FUNDAMENTALS OF EARTH SCIENCES (ESO 213A)

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DEPARTMENT OF EARTH SCIENCES

Lecture: Solar System and Origin of Earth

'we are stardasts'

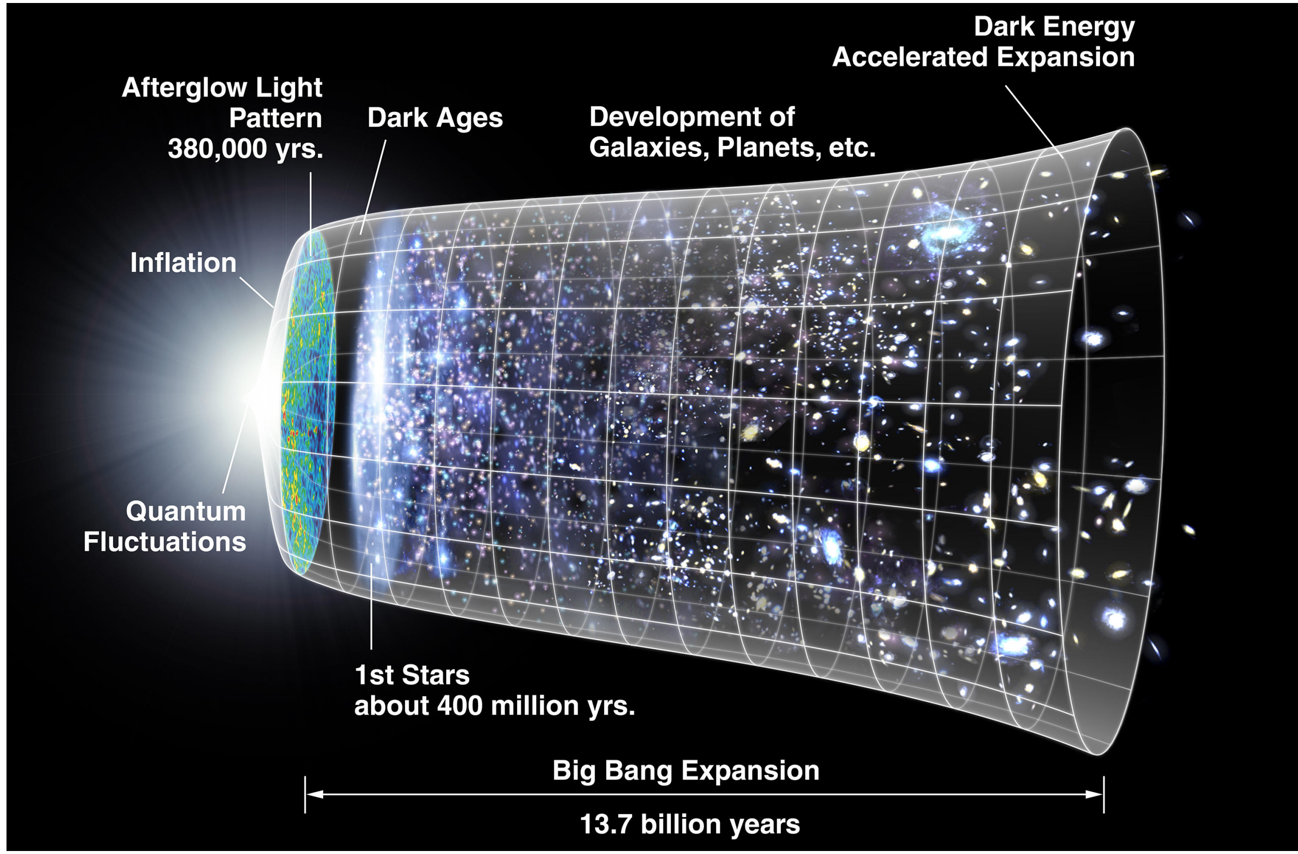
Origin of the Universe

The universe began about ~13.7 billion years ago

The **Big Bang Theory** states that, <u>in the beginning, the universe was all in one place</u>

<u>All of its matter and energy were squished into an infinitely small point</u> (smaller than atom), and then it exploded. In millionth of a millionth second from smaller than a size of atom to galaxy!

After about <u>10 billion years</u>, our <u>solar system began</u> to form



Source: Nasa.gov

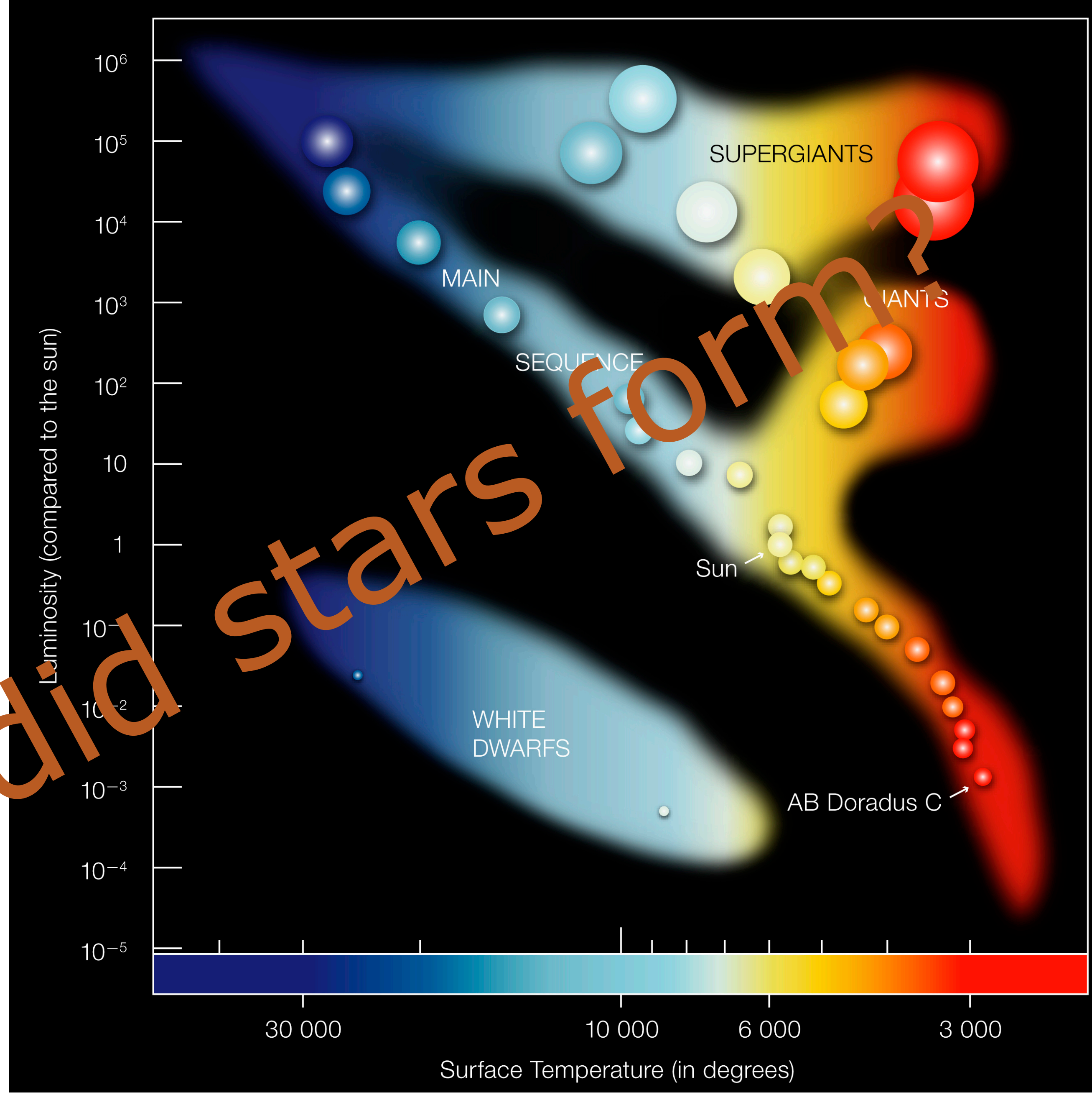
The Big Bang mainly created H and He, and the first stars were formed (but still no planets)

Hertzprung-Russel (H-R) diagram

Most stars, including the sun, are "main sequence stars," fueled by nuclear fusion converting hydrogen into helium.

•As stars begin to die, they become giants and supergiants. These stars have depleted their hydrogen supply and are very old. The core contracts as the outer layers expand. These stars will eventually explode (becoming a planetary nebula or supernova, depending on their mass) and then become white dwarfs, neutron stars, or black holes (again depending on their mass).

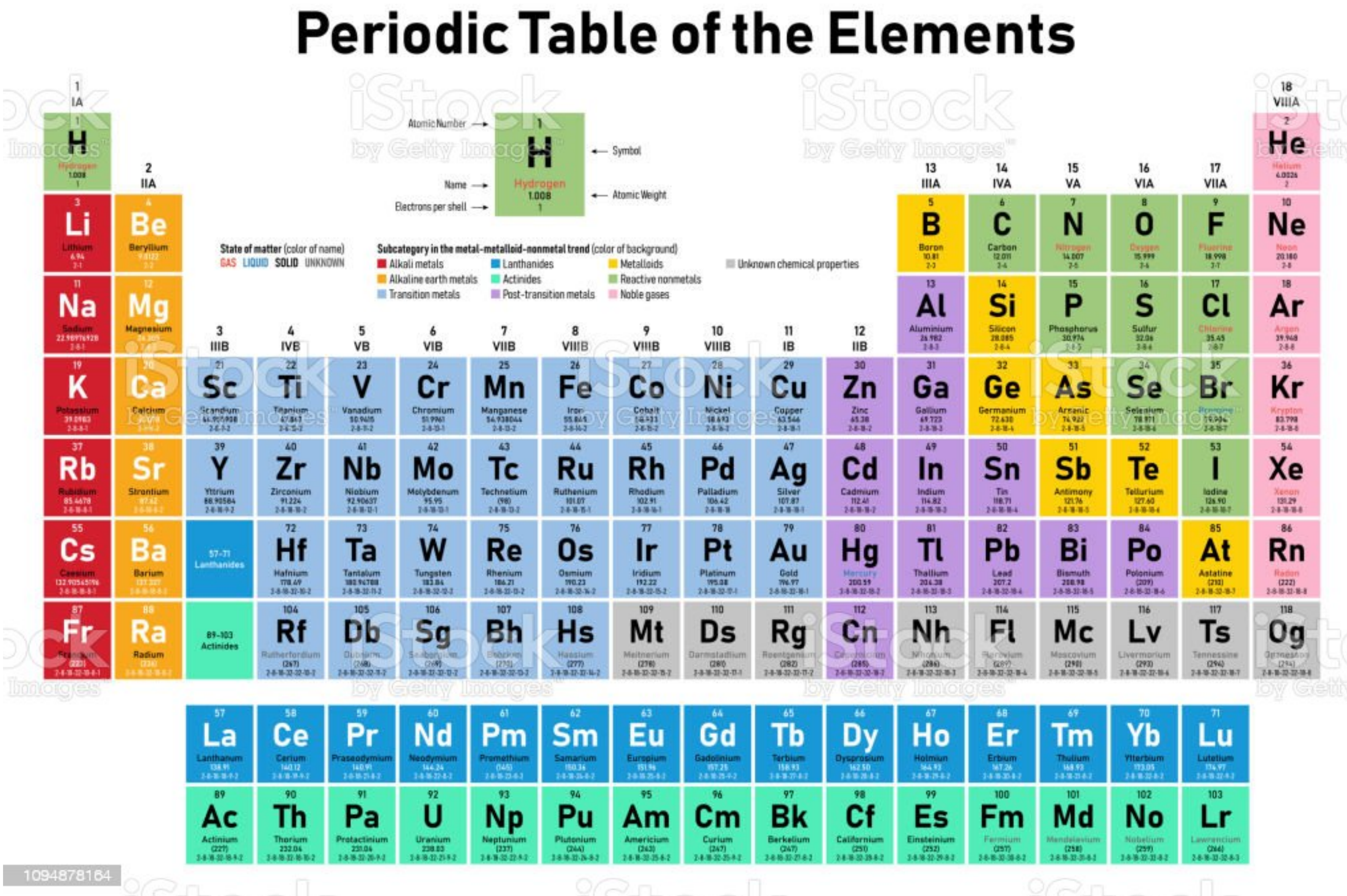
Smaller stars (like our Sun) eventually become faint white dwarfs (hot, white, dim stars) that are below the main sequence.



Luminosity is the total amount of energy that a star radiates each second

How did stars form?

How did elements form?



Nucleosynthesis

Nucleosynthesis is the process that creates new atomic nuclei from pre-existing nucleons and nuclei.

Time	T (K)	Density
10^-43 (s)	10^32	10^96
10^-35 (s)	10^28	10^80
10^-13 (s)	10^16	10^32
15s	3x10^9	10^4
3min	10^9	10^2
10^5 y	4000	10^-20
10^9 y	18	10^-27
13.6x 10^9	2.73	10^-30

1. Big Bang/ Primordial Nucleosynthesis:

According to current theories, the first nuclei were formed a few minutes after the Big Bang.

At the beginning, the universe was only made of "elementary particles", protons, neutrons do not exist, they were not stable (too hot!).

After 10^{-4} seconds temperature was cool enough to form protons and neutrons

After 3 minutes the universe was cool enough to produce ^2H (proton and neutron combined)

2. Stellar Nucleosynthesis:

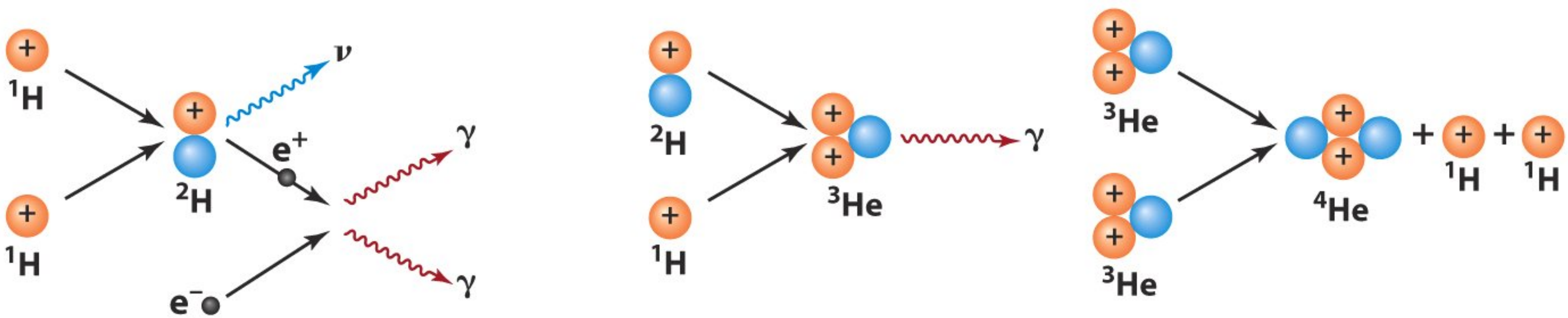
Stellar Nucleosynthesis started more than 12 billion years ago.

Stars are not only the source of light, its an element factory!

Nucleosynthesis

Star "turns on" when nuclear fusion occurs

main sequence star – either proton-proton chain or CNO cycle nucleosynthesis



(a) Step 1:

- Two protons (hydrogen nuclei, ^1H) collide.
- One of the protons changes into a neutron (shown in blue), a neutral, nearly massless neutrino (ν), and a positively charged electron, or positron (e^+).
- The proton and neutron form a hydrogen isotope (^2H).
- The positron encounters an ordinary electron (e^-), annihilating both particles and converting them into gamma-ray photons (γ).

(b) Step 2:

- The ^2H nucleus from the first step collides with a third proton.
- A helium isotope (^3He) is formed and another gamma-ray photon is released.

(c) Step 3:

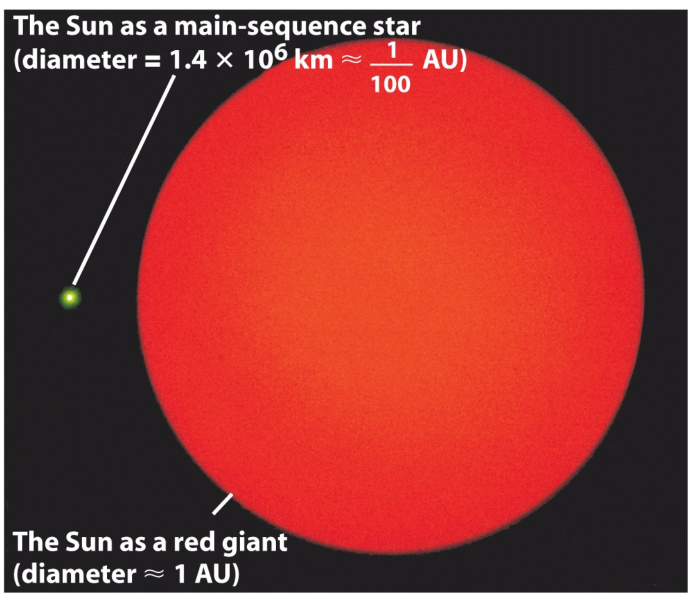
- Two ^3He nuclei collide.
- A different helium isotope with two protons and two neutrons (^4He) is formed and two protons are released.

P-P chain net: 4 H to 1 He

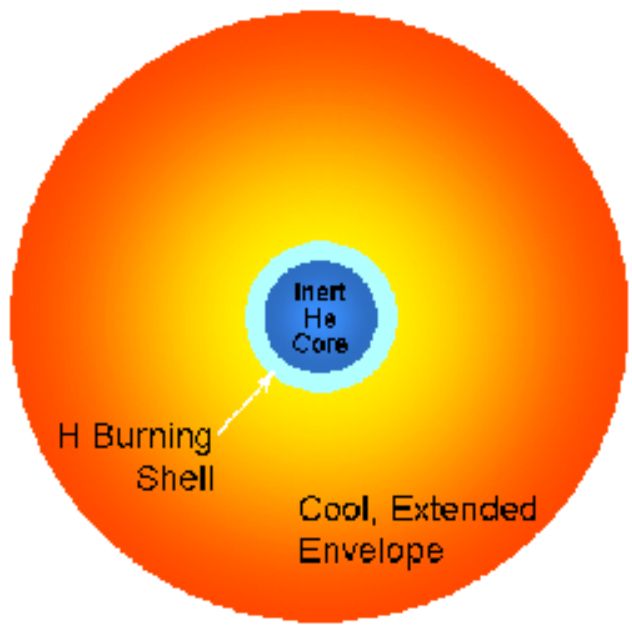
So, what happens when the core runs out of hydrogen?

- Star begins to collapse, heats up
- Core contains He, continues to collapse
- But H fuses to He in shell– greatly inflating star

→ RED GIANT (low mass)
or SUPERGIANT (high mass)



The Sun today and as a red giant



Red Giant (RGB) star: H burning in shell

<u>CNO cycle</u> – more efficient method, but requires higher internal temperature, so only for <u>stars with mass higher than 1.1 solar masses</u>

$^{12}C + p \rightarrow {}^{13}N$ $\qquad$ $^{13}N \rightarrow {}^{13}C$

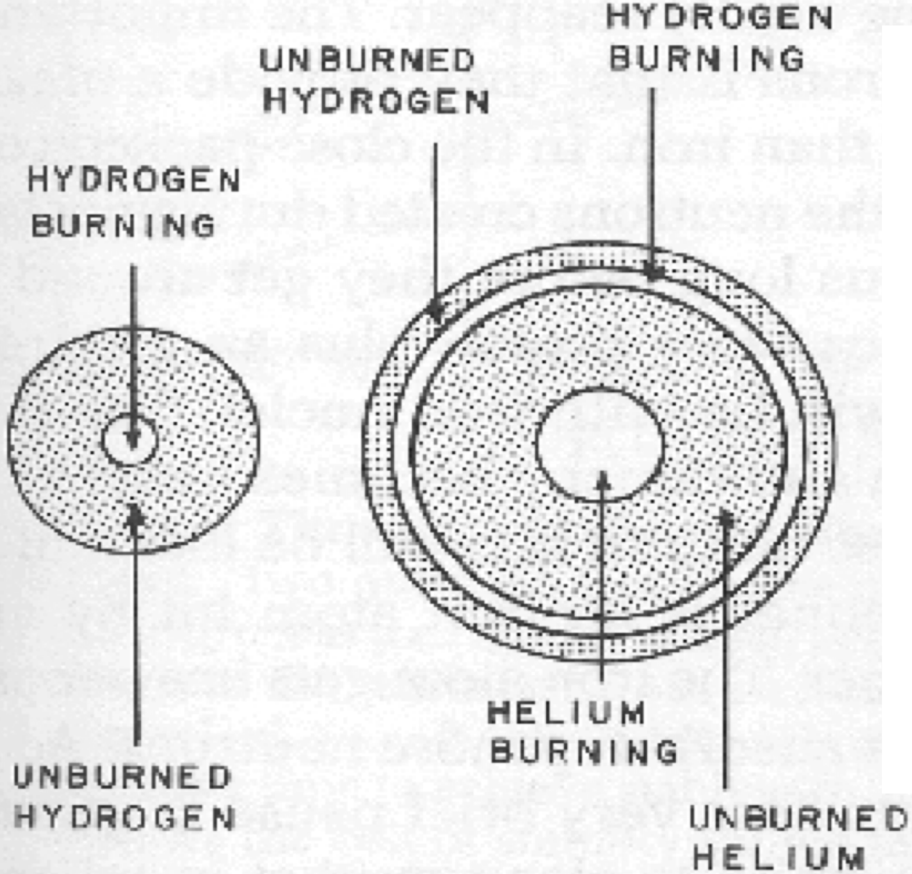
$^{13}C + p \rightarrow {}^{14}N$

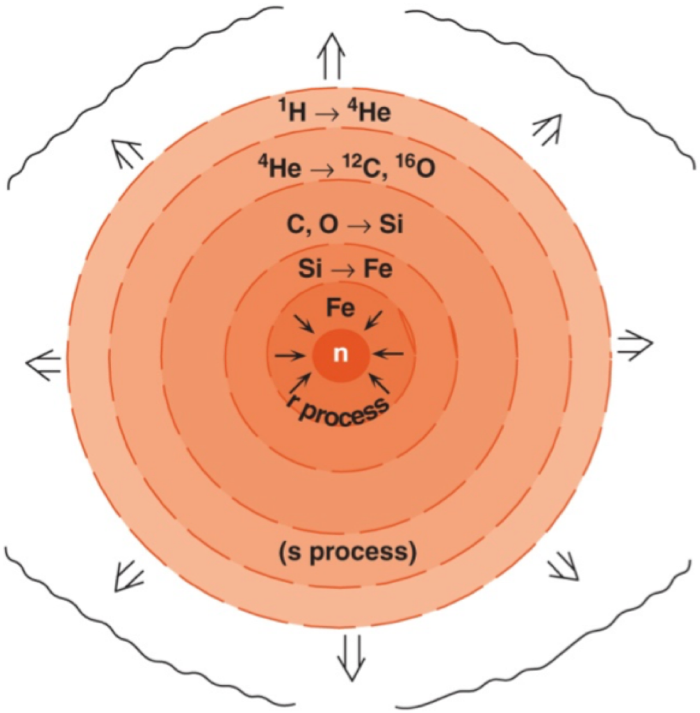
$^{14}N + p \rightarrow {}^{15}O$ $\qquad$ $^{15}O \rightarrow {}^{15}N$

$^{15}N + p \rightarrow {}^{12}C + {}^{4}He$

CNO cycle net reaction : 4 H to 1 He

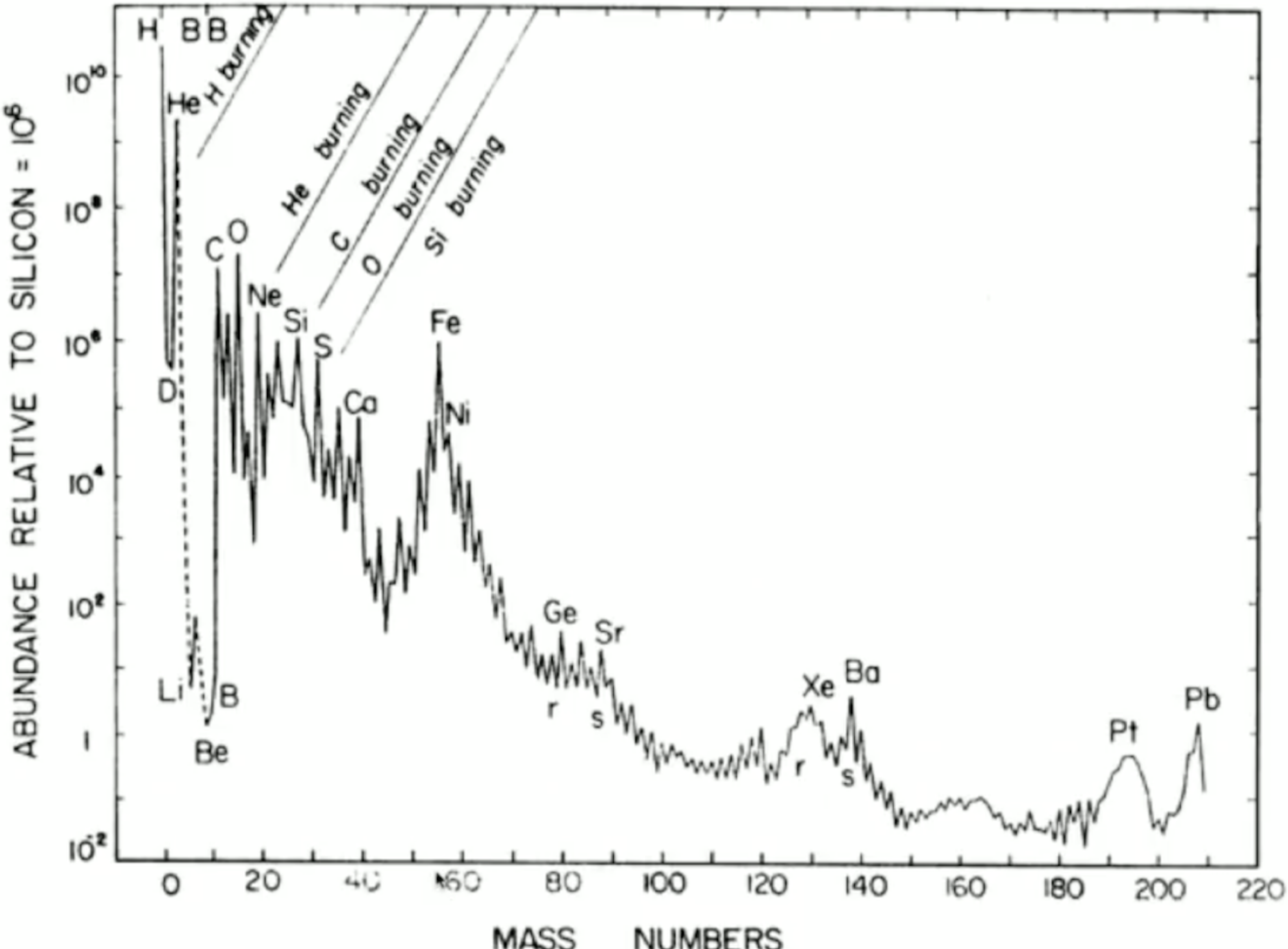
Nucleosynthesis in a Supergiant star





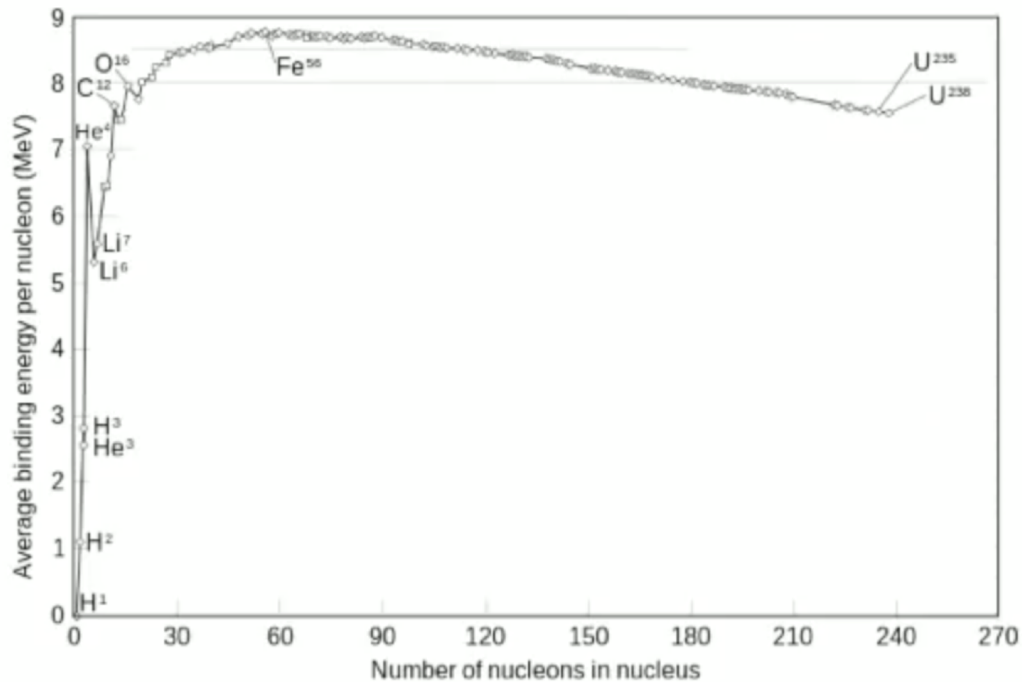
Name of Process	Fuel	Products	Temperature
Hydrogen-Burning	H	He	60×10^6 °K
Helium-Burning	He	C, O	200×10^6 °K
Carbon-Burning	C	O, Ne, Na, Mg	800×10^6 °K
Neon-Burning	Ne	O, Mg	1500×10^6 °K
Oxygen-Burning	O	Mg to S	2000×10^6 °K
Silicon-Burning	Mg to S	Elements near FE	3000×10^6 °K

Is the universe made of iron?



So what happens beyond iron?

- capture of particles requires energy
- capture of charged particles very unlikely
- neutrons still can be captured



- iron from the earlier burning processes exposed to the neutron flux
- two processes possible:
  - slow neutron capture: s-process
  - rapid neutron capture: r-process

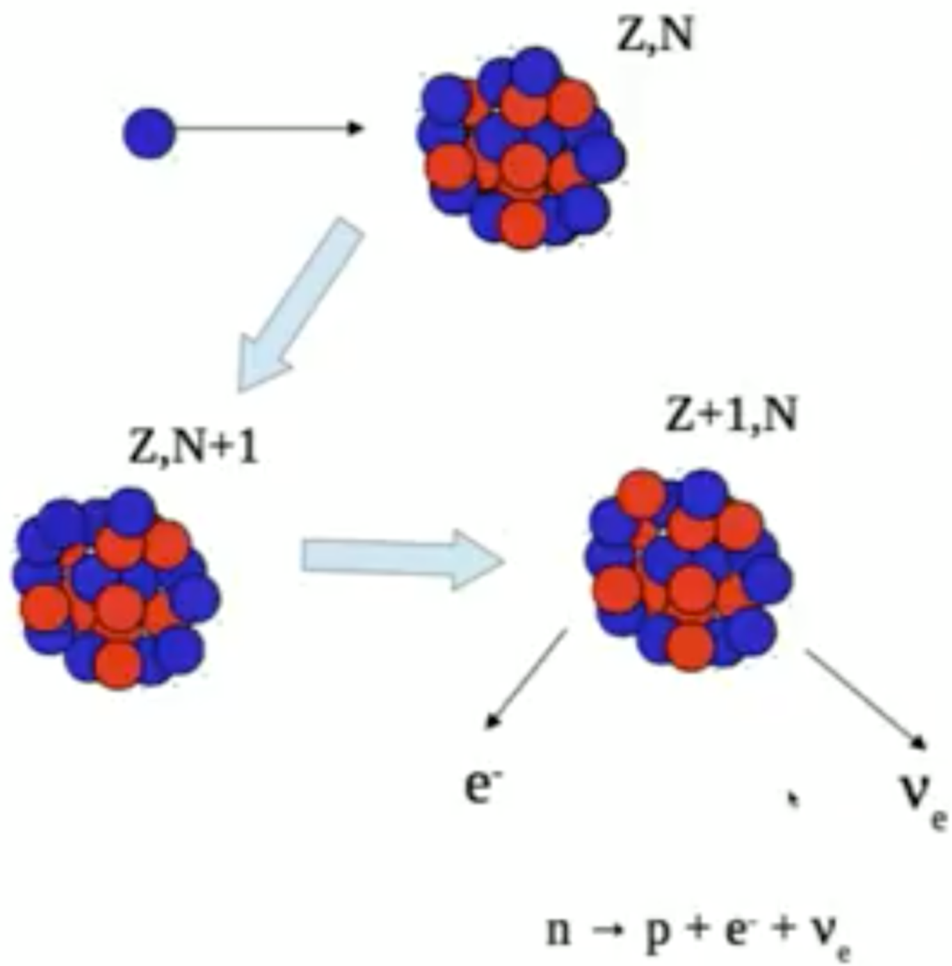
Supernova Explosion

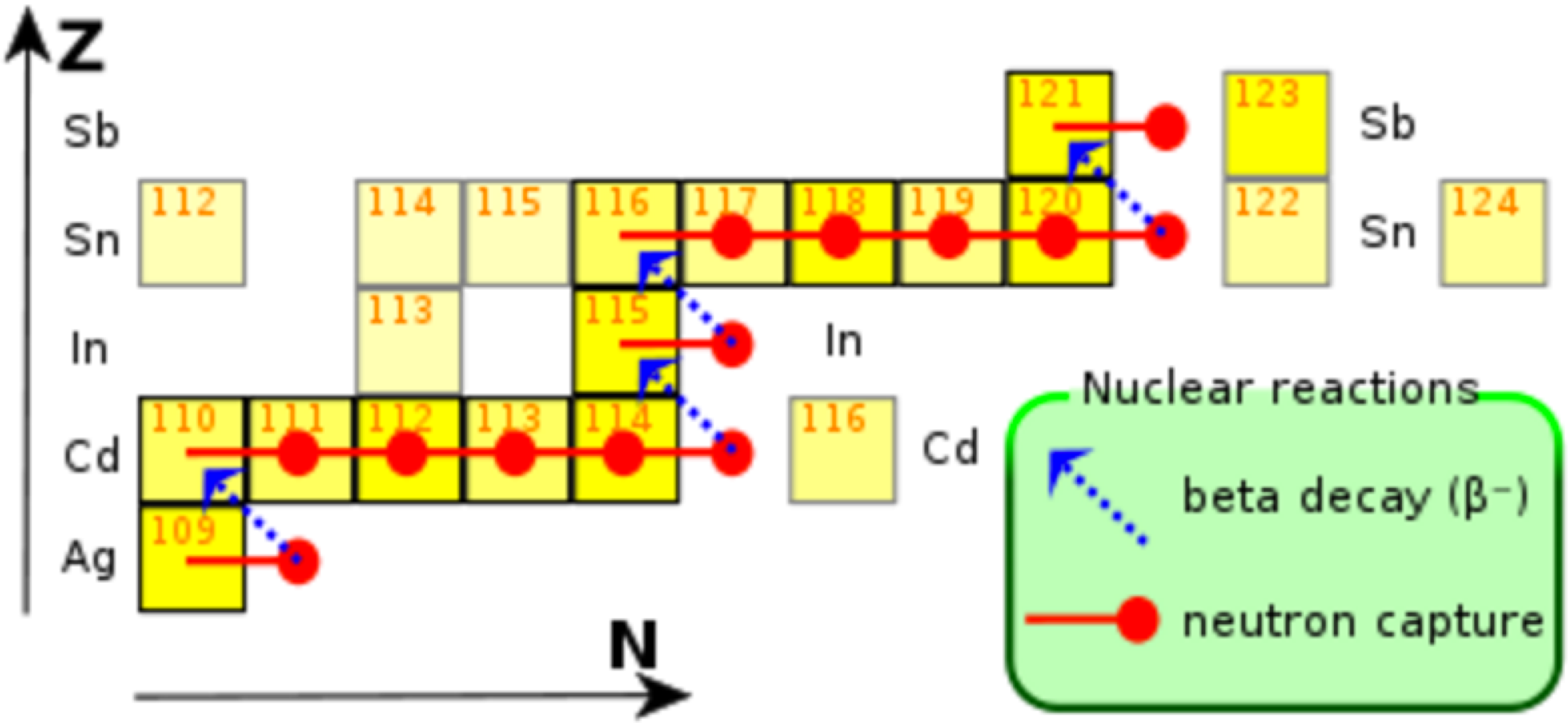
s-process – slow neutron capture

What does it mean 'slow'?

Nucleus half-life – life time of a nucleus before it decays

→ 'slow' = time until a neutron is captured is longer than the half-life of the nucleus





Z
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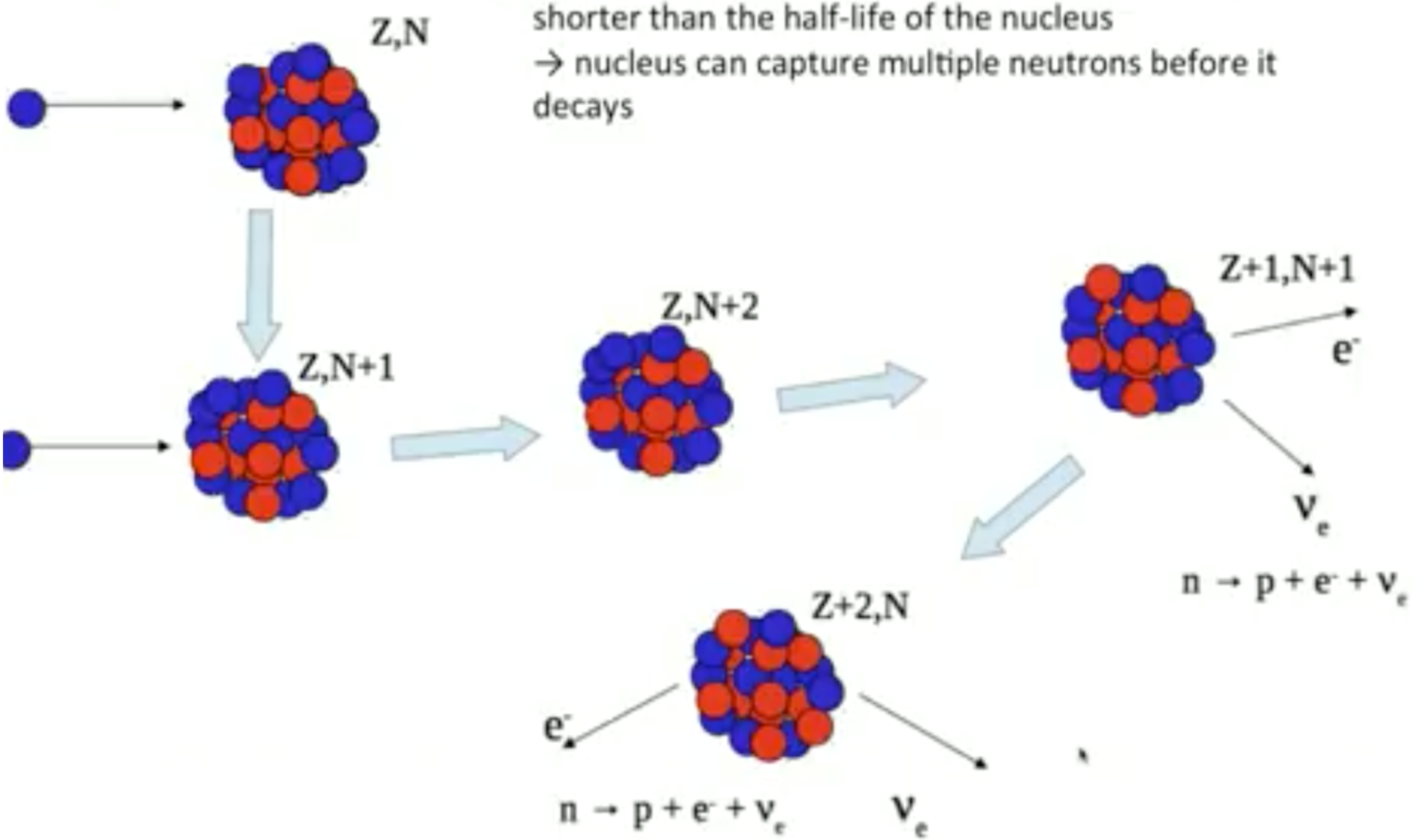
111
112
113
114
116
109
Sb
Sn
In
Cd
Nuclear reactions
beta decay (β⁻)
neutron capture

r-process – rapid neutron capture

→ 'rapid' = time until a neutron is captured is much shorter than the half-life of the nucleus

→ nucleus can capture multiple neutrons before it decays



r-process nucleosynthesis:

rapid neutron addition

beta decay does not keep pace with n addition

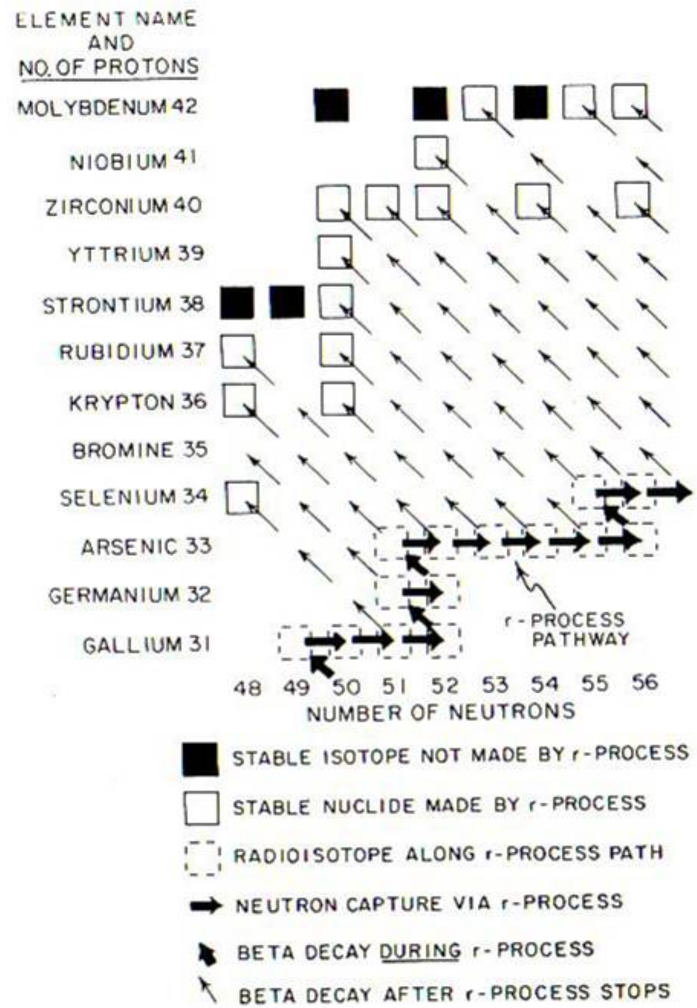
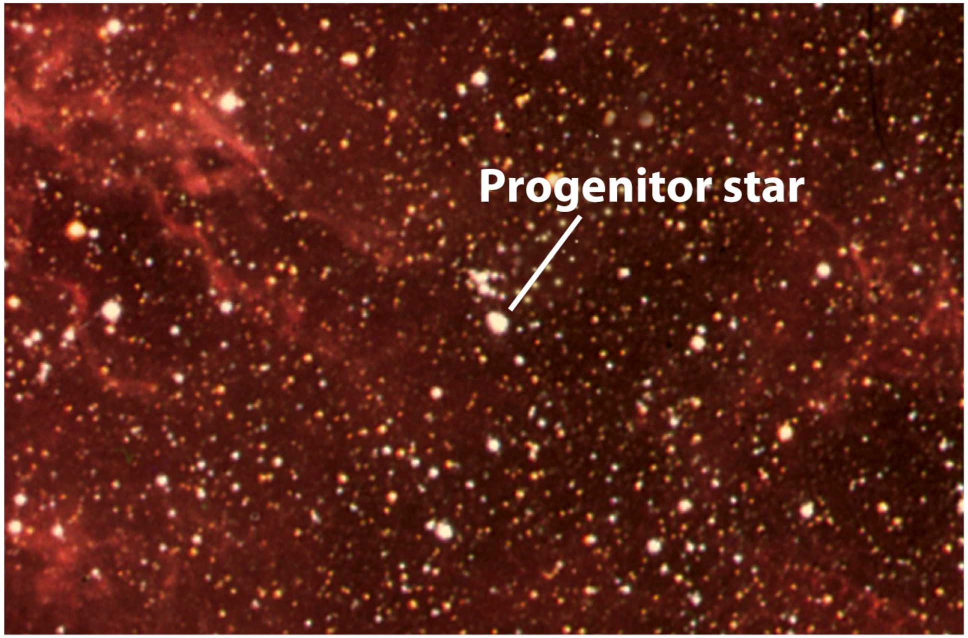


Figure 2-7. A segment of the r-process pathway: Rapid-fire neutron bombardment adds neutrons until a nuclide cannot hold any more. Only then does the nuclide undergo beta decay to become the next heavier element. This process—neutron capture to saturation followed by beta decay—is repeated over and over again, producing successively heavier elements. The r-process buildup occurs during the explosion that destroys the red giant. Hence it ends abruptly. The neutron flux stops and the highly radioactive isotopes on the r-process pathway emit beta particles one after another until stability is achieved. Note that in the case of those isobars for which two stable nuclides exist, only the neutron-rich nuclide of the pair is produced by the r-process.

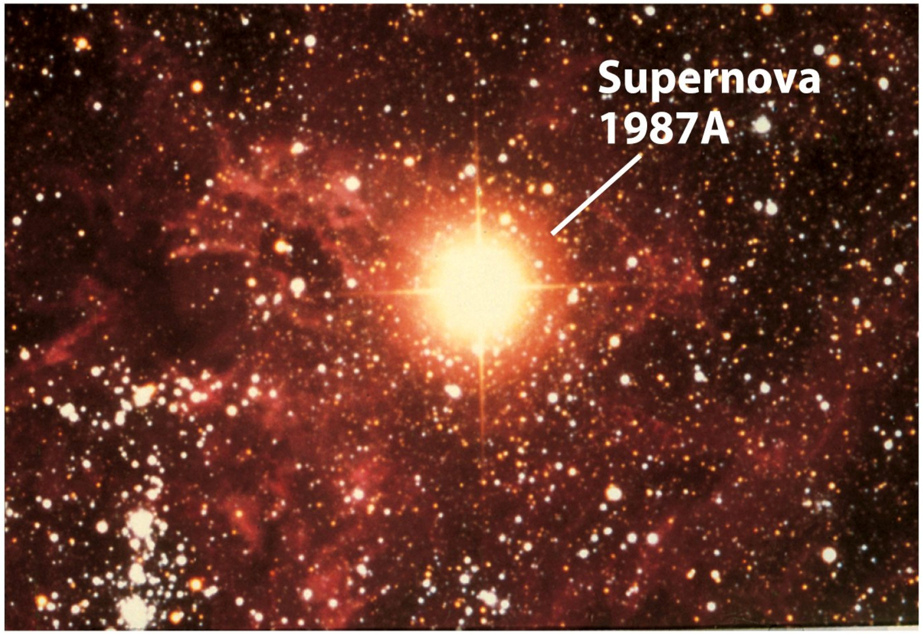
Supernova Explosion

End for high mass star comes as it tries to fuse core Fe into heavier elements– and finds this absorbs energy

STAR COLLAPSES & EXPLODES AS SUPERNOVA

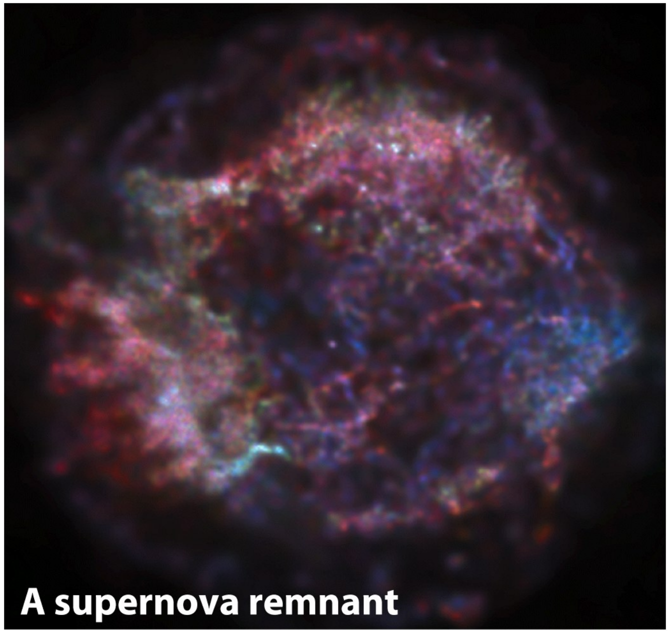


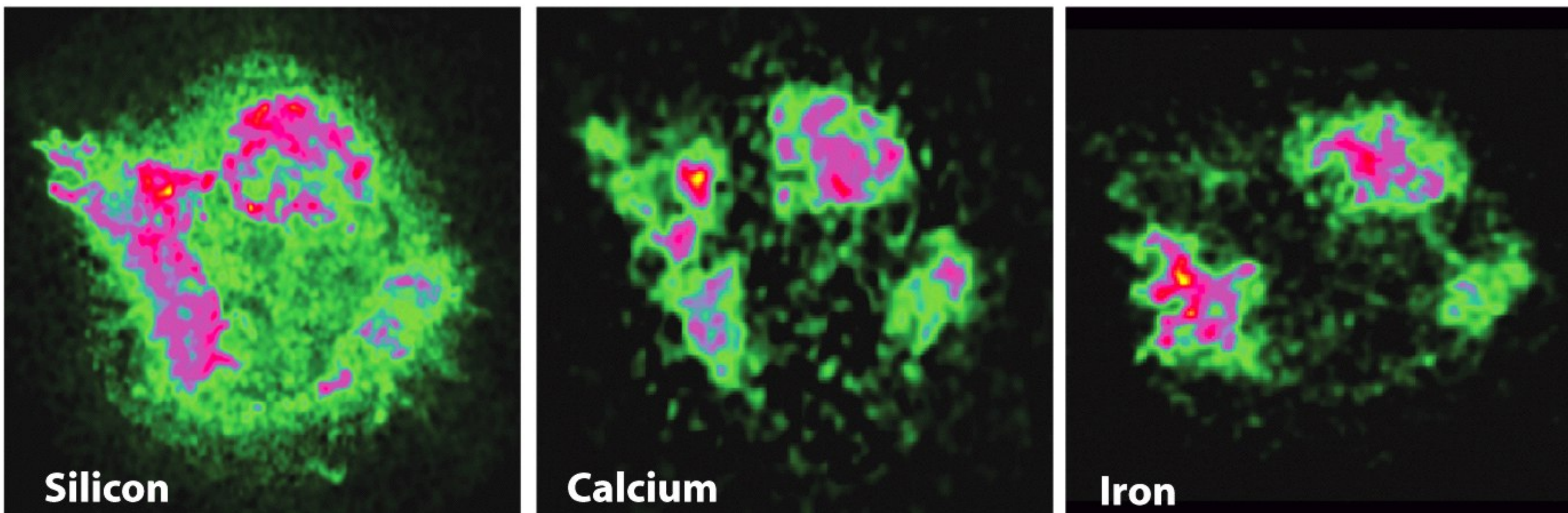
Before the star exploded



After the star exploded

Supernova remnants

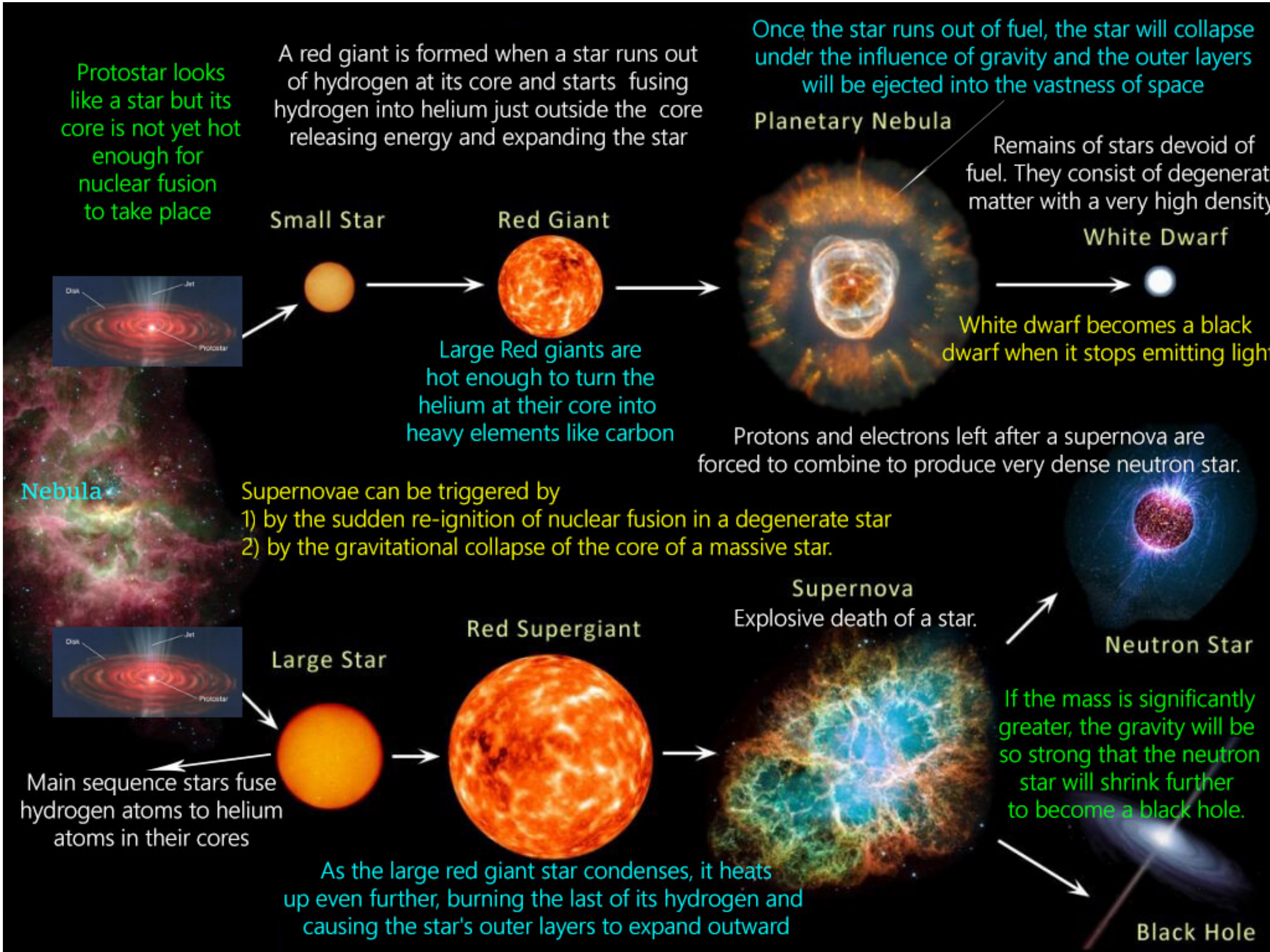




Material was ejected in "blobs" from the supernova that produced the Cassiopeia A supernova remnant

Element (H-Fe) factory "stars", supernova explosion along with s-and r-process continued to produce the building blocks of our universe (hydrogen to uranium)

Life cycle of a star



Summary of nucleosynthesis processes

process	**main products**	**comment**
H-burning	^{4}He	main seq.
He-burning	^{12}C, ^{16}O	Red Giant
C-O-Ne-Si burning	^{20}Ne, ^{28}Si, ^{32}Si, up to ^{56}Fe	Supergiants
s-process	many elements	Red Giants, Supergiants
r-process	many heavy elements	Supernova

Formation of Solar System

4.57 billions years ago

The Nebular Theory

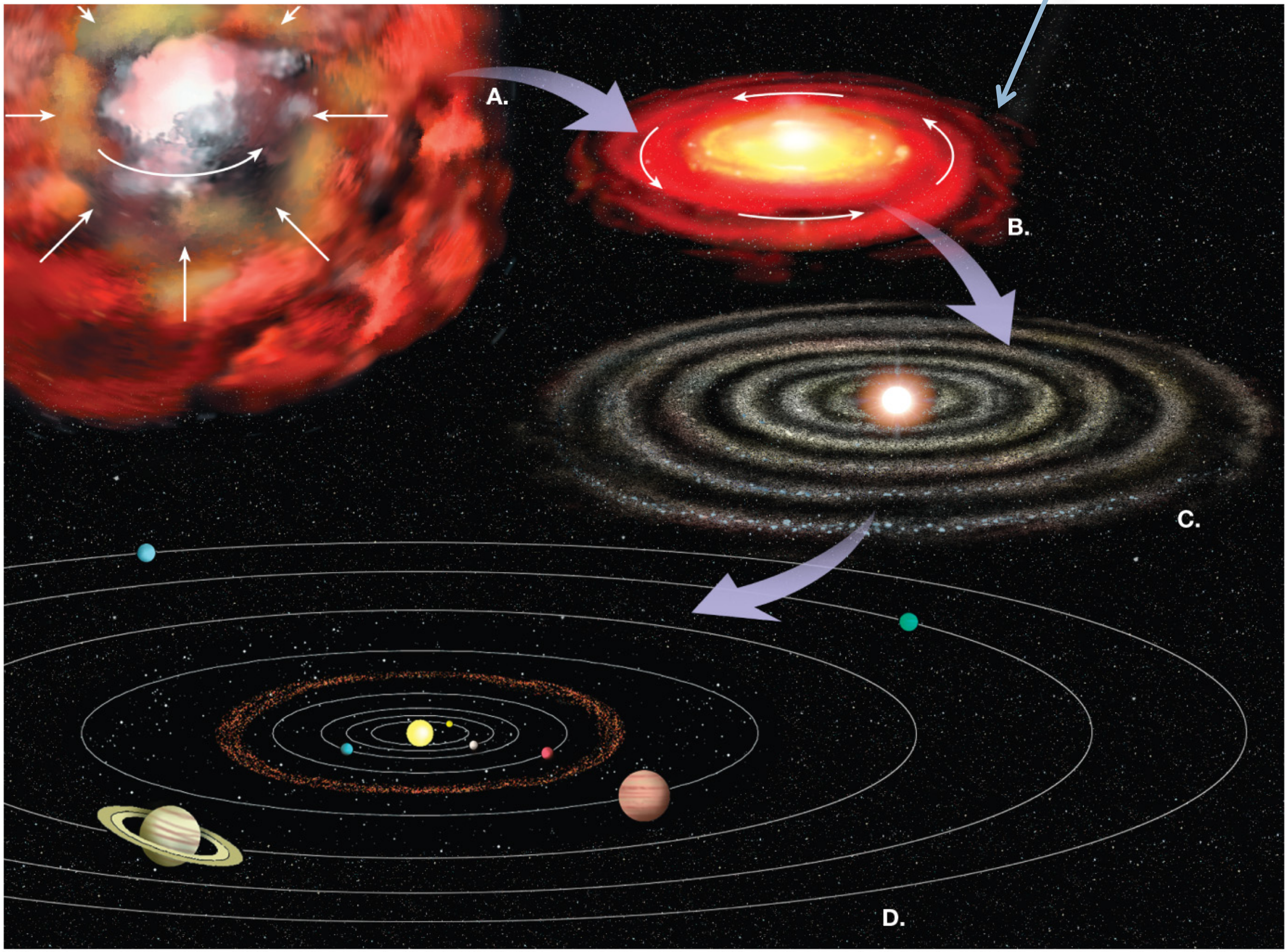
1. Cosmic cloud formed from dust of previous Supernovae

2. Gravity pulls particle closer and increase rotation

3. Nuclear reaction begins ~ 5 billion years ago at the centre of the cloud due to high concentration of material

4. Remaining particle continues to come closer and accretion took place

5. Eventually larger particles accreted and formed ‘planets’



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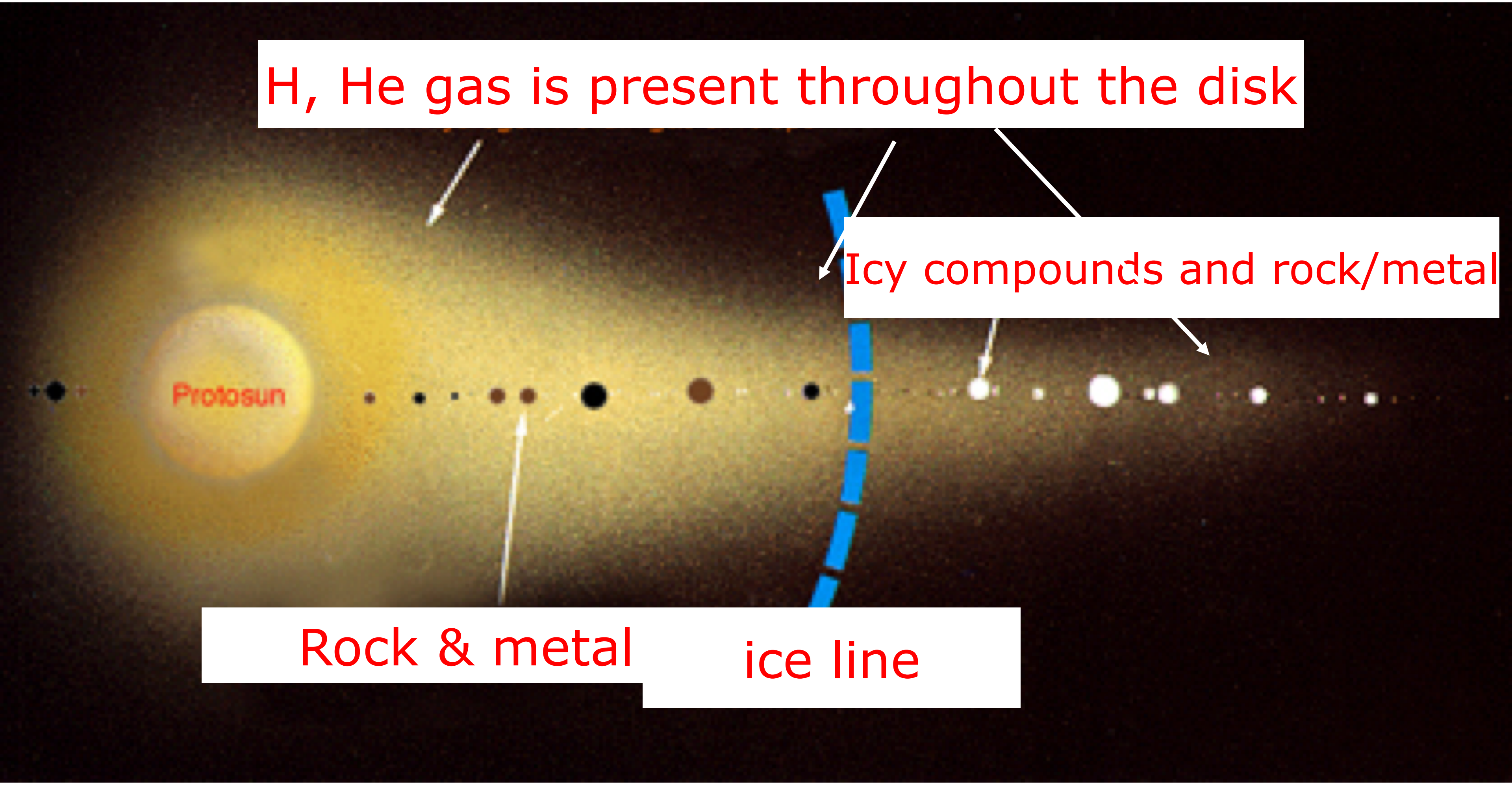
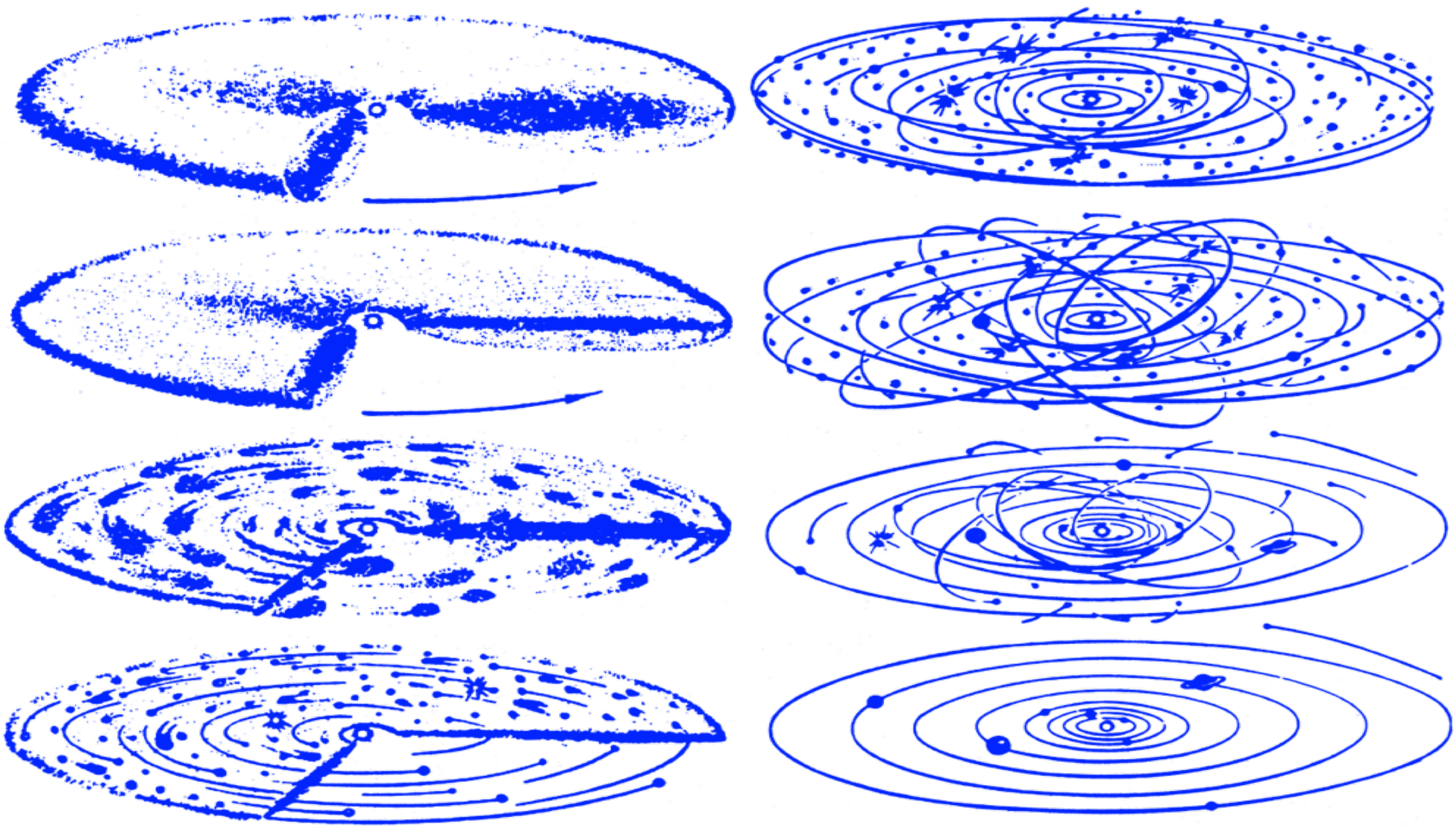
Formation of Solar System



Condensation: gas becomes solid

Terrestrial planets form by accretion of solids

Dust >rocks >planetesimals >embryos >planets



Planet formation: Terrerstrial vs. giant planets

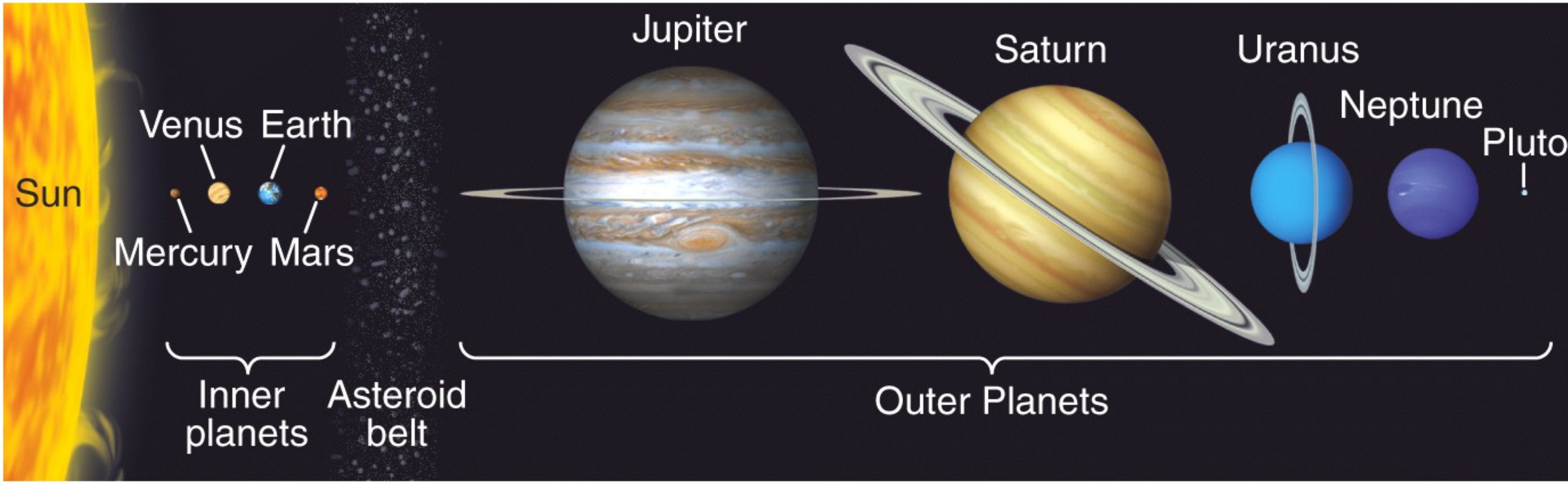
Giant ("jovian")

1. Lots of solids in the disk (cold > 5 AU)
2. Cores form from ice, rock and metal
3. Grow large, quickly (~1 million years)
4. Big enough to trap H and He gas from disk

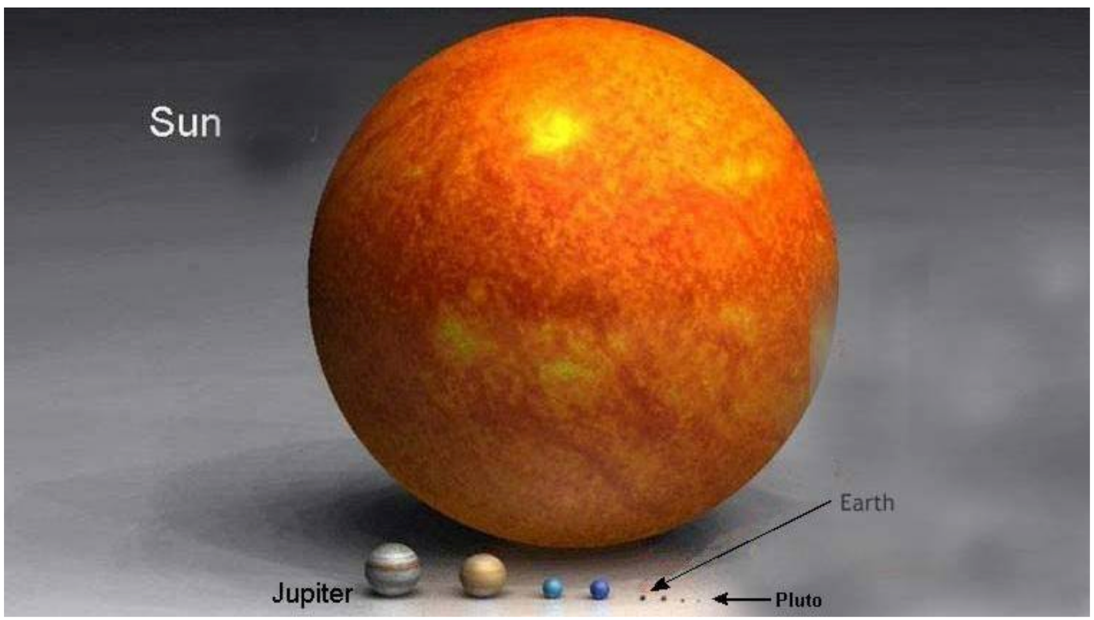
Terrestrial ("earth like")

1. Very little solid material in disk at 1 AU
2. Form from rock and metal only
3. Grow slowly (~100 million years)
4. Too small to trap any gas from disk

Solar System



Sizes of the planets relative to Sun



Sun-planet distance
(relative to Earth: AU)

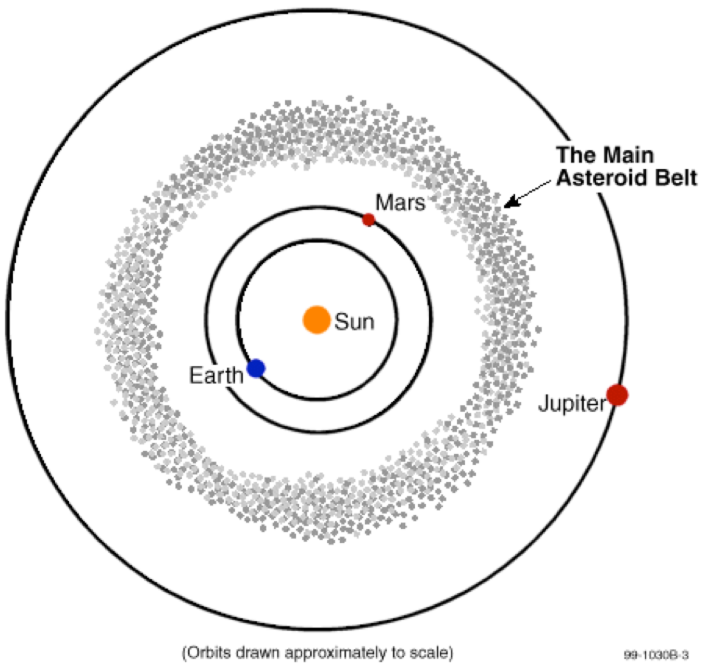
Mercury	0.4 AU
Venus	0.7
Earth	1.0
Mars	1.5
Jupiter	5.2
Saturn	9.5
Uranus	19
Neptune	30

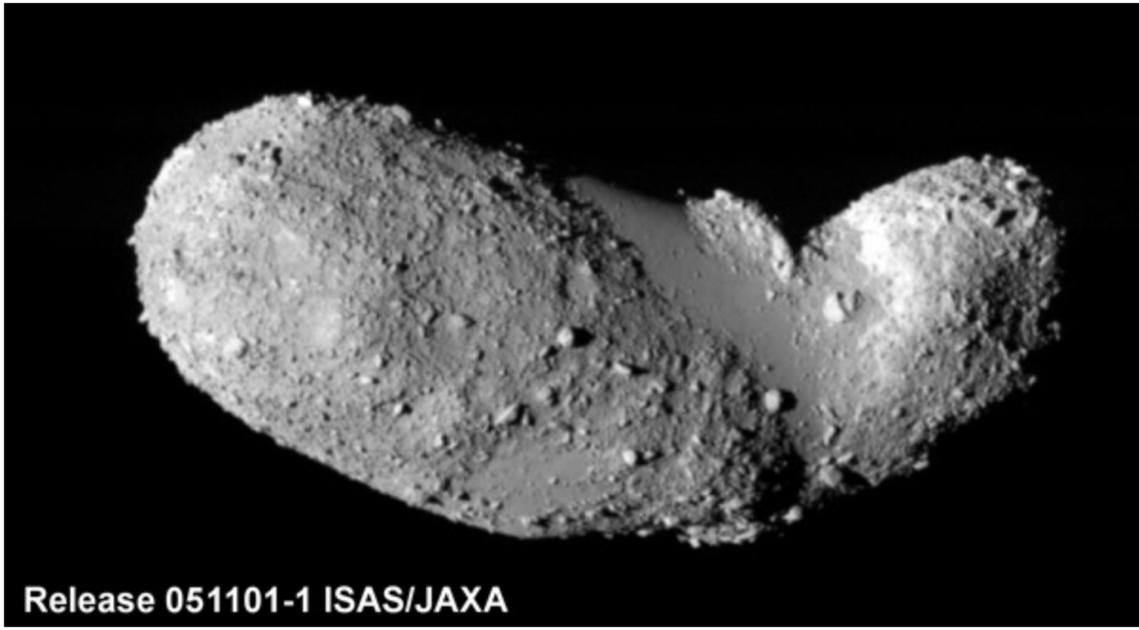
1 AU = 150 million km

Other residents of the solar system

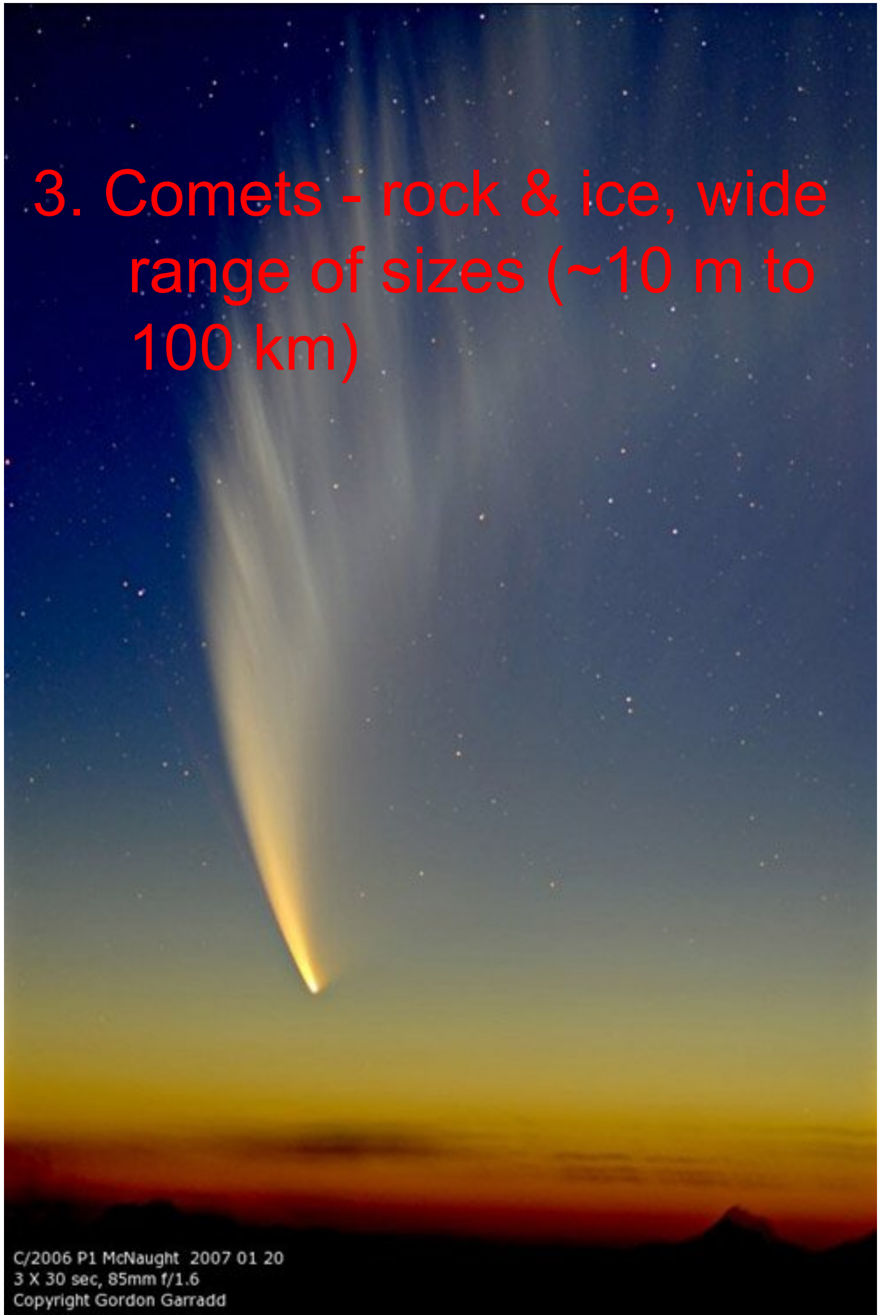
1. Moons - orbit planets, some are larger than Mercury

2. Asteroids - rocky, d < 1000 km, orbit the sun

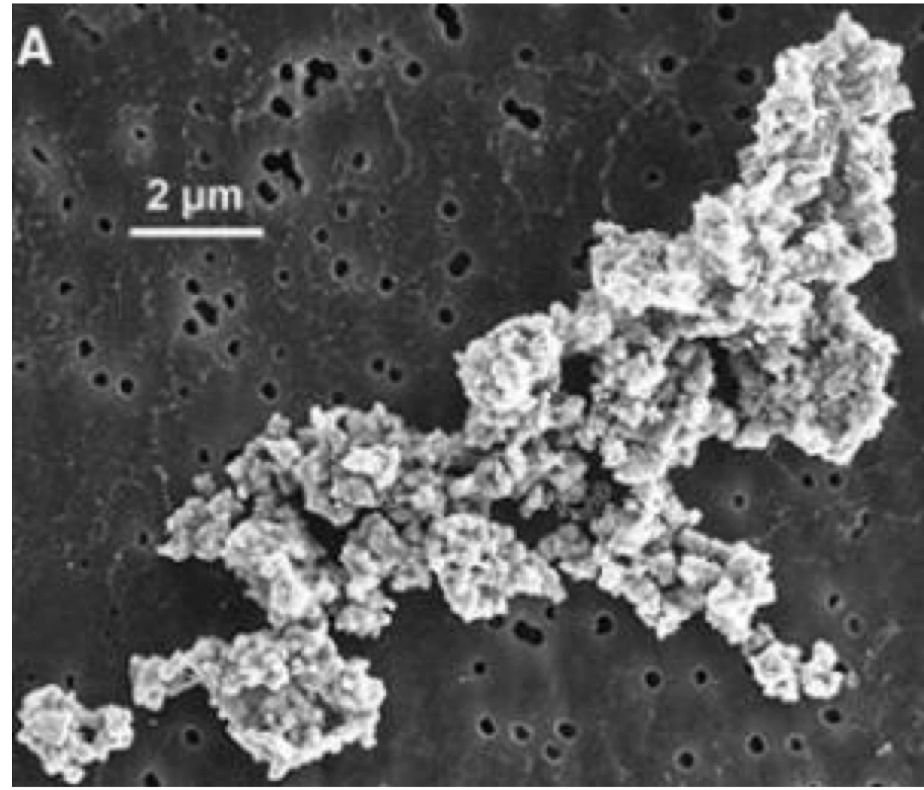




Other residents of the solar system



3. Comets - rock & ice, wide range of sizes (~10 m to 100 km)



4. Meteoroids - small fragments of asteroids that enter earth's atmosphere (dust to boulder sized)