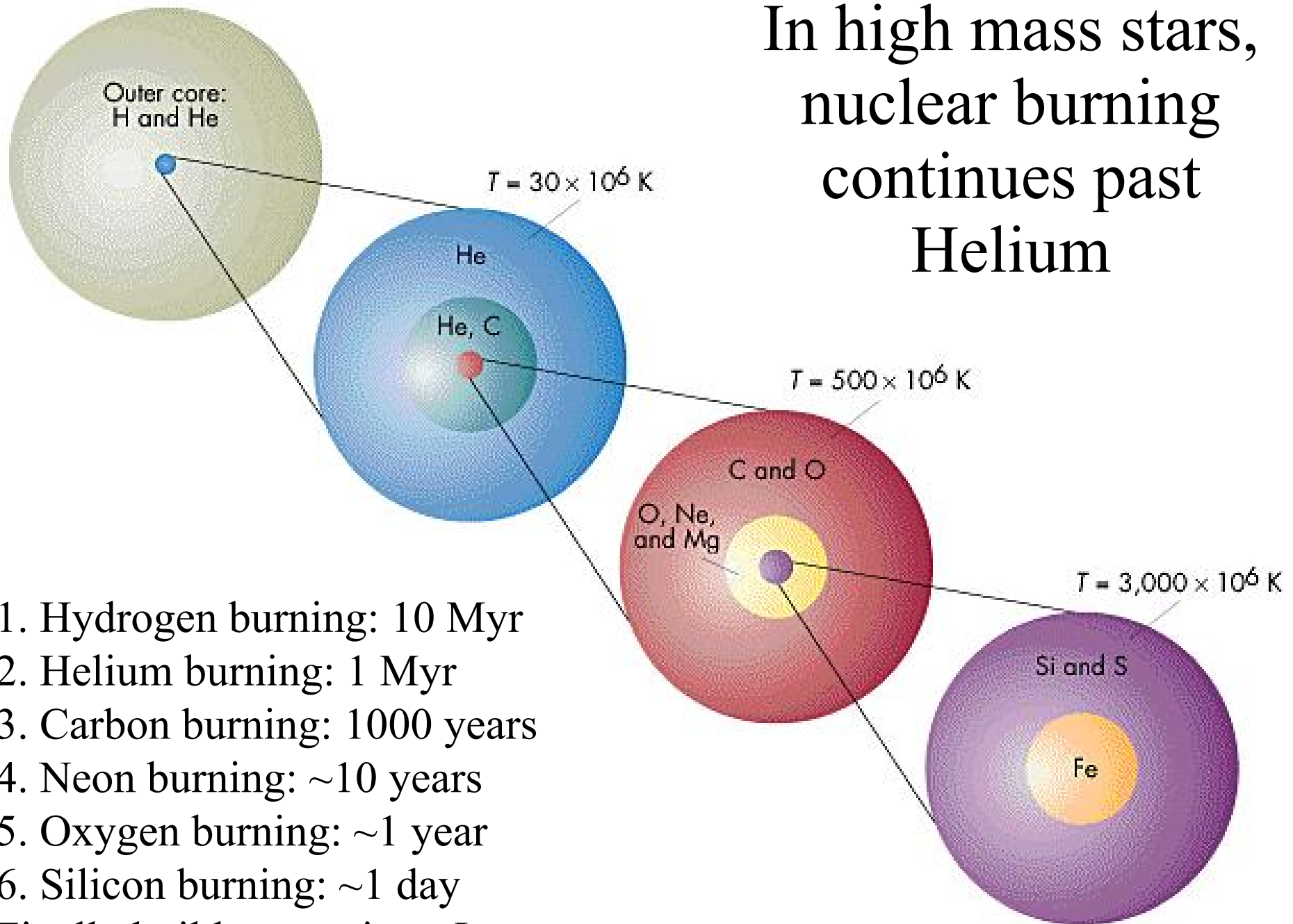


Deaths of stars

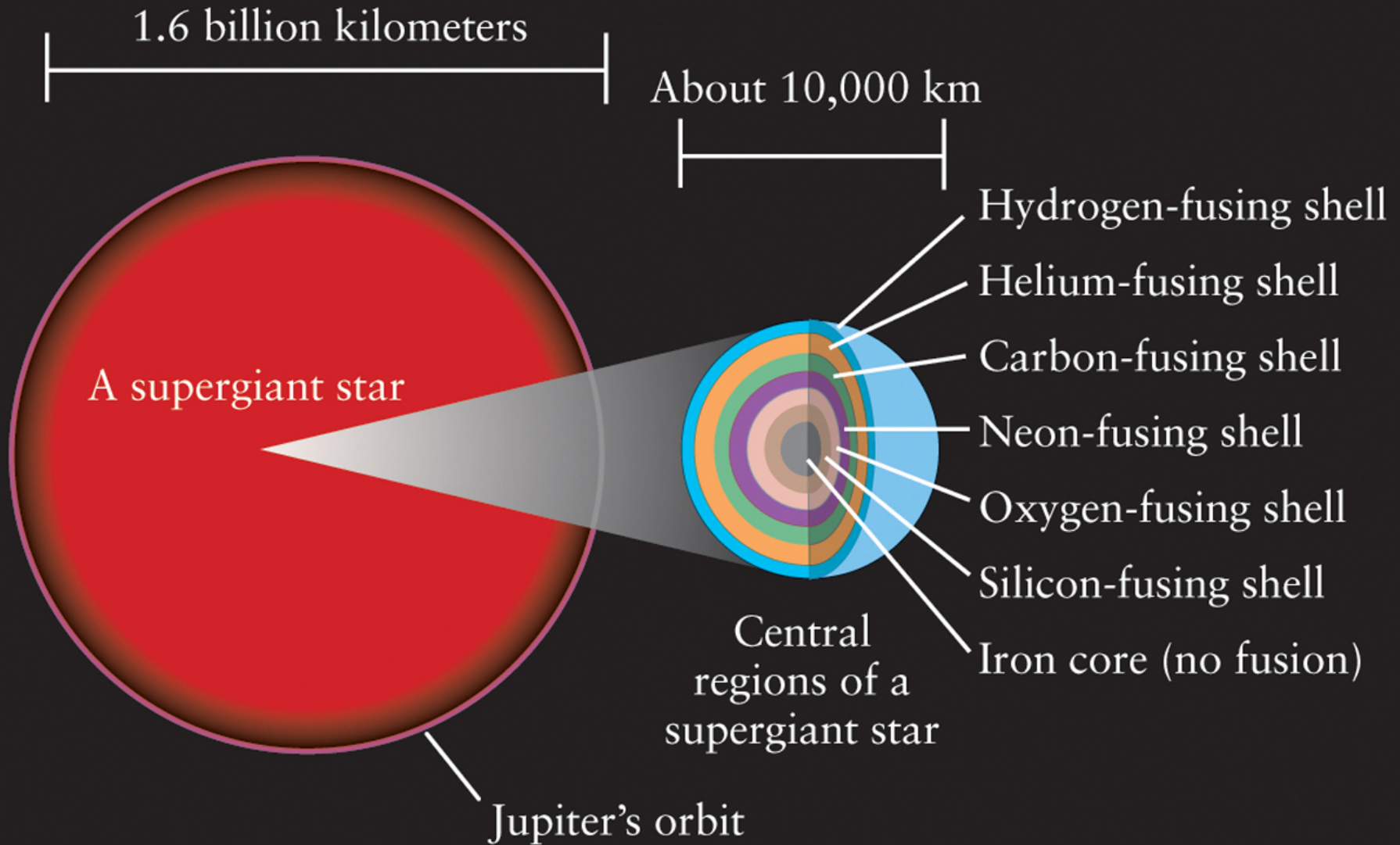
- Evolution of high mass stars
- Where were the elements in your body made?
- Stellar remnants
- Degenerate gases
- White dwarfs
- Neutron stars

In high mass stars, nuclear burning continues past Helium

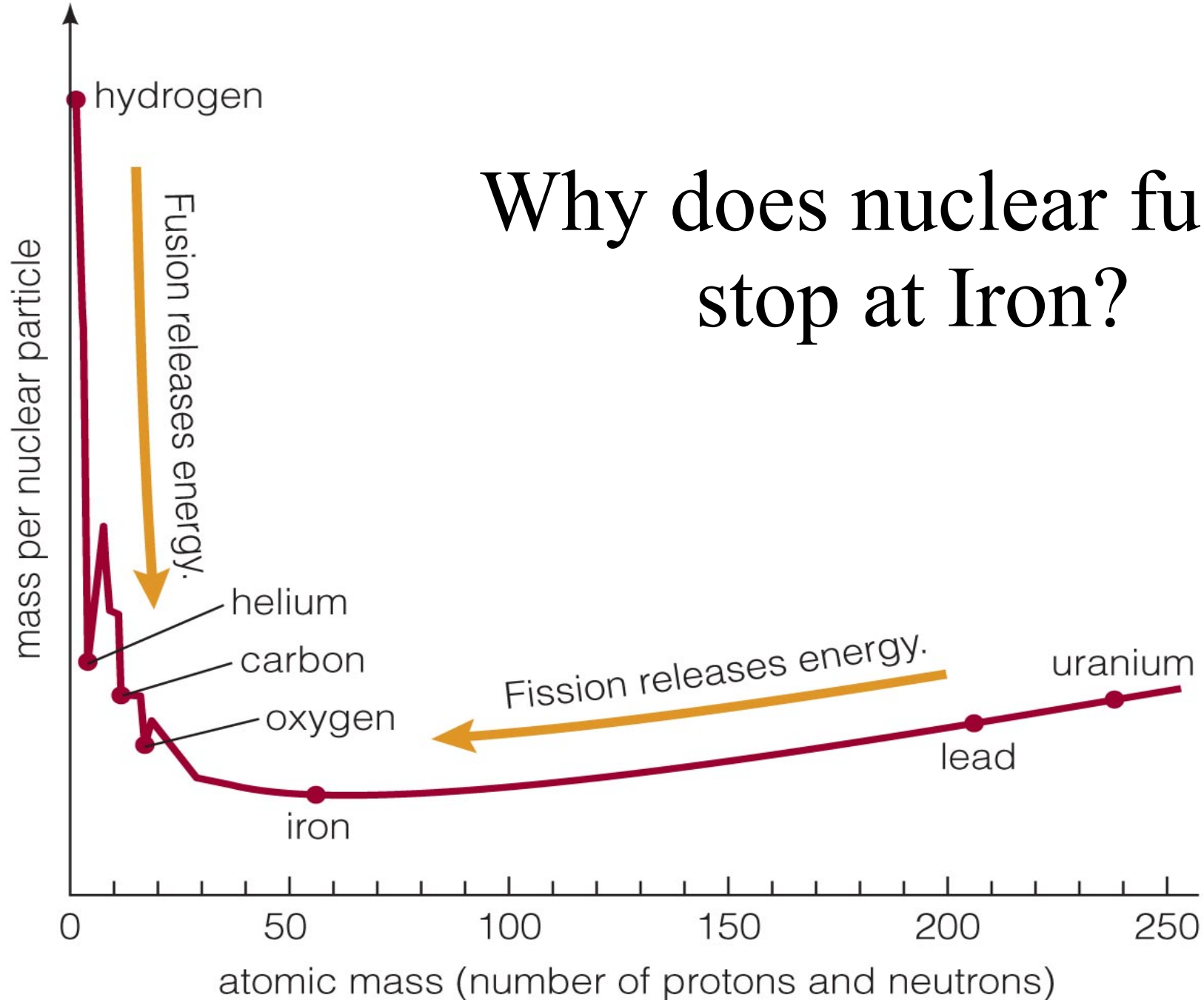


1. Hydrogen burning: 10 Myr
 2. Helium burning: 1 Myr
 3. Carbon burning: 1000 years
 4. Neon burning: ~ 10 years
 5. Oxygen burning: ~ 1 year
 6. Silicon burning: ~ 1 day
- Finally builds up an inert Iron core

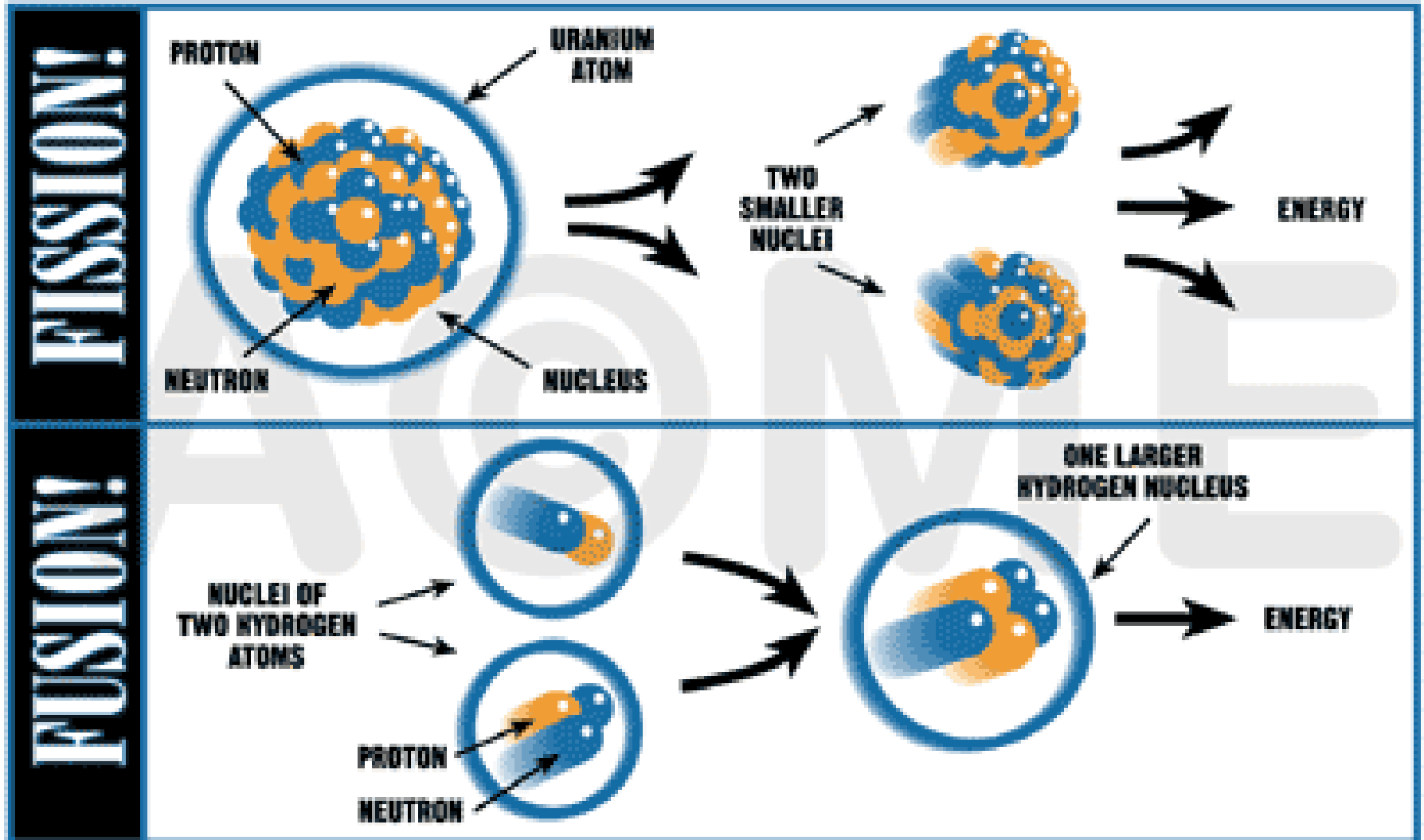
Structure of an Old High-Mass Star



Why does nuclear fusion stop at Iron?



Fusion versus Fission



12

Mg

Magnesium

24.305

Atomic number

Element's symbol

Element's name

Atomic mass*

*Atomic masses are fractions because they represent a weighted average of atomic masses of different isotopes—in proportion to the abundance of each isotope on Earth.

1 H Hydrogen 1.00794	3 Li Lithium 6.941	4 Be Beryllium 9.01218	5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.988	10 Ne Neon 20.179									
11 Na Sodium 22.990	12 Mg Magnesium 24.305	13 Al Aluminum 26.98	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.06	17 Cl Chlorine 35.453	18 Ar Argon 39.948										
19 K Potassium 39.098	20 Ca Calcium 40.08	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.94	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.847	27 Co Cobalt 58.9332	28 Ni Nickel 58.69	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.72	32 Ge Germanium 72.59	33 As Arsenic 74.922	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Fr Francium 83.80
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.9059	40 Zr Zirconium 91.224	41 Nb Niobium 92.91	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.41	49 In Indium 114.82	50 Sn Tin 118.71	51 Sb Antimony 121.75	52 Te Tellurium 127.60	53 I Iodine 126.905	54 Xe Xenon 131.29
55 Cs Cesium 132.91	56 Ba Barium 137.34		72 Hf Hafnium 178.49	73 Ta Tantalum 180.95	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.2	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium 226.0254		104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (262)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 Uun Ununnilium (269)	111 Uuu Unununium (272)	112 Uub Unbibium (277)						

Lanthanide Series

57 La Lanthanum 138.906	58 Ce Cerium 140.12	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.96	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
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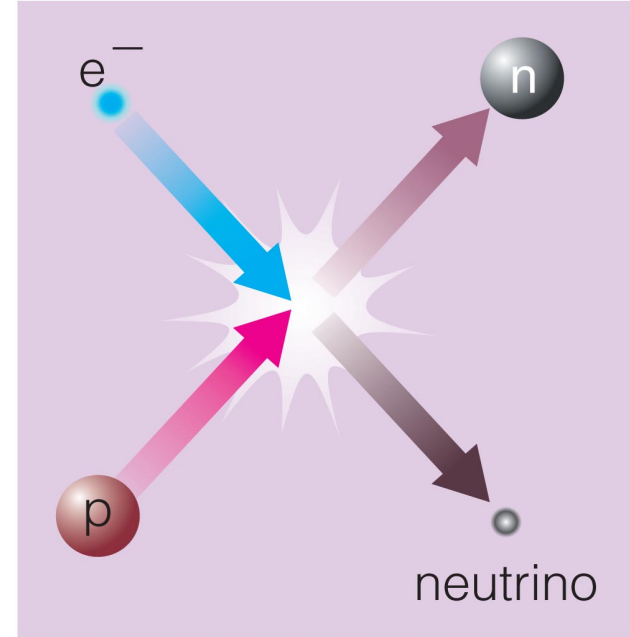
Actinide Series

89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (260)
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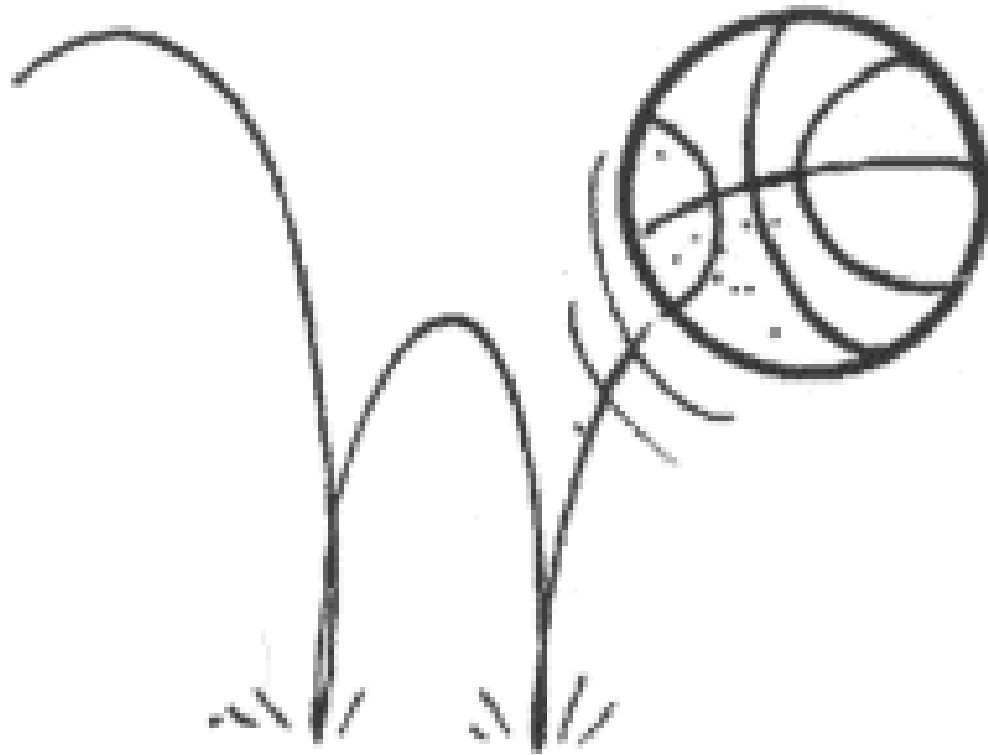
Fusion in massive stars makes elements like Ne, Si, S, Ca, Fe

Core collapse

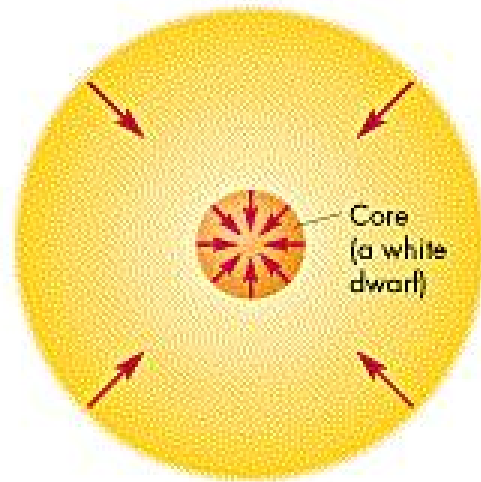
- Iron core is degenerate
- Core grows until it is too heavy to support itself
- Core collapses, density increases, normal iron nuclei are converted into neutrons with the emission of neutrinos
- Core collapse stops, neutron star is formed
- Rest of the star collapses in on the core, but bounces off the new neutron star



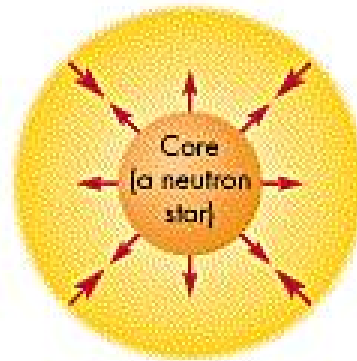
If I drop a ball, will it bounce
higher than it began?



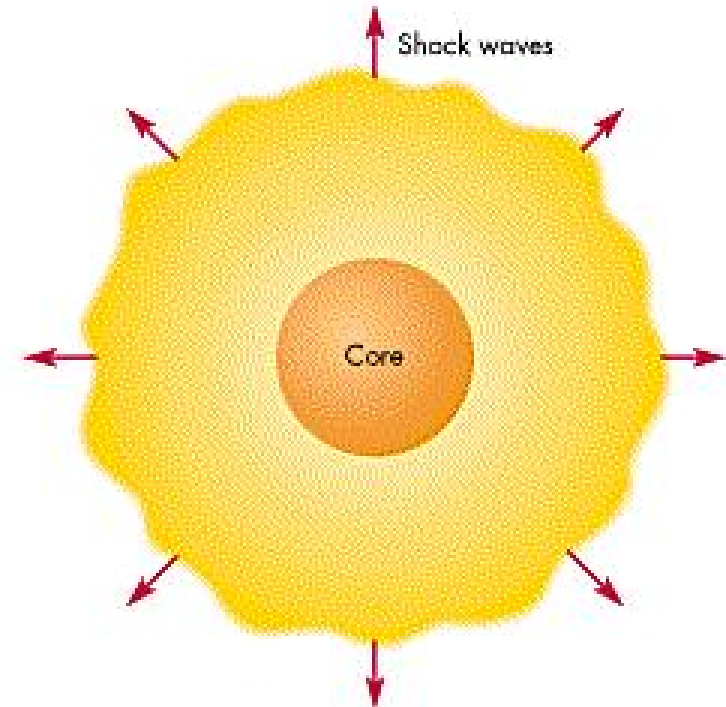
Supernova explosion



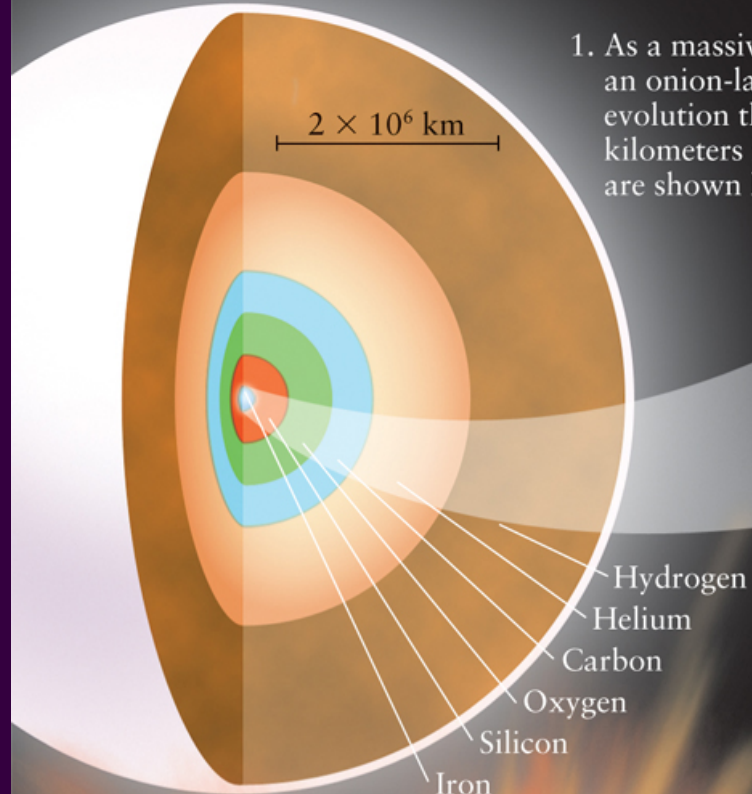
A Step 1: The iron core of the red giant collapses



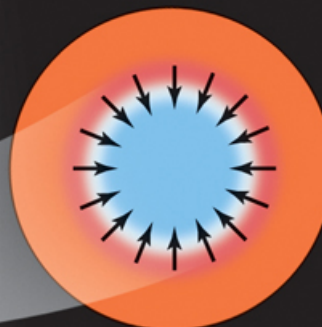
B Step 2: Neutron-rich core rebounds



C Step 3: The shock wave moves outward through the star

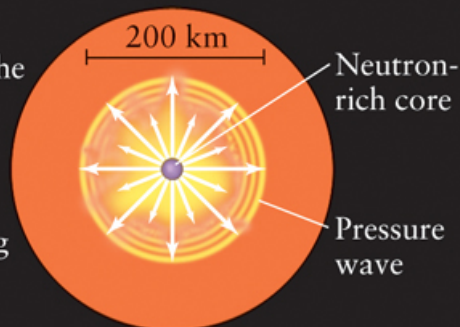


1. As a massive star nears its end, it takes on an onion-layer structure. At this point in its evolution the star is hundreds of millions of kilometers in radius; only its inner regions are shown here.

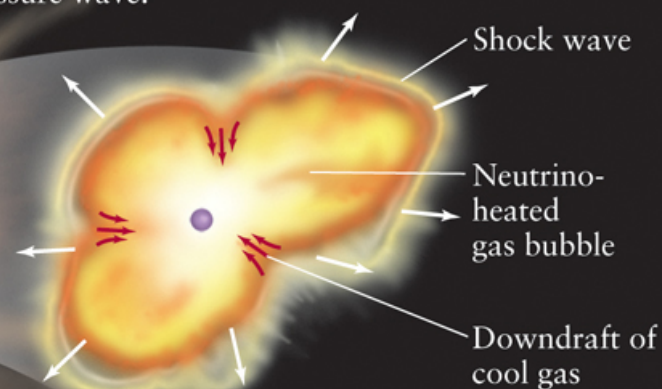


2. Iron does not undergo nuclear fusion, so the core becomes unable to generate heat. The gas pressure drops, and overlying material suddenly rushes in.

3. Within a second, the core collapses to nuclear density. Inward-falling material rebounds off the core, setting up an outward-going pressure wave.

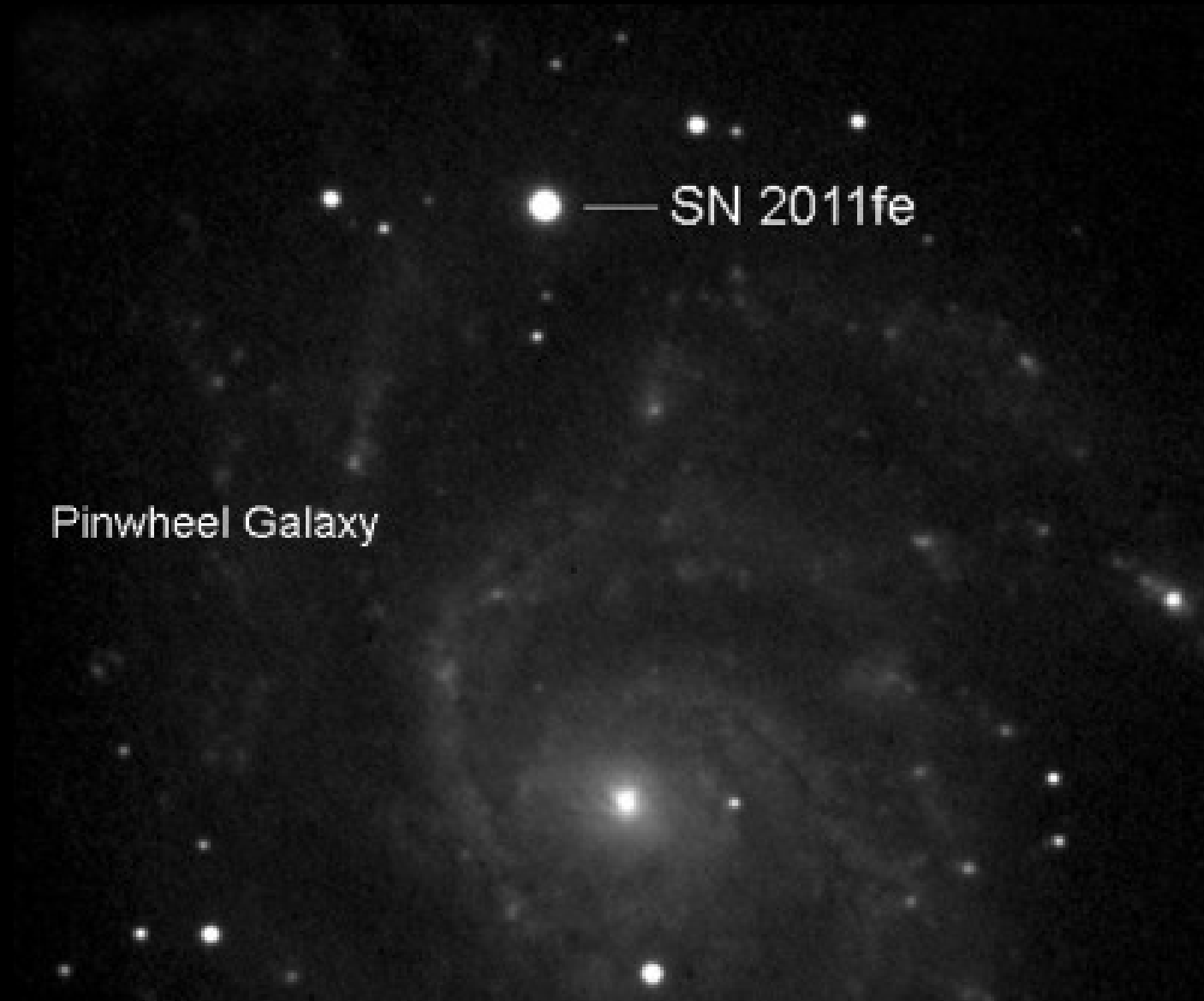


5. The shock wave sweeps through the entire star, blowing it apart.

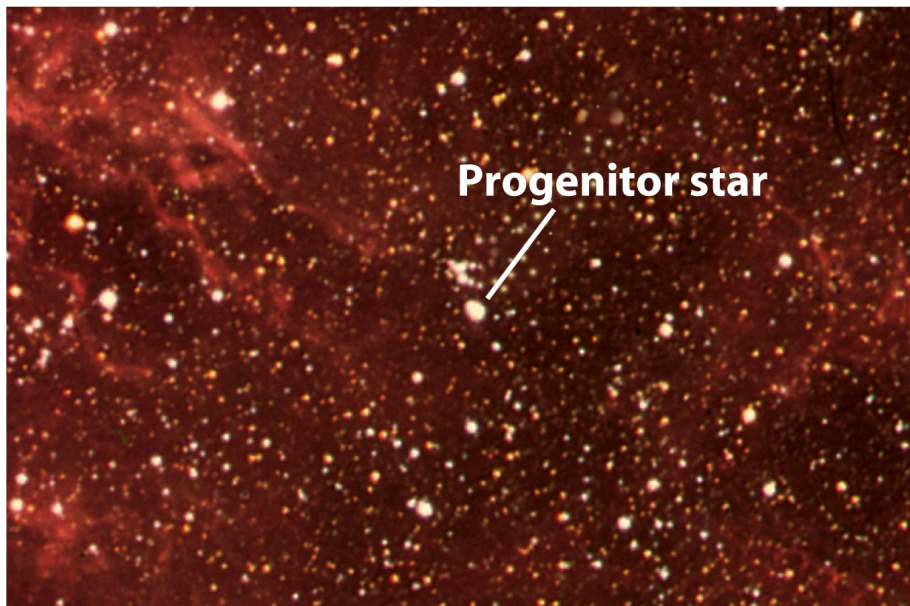


4. Neutrinos pouring out of the developing neutron star propel the shock wave outward, unevenly.

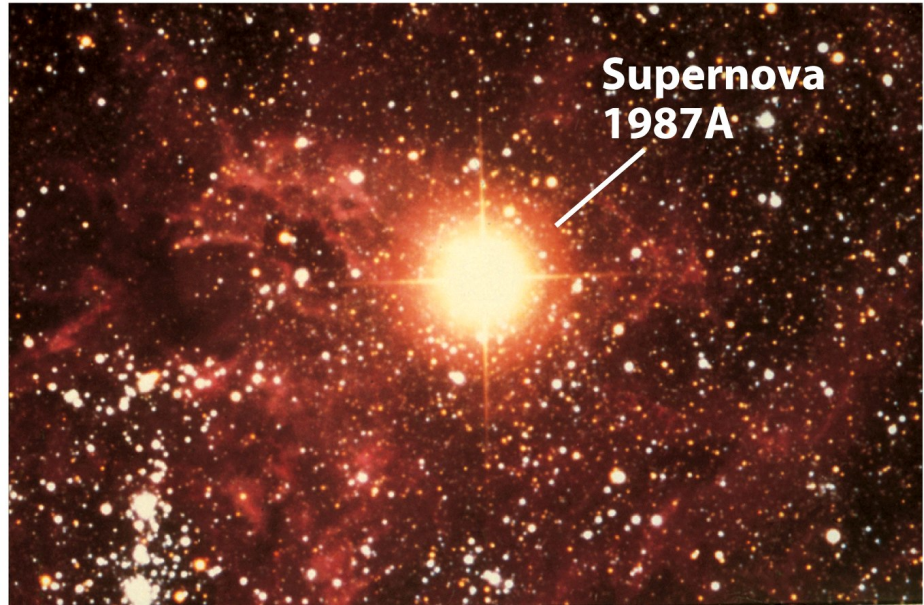
SN 2011fe in M101 (Pinwheel)



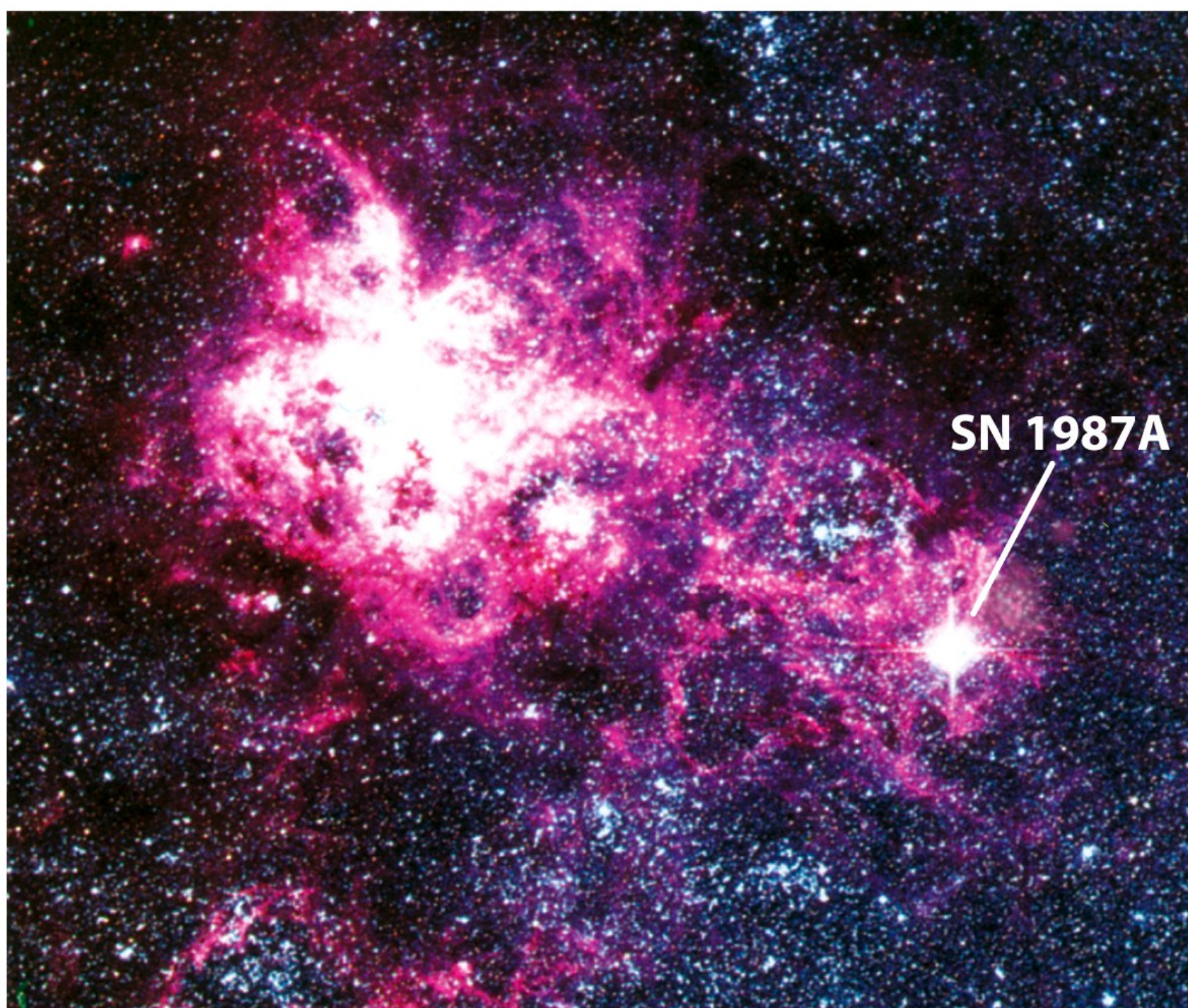
In 1987 a nearby supernova gave us
a close-up look at the death of a
massive star



Before the star exploded



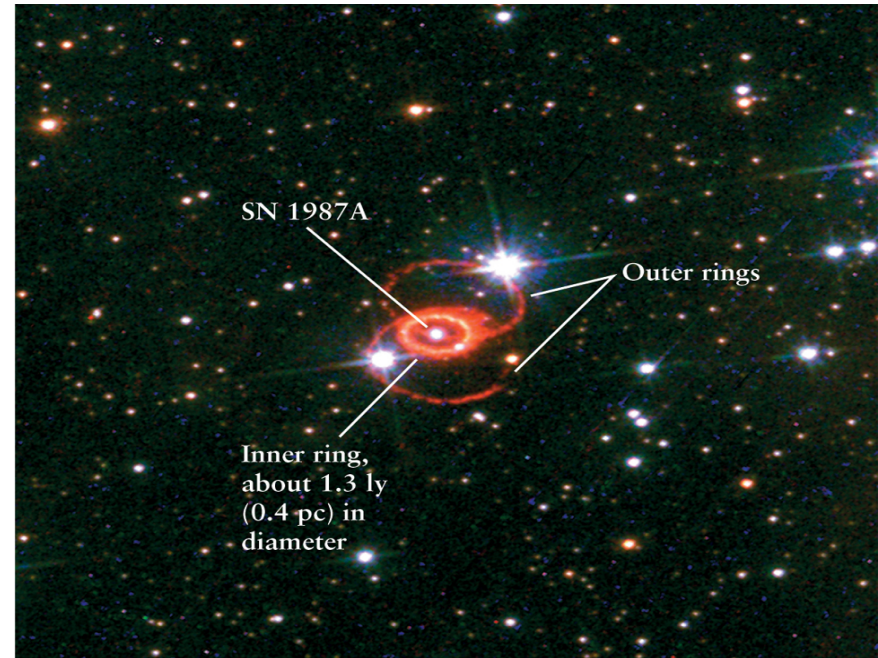
After the star exploded



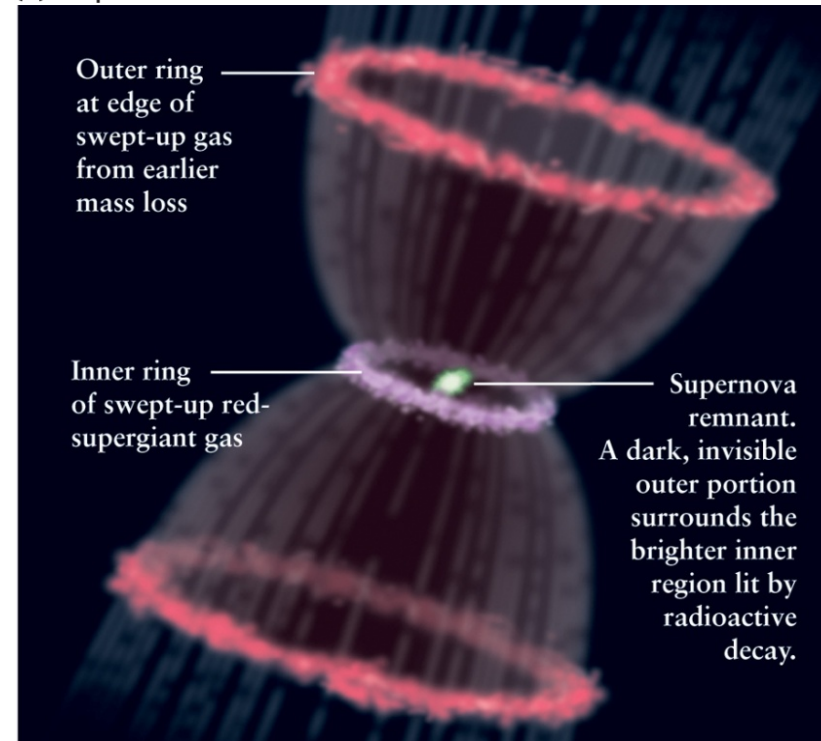
SN 1987A

An Unusual Supernova

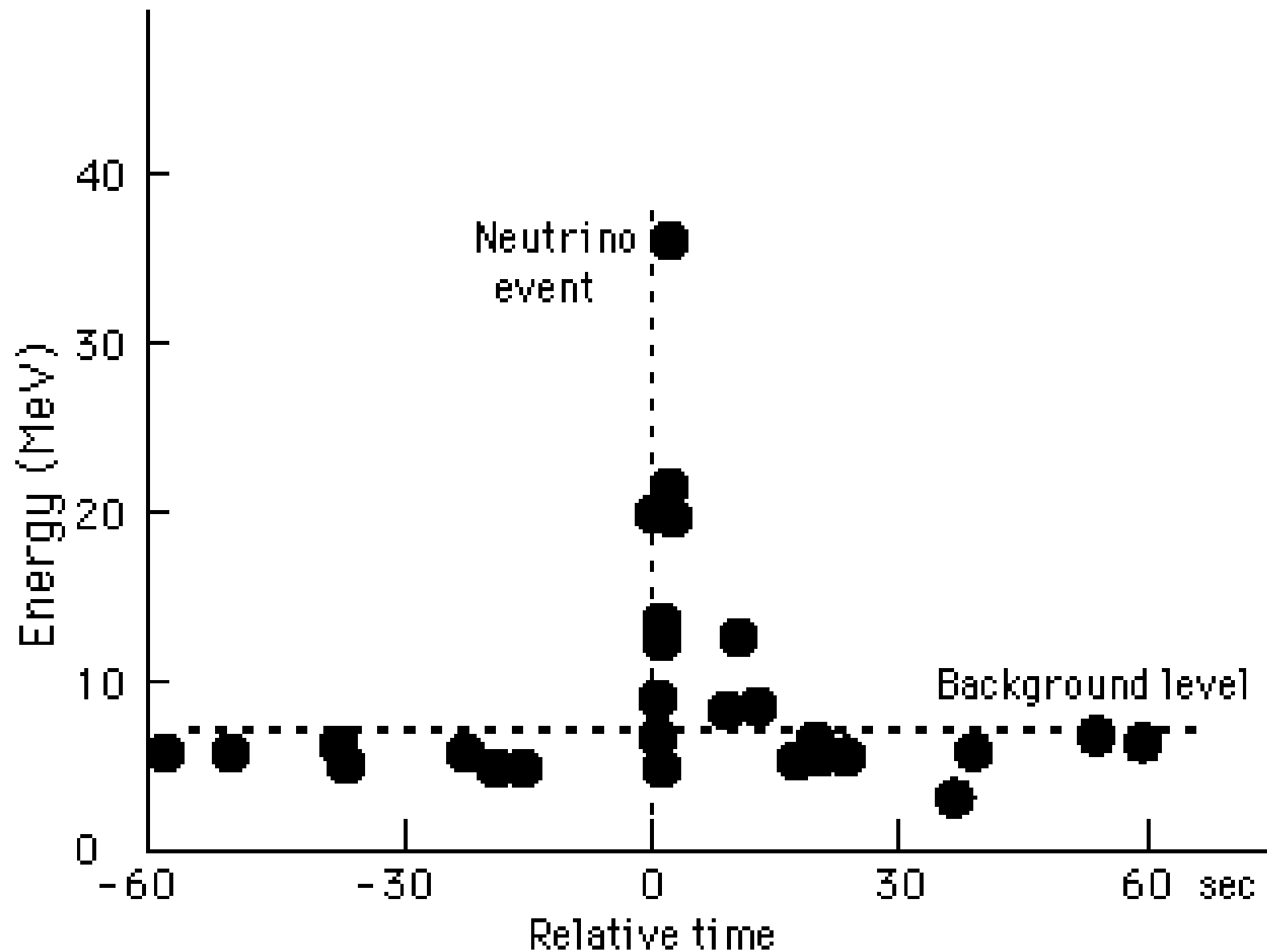
- SN 1987A appears to have a set of three glowing rings
- Relics of a hydrogen-rich outer atmosphere, ejected by gentle stellar winds from the star when it was a red supergiant.
- The gas expanded in a hourglass shape because it was blocked from expanding around the star's equator either by a preexisting ring of gas or by the orbit of an as-yet- unseen companion star.
- These rings were ionized by the initial flash of ultraviolet radiation from the supernova.



(a) Supernova 1987A seen in 1996



Neutrinos from SN1987A



Historical Supernovae



- Historically, supernovae were recorded as “guest stars”
- The supernova that produced the “Crab” pulsar went off in 1054 AD and was brighter than Venus. It was recorded by Arab, Chinese, and Japanese astronomers.
- This Anasazi drawing dates from around 1054 AD.



The Crab Nebula in Taurus (VLT KUEYEN + FORS2)

Nearby Supernova



- The Gum Nebula exploded around 9000 B.C.
- At maximum brilliance, the exploding star probably was as bright as the first-quarter moon.

Where do the elements in your body come from?

- Solar mass star produce elements up to Carbon and Oxygen – these are ejected into planetary nebula and then recycled into new stars and planets
- Supernova produce all of the heavier elements
 - Elements up to Iron can be produced by fusion
 - Elements heavier than Iron are produced by the neutrons and neutrinos interacting with nuclei in the supernova explosion

1

H

Hydrogen

1.00794

2

He

Helium

4.003

3

Li

Lithium

6.941

4

Be

Beryllium

9.01218

11

Na

Sodium

22.990

12

Mg

Magnesium

24.305

19

K

Potassium

39.098

20

Ca

Calcium

40.08

37

Rb

Rubidium

85.468

38

Sr

Strontium

87.62

55

Cs

Cesium

132.91

56

Ba

Barium

137.34

87

Fr

Francium

(223)

88

Ra

Radium

226.0254

21

Sc

Scandium

44.956

22

Ti

Titanium

47.88

23

V

Vanadium

50.94

24

Cr

Chromium

51.996

25

Mn

Manganese

54.938

26

Fe

Iron

55.847

27

Co

Cobalt

58.9332

28

Ni

Nickel

58.69

29

Cu

Copper

63.546

30

Zn

Zinc

65.39

31

Ga

Gallium

69.72

32

Ge

Germanium

72.59

33

As

Arsenic

74.922

34

Se

Selenium

78.96

35

Br

Bromine

79.904

36

Fr

Krypton

83.80

39

Y

Yttrium

88.9059

40

Zr

Zirconium

91.224

41

Nb

Niobium

92.91

42

Mo

Molybdenum

95.94

43

Tc

Technetium

(98)

44

Ru

Ruthenium

101.07

45

Rh

Rhodium

102.906

46

Pd

Palladium

106.42

47

Ag

Silver

107.868

48

Cd

Cadmium

112.41

49

In

Indium

114.82

50

Sn

Tin

118.71

51

Sb

Antimony

121.75

52

Te

Tellurium

127.60

53

I

Iodine

126.905

54

Xe

Xenon

131.29

72

Hf

Hafnium

178.49

73

Ta

Tantalum

180.95

74

W

Tungsten

183.85

75

Re

Rhenium

186.207

76

Os

Osmium

190.2

77

Ir

Iridium

192.22

78

Pt

Platinum

195.08

79

Au

Gold

196.967

80

Hg

Mercury

200.59

81

Tl

Thallium

204.383

82

Pb

Lead

207.2

83

Bi

Bismuth

208.98

84

Po

Polonium

(209)

85

At

Astatine

(210)

86

Rn

Radon

(222)

104

Rf

Rutherfordium

(261)

105

Db

Dubnium

(262)

106

Sg

Seaborgium

(263)

107

Bh

Bohrium

(262)

108

Hs

Hassium

(265)

109

Mt

Meitnerium

(266)

110

Uun

Ununnilium

(269)

111

Uuu

Unununium

(272)

112

Uub

Ununbium

(277)

57

La

Lanthanum

138.906

58

Ce

Cerium

140.12

59

Pr

Praseodymium

140.908

60

Nd

Neodymium

144.24

61

Pm

Promethium

(145)

62

Sm

Samarium

150.36

63

Eu

Europium

151.96

64

Gd

Gadolinium

157.25

65

Tb

Terbium

158.925

66

Dy

Dysprosium

162.50

67

Ho

Holmium

164.93

68

Er

Erbium

167.26

69

Tm

Thulium

168.934

70

Yb

Ytterbium

173.04

71

Lu

Lutetium

174.967

89

Ac

Actinium

227.028

90

Th

Thorium

232.038

91

Pa

Protactinium

231.036

92

U

Uranium

238.029

93

Np

Neptunium

237.048

94

Pu

Plutonium

(244)

95

Am

Americium

(243)

96

Cm

Curium

(247)

97

Bk

Berkelium

(247)

98

Cf

Californium

(251)

99

Es

Einsteinium

(252)

100

Fm

Fermium

(257)

101

Md

Mendelevium

(258)

102

No

Nobelium

(259)

103

Lr

Lawrencium

(260)

12

Mg

Magnesium

24.305

Atomic number

Element's symbol

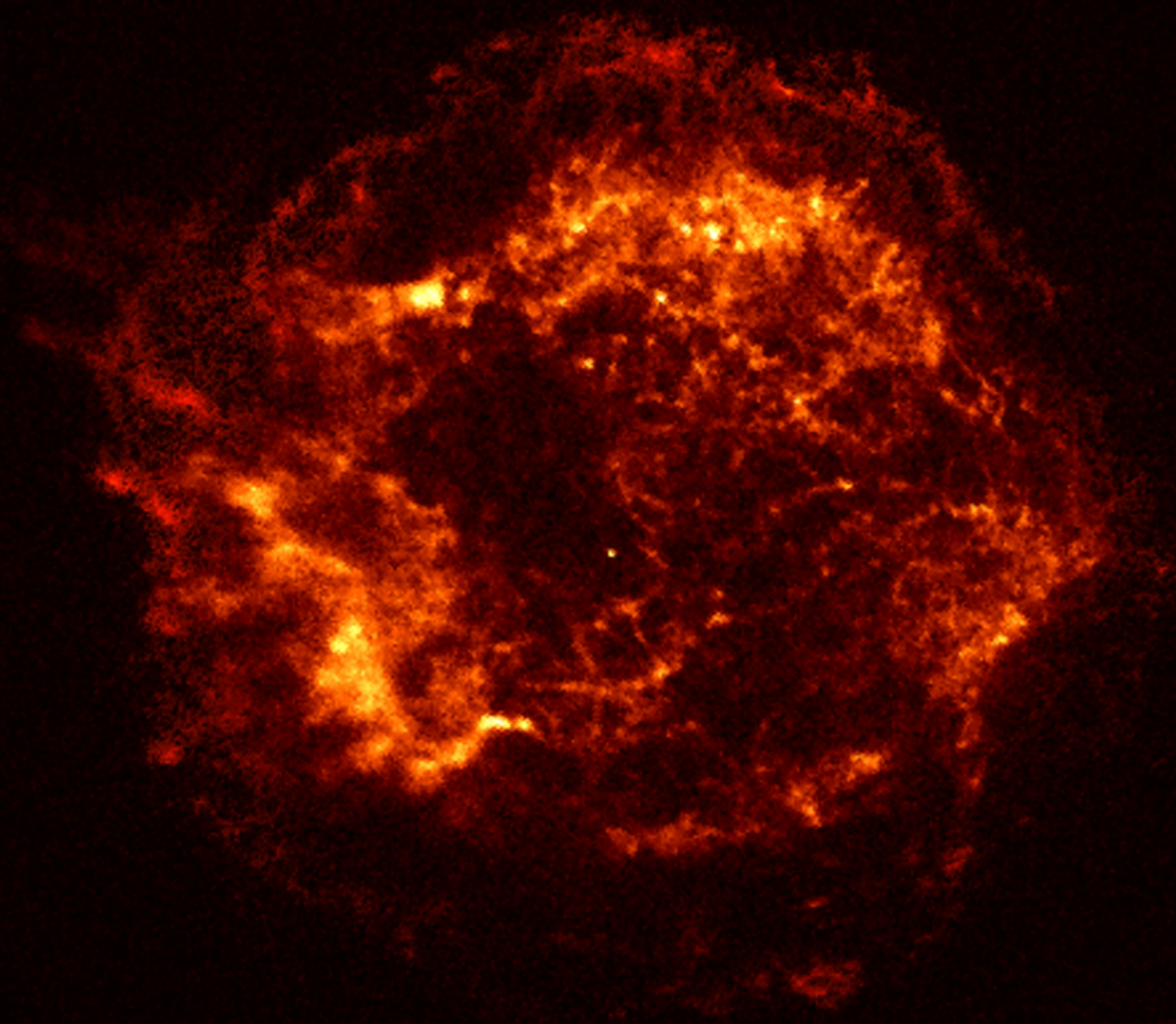
Element's name

Atomic mass*

*Atomic masses are fractions because they represent a weighted average of atomic masses of different isotopes—in proportion to the abundance of each isotope on Earth.

Energy and neutrons in supernova form heavy elements.

Decay of radioactive elements powers supernova after explosion.



How does the life of a high mass star differ from the Sun's life?

- A) It forms much faster
- B) It lives a shorter time on the main sequence
- C) It makes elements heavier than carbon via fusion
- D) When it dies it explodes in a tremendous supernova explosion
- E) All of the above

The most massive stars end all fusion with a core composed of

- A) carbon
- B) neon
- C) iron
- D) silicon
- E) sulfur

How long does the neon fusion stage last
in a one solar mass star?

- A) 1 year
- B) 10 years
- C) 1000 years
- D) A one solar mass star never fuses neon

After the initial explosion of a massive star, how does a supernova continue to radiate?

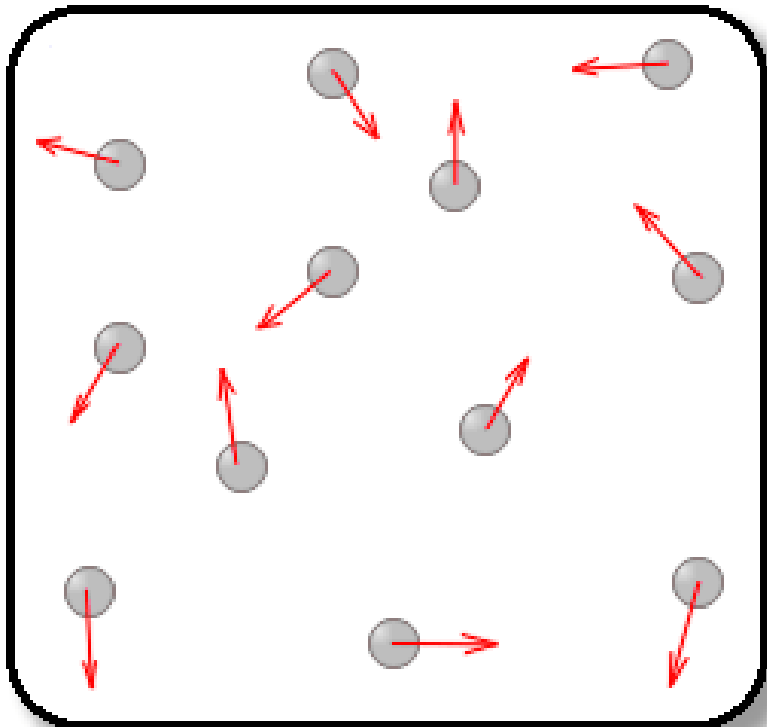
A) High-speed winds from the core remains ionize the ejected material.

B) High-energy radiation is emitted from the core remains due to its high temperature.

C) Unstable elements created in the explosion radioactively decay and emit gamma rays.

Pressure and Temperature

- Pressure is the force exerted by atoms in a gas
- Temperature is a measure of how fast the atoms in a gas move



- Hotter → atoms move faster → higher pressure
- Cooler → atoms move slower → lower pressure

Do cold balloon demo

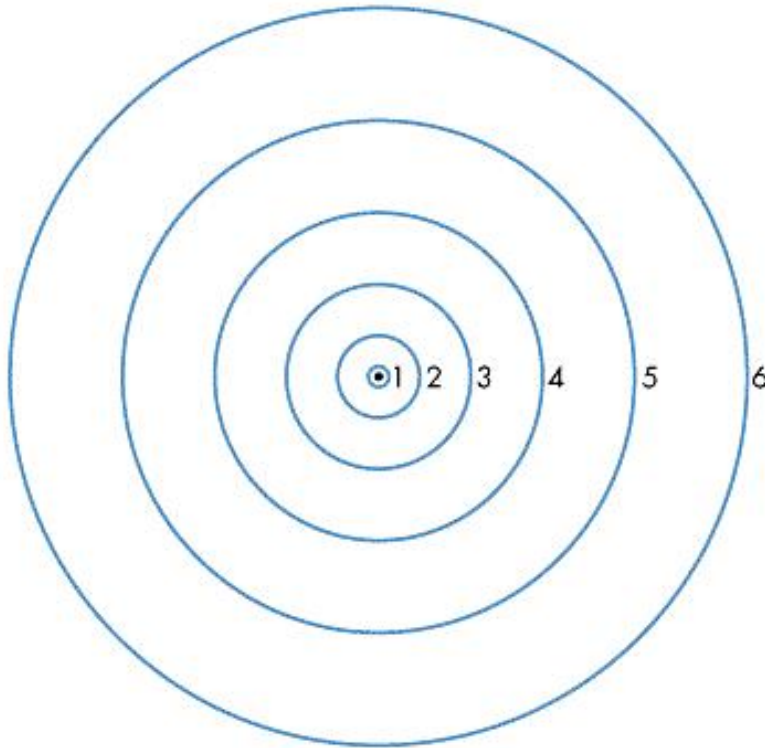
Degenerate gas

- Very high density
- Motion of atoms is not due to kinetic energy, but instead due to quantum mechanical motions
- Pressure no longer depends on temperature
- This type of gas is sometimes found in the cores of stars

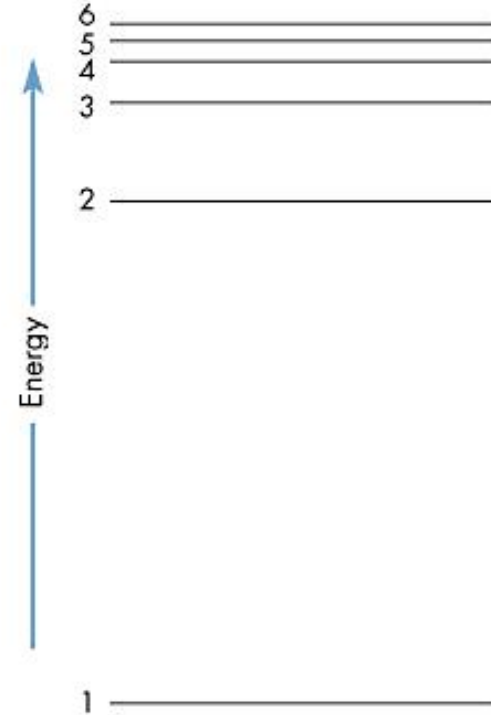
Pauli exclusion principle

- No two electrons can occupy the same quantum state

Electron orbits



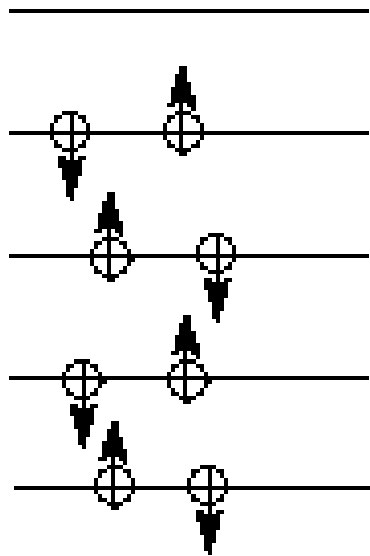
A Possible distances of the electron in a hydrogen atom



B Energy levels for the hydrogen atom

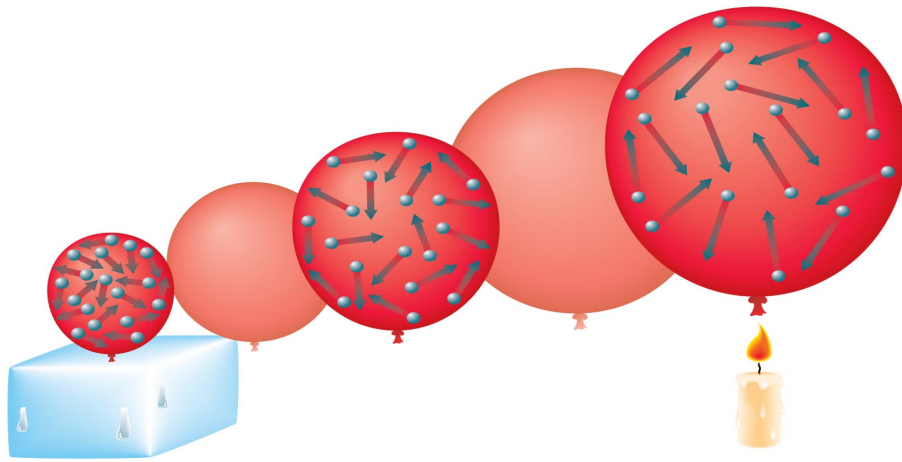
Only two electrons (one up, one down) can go into each energy level

Electron energy levels



Degenerate gas: all lower energy levels filled with two particles each (opposite spins). Particles **locked** in place.

- Only two electrons (one up, one down) can go into each energy level.
- In a degenerate gas, all low energy levels are filled.
- Electrons have energy, and therefore are in motion and exert pressure even if temperature is zero.

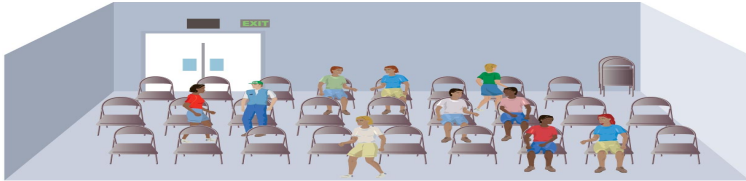


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Thermal Pressure:

Depends on heat content

The main form of pressure in most stars



a When there are many more available quantum states (chairs) than electrons (people), an electron is unlikely to try to enter the same state as another electron. The only pressure comes from the temperature-related motion of the electrons, which is the thermal pressure.



b When the number of electrons (people) approaches the number of available quantum states (chairs), finding an available state requires that the electrons move faster than they would otherwise. This extra motion creates degeneracy pressure.

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Degeneracy Pressure:

Particles can't be in same state in same place

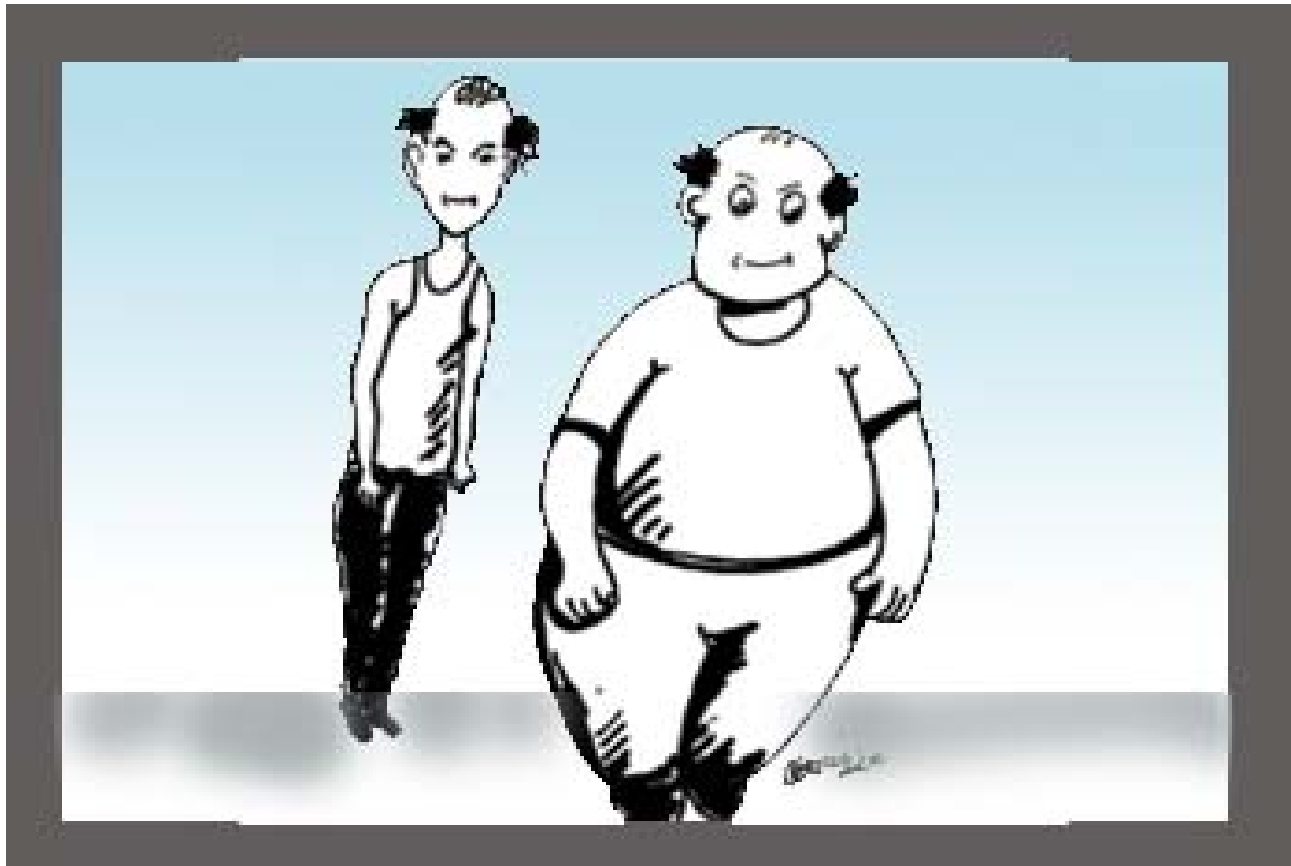
Doesn't depend on heat content

White dwarf



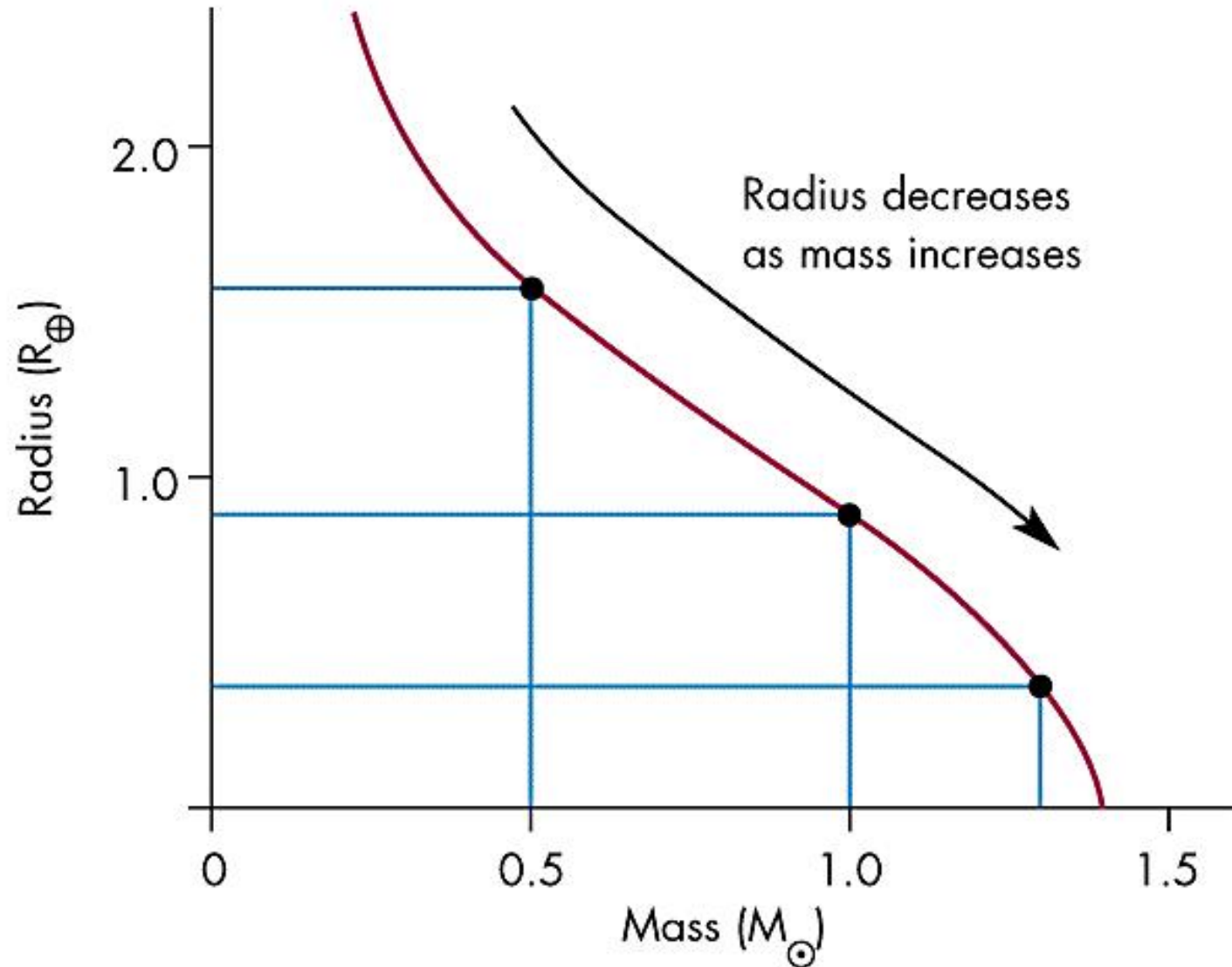
- Core of solar mass star
- Degenerate gas of oxygen and carbon
- No energy from fusion or gravitational contraction

Mass versus radius relation



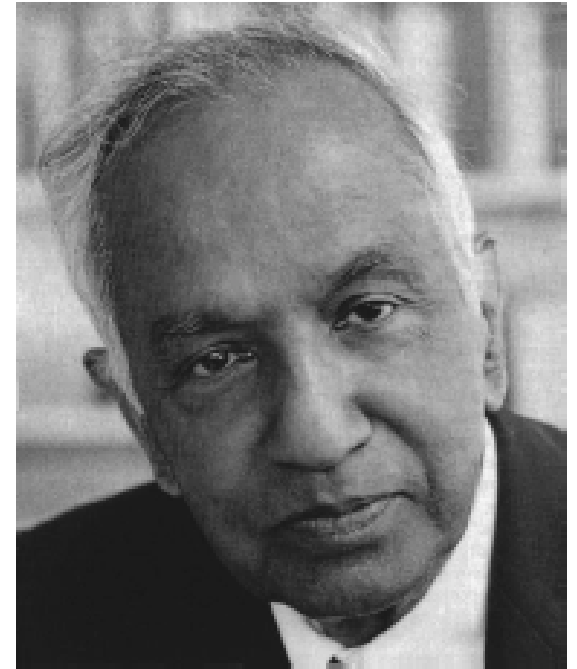
- For objects made of normal matter, radius tends to increase with mass

Mass versus radius relation



Maximum white dwarf mass

- Electron degeneracy cannot support a white dwarf heavier than 1.4 solar masses
- This is the “Chandrasekhar limit”
- Won Chandrasekhar the 1983 Nobel prize in Physics



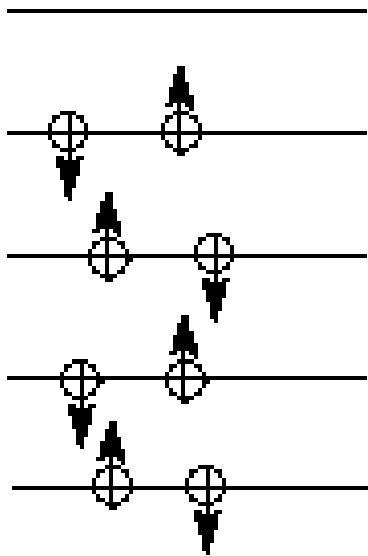
What happens to a star more massive than 1.4 solar masses?

- A) There aren't any
- B) They shrink to zero size
- C) They explode
- D) They become something else

Neutron Stars

- Degenerate stars heavier than 1.4 solar masses collapse to become neutron stars
- Formed in supernova explosions
- Electrons are not separate
 - Combine with nuclei to form neutrons
- Neutron stars are degenerate gas of neutrons

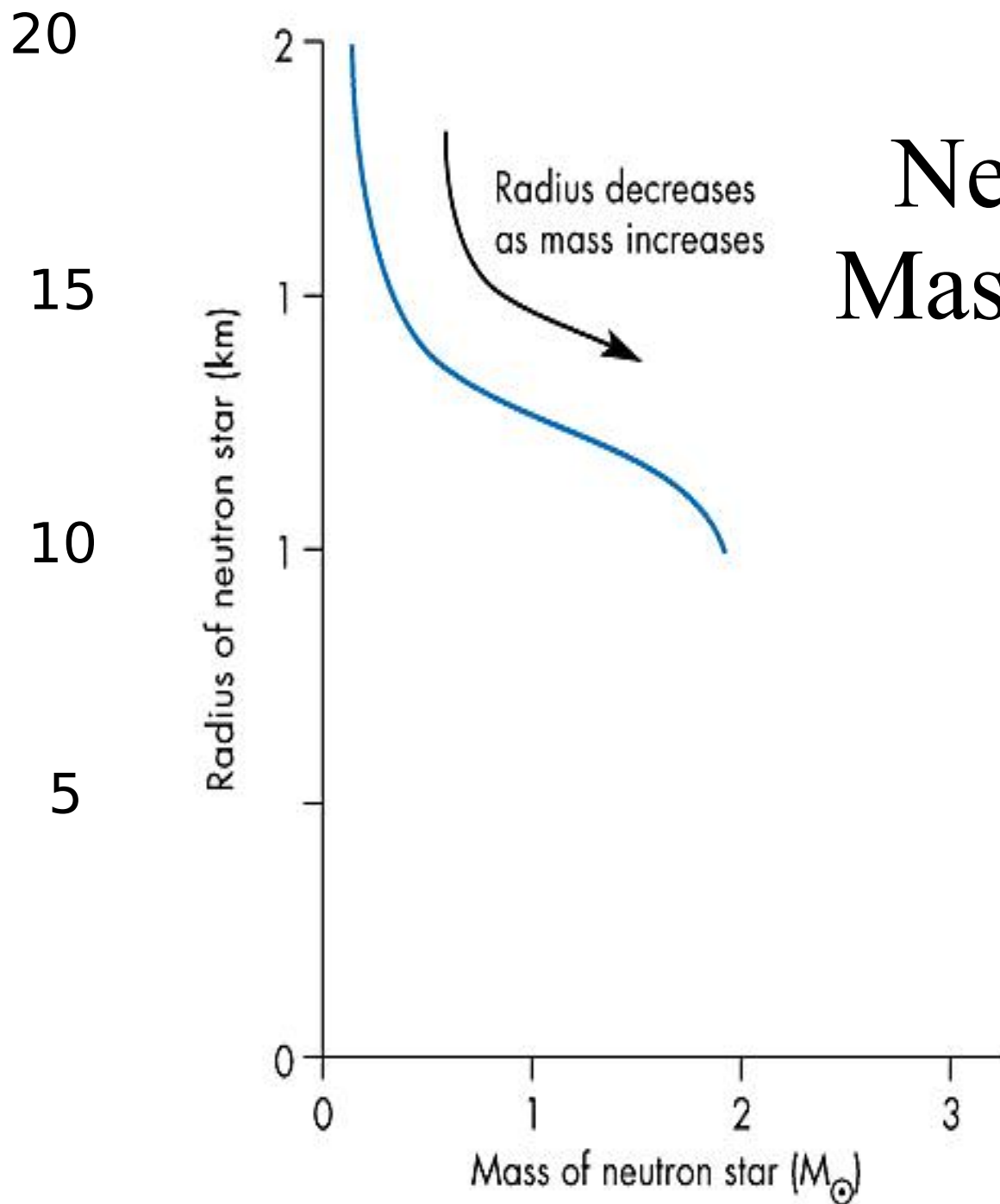
Neutron energy levels



Degenerate gas: all lower energy levels filled with two particles each (opposite spins). Particles **locked** in place.

- Only two neutrons (one up, one down) can go into each energy level.
- In a degenerate gas, all low energy levels are filled.
- Neutrons have energy, and therefore are in motion and exert pressure even if temperature is zero.
- Neutron star are supported by neutron degeneracy.

Neutron Star Mass vs Radius

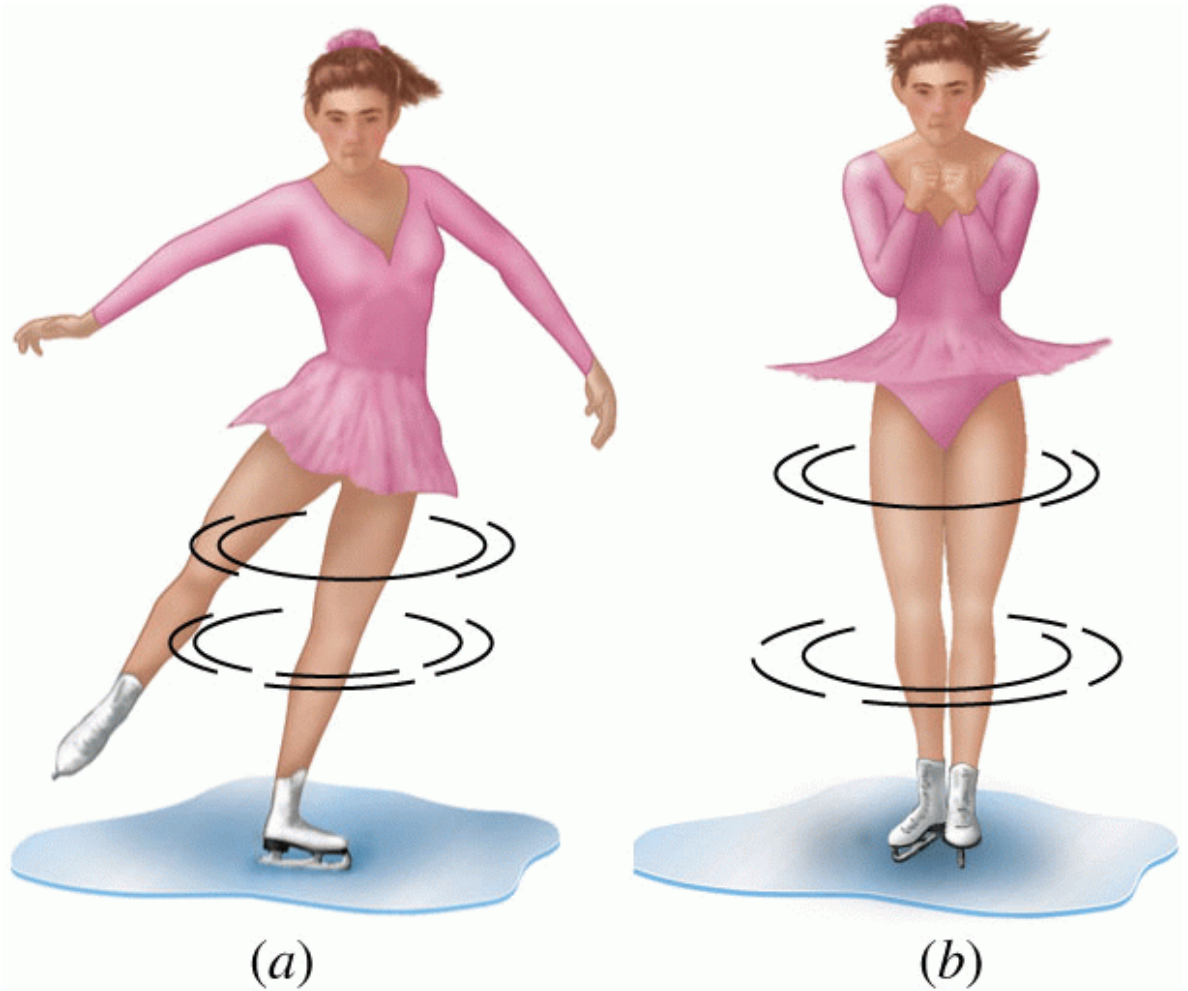


Neutron Stars

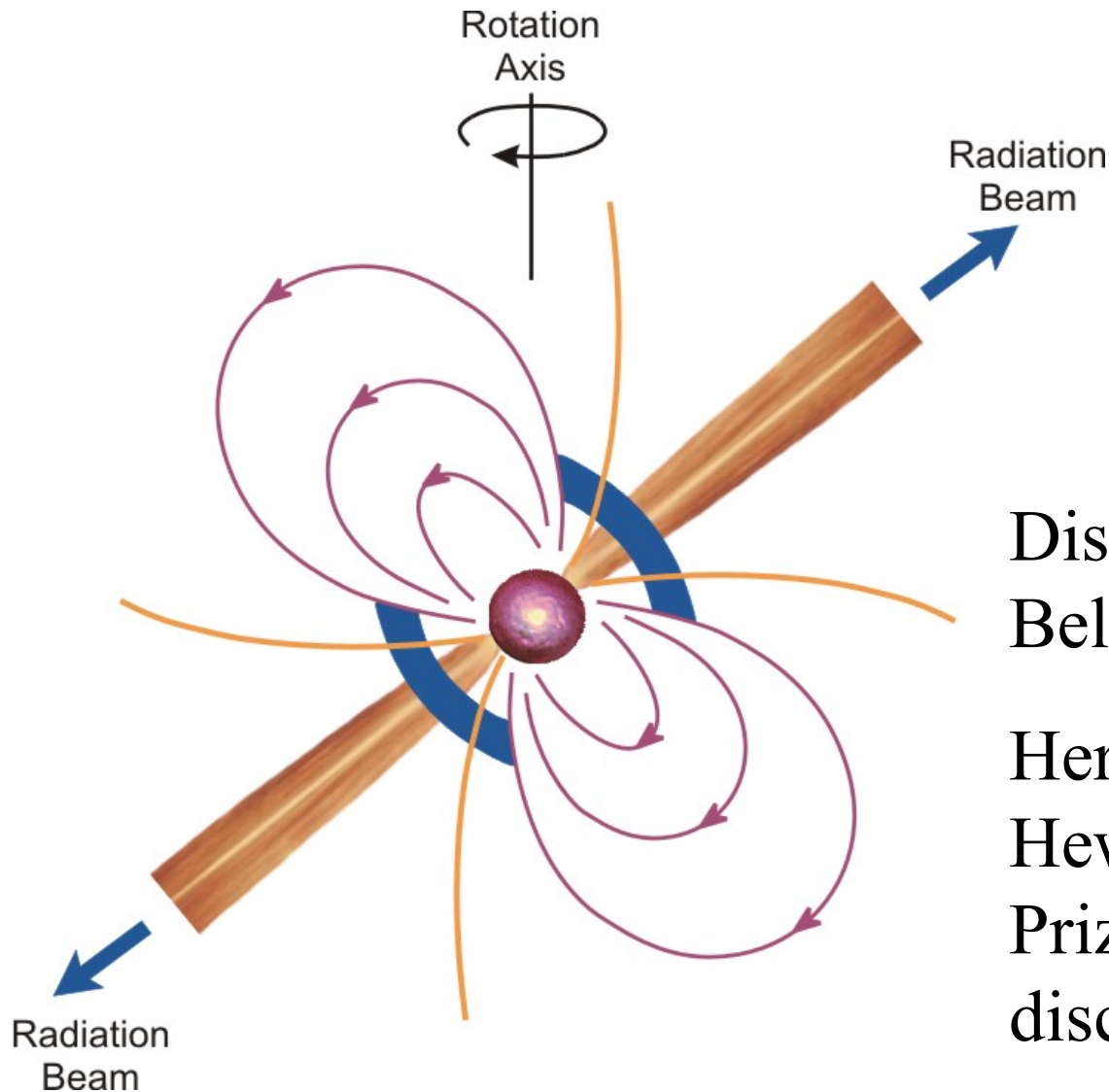
- Very compact – about 10 km radius
- Very dense – one teaspoon of neutron star material weighs as much as all the buildings in Manhattan
- Spin rapidly – as fast as 600 times per second
- High magnetic fields – compressed from magnetic field of progenitor star

Spin up of neutron star

Collapse of star
increases both
spin and
magnetic field



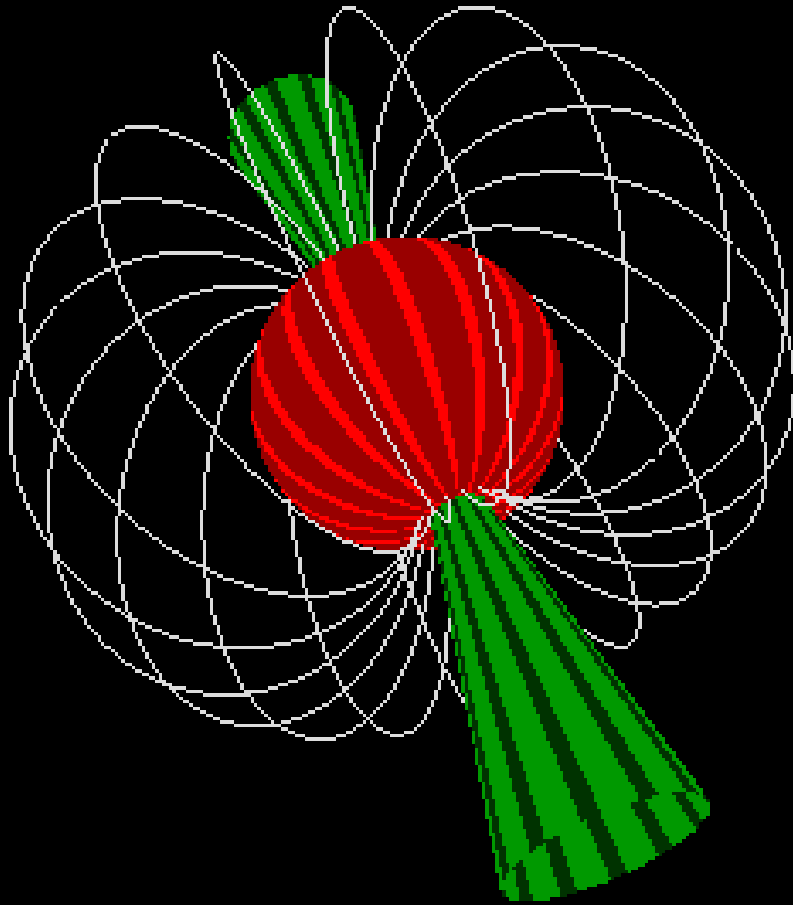
Pulsars



Discovered by Jocelyn Bell in 1967.

Her advisor, Anthony Hewish, won the Nobel Prize in Physics for the discovery in 1974.

Pulsars



Energy source
is spin down of
neutron star.

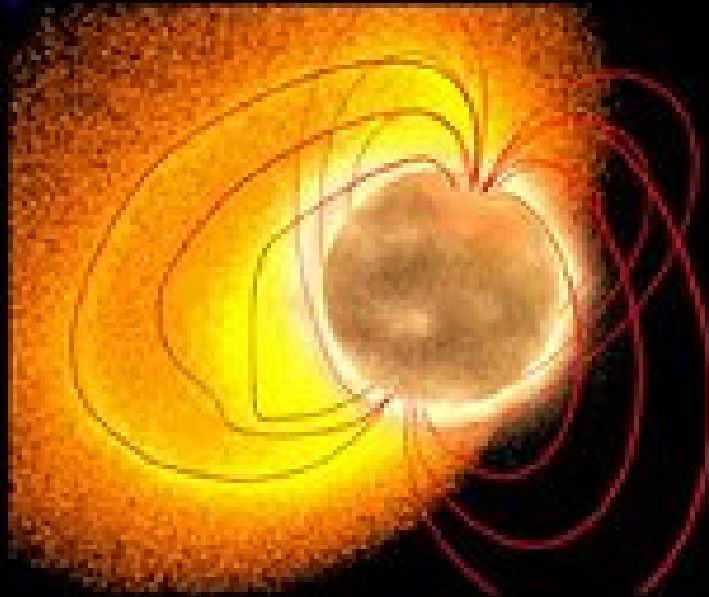
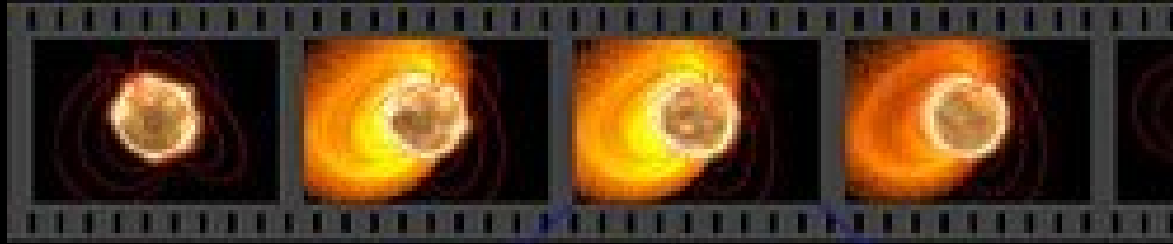
Must lie along
pulsar beam to
see pulsed
signals.

Crab Pulsar



Magnetars

Magnetar burst sequence

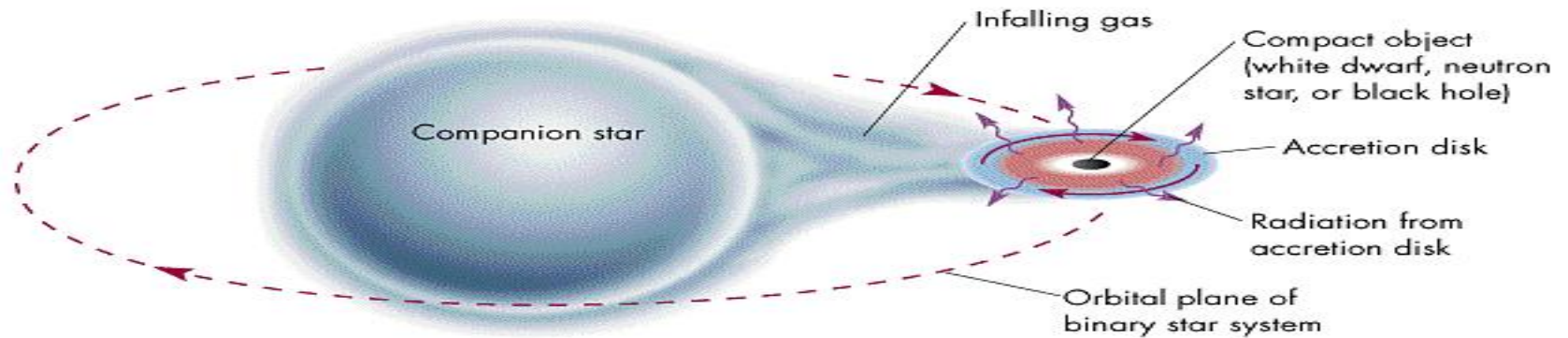


Magnetic fields so strong that they produce starquakes on the neutron star surface.

These quakes produce huge flashes of X-rays and Gamma-rays.

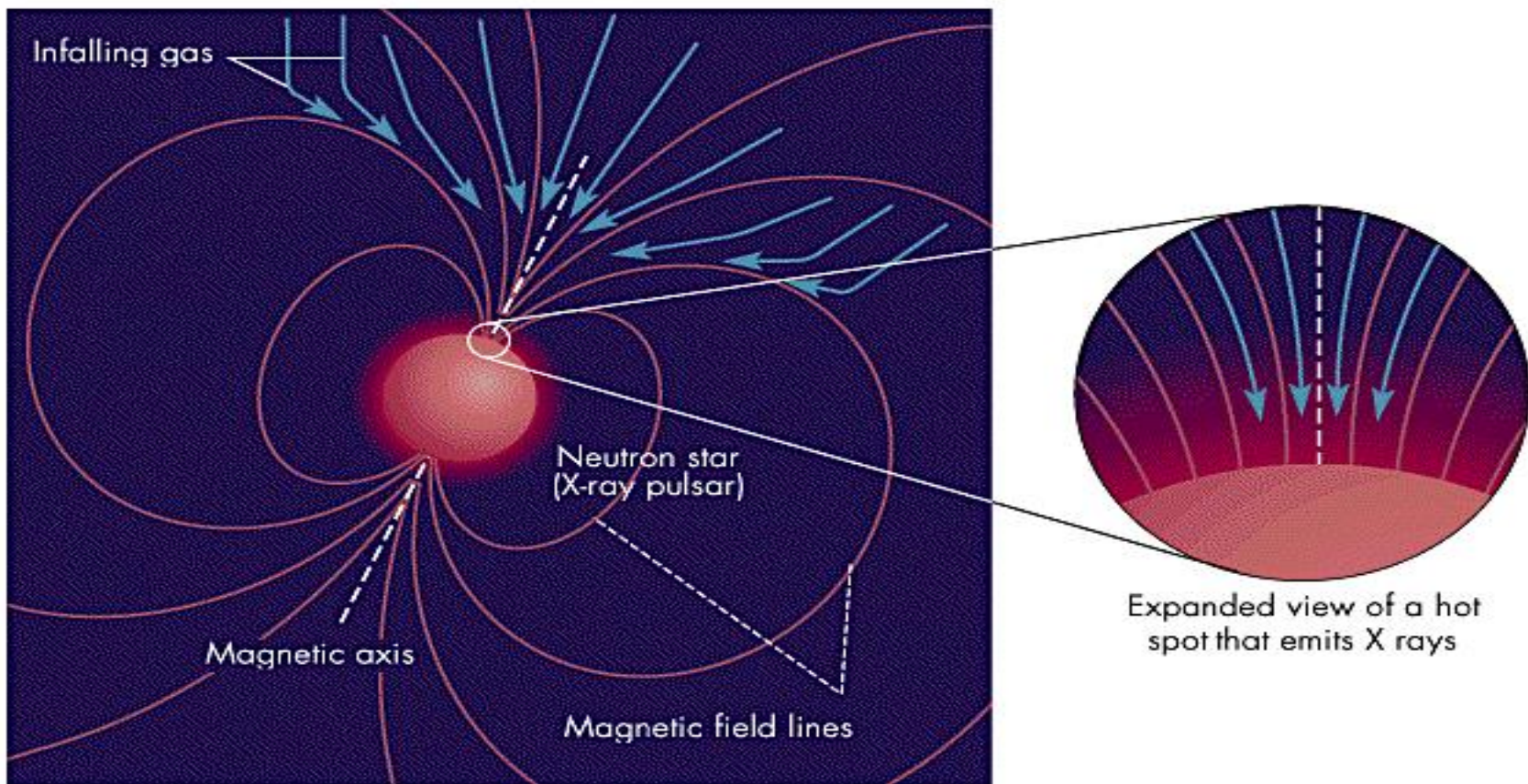
Energy source is magnetic field.

X-Ray Pulsars



Neutron star in binary system with a normal star

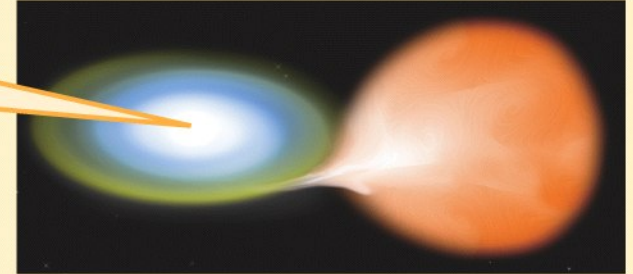
X-Ray Pulsars



High magnetic field neutron stars make regular pulsations. Energy source is gravitational energy of infalling matter.

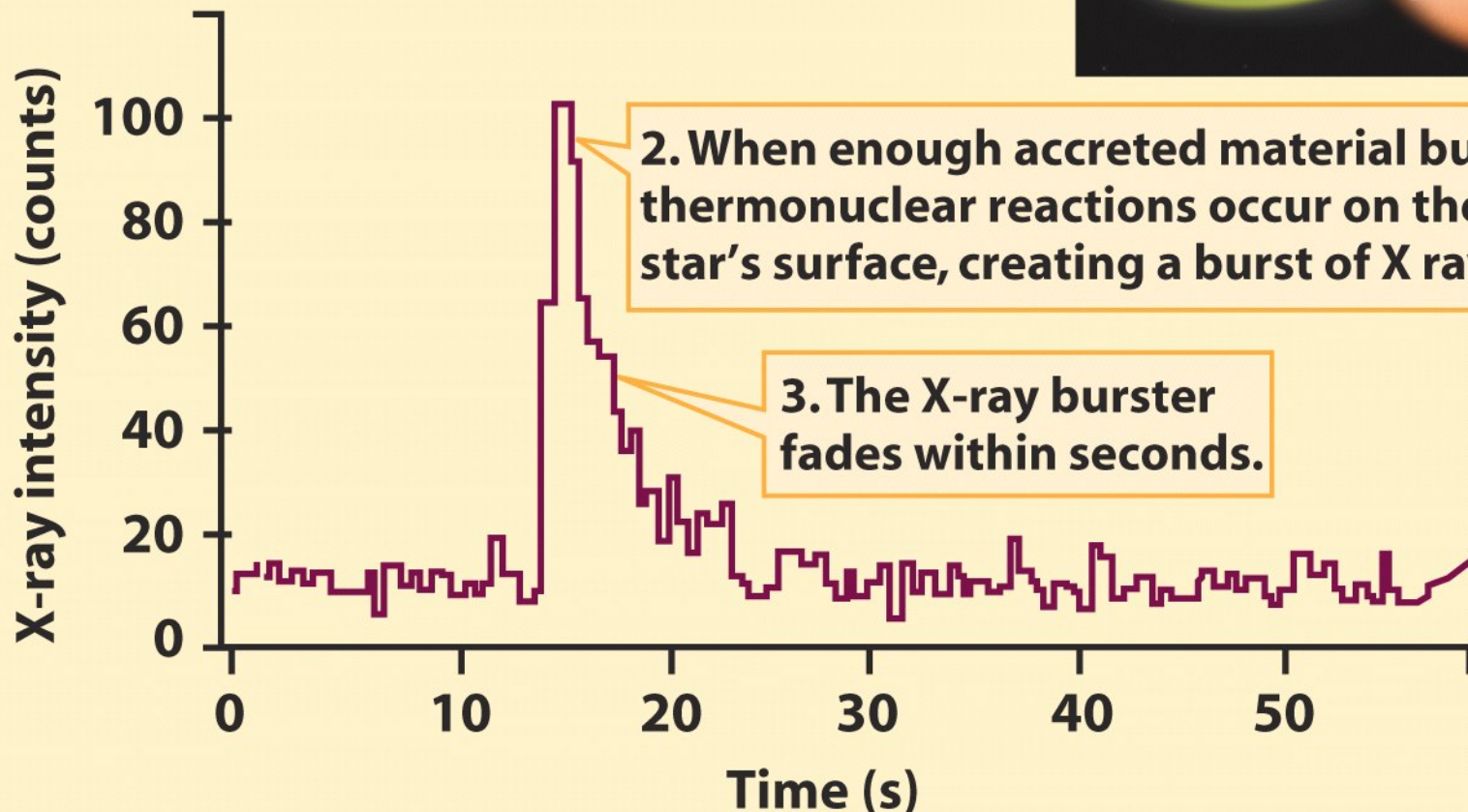
X-ray Bursters

1. Material from a star accretes onto a companion neutron star.



2. When enough accreted material builds up, thermonuclear reactions occur on the neutron star's surface, creating a burst of X rays.

3. The X-ray burster fades within seconds.



X-ray Burst



Low magnetic field neutron stars make X-ray bursts.

Source of energy is nuclear burning.

A pulsar is a rapidly rotating

- A) White dwarf
- B) Neutron star
- C) Black hole
- D) Any of the above

Review Questions

- How does the evolution of a high mass star differ from that of a low mass star?
- How can the age of a cluster of stars, all formed at the same time, be determined?
- Why does fusion stop at Iron?
- How are heavy elements produced?

Review Questions

- What is the Fermi exclusion principle?
- Does a more massive white dwarf have a larger or smaller radius than a less massive one?
- What is the maximum mass of a white dwarf?
- What are some of the properties of neutron stars?
- Why do many neutron stars spin rapidly?
- In what different forms does one find neutron stars?