Variabilities & Instabilities ⋆ in Stars ⋆

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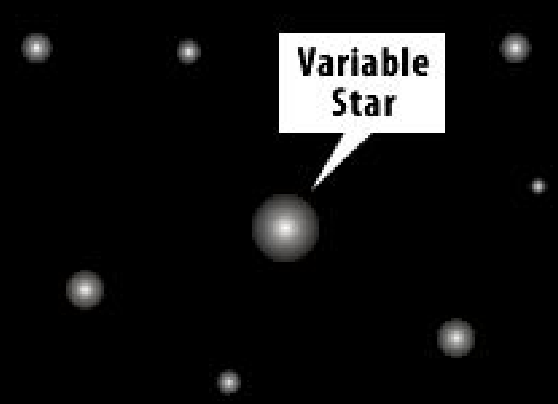
Astronomisches Institut RUB

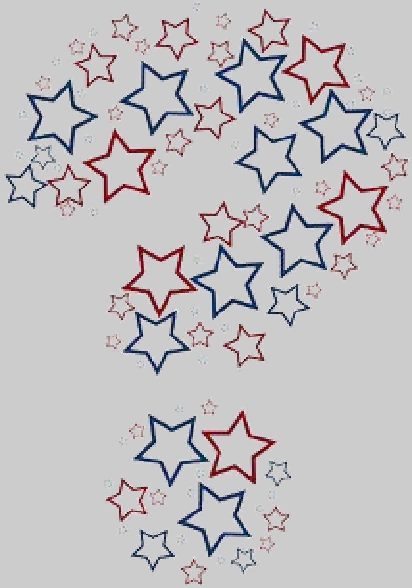


star formation

stellare parameters

stellar structure

What is a star



stellare parameters

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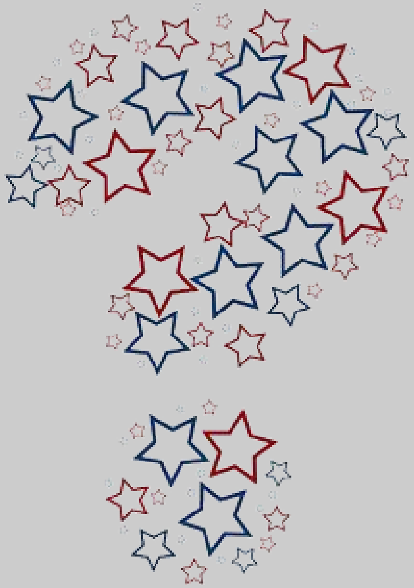

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parameters

initial mass: 0.07 – 120 $M_\odot$

< (approximately) 7 $M_\odot$ low mass stars
> (approximately) 7 $M_\odot$ massive stars

Luminosity:	$10^{-2} – 10^{6}\ L_\odot$
Radius:	$0.01 – 1000\ R_\odot$
temperatur at surface (↔ T_{eff}):	3000 – 100000 K
temperatur in the core:	$10^6 – 5\ 10^9$ K
lifetime:	$10^6 – 10\ 10^9$ years

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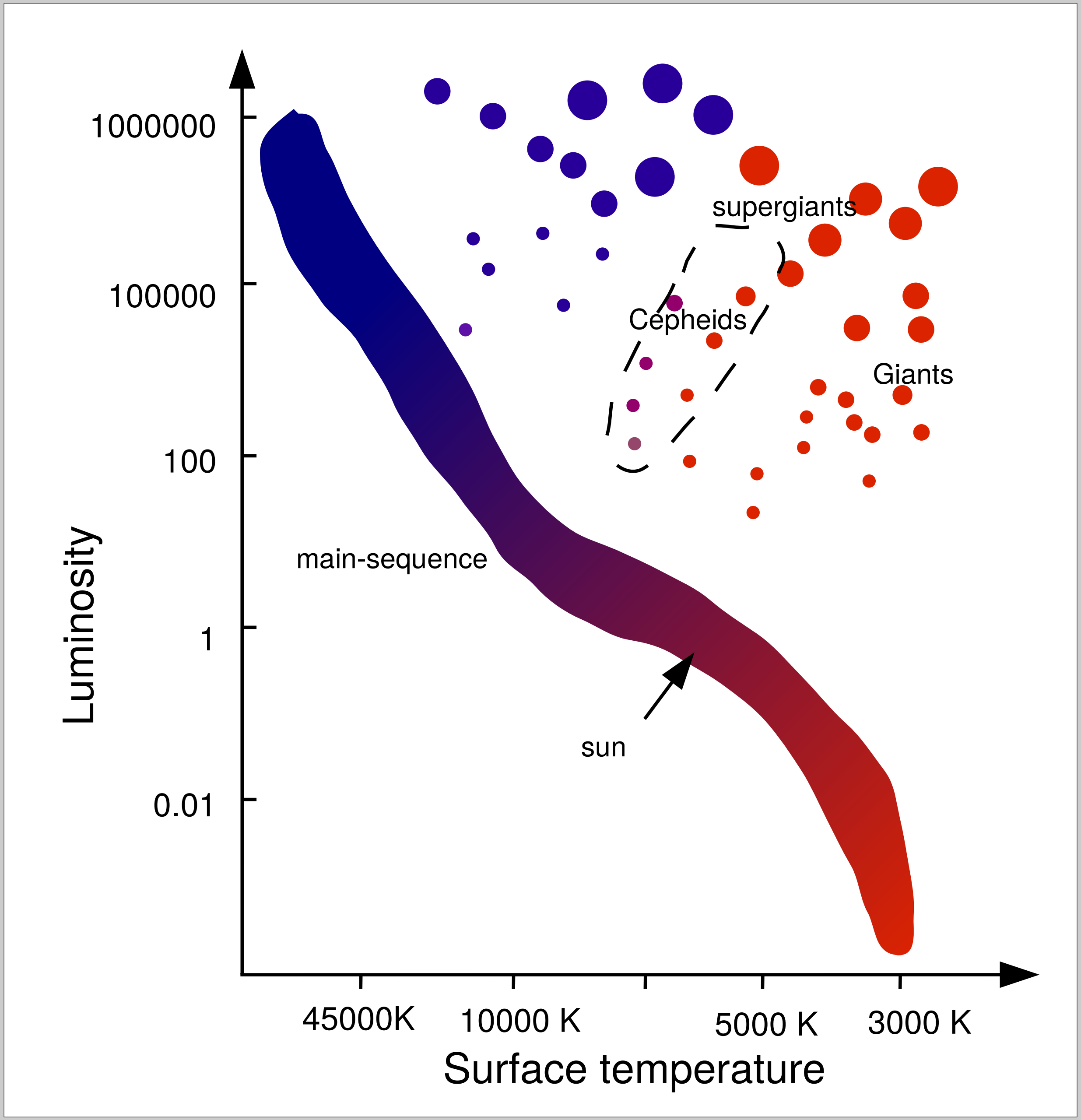
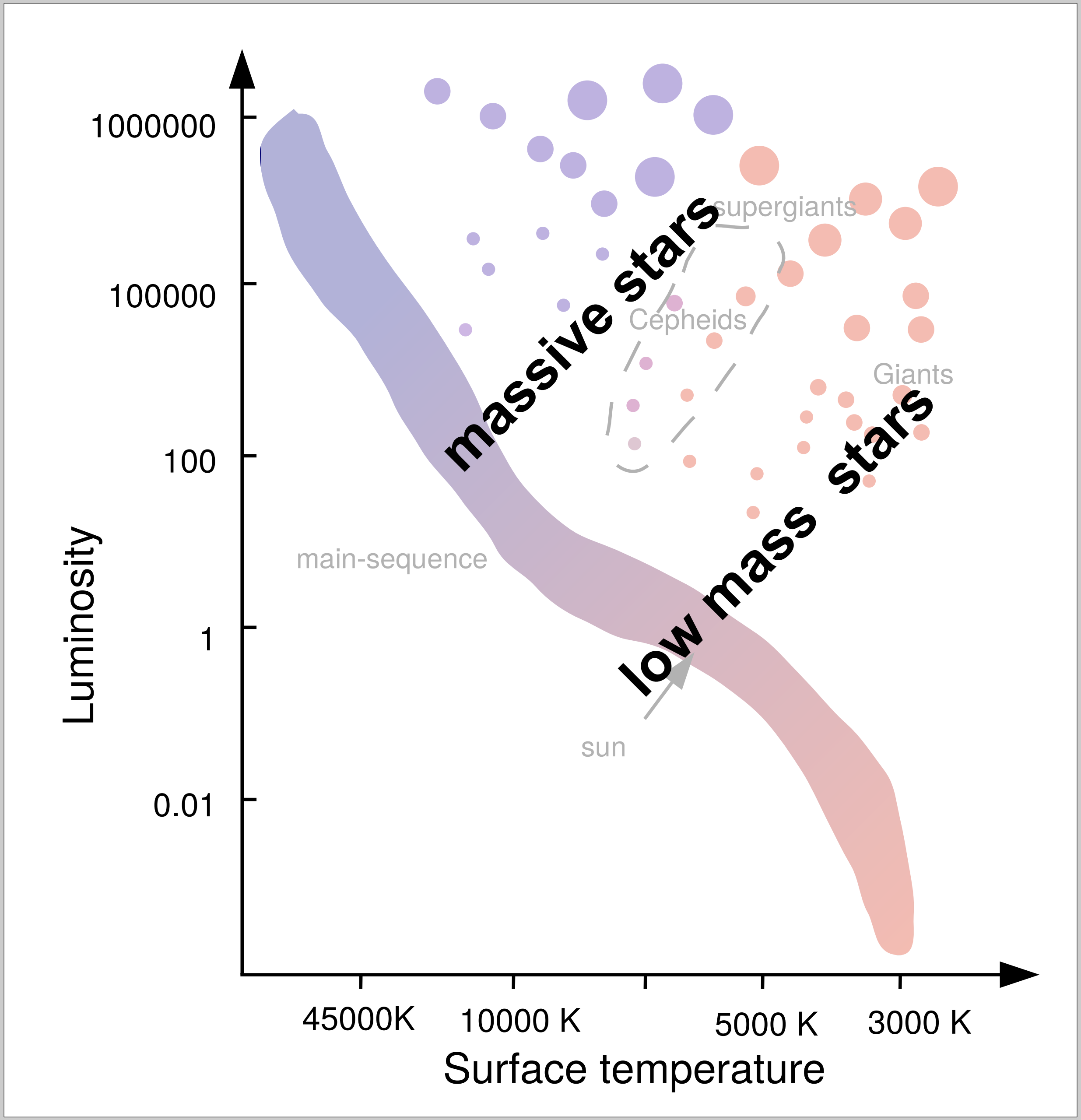
Hertzsprung-Russel-Diagram



schematic

Hertzsprung-Russel-Diagram



schematic

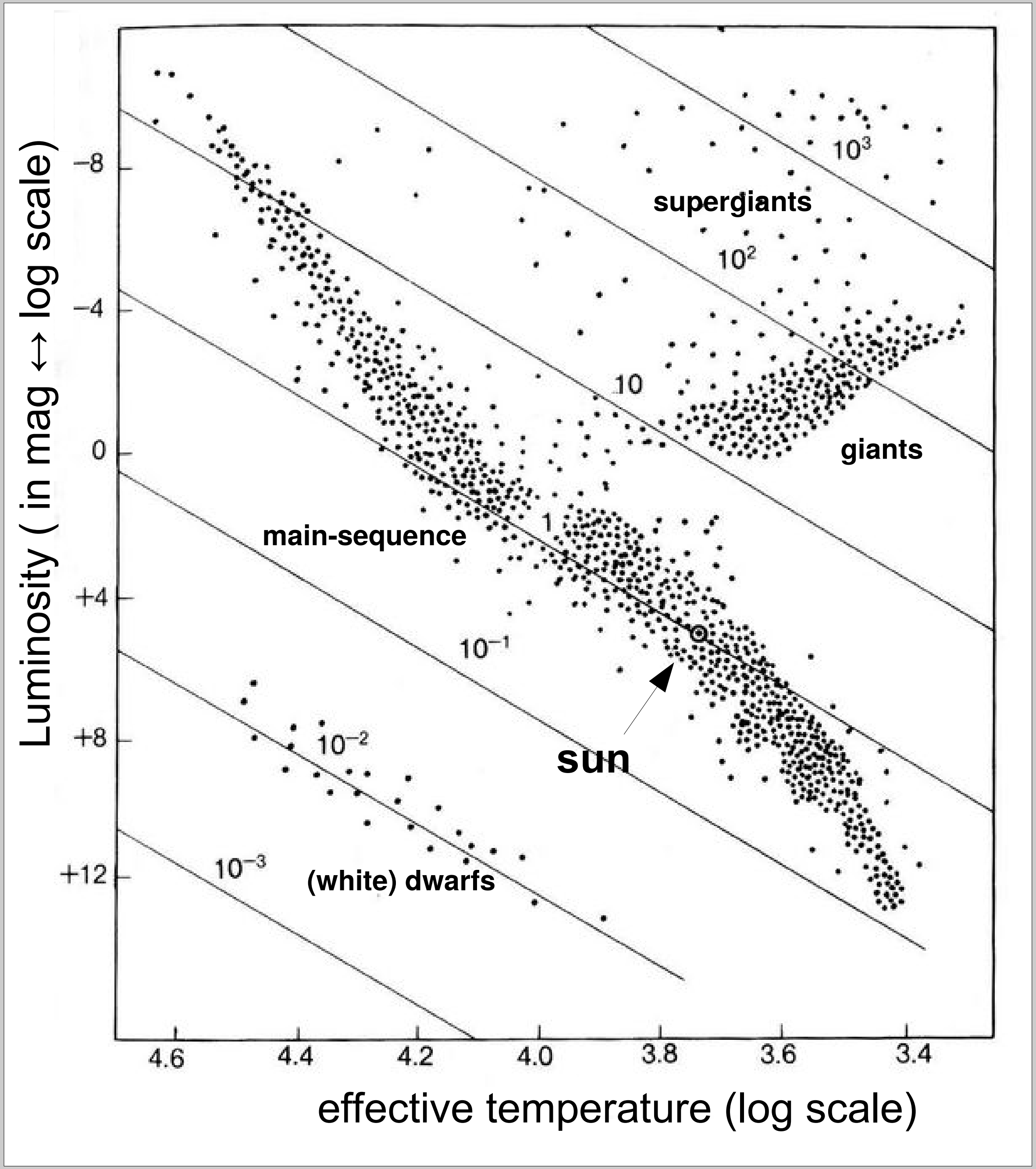
$\gtrsim 7\,M_\odot$

massive stars

$\lesssim 7\,M_\odot$

low mass stars

Stellar radii in the HRD



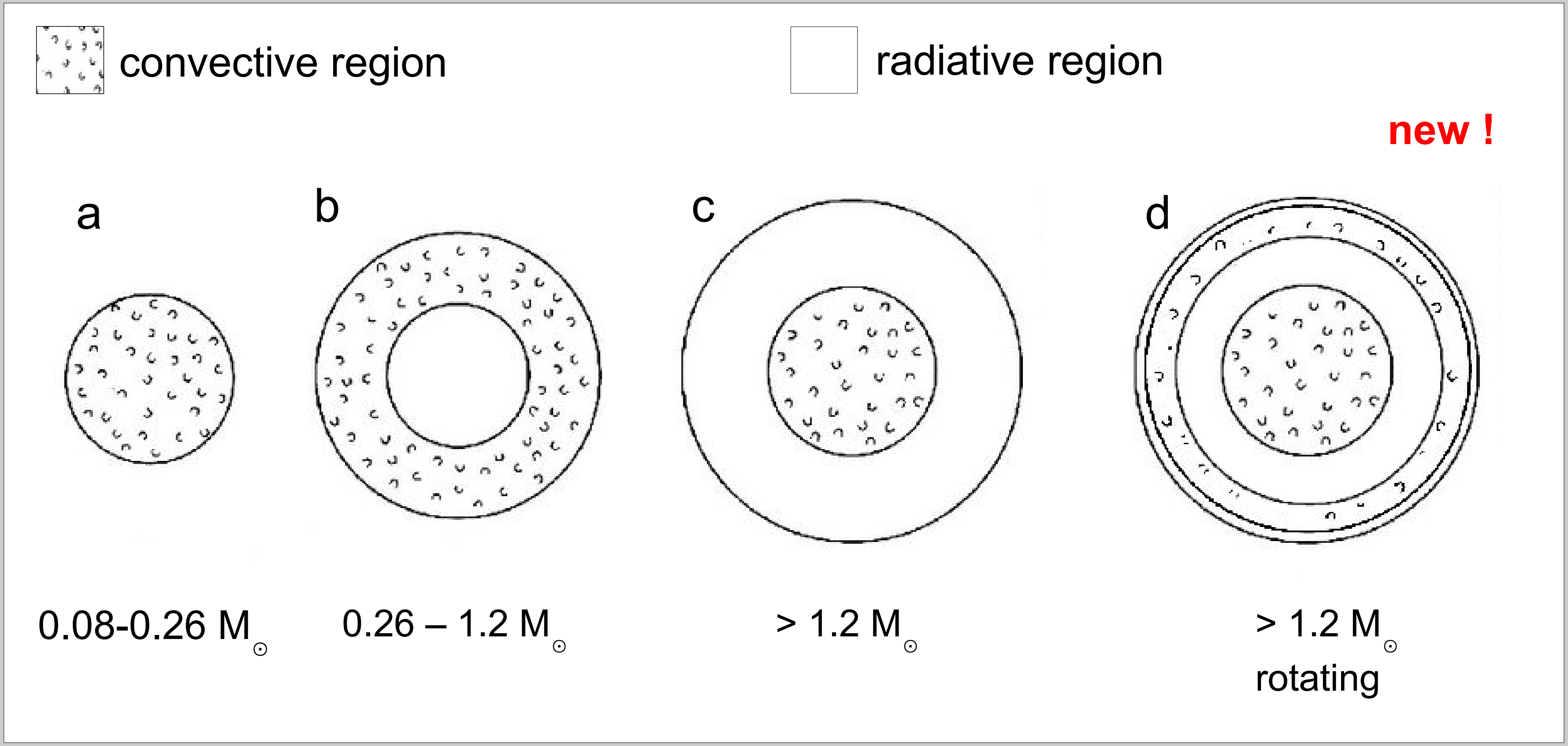
Innere Structure (main-sequence stars)

a) low mass stars 0.08-0.26 $M_\odot$

b) low mass stars up to 1.2 $M_\odot$

c) low mass stars & massive stars above 1.2 $M_\odot$

d) low mass stars & massive stars above 1.2 $M_\odot$ with **Rotation !**



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star formation

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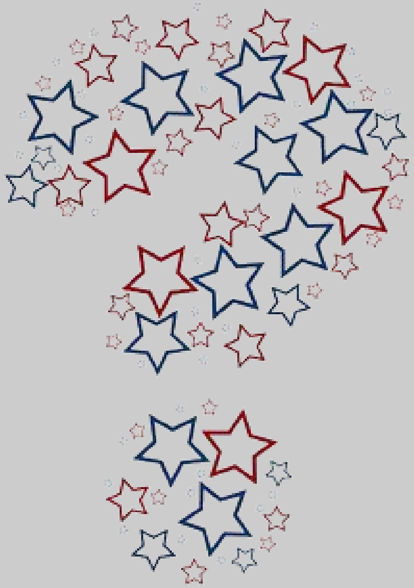
What is a star



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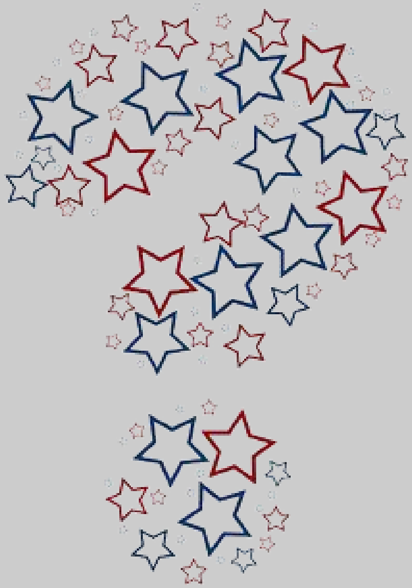
stellar structure

What is a star



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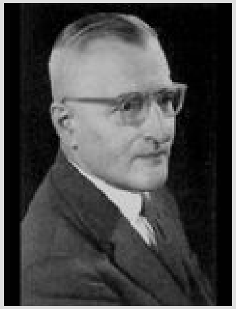
stellar structure

stellar structure Vogt – Russell theorem



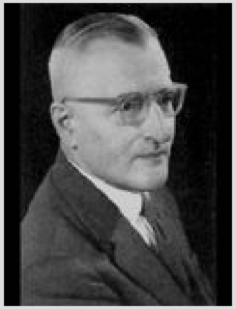
Vogt-Russell theorem:

the structure (radius, luminosity,etc.)
of a star is uniquely
determined by its mass (M) and the amount of
chemical elements ↔ melaticity (Z)

(Vogt 1926, Russell 1927)

OKAY

stellar structure Vogt – Russell theorem



Vogt-Russell theorem:

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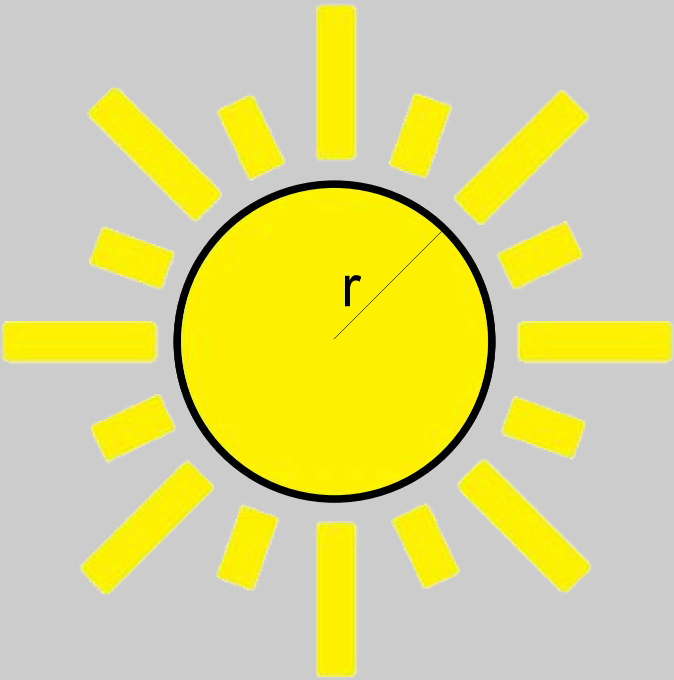
(Vogt 1926, Russell 1927)

OKAY but UPDATES
Mass loss ↔ **stellar winds** (dM/dt)
rotation (v_{rot}) und **magnetic field** (B) are important !!!

mass continuity equation



m ≔ mass   A ≔ surface

assumption the star is a **sphere**
→ sounds trivial but isn't !
→ if a stars rotates fast it is an **ellipsoid** !

$V = A dr$ sphere ↔ $A = 4\pi r^2$

$$\rho = \frac{M}{V} \rightarrow \frac{dm}{4\pi r^2\, dr}$$

$$\frac{dm}{dr} = 4\pi r^2 \rho$$

more commonly used version

$$dm = 4\pi r^2 \rho\, dr$$

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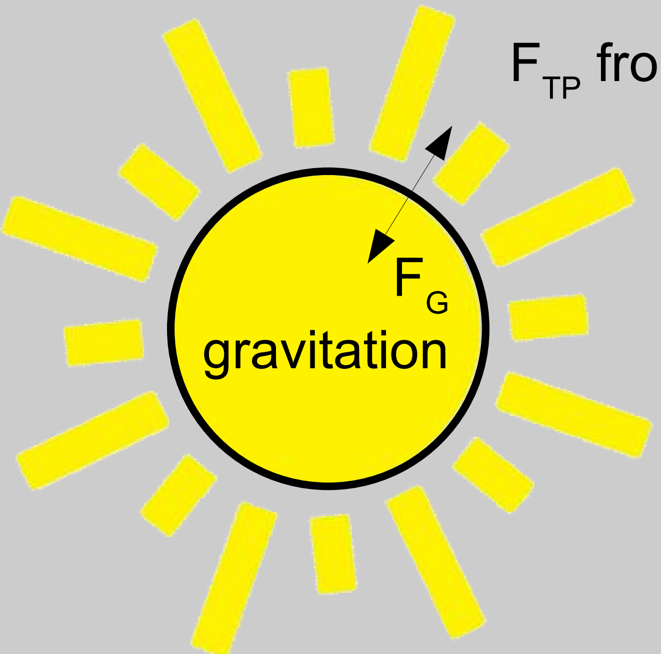
hydrostatic equilibrium



F_{TP} from thermal pressure

$$F_G = m \times g \rightarrow dF_G = G \frac{M\,dm}{r^2}$$

$$F_{TP} = A \times P \rightarrow dF_{TP} = AdP$$

m := mass   P:= pressure   A:= surface

mit density $\rho = m/V = dm / A\,dr \rightarrow A = 1/\rho\; dm/dr$

balance of forces

$$dF = dm \frac{d^2r}{dt^2} = -G \frac{M\,dm}{r^2} - AdP \rightarrow G \frac{M\,dm}{r^2} = -\frac{1}{\rho}\frac{dm}{dr}\,dP$$

$\frac{d^2r}{dt^2} \downarrow = 0$

$$\rightarrow G \frac{M\,\cancel{dm}}{r^2} = -\frac{1}{\rho}\frac{\cancel{dm}}{dr}\,dP$$

$$g = \frac{G\,M}{r^2}$$

$$\boxed{\frac{dP}{dr} = -\rho g}$$

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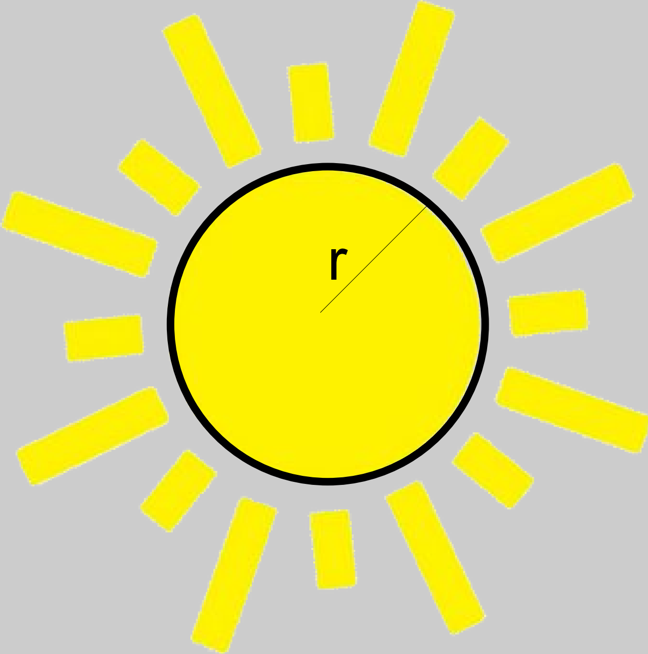
energy equation



L ≔ Luminosity ε ≔ energy generation rate

$\rightarrow \varepsilon = \varepsilon_{Nuklear} + \varepsilon_{Gravitation}$

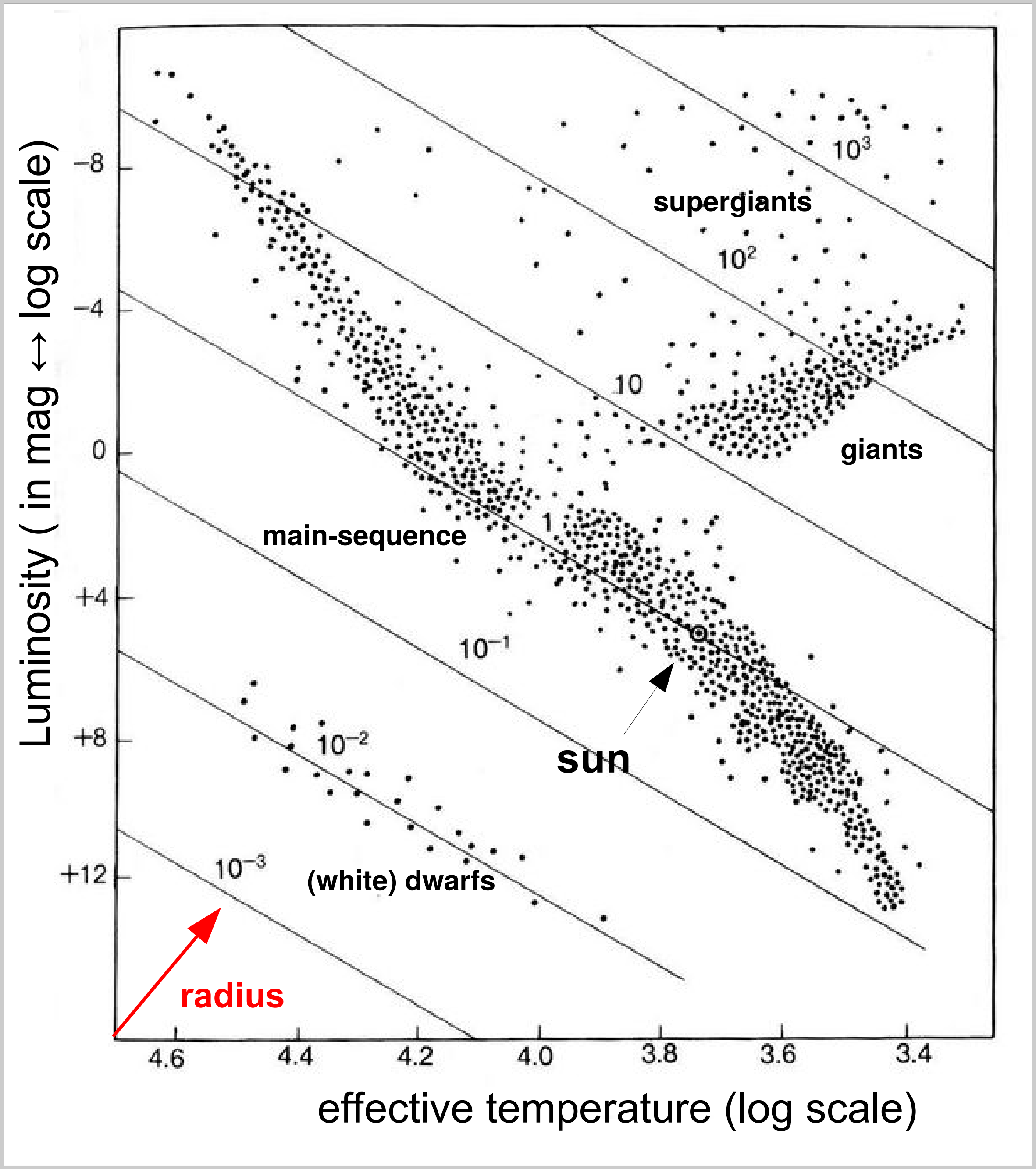
$dL = \varepsilon \, dm$

Using the mass continuity equation

$$dm = 4\pi r^2 \rho \, dr$$

$$\frac{dL}{dr} = 4\pi r^2 \rho \varepsilon$$

Stellar radii in the HRD



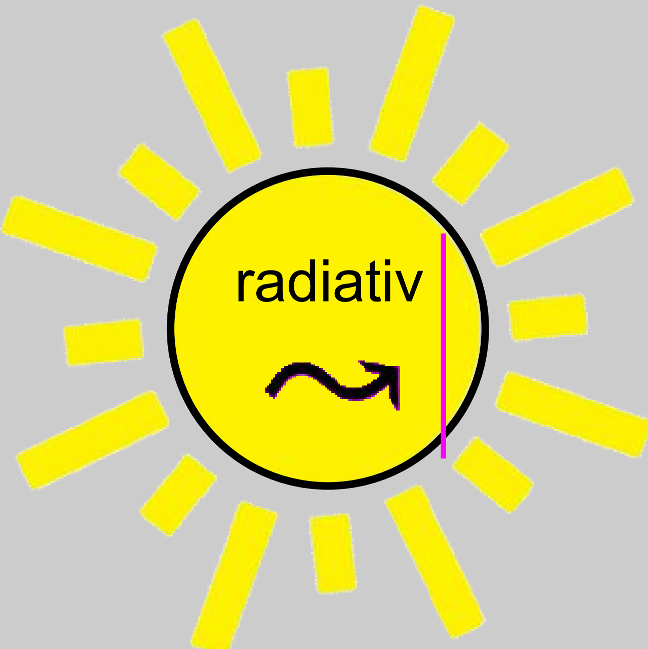
$$\frac{dL}{dr} = 4\pi r^2 \rho \varepsilon$$

↔

$dL = 4\pi r^2 \rho \varepsilon \, dr$

explains radius axis in HRD

energy transport equation



T := Temperature

γ: c_p/c_v adiabtic coefficient $\qquad \kappa$ = opazity

$$\frac{dT_{rad}}{dr} = -\frac{3}{4ac}\frac{\kappa\rho}{T^3}\frac{Lr}{4\pi r^2}$$

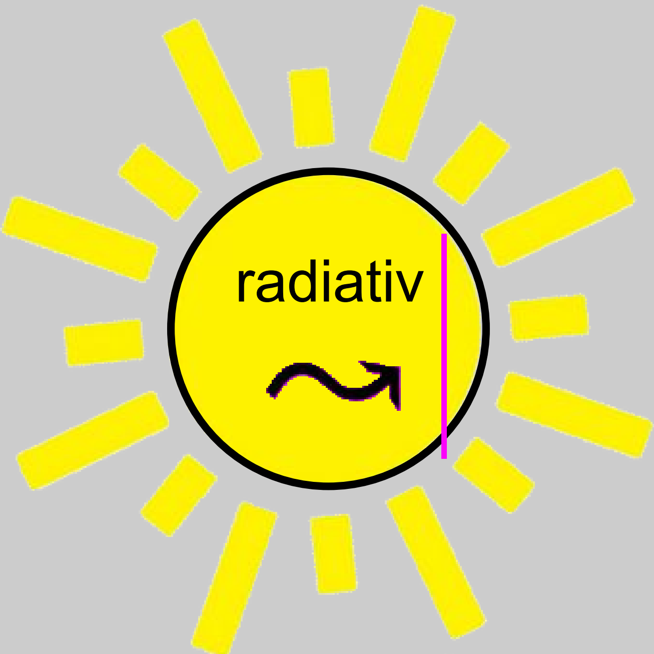
$$\frac{dT_{con}}{dr} = -\left(1-\frac{1}{\gamma}\right)\frac{\mu m_H}{k}\frac{GM}{r^2}$$

sometimes written not as convective but **adiabatic**

$$\frac{dT_{ad}}{dr} = -\left(1-\frac{1}{\gamma}\right)\frac{\mu m_H}{k}\frac{GM}{r^2}$$

energy transport equation

"what dominates where ?"



$$\frac{dT_{con}}{dr} < \frac{dT_{rad}}{dr} \quad \rightarrow \text{radiativ transport}$$

$$\frac{dT_{con}}{dr} > \frac{dT_{rad}}{dr} \quad \rightarrow \text{transport by convection}$$

stellar structure equations

mass continuity equation

$$\frac{dm}{dr} = 4\pi r^2 \rho$$

hydrostatic equilibrium

$$\frac{dP}{dr} = -\rho g$$

energy equation

$$\frac{dL}{dr} = 4\pi r^2 \rho \varepsilon$$

energy transport equation

$$\frac{dT}{dr} = -\frac{3}{4ac}\frac{\kappa\rho}{T^3}\frac{Lr}{4\pi\, r^2}$$

$$\frac{dT}{dr} = -\left(1-\frac{1}{\gamma}\right)\frac{\mu m_H}{k}\frac{GM}{r^2}$$

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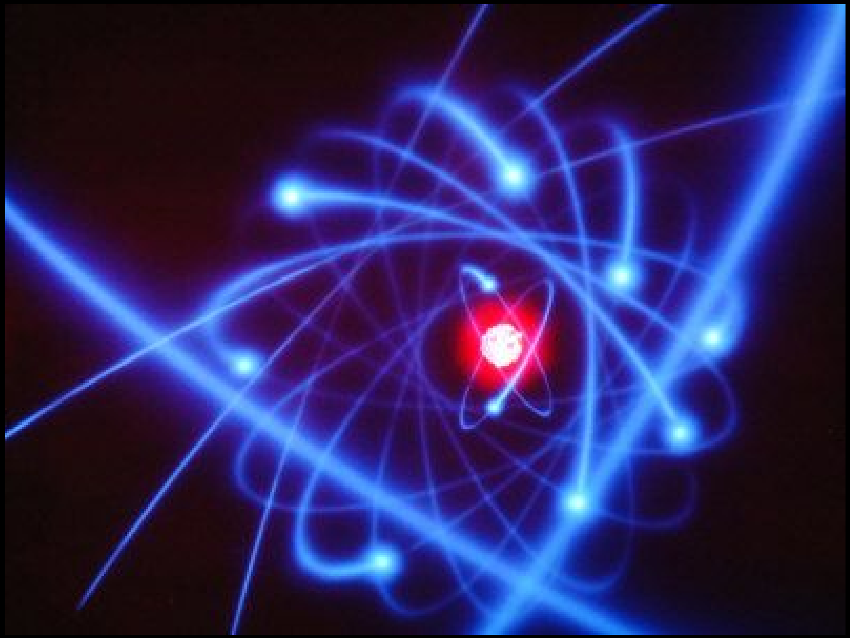
energy

generation



energy generation – nuclear burning process

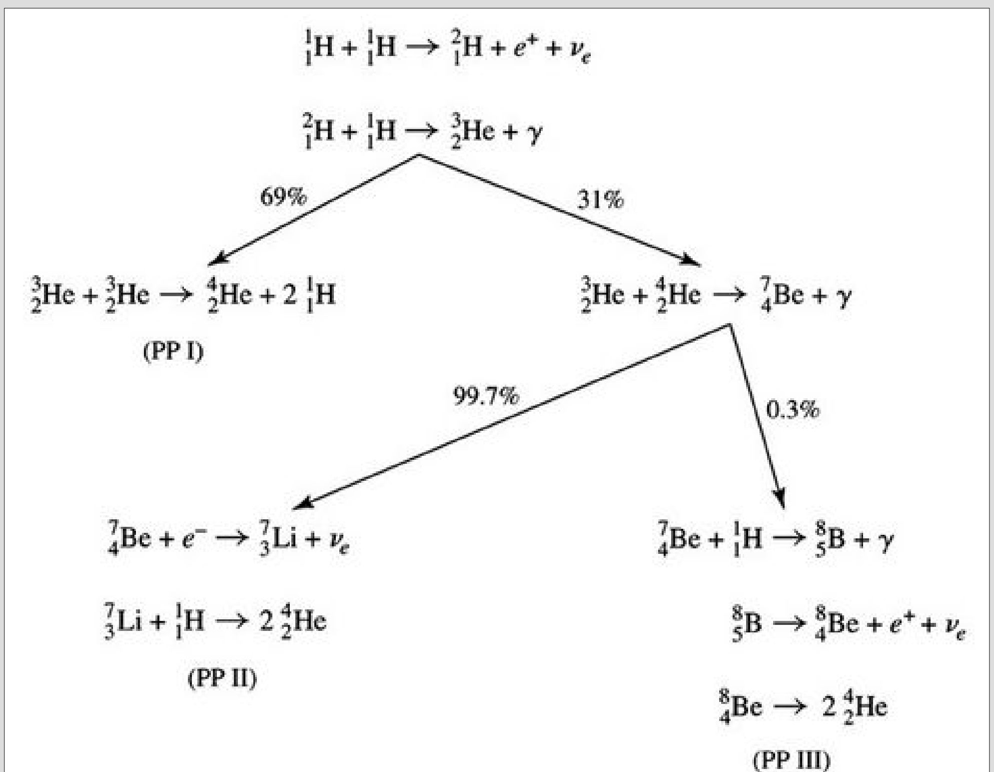
Hydrogen burning the PP-chain(s)

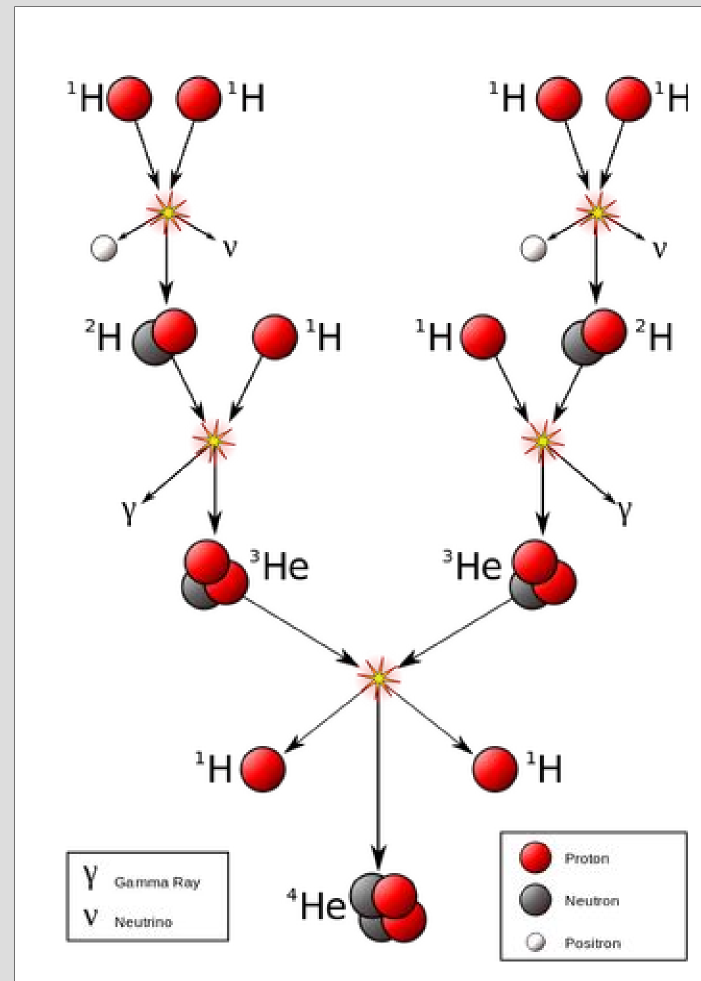
$4H \rightarrow He + 2e^{+} + \nu_e + 2\gamma + \Delta E$

$\Delta E = 26.2$ MeV

$\varepsilon \propto T^{4\text{-}6}$

$T \approx 1.5\ 10^{7}$ K





energy generation – nuclear burning process

Hydrogen burning the CNO-cycle

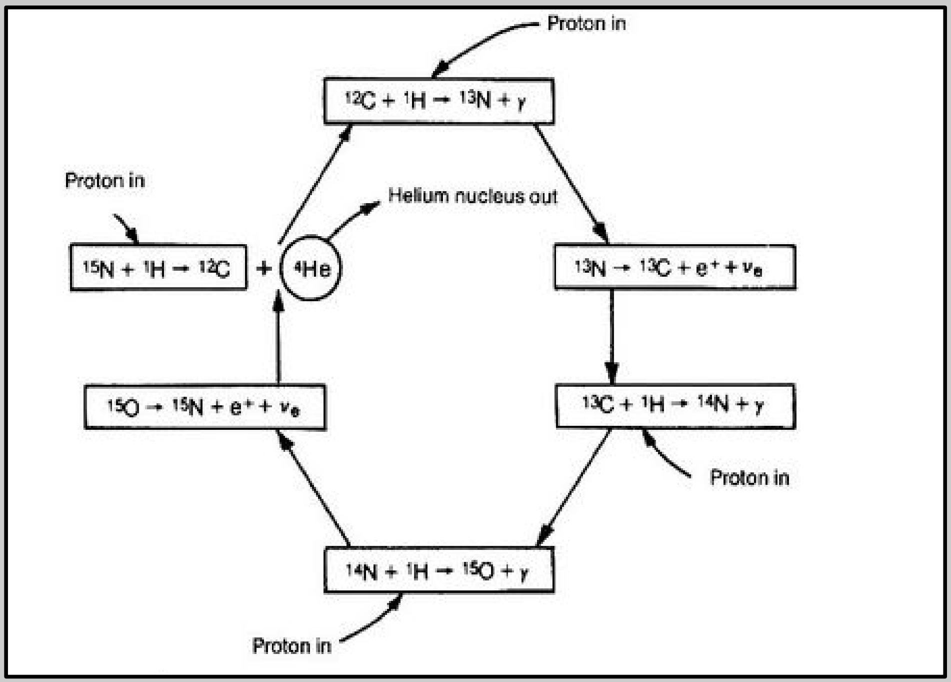
$4H \rightarrow He + 2e^{+} + 2\nu_e + 3\gamma + \Delta E$

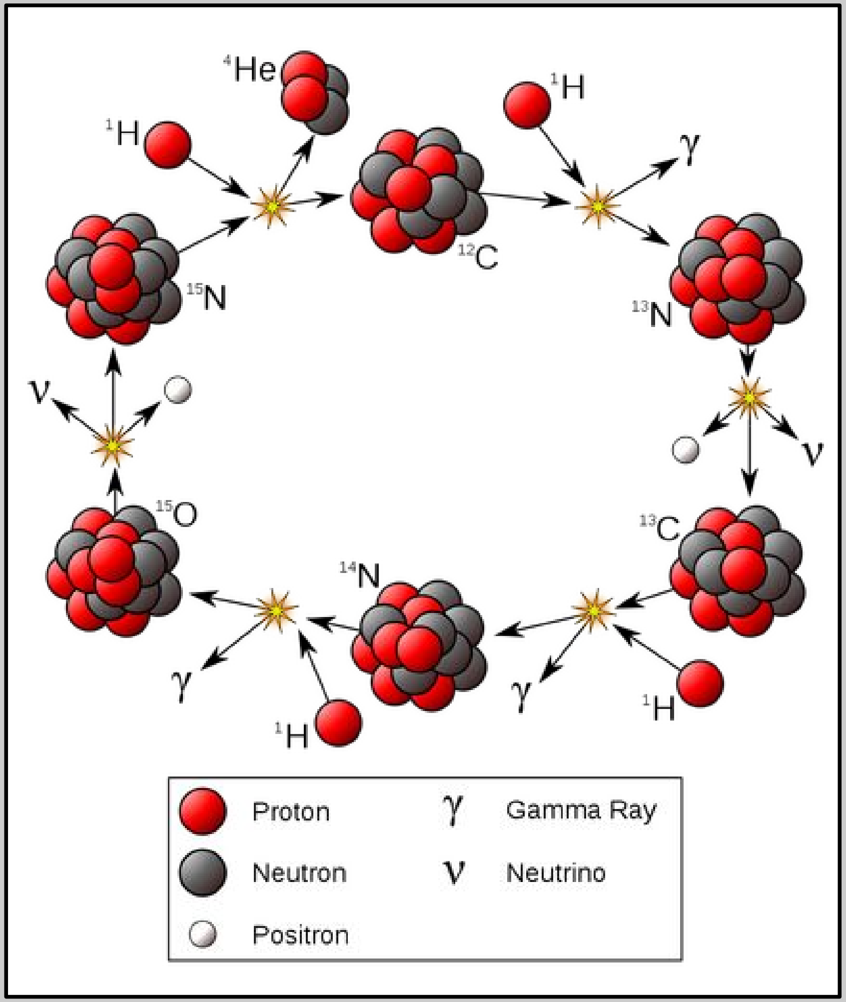
$\rightarrow 2\ He + 3e^{+} + 3\nu_e + 5\gamma + \Delta E$

$\Delta E = 25$ MeV

$\varepsilon \propto T^{15\text{-}16}$

$T \geq 1.5\ 10^{7}$ K





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energy generation – nuclear burning process

Hydrogen burning the CNO-cycle

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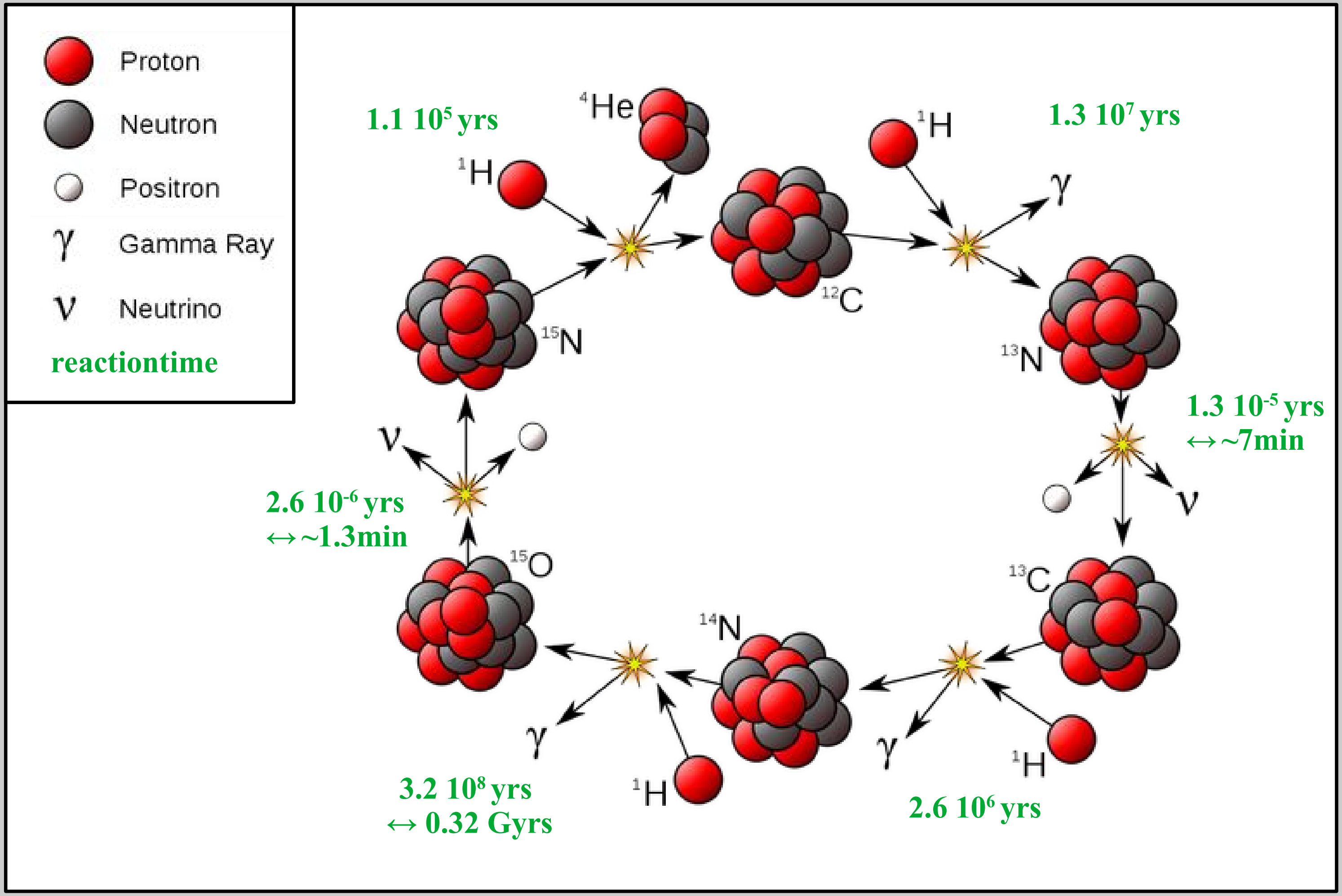
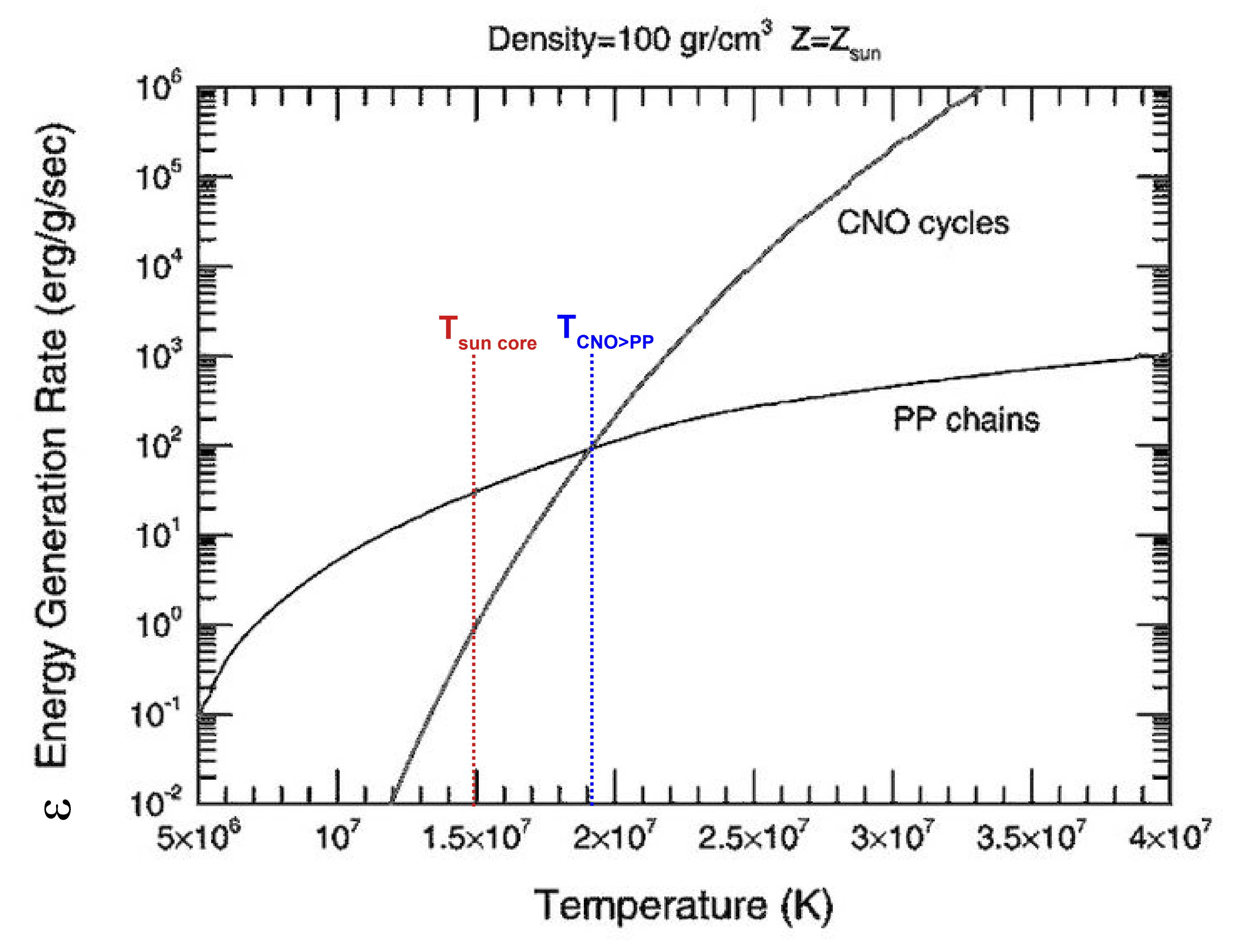


CNO cycle versus pp-chain

Efficiency of the pp and CNO process



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burning phases and stellar lifetimes

The **duration** of the H **buring phase** ↔ the by far longest buring process (= MS lifetime) for all stars and good total lifetime estimate.
It is **shorter** for a higher stellar **mass**.

$$\tau_{MS} \approx 10^{10}\text{years}\left[\frac{M}{M_\odot}\right]\left[\frac{L_\odot}{L}\right] = 10^{10}\text{years}\left[\frac{M}{M_\odot}\right]^{-2.5}$$

H burning ↔ MS lifetime	
1 $M_\odot$	$1\ 10^{10}$ years
$10 M_\odot$	$3\ 10^{7}$ years
$50 M_\odot$	$6\ 10^{5}$ years
$80 M_\odot$	$2\ 10^{5}$ years

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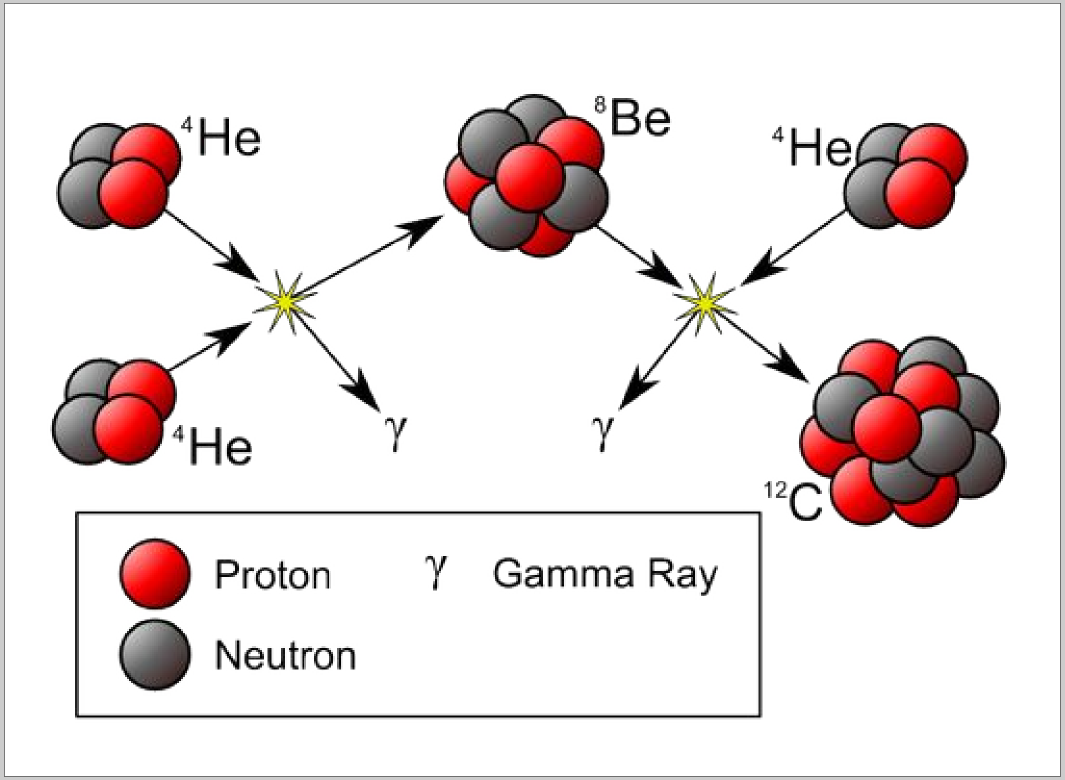
Helium burning

Helium-burning or Triple-α

$$3He \rightarrow C + \gamma + \Delta E$$

$\Delta E = 7.3$ MeV $\qquad \varepsilon \propto T^{30-40}$

$T > 1.5\ 10^8$ K



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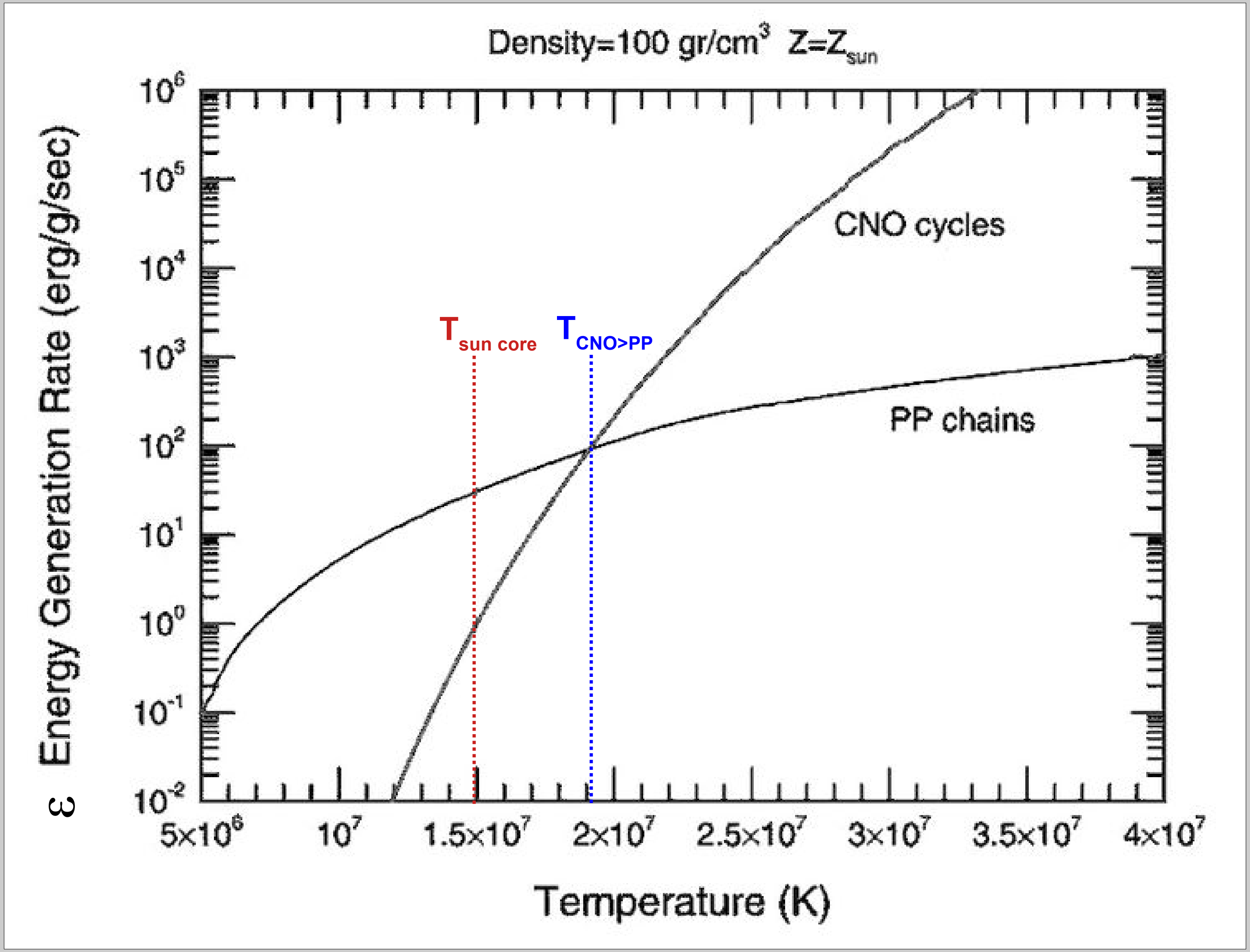
CNO cycle versus pp-chain

Efficiency of the pp and CNO



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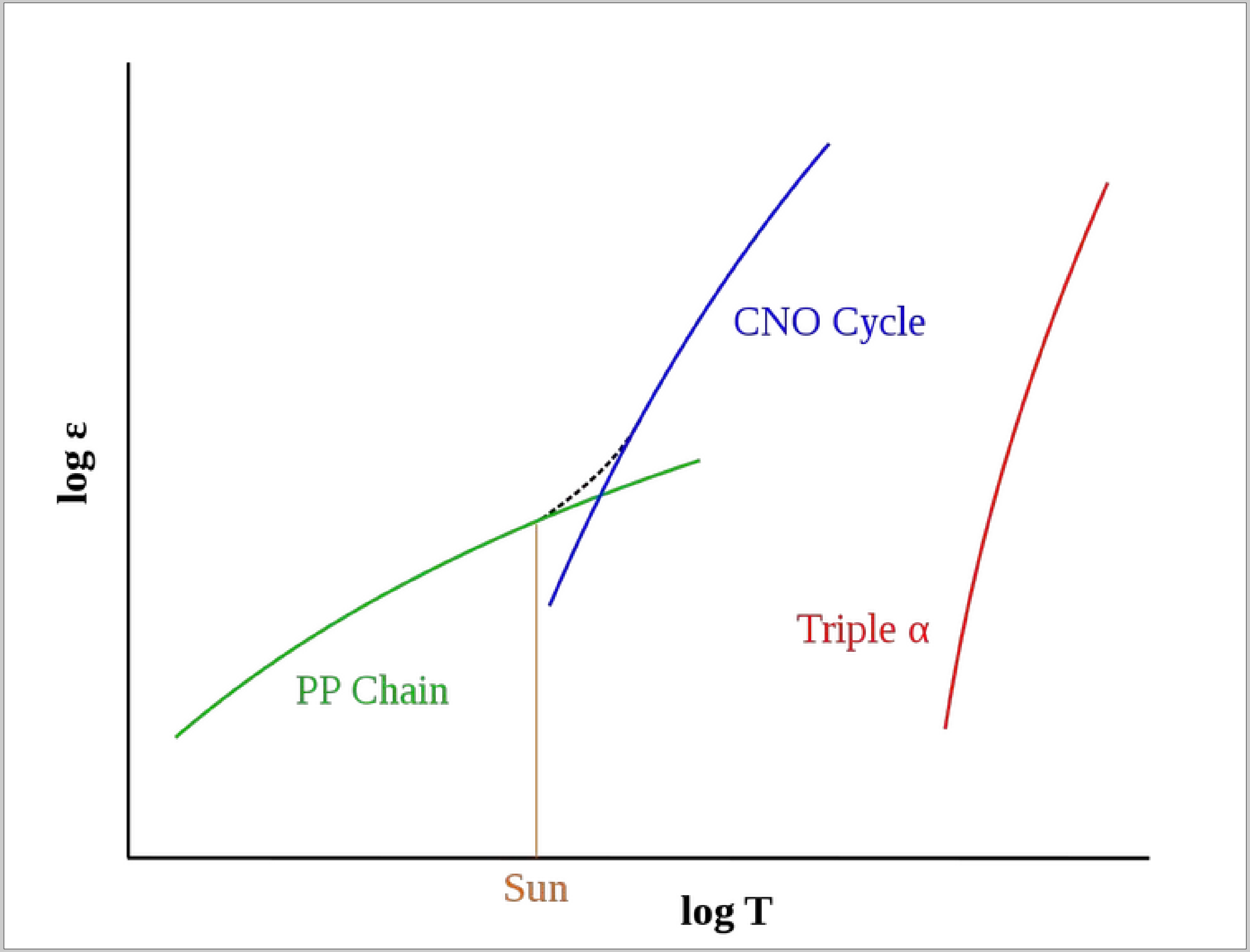
PP ● CNO ● He ↔ Triple α burning

Efficiency of the pp CNO and Triple α process



higher burning phases

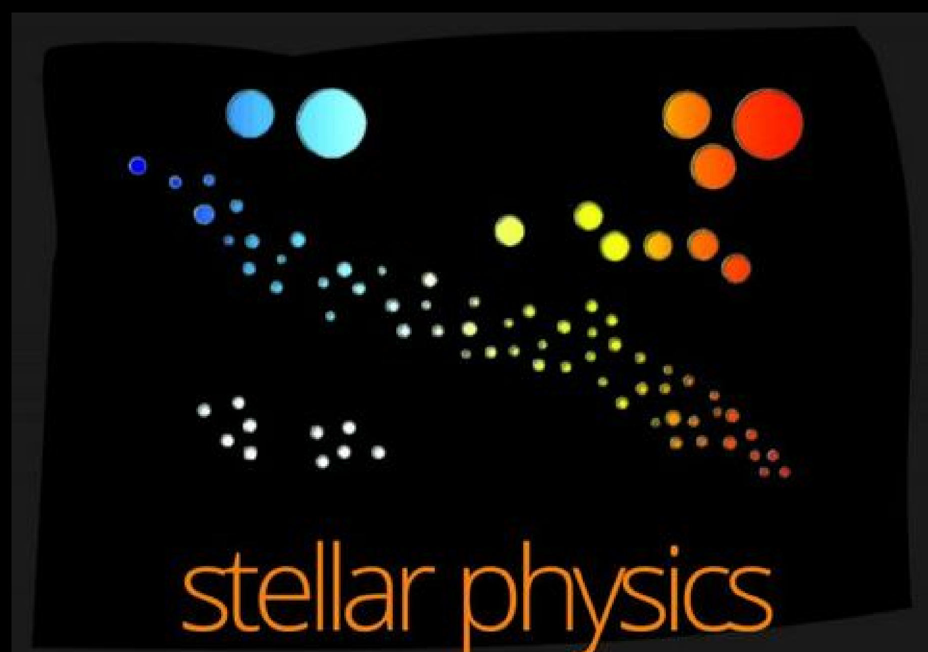
Carbon-burning $C + He \rightarrow O + \gamma + \Delta E \quad \Delta E = 7.2\ \text{MeV}$

Oxygen-burning $O + He \rightarrow Ne + \gamma + \Delta E \quad \Delta E = 4.6\ \text{MeV}$

Massive Stars only !

Neon and Silicon burnings follow and create elements up to **Iron.**

for more details see the lecture on



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Duration of burning phases

The **duration** of the each **buring phase**
is
shorter for **higher elements**
and
faster for stars with **higher mass**

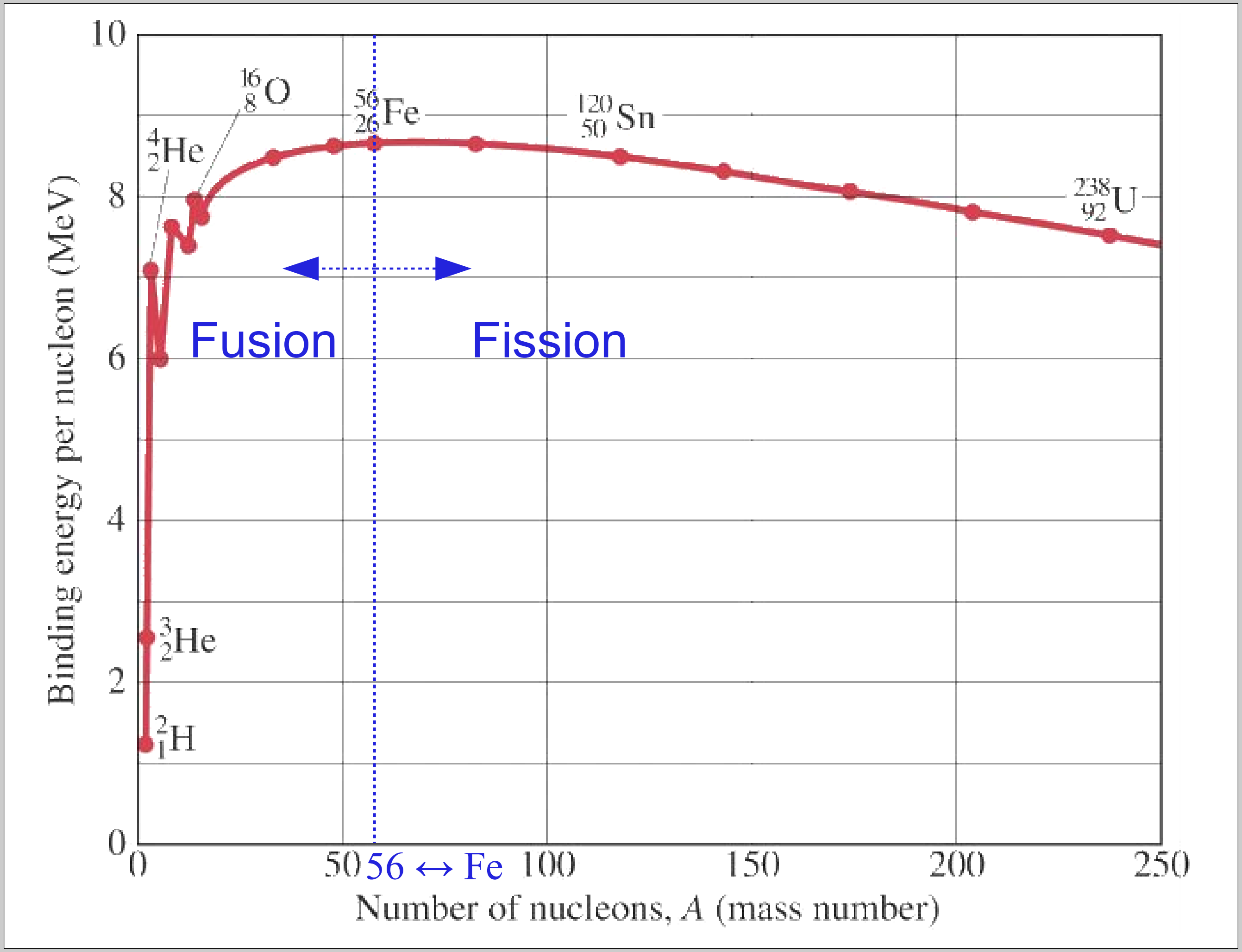
Table 3 Lifetimes of core burning phases

burning phase	time in years
H burning	10^{5-9} years
He burning	10^{6} years
O burning	300 years
Ne burning	200 days
Si burning	2 days

Fusion versus Fission

Neon and Silicon burnings follow and create elements up to **Iron.**

Iron has the highets binding energy per nucleon
→ up to iron energy is set free in **Fusion** processes beyond in **Fission** (spallation)



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So what about gold und silver etc. ?

If Fusion burning stops with Iron how
are elements with a higher atomic number formed ?

So what about gold und silver etc. ?

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So what about gold und silver etc. ?

If Fusion burning stops with Iron how
are elements with a higher atomic number formed ?

Instead of nuclear fusion **capturing** a **proton** or **neutron** leads to the fomation new elements

There are 3 major process

- **p-Prozess** ↔ proton capture
- **s-Prozess** ↔ slow (s) neutron capture
- **r-Prozess** ↔ rapid (r) neutron capture

p-process

p-process → **p** from **proton**

- by capturing **protons** the nucleus has a higher number of protons → new element
- in most cases a **photodesintegration**↔ **γ-process** follows

  (Expample Ne + γ → O + He)

- the higher the element ↔ the higher is the Coulomb Wall and the process becomes more difficult
- so far unusual elementes found with a maxima at ^{92}Molybdenum und ^{144}Samarium

Occurs in: **Oxygen burning & Supernovae**

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r-process

r-process → **r** from **rapid**

- by capturing **neutrons** the nucleus has a higher number of neutrons / protons→ new element/isotope
- competing process here is a β decay

β^+ : $p + \Delta E \rightarrow n + e^+ + \nu$ β^- : $n \rightarrow p + e^- + \nu + \Delta E$

if $T_{\text{n-capture}} \ll T_{\beta\text{-decay}}$

no β **decay** occurs and the nucleus captures another **neutron**
↔ **atoms with higher neutron and mass number!**

- known mass number A=130-190
r process elements ^{80}Se, ^{81}Br, ^{84}Kr, ^{128}Te, ^{130}Te, ^{127}I, ^{192}Os, ^{193}Ir, ^{196}Pl, ^{198}Pt

Occurs in: **Supernovae**

s-process

s-process → **s** from **slow**

- by capturing **neutrons** the nucleus has a higher number of neutrons / protons→ new element/isotope
- competing process here is a β decay

β^{+} : $p + \Delta E \rightarrow n + e^{+} + \nu$ β^{-} : $n \rightarrow p + e^{-} + \nu + \Delta E$

if $T_{n\text{-capture}} \ll T_{\beta\text{-decay}}$

a β **decay** occurs before another **neutron** is captured ↔ **n converted to p atoms with higher proton and mass number!**

- known mass number A=bis 210

s process elements ^{88}Sr, ^{138}Ba, ^{208}Pb, ^{89}Y, ^{90}Zr, ^{139}La)

Occurs in: **Red Giants, Red Supergiants & AGB** in shell burning region


STELLAR
EVOLUTION
NEW GAME
Start the game from the beginning
PASSWORD
Enter a password to continue
QUIT GAME
Return to the Desktop

Stellar evolution – models

Solve the stellar structure equations in time

$$\frac{dm}{dr} = 4\pi r^2 \rho$$

$$\frac{dP}{dr} = -\rho g$$

$$\frac{dT}{dr} = -\frac{3}{4ac}\frac{\kappa\rho}{T^3}\frac{Lr}{4\pi r^2}$$

$$\frac{dL}{dr} = 4\pi r^2 \rho \varepsilon$$

$$\frac{dT}{dr} = -\left(1-\frac{1}{\gamma}\right)\frac{\mu m_H}{k}\frac{GM}{r^2}$$

a) boundery conditions

für $r \rightarrow 0$ $\quad M \rightarrow 0 , L \rightarrow 0$
für $r \rightarrow R_*$ $\quad P \rightarrow 0 , \rho \rightarrow 0$

b) use material functionen

$P(\rho,T,Z)$ **equation of state** (most cases ideal Gas)
$\kappa(\rho,T,Z)$ **opacity** by free free and e^- scattering
$\varepsilon(\rho,T,Z)$ **energy production** (most cases power law)

Input – Output

Input

Stellar structure equations
+
material functionen
+
energy production

radius, temperature, luminosity
of a stars as function a of time
↕
Stellar evolution

Output

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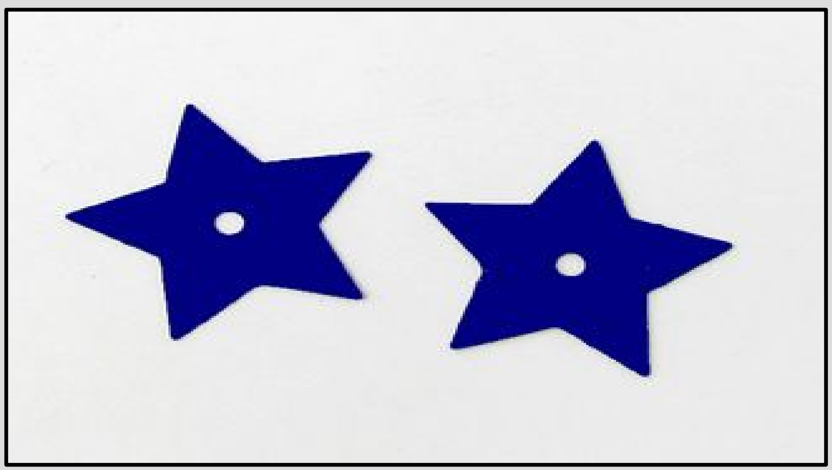
Stellar evolution – models

" Solving the equation one integrates from the inside out as well as from the ouside in hoping that the solutions meet somewhere and are steady…

In our first try in the1970ies we always got solutions that had

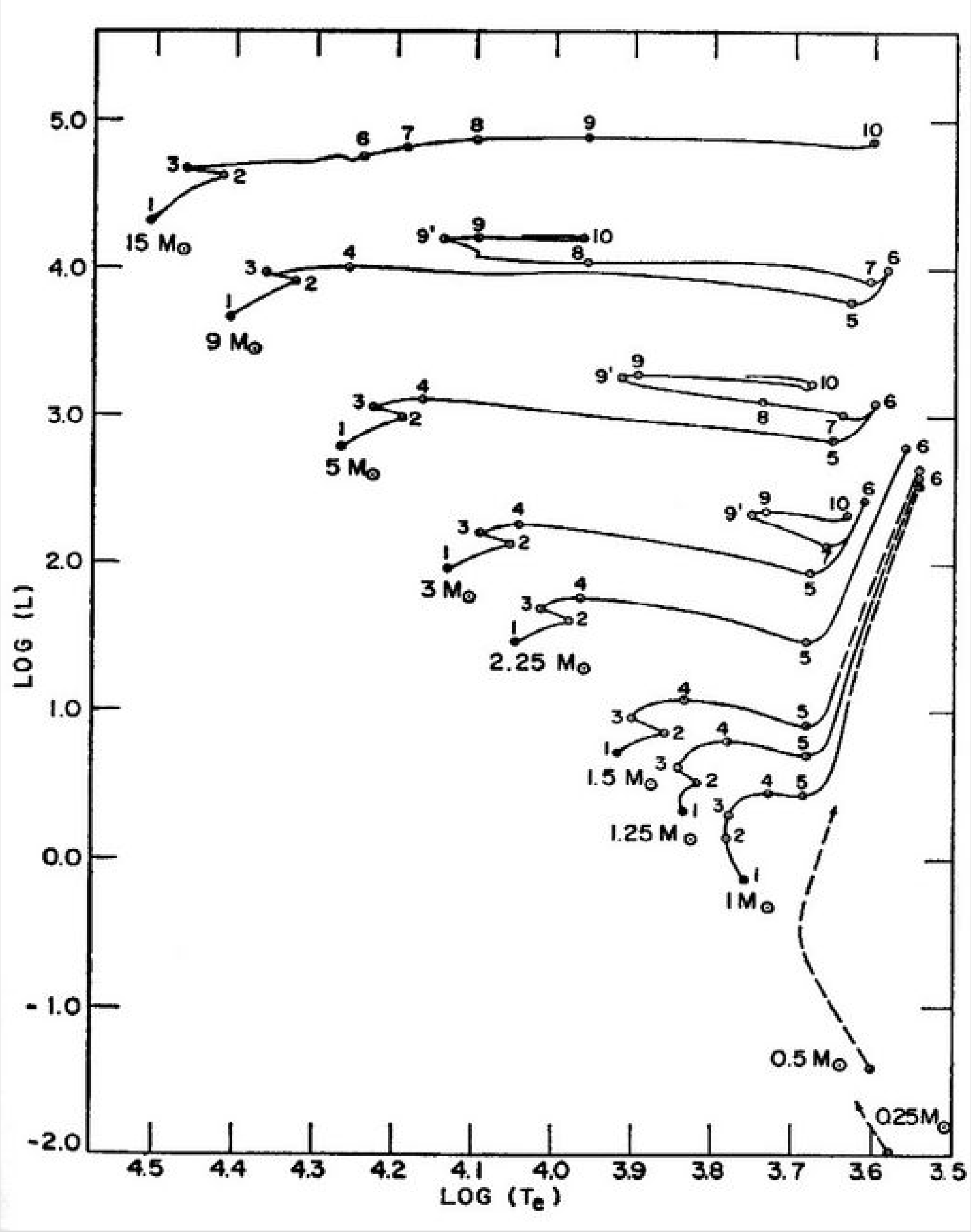
STARS WITH CENTRAL HOLES !!! "

Prof. Rudolf Kippenhahn



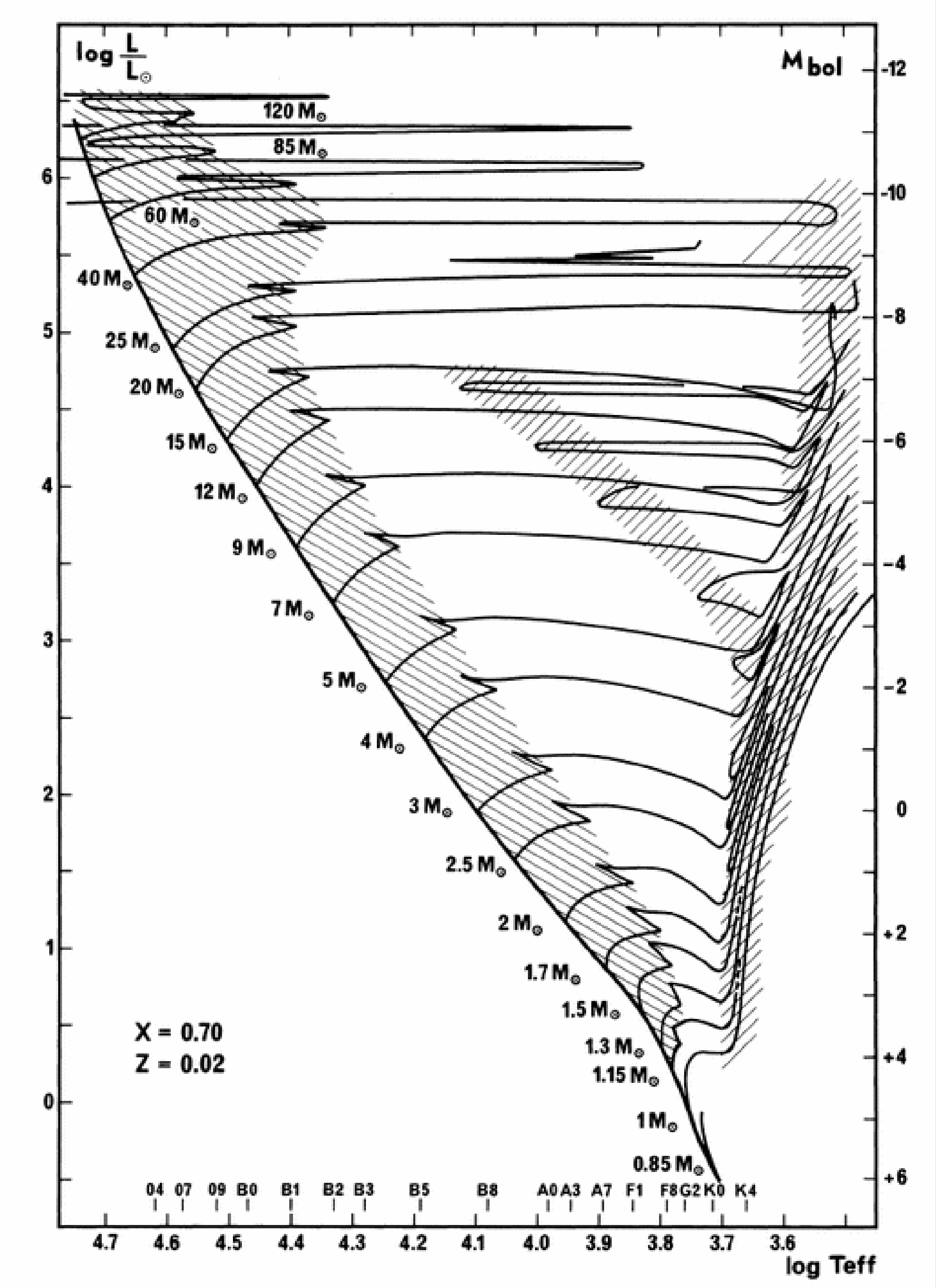
Stellar evolution – models

At the beginning 1965-1980



Stellar evolution – models

early 1980ties →

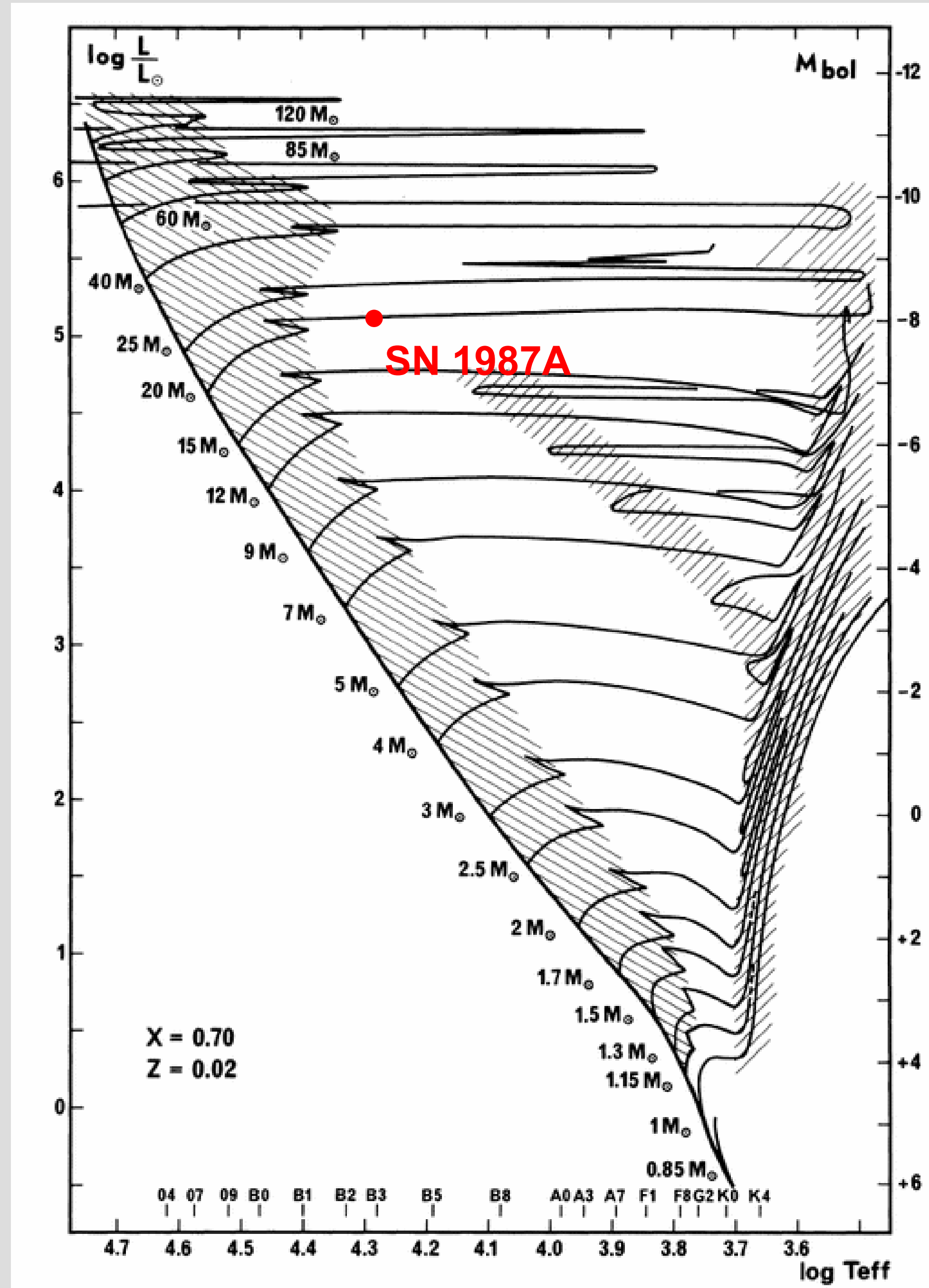


Stellar evolution – models

early 1980ties →

Problem SN 1987A

Progenitor star is **Sk -69° 202** and was **Blue Supergiant !!**



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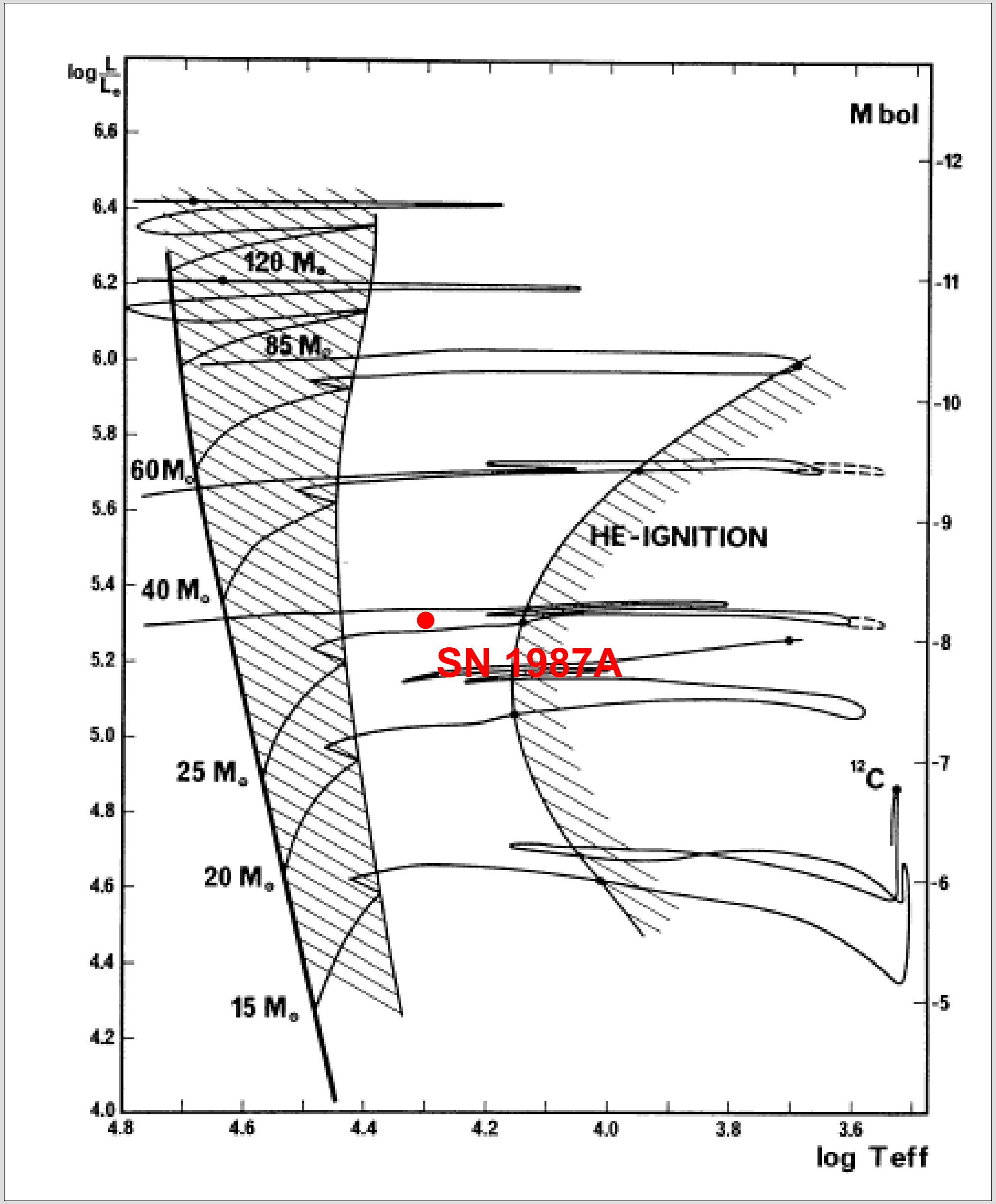
Stellar evolution – models with mass loss !

Now in 1990

→ added stellar winds
mass loss !

→ explained SN1987

→ by including mass loss the models are able to explain a blue spuergiants as final phase before the supernova Since Stars change from the red to the blue.



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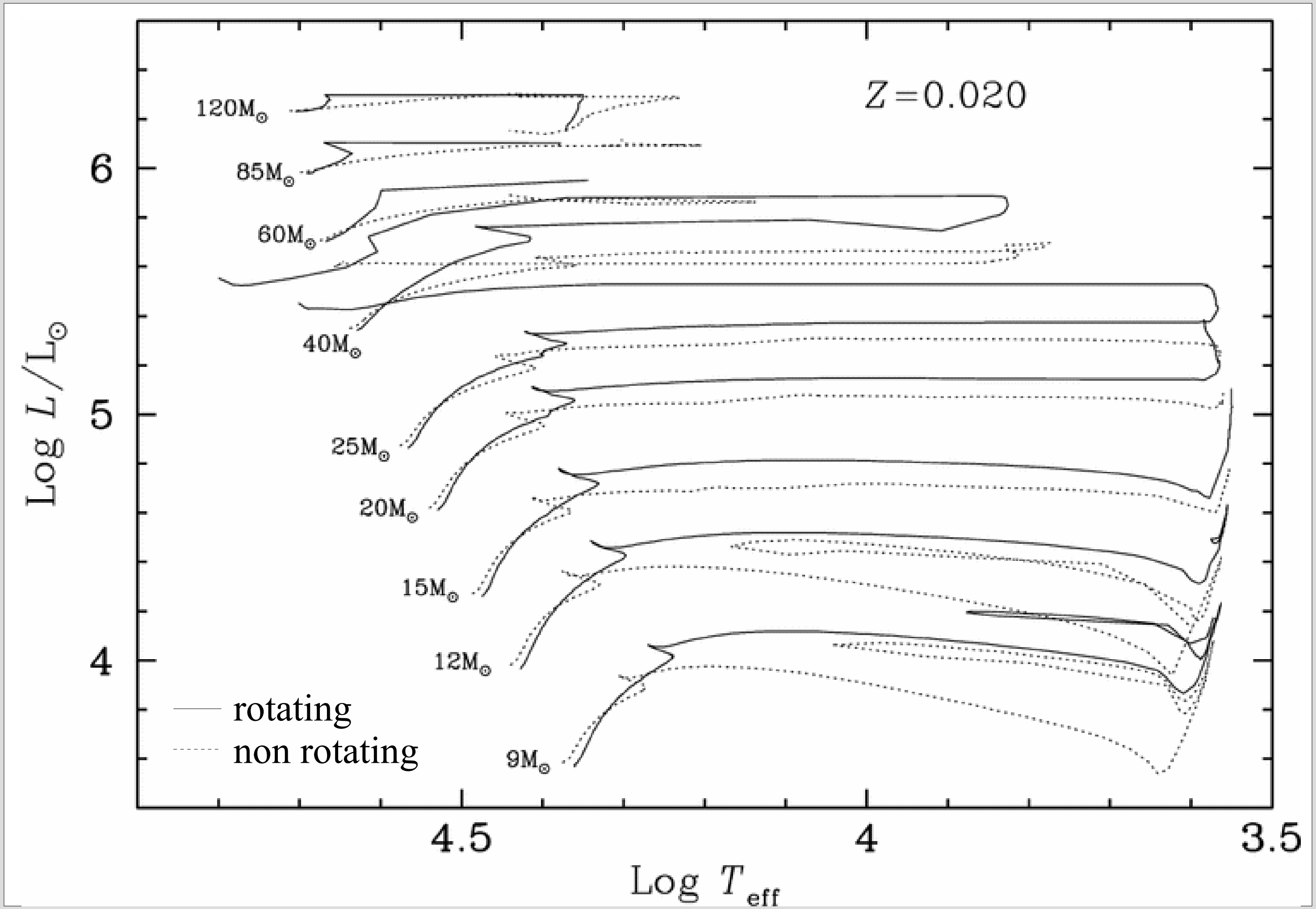
Stellar evolution – models with mass loss AND ROTATION

Starting in 2000

→ model now include **Mass loss** and **Rotation** !



Stellar evolution – models with mass loss AND ROTATION

Starting in 2000

→ model now include **Mass loss** and **Rotation**

First idea and theoretical approaches already 1955

→ no chance to caculate with the Computers at that time
→ **need 3D**

Zeitschrift für Astrophysik, Bd. 38. S. 166—189 (1955)

Kleine Veröffentlichungen der Remeis-Sternwarte Bamberg Nr. 10

Untersuchungen über rotierende Sterne

I. Die Theorie nullter Ordnung

Von

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Mit 1 Textabbildung

(Eingegangen am 21. September 1955)

Es wird die Theorie nullter Ordnung aufgestellt, die das Rotationsgesetz extrem langsam rotierender Sterne bestimmt. Es zeigt sich, daß ein Stern nach hinreichend langer Zeit einem Rotationsgesetz zustrebt, das zwar wegen des ständigen Drehimpulsverlustes durch Strahlung nicht stationär ist, das aber vom Anfangsrotationsgesetz nicht mehr abhängt. Die Bestimmung dieses Gesetzes und die Frage, wie ein Stern aus einem beliebigen Anfangszustand heraus dieses Rotationsgesetz erreicht, führen unter vereinfachenden Annahmen (spezielle Vorschriften für den

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Stellar evolution with rotation and magnetic fields

III. The interplay of circulation and dynamo

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Abstract. We examine the effects of the magnetic field created by the Tayler-Spruit dynamo in differentially rotating stars. Magnetic fields of the order of a few 10^4 G are present through most of the stellar envelope, with the exception of the outer layers. The diffusion coefficient for the transport of angular momentum is very large and it imposes nearly solid body rotation during the MS phase. In turn, solid body rotation drives meridional circulation currents which are much faster than usual and leads to much larger diffusion coefficients than the magnetic diffusivity for the chemical species. The consequence is that the interplay of the thermal and magnetic instabilities favours the chemical transport of elements, while there would be no transport in models with magnetic field only. We also discuss the effects on the stellar interior, lifetimes and HR diagram.

Key words. stars: rotation – stars: magnetic fields – stars: evolution

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