# The Starting Materials
# Part I: The Origins of the Elements

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# The Starting Materials
# Part I: The Origins of the Elements

- Big Bang nucleosynthesis
- Nucleosynthesis in stars
  - Key nucleosynthesis processes
  - Stellar evolution related to nucleosynthetic processes

- Presolar grains (stardust) in meteorites and cosmic dust
  - Stellar sources
  - Probes of specific nuclear reactions
  - Stardust mineralogy – their Galactic history

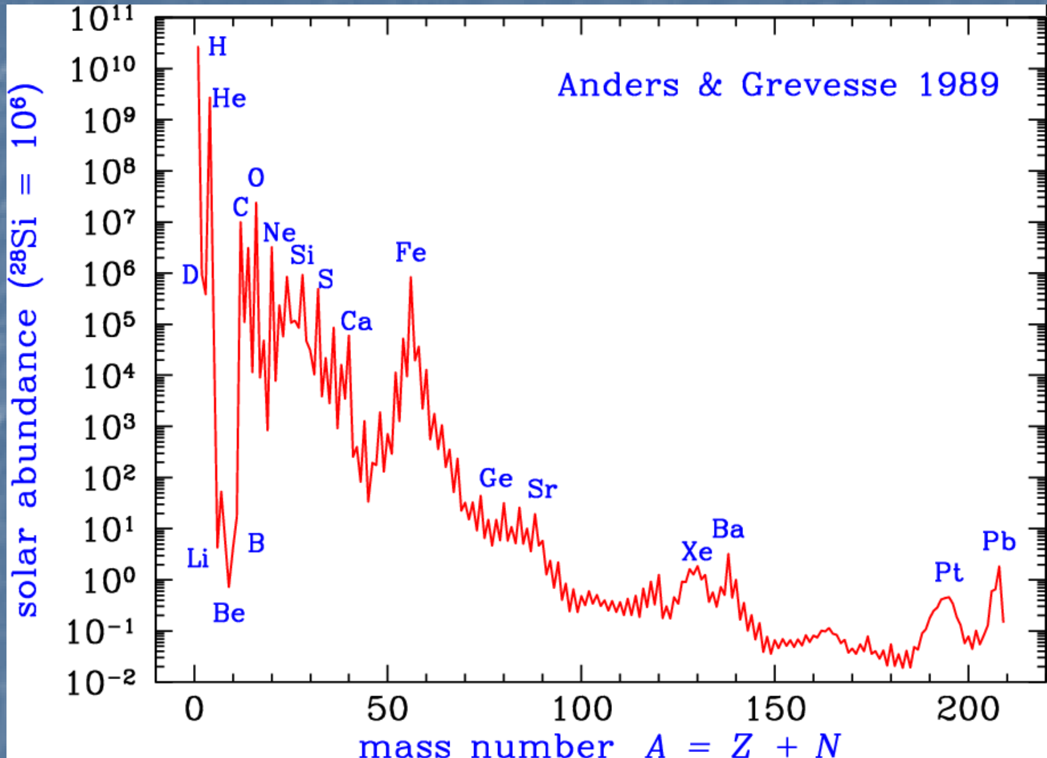
# Big Bang Nucleosynthesis

## The First Atoms

- Almost all fundamental particles (protons, electrons, neutrons) originated within the first few seconds
- ~1 minute later the Universe cooled to <$10^9$ Kelvin, allowing atomic nuclei to form
- All of the Hydrogen, and most of the Helium and Lithium in the Universe formed within the first minute.
- NO heavy elements formed in the Big Bang that permeates the Universe

The light from these galaxies reached us after traveling for 13 billion years
Thus, we see ‘young’ galaxies formed within 1 billion years of “the Beginning”

# Solar System Element Abundances




- H and He are by far most abundant elements
- Li, Be and B are anomalously low in abundance
- Exponential drop in abundance with increasing Z
- Even Z > odd Z
- Fe and neighbors are anomalously abundant

# Nucleosynthesis in Stars

Al Cameron

PUBLICATIONS OF THE
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NUCLEAR REACTIONS IN STARS AND NUCLEOGENESIS*

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Atomic Energy of Canada Limited
Chalk River, Ontario

INTRODUCTION

It was once thought that the stars and the interstellar matter had a uniform chemical composition except for some of the lighter elements, which were destroyed by thermonuclear reactions in stellar interiors. This view has caused astronomers and physicists to look for extreme physical conditions in which all the matter in the universe was gathered together at high density and raised to a high temperature sufficient to produce the observed abundances of the elements by the nuclear reactions that take place under these conditions. However, in recent years it has become apparent not only that thermonuclear reactions in stellar interiors can produce large abundance changes in even the heaviest elements,[1,2] but also that there are intrinsic differences in the chemical compositions of different classes of stars before thermonuclear reactions have started in them.[3] Stars classed as extreme Population II objects—subdwarfs and members of globular clusters—usually have a much smaller ratio of metals to hydrogen than does the sun, the factor of decrease being commonly about 10 or 20. In certain rare objects this factor may be much larger still.[4] On the other hand, in the O- and B-type stars of extreme Population I the ratio of metals to hydrogen has commonly increased over that in the sun by factors of 2 to 4. Light and heavy elements

* One in a series of review articles currently appearing in the *Publications.*

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REVIEWS OF
MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

*Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California*

"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

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* Supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

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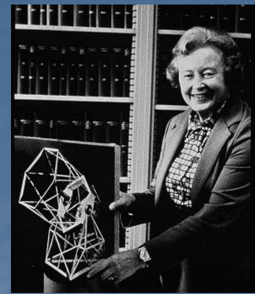
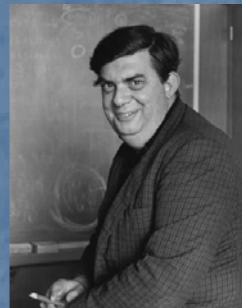
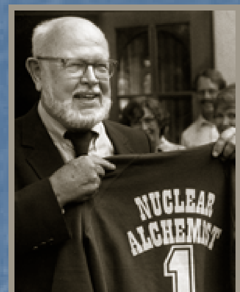


Margaret Burbidge



Geoffrey Burbidge



William Fowler

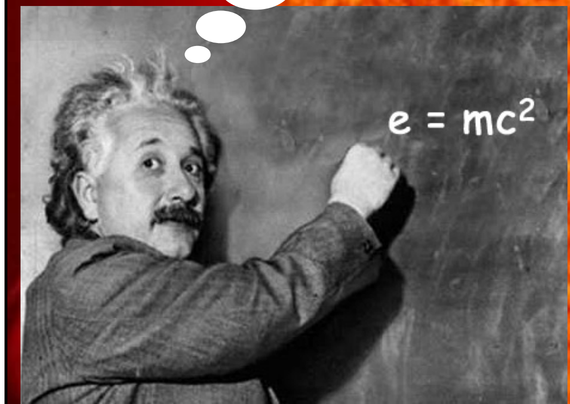
Fred Hoyle

These two papers first explained nuclear reactions in stars responsible for the production of the elements

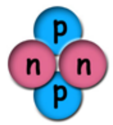
# Energy Generation in Stars

**The Sun's energy comes from the fusion of H into He**

Energy can be created from mass!




The mass of a nucleus is less than the sum of the masses of the protons and neutrons that it is made from!

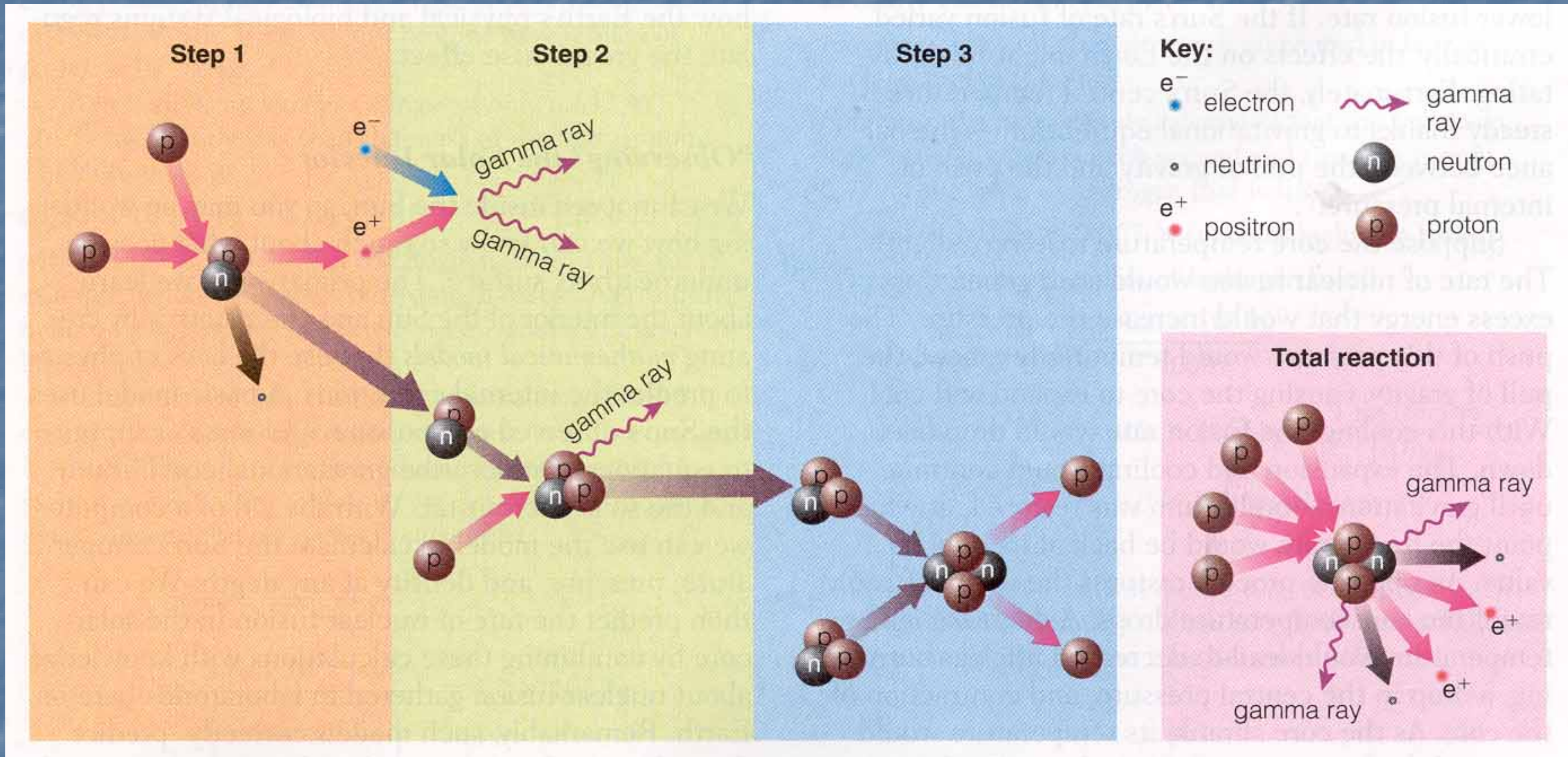
| | |
|---|---|
| p p mass = 2 x 1.00728 u |  |
| n n mass = 2 x 1.00866 u | |
| mass of 2p + 2n = 4.03188 u | mass = 4.00153 u |

$\Delta m = 0.03035 \text{ u} = 5 \times 10^{-26} \text{ g}$

$E = \Delta mc^2 = 28.3 \text{ MeV}$

nuclear binding energy

# Fusion of H into He



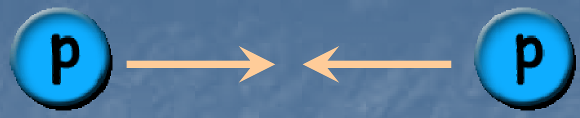

Reaction timescales

$10^9$ years

1 second

$10^6$ years

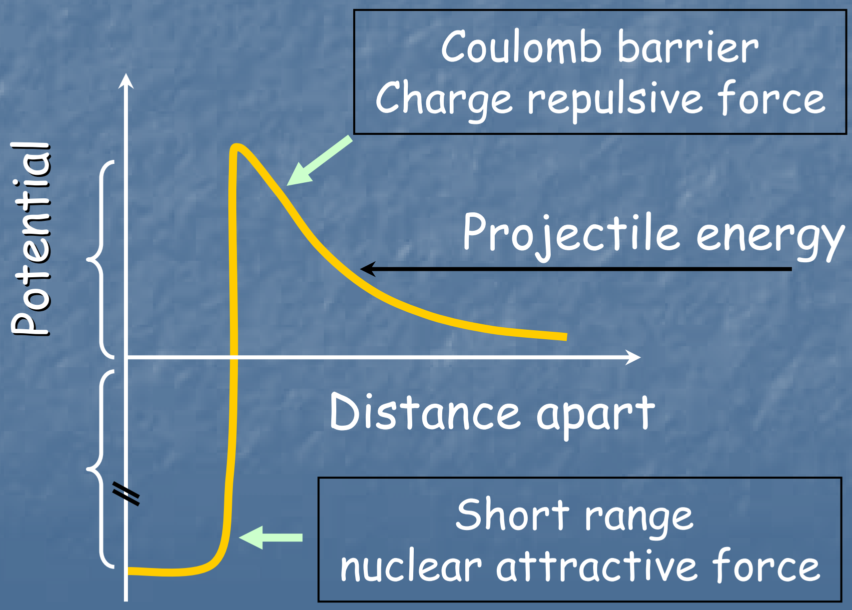
# Nuclear Fusion



Nuclear binding force is strong but *very* short range

Nuclei must overcome Coulomb repulsive force to fuse together

## Potential diagram for nuclear collisions




Temperature ~ 15x$10^6$ K

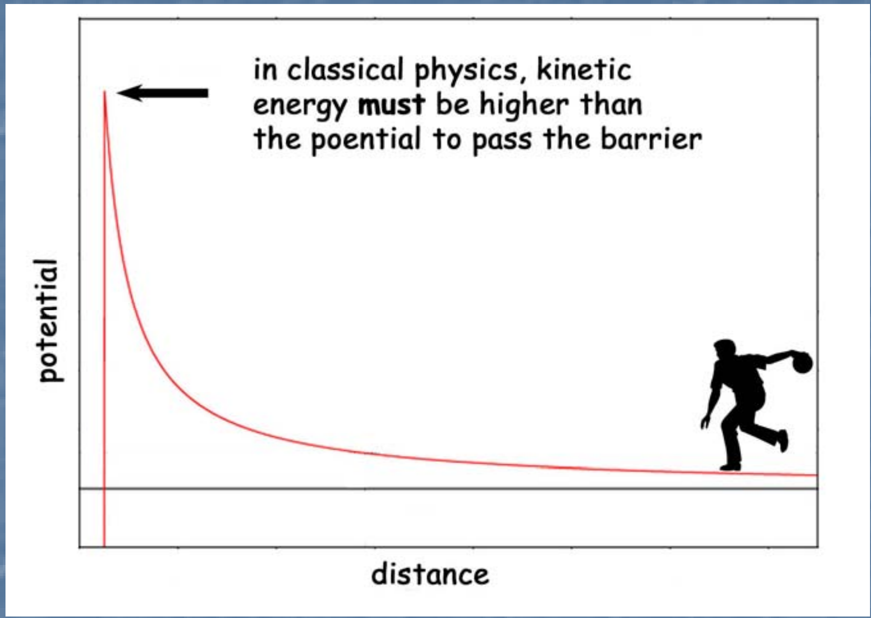
E = kT ~ 1 keV

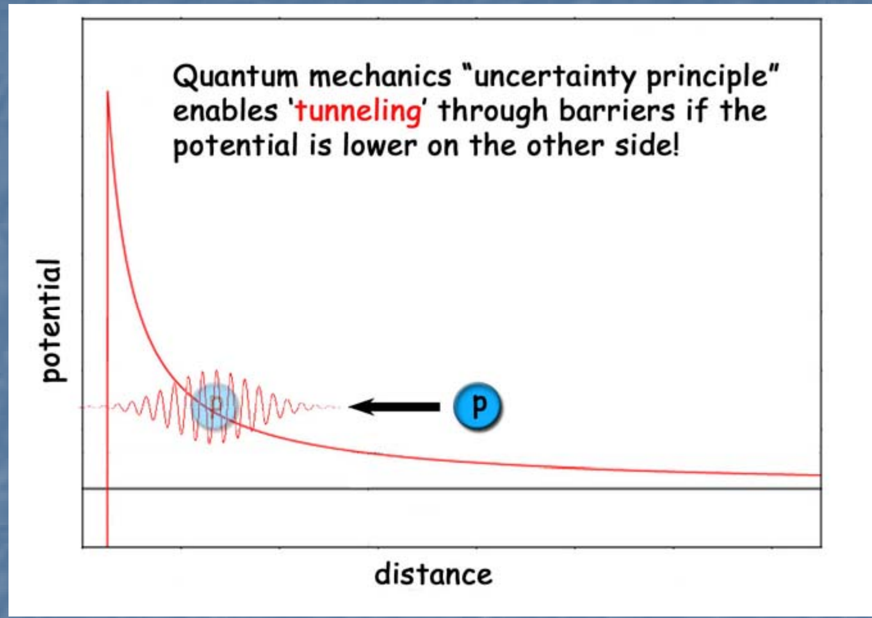
However!

**p + p** barrier E = 550 keV

The sun is not hot enough for fusion ?!

# Quantum Tunneling




Probability of penetrating barrier ~ $\exp[-(E_{barrier}/E_{thermal})^{1/2}]$

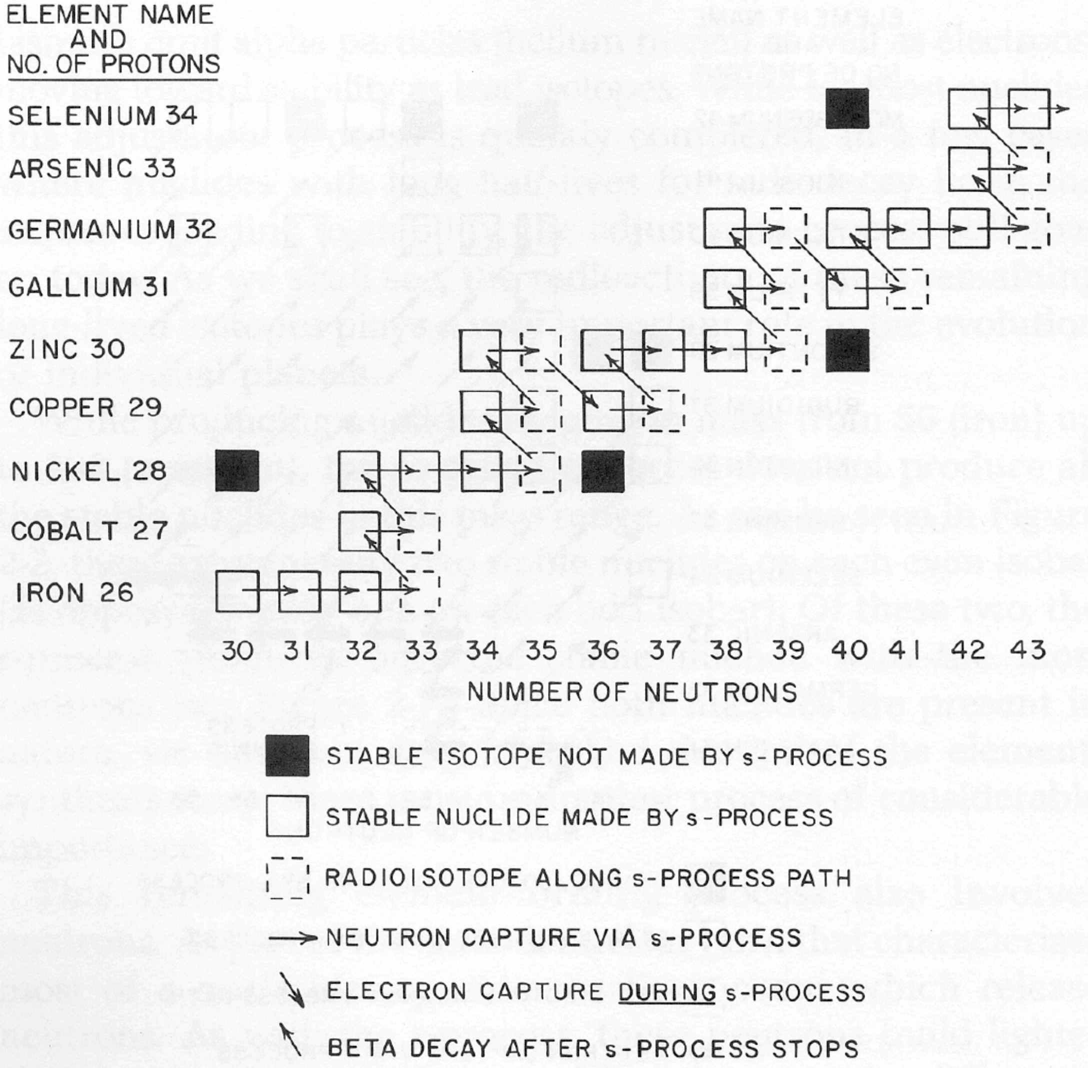
*Fusion reaction rates increase exponentially with Temperature*

For p + p reaction in the Sun, Probability = $10^{-22}$!

*This is why the Sun will live for 10 billion years*

# S Process Nucleosynthesis

## slow neutron capture




Neutron capture reactions are *easy*!
No charge barrier
Can occur even at room temperature

Isotope with excess neutrons

$$n \longrightarrow p + e^-$$

S process is slow addition of neutrons compared with radioactive decay

S process is the most important source of many elements > Fe

This occurs at the late stages of a stars life

# Core Temperatures in Stars

**Stars are balanced in gravitational/thermal equilibrium**

- Thermal pressure in core maintained by fusion reactions
- Evolution and lifetime of a star is "easy to predict"

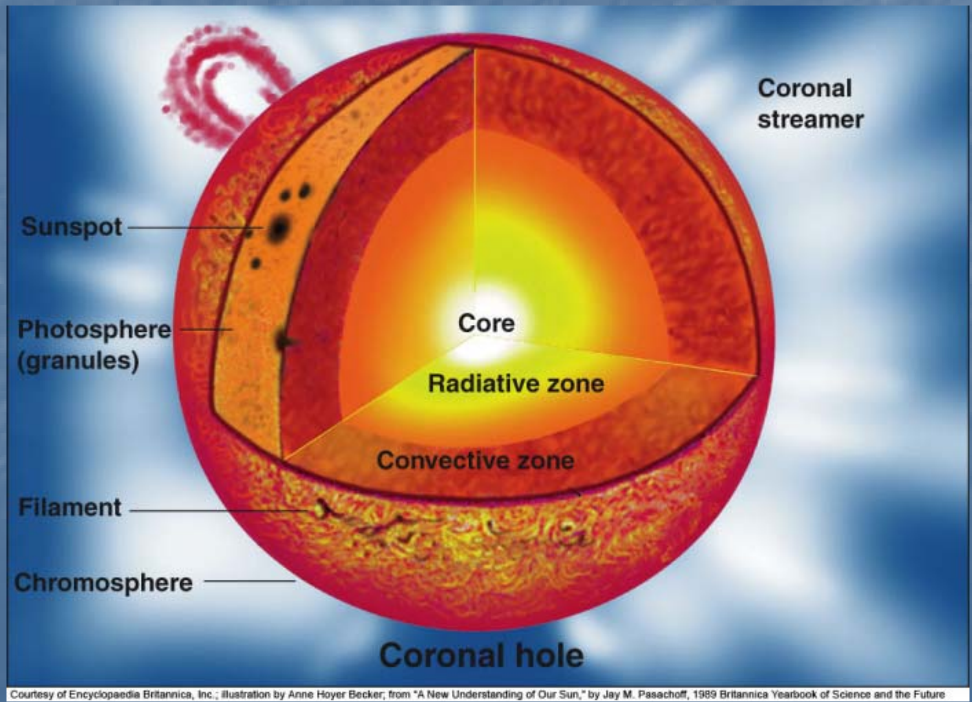
**High mass stars have short lives**

- Higher thermal pressure required to support higher mass
- Fusion rates increase exponentially with temperature

Pressure forces balance gravity force (hydrostatic equilibrium)

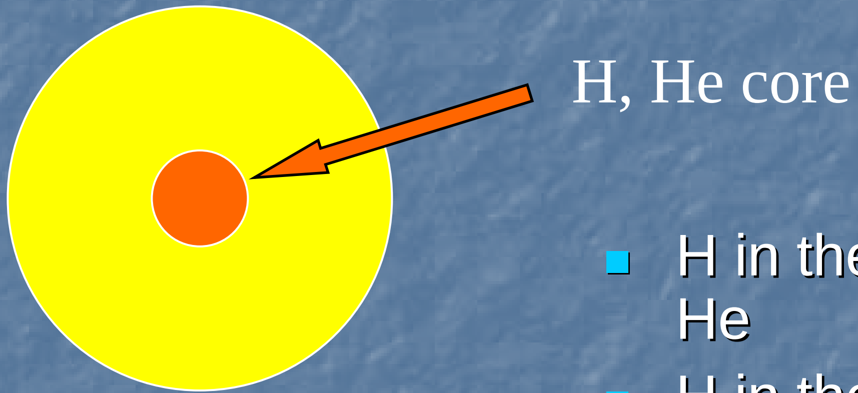
- Fgravity = Pgas + Pradiation
- $mGM/R^2 = rkT + sT^4$

The temperature of the core is proportional to the mass of the star



# Stellar Evolution

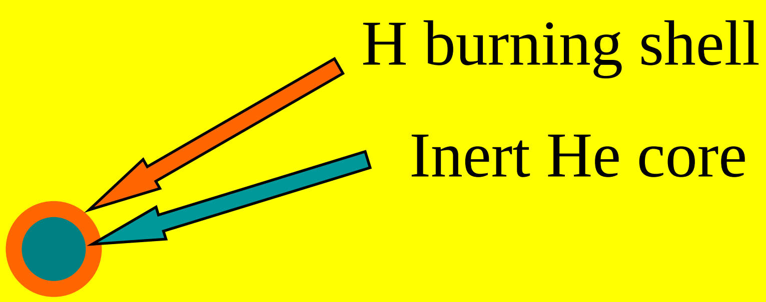
## Main sequence star




- H in the core is gradually converted into He
- H in the core is eventually completely converted into He
- This is the longest lasting stage of a star's life
  - 10 million – 100 billion years, depending on stellar mass

# Stellar Evolution

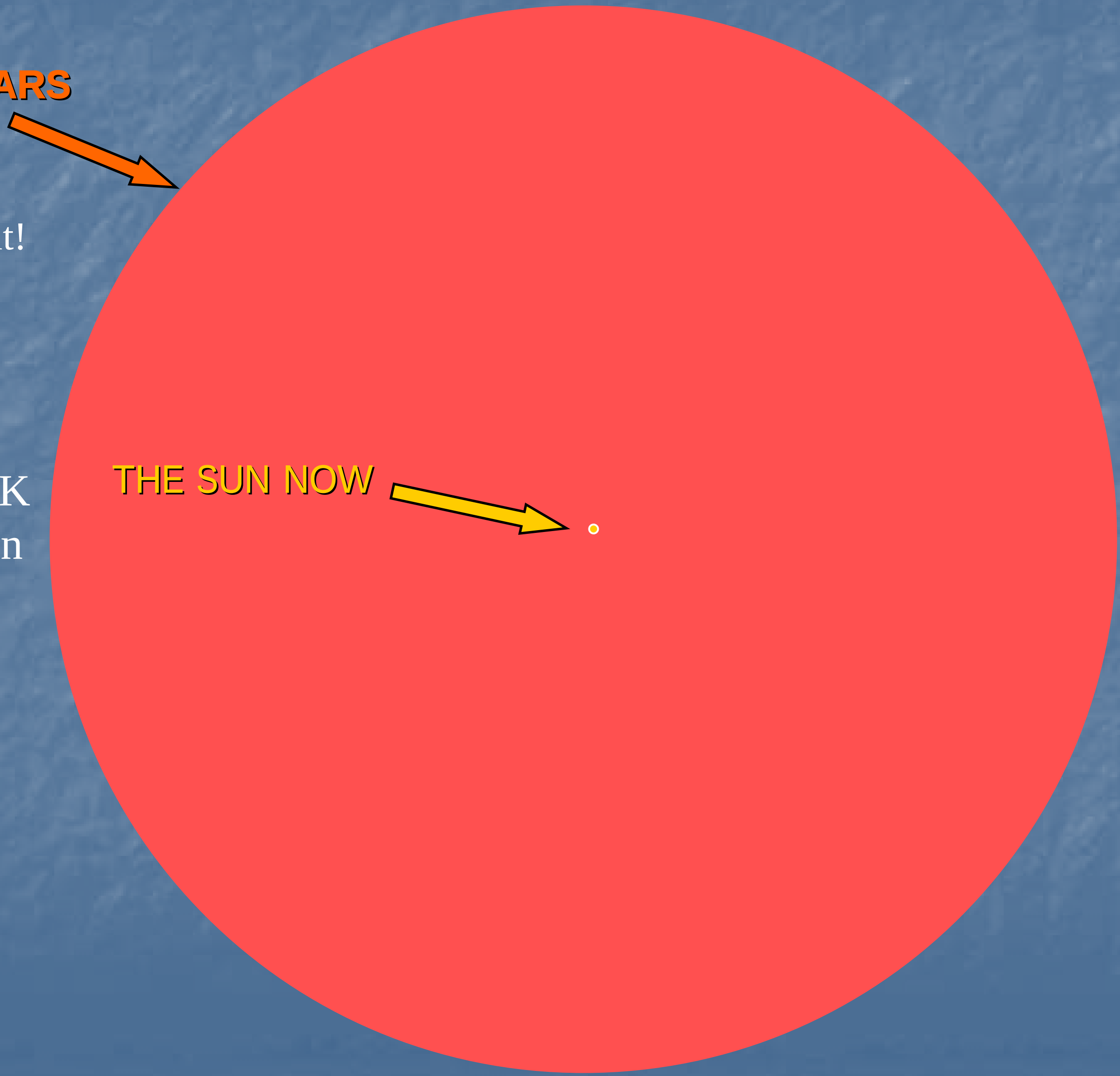
## Red giant star




- Without H fusion, the He core cannot thermally support itself – the He core contracts
- Pressure, temperature increase in the core
- H burning starts on a shell around the core
- With higher core T, the star EXPANDS

# Red Giant Stars

**THE SUN IN 5 BILLION YEARS**

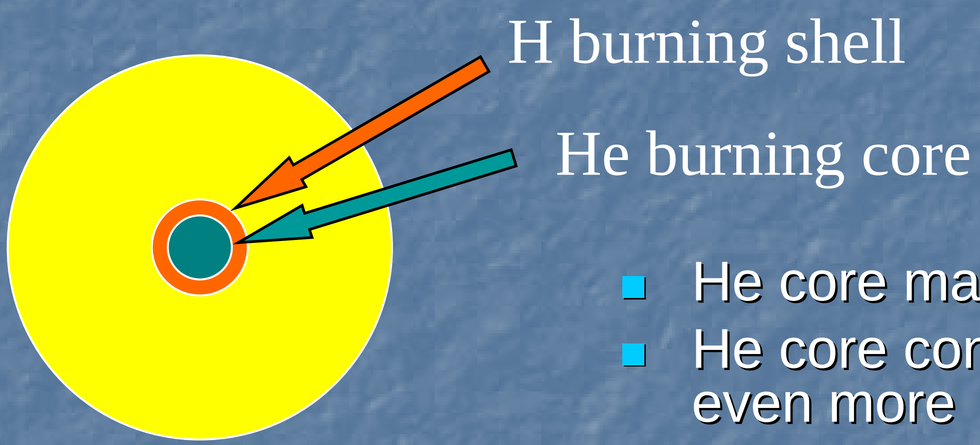



About the size of the Earth's orbit!

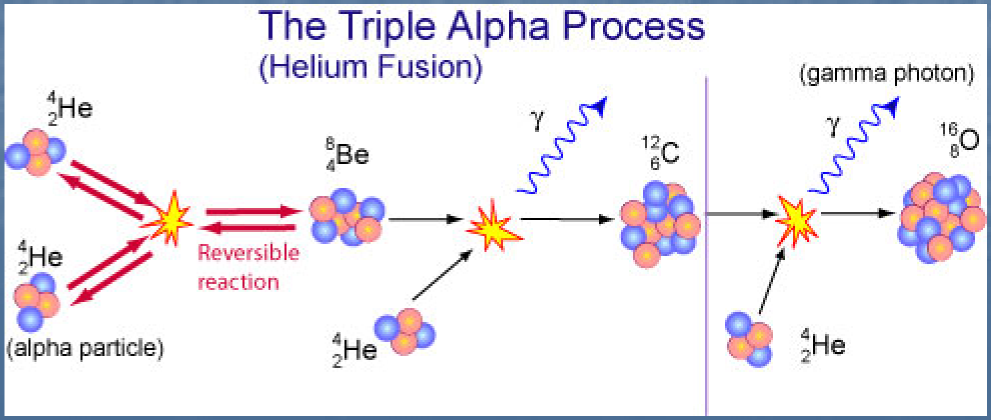
Diameter ~ 300 million km
Core diameter ~ 10,000 km
Core temperature 100 million K
Star luminosity 1,000 x the Sun

# Stellar Evolution

## Red giant star

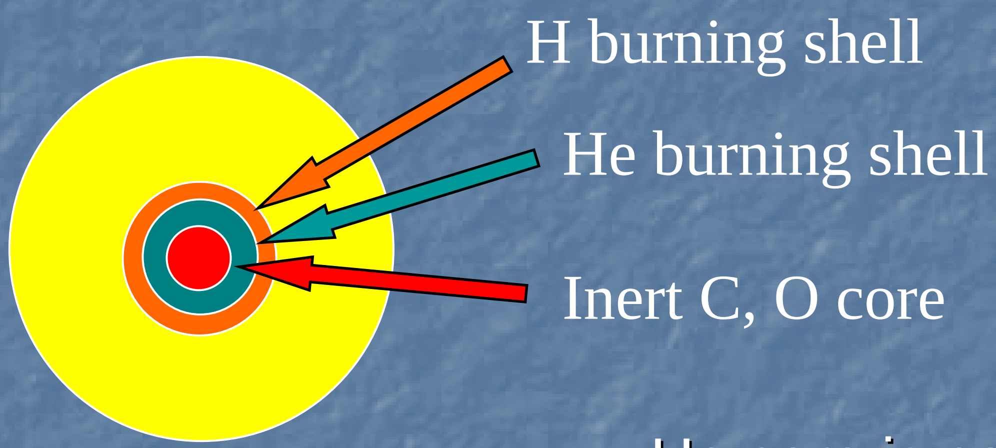



- He core mass continues to increase
- He core continues to contract, raising T even more
- Eventually T is high enough for Helium fusion reactions



# Stellar Evolution

## AGB star transition




(not to scale)

<u>Primary neutron source</u>

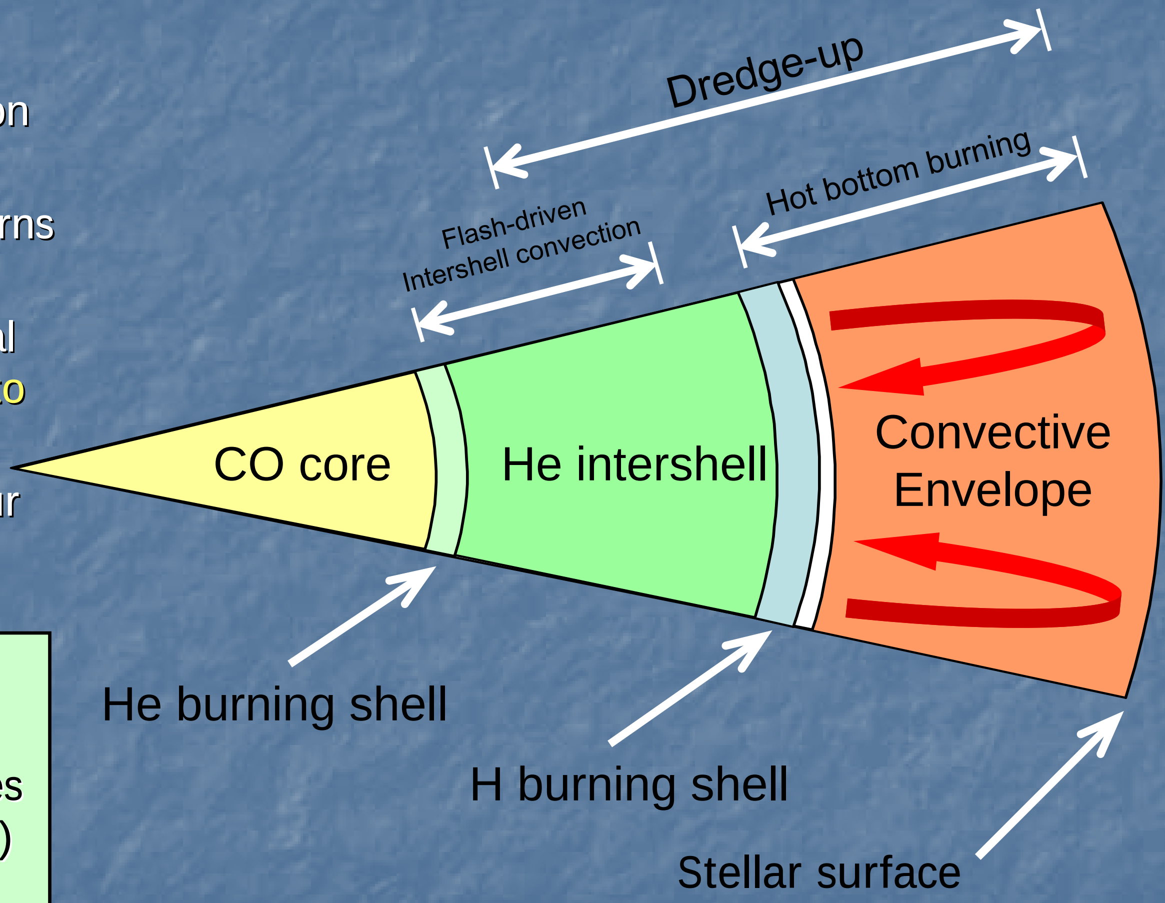
$^{13}C + {}^{4}He \longrightarrow {}^{16}O + n$

- He core is converted from He into C,O
- The star is now an "AGB star"
- He burns in a shell around the core
- S process elements made in He shell
- H burns in a shell around the He shell

# Stellar Evolution

## AGB stars

- He shell gains mass from H fusion shell above
- He shell contracts and briefly burns strongly (flash)
- He flash creates a strong thermal pulse, ejecting some material into space
- He shell thermal pulses can occur many times

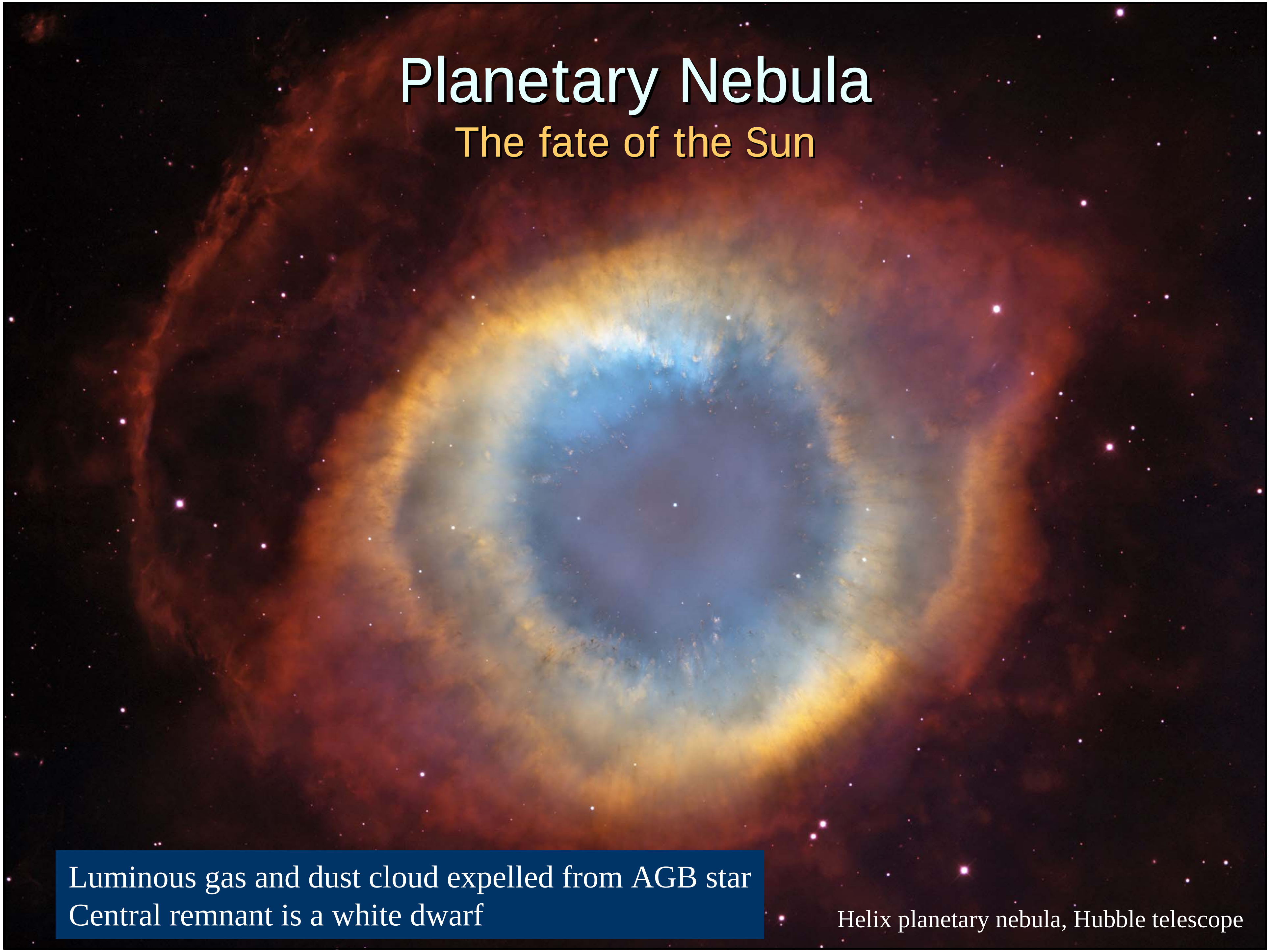



Cross sectional view of an AGB star

- He shell mixes with convective envelope
- C made from He burning makes the surface C-rich (carbon star)
- Thermal pulses eject stellar material into space
- The entire envelope is ejected, making a planetary nebula

# Planetary Nebula

## The fate of the Sun

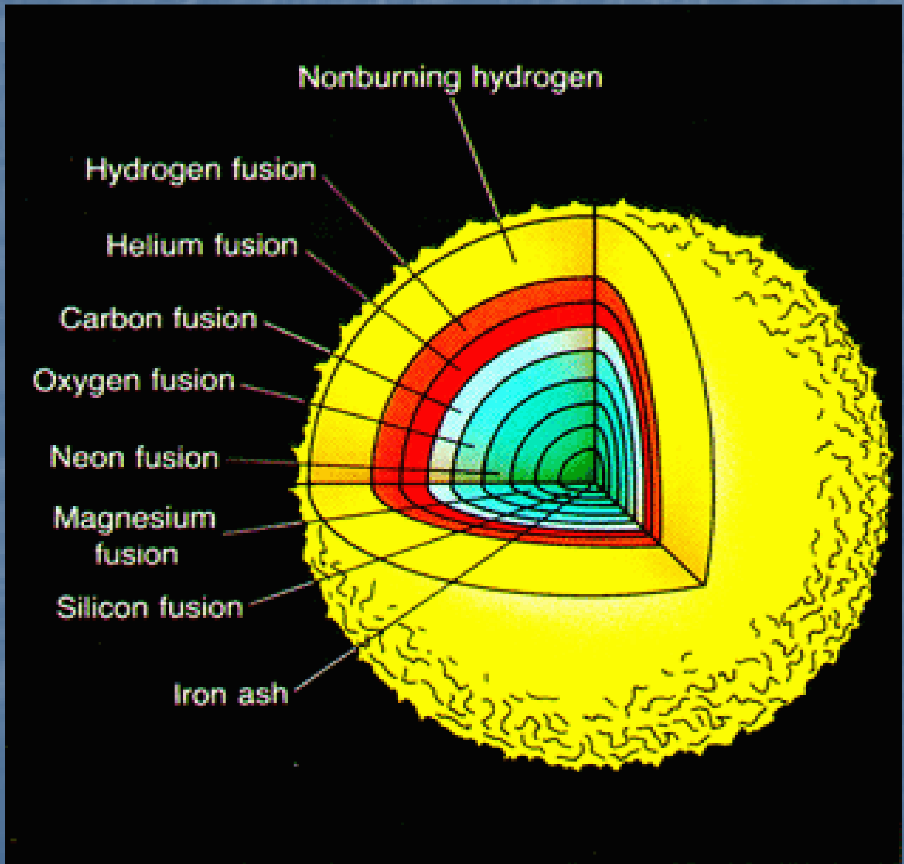


Luminous gas and dust cloud expelled from AGB star
Central remnant is a white dwarf

Helix planetary nebula, Hubble telescope

# Stellar Evolution

## Massive Stars



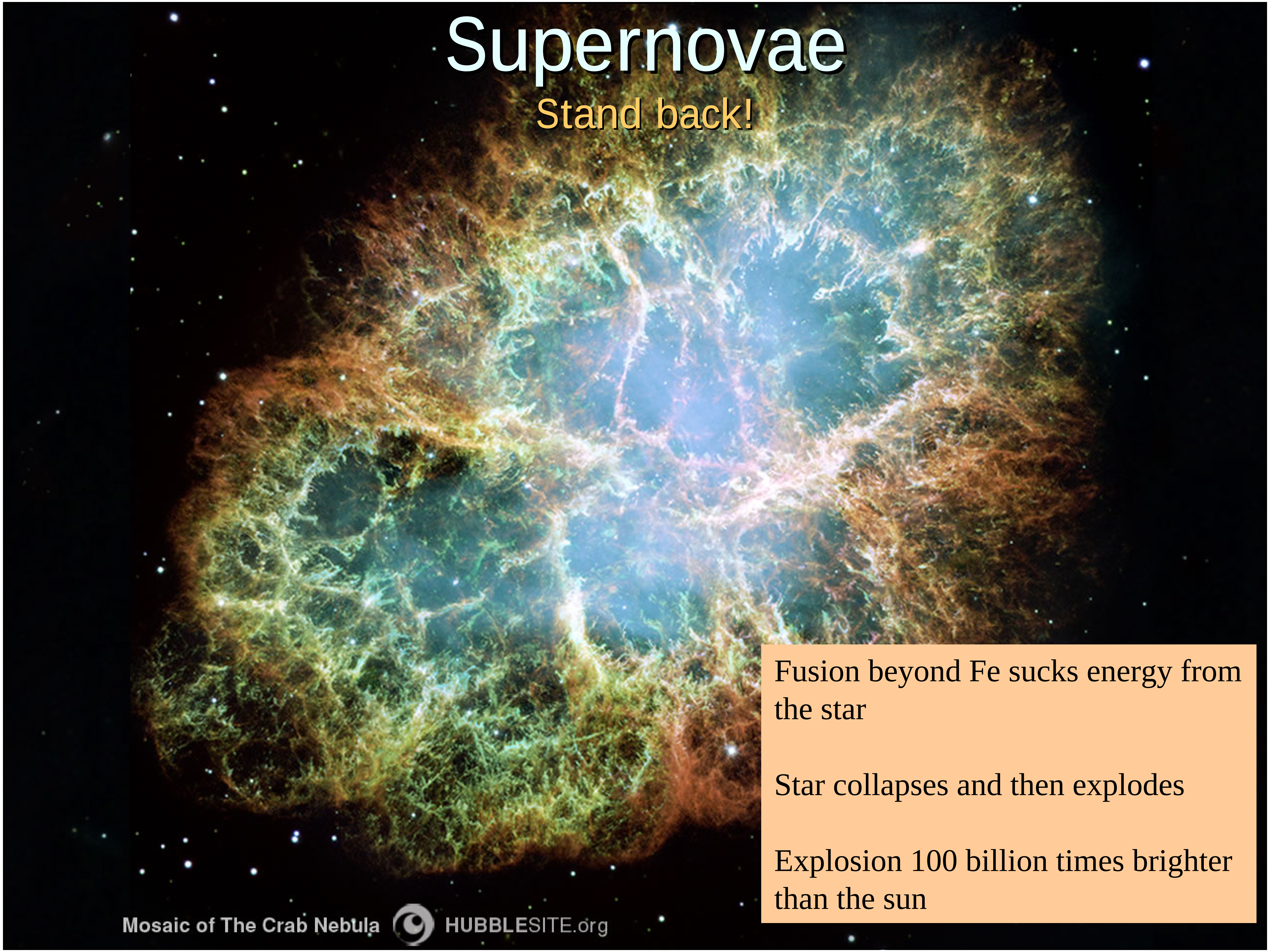

High mass stars have core T high enough to ignite C,O fusion

Fusion of heavier elements continues at increasingly higher T, reaching 3 x $10^9$ K for Si fusion

Fusion ends with Fe, which has the highest binding energy

# Supernovae

## Stand back!



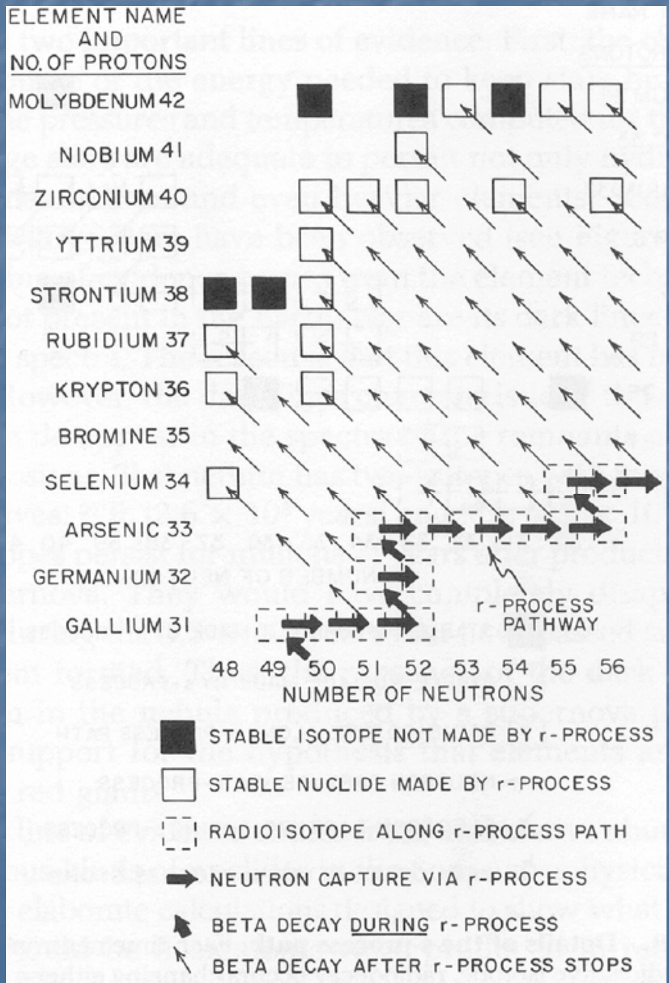

Fusion beyond Fe sucks energy from the star

Star collapses and then explodes

Explosion 100 billion times brighter than the sun

# Explosive Nucleosynthesis

## R Process




$10^{12}$ times greater neutron density compared with s process

Very short-lived isotopes may capture a neutron before decaying

s process, r process have different products

# Nucleosynthesis Summary

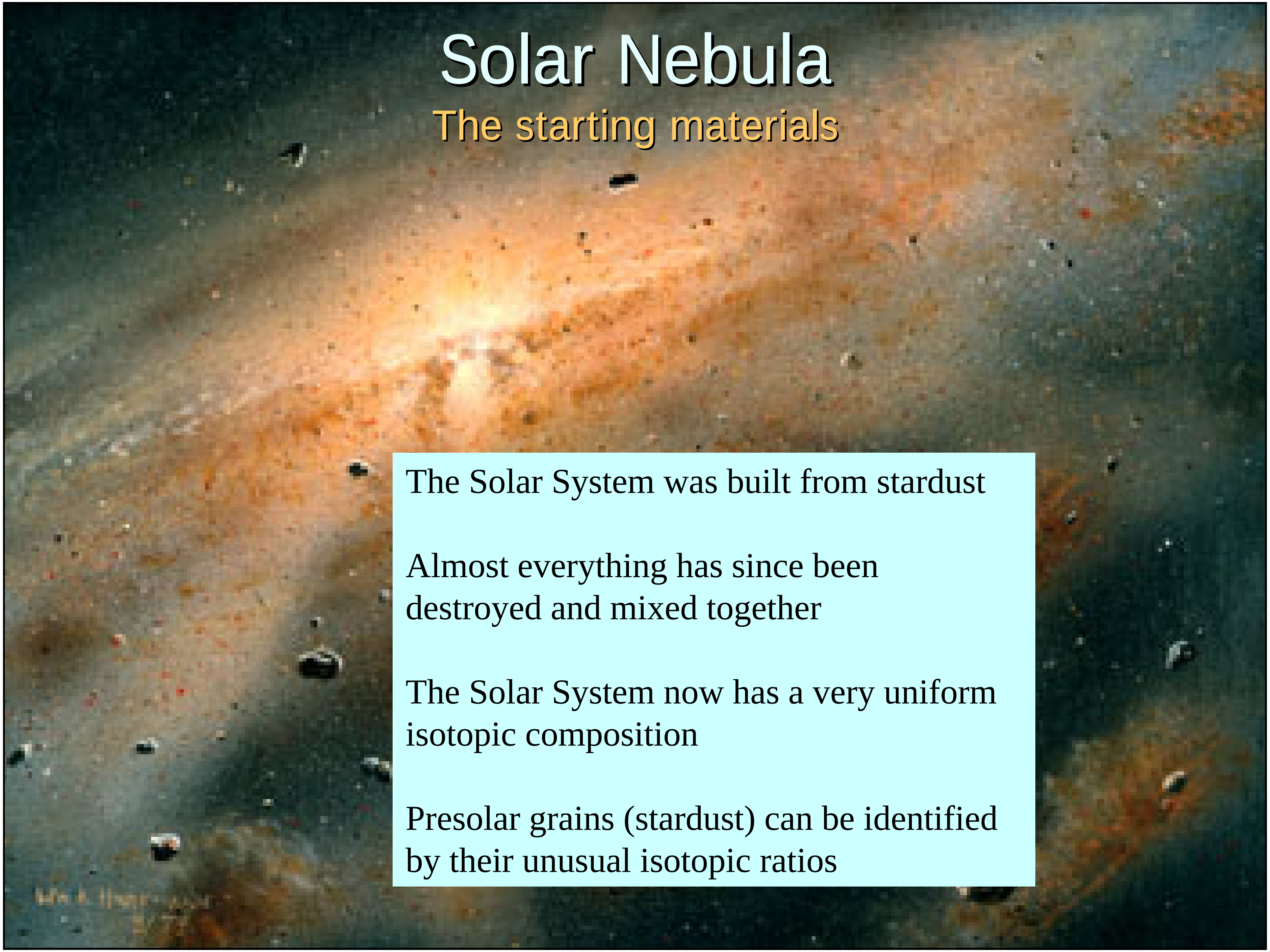
- All H and most He formed in the Big Bang
- He and all other elements form in stars
- Fusion reactions produce most elements up to Fe
- Heavy elements mostly made by s process and r process

# The End is Also the Beginning

- **Stars form from the remnants of previous generations of many other stars**
- **Most stardust resides in the Galaxy for a long time ($10^8$ years)**
- **In large star forming regions such as Orion (shown), massive stars may evolve and die (supernovae) while others are still forming**

# Solar Nebula

## The starting materials



The Solar System was built from stardust

Almost everything has since been destroyed and mixed together

The Solar System now has a very uniform isotopic composition

Presolar grains (stardust) can be identified by their unusual isotopic ratios

# Stardust in Meteorites


Murchison meteorite: well preserved sample of early Solar System

Noble gas carriers found by dissolving 99.9% of the meteorite in acid.

Noble gas carriers survived!

Discovery team:
Ed Anders, Ernst Zinner, Roy Lewis, Sachiko Amari.

Noble gas with exotic isotopic compositions found in meteorites. Finding the carriers was tricky.

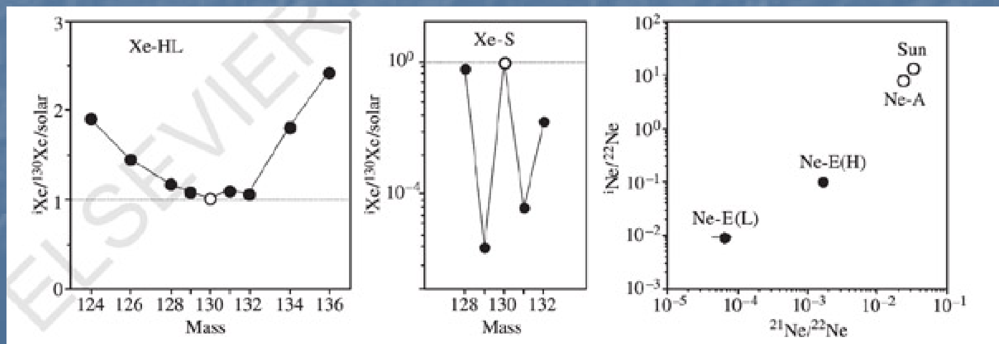
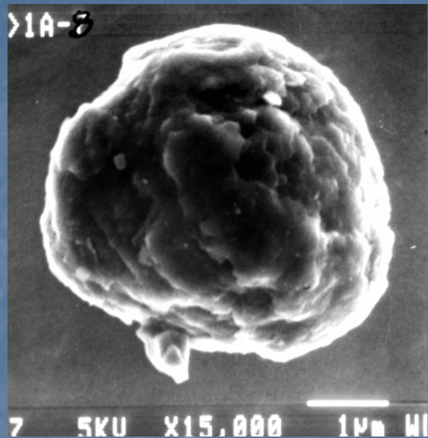


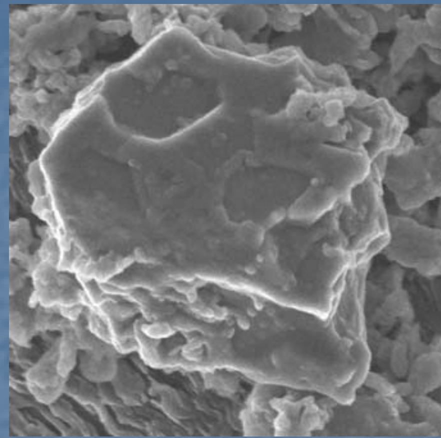

**Figure 1** Exotic noble-gas components present in presolar carbonaceous grains. Diamond is the carrier of Xe-HL, SiC the carrier of Xe-S and Ne-E(H), and graphite the carrier of Ne-E(L) (source Anders and Zinner (1993)).

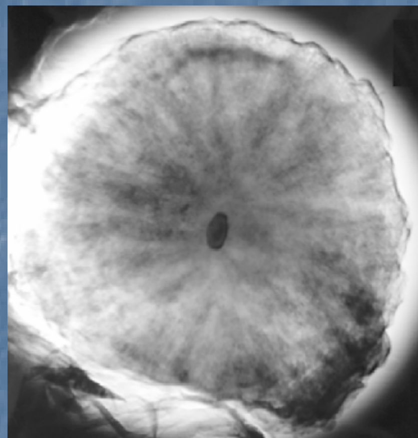
# Stardust Extracted from Meteorites

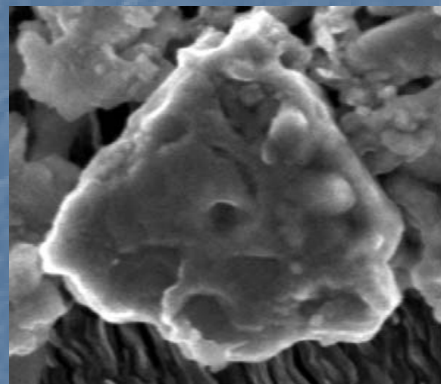
- SiC
- $Si_3N_4$
- Graphite
- Nanodiamonds
- $Al_2O_3$
- Hibonite
- Spinel
- Olivine
- Amorphous silicate



Graphite


Silicon Carbide


**Carbides *Within* Graphite**


Silicon Carbide

Typical size: 1 μm  Abundance: 1 – 100 ppm

# Dust condensation in O-rich stellar outflows

| T | Phase |
|---|---|
| 1633 | Corundum |
| 1562 | Hibonite |
| 1537 | Perovskite |
| 1472 | Melilite |
| 1351 | Spinel |
| 1320 | Plagioclase |
| 1305 | Forsterite |
| 1287 | Metal (Fe+Ni,Co,Cr,Si) |
| 1250 | Titanium Oxide |
| 1246 | Enstatite |
| 1200 | Cr-spinel ($MgAl_2O_4$-$MgCr_2O_4$) |
| <1000 | FeO |

- Equilibrium thermodynamics (solar gas, $10^{-5}$ bars, after Yoneda & Grossman 1995; Ebel MESS-2)
- Identified as presolar grains
- No silicate stardust "rocks" found yet

Figure courtesy L. Nittler

Nittler, Alexander, Stadermann, Zinner (2005) MPS 40, 5208
Nittler, Alexander, Stadermann, Zinner (2005) LPS 36, 2200
Choi, Wasserburg, Huss (1999) ApJ 522, L133

# Isotopic Signatures of Stardust

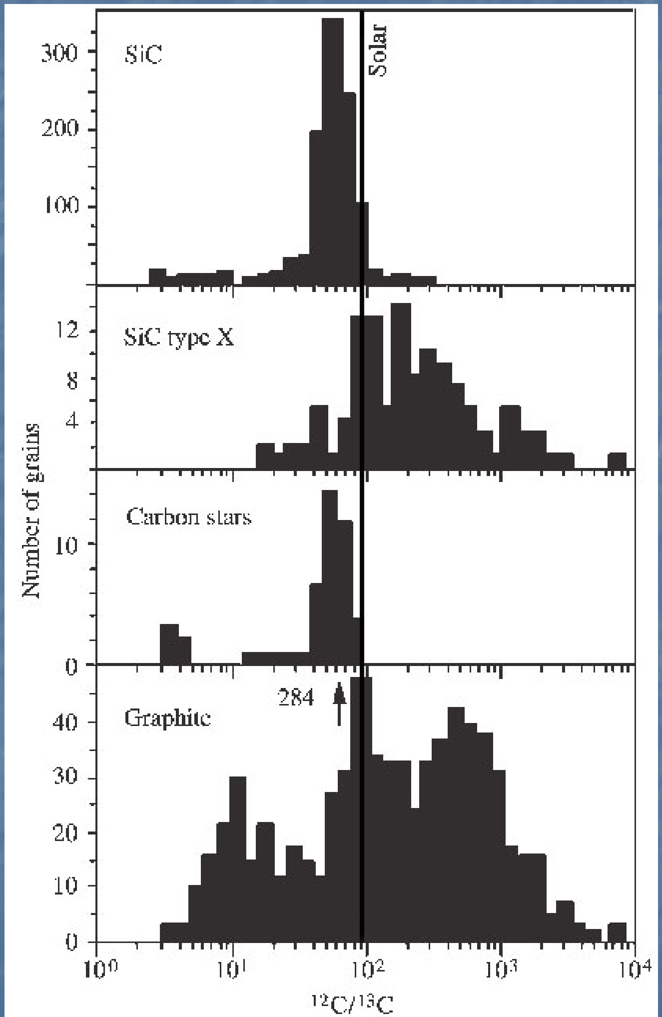



Figure courtesy E. Zinner

**Major and minor element isotopic ratios vary by a factor of 10,000**

**Isotopic compositions reflect distinct nucleosynthetic processes**

**Identify stellar source, age, metallicity**

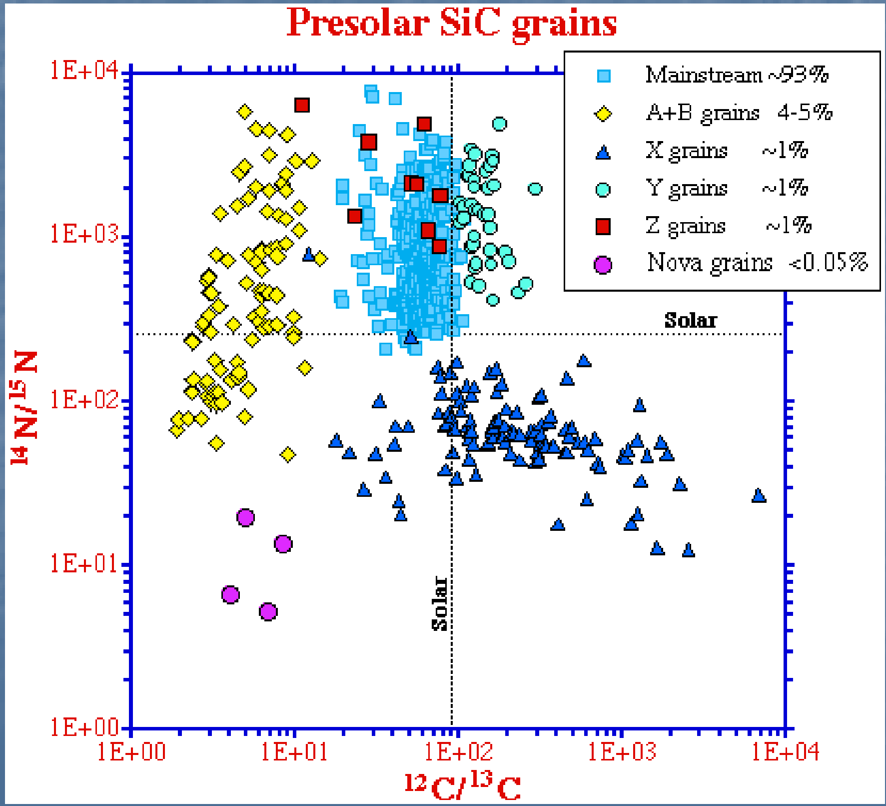


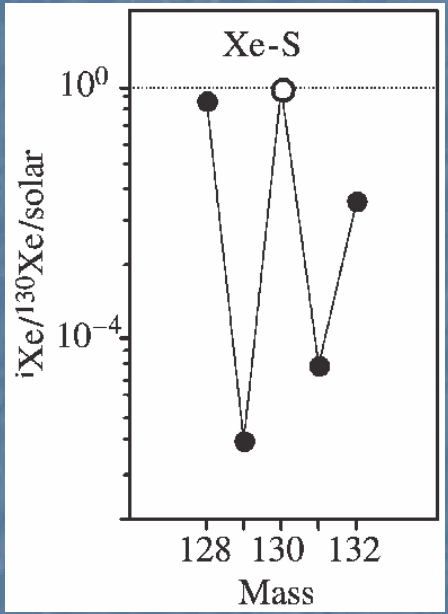

Figure courtesy E. Zinner

# S-Process Signatures in SiC

## Product of AGB stars

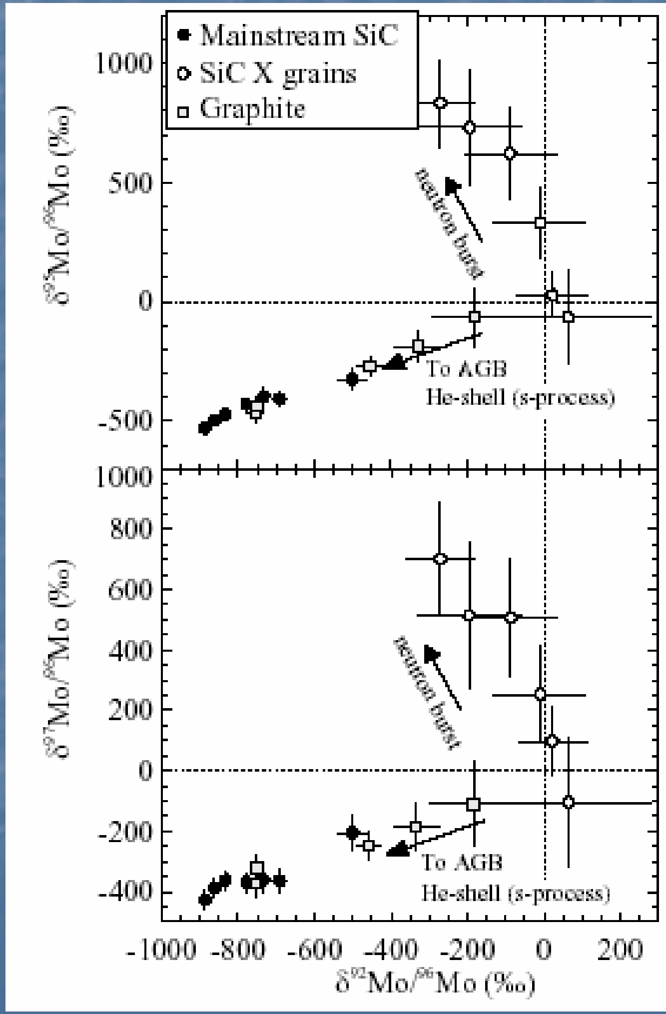
Anomalous Xe found in meteorite acid residues led to the chemical isolation of SiC and nanodiamonds

**Bulk measurement**
***millions of grains***




Anders & Zinner (1993) Meteoritics 28, 490

***Single grain measurements***




Savina et al. (2002) GCA

# Short-Lived Nuclides from Supernovae

- $^{44}Ca$ and $^{49}Ti$ enrichments observed in rare SiC grains
- Grain must have formed shortly after nucleosynthetic production
  - *Requires stellar source*
- Resist loss or isotopic exchange since then (>4.5 billion years)
- *Identify extinct nuclides by isotopic anomaly in daughter product*

<u>Example: $^{44}Ti$</u>

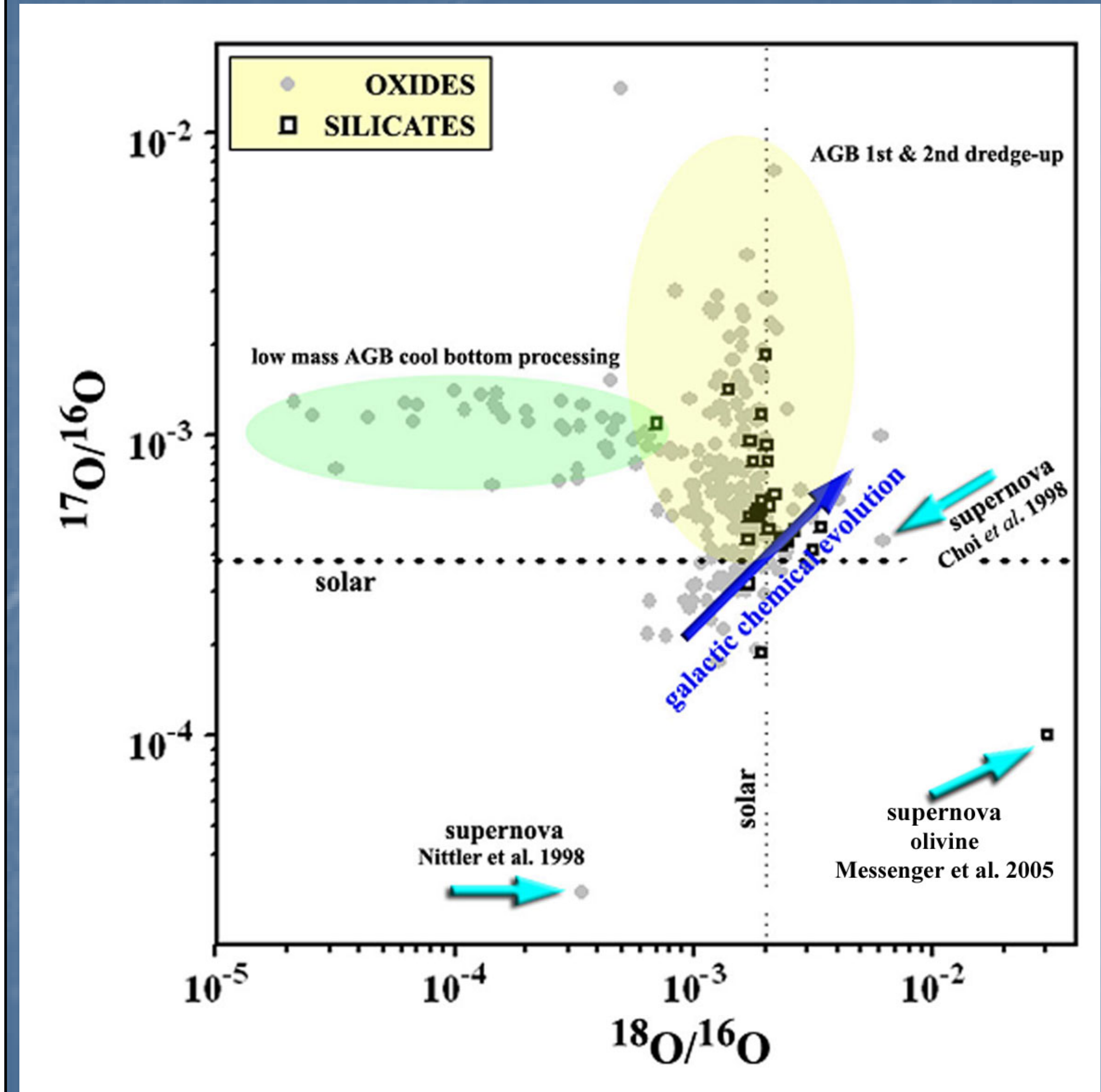
- produced only in supernovae
- $t_{1/2}$ = 60 years
- $^{44}Ti \rightarrow {}^{44}Ca$
- $^{44}Ca/^{42}Ca$ ratios reach 5,000 x solar in stardust

<u>Example: $^{49}V$</u>

- $t_{1/2}$ = 331 days
- $^{49}V \rightarrow {}^{49}Ti$
- *Grains condensed within a few years of nucleosynthesis*

Amari et al. (1992) ApJ 394, L43

# Silicate and Oxide Stardust




- >100 presolar silicates and oxides found so far
- ~99% originate from RG/AGB
- Supernova dust is rare (~1%)
- Galactic chemical evolution
- Estimate for age of the Galaxy

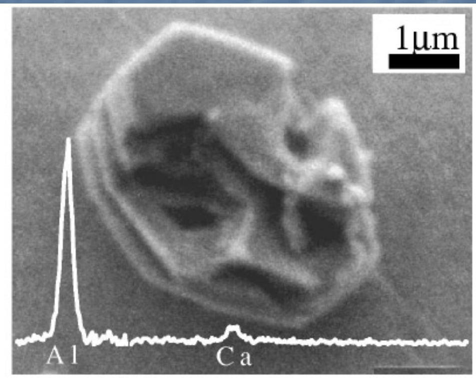



FIG. 1.—Secondary electron image of circumstellar hibonite S-H5323. The X-ray spectrum is shown by the white line. Note the platy structure and the crystal faces on each plate.

Floss & Stadermann (2005)
Huss et al. (1993)
Messenger et al. (2003) *Science*
Nguyen & Zinner (2004) *Science*
Mostefaoui & Hoppe (2004) *ApJ*
Nagashima et al. (2004) *Nature*
Nittler & Cowsik (2004) Phys Rev

# Supernova Dust Formation

## Supernova olivine grain

Olivine: $(Mg,Fe)_2SiO_4$

$^{18}O/^{16}O$ = 13 x solar
$^{17}O/^{16}O$ = 1/3 x solar
$^{29}Si/^{28}Si$ = 0.8 x solar

$^{18}O$-enrichment ... C/O

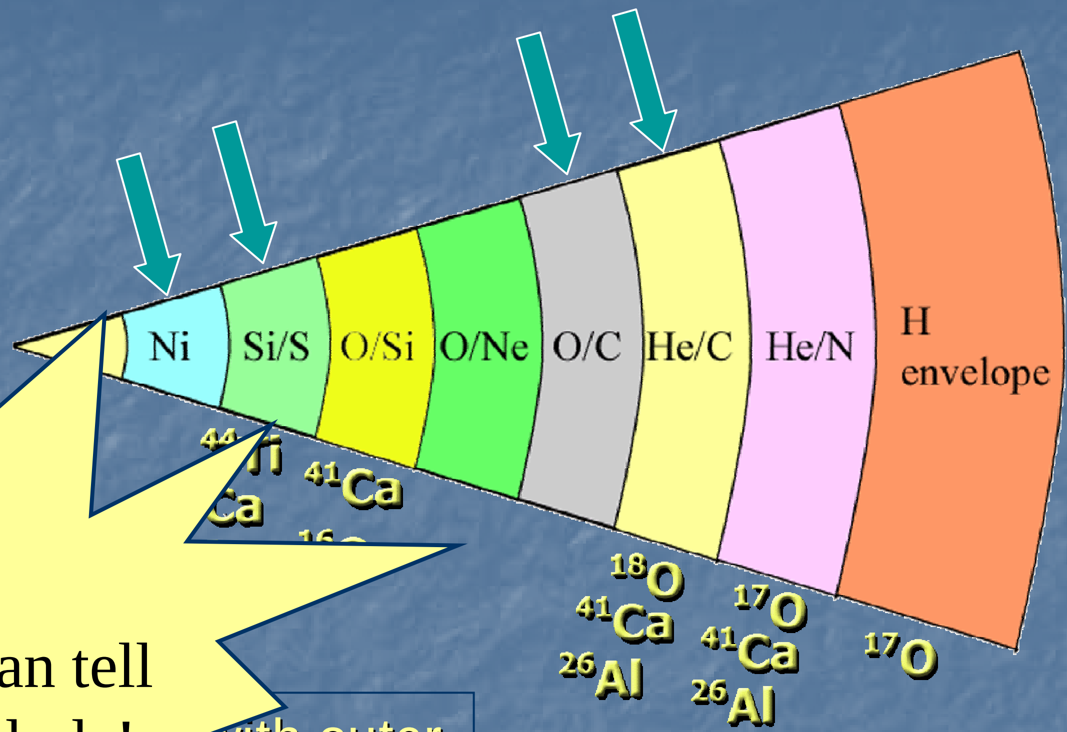


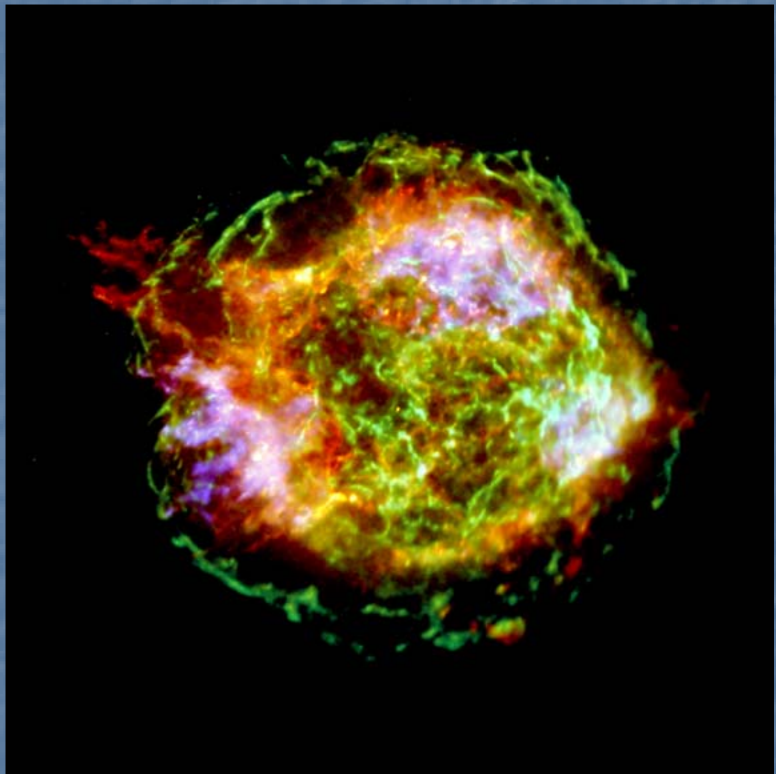

Figure courtesy L. Nittler

Model re... with outer layers w... ...g zones

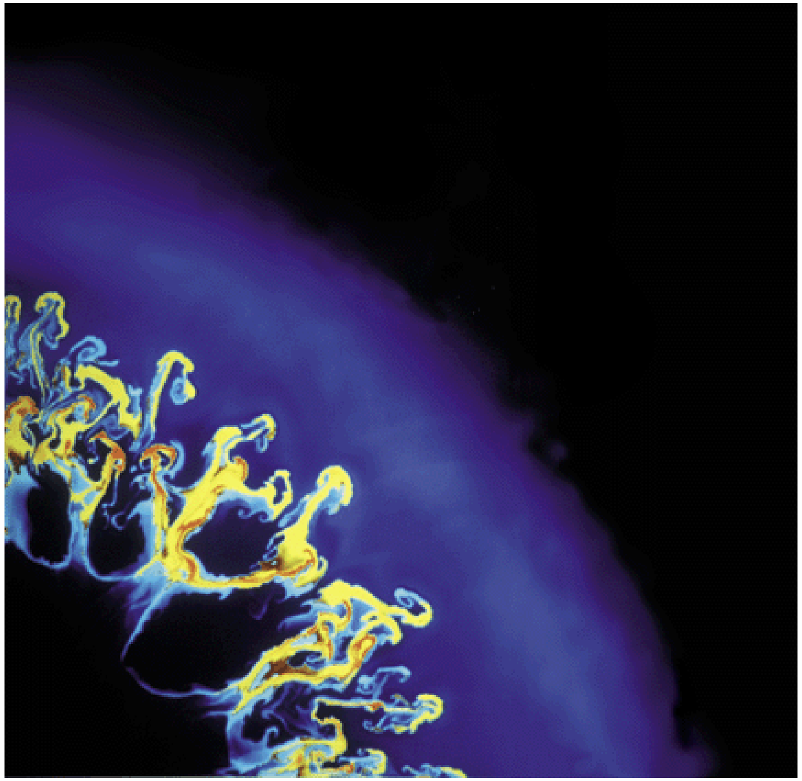
A 500 nm grain can tell us how stars explode!

Messenger et al. (2005) Science
See also supernova SiC & graphite: Nittler *et al*. 1996, Hoppe *et al*. 2000

# Theoretical and Observational Evidence for Complex Mixing in Supernovae



*Chandra* x-ray image of Cassiopeia A Supernova remnant



SN 1987A Muller et al. A&A 251, 505 (1991)

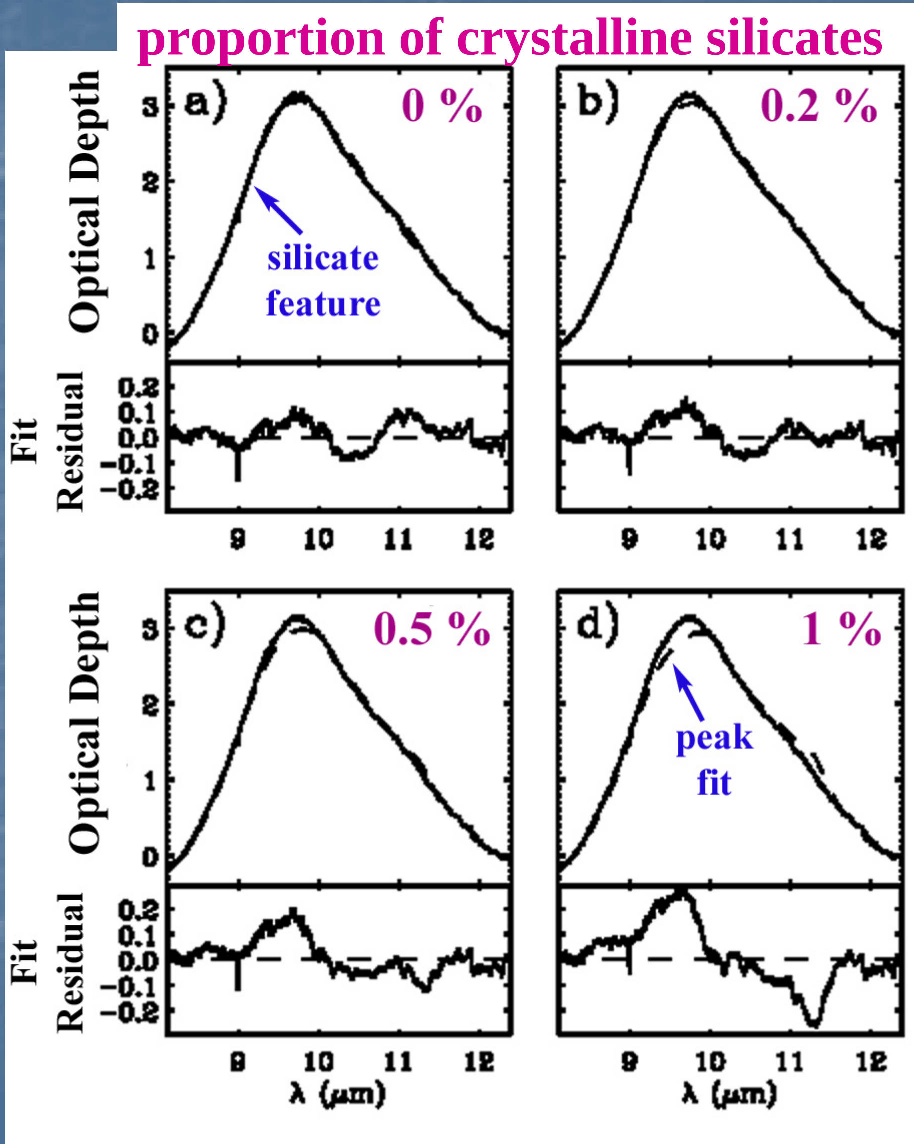
# Stardust Summary

- Meteorites and cosmic dust contain ~100 ppm of μm-size stardust
- 99% originate from red giant/AGB stars
- 1 % originate from novae and supernovae
- Each of the nucleosynthesis processes are recorded among these stardust grains

## Stardust Frontier: Silicates

- Silicates are abundant but only recently found
  - Huge background of Solar System silicates
- Commonly observed throughout the Galaxy by astronomers
- Silicates are sensitive recorders of their history
  - Radiation, thermal processing, aqueous alteration

# Silicate Stardust Evolution




*Kemper, Vriend, & Teilens (2004) ApJ 609, 826*

**Silicate mineralogy from 10 μm feature**

**Evolved stars**: 10 – 20 % crystalline silicates

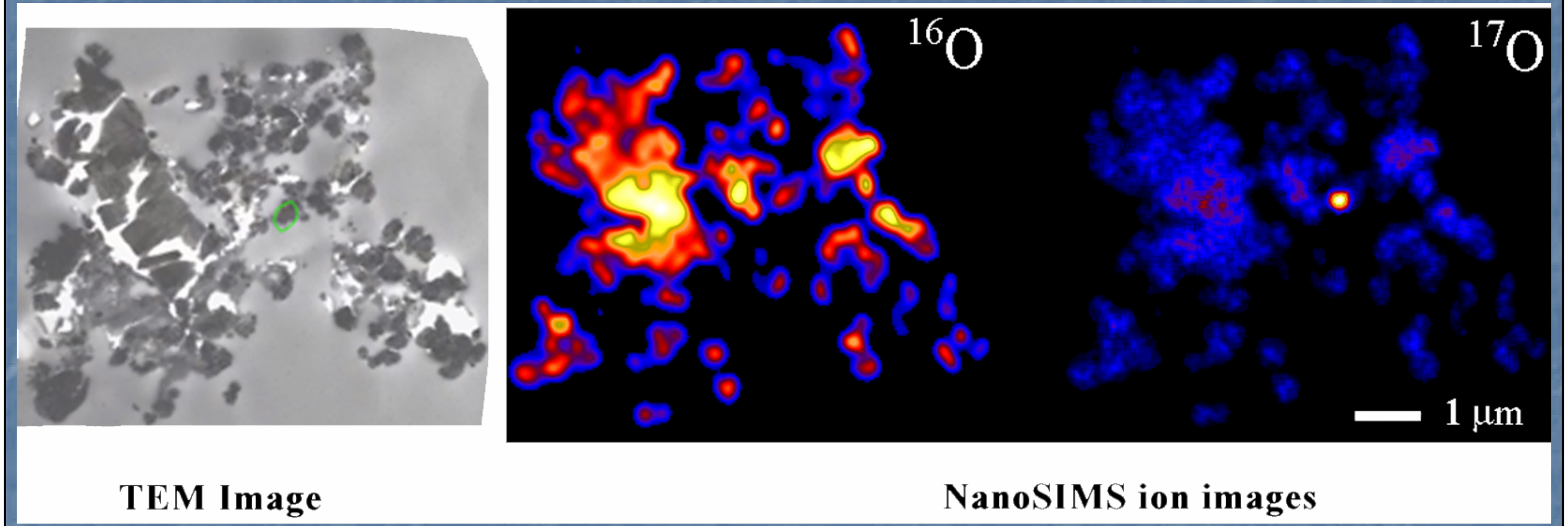
**Diffuse ISM**: ~ 1 % crystalline silicates

**Young stars**: mix of crystalline/amorphous & **Comets** & **IDPs**

**Meteorites**: crystalline silicates dominate

Crystalline silicates are rendered amorphous or destroyed on ~ 10 Ma timescale. Re-formed near young stars

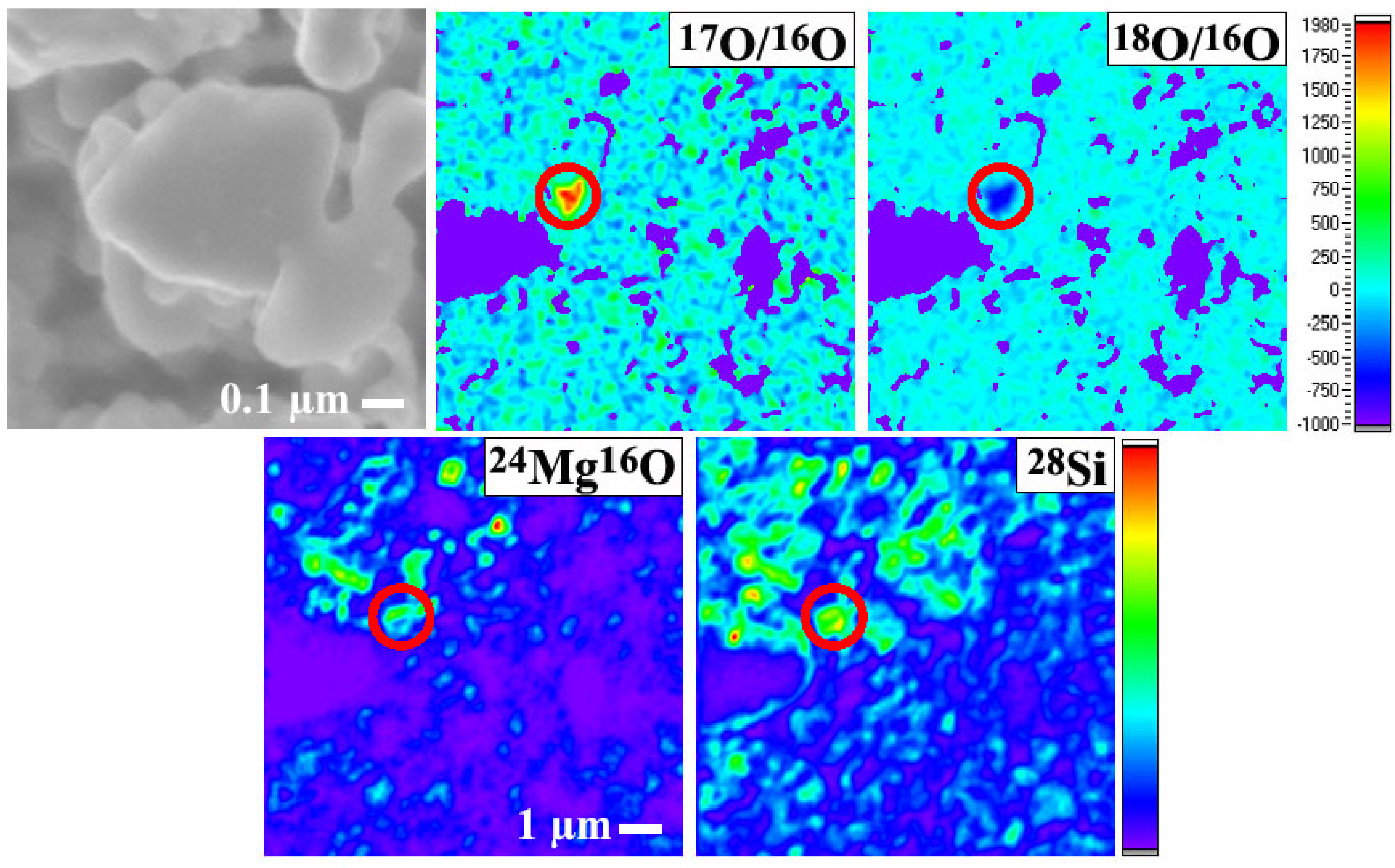
# Found! Silicate Stardust in an Interplanetary Dust Particle




Silicate stardust grains are small (<0.5 µm) and hidden within an overwhelming background of solar system silicates

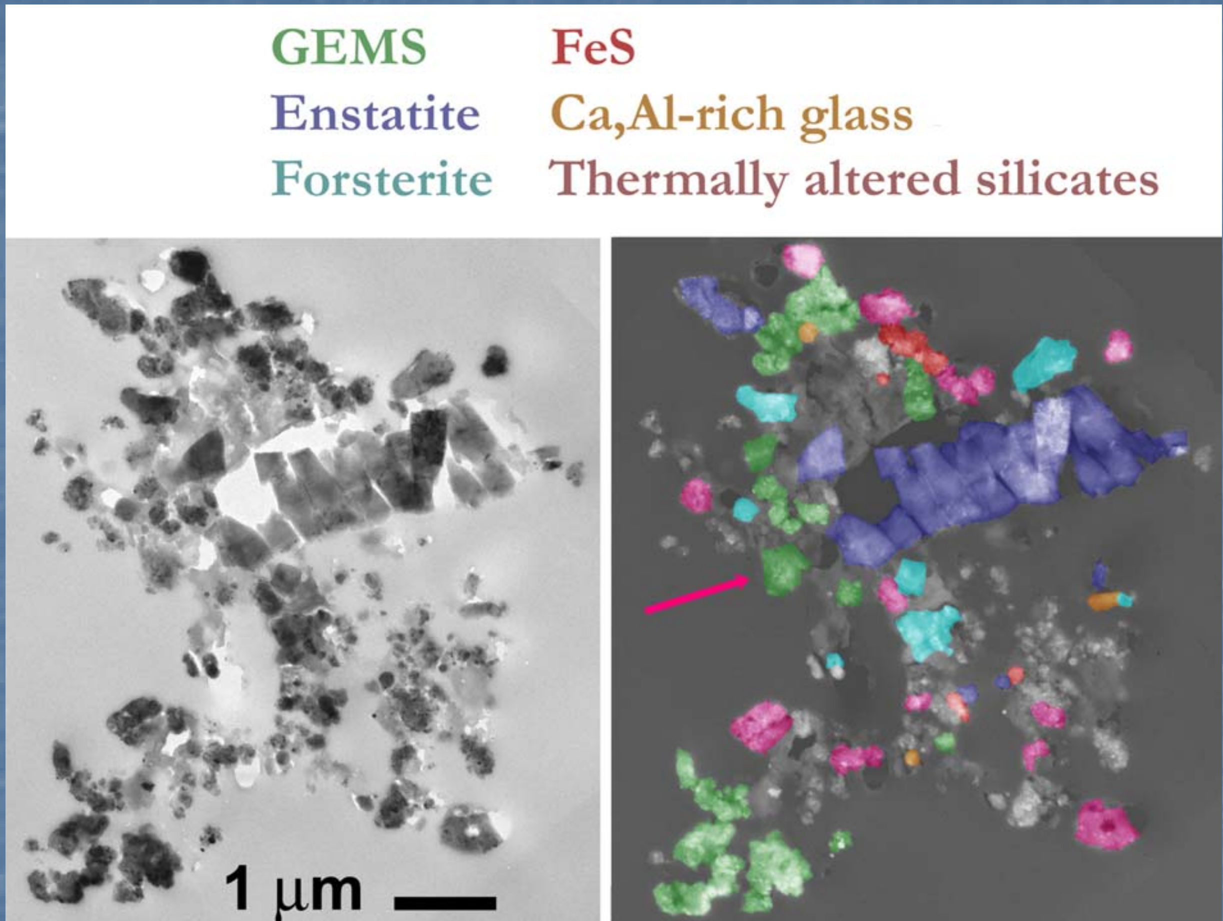
Messenger et al. (2003) Science 300, 105

# Presolar Silicate in Acfer 094




Nguyen & Zinner, Science, 2004

# Identifying Interstellar Dust in IDPs



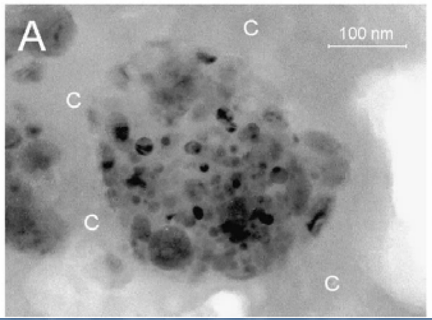

**Presolar grain abundances**:

4 of >100 GEMS
2 of >40 forsterite grains
0 of >40 enstatite grains
0 of 5 anorthite grains

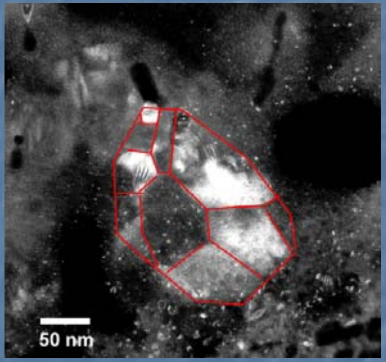
Thin section of IDP studied by TEM with typical anhydrous mineralogy

# Presolar Silicate Mineralogy

- >150 silicate stardust grains
- 8 amorphous silicates




- 2 Olivine grains




**amorphous:crystalline silicate abundances**

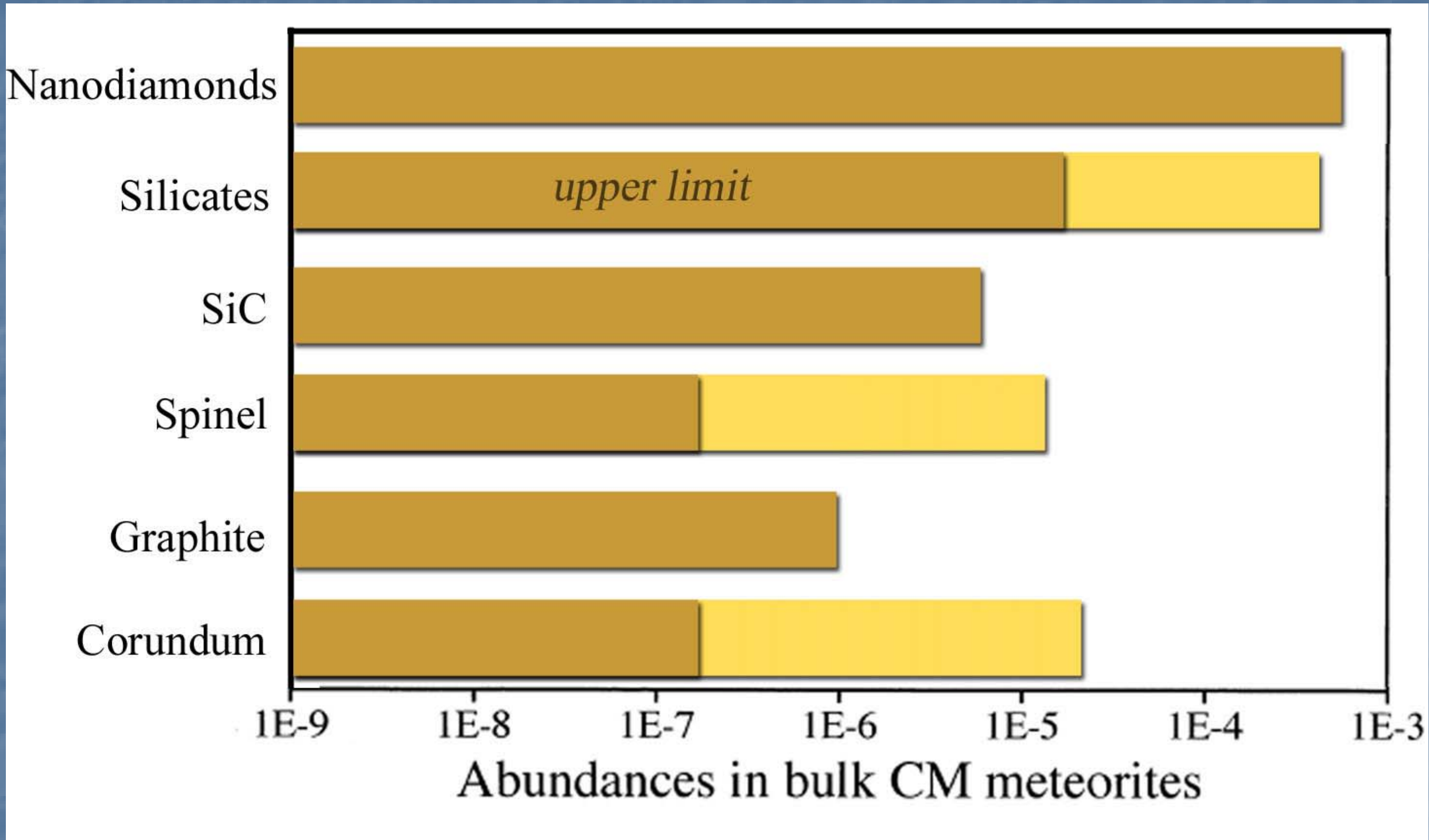
- **Interstellar dust: 100:1**
- **in meteorites, IDPs: 4:1**

**Most amorphous interstellar dust is missing**

- Amorphous grains more easily destroyed?
- Annealed into crystalline silicates?
- Not isotopically distinct?

Nguyen et al. (2007) ApJ, *in press*
Messenger et al. (2003) Science 300, 105
Nguyen & Zinner (2004) Science 303, 1496

# Stardust Abundances




New ability to probe smaller grains (200 nm)
O-rich stardust grains now known to 'outweigh' carbonaceous phases


Nguyen et al. (2007) ApJ, *in press*
Zinner (2003) GCA 67, 5083
Nittler (2003) EPSL 209, 259
Messenger et al. (2003) Science 300, 105

# Stardust Frontiers

- Ancient materials preserved in meteorites are direct samples of evolved stars and supernovae
- >10 to 100 stars seeded our own solar system

- New samples of cometary material now being searched for stardust
- Have comets better preserved the Solar System starting materials?

First look at the Stardust samples