ASTRONOMY
STATE OF THE ART

4. Stars

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Stars and Life

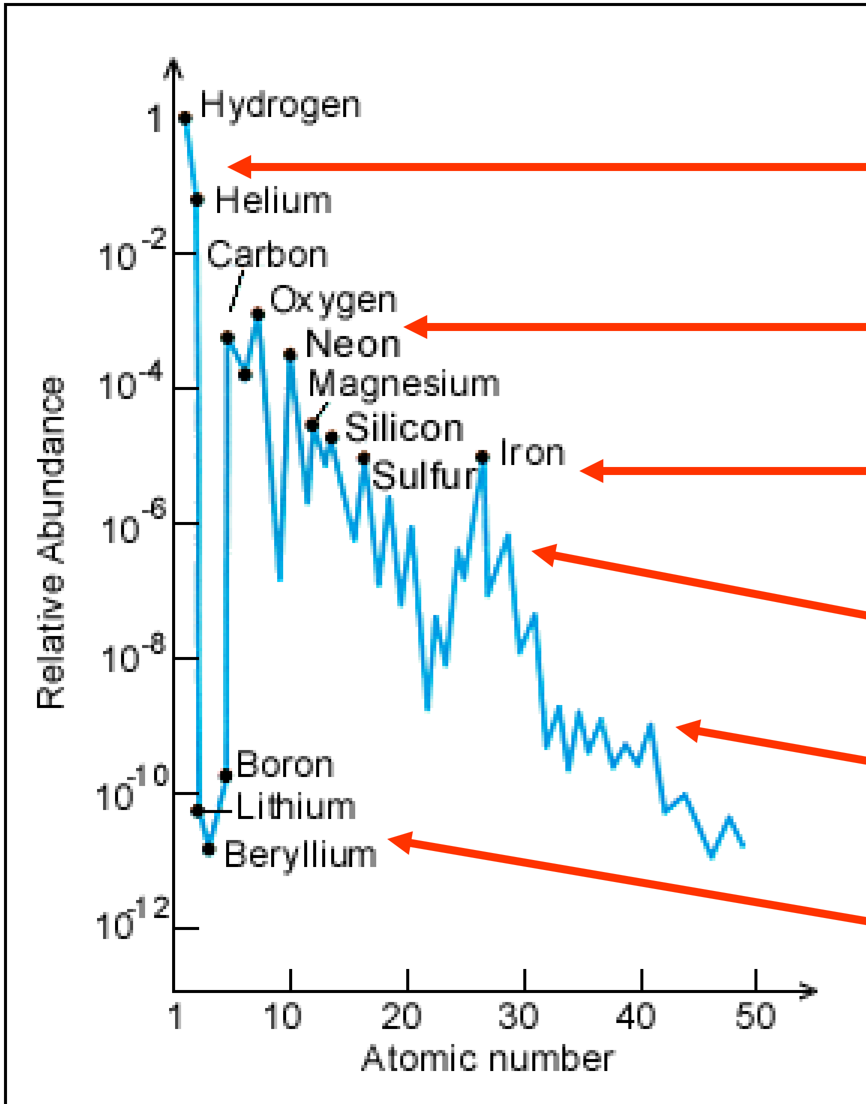
To understand the role of life in the universe, we first have to look at where the ingredients for life come from. These are the percentage of atoms in a typical sample of:

The Sun		Humans		Earth's Crust	
H	91%	H	61%	O	47%
He	9%	O	26%	Si	28%
O	0.078%	C	11%	Al	8%
C	0.033%	N	2.4%	Fe	5%
Ne	0.011%	Ca	0.23%	Ca	3.6%
N	0.010%	Ph	0.13%	Na	2.8%
Mg	0.004%	S	0.13%	K	2.6%

We see that C,N and O are enriched in living organisms by a factor of 300 relative to the typical stuff of stars and the universe as a whole, much of it in the form of water:

The Sun		**Humans**		**Earth's Crust**	
H	**91%**	**H**	**61%**	**O**	**47%**
He	**9%**	**O**	**26%**	**Si**	**28%**
O	**0.078%**	**C**	**11%**	**Al**	**8%**
C	**0.033%**	**N**	**2.4%**	**Fe**	**5%**
Ne	**0.011%**	**Ca**	**0.23%**	**Ca**	**3.6%**
N	**0.010%**	**Ph**	**0.13%**	**Na**	**2.8%**
Mg	**0.004%**	**S**	**0.13%**	**K**	**2.6%**

Cosmic Element Abundance



Main features are:

H and He are dominant

Second peak at C, N and O

Third peak at Iron

Overall saw-tooth pattern

Extreme rarity beyond Iron

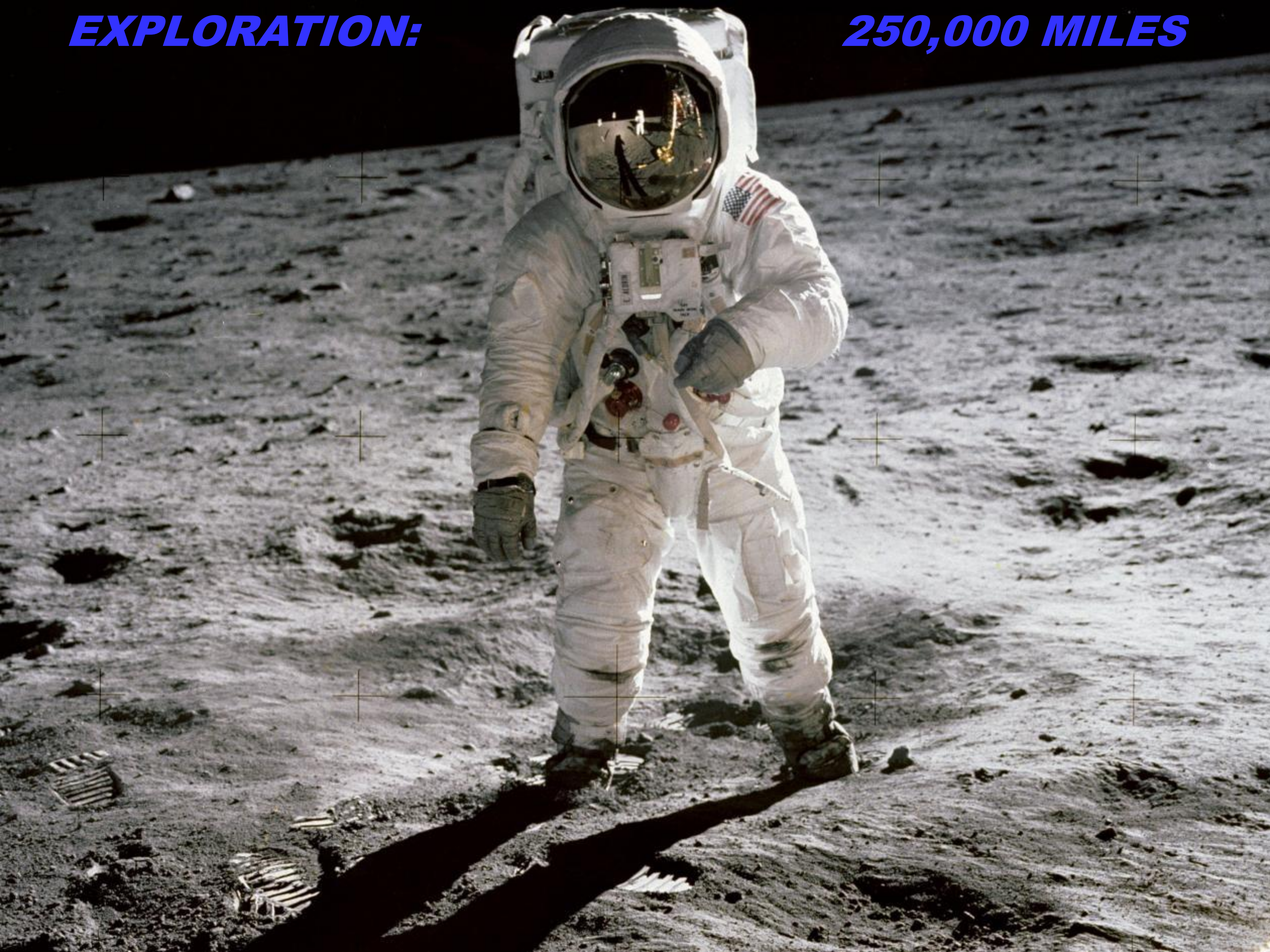
Light element trough

How can we explain this?

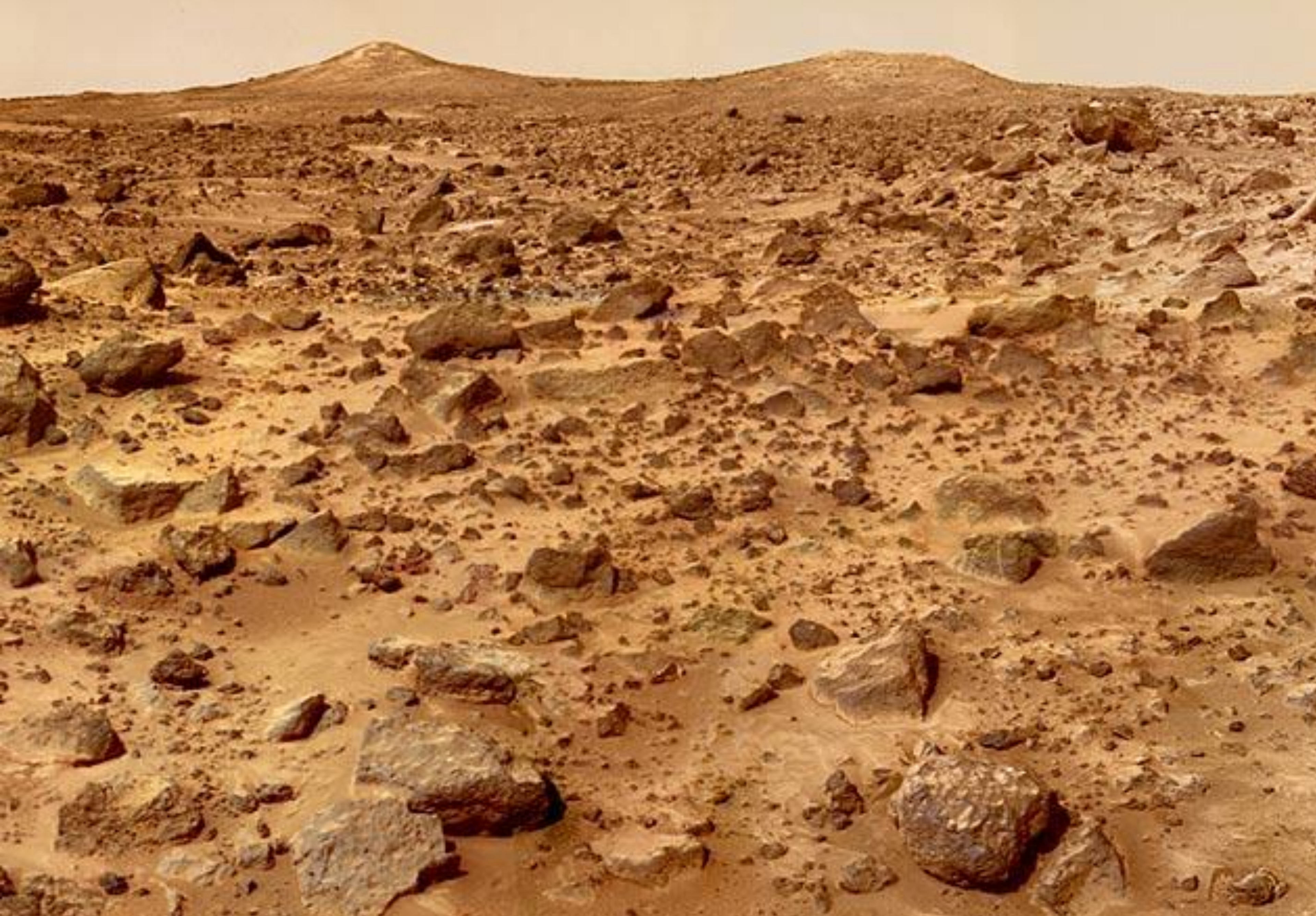
Origin of the Lightest Elements

The lightest elements — hydrogen, helium, and a smattering of deuterium (heavy hydrogen isotope) and lithium — were from the big bang itself, produced by fusion in the first three minutes when the universe was as hot as the core of a star like the Sun!

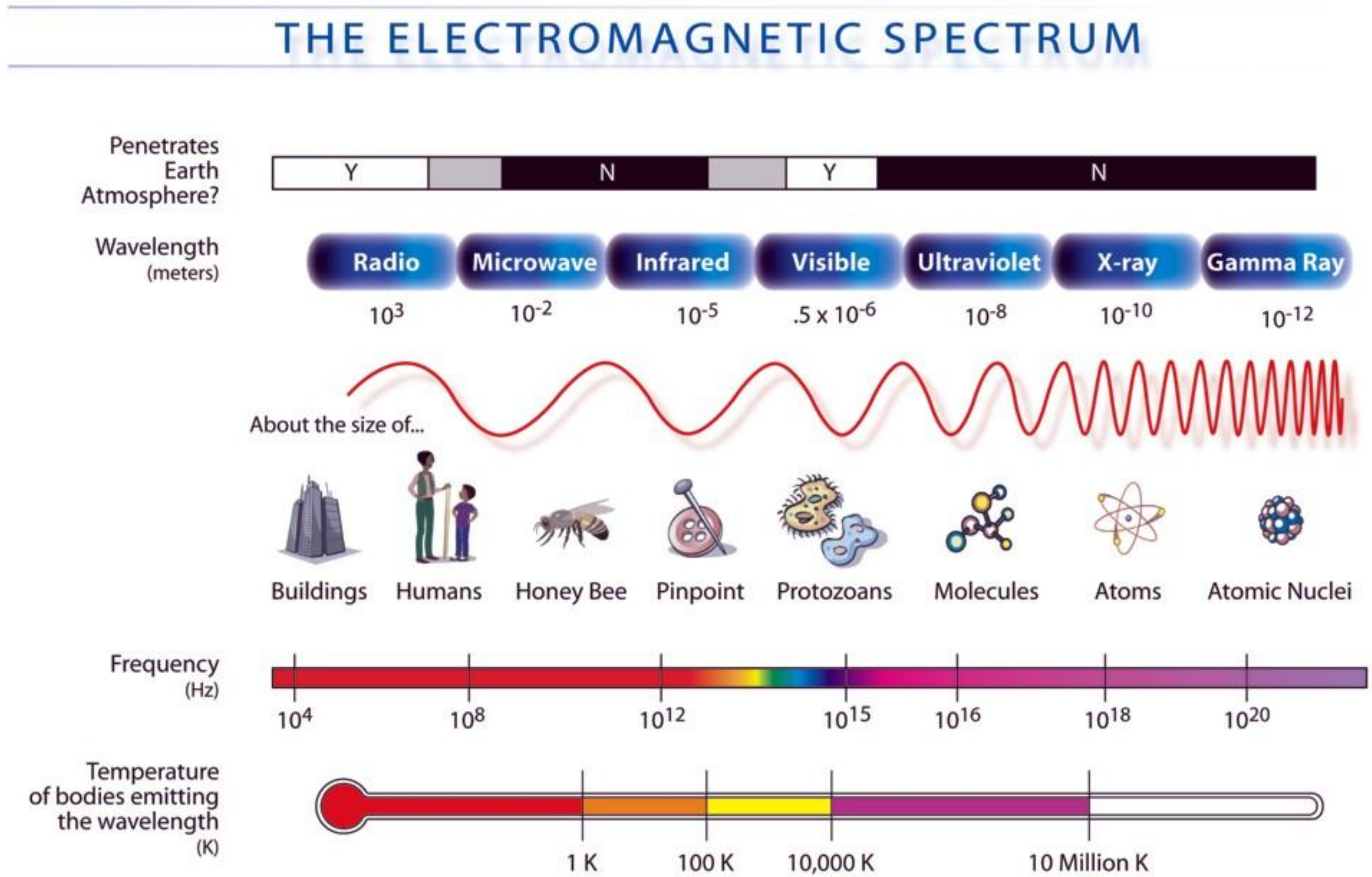
If no stars had formed in the expanding universe, we would not be here to have this discussion, since hydrogen and helium can combine to form…. nothing! Chemistry and biology impossible.


EXPLORATION:
250,000 MILES

REMOTE SENSING: 1 BILLION MILES




FREE SAMPLES:
10 BILLION MILES



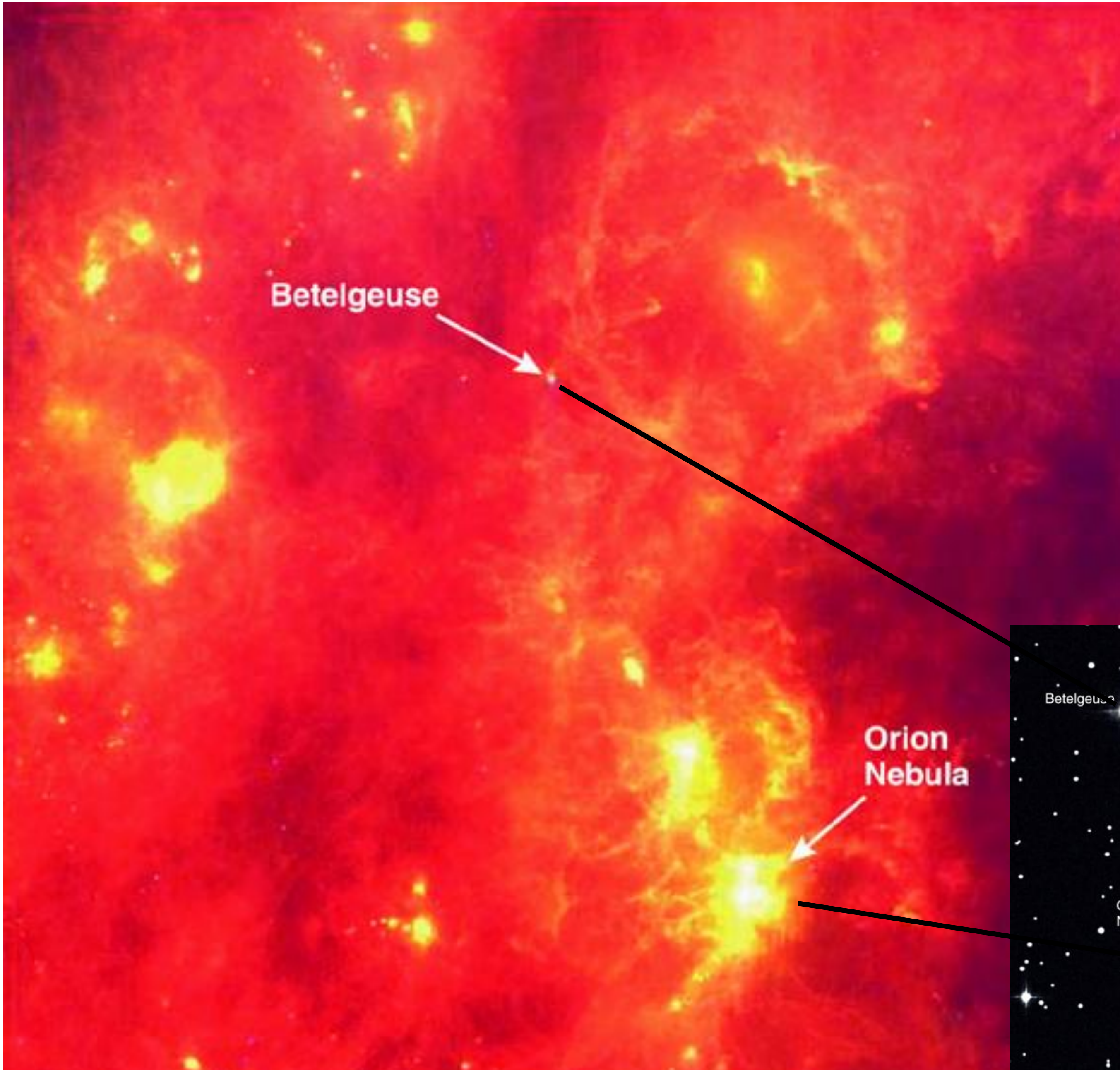
For 99.999999999999999999999999999% of the universe, including all stars and all galaxies, the evidence is indirect.

Formation

How Stars and Planets Form

Stars are born in ***molecular clouds*** consisting mostly of hydrogen molecules, with some heavier elements and dust.

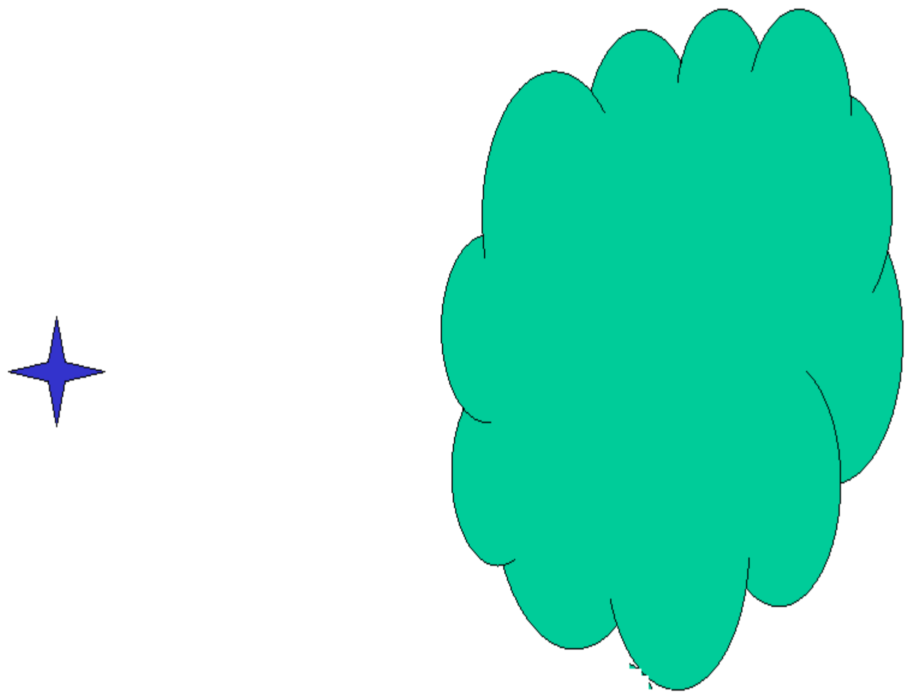
Orion Nebula is one of the most massive regions of star-forming clouds. Infrared waves are little affected by dust.



Infrared light from Orion

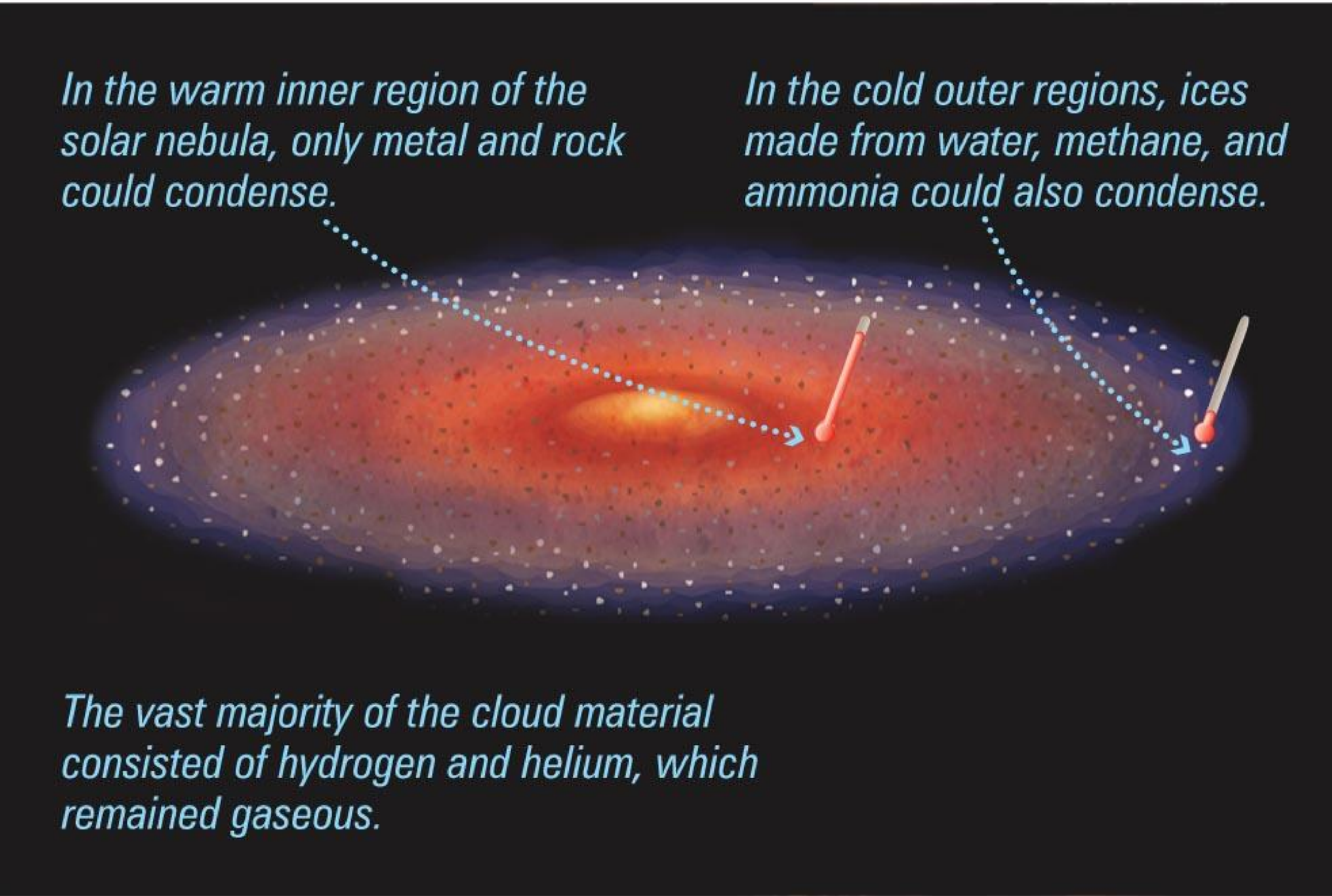
Eta Carina

Induced Star Formation

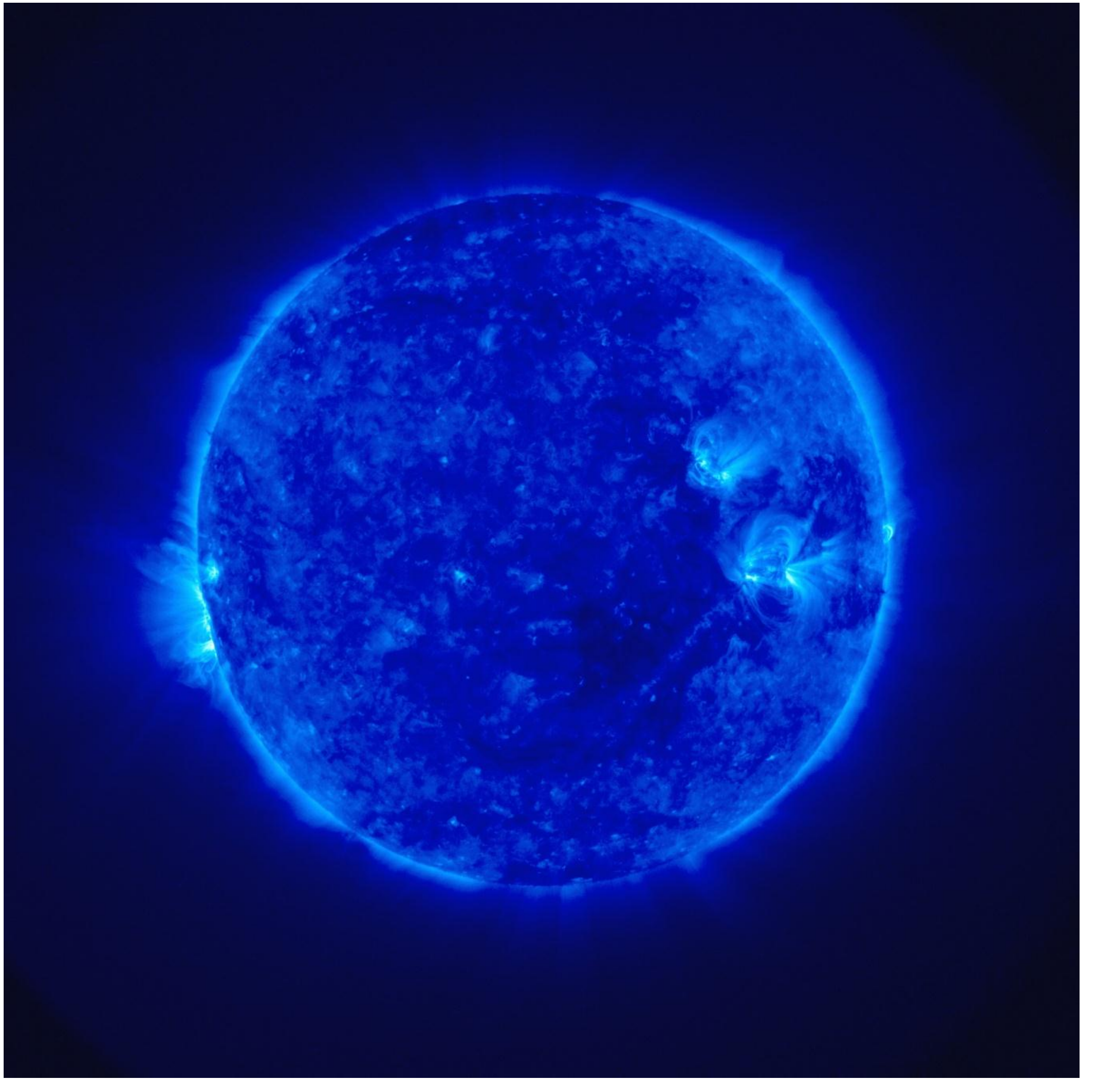


A diffuse cloud can be “triggered” into collapse and star formation by the death of a nearby star. The presence of radioactive isotopes in the Solar System may indicate this.

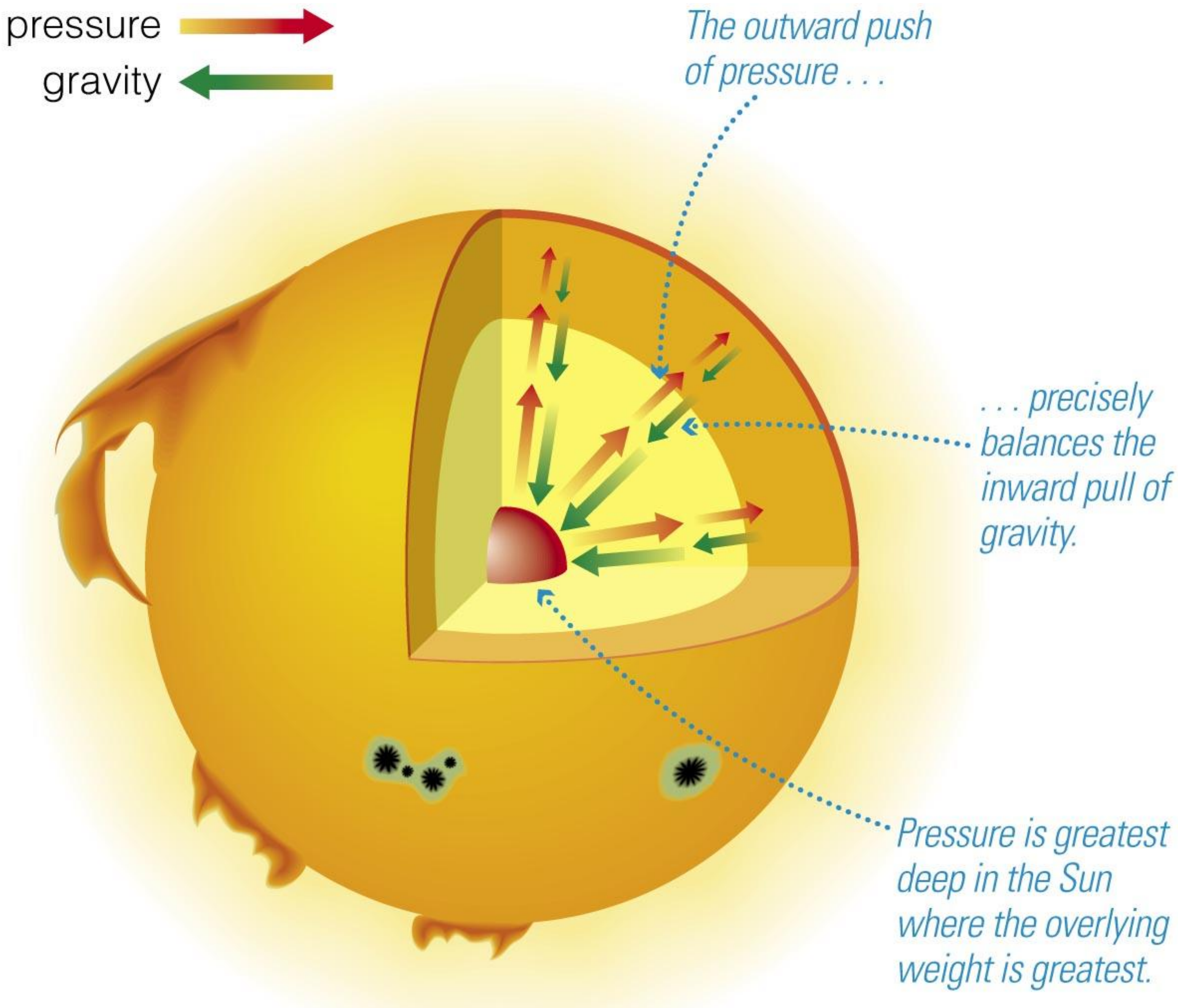
Planets form in the solar nebula



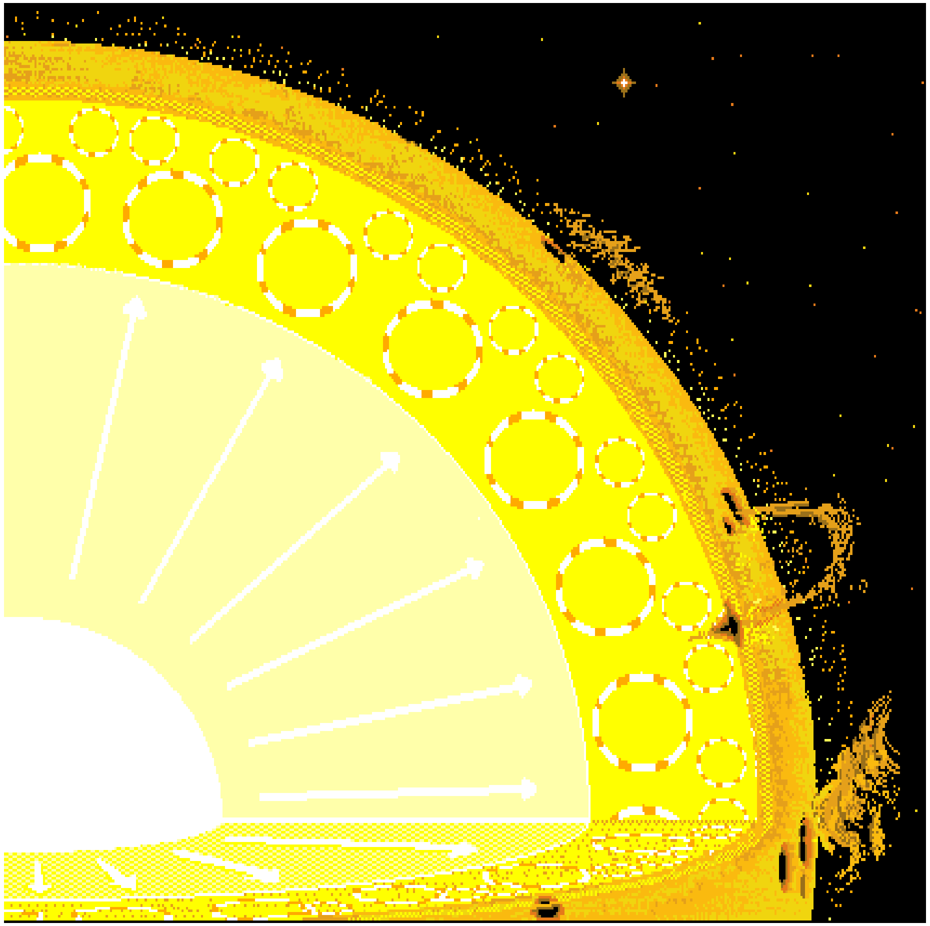
The Sun



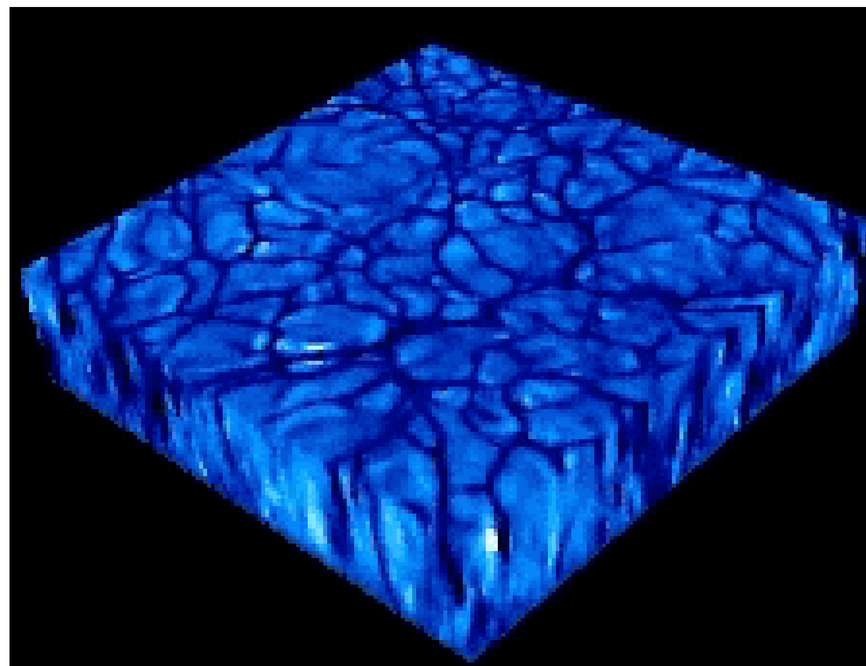
Hydrostatic Equilibrium



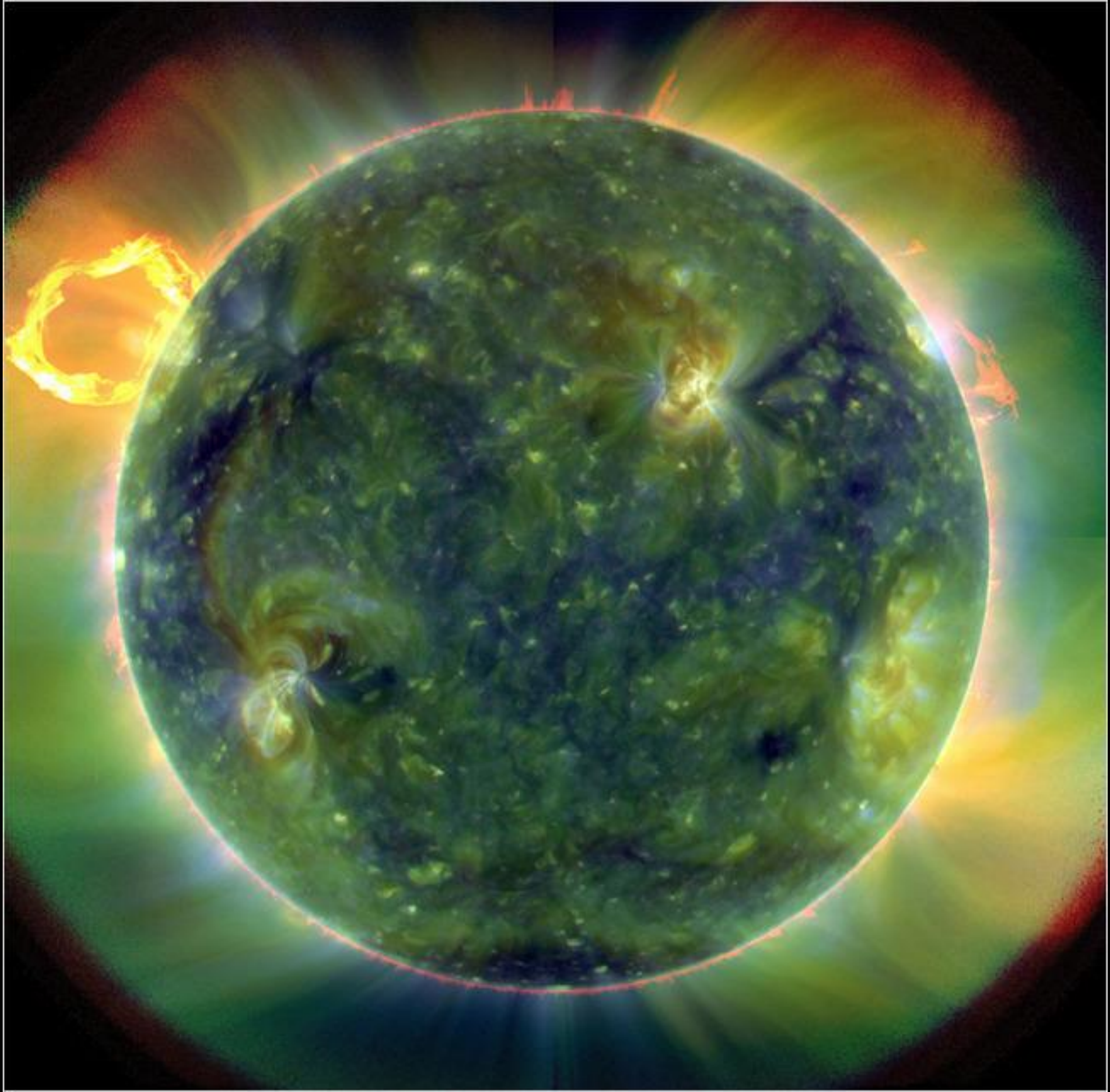
Active Sun



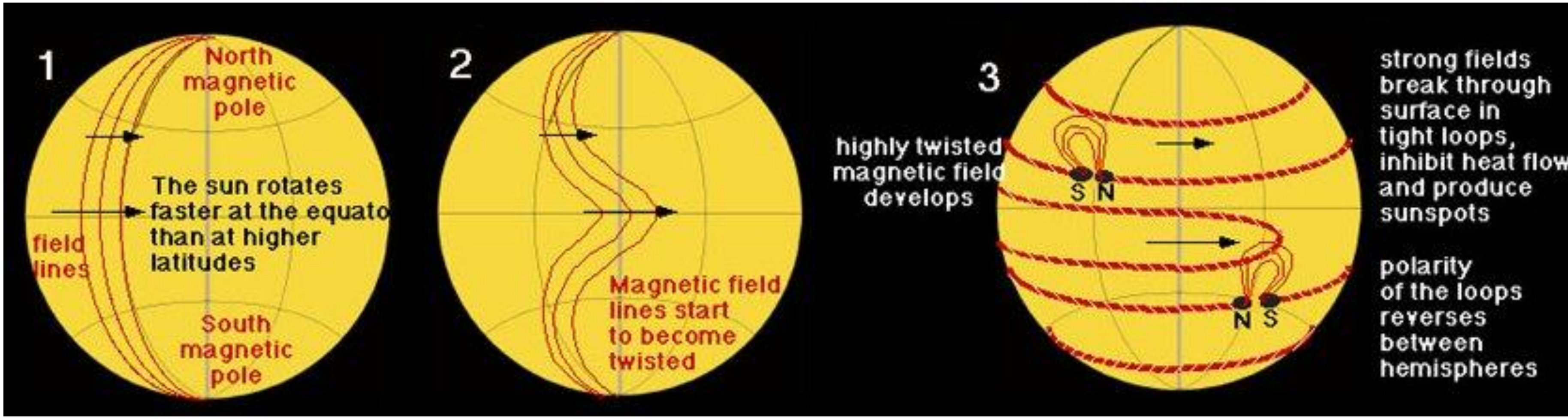
Fusion occurs in the central 25% by radius, where T > 10 million Kelvin. Then energy travels by radiation followed by convection towards the surface, taking 170,000 yrs.

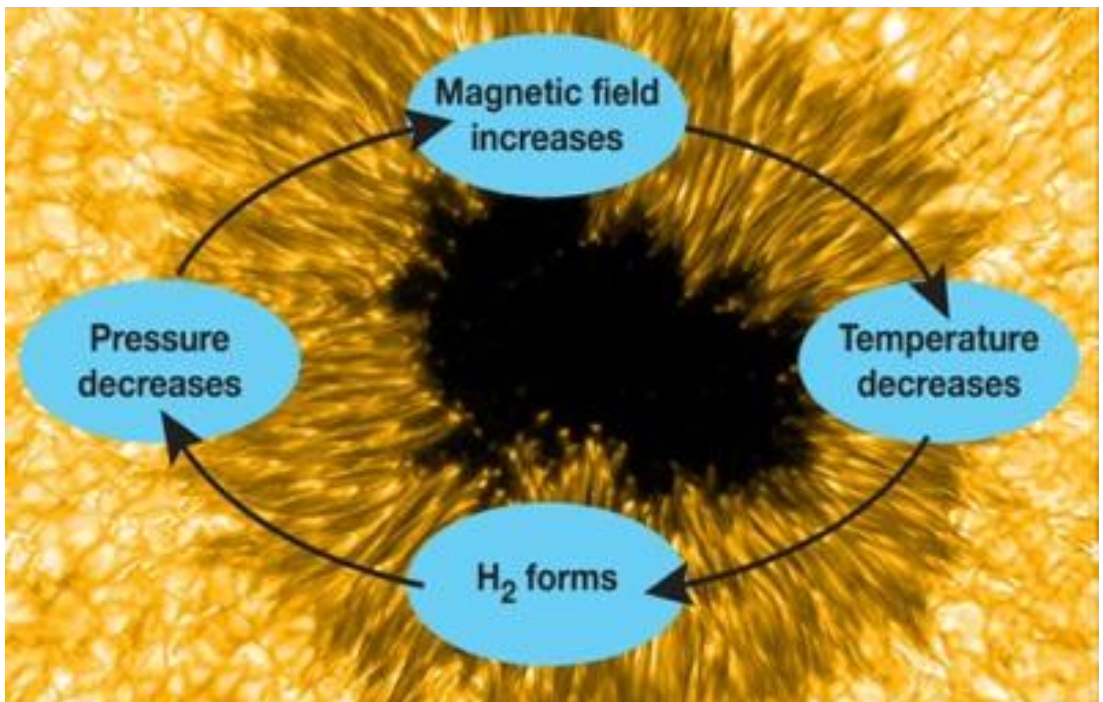


Turbulent convection cells in the photosphere that mark the visible edge of the Sun.

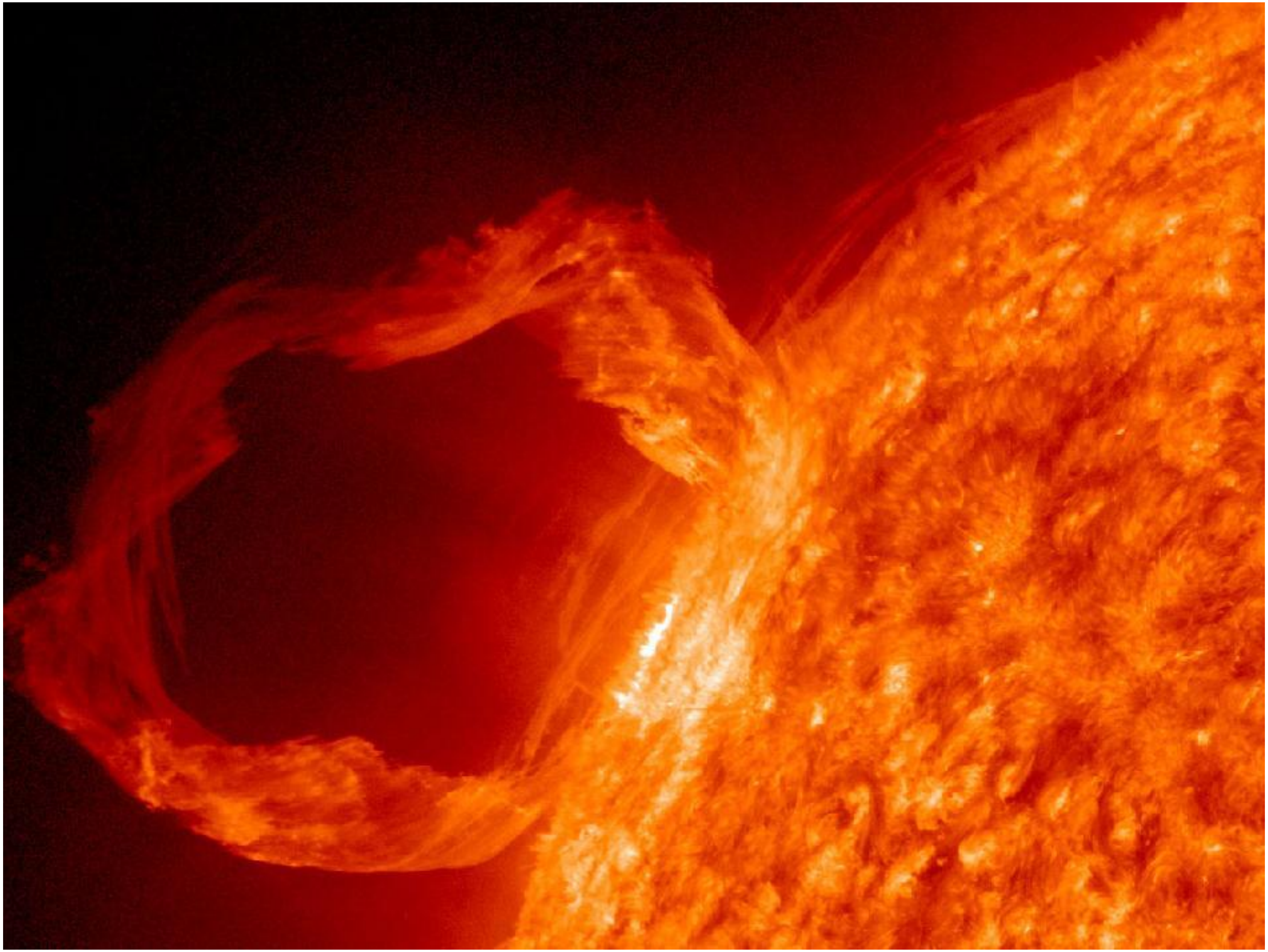


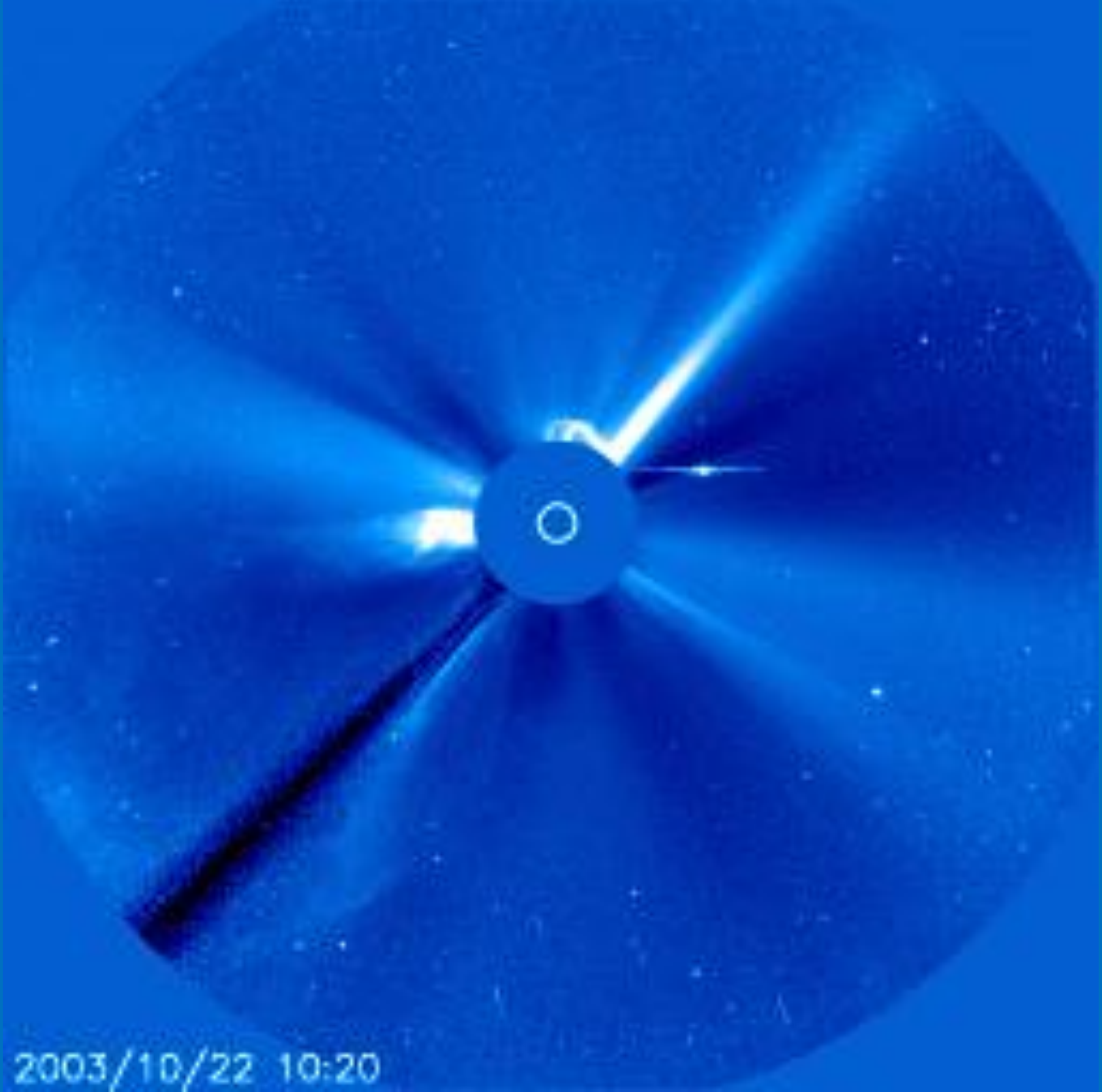
Sunspot Formation





High Energy Activity

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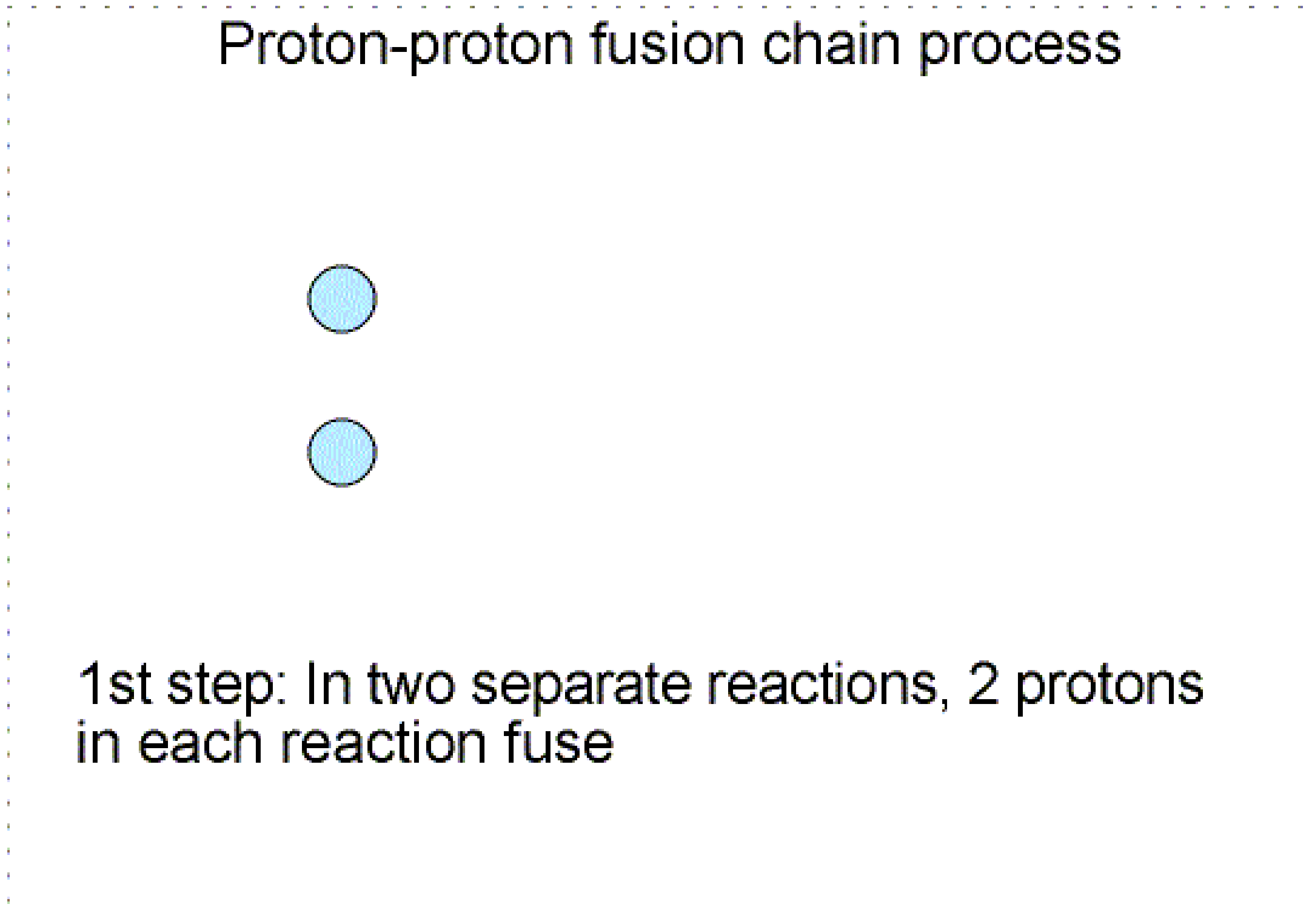
Proton-Proton Chain



Three step fusion process by which hydrogen nuclei turn into helium nuclei, with the release of gamma ray energy at each step. Protons are recycled for further reactions.

Life Stages of a Star

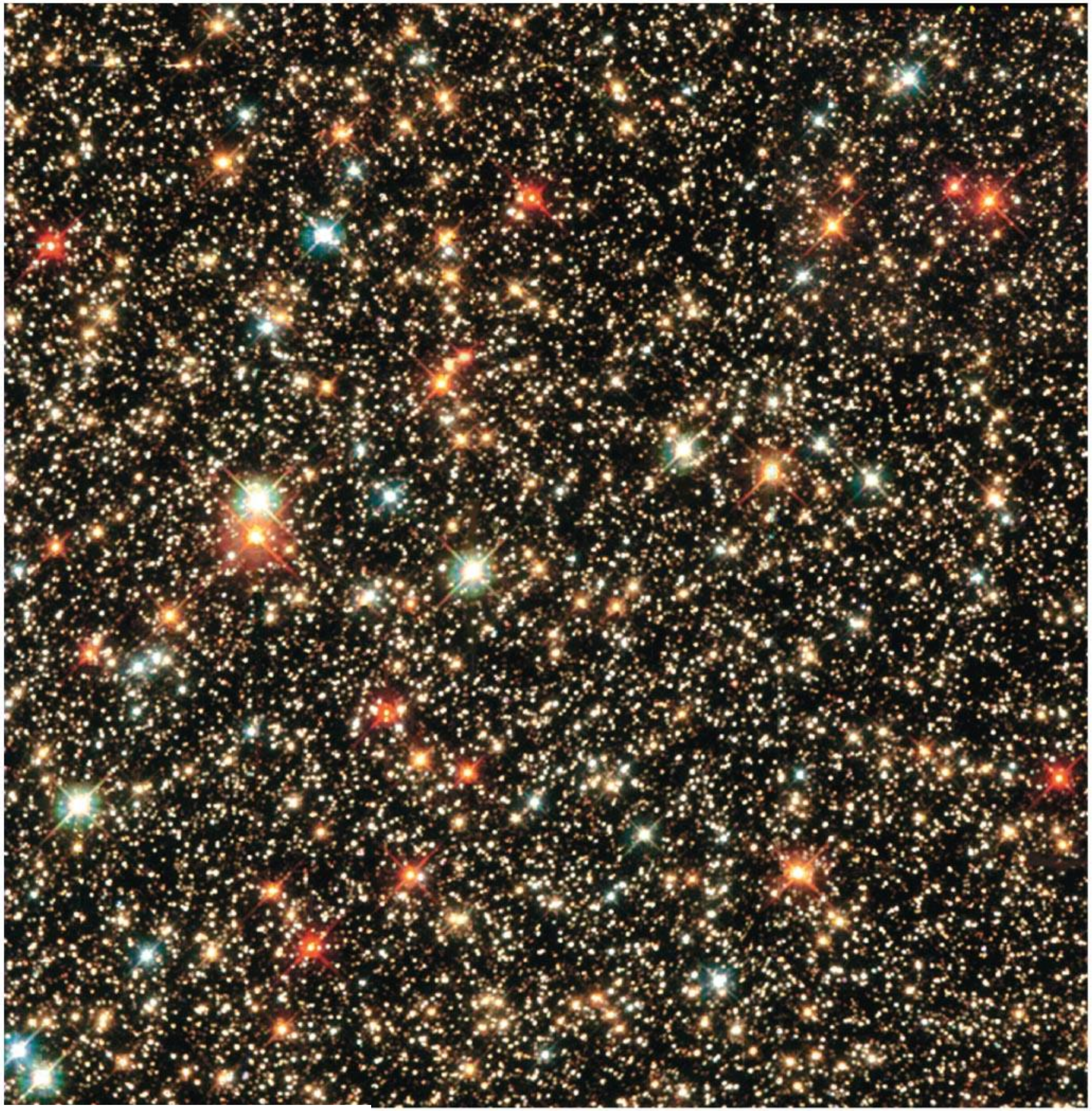
Stars are gravity engines. The pressure of gravity in a star's core raises the temperature to millions of degrees, so hot that atomic nuclei move fast enough to overcome electrical repulsion and "stick" in the process called nuclear fusion.

In fusion, the product is slightly lighter than the sum of the nuclei that went into the reaction. The mass difference is converted into energy that makes its way out of the star:

$$E = mc^2$$

Sunlight!

Properties



Stellar Properties Review

Luminosity: from brightness and distance

$10^{-4}\ L_{Sun}$ - $10^{6}\ L_{Sun}$

Temperature: from color and spectral type

3,000 K - 50,000 K

Mass: from period (p) and average separation (a) of binary-star orbit

$0.08\ M_{Sun}$ - $100\ M_{Sun}$

Stellar Properties Review

Luminosity: from brightness and distance

($0.08\ M_{Sun}$) $10^{-4}\ L_{Sun}$ - $10^{6}\ L_{Sun}$ **($100\ M_{Sun}$)**

Temperature: from color and spectral type

($0.08\ M_{Sun}$) 3,000 K - 50,000 K **($100\ M_{Sun}$)**

Mass: calculated from period (p) and average separation (a) of a binary-star orbit

$0.08\ M_{Sun}$ - $100\ M_{Sun}$

Mass and Lifetime

Until core hydrogen (10% of the total) is nearly all used up

Sun's life expectancy: <u>10 billion years</u>

Life expectancy of 10 M_{Sun} star:

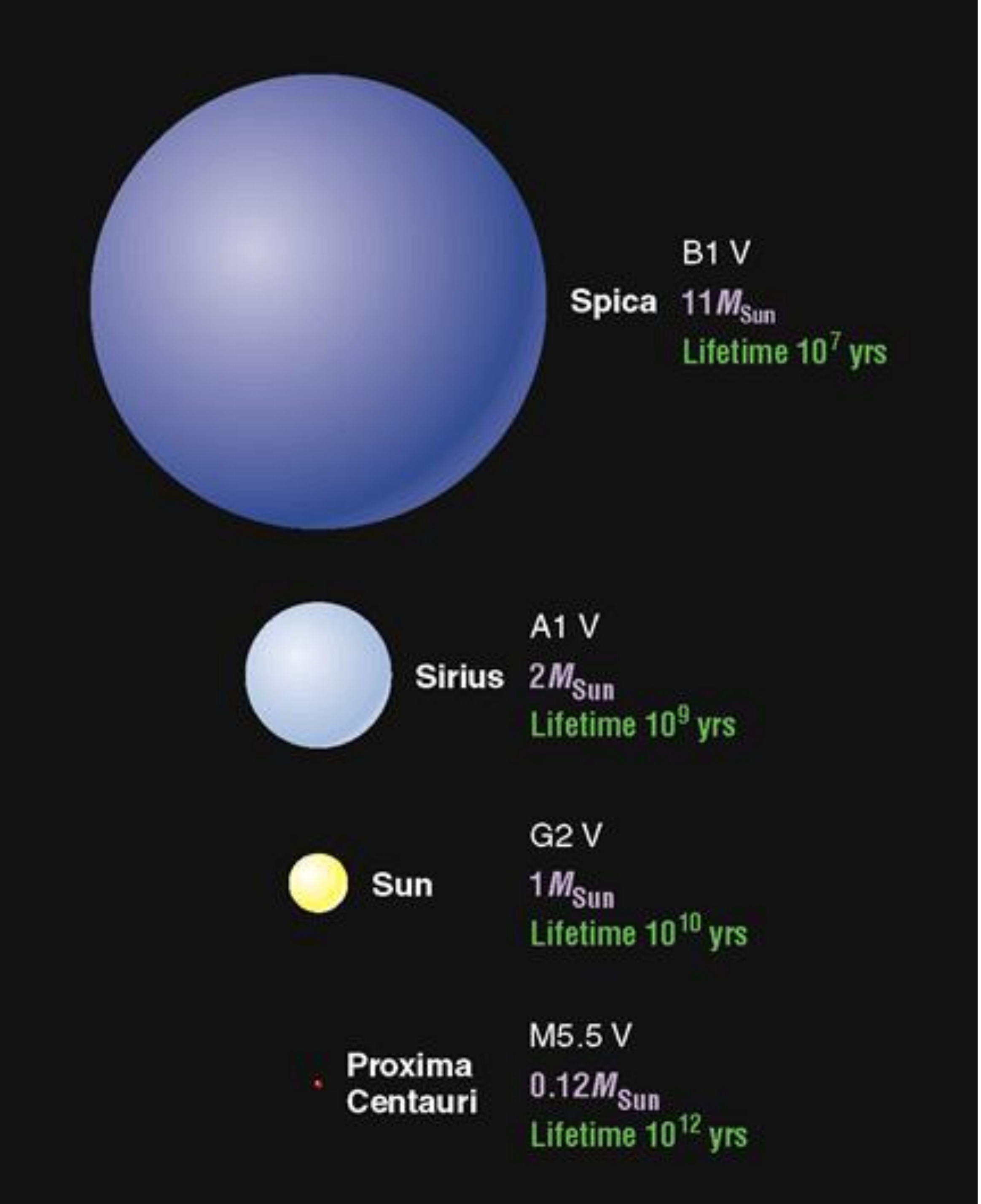
10 times as much fuel, uses it 10^4 times as fast

<u>10 million years</u> ~ 10 billion years x 10 / 10^4

Life expectancy of 0.1 M_{Sun} star:

0.1 times as much fuel, uses it 0.01 times as fast

<u>100 billion years</u> ~ 10 billion years x 0.1 / 0.01

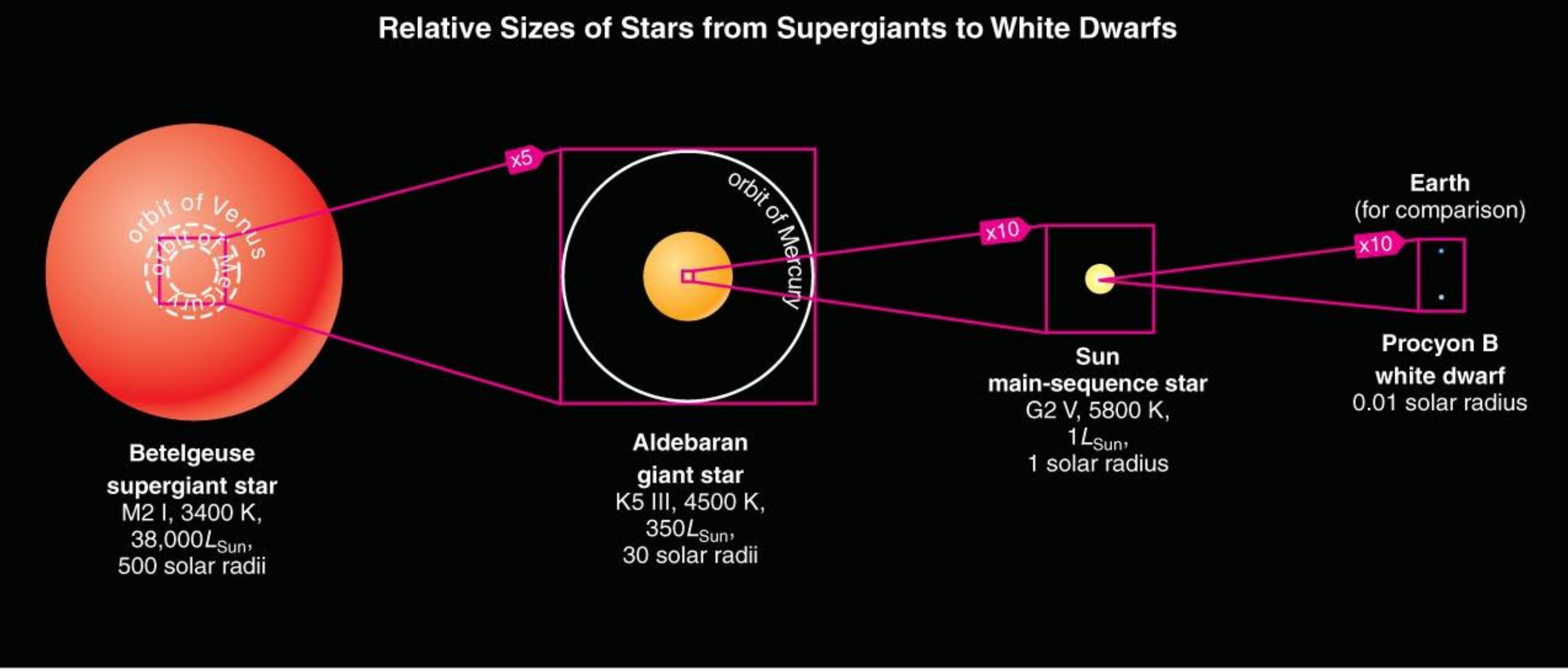


High Mass:

High Luminosity
Short-Lived
Large Radius
Blue

Low Mass:

Low Luminosity
Long-Lived
Small Radius
Red



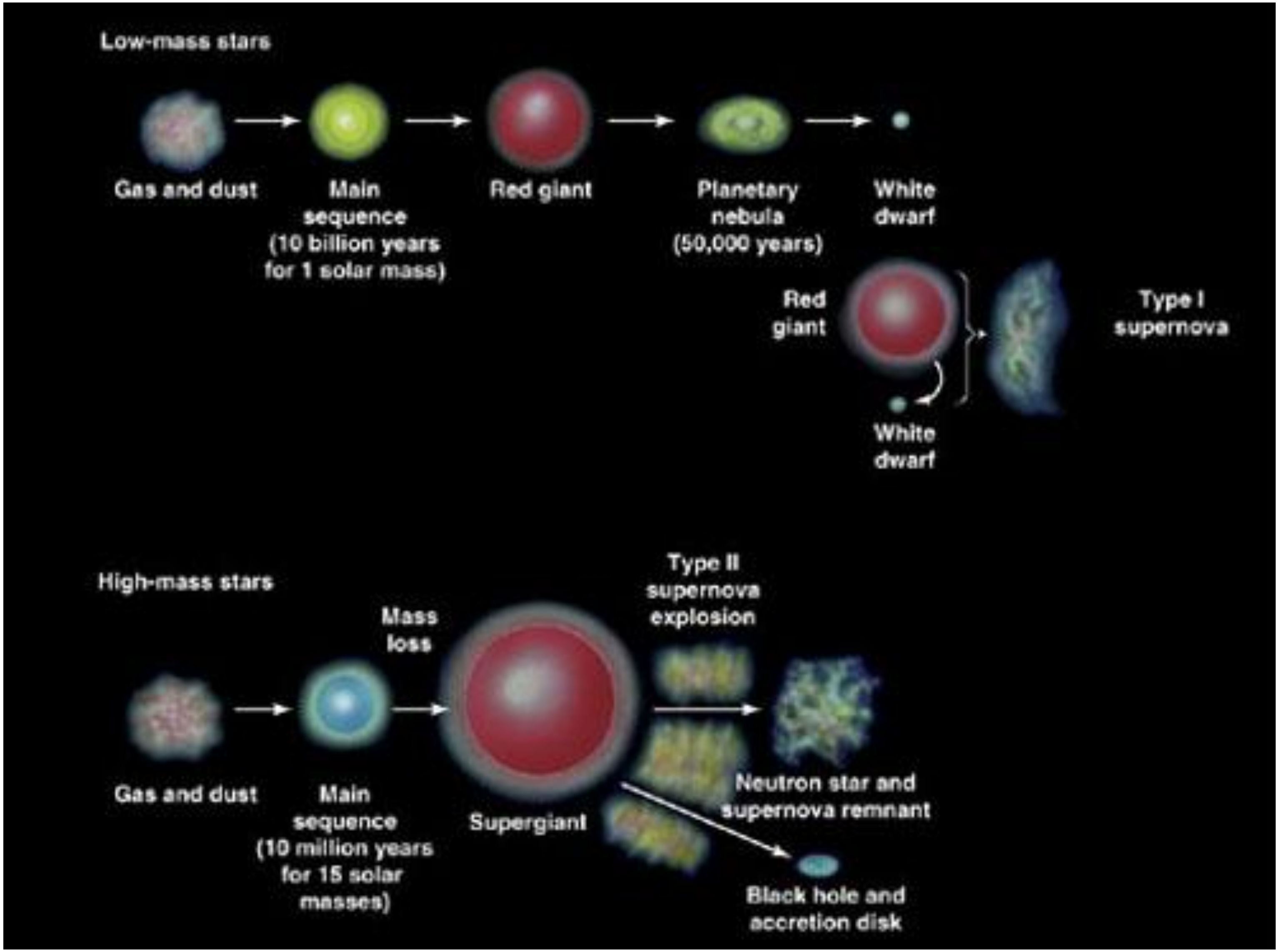
Large Stars:

Giants and supergiants are massive stars near the end of their lives, with very hot cores.

Small Stars:

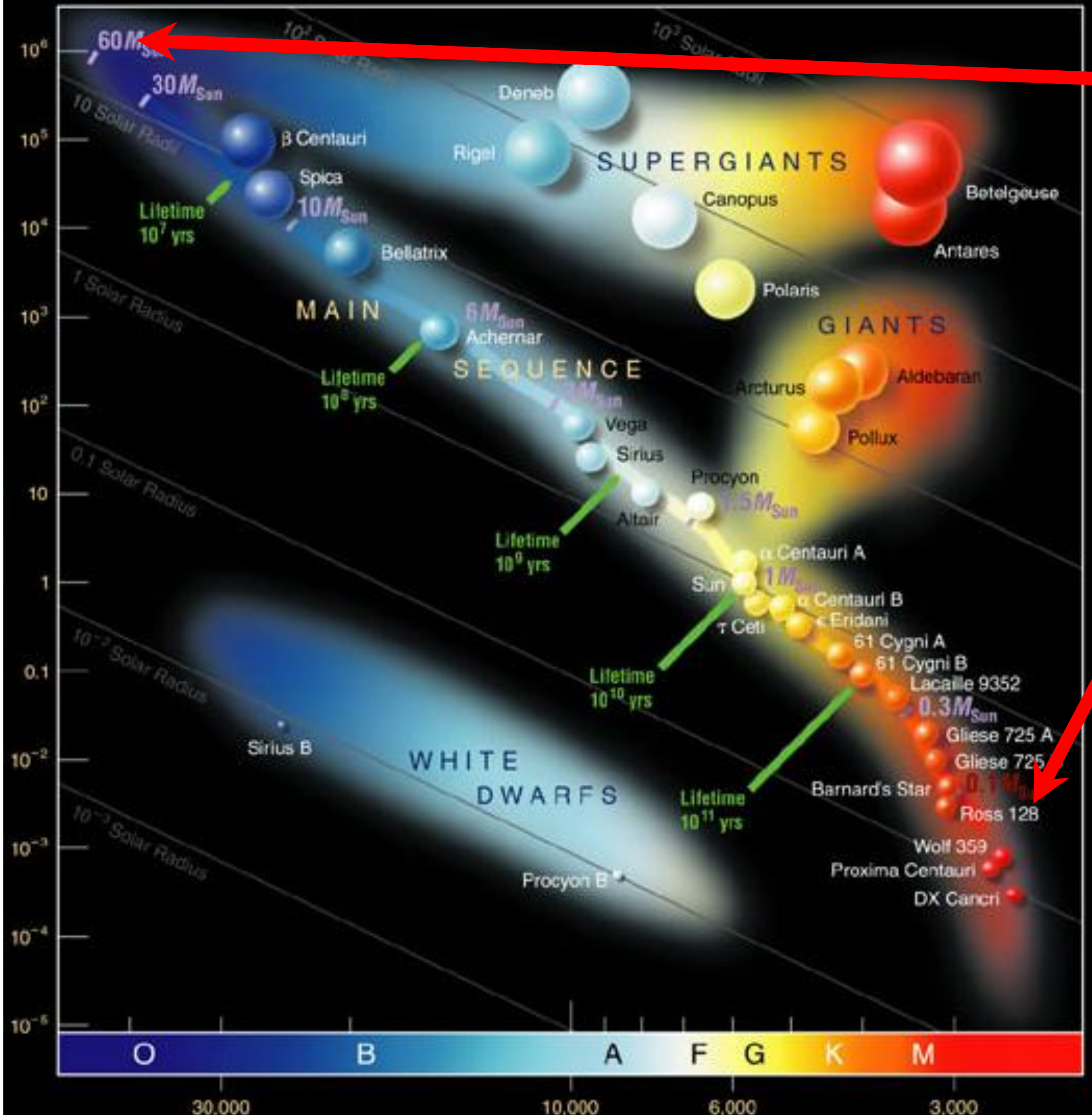
Dwarfs are low mass stars, either cool and on the main sequence or hot stellar embers.

Evolution



Low-mass stars
Gas and dust
Main sequence (10 billion years for 1 solar mass)
Red giant
Planetary nebula (50,000 years)
White dwarf
Red giant
White dwarf
Type I supernova
High-mass stars
Gas and dust
Main sequence (10 million years for 15 solar masses)
Mass loss
Supergiant
Type II supernova explosion
Neutron star and supernova remnant
Black hole and accretion disk

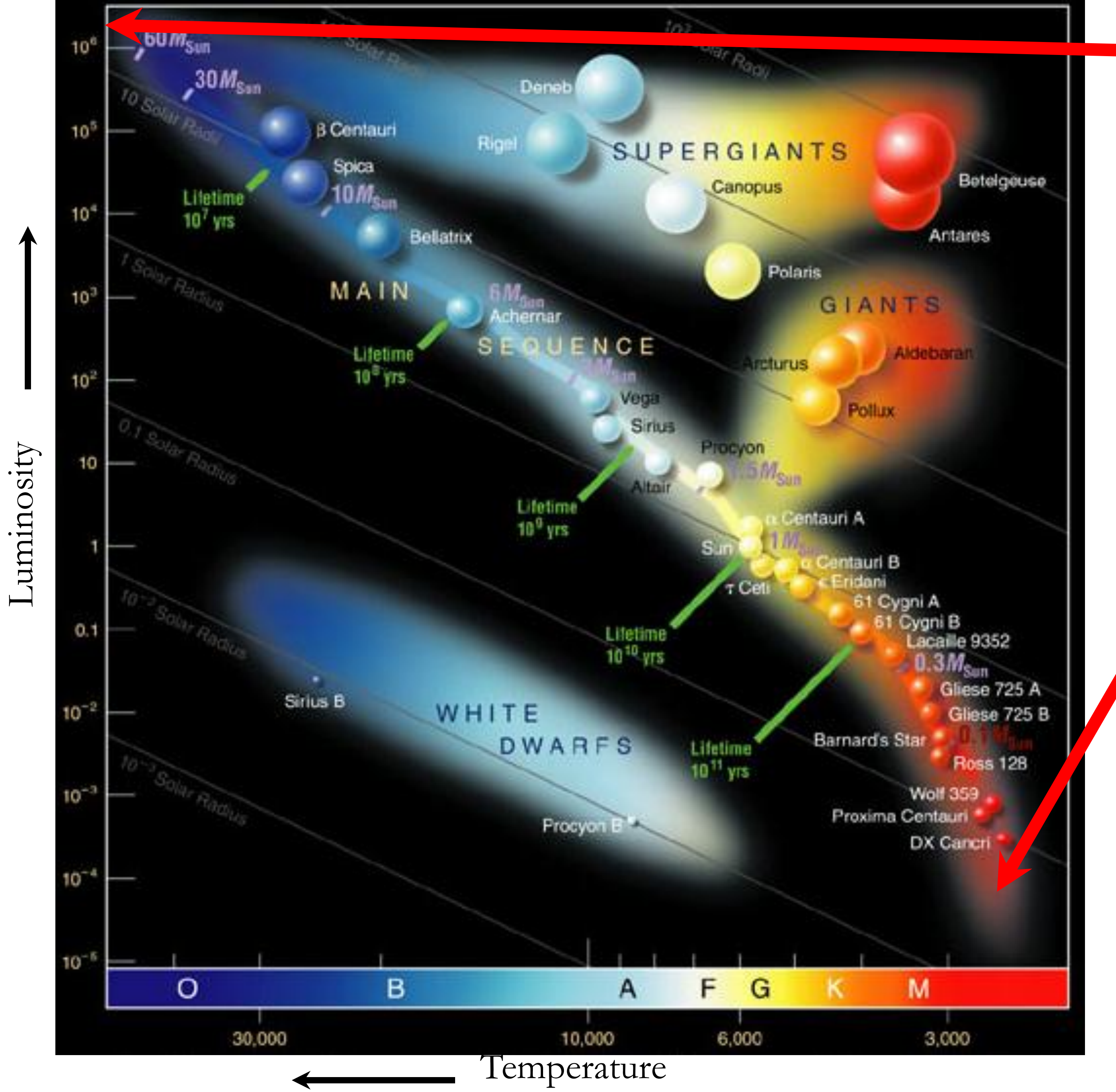
Luminosity



Very massive stars are rare

Low-mass stars are common

Temperature

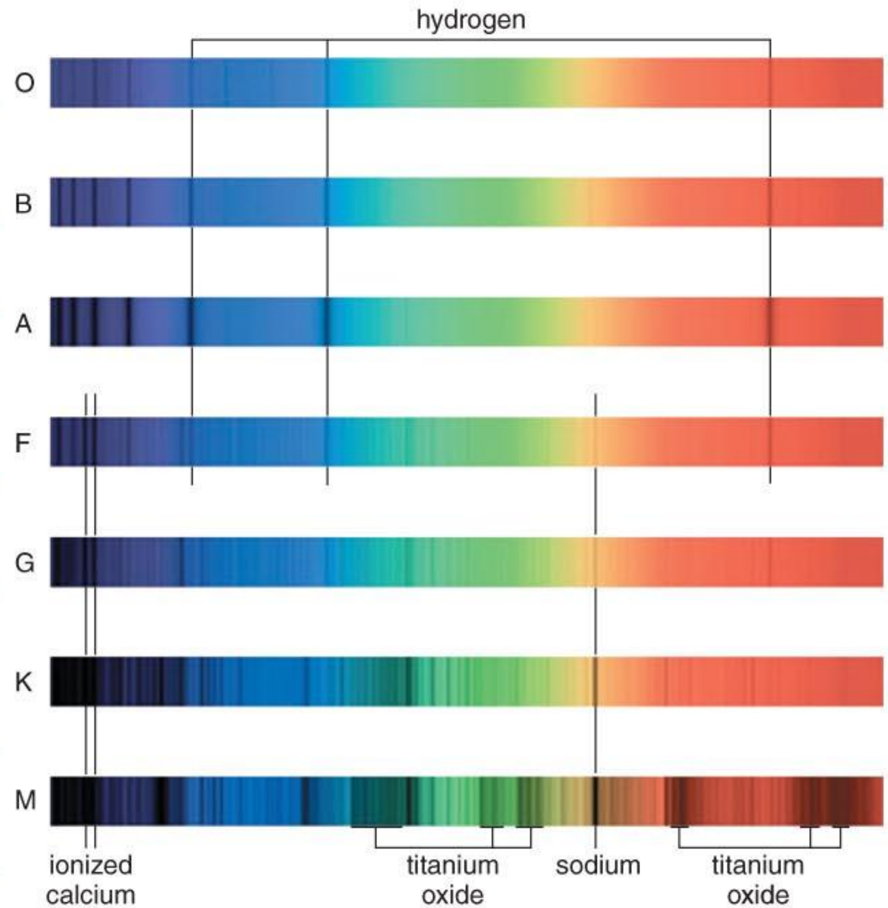


Stars more massive than ~100 M_{Sun} would blow apart before stabilizing

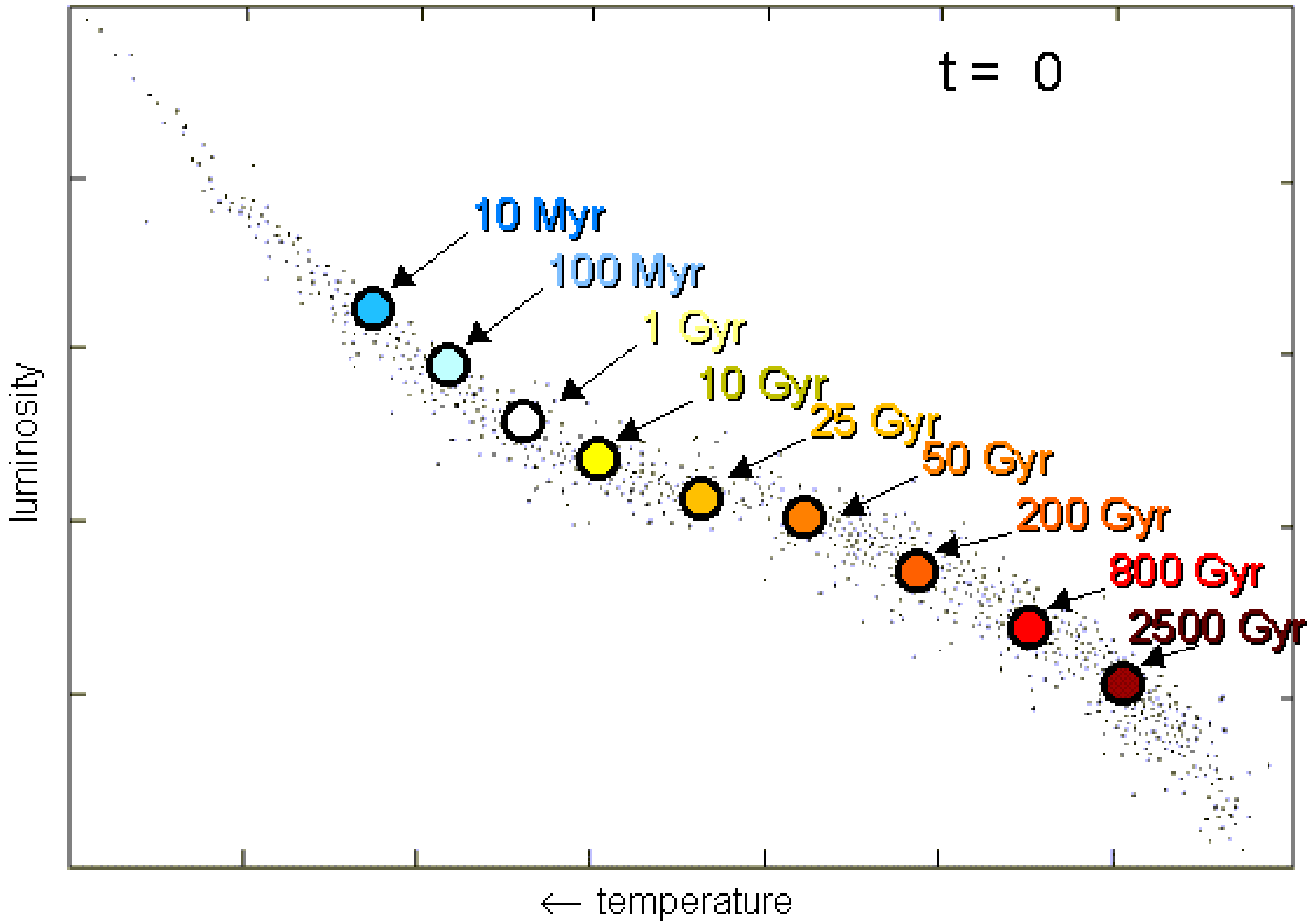
Stars less massive than ~0.08 M_{sun} are too cool to sustain any fusion

Spectral Sequence

Spectral Type	Example(s)	Temperature Range	Key Absorption Line Features	Brightest Wavelength (color)	Typical Spectrum
O	Stars of Orion's Belt	>30,000 K	Lines of ionised helium, weak hydrogen lines	>97 nm (ultraviolet)*	
B	Rigel	30,000 K–10,000 K	Lines of neutral helium, moderate hydrogen lines	97–290 nm (ultraviolet)*	
A	Sirius	10,000 K–7500 K	Very strong hydrogen lines	290–390 nm (violet)*	
F	Polaris	7500 K–6000 K	Moderate hydrogen lines, moderate lines of ionized calcium	390–480 nm (blue)*	
G	Sun, Alpha Centauri A	6000 K–5000 K	Weak hydrogen lines, strong lines of ionized calcium	480–580 nm (yellow)	
K	Arcturus	5000 K–3500 K	Lines of neutral and singly ionised metals, some molecules	580–830 nm (red)	
M	Betelgeuse, Proxima Centauri	<3500 K	Strong molecular lines	> 830 nm (infrared)	



Main Sequence Evolution



At the end of a star's main sequence (hydrogen to helium fusing) life its properties change and it moves off the main sequence. Evolution is much quicker for high mass stars.

Main Sequence Lifetime of Stars

The definition of the luminosity (*L*) of a star is the amount of energy (*E*) that is produced in a certain amount of time (T).

$$L = \frac{E}{T}$$

During the main sequence stage of a star's life, energy is produced via nuclear fusion, where *M* is the mass of the star and *c* the speed of light.

$$E = Mc^2$$

Additionally, the luminosity of a main sequence star is related to its mass (where *f* is a proportionality constant).

$$L = f\,M^{2.5}$$

Substituting these relationships into the definition of luminosity and solving for time provides an expression for the main sequence lifetime of a star.

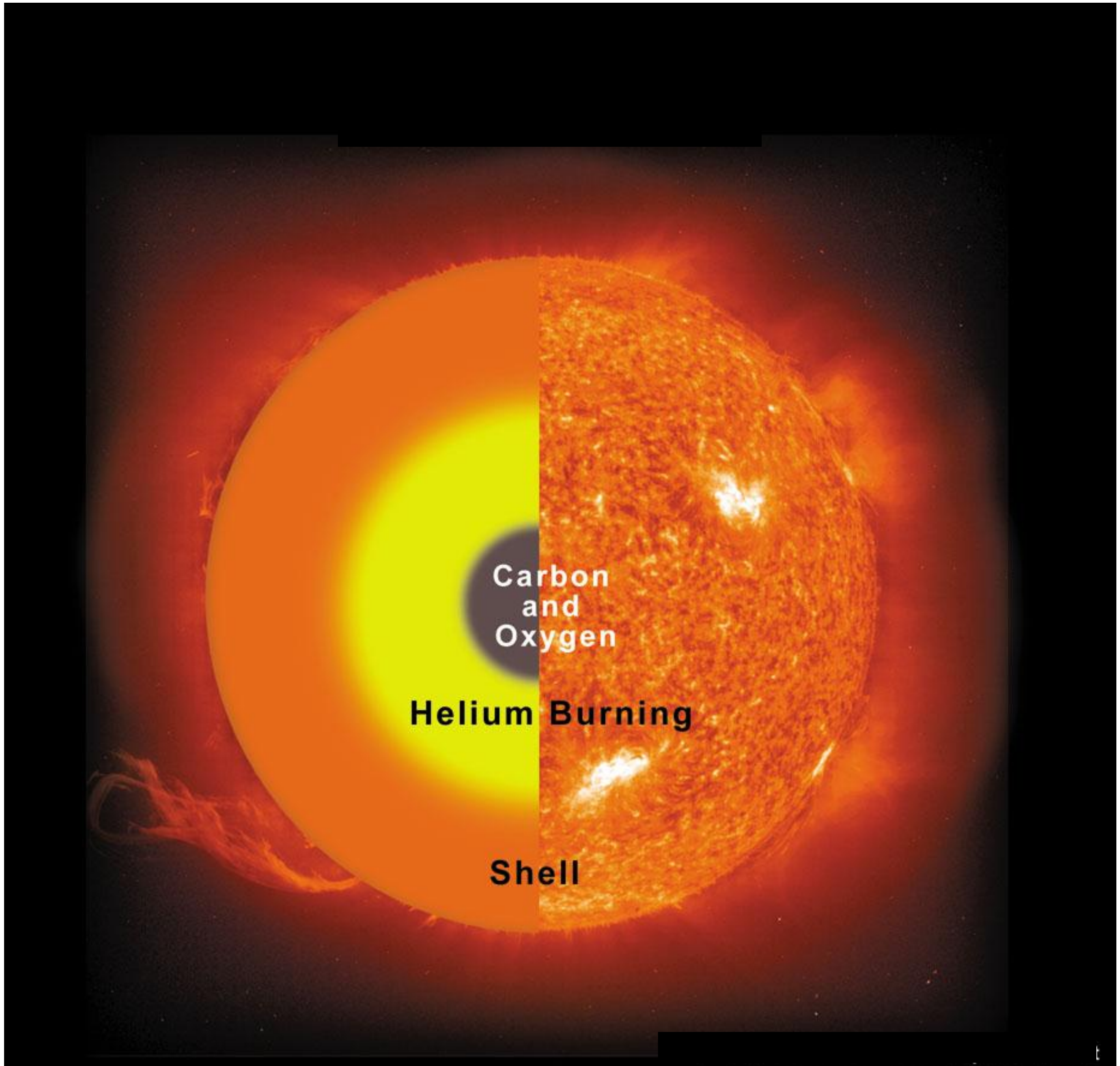
$$T = \frac{c^2}{f\,M^{2.5}}$$

Dividing this by the main sequence lifetime of our Sun simplifies this expression to:

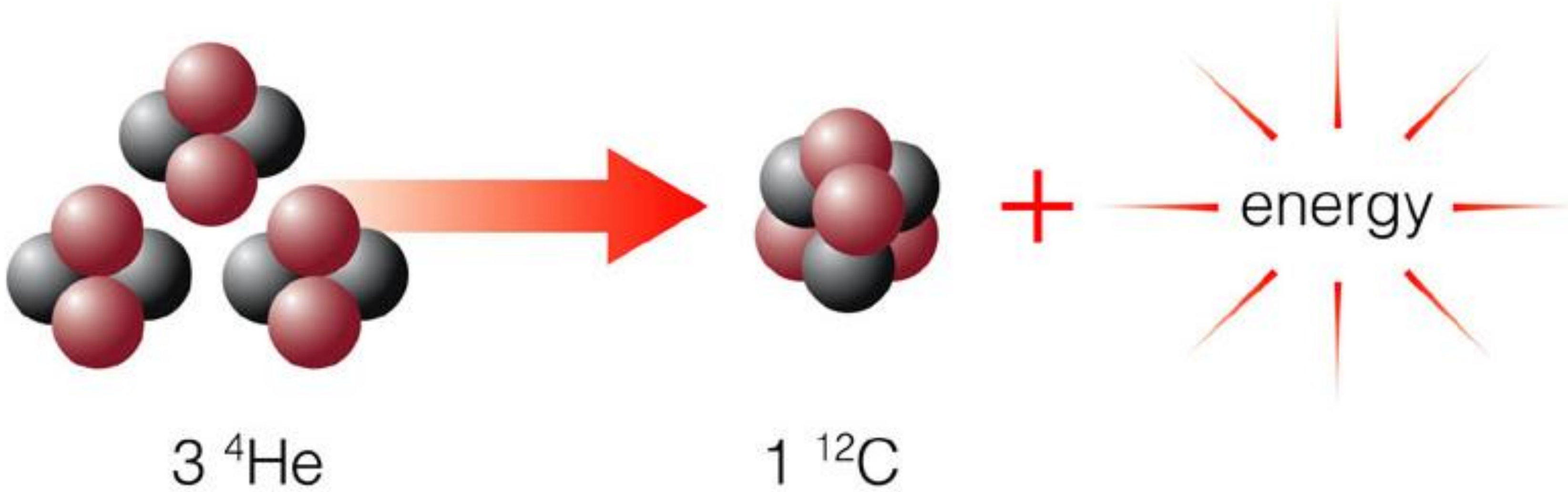
$$T = \left(\frac{M_{Sun}}{M}\right)^{2.5} x\ \ 10^{10}\,years$$

where the main sequence lifetime of the Sun is given a value of 10 billion years.

Nucleosynthesis



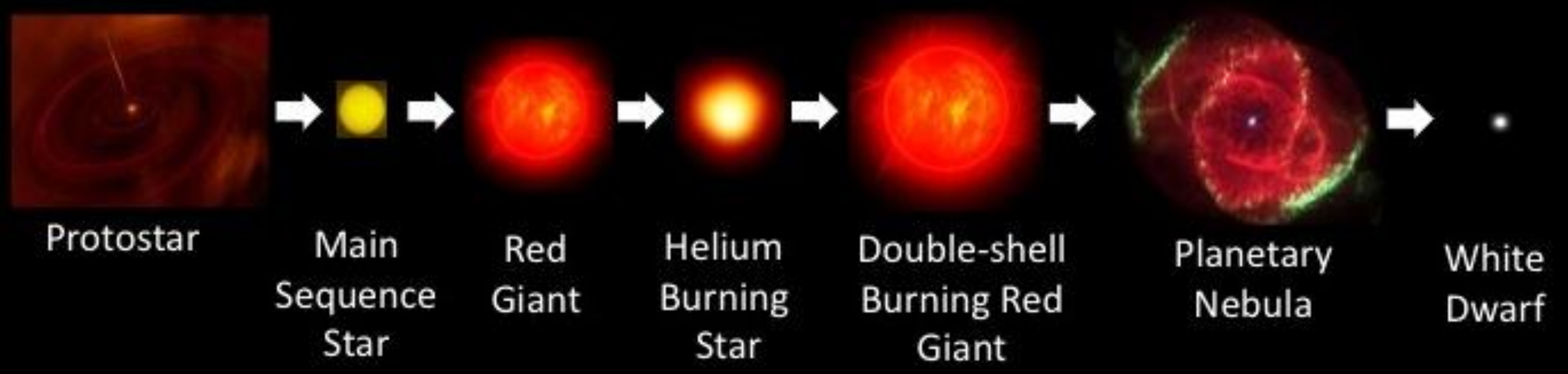
Low mass stars can make carbon



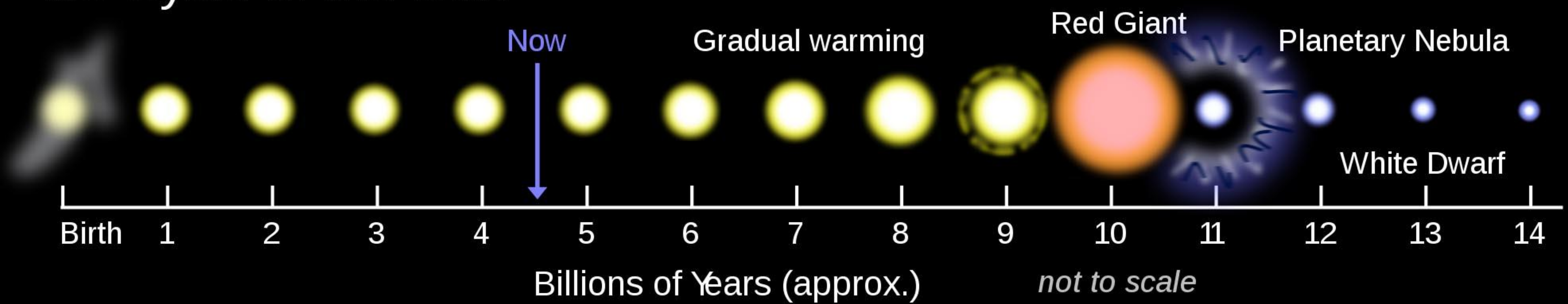
Helium fusion requires higher temperatures than hydrogen fusion because larger charge leads to greater repulsion

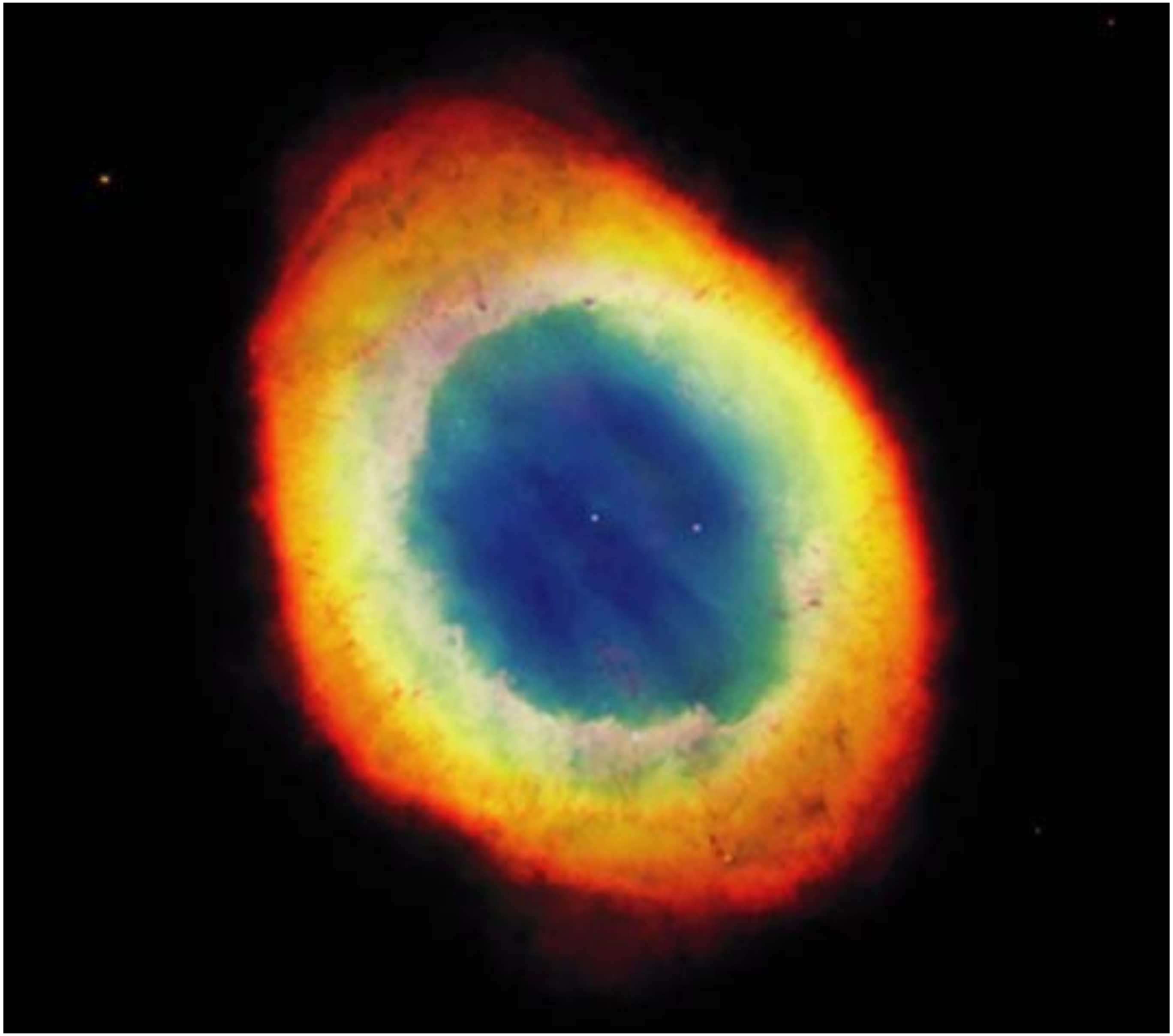
Fusion of two helium nuclei doesn’t work, so helium fusion must combine three He nuclei to make carbon

Life Cycle of a Low-Mass Star



Life Cycle of the Sun

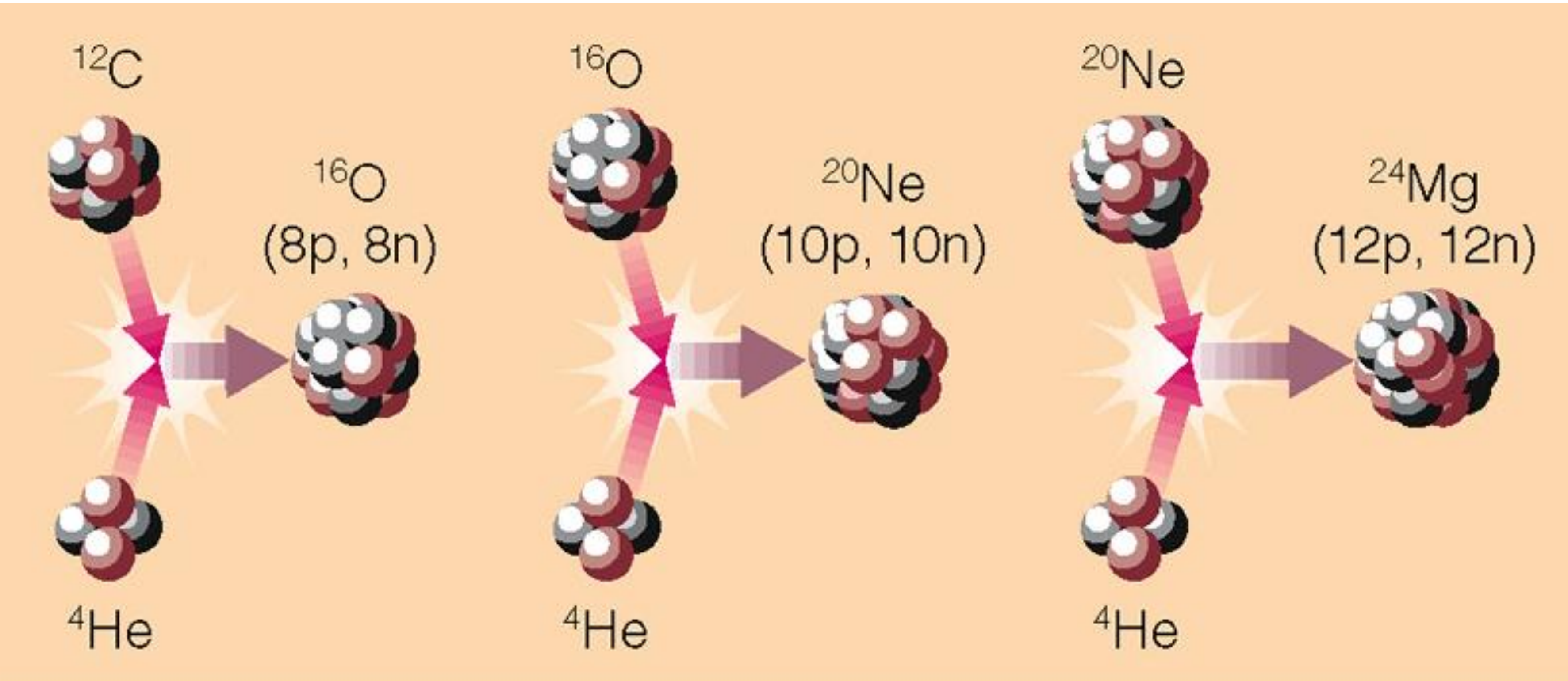




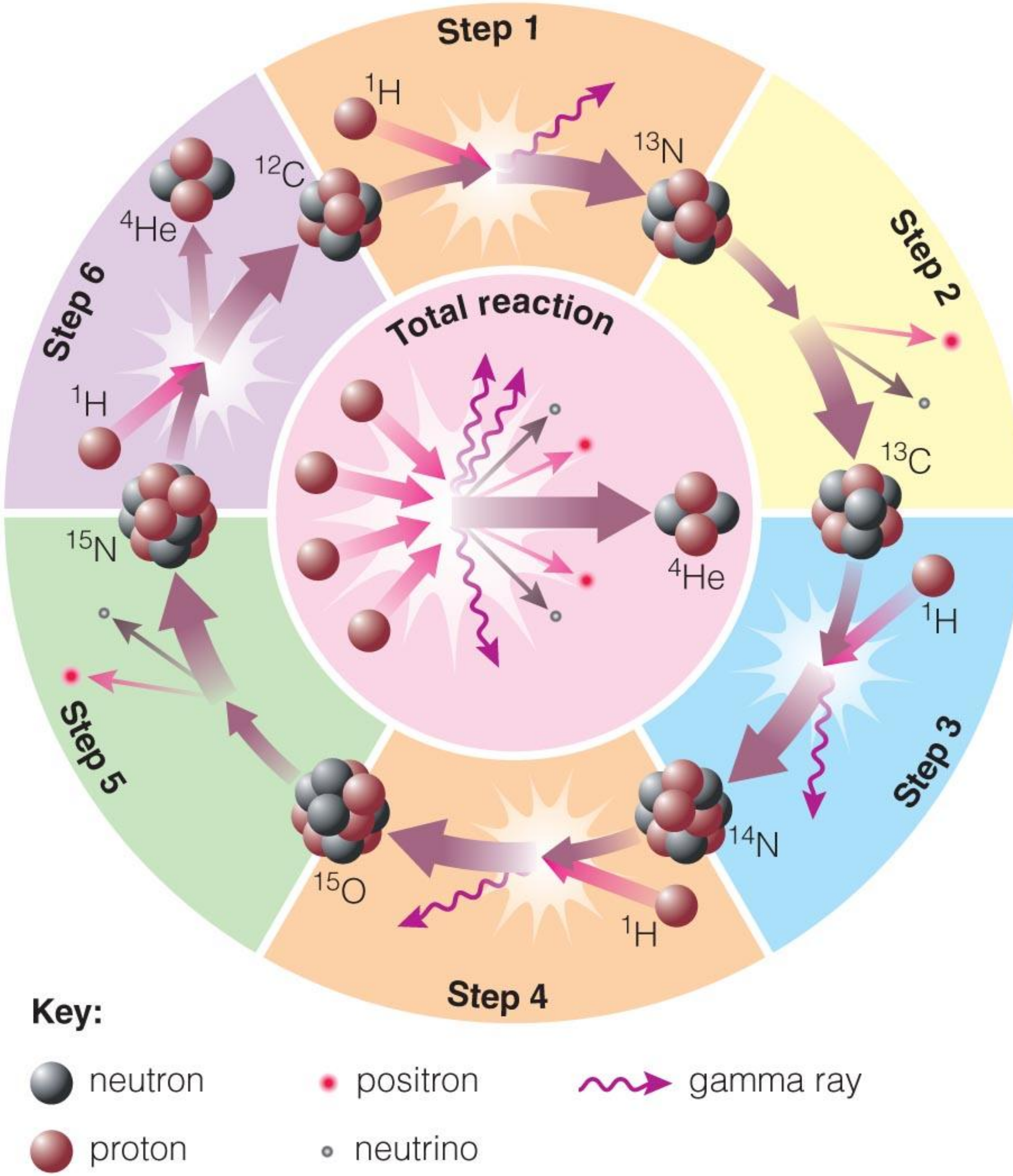
A star like our Sun dies by puffing off its outer layers, creating a ***planetary nebula***.

Only a white dwarf is left behind, slowly eking radiation into space.

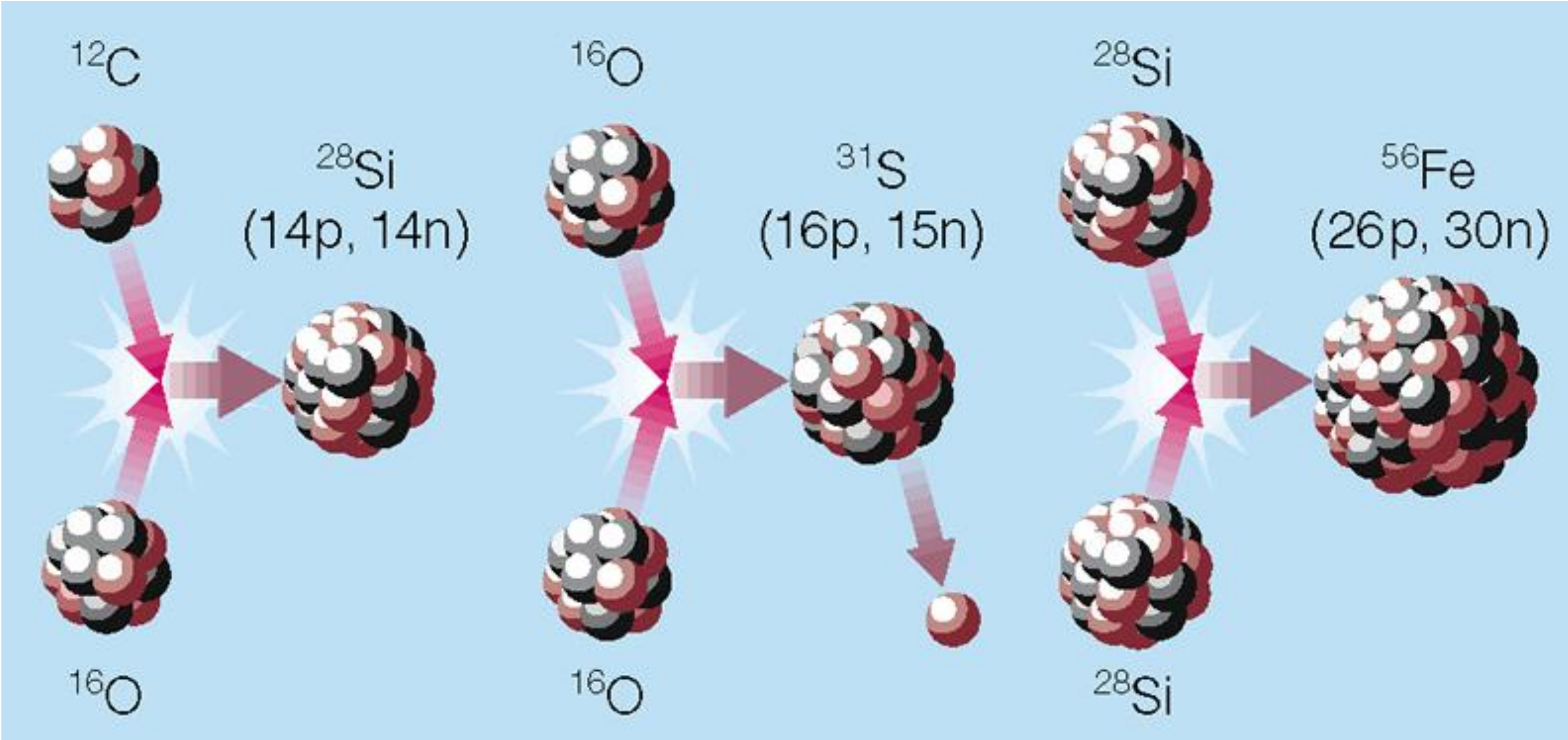
High mass stars make heavy elements



Helium-capture reactions add two protons at a time.

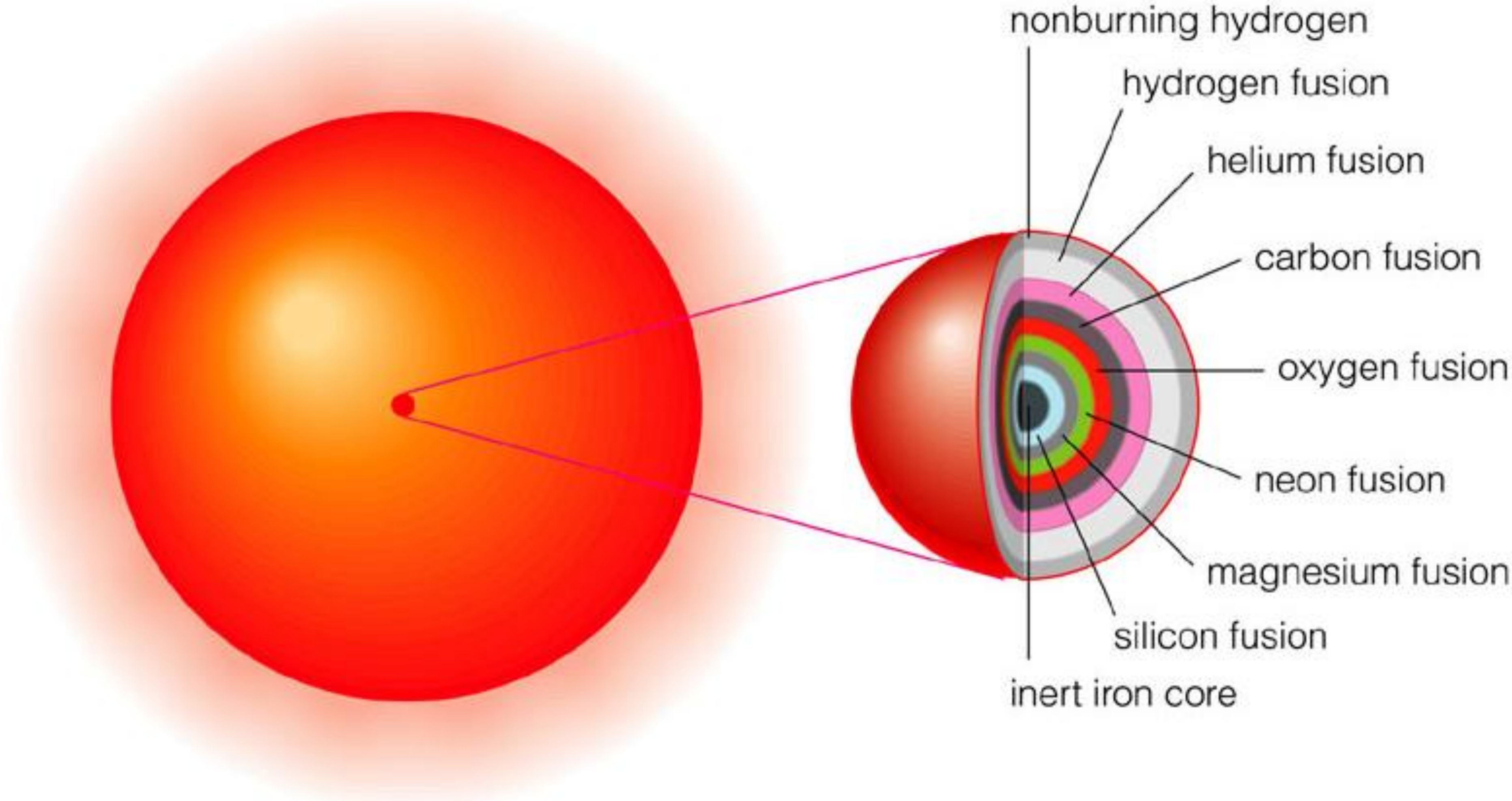


Step 1
Step 2
Step 3
Step 4
Step 5
Step 6
Total reaction
1H
13N
13C
14N
15O
15N
12C
4He
Key:
neutron
proton
positron
neutrino
gamma ray

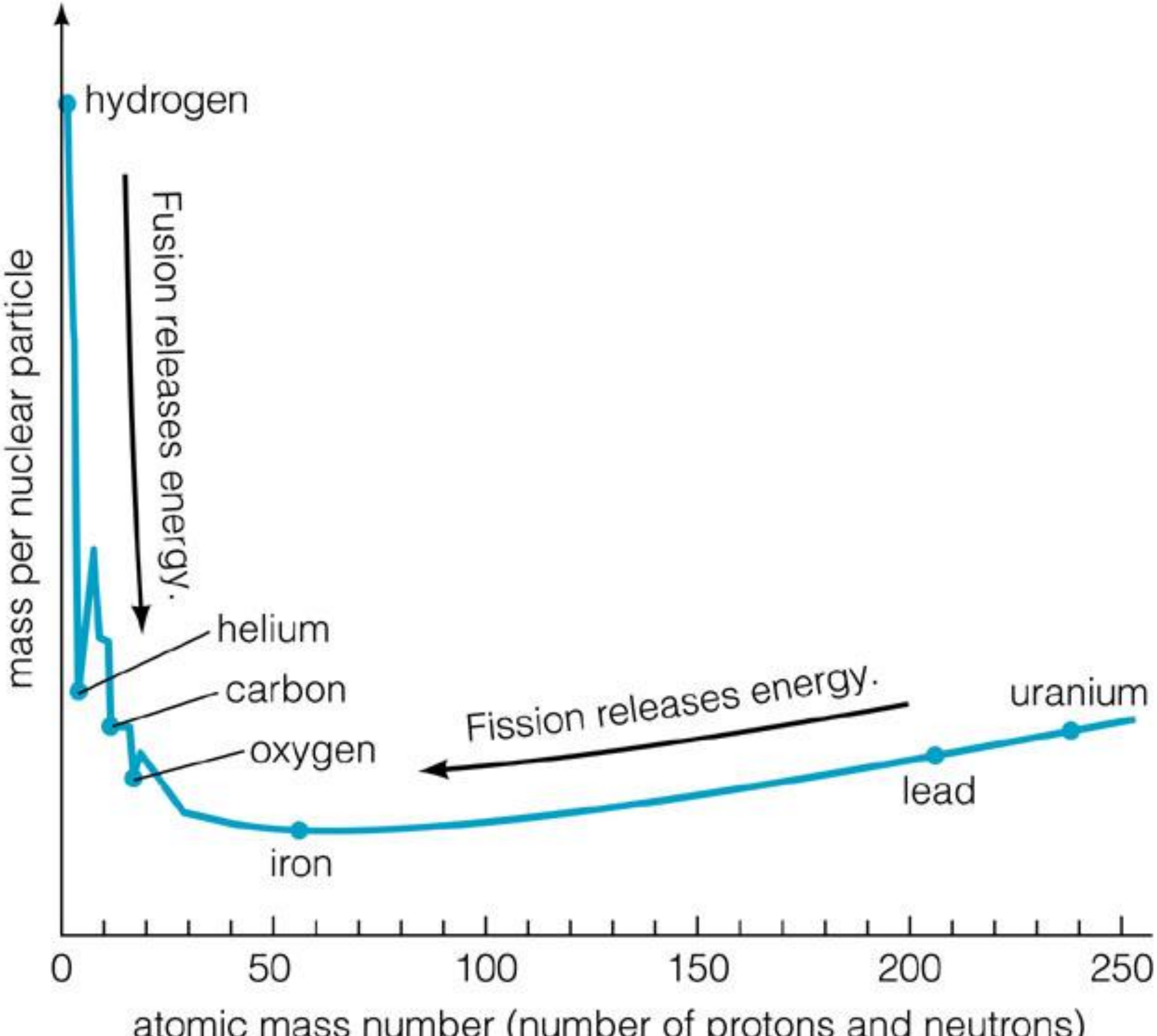


Advanced nuclear fusion reactions require extremely high temperatures, several billion degrees.

Only high-mass stars can attain high enough core temperatures to create the elements up to iron.



Advanced nuclear burning occurs in multiple shells.



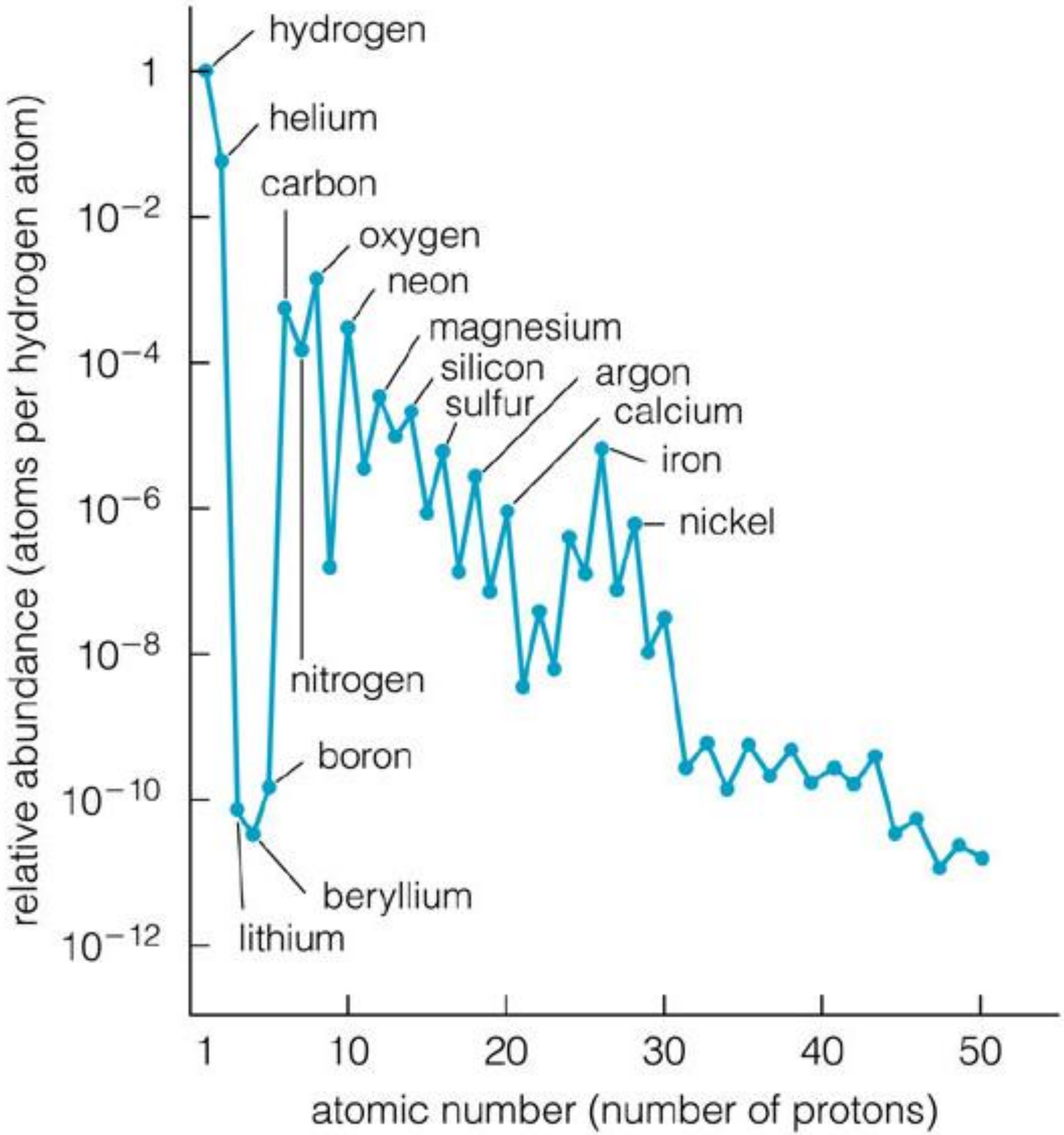
Iron is a dead end for fusion because nuclear reactions using iron do not release energy.

Iron is the most stable element; energy must be put in to get fusion past Fe.

High Mass Evolution

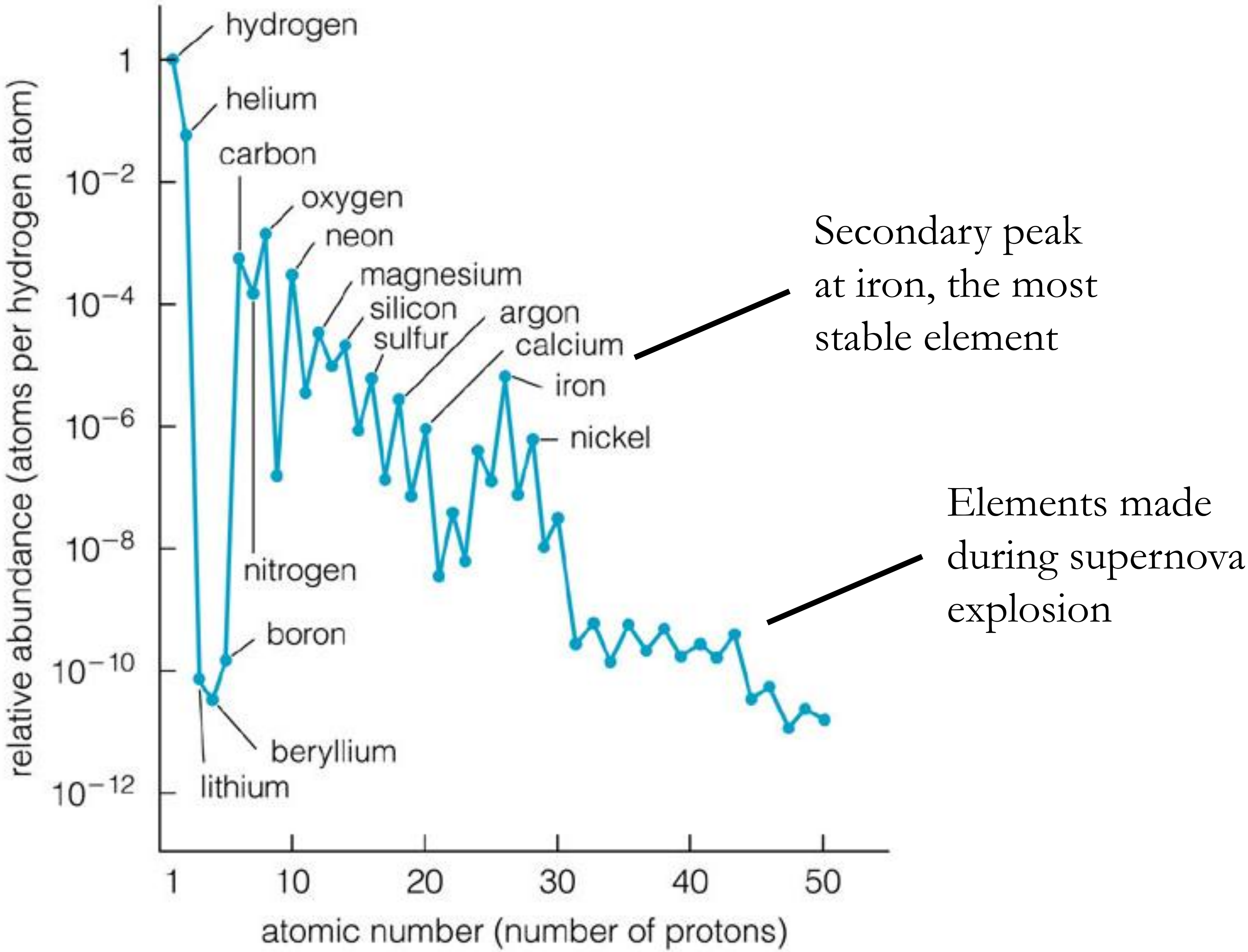
Evolutionary Stages of a 25 $M_\odot$ Star

Stage	Time Scale	Temperature (T_9)	Density (g cm^{-3})
Hydrogen burning	7×10^6 y	0.06	5
Helium burning	5×10^5 y	0.23	7×10^2
Carbon burning	600 y	0.93	2×10^5
Neon burning	1 y	1.7	4×10^6
Oxygen burning	6 months	2.3	1×10^7
Silicon burning	1 d	4.1	3×10^7
Core collapse	seconds	8.1	3×10^9
Core bounce	milliseconds	34.8	$\simeq 3 \times 10^{14}$
Explosive burning	0.1–10 s	1.2–7.0	Varies

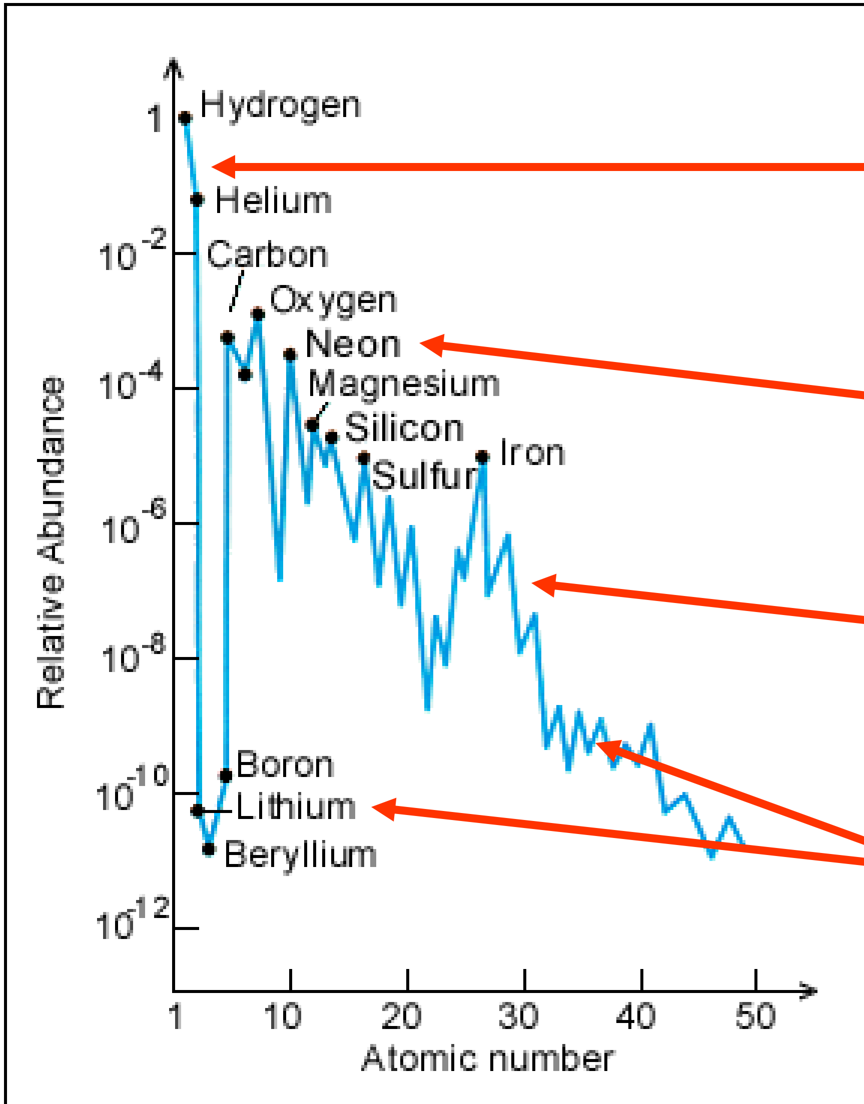


Evidence for helium capture:

Note the higher abundances of elements with even numbers of protons (the saw tooth…)


hydrogen
helium
carbon
oxygen
neon
magnesium
silicon
sulfur
argon
calcium
iron
nickel
nitrogen
boron
beryllium
lithium
Secondary peak at iron, the most stable element
Elements made during supernova explosion
relative abundance (atoms per hydrogen atom)
atomic number (number of protons)
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
1
10
20
30
40
50

Cosmic Element Abundance



Cosmic chemistry:

H is fundamental and the He is fused in the early hot big bang

Elements from C to Fe fused in moderately massive stars

Elements beyond Fe are mostly fused in supernova blast waves

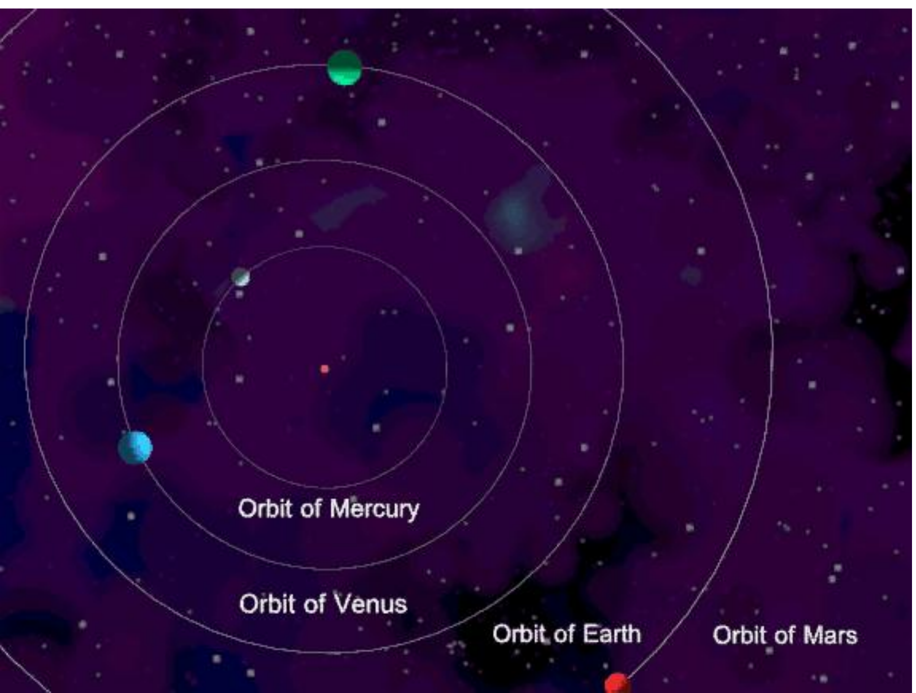
Sawtooth is He nucleus added, trough due to unstable atoms

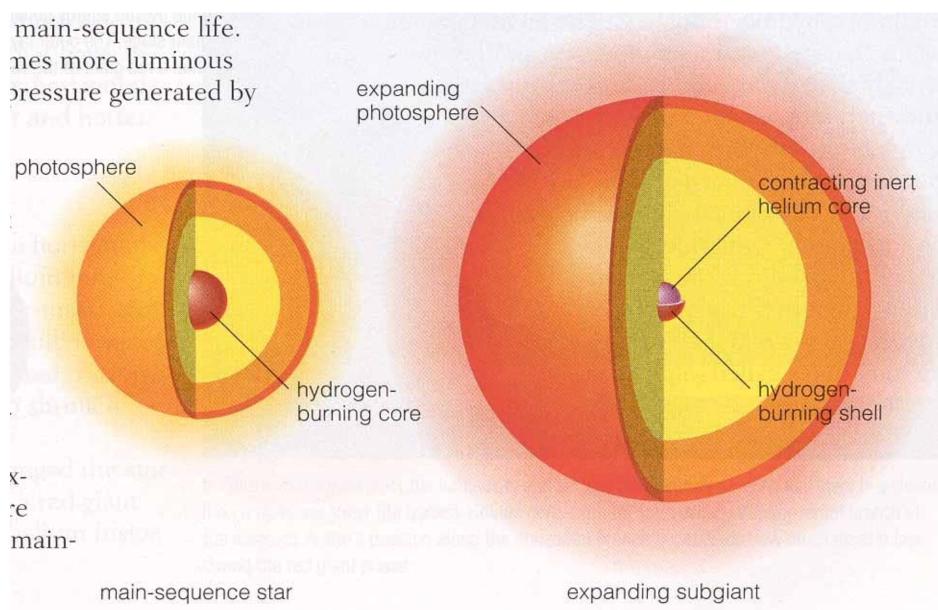
Stars are chemical factories. The universe is built for life!

Late Stages

Leaving the Main Sequence

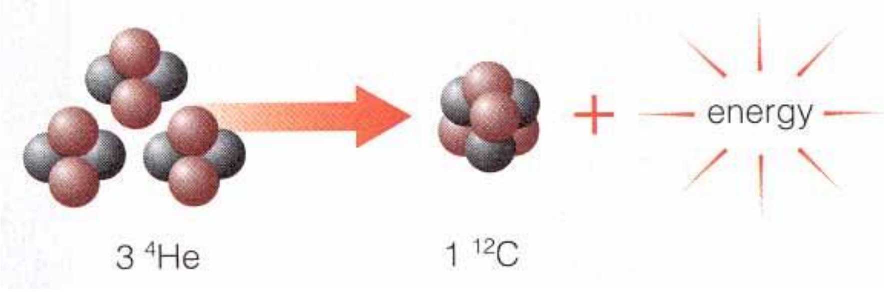
- Lifetime ~ M / L = M / $M^{3.5}$ = 1 / $M^{2.5}$ = $M^{-2.5}$
- The core begins to collapse
  - H shell heats up and H fusion begins there
  - There is less gravity to balance it, so shell gets bigger



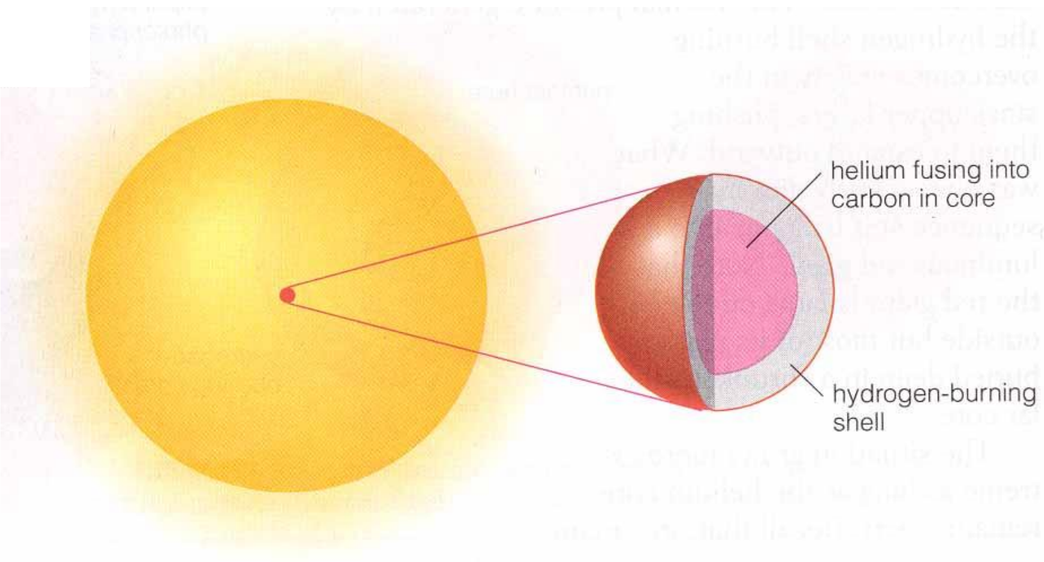


Red Giants

- The He core collapses until it heats to 10^8 K
  – He fusion begins (He ⇨ C)
  – sometimes called the "triple-α process"

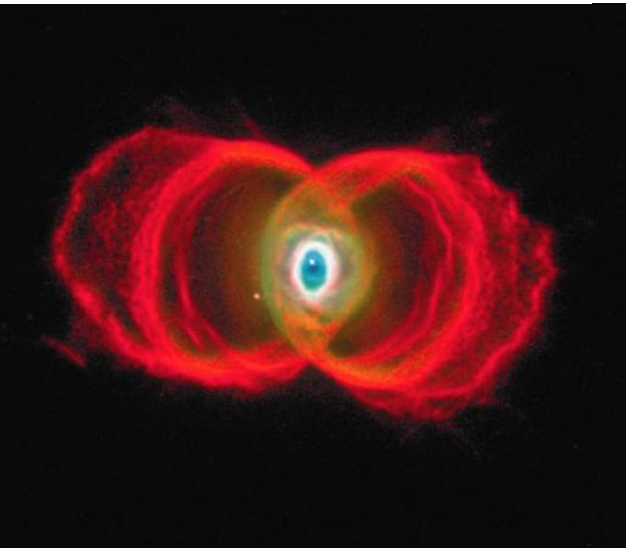


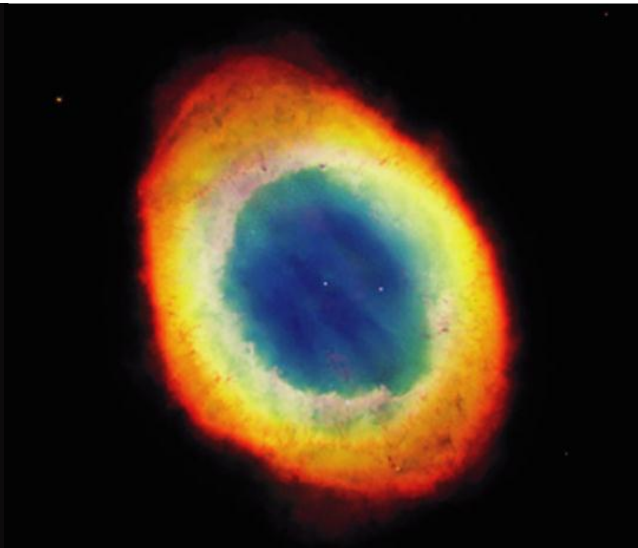
- The star, called a Red Giant, is once again stable
- Gravity vs. pressure from He fusion reactions



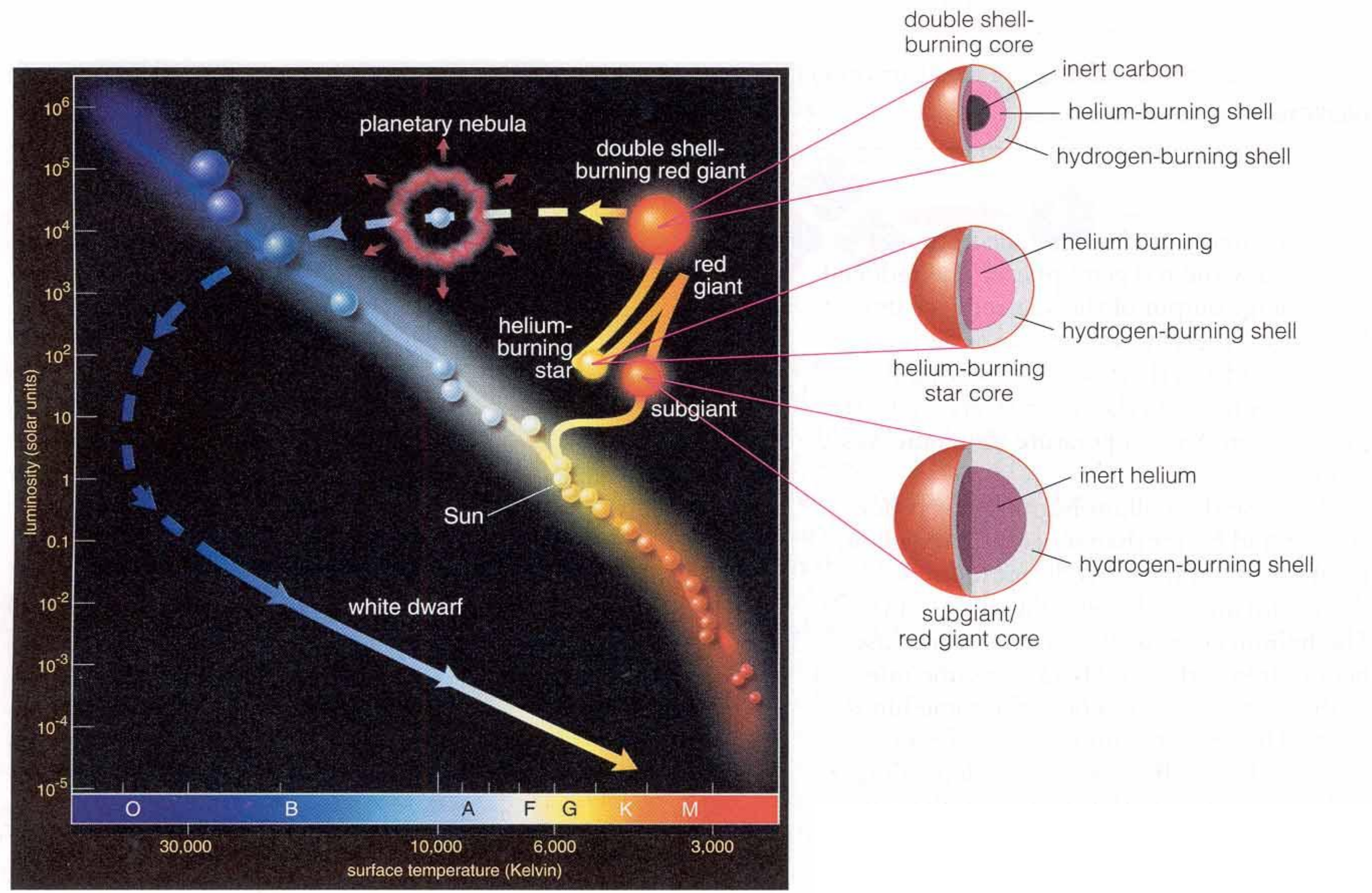
Planetary Nebulae

- When the Red Giant exhausts its He fuel
  - the C core collapses
  - Low & intermediate-mass stars don't have enough gravitational energy to heat to 6 x 10^8 K (temperature at which C can fuse)
- The He & H burning shells overcome gravity
  - the outer envelope of the star is gently blown away
  - this forms a planetary nebula

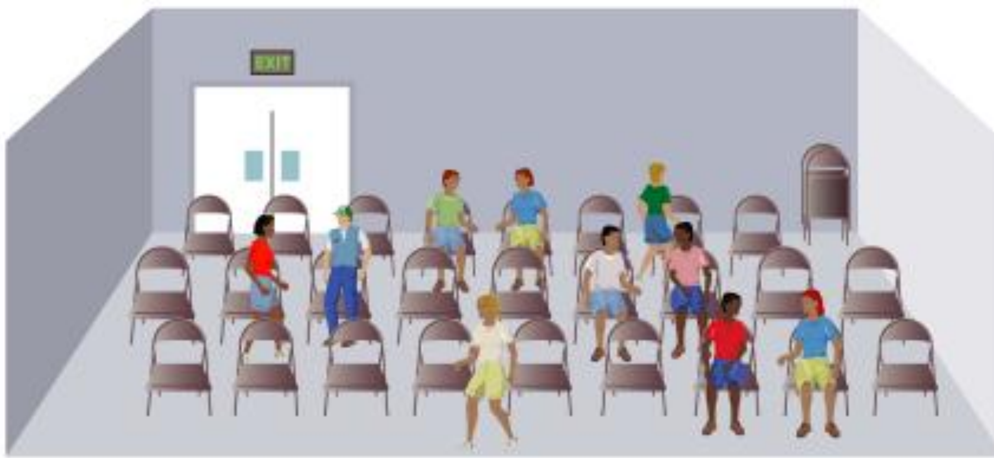




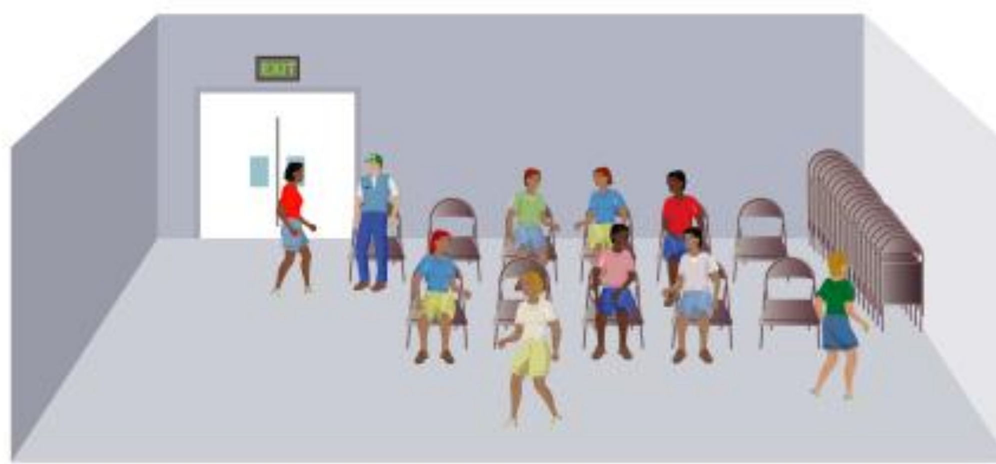
Planetary Nebulae



- In **degenerate matter**, two particles cannot occupy the same space with the same momentum (energy)
- For **very** dense solids, the electrons cannot be in their ground states, they become very energetic---approaching the speed of light
- The pressure holding up the star no longer depends on temperature



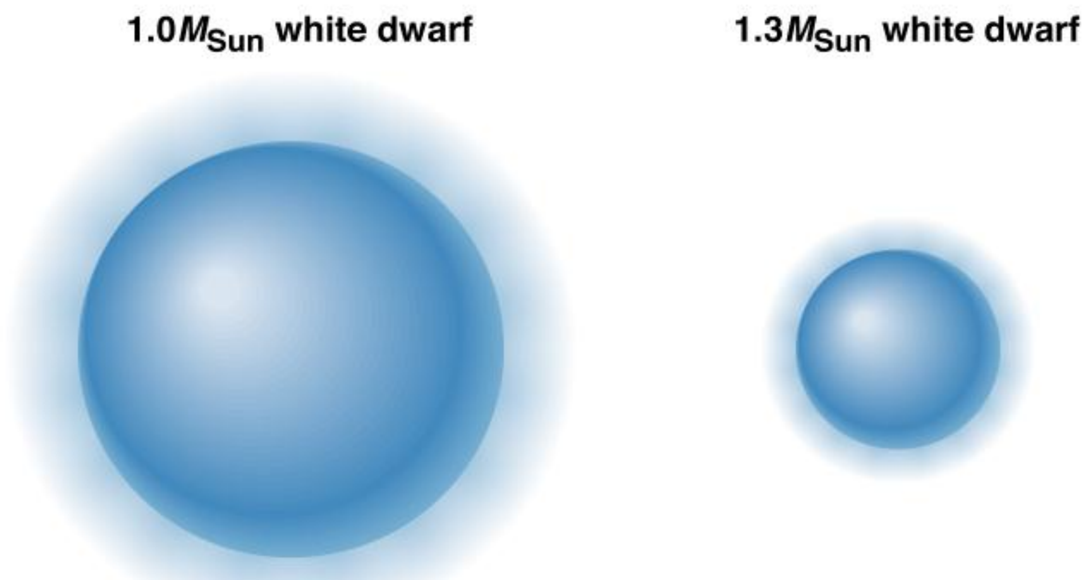
(a)



(b)

Degenerate Stars

- Degenerate matter obeys different laws of physics
- The more mass the star has, the *smaller* the star becomes!



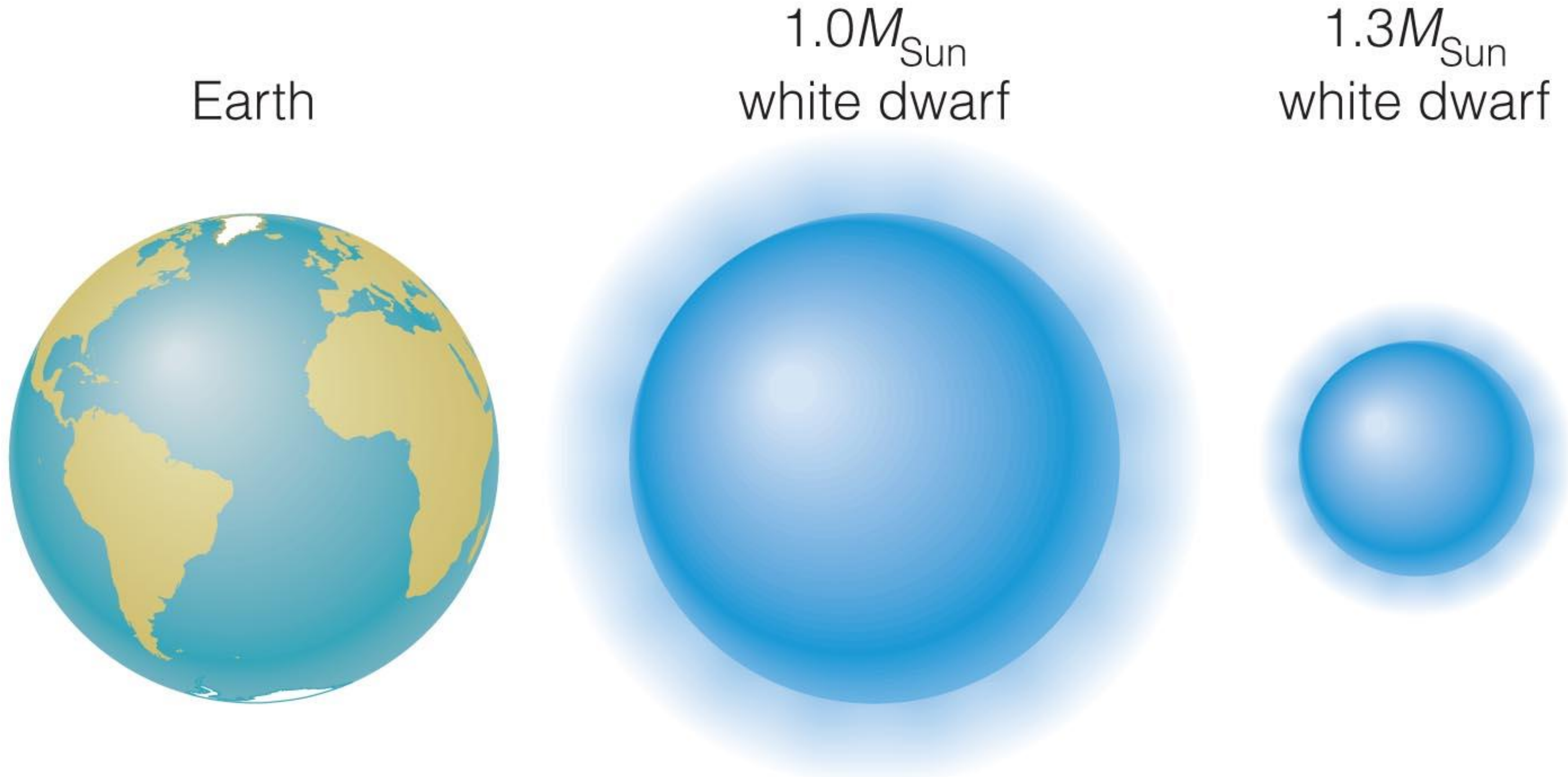
- The central star of the Planetary Nebula heats up as it collapses
- The star has insufficient mass to get hot enough to fuse Carbon
- Gravity is finally stopped by the force of **electron degeneracy**.
- The star is now stable……

White Dwarf

White Dwarf

Degenerate Stars

- In the leftover core of a dead star…
  - degeneracy pressure supports the star against the gravity
- A degenerate star which is supported by:
  - electron degeneracy pressure is a **white dwarf**
  - neutron degeneracy pressure is a **neutron star**
- If the remnant core is so massive that the force of gravity is greater than the , neutron degeneracy pressure…
  - the star collapses out of existence beyond an event horizon and is called a **black hole**

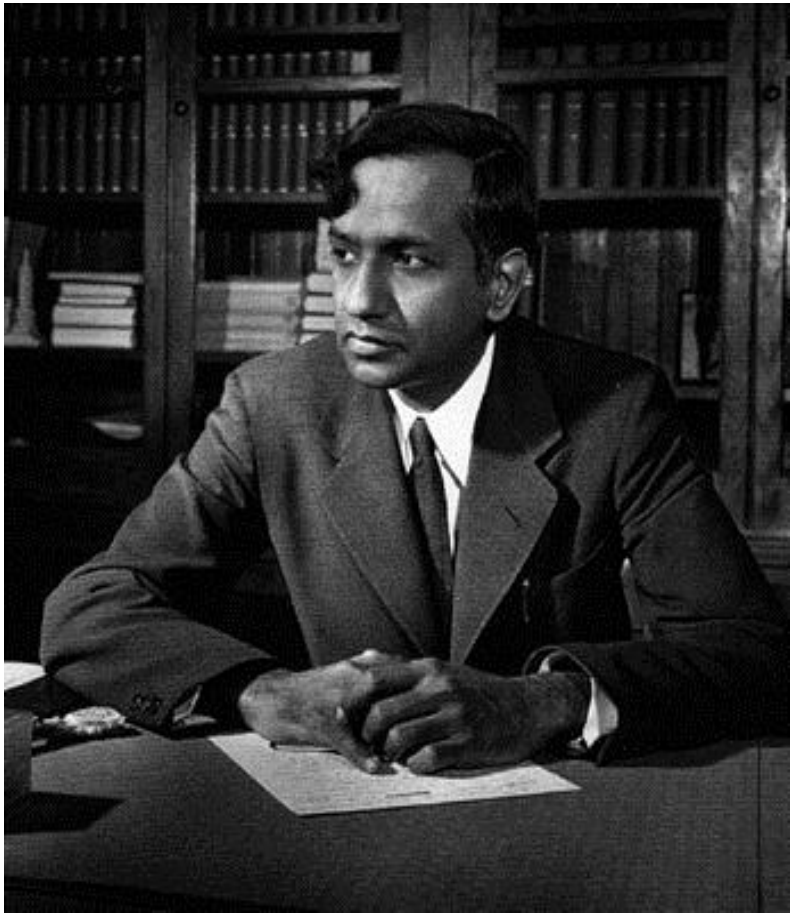


A Sun-mass white dwarf is 200,000 x denser than the Earth, or 10^9 kg/m^3, which equals about 10,000 tons per cubic inch!

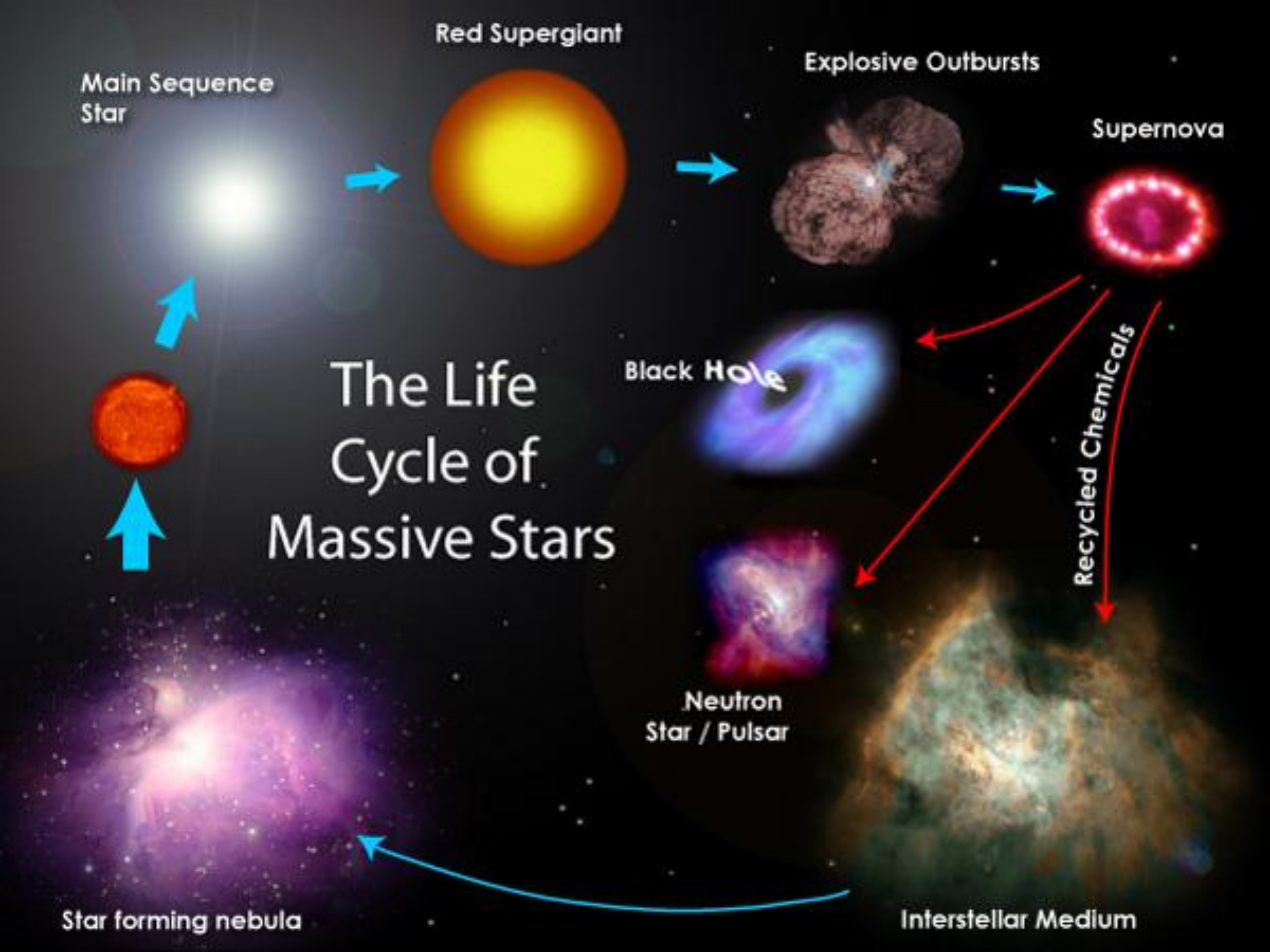
Limit on White Dwarf Mass

- Chandra formulated the laws of degenerate matter.
  - for this he won the Nobel Prize in Physics
- He also predicted that gravity will overcome the pressure of electron degeneracy if a white dwarf has a mass > $\boxed{1.4\ M_{\odot}}$
  - energetic electrons, which cause this pressure, reach the speed of light (i.e. they are relativistic)

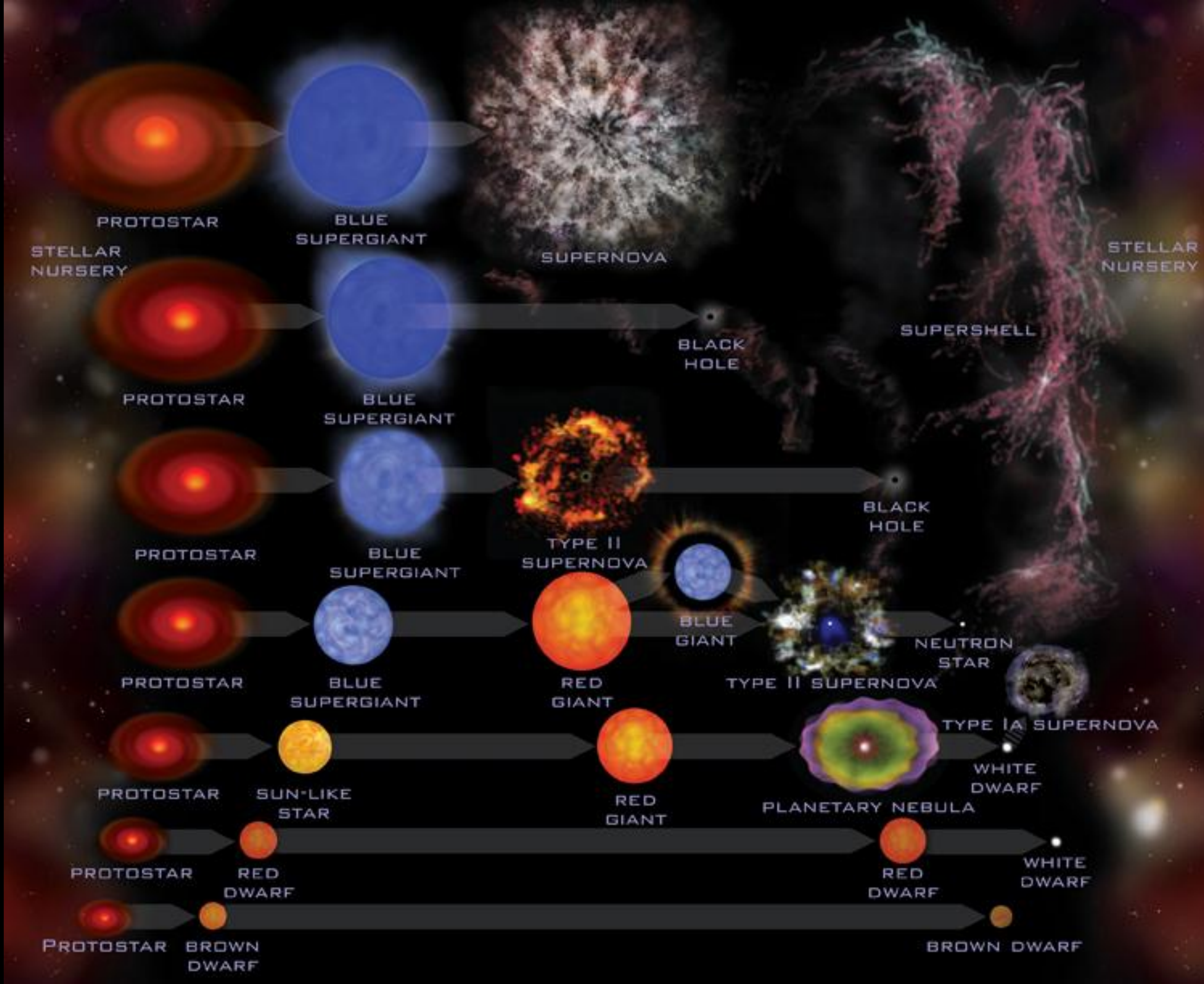
This mass boundary is the
Chandrasekhar Limit



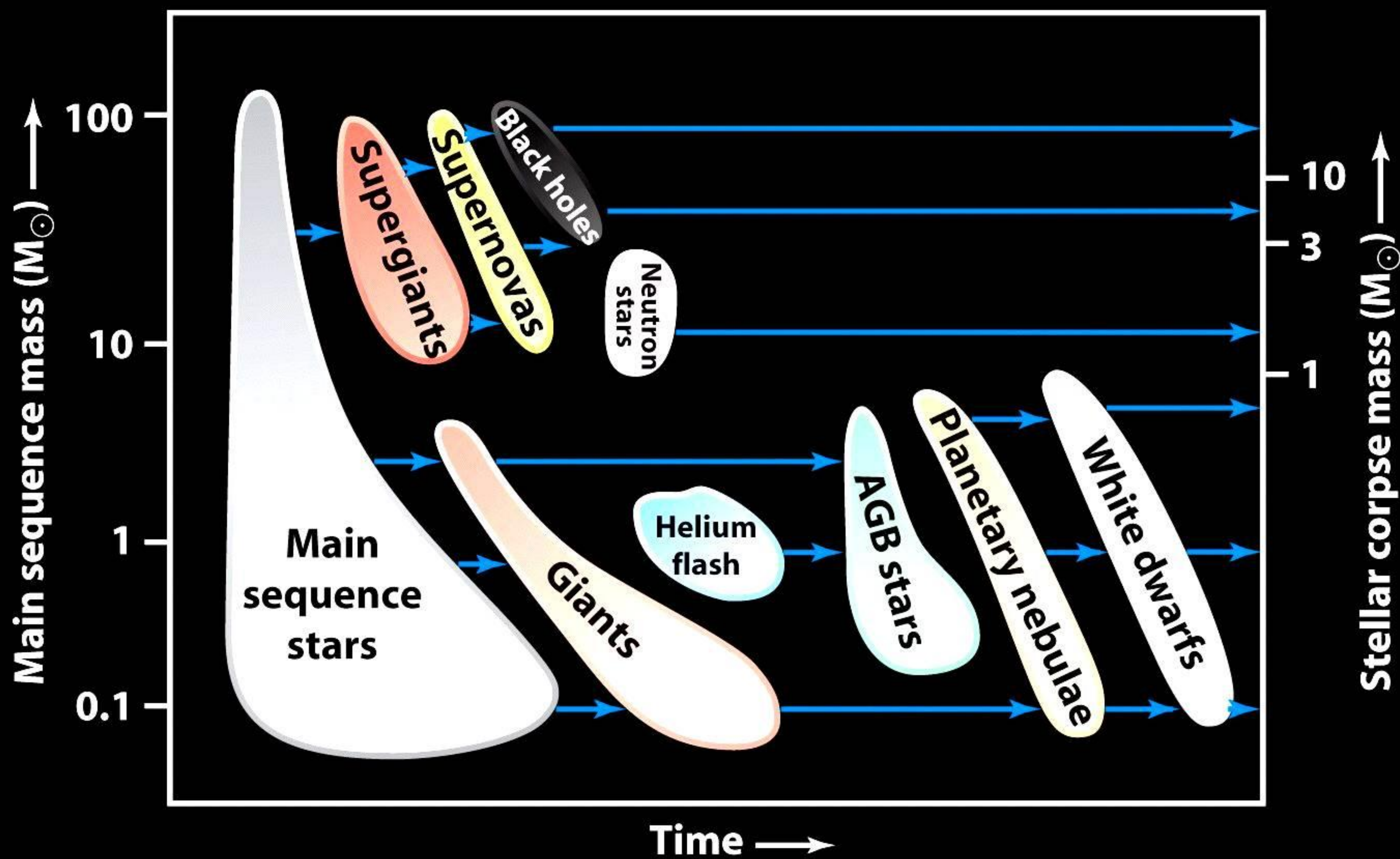
Subrahmanyan Chandrasekhar (1910-1995)



Red Supergiant
Explosive Outbursts
Main Sequence Star
Supernova
Black Hole
The Life Cycle of Massive Stars
Recycled Chemicals
Neutron Star / Pulsar
Star forming nebula
Interstellar Medium



PROTOSTAR
BLUE SUPERGIANT
SUPERNOVA
STELLAR NURSERY
STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
SUPERSHELL
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
BLUE GIANT
TYPE II SUPERNOVA
NEUTRON STAR
TYPE IA SUPERNOVA
PROTOSTAR
SUN-LIKE STAR
RED GIANT
PLANETARY NEBULA
WHITE DWARF
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF



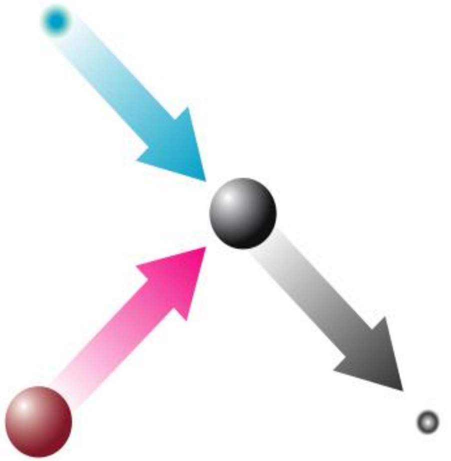
Main sequence mass ($M_\odot$)
100
10
1
0.1
Stellar corpse mass ($M_\odot$)
10
3
1
Main sequence stars
Supergiants
Supernovas
Black holes
Neutron stars
Giants
Helium flash
AGB stars
Planetary nebulae
White dwarfs
Time

Supernovas

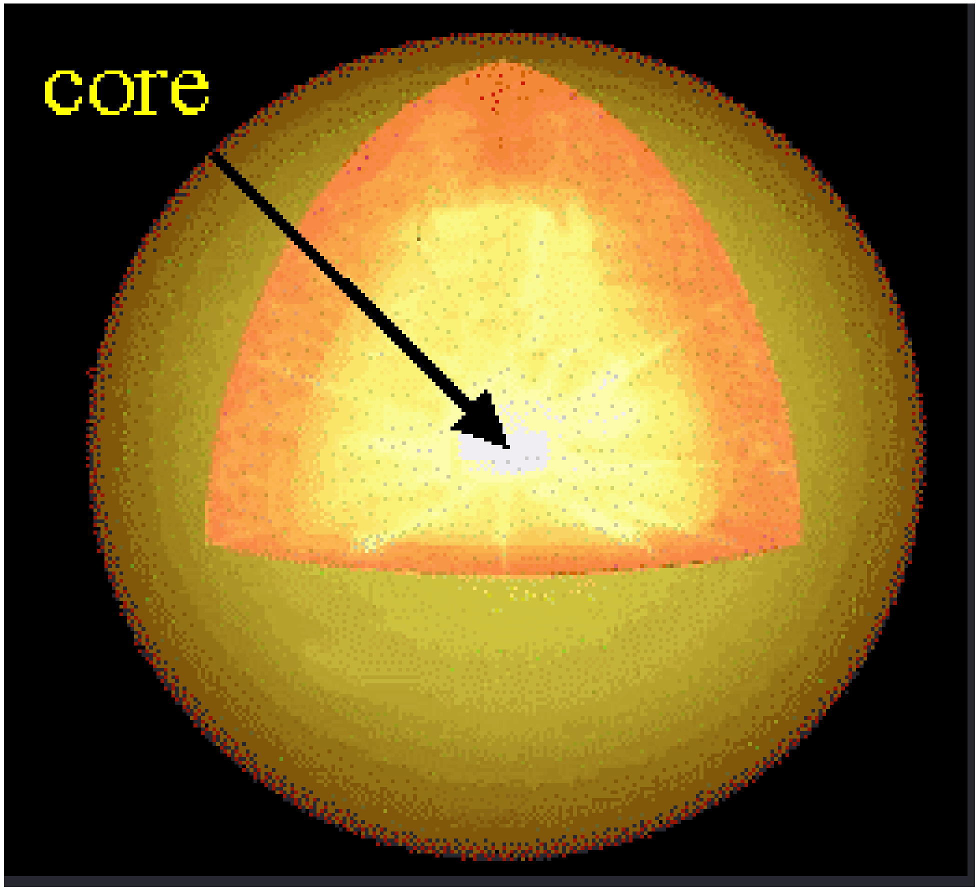
Core Collapse

- **BUT**… the force of gravity increases as the mass of the Fe core increases
  - Gravity overcomes electron degeneracy
  - Electrons are smashed into protons ⇨ neutrons

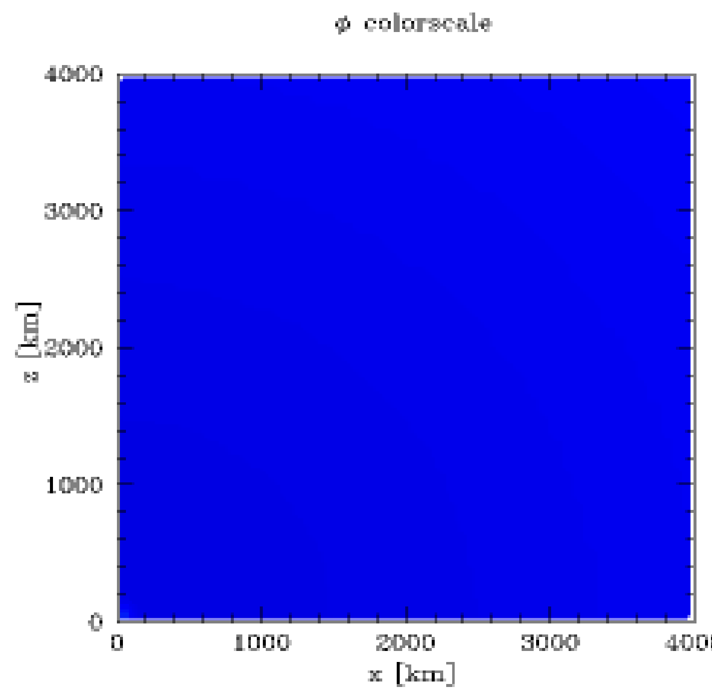
➲ The neutron core collapses until it is abruptly stopped by neutron degeneracy pressure
- this takes only seconds
- The core recoils and sends the rest of the star flying into space



Simulations



Zooming in to a region 300 km across (left, lower left corner), the star falls in on the neutron star core, leading to neutrinos and a gravitational wave burst.



The expanding blast wave (right), creates temperatures of billions of degrees and heavy elements.

Supernova Rate

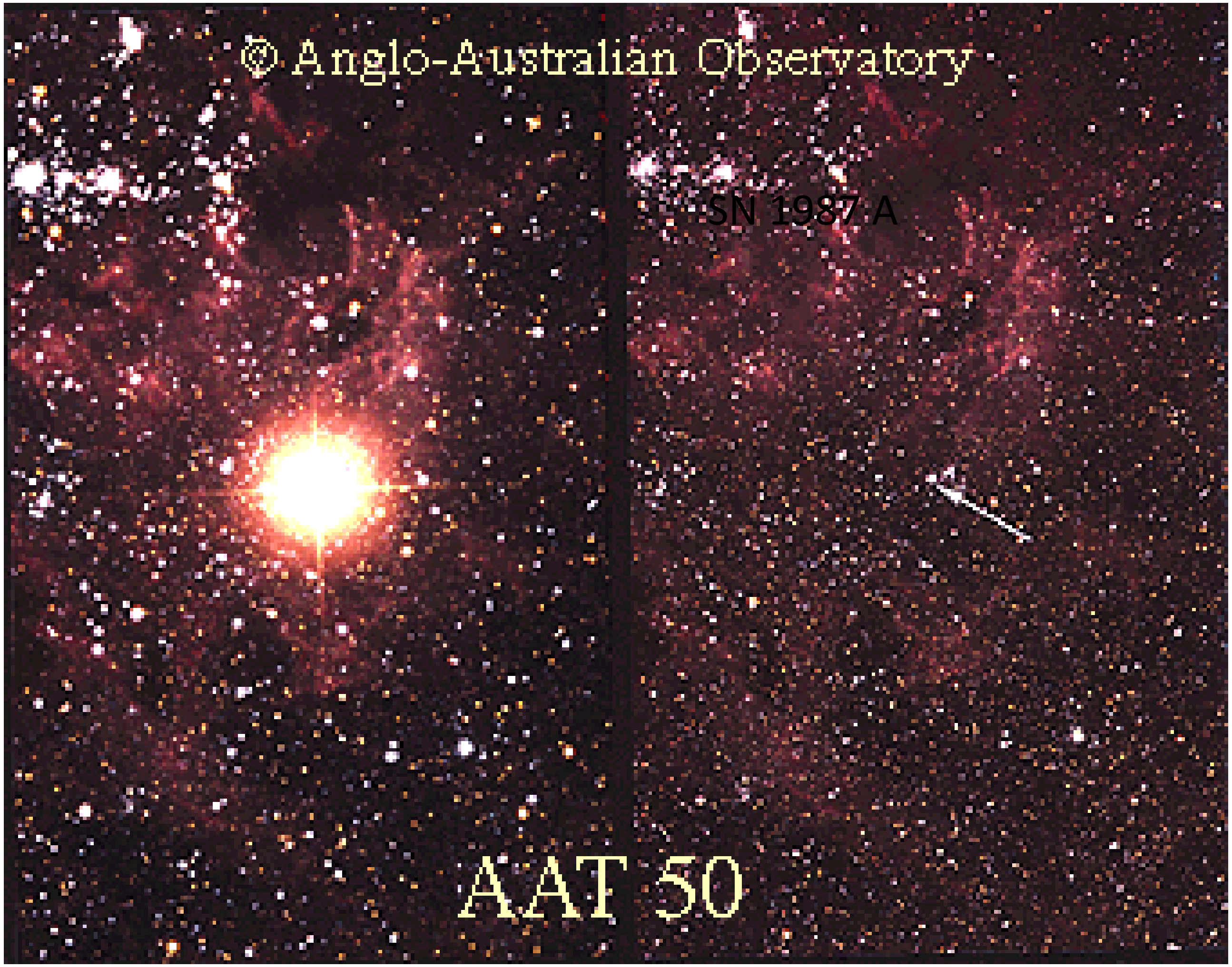
The *Crab Nebula* in *Taurus* supernova exploded in 1054

The amount of energy released is so great, that most elements **heavier** than Fe are instantly created in an immense blast wave.

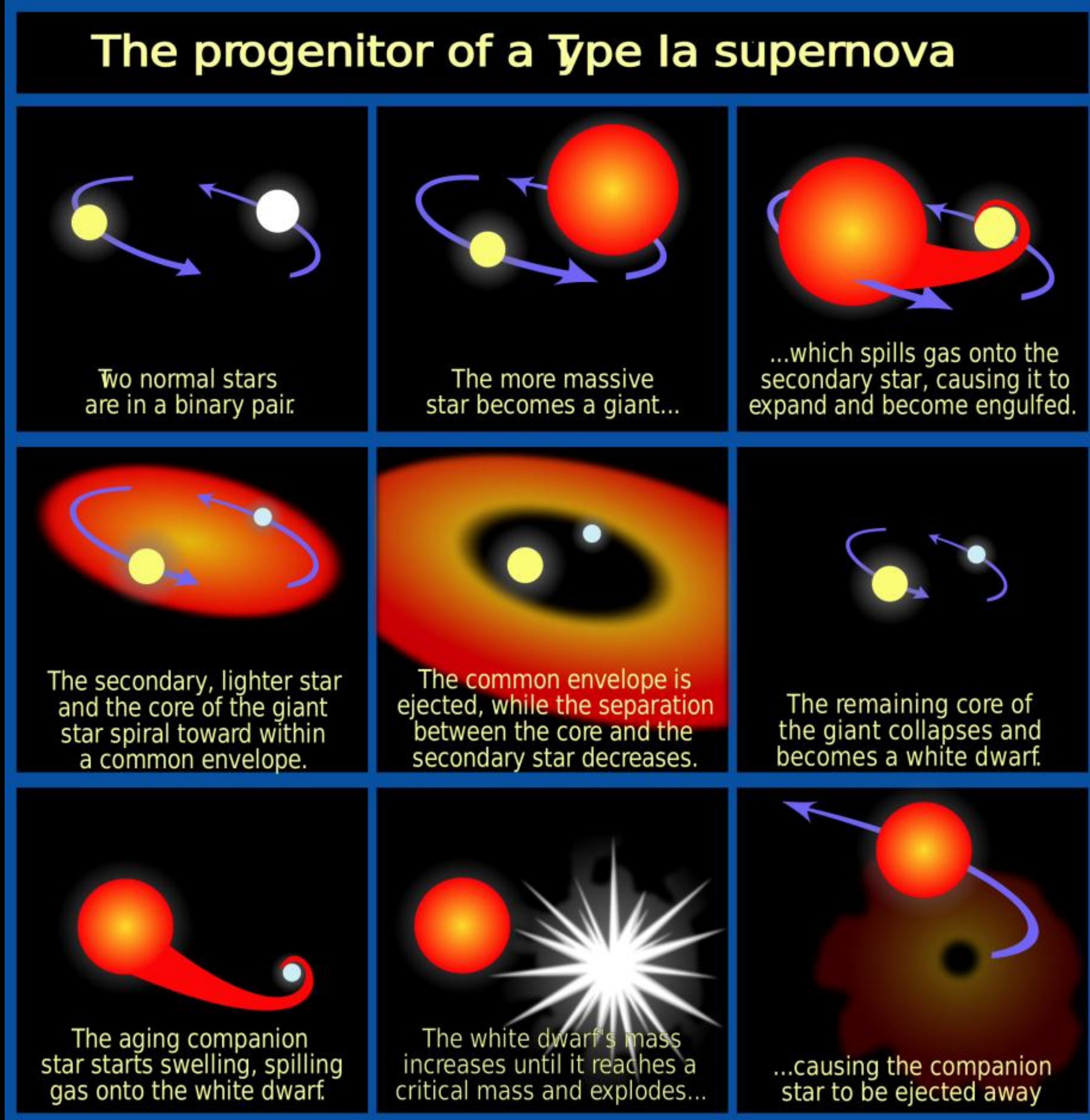
In the last millennium, four supernovae have been observed in our part of the Milky Way Galaxy: in 1006, 1054, 1572, and 1604. Once per 100 years is typical so we're overdue….

SN 1987A in the LMC

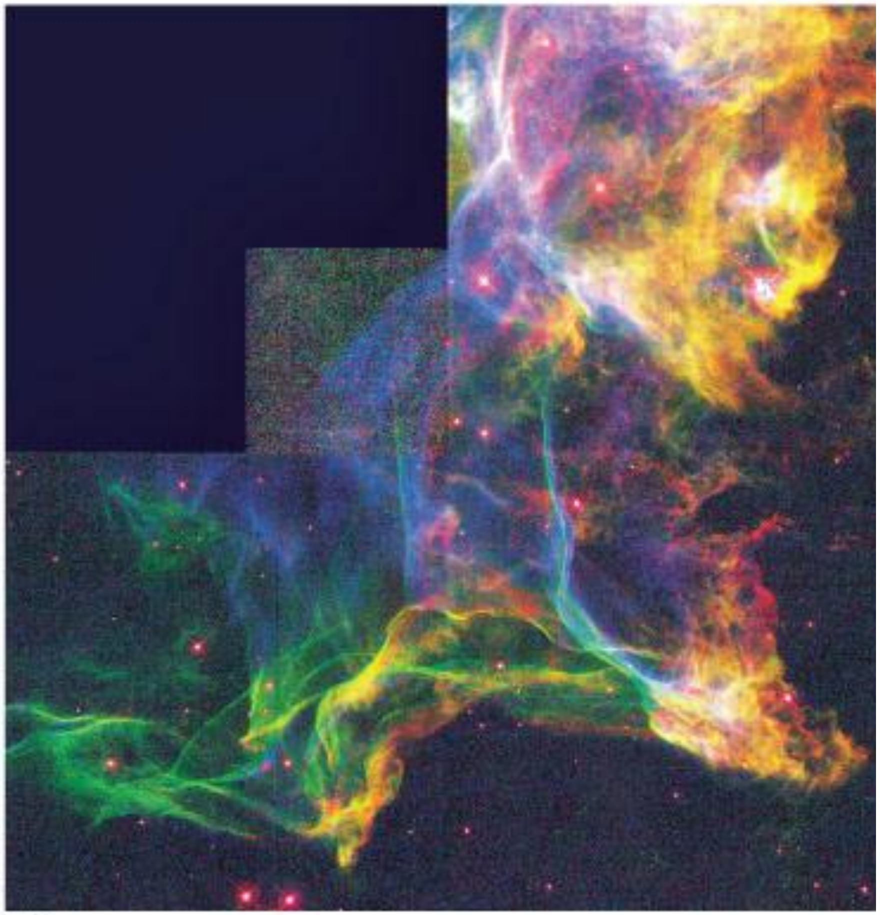
SN 1987A is the nearest supernova to explode since the invention of the telescope; it was a massive star that detonated in a nearby galaxy, the LMC or Large Magellanic Cloud, which is 50,000 kpc, or 170,000 light years away.



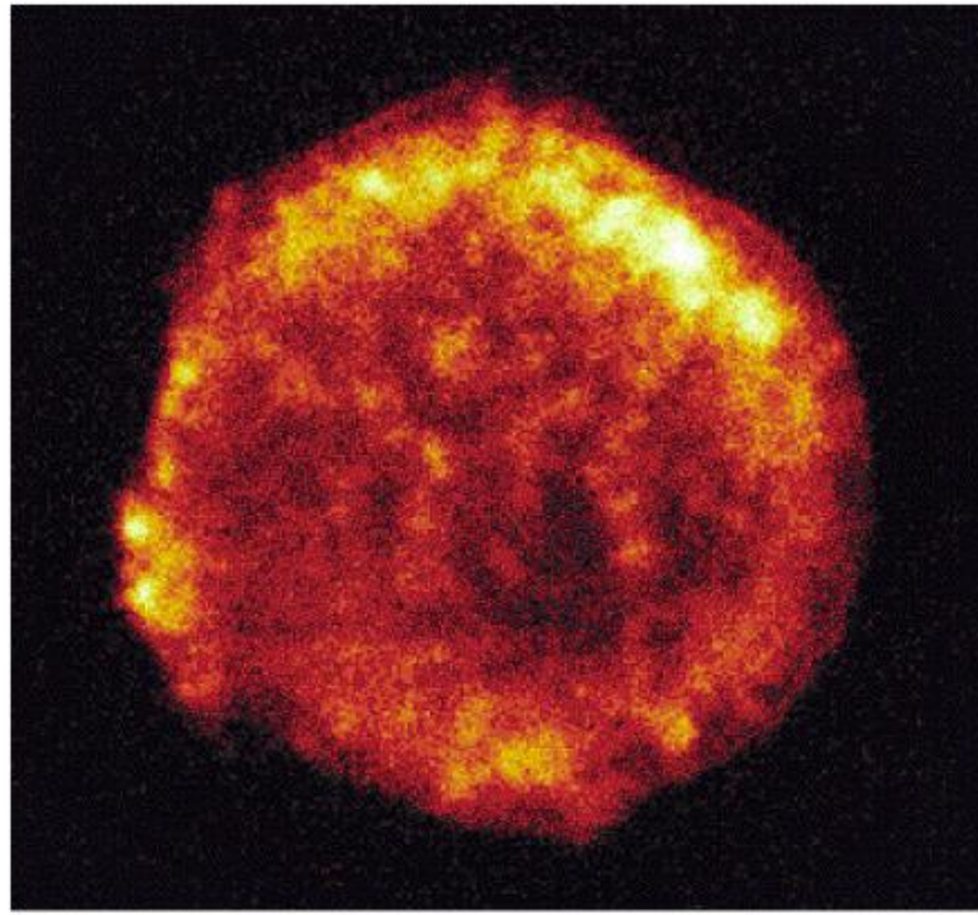
during **after**


The progenitor of a Type Ia supernova
Two normal stars are in a binary pair.
The more massive star becomes a giant...
...which spills gas onto the secondary star, causing it to expand and become engulfed.
The secondary, lighter star and the core of the giant star spiral toward within a common envelope.
The common envelope is ejected, while the separation between the core and the secondary star decreases.
The remaining core of the giant collapses and becomes a white dwarf.
The aging companion star starts swelling, spilling gas onto the white dwarf.
The white dwarf's mass increases until it reaches a critical mass and explodes...
...causing the companion star to be ejected away

Examples

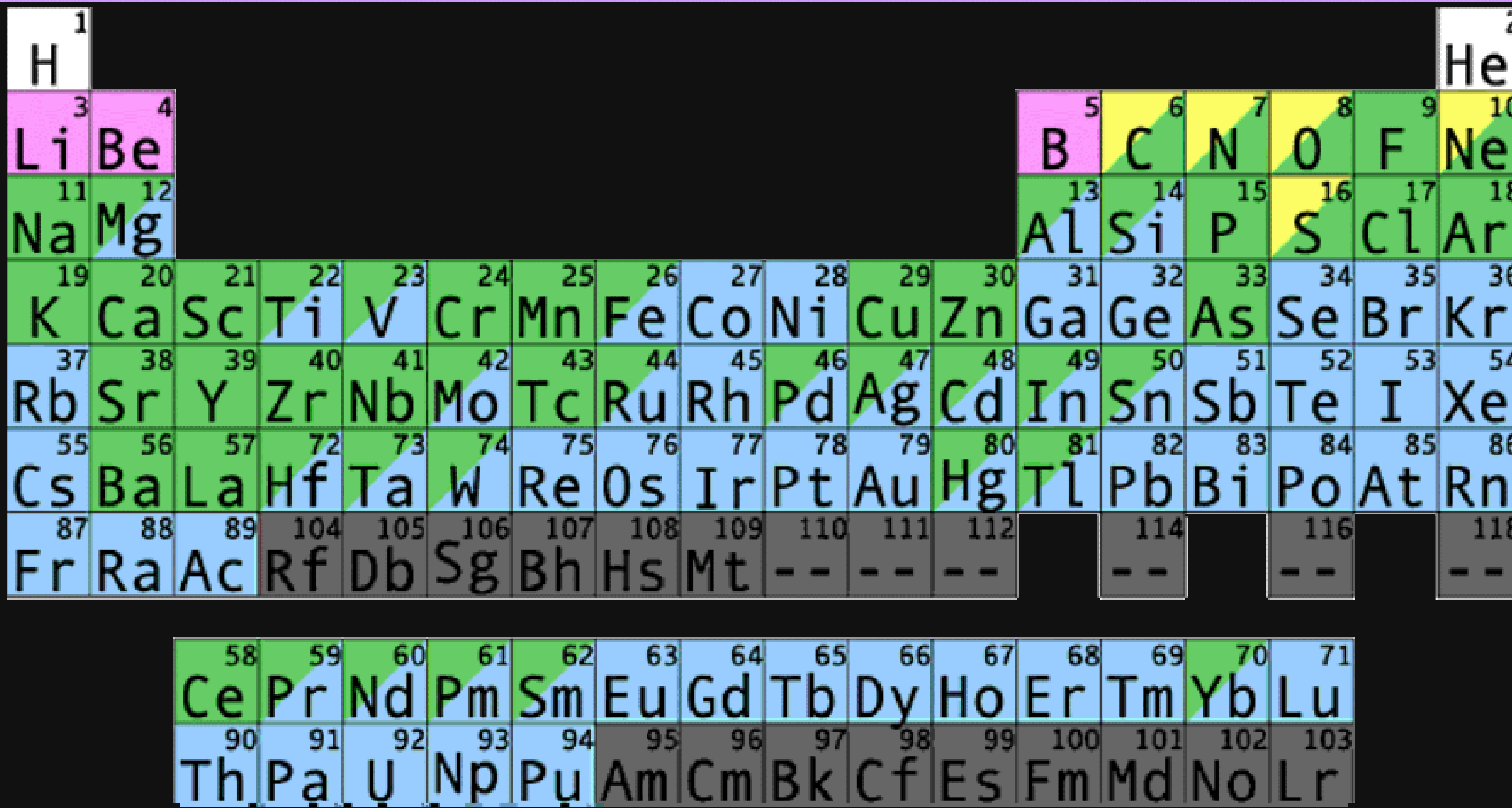


Veil Nebula (Visible)



Tycho's Supernova (X-rays)

Cosmic Elements



White - Big Bang

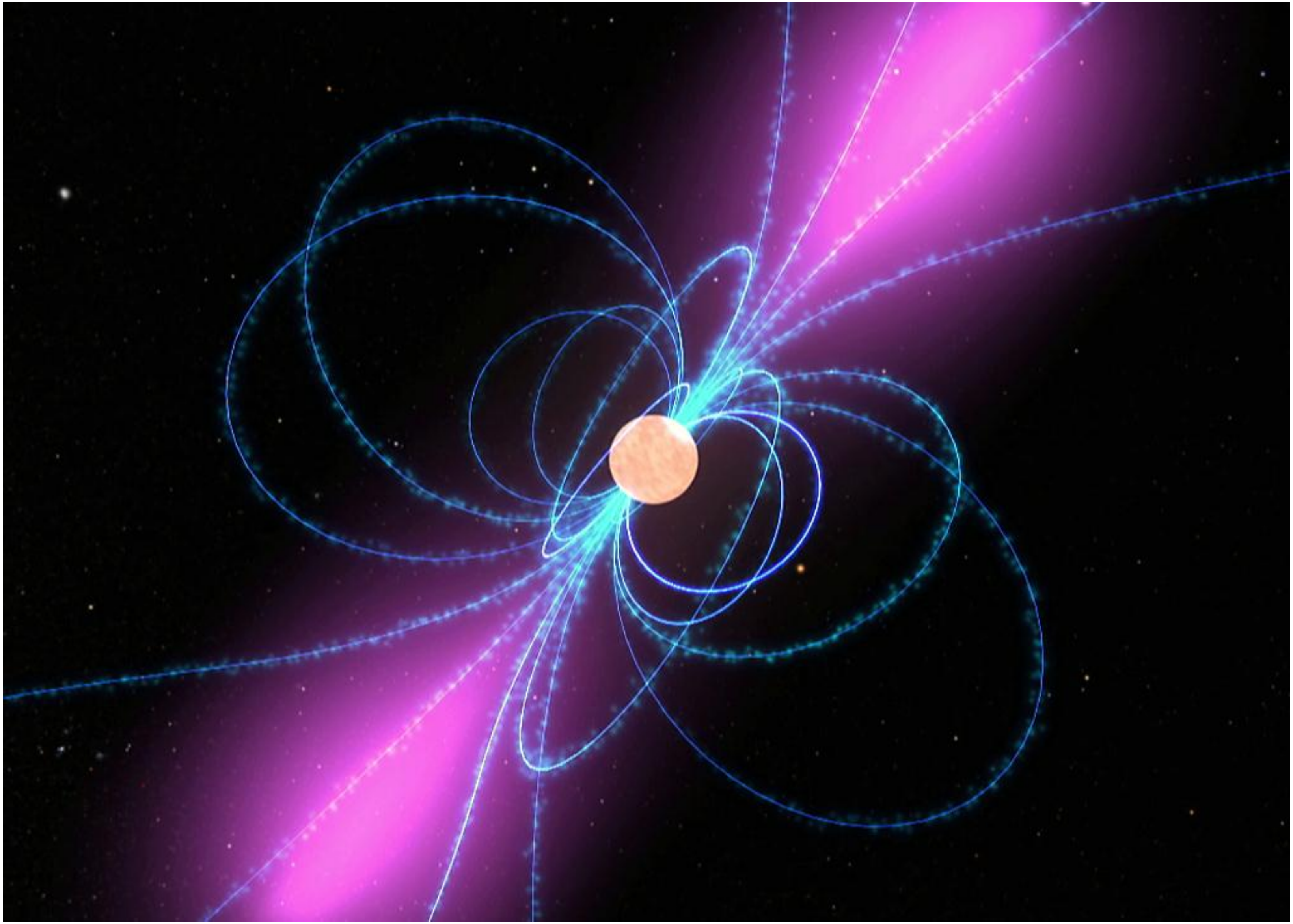
Pink - Cosmic Rays

Yellow - Small Stars

Green - Large Stars

Blue - Supernovae

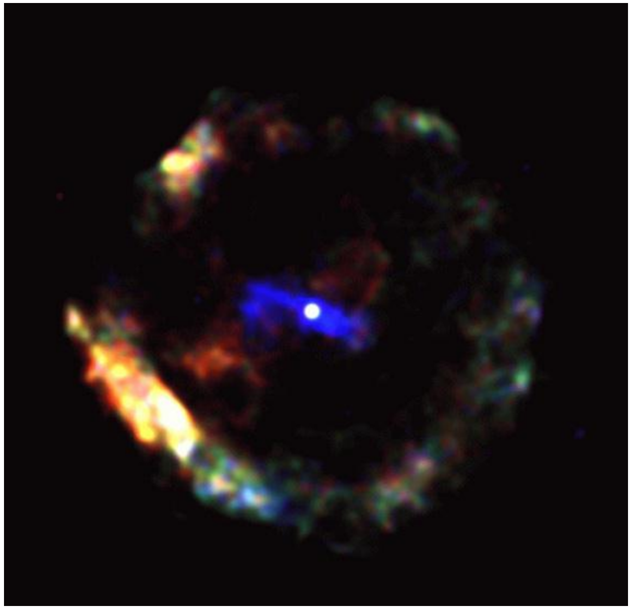
Pulsars



Neutron Stars

- ...are the leftover cores from supernova explosions.
- If the core < 3 $M_\odot$, it will stop collapsing and be held up by neutron degeneracy pressure.
- Neutron stars are very dense (10^{12} g/cm^3)
  - 1.5 $M_\odot$ with a diameter of 10 to 20 km
- They rotate very rapidly: Period = 0.0003 to 4 sec
- Their magnetic fields are 10^{13} times stronger than Earth's.

Earth's magnetic field	**1 Gauss**
Refrigerator magnet	**100 Gauss**
Sunspot	**1000 Gauss**
White dwarf	**10^6 Gauss**
Neutron star	**10^{12} Gauss**
Magnetar	**10^{15} Gauss**

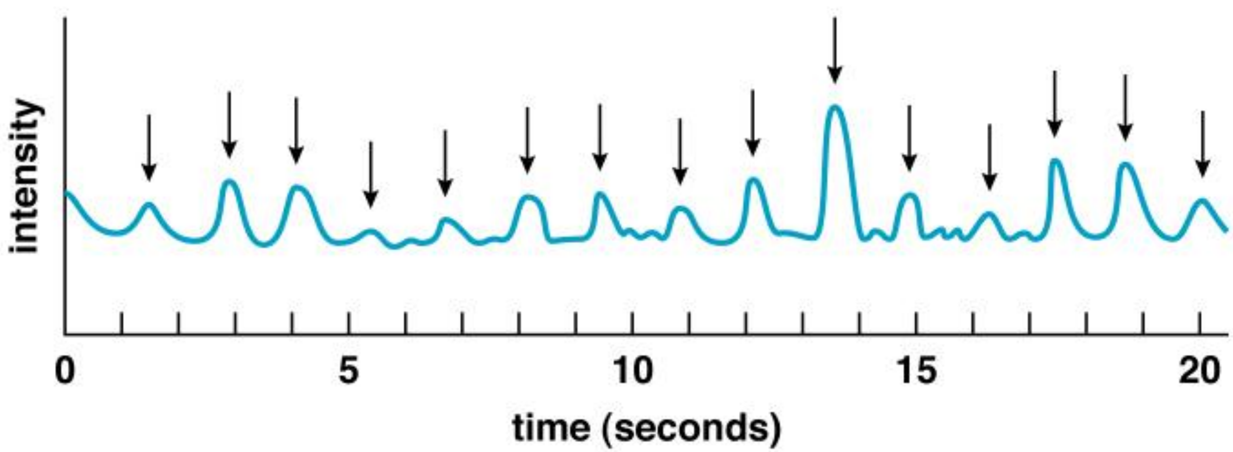


Chandra X-ray image of the neutron star left behind by a bright supernova observed in A.D. 386 by the Chinese.

Pulsars

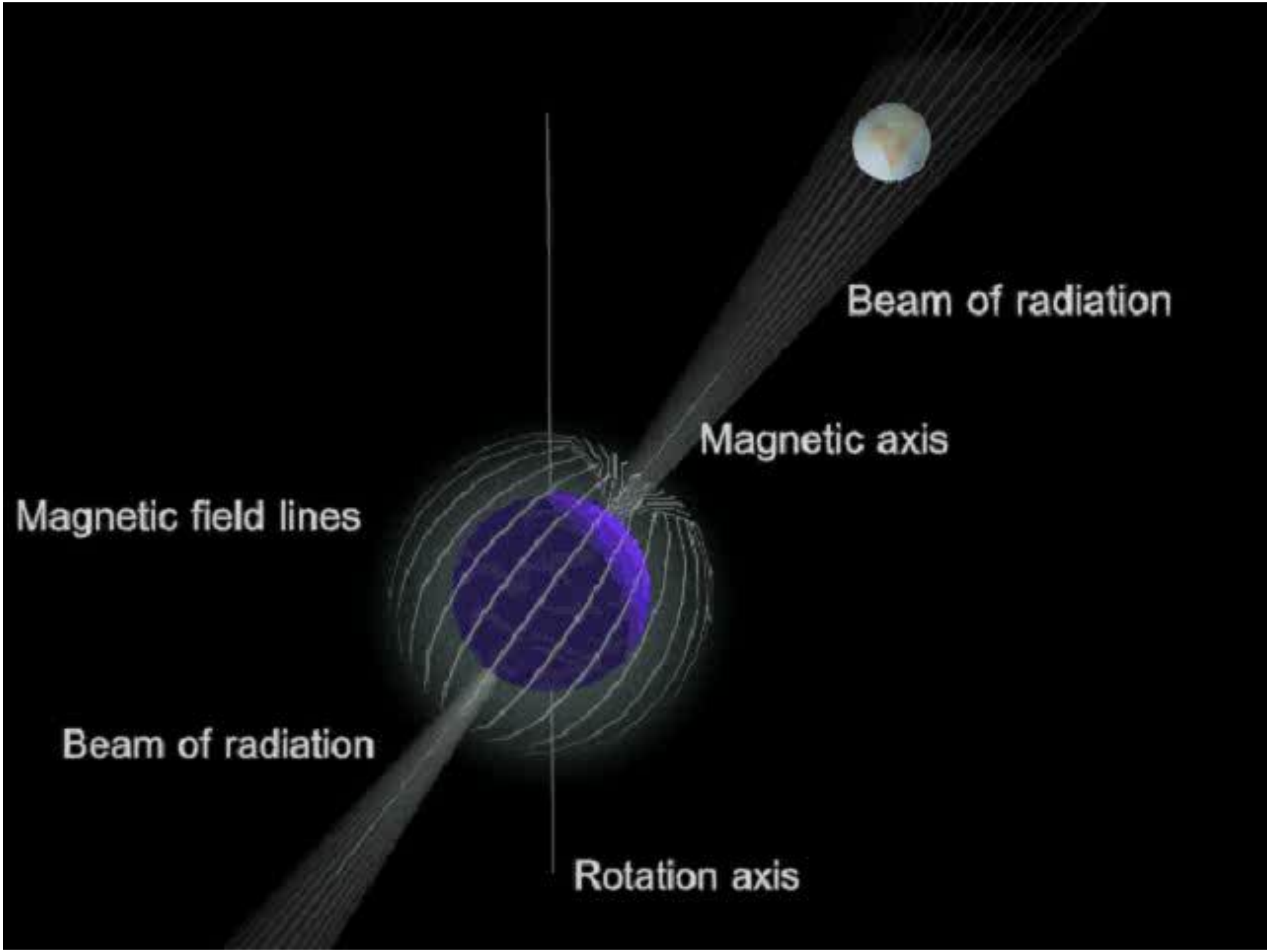
- In 1967, graduate student Jocelyn Bell and her advisor Dr. Anthony Hewish accidentally discovered a radio source in *Vulpecula*.
- It was a sharp pulse which recurred every 1.3 sec, more accurate than any clock.
- They determined it was 300 pc away.
- They called it a **pulsar**, but what was it?

Jocelyn Bell

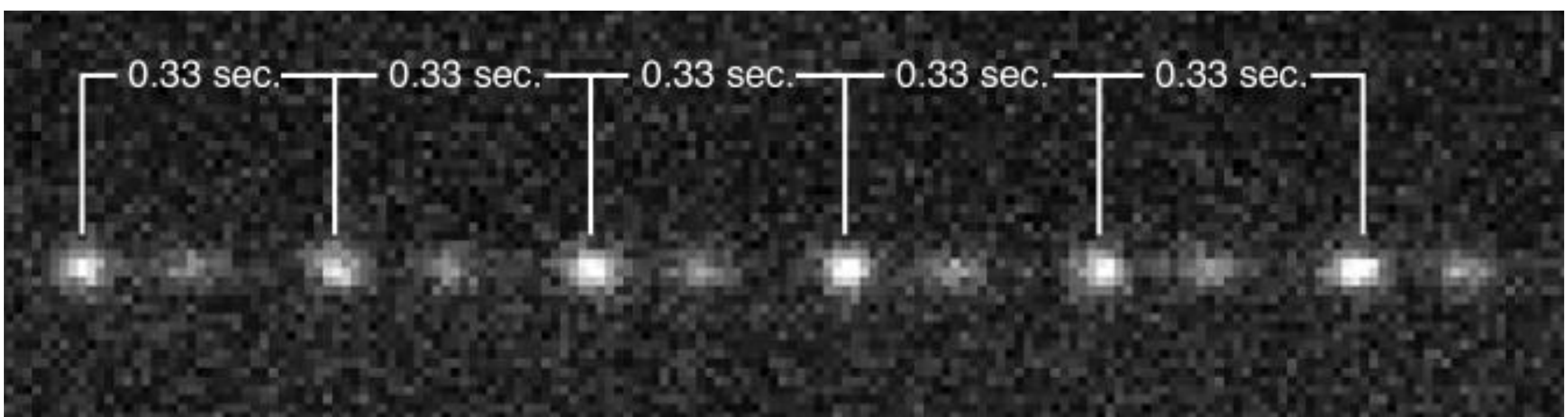


Radio trace of Jocelyn Bell's discovery pulsar

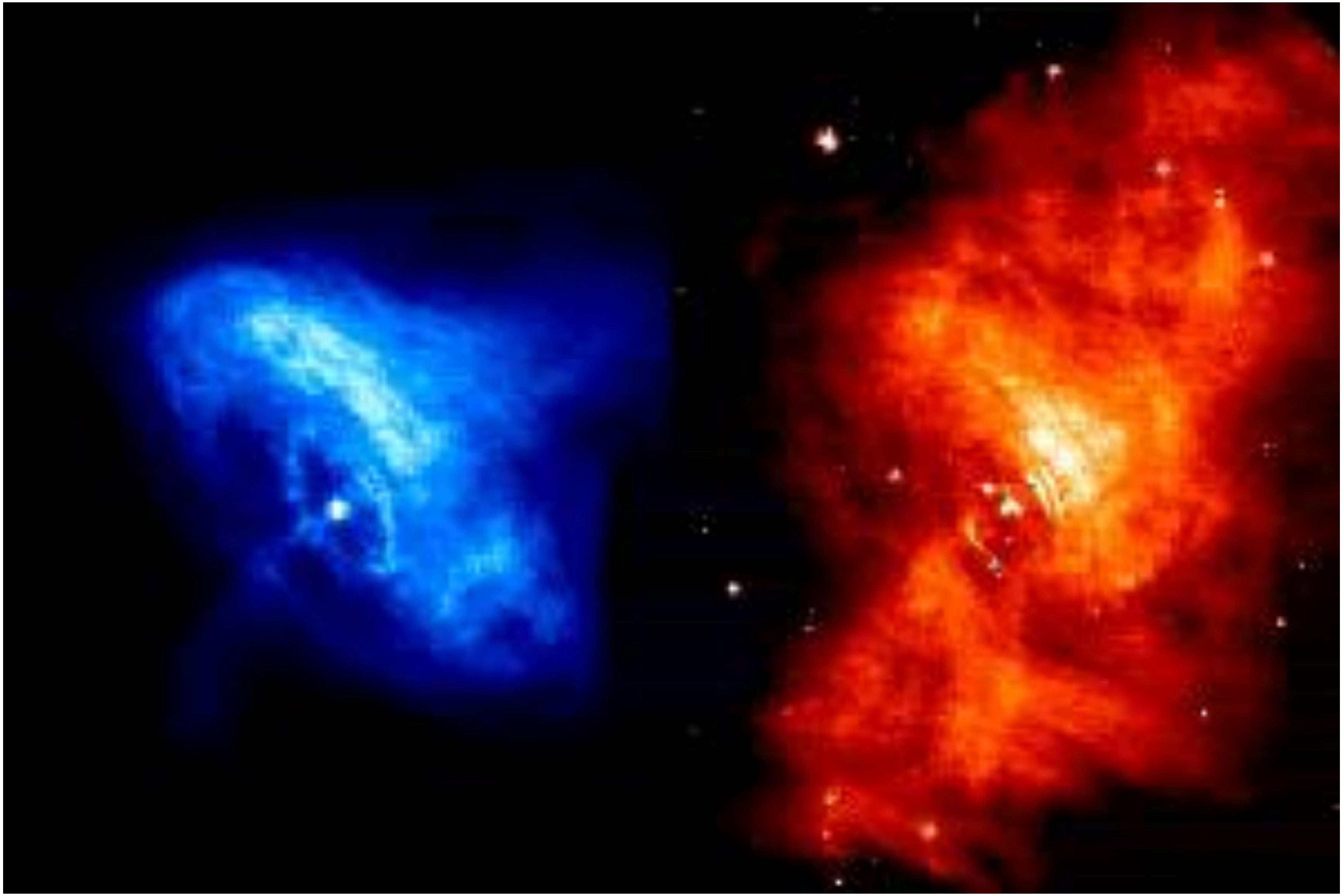
Pulsar


Beam of radiation
Magnetic axis
Magnetic field lines
Beam of radiation
Rotation axis

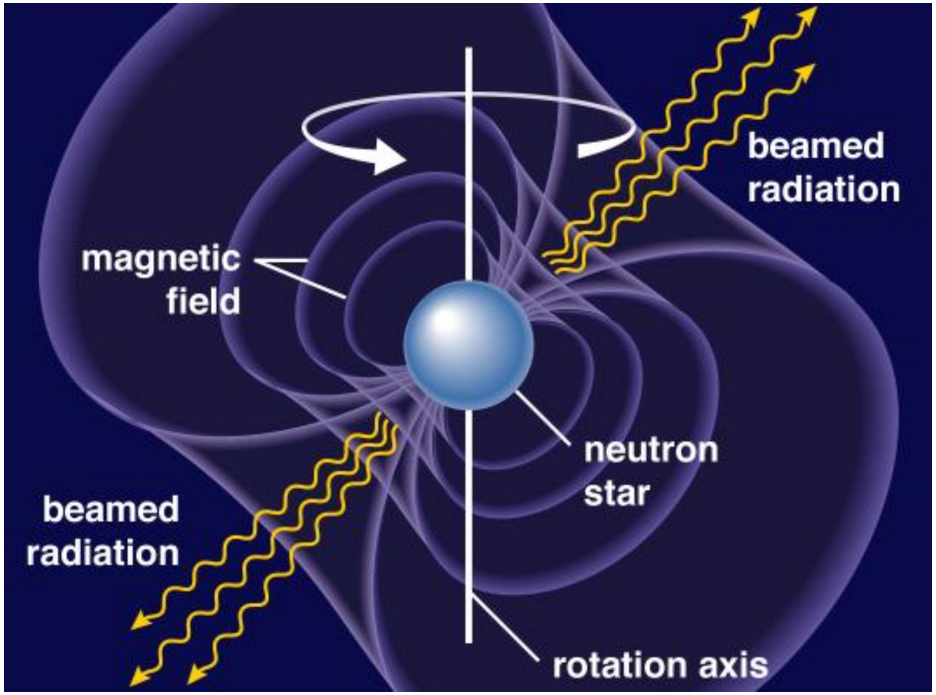
The most famous pulsar is in the heart of the Crab Nebula



The Crab Nebula in X-rays and optical



Pulsars and Neutron Stars



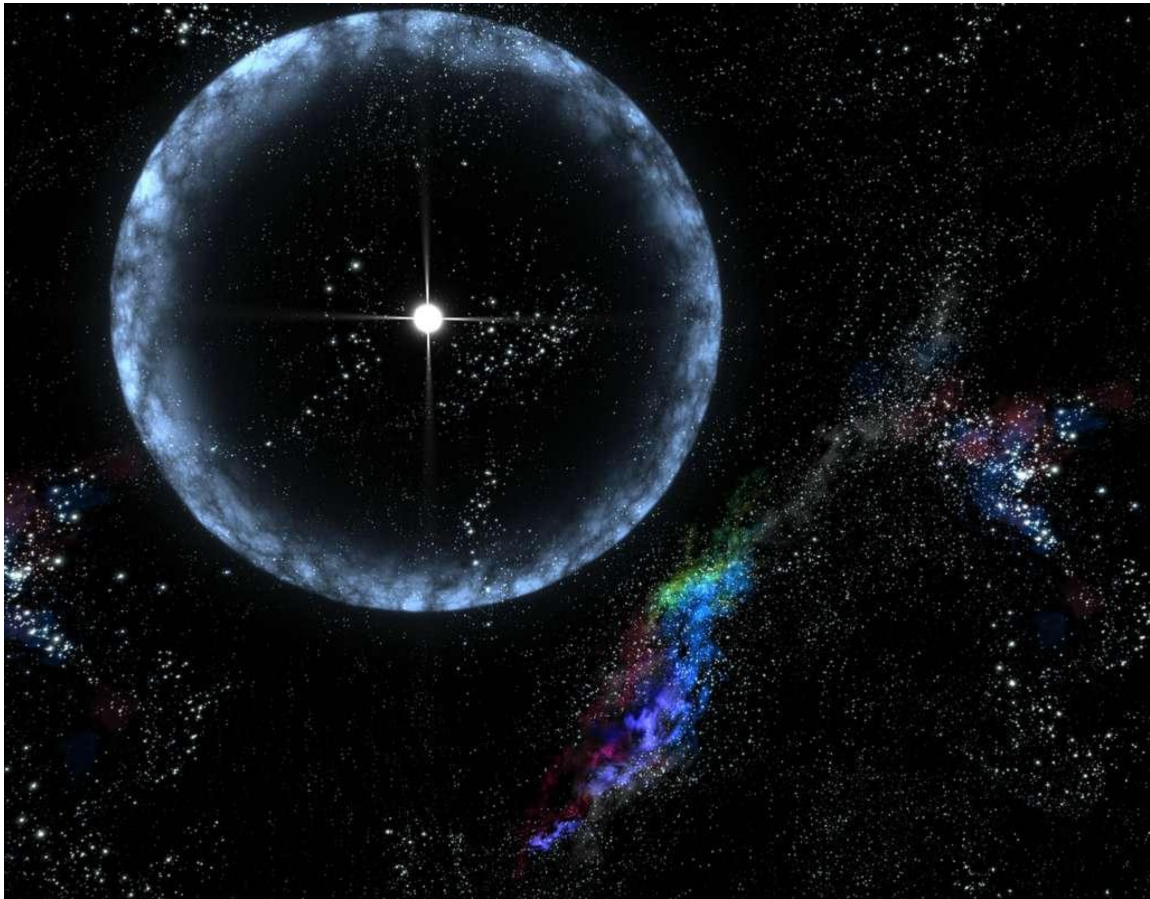
PSR 0329+54   1.4 rev/s

PSR 0532+21   33.1 rev/s

PSR 1937+21   642 rev/s

Schematic view of a neutron star, where each patch is 30x30 degrees. Gravitational deflection means that more than half the surface is visible.

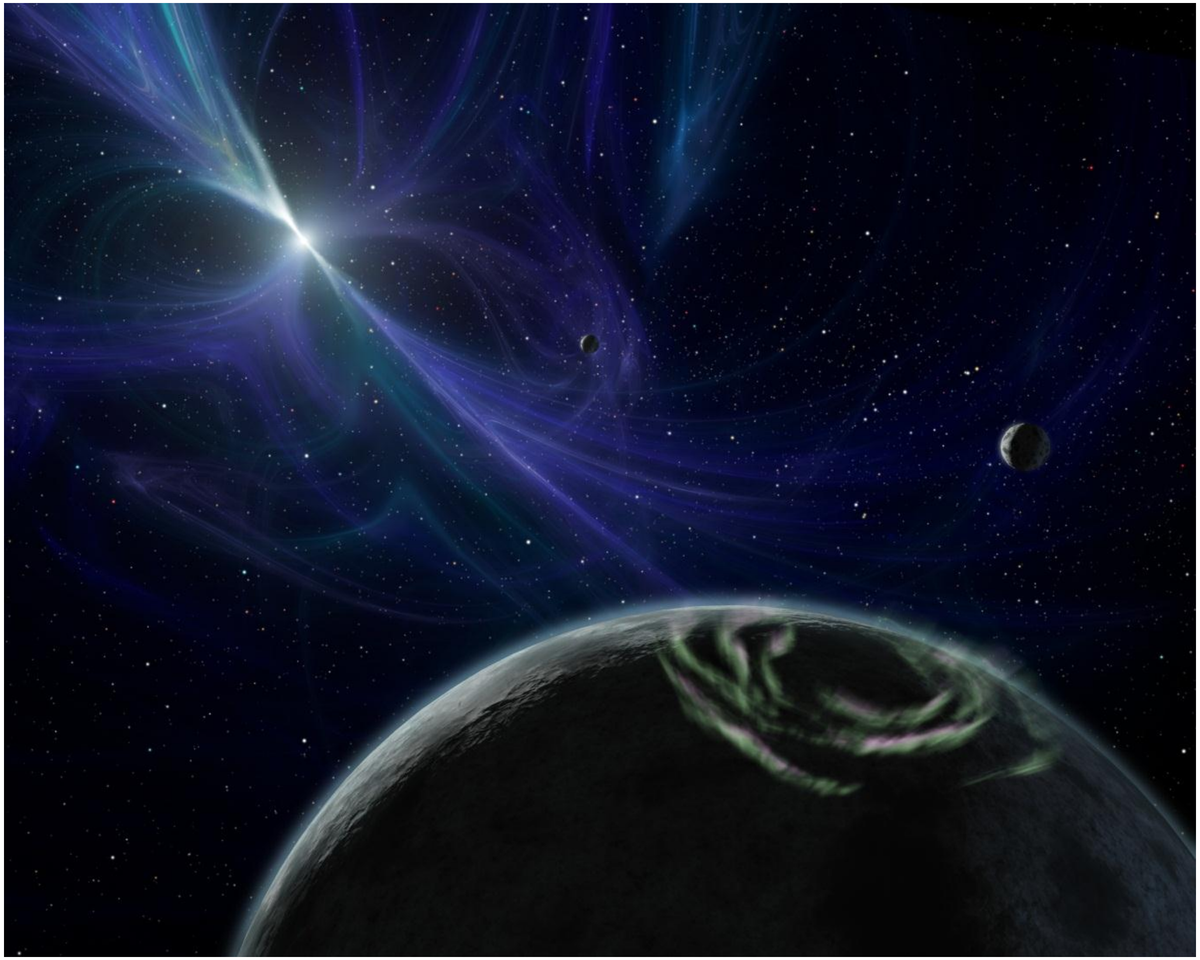
Pulsars show timing "glitches" when the neutron crust suffers a quake, releasing copious amounts of X-rays and blinding X-ray satellites.



Pulsar Planets

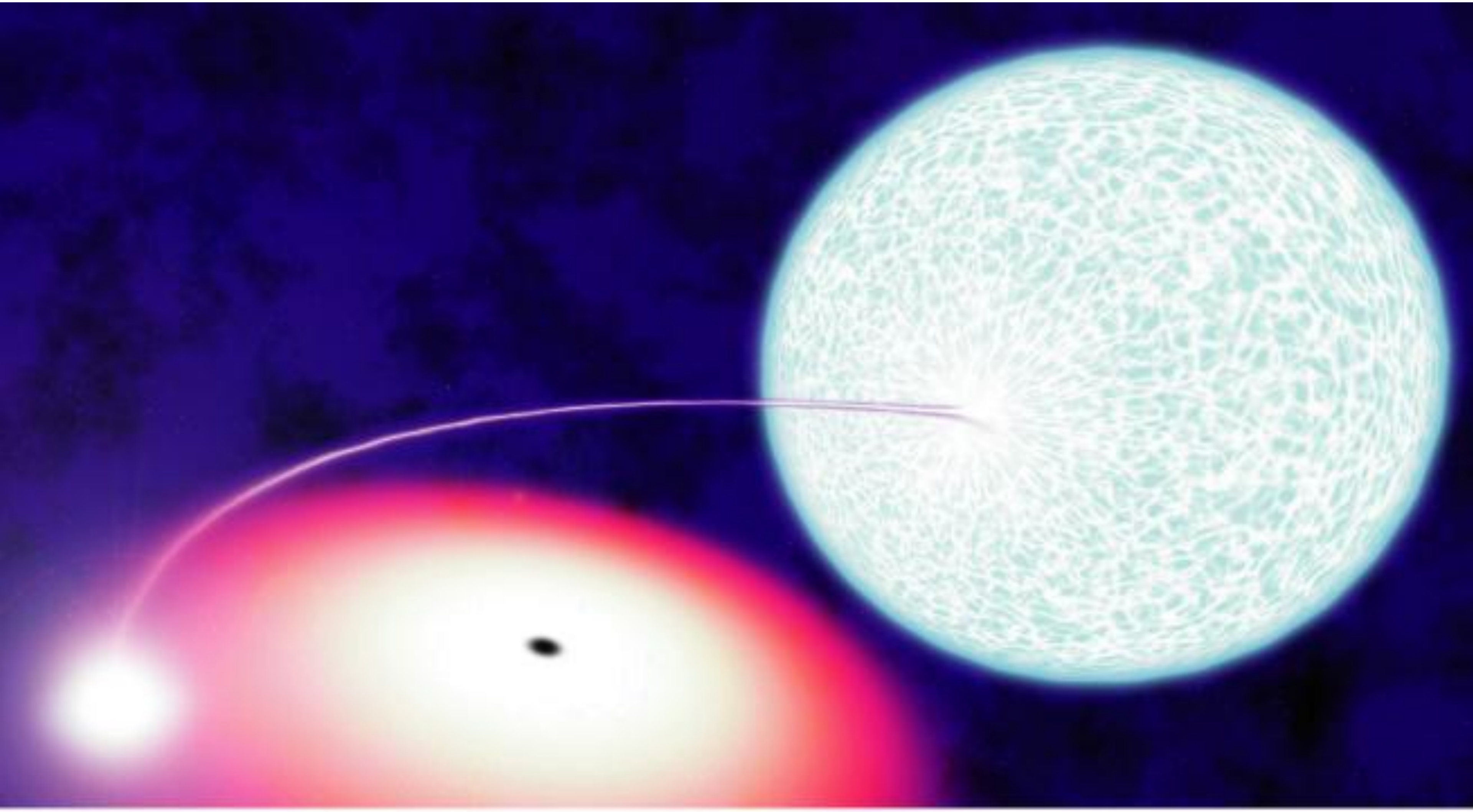
Pulsar timing can be used to find planets. In 1992, two planets were discovered in orbit of the 10,000 rpm pulsar 1257+12, **three years before the 51 Peg discovery**.

4.3 Earth mass, 66 days
3.9 Earth mass, 98 days
0.02 Earth mass, 22 days



PSR B1257+12

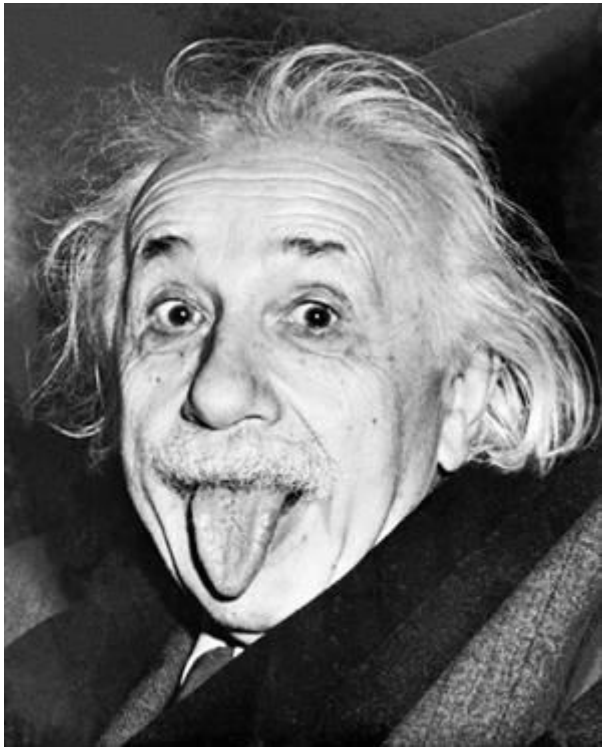
Black Holes



Einstein’s view of space involves very complex mathematics, using tensors and 2nd order differential equations.

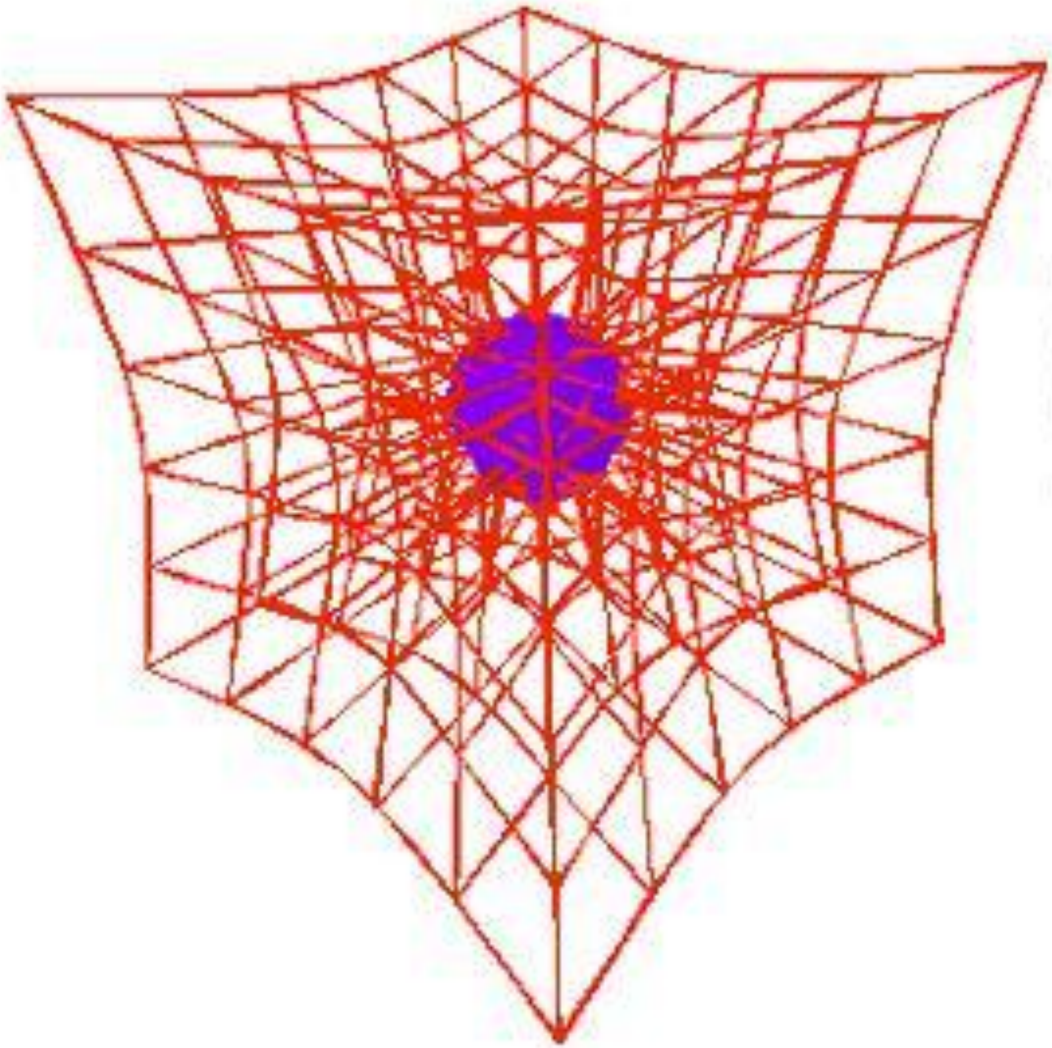
For weak gravity, results are identical to Newton’s theory, but when gravity is strong, it gives much better results.

It’s hard enough to do real problems so only ideal situations have solutions.

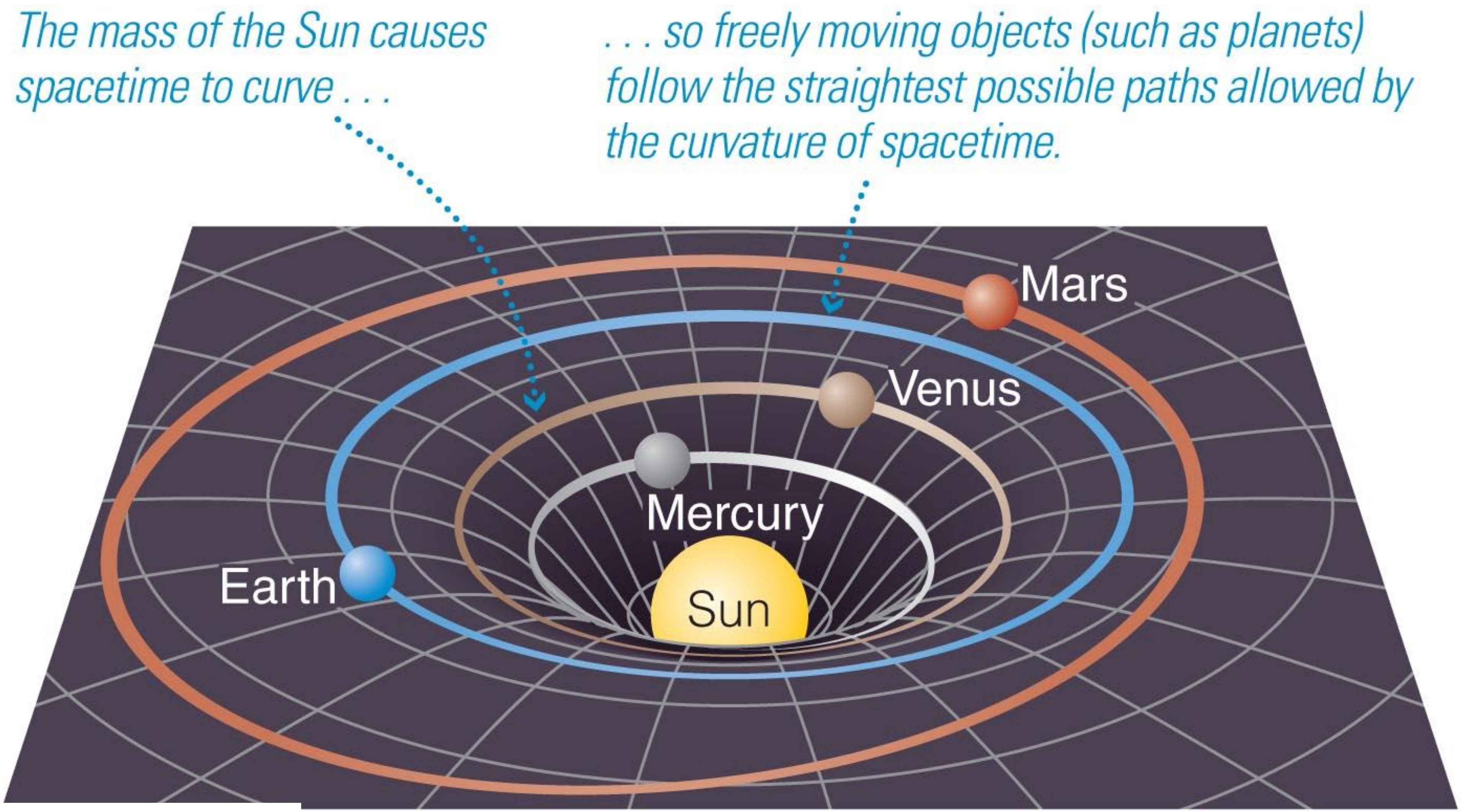


Einstein’s triumphs: Gravitational lensing by the Sun in 1916, the Orbit of Mercury (closest planet to Sun). Since then, precision tests all passed with flying colors by the theory. It was recently tested by NASA’s Gravity Probe B.

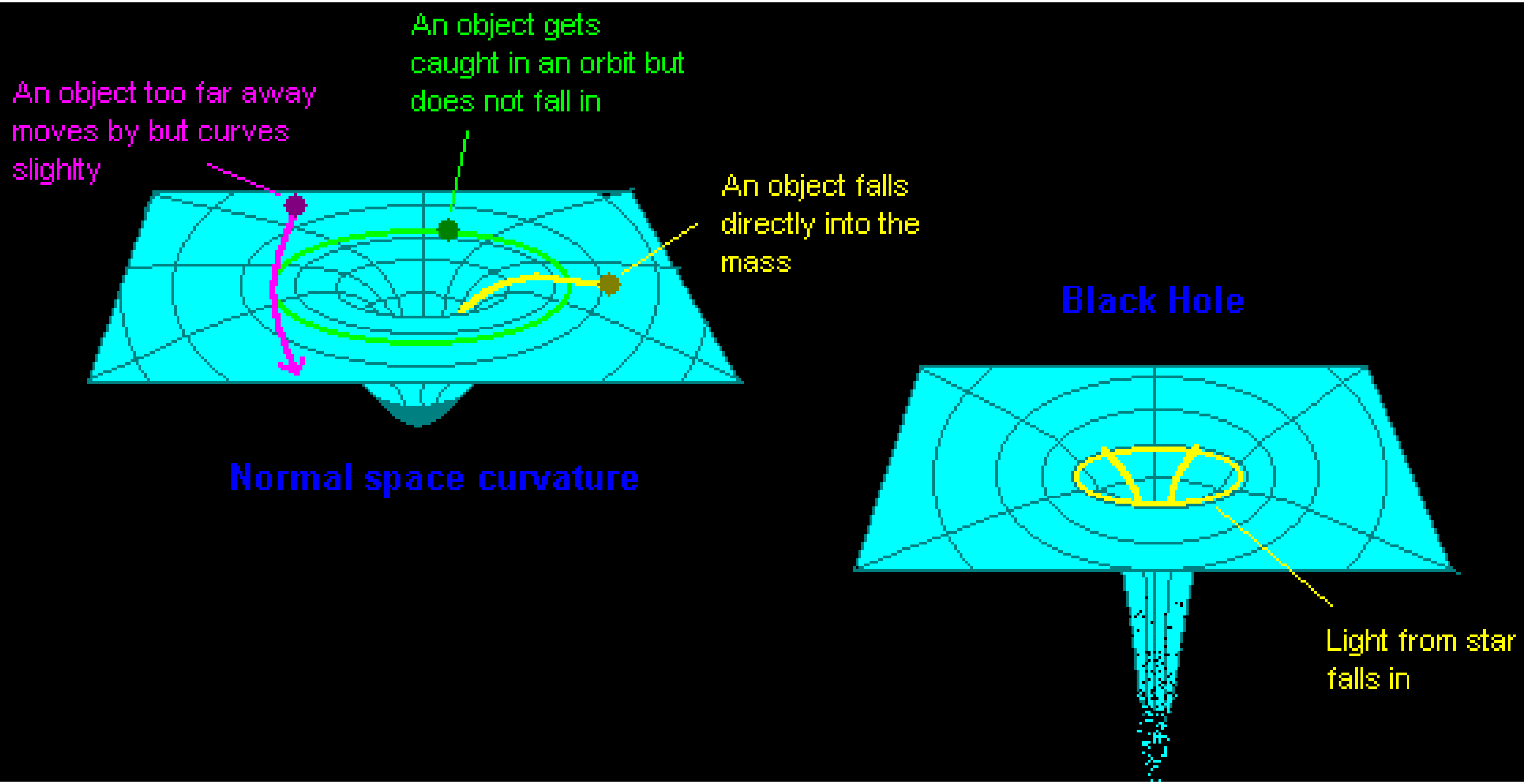
Conceptual shift: Space is curved by the presence of **mass** and **energy**.



This three-dimensional grid gives a better idea of what curved space-time might look like than the two-dimensional analogies do.

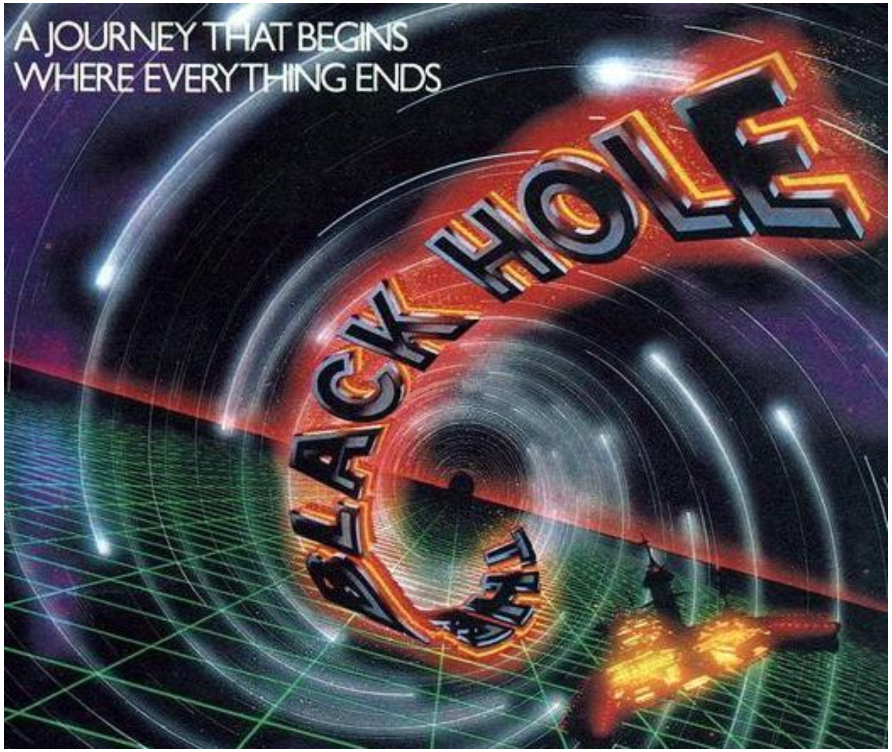

The mass of the Sun causes spacetime to curve . . .
. . . so freely moving objects (such as planets) follow the straightest possible paths allowed by the curvature of spacetime.
Mars
Venus
Mercury
Earth
Sun

General rule: high density (of either mass or energy) leads to highly curved space.



Black holes: extreme curvature, space-time is “pinched-off”

Defining a Black Hole



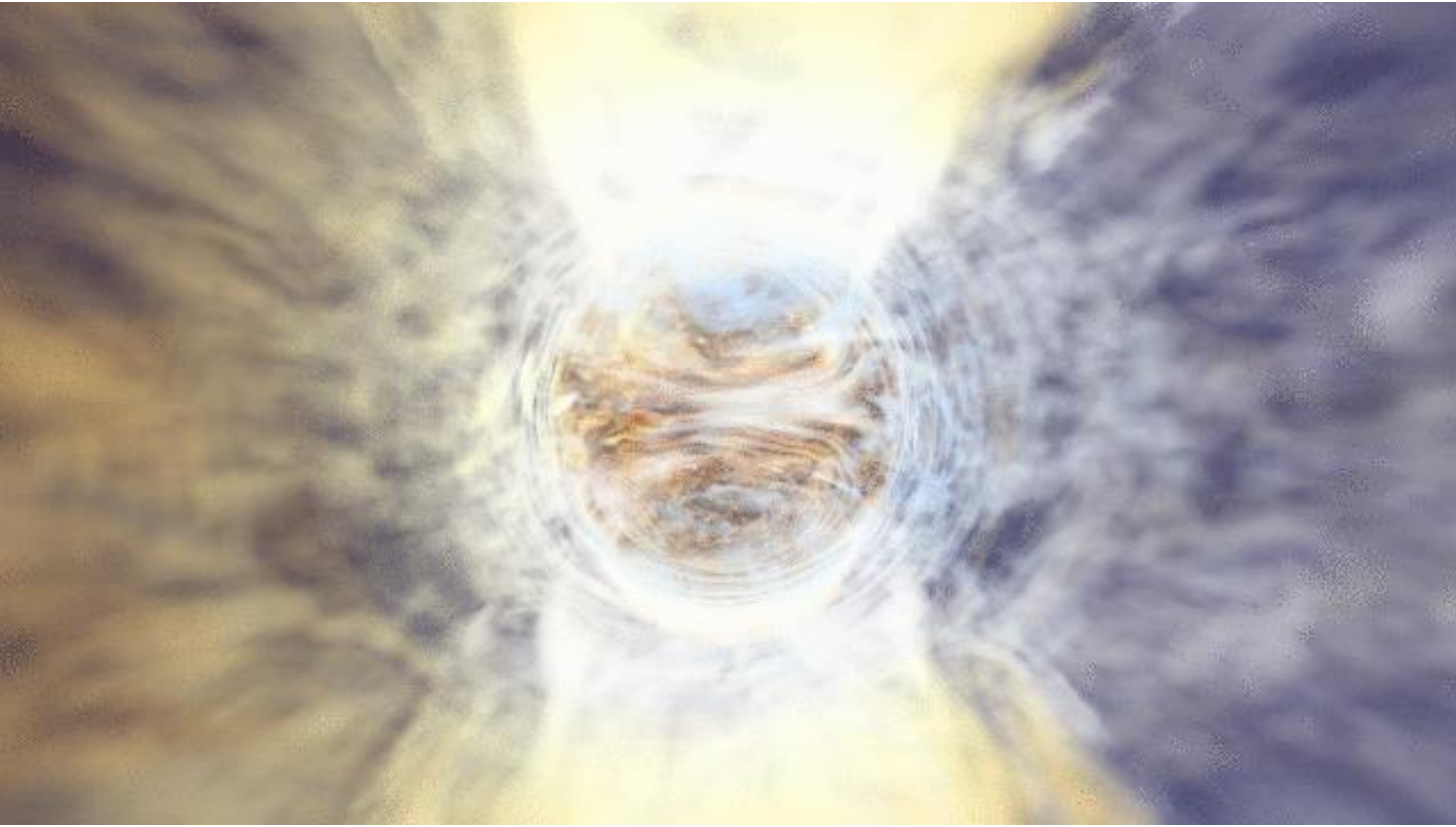
A black hole is any object with an escape velocity greater than the speed of light. The sphere at this radius is called the event horizon. This is an information barrier rather than a physical barrier. The center of a black hole is called a singularity.

Earth: escape velocity = 11 km/sec

Sun: escape velocity = 600 km/sec

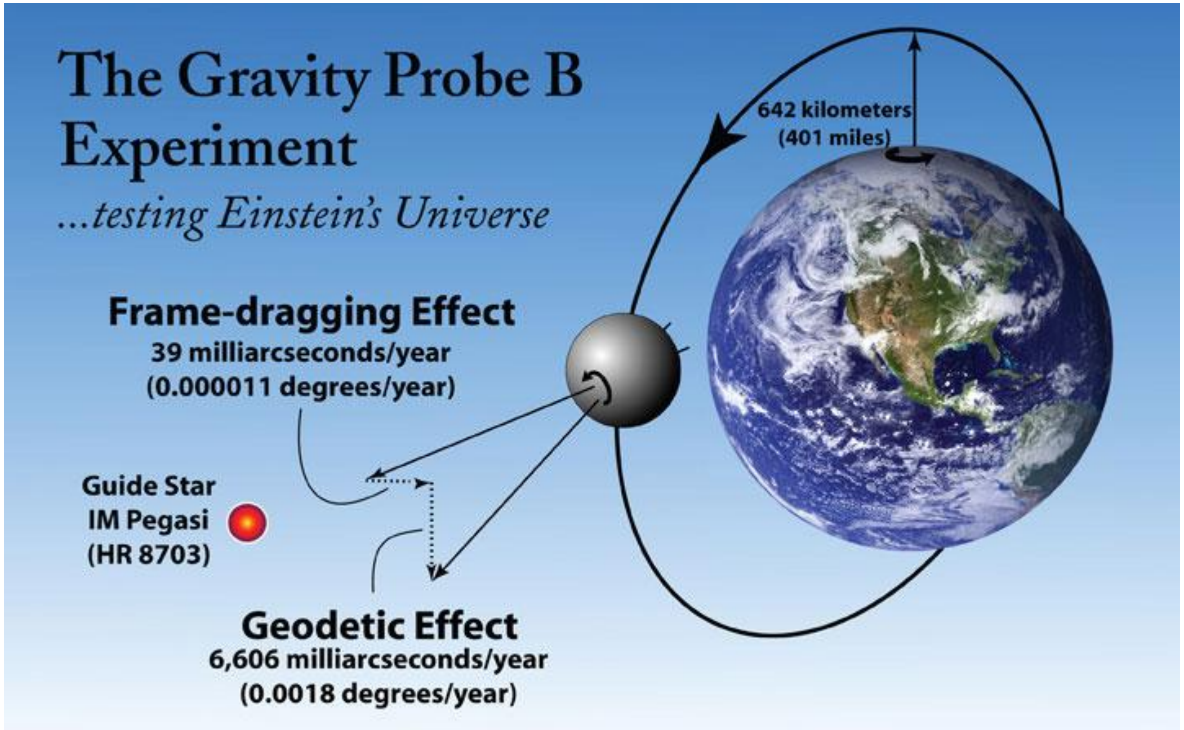
Black hole: escape velocity = 300,000 km/sec

Spinning Black Hole

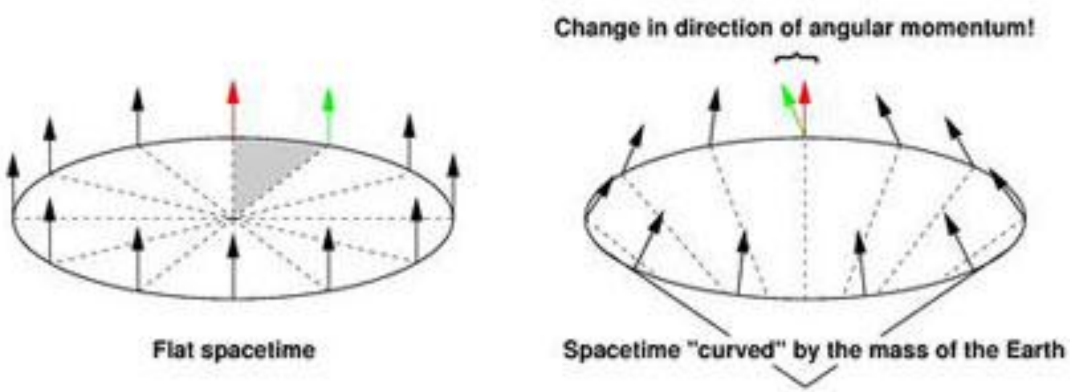


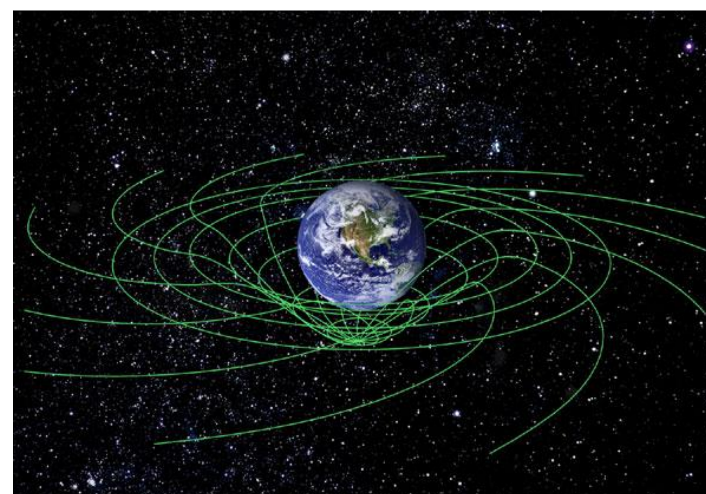
Testing Gravity

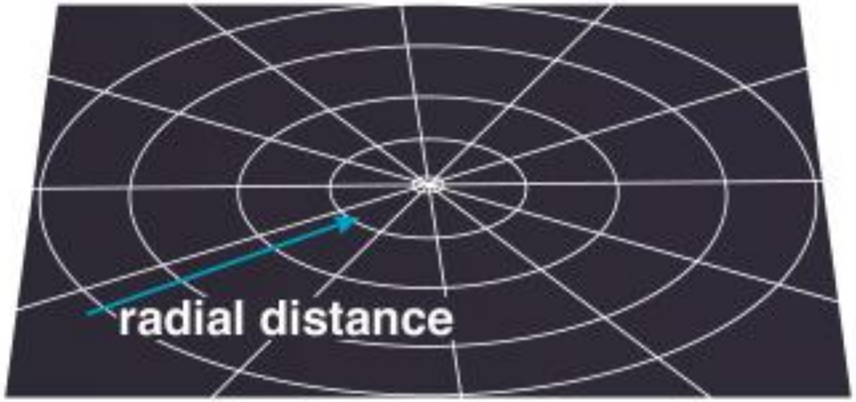
Gravity Probe B had four gyros and a telescope locked on a star. The gyros spun in superfuid helium at 2K, each was accurate to 40 atoms over 1cm, like hills under 8 feet high across the Earth.

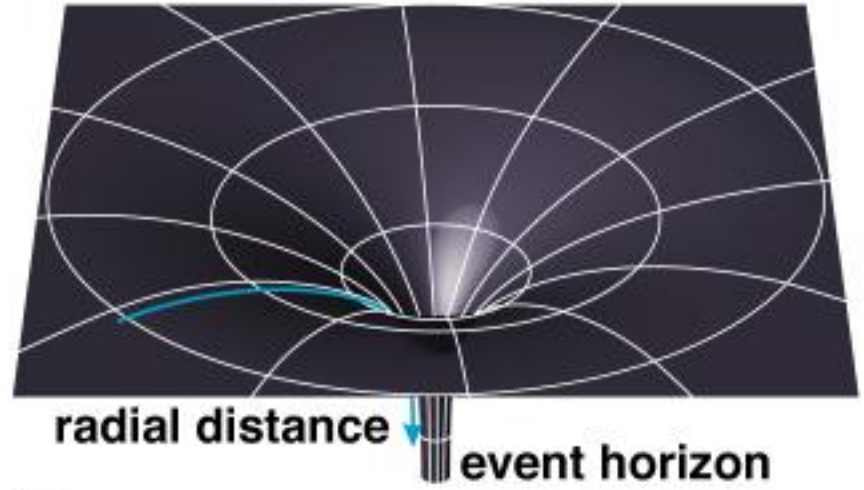


The spinning Earth distorts space-time and skews the actual orbit by one inch out of 30,000 miles. This can be detected by a high-precision gyro. Gravity Probe B was short of its goals but it did confirm GR.

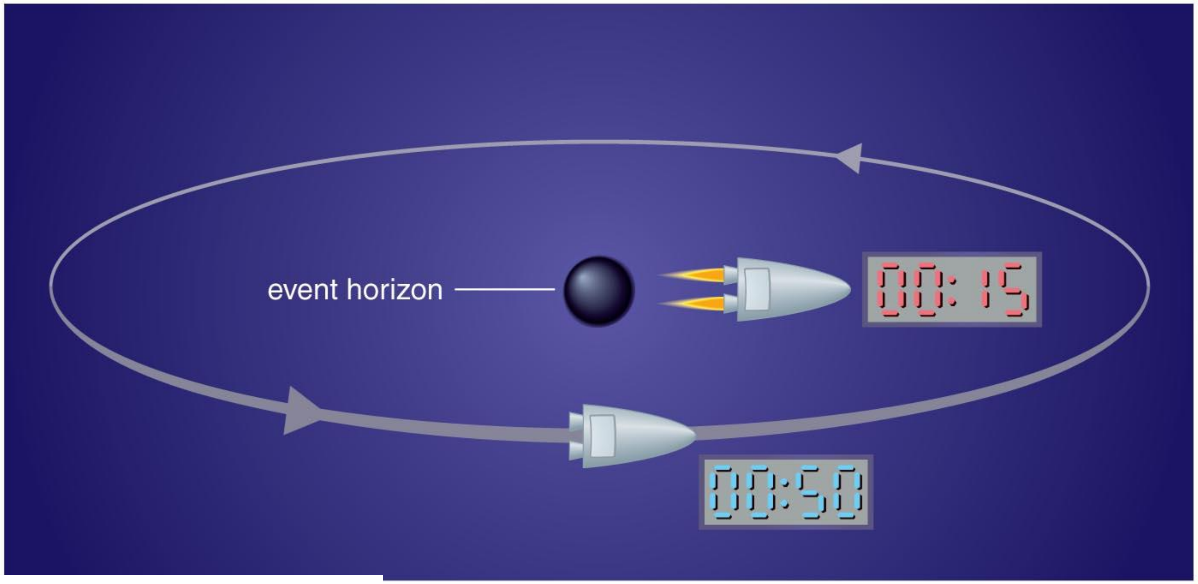


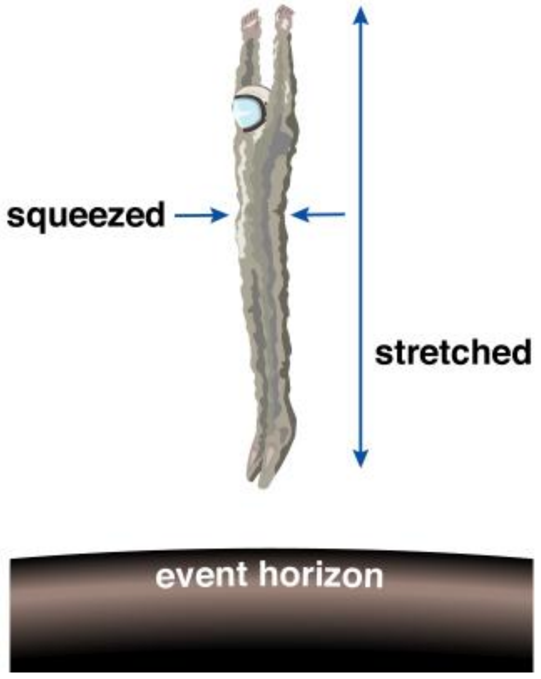




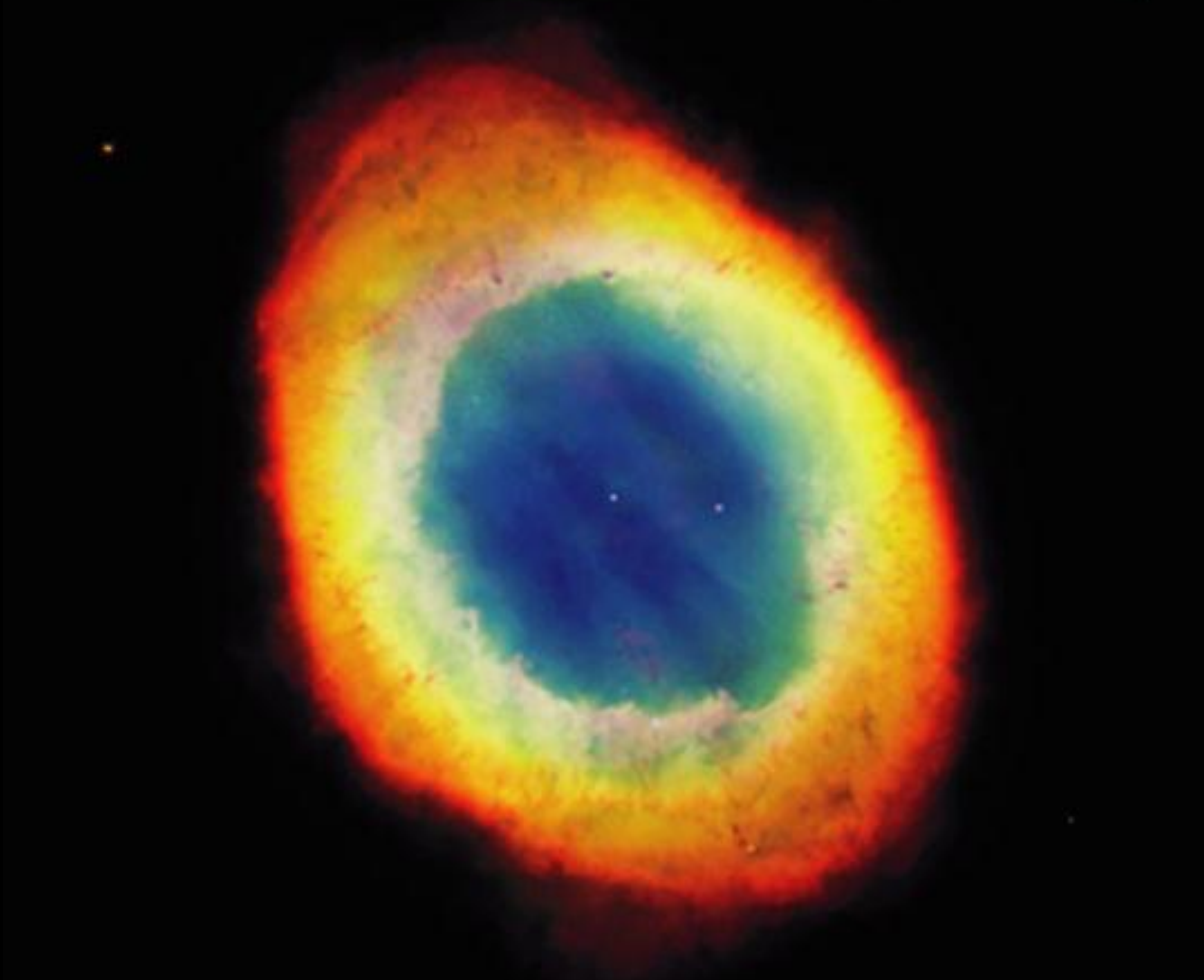


Space, time, and people (!) get stretched near the event horizon.
In particular, time as seen from the outside slows asymptotically.





Shine On You Crazy Diamond



Shine on you Crazy Diamond (Pink Floyd, 1975)

Remember when you were young, you shone like the sun.
Shine on you crazy diamond.
Now there's a look in your eyes, like black holes in the sky.
Shine on you crazy diamond.
You were caught on the cross fire of childhood and stardom,
blown on the steel breeze.
Come on you target for faraway laughter, come on you stranger,
you legend, you martyr, and shine!

Nobody knows where you are, how near or how far.
Shine on you crazy diamond.
Pile on many more layers and I'll be joining you there.
Shine on you crazy diamond.
And we'll bask in the shadow of yesterday's triumph,
and sail on the steel breeze.
Come on you boy child, you winner and loser,
come on you miner for truth and delusion, and shine!

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Main sequence

Carbon-rich white dwarf

End state of massive star

Difficulty of stellar parallax

Recycling of life elements to ISM

Onion-skin model of the red giants

Dark stages after the end of fusion

Metals ejected by a supernova wind

Astronomy
State of the Art

With Chris Impey
of the University
of Arizona