# LECTURE #2: HYDROSTATIC STELLAR BURNING

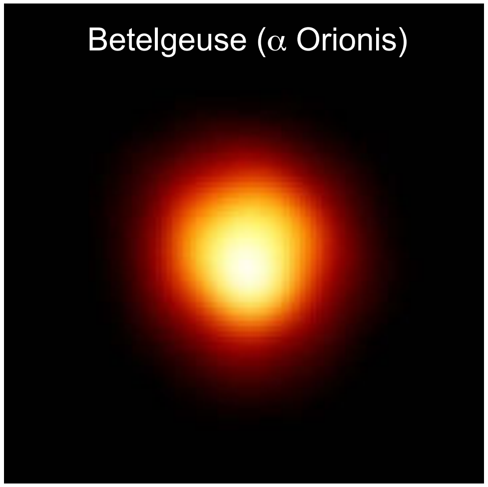
CHRISTIAN ILIADIS

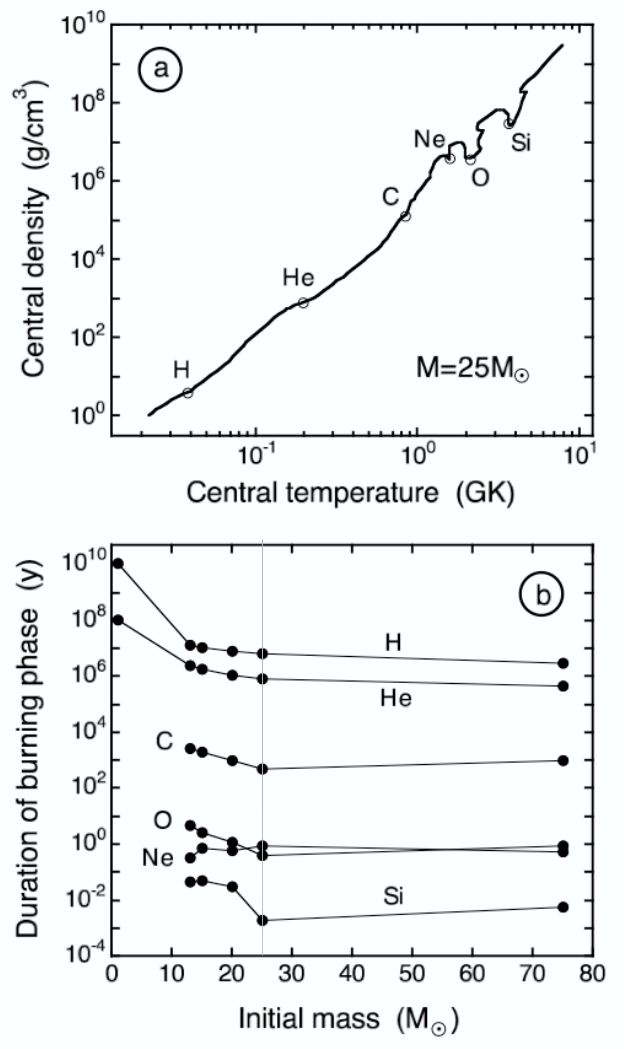
THE UNIVERSITY
of NORTH CAROLINA
at CHAPEL HILL

TUNL

# NUCLEAR BURNING STAGES OF MASSIVE STARS

- reactions with smallest Coulomb barrier proceed first, stabilizing star
- when nuclear fuel is consumed, star contracts gravitationally, T increases
- next available nuclear fuel (ashes of previous stage) burns, stabilizing star


Betelgeuse (α Orionis)



Woosley, Heger & Weaver, Rev. Mod. Phys. 74, 1015 (2002)

nuclear energy release: H-burning (6x10$^{24}$ MeV/g)
He-burning (6x10$^{23}$ MeV/g)

hydrogen fuel is consumed slower

stellar energy loss: H/He-burning (photons)
advanced stages (neutrinos)

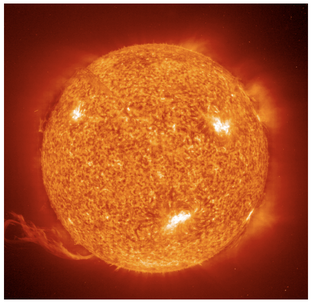
electron - positron pair annihilation : $e^+ + e^- \rightarrow \nu + \overline{\nu}$

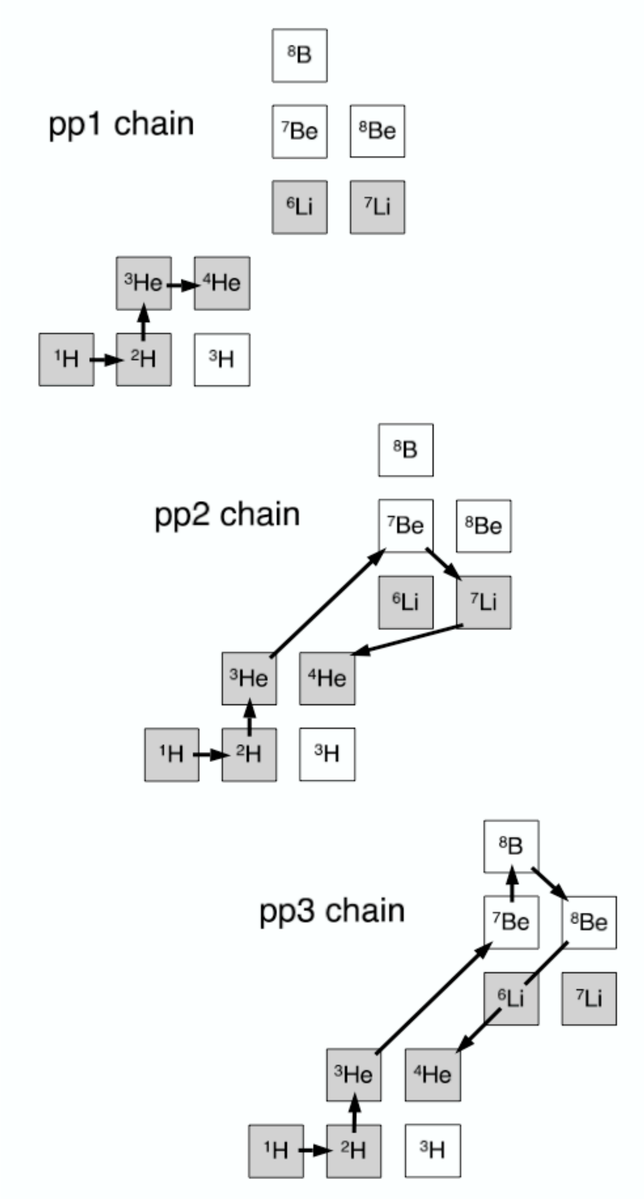
photo - neutrino process : $\gamma + e^- \rightarrow e^- + \nu + \overline{\nu}$

fuel consumption increases rapidly during later stages

# HYDROGEN BURNING I

Sun (T=15.6 MK), stellar cores (T=8-55 MK),
shell of AGB stars (T=45-140 MK)

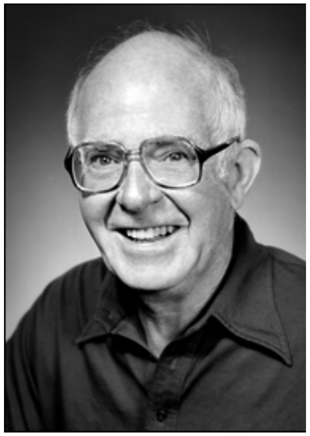




| pp1 chain | pp2 chain | pp3 chain |
|---|---|---|
| $p(p,e^+\nu)d$ | $p(p,e^+\nu)d$ | $p(p,e^+\nu)d$ |
| $d(p,\gamma)^3He$ | $d(p,\gamma)^3He$ | $d(p,\gamma)^3He$ |
| $^3He(^3He,2p)\alpha$ | $^3He(\alpha,\gamma)^7Be$ | $^3He(\alpha,\gamma)^7Be$ |
| | $^7Be(e^-,\nu)^7Li$ | $^7Be(p,\gamma)^8B$ |
| | $^7Li(p,\alpha)\alpha$ | $^8B(\beta^+\nu)^8Be$ |
| | | $^8Be(\alpha)\alpha$ |

- $4H \rightarrow {}^4He$ releases 26.7 MeV
- reactions are non-resonant at low energies
- p+p [slowest reaction] has not been measured
- d+p, $^3He+^3He$, $^3He+\alpha$ have been measured by LUNA collaboration
- 90% of Sun's energy produced by pp1 chain

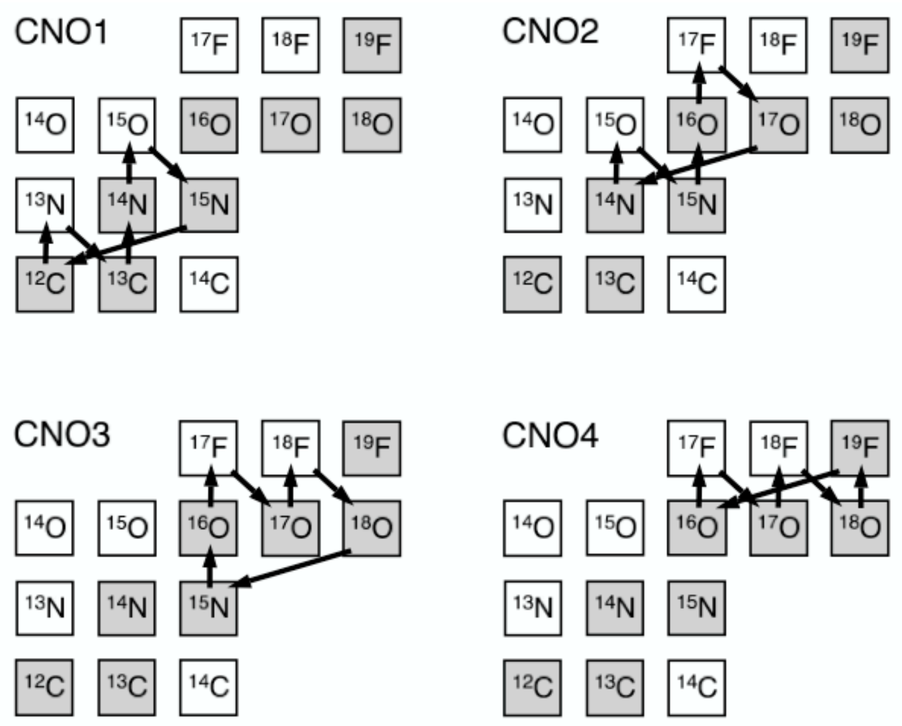
- neutrinos provide direct evidence that nuclear reactions occur
- $^8$B neutrinos discovered at Homestake [0.02%]; solar neutrino problem
- Super-Kamiokande/SNO experiments; neutrino oscillations [Takaaki Kajita & Art McDonald, Nobel Prize 2015]; first p+p neutrino detection: BOREXINO (2014)



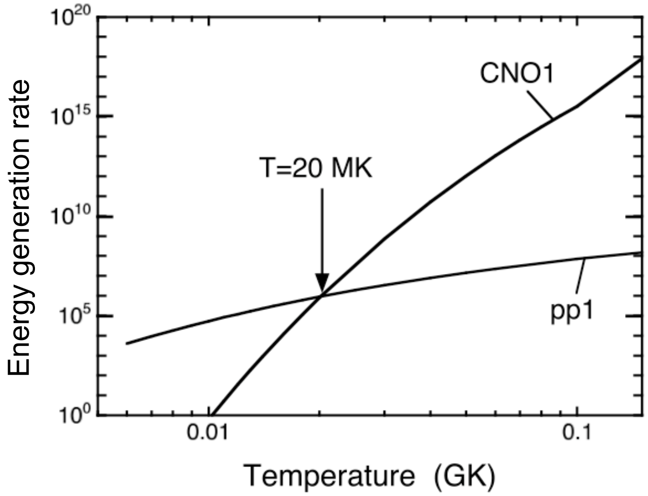
Ray Davis
(1914-2006)
Nobel Prize 2002

# HYDROGEN BURNING II

Sun (T=15.6 MK), stellar cores (T=8-55 MK), shell of AGB stars (T=45-140 MK)



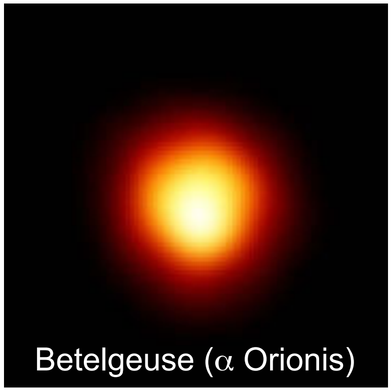
- $^{12}$C and $^{16}$O nuclei act as catalysts
- branchings: $(p,\alpha)$ stronger than $(p,\gamma)$
- $^{14}N(p,\gamma)^{15}O$ slowest reaction in CNO1
  has been measured by LUNA and LENA
- solar: $^{13}C/^{12}C=0.01$;
  CNO1: $^{13}C/^{12}C=0.25$ (“steady state”)
- T>20 MK: CNO1 faster than pp1



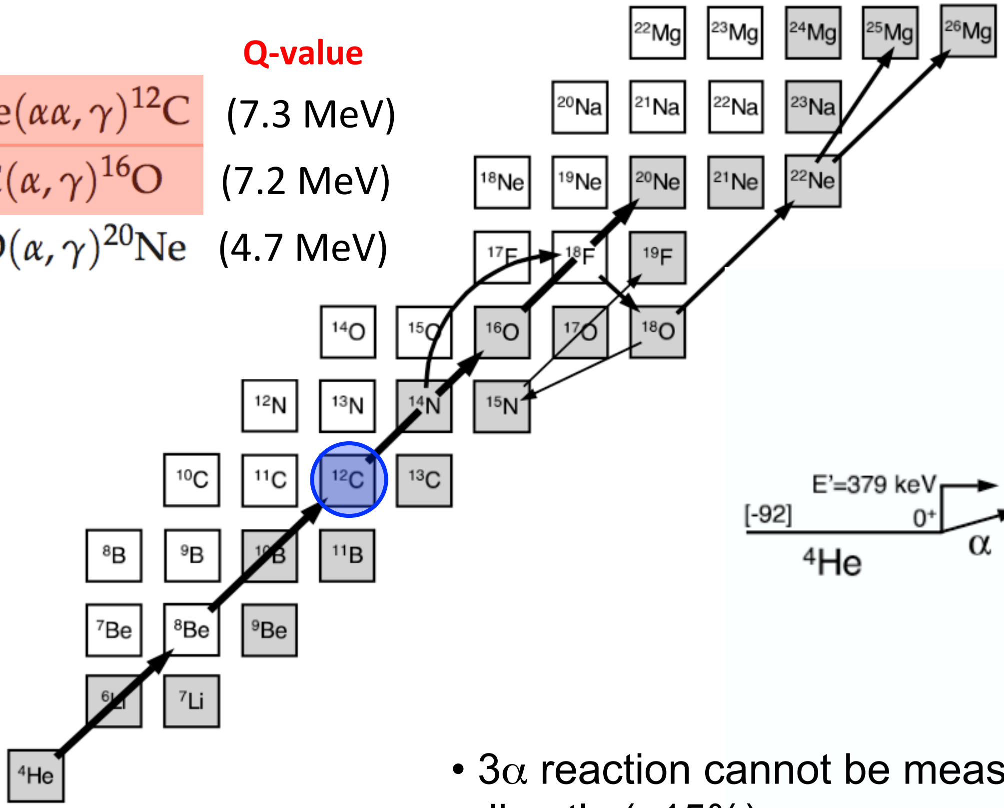
| CNO1 | CNO2 | CNO3 | CNO4 |
|---|---|---|---|
| $^{12}C(p,\gamma)^{13}N$ | $^{14}N(p,\gamma)^{15}O$ | $^{15}N(p,\gamma)^{16}O$ | $^{16}O(p,\gamma)^{17}F$ |
| $^{13}N(\beta^+\nu)^{13}C$ | $^{15}O(\beta^+\nu)^{15}N$ | $^{16}O(p,\gamma)^{17}F$ | $^{17}F(\beta^+\nu)^{17}O$ |
| $^{13}C(p,\gamma)^{14}N$ | $^{15}N(p,\gamma)^{16}O$ | $^{17}F(\beta^+\nu)^{17}O$ | $^{17}O(p,\gamma)^{18}F$ |
| $^{14}N(p,\gamma)^{15}O$ | $^{16}O(p,\gamma)^{17}F$ | $^{17}O(p,\gamma)^{18}F$ | $^{18}F(\beta^+\nu)^{18}O$ |
| $^{15}O(\beta^+\nu)^{15}N$ | $^{17}F(\beta^+\nu)^{17}O$ | $^{18}F(\beta^+\nu)^{18}O$ | $^{18}O(p,\gamma)^{19}F$ |
| $^{15}N(p,\alpha)^{12}C$ | $^{17}O(p,\alpha)^{14}N$ | $^{18}O(p,\alpha)^{15}N$ | $^{19}F(p,\alpha)^{16}O$ |

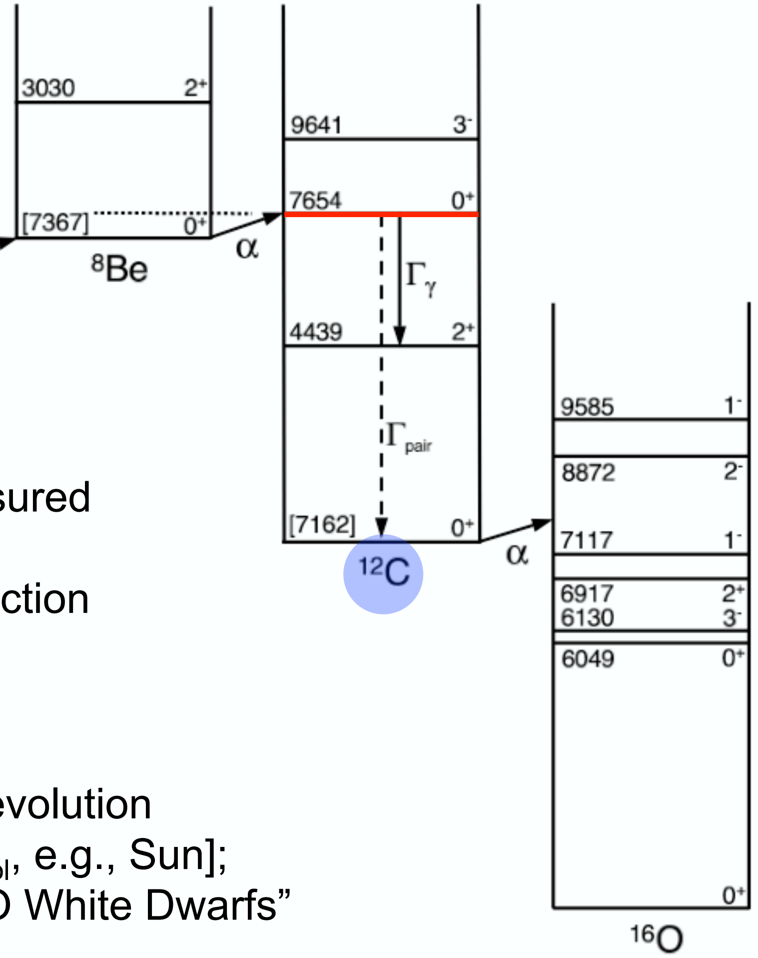
# HELIUM BURNING

massive stars (T=100-400 MK)

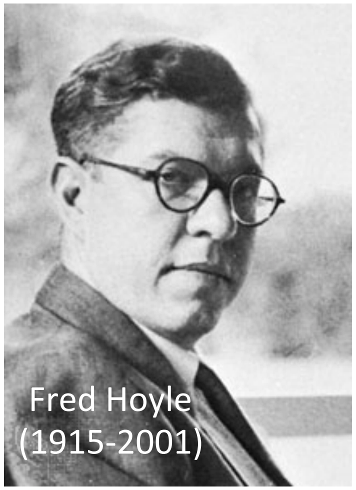

Betelgeuse (α Orionis)

| | **Q-value** |
|---|---|
| $^{4}\mathrm{He}(\alpha\alpha,\gamma)^{12}\mathrm{C}$ | (7.3 MeV) |
| $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ | (7.2 MeV) |
| $^{16}\mathrm{O}(\alpha,\gamma)^{20}\mathrm{Ne}$ | (4.7 MeV) |

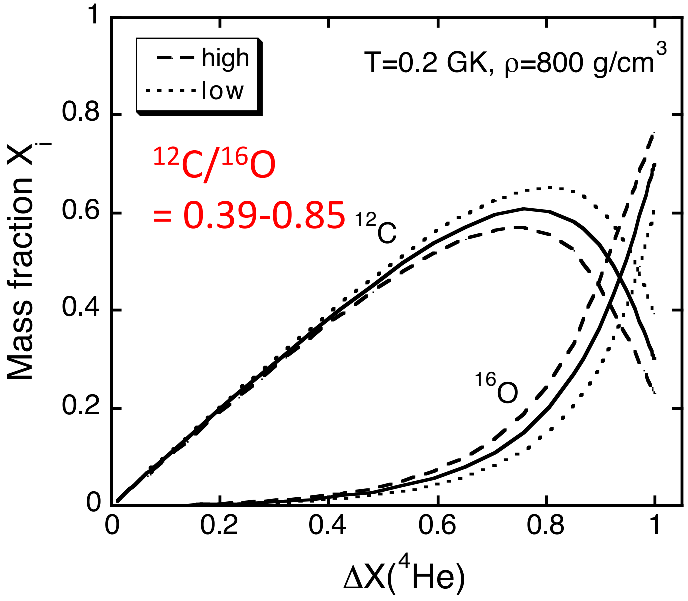


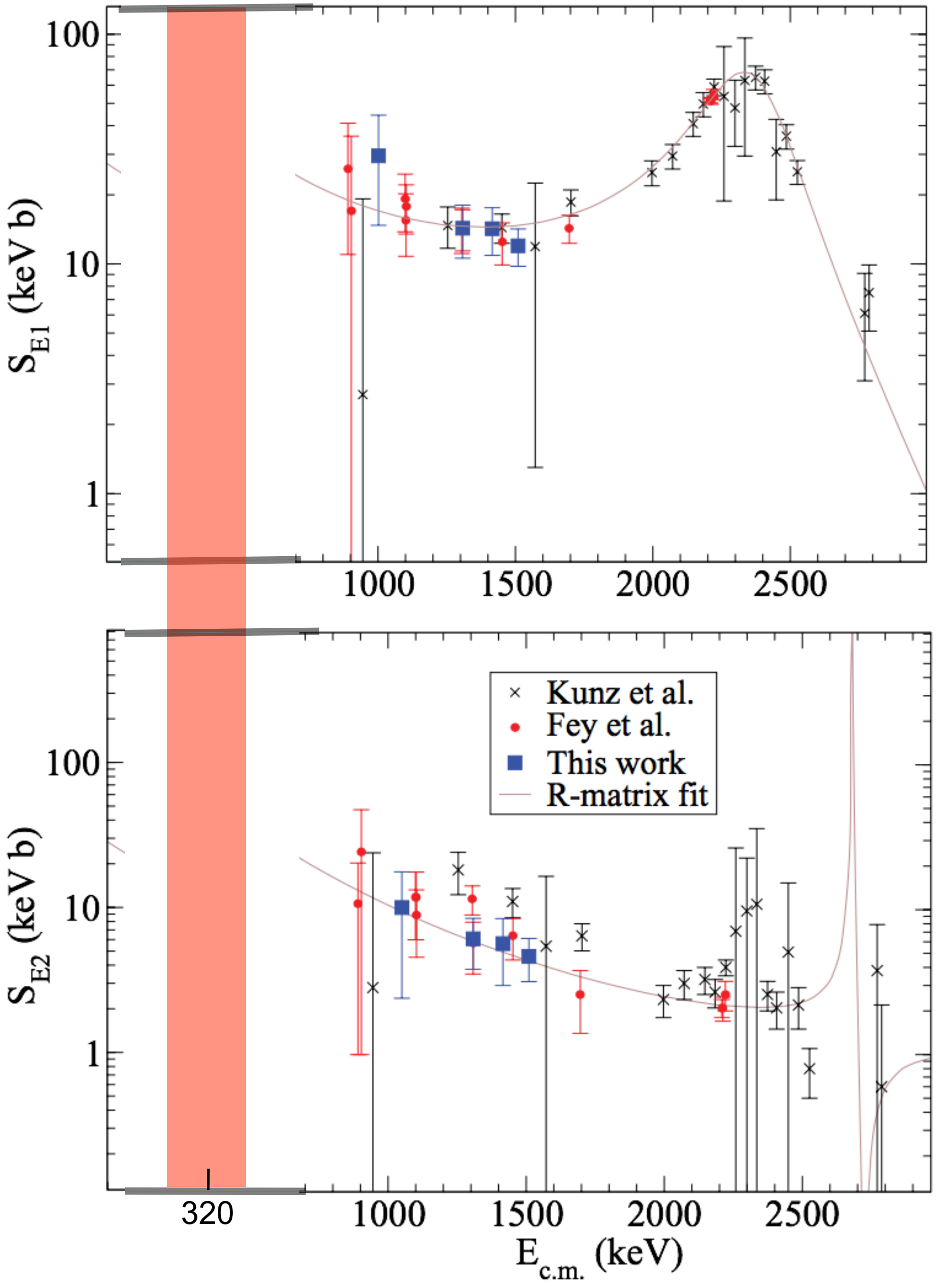


- 3α reaction cannot be measured directly (±15%)
- $^{12}$C(α,γ)$^{16}$O slow, crucial reaction [determines $^{12}$C/$^{16}$O ratio]
- $^{16}$O(α,γ)$^{20}$Ne very slow
- ashes: $^{12}$C, $^{16}$O
- last core burning stage for evolution of low-mass stars [0.4-9 $M_{sol}$, e.g., Sun]; they eventually become “CO White Dwarfs”


Fred Hoyle
(1915-2001)

# A CLOSER LOOK AT $^{12}C(\alpha,\gamma)^{16}O$





Plag, Reifahrt, Heil, Kaeppeler, Rupp, Voss & Wisshak, PRC 86, 015805 (2012)

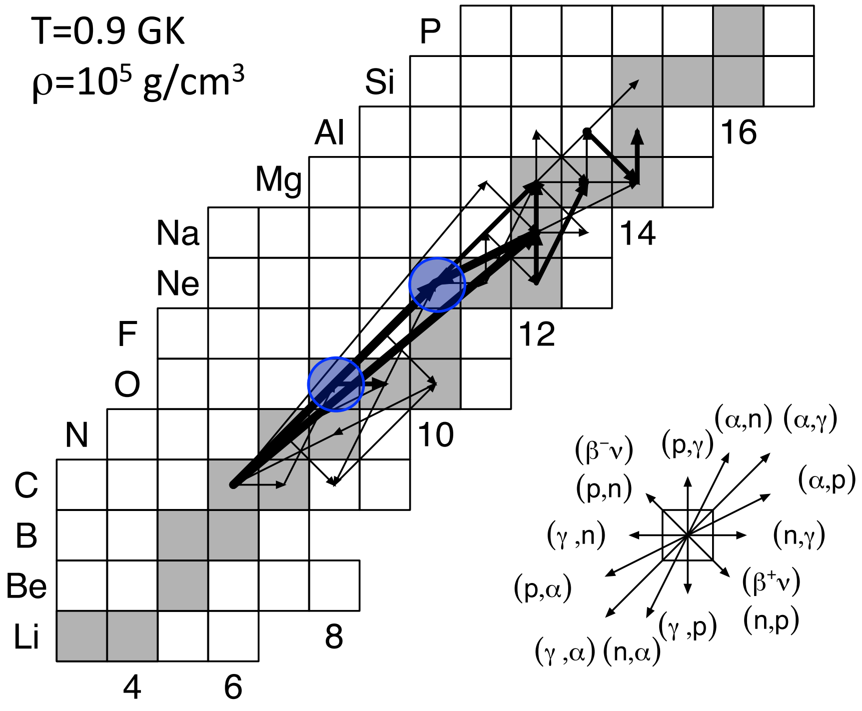
determines:

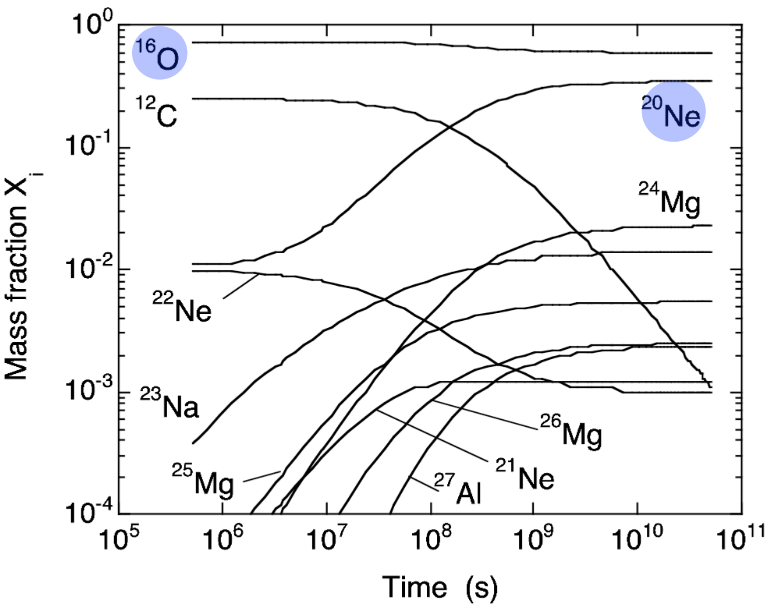
- C/O ratio at end of He burning
- advanced burning stages
- structure of pre-supernova star
- evolution in low-mass stars

# CARBON BURNING

core (T=0.6-1.0 GK)

T=0.9 GK
$\rho=10^5$ g/cm$^3$

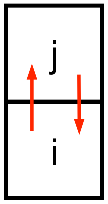




“Abundance flows”

$$F_{ij} = \int f_{ij}\,dt = \int \left[ \left( \frac{dN_i}{dt} \right)_{i \to j} - \left( \frac{dN_j}{dt} \right)_{j \to i} \right] dt$$

“time-integrated
net abundance flow”



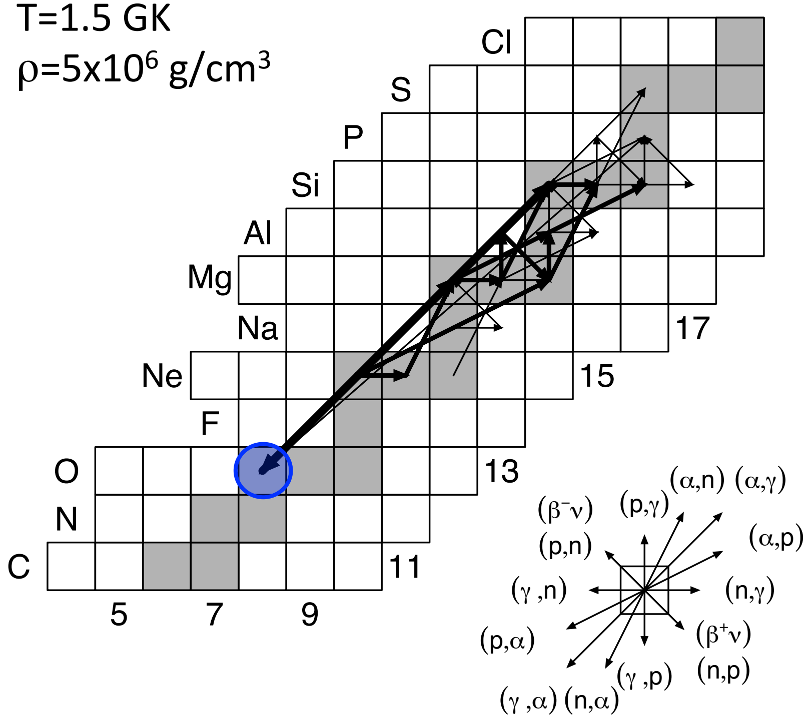
- Primary reactions:
  $^{12}$C($^{12}$C,p)$^{23}$Na (Q=2.2 MeV)
  $^{12}$C($^{12}$C,α)$^{20}$Ne (Q=4.6 MeV)
  $^{12}$C($^{12}$C,n)$^{23}$Mg (Q=-2.6 MeV
  + several secondary reactions
- ashes: $^{16}$O, $^{20}$Ne
- last core burning stage for evolution of intermediate-mass stars [9-11 $M_{sol}$]; they eventually become “ONe White Dwarfs”

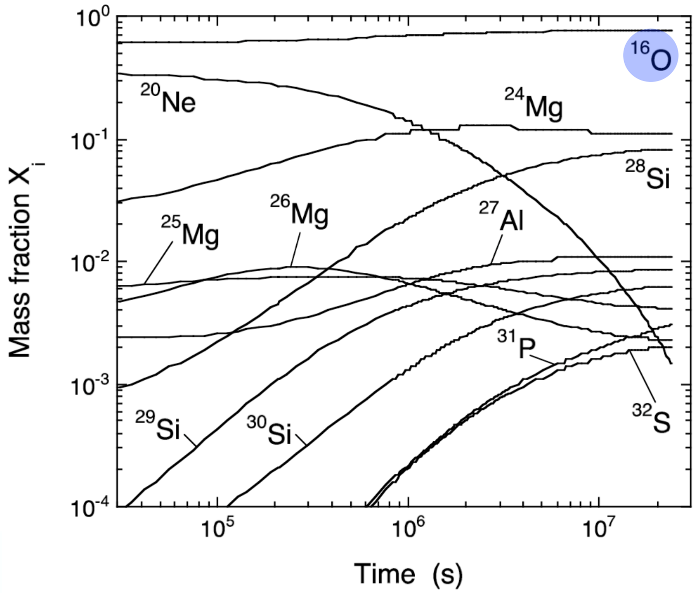
# NEON BURNING

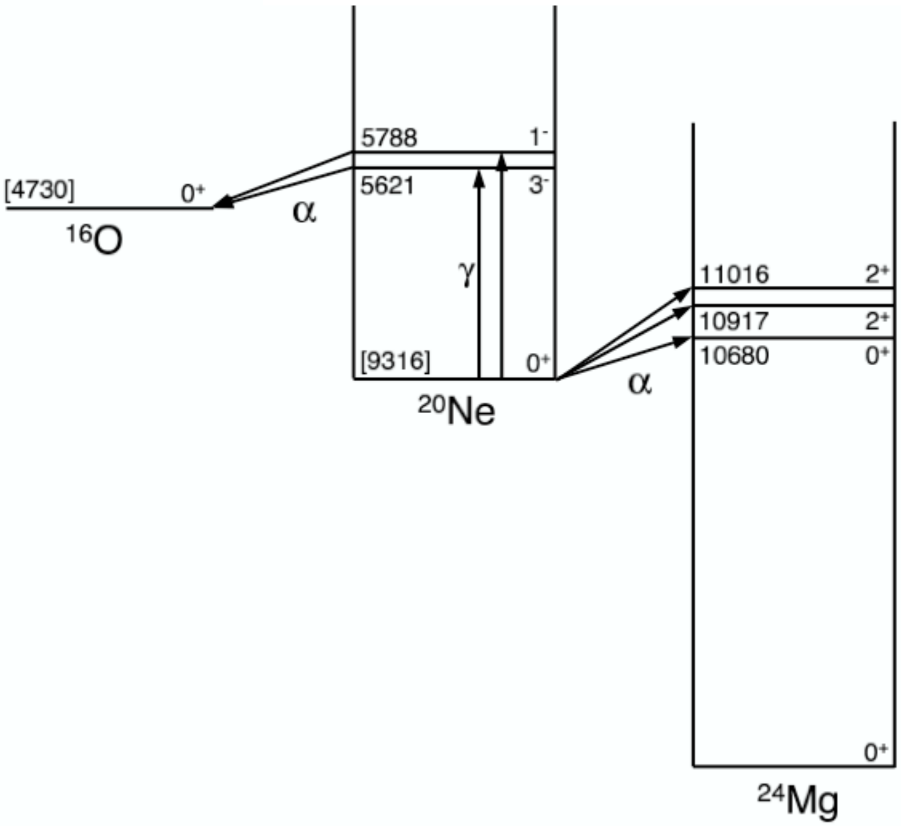
core (T=1.2-1.8 GK)

T=1.5 GK

$\rho=5\times10^6$ g/cm$^3$







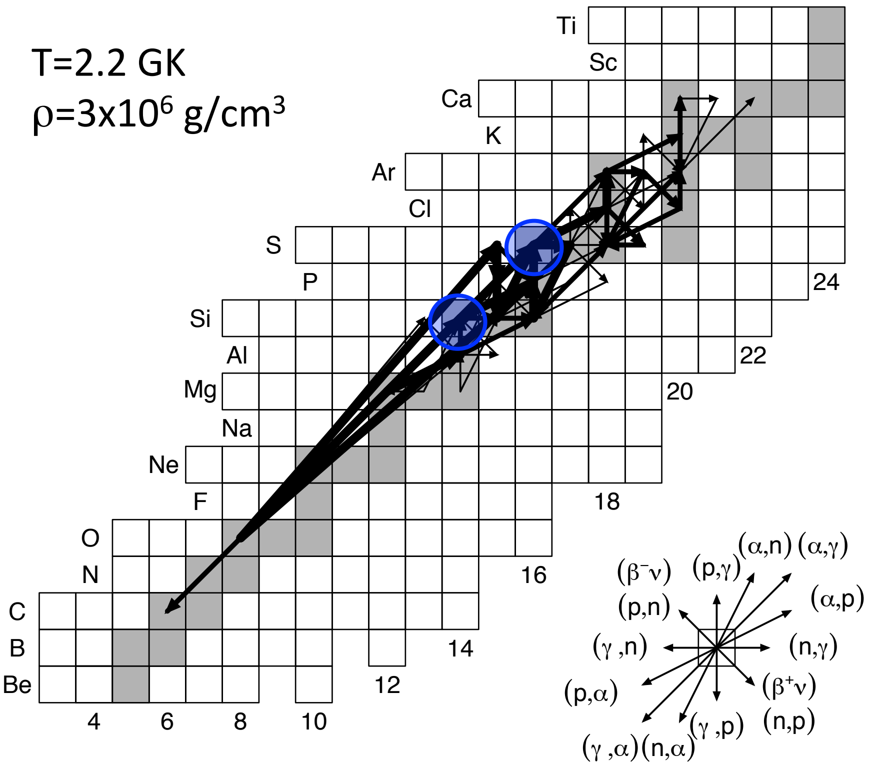
- Primary reaction:
  $^{20}\mathrm{Ne}(\gamma,\alpha)^{16}\mathrm{O}$ (Q=-4730 keV)
- Secondary reactions
  $^{20}\mathrm{Ne}(\alpha,\gamma)^{24}\mathrm{Mg}(\alpha,\gamma)^{28}\mathrm{Si}$
  + more
- ashes: $^{16}\mathrm{O}$

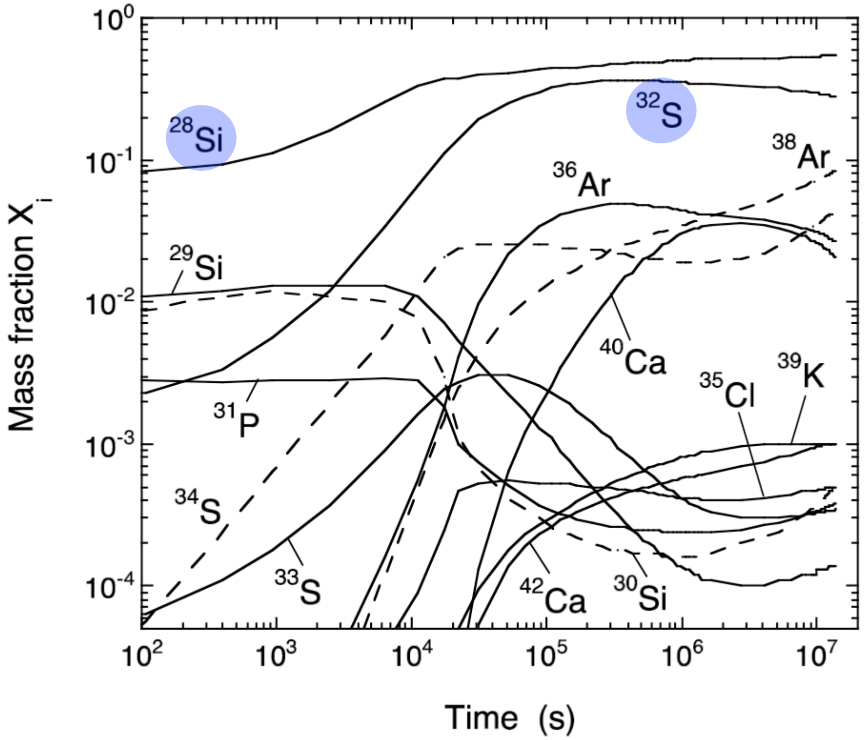
# OXYGEN BURNING

core (T=1.5-2.7 GK)

T=2.2 GK

ρ=3x10$^6$ g/cm$^3$



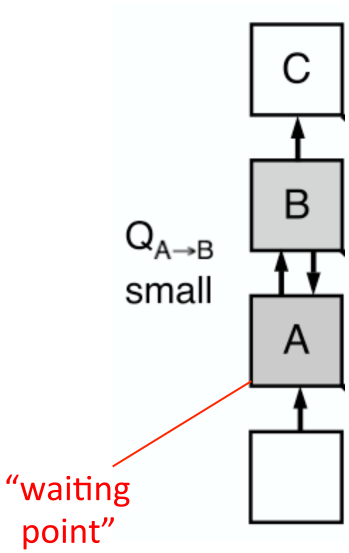


- Primary reactions:
  $^{16}O(^{16}O,p)^{31}P$
  $^{16}O(^{16}O,\alpha)^{28}Si$
  …

  \+ several secondary reactions
- ashes: $^{28}Si$, $^{32}S$

# REACTION RATE EQUILIBRIA

$$\lambda_1(0) = \rho \frac{X_1}{M_1} N_A \langle \sigma v \rangle_{01}$$



reciprocity theorem

$$\frac{\sigma_{23\to 01}}{\sigma_{01\to 23}} = \frac{(2j_0+1)(2j_1+1)}{(2j_2+1)(2j_3+1)} \frac{m_{01}E_{01}}{m_{23}E_{23}} \frac{(1+\delta_{23})}{(1+\delta_{01})}$$

Saha statistical equation

$$r = r_{01\to 23} - r_{23\to 01} = \frac{N_0 N_1 \langle \sigma v \rangle_{01\to 23}}{(1+\delta_{01})} - \frac{N_2 N_3 \langle \sigma v \rangle_{23\to 01}}{(1+\delta_{23})}$$

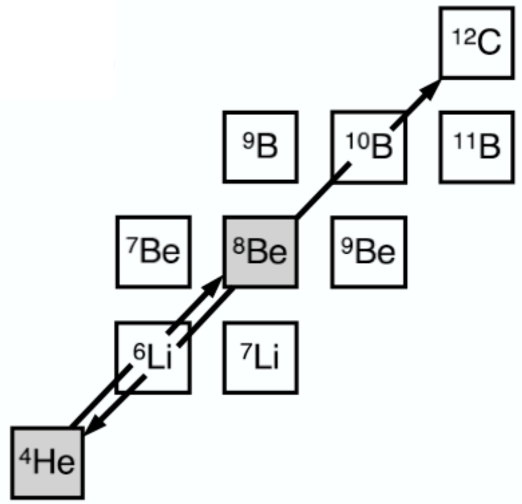
=0

$$\lambda_{A\to B\to C} = \frac{\lambda_{A\to B}}{\lambda_{B\to A}} \lambda_{B\to C} = N_a \left(\frac{h^2}{2\pi}\right)^{3/2} \frac{1}{(m_{Aa}kT)^{3/2}} \frac{(2j_B+1)}{(2j_A+1)(2j_a+1)}$$

$$\times \frac{G_B^{\text{norm}}}{G_A^{\text{norm}} G_a^{\text{norm}}} e^{Q_{A\to B}/kT} \lambda_{B\to C}$$

independent
of reaction
rate for A→B!

$$\lambda_{3\alpha} = 0.23673 \frac{(\rho X_\alpha)^2}{T_9^3} e^{-11.6048E'/T_9} \omega\gamma_{^8\text{Be}(\alpha,\gamma)} \qquad (\text{s}^{-1})$$



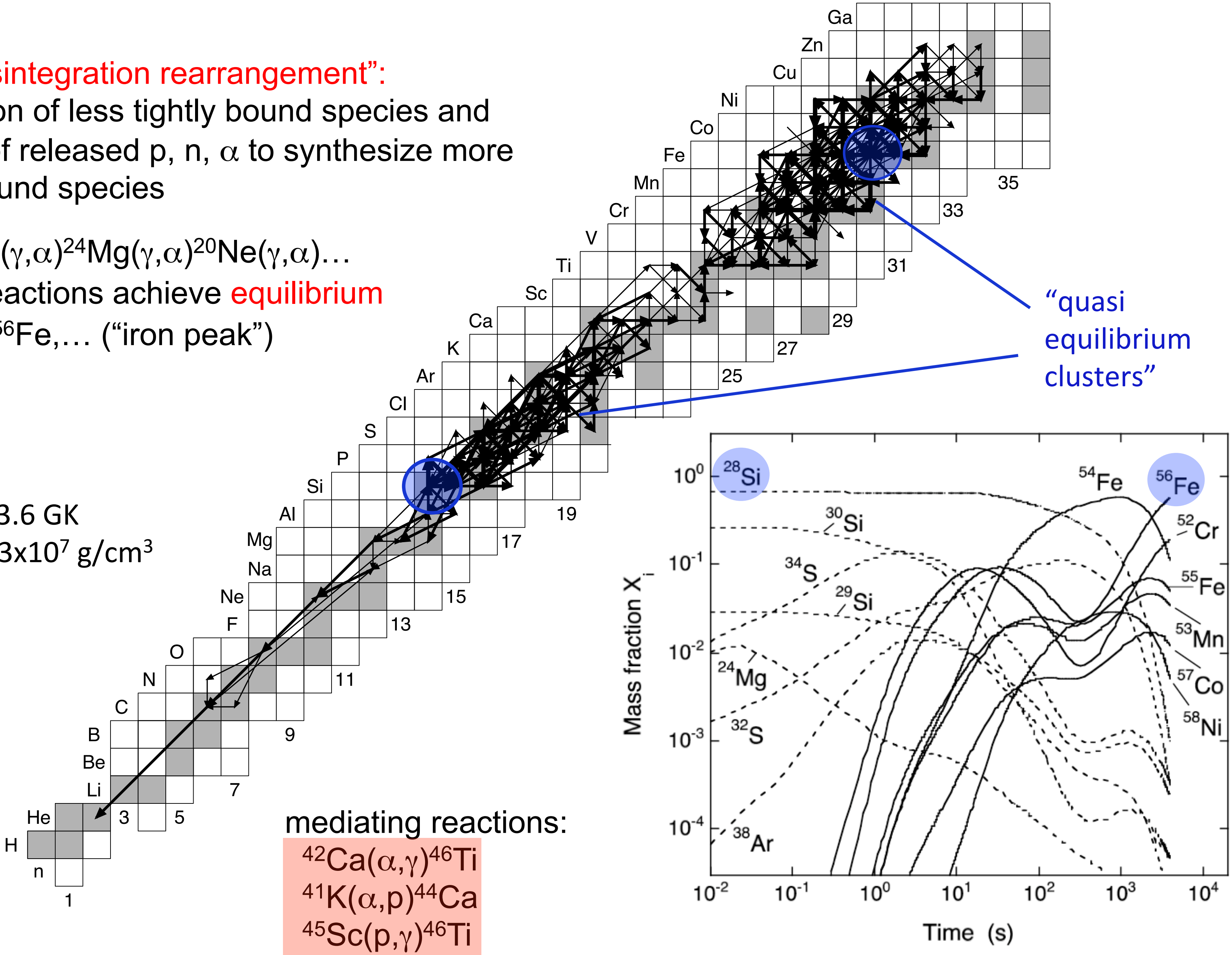
# SILICON BURNING

core (T=2.8-4.1 GK)

“Photodisintegration rearrangement”:
destruction of less tightly bound species and capture of released p, n, $\alpha$ to synthesize more tightly bound species

start: $^{28}Si(\gamma,\alpha)^{24}Mg(\gamma,\alpha)^{20}Ne(\gamma,\alpha)\ldots$

- many reactions achieve equilibrium
- ashes: $^{56}Fe$,… (“iron peak”)

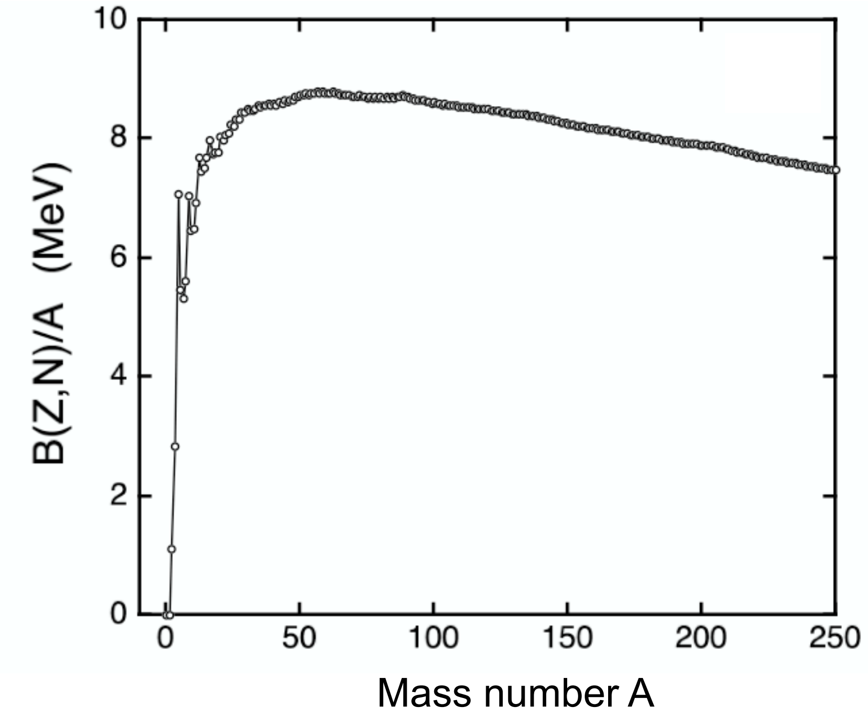


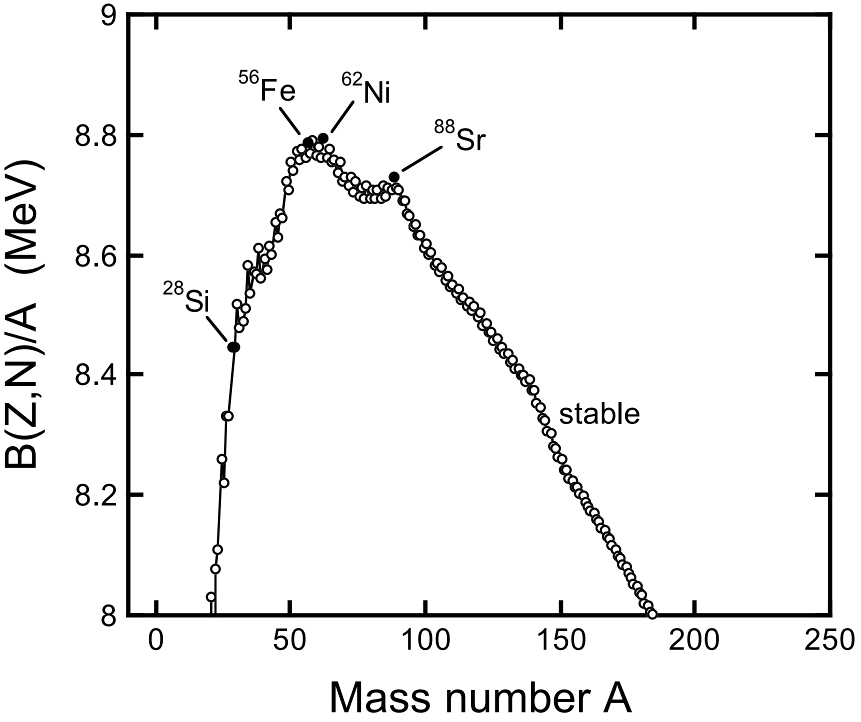
“quasi equilibrium clusters”

T=3.6 GK
$\rho=3\times10^7$ g/cm$^3$

mediating reactions:
$^{42}Ca(\alpha,\gamma)^{46}Ti$
$^{41}K(\alpha,p)^{44}Ca$
$^{45}Sc(p,\gamma)^{46}Ti$

# EXPERIMENTAL BINDING ENERGY PER NUCLEON





# NUCLEAR STATISTICAL EQUILIBRIUM: GENERAL IDEAS

as $^{28}$Si disappears in the core at the end of Si burning, T increases, until all non-equilibrated reactions come into equilibrium [last reaction: 3α reaction]

one large equilibrium cluster stretches from p, n, α to Fe peak:
"Nuclear Statistical Equilibrium" (NSE)

abundance of each nuclide can be calculated from repeated application of Saha equation:

$$\text{For species } {}^{A}_{\pi}Y_{\nu} : \quad N_Y = N_p^{\pi} N_n^{\nu} \frac{1}{\theta^{A-1}} \left( \frac{M_Y}{M_p^{\pi} M_n^{\nu}} \right)^{3/2} \frac{g_Y}{2^A} G_Y^{\text{norm}} e^{B(Y)/kT}$$

$$\theta \equiv (2\pi m_u kT/h^2)^{3/2}$$

$$\eta \equiv \sum_i \frac{(N_i - Z_i)}{M_i} X_i$$

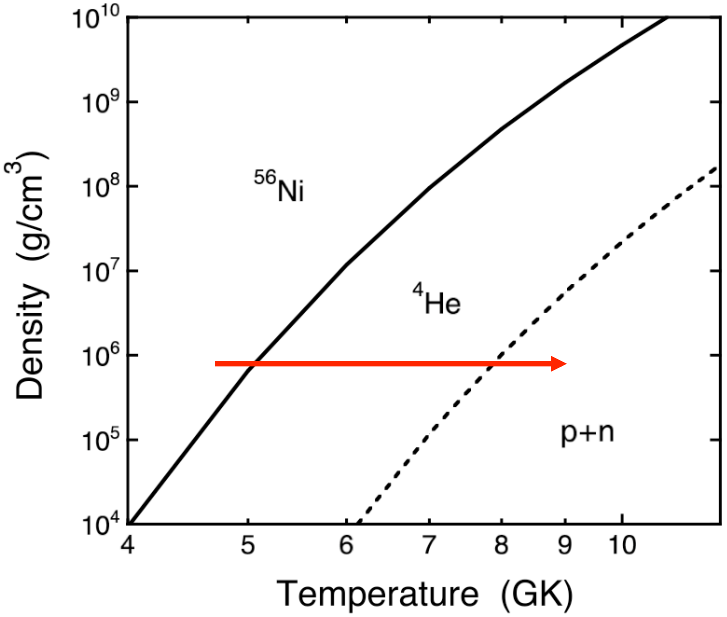
$N_i, Z_i$: number of neutrons, protons [bound or free]

$M_i, X_i$: atomic mass, mass fraction

represents number of excess neutrons per nucleon (can only change as result of weak interactions!)

in NSE, abundance of any nuclide is determined by: temperature, density, neutron excess

# NUCLEAR STATISTICAL EQUILIBRIUM: INTERESTING PROPERTIES



assume plasma consists only of:

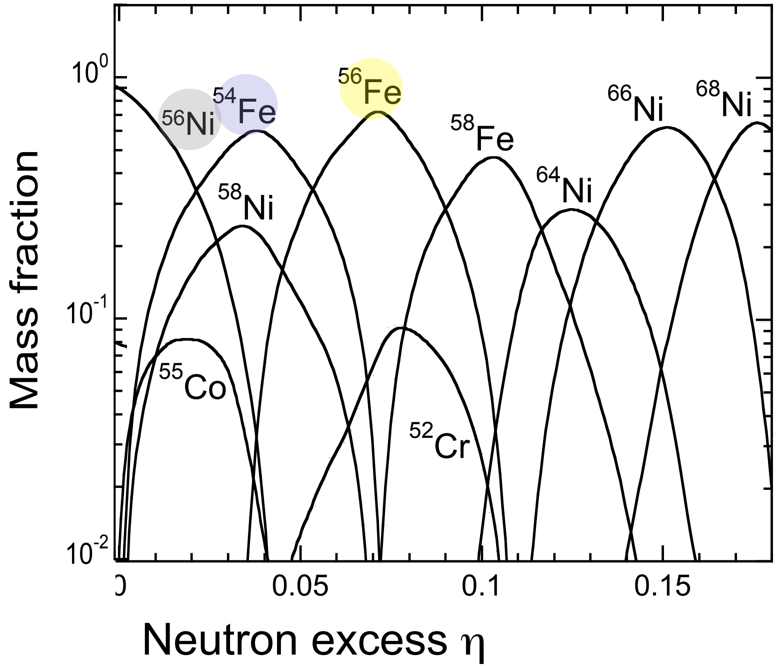
**$^{56}$Fe $\eta=(N-Z)/M=(30-26)/56=0.07$**

$^{56}$Ni $\eta=(N-Z)/M=(28-28)/56=0$
$^{54}$Fe $\eta=(N-Z)/M=(28-26)/54=0.04$

$\eta$ needs to be monitored very carefully at each of the previous burning stages!
[stellar weak interaction rates need to be known]

assume first that $\eta=0$ when NSE is established and Si burning has mainly produced $^{56}$Ni (N=Z=28) in the Fe peak besides $^{4}$He, p, n…

at $\rho$=const and T rising: increasing fraction of composition resides in light particles (p, n, $\alpha$)

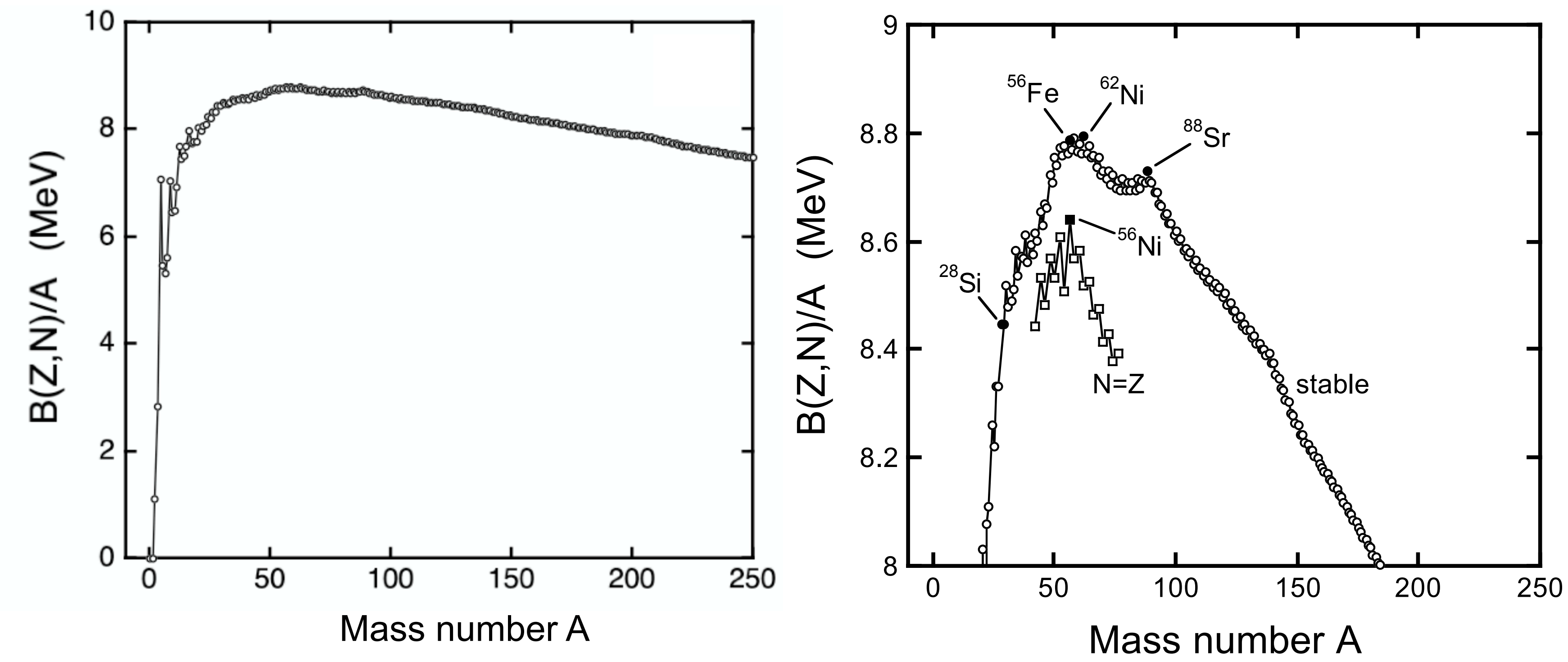


T=3.5 GK, $\rho=10^7$ g/cm$^3$

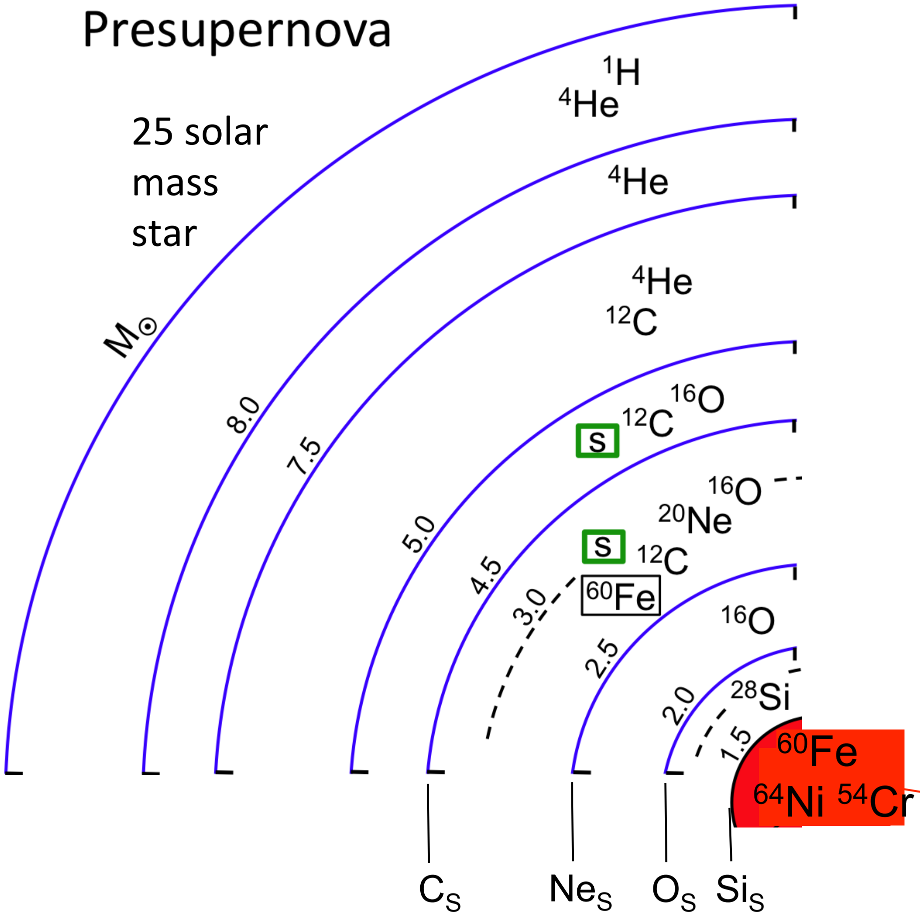
Seitenzahl, Timmes et al., ApJL 685, 129 (2008)

# WHY, AGAIN, IS $^{56}$Ni FAVORED AT $\eta$=0?

experimental binding energies per nucleon



# Onion Shell Structure: Massive Star at Instant Before Core Collapse



- we discussed burning in the core
- burning also takes place in thin regions (burning shells) at the interface of different compositional layers
- each burning shell migrated outward to the position indicated by blue lines

$25M_{sol}$, solar metallicity star:
$\eta=0.13$
$T_c=5.5$ GK
$\rho_c=1.6\times10^9$ g/cm$^3$

J. Jose & C. Iliadis, "The Unfinished Quest for the Origin of the Elements", Rep. Prog. Phys. 74, 096901 (2011)