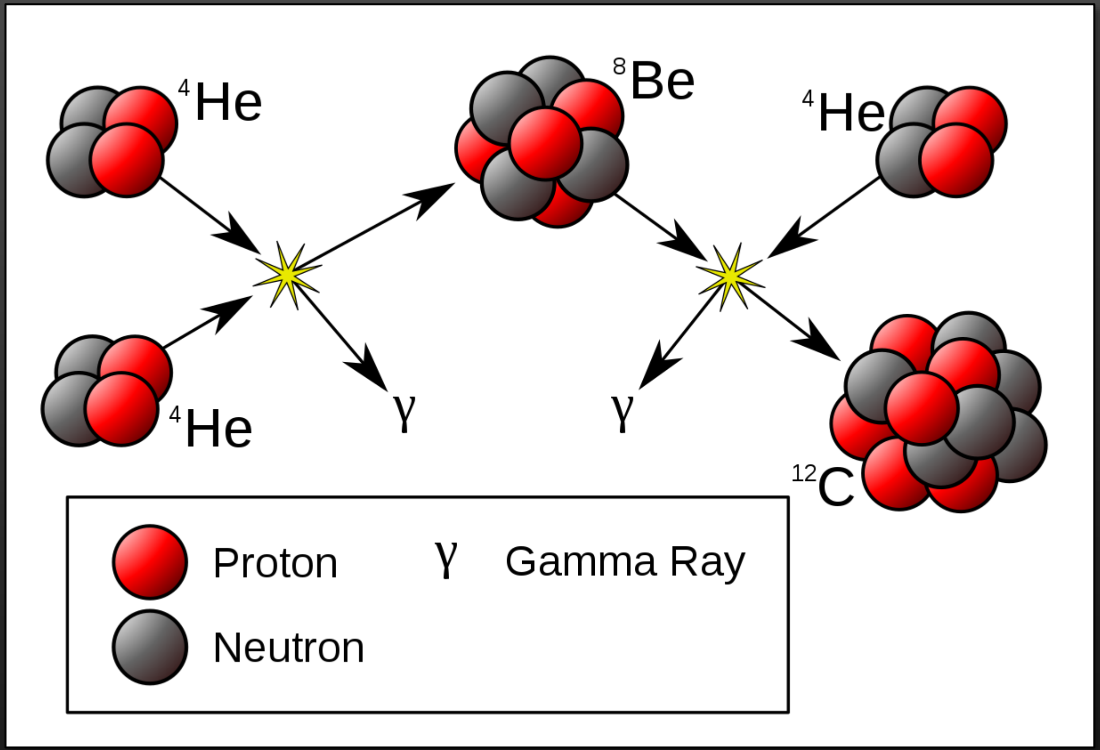
Proton-proton chain



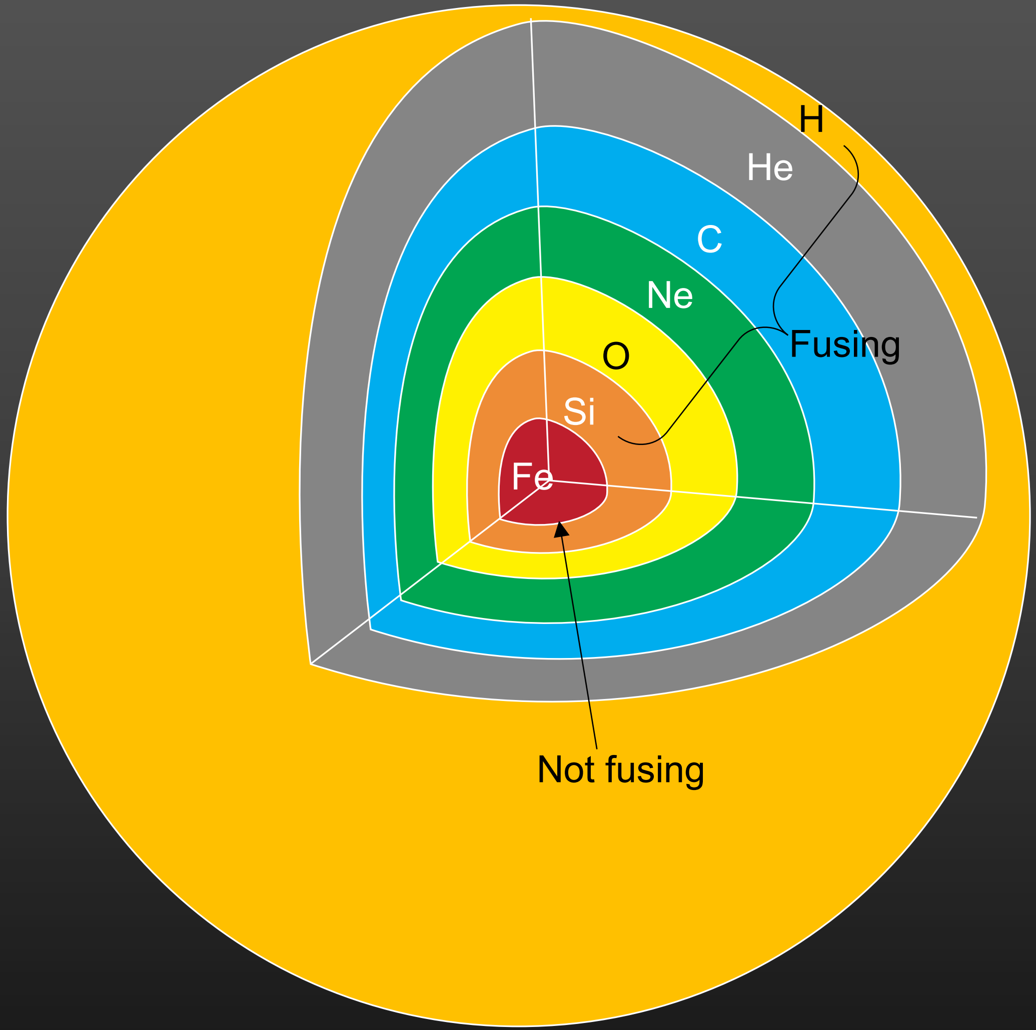
CNO cycle

Nucleosynthesis in Stellar Cores

>He



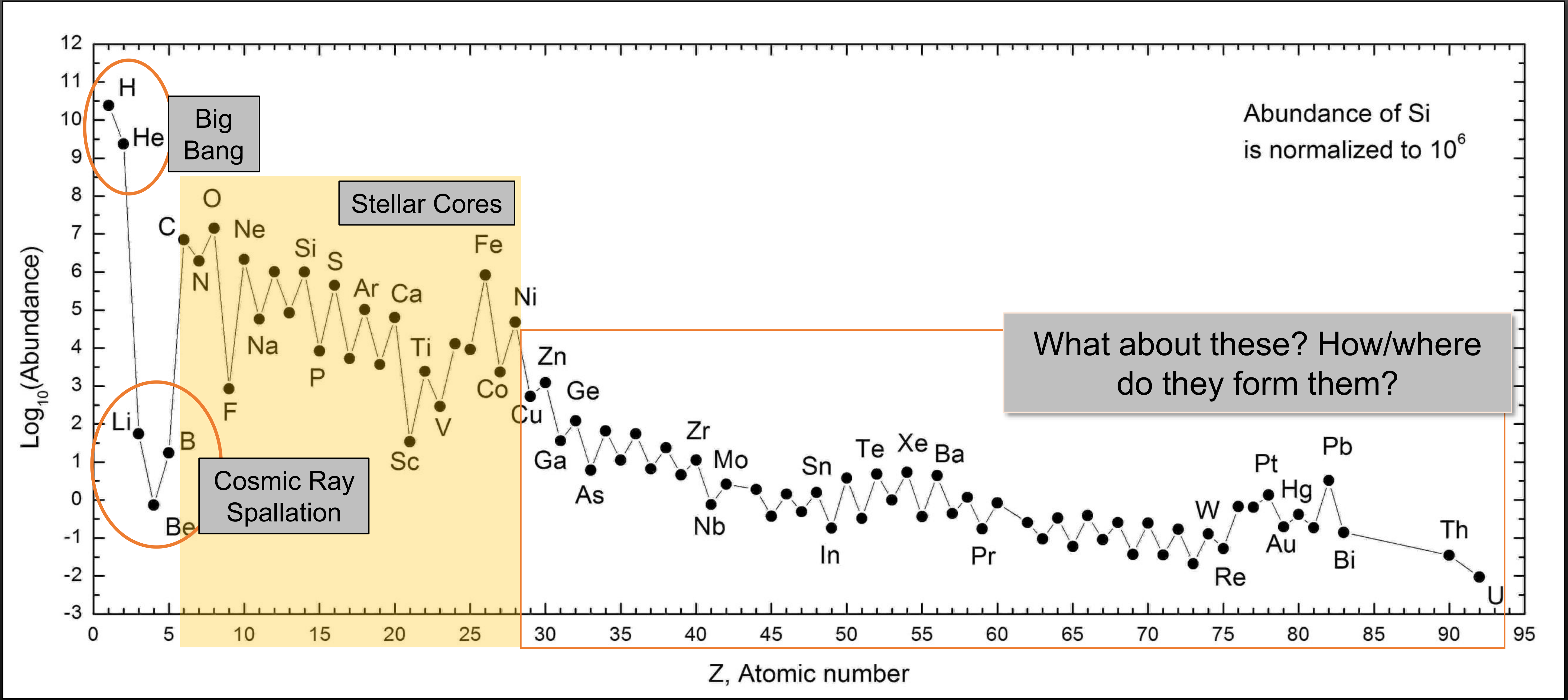
Triple alpha process



Other types of fusion

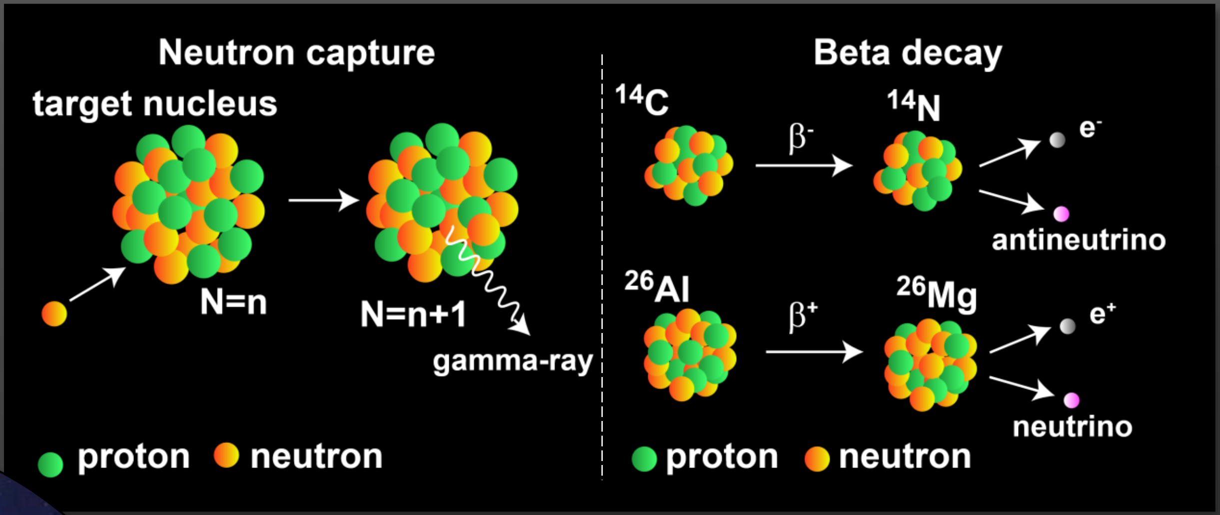
(C, Ne, O, Si)

Nucleosynthesis in Stellar Cores



Neutron Capture

- Produces elements that fusion cannot!
- Capture of a neutron by a nucleus
  (increases atomic mass by 1)
- Types = *s*-process and *r*-process

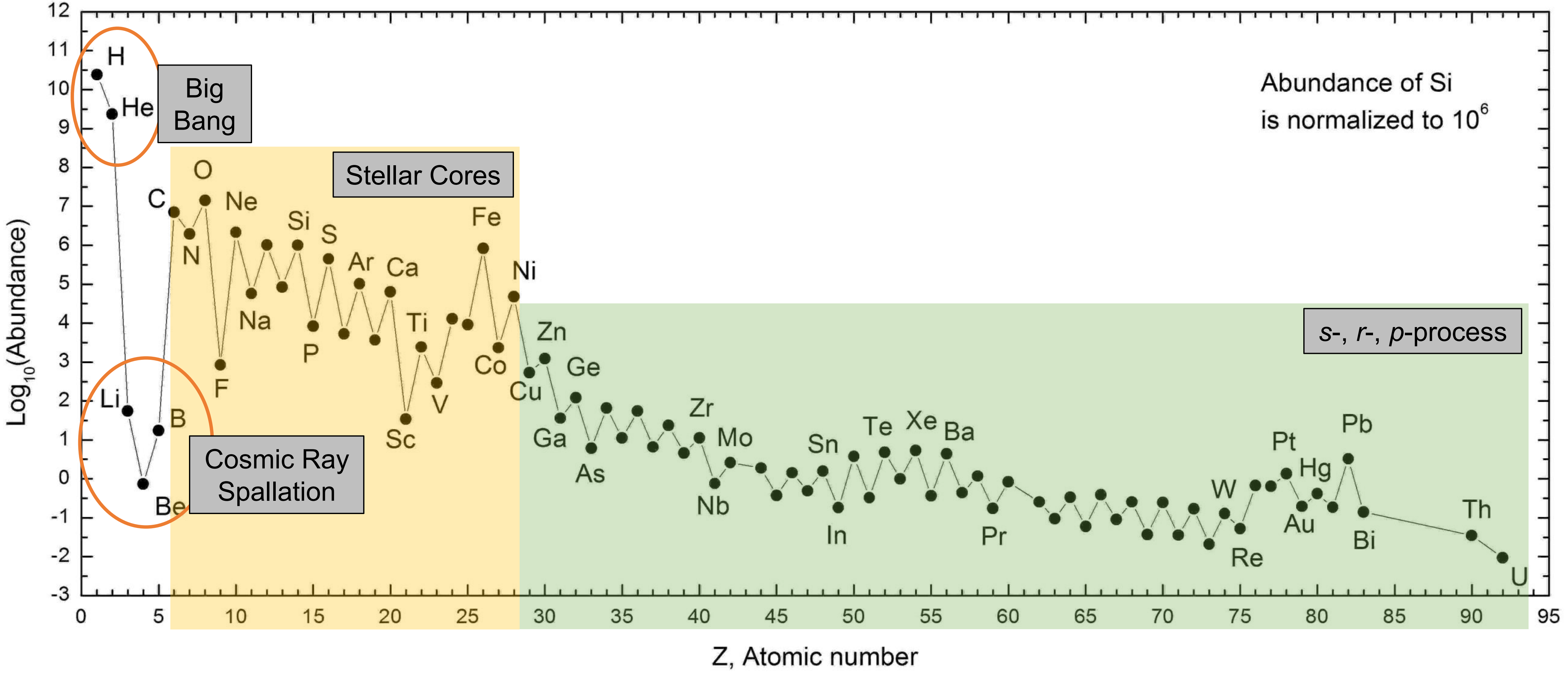


s-process
AGB stars

r-process
Type II supernovae?

p-process
Type Ia supernovae?

Nucleosynthesis



Cosmochemistry:
Presolar Grains/Stardust

Part 3: Presolar Grain Formation

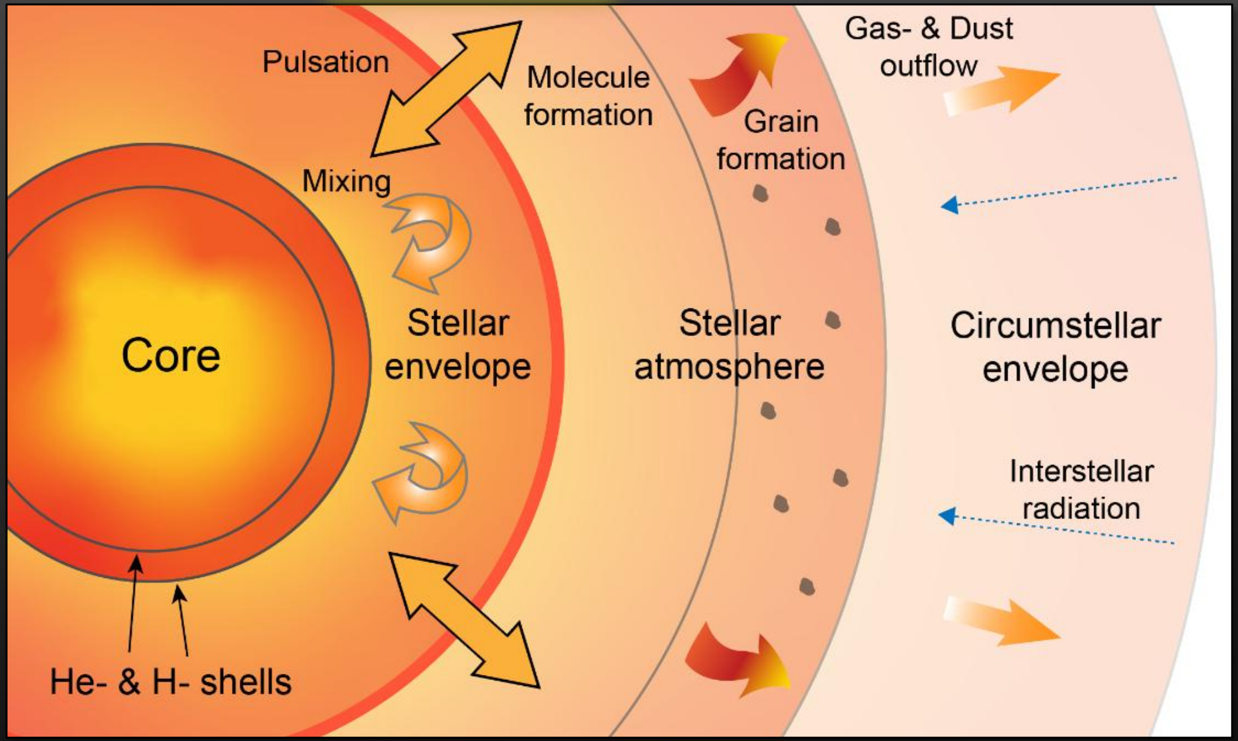
Dr. Sheri Singerling
NIC School 2025
Day 1

Circumstellar Environments

- Regions surrounding stars where material has been expelled or accumulated

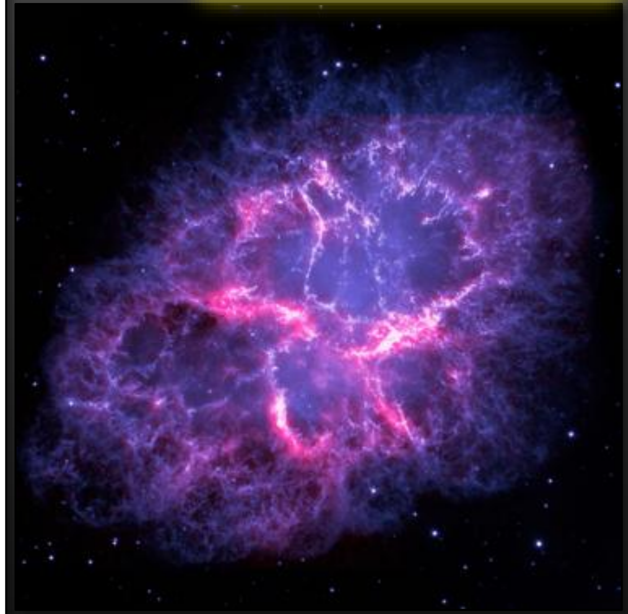
Circumstellar shells

AGB stars | RGB stars



Supernova remnants

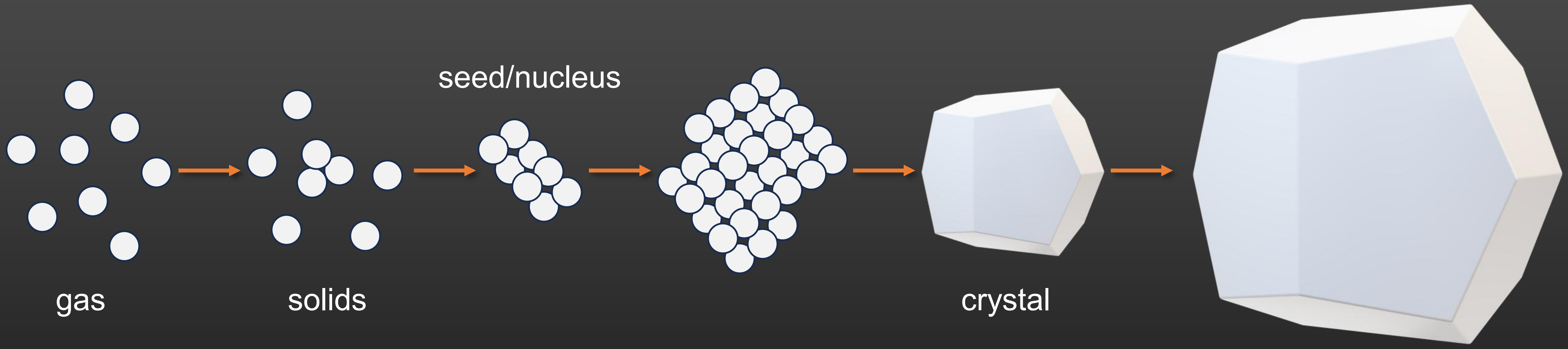
Type II supernovae (SNe)



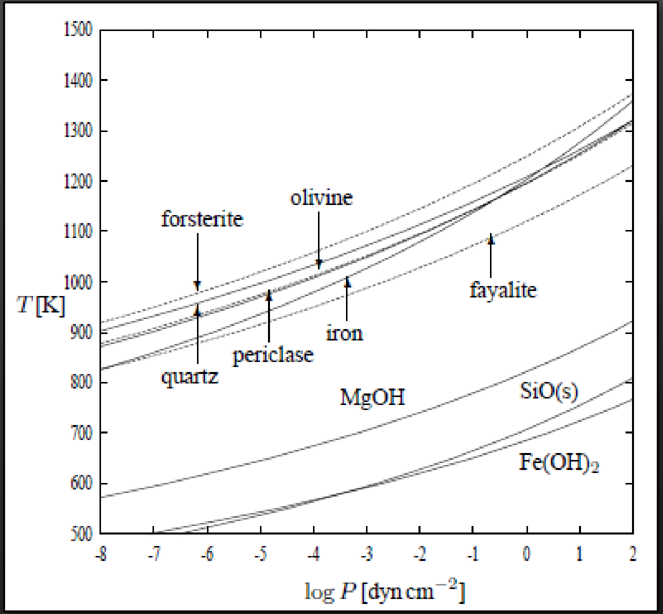
Type Ia supernovae (SNe)

Gas-Phase Condensation

Nucleation and growth



Gas-Phase Condensation
Equilibrium vs non-equilibrium



$dG = VdP - SdT$

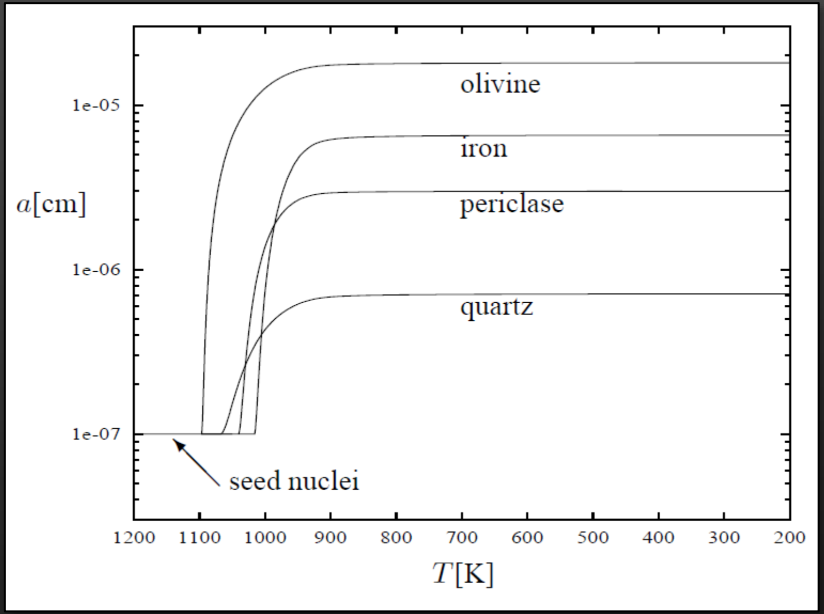
Equilibrium

- All about minimizing the **Gibbs free energy** (stability of phases as a function of T and P)

Non-Equilibrium

- **Kinetic effects** play a role (reaction rates, sticking coefficients, surface energies, etc.)

Both <u>can</u> and <u>do</u> form presolar grains!



Isotopic Signatures

AGB stars

s-process elements (especially for subgrains)

Type II SNe

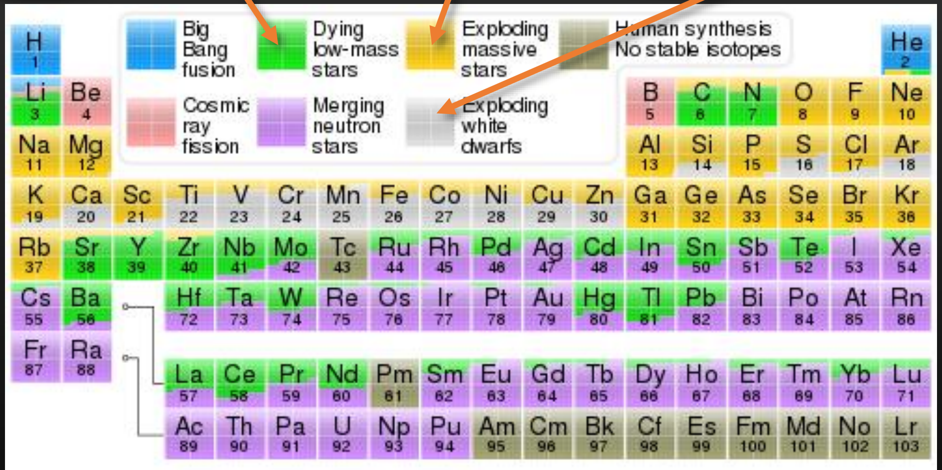
r-process elements

Type Ia SNe

p-process elements

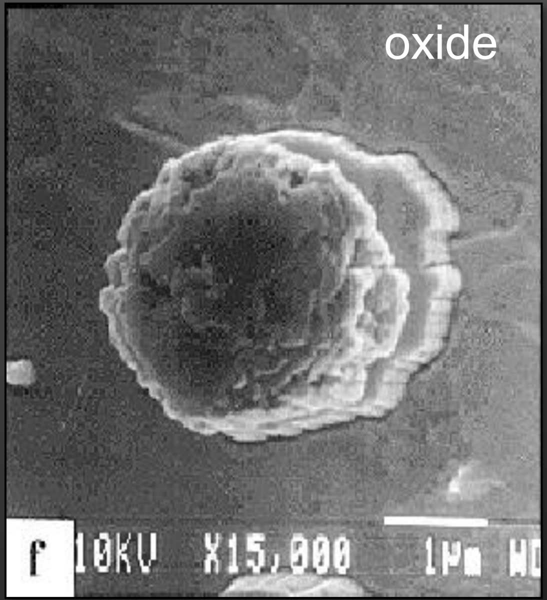
RGB stars

NO *s*- or *r*-process elements



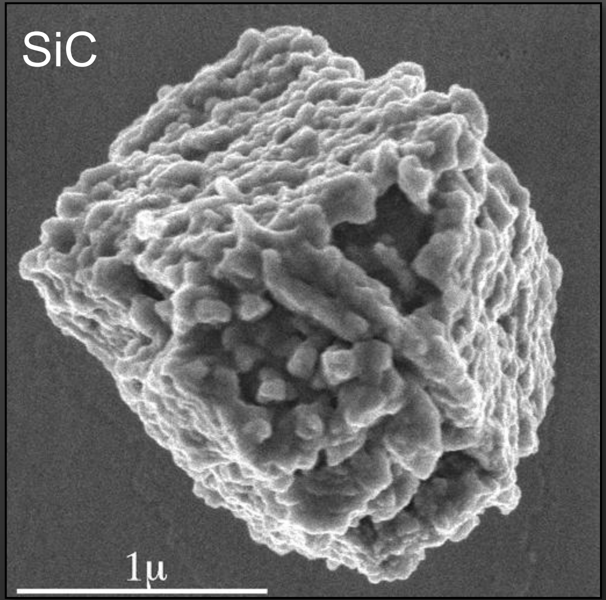
Condensation in Circumstellar Shells

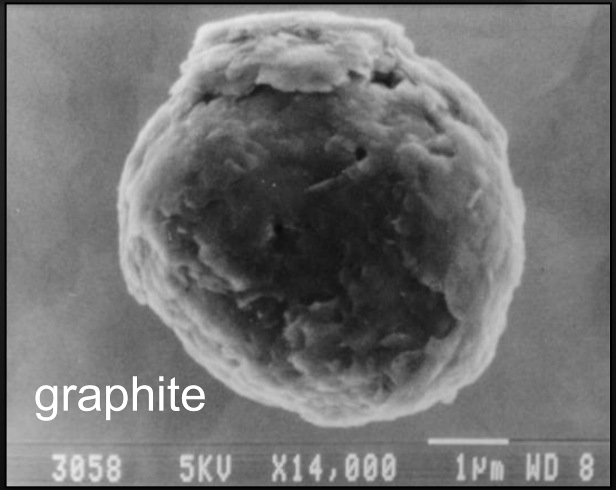
AGB star presolar grains



O-rich	C-rich
• Oxides and silicates	• SiC and graphite
• Requires C/O ratio < 1	• Requires C/O ratio > 1
• Younger AGB stars (less time)	• Older AGB stars (more time)

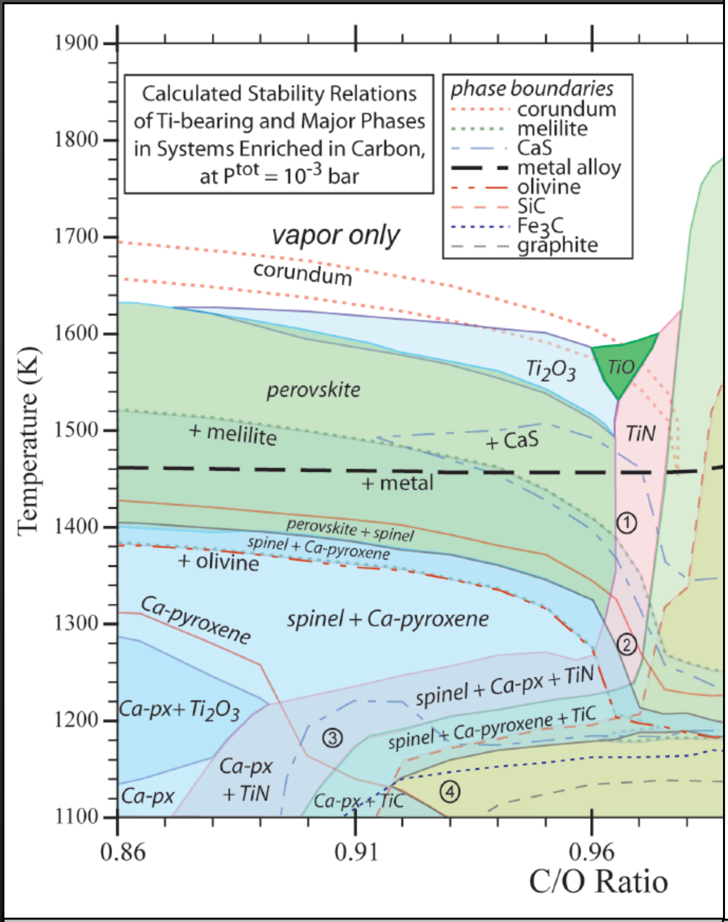
AGB stars form O-rich or C-rich presolar grains, depending on how long they have been in the AGB phase

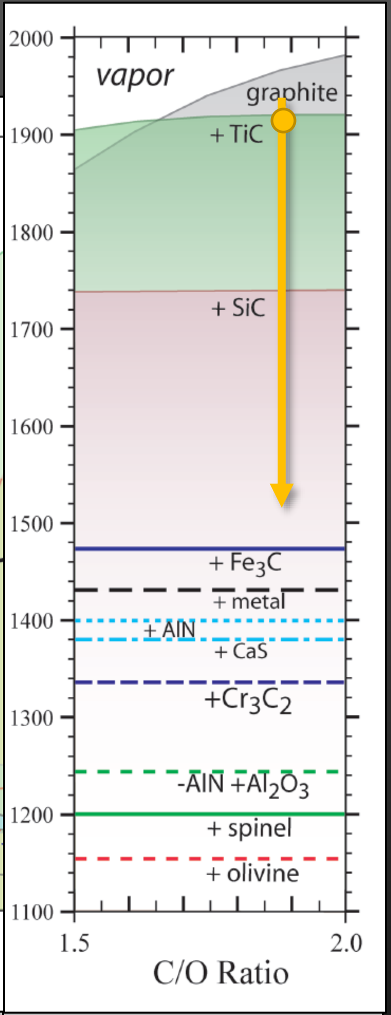




Condensation in Circumstellar Shells

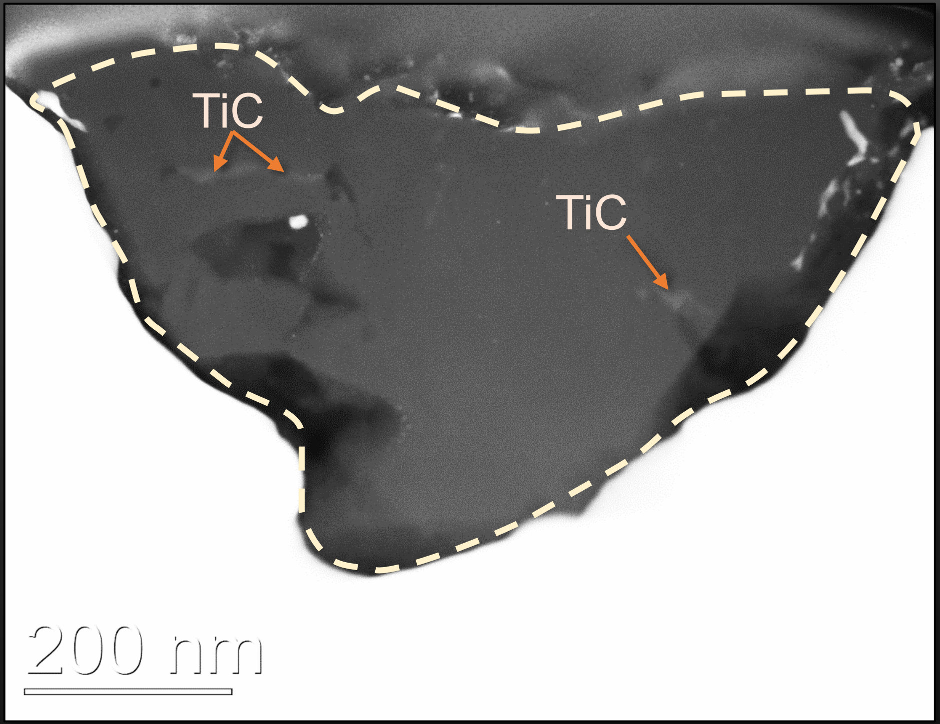
AGB star presolar grains





S type

C type

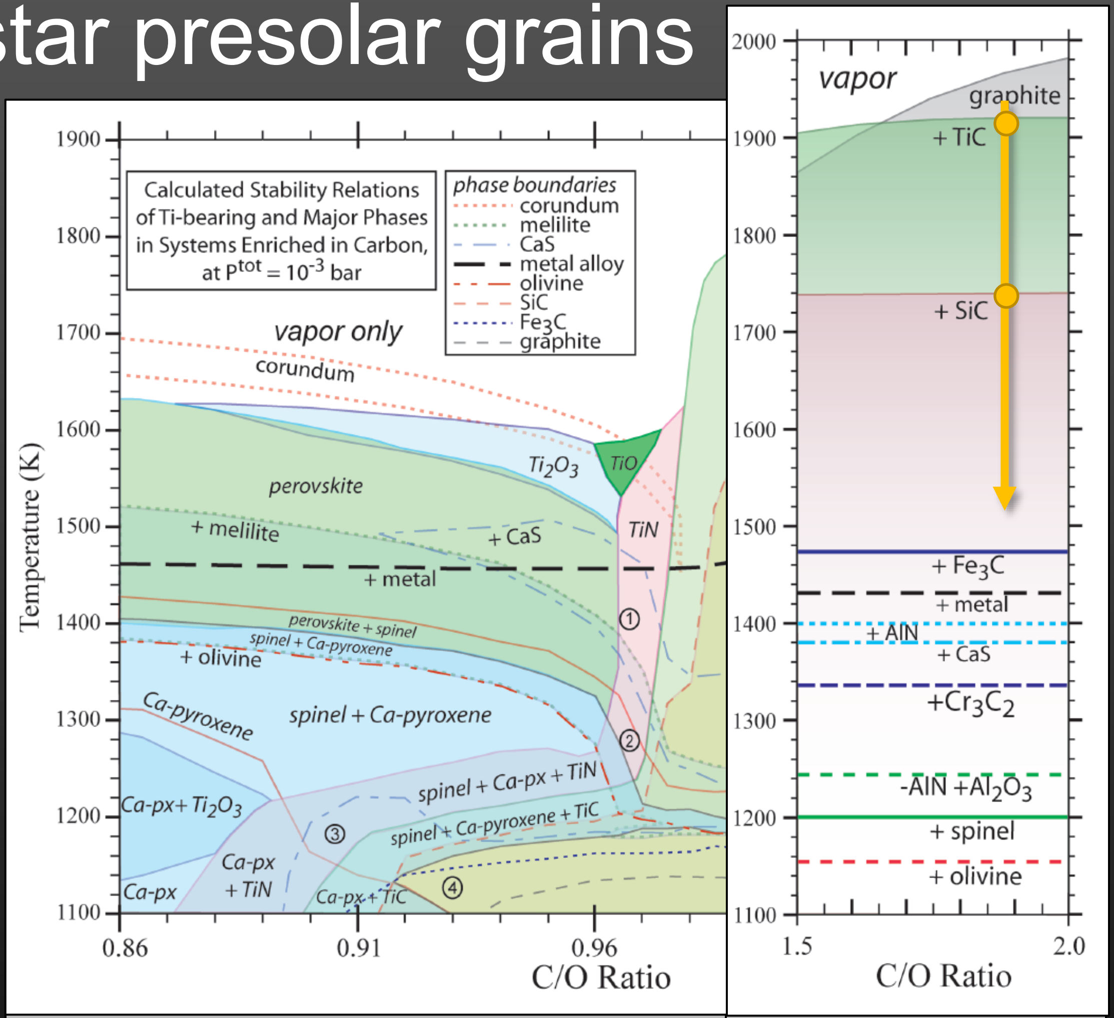


C/O ~1
AGB stars

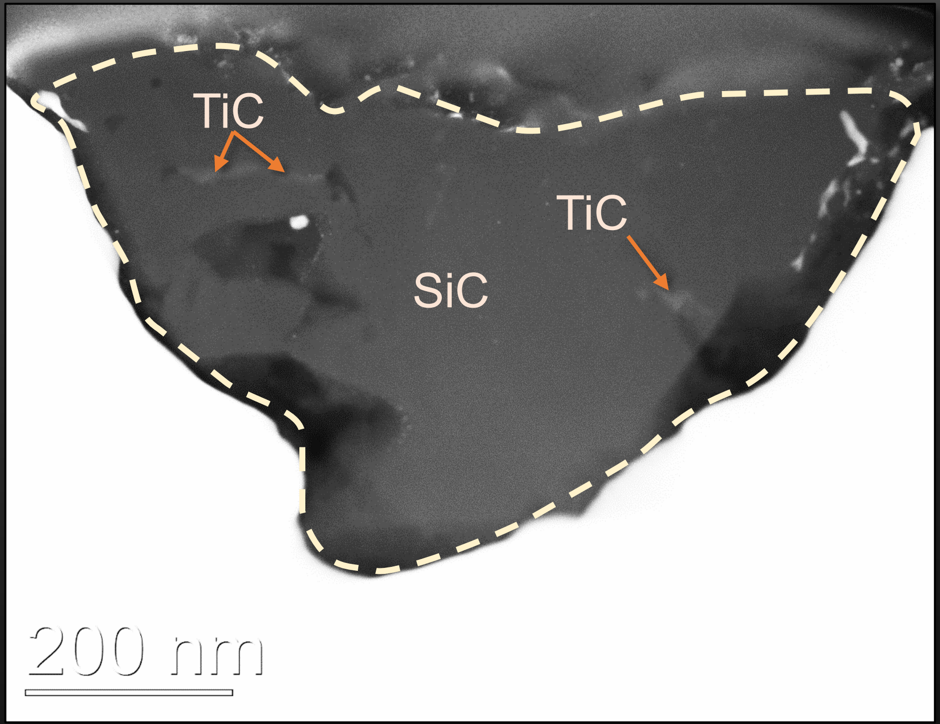
C/O >1
AGB stars (multiple 3rd DUP)

Condensation in Circumstellar Shells

AGB star presolar grains

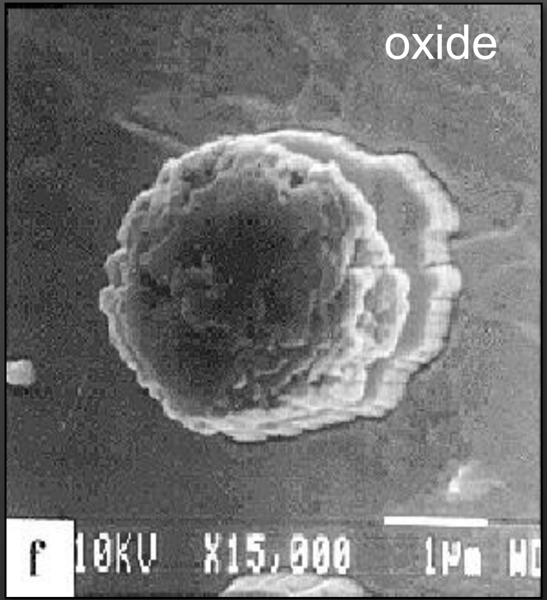


S type	C type
C/O ~1 AGB stars	C/O >1 AGB stars (multiple 3rd DUP)



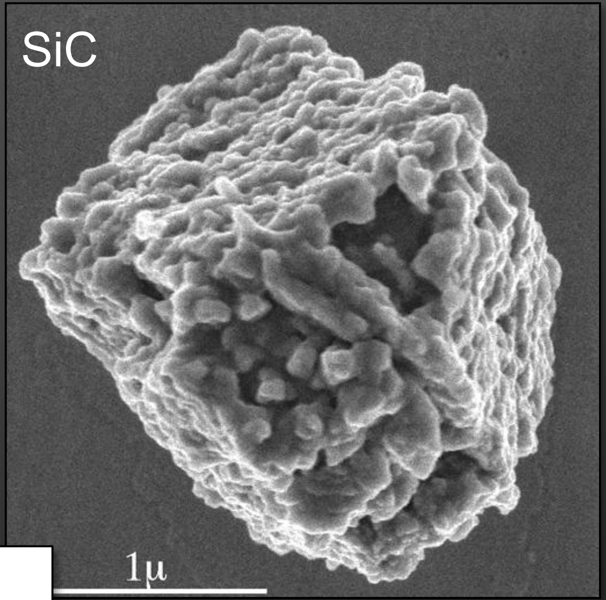
Condensation in Circumstellar Shells

Type II SNe presolar grains

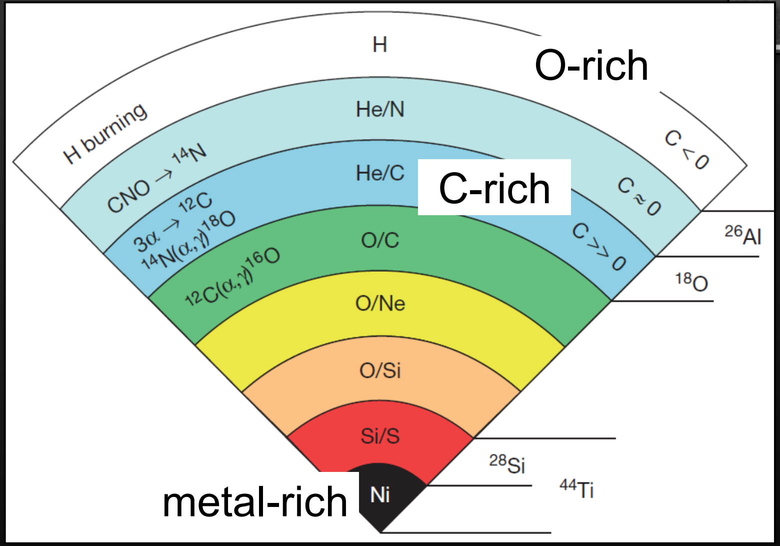


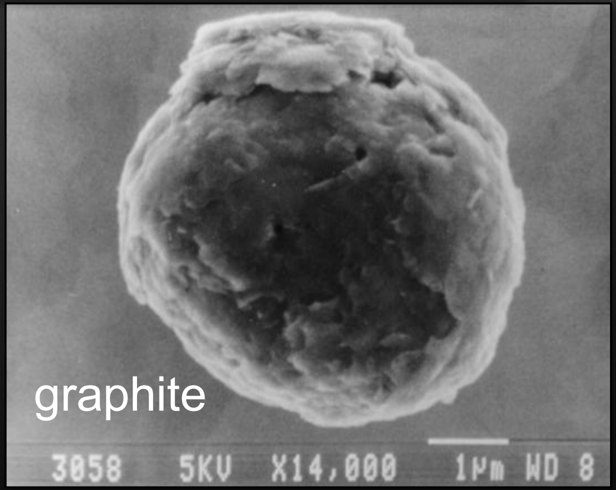
O-rich	C-rich
• Oxides and silicates • Requires C < O	• SiC and graphite • Requires C > O

Type II supernovae form O-rich or C-rich presolar grains, depending on the shell



And many other mineral phases as well! The situation is incredibly complex with supernovae dust.





Day 1 Summary

To date, **numerous** presolar grains have been identified. Their **isotopic compositions** reflect their formation in **circumstellar environments**.

These include:

- **Red giant branch (RGB)** stars
- **Asymptotic giant branch (AGB)** stars
- **Type II supernovae**
- **Type Ia supernovae**