Star Factories: Nuclear Fusion and the Creation of the Elements

Science In the River City workshop
3/22/11

Chris Taylor
Department of Physics and Astronomy
Sacramento State

Introductions!

Science Content Standards, Grades 9 - 12

Earth Sciences:

Earth's Place in the Universe

1.e *"Students know the Sun is a typical star and is powered by nuclear reactions, primarily the fusion of hydrogen to form helium."*

2.c *" Students know the evidence indicating that all elements with an atomic number greater than that of lithium have been formed by nuclear fusion in stars."*

Three topics tonight:

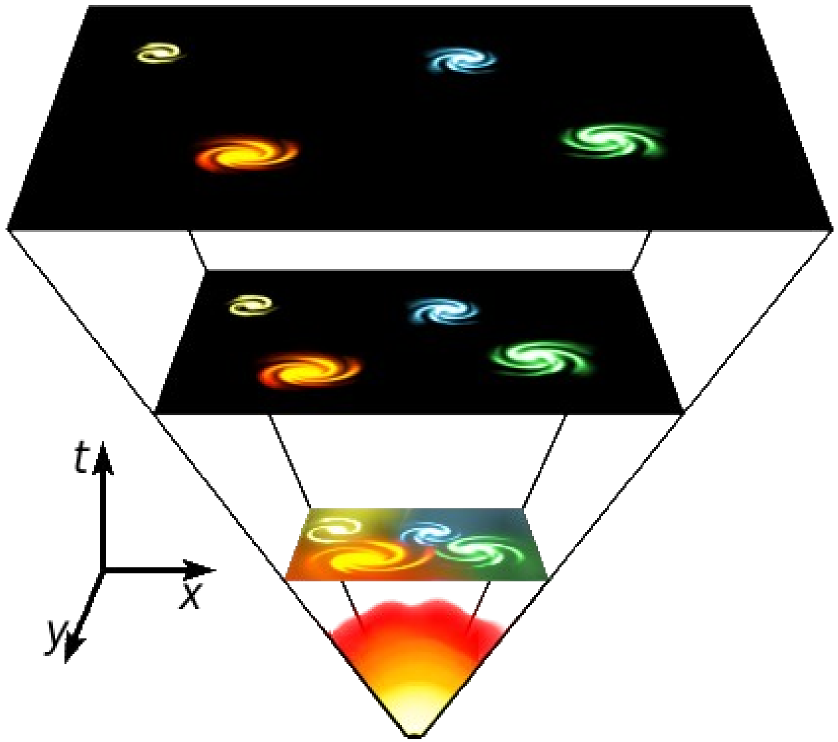
1) how do we know all the heavier elements are made in stars? *(Big Bang theory)*

2) How do stars make elements as heavy as or less heavy than iron? *(Stellar nucleosynthesis)*

3) How do stars make elements heavier than iron? *(Supernovae)*

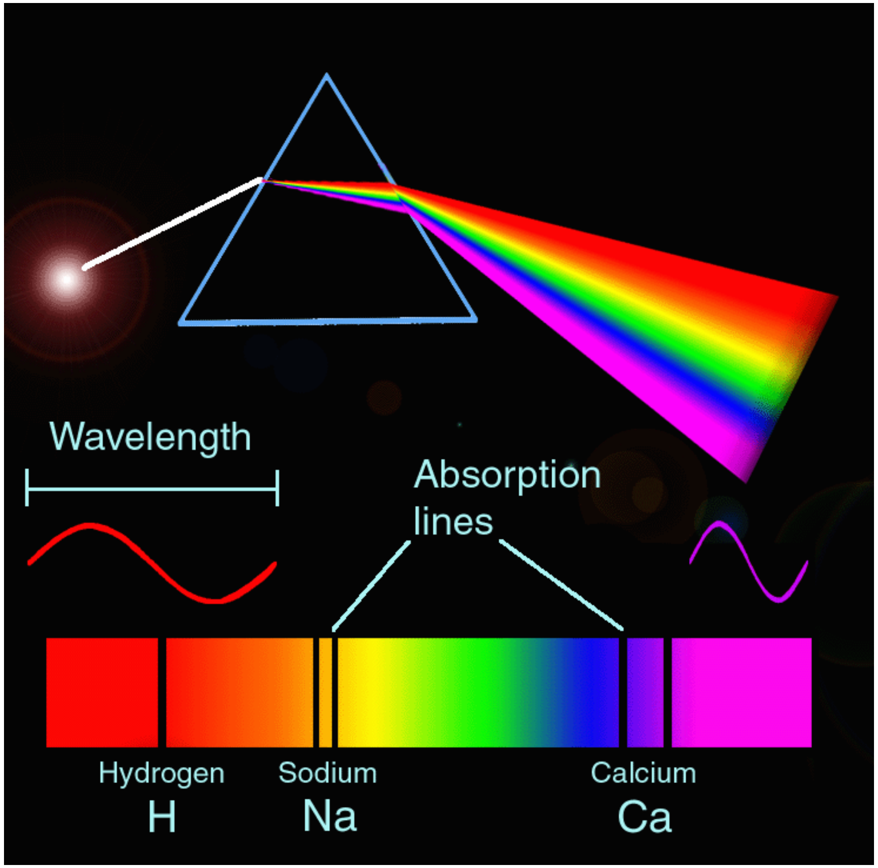
Big Bang Nucleosynthesis

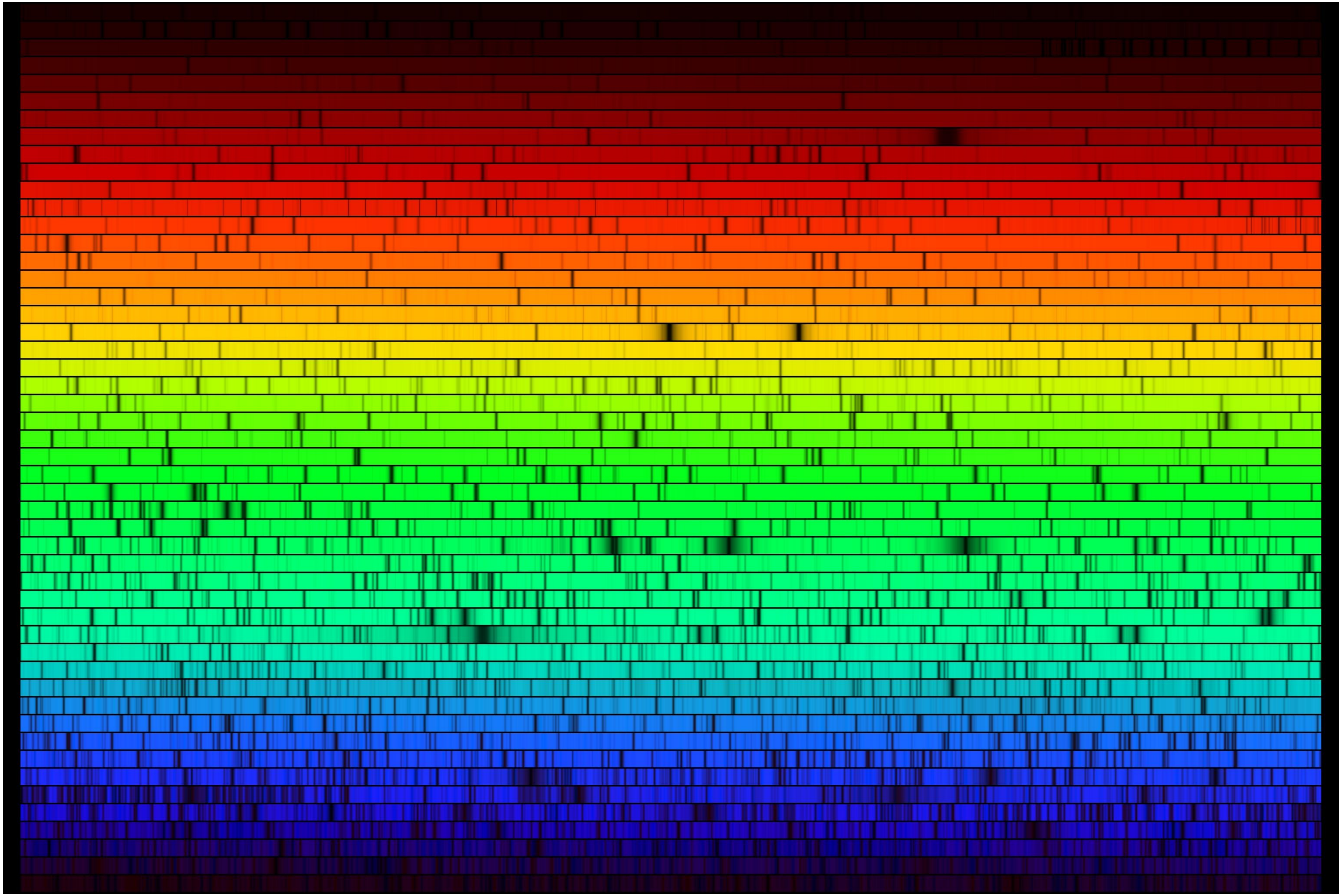
The Big Bang theory predicts that when the universe first formed, the only matter that existed was hydrogen, helium, and very tiny amounts of lithium. If this is true, then all other elements must have been created in stars.



Astronomers use spectroscopy to examine the light emitted by distant stars to determine what kinds of atoms are in them.

We've learned that most stars contain nearly every element in the periodic table.





The spectrum of the Sun

In order to measure measure what kinds of atoms were around in the earliest days of the Universe, we look for stars that were made out of fresh, primordial gas.

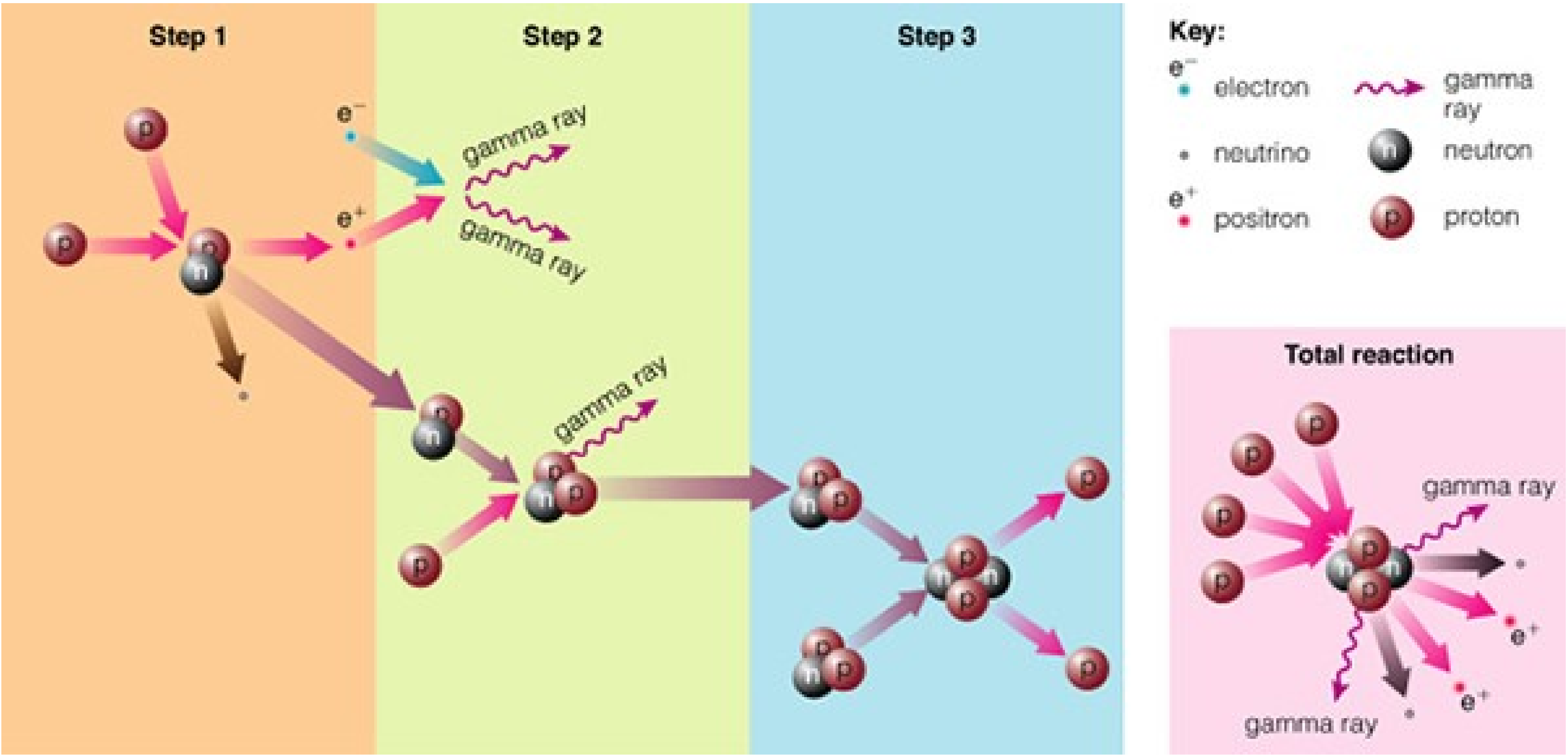
The closest we can get to this is looking at dwarf galaxies, which show extremely low levels of elements heavier than helium.

*

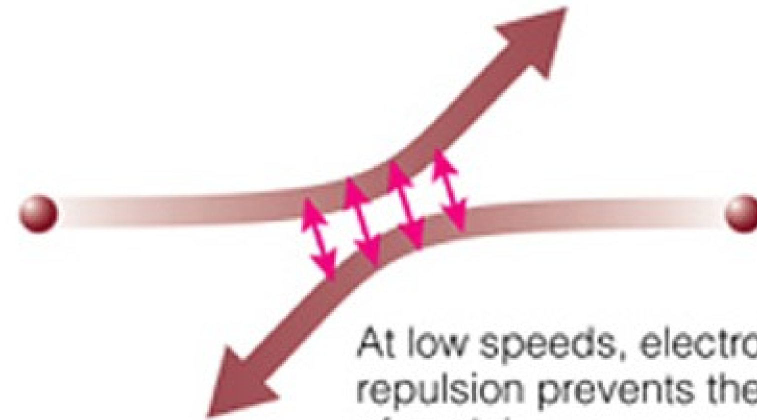
Stellar Nucleosynthesis

If heavy elements didn't get formed during the Big Bang, then where do they come from?

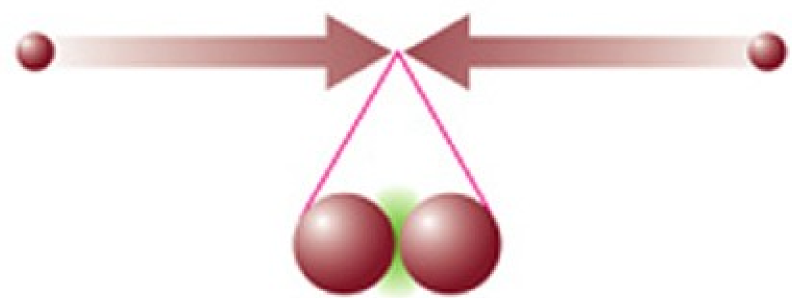
The Proton-Proton Chain



In fusion, atomic nuclei are smashed together at speeds high enough to overcome the electric repulsion of their positive charges. The nuclei then join together to form a single larger nucleus.



At low speeds, electromagnetic repulsion prevents the collision of nuclei.



At high speeds, nuclei come close enough for the strong nuclear force to bind them together.

* The only place we know that fusion can build heavy elements is inside the cores of stars. The question now is:

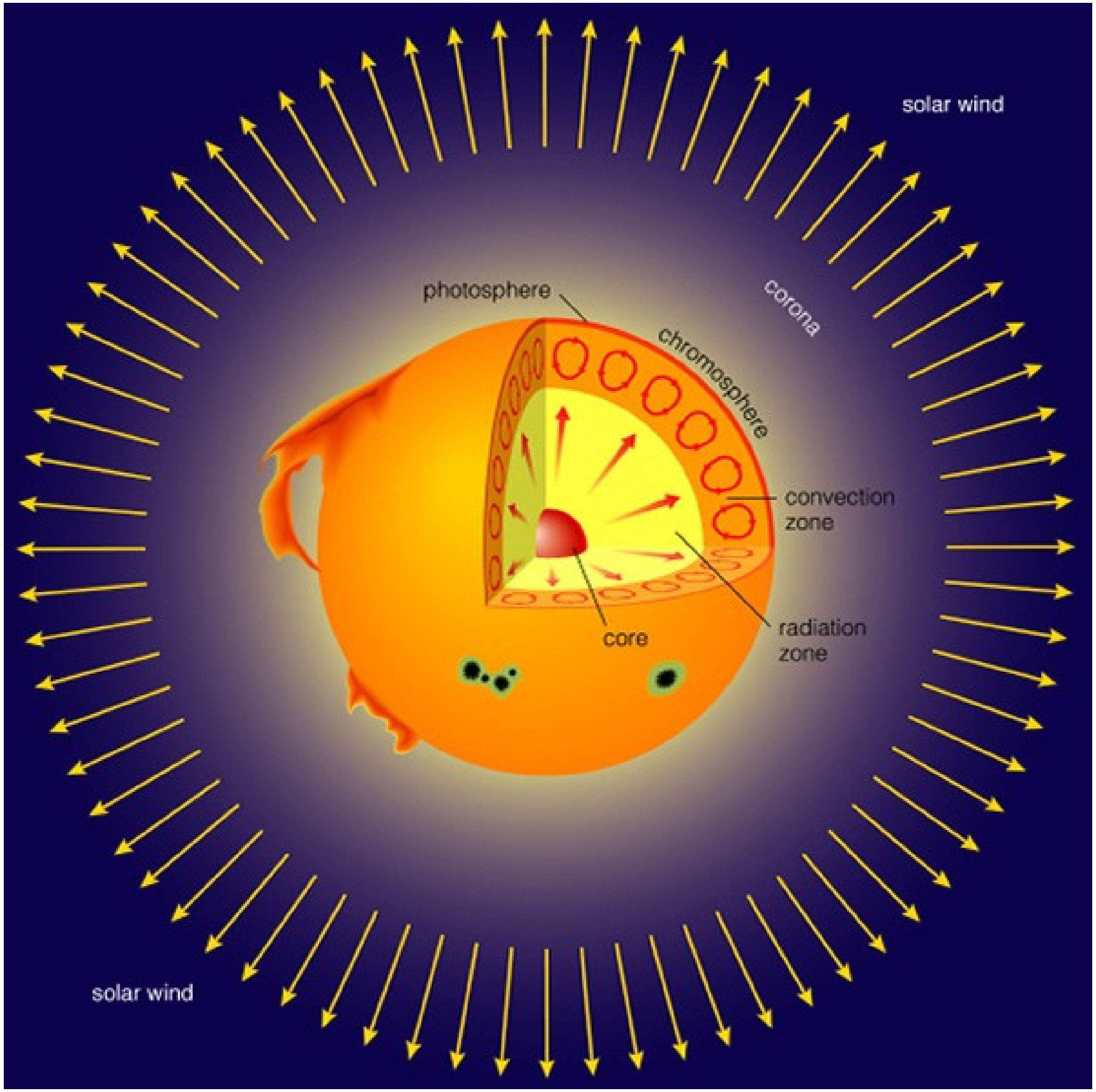
What is it about the environment inside stars that makes nuclear fusion possible?

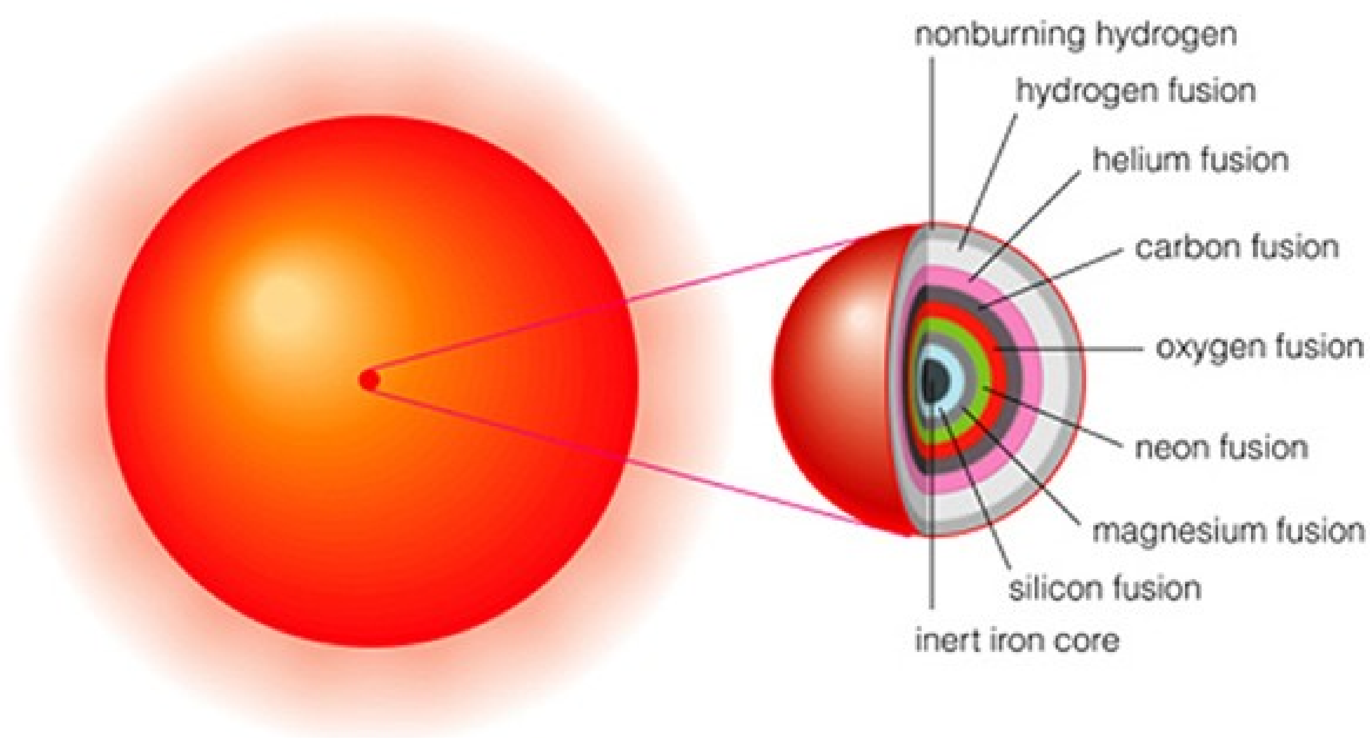
High temperature; and

high density.

Demo

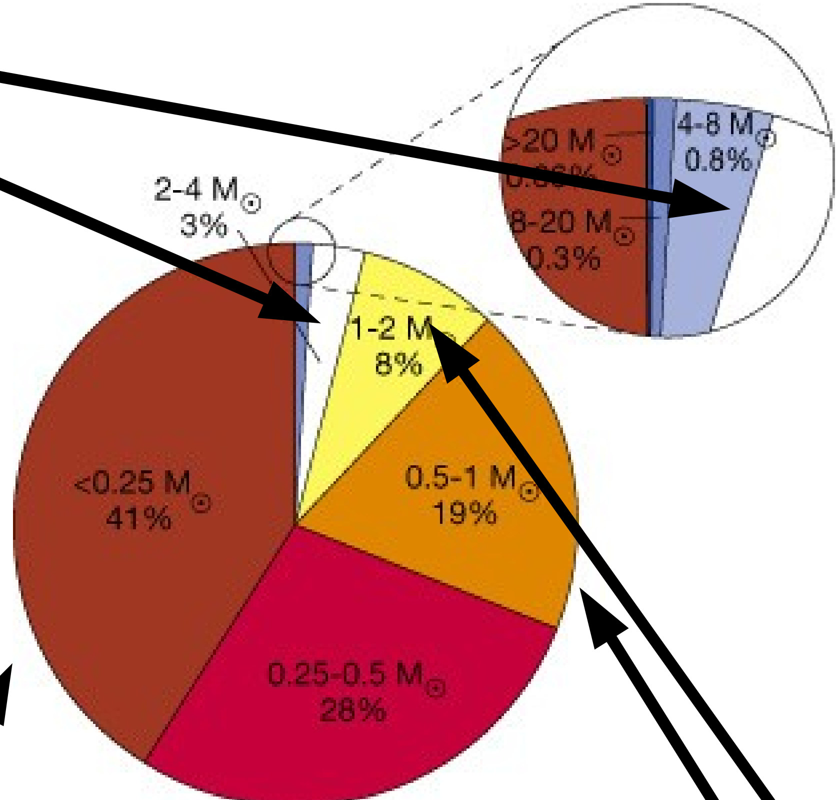
Stars like the Sun will make helium in their cores until the hydrogen fuel runs out. Some, but not all, stars will then switch over to fusing helium into carbon. This is the origin of all carbon in the Universe.





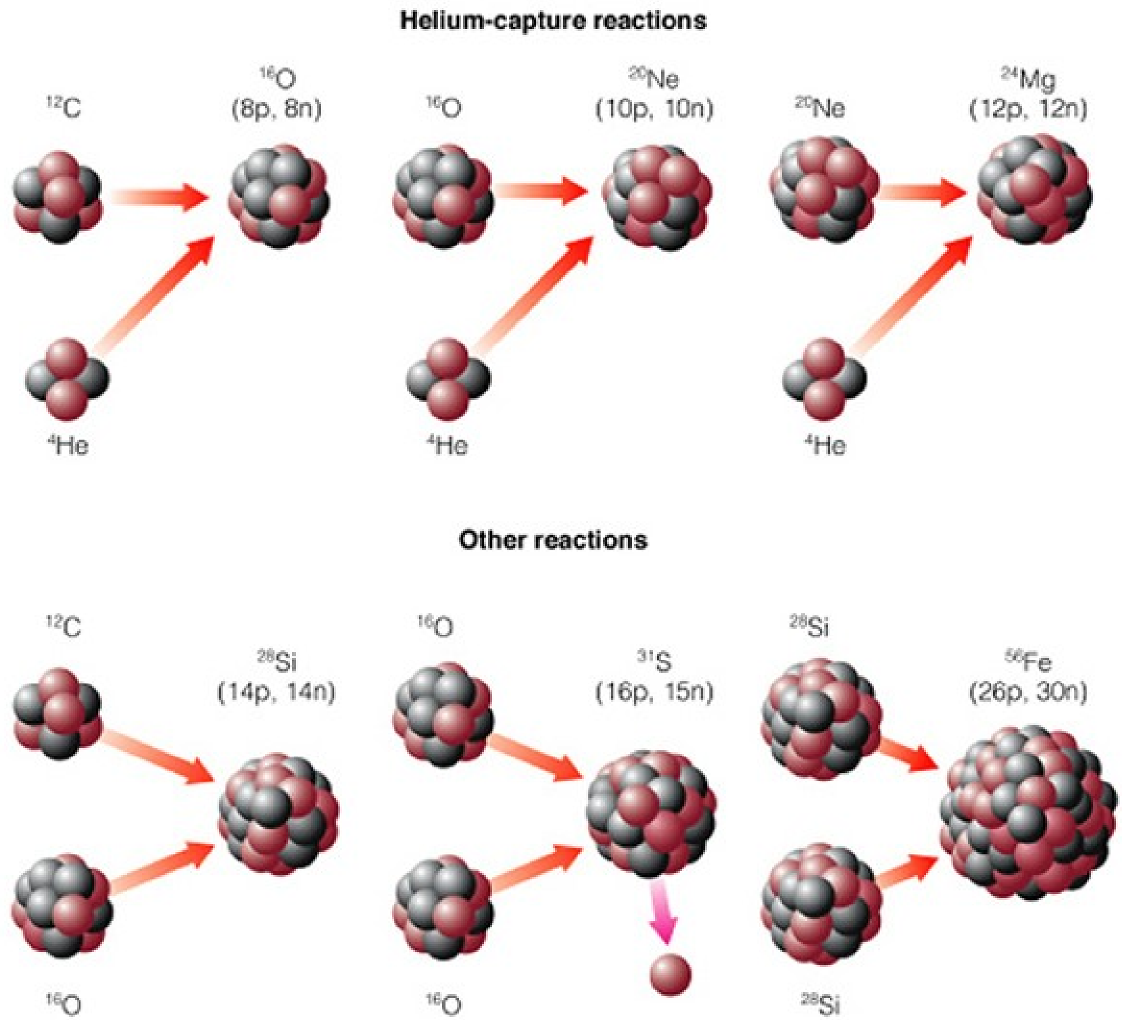
The higher the mass of the star, the heavier elements it can create in its core. This is because heavy element fusion requires higher temperatures, which only the most massive stars can attain.

Helium, carbon and oxygen.



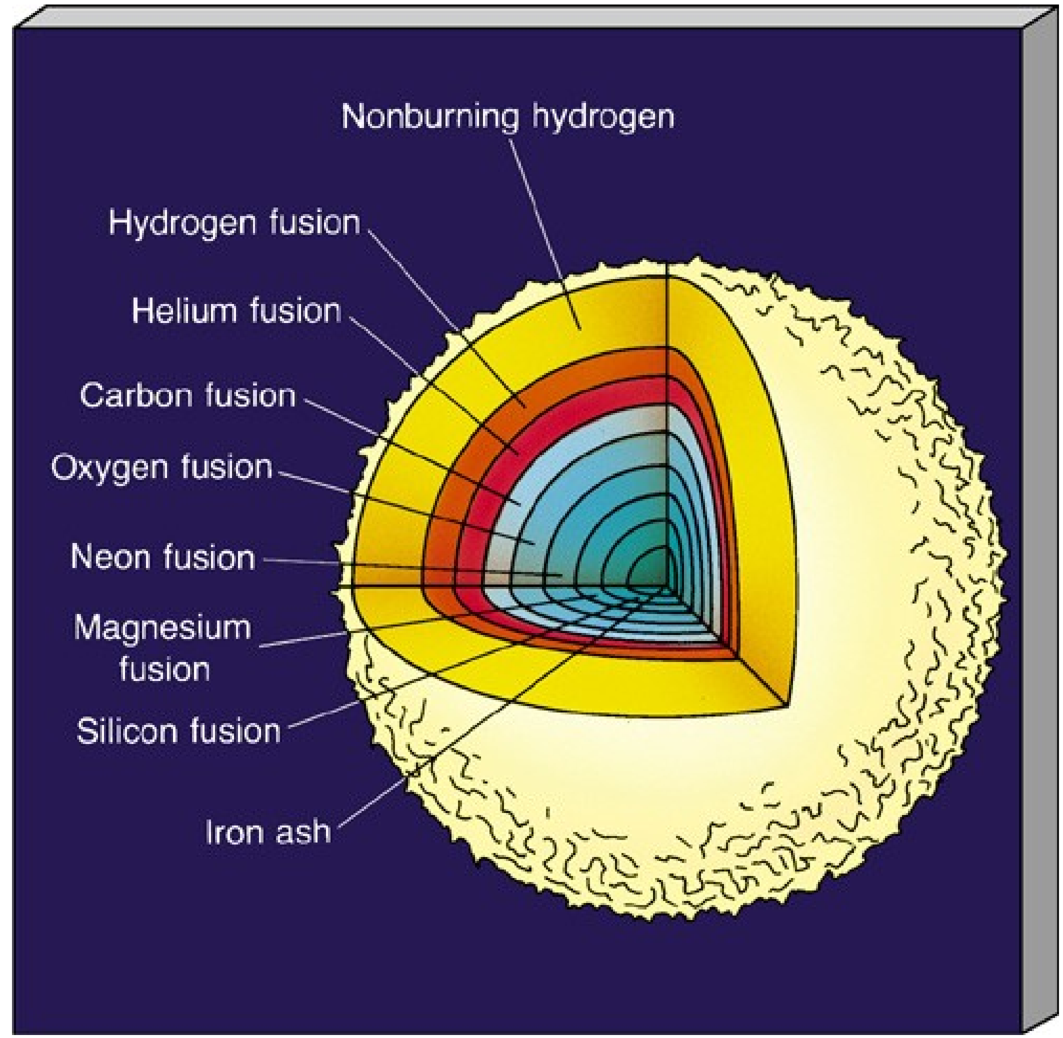
Helium only

Helium and carbon


Helium-capture reactions
12C
16O (8p, 8n)
4He
16O
20Ne (10p, 10n)
4He
20Ne
24Mg (12p, 12n)
4He
Other reactions
12C
28Si (14p, 14n)
16O
16O
31S (16p, 15n)
16O
28Si
56Fe (26p, 30n)
28Si

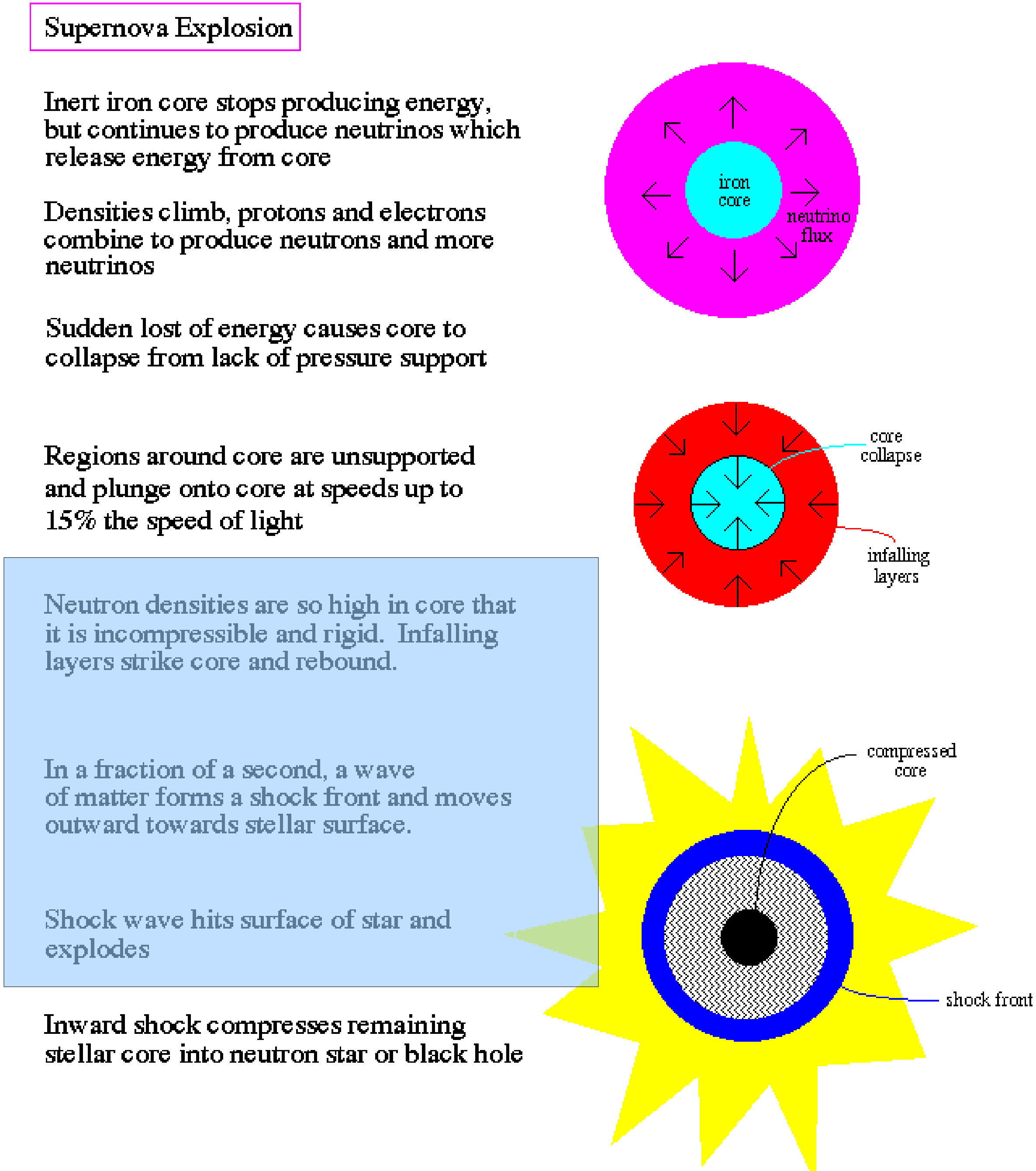
The highest mass stars can make all elements up to and including iron in their cores.

But iron is the heaviest element they can make. Fusion of iron does not create energy, and without an energy supply, the star will soon die.



* Nucleosynthesis in Supernovae

If stars can only fuse elements upto and including iron (Number 26 on the periodic table) then where do all the gold, silver, lead, uranium, etc... come from?



When a high mass star's core runs out of fusion fuel, the core collapses, causing the regions near the core to fall in and bounce off the core.

This creates an outward moving shockwave of atoms.

Demo

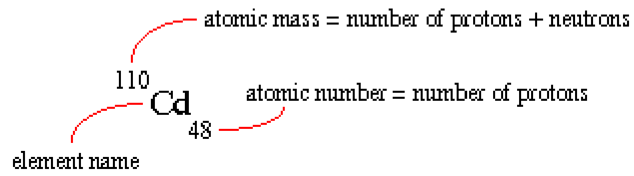
The R-Process

When the supernova explodes, large numbers of neutrons are shot out of the interior of the star at high velocities. Think of these like pellets in a shot gun shell that has been fired.

These neutrons pass through the outer regions of the star, colliding with the atoms already there (mostly hydrogen). The collisions happen very rapidly and quickly build up very large atoms.

Nucleosynthesis by Neutron Capture

construction of elements beyond iron involves the capture of a neutron to produce isophotes. Unstable isotopes decay into new elements



$$^{110}_{48}Cd + {}^{1}_{0}n \longrightarrow {}^{111}_{48}Cd$$ neutron capture

$$^{111}_{48}Cd + {}^{1}_{0}n \longrightarrow {}^{112}_{48}Cd$$ stable isotope

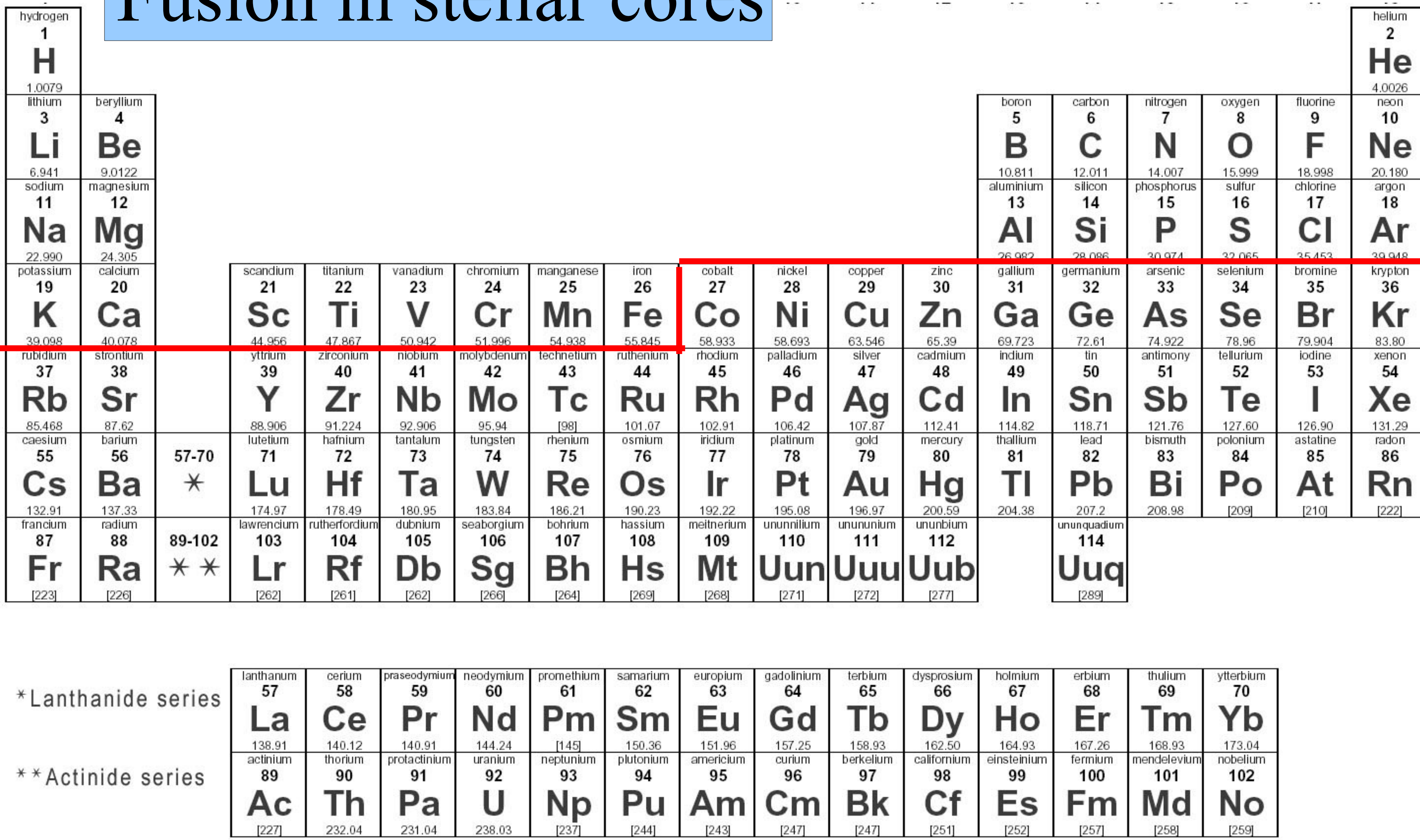
$$^{112}_{48}Cd + {}^{1}_{0}n \longrightarrow {}^{113}_{48}Cd$$ stable isotope

$$^{113}_{48}Cd + {}^{1}_{0}n \longrightarrow {}^{114}_{48}Cd$$ stable isotope

$$^{114}_{48}Cd + {}^{1}_{0}n \longrightarrow {}^{115}_{48}Cd$$ unstable isotope

$$^{115}_{48}Cd \longrightarrow {}^{115}_{49}In + e^{-} + \nu$$ radioactive decay

Fusion in stellar cores



Fusion in supernova explosions

Thanks!