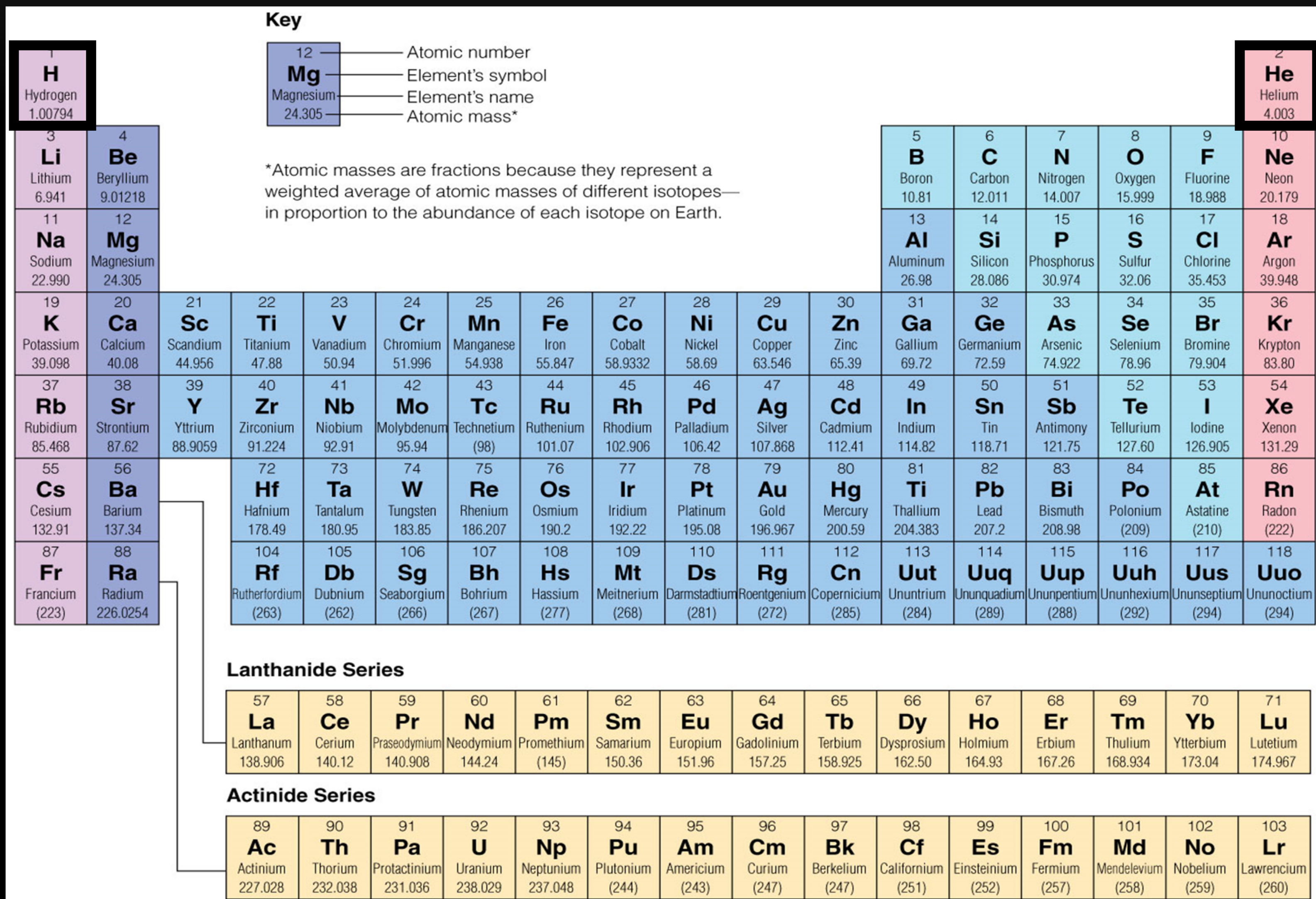
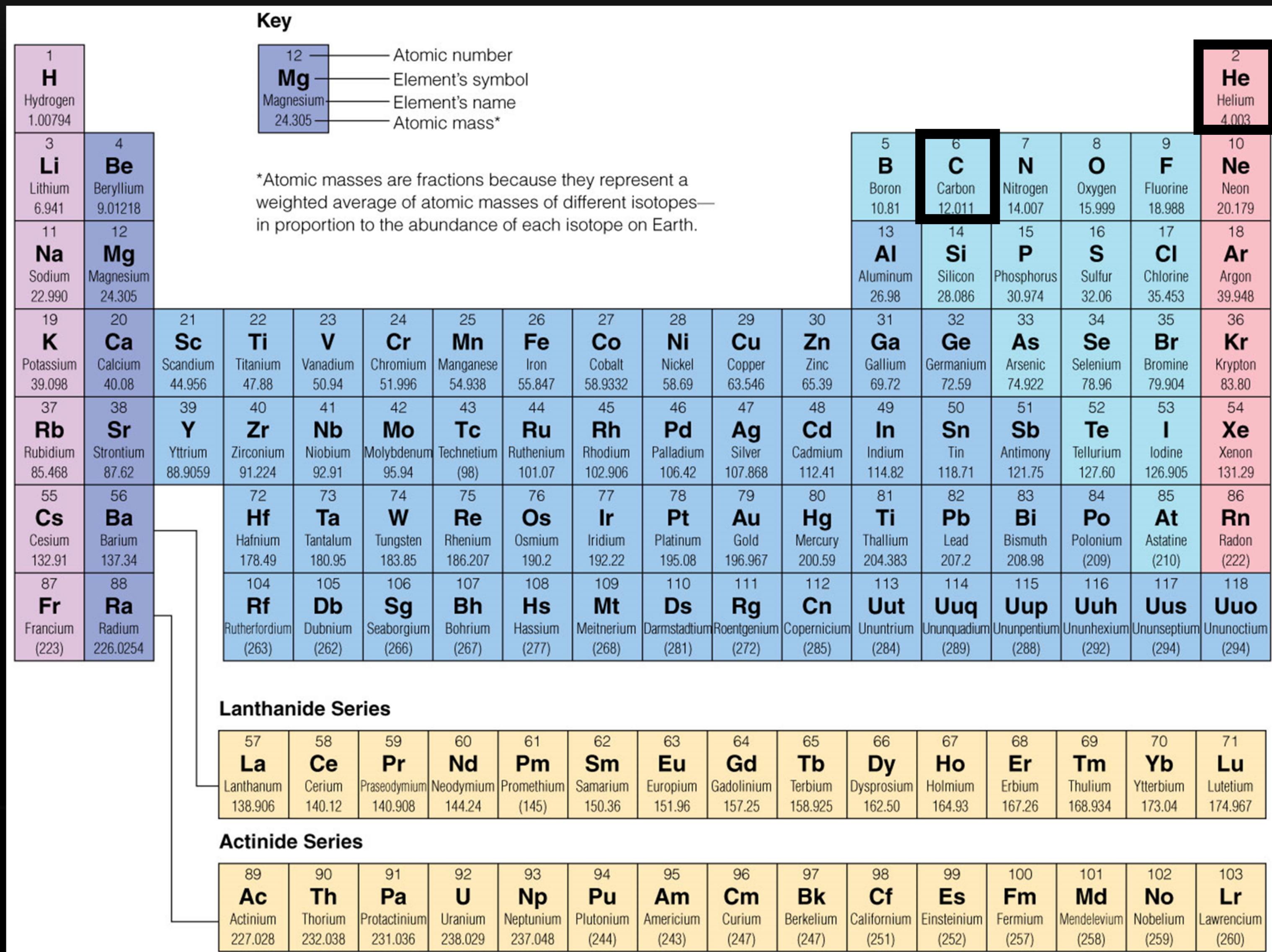
LIFE STAGES OF HIGH-MASS STARS

- Late life stages of high-mass stars are similar to those of low-mass stars:
  - Hydrogen core fusion (main sequence)
  - Hydrogen shell fusion (giant)
  - Helium core fusion (horizontal branch)
  - Double-shell burning (supergiant)
- … only they're more massive, so everything happens faster

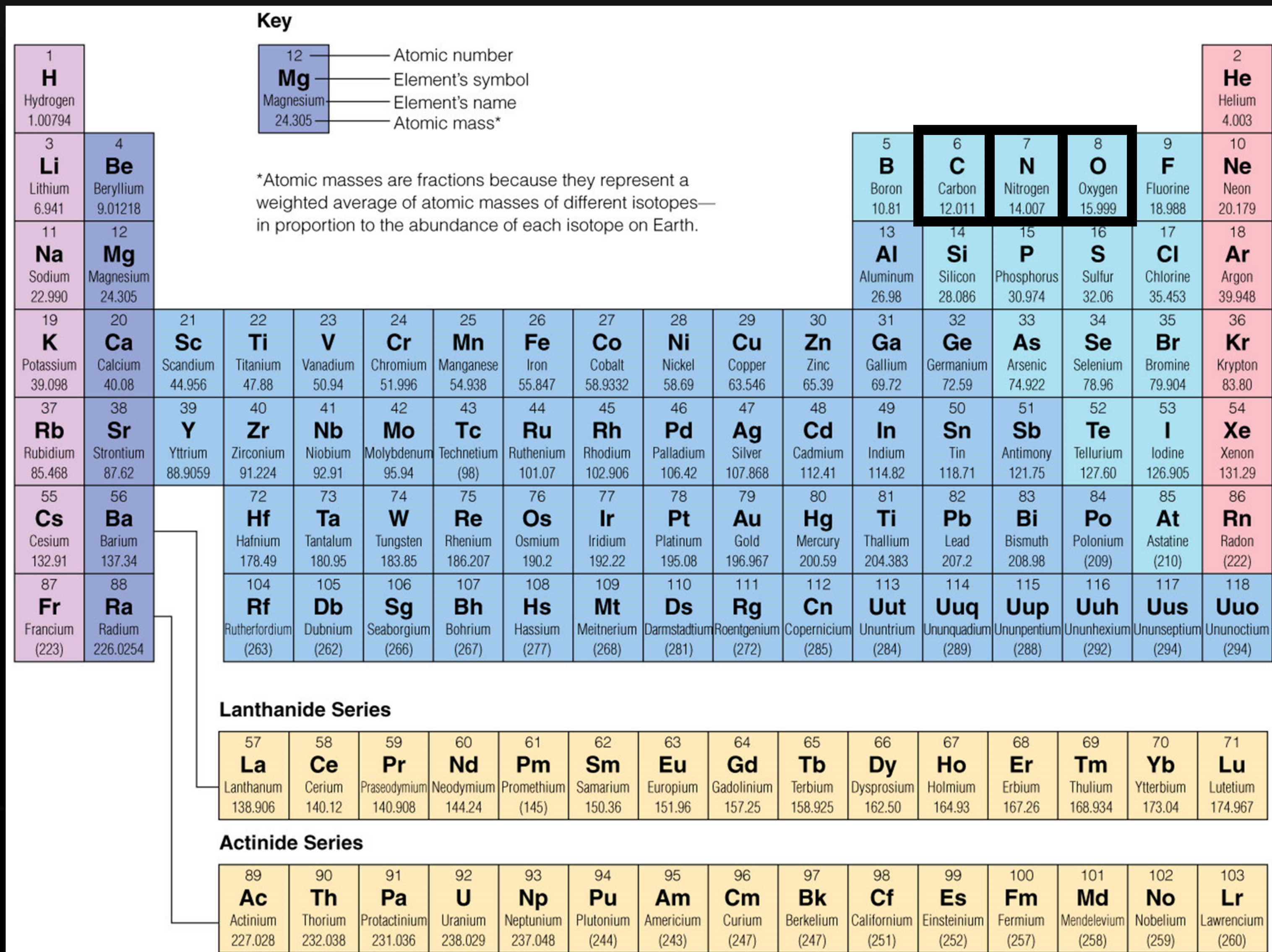
BIG BANG MADE 75% H, 25% HE—STARS MAKE EVERYTHING ELSE.



HELIUM FUSION CAN MAKE CARBON IN LOW-MASS STARS.



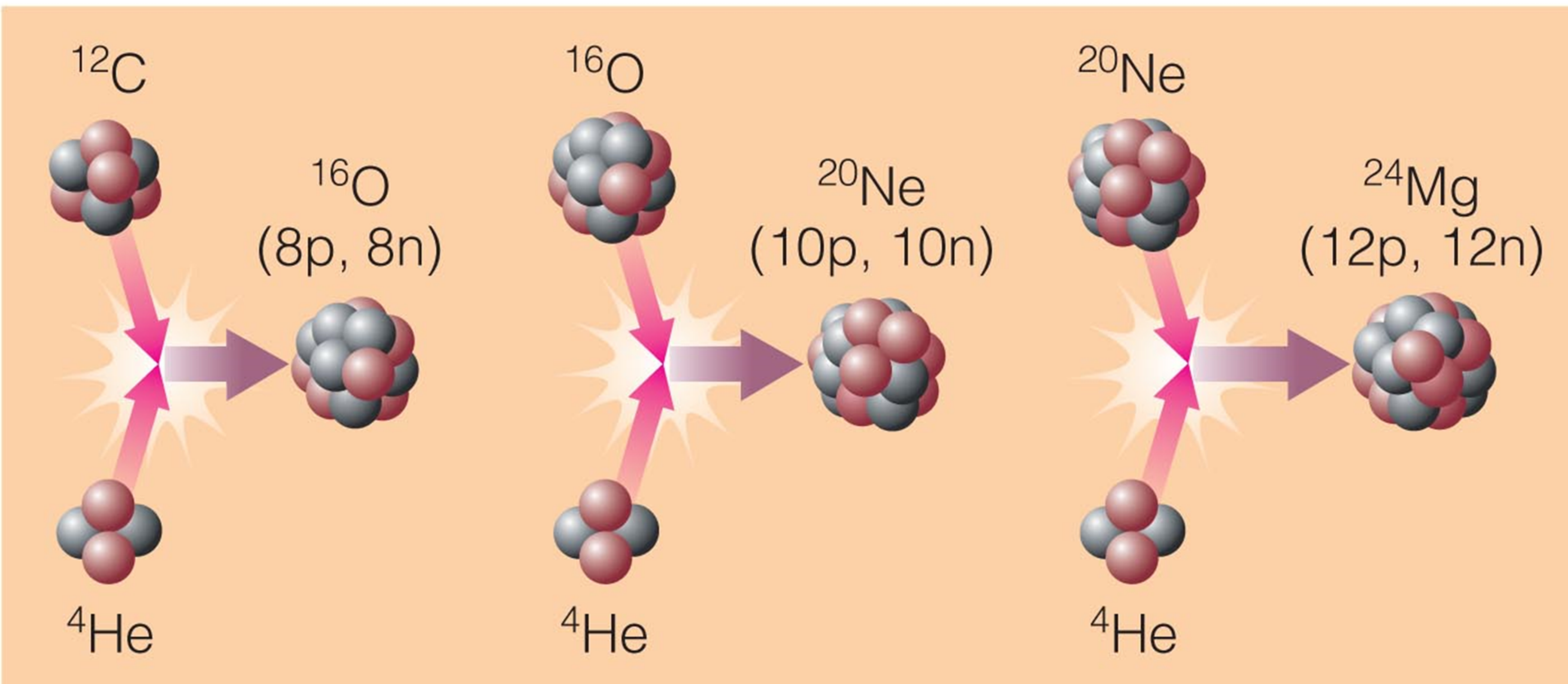
THE CNO CYCLE CAN CHANGE C INTO N AND O



BIGGER STARS, MORE GRAVITY, MORE PRESSURE, HOTTER, DENSER…

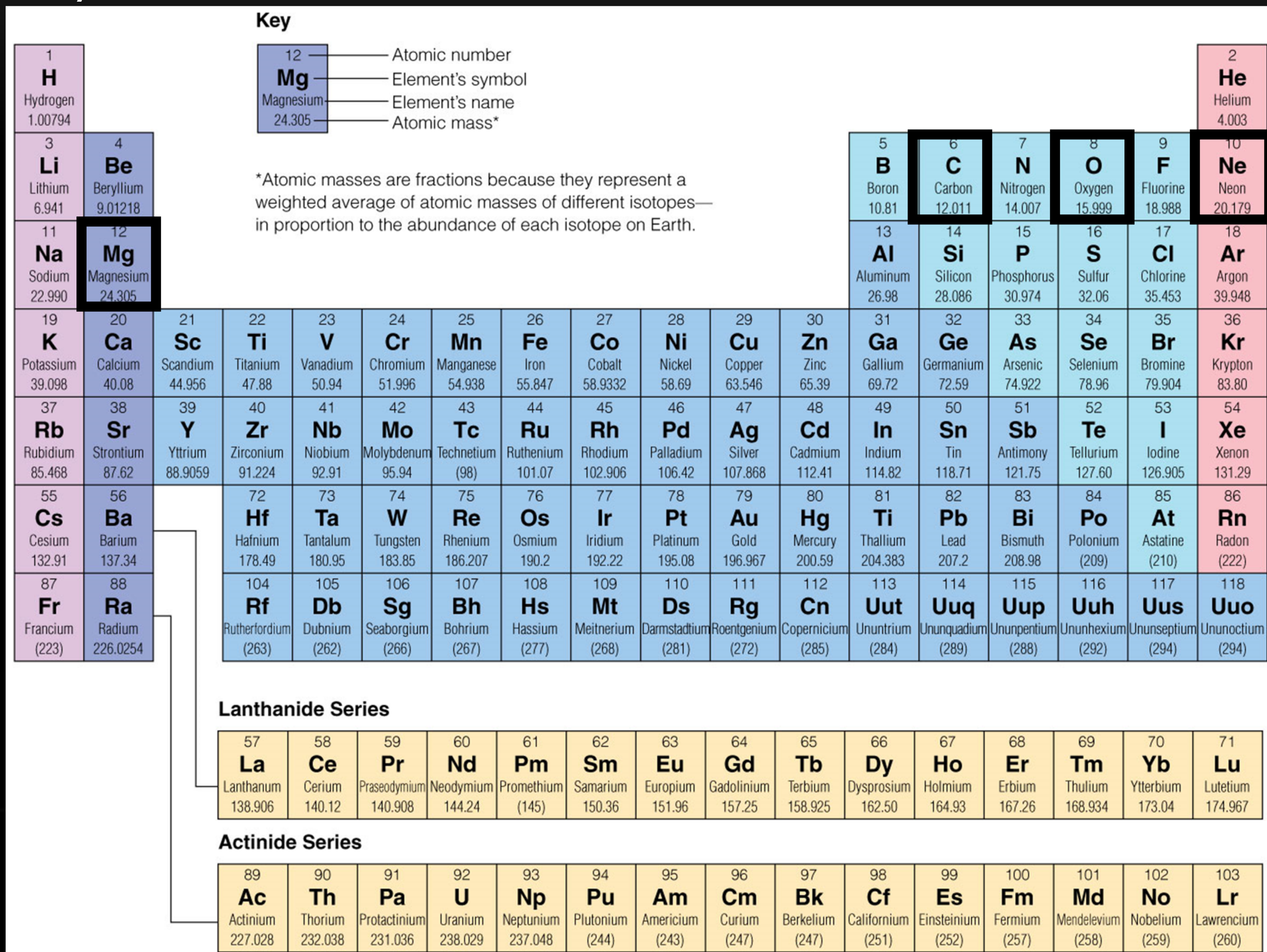
- Can squash together bigger, more repulsive things

Fig.13.16a



a Helium-capture reactions.

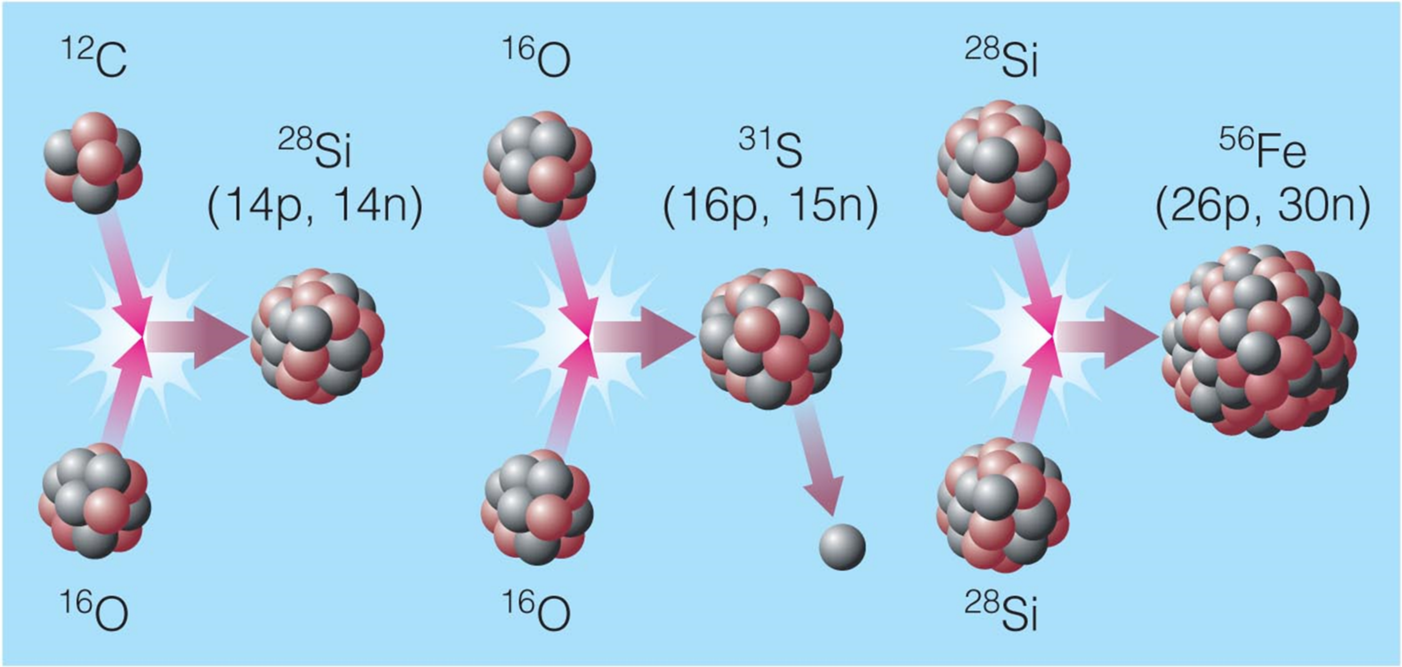
HELIUM CAPTURE BUILDS C INTO O, NE, MG …



BIGGER STARS, MORE GRAVITY, MORE PRESSURE, HOTTER, DENSER…

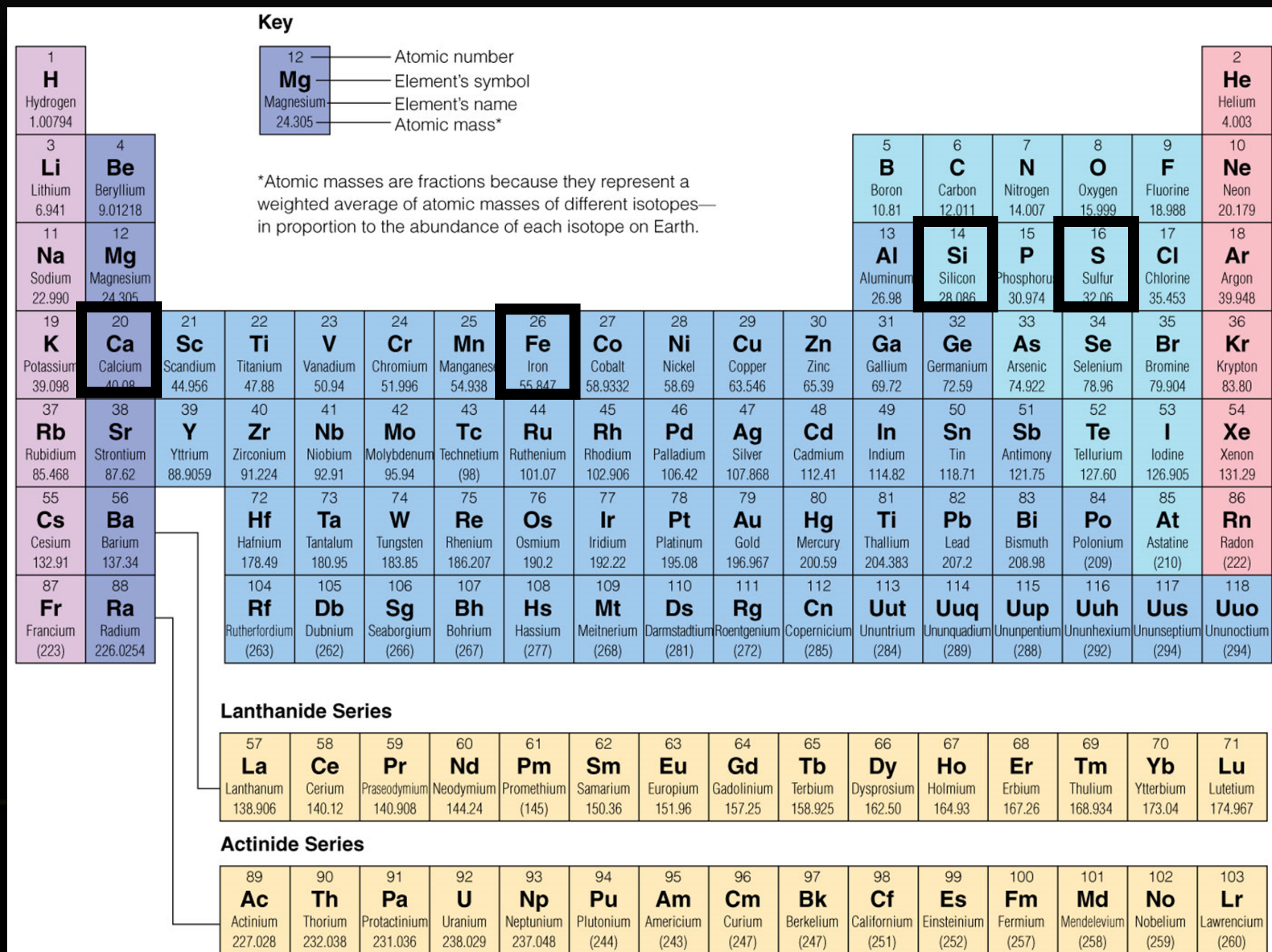
- Can squash together bigger, more repulsive things

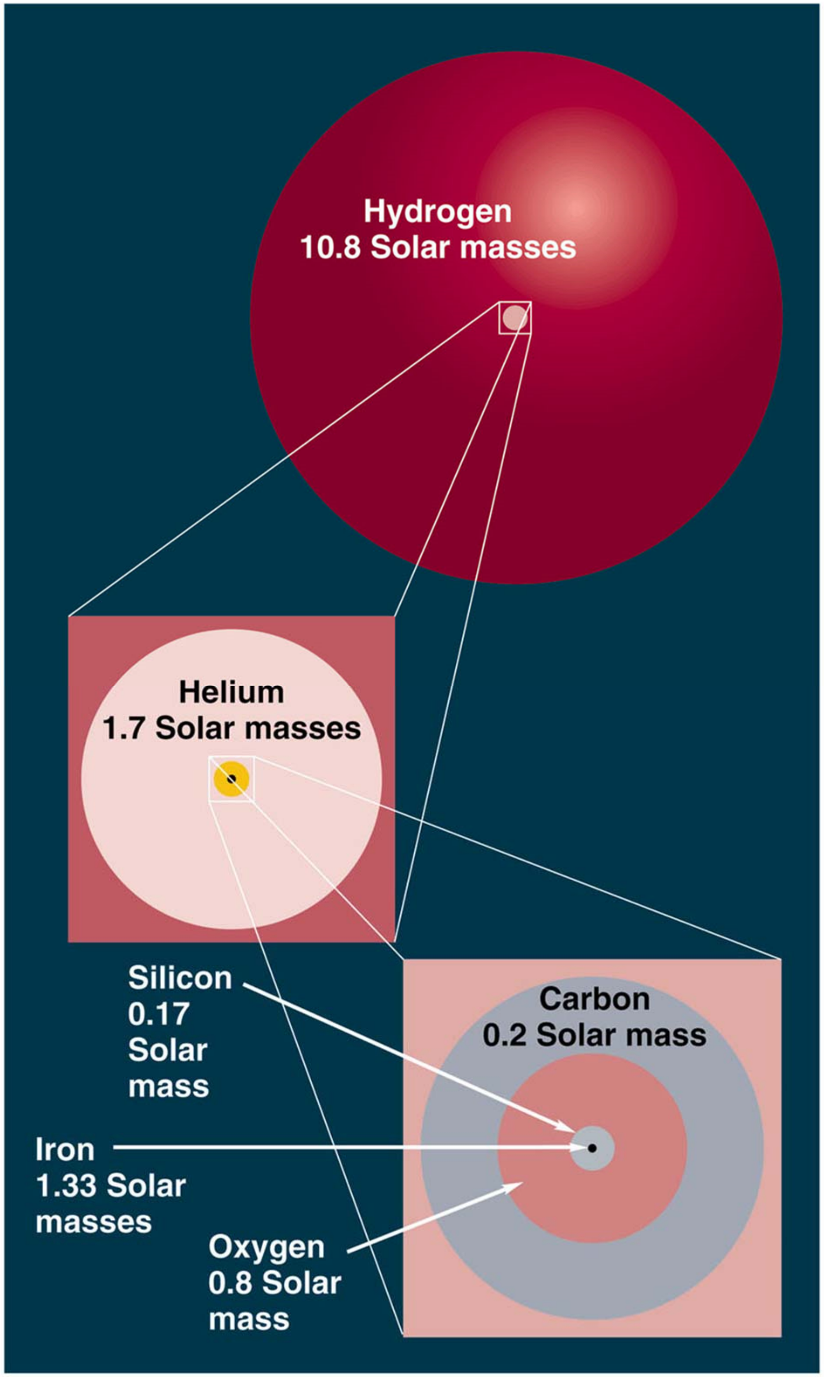
Fig.13.16b



b Other reactions. (Note: Fusion of two silicon nuclei first produces nickel-56, which decays rapidly to cobalt-56 and then to iron-56.)

ADVANCED NUCLEAR BURNING $(M > 4\ M_{\odot})$ MAKES SI, S, CA, FE



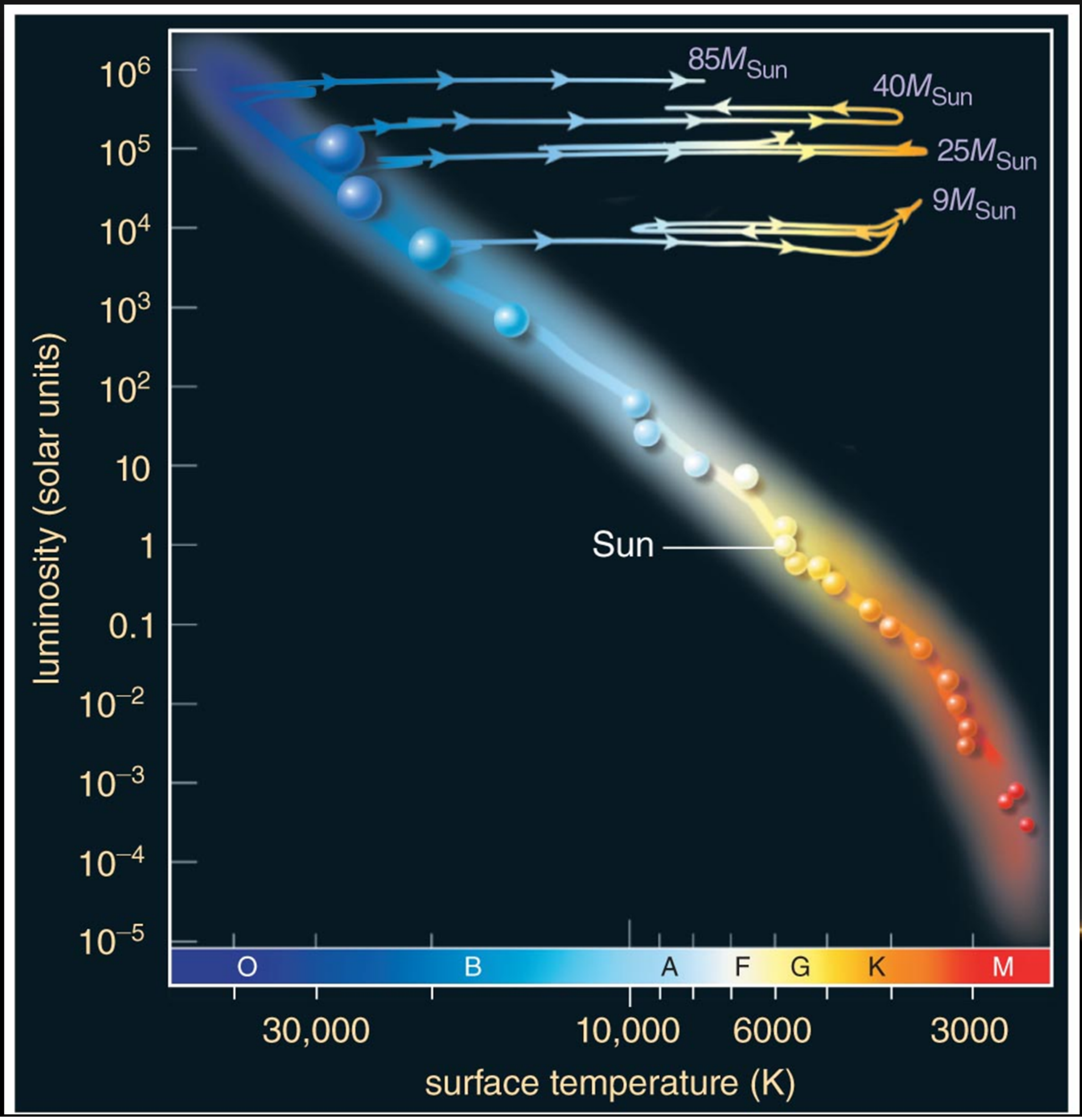


WHEN ONE FUEL RUNS OUT

- A 15 $M_{\odot}$ star in its Red Supergiant Phase
- Greater temperatures allow fusing of
  - Carbon
  - Neon
  - Oxygen
  - Silicon
- End up with Iron
  - Can't get energy out of iron fusion

PLAY

EVOLUTIONARY TRACKS



- With each successive fuel & shell burning, the star swells and contracts
- Like lower mass stars did for H shell then He core and He shell burning

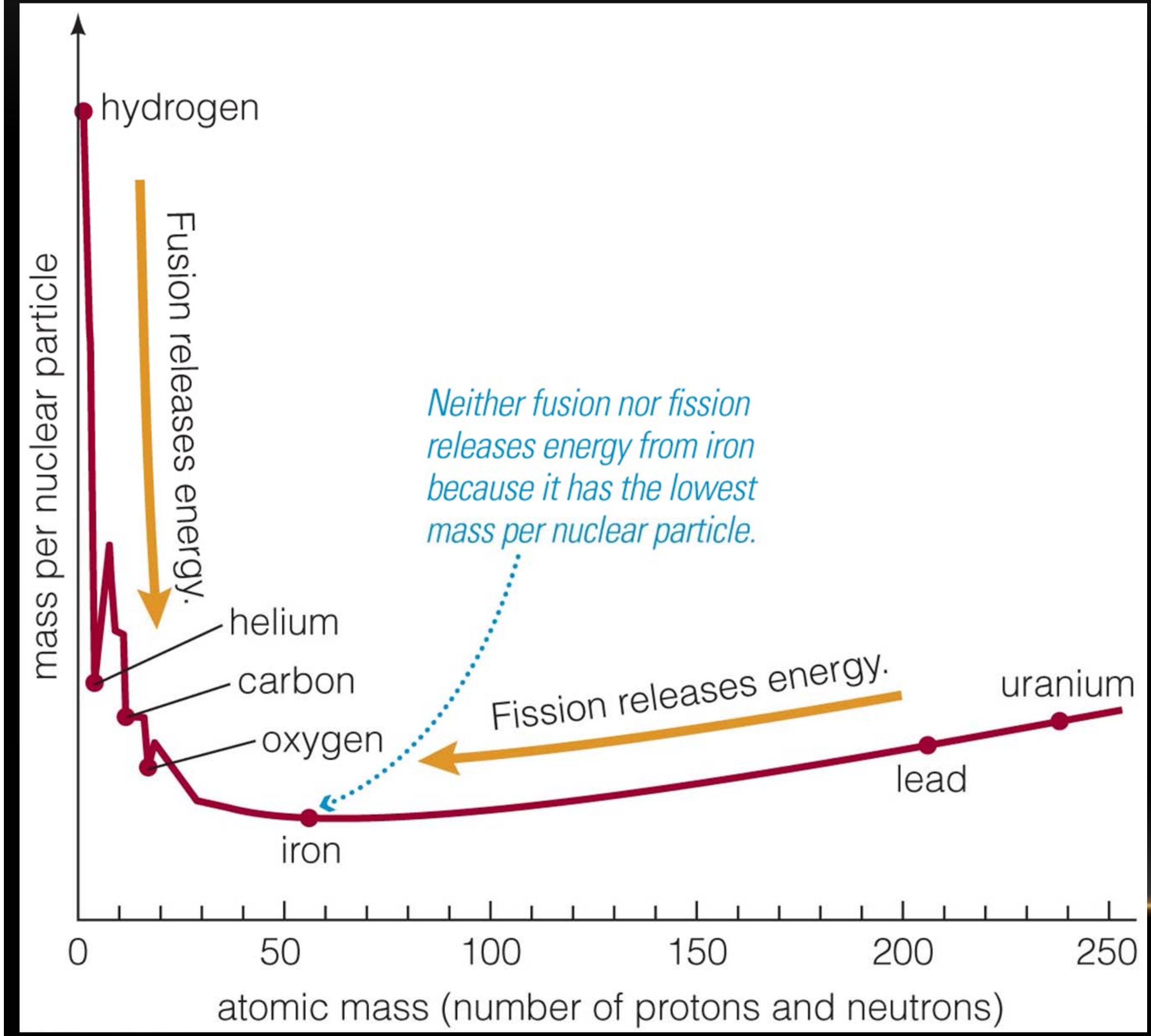
Fig.13.15

THE SLIPPERY SLOPE

- Each fuel lasts for a shorter time than the last
  - Higher temperatures, and less energy per fusion

Fuel	Ash	Time	T (x10^6 K)
H	He	10 million y	4
He	C	1 million y	100
C	O, Ne, Mg	1,000 y	600
Ne	O, Mg	Few years	1,000
O	Si, S	1 year	2,000
Si	Fe	days	3,000

IRON AND AVAILABLE ENERGY



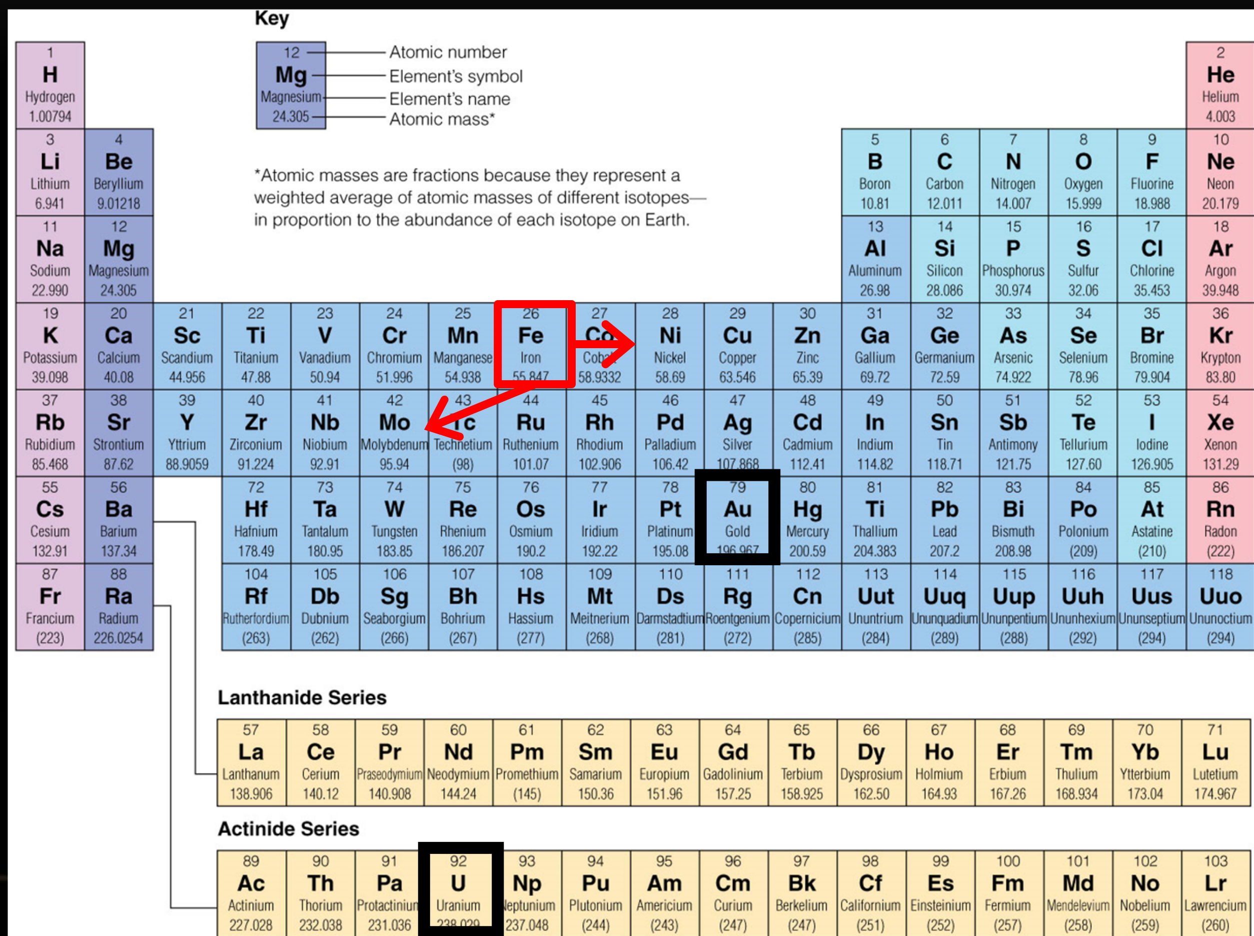
- Iron is the most stable nucleus
- Can’t get energy out by adding things
- Can’t get energy out by breaking it up

Fig.13.18

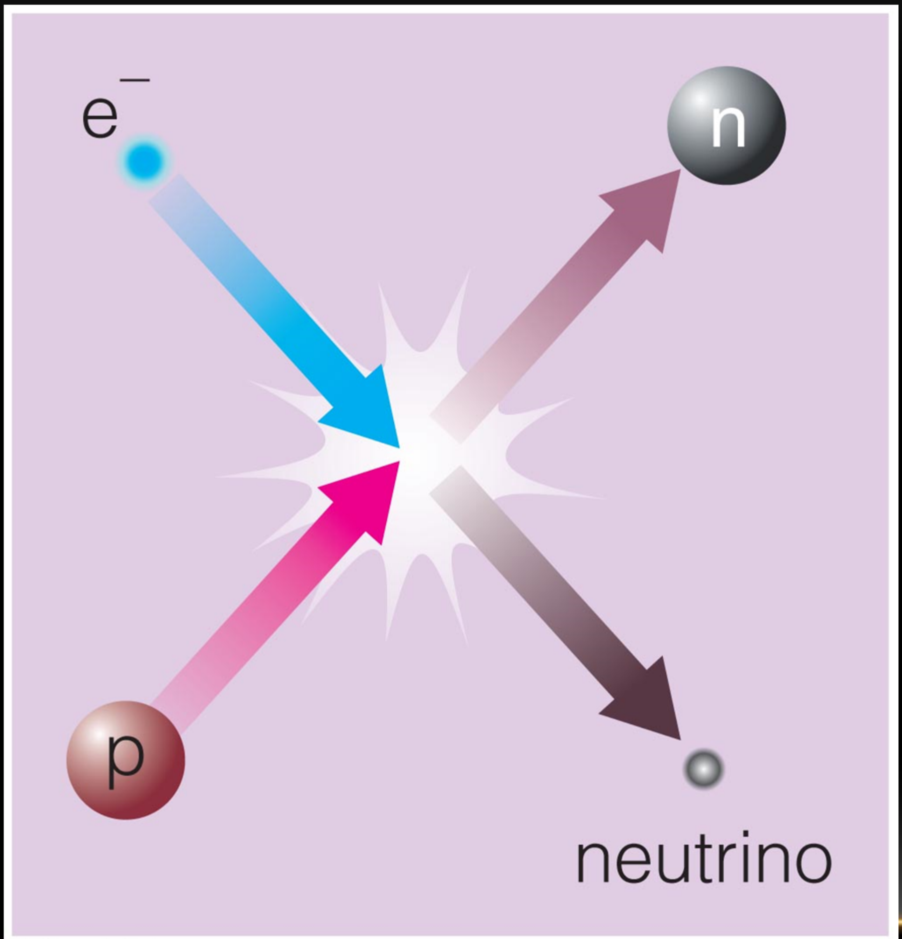
IRON CORE?

- Can’t fuse Iron
- No more energy to supply upward pressure
- Still lots of gravitational pressure
  - More than a Chandrasekhar Limit worth of mass
- Core collapses into a neutron star
- Shockwave blows apart star

ENERGY AND NEUTRONS RELEASED IN A SUPERNOVA EXPLOSION ENABLE ELEMENTS HEAVIER THAN IRON TO FORM, INCLUDING AU AND U.



COLLAPSE?



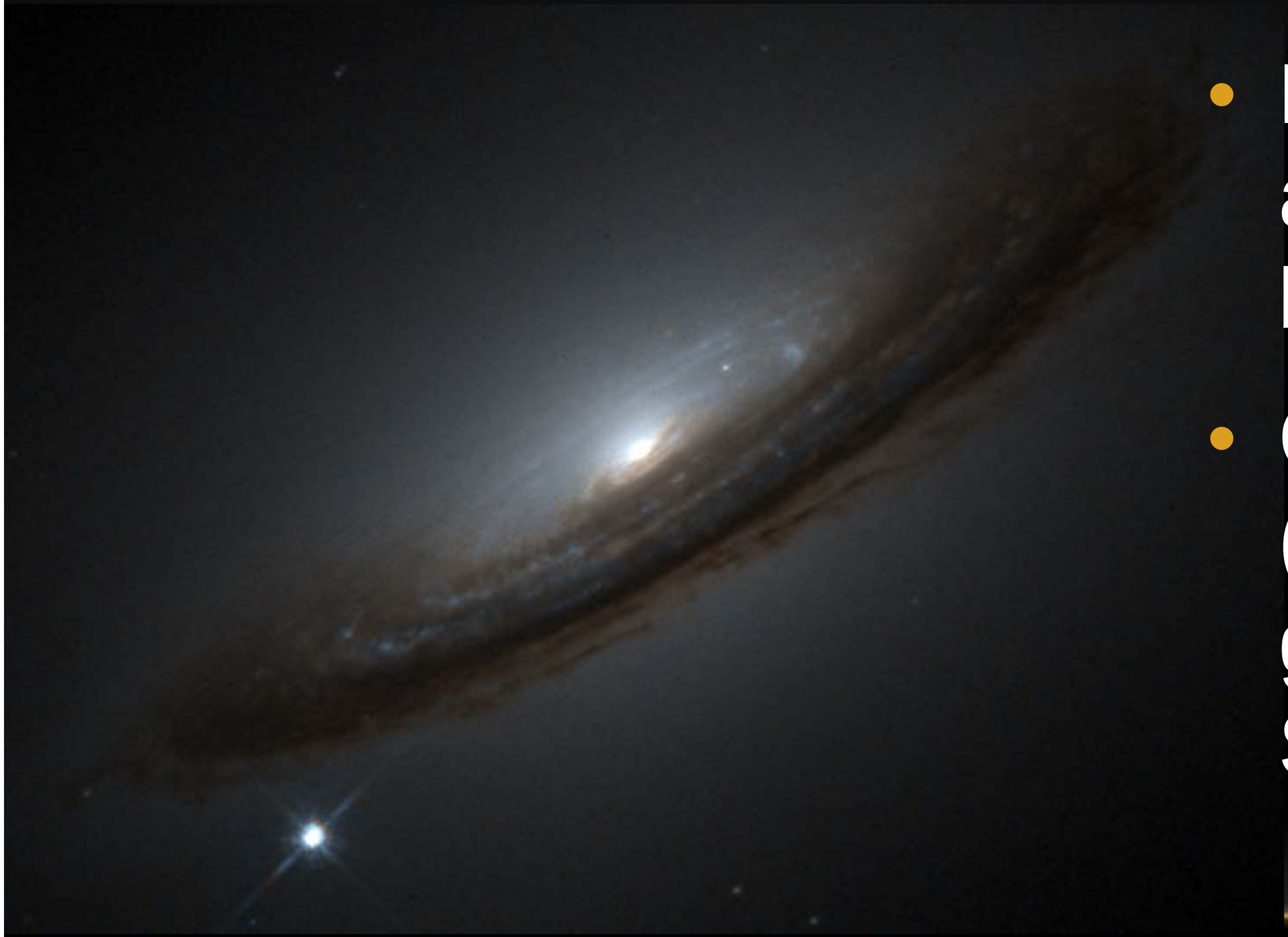
- Core degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos.
- Neutrons collapse to the center, forming a neutron star.

Fig.13.20

TYPE II SUPERNOVA

- Type I is a white dwarf getting too much extra mass from a binary companion, then burning up all at once
  - See next chapter
- Type II are the core collapse of a massive star
  - All burned up
  - Collapses into a neutron star
  - Shock wave of this collapse blows apart rest of star

BRIGHT AS A GALAXY



- For a few weeks, a SN glows with billions of $L_\odot$
- Compare stars (haze) in this galaxy with the SN

HST photo by High-Z SN Search Team
A “nearby” SNIa in NGC 4526

SUPERNOVA REMNANTS

- All that stuff makes a nebula
  - Expands with time
  - Fades out
- This one is the remnant of the SN of 1054
  - We can measure its expansion over a few years

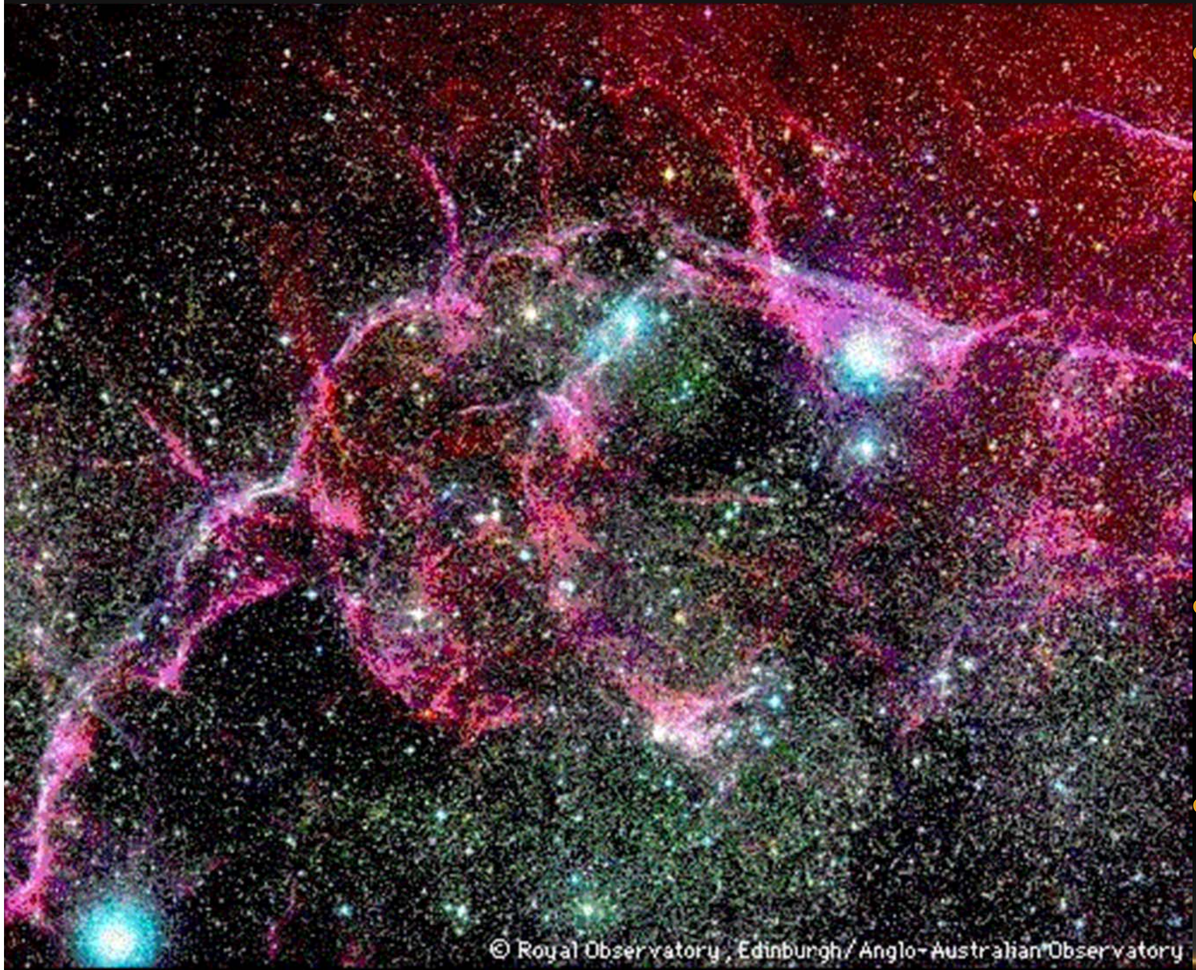
Crab Nebula photo
by FORS team, 8.2m VLT

EXPANDING CRAB

- Comparison of 1973 and 2001 images
- Taken with the Kitt Peak 4m telescope

Animation by Adam Block, NOAO

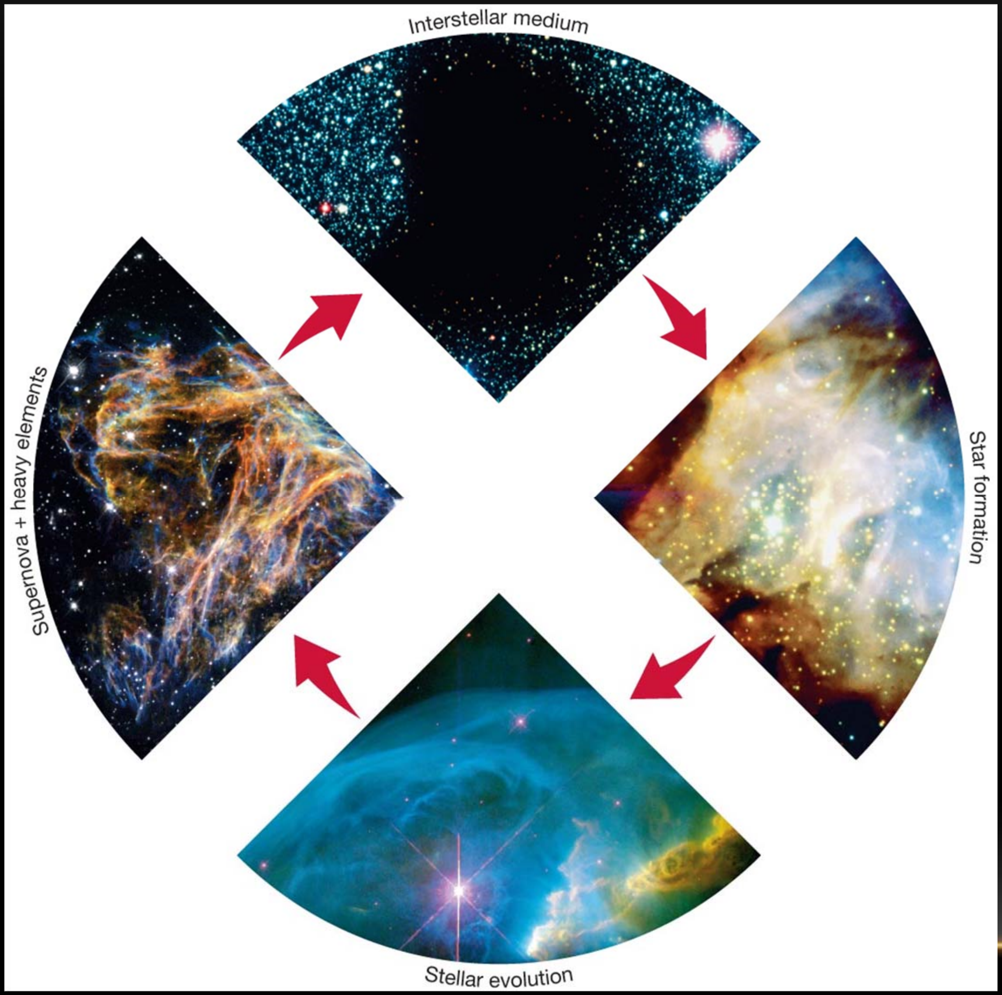
OLDER REMNANTS



- The ejecta expands, cools, fades out
- Stuff becomes just part of the ISM
- Will later condense to form new stars
  - Perhaps helped by a SN shock wave!
- All our heavy elements were formed in some long-ago SN
- This one is 11,000 years old

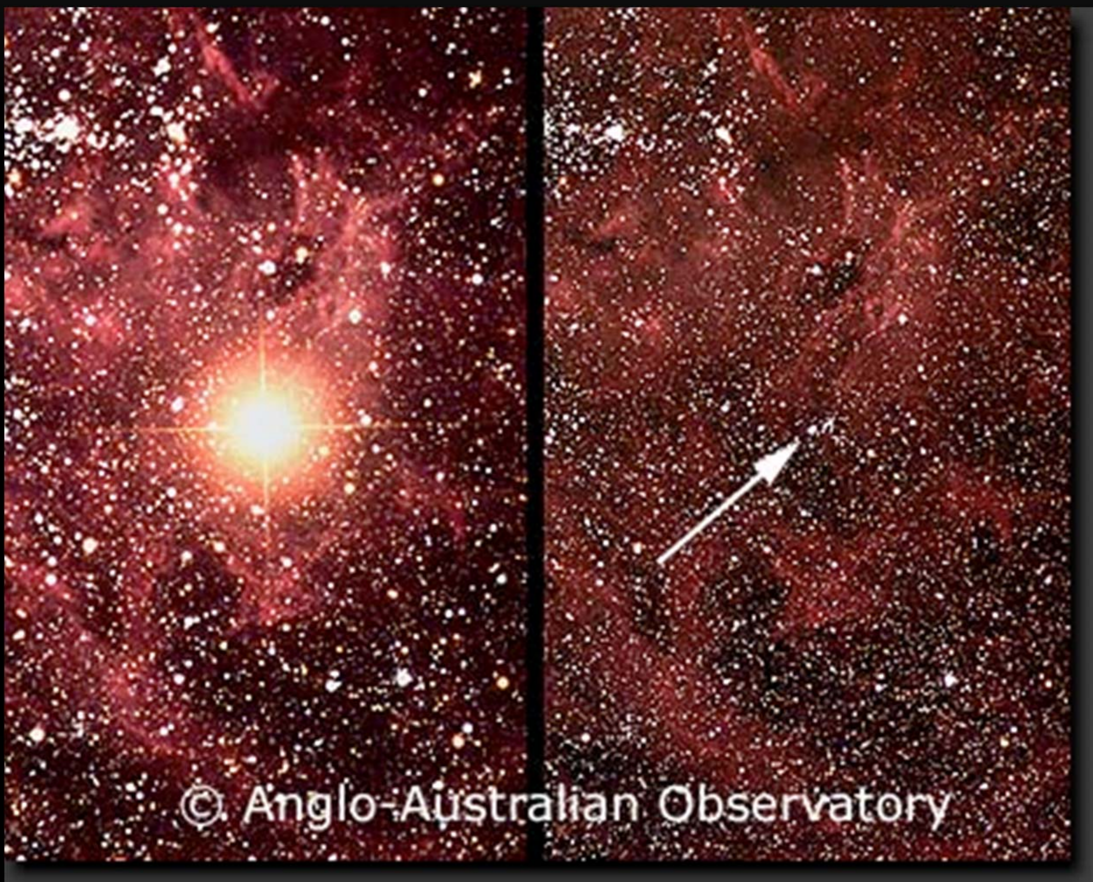
Vela SNR photo
by David Malin, AAT

THE CYCLE OF STELLAR EVOLUTION



- Star formation is cyclical: stars form, evolve, and die.
- In dying, they send heavy elements into the interstellar medium.
- These elements then become parts of new stars.
- And so it goes.

SN1987A



- SNe get named by year, then sequentially by letter
- In Feb. 1987, a blue giant in the nearby Large Magellenic Cloud

SN1987A

Blue Giant
SK -69 202

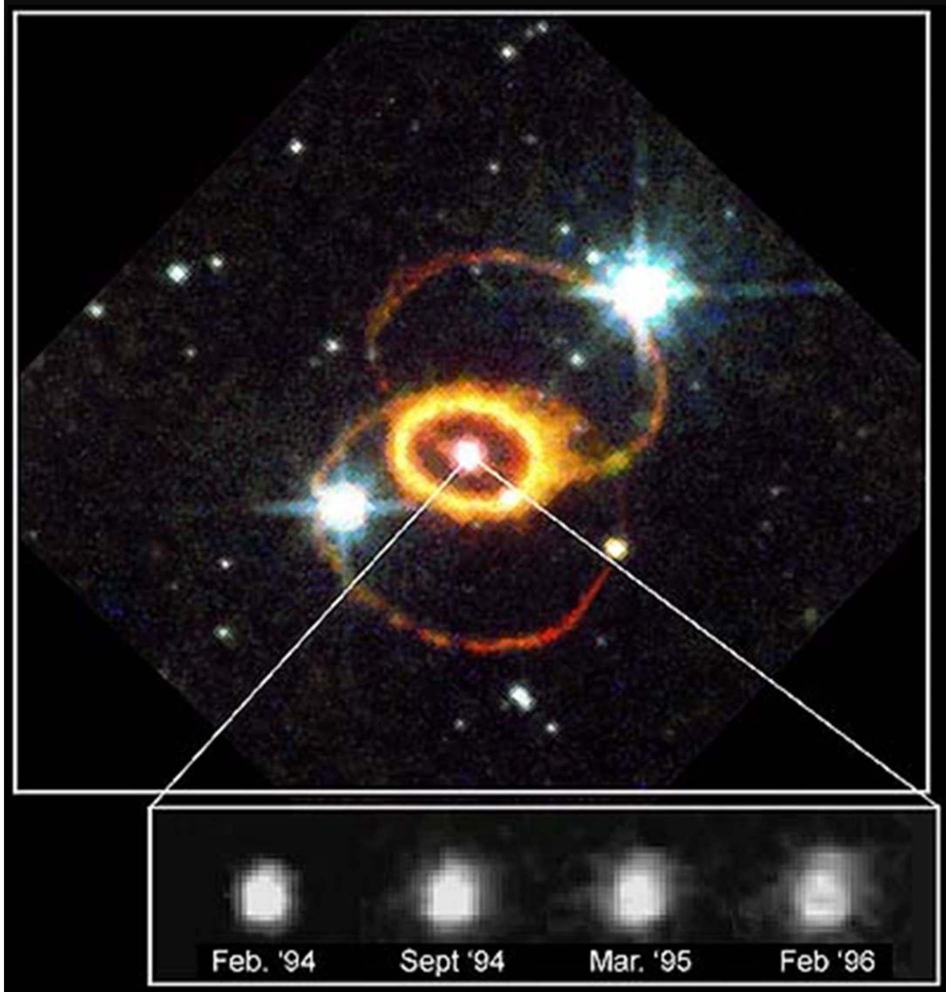
A VERY USEFUL SN

- Only 169,000 ly away
- Close enough we could get a good look
  - Identify the progenitor star for the only time
  - It is (oddly enough) a blue supergiant
  - SN light curve also dim and weird
- Observed only hours after it started
  - Usually it’s days to weeks before someone notices

BLUE GIANT?

- SN1987A is an odd SN
- Could be because it was a Blue Giant star
  - Outer layers already blown off by stellar wind
  - Leaves hotter, more compact inner layers
- SK -69 202 was name of star
  - $L = 100{,}000\ L_{\odot}$
  - $M = \sim 20\ M_{\odot}$
  - B3 Supergiant, T= 16,000 K

WATCH THE ACTION

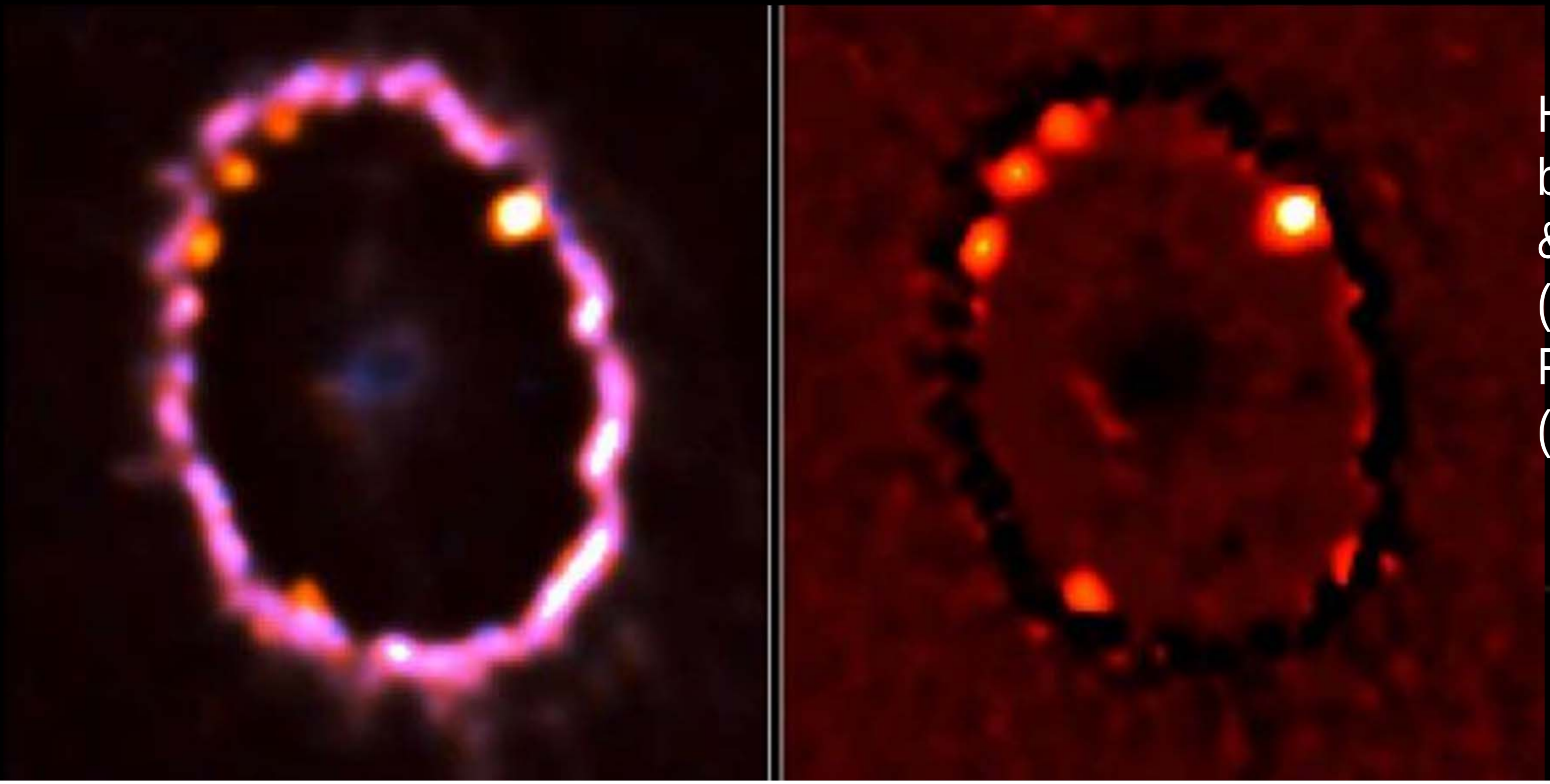


- We can see the fireball (lower)
- The shock wave crashing into previously-ejected stellar winds (above, the rings)

Photos by C. S. J. Pun (GSFC) & R. Kirshner (CfA) with HST

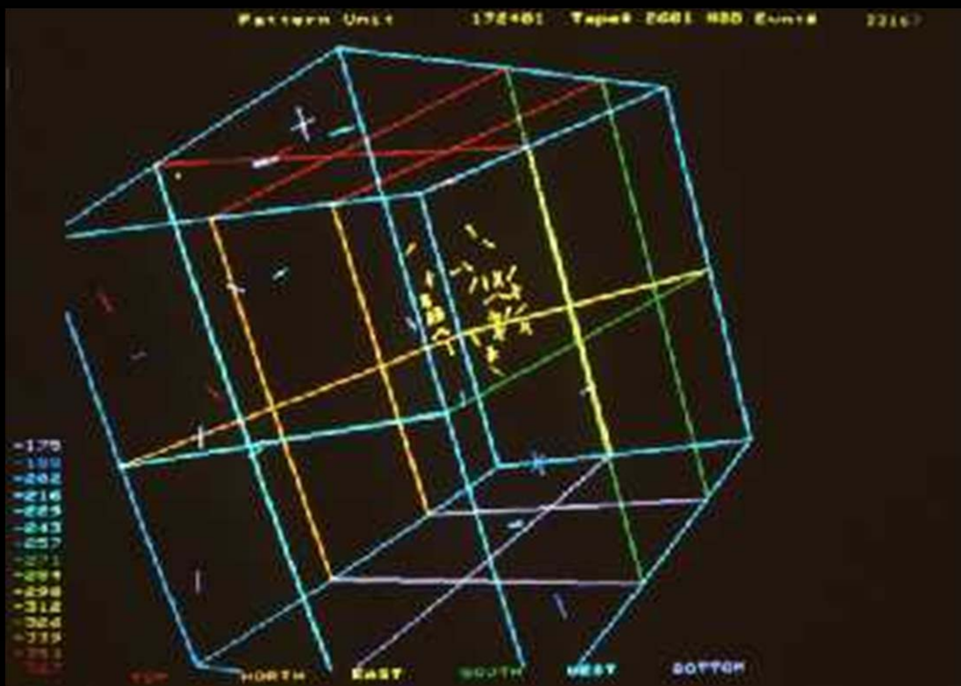
EXPANDING SHOCKS

- Right image in 1997, bright spots where the shock is hitting globs of matter
- Left image in 2000, shock catches up with whole shell



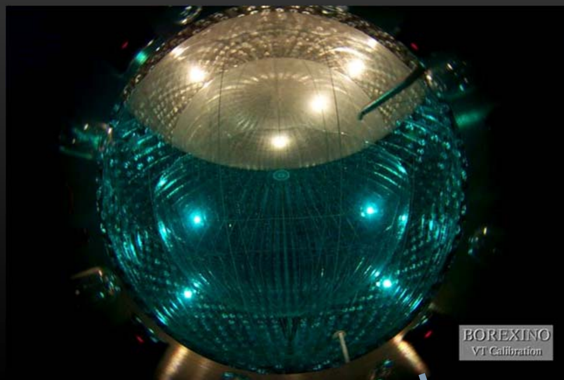
HST images
by P. Challis
& R. Kirshner
(CfA),
P. Garnavich
(Notre Dame)

NEUTRINOS!



- IMB in Cleveland. Kamiokande in Japan (predecessors to Super-K) both saw bursts of neutrinos from SN1987A
- Neutrinos get right out, ~3 h before the shock
- Produced by the formation of the neutron star

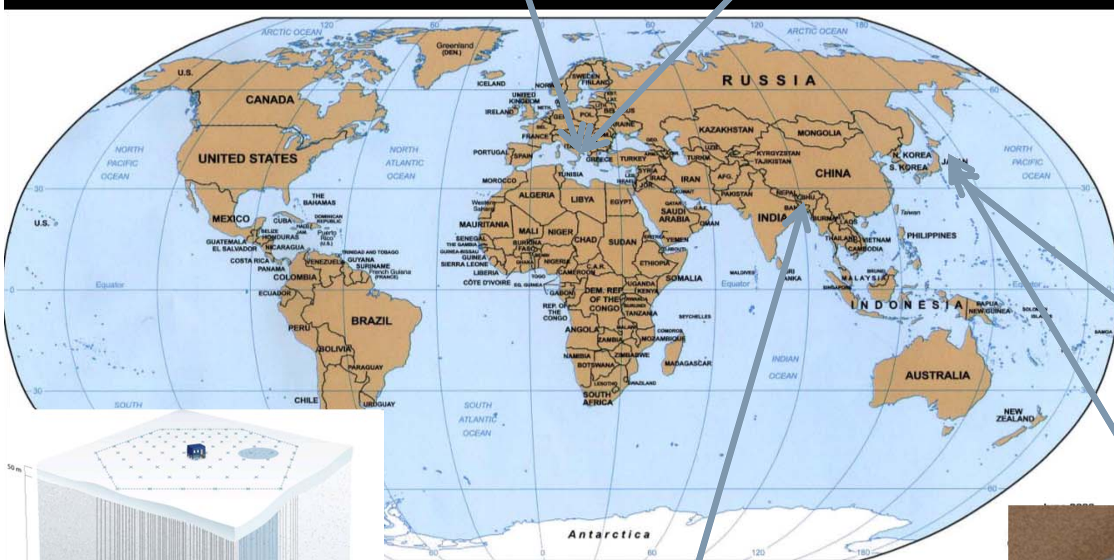
IMB SN1987A
ν event

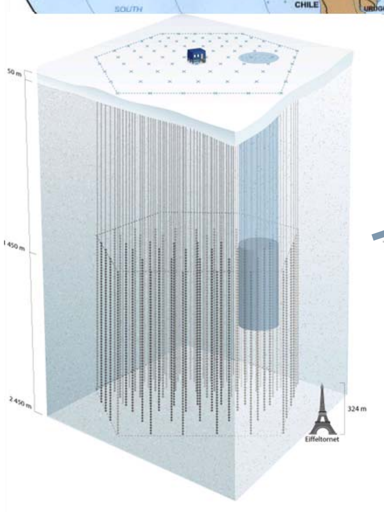


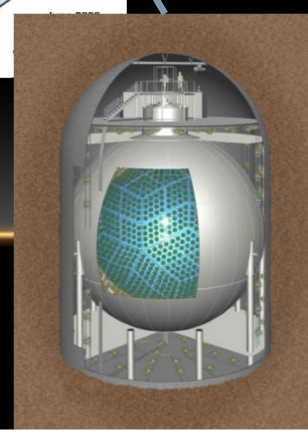
SNEWS

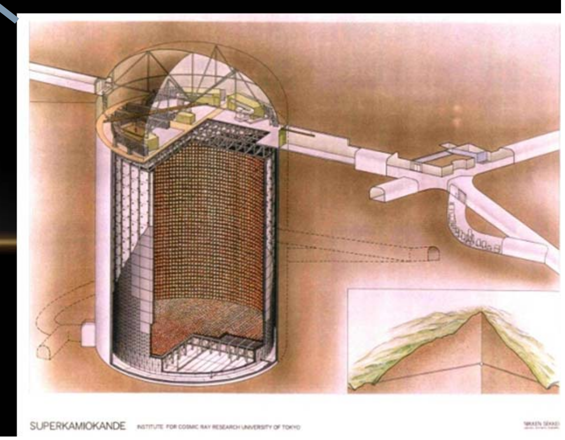
http://snews.bnl.gov

- Supernova Early Warning System
- Watch for coincidence from world's ν detectors
- Issue SN alarm, ~hours before light breaks out!





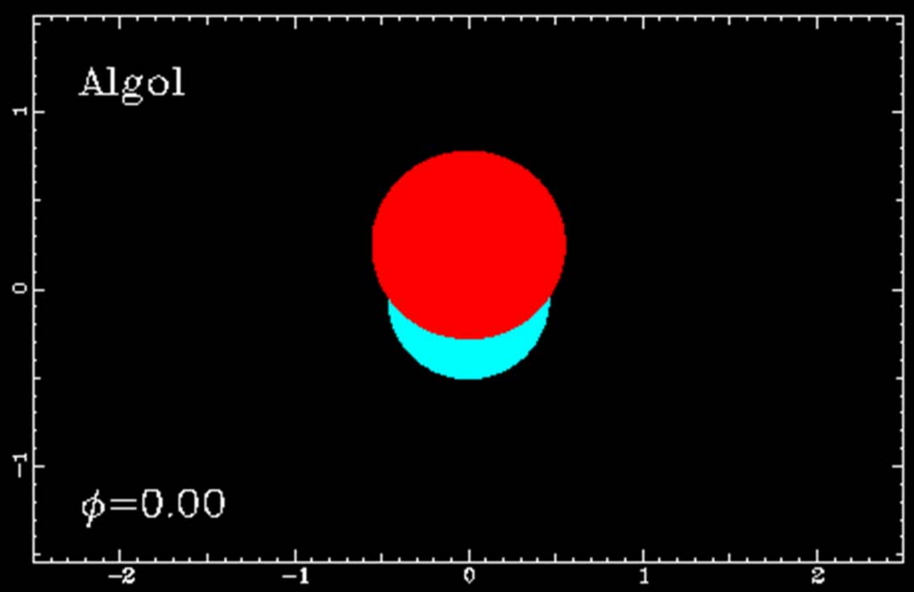




STARS IN CLOSE BINARIES

- When stars orbit very close to each other, what changes about how they age?
- For example, we looked at Algol as an example of an eclipsing binary
  - Algol consists of a $3.7M_{Sun}$ main-sequence star and a $0.8M_{Sun}$ subgiant star.

ALGOL



- The stars are a 3.5 $R_\odot$ K2 star and a 3$R_\odot$ B8 star
  - Primary eclipse is when you can't see much of the hot B8
- Note tidal distortion of larger star!

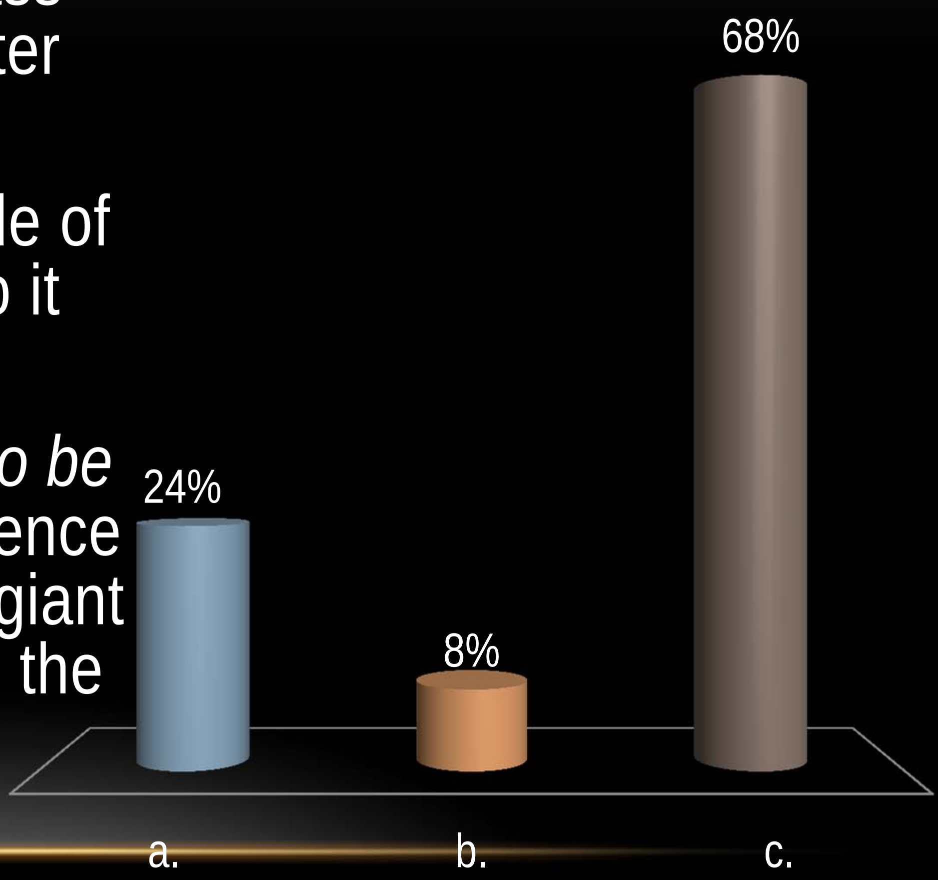
Animation by Larry Molnar

THE BINARY STAR ALGOL HAS A 3.7 SOLAR MASS MAIN SEQUENCE STAR AND A 0.8 SOLAR MASS RED GIANT. HOW COULD THAT BE?

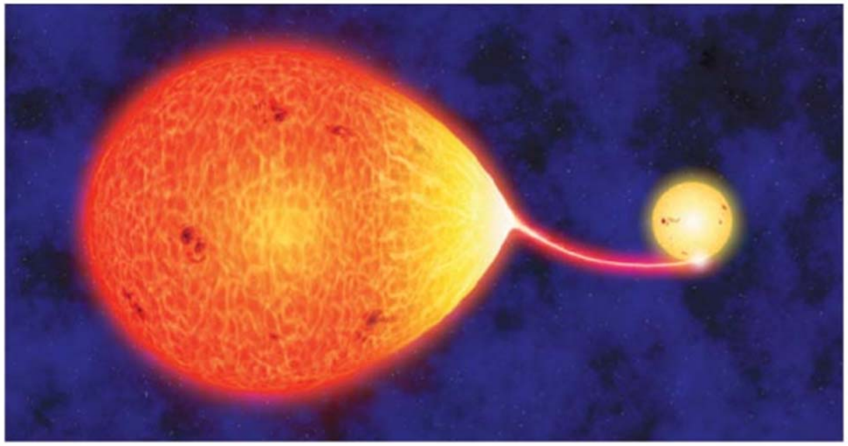
a. In this system the lower mass star must have evolved faster than the higher mass one.

b. The red giant might be made of some different elements, so it evolved faster.

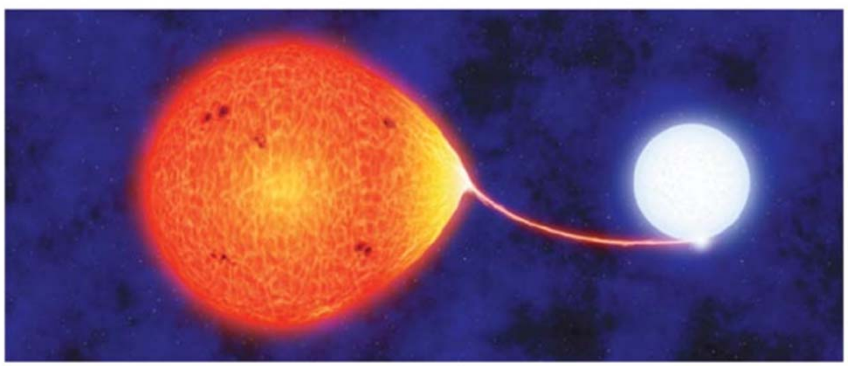
✓ c. The lower mass star *used to be* a more massive main sequence star, but when it became a giant some of its mass went onto the other star.



Algol shortly after its birth. The higher-mass star (left) evolved more quickly than its lower-mass companion (right).



Algol at onset of mass transfer. When the more massive star expanded into a red giant, it began losing some of its mass to its normal, hydrogen core fusion companion.



Algol today. As a result of the mass transfer, the red giant has shrunk to a subgiant, and the normal star on the right is now the more massive of the two stars.

THE ALGOL PARADOX

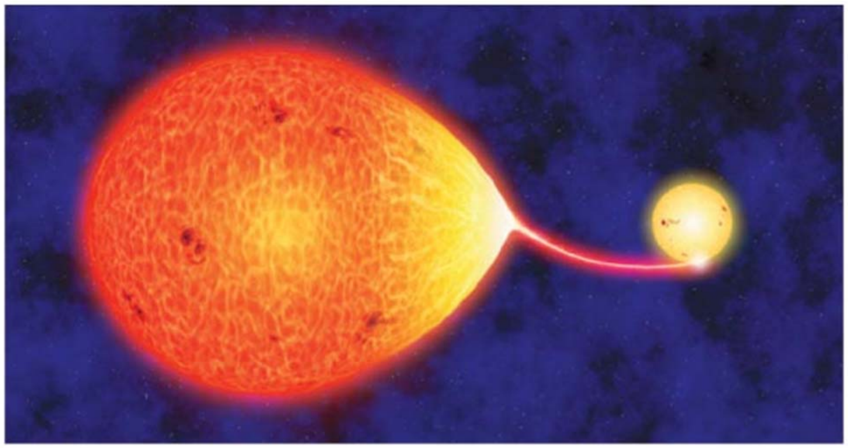
- Algol’s two stars are close enough that matter can flow from the subgiant onto the main-sequence star.
- We see evidence of this happening because that hot spot where it hits the other star shows up in spectra and eclipse data

Fig.13.24

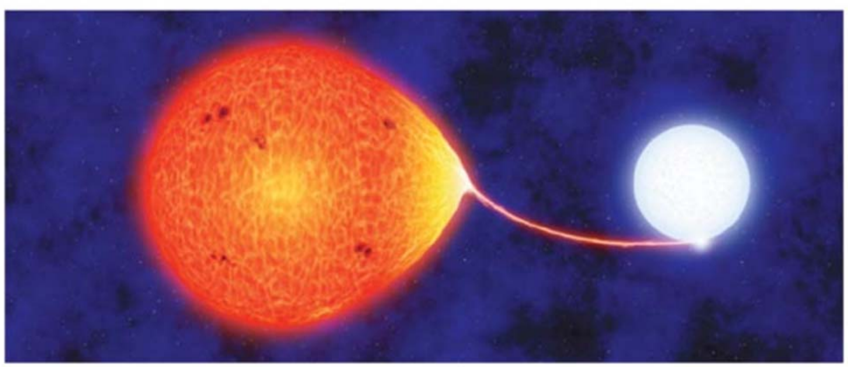
THE ALGOL PARADOX

- The star that is now a subgiant was originally more massive.
- As it reached the end of its life and started to grow, it began to transfer mass to its companion (*mass exchange*).

Algol shortly after its birth. The higher-mass star (left) evolved more quickly than its lower-mass companion (right).



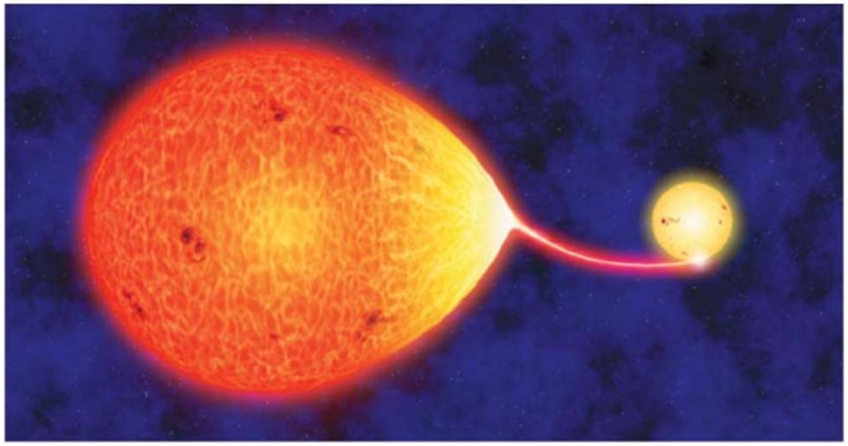
Algol at onset of mass transfer. When the more massive star expanded into a red giant, it began losing some of its mass to its normal, hydrogen core fusion companion.



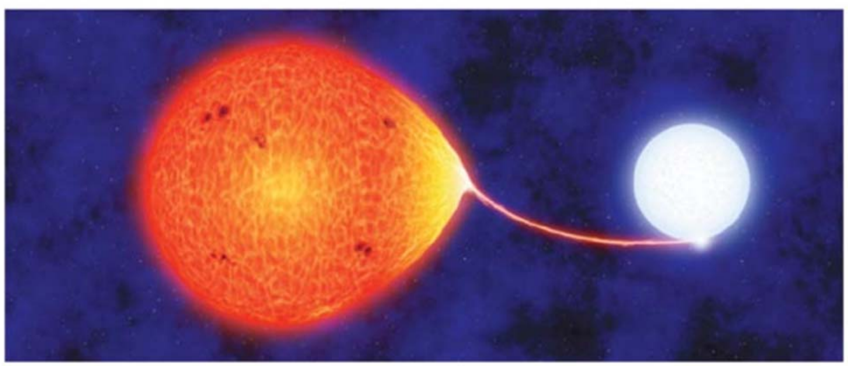
Algol today. As a result of the mass transfer, the red giant has shrunk to a subgiant, and the normal star on the right is now the more massive of the two stars.

Fig.13.24

Algol shortly after its birth. The higher-mass star (left) evolved more quickly than its lower-mass companion (right).



Algol at onset of mass transfer. When the more massive star expanded into a red giant, it began losing some of its mass to its normal, hydrogen core fusion companion.



Algol today. As a result of the mass transfer, the red giant has shrunk to a subgiant, and the normal star on the right is now the more massive of the two stars.

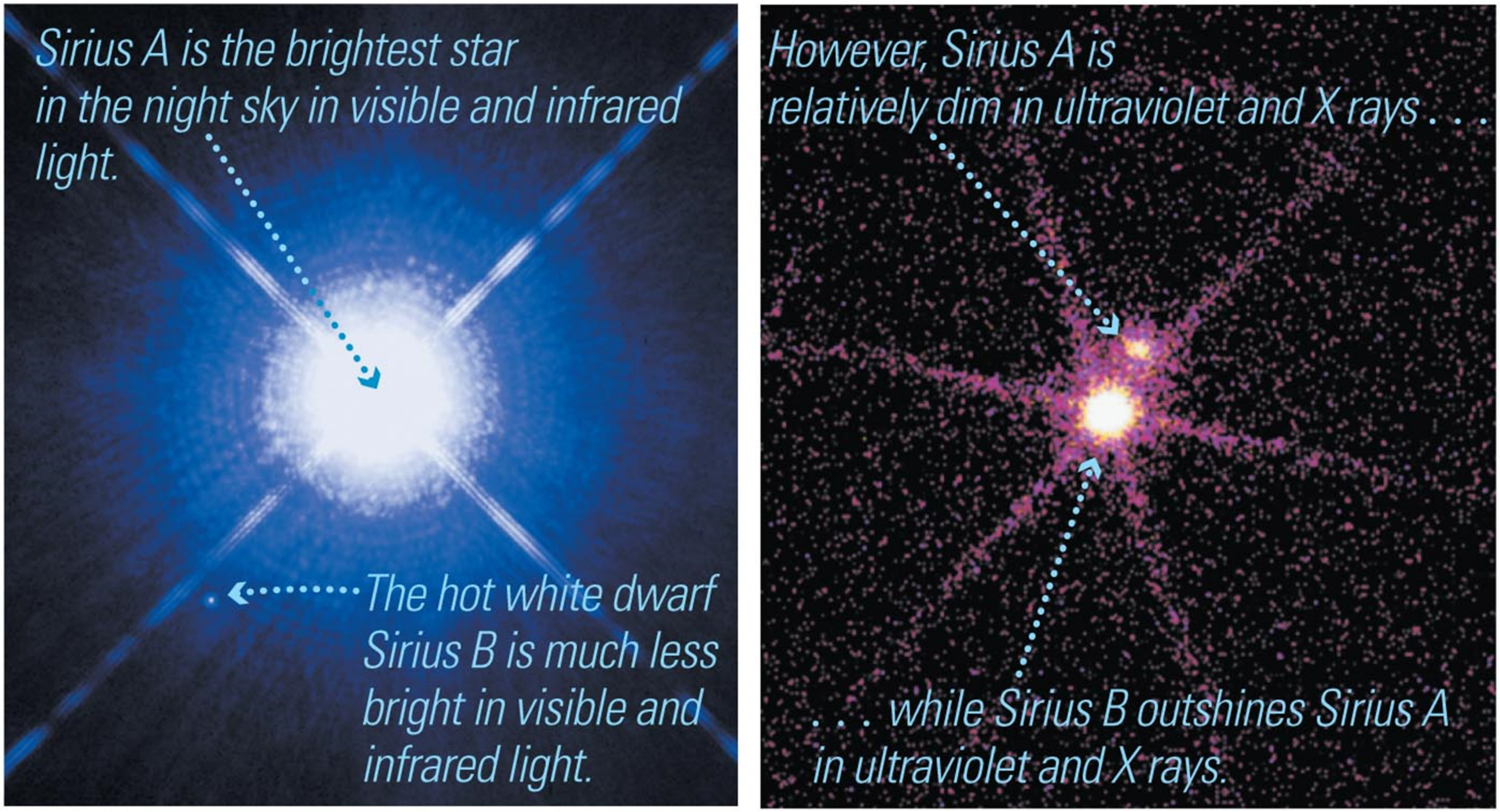
THE ALGOL PARADOX

- Now the companion star is more massive.
- We'll see more ways mass exchange messes with things in the next chapter

Fig.13.24

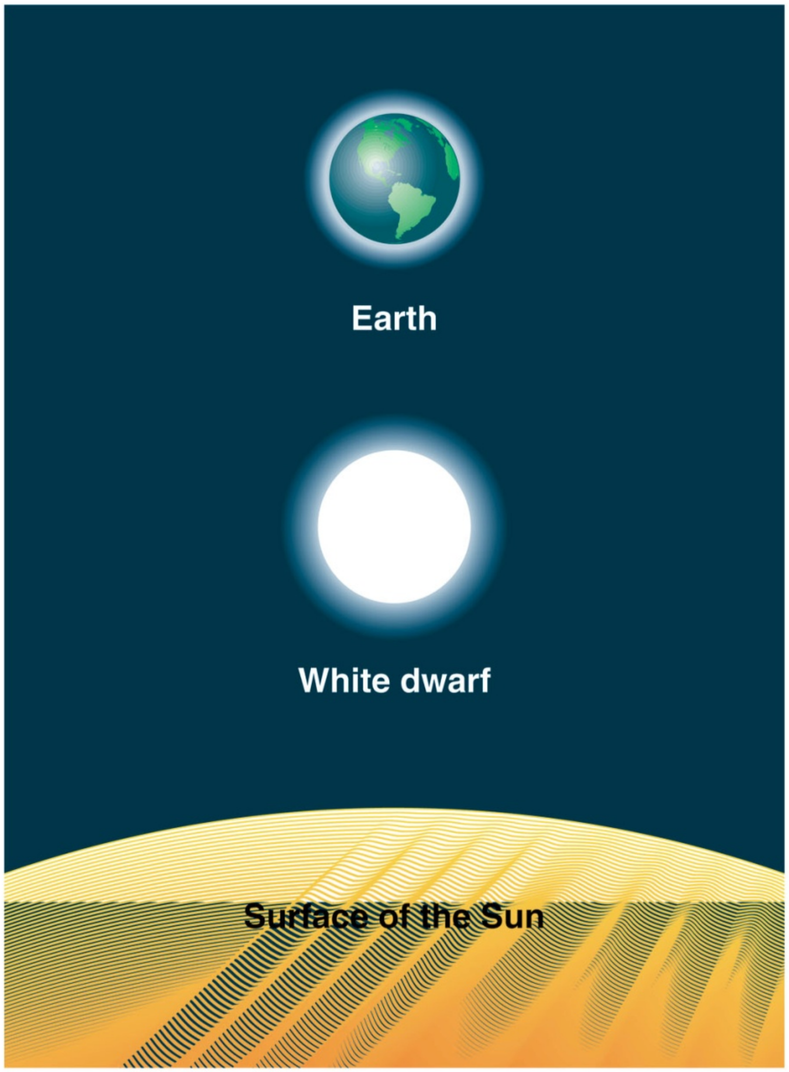
WHITE DWARFS

Fig.14.1



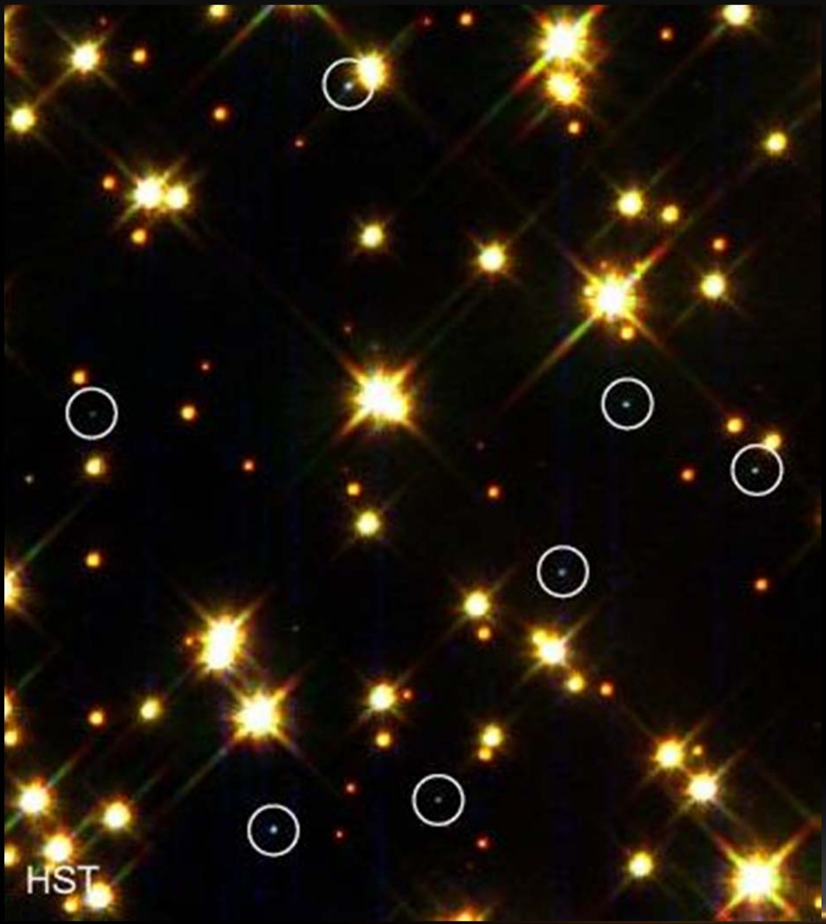
a Sirius as seen in infrared light by the Hubble Space Telescope. **b** Sirius as seen by the Chandra X-Ray Telescope.

WHITE DWARFS



- 0.02-1.5 $M_{\odot}$ left in core
- 15,000 K surface temperature
- Very dense
  - 10^6 g/cm^3
- About Earth sized
- “Degenerate” – as compact as normal matter can get
- Cool off slowly over a long time

DEGENERATE?



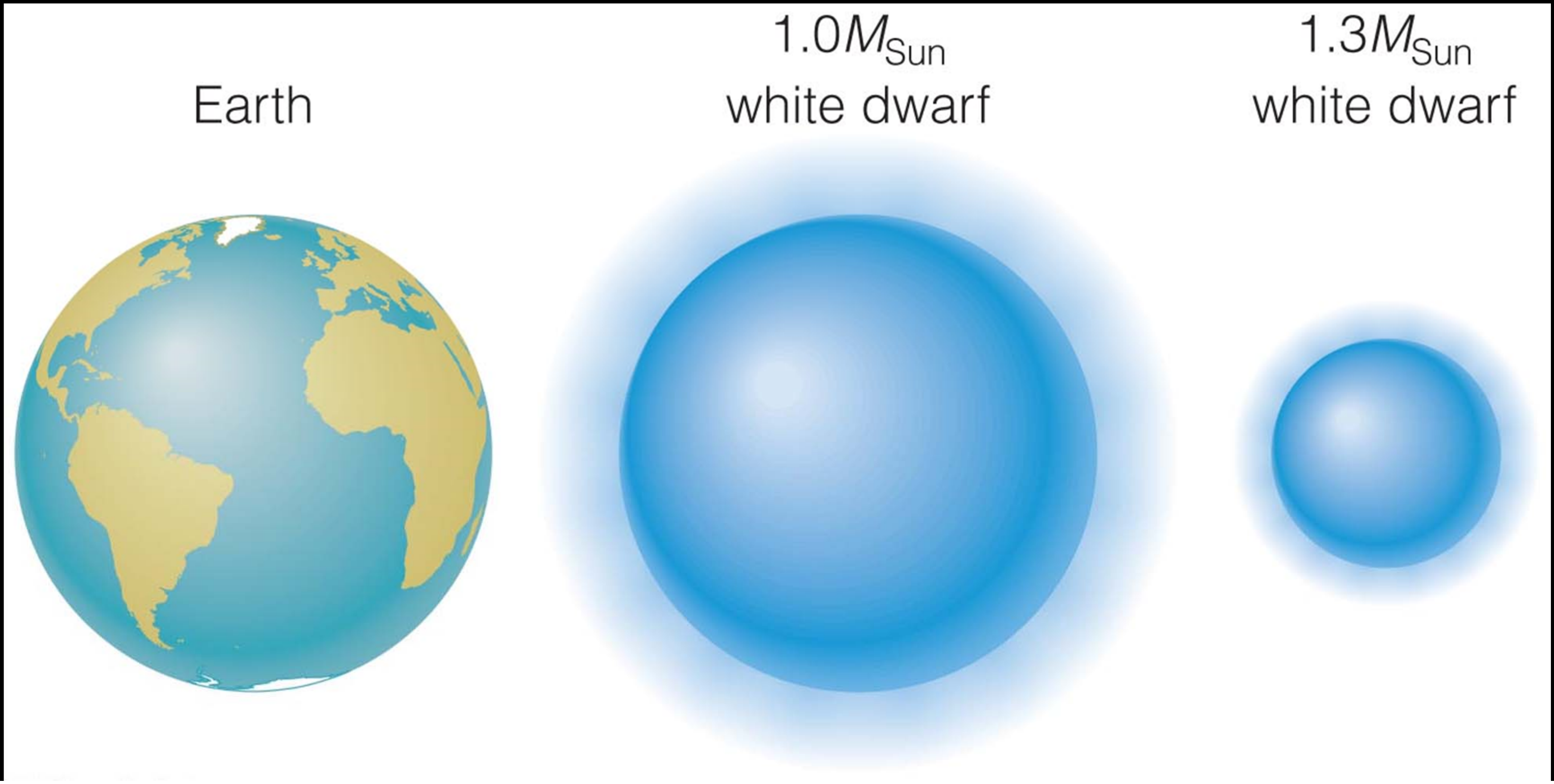
A small section of globular cluster M4 - White Dwarfs all over! by H. Richer

- All the protons, electrons, and neutrons are packed as close as quantum mechanics allows
- This provides the pressure to balance the gravity and keeps it from collapsing further
- Gravity for a white dwarf of over 1.4 $M_{\odot}$ is too strong for this even
  - Electrons would have to be moving more than the speed of light
  - "Chandrasekar Limit"
  - Will collapse into a neutron star

MASS VS. RADIUS

- Pile more mass on, more gravity crushes things down even more

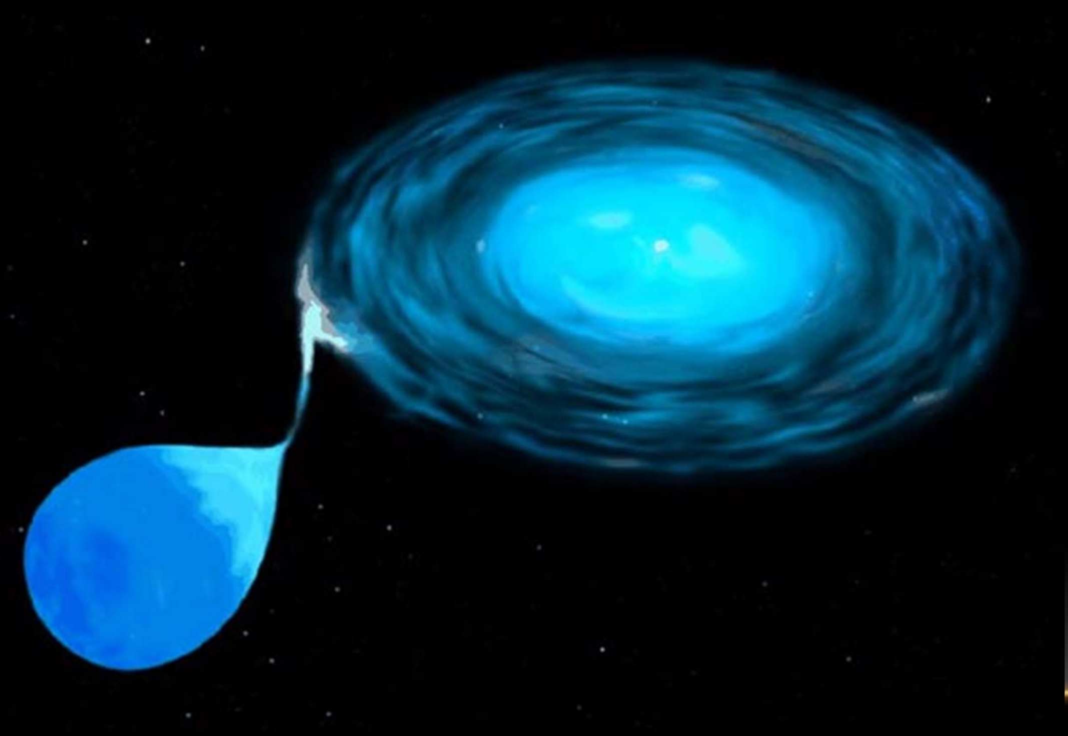
Fig.14.2



WHITE DWARFS IN CLOSE BINARIES

- What if one star in a binary system burns out and leaves a white dwarf before the other?
- When the 2nd star becomes a red giant, mass transfer happens if they're close enough

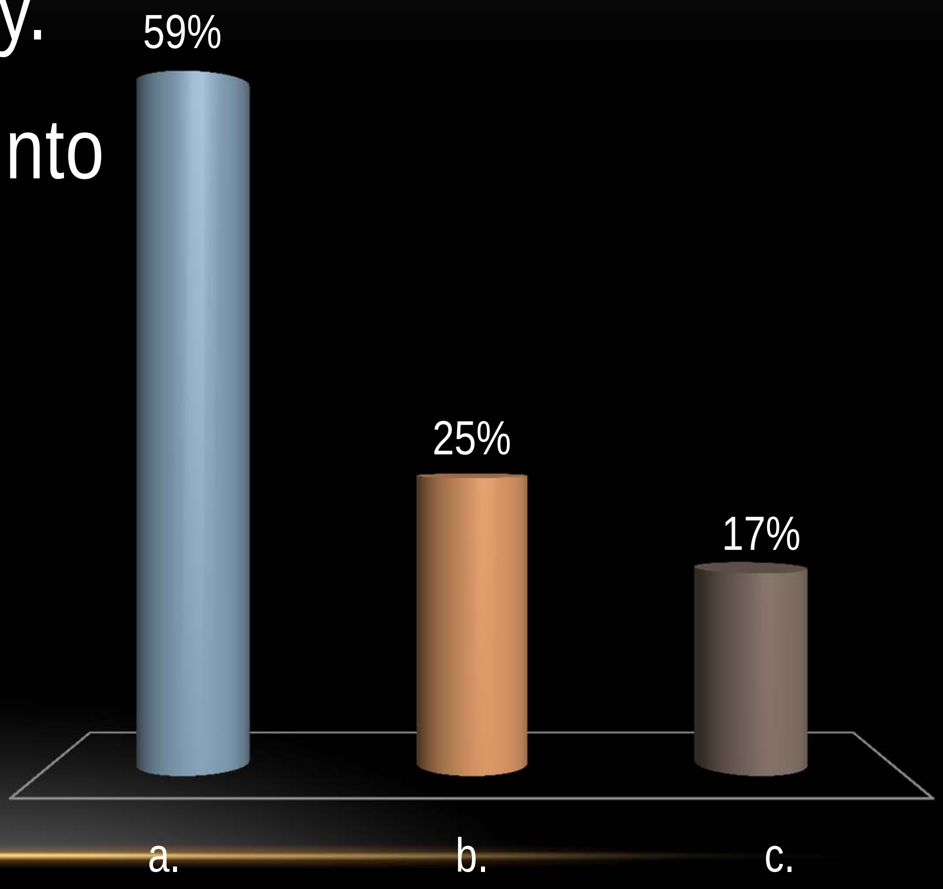
ACCRETION DISKS



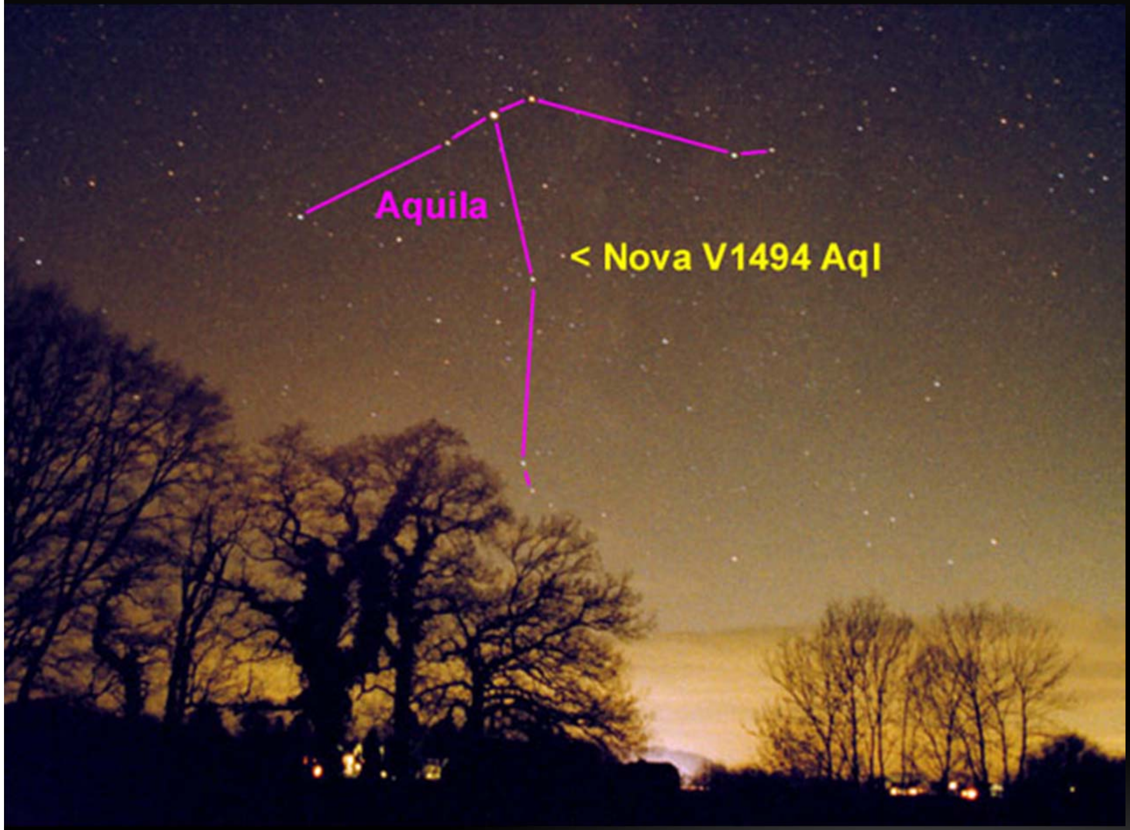
- Stuff spirals into the WD in an “accretion disk”
  - Because of friction in the disk
- Fresh star-stuff builds up on the surface of the WD

WHAT WOULD GAS IN THE DISK DO IF THERE WERE NO FRICTION?

a. It would orbit indefinitely.
b. It would eventually fall into the star.
c. It would blow away.



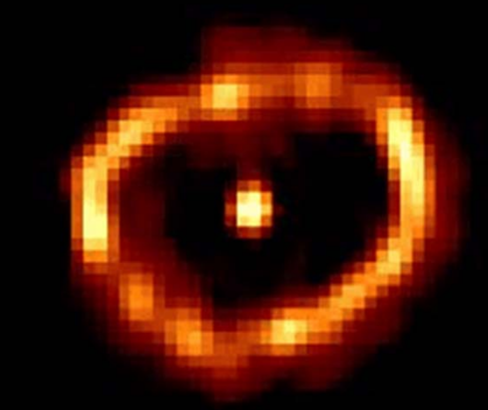
NOVA!



- A "new star"
- Really, just an old star suddenly burning 70,000x brighter
- Novae are mostly the stuff piling onto a white dwarf all undergoing fusion at once
- Will recur semi-regularly as long as the mass keeps coming
  - Supernovae are different

A nova on 12/1/99
by Till Credner

MORE CLUES



Nova Cygni 1992 seen by HST in 1995
by F. Paresce, R. Jedrzejewski

- Spectral analysis confirms this model
- We also see material flying off

Nova Velorum 1999
By Gordon Garradd

WHAT HAPPENS TO A WHITE DWARF WHEN IT ACCRETES ENOUGH MATTER TO REACH THE 1.4M_{SUN} LIMIT?

✓ a. It explodes.

b. It collapses into a neutron star.

c. It gradually begins fusing carbon in its core.