dx

secz dx

z

thin, plane-parallel layer

x

z

observer

Observer
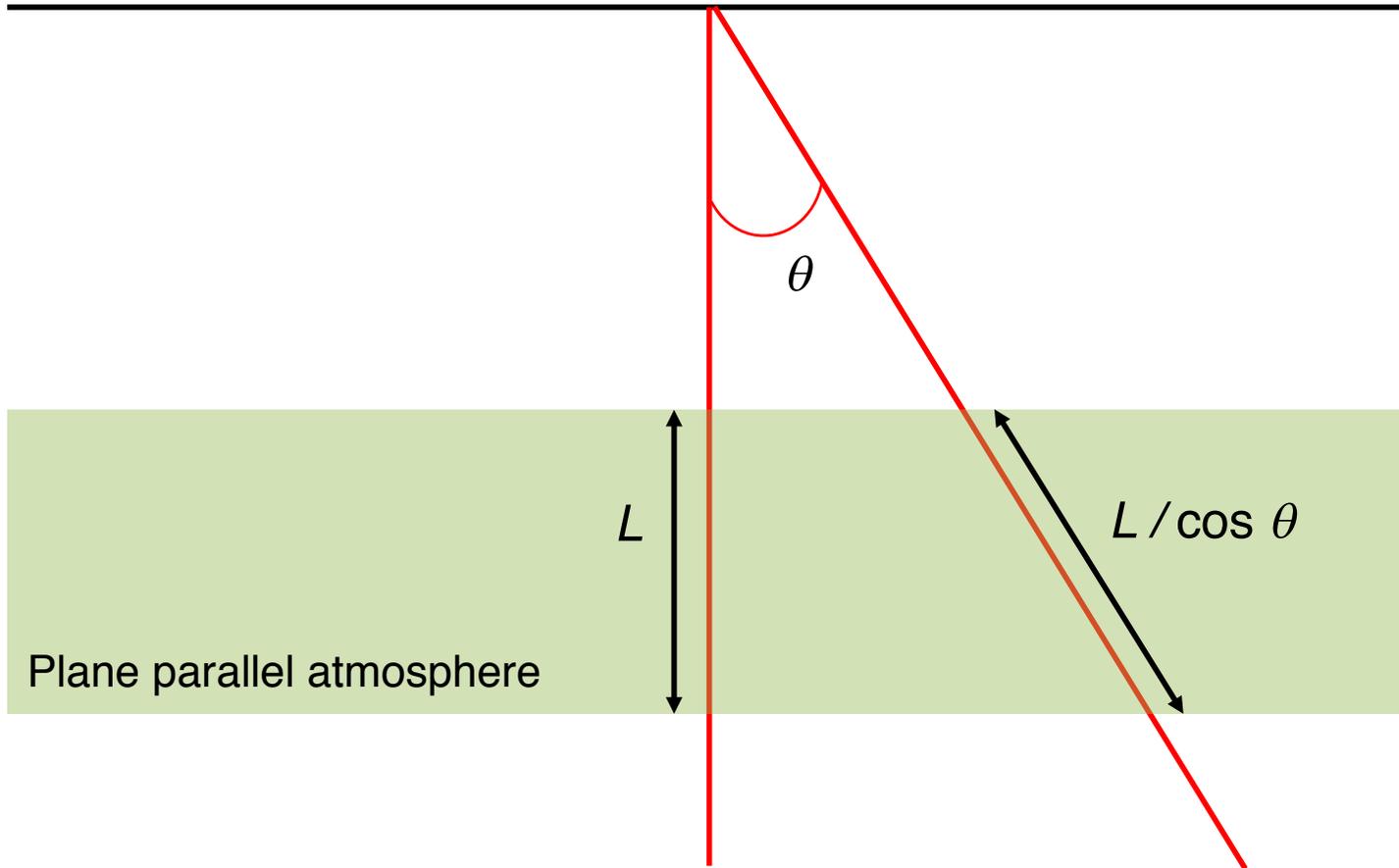
θ

L

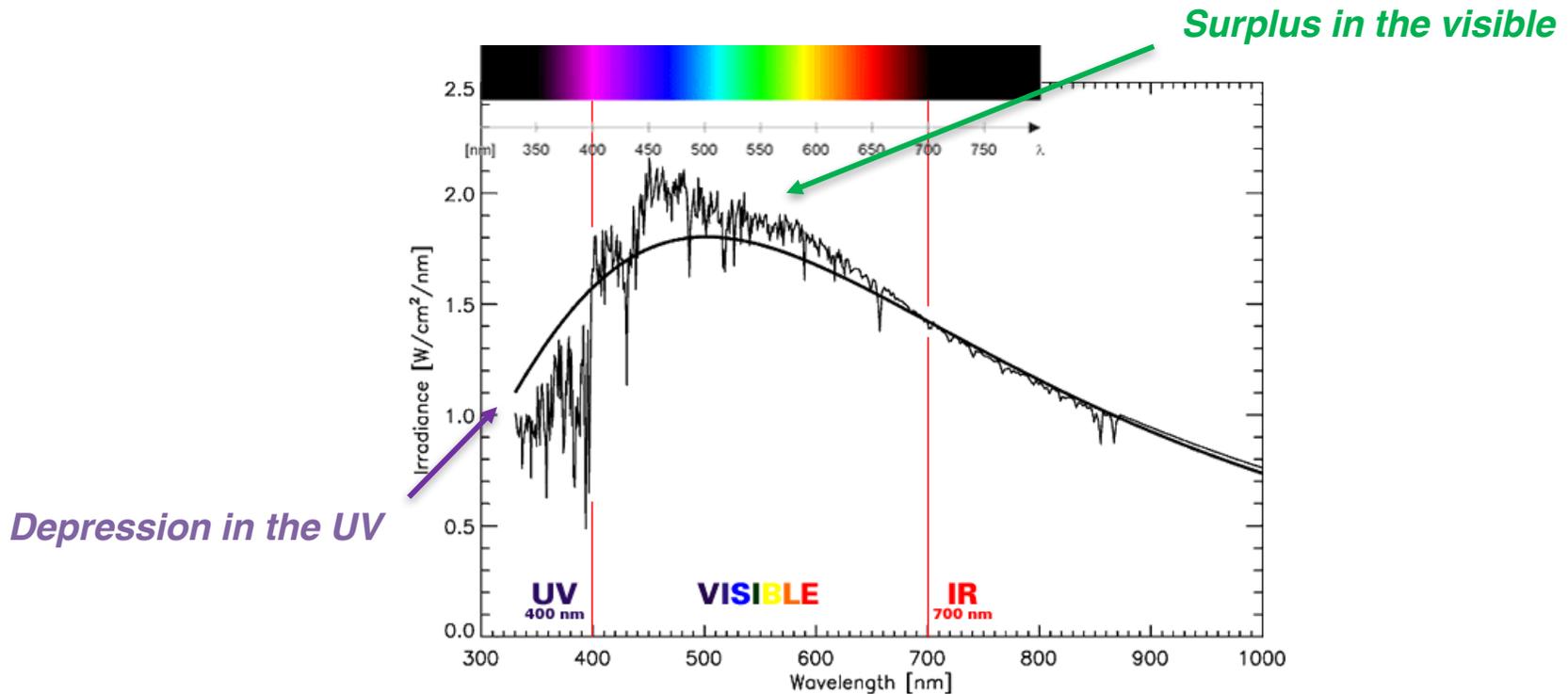$L / \cos \theta$

Plane parallel atmosphere

Radiative Equilibrium

$$\int \kappa_\nu \, S_\nu \, d\nu = \int \kappa_\nu \, J_\nu \, d\nu$$

Bolometric emission = Bolometric absorption
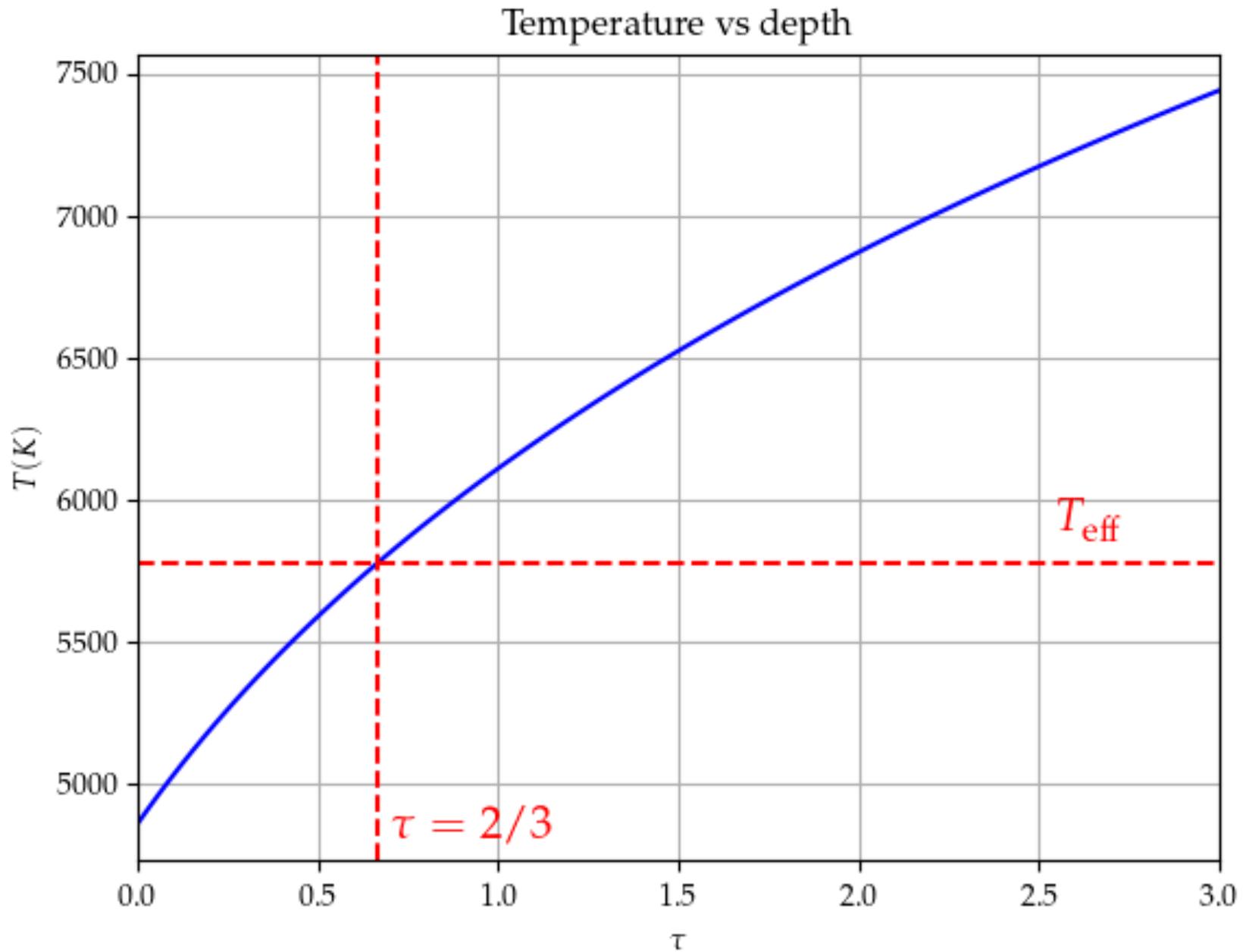
Surplus in the visible

Depression in the UV

The solar irradiance spectrum from 300 to 1000nm as measured by Labs and Neckel (1962)
and corrected by Neckel and Labs (1984).
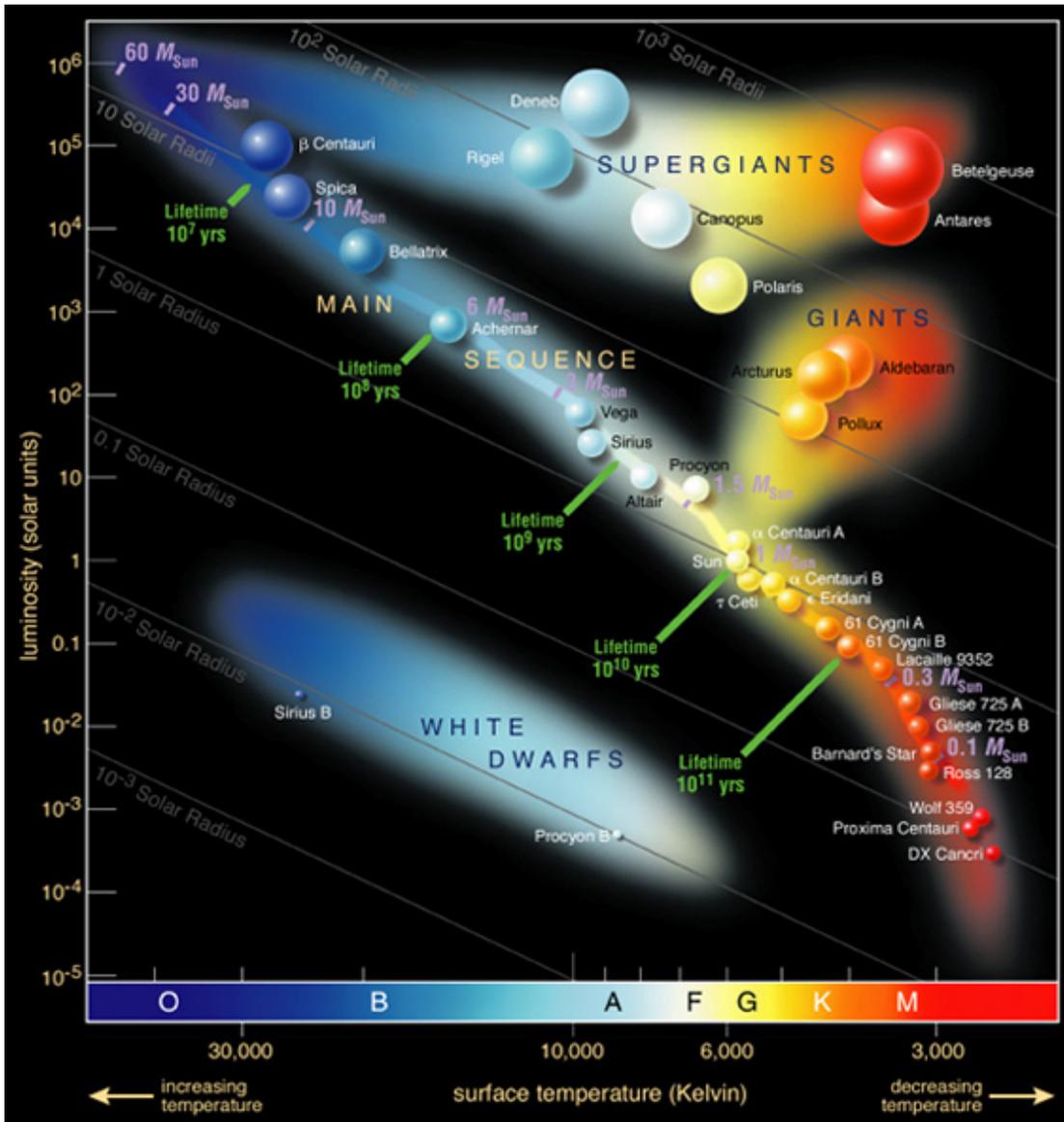It roughly follows a black body radiation curve of 5777 K (thick line), particularly in the IR.

Eddington Approximation
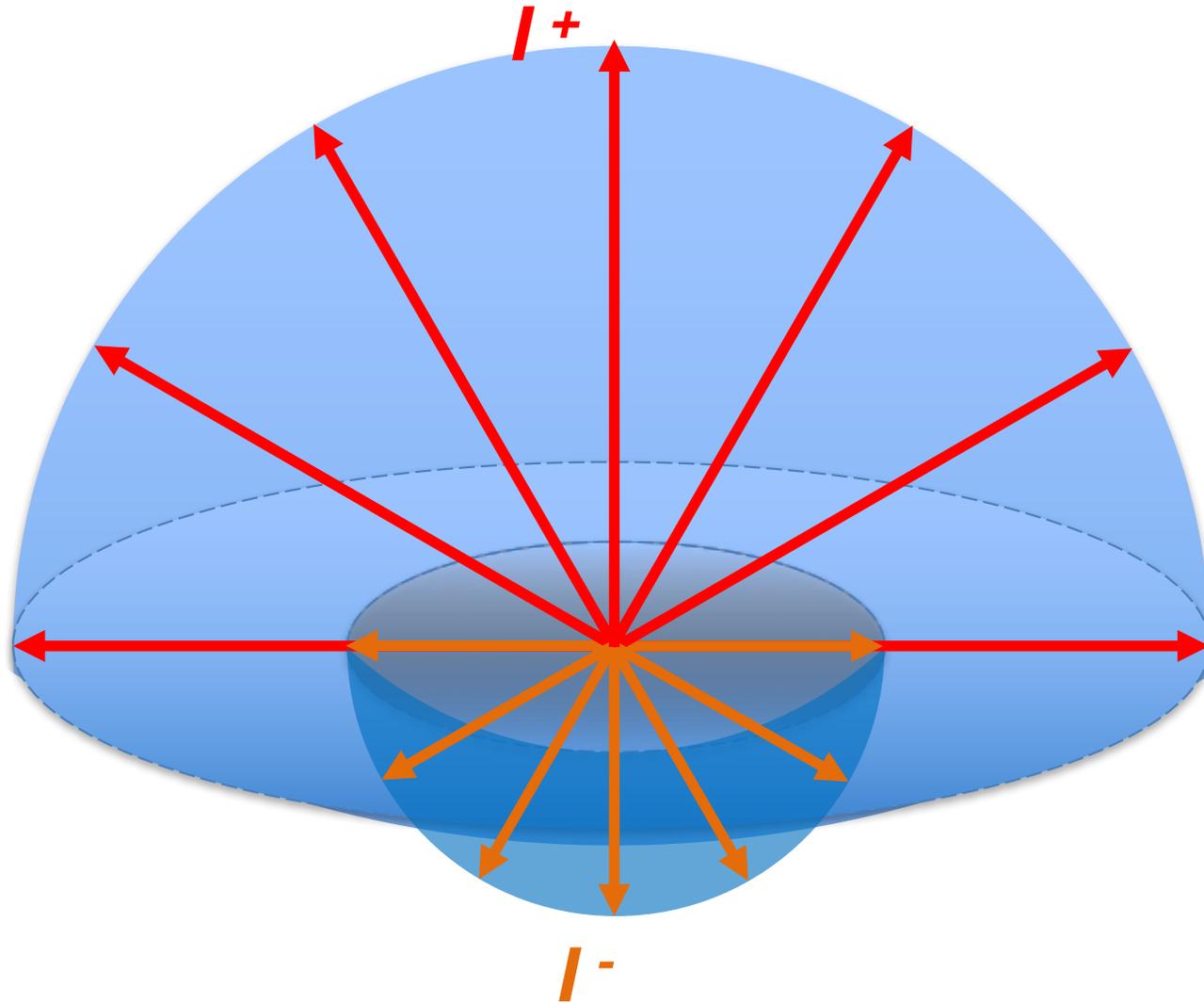
Eddington Solution

Temperature vs depth

Types of stars – The HR diagram

HR stands for "Hertzsprung-Russel"

Temperature x Luminosity

Spectral Types

OBAFGKM

Each type is subdivided into ten numbered subtypes (eg, K8, B6)

Spectral Types

O B A F G K M

Types of stars – The HR diagram

OBAFGKM

Each type is subdivided into ten numbered subtypes (eg, K8, B6)

Luminosity classes

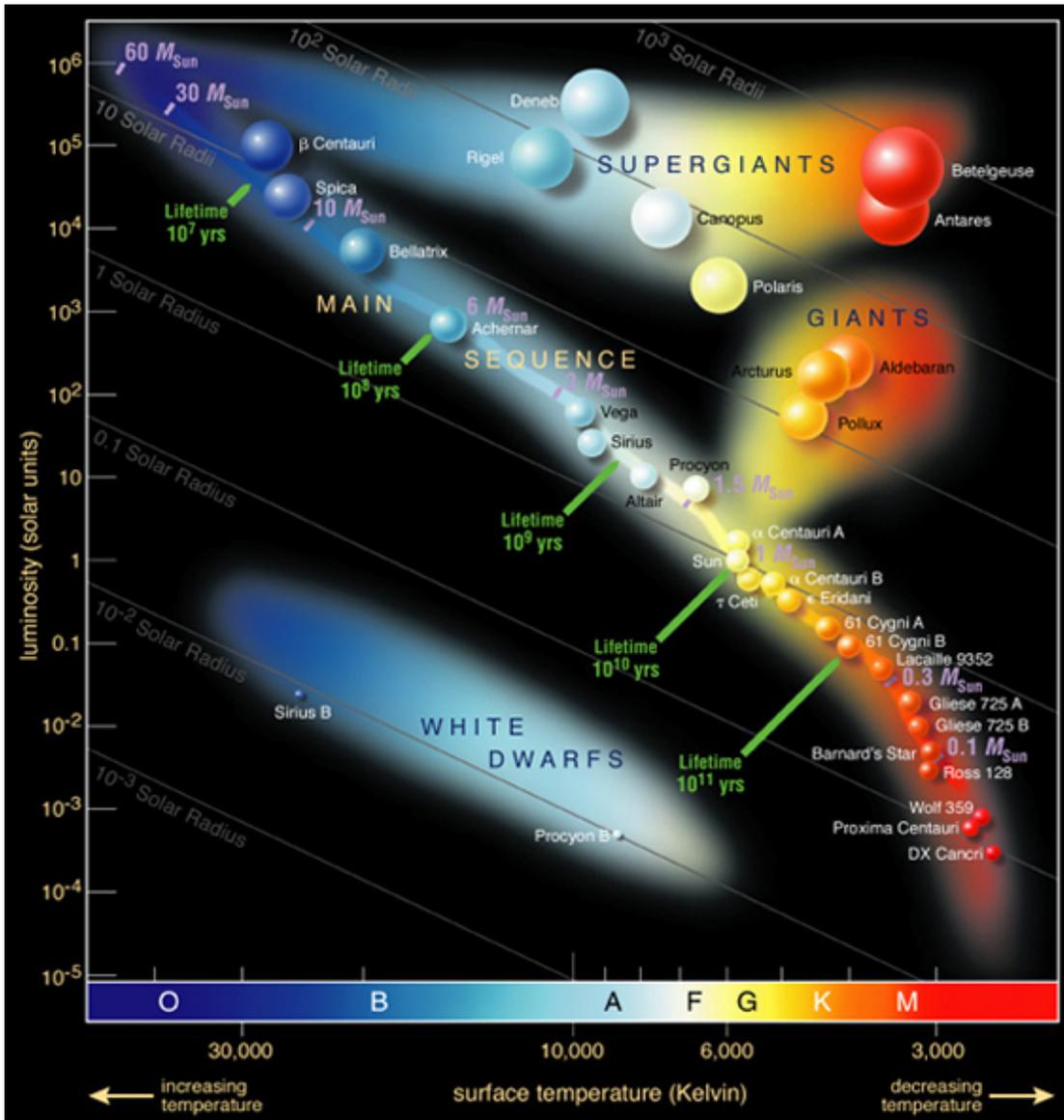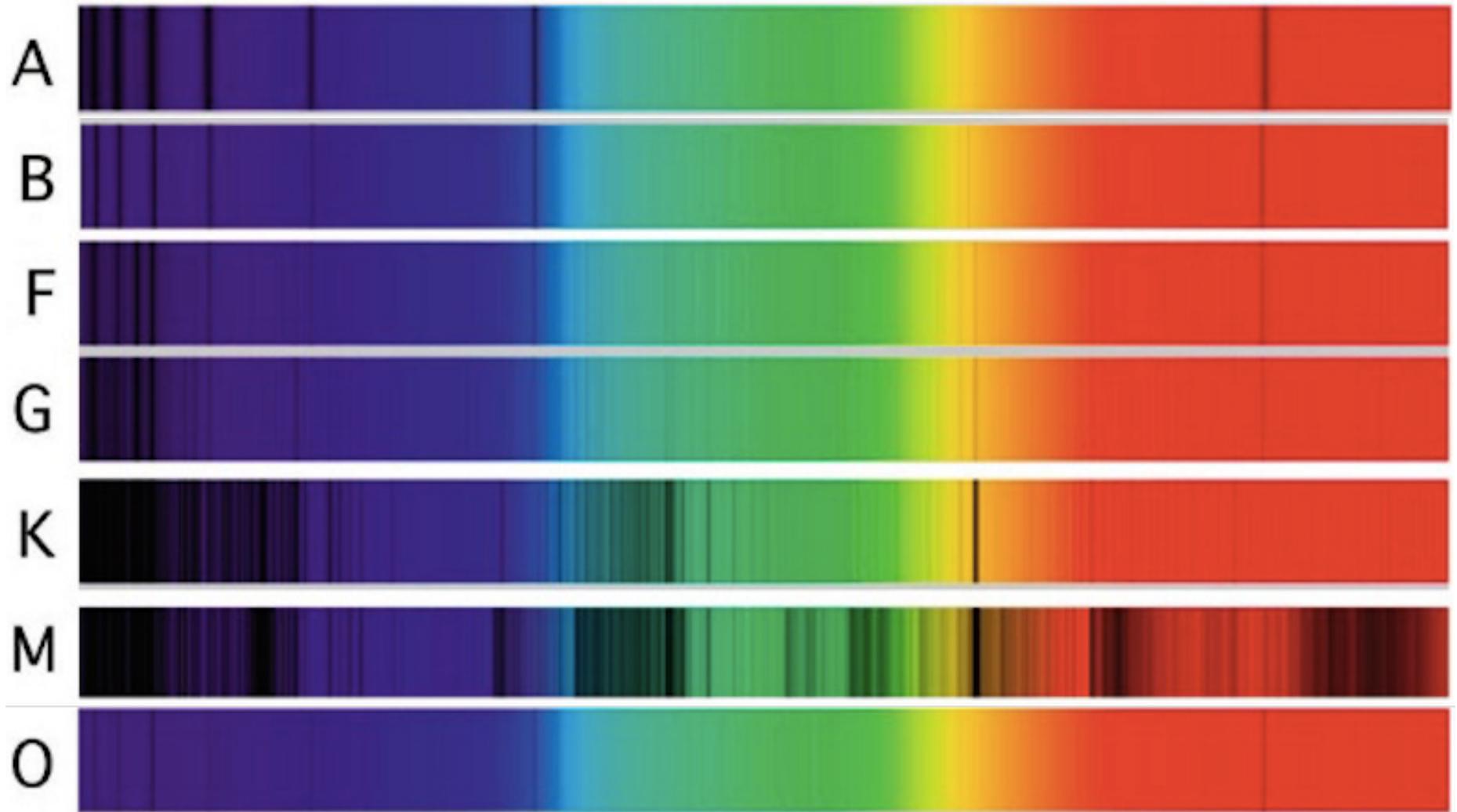|	
I	- Supergiants
II	- Bright giants
III	- Giants
IV	- Subgiants
V	- Dwarfs
VI	- Subdwarfs
VII	- White Dwarfs

The **Sun** is a **G2V** star
Sirius is a **A1V** star
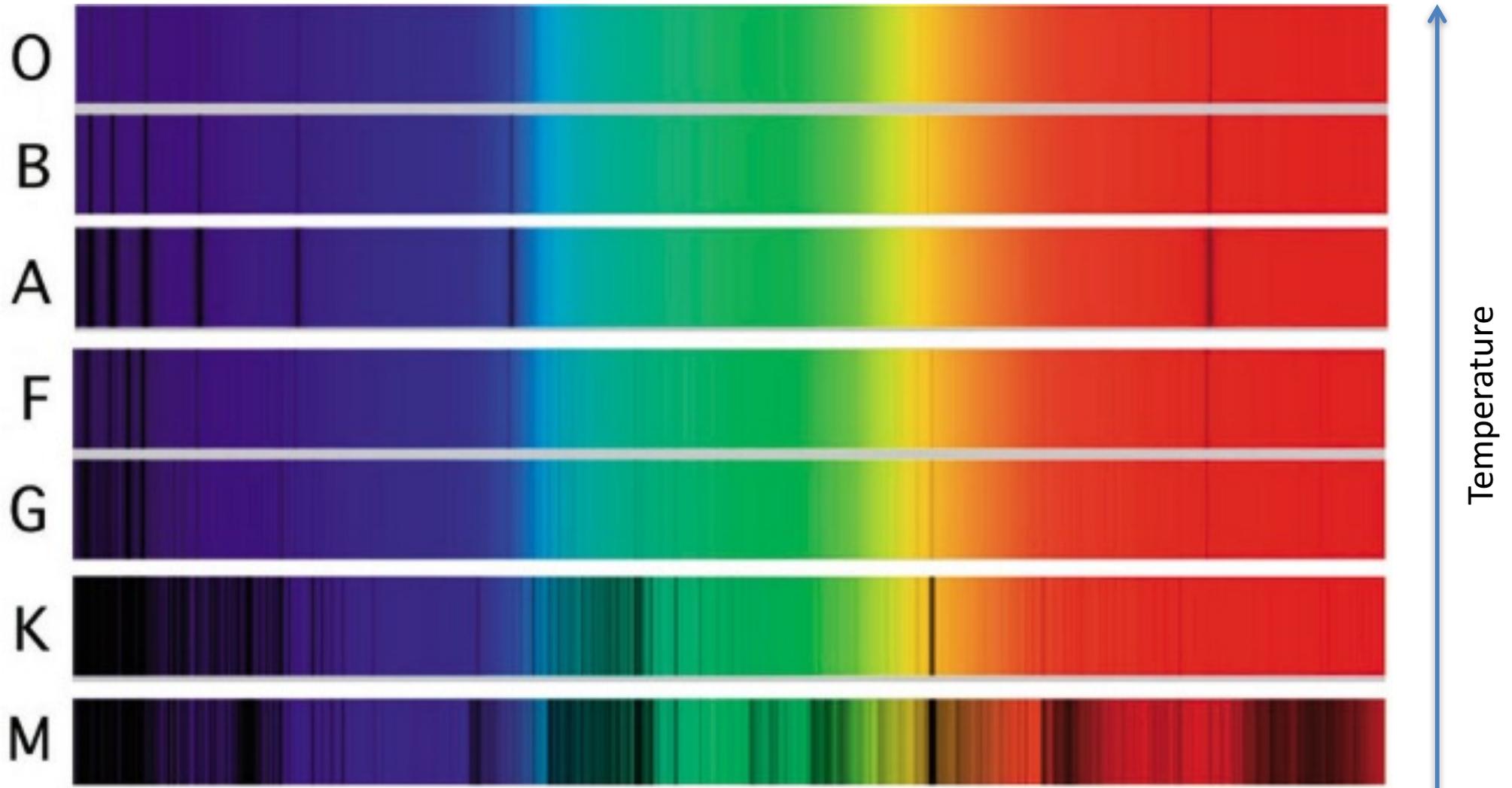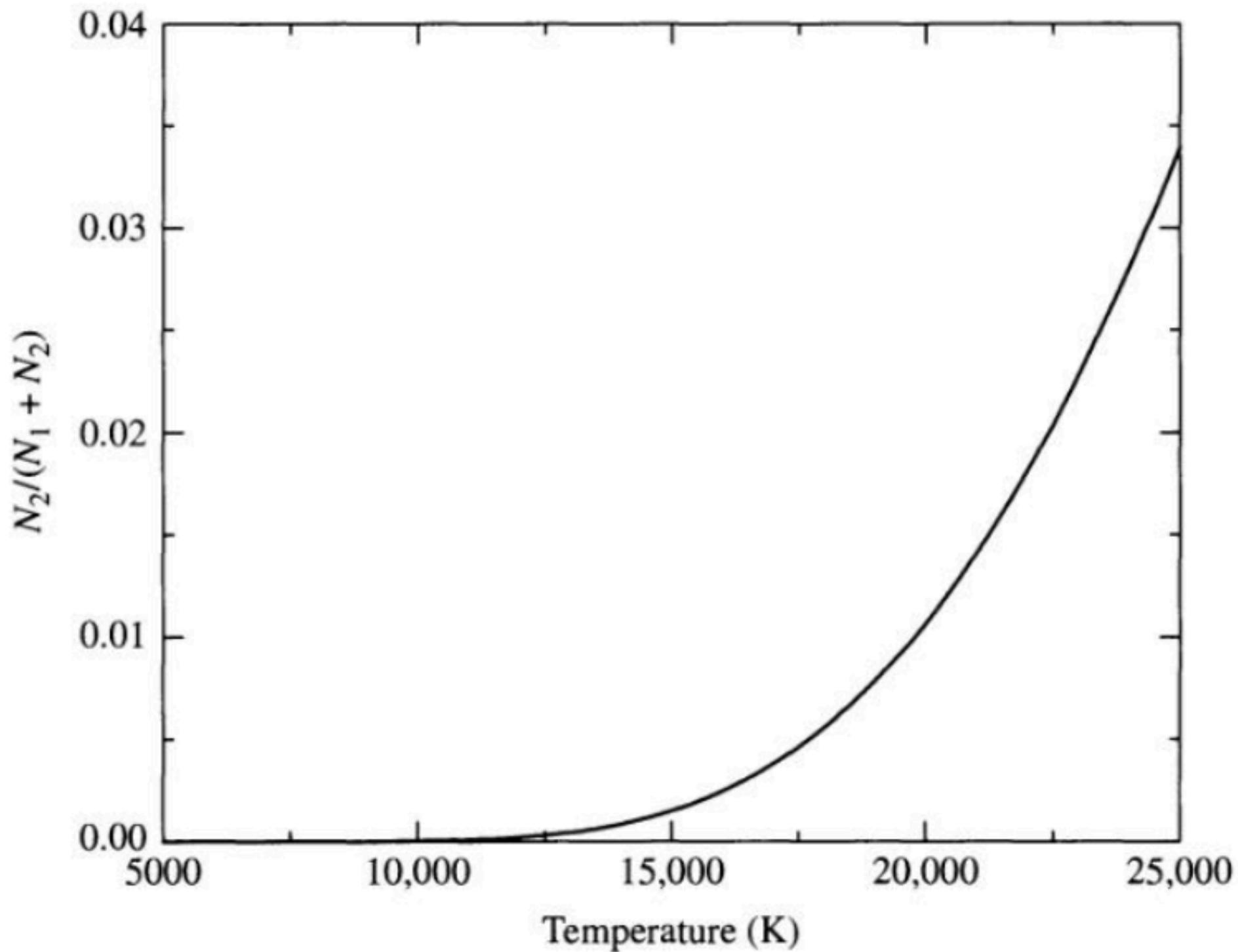**Betelgeuse** is a **M2I** star
Pollux is a **K2III** star

Origin of spectral class nomenclature – Strength of Hydrogen lines

Ordering in Temperature
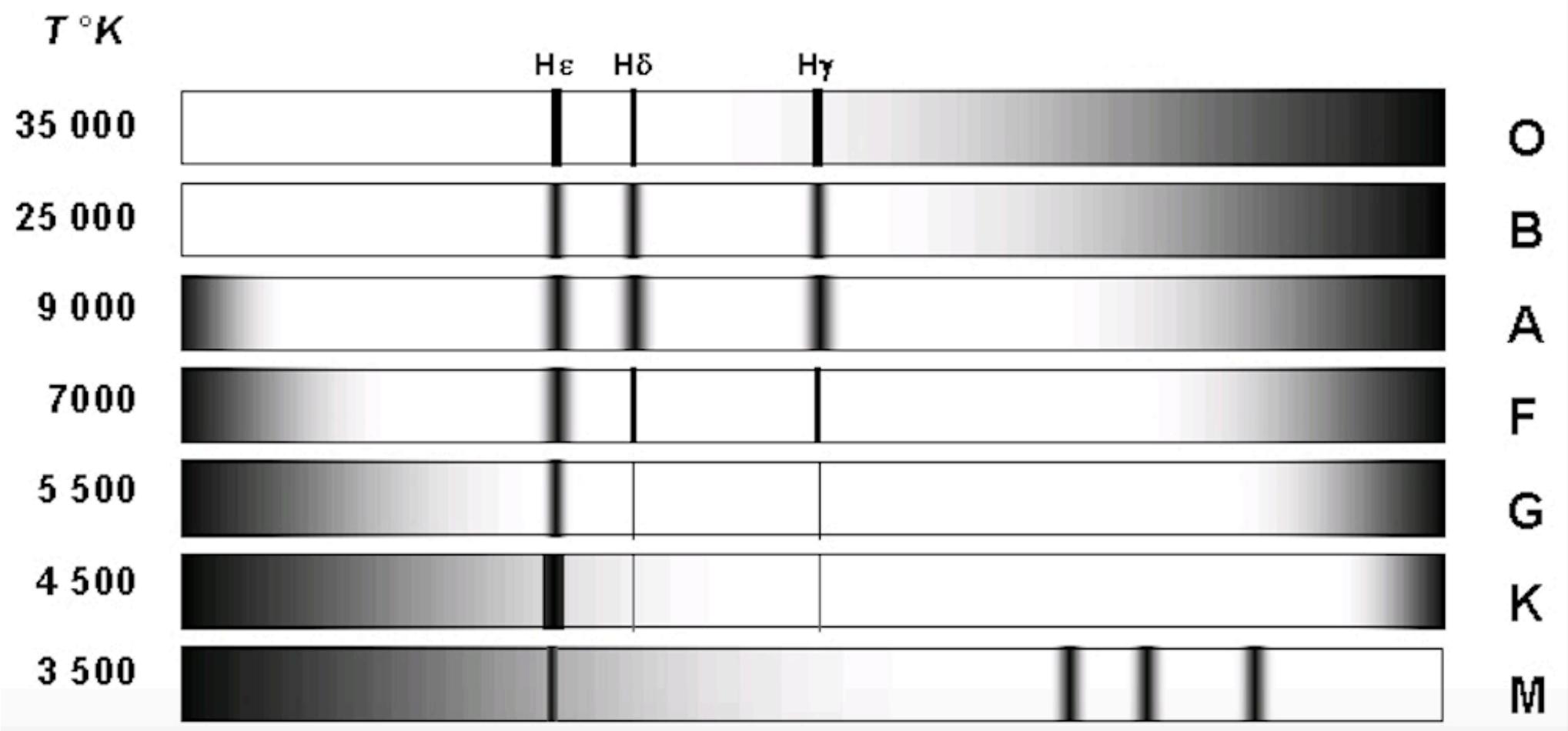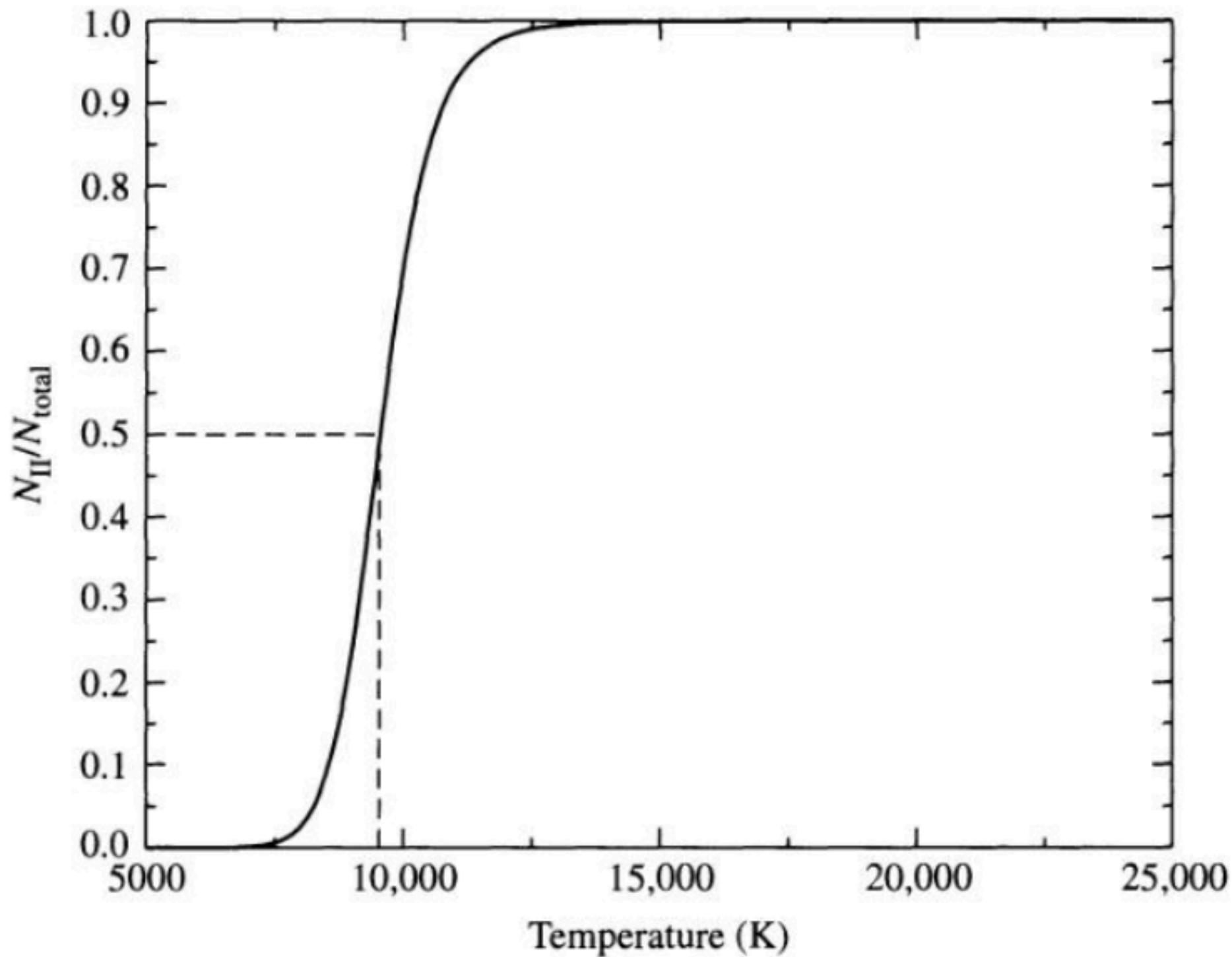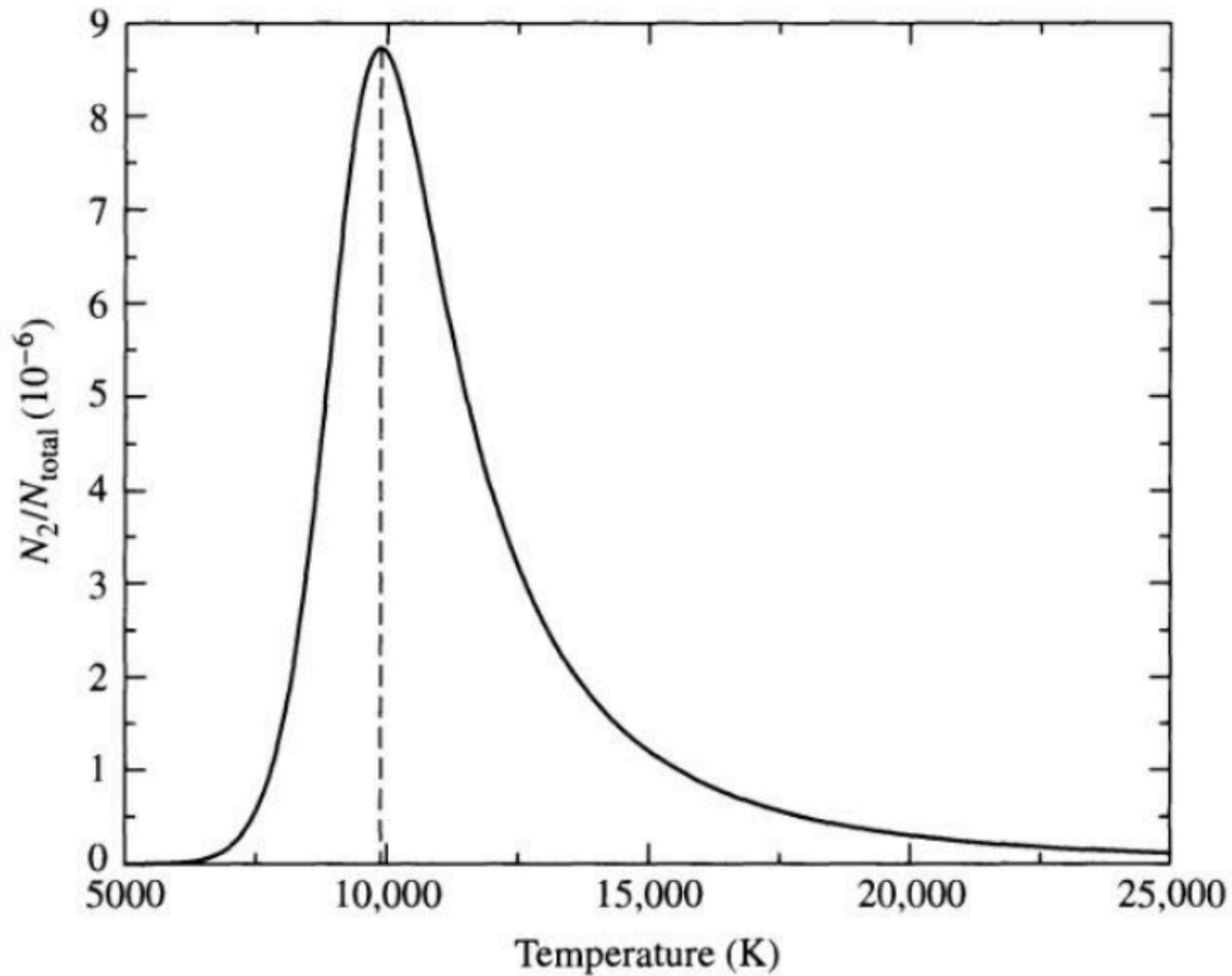
Saha Equation

Excitation

X

Ionization

=

Spectral type

O3 B0 A0 F0 G0 K0 M0

Dominant Lines in Stellar Spectra

Ionized helium   Neutral helium   Hydrogen   Ionized metals   Neutral metals   Molecules (TiO)

Relative line strengths →

30,000° 9,400° 7000° 5,900° 5,200° 3,900°

Temperature of main-sequence stars (Kelvin)

5,800° 4,300° 3,700°

Temperature of giants

$p_{top}A$

$z+\Delta z$

$\rho A\Delta zg$

z

A

$p_{bottom}A$
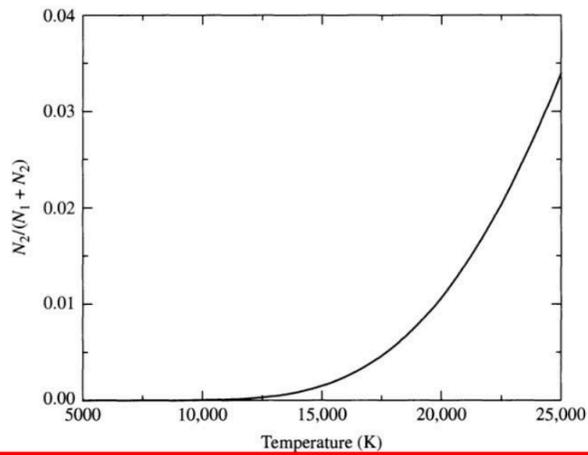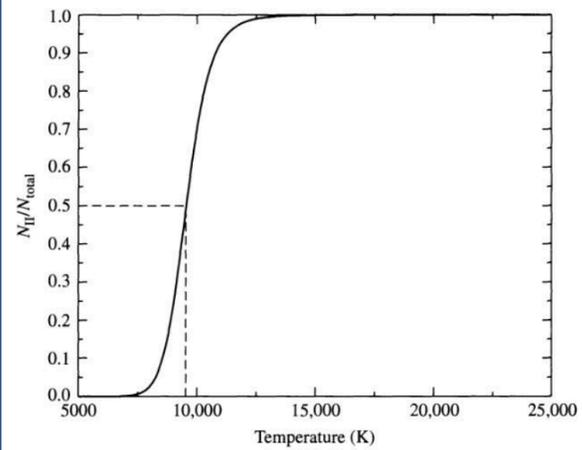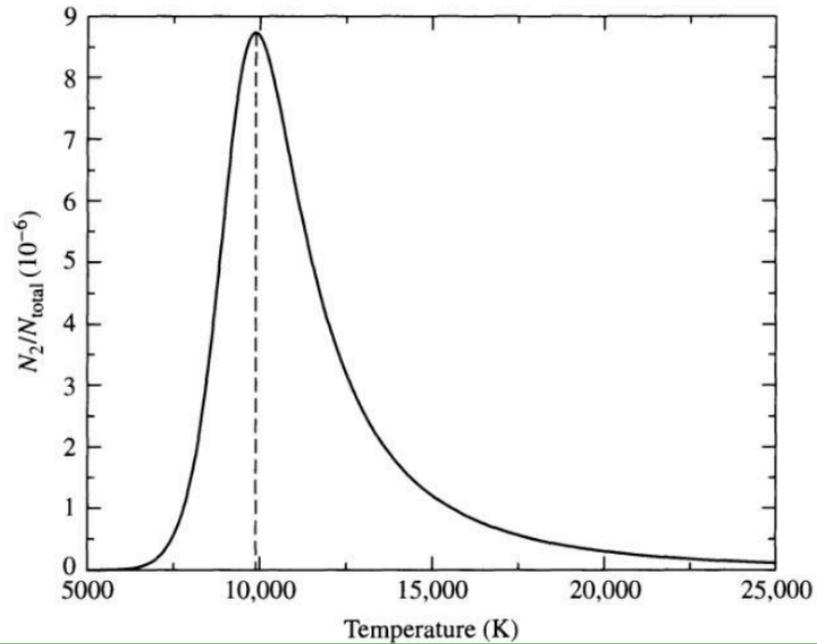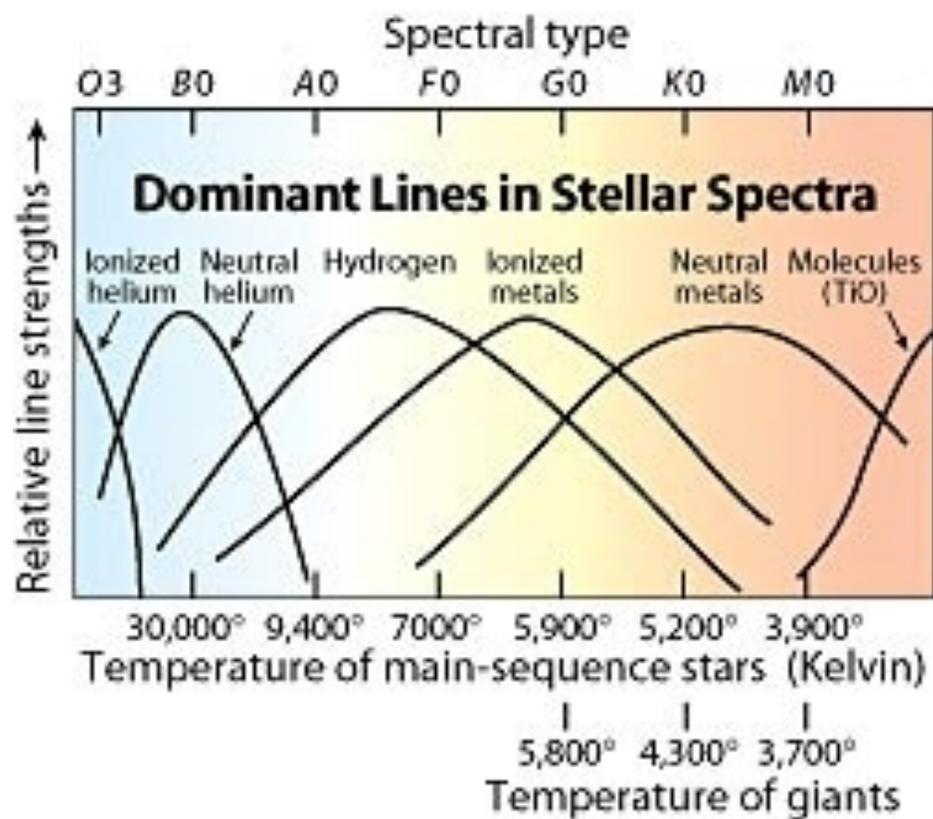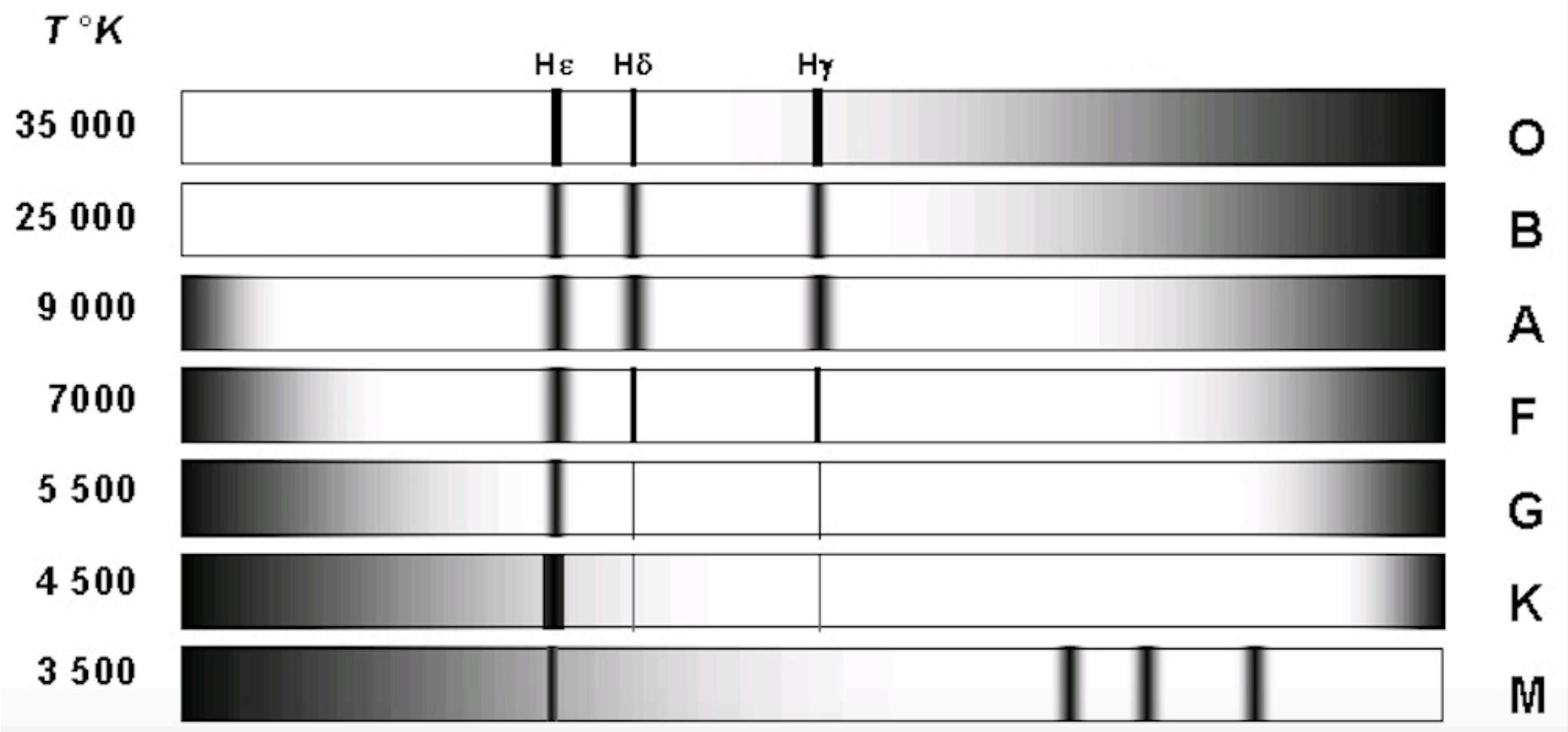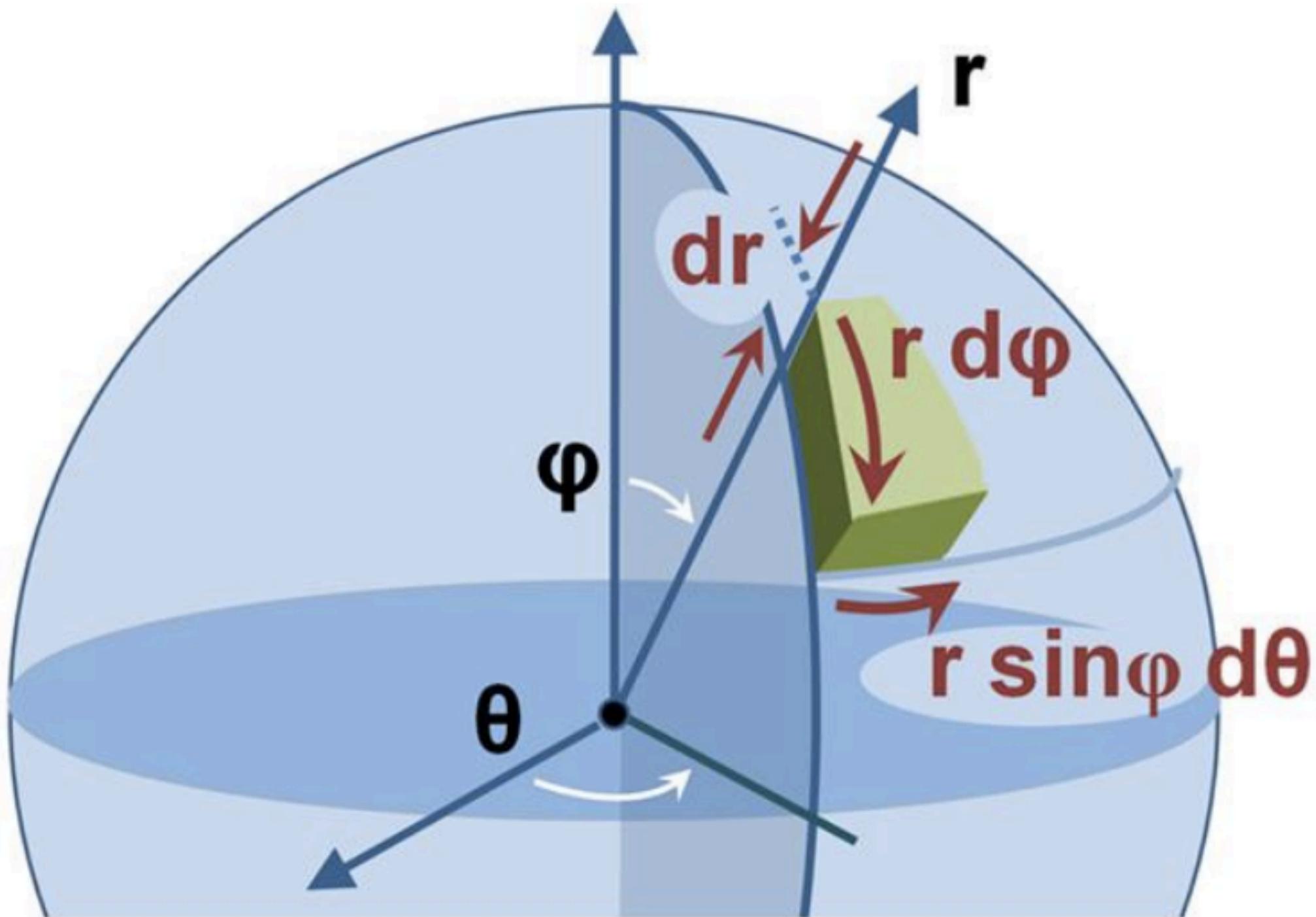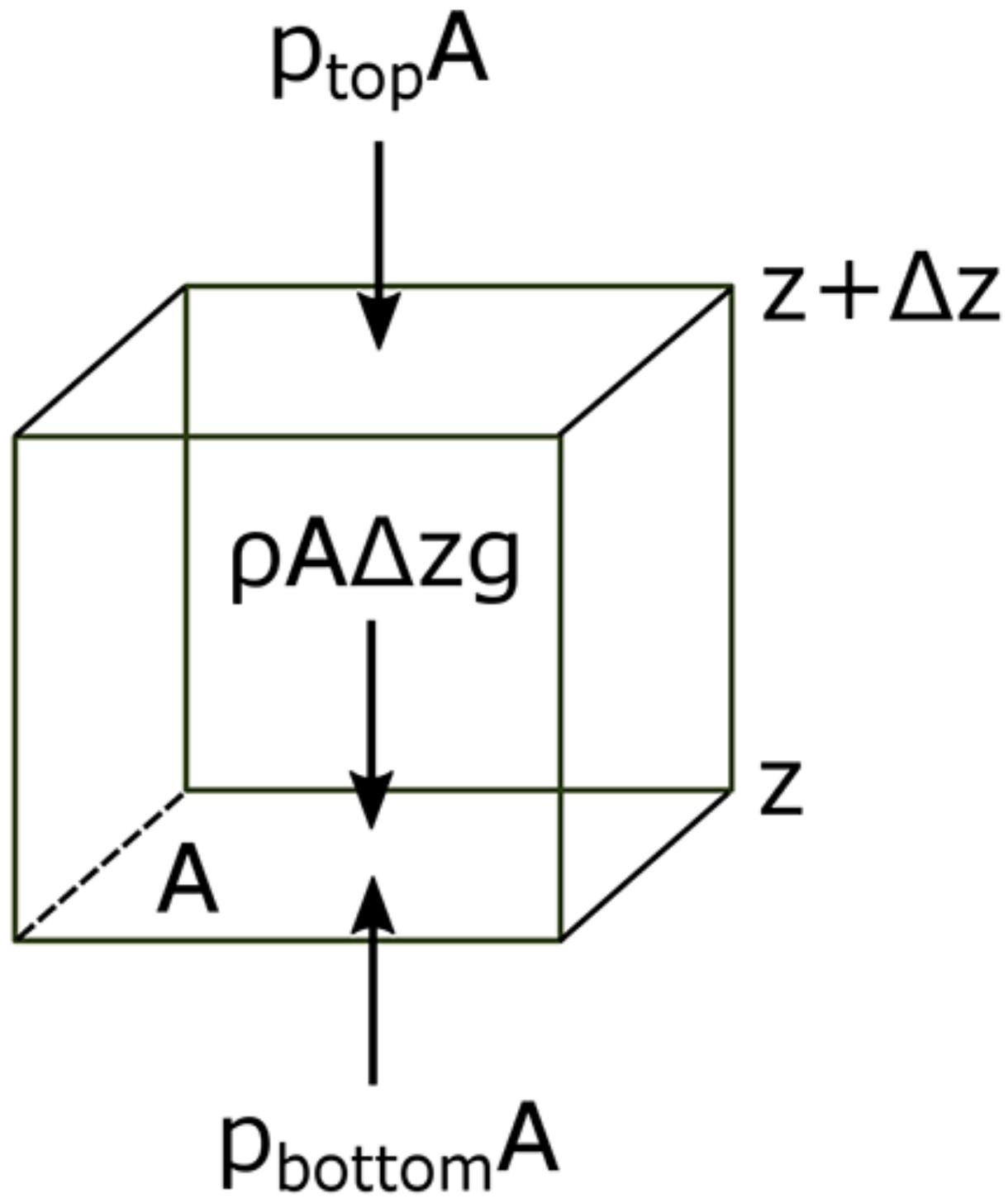
Solutions of the Lane-Endem equation
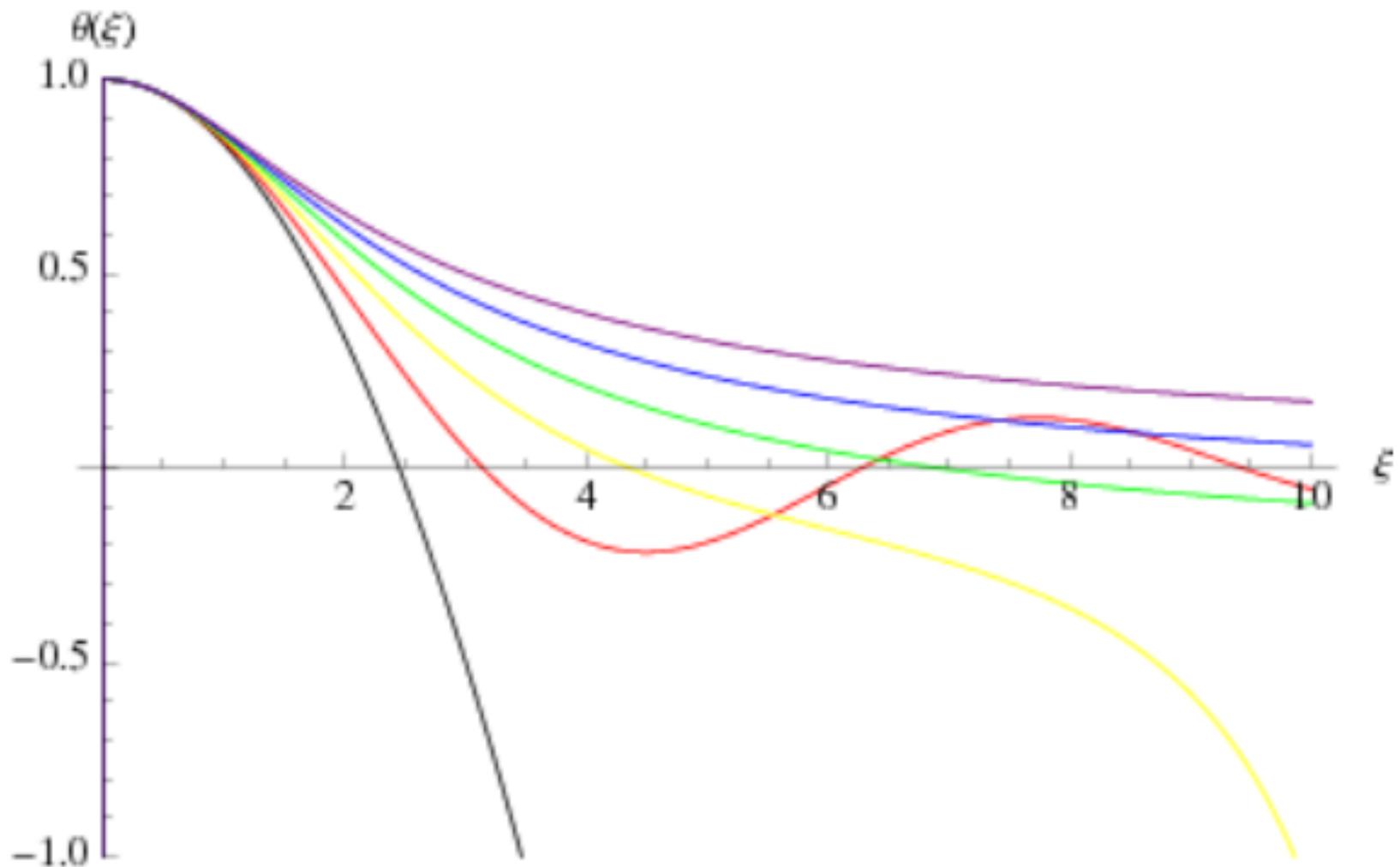
Solar Model

Density
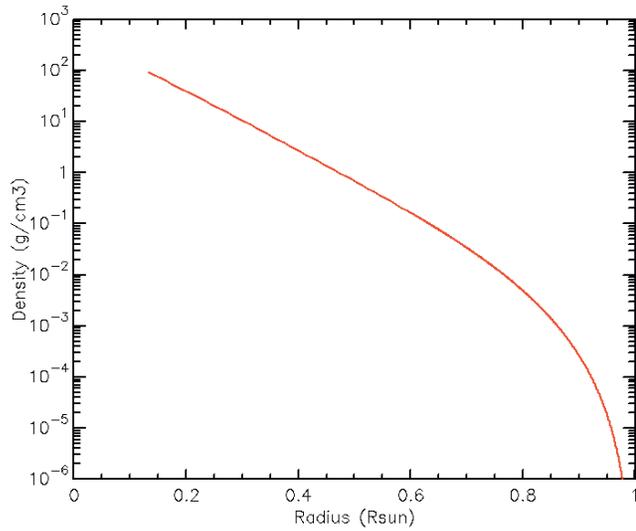
Mass
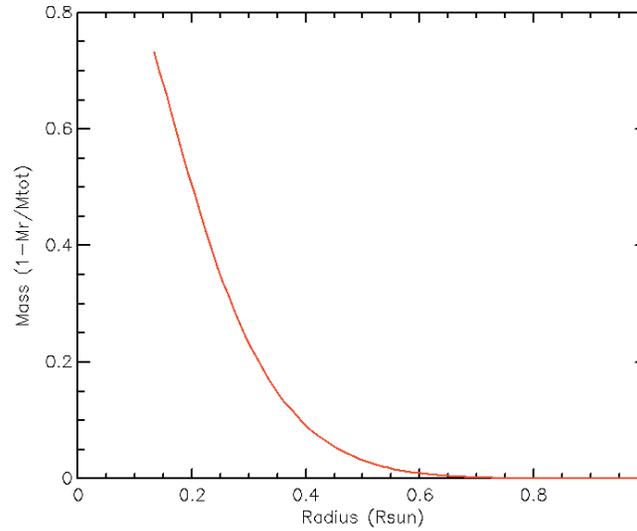
Luminosity
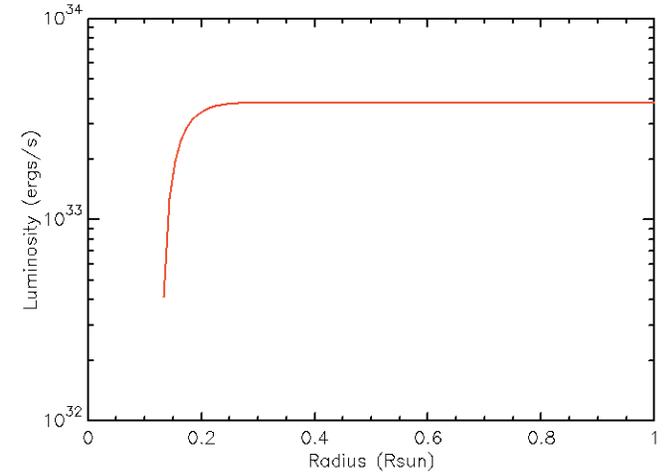
Temperature
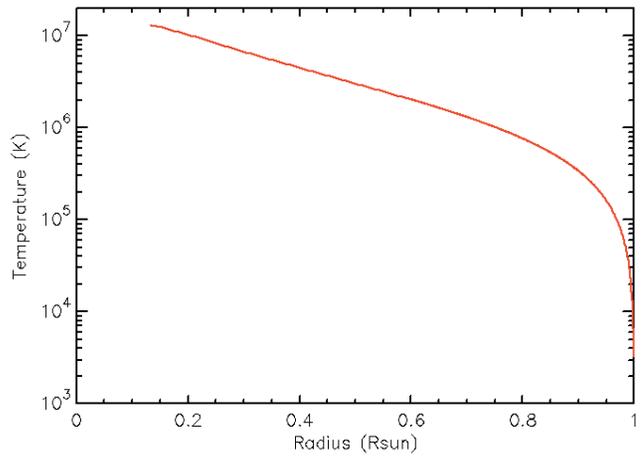
Nuclear Reaction Rate
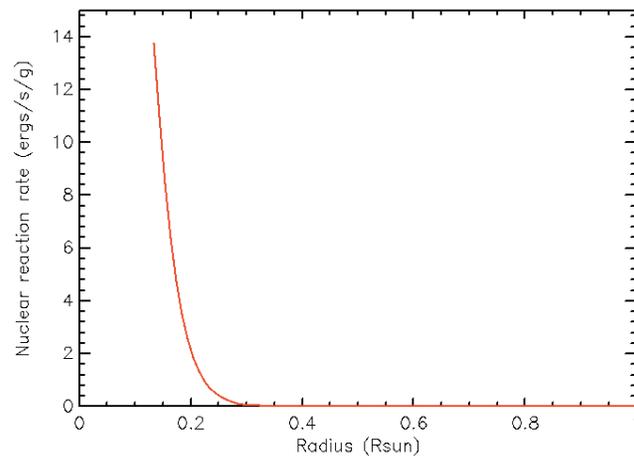
Pressure
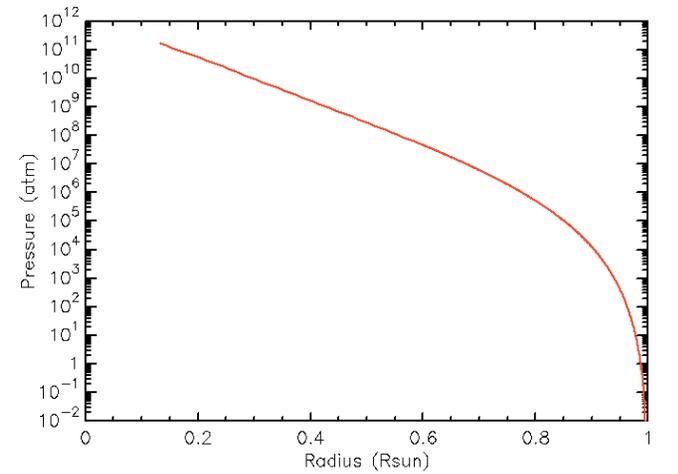
Stable and Unstable Equilibria

stable | unstable

Stable Equilibrium

Returns to equilibrium position when disturbed
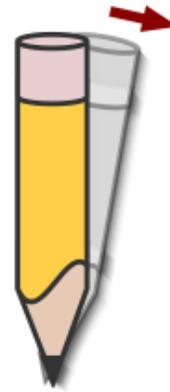
Unstable Equilibrium

Does not return to equilibrium position when disturbed

Thermal stability

to surface

to core
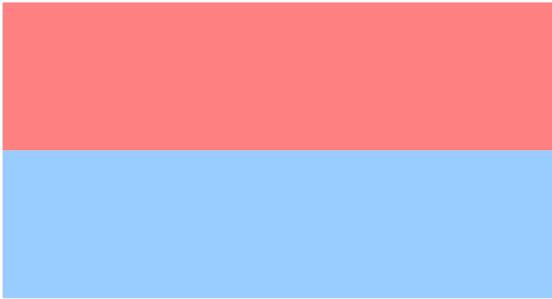
Equilibrium
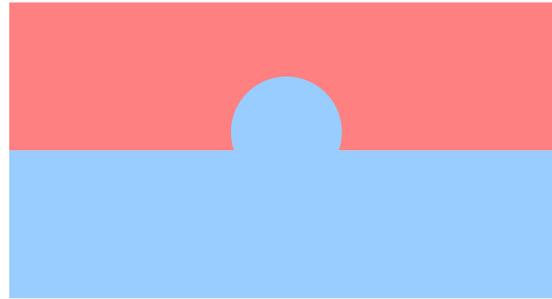
a perturbation
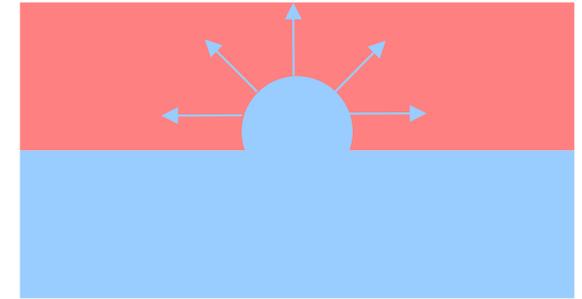
Hotter than the surroundings, it expands and rises
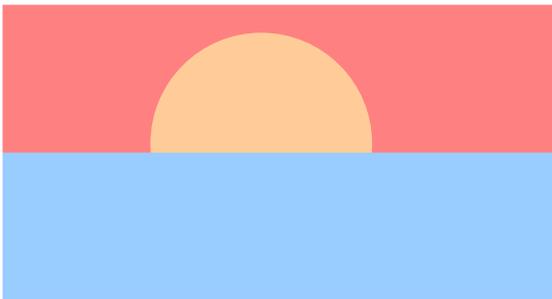
Expansion cools the blob

It cools further and sinks
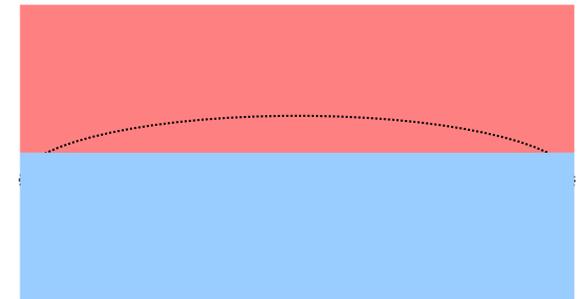
Equilibrium

Thermal instability
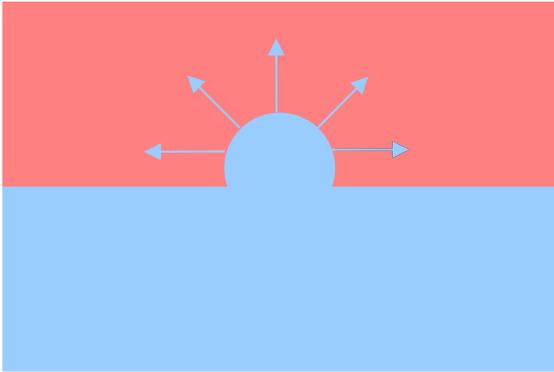
Hotter than the surroundings
The blob expands and rises
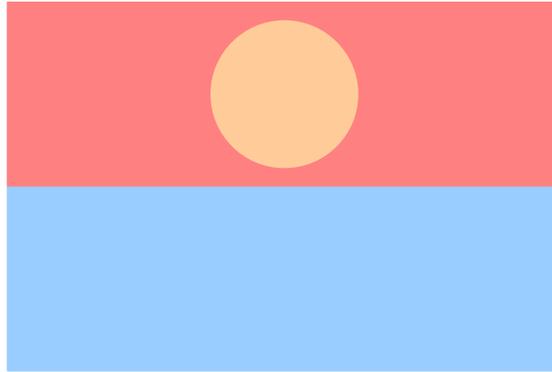
It rises faster than it cools
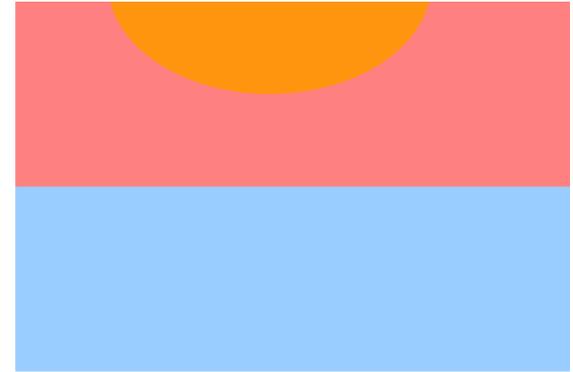
It keeps rising
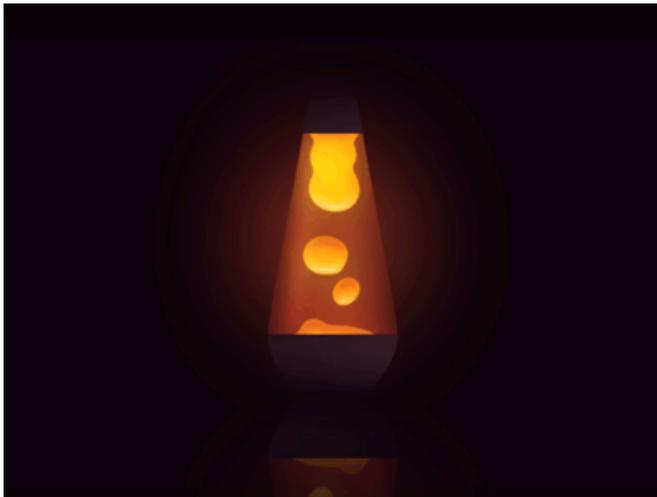
It travels a great distance
before cooling and sinking

CONVECTION

ρ^*

p^*
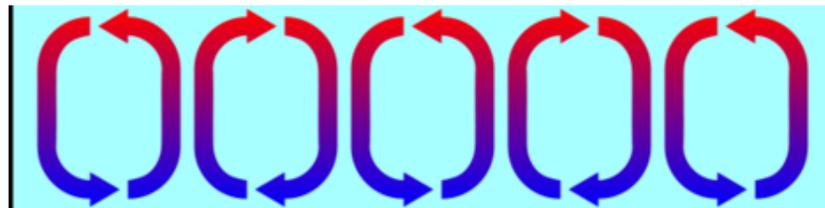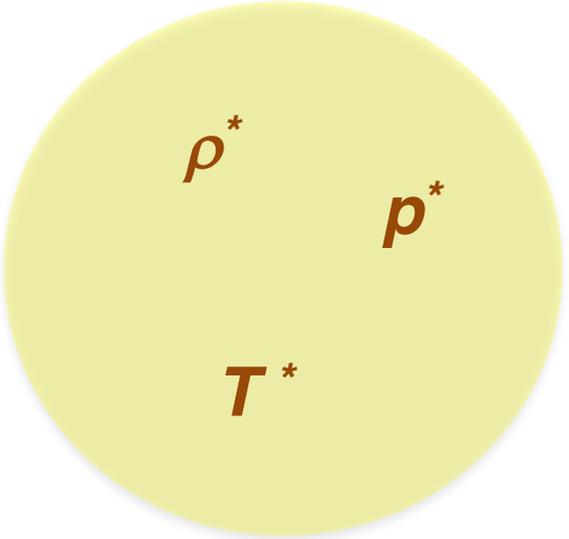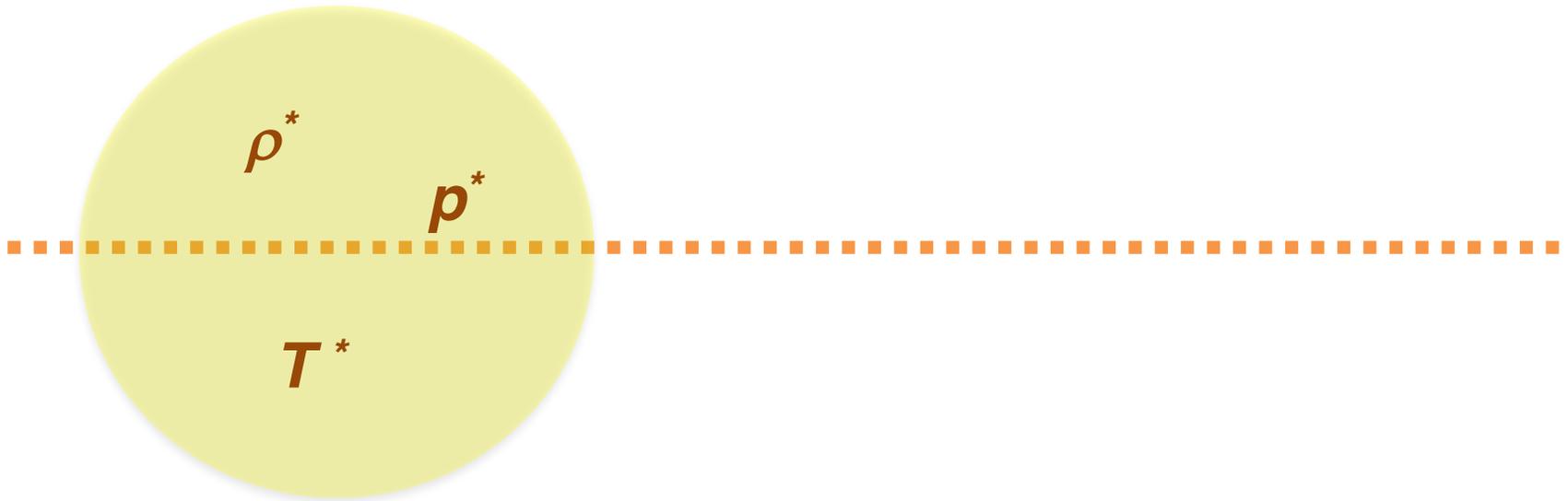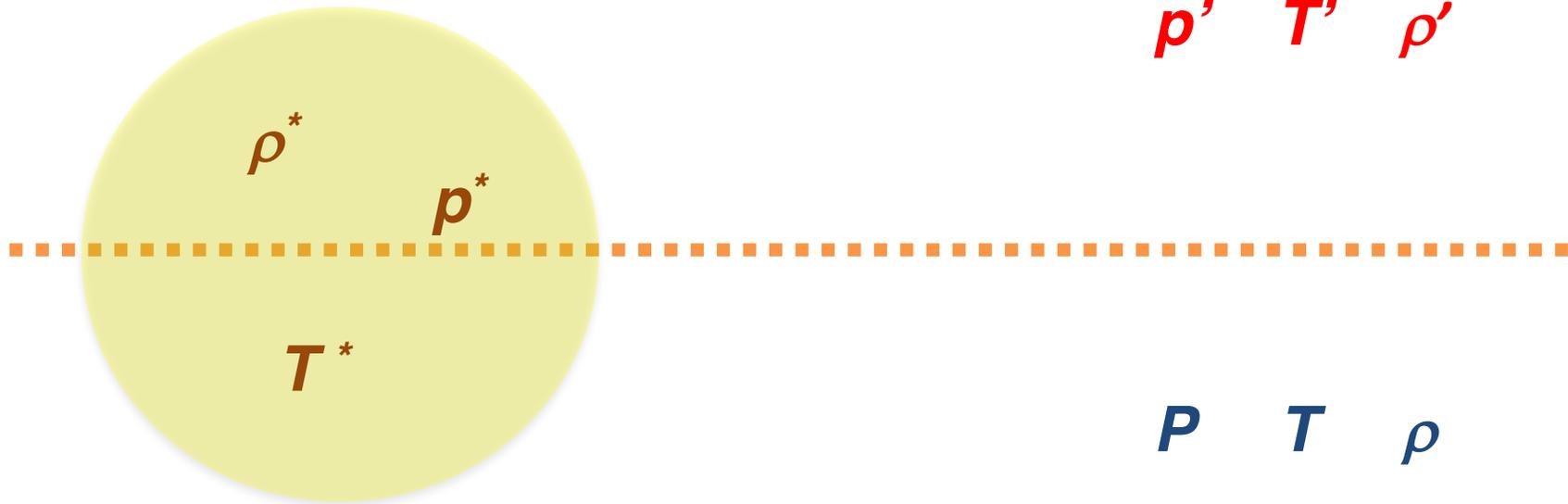
T^*

Solar Structure

In **stable equilibrium**,
heat is transported by **radiation**
(without transport of mass).

In **unstable equilibrium**,
heat is transported by **convection**
(with transport of mass).
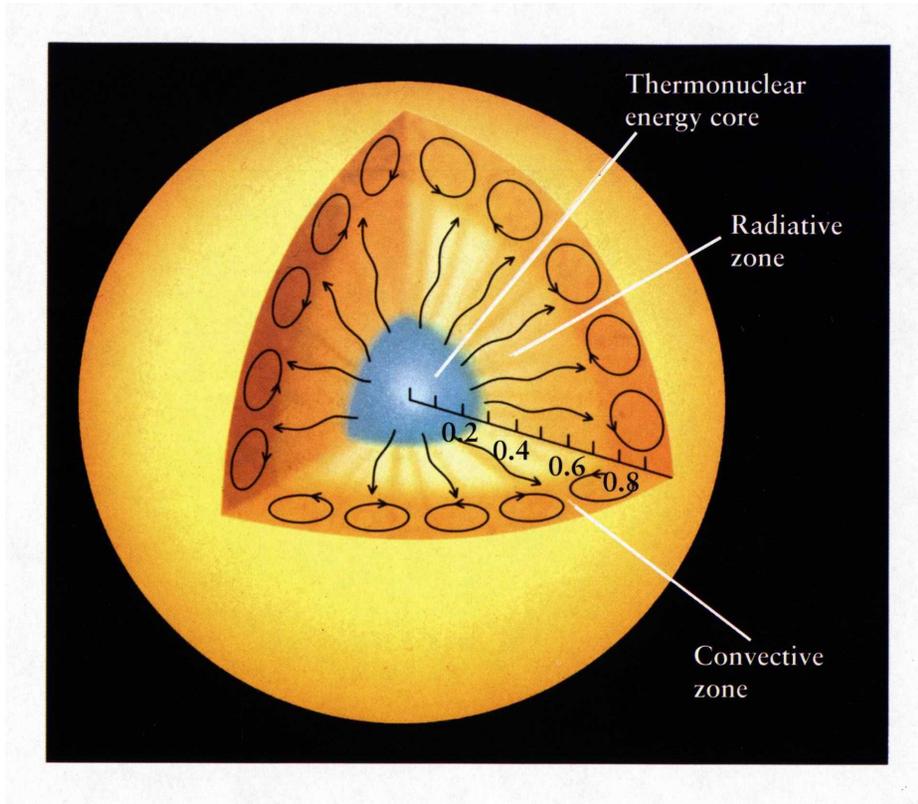
The Sun has a
**radiative zone
in the interior**

And a

**convective zone
near the surface**

Granulation
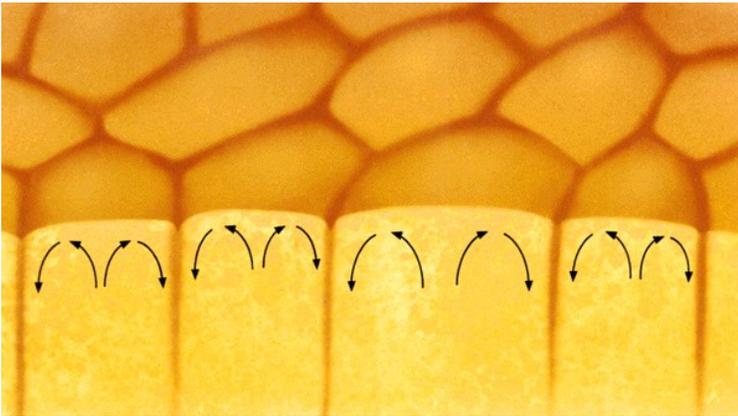
Convective cells
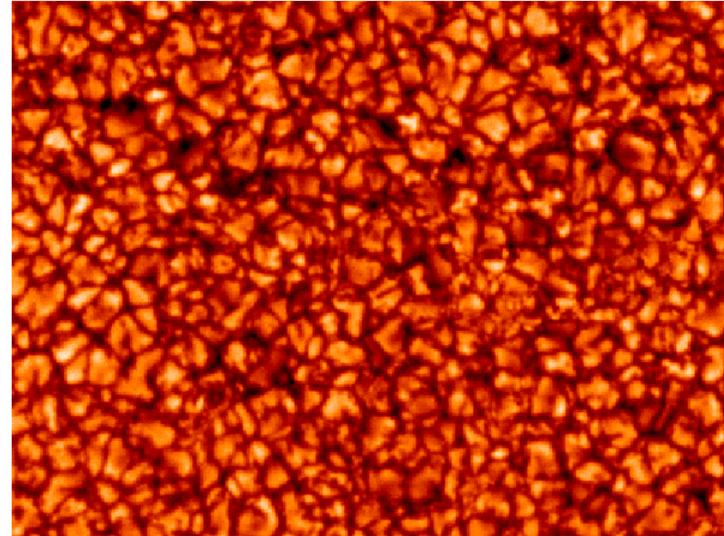
Close-up of the surface of the Sun
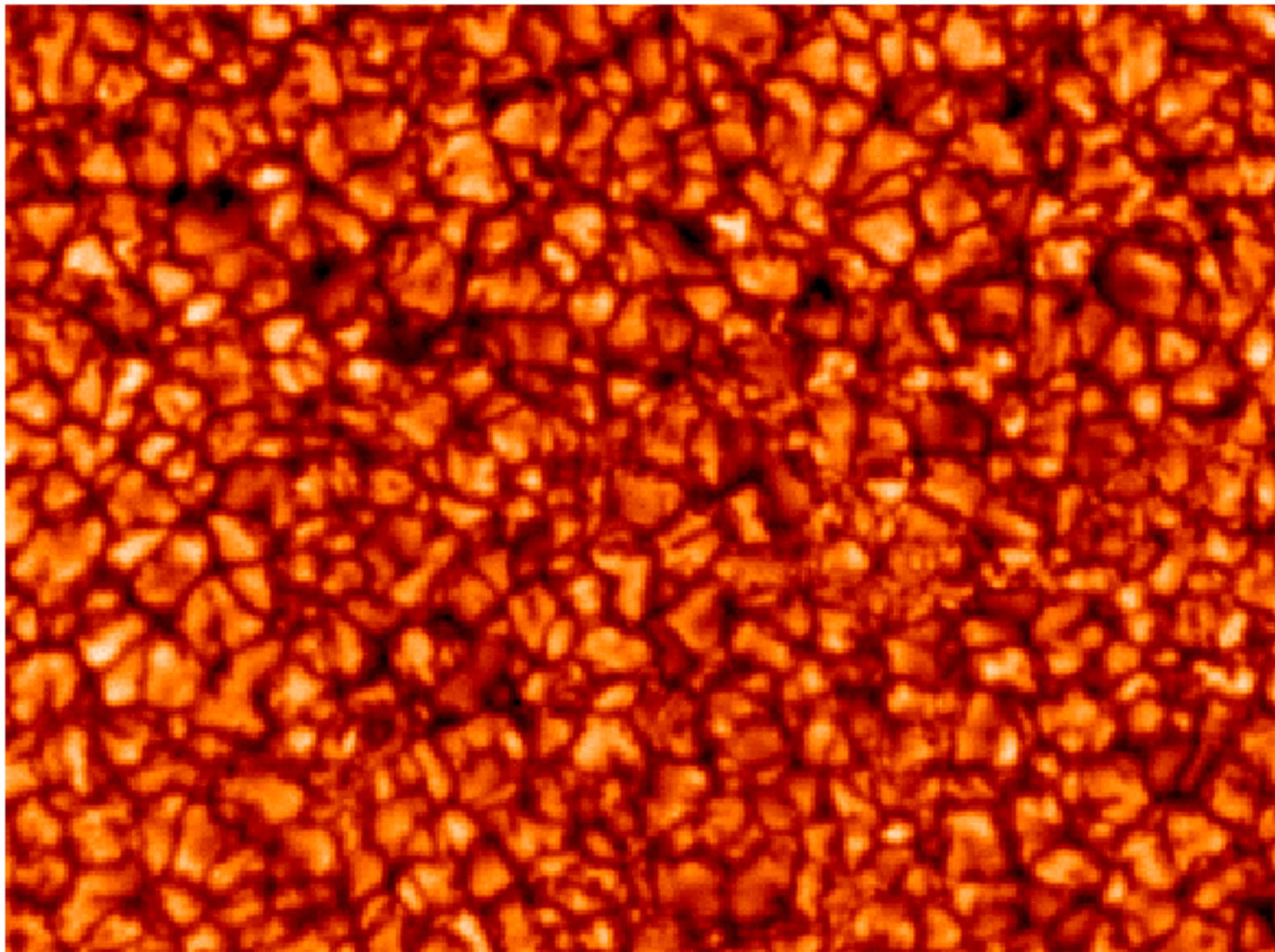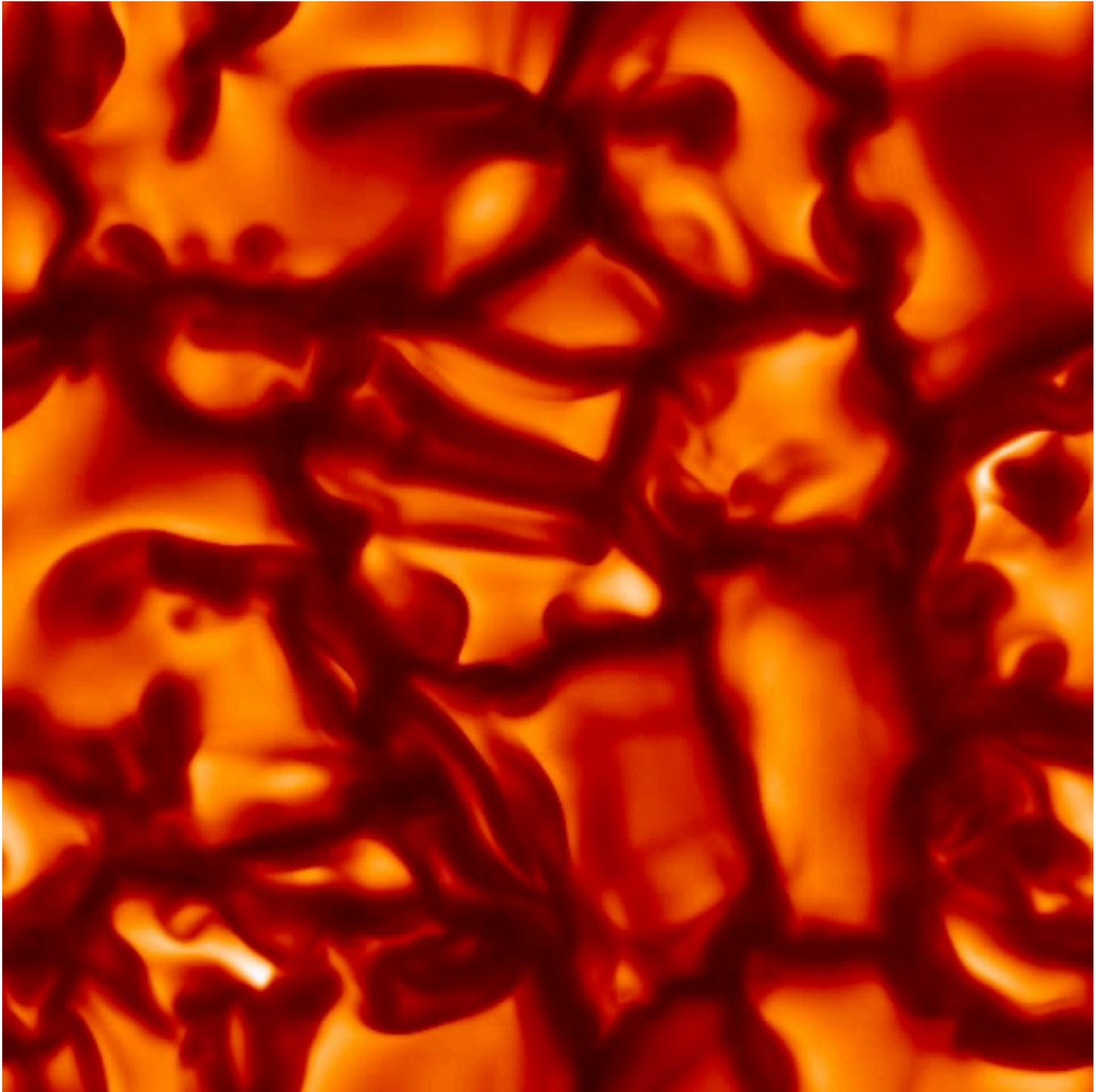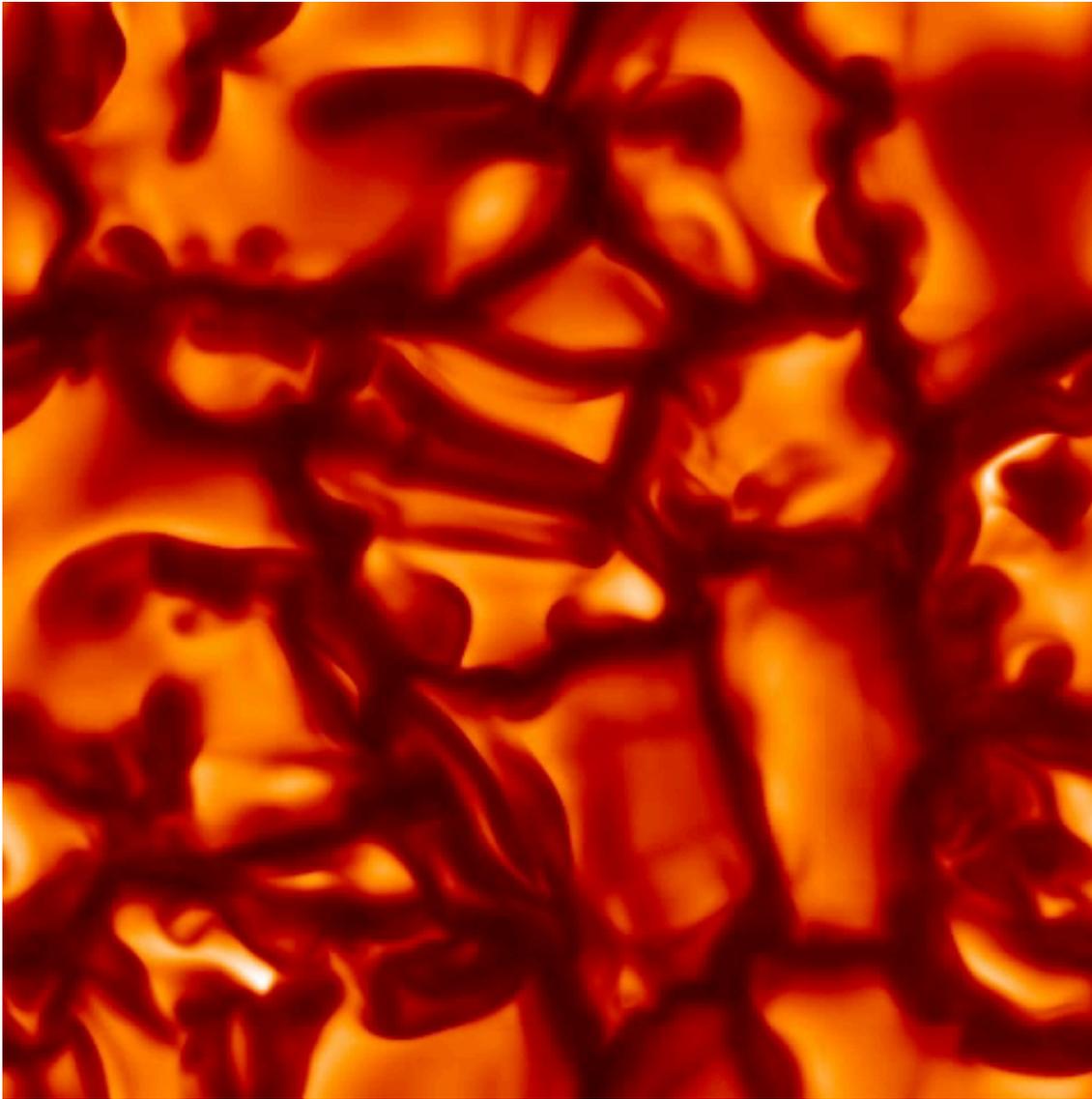
Simulation by Remo Collet.

Surface intensity

T_{eff} = 4400 K
L = 4.4x10^6 km

Atmosphere

Photosphere

Interior

$L_z = 2 \times 10^6$ km

Radiative Zone

Convective Zone
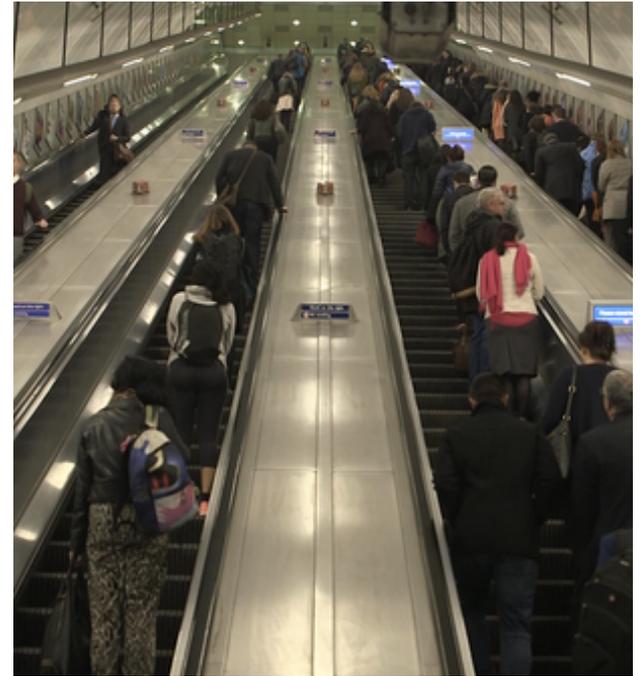
Stellar Structure
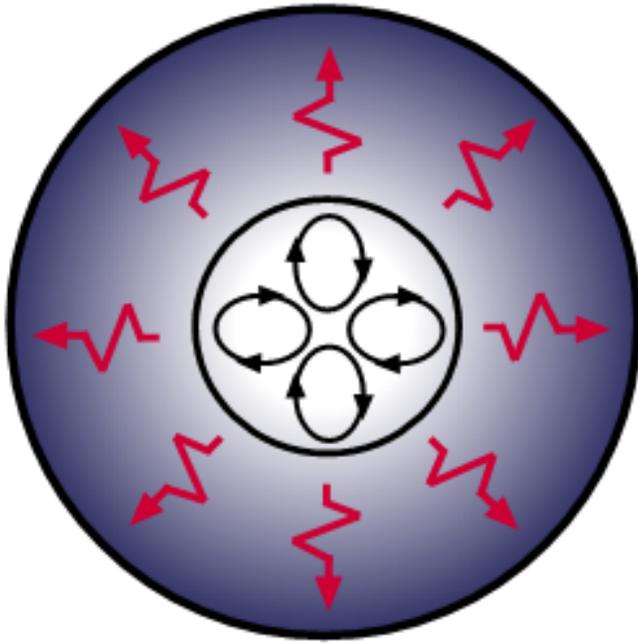
M > 1.5	0.5 < M < 1.5	M < 0.5
Convective Core	Radiative Core	Fully Convective
Radiative Envelope	Convective Envelope	

Mass (solar units) vs *Luminosity (solar units)*, with the Sun labeled at Mass = 1, Luminosity = 1.0.
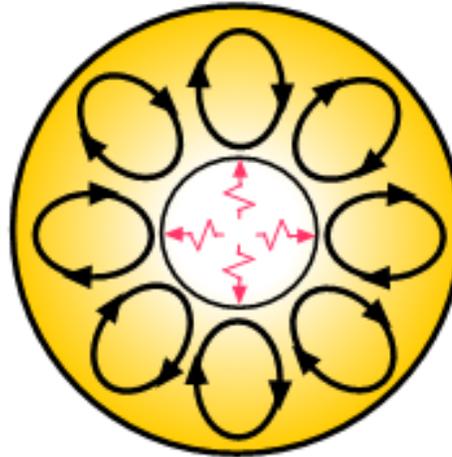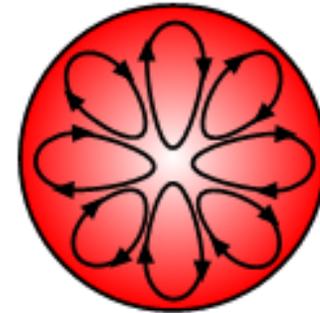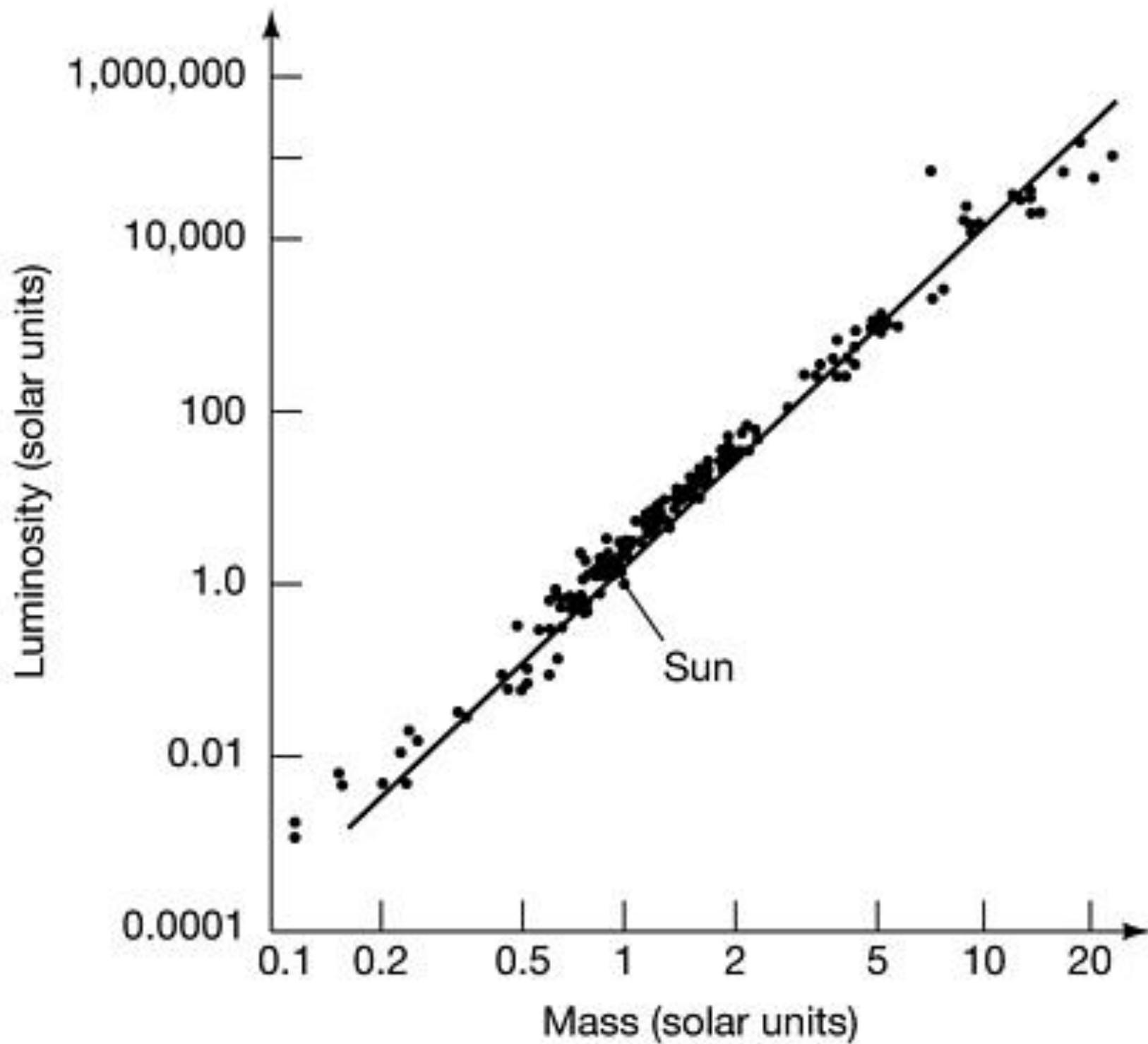
Main Sequence: Temperature-Luminosity relation
L propto T^6
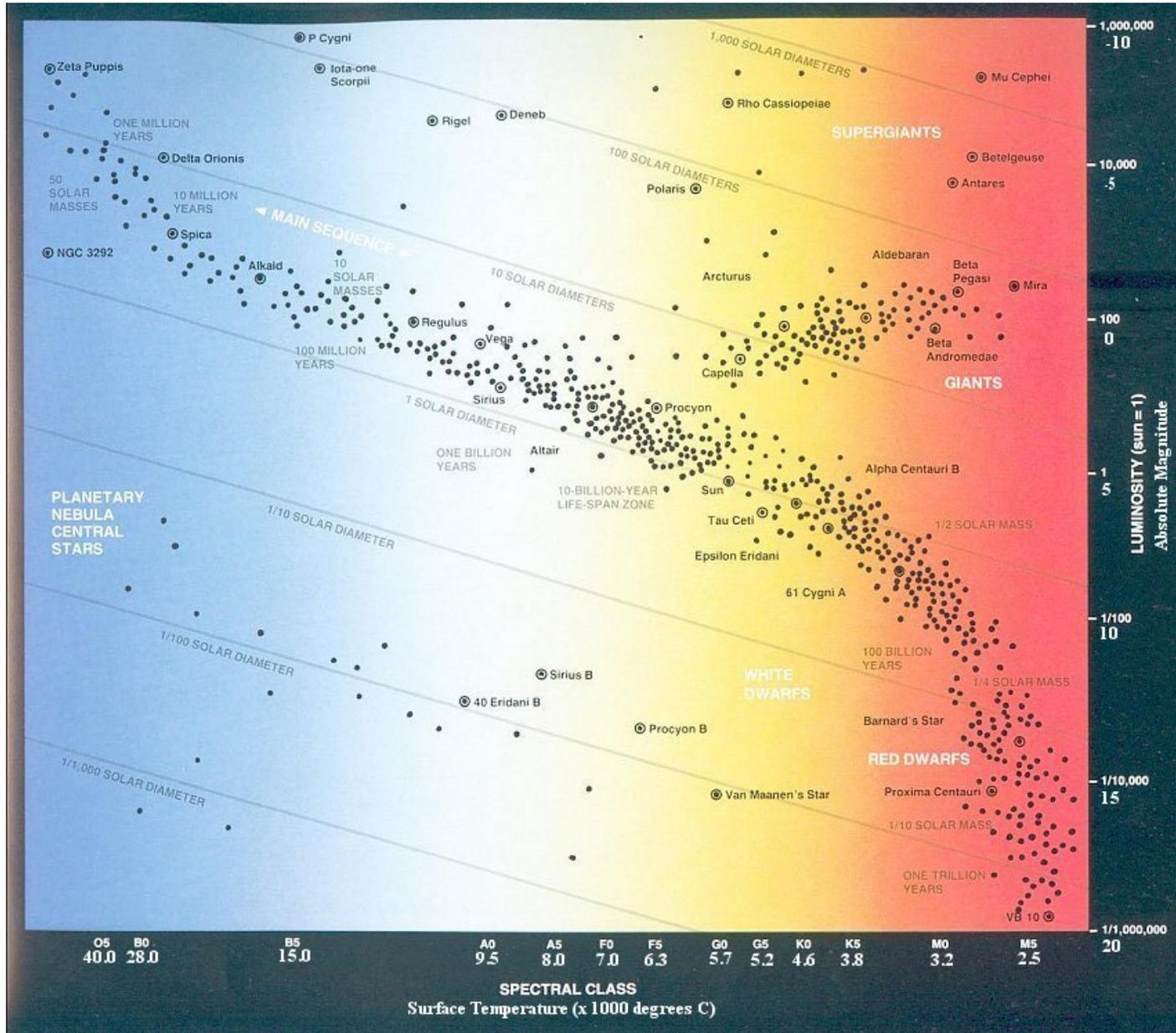
Nucleosynthesis

A nucleus is always found to be less massive than the combined mass of nucleons.
The difference is the ***binding energy***.

When a nucleus is formed, this binding energy is released.
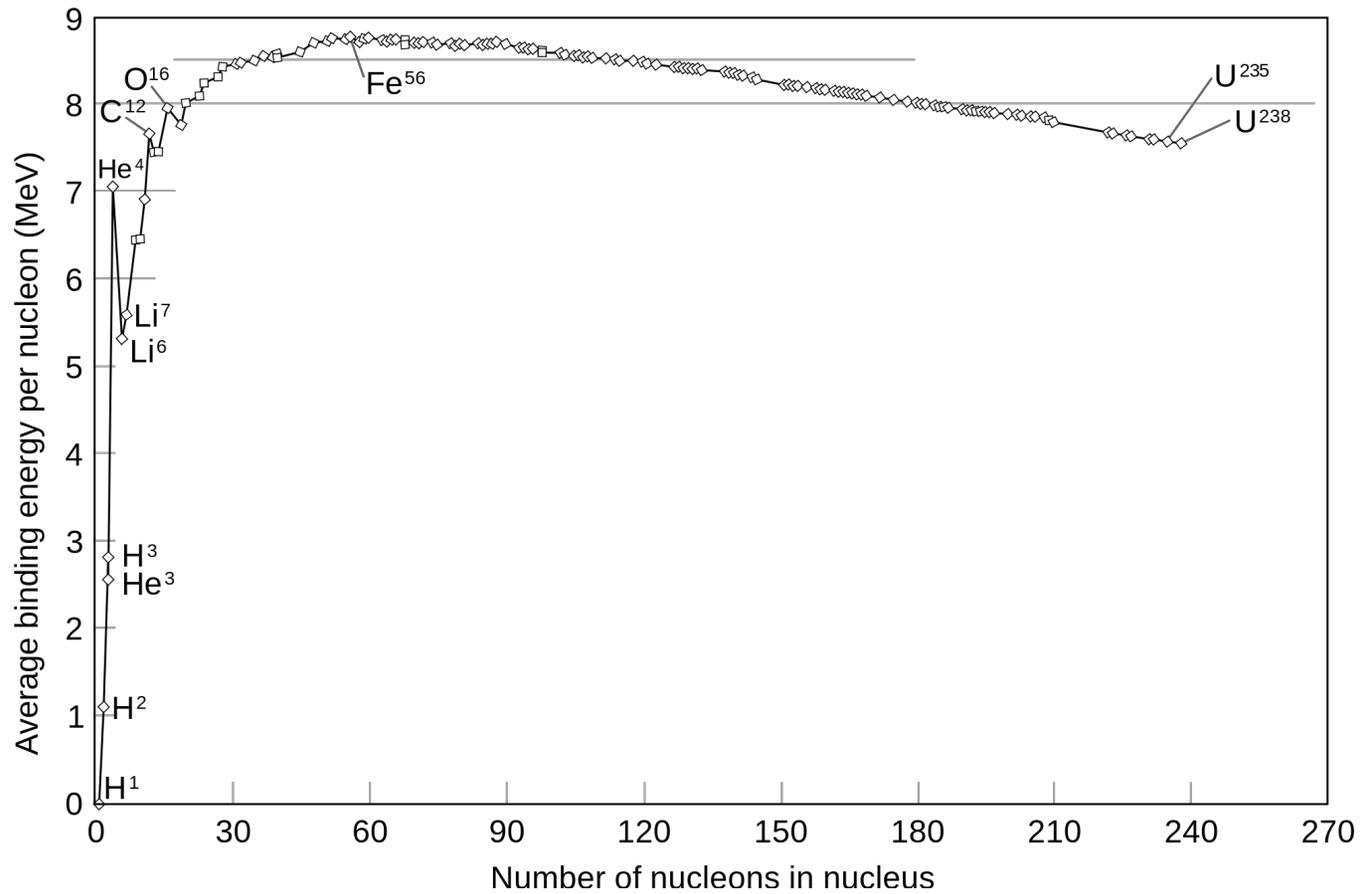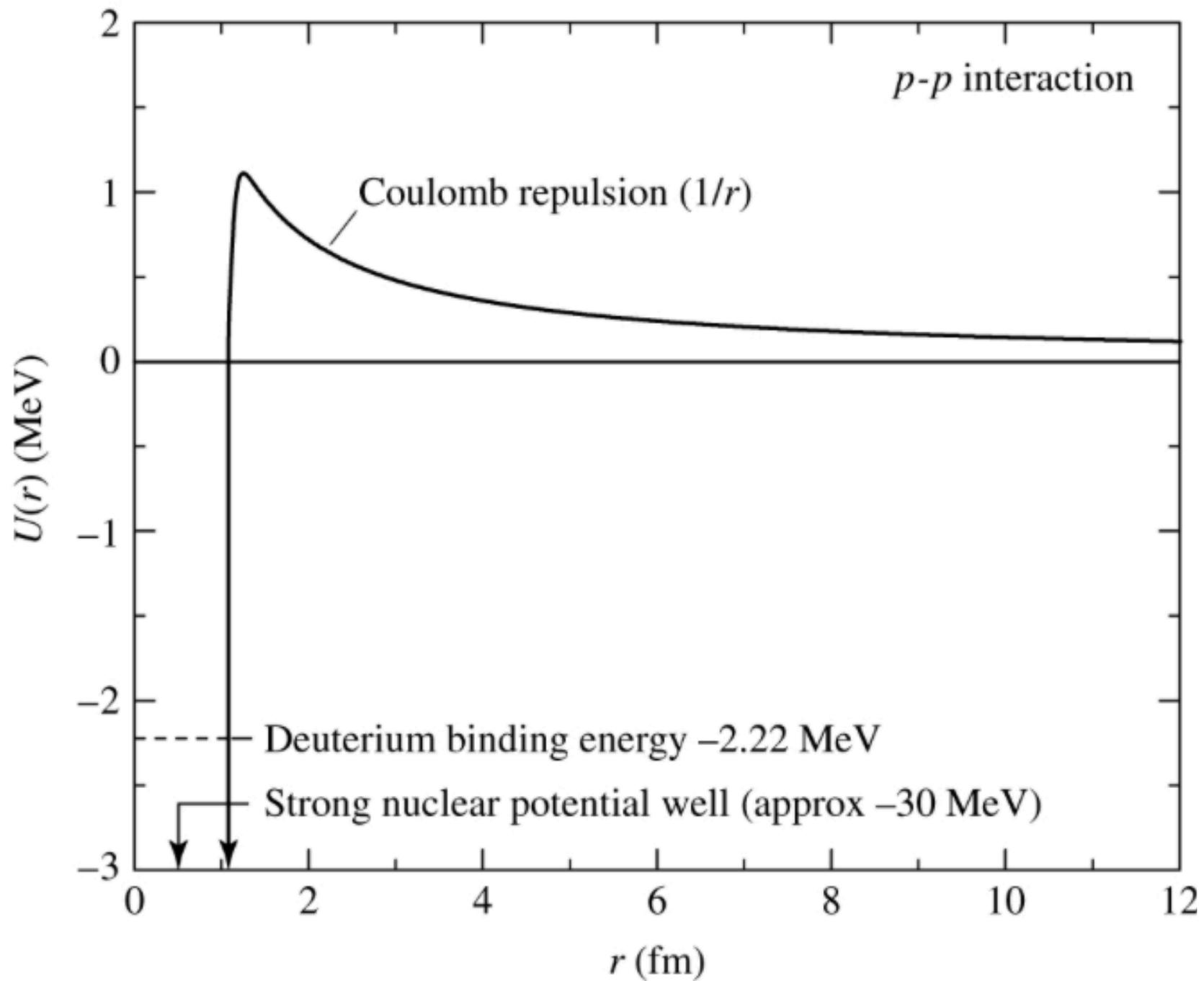
Figure: p-p interaction potential showing Coulomb repulsion (1/r), Deuterium binding energy −2.22 MeV, and Strong nuclear potential well (approx −30 MeV). Axes: $U(r)$ (MeV) versus r (fm).

How is an atomic nucleus bound together if the protons are like-charged?

proton

neutron

How is an atomic nucleus bound together if the protons are like-charged?

proton   neutron
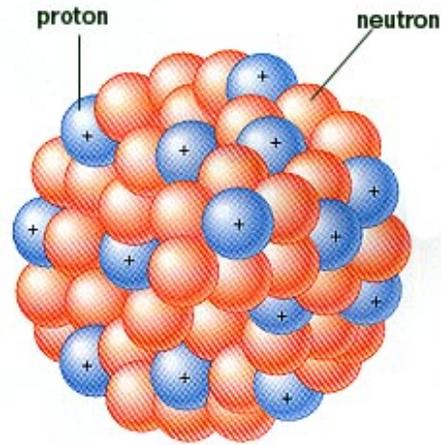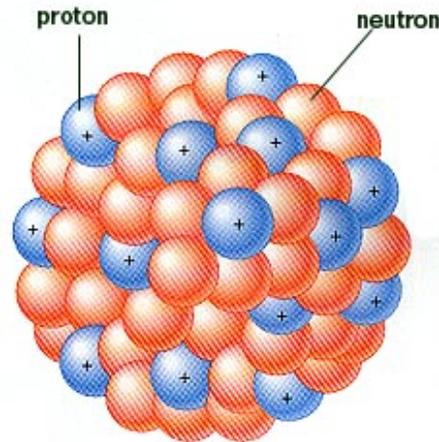
Another force of nature exists at nuclear distances
Not Gravity. Not Electromagnetism.

Strong Force

The Coulomb force (EM) between protons is repulsive,
but the strong force between protons is attractive!

The Coulomb Barrier

Protons are like-charged and thus repel each other

You need to get them really close so that nuclear forces start to operate
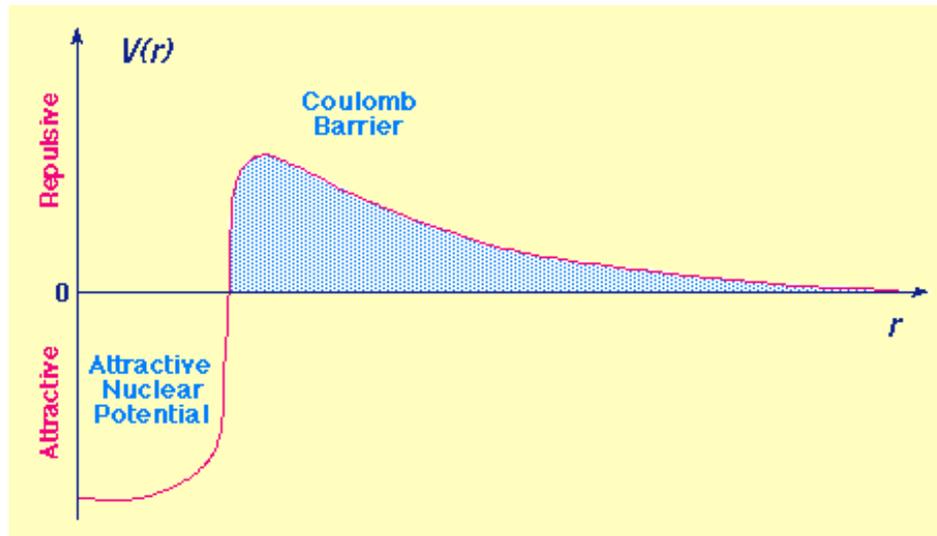
Really close means: packed together   - HIGH DENSITY
                       fast speeds   - HIGH TEMPERATURE

Roughly spherical atoms of an ideal gas should not be attracted nor repelled by one another.
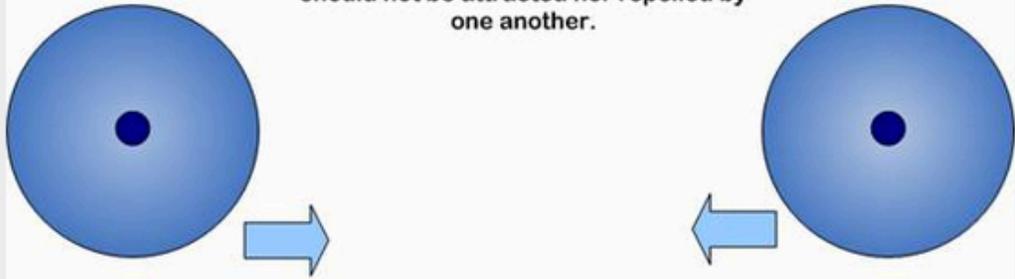
A real gas atom can have an instantaneous dipole. Partial charges on one atom cause a neighboring atom to distort due to the electrostatic attractions/repulsions of their electron clouds.

δ-   δ+
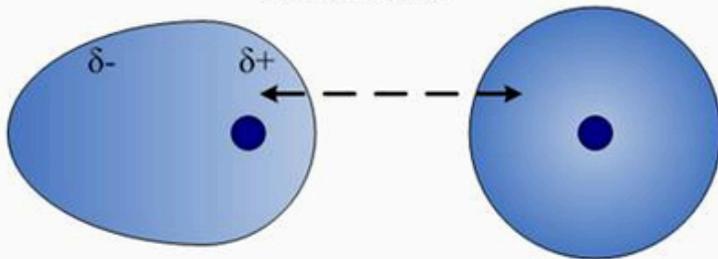
Attractions between opposite partial charges of neighboring induced dipoles cause atoms to "stick together" for a very short time.

δ-   δ+   δ-   δ+
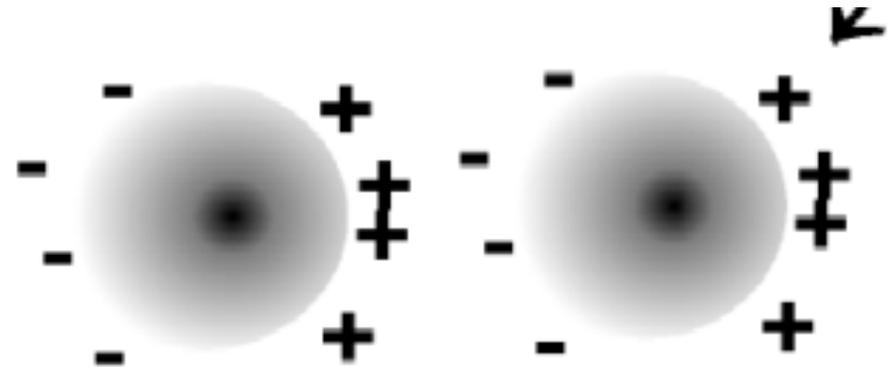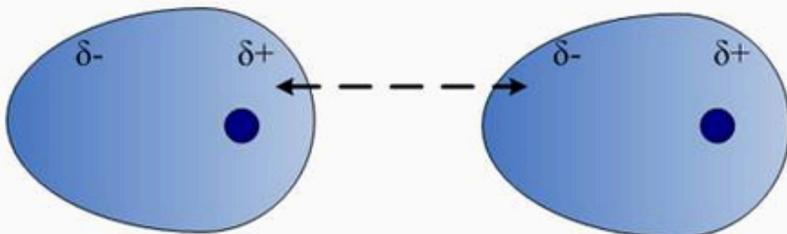
Van der Waals interaction
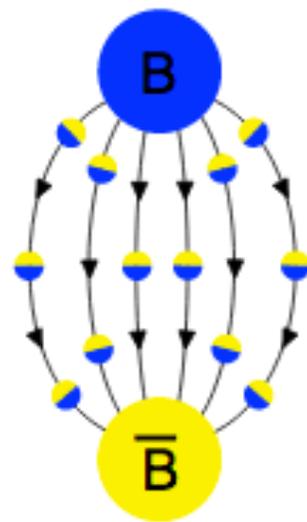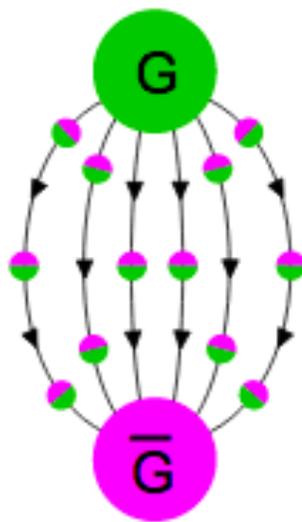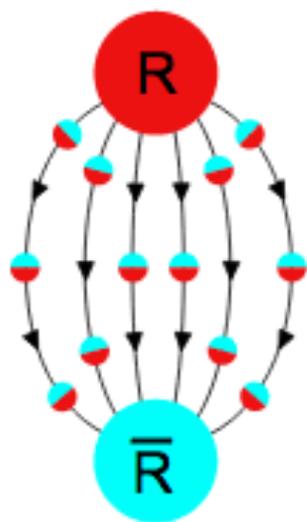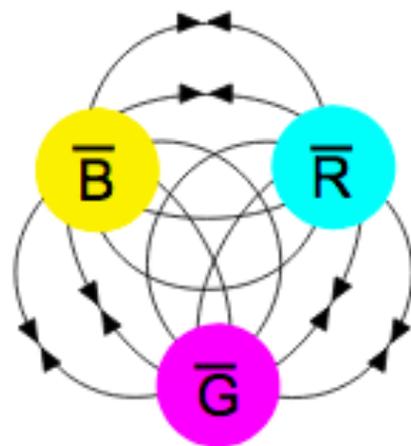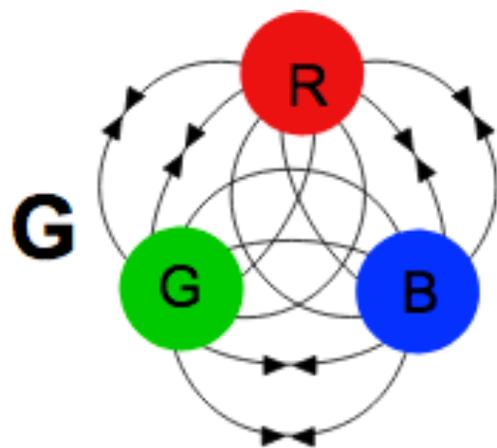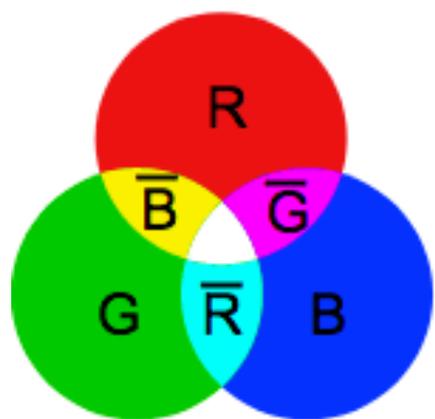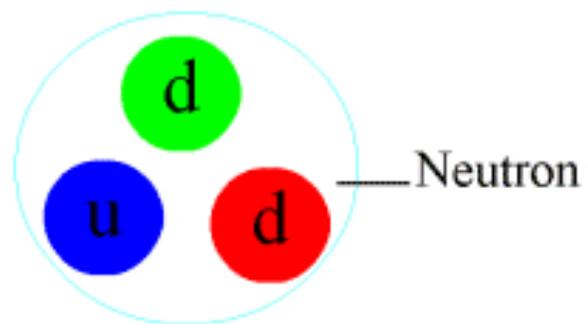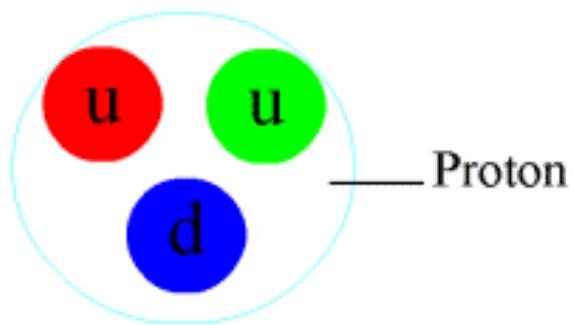
$$V_{\text{Yukawa}}(r) = -g^2 \frac{e^{-\mu r}}{r},$$

Quantum Tunneling
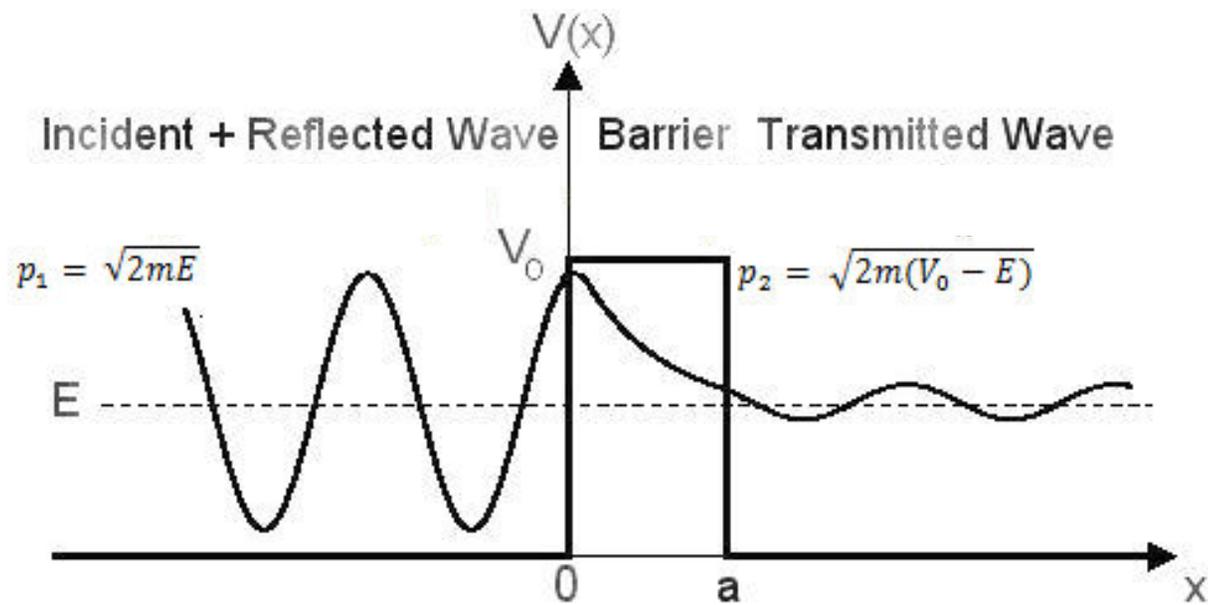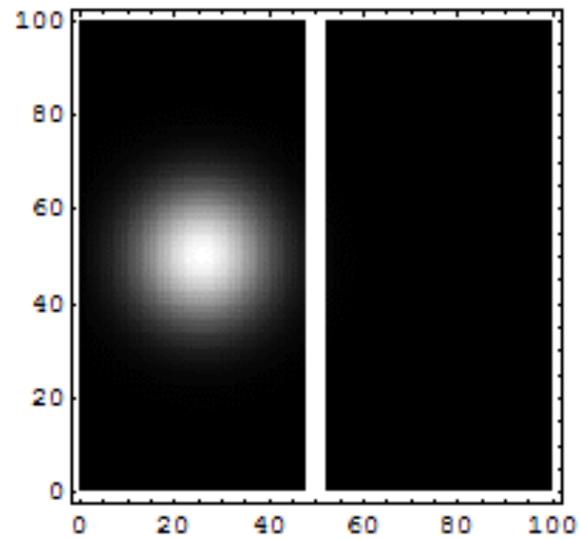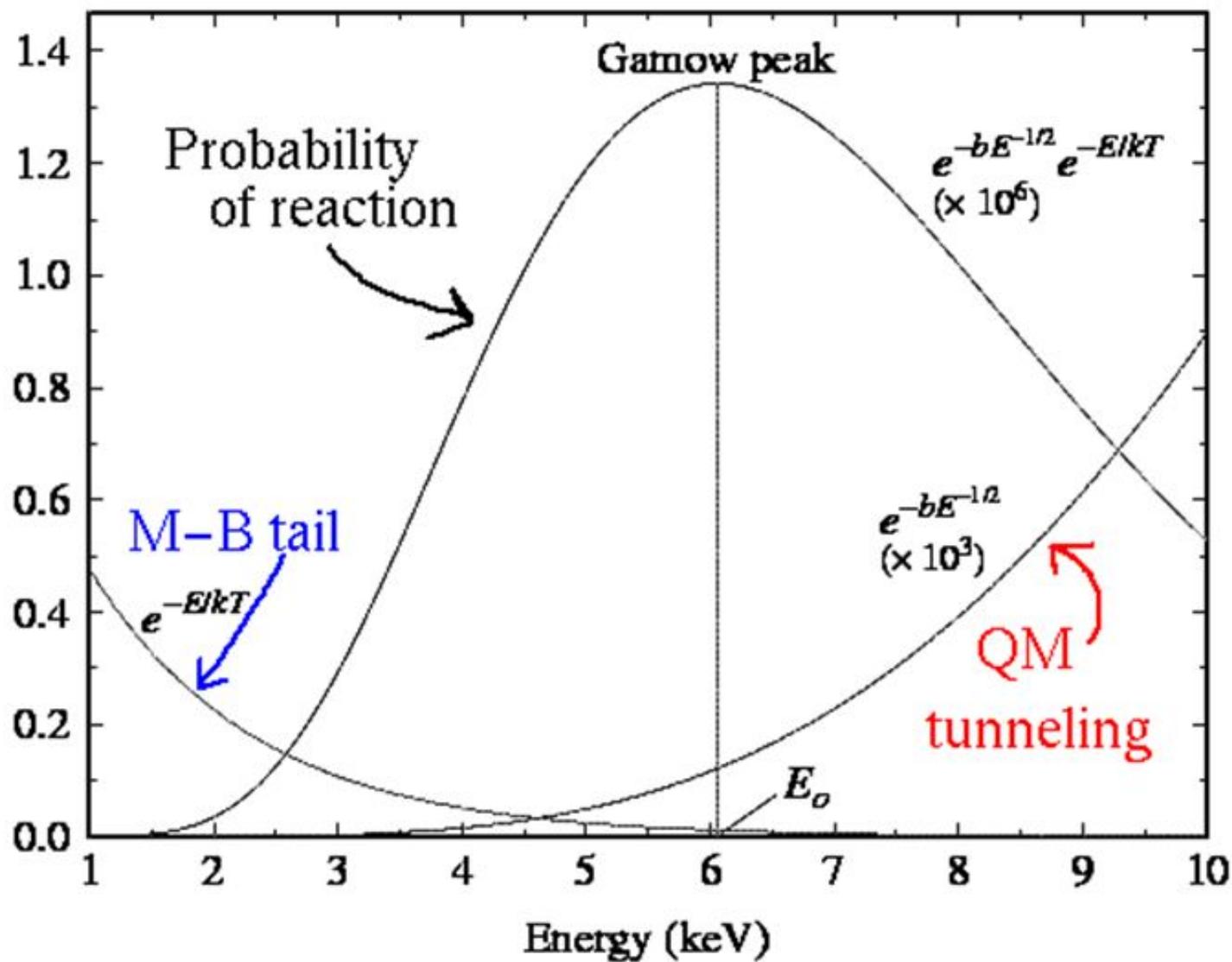
Proton-proton chain

γ   Gamma Ray

ν   Neutrino

Proton

Neutron

Positron

CNO cycle

$$C_6^{12} + H_1^1 \rightarrow N_7^{13} + \gamma_0^0$$

$$N_7^{13} \rightarrow C_6^{13} + \overline{e}_1^0 + \nu_0^0$$

$$C_6^{13} + H_1^1 \rightarrow N_7^{14} + \gamma_0^0$$

$$N_7^{14} + H_1^1 \rightarrow O_8^{15} + \gamma_0^0$$

$$O_8^{15} \rightarrow N_7^{15} + \overline{e}_1^0 + \nu_0^0$$

$$N_7^{15} + H_1^1 \rightarrow C_6^{12} + He_2^4$$
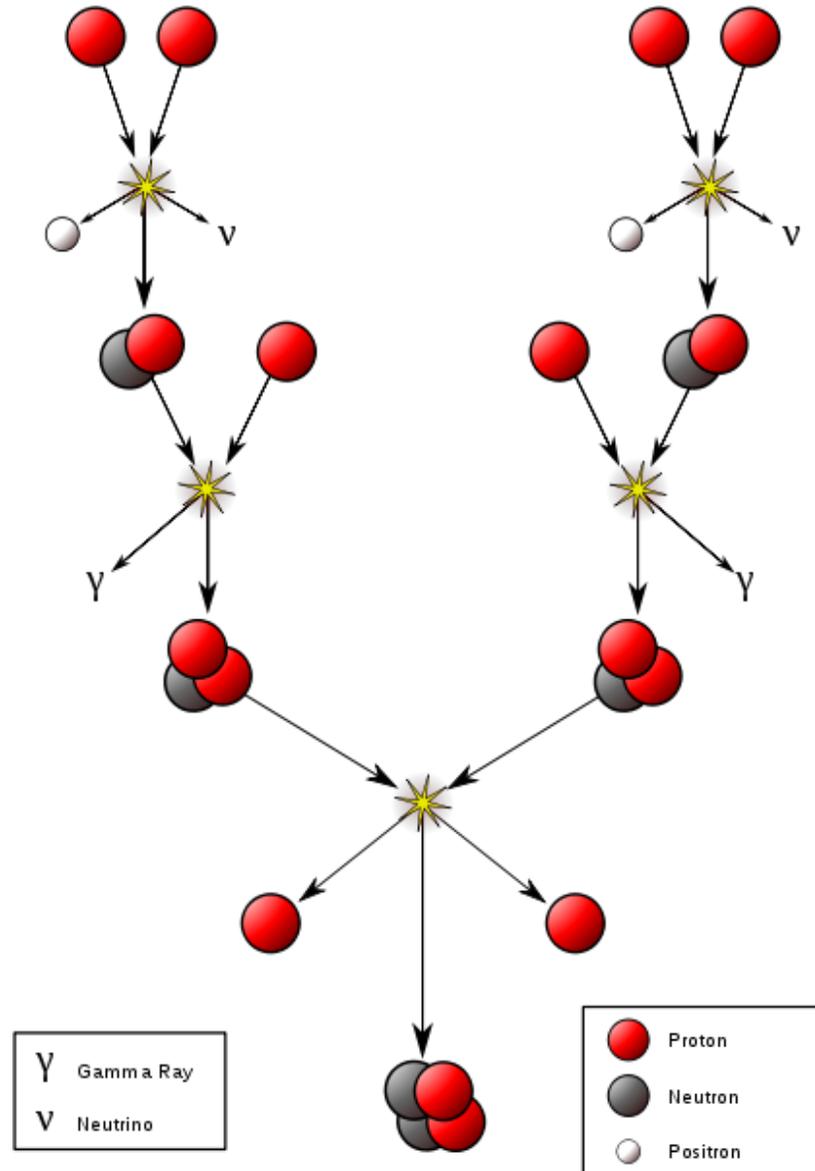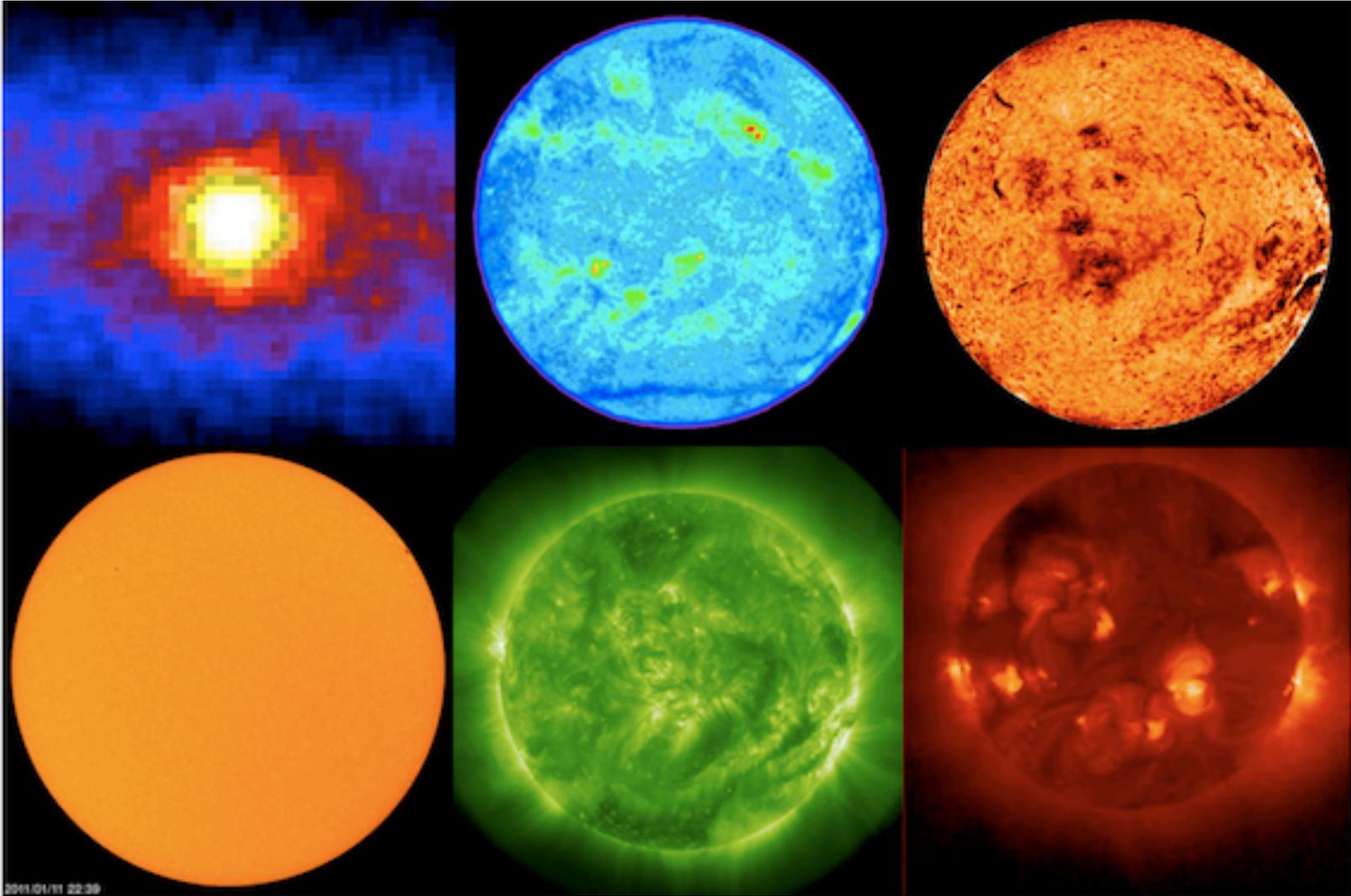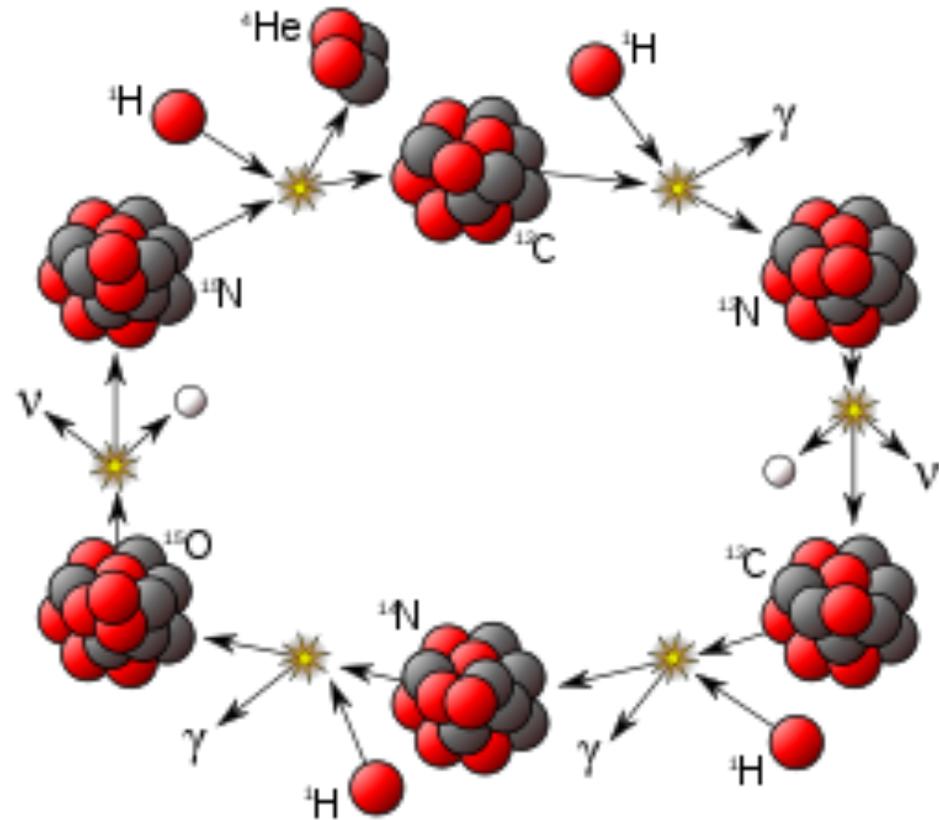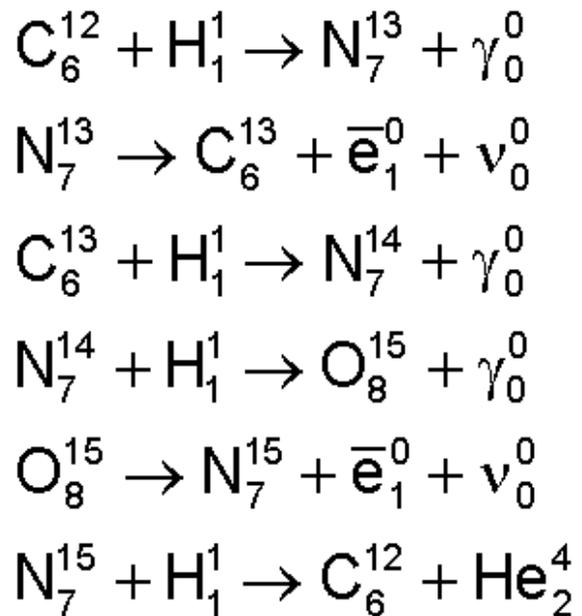
End of cycle:
4 H burned into He
C used as catalyst

Proton		γ	Gamma Ray
Neutron		ν	Neutrino
Positron			

Chart of the nuclides (neutron number on vertical axis, 0–17)

17 — Cl:
Cl28 | Cl29 <20 NS | Cl30 <30 NS | Cl31 1.50 MS | Cl32 298 MS | Cl33 2.511 S | Cl34 1.5264 S | Cl35 75.77 | Cl36 301000 Y | Cl37 24.23 | Cl38 37.24 M

16 — S:
S26 ~10 MS | S27 21 MS | S28 125 MS | S29 187 MS | S30 1.178 S | S31 2.572 S | S32 95.02 | S33 0.75 | S34 4.21 | S35 87.38 D | S36 0.02 | S37 5.05 M

15 — P:
P24 | P25 <30 NS | P26 20 MS | P27 260 MS | P28 270.3 MS | P29 4.142 S | P30 2.498 M | P31 100 | P32 14.262 D | P33 25.34 D | P34 12.43 S | P35 47.3 S | P36 5.6 S

14 — Si:
Si22 29 MS | Si23 >200 NS | Si24 102 MS | Si25 220 MS | Si26 2.234 S | Si27 4.16 S | Si28 92.230 | Si29 4.683 | Si30 3.087 | Si31 157.3 M | Si32 172 Y | Si33 6.332 S | Si34 2.77 S | Si35 0.78 S

13 — Al:
Al21 <35 NS | Al22 59 MS | Al23 0.47 S | Al24 2.053 S | Al25 7.183 S | Al26 717000 Y | Al27 100 | Al28 2.2414 M | Al29 6.56 M | Al30 3.60 S | Al31 644 MS | Al32 33 MS | Al33 >1 US | Al34 60 MS

12 — Mg:
Mg19 | Mg20 90.8 MS | Mg21 122 MS | Mg22 3.857 S | Mg23 11.317 S | Mg24 78.99 | Mg25 10.00 | Mg26 11.01 | Mg27 9.458 M | Mg28 20.915 H | Mg29 1.30 S | Mg30 335 MS | Mg31 230 MS | Mg32 120 MS | Mg33 90 MS

11 — Na:
Na17 | Na18 | Na19 <40 NS | Na20 447.9 MS | Na21 22.49 S | Na22 2.6019 Y | Na23 100 | Na24 14.9512 H | Na25 59.1 S | Na26 1.072 S | Na27 301 MS | Na28 30.5 MS | Na29 44.9 MS | Na30 17.0 MS | Na31 13.2 MS | Na32

10 — Ne:
Ne15 | Ne17 109.2 MS | Ne18 1.672 S | Ne19 17.22 S | Ne20 90.48 | Ne21 0.27 | Ne22 9.25 | Ne23 37.24 S | Ne24 3.38 M | Ne25 602 MS | Ne26 0.197 S | Ne27 32 MS | Ne28 17 MS | Ne29 200 MS | Ne30 >200 NS | Ne31 >260 NS

9 — F:
F14 | F17 64.49 S | F18 109.77 M | F19 100 | F20 11.163 S | F21 4.158 S | F22 4.23 S | F23 2.23 S | F24 0.34 S | F25 59 MS | F26 190 MS | F27 >200 NS | F28 <40 NS | F29 >200 NS

8 — O:
O13 8.58 MS | O14 70.606 S | O15 122.24 S | O16 99.762 | O17 0.038 | O18 0.200 | O19 26.91 S | O20 13.51 S | O21 3.42 S | O22 2.25 S | O23 82 MS | O24 61 MS | O25 <50 NS | O26 <40 NS

7 — N:
N10 | N12 11.000 MS | N13 9.965 M | N14 99.634 | N15 0.366 | N16 7.13 S | N17 4.173 S | N18 624 MS | N19 290 MS | N20 142 MS | N21 87 MS | N22 18 MS | N23 >200 NS | N24 <52 NS

6 — C:
C9 126.5 MS | C10 19.255 S | C11 20.39 M | C12 98.89 | C13 1.11 | C14 5730 Y | C15 2.449 S | C16 0.747 S | C17 193 MS | C18 95 MS | C19 49 MS | C20 14 MS | C21 <30 NS | C22 >200 NS

5 — B:
B8 770 MS | B10 19.9 | B11 80.1 | B12 20.20 MS | B13 17.36 MS | B14 12.3 MS | B15 9.87 MS | B16 <190 PS | B17 5.08 MS | B18 <26 NS | B19 >200 NS

4 — Be:
Be5 | Be7 53.29 D | Be9 100 | Be10 1510000 Y | Be11 13.81 S | Be12 21.3 MS | Be14 4.35 MS

3 — Li:
Li6 7.59 | Li7 92.41 | Li8 838 MS | Li9 178.3 MS | Li11 8.5 MS | Li12 <10 NS

2 — He:
He3 0.000137 | He4 99.999863 | He6 806.7 MS | He8 119.0 MS

1 — H:
H1 99.985 | H2 0.015 | H3 12.33 Y

0 — n:
N1 10.24 M

Beyond Helium

$$^1H + {}^4He = {}^5X$$

$$^4He + {}^4He = {}^8X$$

But there is no stable nuclide of mass 5 or 8….

Triple alpha

Alpha Ladder

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)

Helium-capture reactions

^{12}C

^{16}O (8p, 8n)

^4He

^{16}O

^{20}Ne (10p, 10n)

^4He

^{20}Ne

^{24}Mg (12p, 12n)

^4He

Other reactions

^{12}C

^{28}Si (14p, 14n)

^{16}O

^{16}O

^{31}S (16p, 15n)

^{16}O

^{28}Si

^{56}Fe (26p, 30n)

^{28}Si

The Sun's abundance pattern

Elements with even atomic number are more abundant than those with odd

Solar evolution in the main sequence

Bahcall et al. 2001
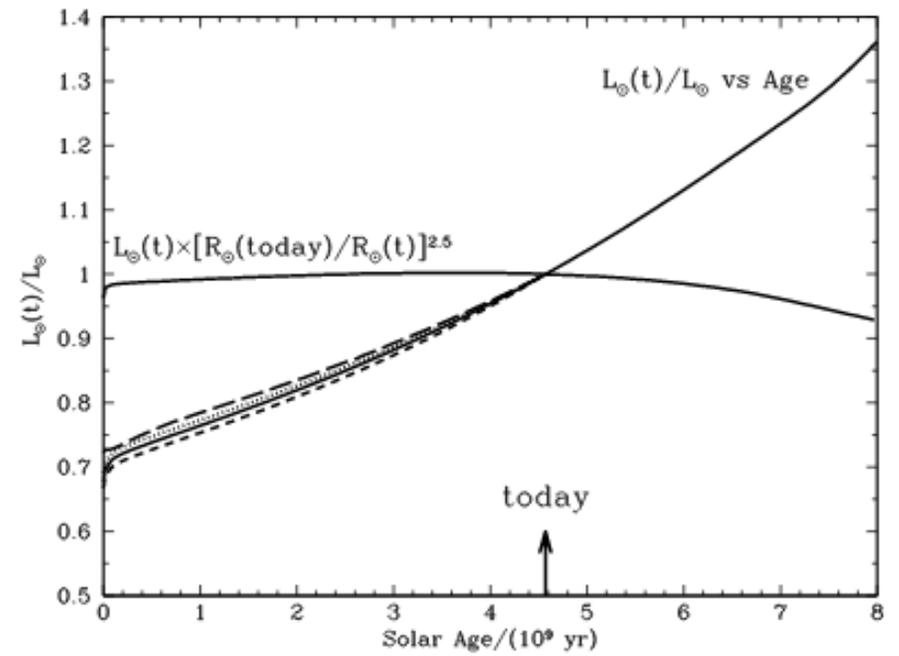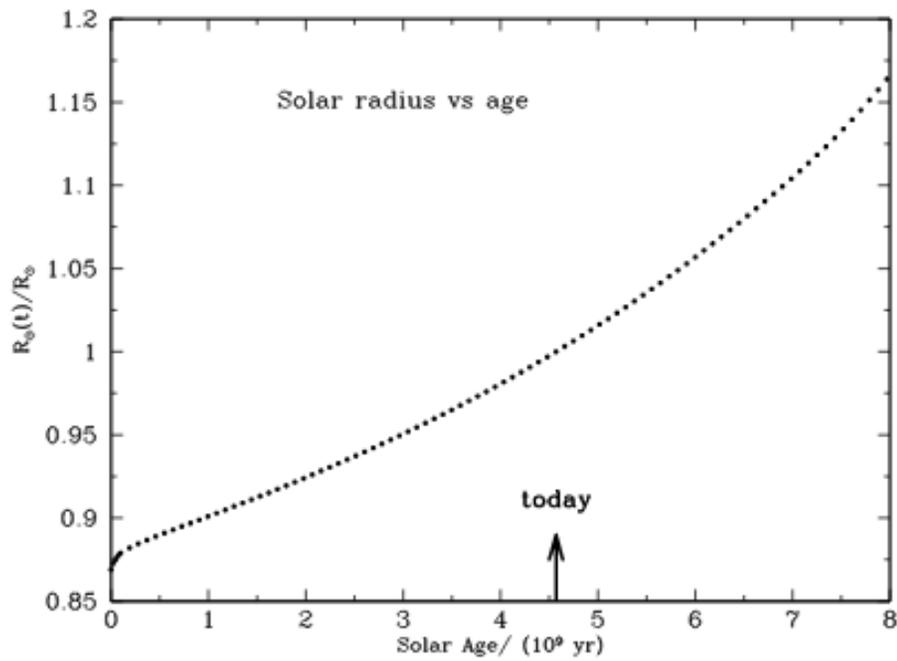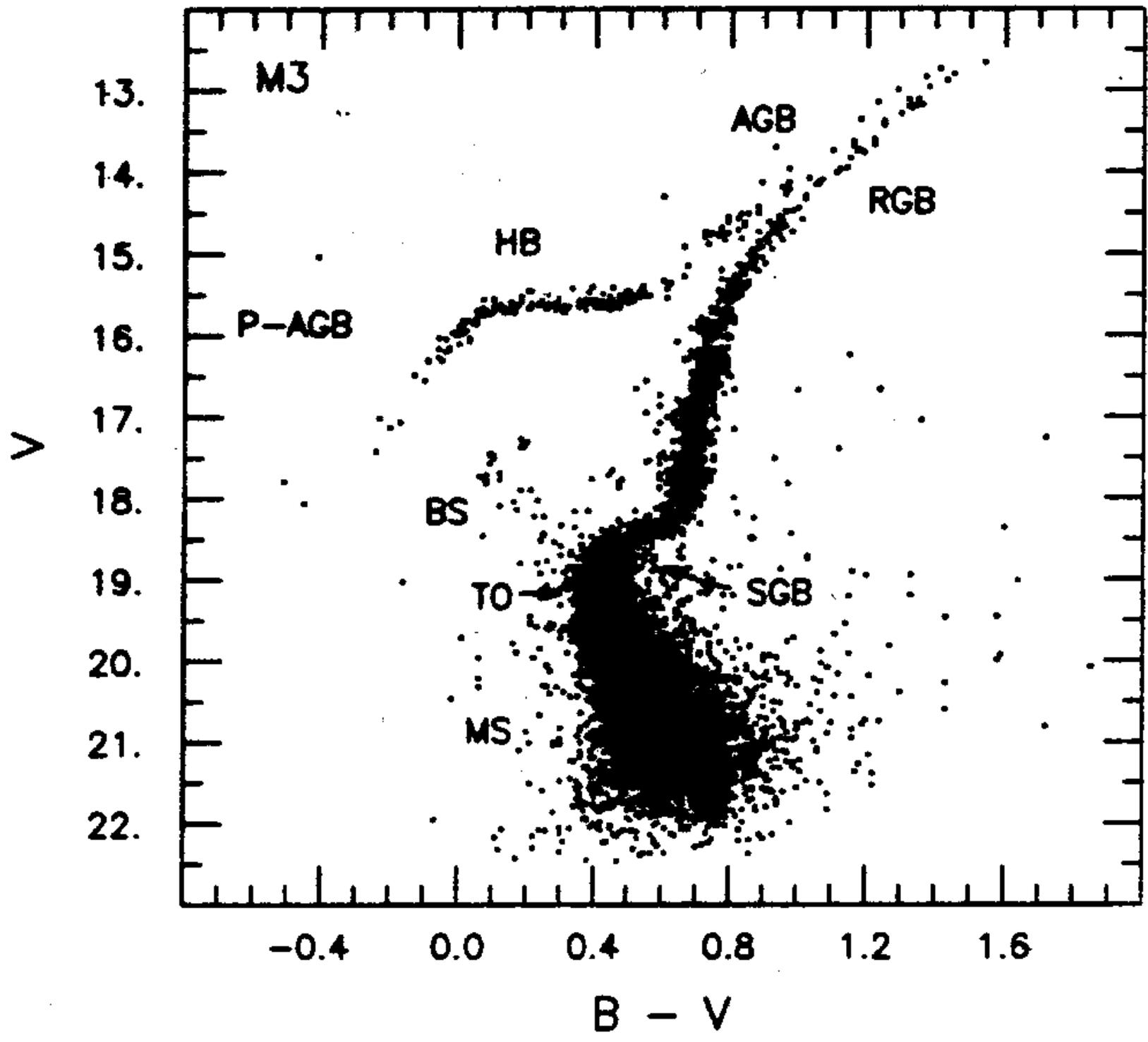
Evolutionary tracks

Schaller et al. (1992)

CORE NEUTRINO LOSS, THIN HELIUM-BURNING SHELL

THICK HELIUM-BURNING SHELL

13

12

10^5 10

10^6 YR

MAJOR PHASE OF CORE HELIUM BURNING (9×10^6 YR)

11

14

OVERALL CONTRACTION WITH EXHAUSTION OF CENTRAL HELIUM

ESTABLISHMENT OF SHELL SOURCE (1.4×10^5 YR)

HYDROGEN BURNING IN THICK SHELL (1.2×10^6 YR)

IGNITION OF TRIPLE-ALPHA PROCESS

DISAPPEARANCE OF DEEP CONVECTIVE ENVELOPE, RAPID CONTRACTION (10^6 YR)

9

7

5

3 4

OVERALL CONTRACTION PHASE (2.2×10^6 YR)

2

SHELL-NARROWING PHASE (8×10^5 YR)

FIRST PHASE OF CORE HELIUM BURING (6×10^6 YR)

8

RED-GIANT PHASE (5×10^5 YR)

HYDROGEN BURNING IN CORE (6.44×10^7 YR)

CONVECTIVE ENVELOPE BEGINS TO EXTEND INWARD RAPIDLY— SURFACE ABUNDANCES BEGIN TO CHANGE

6

1

LOG (L)

LOG (T_e)

3.50
3.45
3.40
3.35
3.30
3.25
3.20
3.15
3.10
3.05
3.00
2.95
2.90
2.85
2.80

4.3 4.2 4.1 4.0 3.9 3.8 3.7 3.6

Hydrogen gone in the core

Star stops producing energy.

The star **contracts** and **heats** up.

Eventually, the temperature becomes high enough to
burn hydrogen _around_ the Helium core

Hydrogen shell burning

Hydrogen-burning shell

Nonburning envelope

Nonburning helium "ash"
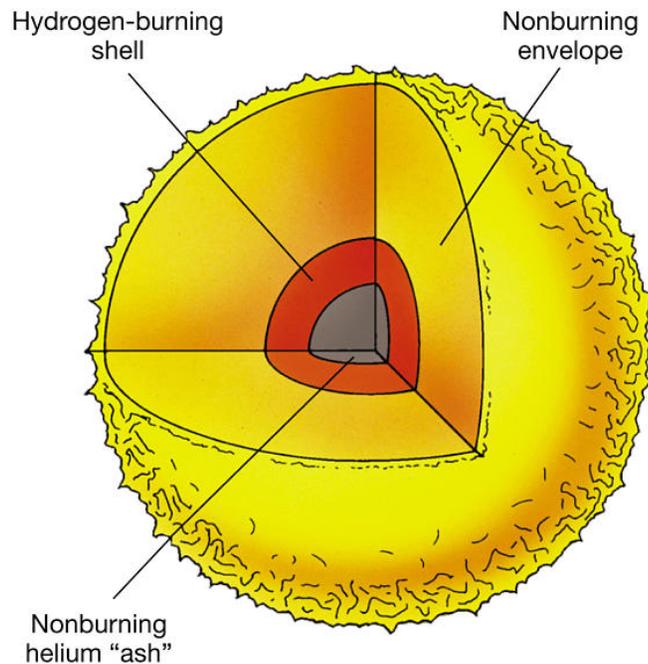
Copyright © 2005 Pearson Prentice Hall, Inc.

The star reaches
the subgiant branch

13.1 Evolution on the Main Sequence   485
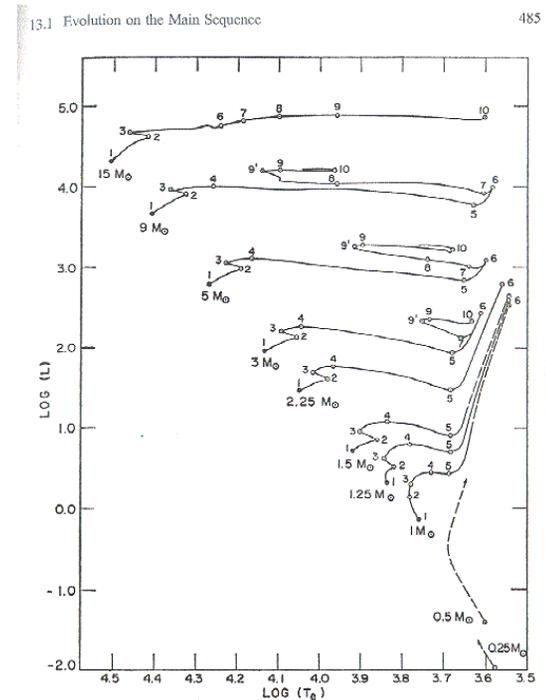
Red giant branch

Hydrogen shell burning involves:

More fuel than in MS-hydrogen burning
Higher temperatures
(thus more efficient)

A lot more of energy is being
produced than in the MS-phase.

The star gets very luminous and *swells*.
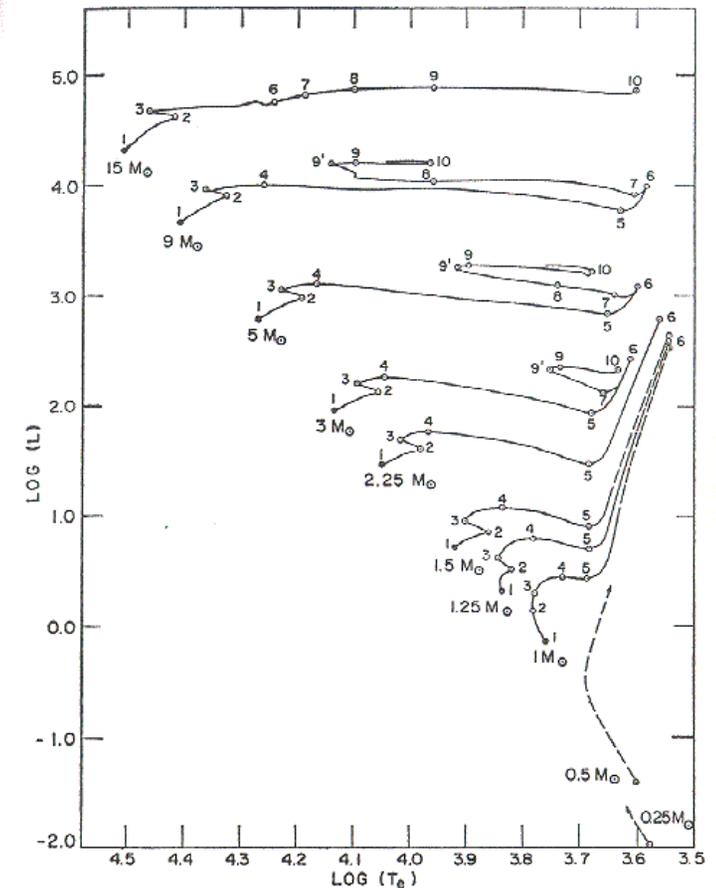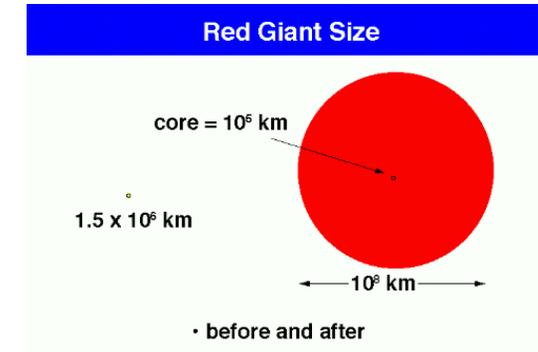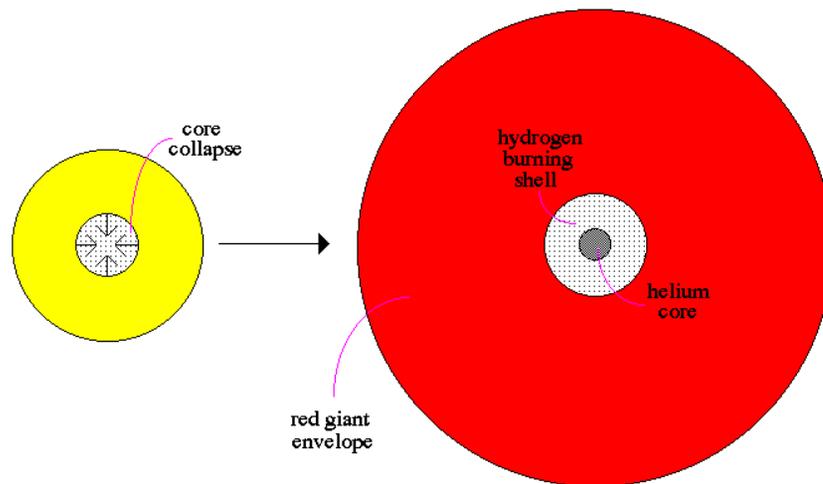
st35gm04n26: Surface Intensity(1l), time(0.0)=30.263 yrs

What happens to the inert Helium core?

Hydrogen shell burning

What happens to the inert Helium core?

It keeps contracting and heating

At some point the density is so
high it goes *degenerate*

A *phase transition* has occured

The core stops behaving like a gas
and starts behaving more *like a solid*

Core Dengeneracy

helium core

hydrogen burning shell

degenerate

What happens to the inert Helium core?

It keeps contracting and heating

At some point the density is so
high it goes *degenerate*

A *phase transition* has occured

The core stops behaving like a gas
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Core Dengeneracy

helium core

degenerate

hydrogen burning shell
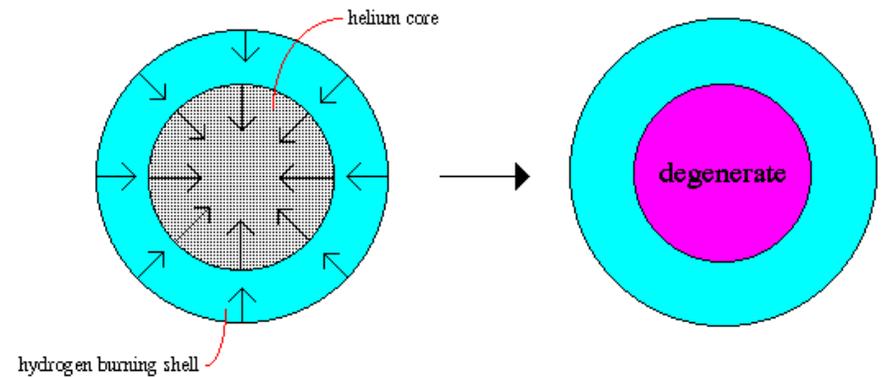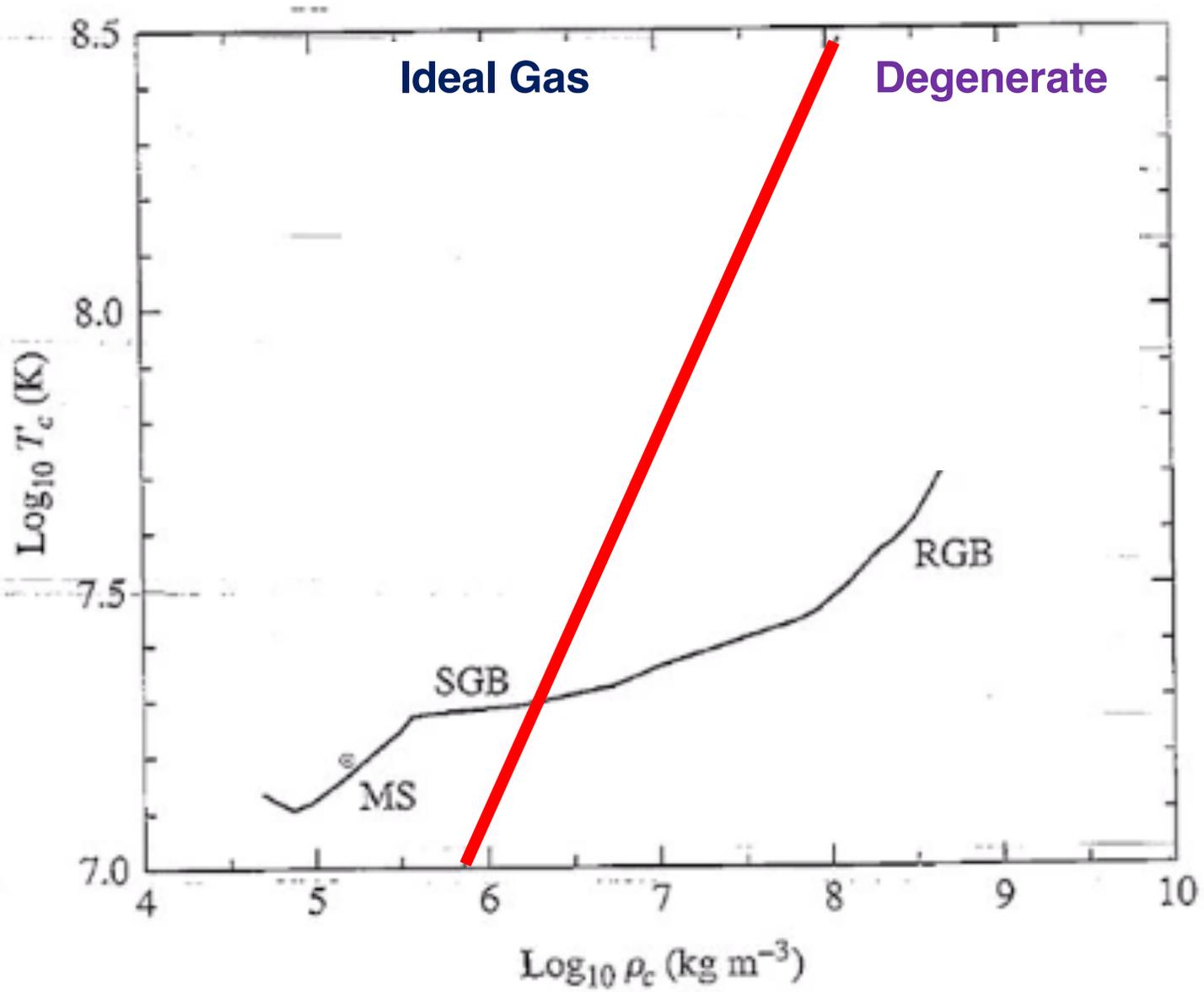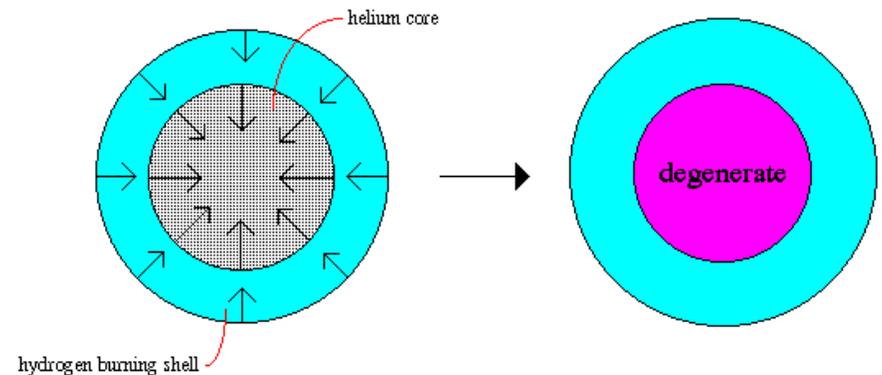
Ideal Gas

$$P \propto \rho T$$

Temperature rises, pressure rises
Temperature falls, pressure falls

Radiative loss $\rightarrow$ cooling $\rightarrow$
less support against gravity $\rightarrow$ **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

Helium Fusion

The inner degenerate Helium core is stable
But the outer Helium core keeps contracting and heating

At the tip of the Red Giant Branch,
when the temperature reaches 100 million K,
HELIUM FUSION begins

Triple Alpha

3 He → C + energy
(C + He → O + energy)
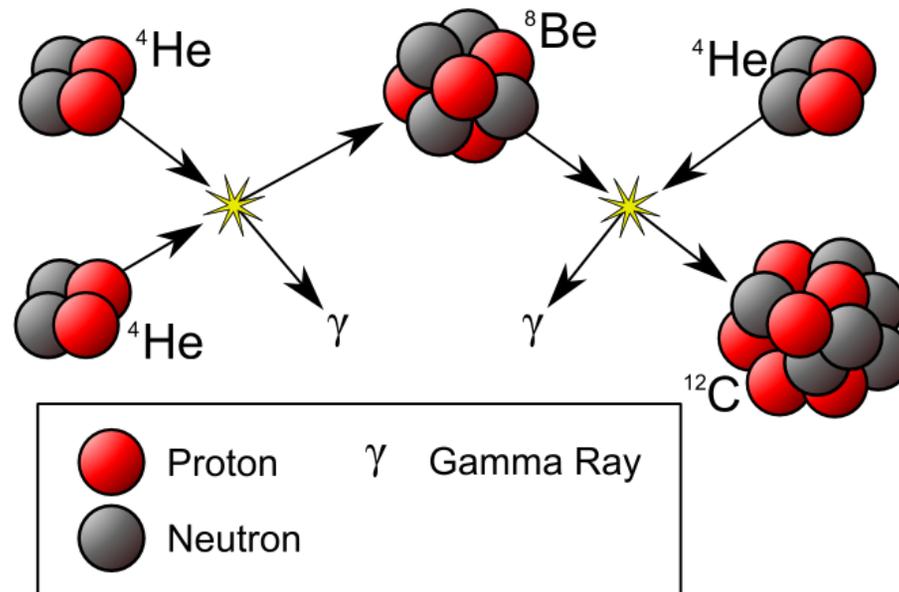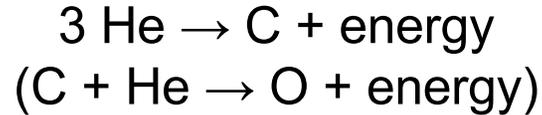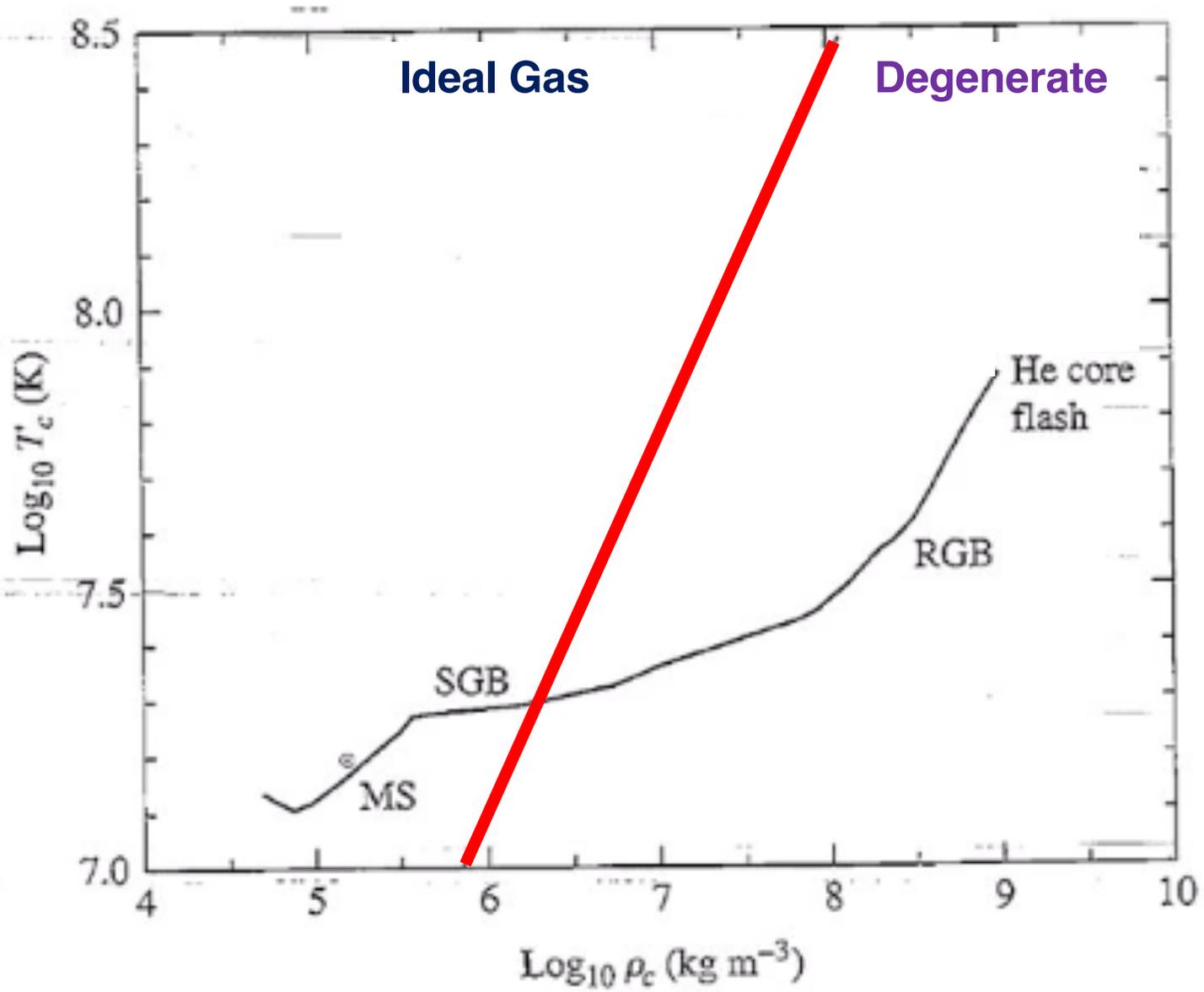
The Helium Flash

Under normal (non-degenerate) conditions …

Ideal Gas

$$P \propto \rho T$$

Nuclear reactions start

Heating → Expansion → Cooling

Cooling = Less nuclear reactions

Cooling → Contraction → Heating

Thermostat keeps nuclear reactions "tuned"
Controlled fusion

The Helium Flash

Non-degenerate vs degenerate

Ideal Gas

$$P \propto \rho T$$

Nuclear reactions start

Heating → Expansion → Cooling

Cooling = Less nuclear reactions

Cooling → Contraction → Heating

Thermostat keeps nuclear reactions "tuned"
Controlled fusion

Degenerate Matter

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

Nuclear reactions start
Heating
Star does not expand

Nuclear burning increases
More heating

The Helium Flash

Fusion ignition in degenerate matter is a bomb ready to explode

Ideal Gas

$$P \propto \rho T$$

Nuclear reactions start

Heating → Expansion → Cooling

Cooling = Less nuclear reactions

Cooling → Contraction → Heating

Thermostat keeps nuclear reactions "tuned"
Controlled fusion

Degenerate Matter

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

Nuclear reactions start
Heating
Star does not expand

Nuclear burning increases
More heating

No thermostat

Runaway temperature rise
Runaway fusion

The Helium Flash

Fusion ignition in degenerate matter is a bomb ready to explode

No thermostat! Core just gets hotter and hotter

Runaway Helium burning: **100 billion times the Solar output** in just a few seconds
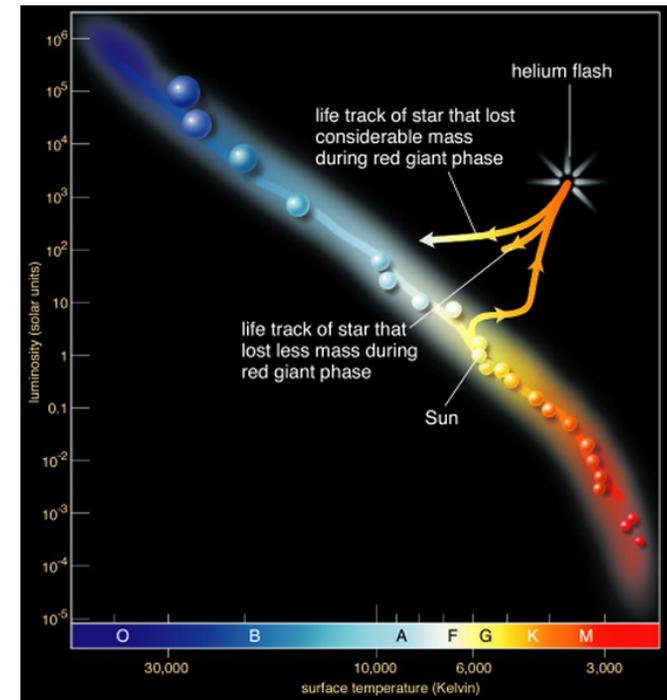
Helium Flash

The Helium Flash

Fusion ignition in degenerate matter is a bomb ready to explode

No thermostat! Core just gets hotter and hotter

Runaway Helium burning: **100 billion times the Solar output** in just a few seconds

Helium Flash

Yet, nothing is seen

Why?
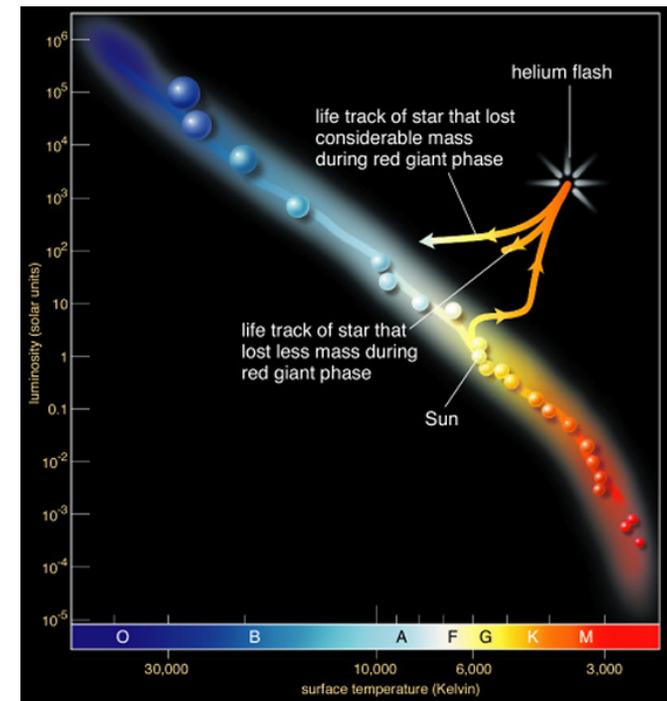
The Helium Flash

Fusion ignition in degenerate matter is a bomb ready to explode

No thermostat! Core just gets hotter and hotter

Runaway Helium burning: **100 billion times the Solar output** in just a few seconds

Helium Flash

Yet, nothing is seen

Why?

The energy is _ALL_ used to lift the degeneracy

(i.e., to "melt" the degenerate
core back into a normal gas)

Helium then burns *steadily* in a core of ideal gas
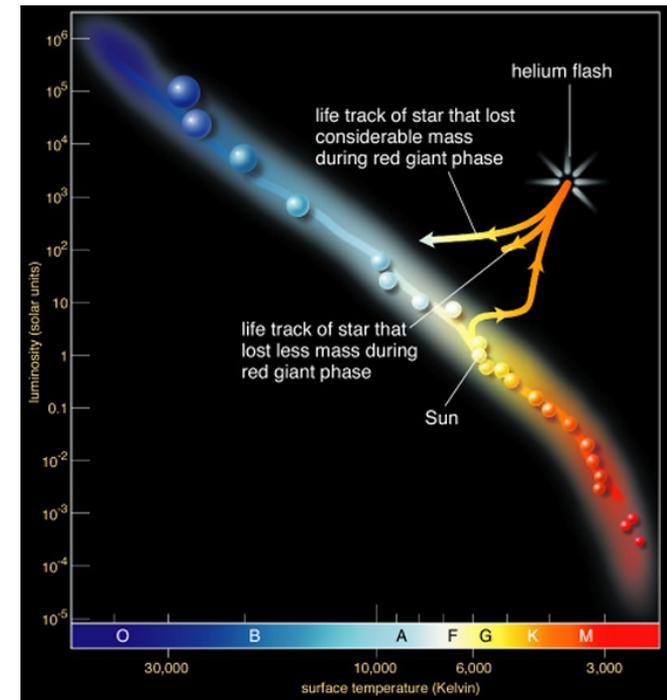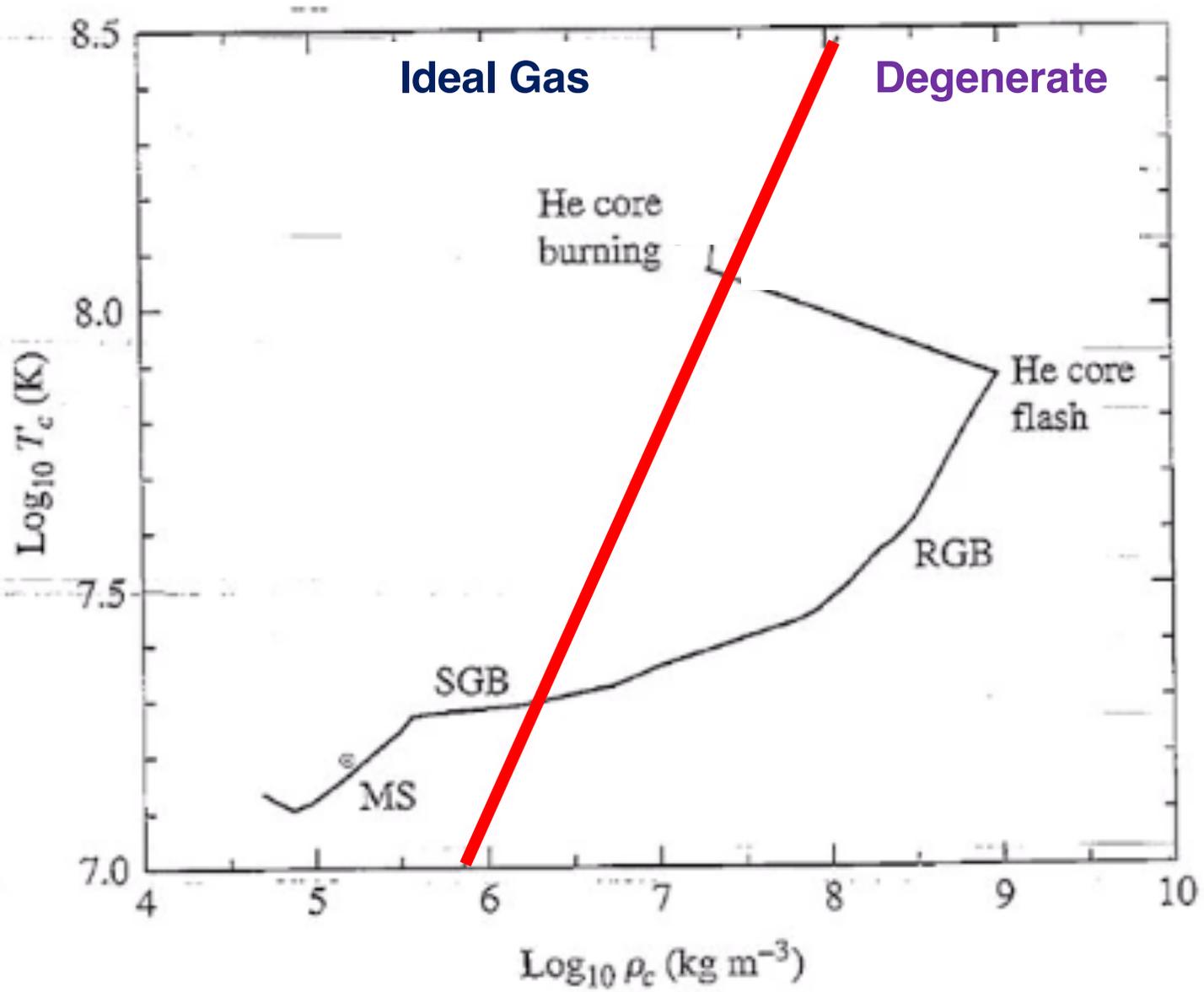
The Horizontal Branch

Helium burning in the core

Hydrogen shell burning

In the HR diagram, the star sets in the **Horizontal Branch**

The Horizontal Branch is the Helium Main Sequence

- Envelope
- H burning shell
- He intershell
- He core burning
  CO in centre builds up
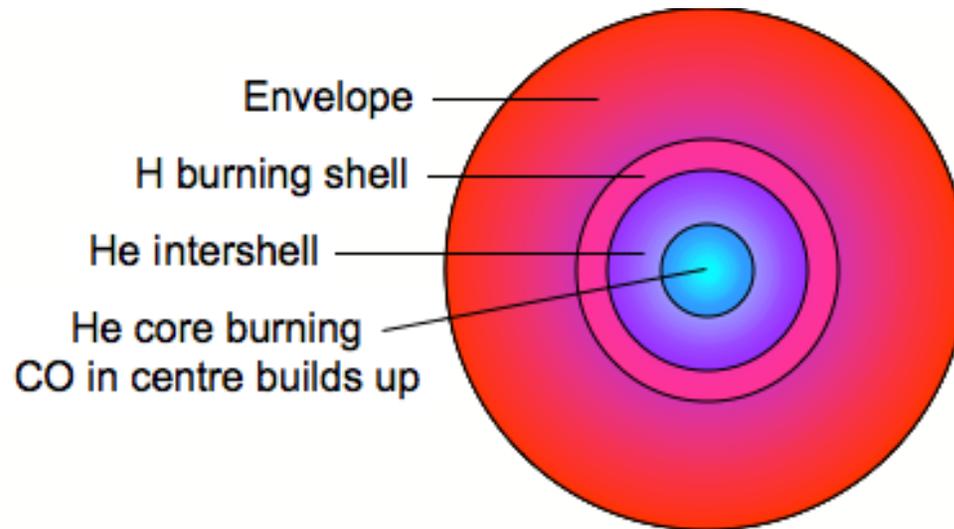
Helium exhausted in the core

The Carbon-Oxygen core **contracts** and **heats** up.

Helium shell burning

More energy is available, the star swells and becomes a red giant *again*

The star reaches the *Asymptotic Giant Branch*

- C-O core
- He burning shell
- H burning shell
- H envelope
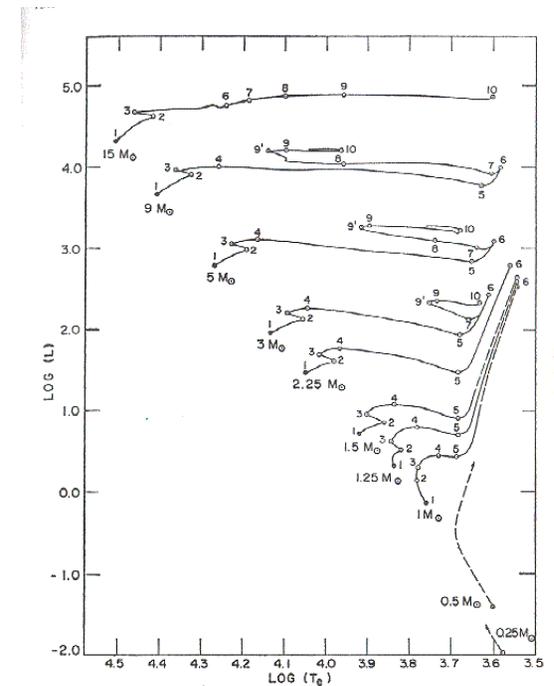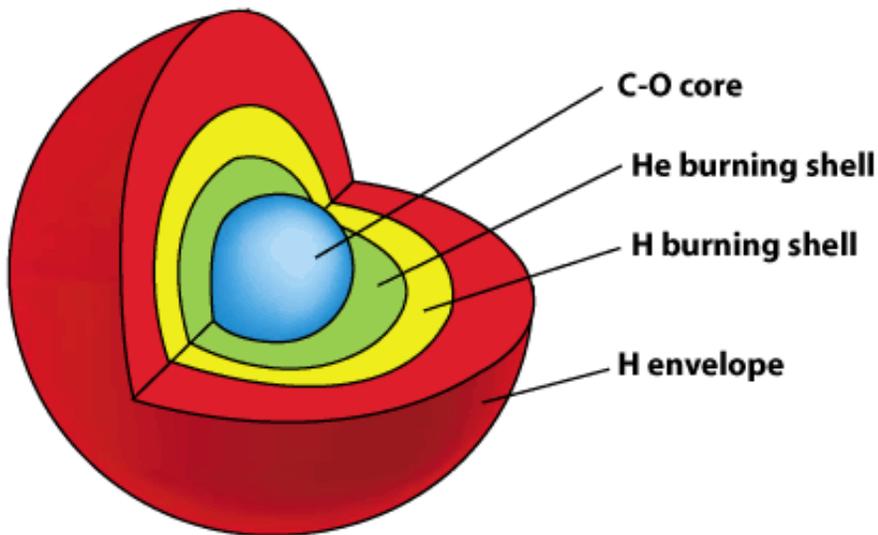
Thermal pulses in AGB stars

A series of Helium flashes
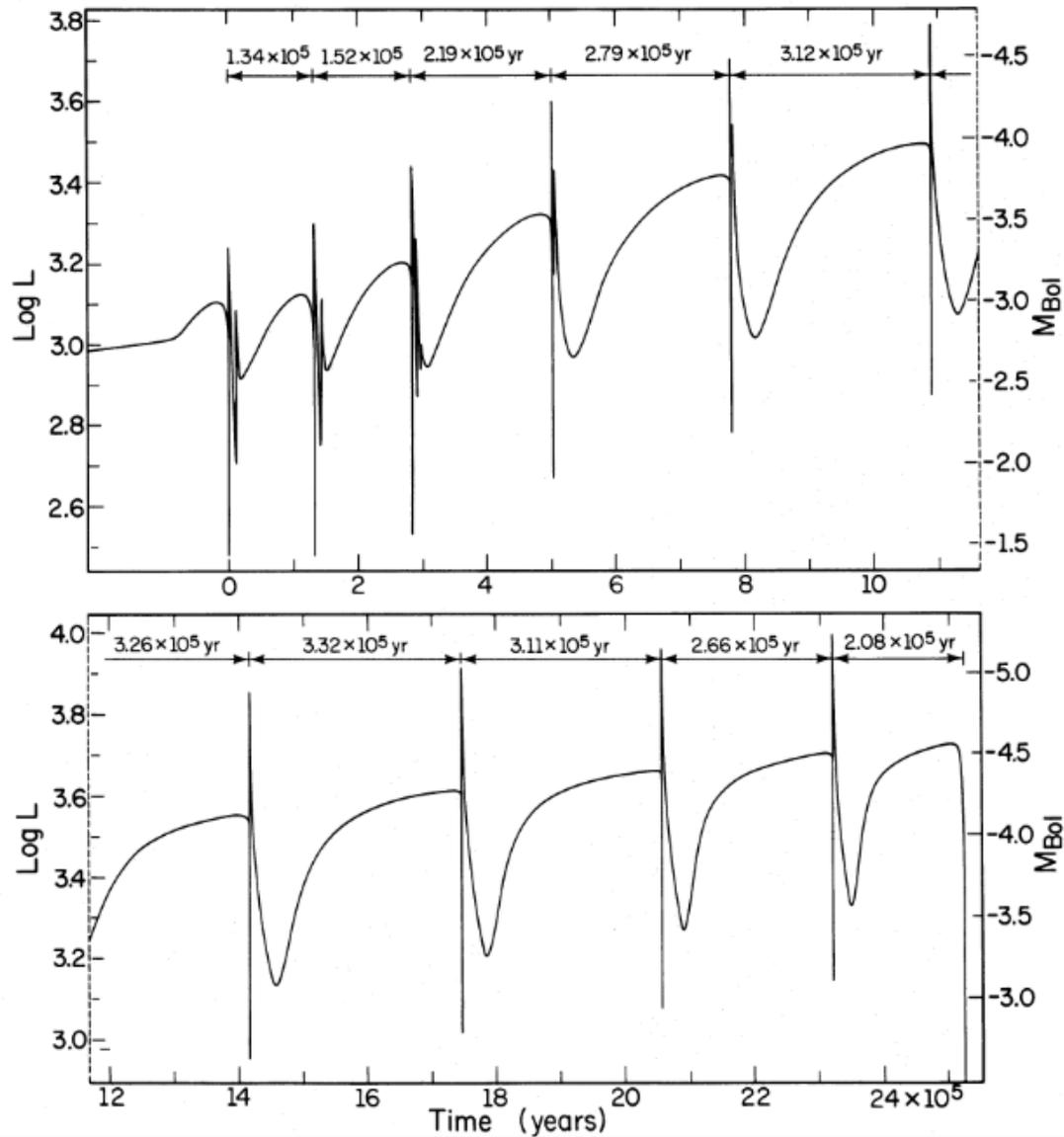
PLANETARY NEBULA
The gracious death of low mass stars
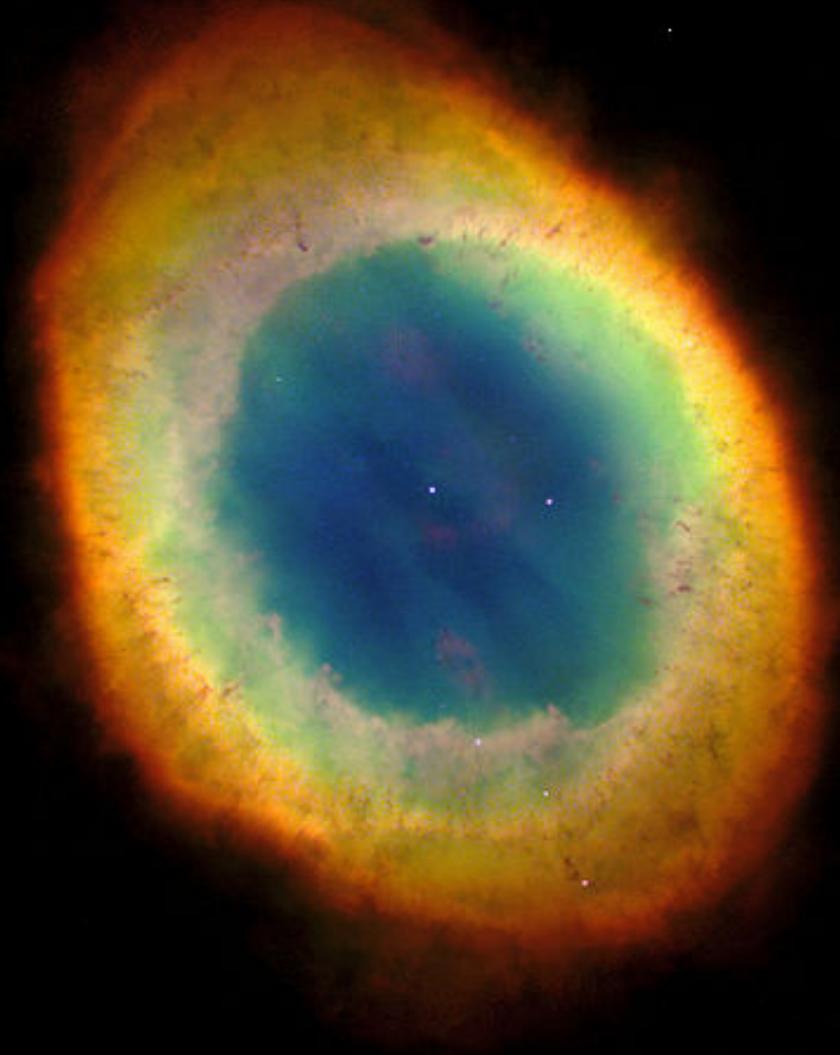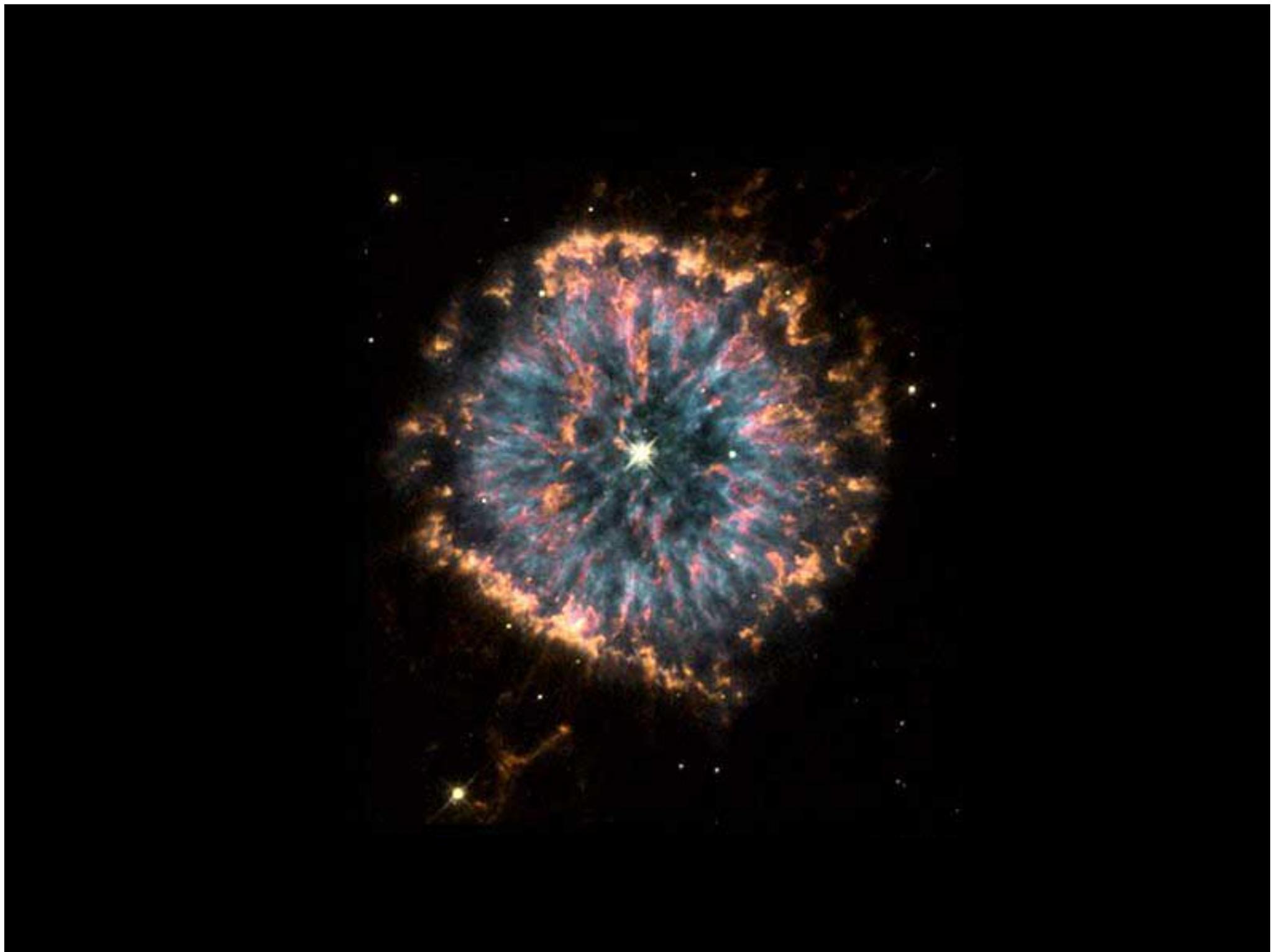
White dwarfs

White dwarfs are the exposed degenerate core of the star
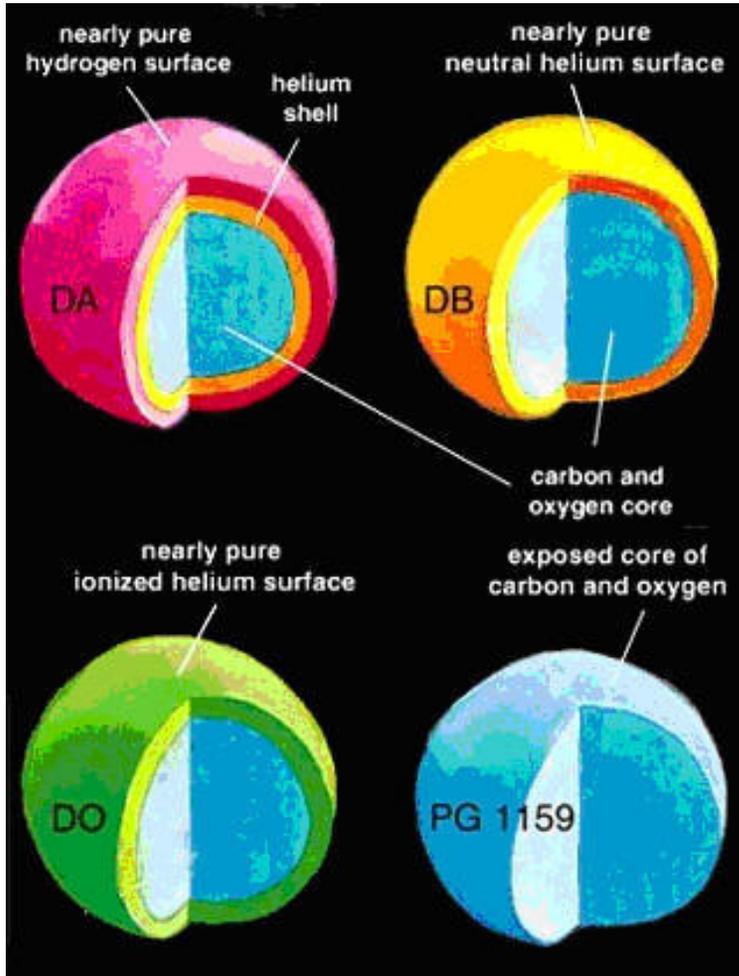
Types of white dwarfs
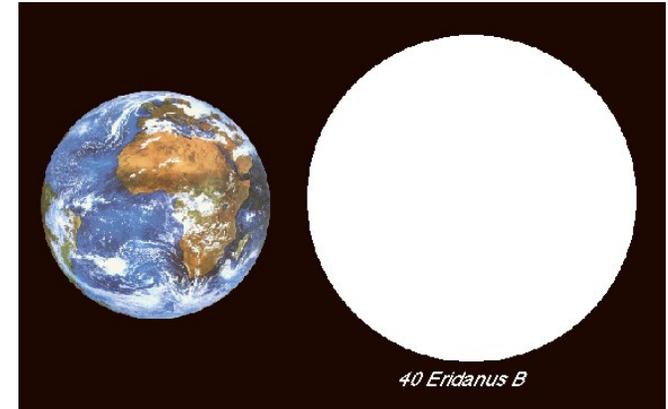
White dwarfs have planetary dimensions...
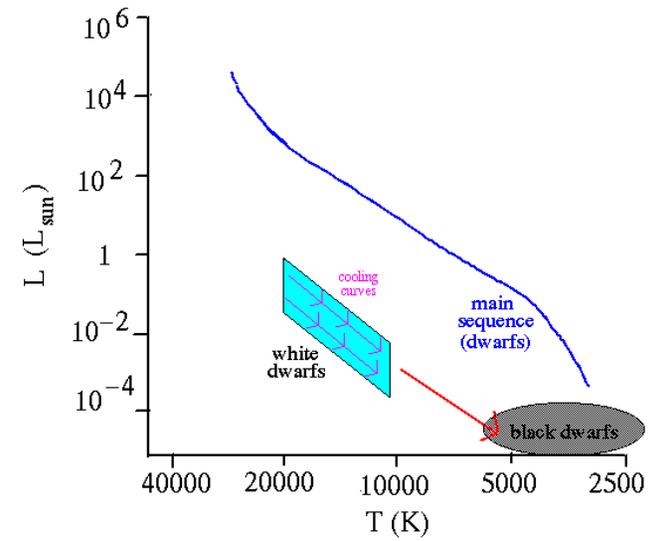
… and they do little but cooling.

White dwarfs

White dwarfs are the exposed degenerate core of the star

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.
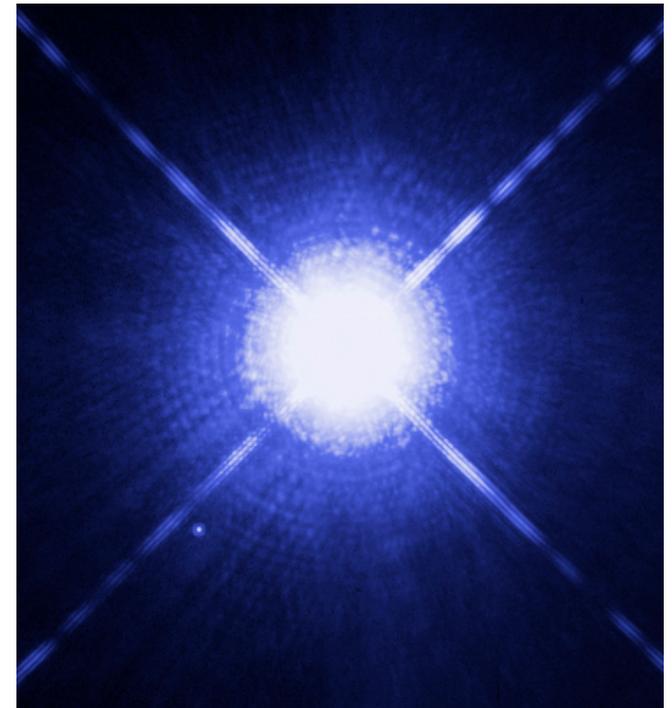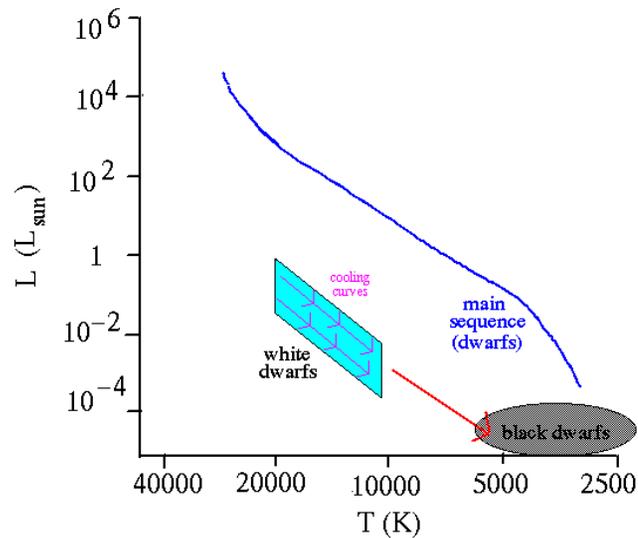
Sirius A (Main Sequence star)
and **Sirius B** (White Dwarf)

White Dwarf Structure

Atmosphere (1-10 km)

Zone of temperature change

Isothermal core

5 000 km

Relative density

Relative temperature

1.0

0.5

1.0

0.5

0.7 1.0

Radius fraction
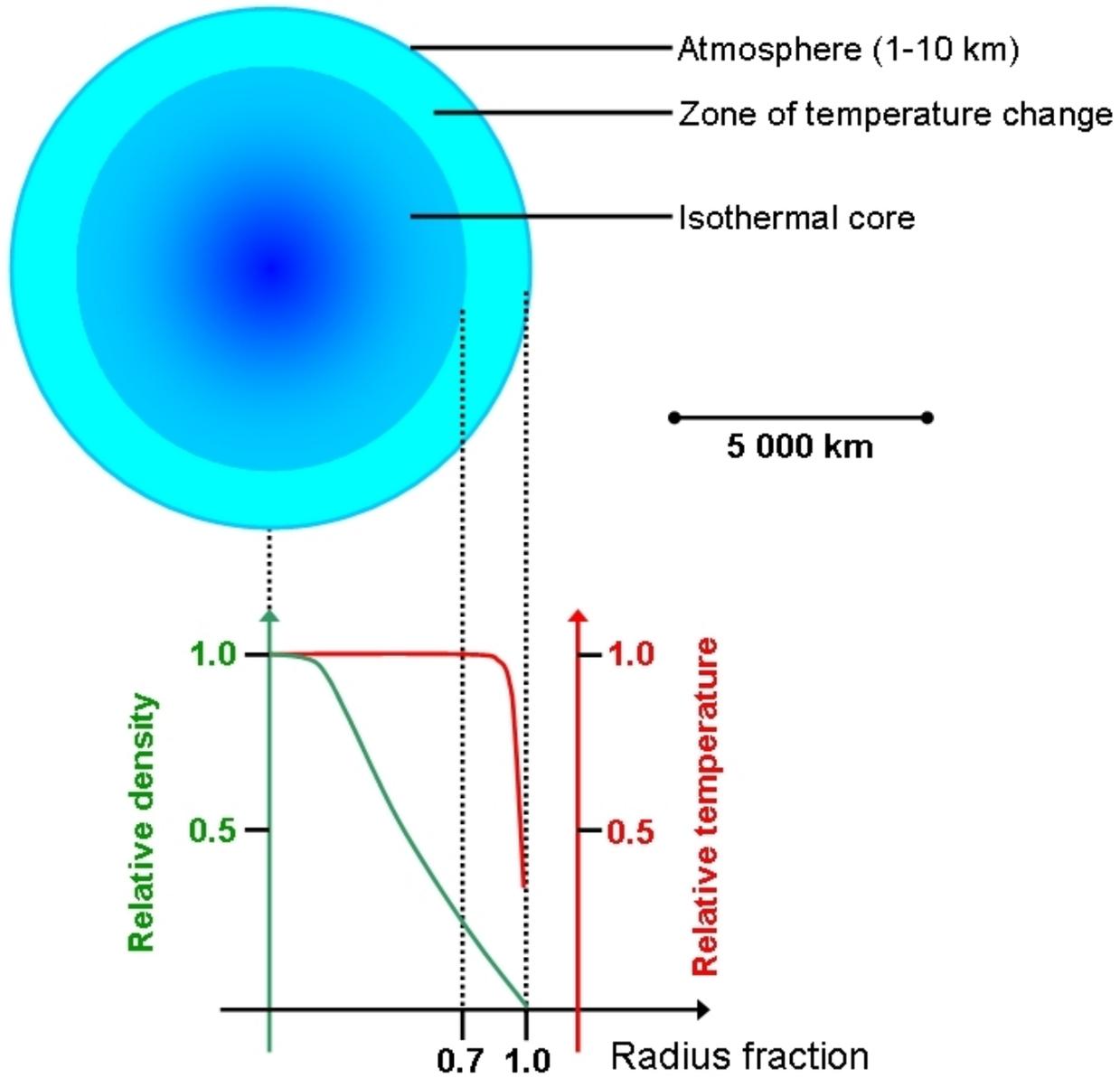
White dwarf Mass-Radius relationship
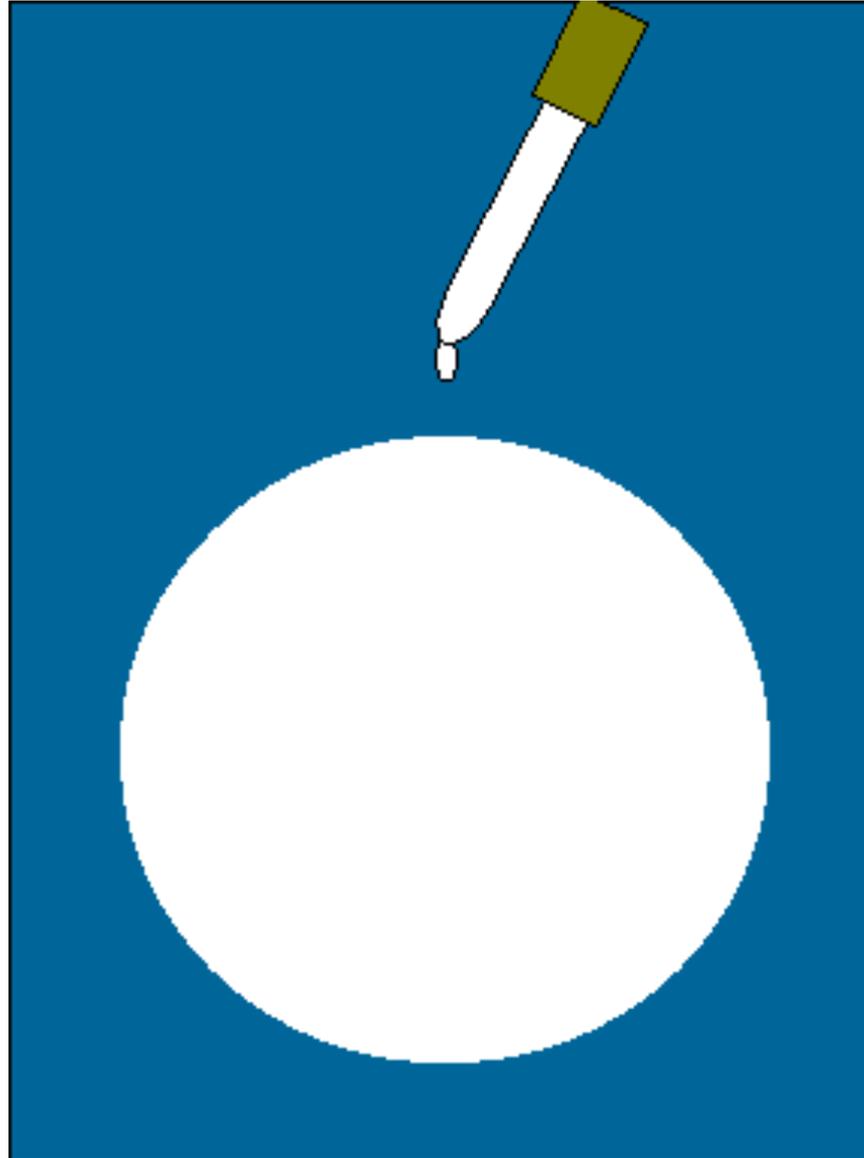
White dwarf Mass-Radius relationship
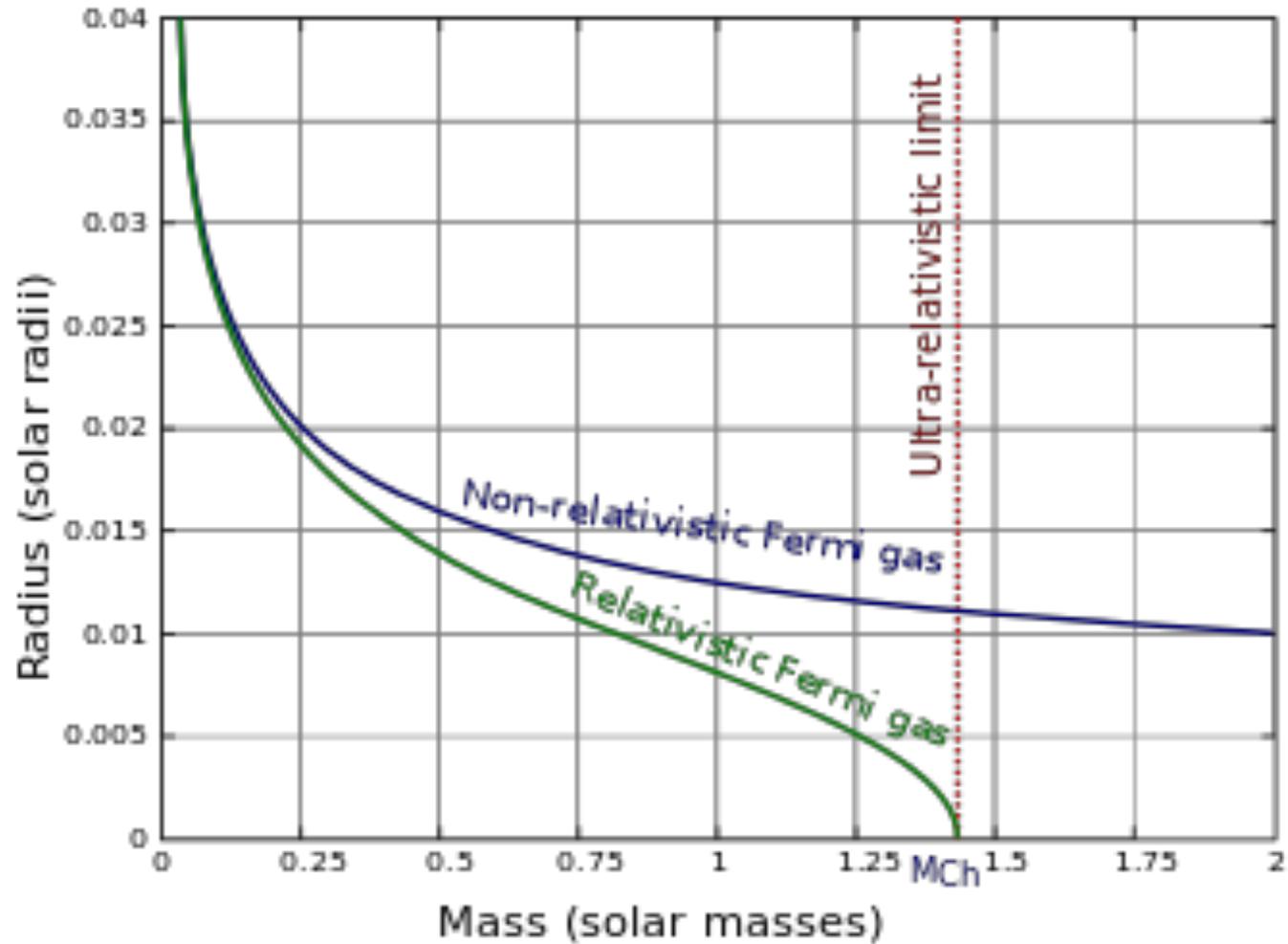
Evolution of a low mass star

Post-Main Sequence Evolution - Timescales

	~9 billion yrs	~1 billion yrs	~100 million yrs	~10,000 yrs	
Time spent as	Main sequence →	Red giant →	Yellow giant →	Planetary nebula →	White dwarf
Sun's age	4.5 billion yrs (now)	12.2 billion yrs	12.3 billion yrs	12.3305 billion yrs	12.3306 billion yrs
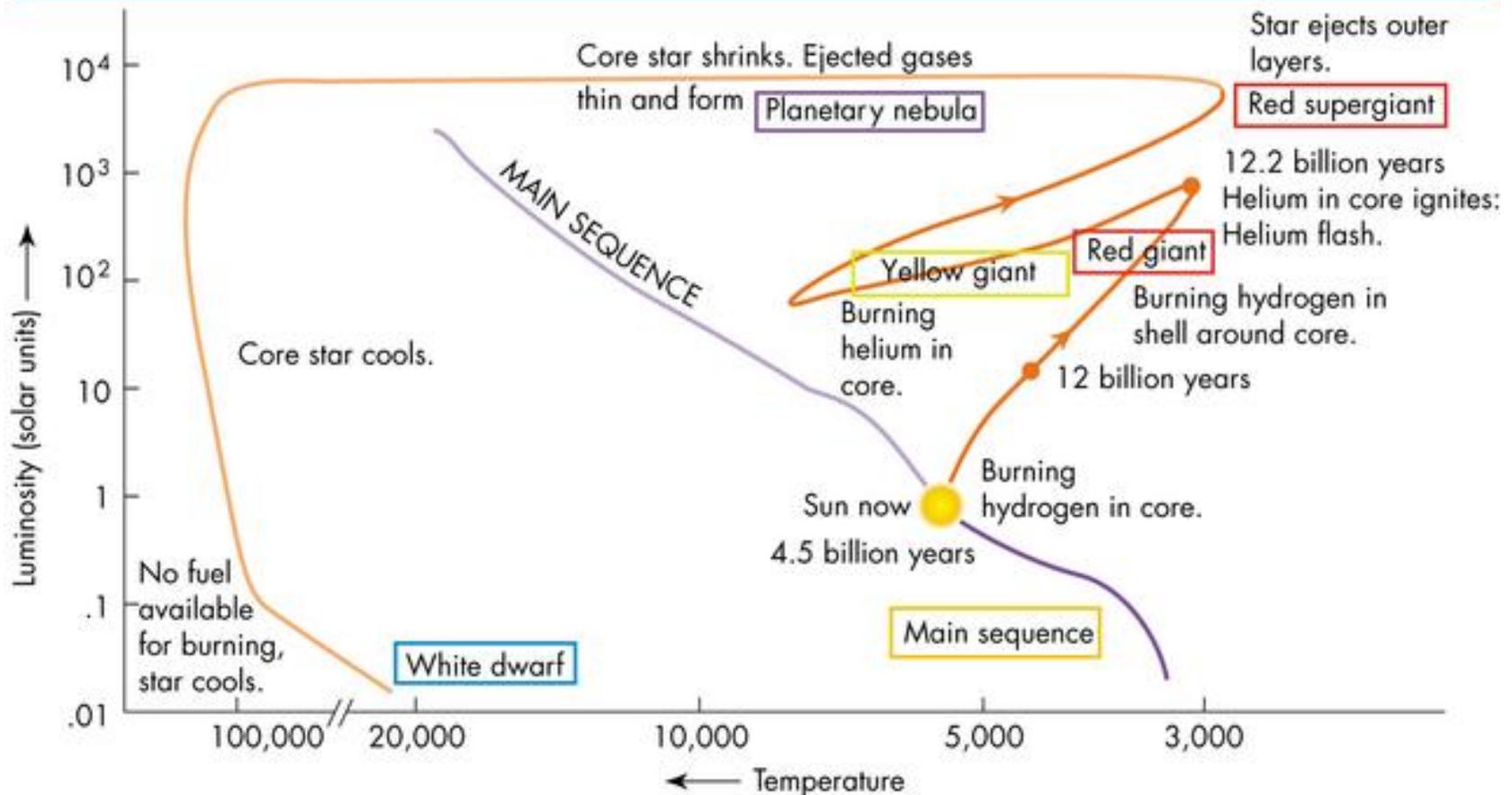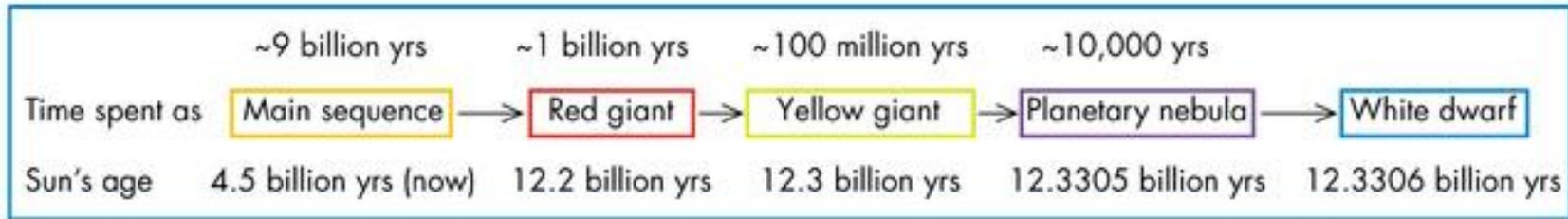
Evolution of high mass stars

The evolution we covered in last class is for low mass stars ($M < 4 M_\odot$)
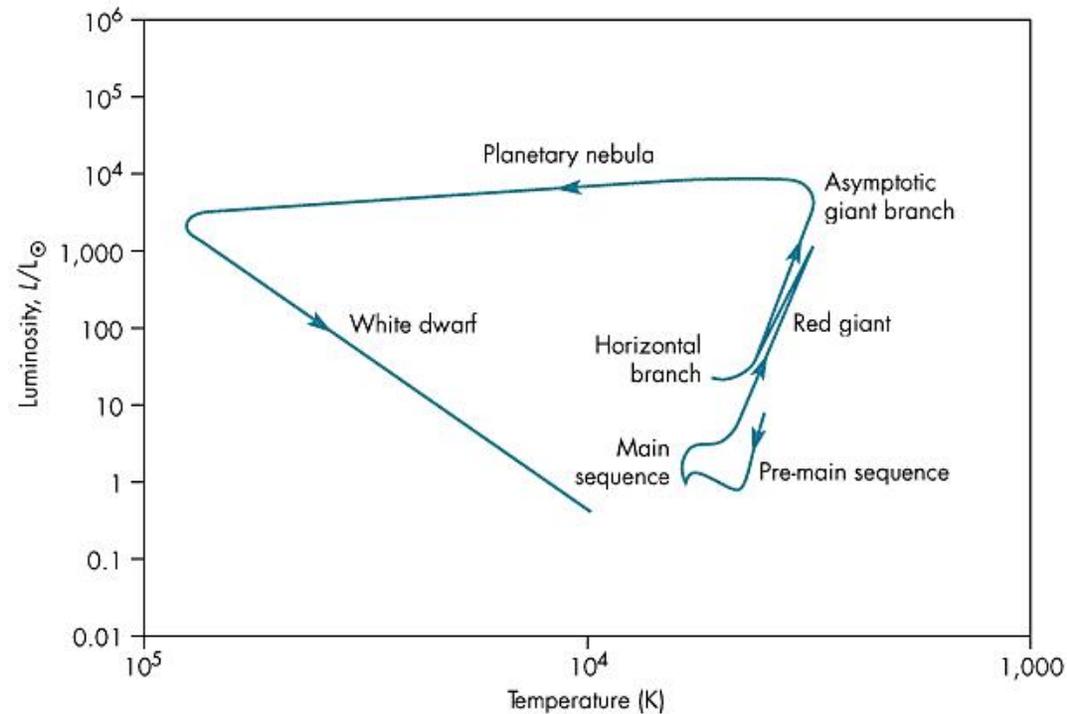
High mass stars differ basically due to the ***temperature of the core***.

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.

H Burning
Shell

He Burning
Shell

Inert
O-Ne-Mg
Core

C Burning
Shell

Red Supergiant
Envelope
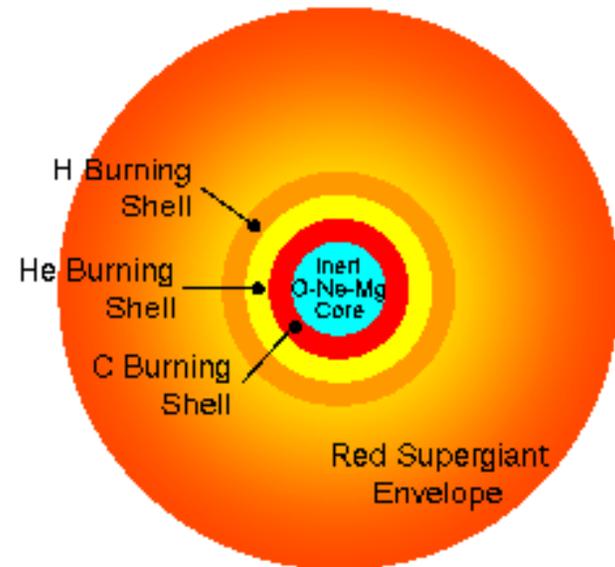
Evolution of high mass stars

$M > 8\,M_\odot$

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)

Helium-capture reactions

^{12}C → ^{16}O (8p, 8n) + ^{4}He

^{16}O → ^{20}Ne (10p, 10n) + ^{4}He

^{20}Ne → ^{24}Mg (12p, 12n) + ^{4}He

Other reactions

^{12}C + ^{16}O → ^{28}Si (14p, 14n)

^{16}O + ^{16}O → ^{31}S (16p, 15n)

^{28}Si + ^{28}Si → ^{56}Fe (26p, 30n)
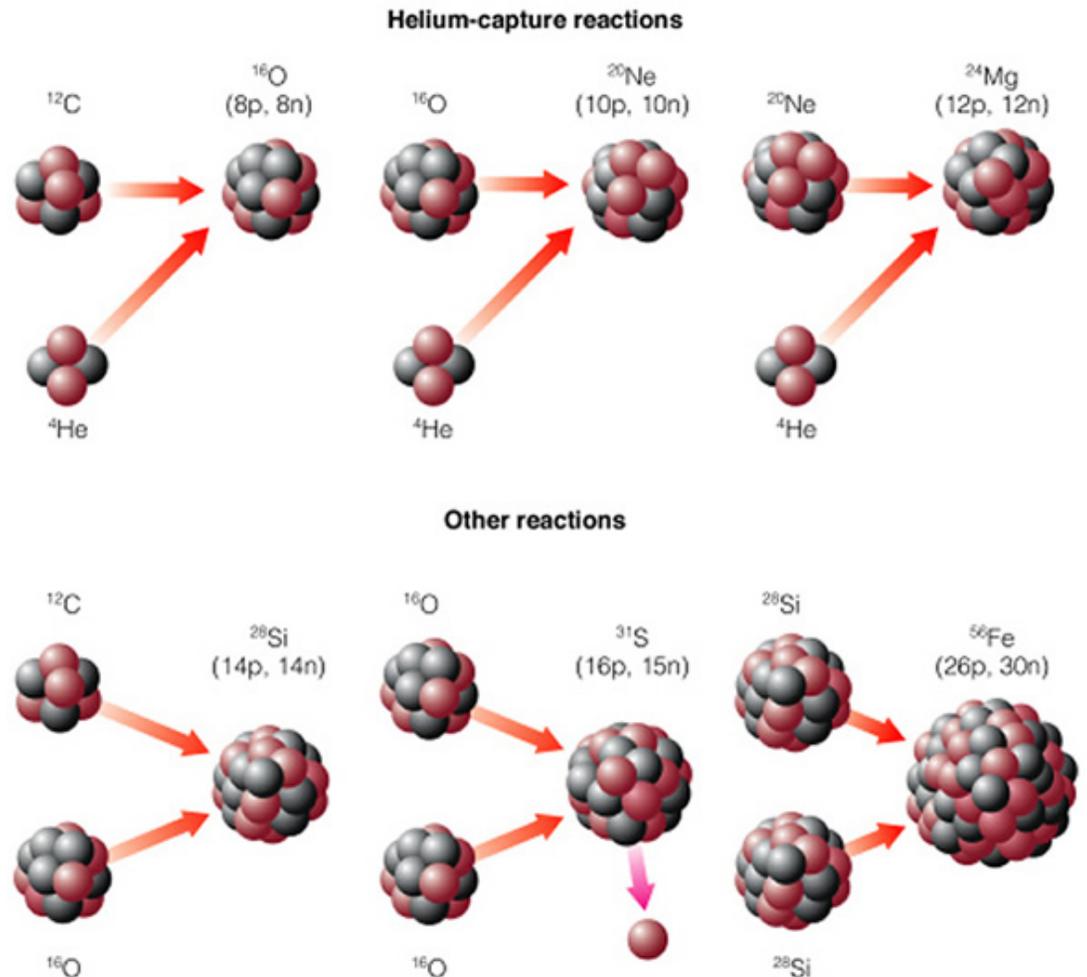
Alpha ladder

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
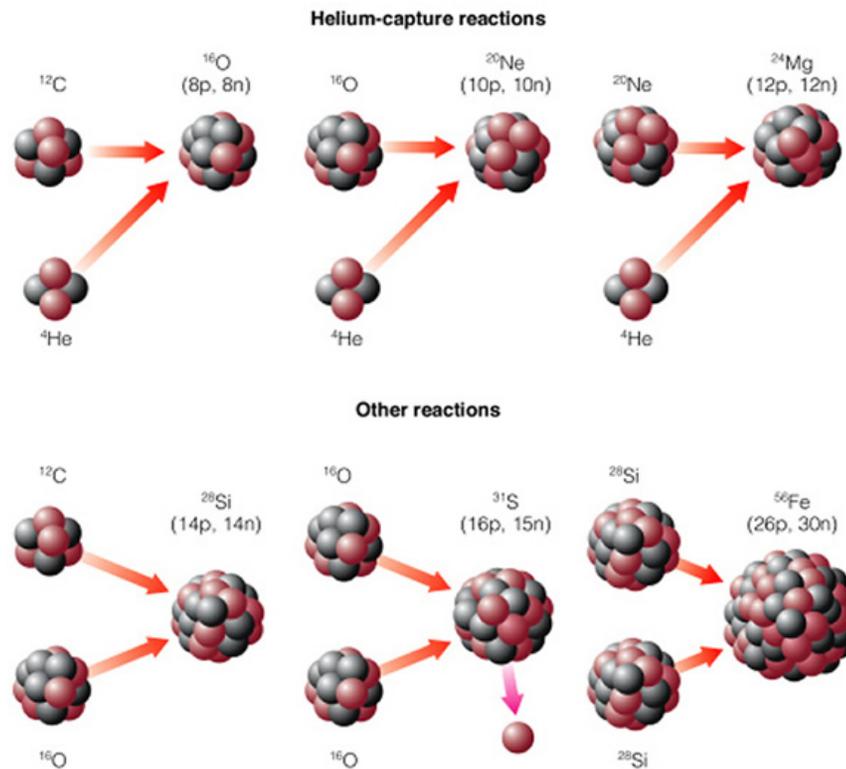
The Sun's abundance pattern

Because of the alpha ladder, elements with even atomic number are more abundant than those with odd
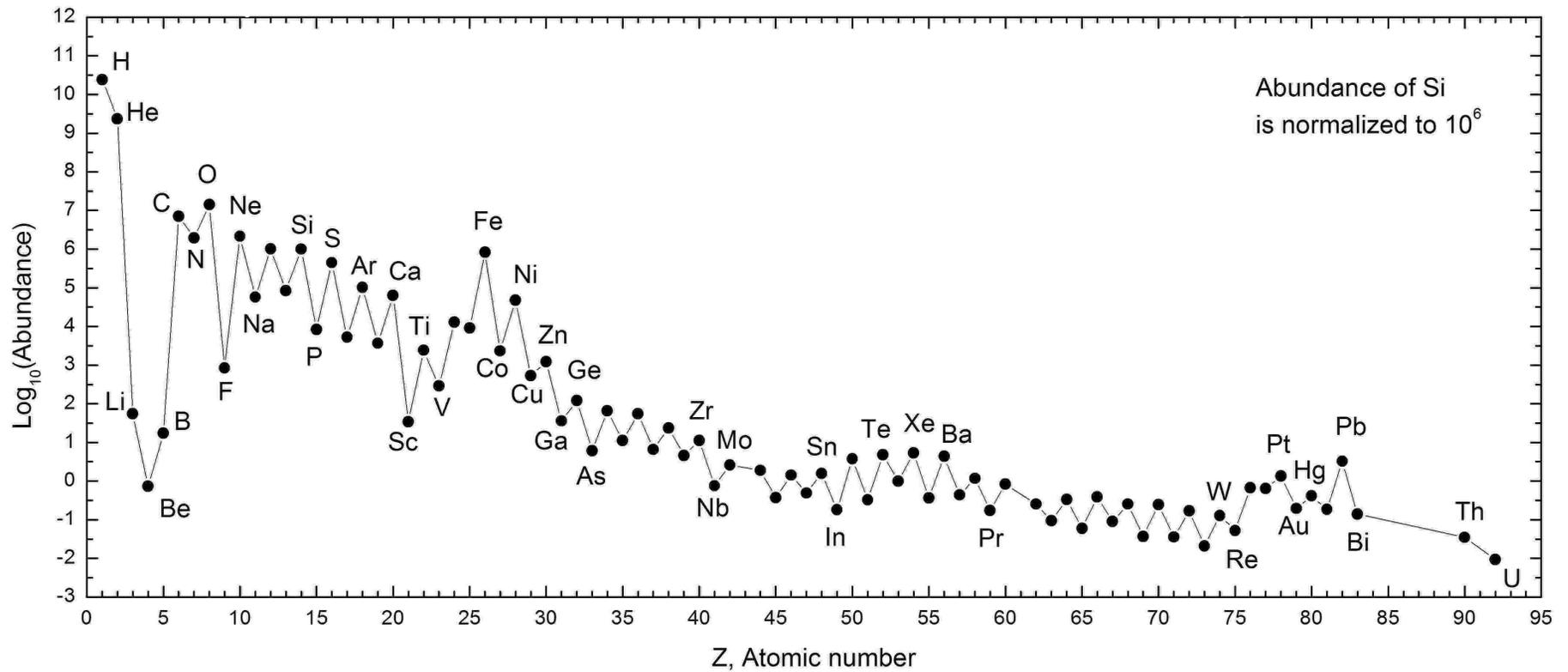
Evolution of high mass stars

$M > 8\,M_{\odot}$

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

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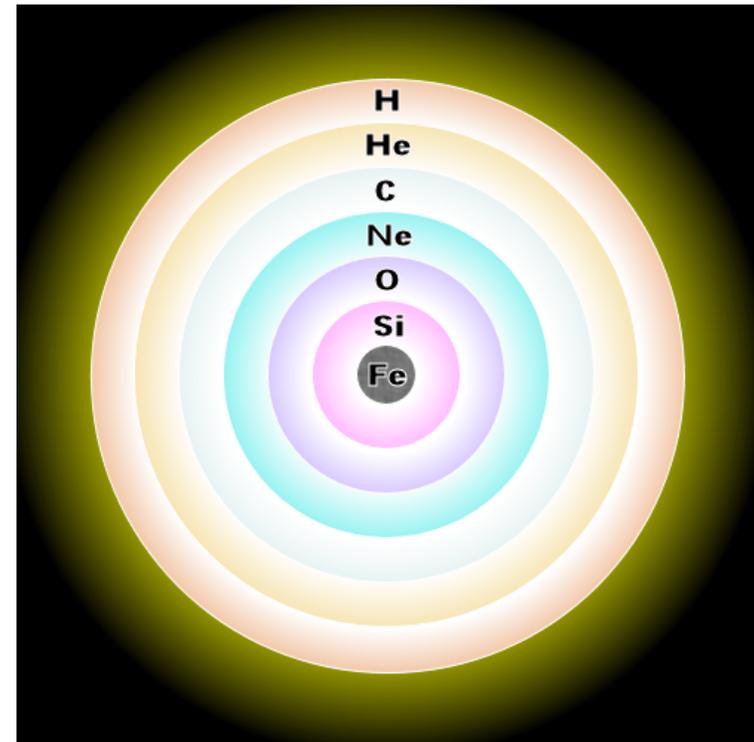
*But **Iron** is a **DEAD END** !!*

Iron is a dead end

Iron is the most tightly bound element
Fusion beyond Iron TAKES energy
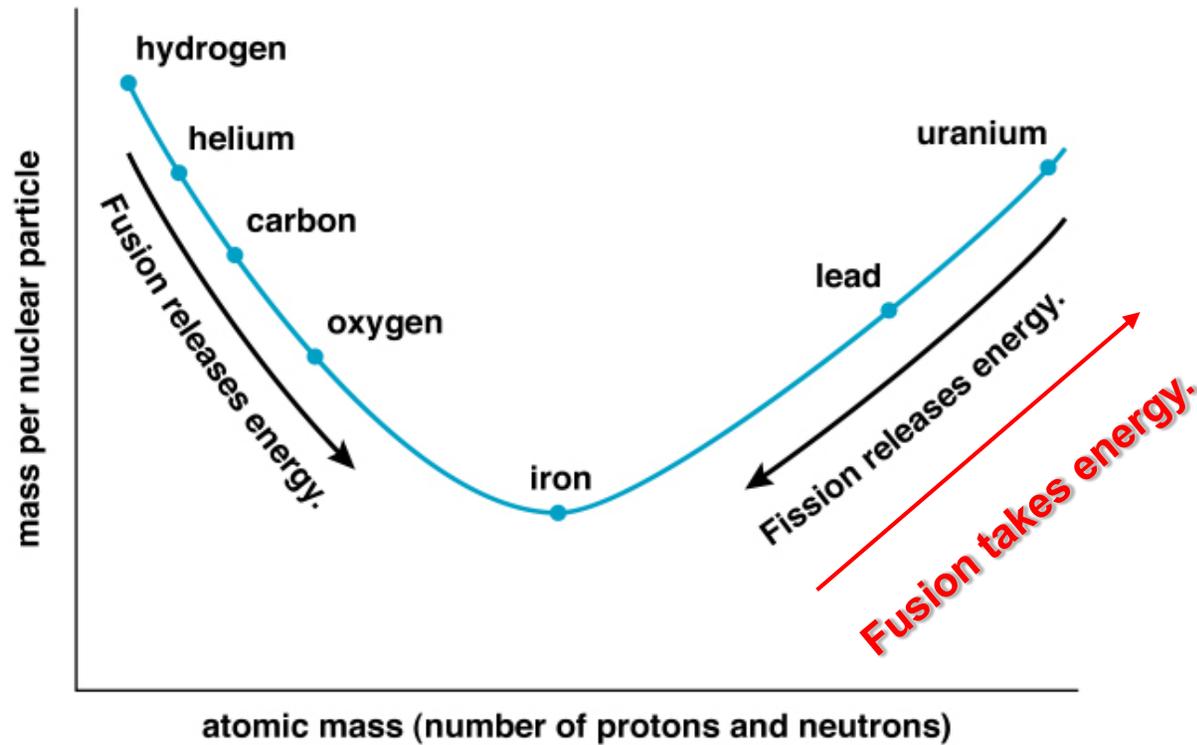
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No fusion reactions left to yield energy!!

Neutronization

At densities of 10^{10} g/cm^3
(remember: nuclear densities are ~10^{14} g/cm^3)
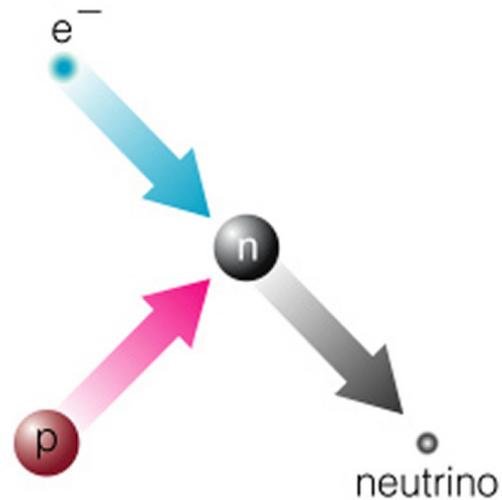
Proton + electron $\longrightarrow$ neutron + neutrino

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

Neutronization

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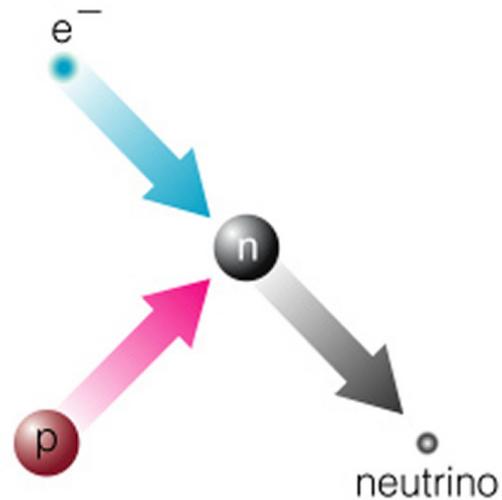
Electrons lost!

**electron degeneracy
pressure is gone!!**

Proton + electron $\longrightarrow$ neutron + neutrino

(p + e$^-$ $\longrightarrow$ n + ν)

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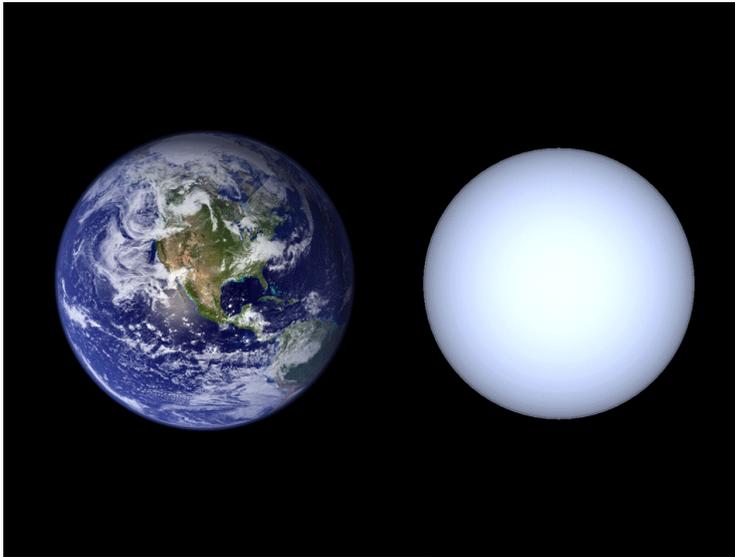
6000 km
10^{10} g/cm^3

A second later

Collapse speed: 0.25c

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

Nuclear densities!
*Neutron degeneracy
provides support against gravity*

The Thermonuclear Shock Wave

The sudden release of gravitational energy generates a ***shock wave***

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

Violently heats and accelerates the stellar envelope
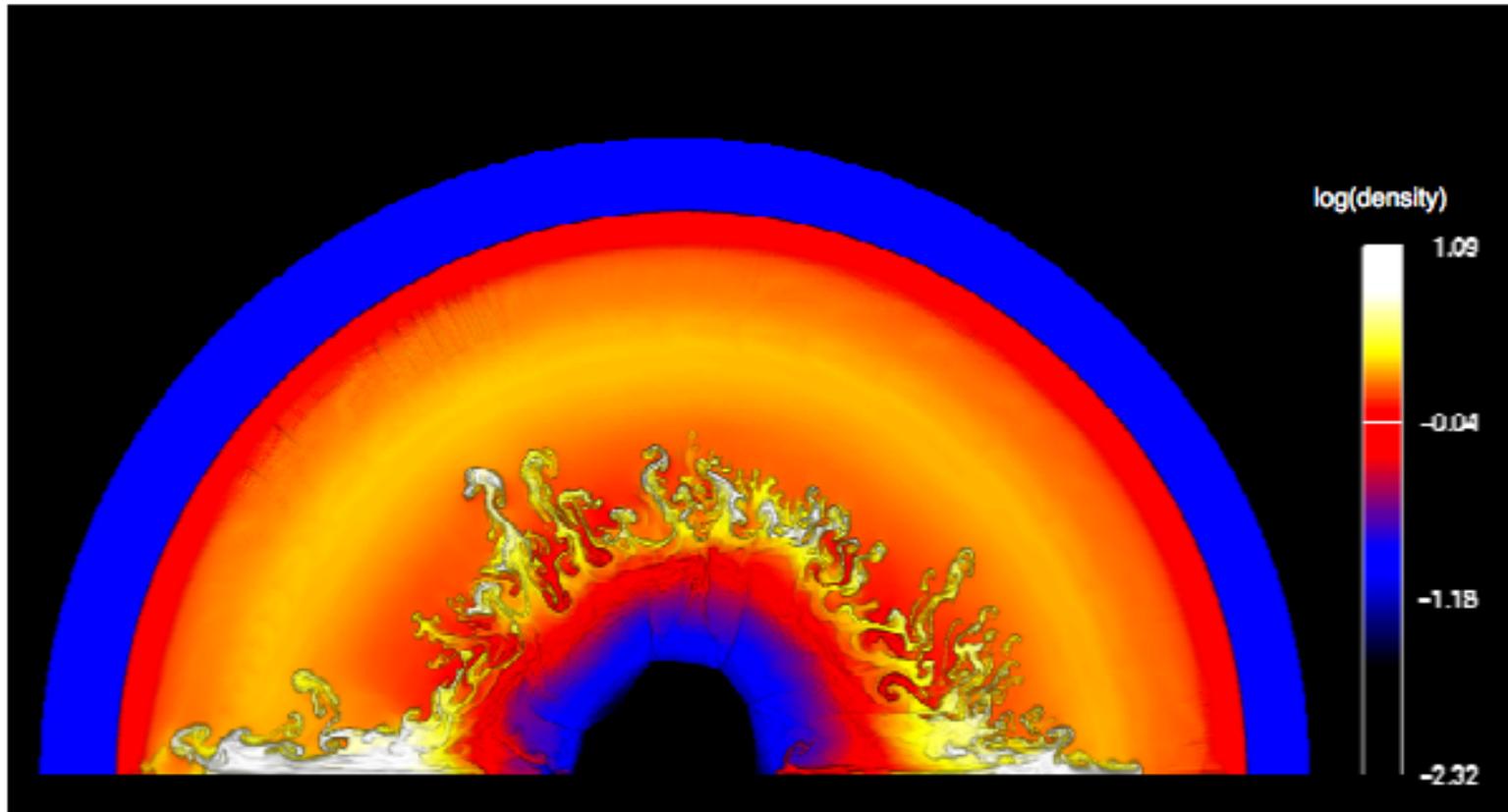
Supernova!

In a few hours, the shockwave reaches the surface

From the outside, the star is seen to explode.
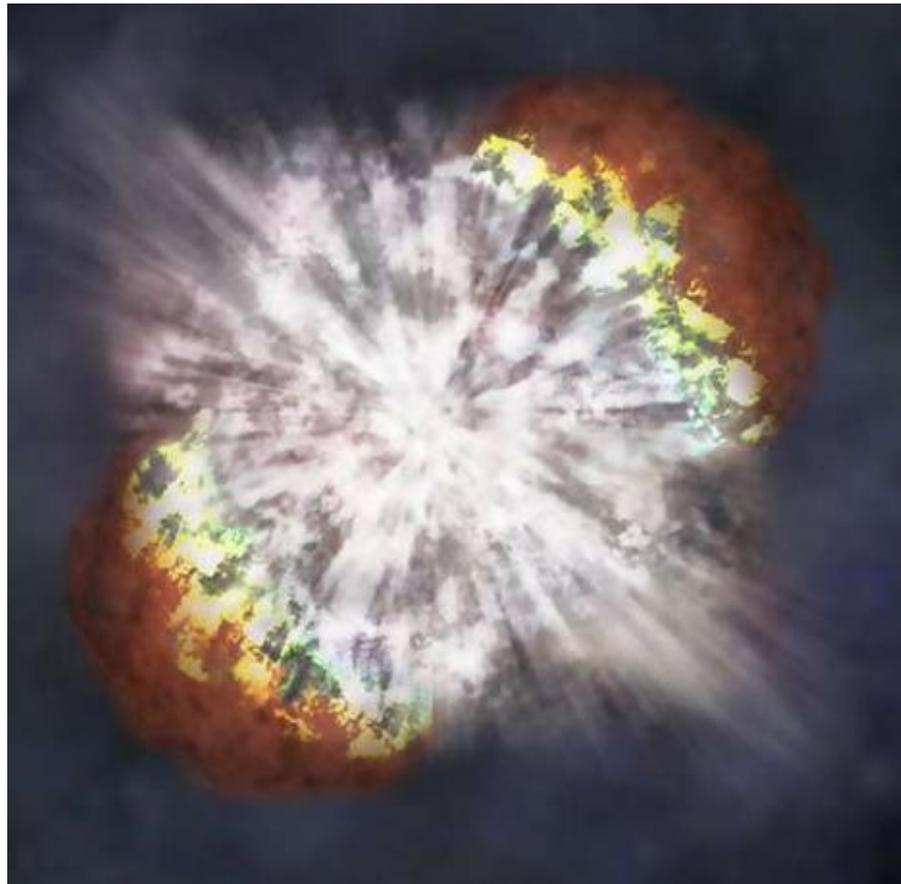
Supernova 1987A

Confirmation of the theory

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

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

Urca process

Free neutrons are unstable!

Neutron $\longrightarrow$ Proton + electron + neutrino

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

Proton + electron $\longrightarrow$ neutron + neutrino

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

Urca process

Free neutrons are unstable!

Beta decay

Neutron $\longrightarrow$ Proton + electron + neutrino

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

Inverse Beta Decay

Proton + electron $\longrightarrow$ neutron + neutrino

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

Urca process

Free neutrons are unstable!

Beta decay

Neutron $\longrightarrow$ Proton + electron + neutrino

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

Inverse Beta Decay

Proton + electron $\longrightarrow$ neutron + neutrino

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

Urca process

Free neutrons are unstable!

Beta decay

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

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

Inverse Beta Decay

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

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

A flood of neutrinos!!

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"

Surface of
Iron Core

Stalled shock front

heating region

Gain radius

Cooling region

Proto-neutron
Star
(mass 1.4 M$_{sun}$)

Fe

Fe

Fe

neutrinos

~80 km   100 km   200 km   1000 km
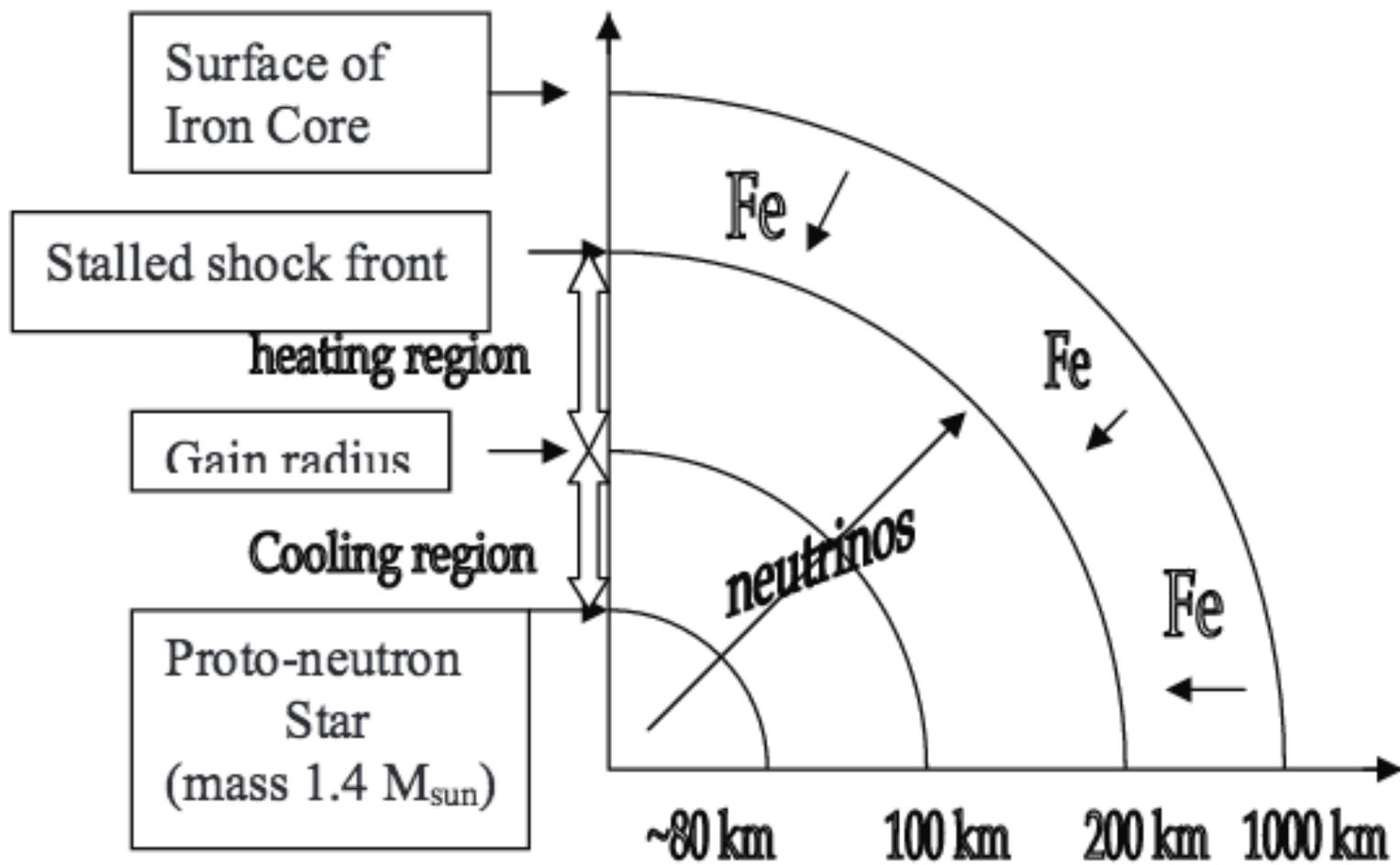
Figure 1. Core collapse Supernova

Neutron capture

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

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

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

Neutron capture

Beyond the Iron peak, nucleosynthesis occurs by
neutron capture and **beta decay**
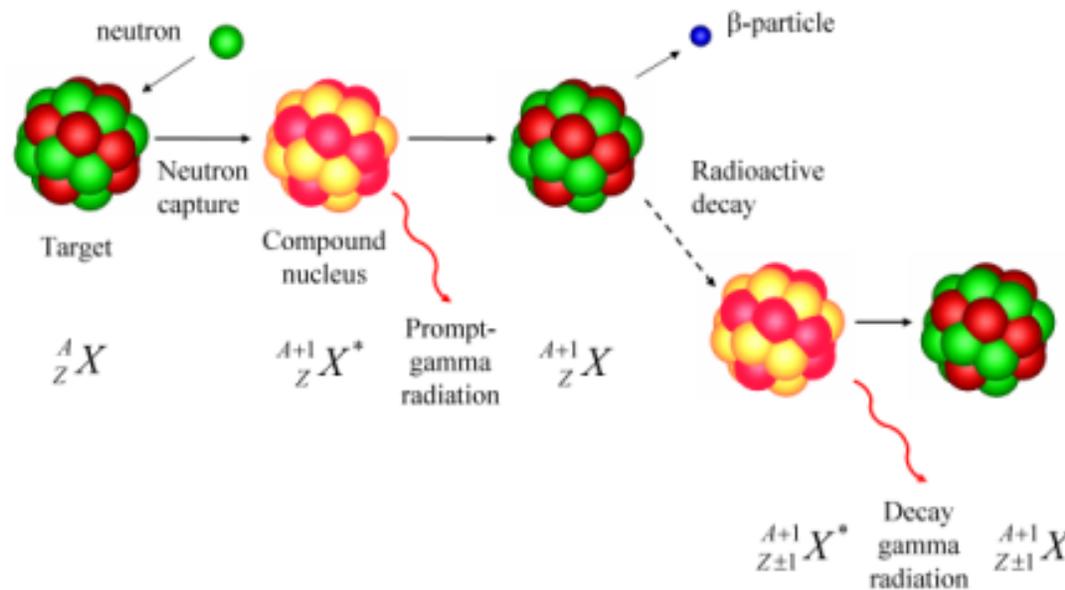
Neutron capture produces isotopes
Neutron capture proceeds until the nuclide goes unstable (radioactive)

If a proton decays, the atomic number decreases
But if a neutron decays, the atomic number increases!

Climbing the periodic table

Proton decays

Neutron decays

Chart of nuclides (proton number Z on the vertical axis).

Z = 33 (As): As60 | As61 | As62 | As63 | As64 >1.2 US | As65 0.19 S | As66 95.77 MS | As67 42.5 S | As68 151.6 S | As69 152 M | As70 52.6 M | As71 65.28 H | As72 26.0 H | As73 80.30 D | As74 17.77 D

Z = 32 (Ge): Ge58 | Ge59 | Ge60 ~30 MS | Ge61 40 MS | Ge62 >150 NS | Ge63 95 MS | Ge64 63.7 S | Ge65 30.9 S | Ge66 2.26 H | Ge67 18.9 M | Ge68 270.8 D | Ge69 39.05 H | Ge70 20.37 | Ge71 11.43 D | Ge72 27.31 | Ge73 7.76

Z = 31 (Ga): Ga56 | Ga57 | Ga58 | Ga59 | Ga60 >1.2 US | Ga61 | Ga62 116.12 MS | Ga63 32.4 S | Ga64 2.627 M | Ga65 1.52 M | Ga66 9.49 H | Ga67 3.2612 D | Ga68 67.629 M | Ga69 60.108 | Ga70 21.14 M | Ga71 39.892 | Ga72 14.10 H

Z = 30 (Zn): Zn54 | Zn55 | Zn56 36 MS | Zn57 40 MS | Zn58 86 MS | Zn59 182.0 MS | Zn60 2.38 M | Zn61 89.1 S | Zn62 9.186 H | Zn63 38.47 M | Zn64 48.63 | Zn65 244.26 D | Zn66 27.90 | Zn67 4.10 | Zn68 18.75 | Zn69 56.4 M | Zn70 0.62 | Zn71 2.45 M

Z = 29 (Cu): Cu52 | Cu53 <300 NS | Cu54 <75 NS | Cu55 >200 NS | Cu56 78 MS | Cu57 196.3 MS | Cu58 3.204 S | Cu59 81.5 S | Cu60 23.7 M | Cu61 3.333 H | Cu62 9.67 M | Cu63 69.17 | Cu64 12.700 H | Cu65 30.83 | Cu66 5.120 M | Cu67 61.83 H | Cu68 31.1 S | Cu69 2.85 M | Cu70 4.5 S

Z = 28 (Ni): Ni49 >350 NS | Ni50 >500 NS | Ni51 >200 NS | Ni52 38 MS | Ni53 45 MS | Ni54 143 MS | Ni55 204 MS | Ni56 6.075 D | Ni57 35.60 H | Ni58 68.077 | Ni59 76000 Y | Ni60 26.223 | Ni61 1.140 | Ni62 3.634 | Ni63 100.1 Y | Ni64 0.926 | Ni65 2.5172 H | Ni66 54.6 H | Ni67 21 S | Ni68 29 S | Ni69 11.4 S

Z = 27 (Co): Co48 | Co49 <35 NS | Co50 44 MS | Co51 >200 NS | Co52 115 MS | Co53 240 MS | Co54 193.28 MS | Co55 17.53 H | Co56 77.233 D | Co57 271.74 D | Co58 70.86 D | Co59 100 | Co60 1925.1 D | Co61 1.650 H | Co62 1.50 M | Co63 27.4 S | Co64 0.30 S | Co65 1.20 S | Co66 0.233 S | Co67 0.425 S | Co68 0.18 S

Z = 26 (Fe): Fe46 20 MS | Fe47 27 MS | Fe48 44 MS | Fe49 70 MS | Fe50 155 MS | Fe51 305 MS | Fe52 8.275 H | Fe53 8.51 M | Fe54 5.845 | Fe55 2.73 Y | Fe56 91.754 | Fe57 2.119 | Fe58 0.282 | Fe59 44.472 D | Fe60 1.500000 Y | Fe61 5.98 M | Fe62 68 S | Fe63 6.1 S | Fe64 0.4 S | Fe65 0.4 S | Fe66 0.44 S | Fe67 0.47 S

Z = 25 (Mn): Mn45 <70 NS | Mn46 41 MS | Mn47 100 MS | Mn48 158.1 MS | Mn49 382 MS | Mn50 283.29 MS | Mn51 46.2 M | Mn52 5.591 D | Mn53 3740000 Y | Mn54 312.11 D | Mn55 100 | Mn56 2.5789 H | Mn57 85.4 S | Mn58 3.0 S | Mn59 4.6 S | Mn60 51 S | Mn61 0.67 S | Mn62 671 MS | Mn63 275 MS | Mn64 89 MS | Mn65 88 MS | Mn66 66 MS

Z = 24 (Cr): Cr44 53 MS | Cr45 50 MS | Cr46 0.26 S | Cr47 500 MS | Cr48 21.56 H | Cr49 42.3 M | Cr50 4.345 | Cr51 27.7025 D | Cr52 83.789 | Cr53 9.501 | Cr54 2.365 | Cr55 3.497 M | Cr56 5.94 M | Cr57 21.1 S | Cr58 7.0 S | Cr59 0.74 S | Cr60 0.57 S | Cr61 0.27 S | Cr62 0.19 S | Cr63 0.11 S | Cr64 >1 US | Cr65 >150 NS

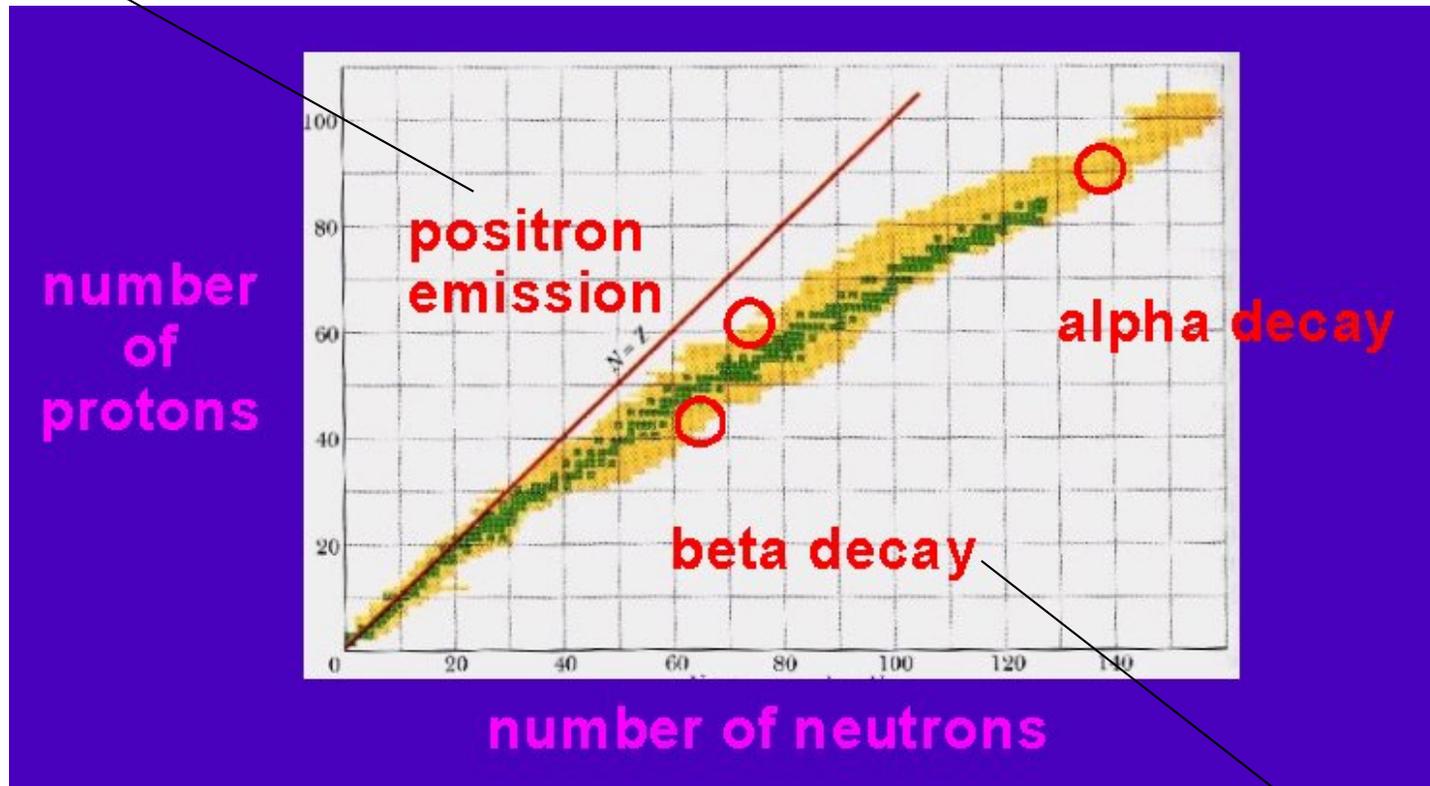**Z = 23 (V):** V43 >800 MS | V44 111 MS | V45 547 MS | V46 422.50 MS | V47 32.6 M | V48 15.9735 D | V49 330 D | V50 0.250 | V51 99.750 | V52 3.743 M | V53 1.60 M | V54 49.8 S | V55 6.54 S | V56 0.24 S | V57 0.34 S | V58 205 MS | V59 118 MS | V60 0.20 S | V61 >150 NS | V62 >150 NS | V63 >150 NS | V64 >150 NS

Z = 22 (Ti): Ti42 199 MS | Ti43 509 MS | Ti44 60.0 Y | Ti45 184.8 M | Ti46 8.25 | Ti47 7.44 | Ti48 73.72 | Ti49 5.41 | Ti50 5.18 | Ti51 5.76 M | Ti52 1.7 M | Ti53 32.7 S | Ti54 >1 US | Ti55 0.32 S | Ti56 0.19 S | Ti57 0.18 S | Ti58 >150 NS | Ti61 ~10 MS

Z = 21 (Sc): Sc41 596.3 MS | Sc42 680.67 MS | Sc43 3.891 H | Sc44 3.97 H | Sc45 100 | Sc46 83.79 D | Sc47 3.3492 D | Sc48 43.67 H | Sc49 57.2 M | Sc50 102.5 S | Sc51 12.4 S | Sc52 8.2 S | Sc53 >3 S | Sc54 225 MS | Sc55 120 MS | Sc56 80 MS | Sc57

Z = 20 (Ca): Ca40 96.94 | Ca41 103000 Y | Ca42 0.647 | Ca43 0.135 | Ca44 2.09 | Ca45 162.61 D | Ca46 0.004 | Ca47 4.536 D | Ca48 0.187 | Ca49 8.718 M | Ca50 13.9 S | Ca51 10.0 S | Ca52 4.6 S | Ca53 90 MS | Ca54 | Ca56 10 MS

Z = 19 (K): K39 93.2581 | K40 0.0117 | K41 6.7302 | K42 12.360 H | K43 22.3 H | K44 22.13 M | K45 17.3 M | K46 105 S | K47 17.50 S | K48 6.8 S | K49 1.26 S | K50 472 MS | K51 365 MS | K52 105 MS | K53 30 MS | K54 10 MS

Z = 18 (Ar): Ar38 0.0632 | Ar39 269 Y | Ar40 99.6003 | Ar41 109.34 M | Ar42 32.9 Y | Ar43 5.37 M | Ar44 11.87 M | Ar45 21.48 S | Ar46 8.4 S | Ar47 ~700 MS | Ar48 | Ar49 ~170 NS | Ar50 ~170 NS | Ar51 >200 NS | Ar52 10 MS | Ar53 3 MS

Z = 17 (Cl): Cl37 24.23 | Cl38 37.24 M | Cl39 55.6 M | Cl40 1.35 M | Cl41 38.4 S | Cl42 6.8 S | Cl43 3.3 S | Cl44 0.56 S | Cl45 400 MS | Cl46 223 MS | Cl47 >200 MS | Cl48 >200 NS | Cl49 ~170 NS | Cl51 >200 NS

Z = 16 (S): S36 0.02 | S37 5.05 M | S38 170.3 M | S39 11.5 S | S40 8.8 S | S41 2.6 S | S42 0.56 S | S43 220 MS | S44 123 MS | S45 82 MS | S46 >200 NS | S47 >200 NS | S48 >200 NS | S49 <200 NS

Nucleosynthesis summary

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, AGB and SN
Po - U	84-92	R process in SN