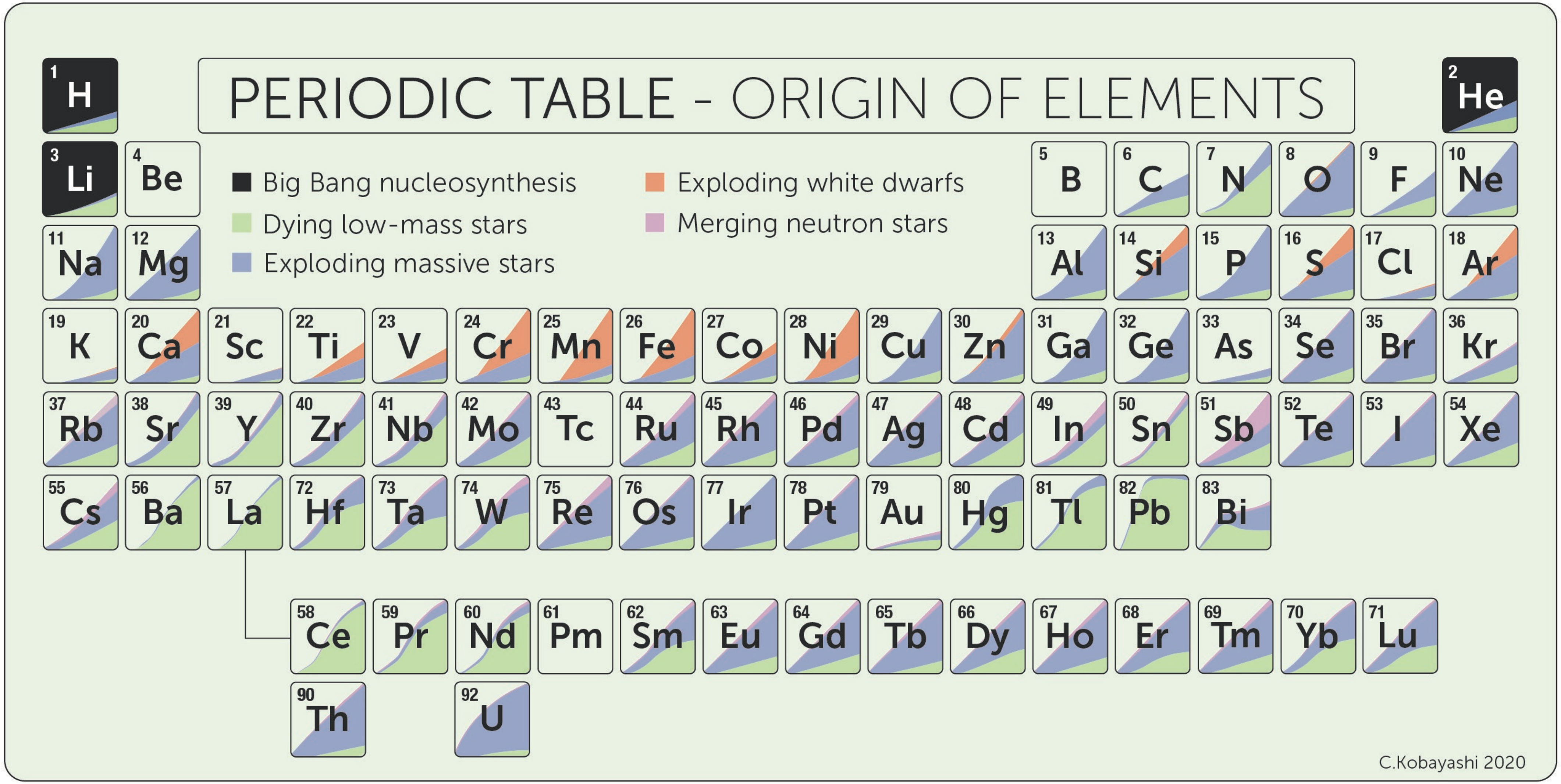
Introduction to stellar modelling

Flavia Dell'Agli


[261]
Db
[262]
Sg
cerium
58
Ce
140.12
Pr
Nd
thorium

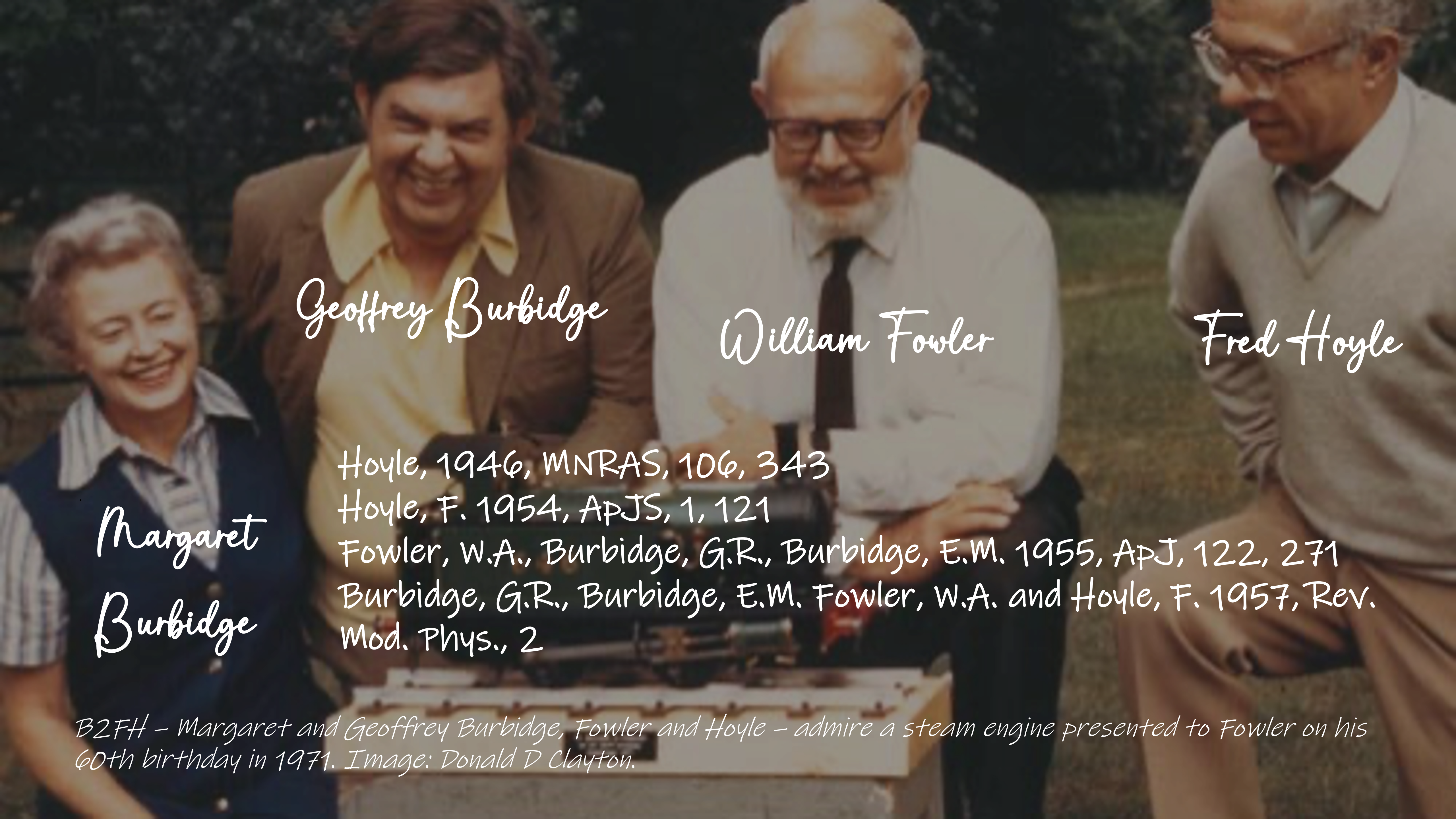


The Origin of Elements from Carbon to Uranium Chiaki Kobayashi, Amanda I. Karakas and Maria Lugaro, 2020, ApJ, 900, 179.

First stellar evolution models?

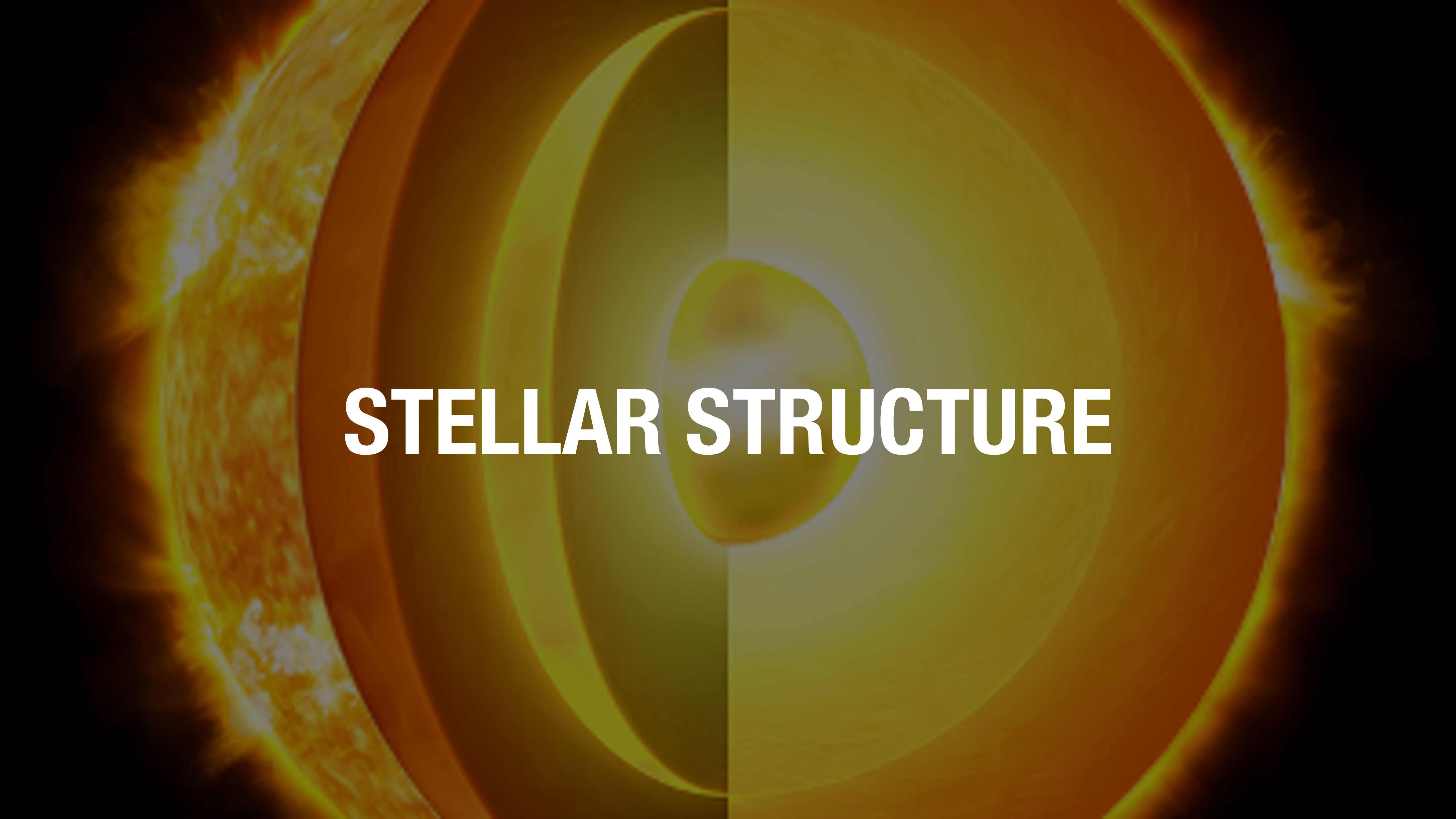
Back to the early 20th century with the work of scientists such as Sir Arthur Eddington

In the picture: Einstein, Ehrenfest & De Sitter; Eddington & Lorentz.
Location: office of W. de Sitter in Leiden
Date: 26 Sept. 1923



Hoyle, 1946, MNRAS, 106, 343
Hoyle, F. 1954, ApJS, 1, 121
Fowler, W.A., Burbidge, G.R., Burbidge, E.M. 1955, ApJ, 122, 271
Burbidge, G.R., Burbidge, E.M. Fowler, W.A. and Hoyle, F. 1957, Rev. Mod. Phys., 2

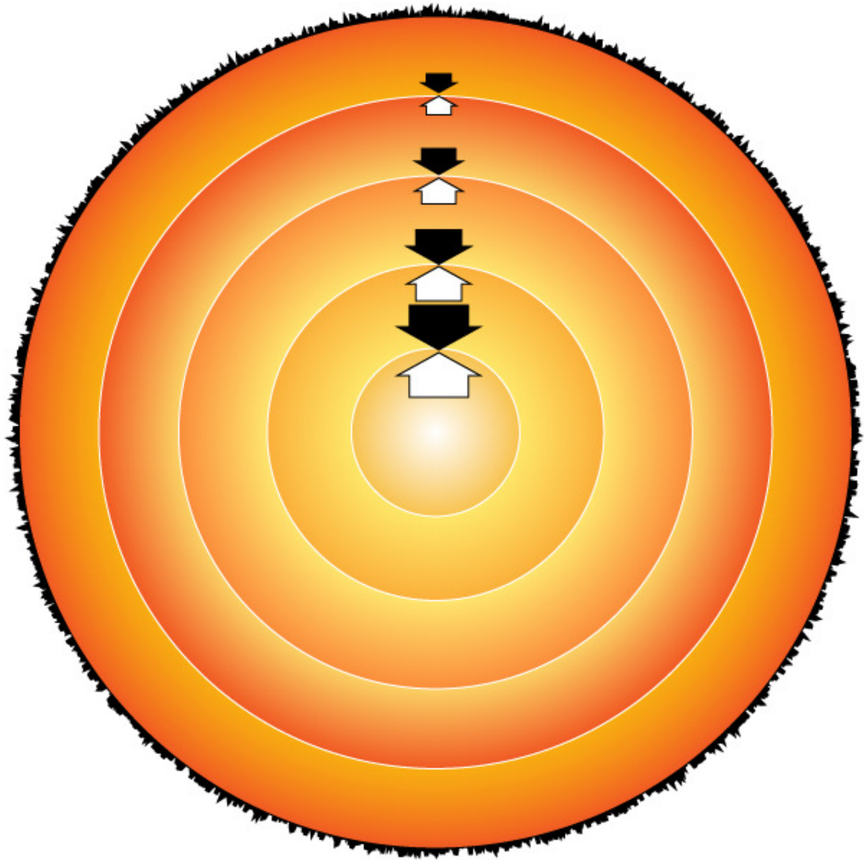
B2FH – Margaret and Geoffrey Burbidge, Fowler and Hoyle – admire a steam engine presented to Fowler on his 60th birthday in 1971. Image: Donald D Clayton.



STELLAR STRUCTURE

HYDROSTATIC EQUILIBRIUM

The pressure gradient force pushing outward from the center exactly balances the gravitational force pulling inward towards the center.



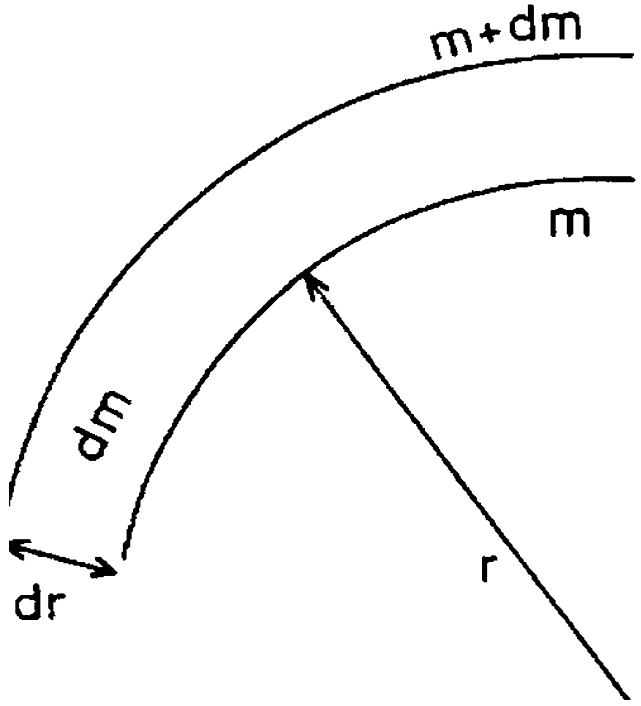
$$\frac{dP}{dr} = -\frac{GM_r}{r^2}\rho$$

MASS CONSERVATION

$$M(r) = \int_0^r 4\pi r^2 \rho(r')dr'$$

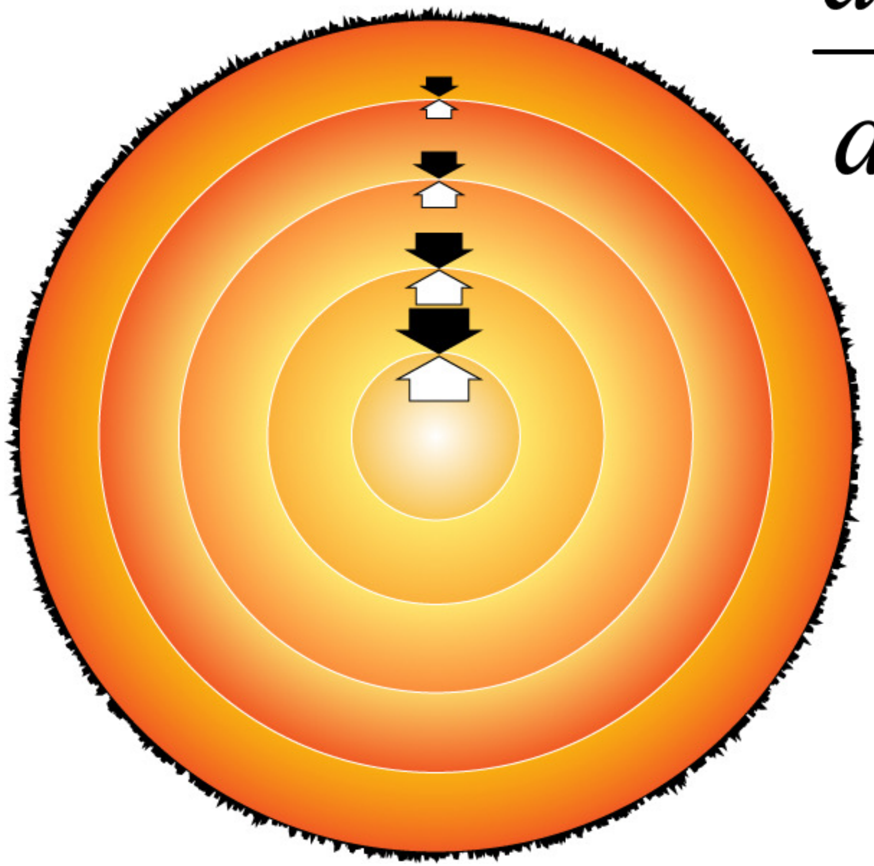
$$\frac{dM(r)}{dr} = 4\pi r^2 \rho(r)$$

$$\frac{dr}{dM} = \frac{1}{4\pi r^2 \rho}$$



HYDROSTATIC EQUILIBRIUM

The pressure gradient force pushing outward from the center of the fluid exactly balances the gravitational force pulling inward towards the center.

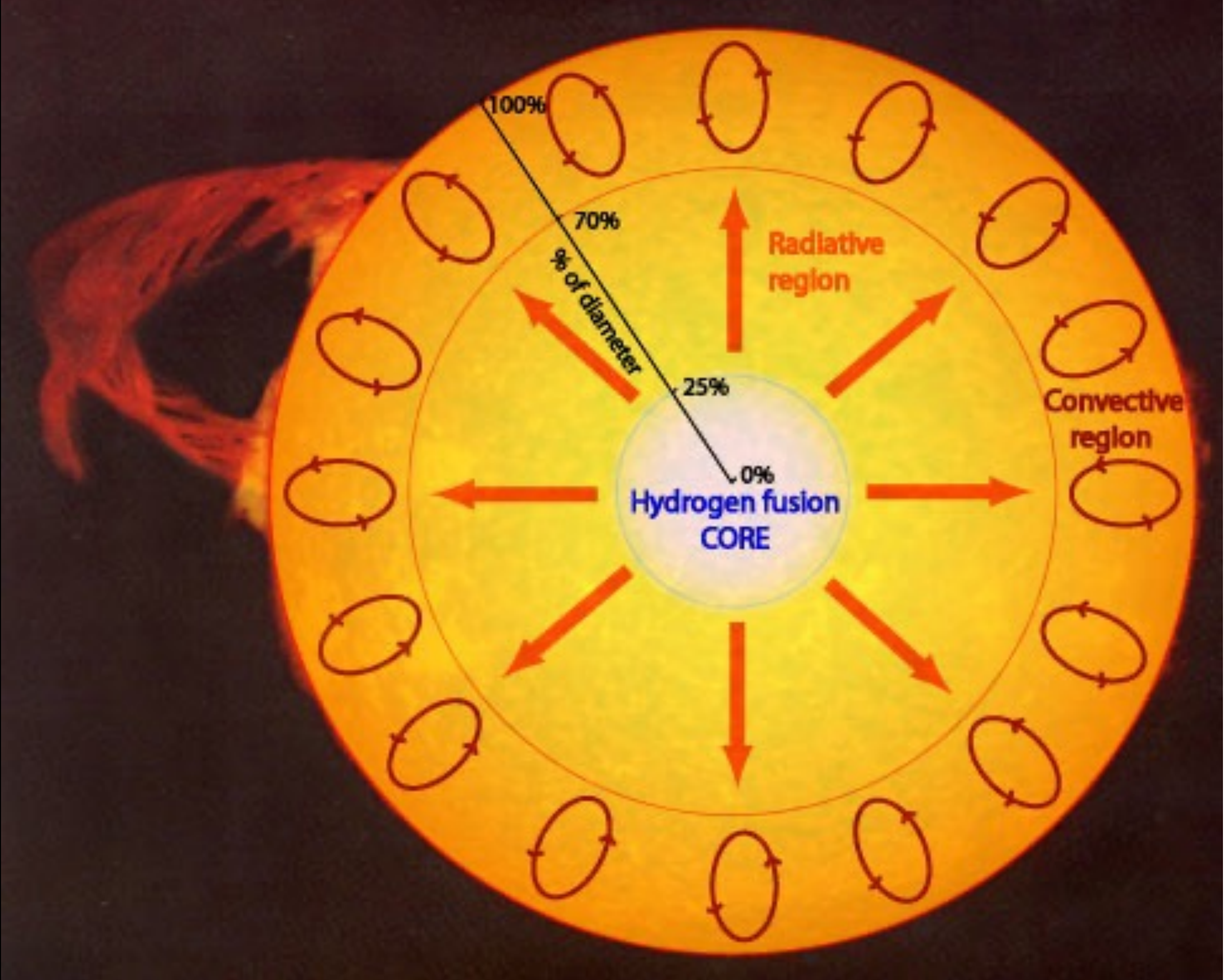


$$\frac{dP}{dr} = -\frac{GM_r}{r^2}\rho \quad + \quad \frac{dr}{dM} = \frac{1}{4\pi r^2 \rho}$$

$$\frac{dP}{dr}\frac{dr}{dM} = -\frac{GM\rho}{r^2}\frac{1}{4\pi r^2 \rho}$$

$$\frac{dP}{dM} = -\frac{GM}{4\pi r^4}$$

ENERGY TRANSPORT



ENERGY TRANSPORT

$$\frac{d\ln T}{d\ln P} = \nabla \longrightarrow \frac{dT}{dM}\frac{P}{T}\frac{dM}{dP} = \nabla \longrightarrow$$

$$\frac{dT}{dM} = -\frac{GMT}{4\pi Pr^4}\nabla$$

∇_{rad} Radiative zone

∇_{conv} Convective zone

ENERGY CONSERVATION

Nuclear   Neutrinos

$$\frac{dL}{dM} = \varepsilon_n + \varepsilon_g - \varepsilon_\nu$$

Gravitational

STELLAR EQUATIONS

$$\frac{dr}{dM} = \frac{1}{4\pi r^2 \rho}$$

Mass conservation

$$\frac{dP}{dM} = -\frac{GM}{4\pi r^4}$$

Hydrostatic equilibrium

$$\frac{dT}{dM} = -\frac{GMT}{4\pi\ \mathrm{P} r^4} \nabla$$

Energy transport

$$\frac{dL}{dM} = \varepsilon_n + \varepsilon_g + \varepsilon_\nu$$

Energy conservation

STELLAR EQUATIONS

$$\frac{dr}{dM} = \frac{1}{4\pi r^2 \rho}$$

Mass conservation

$$\frac{dP}{dM} = -\frac{GM}{4\pi r^4}$$

Hydrostatic equilibrium

$$\frac{dT}{dM} = -\frac{GMT}{4\pi \, \mathrm{P} r^4} \nabla$$

Energy transport

$$\frac{dL}{dM} = \varepsilon_n + \varepsilon_g + \varepsilon_\nu$$

Energy conservation

+

Equation of state

Opacities

Nuclear cross sections

Book: Kippenhahn, Weigert, Weiss, *Stellar structure and evolution*, A&A Library
Book: Bohm-Vitense, *Introduction to stellar astrophysics,* Cambridge University Press.
,

STELLAR EQUATIONS

$$\frac{dr}{dM} = \frac{1}{4\pi r^2 \rho}$$

Mass conservation

$$\frac{dP}{dM} = -\frac{GM}{4\pi r^4}$$

Hydrostatic equilibrium

$$\frac{dT}{dM} = -\frac{GMT}{4\pi P r^4}\nabla$$

Energy transport

$$\frac{dL}{dM} = \varepsilon_n + \varepsilon_g + \varepsilon_\nu$$

Energy conservation

+

Equation of state

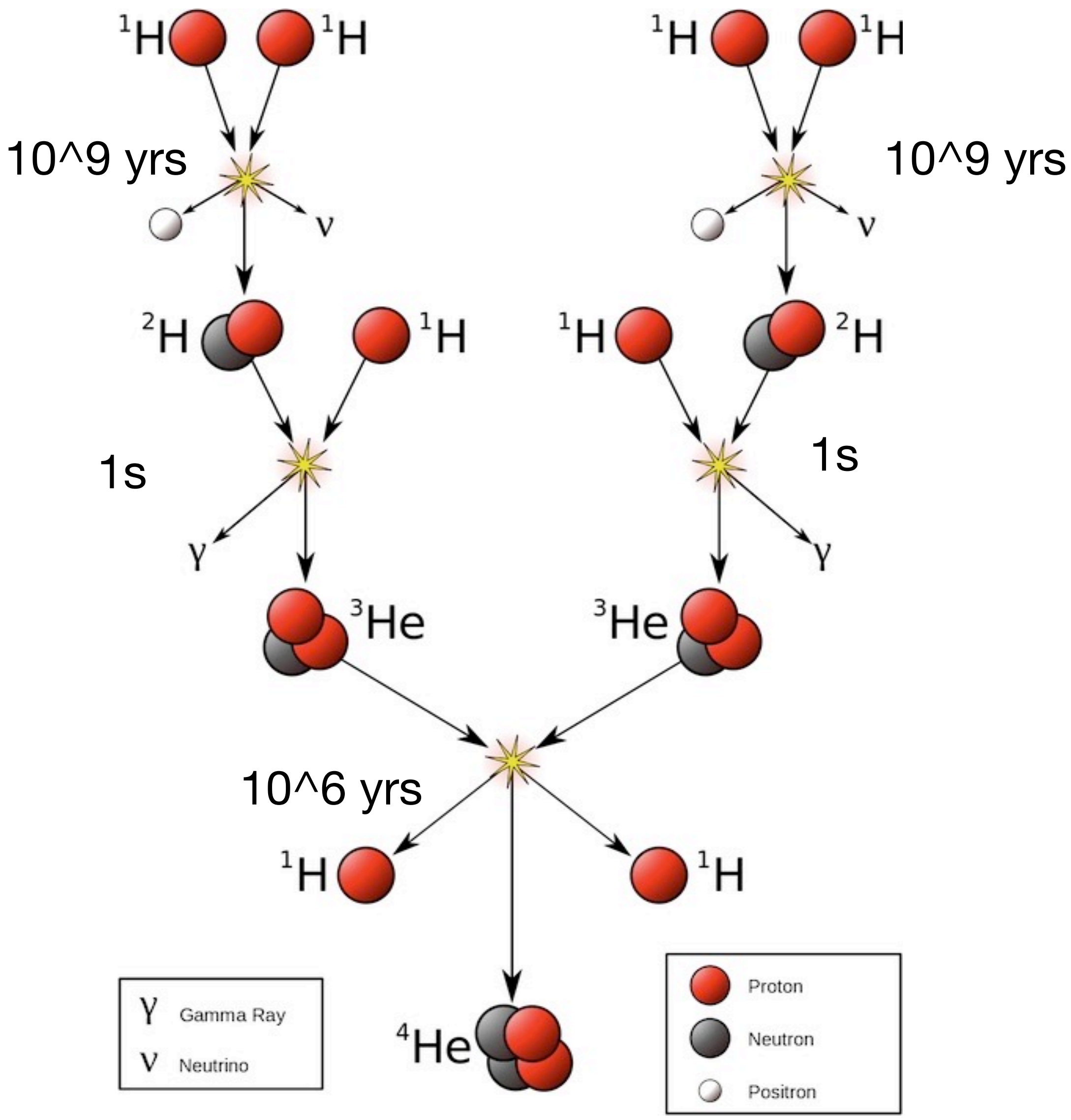
Opacities

Nuclear cross sections

H-BURNING IN STARS:

The p-p chain

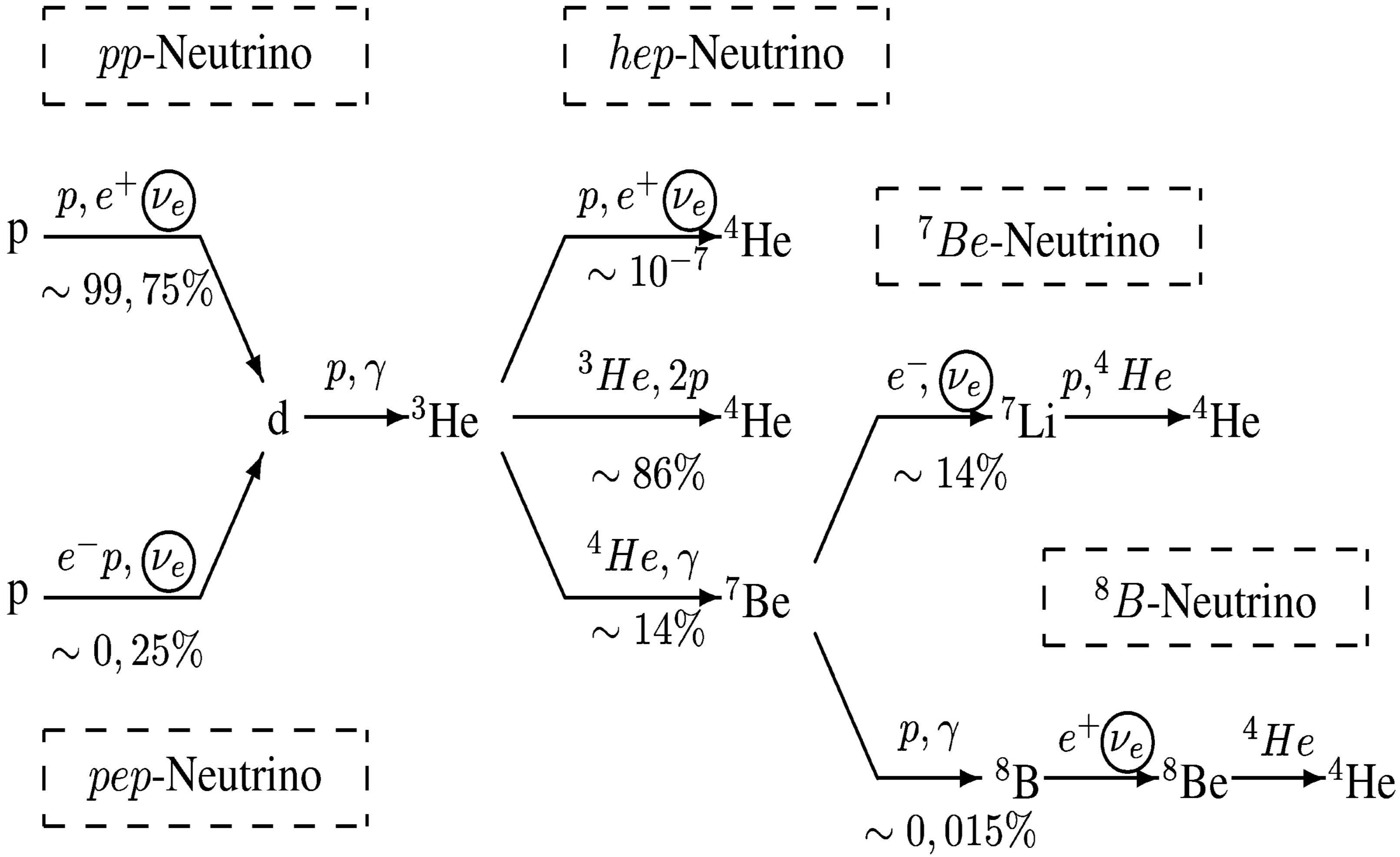
Q=26.5 MeV



H-BURNING IN STARS:

The p-p chain

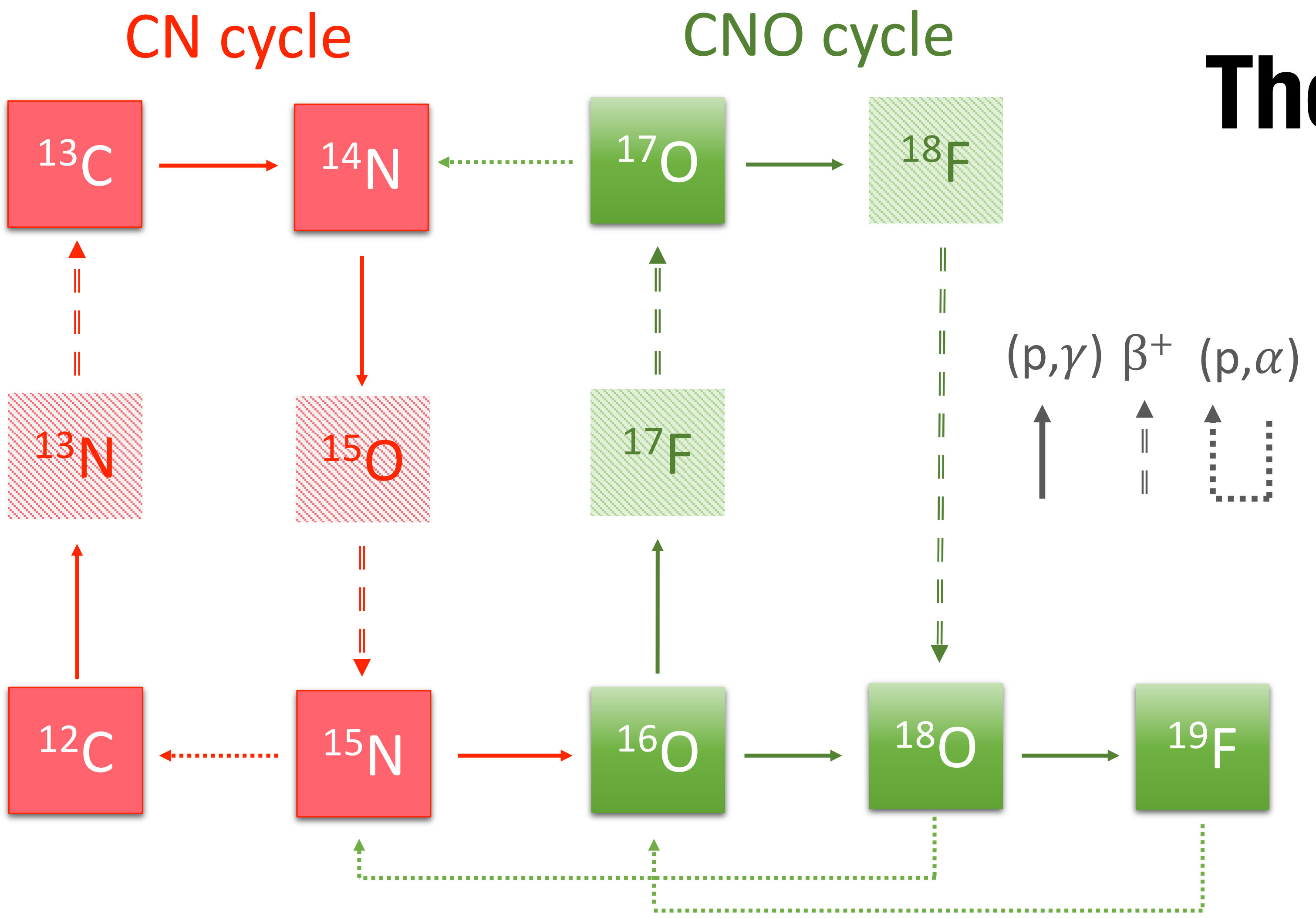
Q=26.5 MeV



H-BURNING IN STARS:

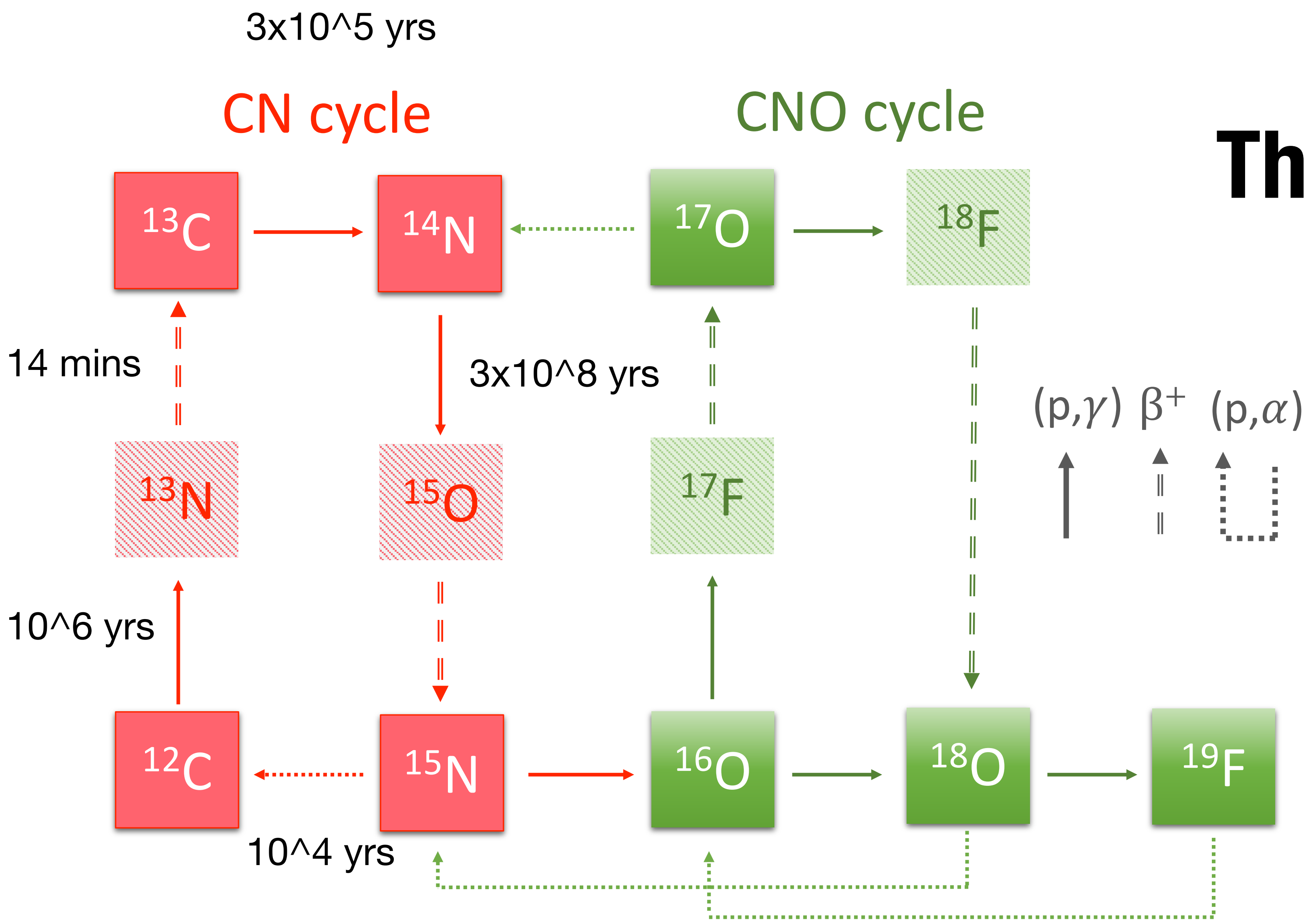
The CNO cycle

Q=25 MeV



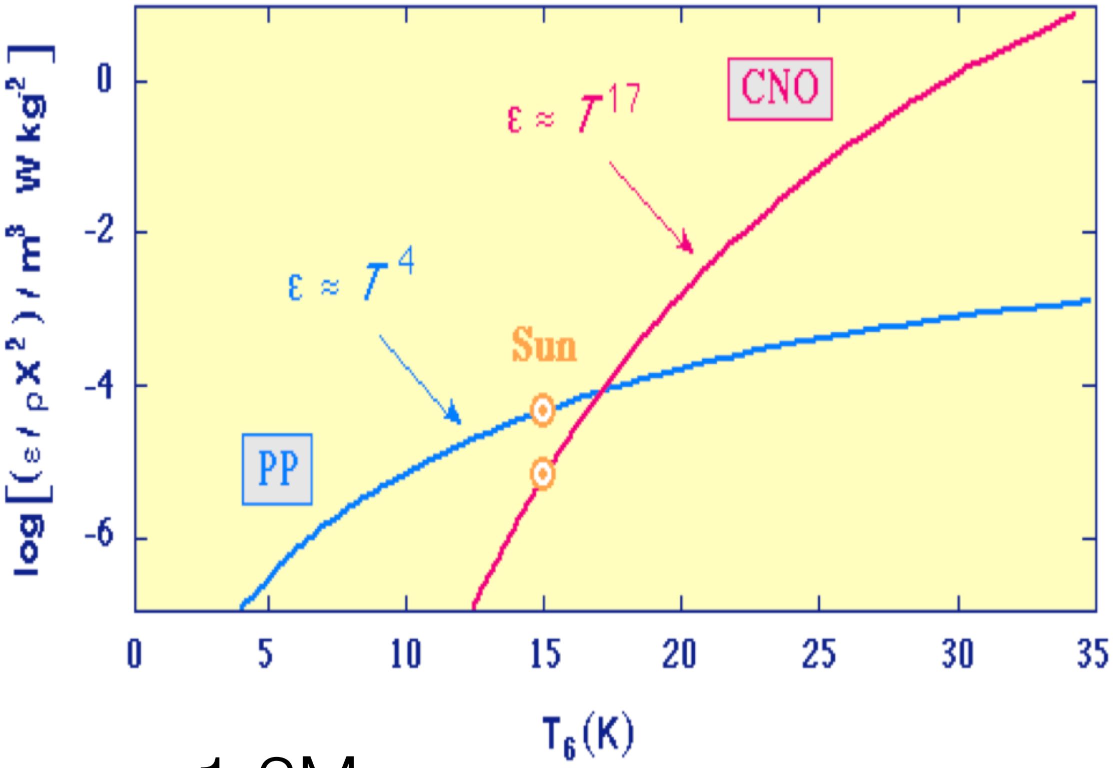
H-BURNING IN STARS:

The CNO cycle



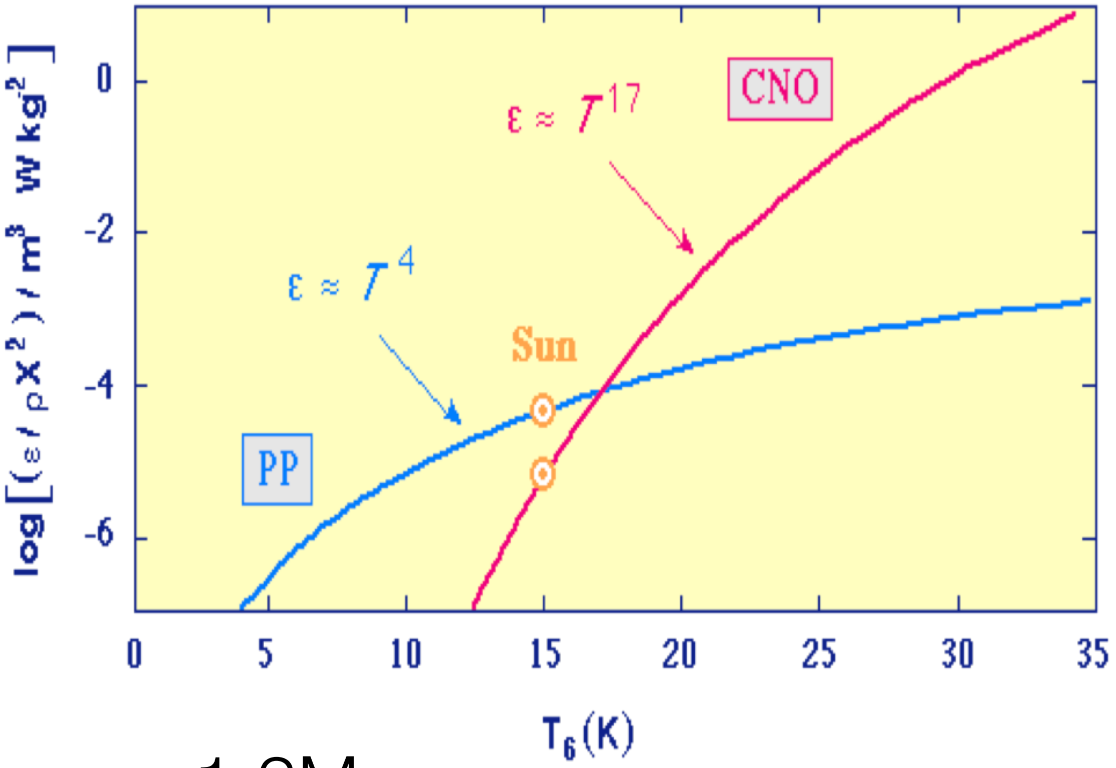
H-BURNING IN STARS:

>1.2Msun

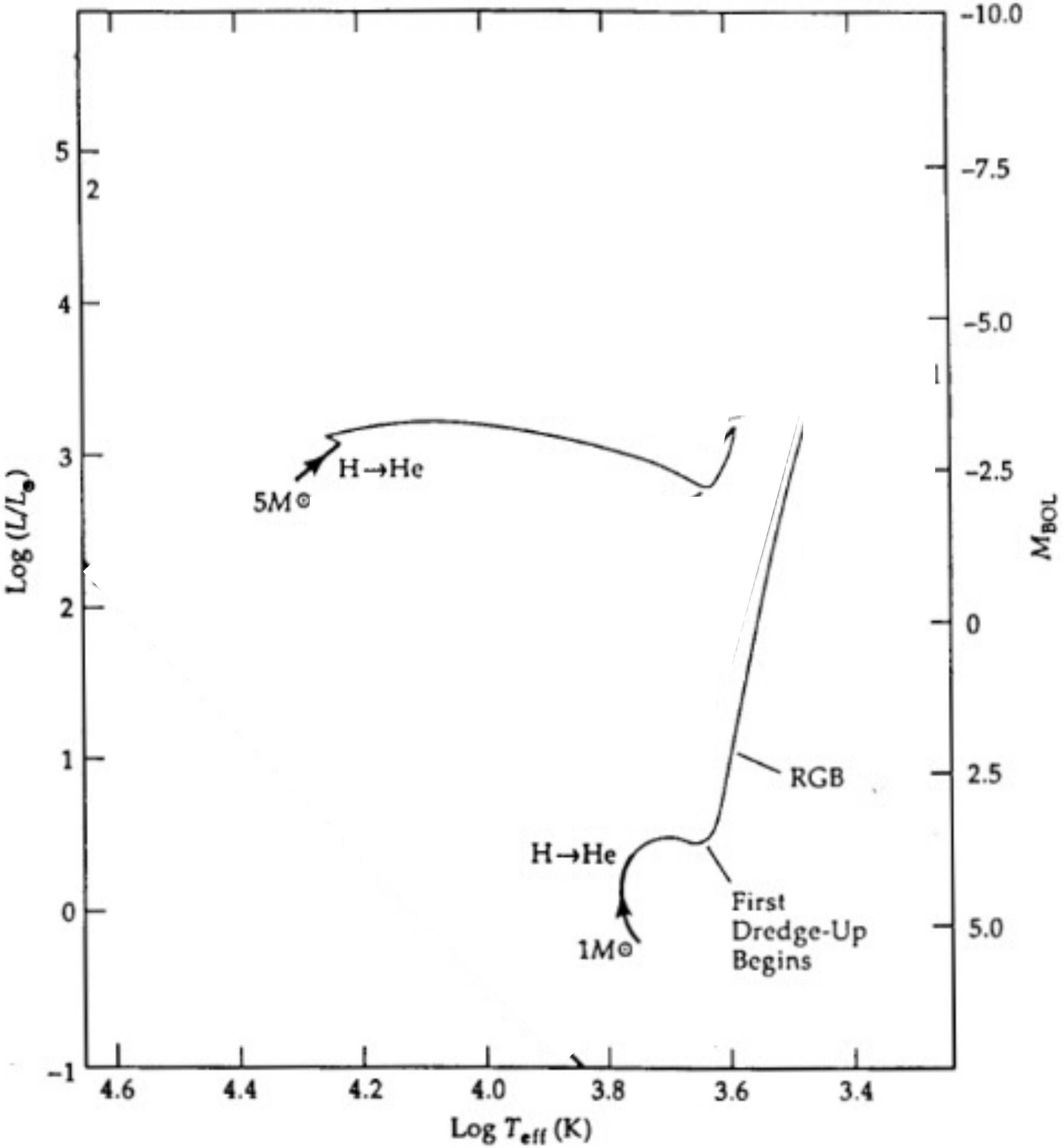


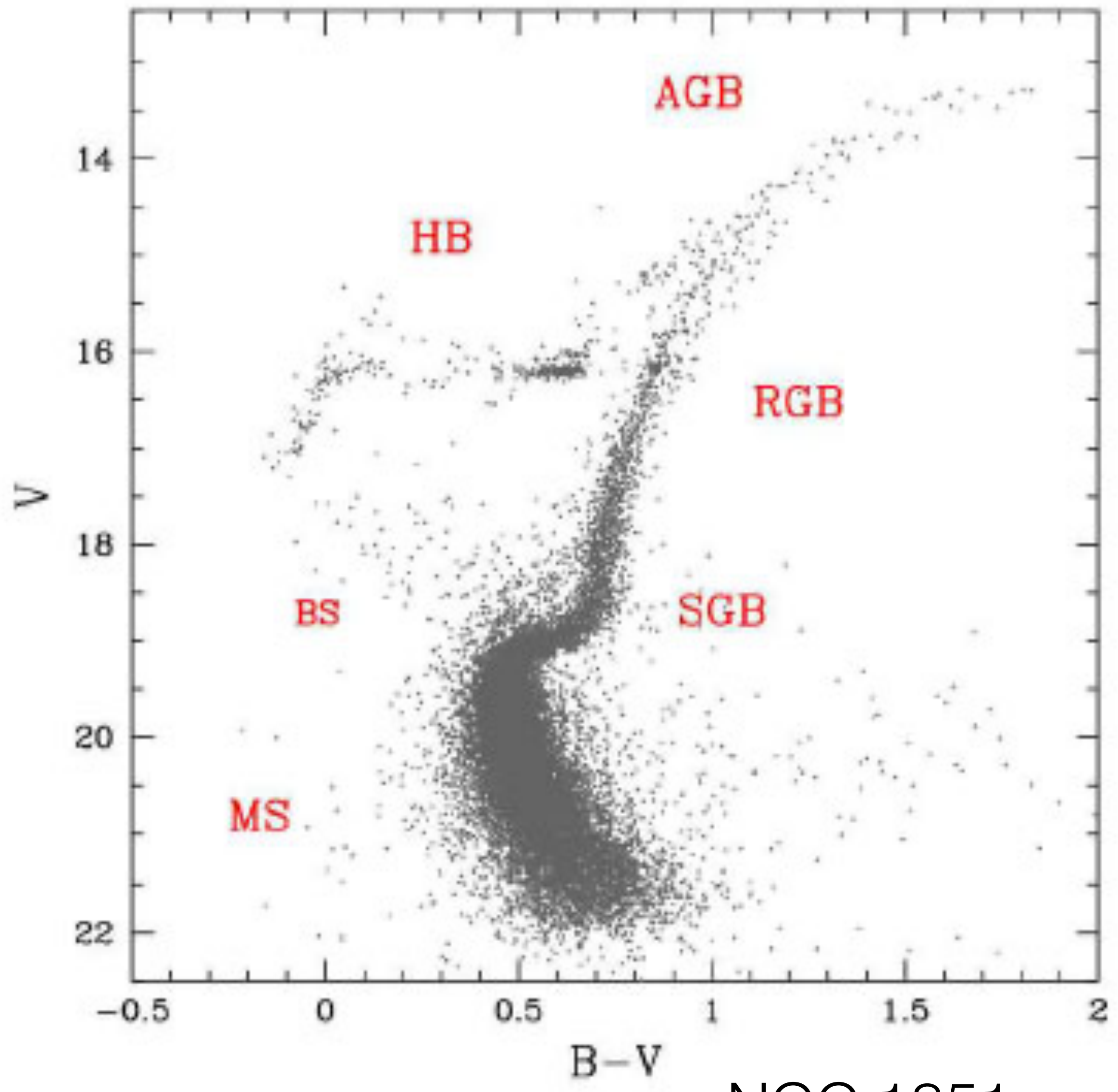
<1.2Msun

>1.2Msun

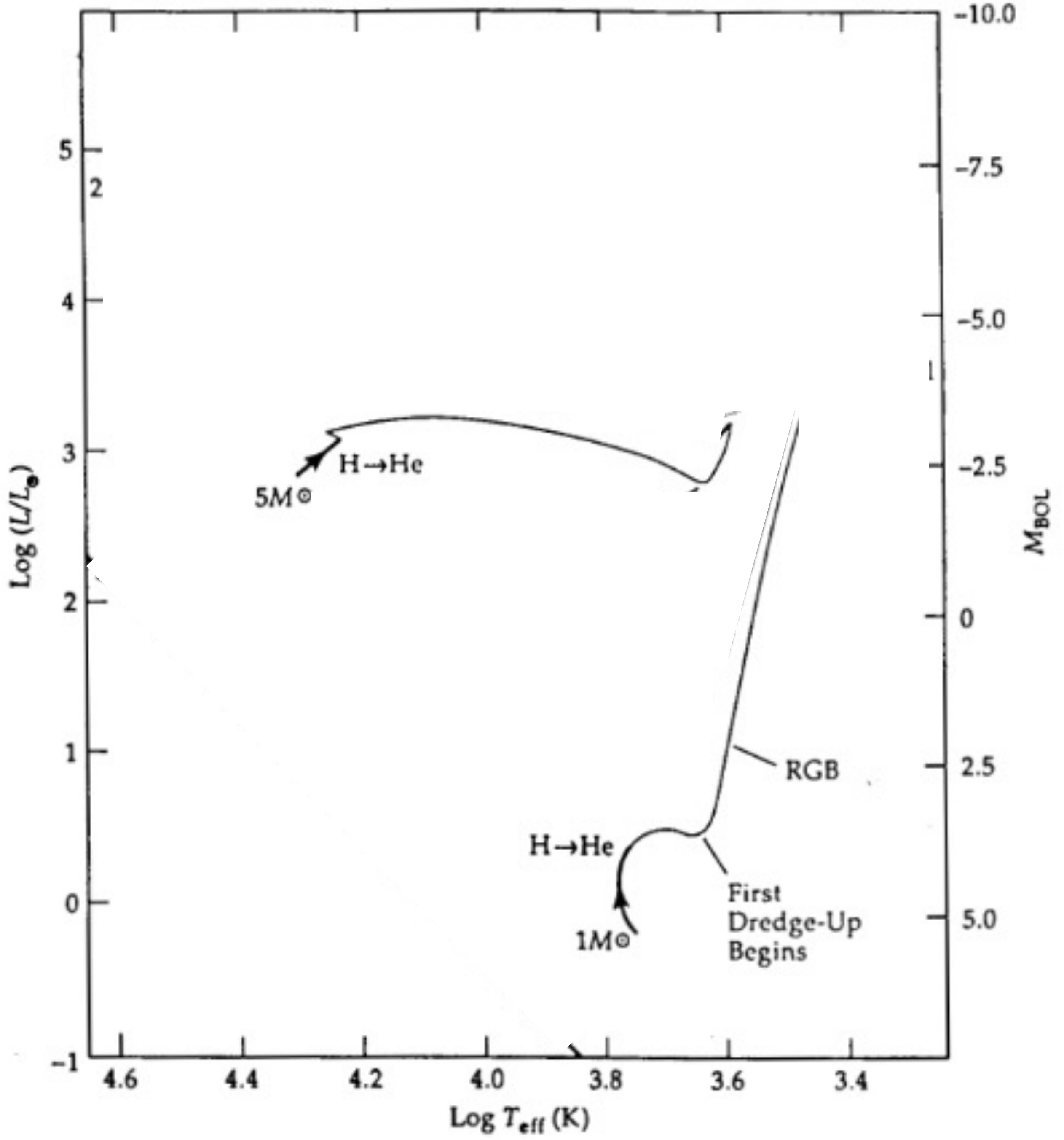


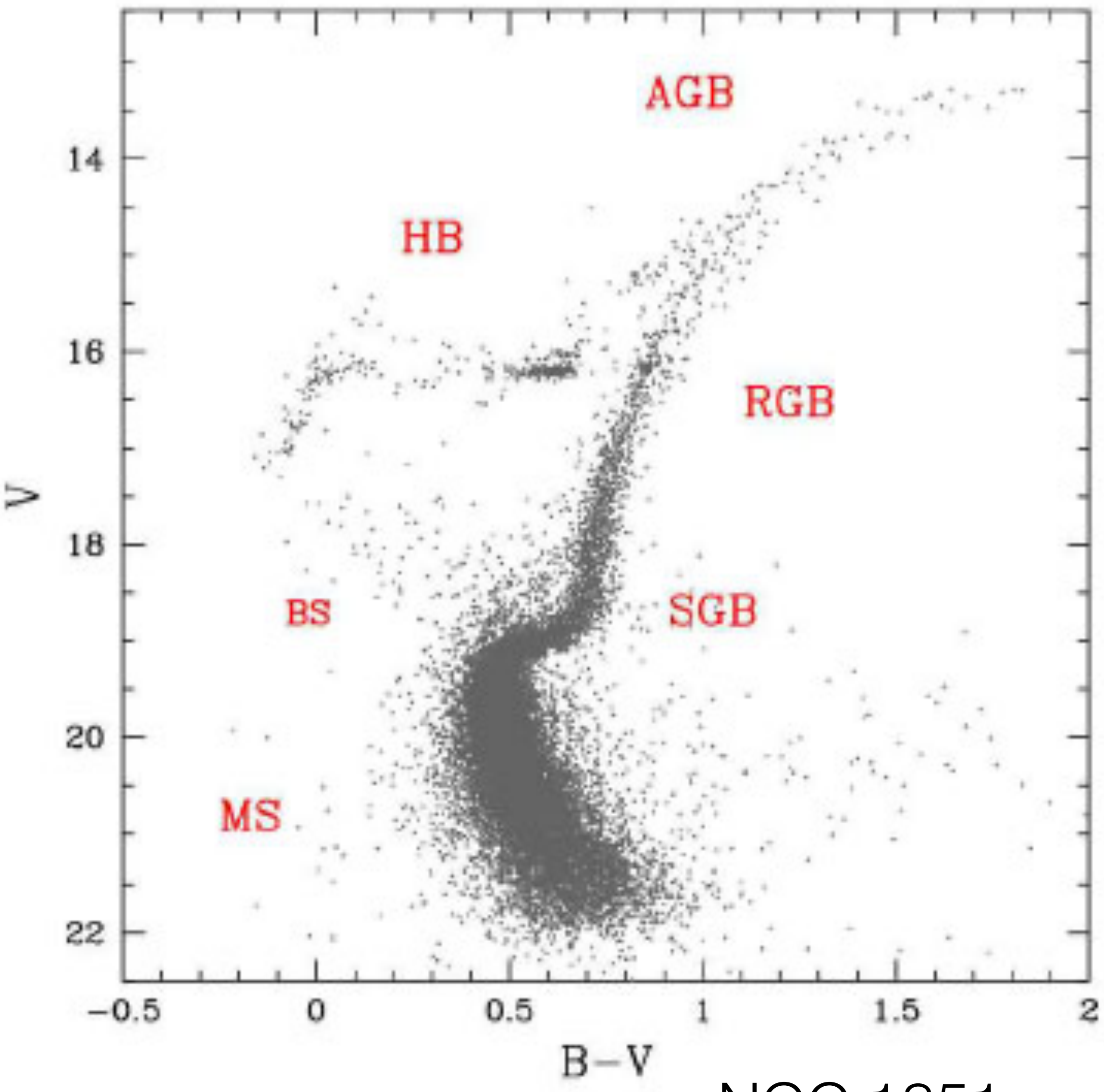
<1.2Msun



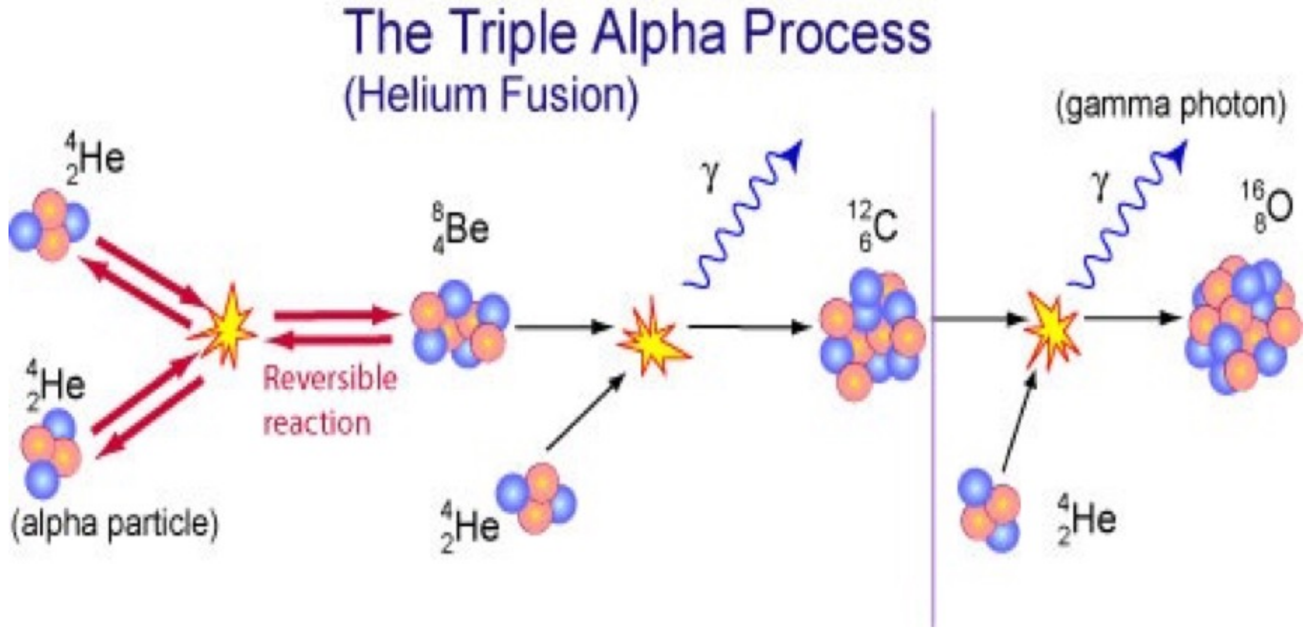

AGB
HB
RGB
BS
SGB
MS
V
B−V
14
16
18
20
22
−0.5
0
0.5
1
1.5
2

NGC 1851

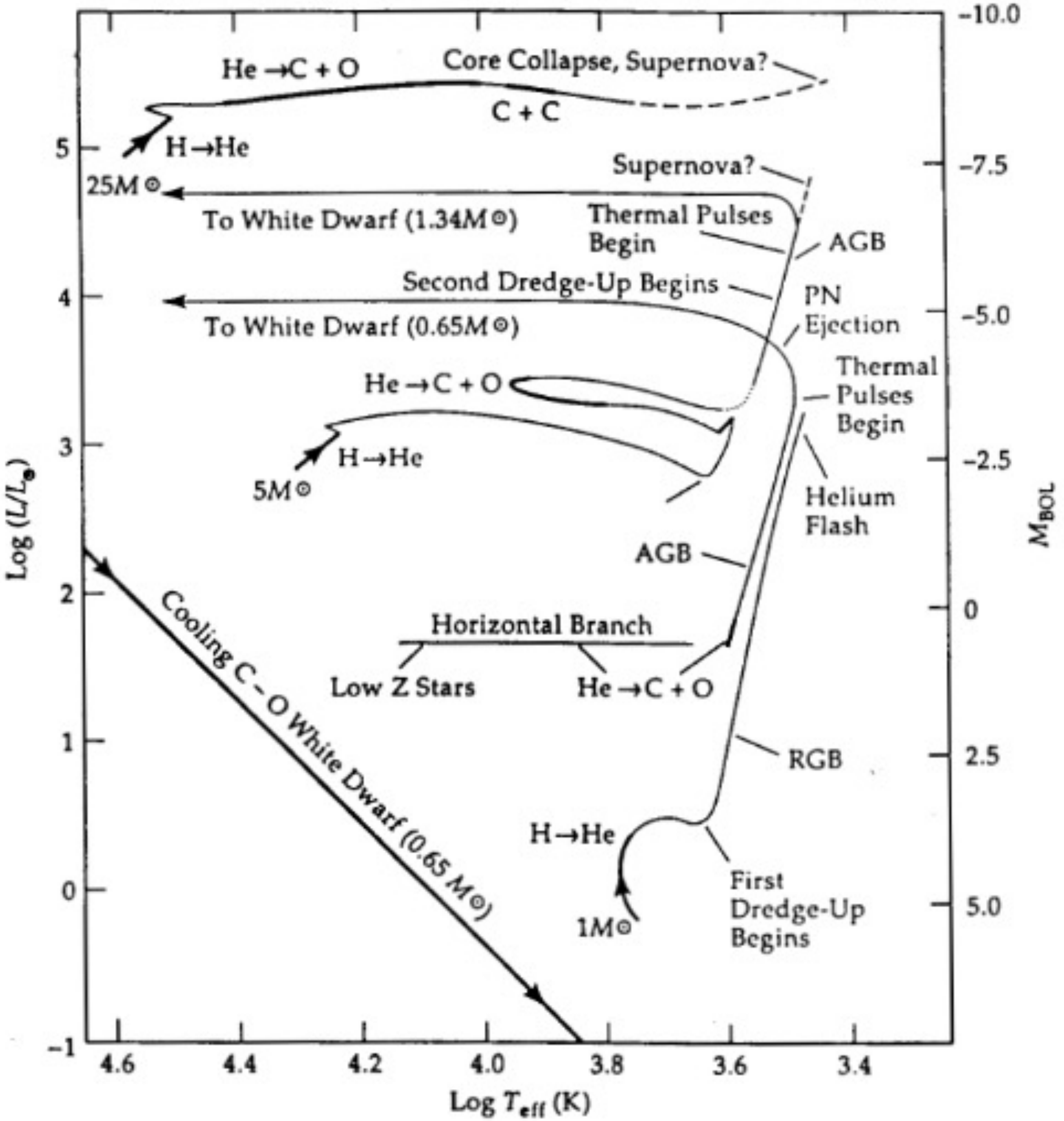

H→He
5M⊙
H→He
1M⊙
RGB
First
Dredge-Up
Begins
Log (L/L⊙)
Log Teff (K)
MBOL
4.6
4.4
4.2
4.0
3.8
3.6
3.4
-10.0
-7.5
-5.0
-2.5
0
2.5
5.0



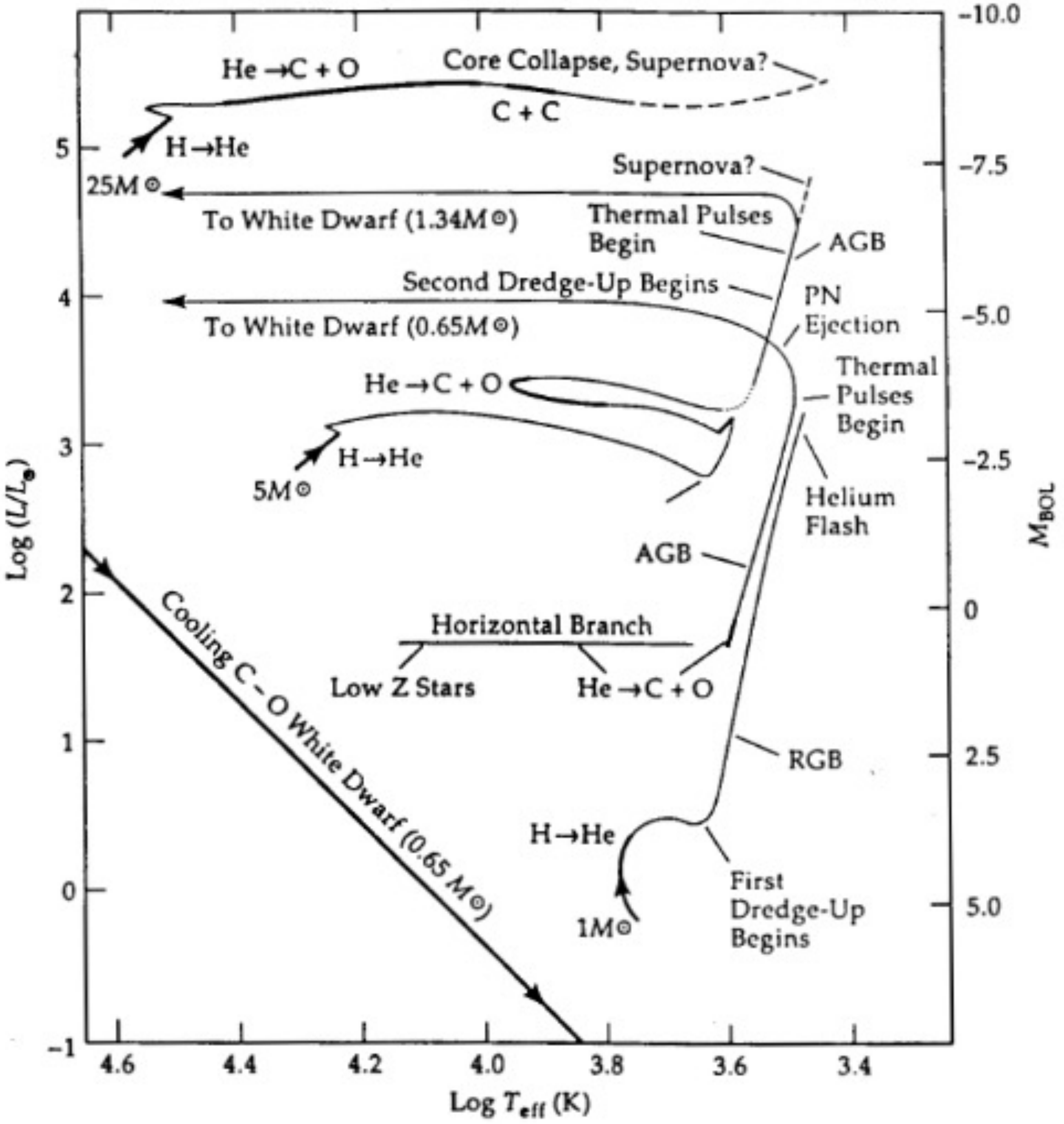
NGC 1851



T>10^8K



He →C + O
Core Collapse, Supernova?
C + C
H→He
25M⊙
Supernova?
To White Dwarf (1.34M⊙)
Thermal Pulses Begin
AGB
Second Dredge-Up Begins
PN Ejection
To White Dwarf (0.65M⊙)
He →C + O
Thermal Pulses Begin
H→He
5M⊙
Helium Flash
AGB
Horizontal Branch
Low Z Stars
He →C + O
Cooling C – O White Dwarf (0.65 M⊙)
RGB
H→He
1M⊙
First Dredge-Up Begins
Log (L/L⊙)
Log T_{eff} (K)
M_{BOL}
5
4
3
2
1
0
−1
4.6
4.4
4.2
4.0
3.8
3.6
3.4
−10.0
−7.5
−5.0
−2.5
0
2.5
5.0



AGB STARS

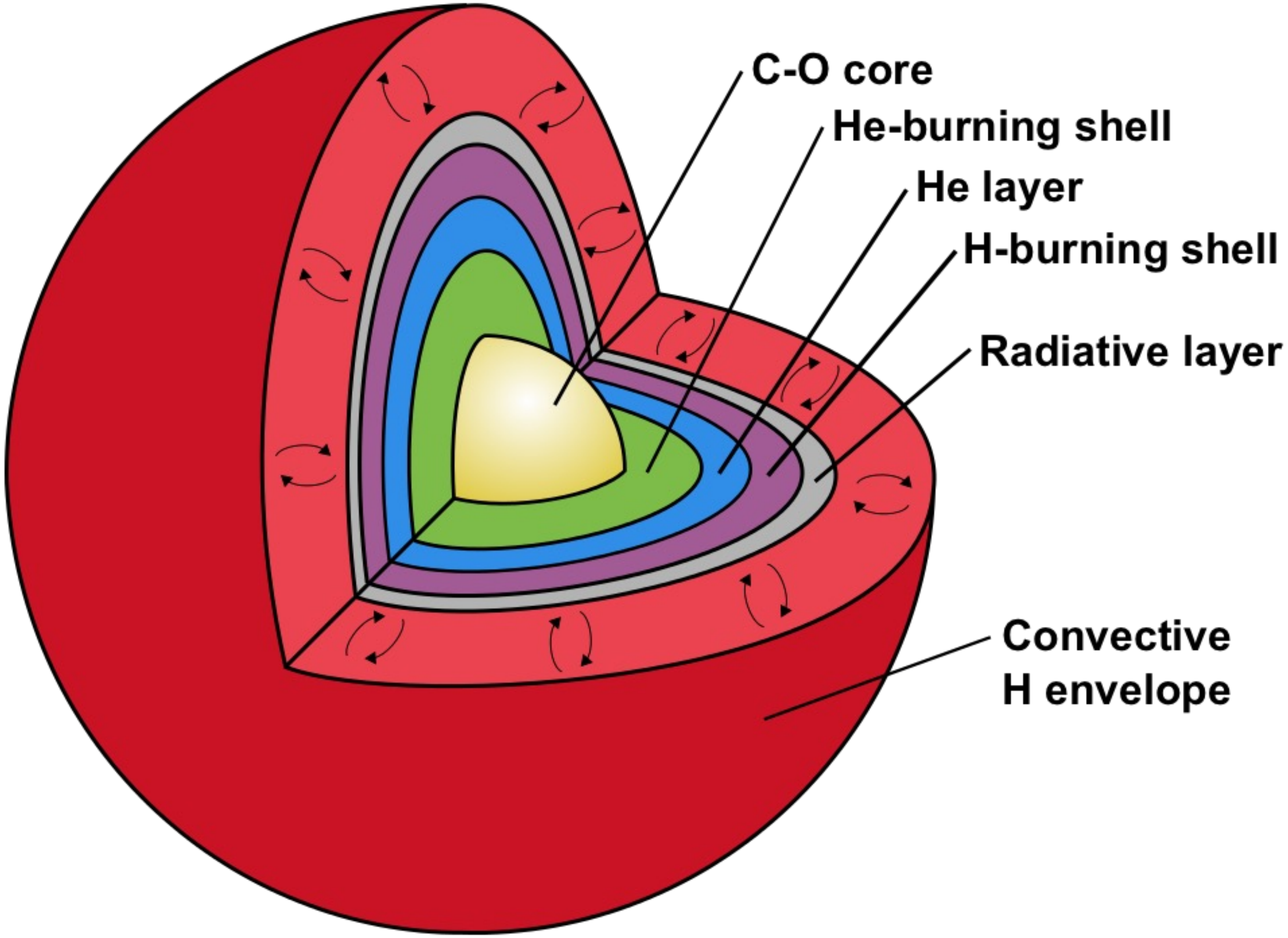
Low-intermediate mass stars:
1 ≤ M/Msun ≤ 8

Bright stars:
Lmax =104 -105 Lsun

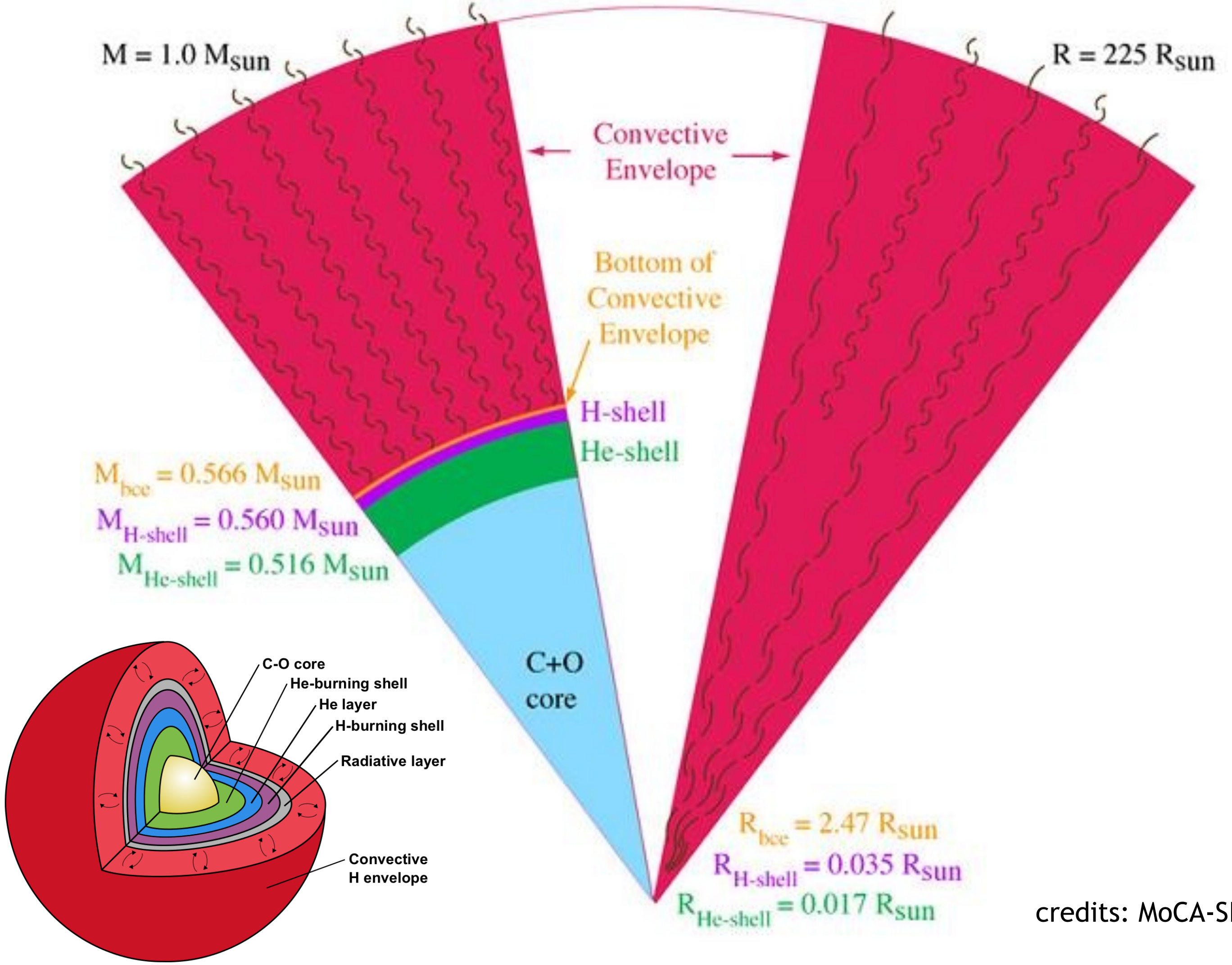
Cool stars:
Teff = 4000-2000 K

High mass loss rates:
Mass loss rates up to 10-4 Msun/yr

AGB STARS

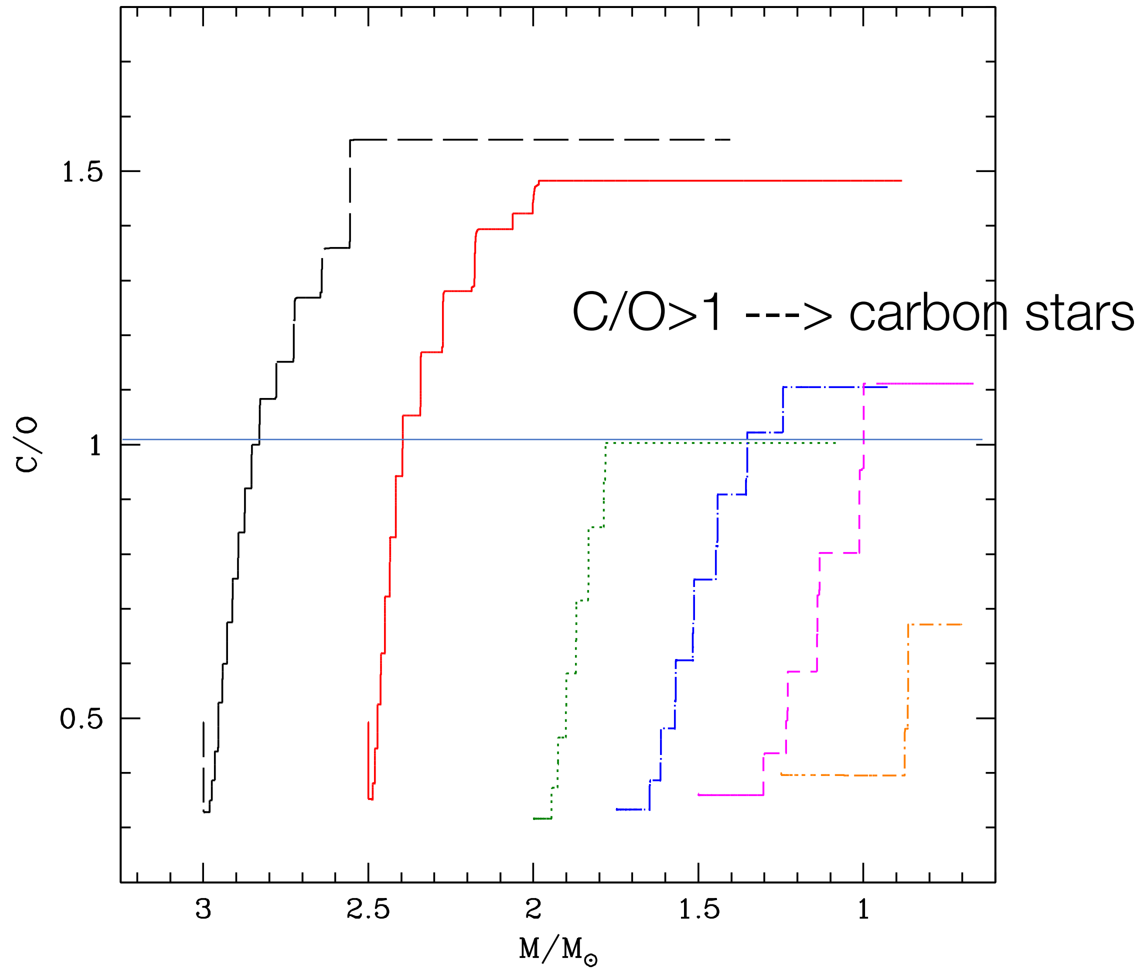

C-O core
He-burning shell
He layer
H-burning shell
Radiative layer
Convective
H envelope

AGB STARS

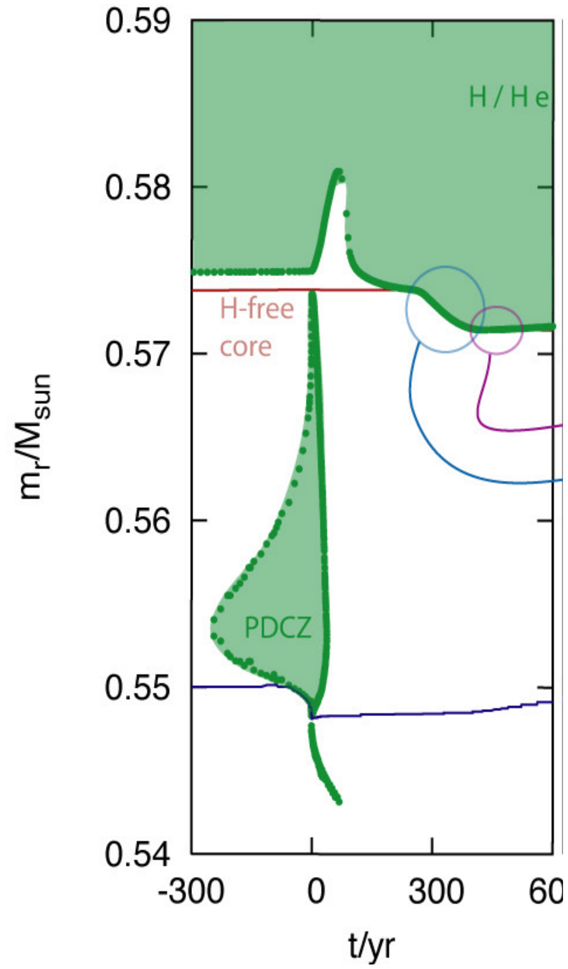


credits: MoCA-SINs

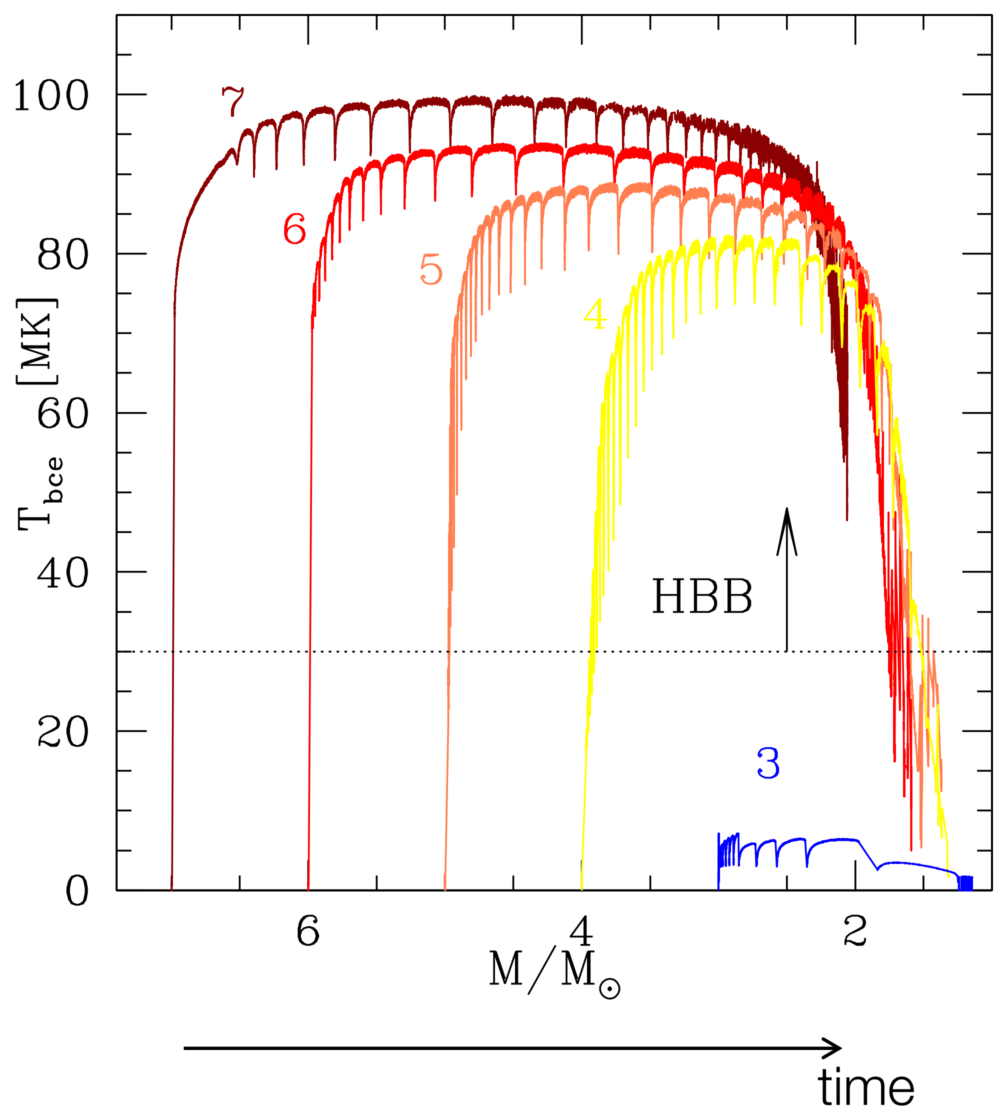
Third dredge-up

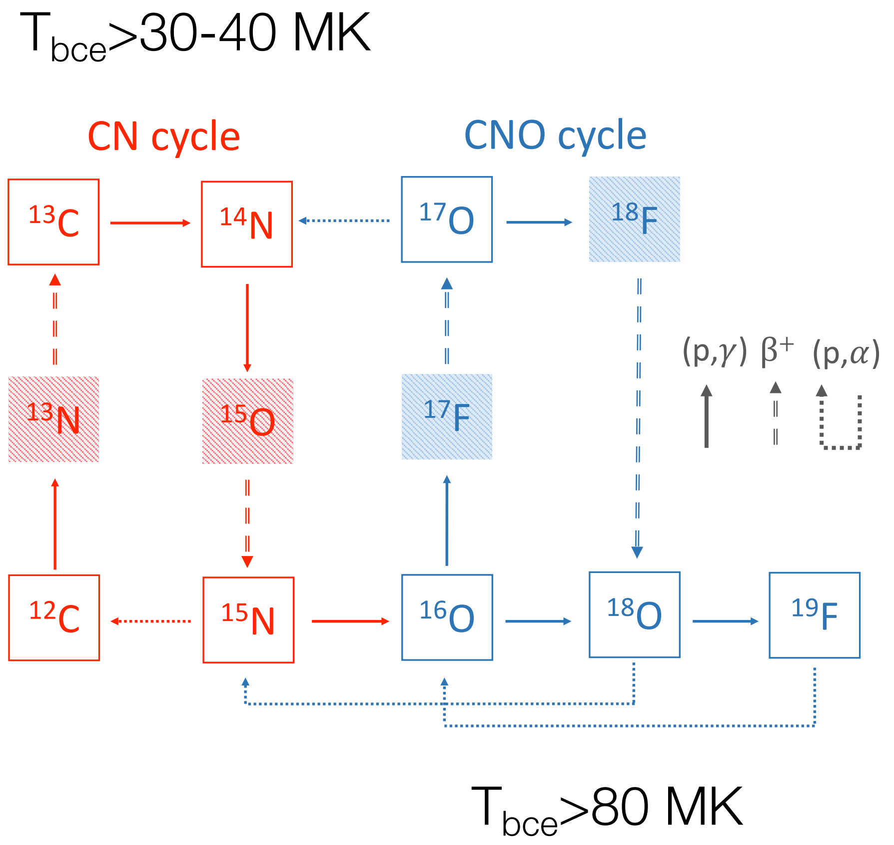


time

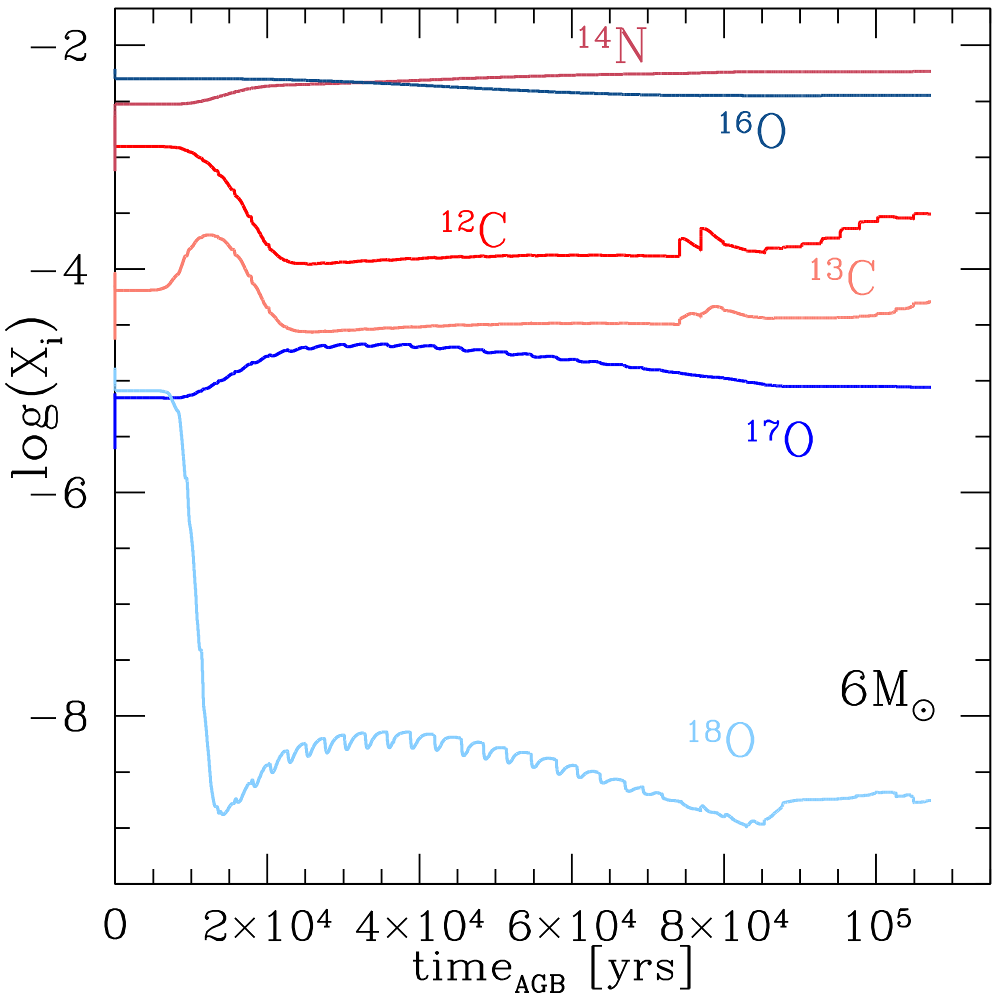


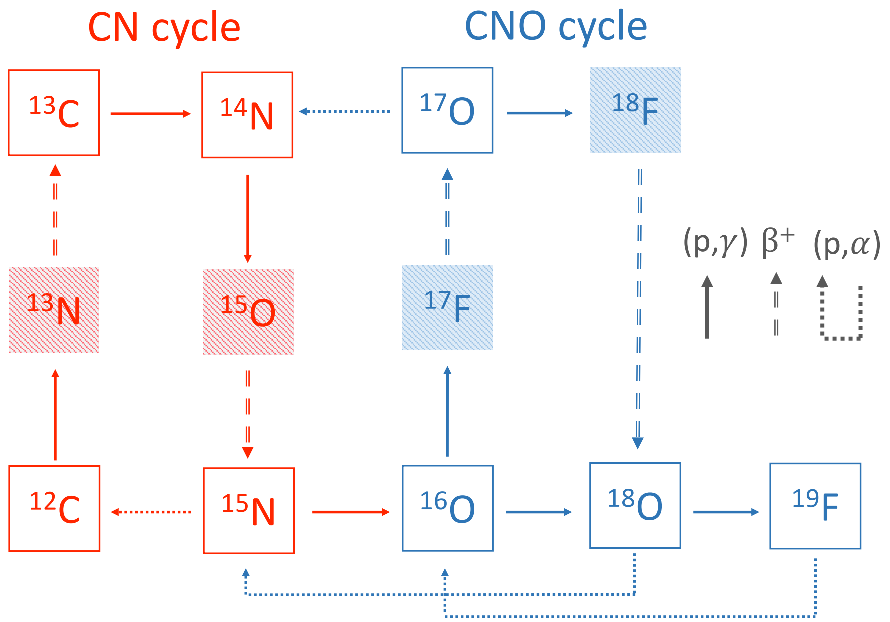
HOT BOTTOM BURNING



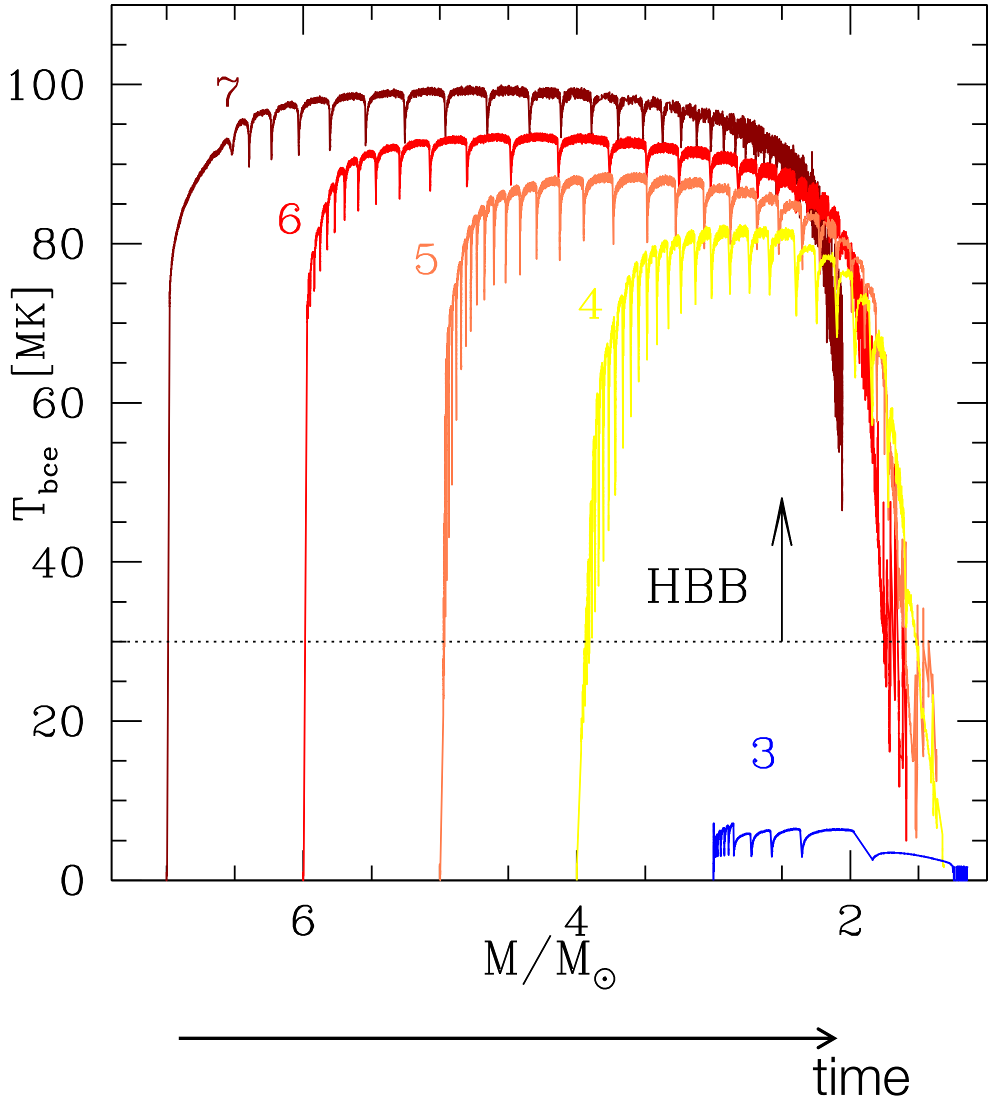


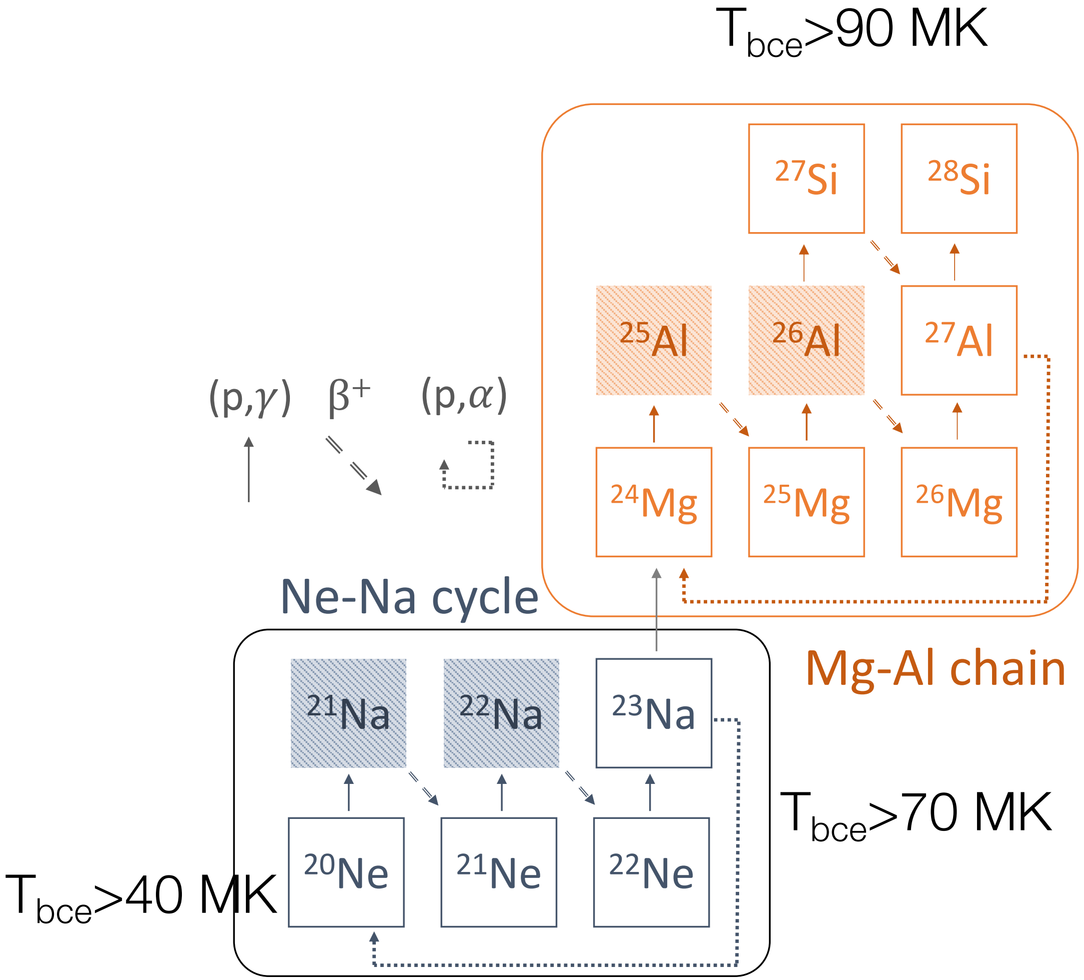
SURFACE CHEMISTRY



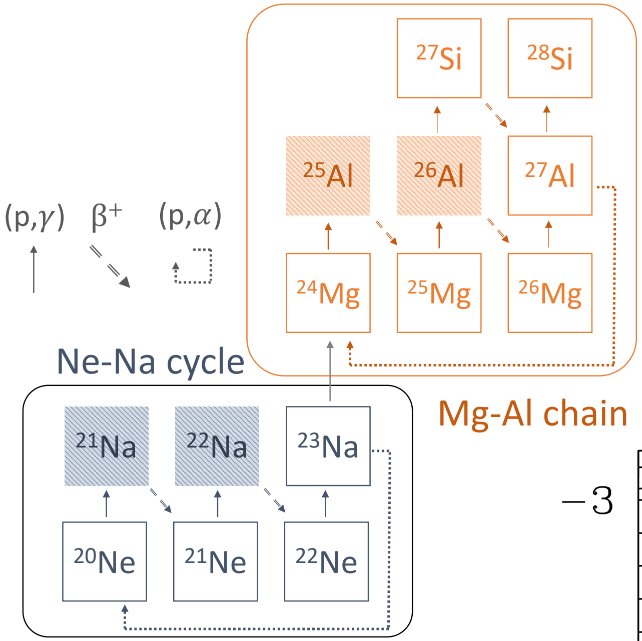


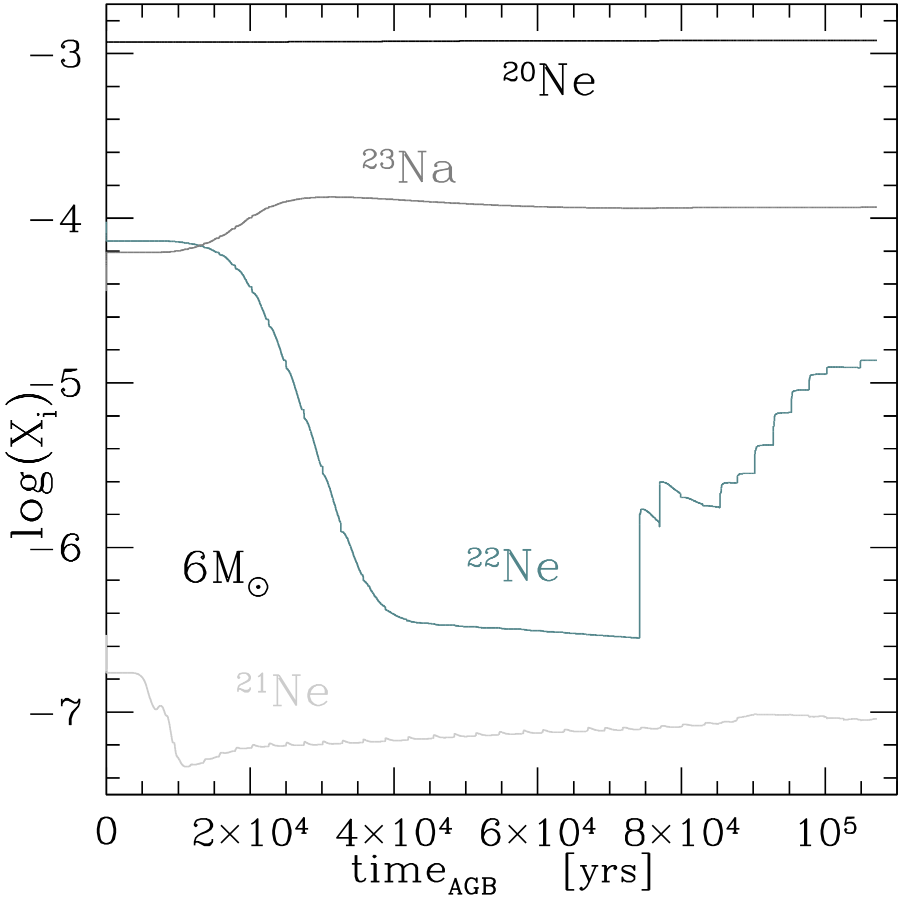
HOT BOTTOM BURNING

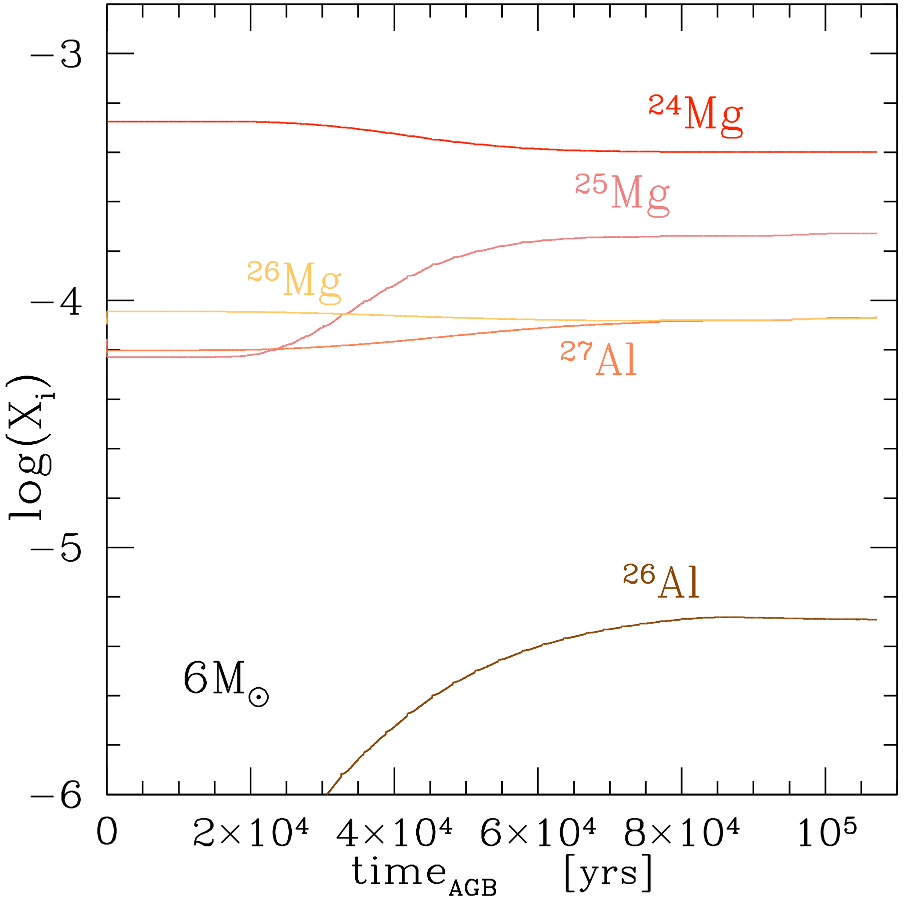




SURFACE CHEMISTRY







HOT BOTTOM BURNING