# The stellar yields


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**GREAT–ESF WORKSHOP**

**The metallicity distribution in the Milky Way discs**

**(Bologna, 29-31 May 2012)**

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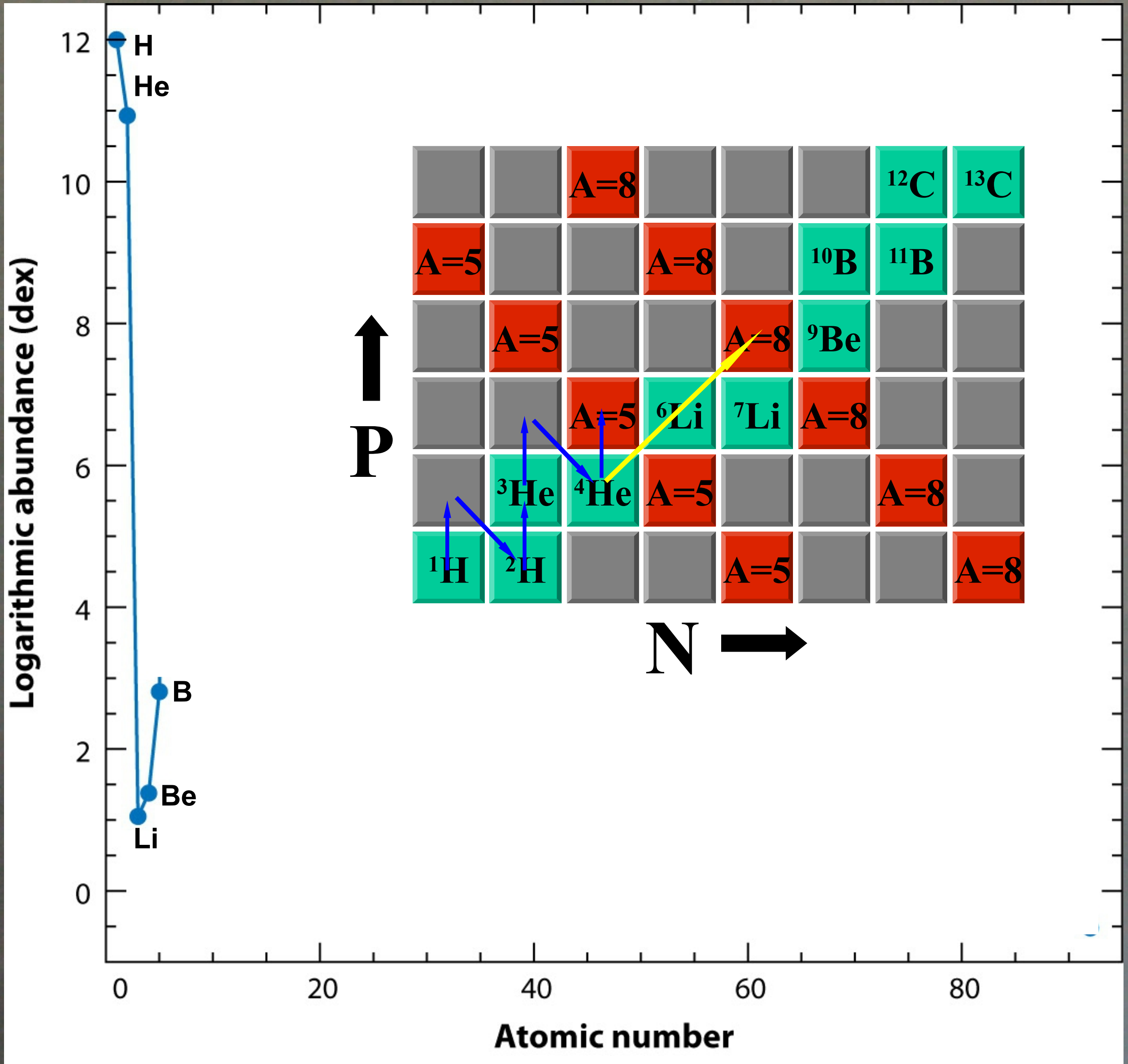
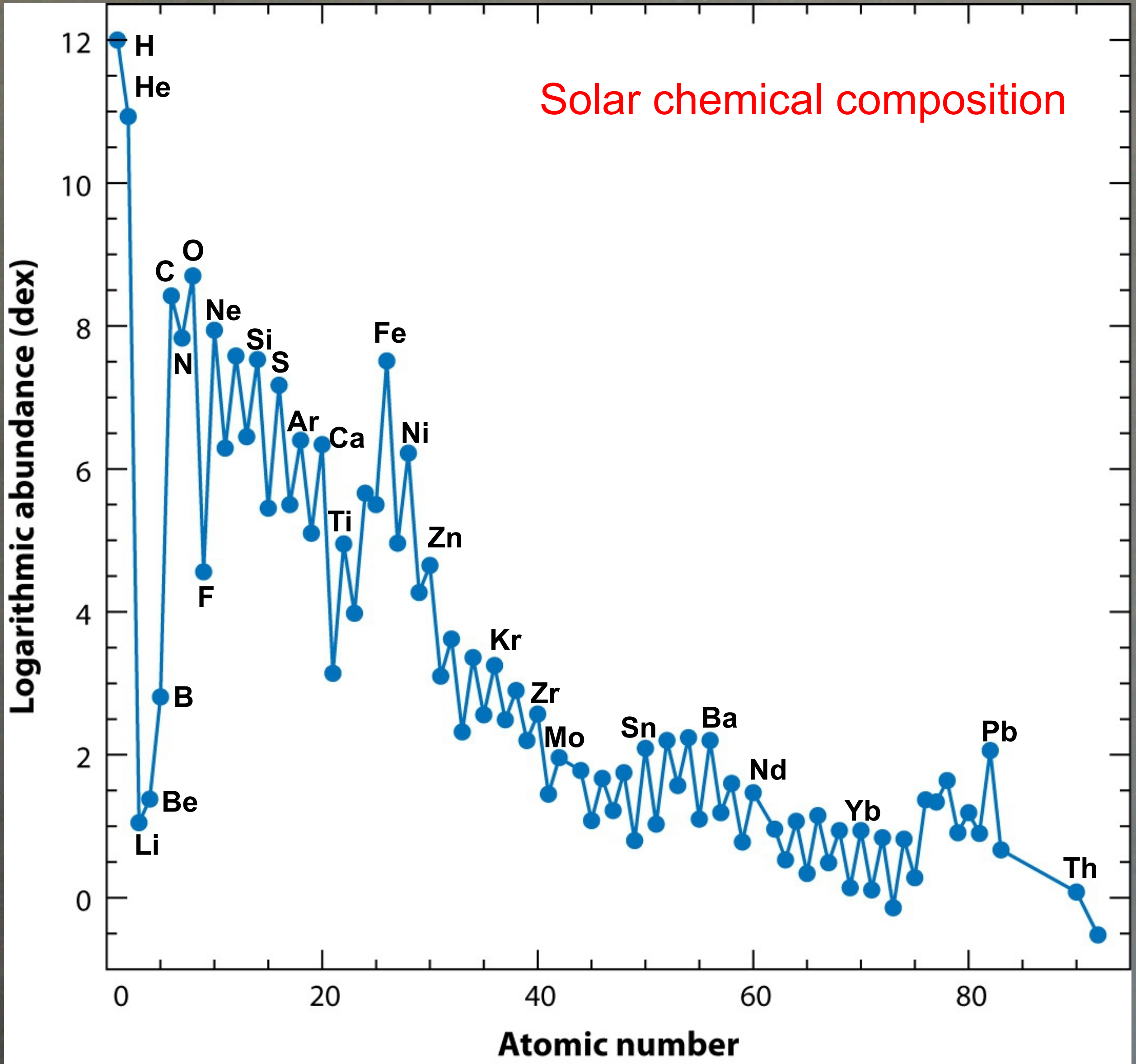
Image credits: ESO




Asplund M, et al. 2009.
Annu. Rev. Astron. Astrophys. 47:481–522

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# Evidence

The **Coulomb barrier** prevents an easy fusion between charged particles: only a combination of **high temperatures**, **high densities** and **long timescales** may lead to a substantial amount of fusion.

**Even the fusion of the lightest nuclei, protons, requires**

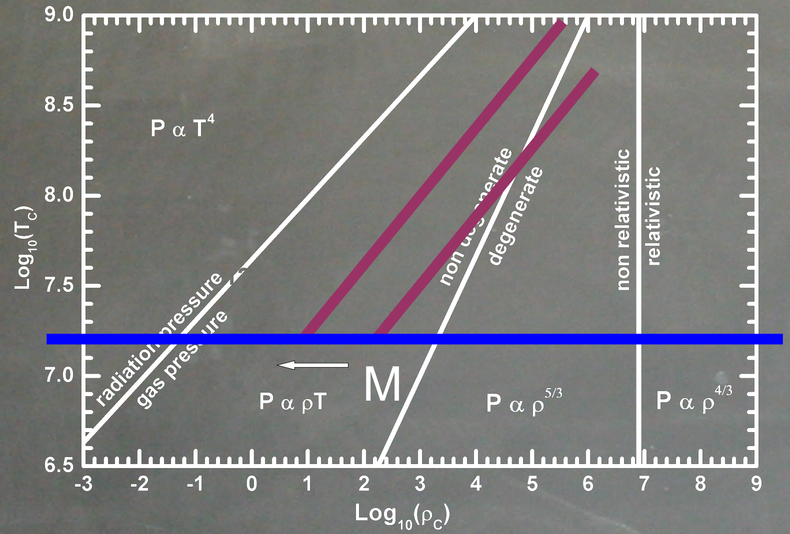
**$T >$ several $10^6$ K**
**$\rho >$ several grams / $cm^3$**

**to burn a significant amount of nuclei on a timescale shorter than the age of the Universe**

**These conditions are met only in stars**

# Basic flavor of the evolution of a star

$$\log_{10} T_c \propto \frac{1}{3} \log_{10} \rho_c \qquad \frac{T_c}{\rho_c} \propto M$$




**M>10 $M_O$ reach $T_C$ = $10^{10}$ K , collapse & explode**

**M<10 $M_O$ form an e-degenerate core, lose their envelope and end up as white dwards**

**From a nucleosynthetic point of view we can consider two main classes of stars:**

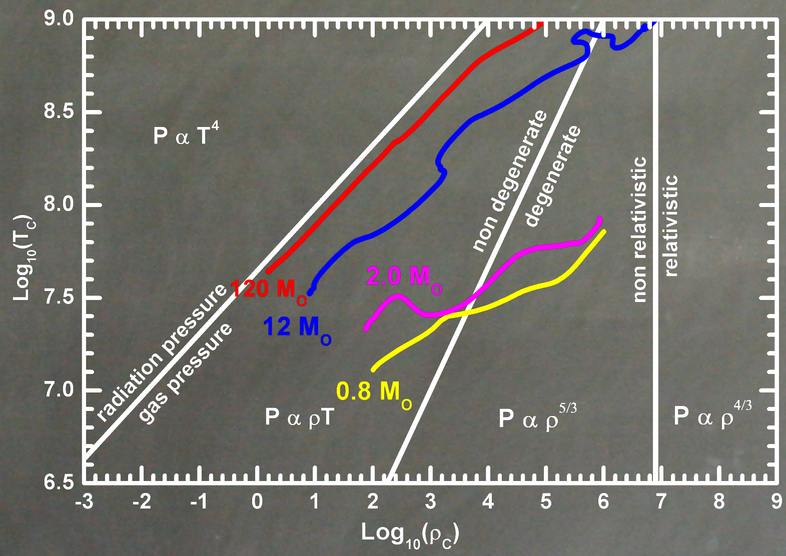
**Intermediate mass stars**

**&**

**massive stars.**

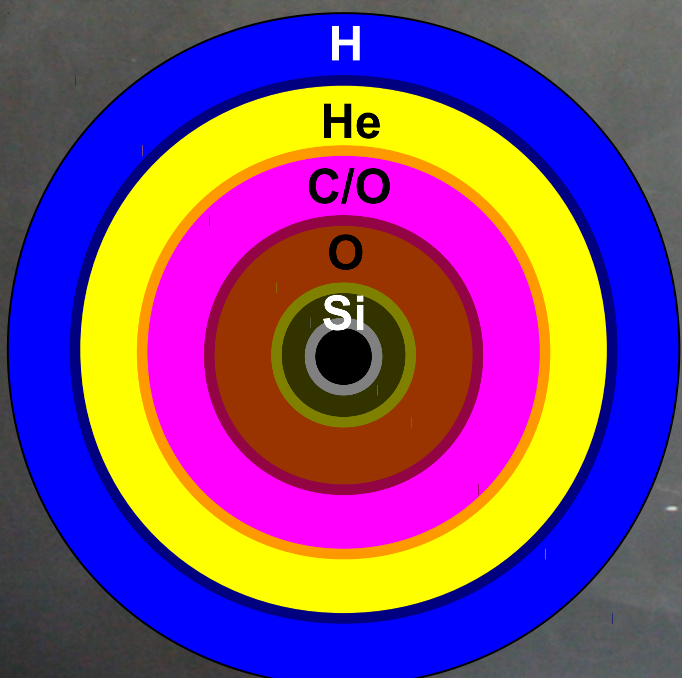
**(+Type Ia Supernovae)**

# Massive stars

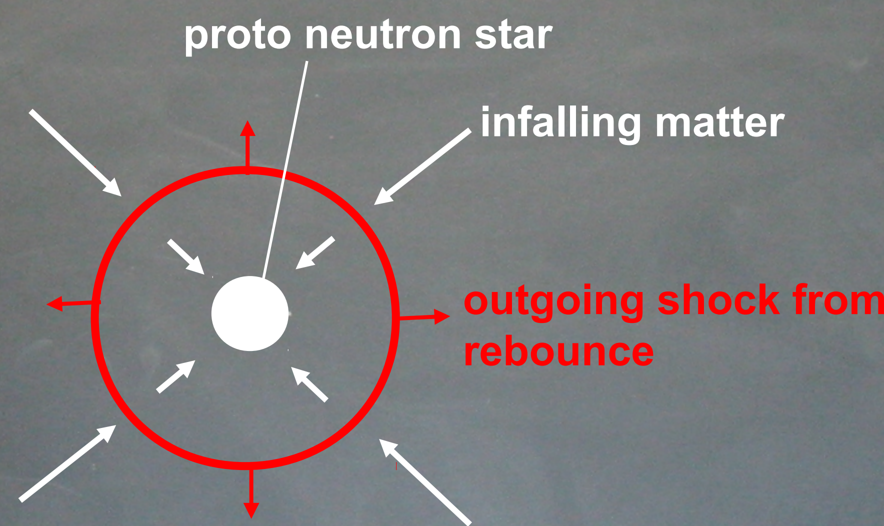


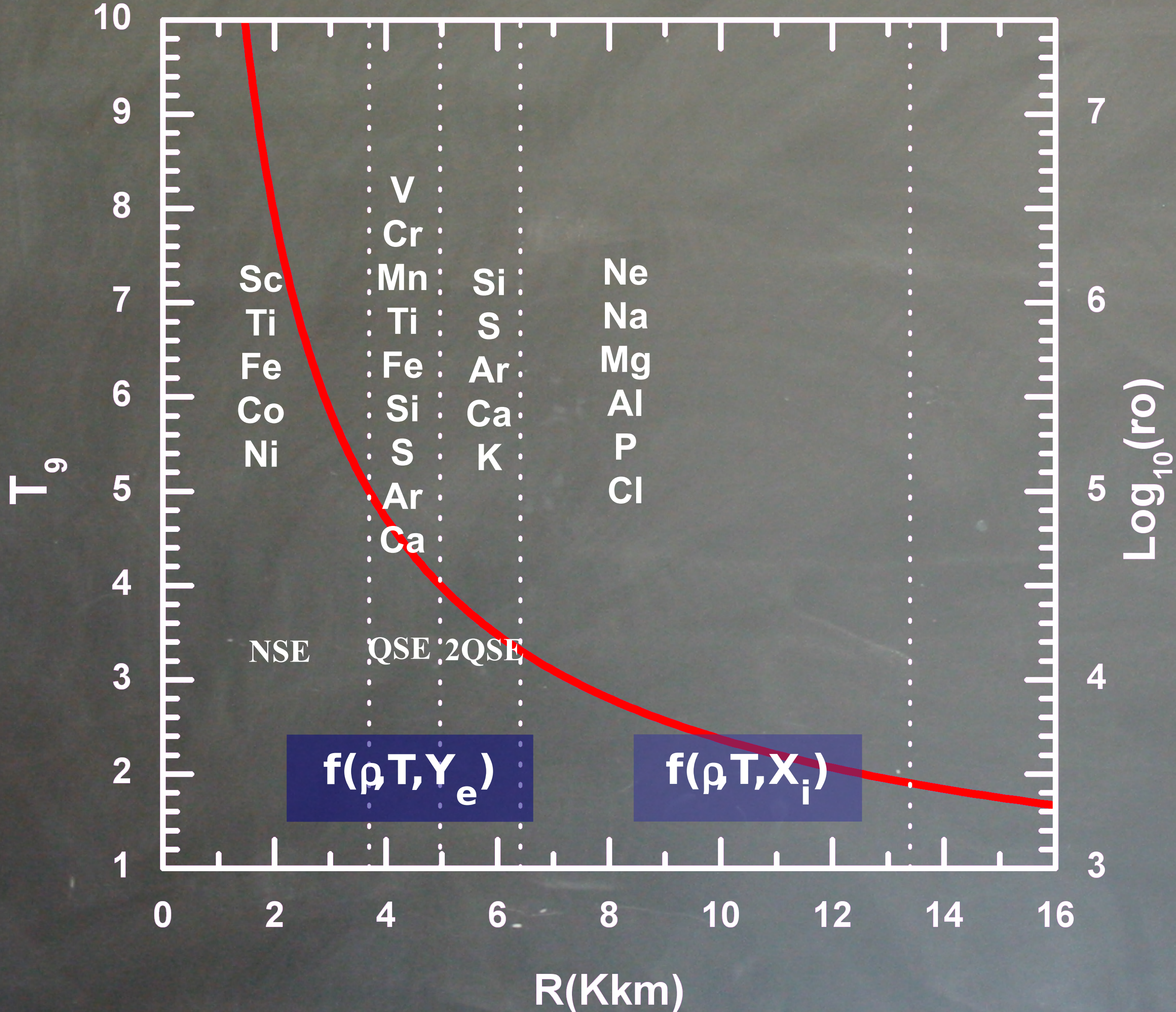

## Hydrostatic Evolution

**H-burning (T~ $4\cdot10^7$)**
**He-burning (T~ $1.5\cdot10^8$)**
**C-burning (T~ $7\cdot10^8$)**
**Ne-burning (T~ $1.2\cdot10^9$)**
**O-burning (T~ $1.8\cdot10^9$)**
**Si-burning (T~ $2.8\cdot10^9$)**

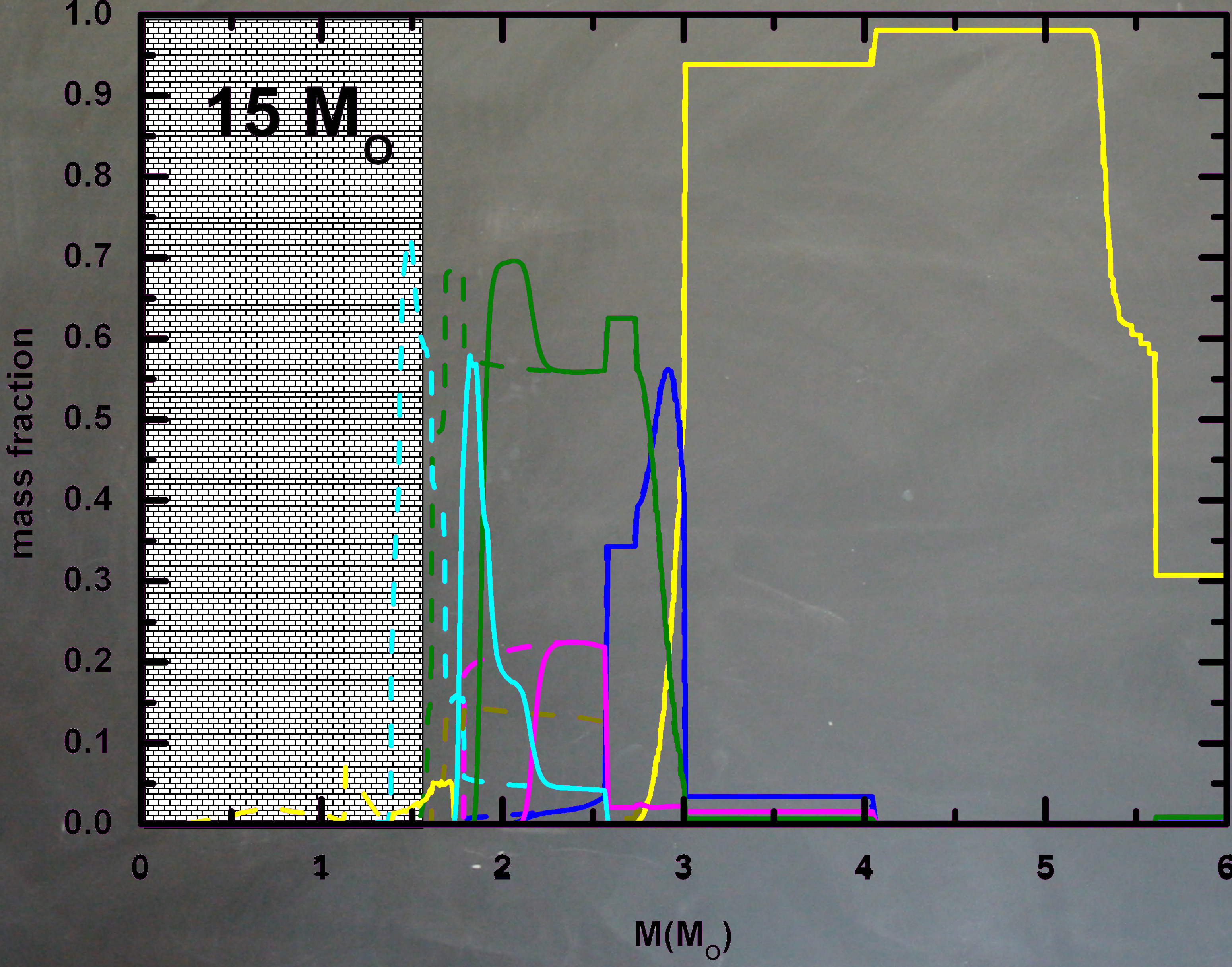



**ATTENTION: photodisintegrations activate for 30 KT=Q**
**i.e. T(BK) = 0.4 Q (MeV)**

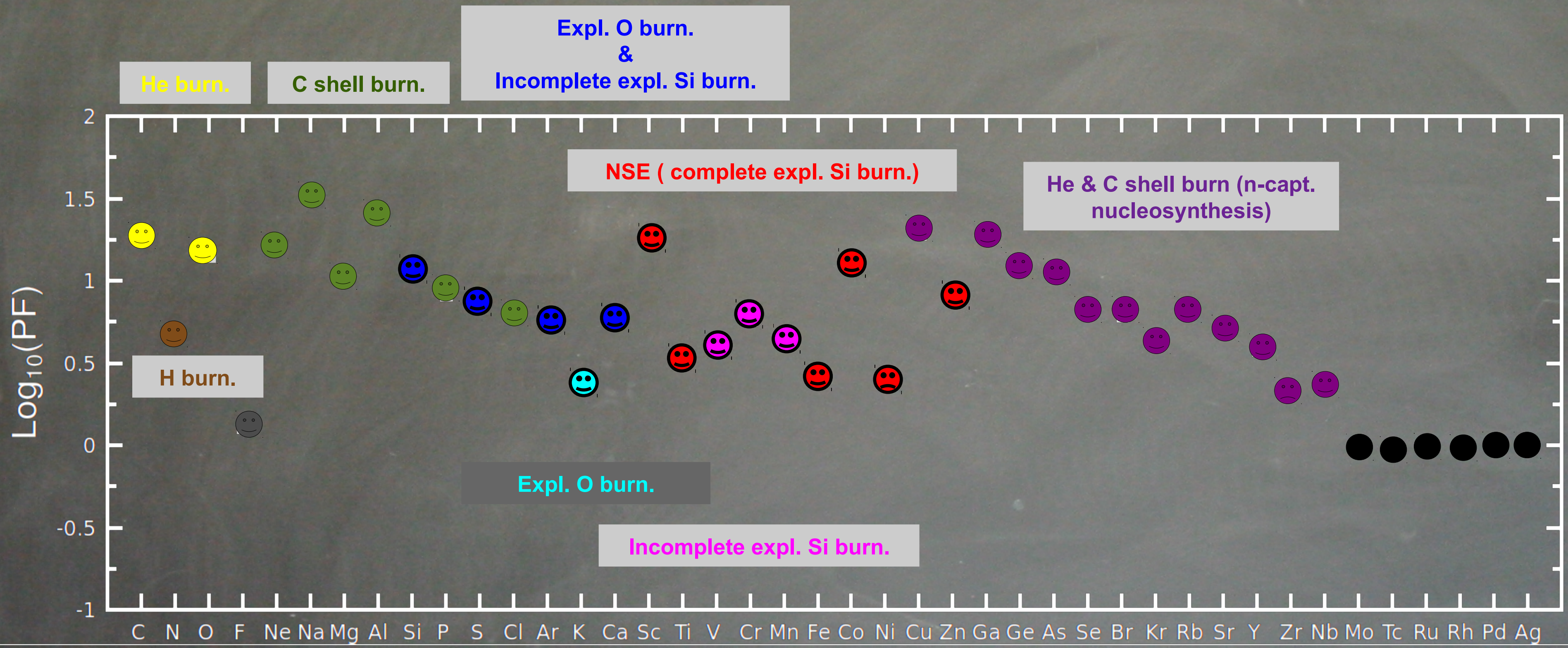




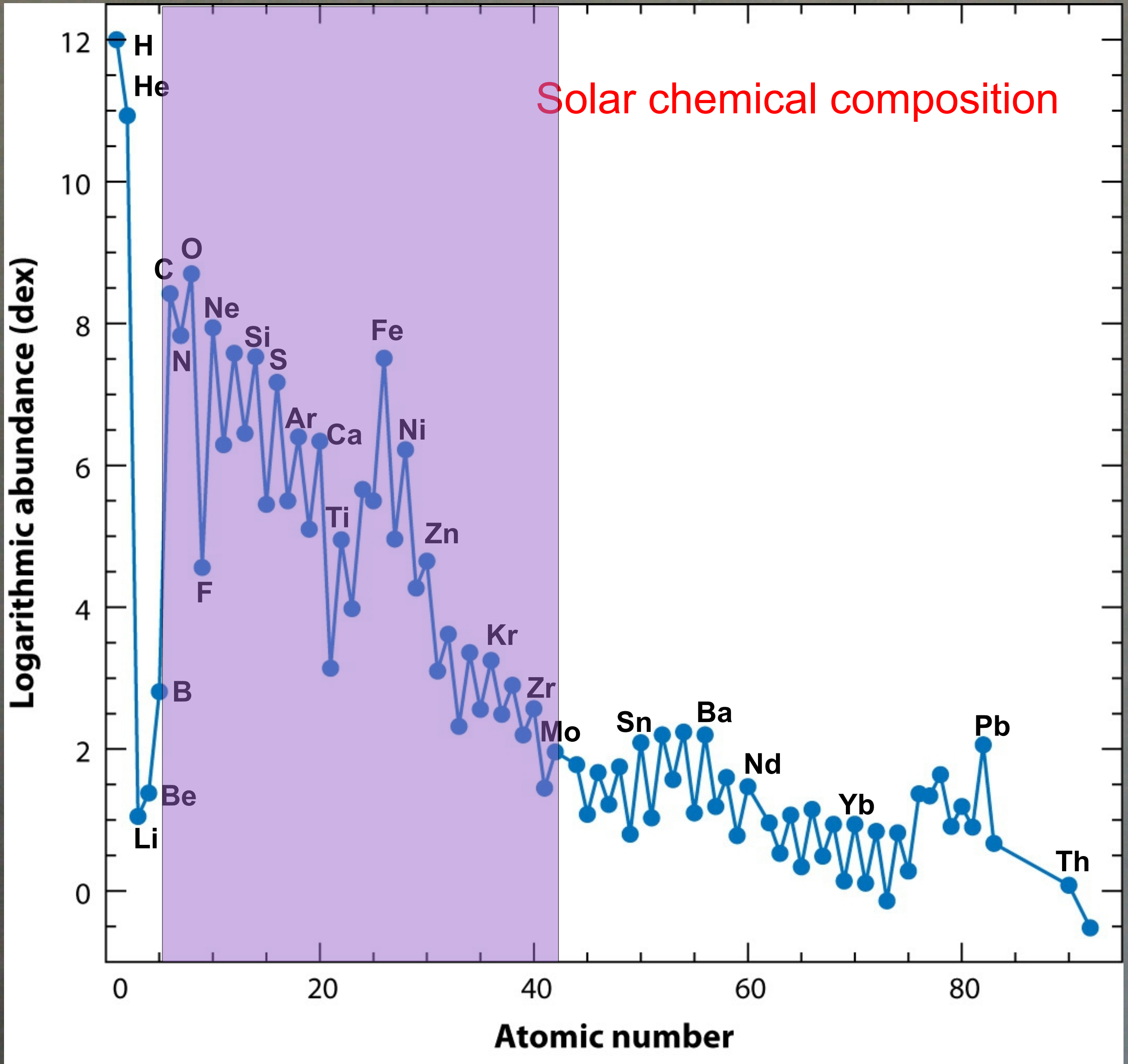
$T_9$
$Log_{10}(ro)$
R(Kkm)
Sc
Ti
Fe
Co
Ni
V
Cr
Mn
Ti
Fe
Si
S
Ar
Ca
Si
S
Ar
Ca
K
Ne
Na
Mg
Al
P
Cl
NSE
QSE
2QSE
$f(\rho, T, Y_e)$
$f(\rho, T, X_i)$



15 $M_O$
mass fraction
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
1
2
3
4
5
6
M($M_O$)



He burn.
C shell burn.
Expl. O burn.
&
Incomplete expl. Si burn.
NSE ( complete expl. Si burn.)
He & C shell burn (n-capt. nucleosynthesis)
H burn.
Expl. O burn.
Incomplete expl. Si burn.
Log10(PF)
2
1.5
1
0.5
0
-0.5
-1
C N O F Ne Na Mg Al Si P S Cl Ar K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag

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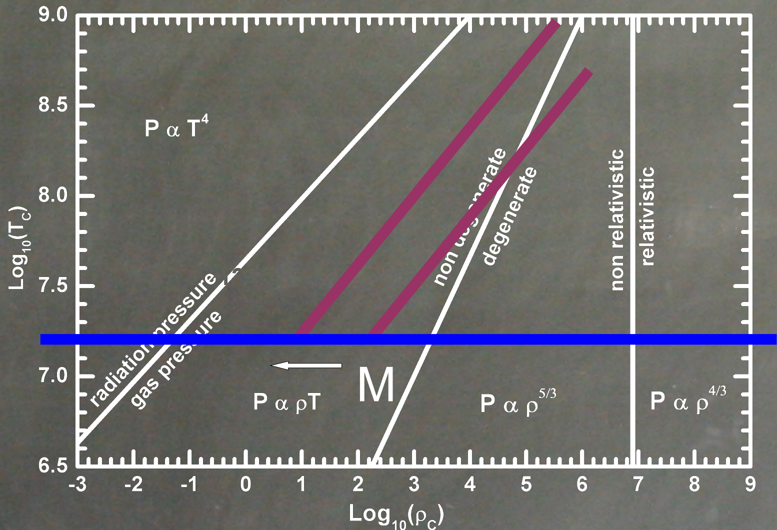
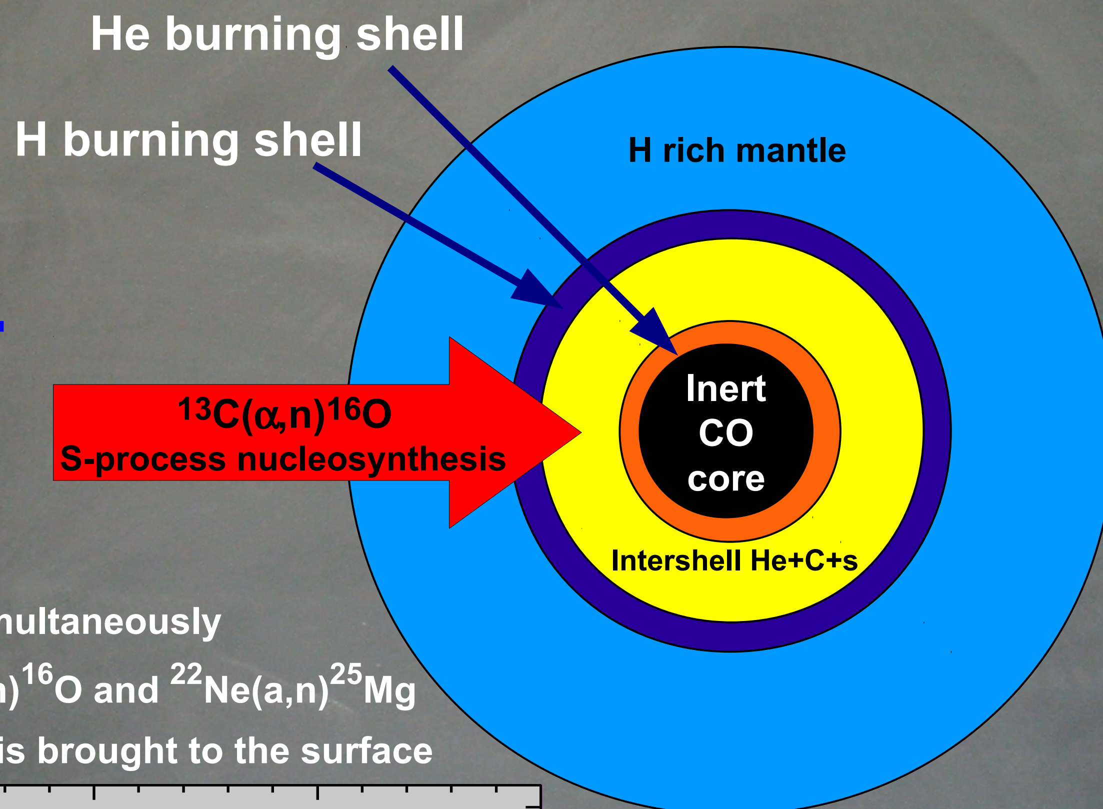
# Basic flavor of the evolution of an intermediate mass star



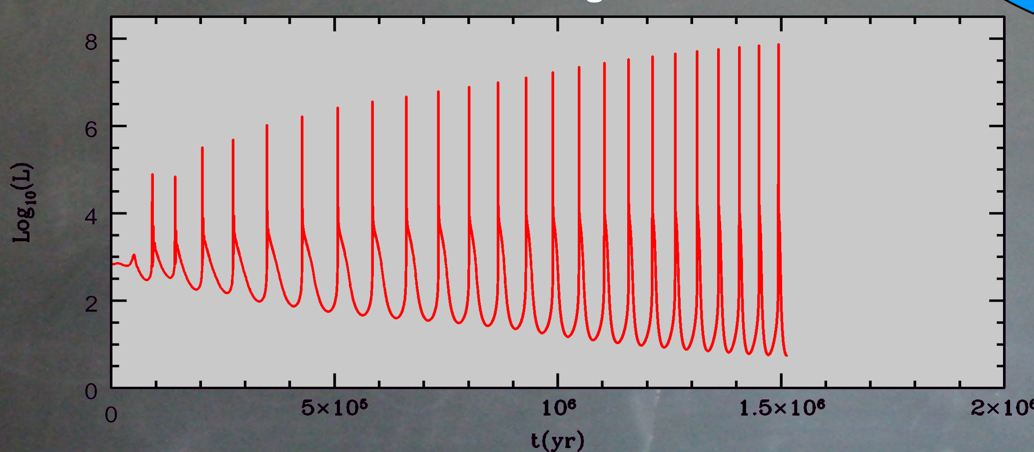



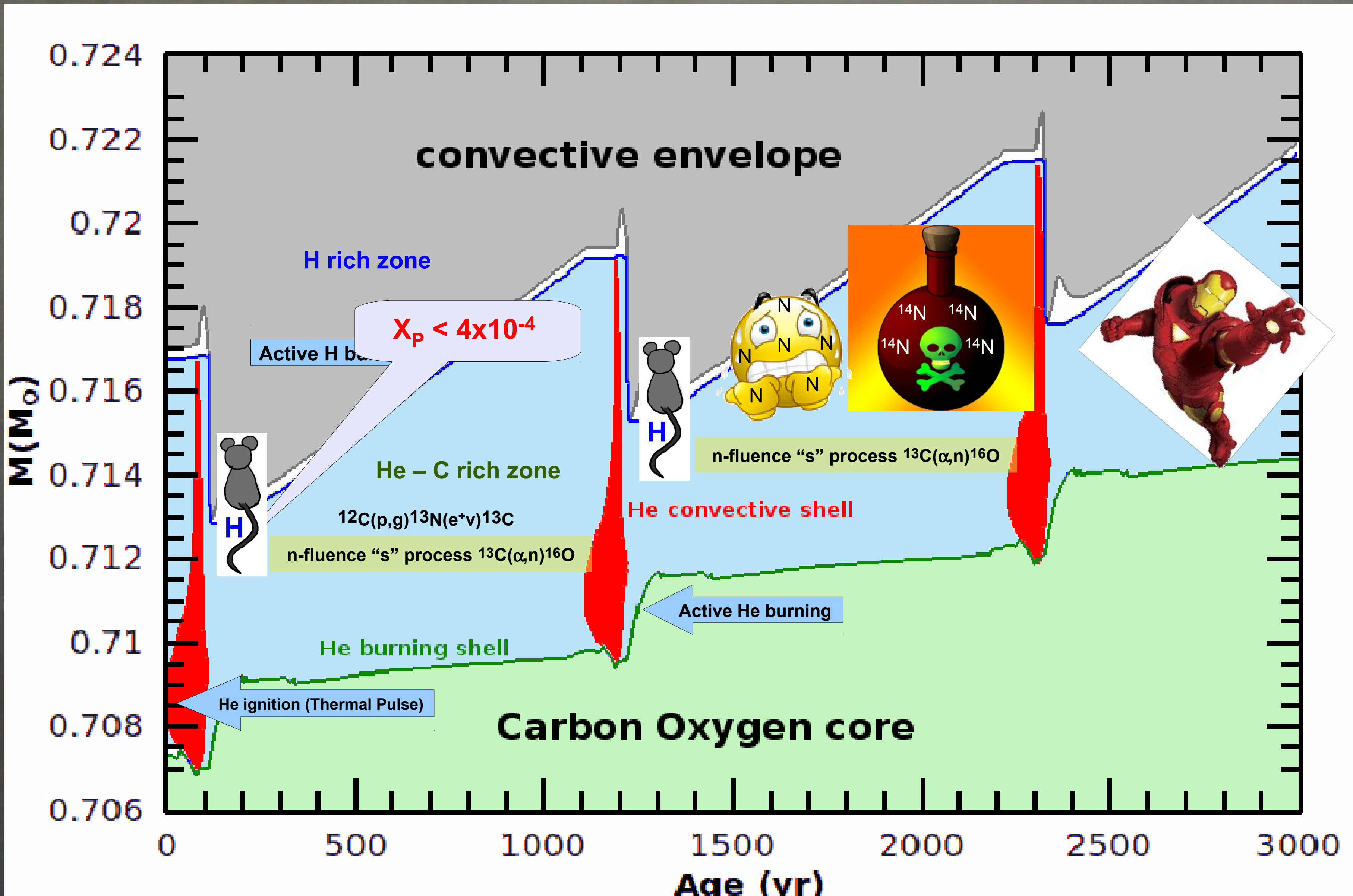

**Main characteristics:**

The two burning shells cannot be active simultaneously

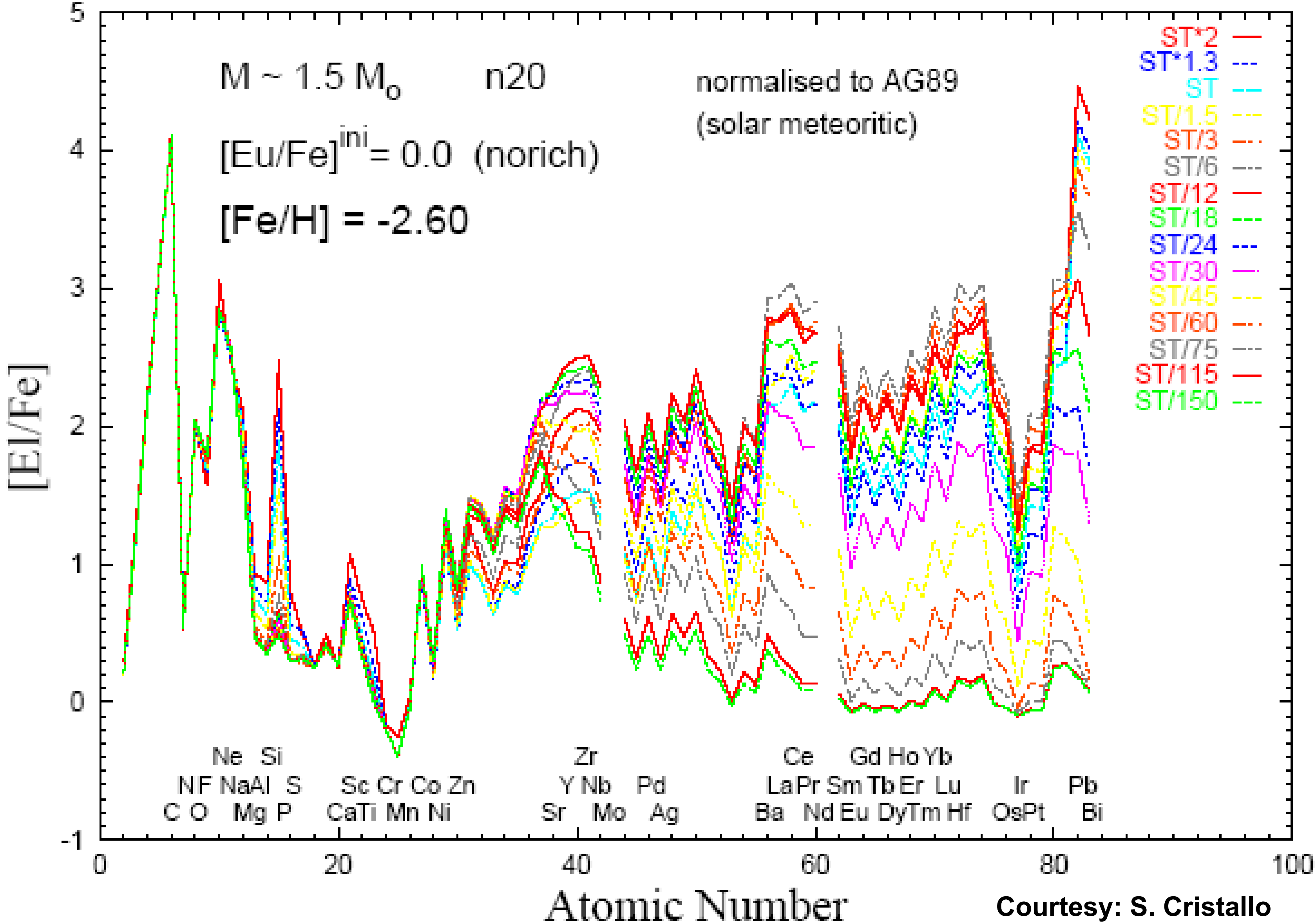
Neutrons produced by 2 processes: $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(a,n)^{25}Mg$

Matter freshly synthesized in the intershell is brought to the surface





convective envelope
H rich zone
Active H bu
$X_P < 4x10^{-4}$
He – C rich zone
12C(p,g)13N(e+v)13C
n-fluence "s" process 13C(α,n)16O
H
H
N N N N N N
14N 14N 14N 14N
n-fluence "s" process 13C(α,n)16O
He convective shell
Active He burning
He burning shell
He ignition (Thermal Pulse)
Carbon Oxygen core
M(M☉)
0.724
0.722
0.72
0.718
0.716
0.714
0.712
0.71
0.708
0.706
0
500
1000
1500
2000
2500
3000
Age (yr)

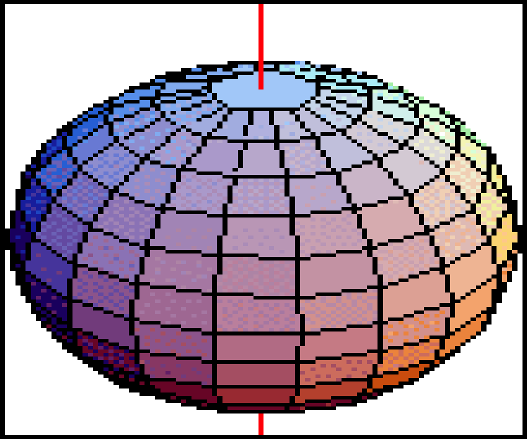

M ~ 1.5 M$_o$ n20
[Eu/Fe]$^{ini}$= 0.0 (norich)
[Fe/H] = -2.60
normalised to AG89
(solar meteoritic)
ST*2
ST*1.3
ST
ST/1.5
ST/3
ST/6
ST/12
ST/18
ST/24
ST/30
ST/45
ST/60
ST/75
ST/115
ST/150
[El/Fe]
Atomic Number
C N O F Ne Na Mg Al Si P S Ca Sc Ti Cr Mn Co Ni Zn
Sr Y Zr Nb Mo Pd Ag
Ba La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tm Yb Lu Hf
Os Ir Pt Pb Bi
Courtesy: S. Cristallo

# PHYSICS OF ROTATION

STRUCTURE

- Oblateness (interior, surface)
  - New structure equations

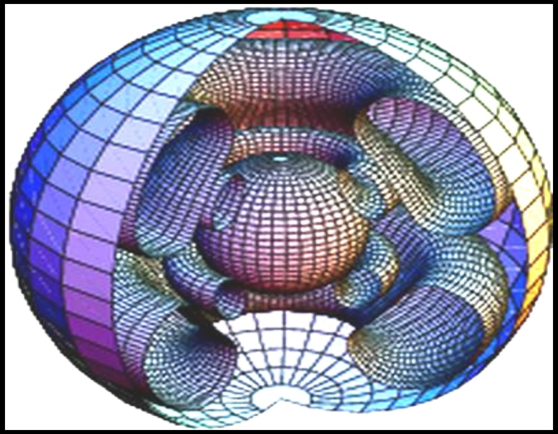
Meridional Circulation



Courtesy: G. Meynet

Von Zeipel Theorem

$$F_{\rm rad} \propto g_{\rm eff}$$



Courtesy: G. Meynet

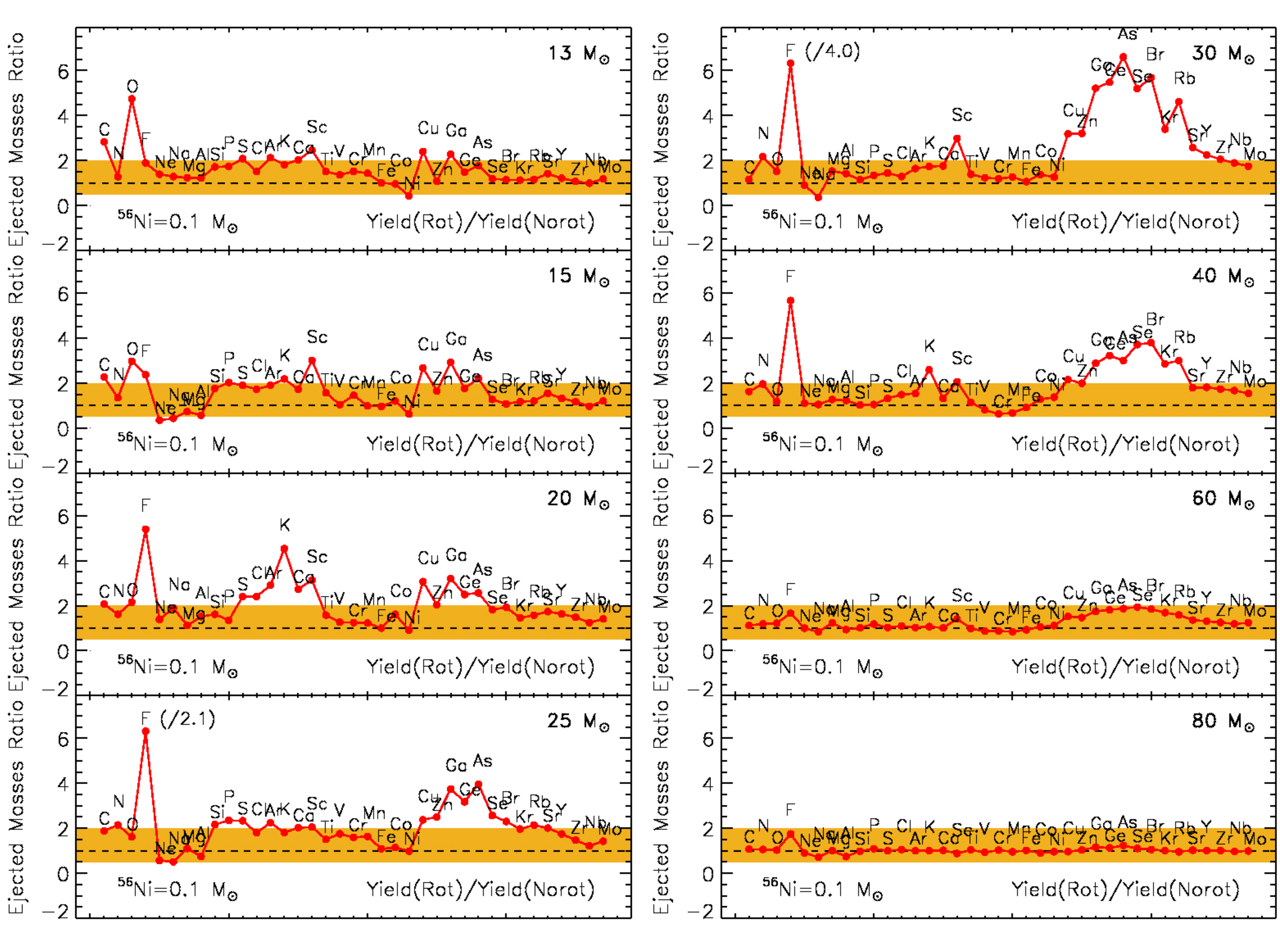
Local conservation Meridional circulation → Advection of angular momentum → Increase the gradient of angular velocity → Shear Instabilities

Transport of Angular Momentum

$$\rho \frac{d}{dt}\left(r^2\omega\right) = \frac{1}{5r^2}\frac{\partial}{\partial r}\left(\rho r^4 \omega U\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho D_{\rm shear} r^4 \frac{\partial \omega}{\partial r}\right)$$

Transport of Chemical Species

$$\frac{\partial Y_i}{\partial t} = \left(\frac{\partial Y_i}{\partial t}\right)_{\rm nuc} + \frac{\partial}{\partial m}\left[\left(4\pi\rho r^2\right)^2 D_{\rm rot}\left(\frac{\partial X_i}{\partial m}\right)\right]$$


Ejected Masses Ratio
13 M⊙
15 M⊙
20 M⊙
25 M⊙
30 M⊙
40 M⊙
60 M⊙
80 M⊙
F (/2.1)
F (/4.0)
56Ni=0.1 M⊙
Yield(Rot)/Yield(Norot)

Thank You !