STARS - S07

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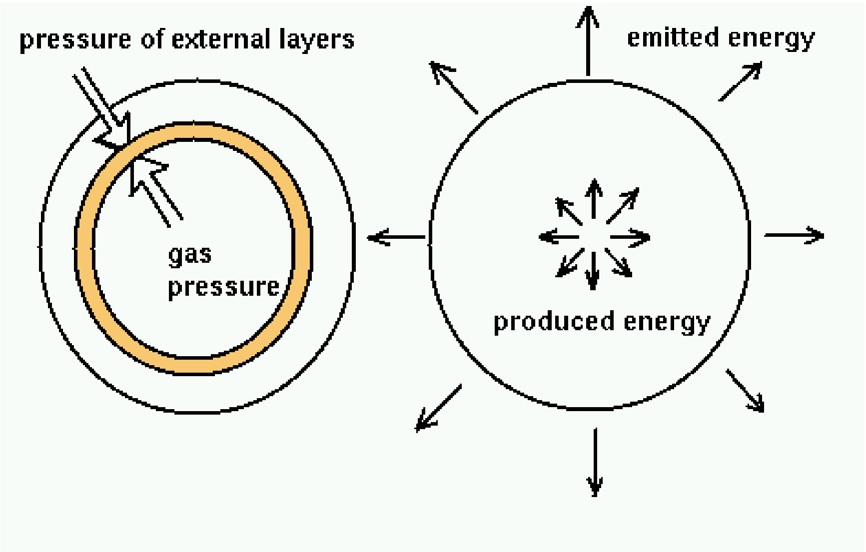
AMNH After-School Program

AMERICAN MUSEUM OF NATURAL HISTORY

From last class

Radiative equilibrium: Heating is matched by cooling



What we call “heat” is actually radiation

Radiative loss = Cooling

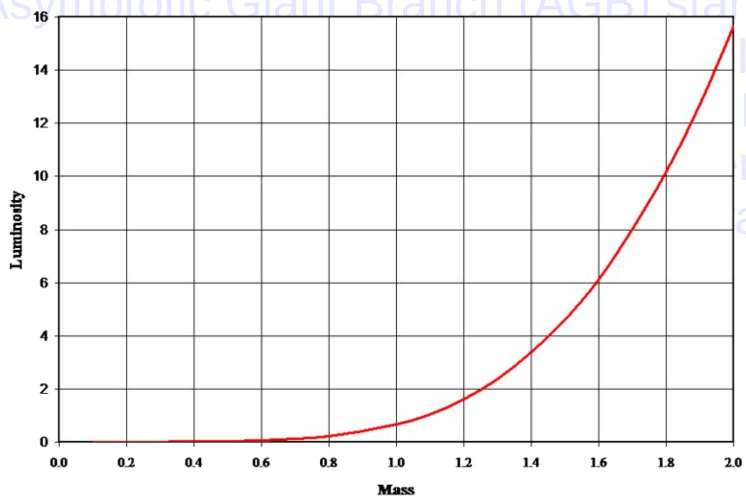
In a star in radiative equilibrium,
radiative losses (cooling)
are matched by
energy production (heating)
from nuclear reactions

From last class

Turbulence is a self-similar flow. Size spectrum is well defined.
Turbulent fragmentation of a molecular cloud leads to a well defined mass spectrum.
Mass spectrum: Initial Mass Function. Lots of low mass stars, few high mass stars.
Lifetime on the Main Sequence: A strong function of mass.
Main Sequence Turn-Off Point. An indicator of age.
Post Main Sequence Evolution
Hydrogen is gone: Helium core contracts and heats
Red Giants – inert Helium core, Hydrogen Shell Burning
Core degeneracy – a phase transition to "solid-like" behavior. Core contraction stops.

$$t_{star}/t_{Sun} = \left(M_{star}/M_{Sun}\right)^{-2.5}$$

100 Million K – Helium ignition. Degeneracy is lifted (Helium Flash).
Horizontal Branch – Helium Main Sequence
Helium is gone: Carbon-Oxygen core contracts and heats
Asymptotic Giant Branch (AGB) star – inert CO core, Helium and Hydrogen Shell Burning
...lsations eventually eject the whole atmosphere
...Planetary Nebula
...nerate core is seen as a white dwarf
...arfs cool in long timescales



High mass stars life fast and die young.

Low mass stars will still be around long after we're gone

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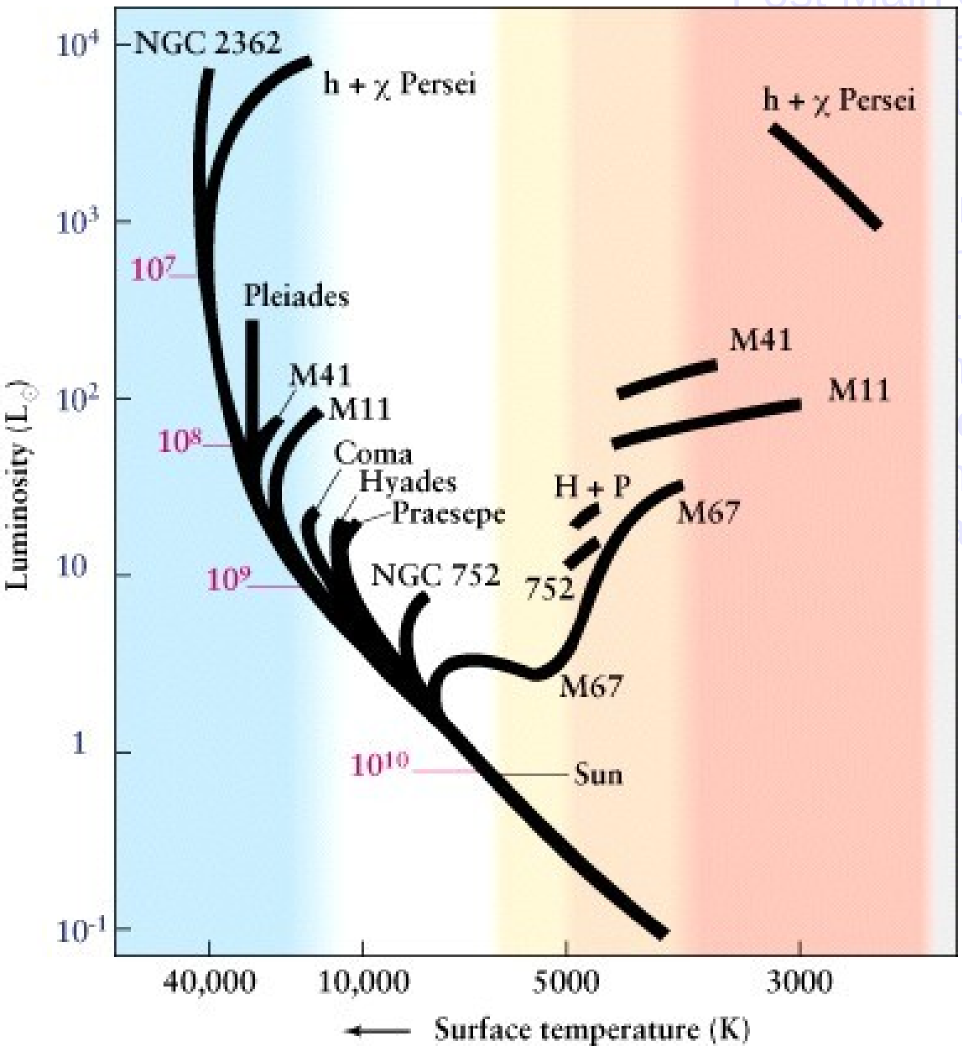

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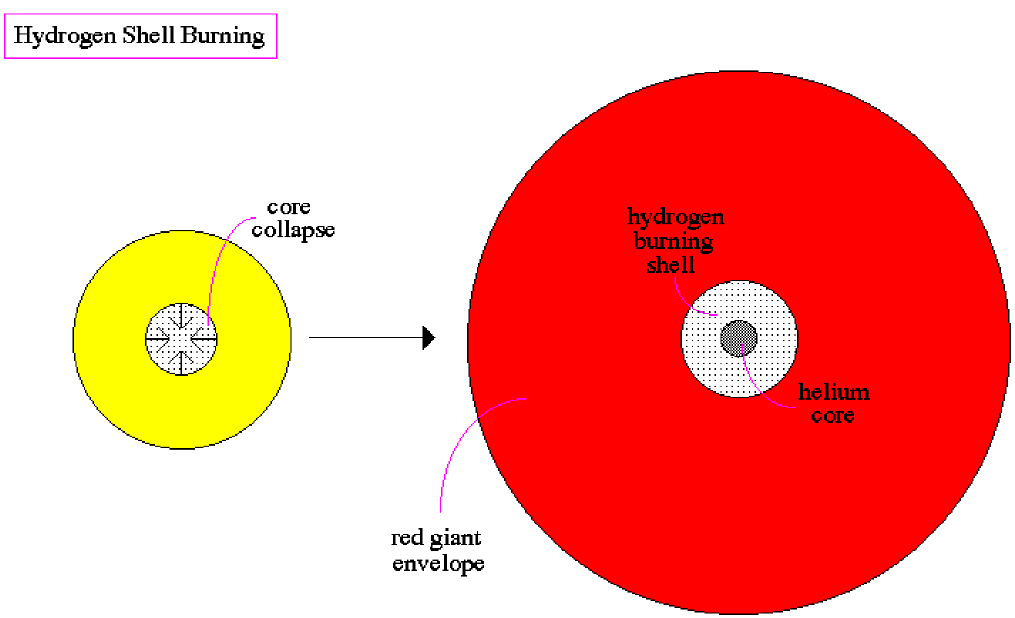
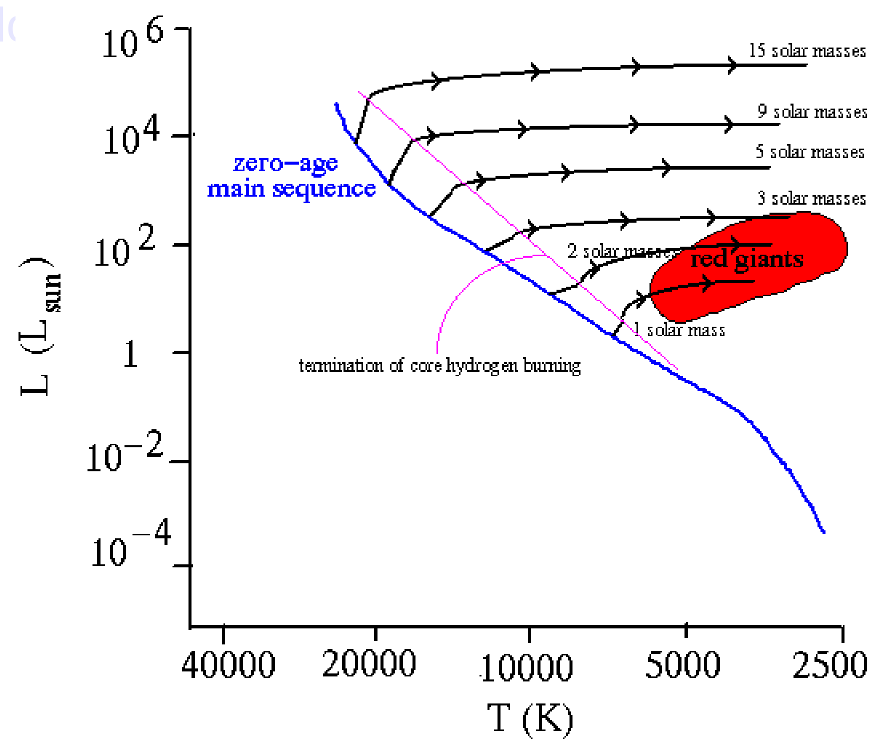
The exposed degenerate core is seen as a white dwarf





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The exposed degenerate core is seen as a white dwarf

White dwarfs cool in long timescales

Ideal Gas

$$p \propto \rho T$$

Temperature rises, pressure rises

Temperature falls, pressure falls

Radiation → less support against gravity

→ **contraction**

Degenerate Matter

$$p \propto \rho^{4/3}$$

If temperature rises or falls, pressure couldn't care less

Radiative losses can continue indefinitely

The degenerate core is stable

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The exposed degenerate core ...

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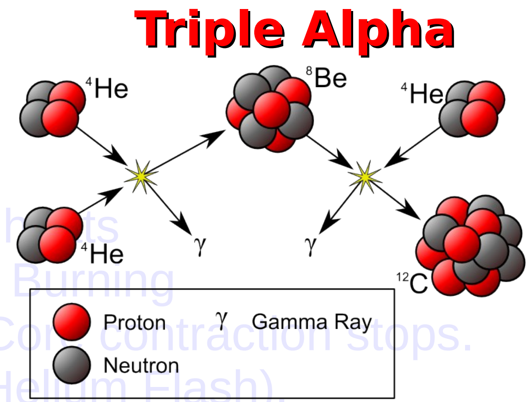
Controlled fusion

Runaway fusion

From last class



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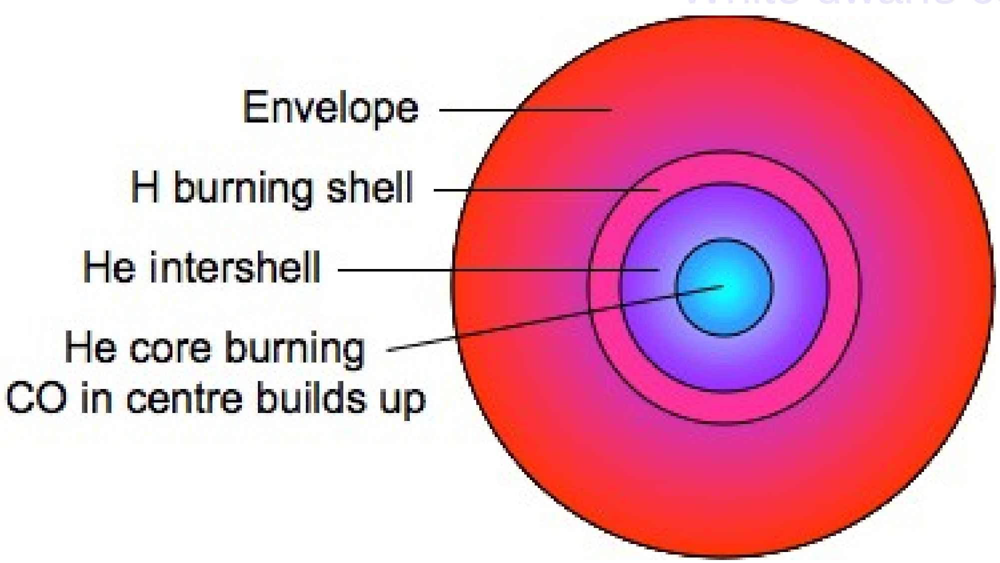

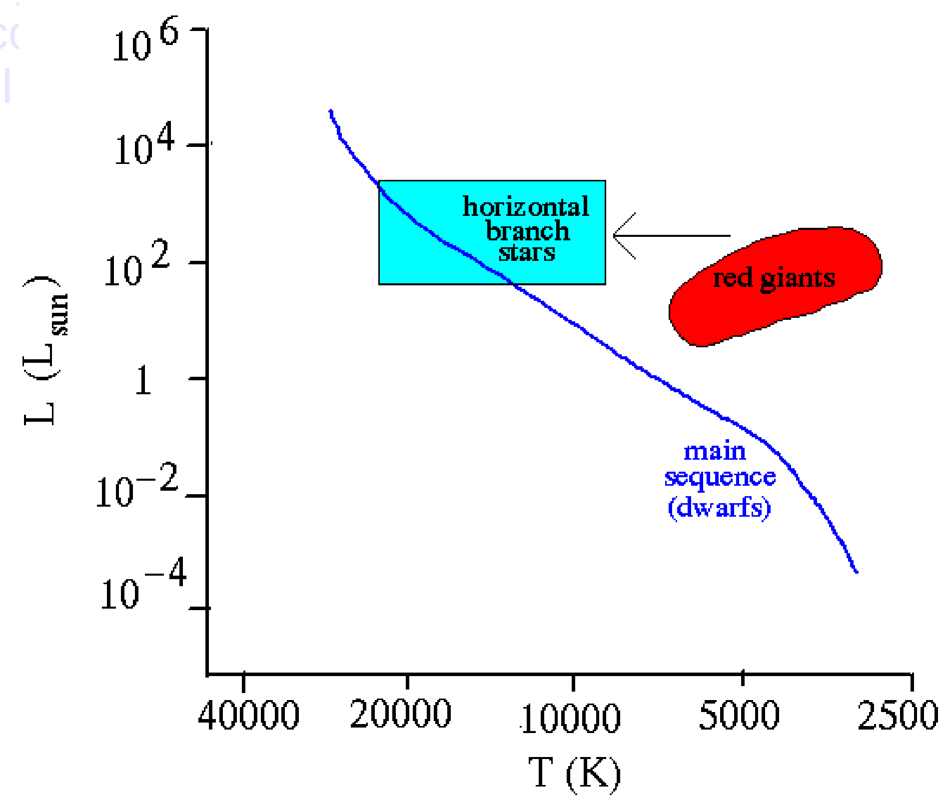

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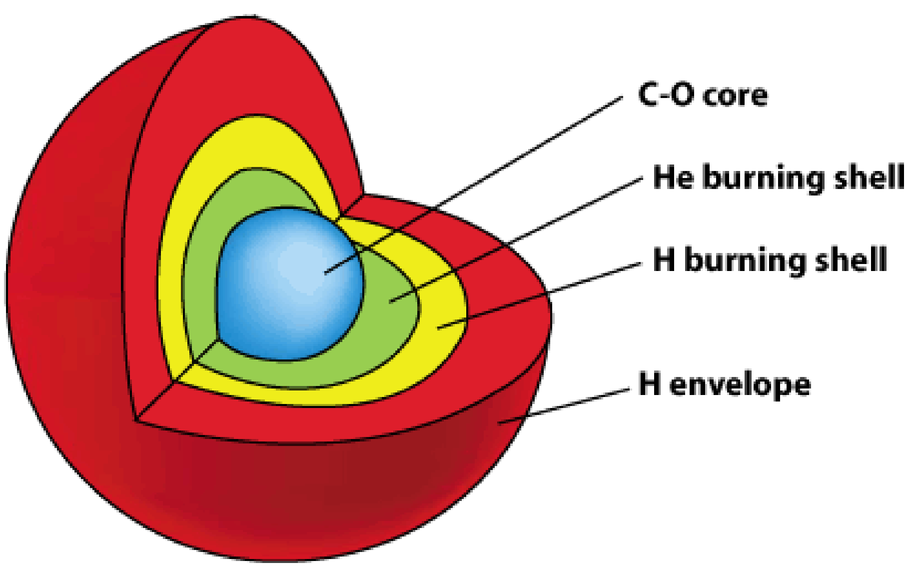
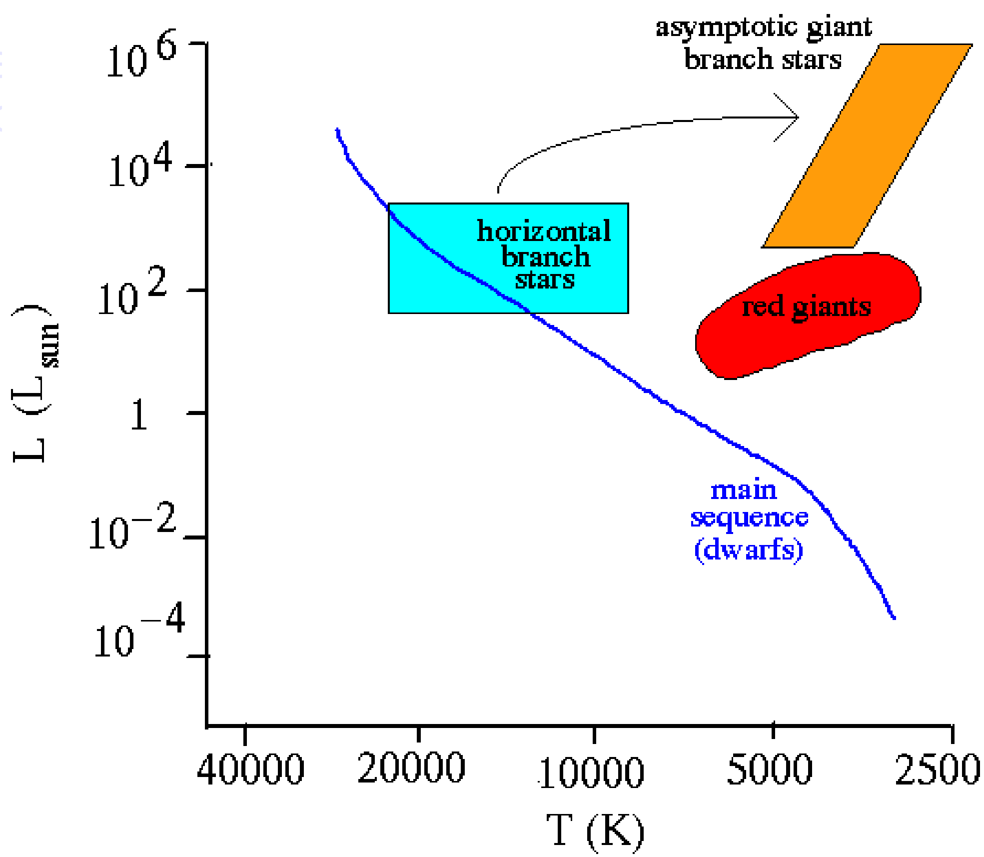
Plane

The exposed degenerate





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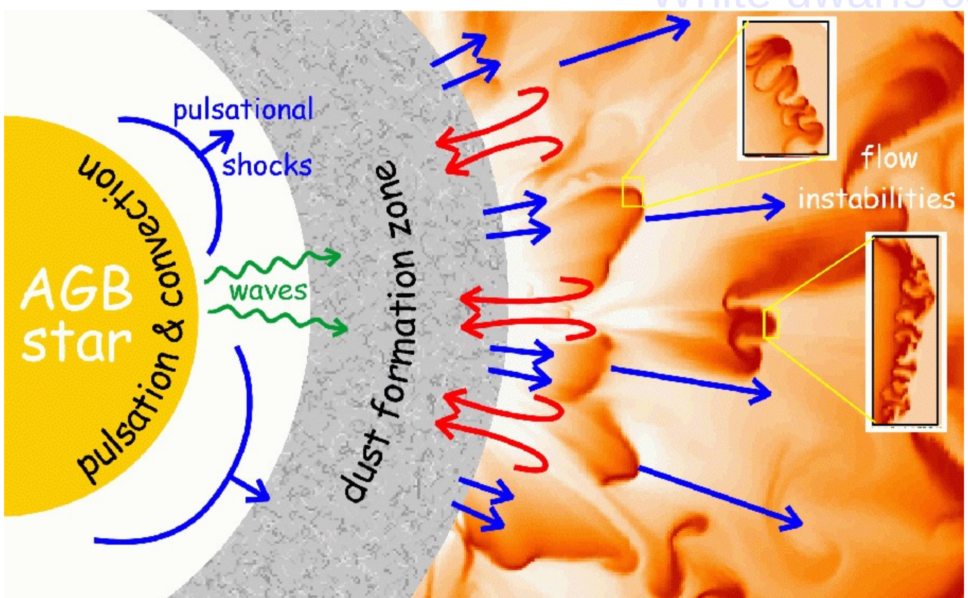
AGB stars are unstable. Violent pulsations eventually eject the whole atmosphere

Planetary Nebula – A graceful death

The exposed degenerate core is seen as a white dwarf

White dwarfs cool in long timescales



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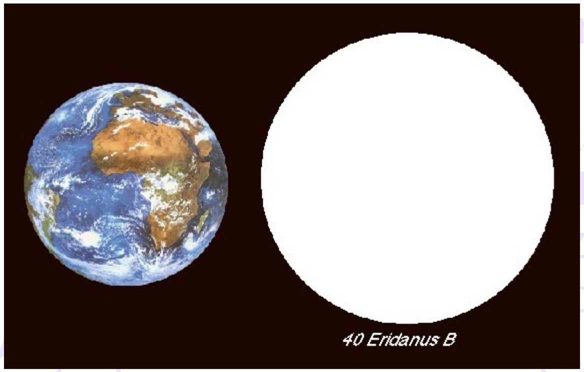

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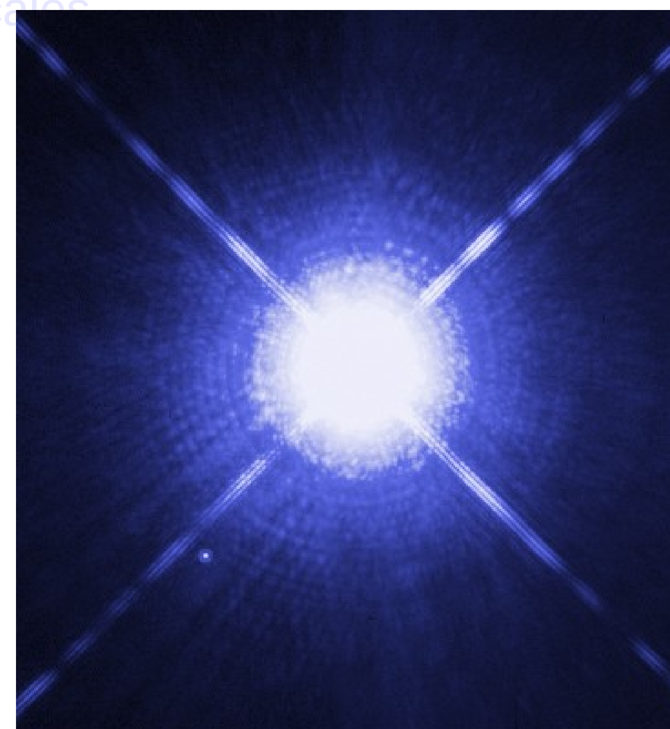
Planetary Nebula

The exposed degenerate CO core is seen as a white dwarf

White dwarfs cool in long timescales



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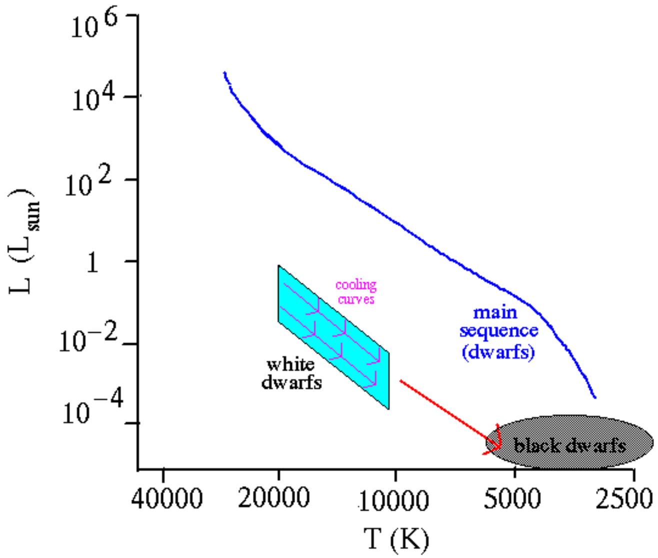


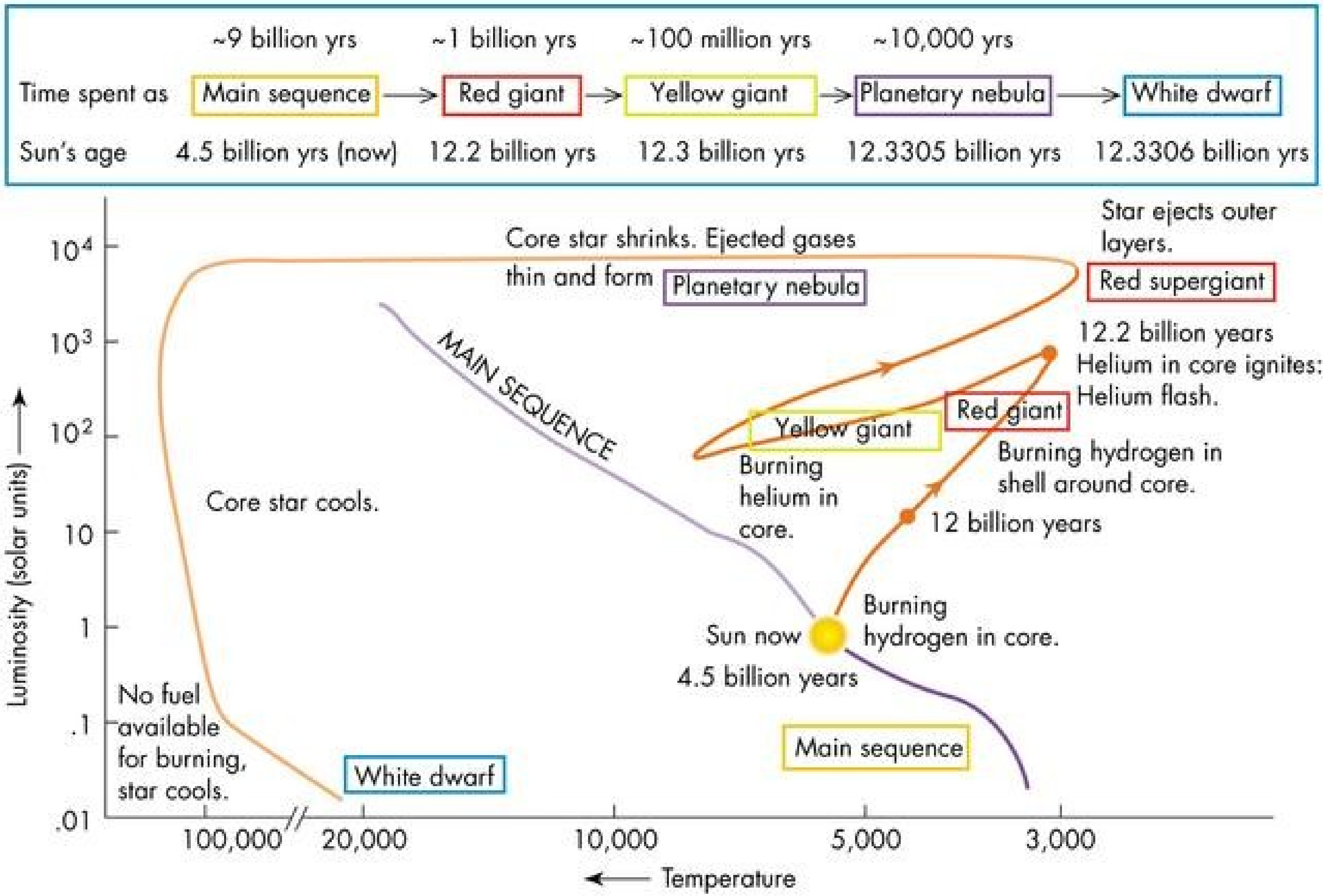
No energy production
Supported by degenerate pressure

Cooling takes a long time
10^{15} yr to cool down to background temperature

The universe is not old enough to have black dwarfs
Coldest white dwarfs ~5000 K.

From last class

Evolutionary track of a low mass star



Outline

- Evolution of high mass stars

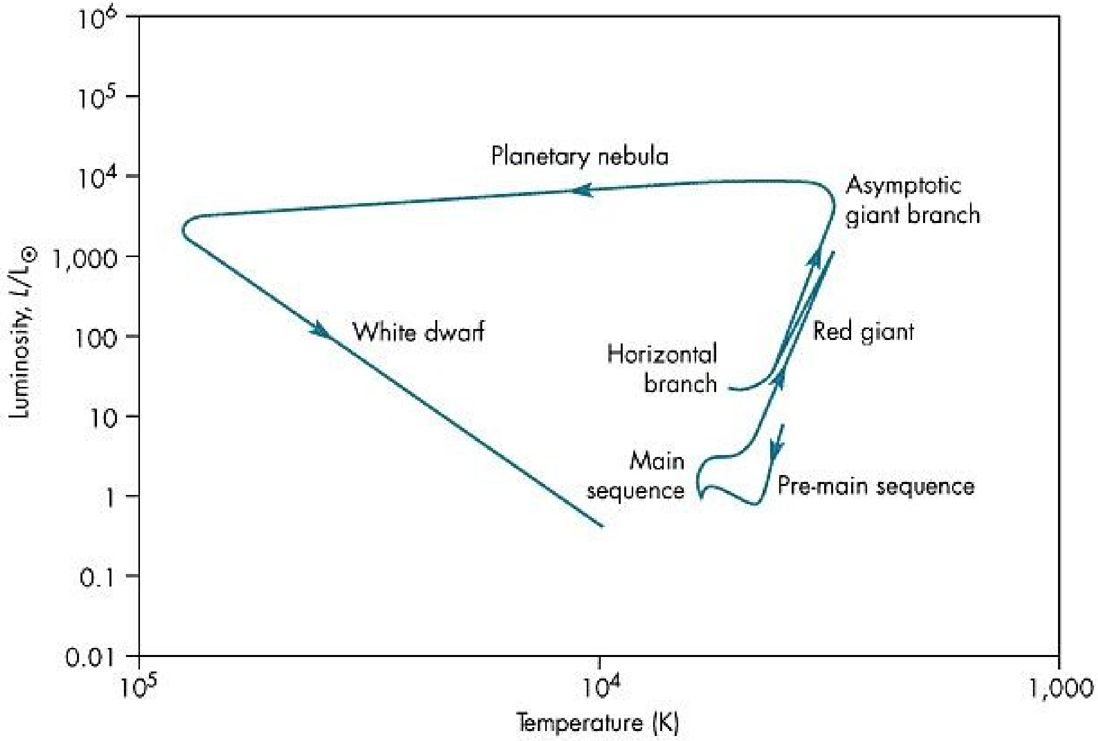
- Core collapse Supernovae (Type II)
  - Neutronization
  - Urca process
  - Core bounce
  - Thermonuclear shockwave

- Remnants
  - Neutron stars (Pulsars)
  - Black holes

- Nucleosynthesis

Evolution of high mass stars

The evolution we covered in last class is for low mass stars ($M < 4\ M_\odot$)



High mass stars differ basically due to the ***temperature of the core***.

Evolution of high mass stars ($4 < M/M_\odot < 8$)

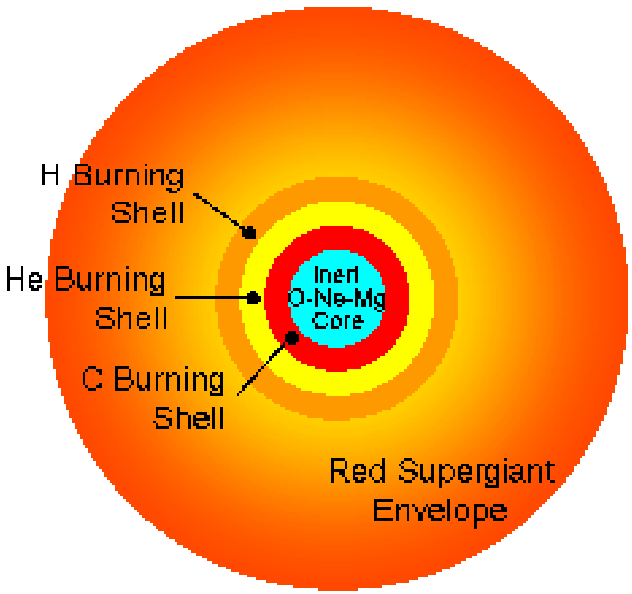
The Helium Flash never happens

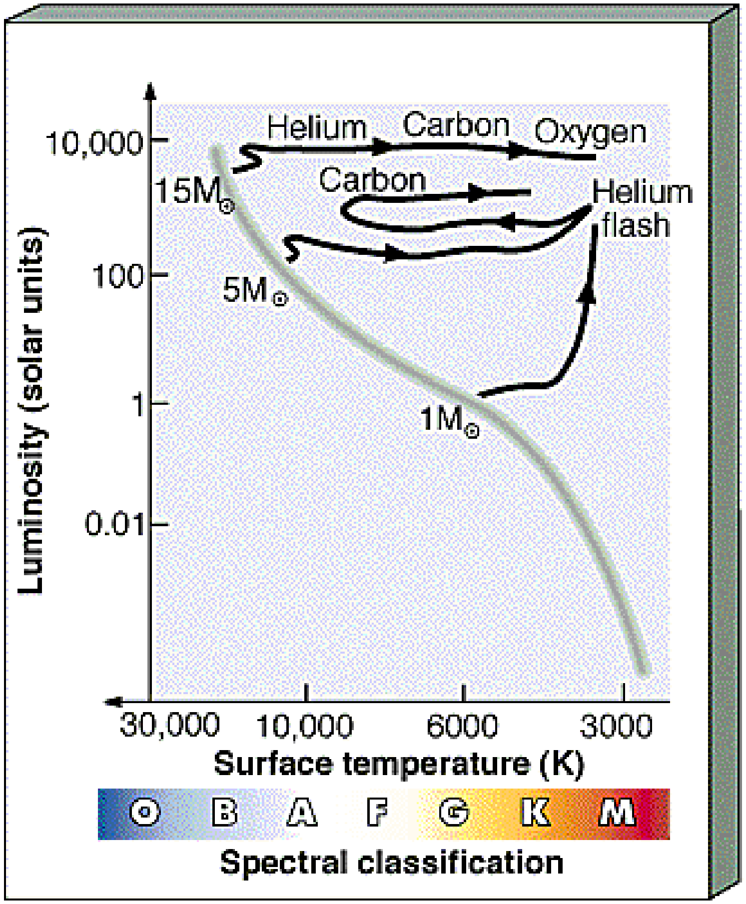
The star reaches Helium burning temperatures ***before*** the core becomes degenerate

They also reach temperatures hot enough to burn **Carbon**

600 million K

Leaves a O-Ne-(Mg) white dwarf.





Evolution of high mass stars

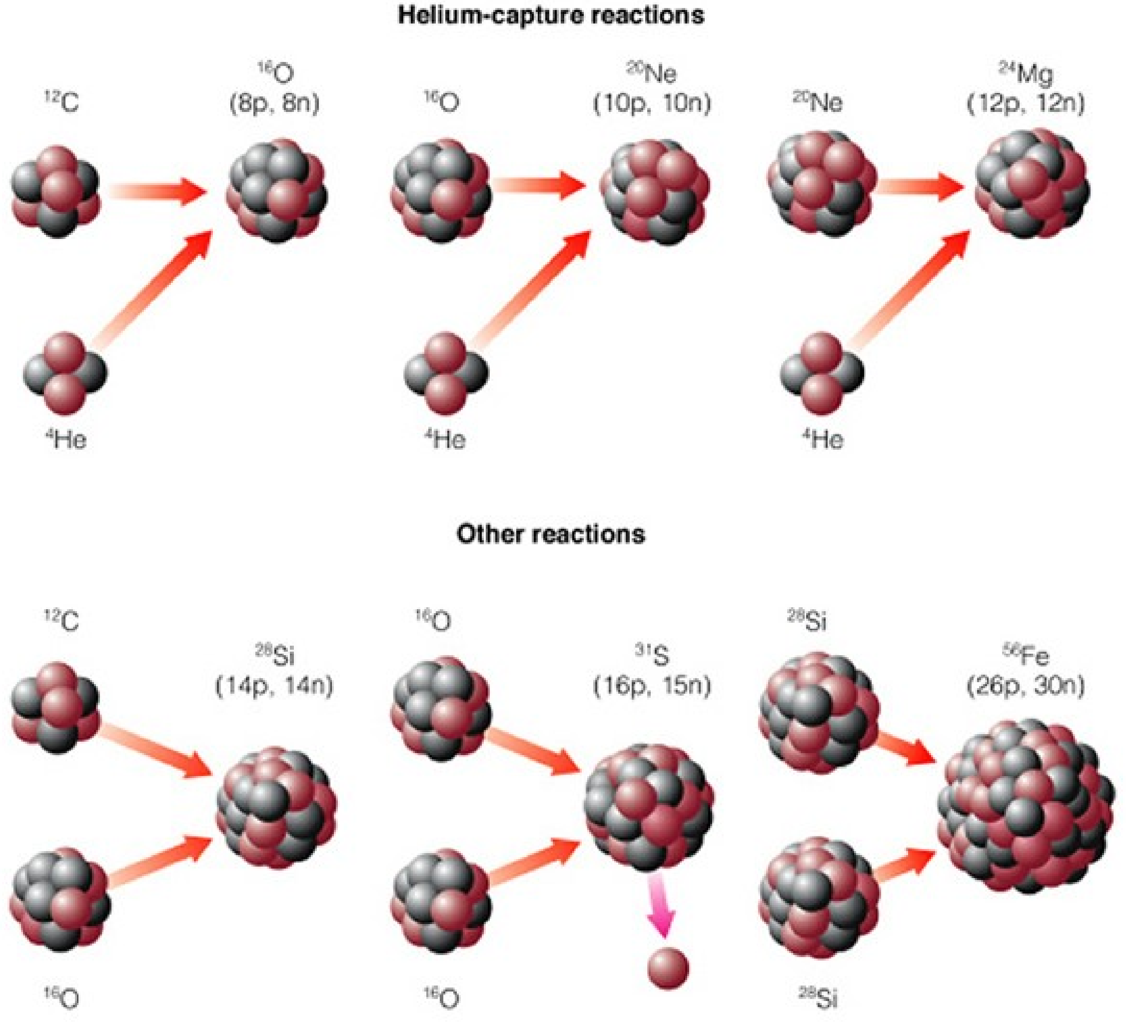
$M > 8\ M_\odot$

Carbon → O,Ne,Mg (600 million K)

Neon → O, Mg (1.5 Billion K)

Oxygen → Si, S, P (2.1 Billion K)

Silicon → Fe, Ni (3.5 Billion K)



Evolution of high mass stars

$M > 8\ M_\odot$

TIMESCALES FOR NUCLEAR BURNING

Hydrogen – 10 Myr
Helium – 1 Myr
Carbon – 1000 yr
Neon ~ 10 yr
Oxygen ~ 1 yr
Silicon ~ 1 day

Evolution of high mass stars $M > 8\ M_\odot$

The star develops an **"onion layers structure"** of burning shells

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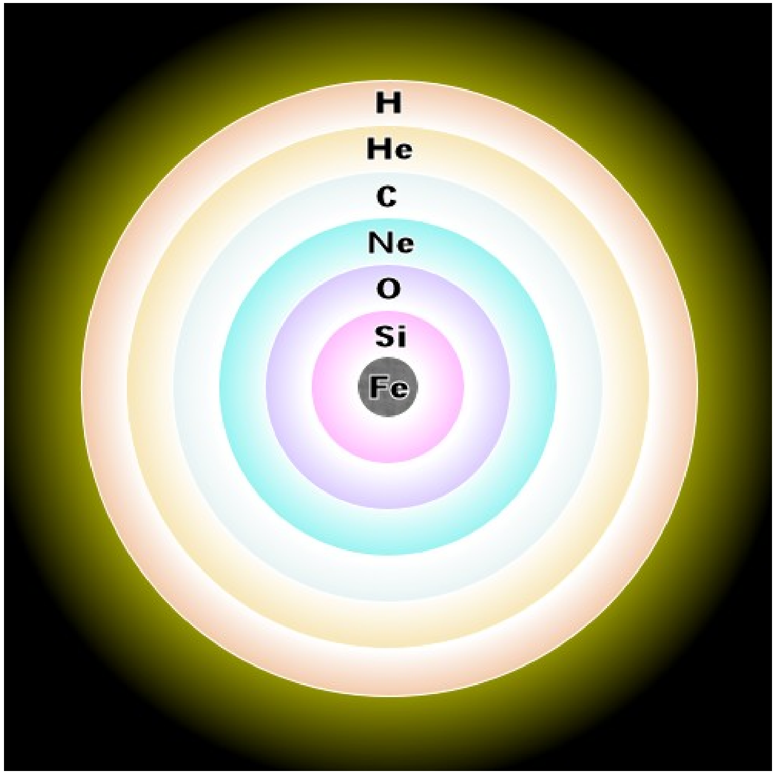

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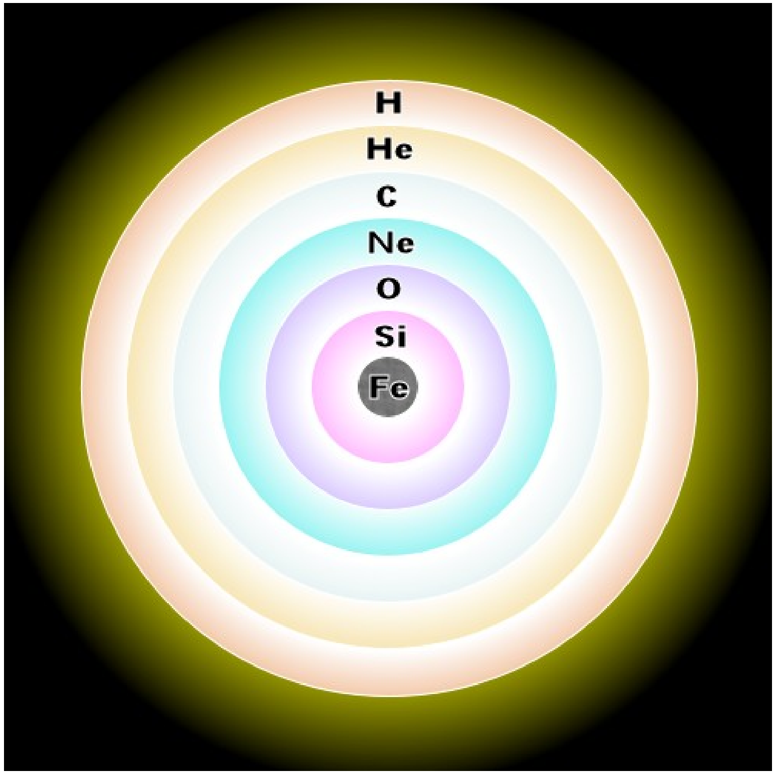
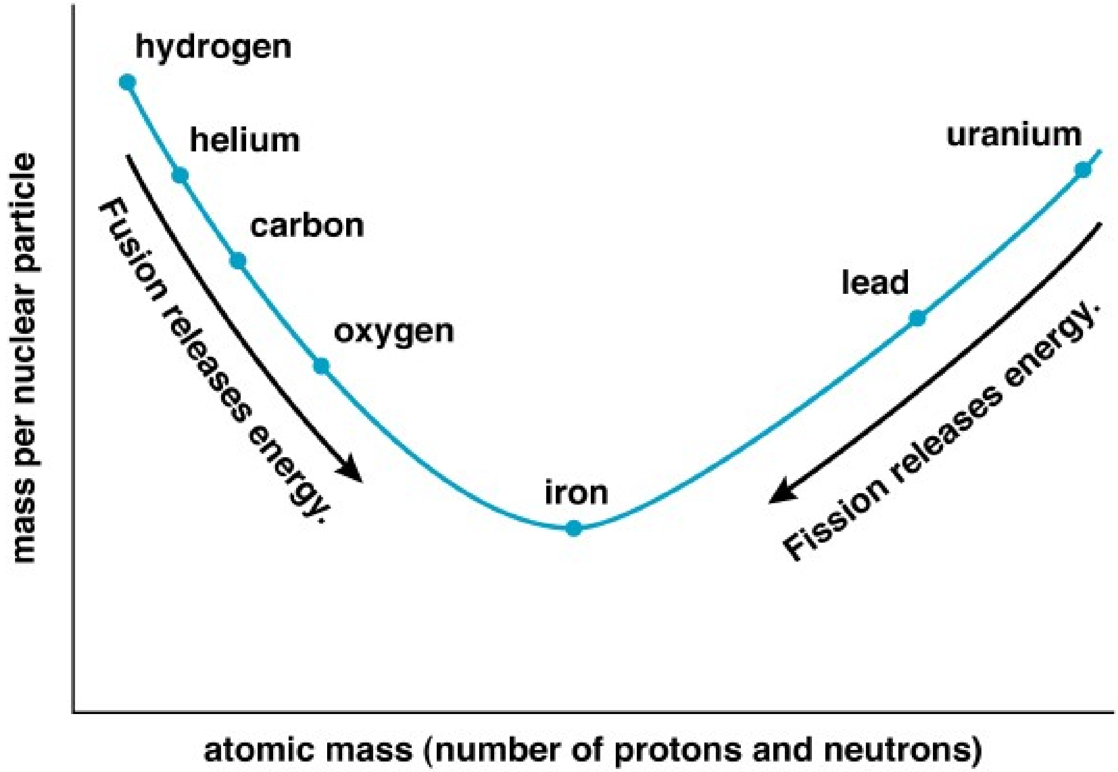


*But **Iron** is a **DEAD END** !!*

Iron is a dead end

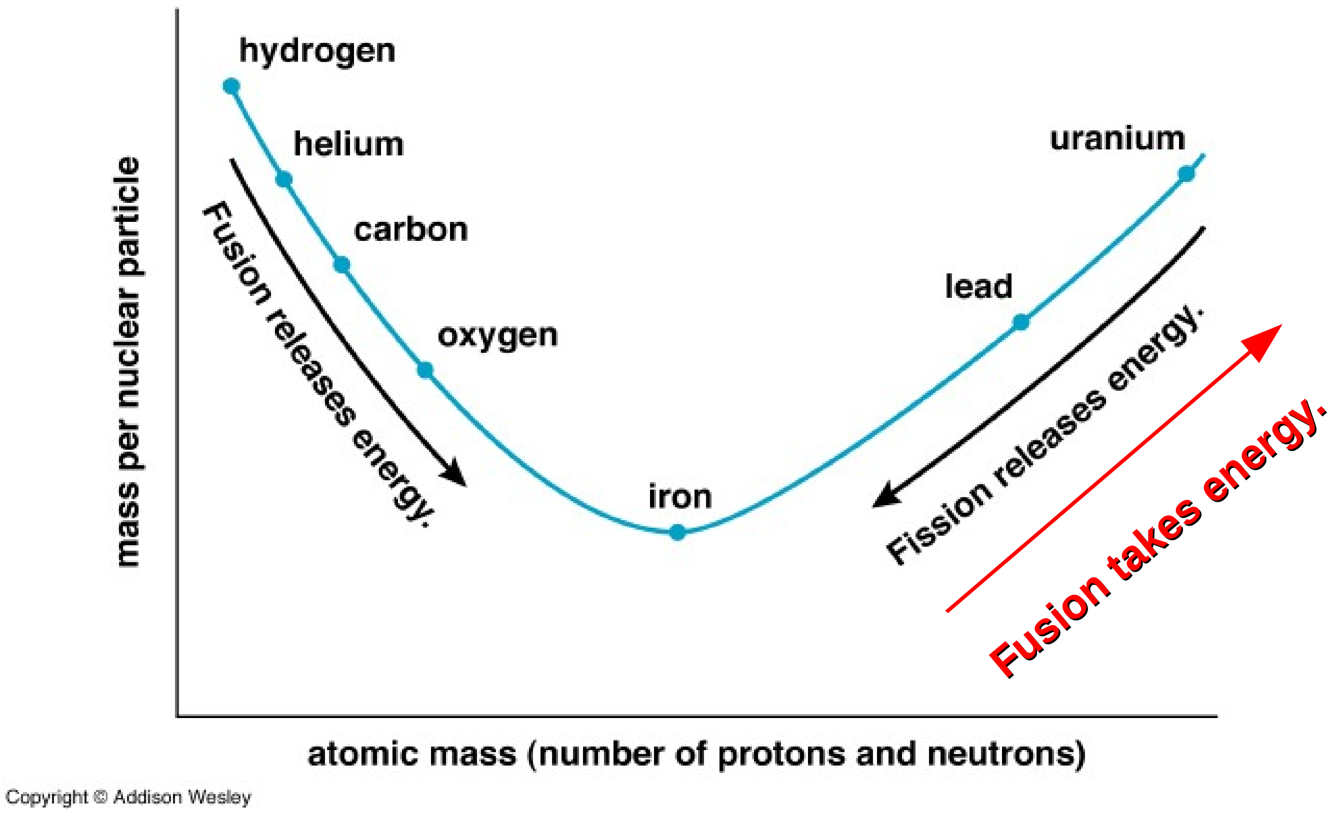
Iron is the most tightly bound element



Iron is a dead end

Iron is the most tightly bound element

Fusion beyond Iron TAKES energy



No fusion reactions left to yield energy!!

An Iron core!

End of the road for nuclear fusion!!

Now what?

What will happen to me?

End of

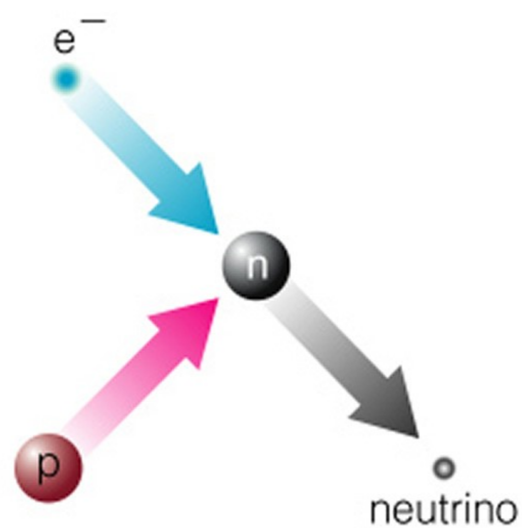
sion!!

Core collapse

Iron core contracts

At densities of 10^{10} g/cm^3
(remember: nuclear densities are ~10^{14} g/cm^3)

Neutronization



Proton + electron $\longrightarrow$ neutron + neutrino

$(p + e^- \rightarrow n + \nu)$

Urca process

Free neutrons are unstable!

Neutron $\rightarrow$ Proton + electron + neutrino

$$(n \rightarrow p + e^{-} + \nu)$$

Proton + electron $\rightarrow$ neutron + neutrino

$$(p + e^{-} \rightarrow n + \nu)$$

Urca process

Free neutrons are unstable!

Beta decay

Neutron → Proton + electron + neutrino

$$(n \rightarrow p + e^- + \nu)$$

Inverse Beta Decay

Proton + electron → neutron + neutrino

$$(p + e^- \rightarrow n + \nu)$$

Urca process

Free neutrons are unstable!

Beta decay

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Inverse Beta Decay

Proton + electron $\rightarrow$ neutron + neutrino

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Urca process

Free neutrons are unstable!

Beta decay

Neutron → Proton + electron + ***neutrino***

$(n \rightarrow p + e^- + \nu)$

Inverse Beta Decay

Proton + electron → neutron + ***neutrino***

$(p + e^- \rightarrow n + \nu)$

A flood of neutrinos!!

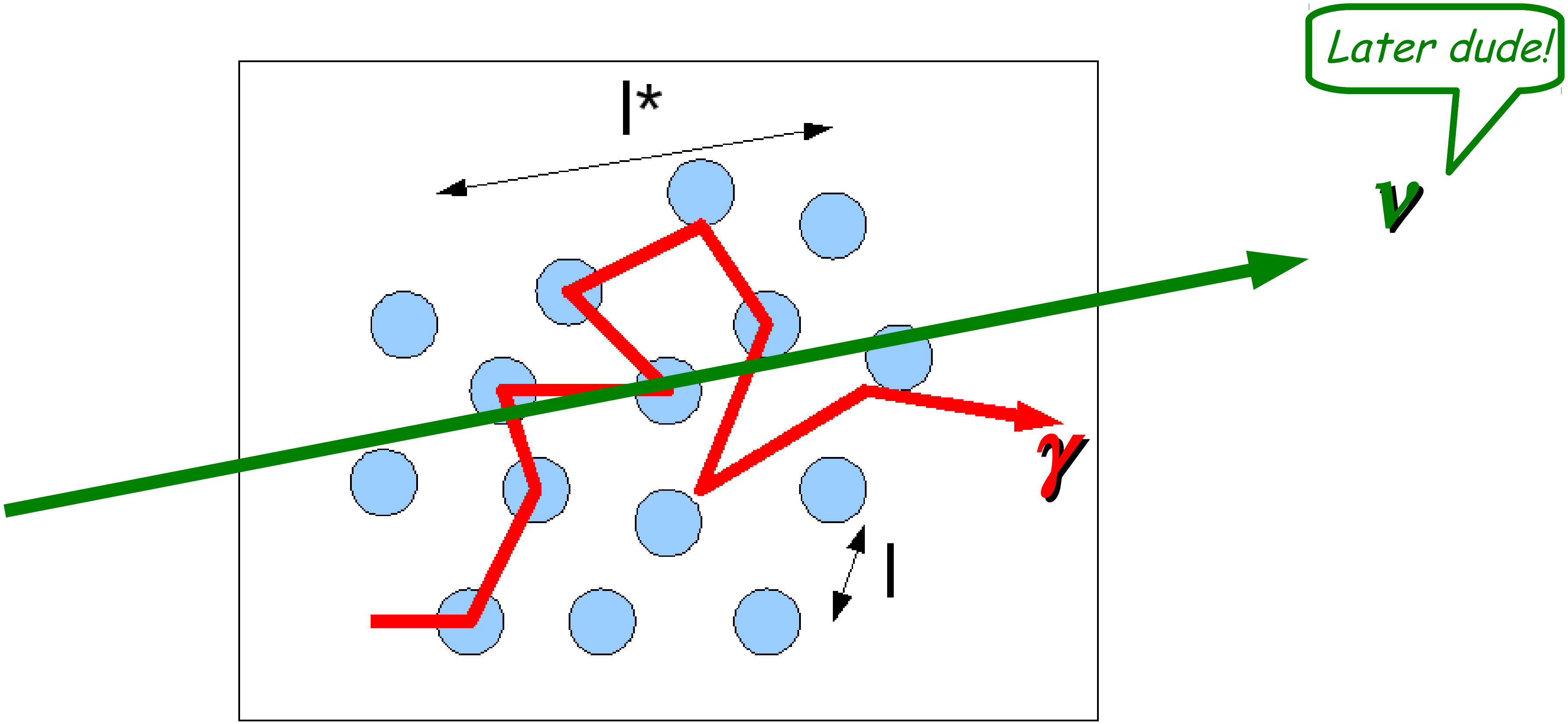
Urca process

$(n \rightarrow p + e^- + \nu)$

$(p + e^- \rightarrow n + \nu)$

A flood of neutrinos!!

Neutrinos interact **very weakly** with matter
(they can traverse light-years of lead without being absorbed)



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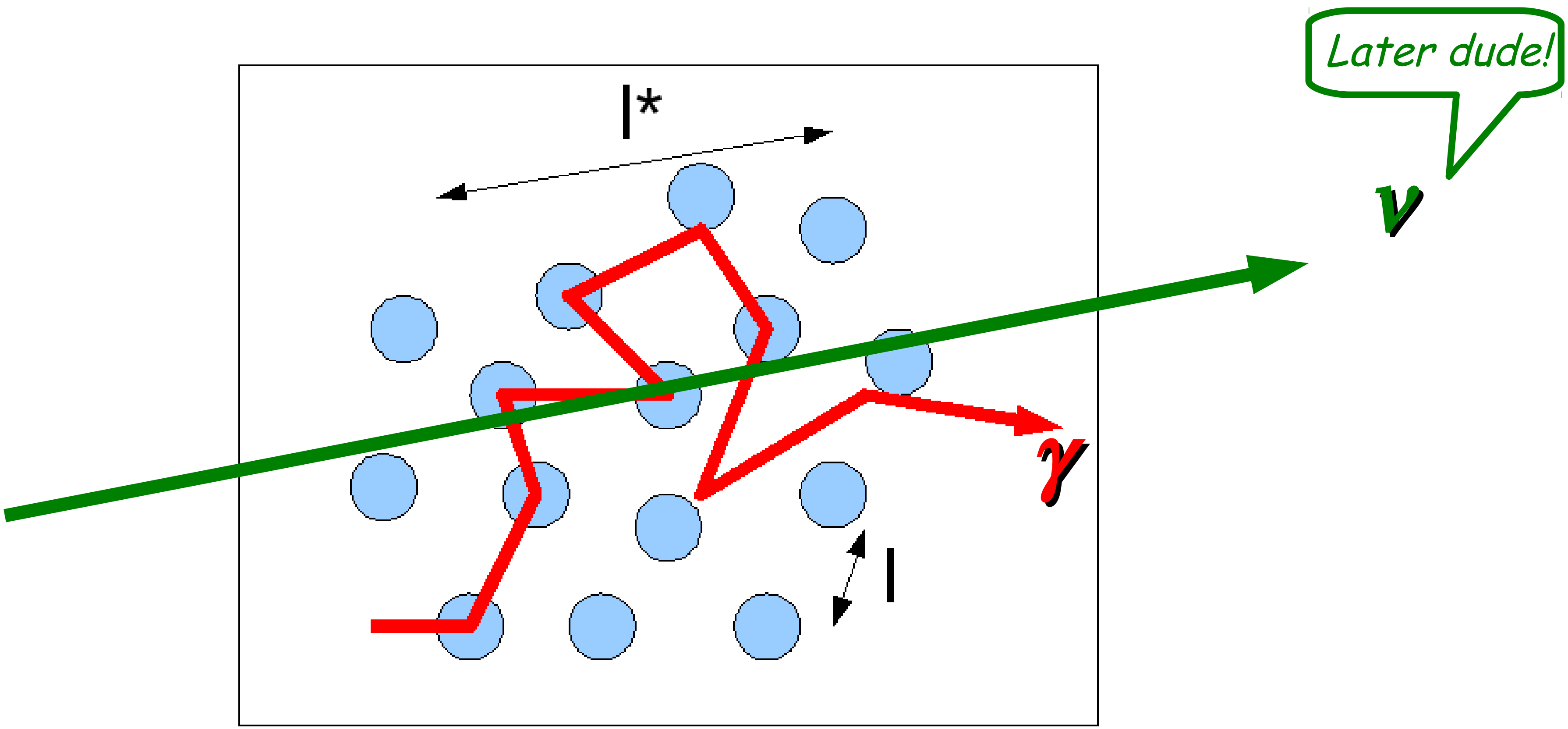


The neutrinos carry the energy away

Hastening the collapse of the core!

Urca process

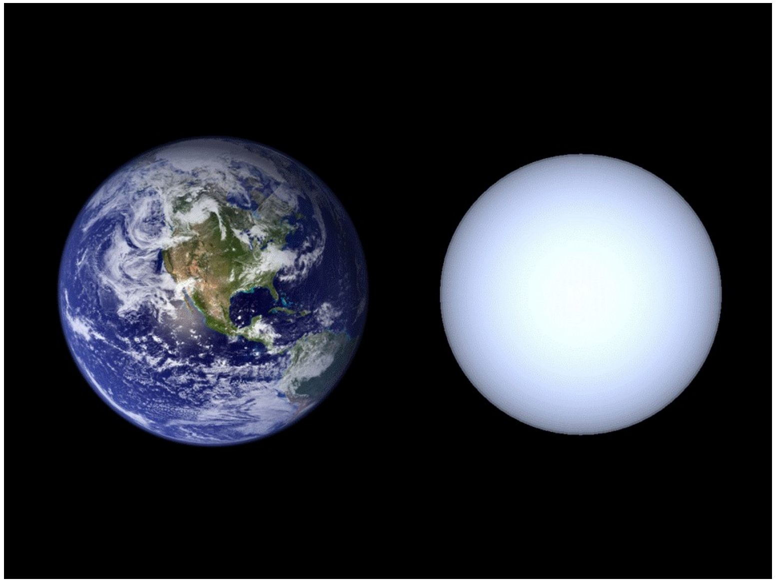
Mario Schenberg

George Gamow

Urca Casino

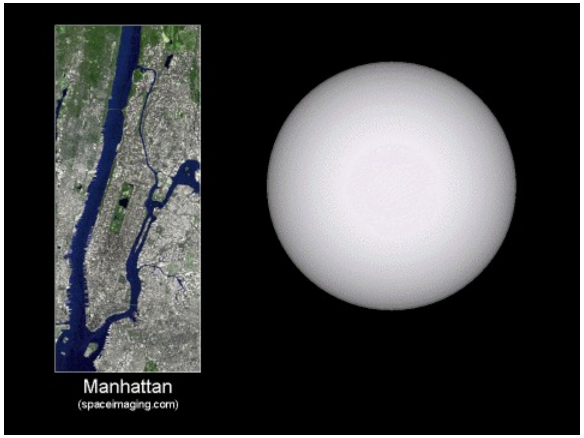
"The energy disappears from the core of the star as quickly as the money disappeared at that roulette table"

Catastrophic collapse



A second later

Collapse speed: 0.25c



6000 km
10^{10} g/cm^3

10 km
10^{14} g/cm^3

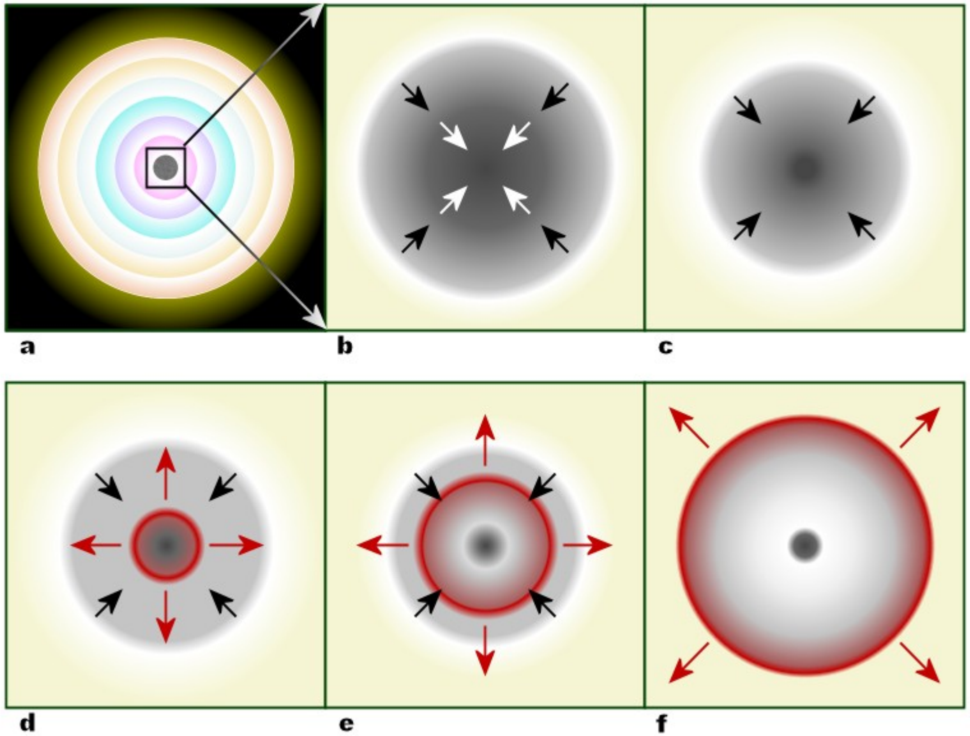
Nuclear densities!
The ***STRONG FORCE*** *comes into play and provides support against gravity*

Core Bounce

Neutronization

Iron core collapses

The inner core stabilizes and stops collapsing.



The core overshoots the equilibrium radius and bounces.

The kinetic energy that was directed inwards is redirected outwards

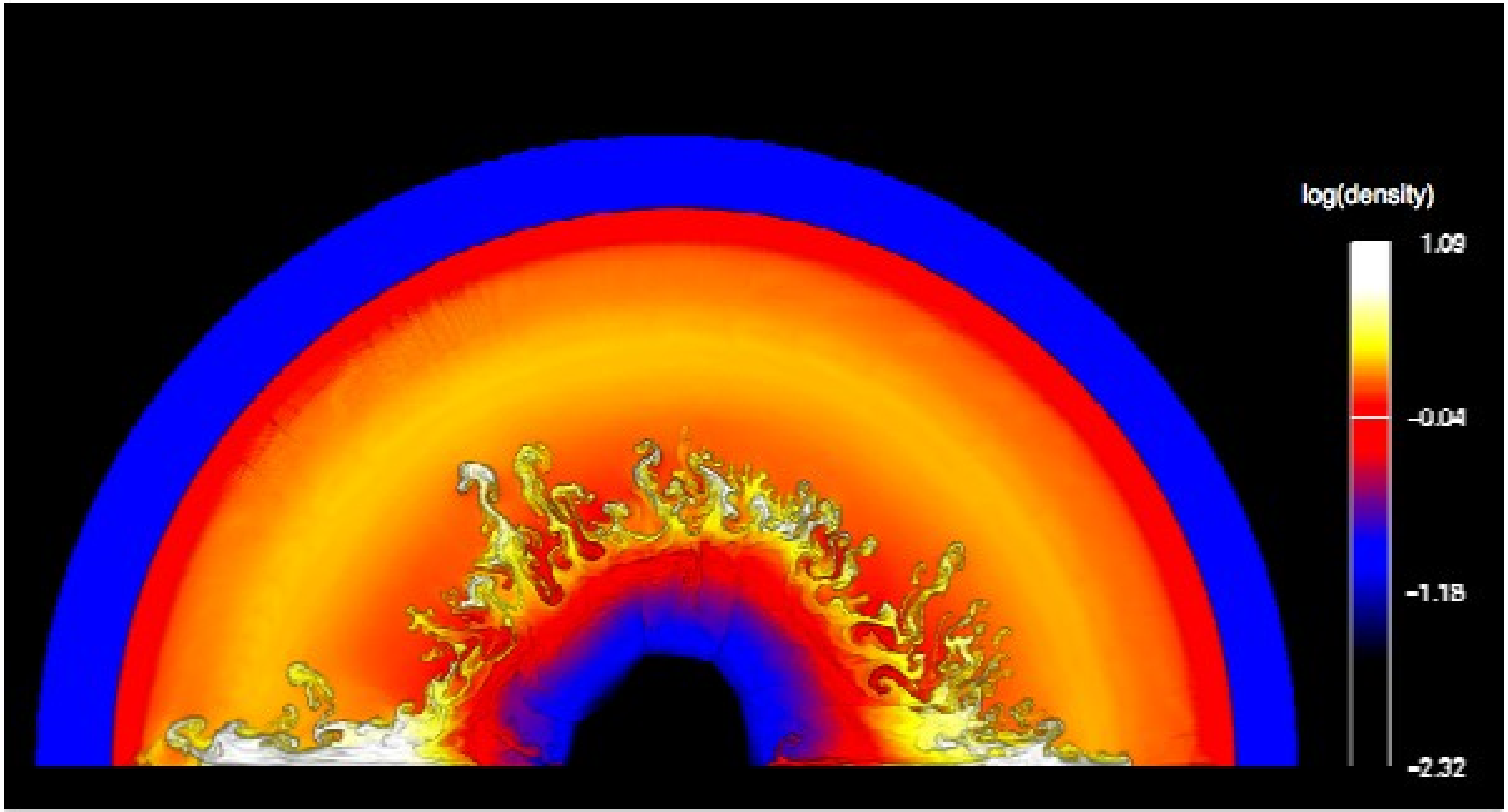
Infalling gas hits the rebouncing gas

The Thermonuclear Shock Wave

Infalling gas meeting the rebouncing core generates a ***shock wave***

The blastwave generates ***explosive nuclear reactions*** along its path

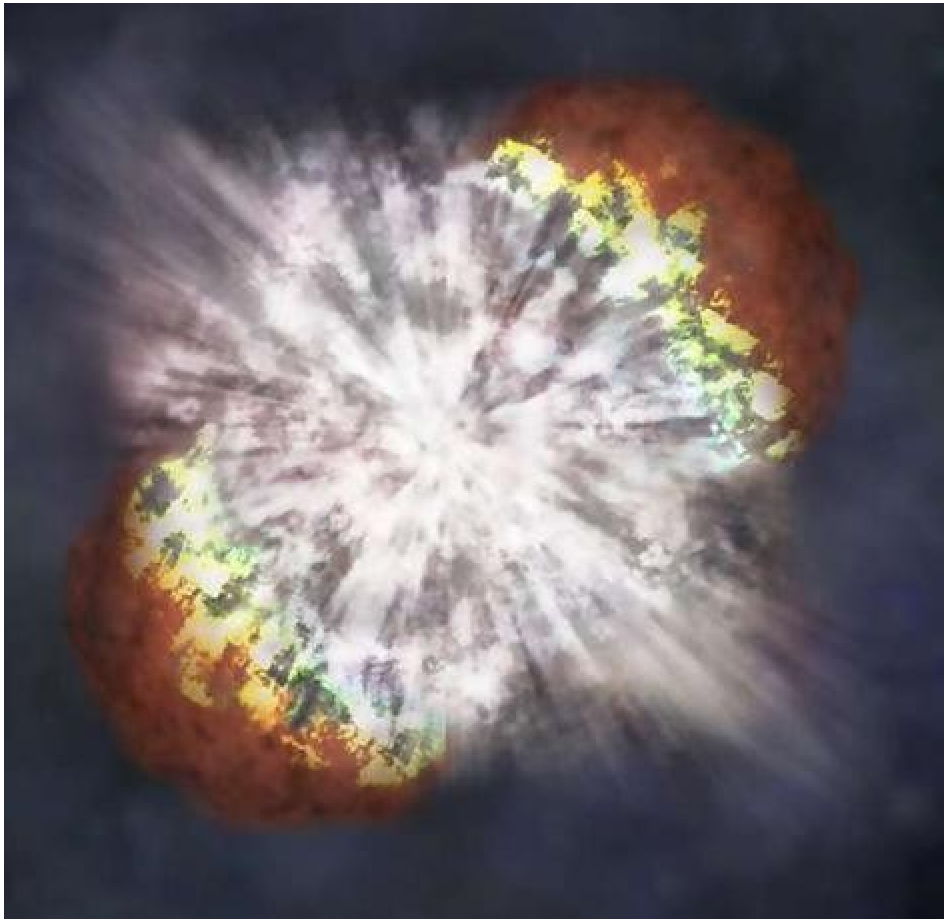
Violently heats and accelerates the stellar envelope



Supernova!

In a few hours, the shockwave reaches the surface

From the outside, the star is seen to explode.



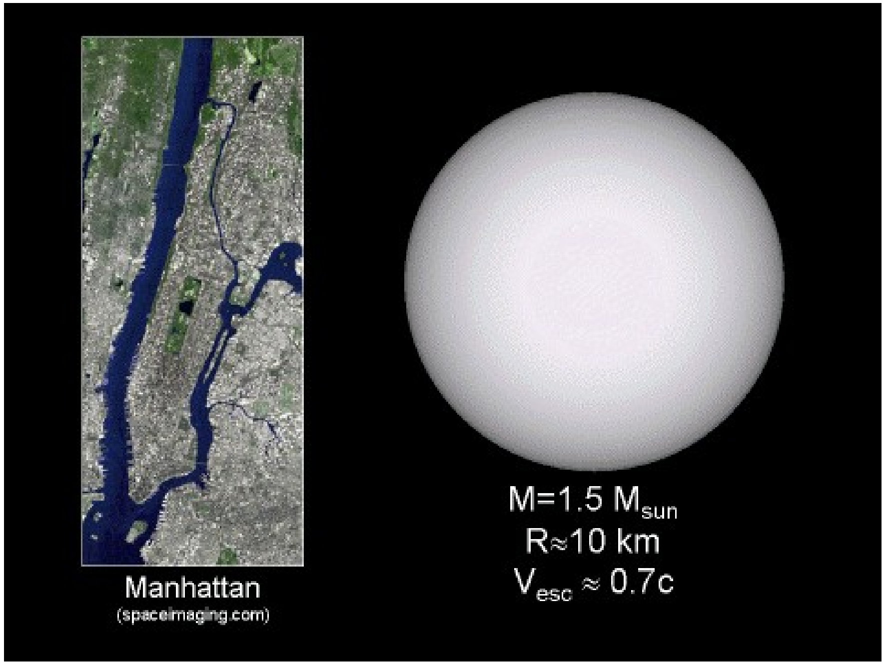
Supernova 1987A

Confirmation of the theory

A **burst of neutrinos** 4 hours before the event

The progenitor had a mass of **20 $M_\odot$**. ***BINGO!***

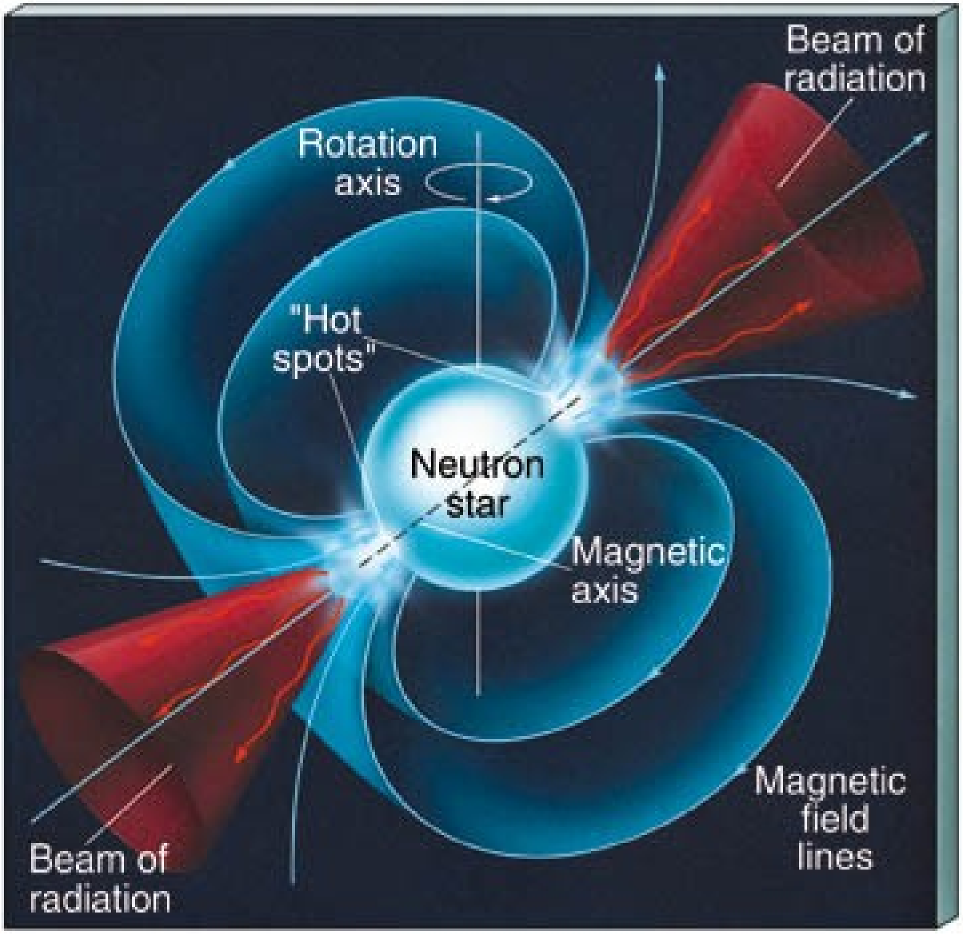
The Remnant



Neutron star

1.5 Msun compressed to the size of Manhattan
Though very hot, it is too small to be seen through thermal radiation
$L = 4\pi R^2 \sigma T^4$, remember?

The Remnant



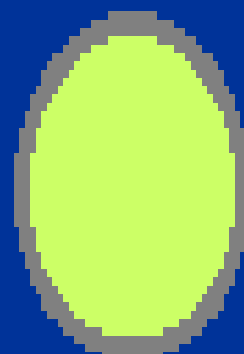
Pulsar

Spinning neutron star

The collapse increases the rotation rate

Intense magnetic fields give out non-thermal radiation

(like Earth's aurorae, but A LOT more luminous)



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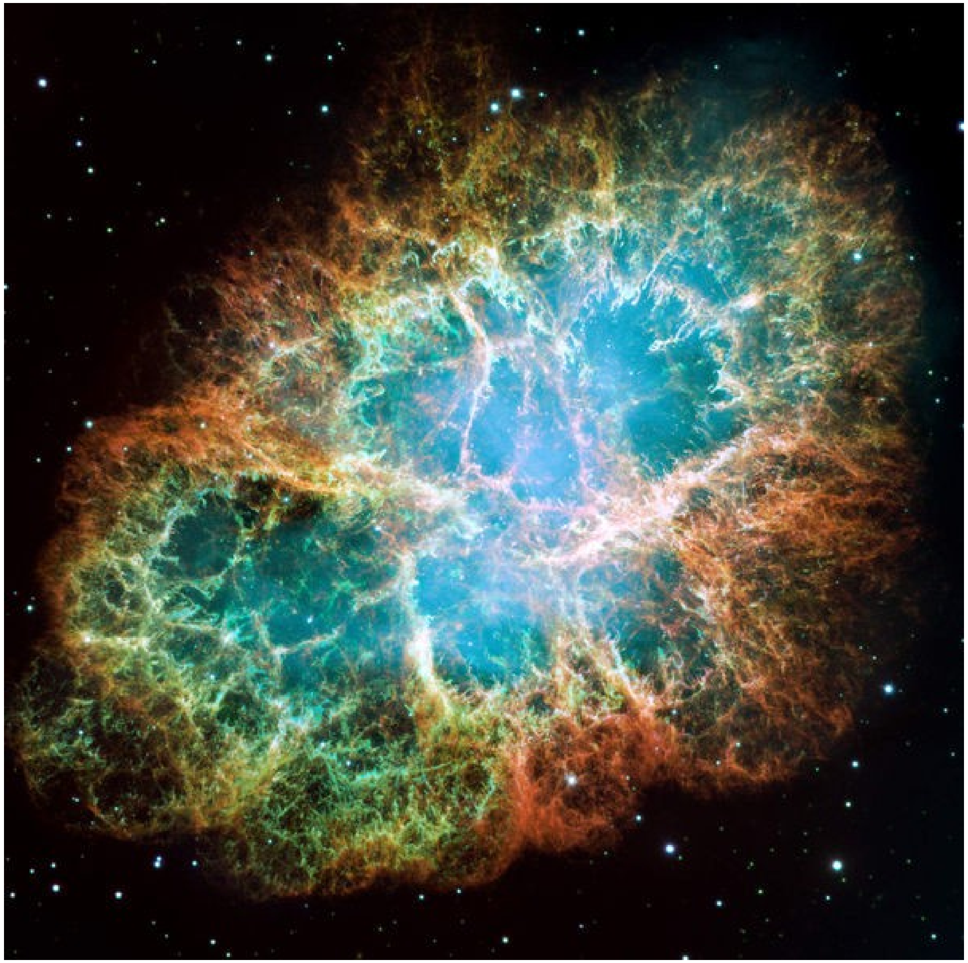
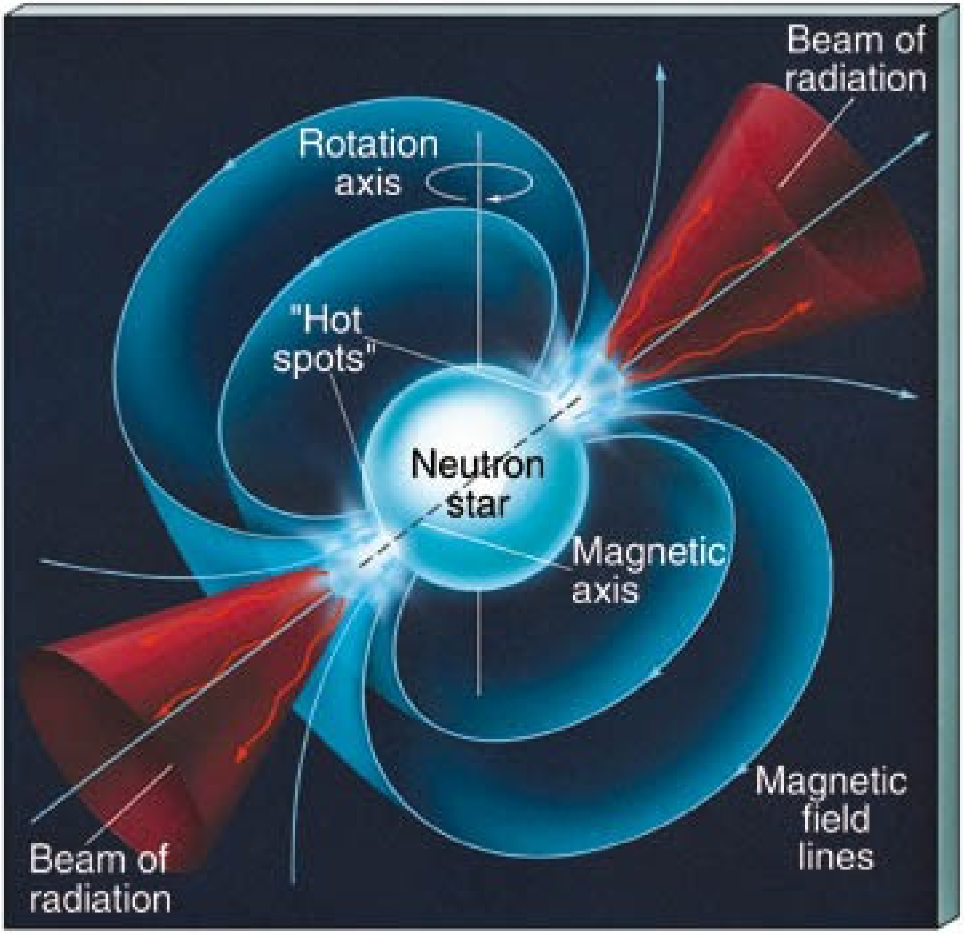


Crab Nebula
Expanding shell of the supernova seen in 1054AD

Crab Pulsar
Pulsar detected at the center of the shell

The Remnant



Are all pulsars neutron stars?

Yes

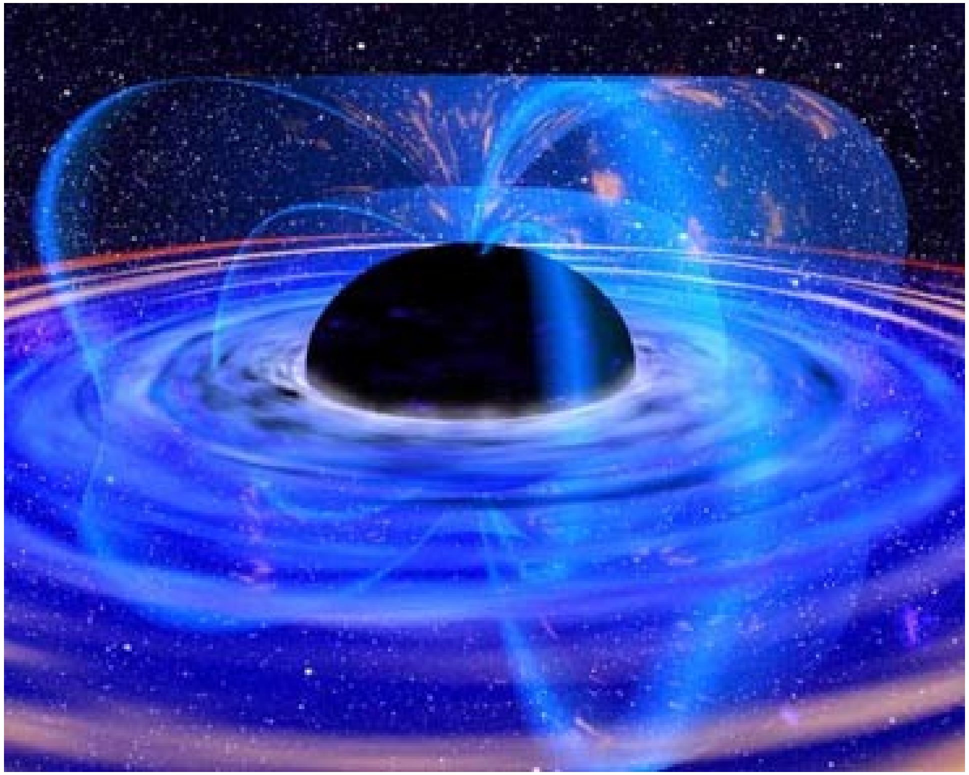
Are all neutron stars pulsars?

No, the beam may not point towards us, in which case we will not see the pulses

Black Hole – Gravity's ultimate victory

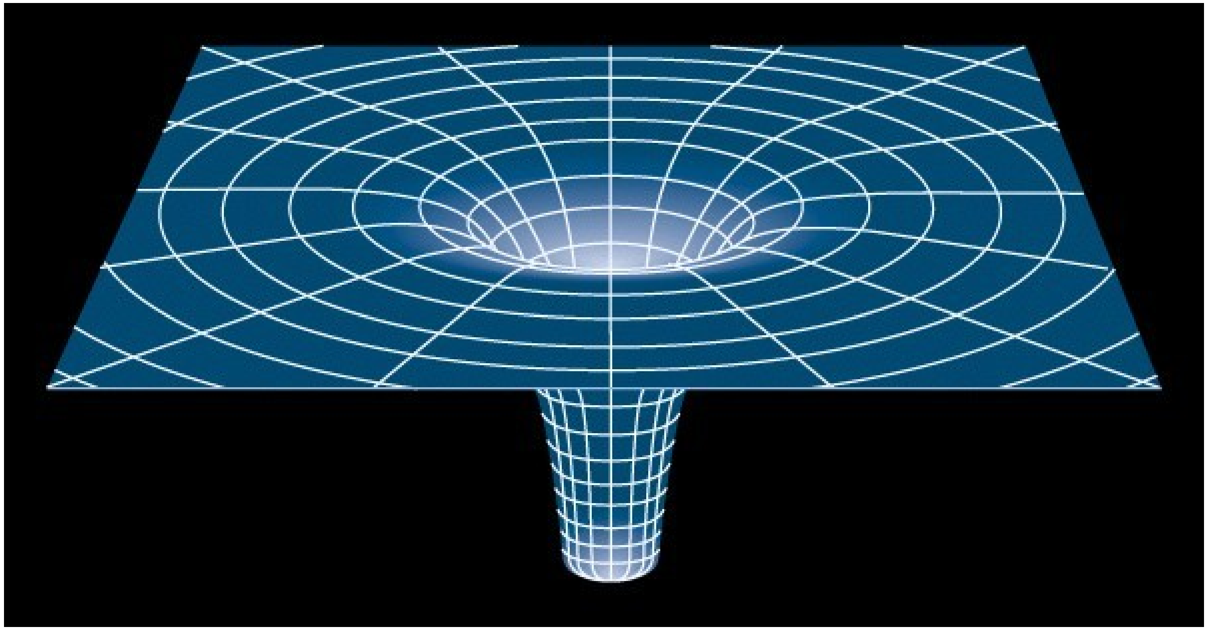
If the remnant has more than 3 solar masses,
neutron degeneracy cannot hold gravity

Actually, no known force can hold gravity at that point

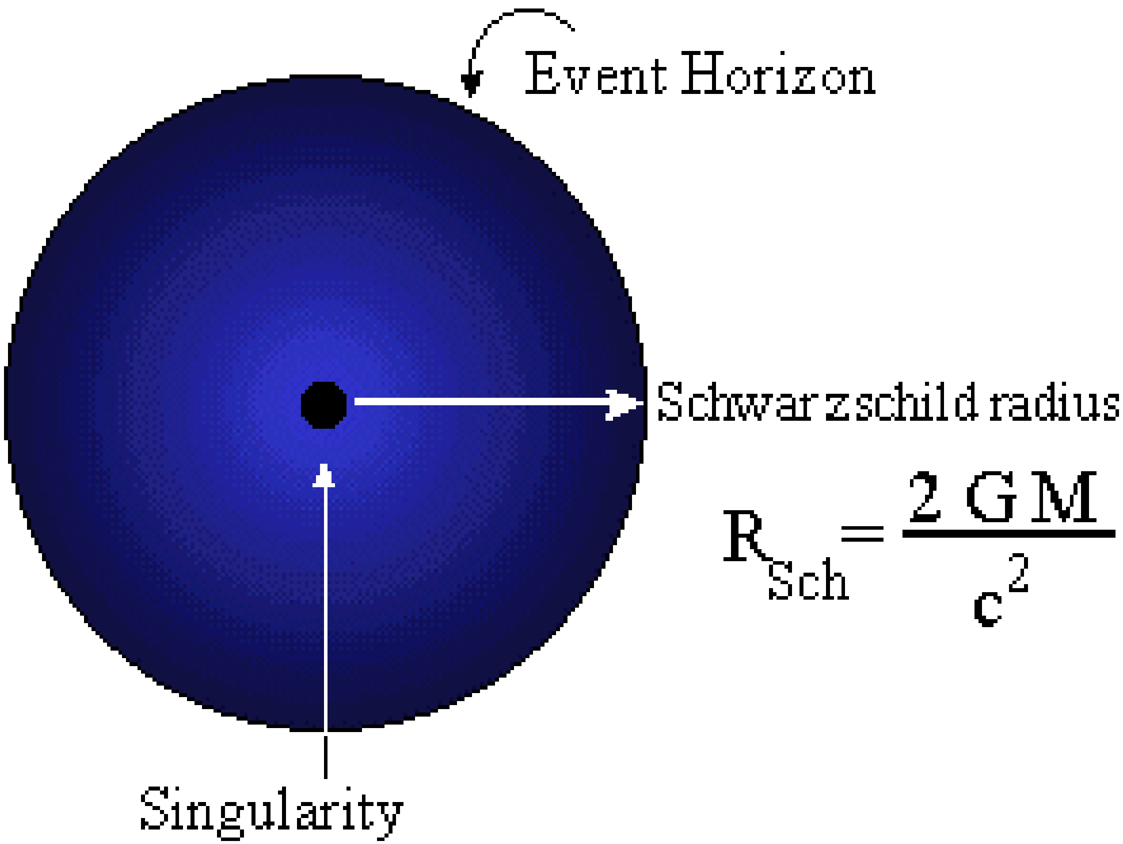


The star implodes to a point of infinite density and finally rests in peace.

A hole in spacetime



Black Hole Anatomy



$$R_{Sch} = \frac{2\,G\,M}{c^2}$$

Schwarzschild radius

Radius beyond which not even light can escape

Event Horizon

The sphere of radius R_s

The event horizon is ***not*** a physical boundary

Where does the mass go?
Good question...
We cannot see the **singularity**

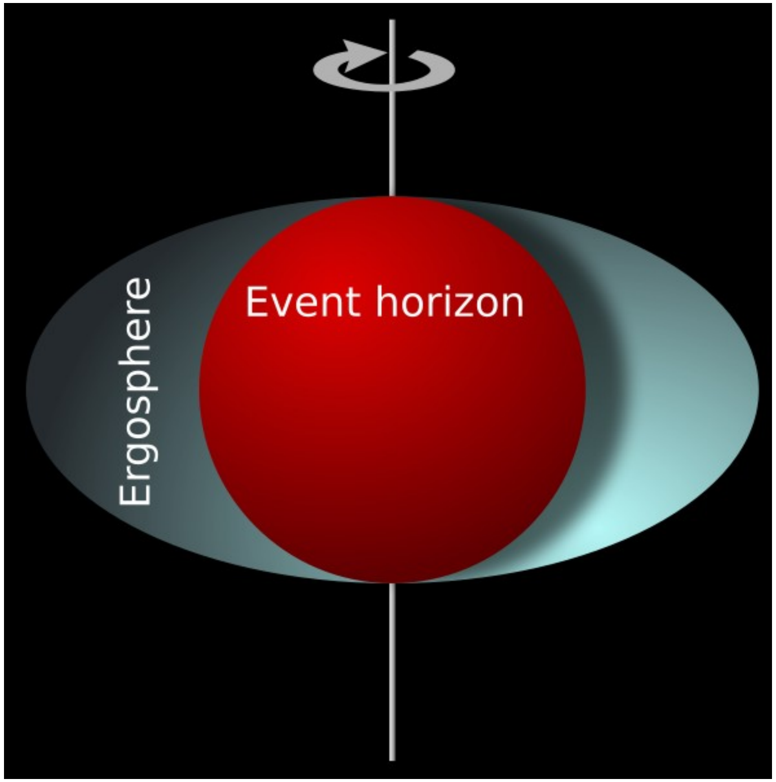
The "No-Hair" Theorem

"Black holes have no hair"

Black holes are very simple stuff. All information is lost apart from

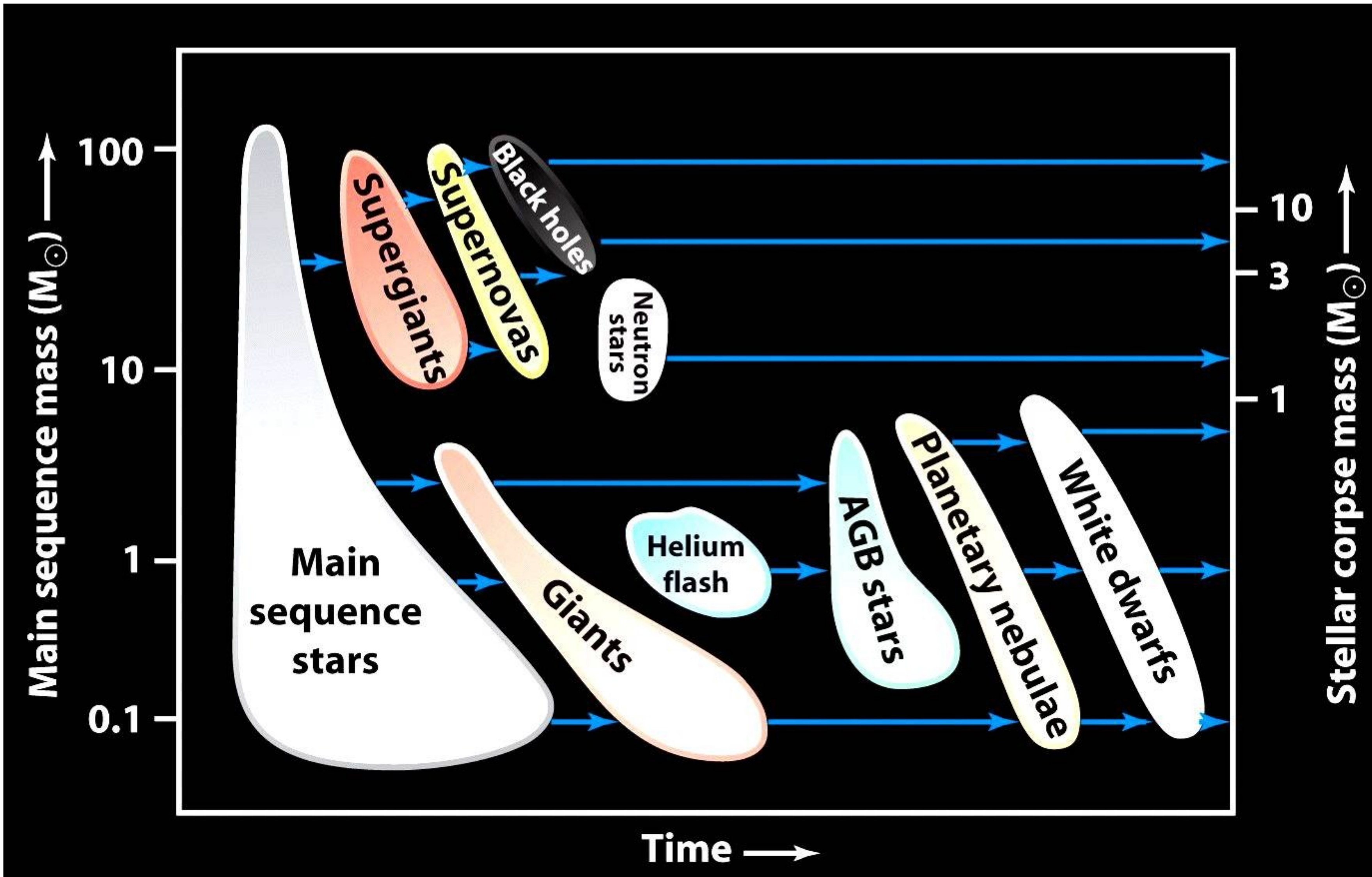
MASS, ***CHARGE***, and ***SPIN***

These 3 quantities completely specify a black hole



A spinning black hole

Summary of Stellar Evolution



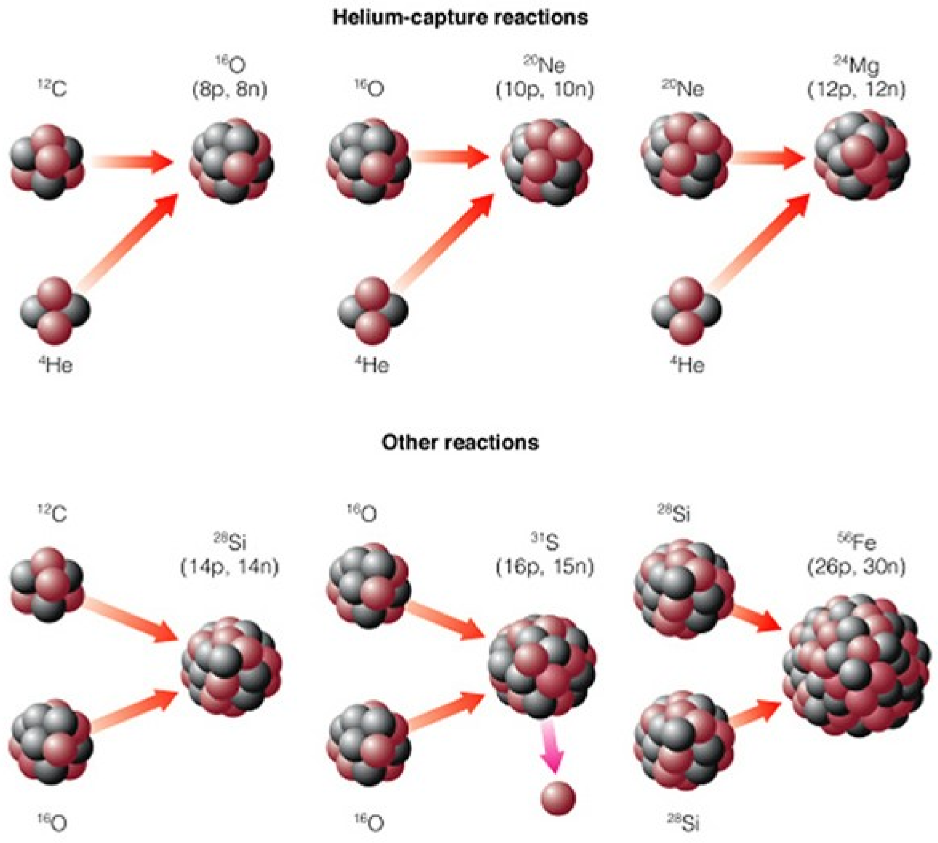
Nucleosynthesis

In the beginning there was Hydrogen and Helium

Low mass stars produce elements up to Carbon and Oxygen

High mass stars produce all the rest of the periodic table

Up to Iron we have basically alpha reactions



Nucleosynthesis

Beyond the Iron peak, nucleosynthesis occur by neutron capture and beta decay

$$(n \rightarrow p + e^- + \nu)$$

The process is classified according to the neutron flux

S-process

(slow neutron capture)

Neutron capture occurs
slower
than beta decay

Works up to bismuth (Z=83)

Where?
AGB stars + Supernovae

R-process

(rapid neutron capture)

Neutron capture occurs
faster
than beta decay

Really heavy stuff
All the way to Uranium

Where?
Supernovae

Nucleosynthesis

Element	# of Protons	Site
H	1	Big Bang
He, C, O	2,6,8	Big Bang + Low and High Mass stars
Ne - Fe	10-26	High mass stars
Co - Bi	27-83	S and R process, ABG and SN
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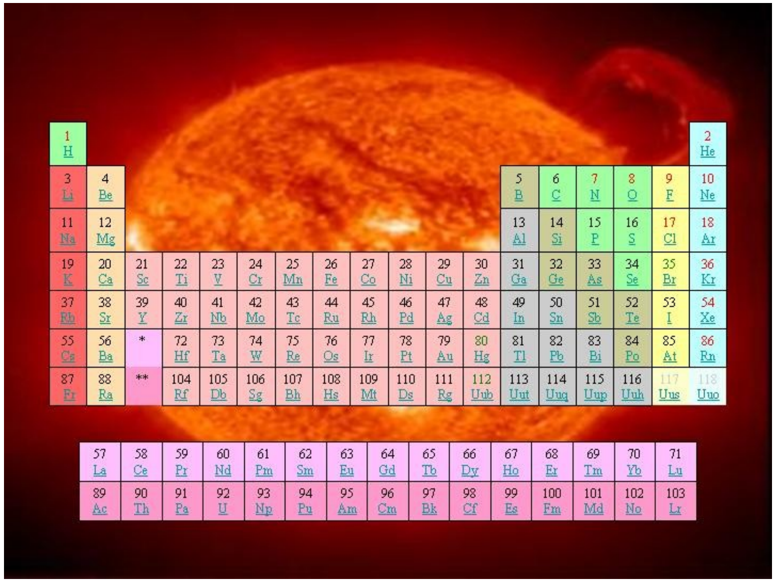


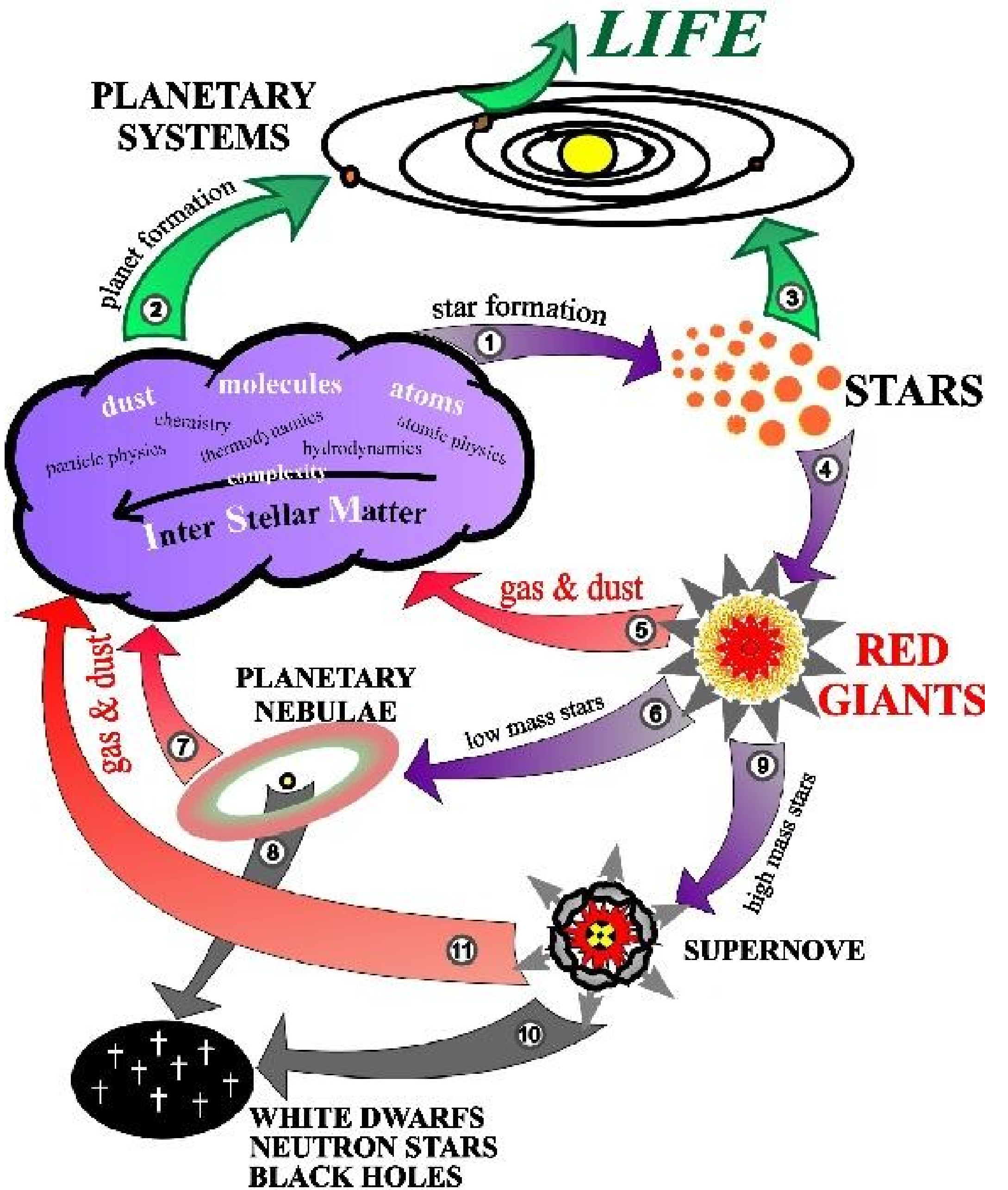
Chemical Enrichment of the Galaxy

Planetary Nebulae and **Supernovae** eject gas **enriched in metals** into the ISM

Recycling of matter

Remember, supernovae are massive stars, they live shortly (10 Myr or less). The SN recycling is practically instantaneous!

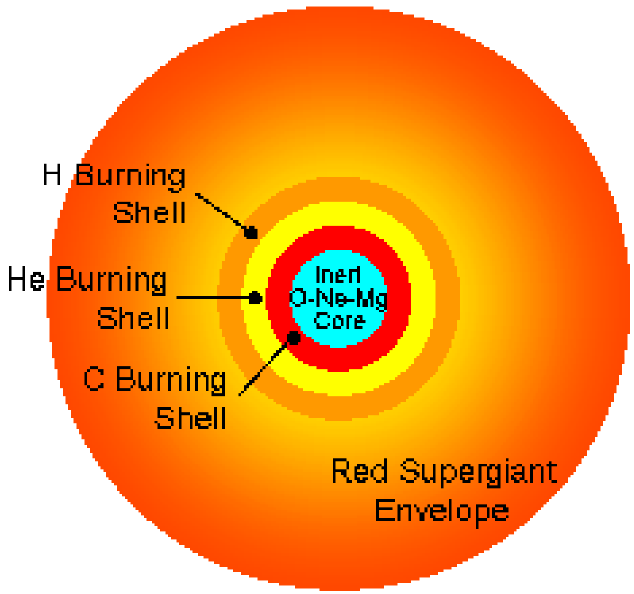
New generations of stars are enriched in metals.

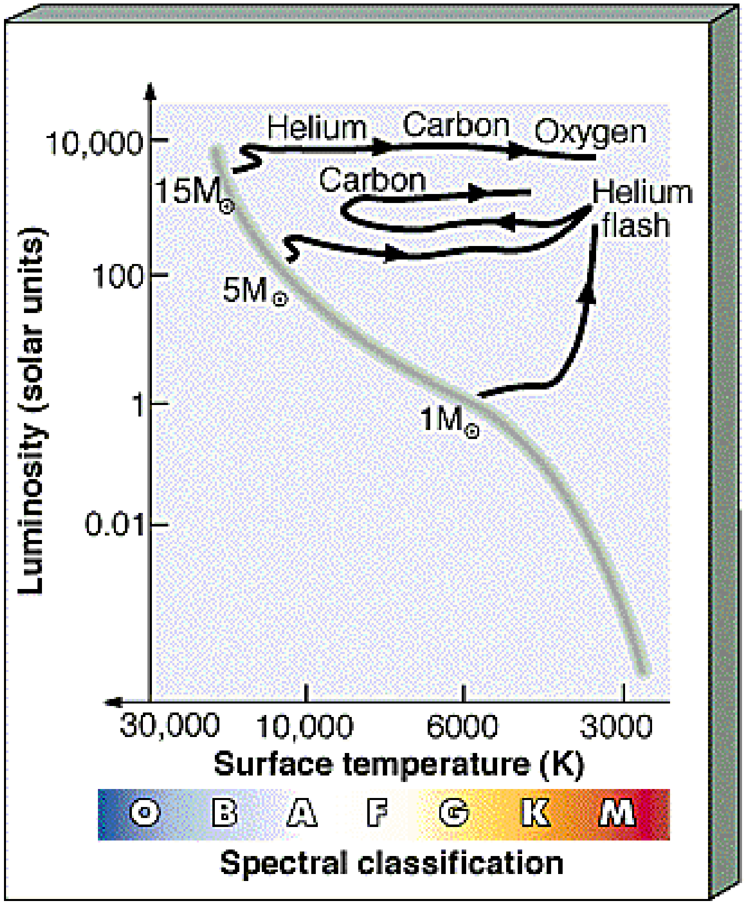


Chemical Enrichment of the Galaxy

Let's summarize

High mass stars have much hotter cores than low mass stars and get to fuse beyond Helium





Let's summarize

High mass stars have much hotter cores than low mass stars and get to fuse beyond Helium

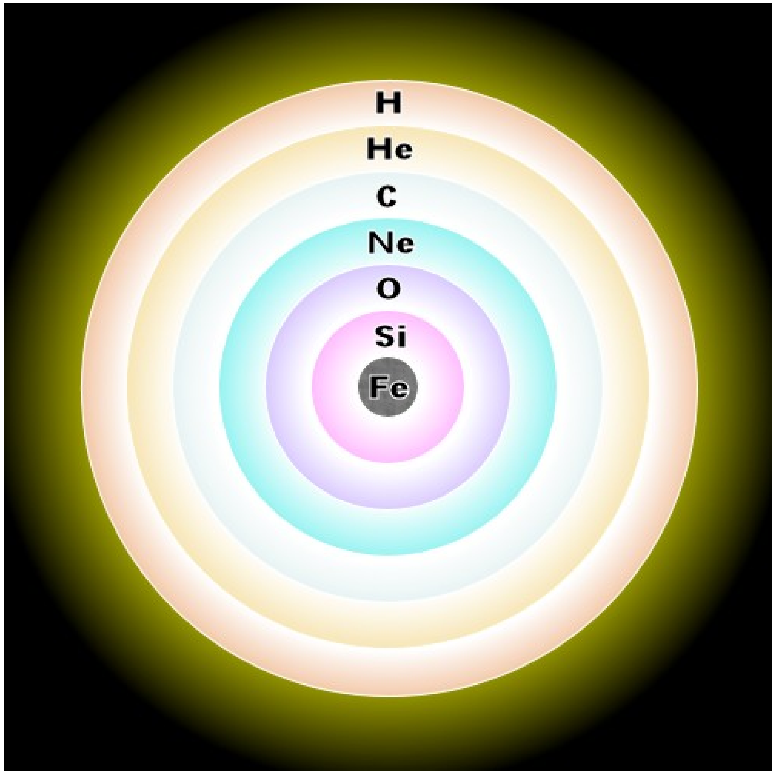
Higher mass stars develop onion-like structure of nuclear burning shells

Carbon → O,Ne,Mg (600 million K)

Neon → O, Mg (1.5 Billion K)

Oxygen → Si, S, P (2.1 Billion K)

Silicon → Fe, Ni (3.5 Billion K)



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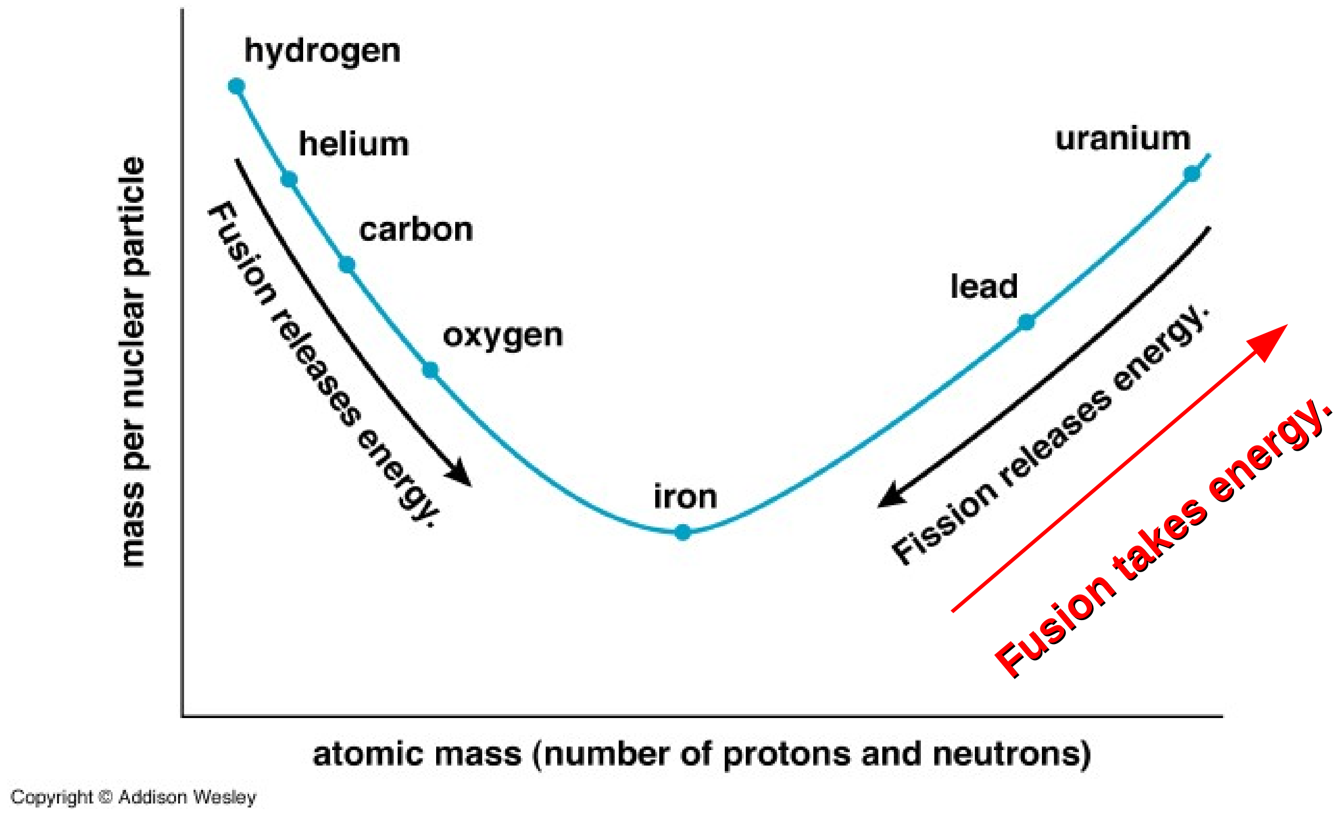
Iron is a dead end. Fusion beyond it consumes energy.



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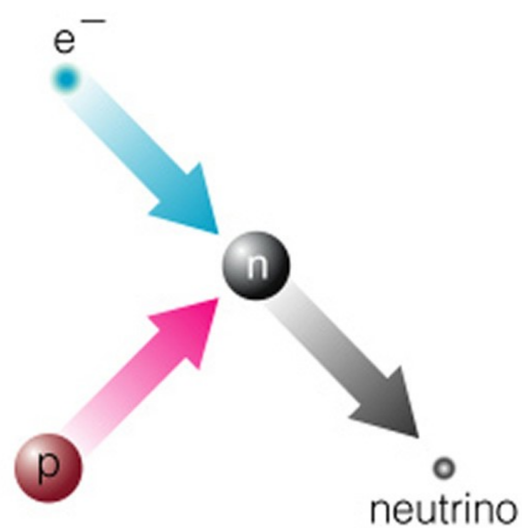

Proton + electron $\rightarrow$ neutron + neutrino

$$(p + e^{-} \rightarrow n + \nu)$$

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Urca process produce a flood of neutrinos, that carry energy away and hasten the collapse

Beta decay

Neutron $\rightarrow$ Proton + electron + ***neutrino***

$(n \rightarrow p + e^- + \nu)$

Inverse Beta Decay

Proton + electron $\rightarrow$ neutron + ***neutrino***

$(p + e^- \rightarrow n + \nu)$

A flood of neutrinos!!

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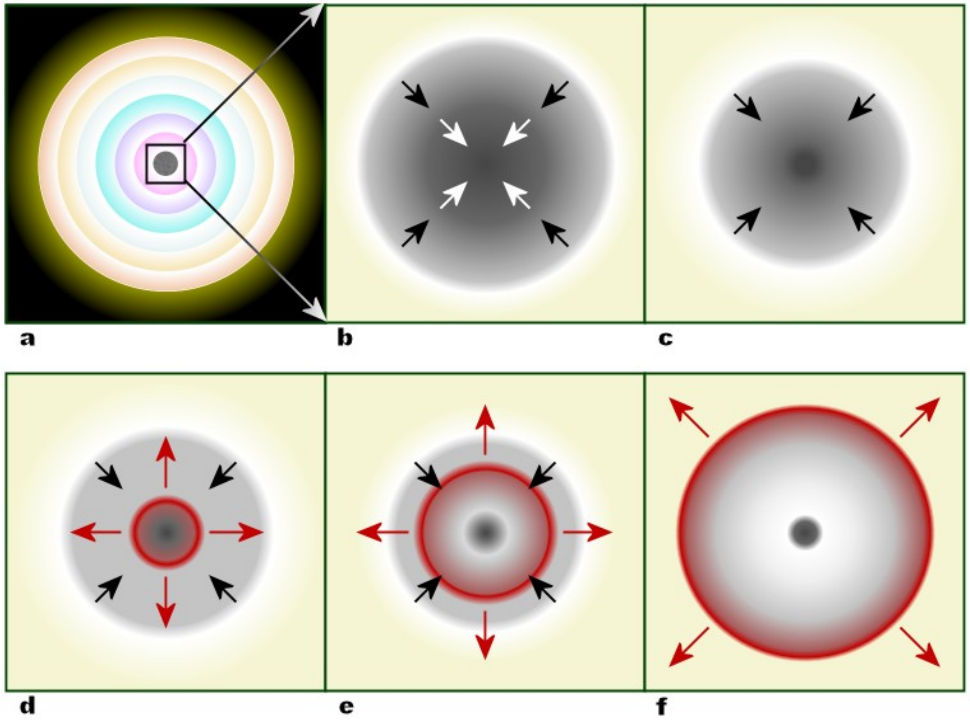

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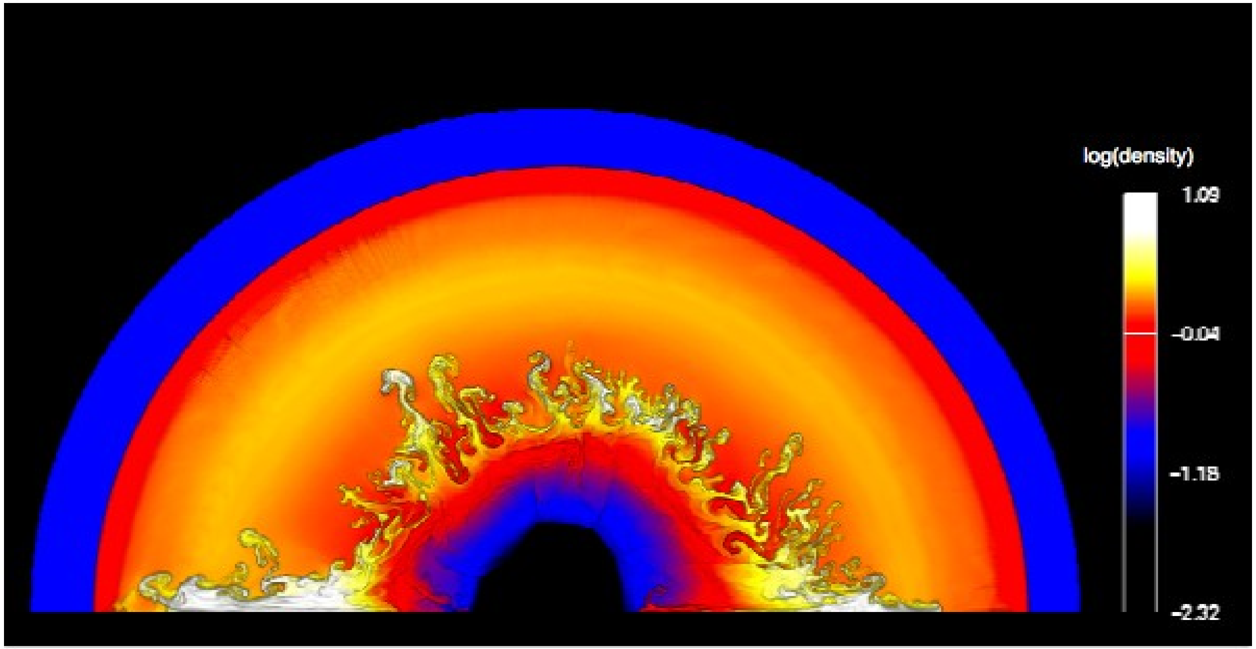

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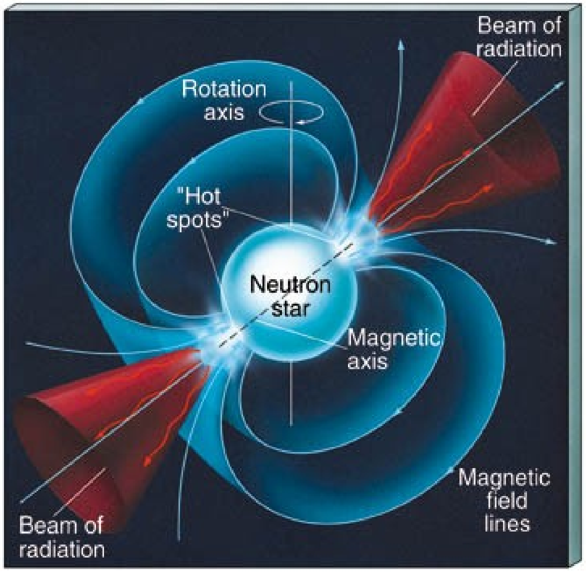

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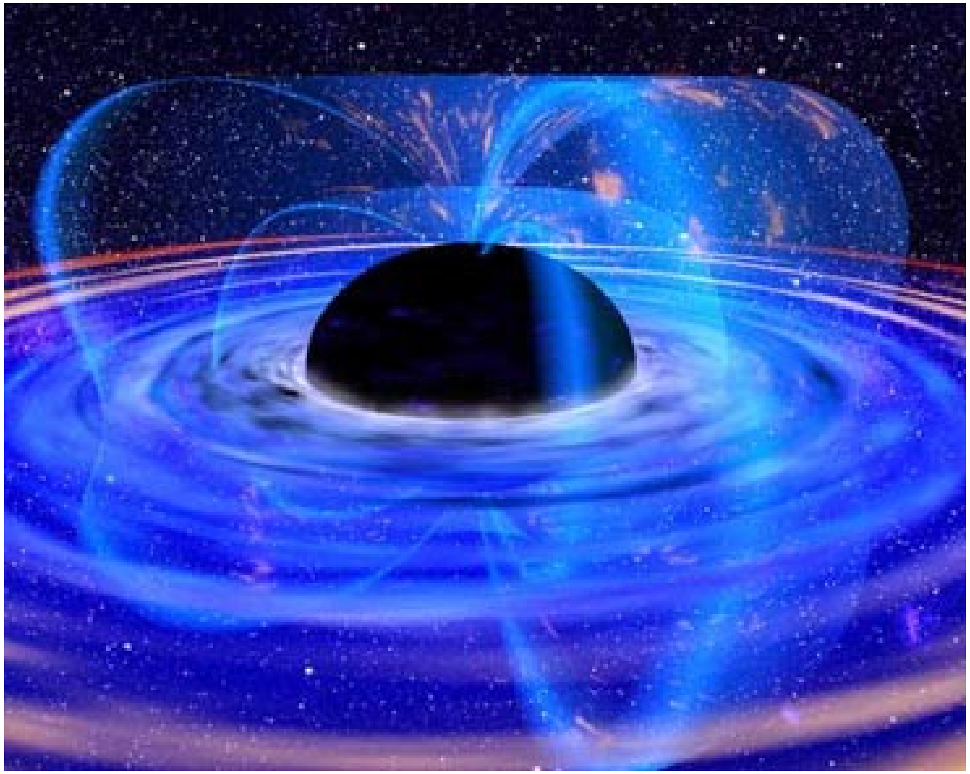
Remnant is either a pulsar (neutron star) or a black hole, depending of the mass.



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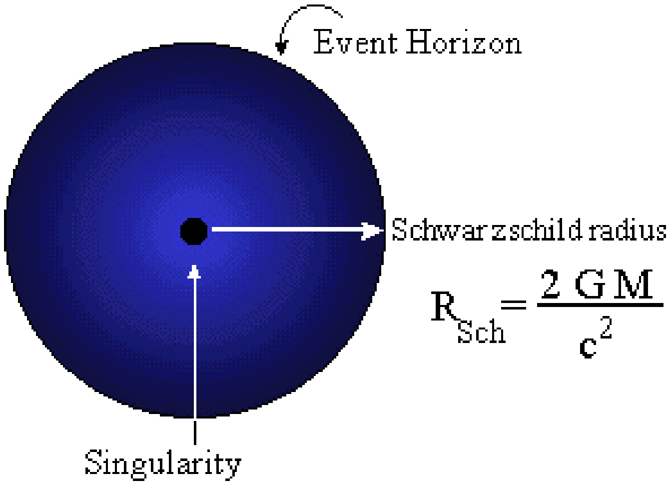
Black holes are simple stuff. They have "no hair".



Let's summarize

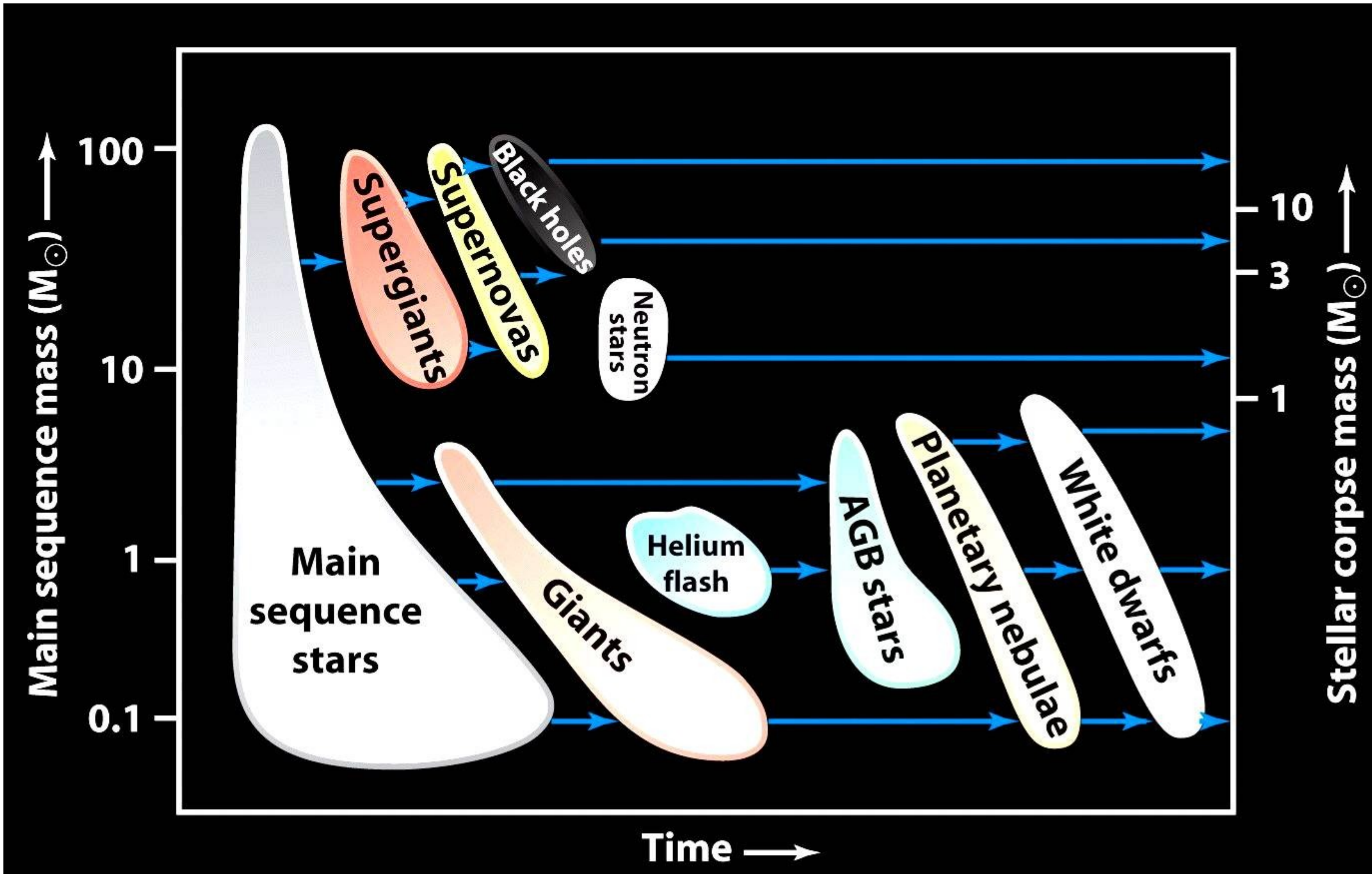
Stellar evolution summary

Higher mass stars develop onion-like structure of nuclear burning shells

Iron is a dead end. Fusion beyond it consumes energy.

Urca ... se

The c ... ed.



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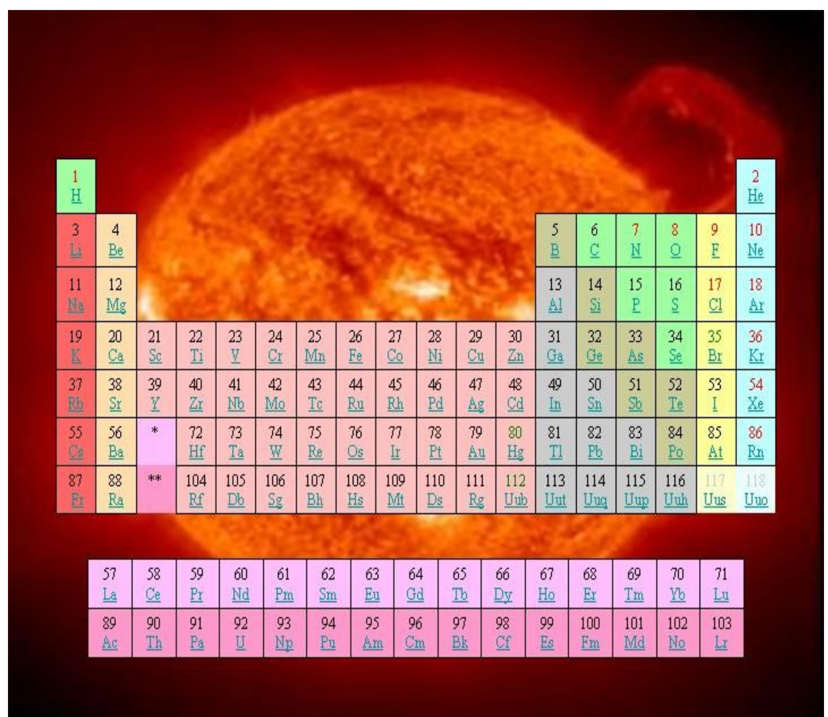
Nucleosynthesis: Stars are where the periodic table is cooked



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