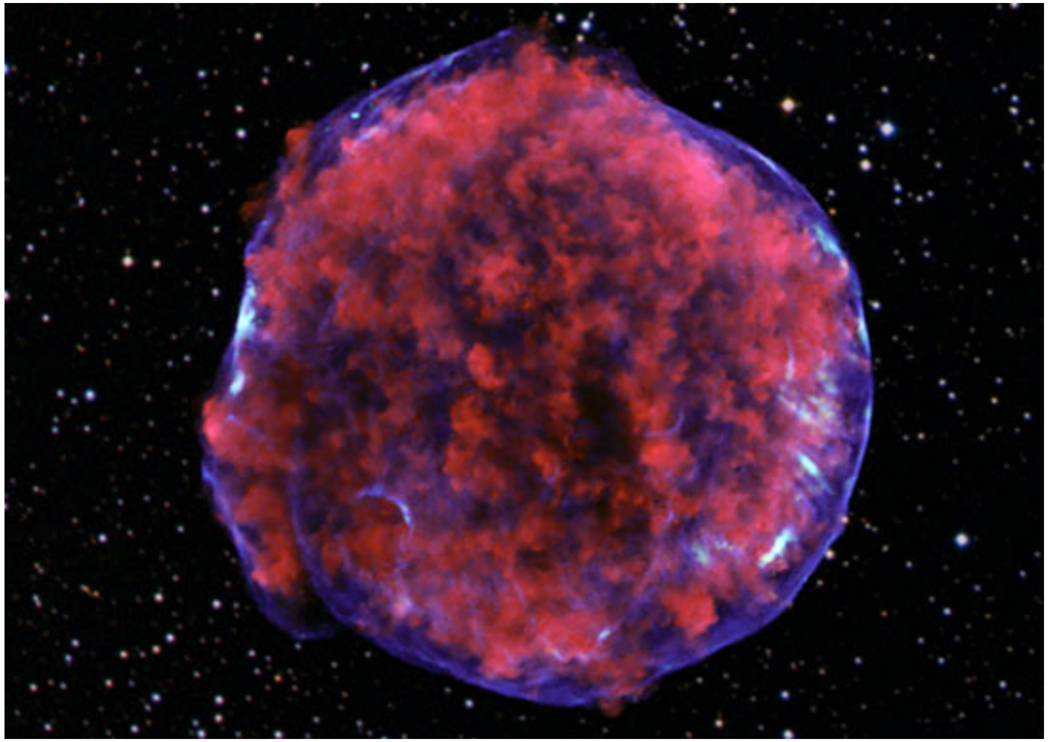


ASTRO 310:
Galactic & Extragalactic Astronomy

Prof. Jeff Kenney

Basics on the Formation of the Elements

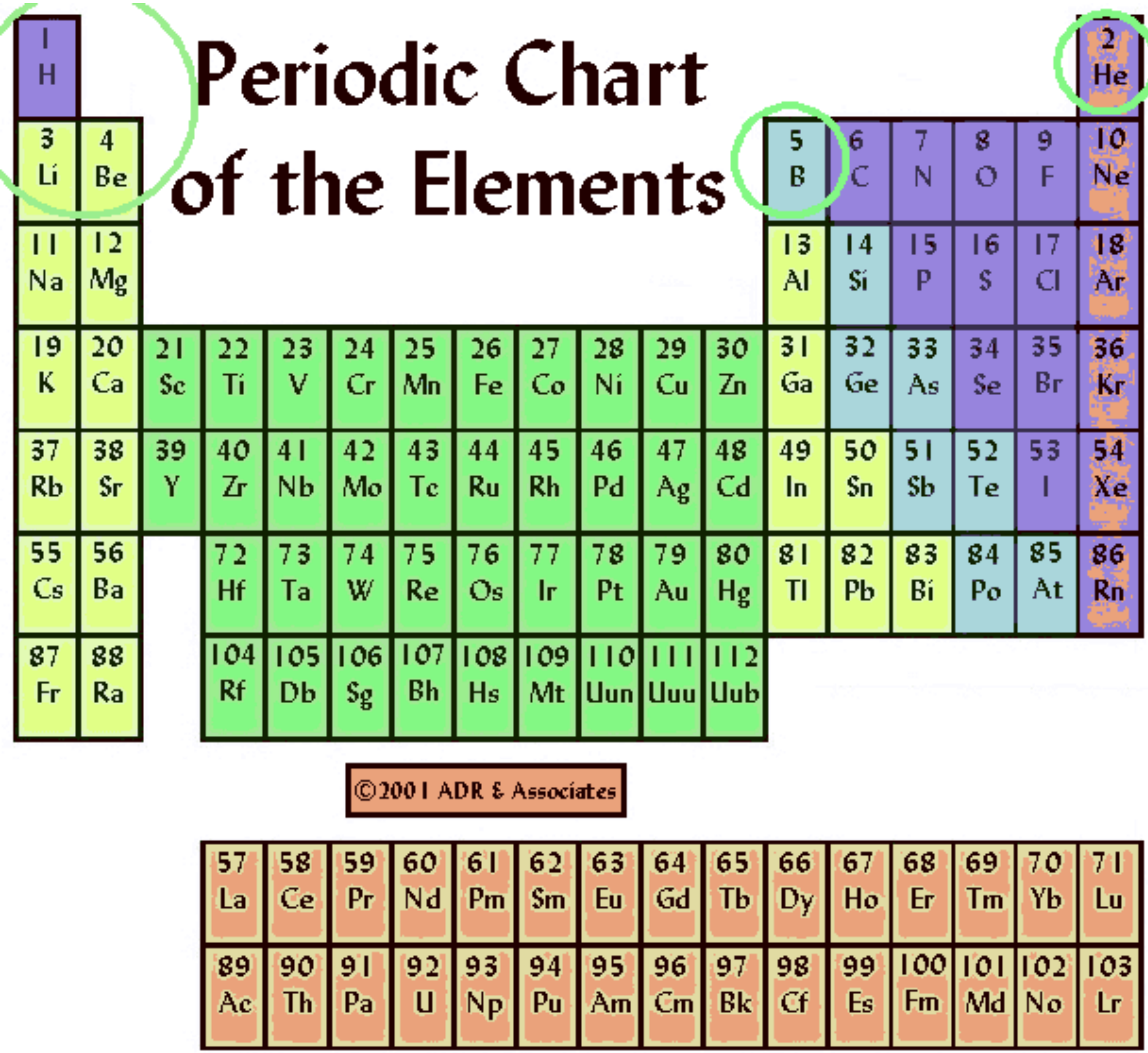
these slides won't be covered in class. please review before Lecture 16 (Mon Oct 29)!

Elemental abundances

- Heavy elements are produced in stars, and elemental ("chemical") abundances offer a record through which we can trace star formation history of galaxies & galaxy evolution

- Abundances of elements heavier than helium ("metals") vary among stars and galaxies

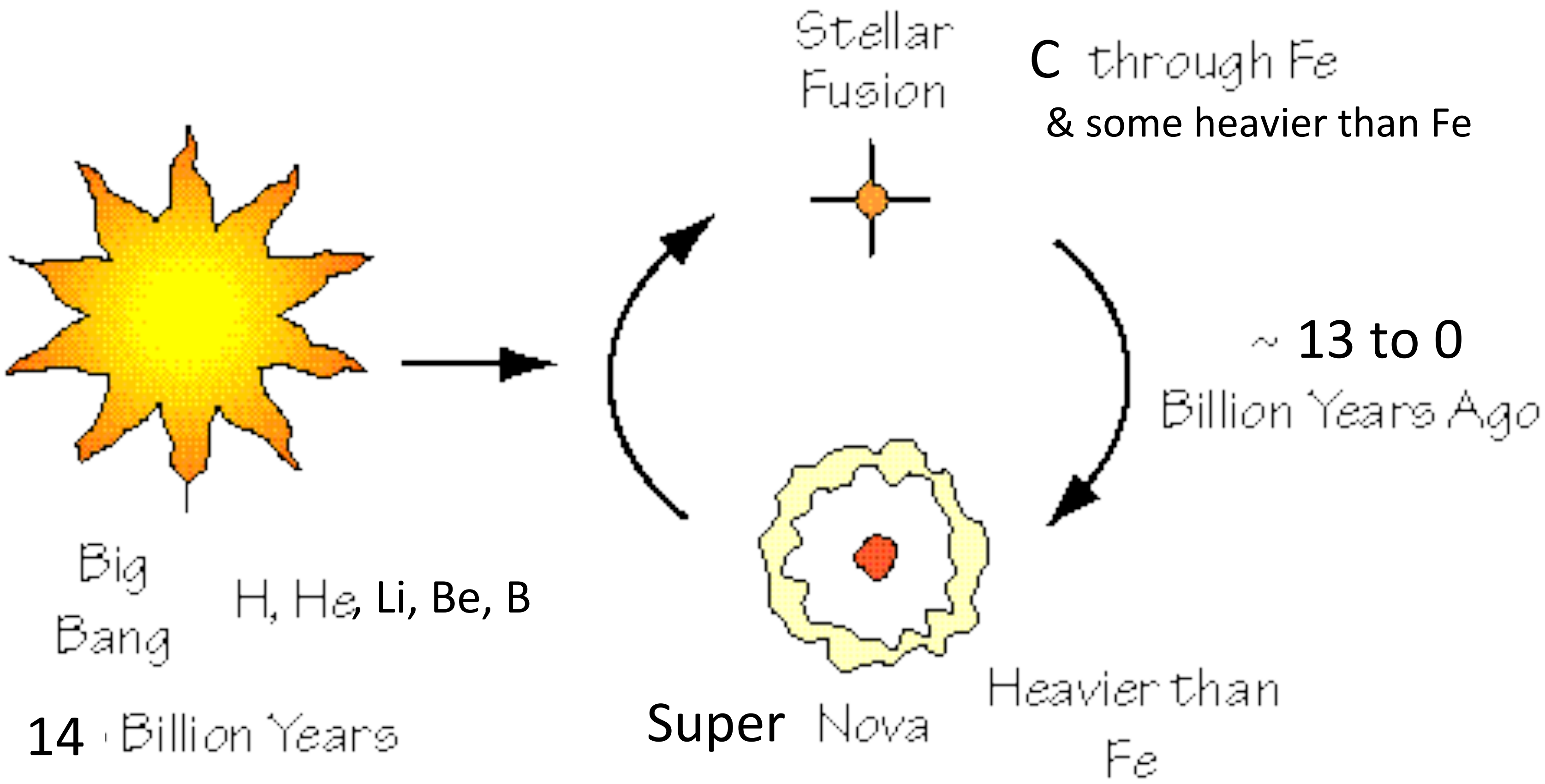
- In most small systems (star clusters and dwarf galaxies), abundances are relatively uniform, but in larger galaxies there are systematic variations with radius and large dispersions at any location



elements A=1-5 made mostly in Big Bang

Where elements come from

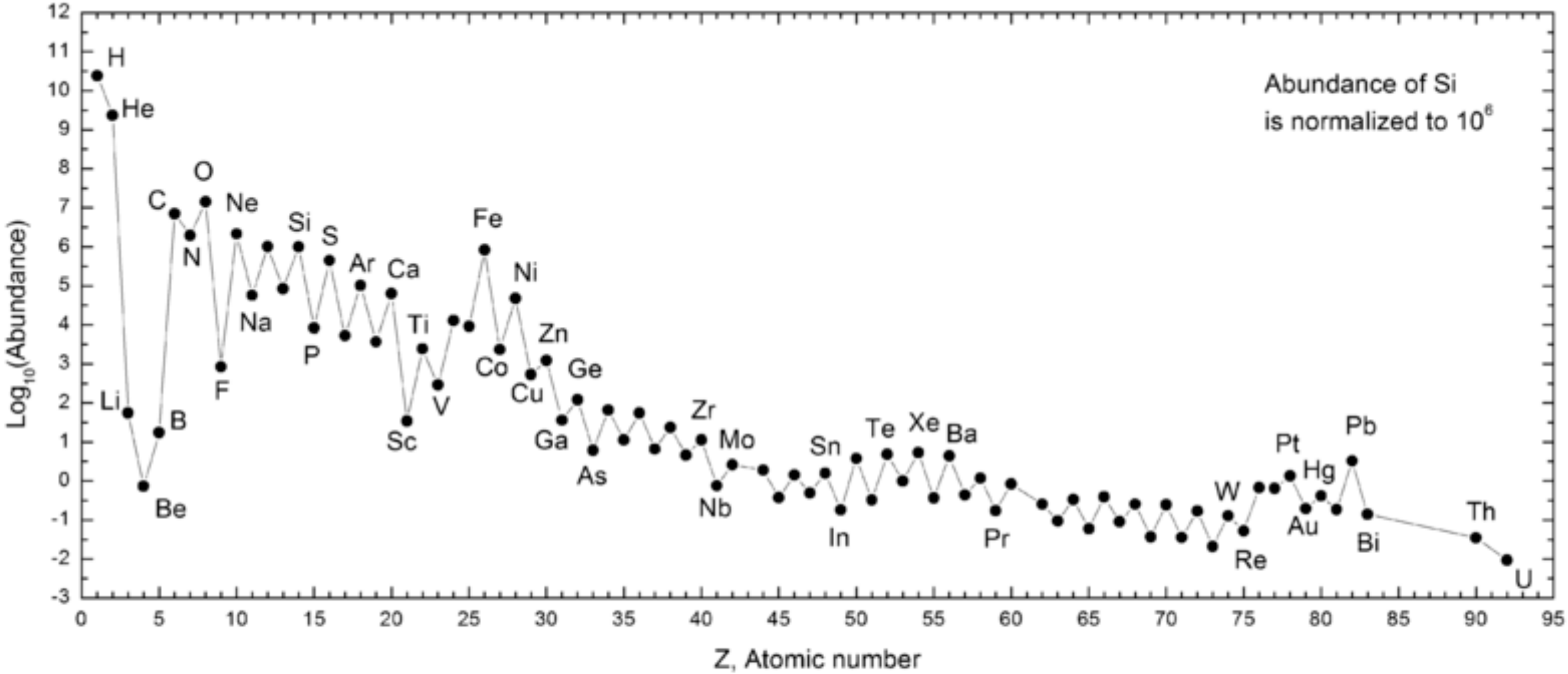
A=1-5 (H, He, Li, Be, B) mostly in Big Bang
A=6-100+ (C,N,O….) mostly in stars + SN



Where elements come from

- H, He, Li, Be, B – Big Bang
- C, N – much of this comes from stars with M~1-few M_{sun}, which eject envelopes as PN, (happens 'slow' > 1 Gyr, so IR appx not great)(some also comes from Type Ia & II SN)
- "α-elements": (O, Ne, Mg, Si, S, Ar, Ca and Ti) made by adding He (α particle) to C, O, etc; happens mostly in $M>10M_{sun}$ stars which return elements to ISM thru Type II SN (happens 'fast', >100 Myr, so IR appx OK)(Fe and other heavier elements get locked into NS or BH core)(these are "primary" elements, whose production does not depend on the presence of other heavy elements)
- "iron peak" (V, Cr, Mn, Fe, Co & Ni) made mostly in white dwarf stars which explode as Type Ia SN, no core left (happens 'slow' > 1 Gyr, so IR appx is poor)
- heavier than iron – made in low mass stars (s-process, slow neutron capture or supernovae explosions (r-process, rapid neutron capture)

Solar system elemental abundances



Solar abundances:

Hydrogen: $M_H/M_{gas} = 0.74$

Helium: $M_{He}/M_{gas} = 0.24$

heavies (Everything else): $M_h/M_{gas} = 0.02 = Z_{sun}$
("metals")

Astronomy definition of abundance ratio:

$$[A/B] \equiv \log_{10}\left\{\frac{(\text{number of A atoms}/\text{number of B atoms})_\star}{(\text{number of A atoms}/\text{number of B atoms})_\odot}\right\}$$

[Fe/H] is logarithmic ratio of Fe/H in star relative to sun

Fe is pretty good indicator of overall heavy element abundance.

Sometimes [Fe/H] represents average heavy-element abundance not just Iron.

[Fe/H] = 0 solar abundance

[Fe/H] = -1 1/10th solar abundance

[Fe/H] = -2 1/100th solar abundance

[Fe/H] = -3 1/1000th solar abundance

formation of light elements in Big Bang

Main nuclear reactions in first few minutes of Big Bang

$p + e^- \longleftrightarrow n + \nu$

$n + e^+ \longleftrightarrow p + \bar{\nu}$

<1 sec

$n \longrightarrow p + e^- + \bar{\nu}$

1-100 sec

$p + n \longleftrightarrow d + \gamma$

100-300 sec

$d + n \longrightarrow H^3 + \gamma$

$H^3 + p \longrightarrow He^4 + \gamma$

$d + p \longrightarrow He^3 + \gamma$

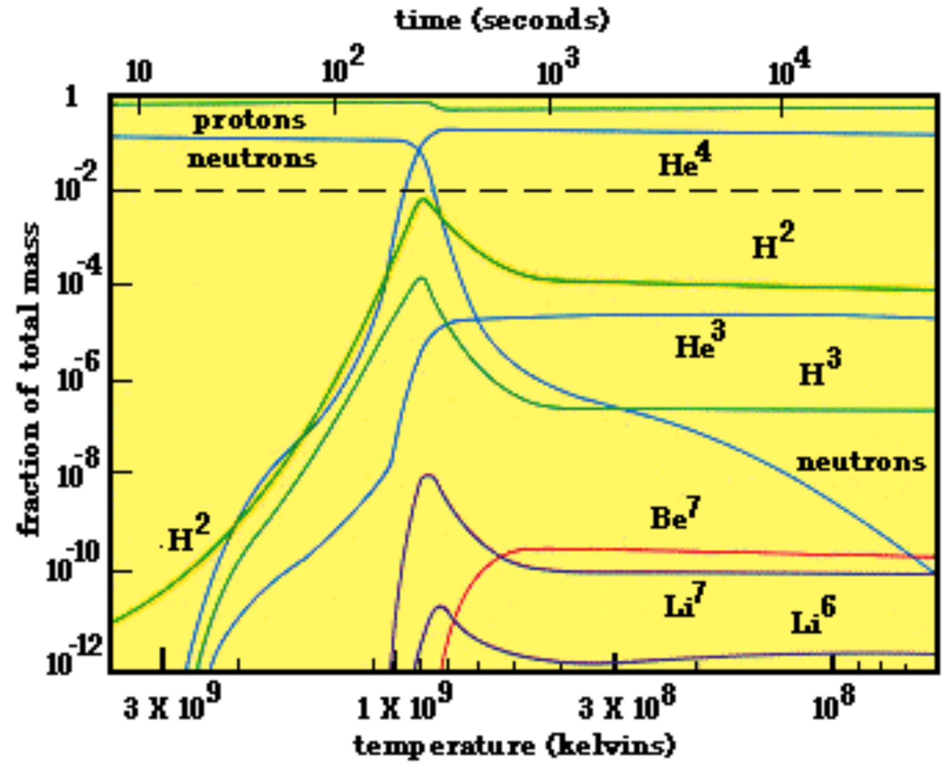
$He^3 + n \longrightarrow He^4 + \gamma$

$d + d \longrightarrow He^3 + n$

$d + d \longrightarrow H^3 + p$

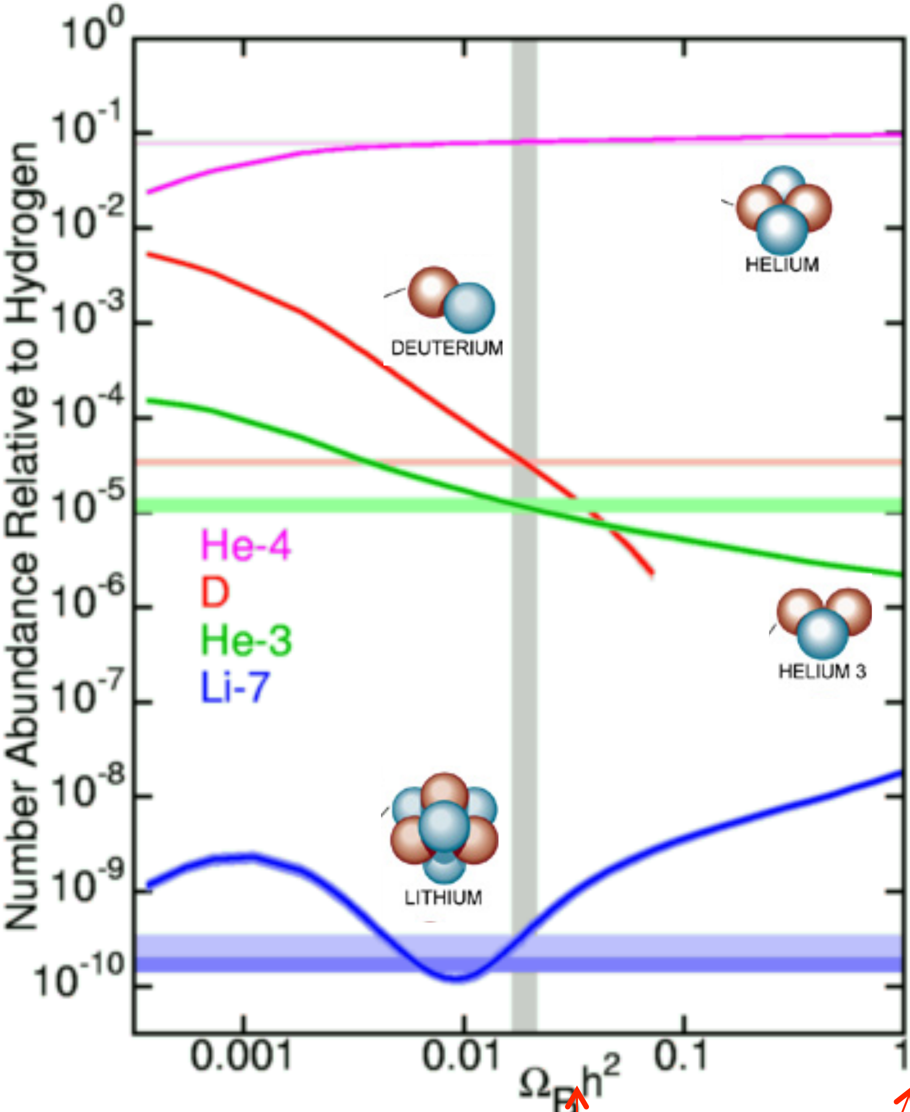
$H^3 + d \longrightarrow He^4 + n$

$He^3 + d \longrightarrow He^4 + p$



Reaction products for $\Omega_B = 0.04$

Big Bang nucleosynthesis



Predicted abundance from BB nucleosynthesis

Measured abundance

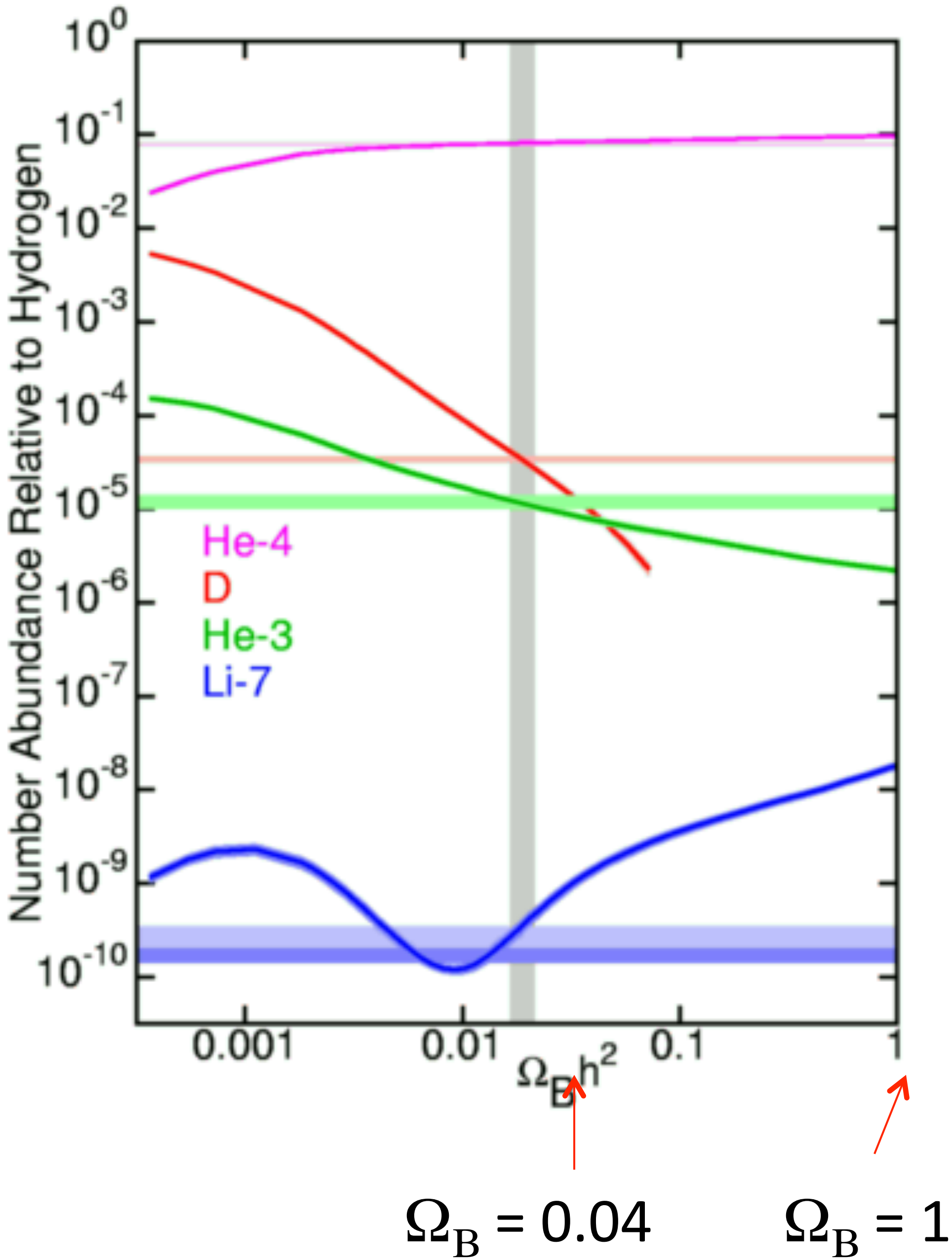
$\Omega_B = 0.04$ $\Omega_B = 1$

Q: Why do the abundances of light elements depend on the overall density of nuclei?

Q: Why do the abundances of light elements depend on the overall density of nuclei?

A: products of nuclear reactions depend on collision rate, which depends on density

Big Bang nucleosynthesis



The relative abundances of the light elements (H,He,Li,Be,B) are consistent with conditions expected in Big Bang

AND…

Provide strong evidence on the density of baryons in the universe, relative to the total mass-energy density of the universe ($\Omega_B = 0.04$)

Mass-energy content of universe

$\Omega_{Baryon} = 0.04$ (from big bang nucleosynthesis)

$\Omega_{mass} = \Omega_{Baryon} + \Omega_{dark} = 0.31$ (from dynamics of galaxy clusters, etc)

$\Omega = \Omega_{mass} + \Omega_{\Lambda=darkenergy} = 1.00$ (from CMB)

Baryons make up:

16% of mass in universe overall (0.04/0.31)

16% of mass in milky way-sized galaxies

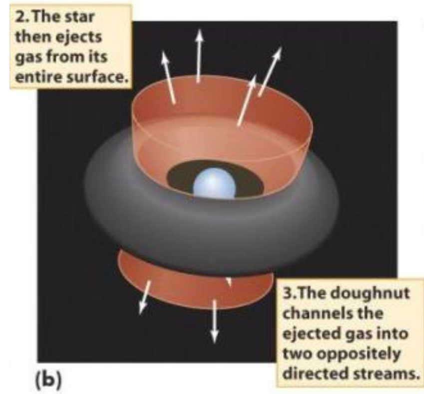
<1% of mass in small galaxies

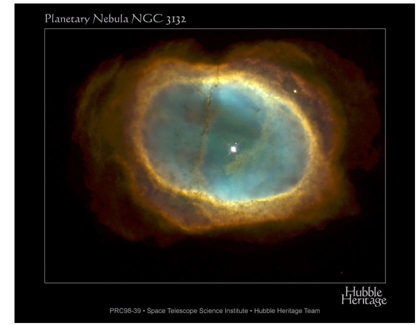
Why do small galaxies have so few baryons?

formation of heavier elements in stars and supernovae

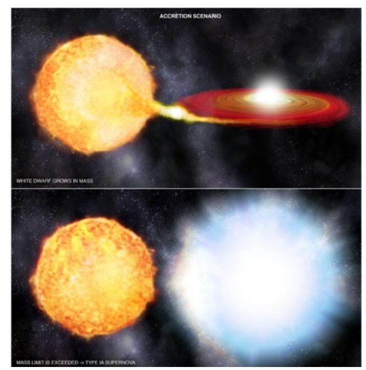
Recycling by stars back into the ISM

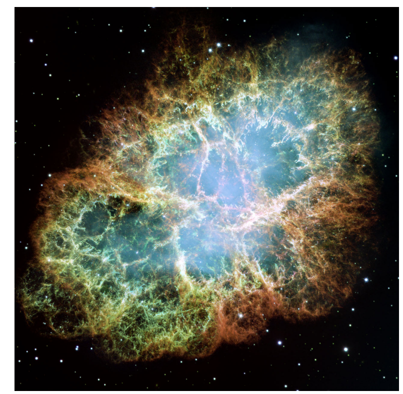
Low mass stars:
Planetary nebulae



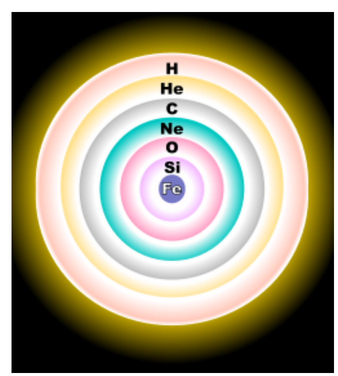


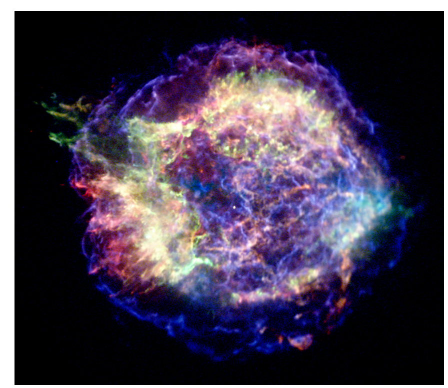
Medium mass stars in binaries:
Type Ia Supernovae



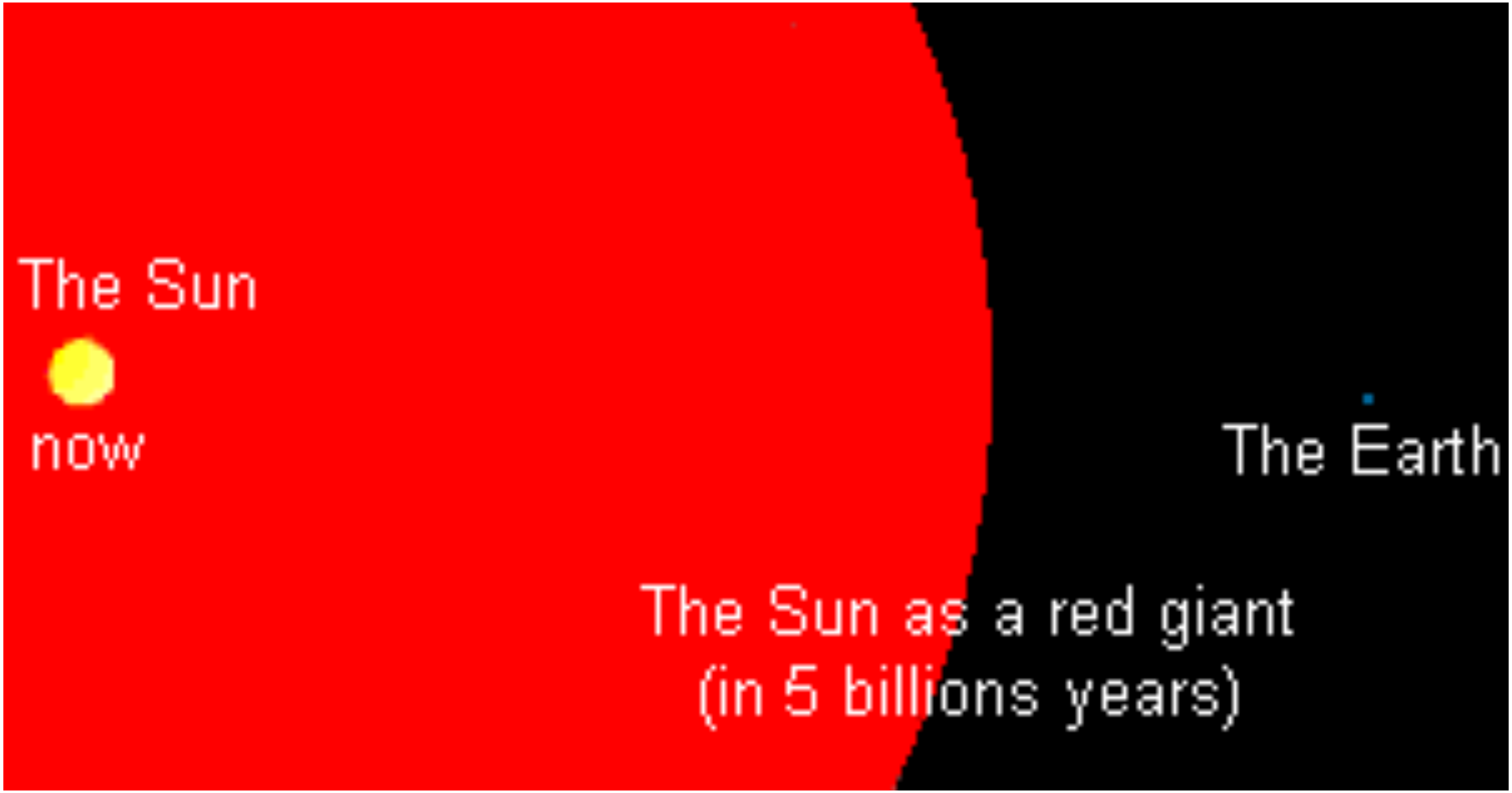


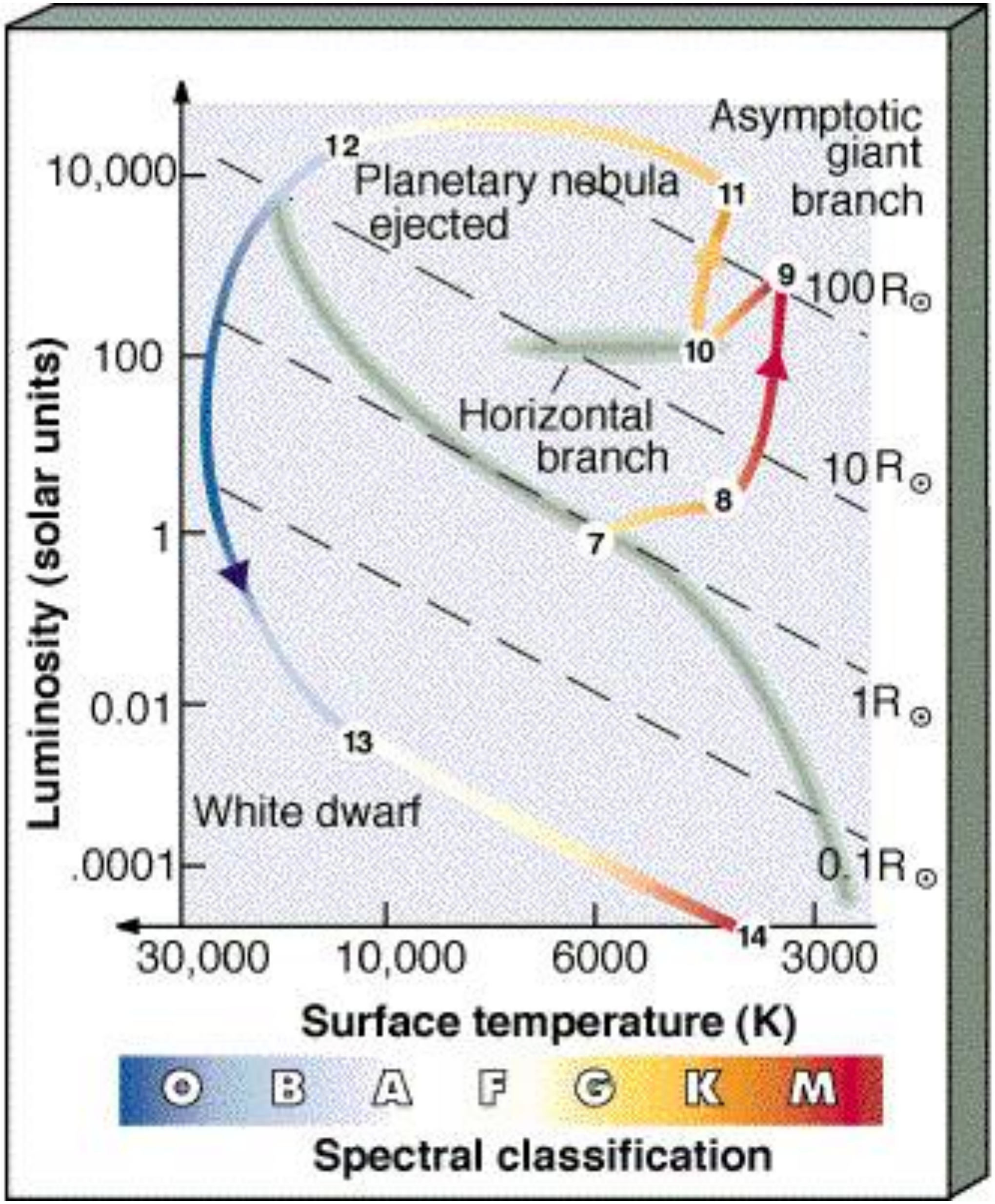
High mass stars:
Type II Supernovae





Evolution of low mass stars ($M<8M_{sun}$)

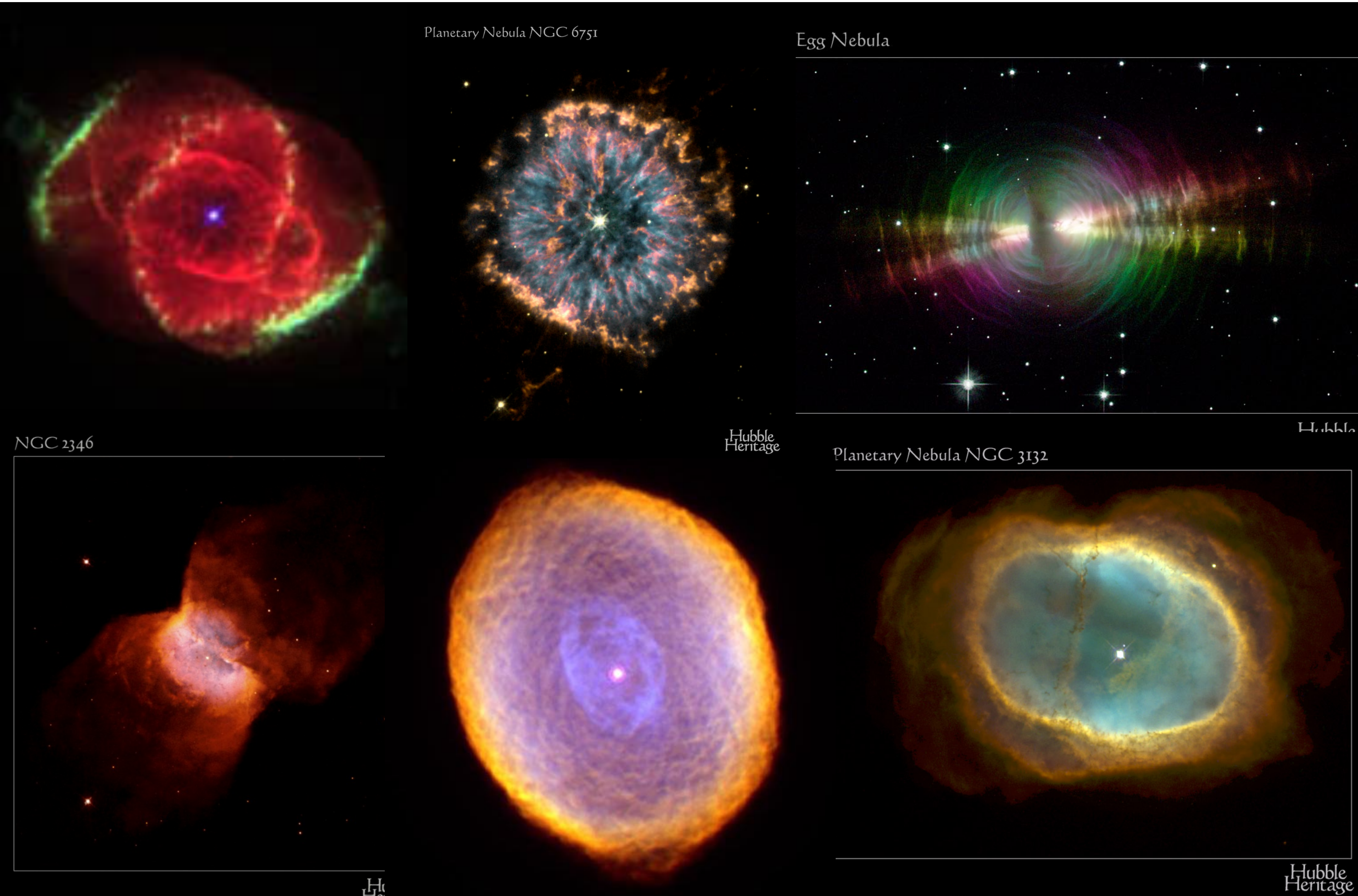




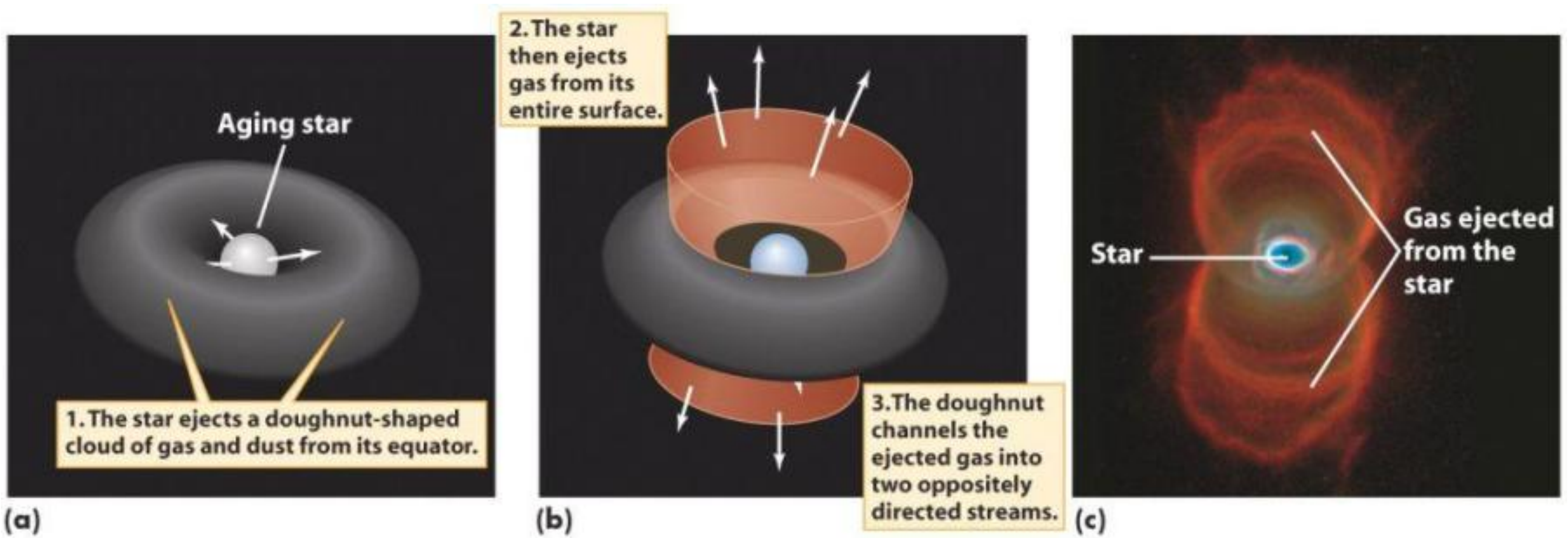
Low mass stars ($M<8M_{sun}$)

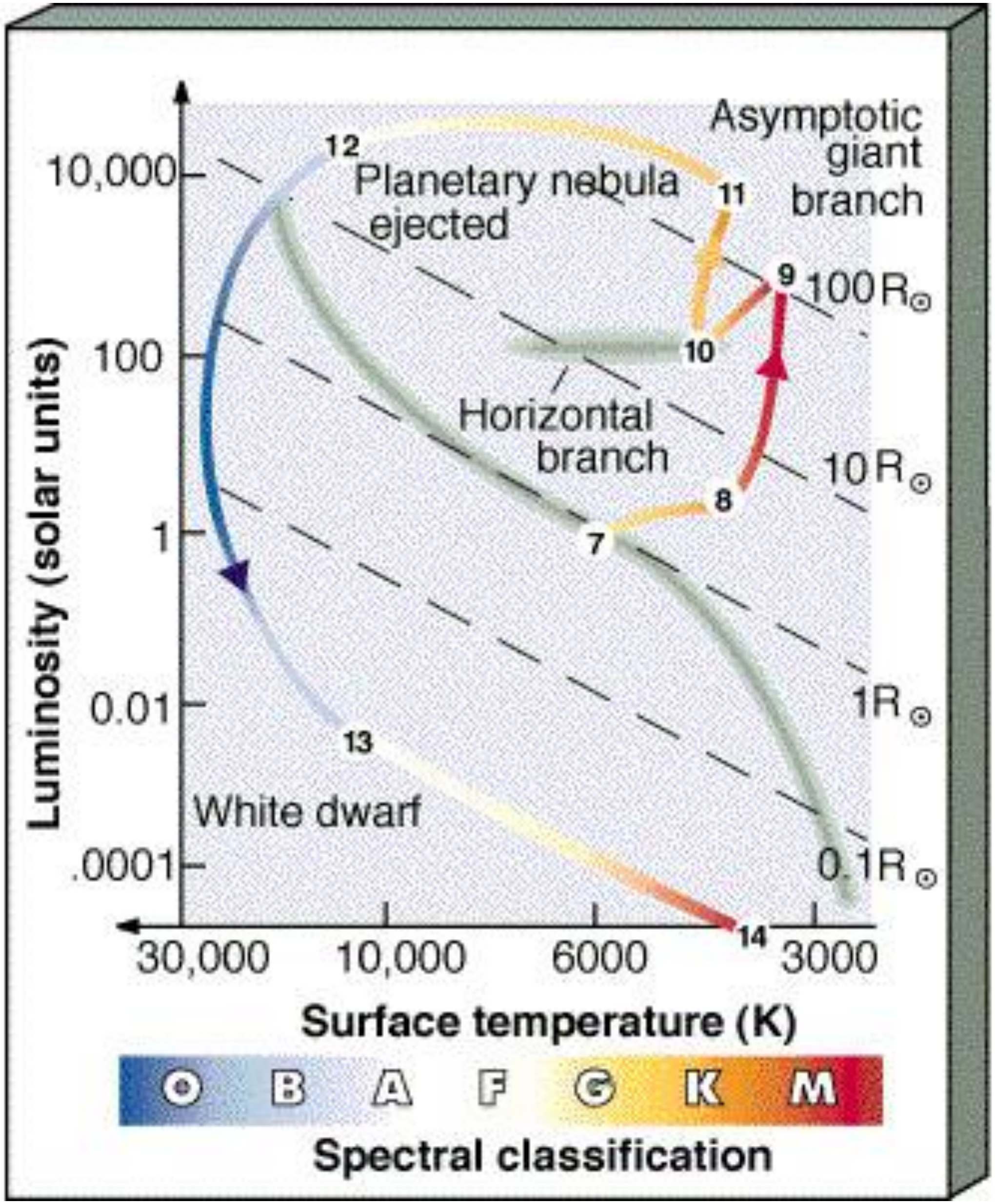
- At end of red giant phase of life, outer envelope of star ejected into space

Variety of Planetary Nebulae



Formation of planetary nebula

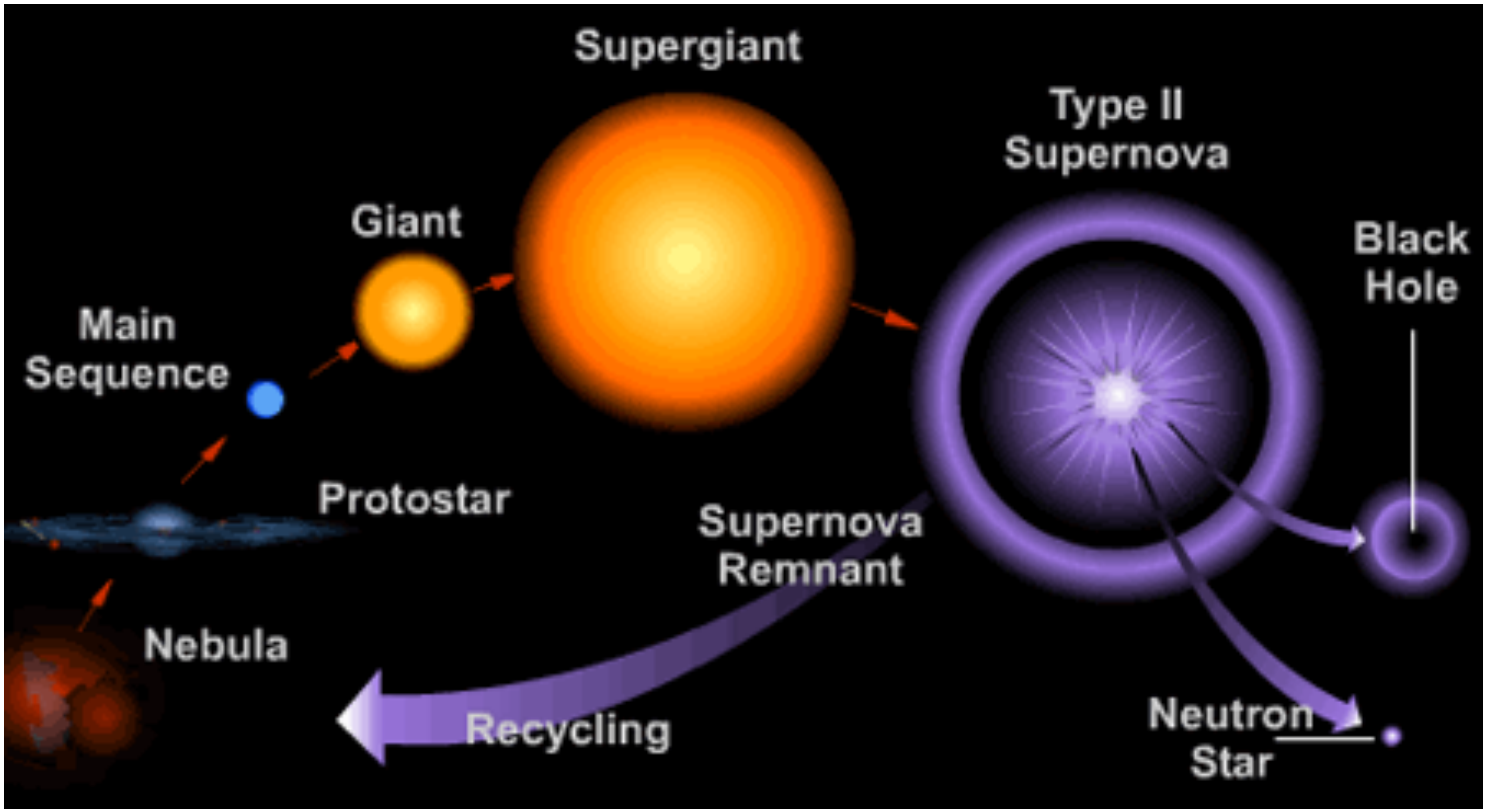




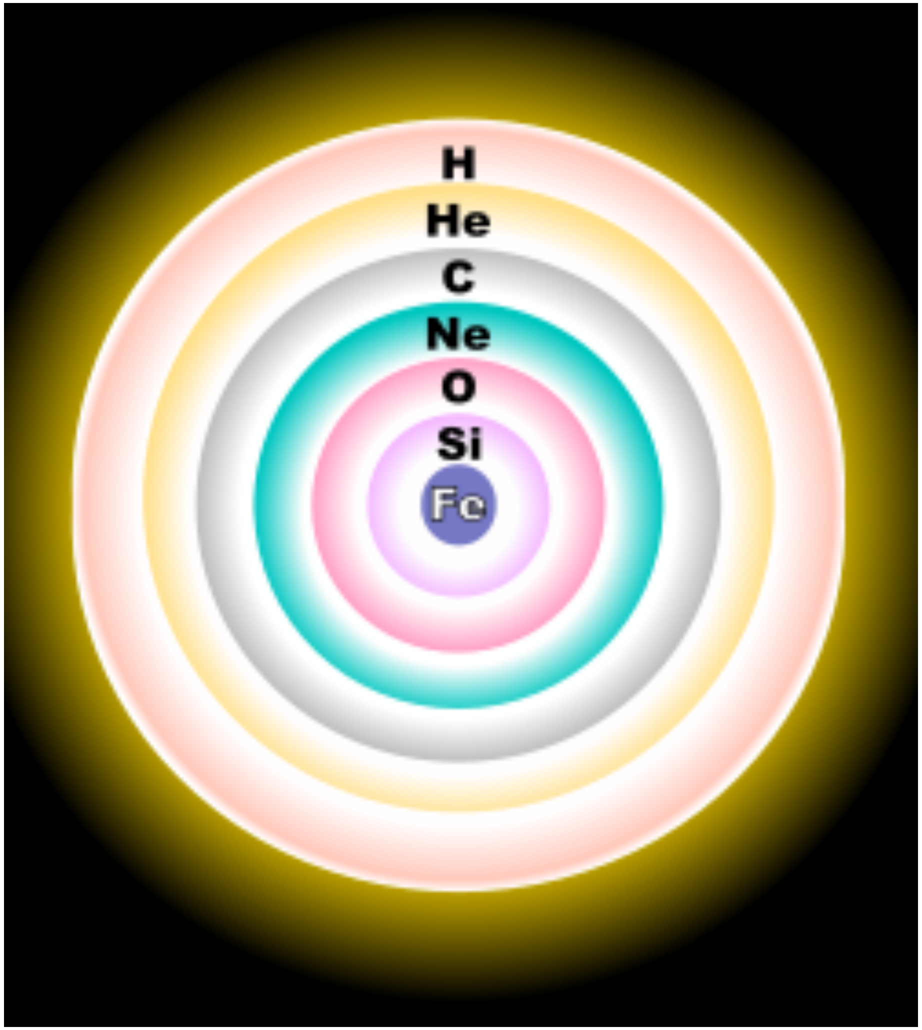
Low mass stars ($M<8M_{sun}$)

- At end of red giant phase of life, outer envelope of star ejected into space
- Injects elements H, He, C, N, O into ISM – including elements C, N, O made by fusion in star's interior

Massive stars ($M > 8M_{sun}$) explode as Type II Supernovae



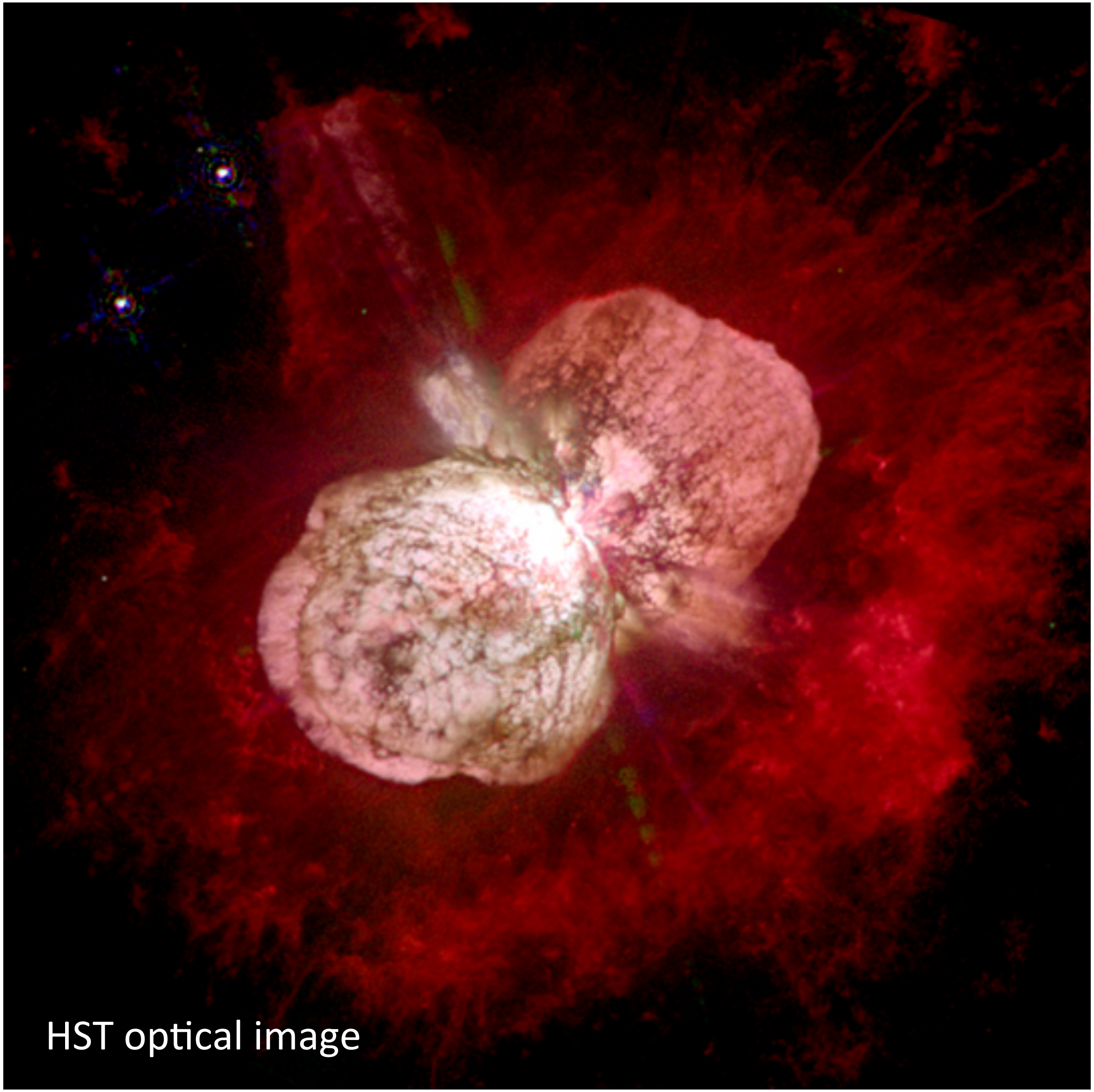
Structure of massive star before Type II Supernova explosion



- "α-elements" (O, Ne, Mg, Si, S, Ar, Ca and Ti) made by adding He (α particle) to C, O, etc; happens mostly in $M>10M_{sun}$ stars which return elements to ISM thru Type II SN

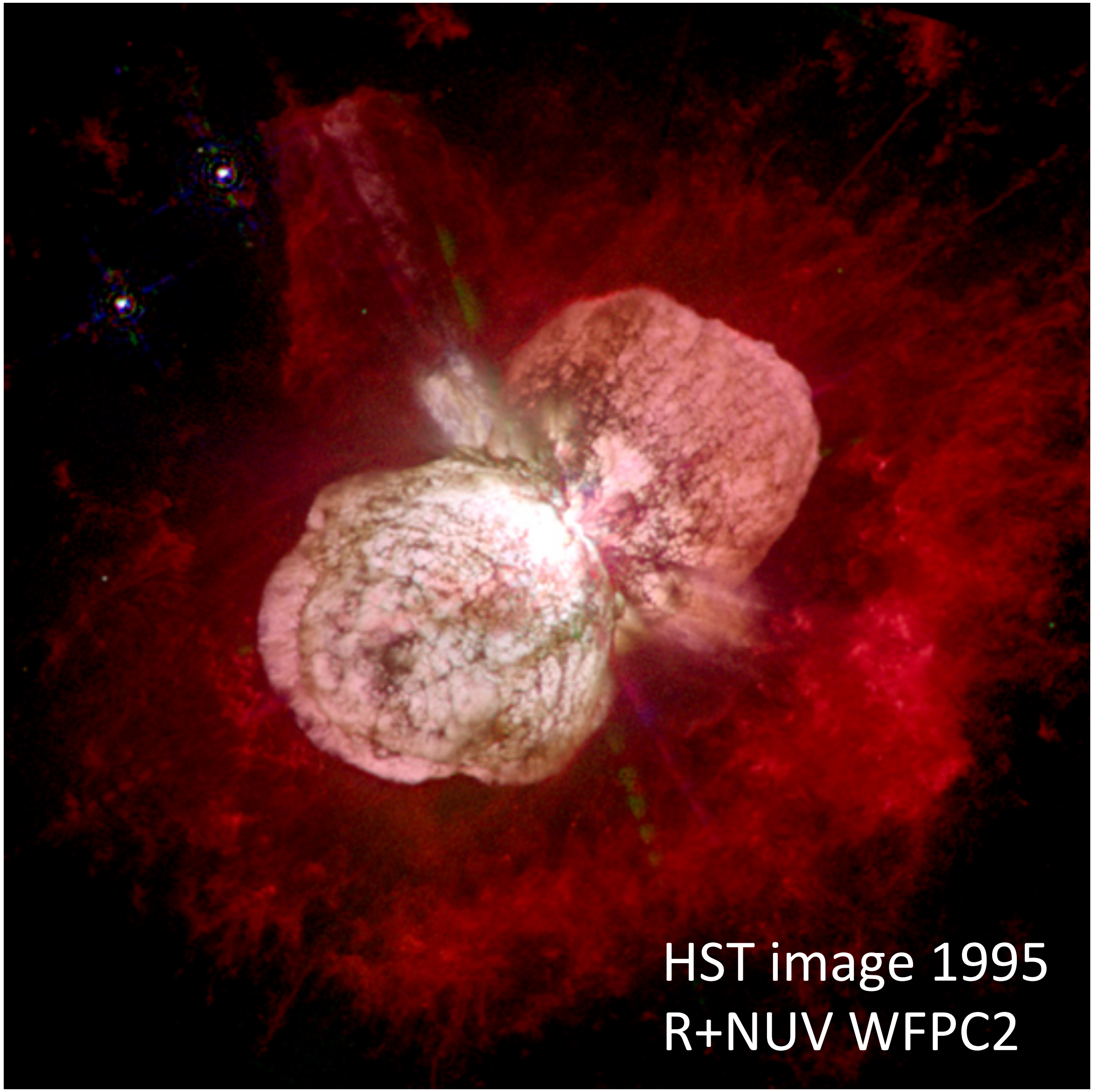
- Fe and other heavier elements made in core of star *during normal stellar evolution* get locked into NS or BH core

Q: Why does fusion of heavier elements occur in more massive stars?



Eta Carina

Massive star ($\sim$100 M_{sun}) ejecting outer layers into ISM (before supernova stage)



Eta Carina

Massive star (~100 M_{sun}) ejecting outer layers into ISM
before supernova stage

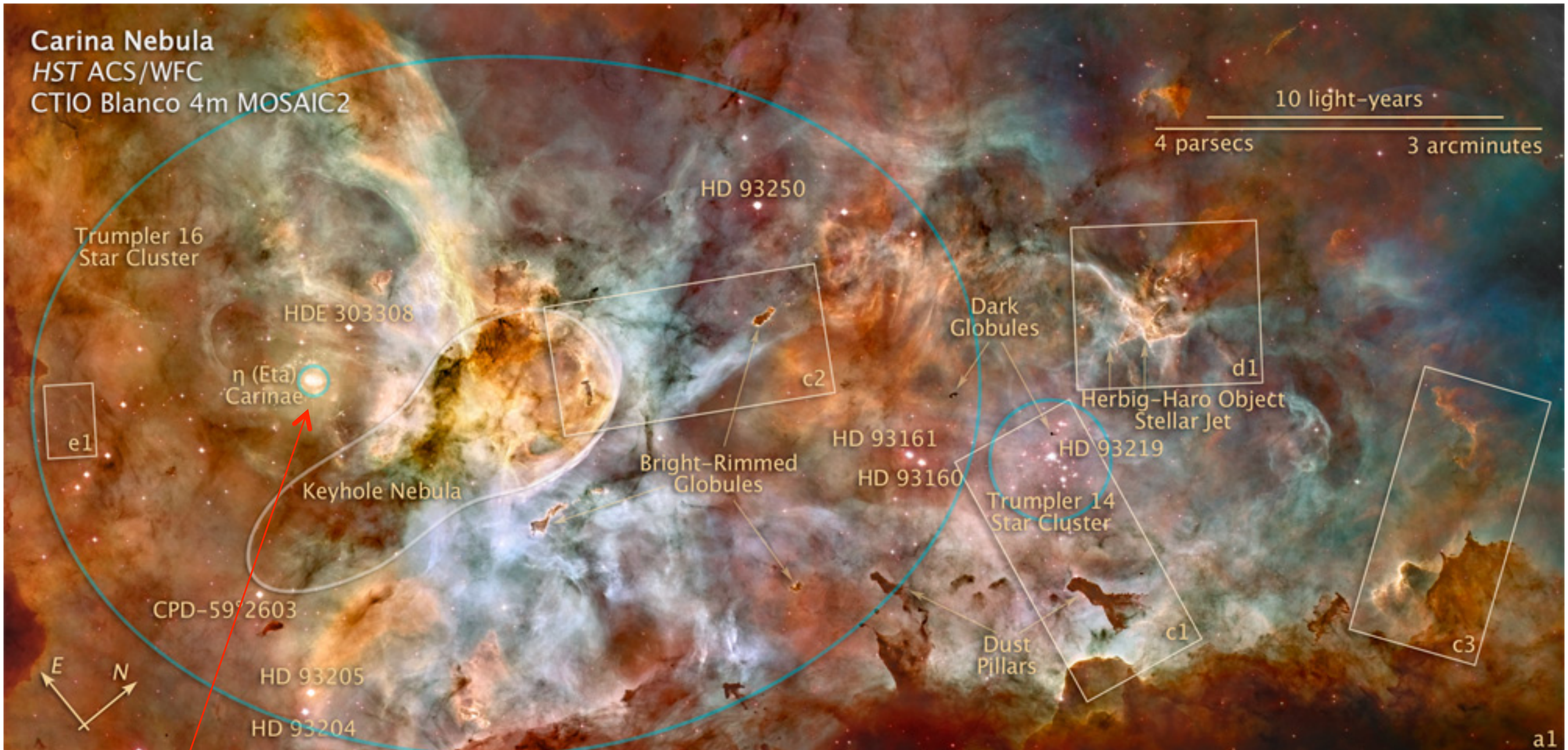
outburst in 1840s ejected 20 M_{sun} of material in dusty bipolar outflow

the Eta Carina story

(NASA News Release) A huge, billowing pair of gas and dust clouds are captured in this stunning NASA Hubble Space Telescope image of the supermassive star Eta Carinae. Using a combination of image processing techniques (dithering, subsampling and deconvolution), astronomers created one of the highest resolution images of an extended object ever produced by Hubble Space Telescope. The resulting picture reveals astonishing detail. Even though Eta Carinae is more than 8,000 light-years away, structures only 10 billion miles across (about the diameter of our solar system) can be distinguished. Dust lanes, tiny condensations, and strange radial streaks all appear with unprecedented clarity. Eta Carinae was observed by Hubble in September 1995 with the Wide Field Planetary Camera 2 (WFPC2). Images taken through red and near-ultraviolet filters were subsequently combined to produce the color image shown. A sequence of eight exposures was necessary to cover the object's huge dynamic range: the outer ejecta blobs are 100,000 times fainter than the brilliant central star. Eta Carinae was the site of a giant outburst about 150 years ago, when it became one of the brightest stars in the southern sky. Though the star released as much visible light as a supernova explosion, it survived the outburst. Somehow, the explosion produced two polar lobes and a large thin equatorial disk, all moving outward at about 1.5 million miles per hour. The new observation shows that excess violet light escapes along the equatorial plane between the bipolar lobes. Apparently there is relatively little dusty debris between the lobes down by the star; most of the blue light is able to escape. The lobes, on the other hand, contain large amounts of dust which preferentially absorb blue light, causing the lobes to appear reddish. Estimated to be 100 times more massive than our Sun, Eta Carinae may be one of the most massive stars in our Galaxy. It radiates about five million times more power than our Sun. The star remains one of the great mysteries of stellar astronomy, and the new Hubble images raise further puzzles. Eventually, this star's outburst may provide unique clues to other, more modest stellar bipolar explosions and to hydrodynamic flows from stars in general.

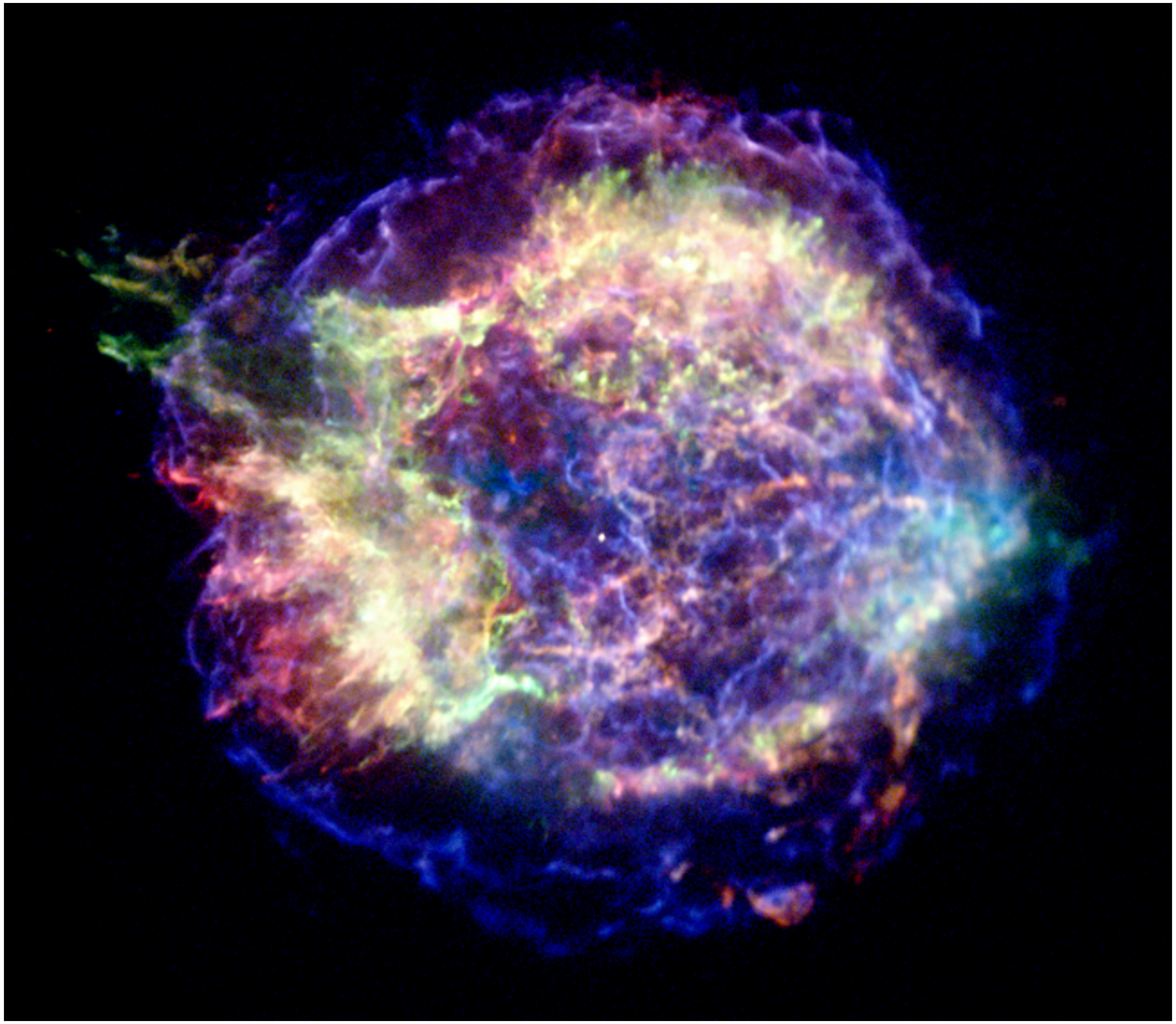
Jon Morse (University of Colorado) & NASA Hubble Space Telescope - Hubble Site

Carina star-forming region



Eta Carina

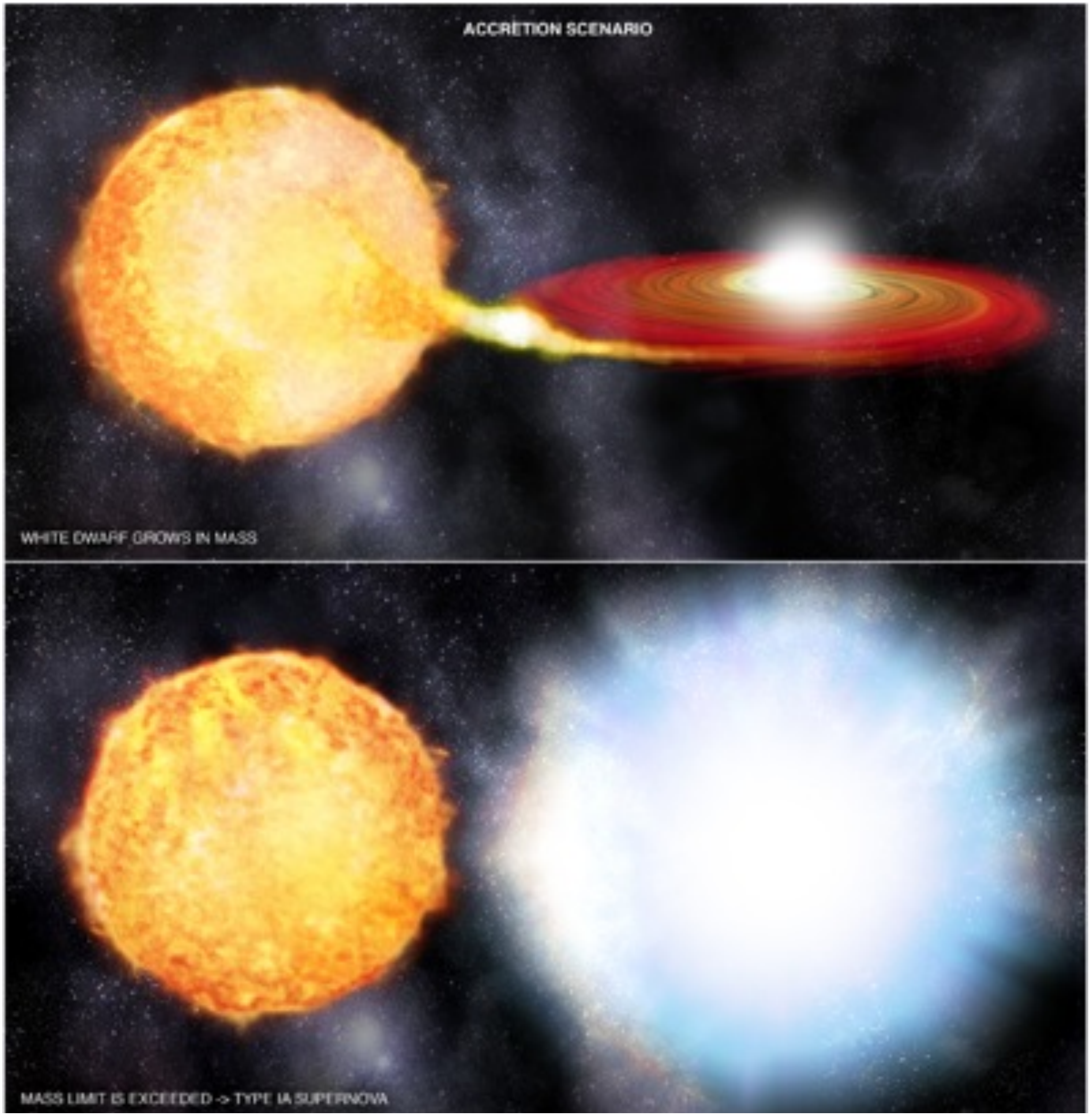
Cassiopeia A Supernova Remnant from Type II supernova in 1680 A.D.



X-Ray image from Chandra telescope

Red & Yellow: low energy x-rays from debris of star

Blue: high energy x-rays from blast wave – high energy electrons



Type Ia Supernova

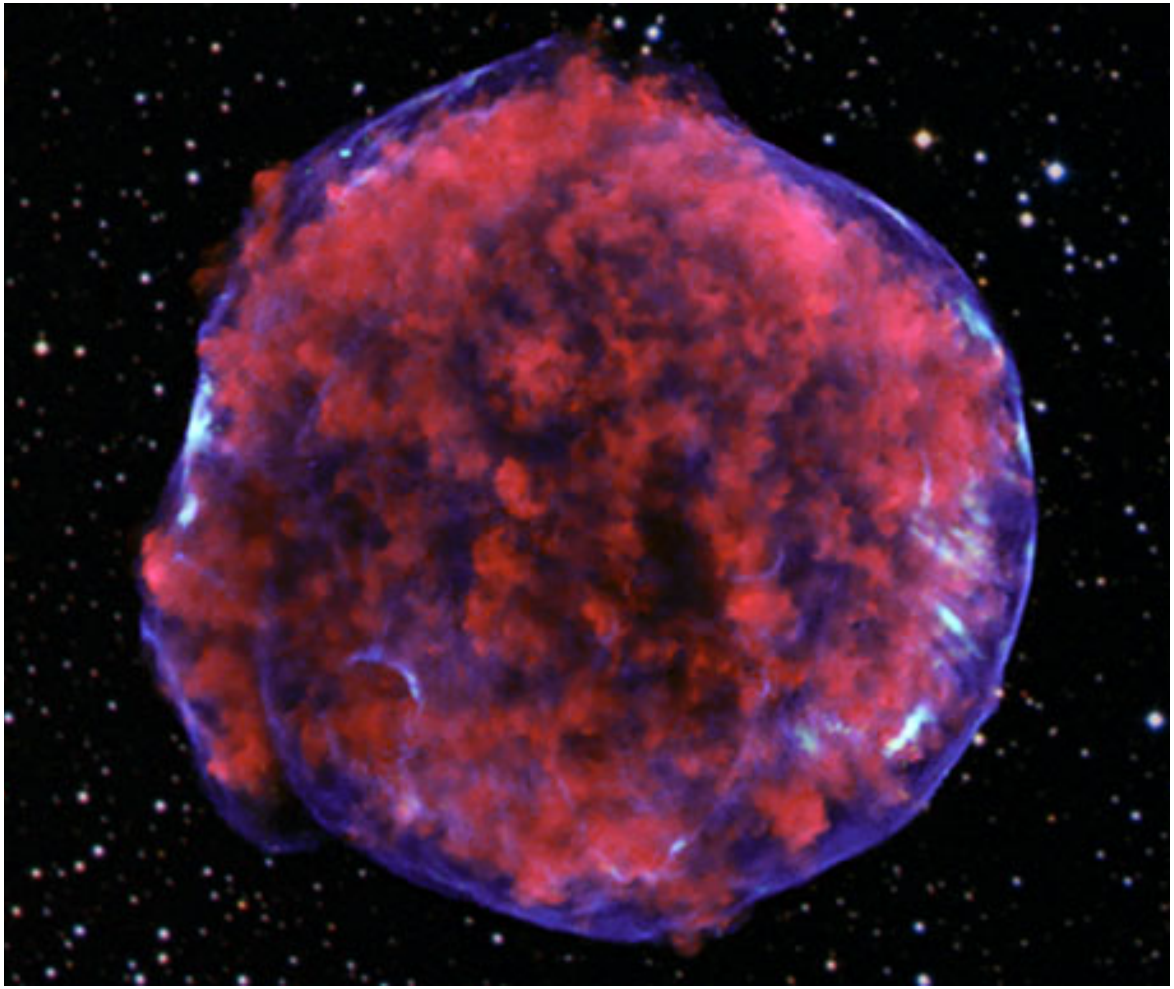
(from intermediate mass stars M ~ 3-8M_{sun})

White dwarf in binary pair accretes mass from companion, causing it to explode as supernova *if its mass exceeds "Chandrasekhar limit"*

Entire star explodes (probably?), returning elements to ISM

Most of Mn, Fe, Co, Ni in ISM come from Type Ia SN

Tycho's Supernova Remnant
from Type Ia Supernova in 1572 A.D.



X-Ray image from Chandra telescope

Red: low energy x-rays from debris of star

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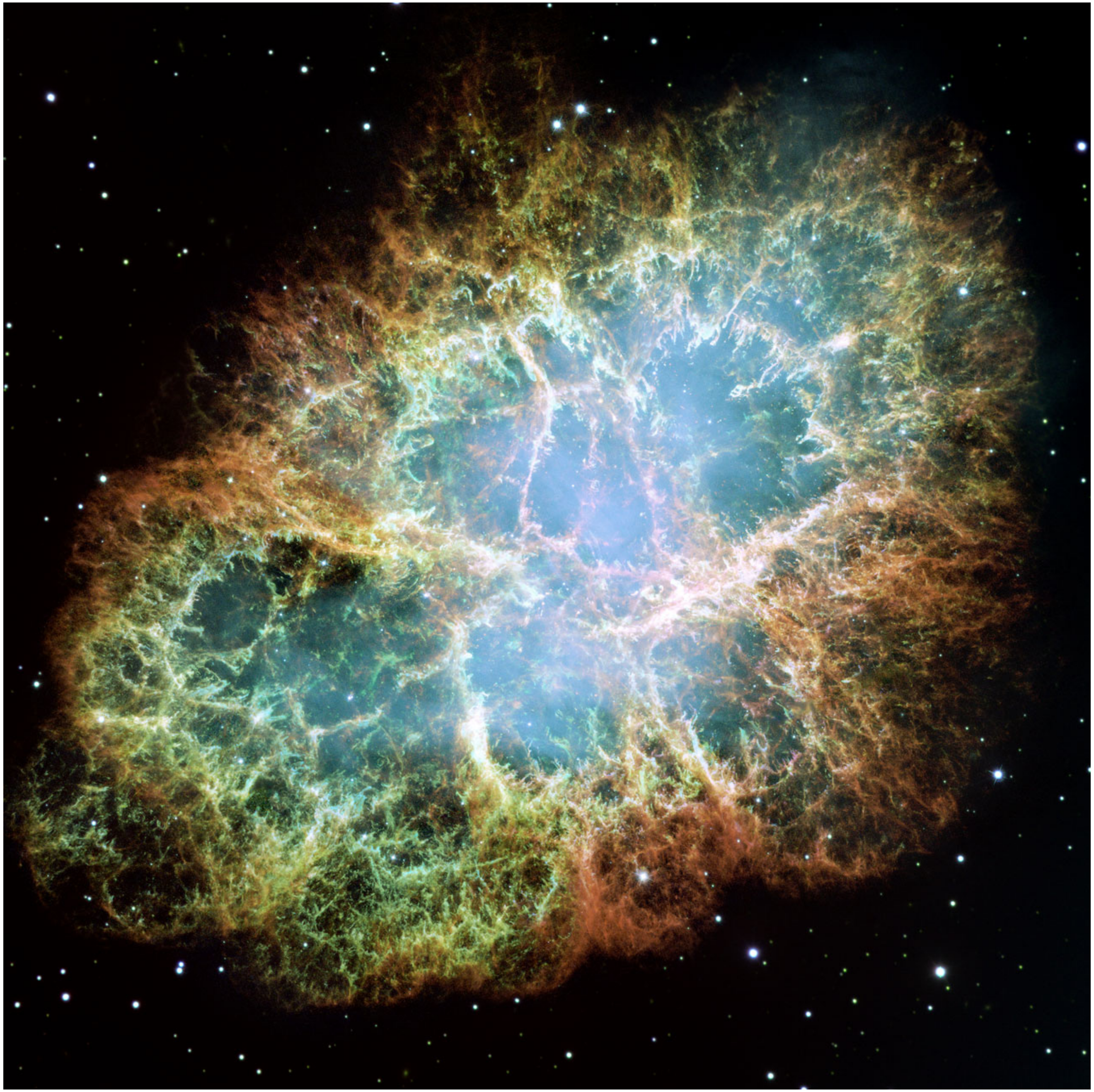
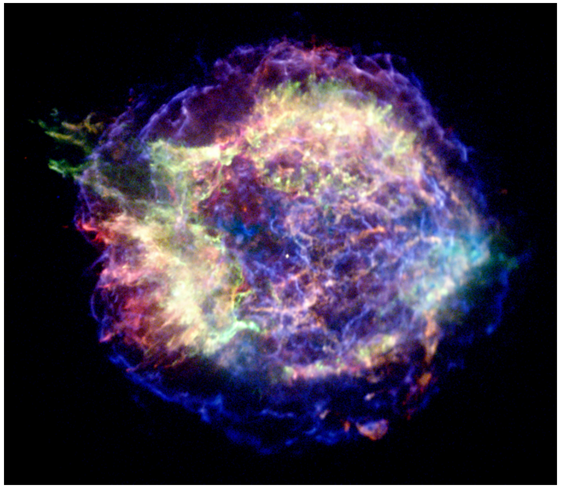


Crab Nebula Supernova Remnant

produced by Type Ia supernova explosion in 1054 A.D.

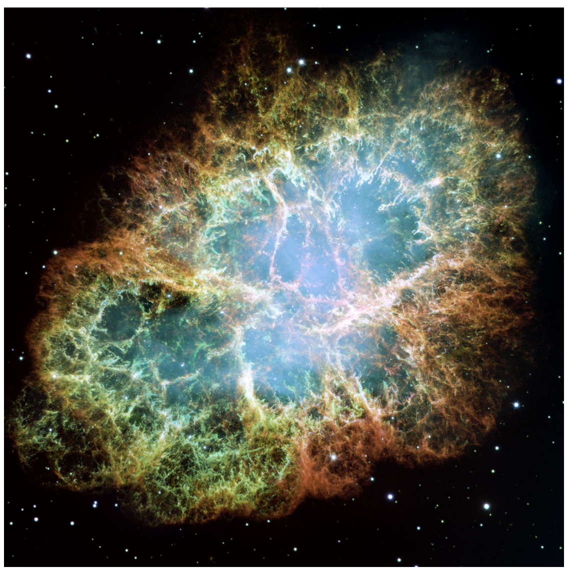
Supernova explosions (both Type Ia and II) produce elements heavier than Fe



Cas A SNR

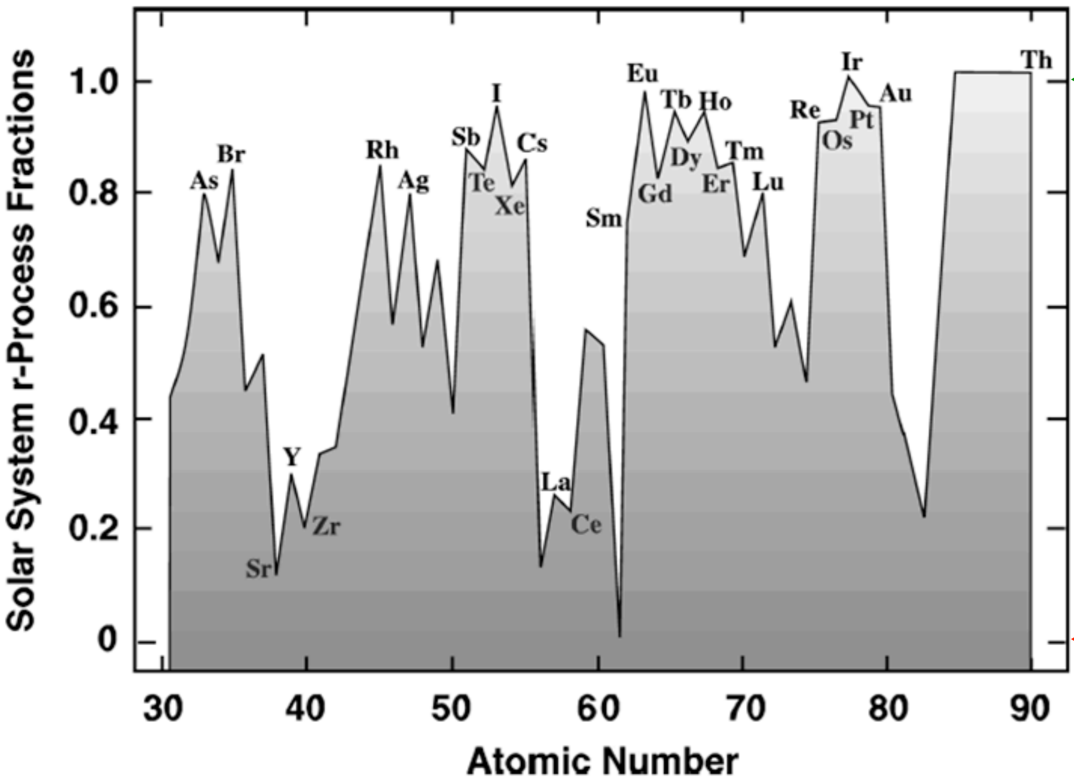
(Type II SN 1680 A.D.)

some of the elements heavier than Fe are made by fusion in violent supernova explosion, and injected to ISM (some are also made in normal stars)



Crab Nebula SNR
(Type Ia SN 1054 A.D.)

elements heavier than Iron



Fraction of solar system abundances manufactured in the r-process: from Wallerstein et al. (1997, Reviews of Modern Physics, 69, 995)

all r-process
(rapid neutron capture)
happens in supernovae
& neutron star mergers

all s-process
(slow neutron capture)
happens in normal stars

Supernovae return to ISM:

1. Elements made during normal stellar evolution are released to ISM via explosion

2. New elements are made in the SN explosion

Q: What is special about iron?

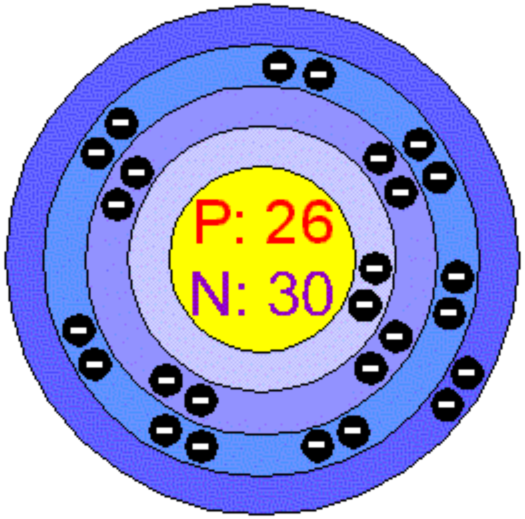
"Iron is the ultimate slag heap of the universe."

Frank Shu, real astronomer

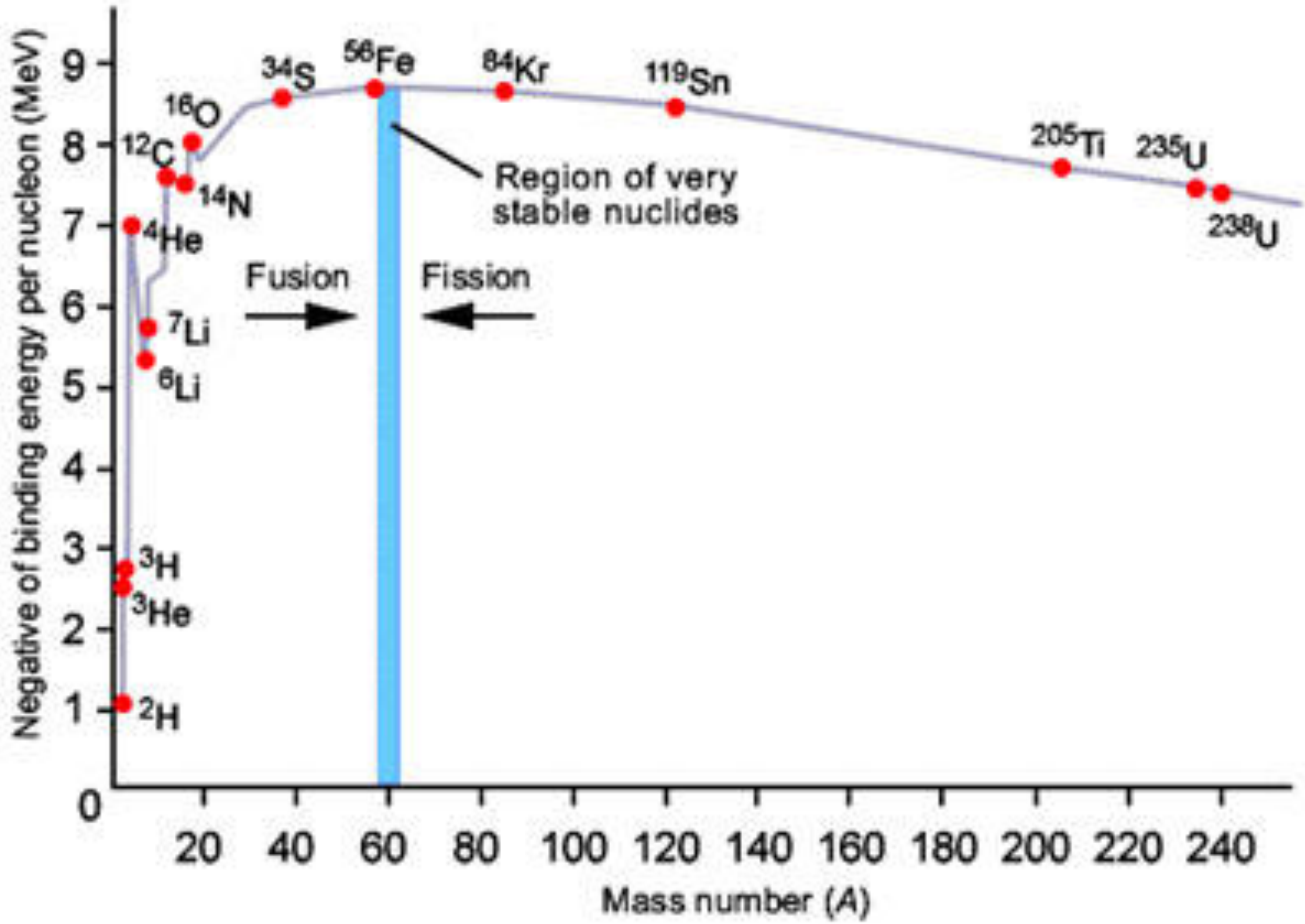
Iron ^{56}Fe 26 protons, 30 neutrons

- The most strongly bound nucleus!

- Nuclear reactions involving Fe *require energy* rather than *release energy*



Iron is the most tightly bound nucleus



For elements **lighter than** Fe:

Elem 1 + Elem 2 → (bigger) Elem 3 + energy

Lighter than Fe | Lighter than Fe | Lighter than Fe

Energy released by fusion!

For elements **lighter than** Fe:

Elem 1 + Elem 2 → (bigger) Elem 3 + energy

Lighter than Fe	Lighter than Fe	Lighter than Fe

Energy released by fusion!

For elements **heavier than** Fe:

Elem 4 + Elem 5 +energy → (bigger) Elem 6

Fe or heavier   anything

Energy *required for* fusion!

For elements **lighter than** Fe:

Elem 1 + Elem 2 → (bigger) Elem 3 + energy

Lighter than Fe | Lighter than Fe | Lighter than Fe

Happens in stars! Energy released by fusion!

For elements **heavier than** Fe:

Elem 4 + Elem 5 +energy → (bigger) Elem 6

Fe or heavier | anything

Happens in supernovae! Energy *required for* fusion!