High-Mass Stars

- At no point in the evolution is electron degeneracy pressure sufficient to establish hydrostatic equilibrium

- If we take the star to be a polytrope

$$\frac{P_c^3}{\rho_c^4} = 4\pi G \left(\frac{M}{\phi}\right)^2$$

$$\Phi = 4.899, 10.73, 16.15 \quad \text{for } n = 0, 1.5, 3$$

- $$P_{ideal} = \frac{\rho}{\mu} N_A k T$$

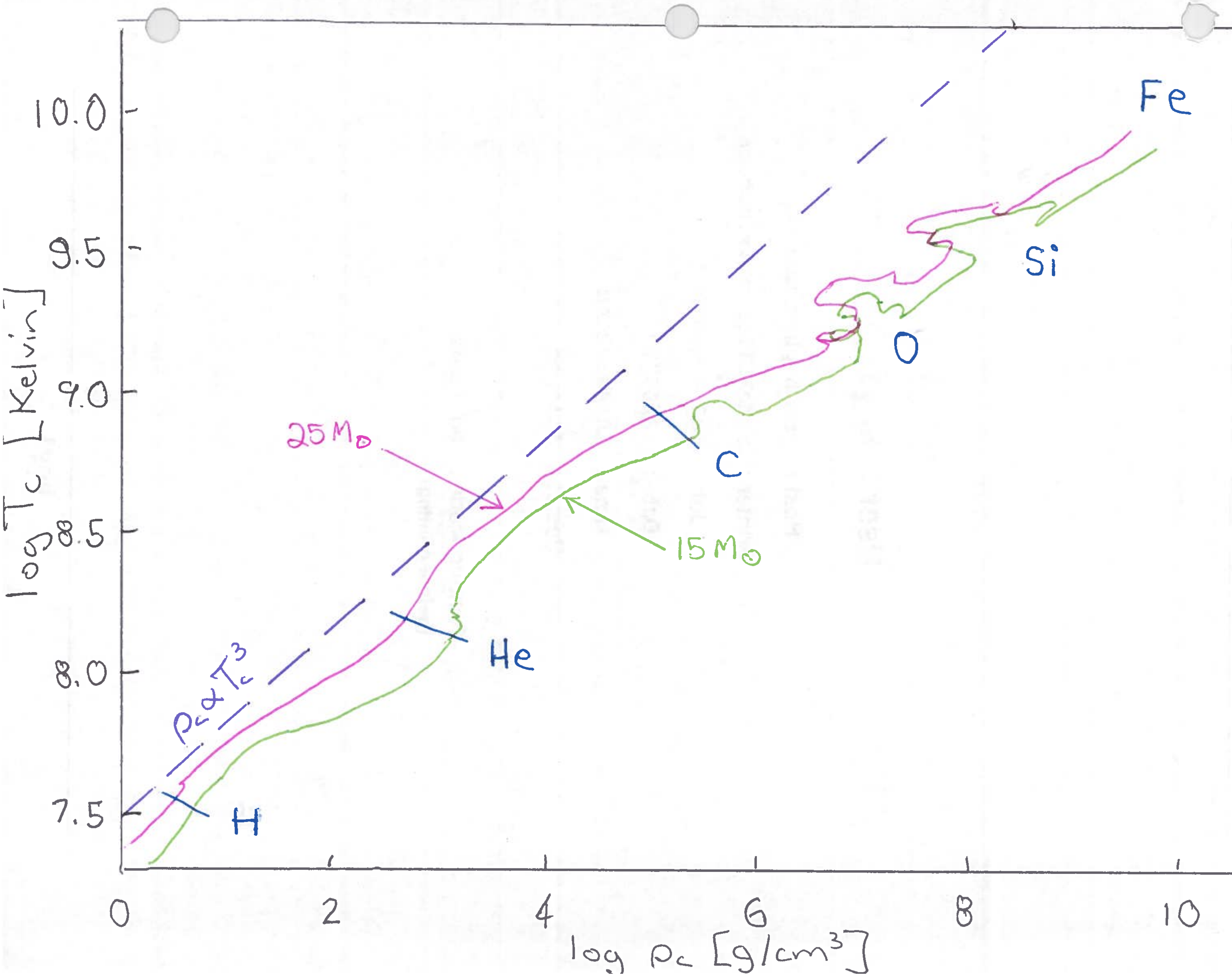
  Assume constant $\beta = \frac{P_{gas}}{P_T}$ and constant n

$$\frac{T_c^3}{\rho_c} \propto M^3 \mu^3$$

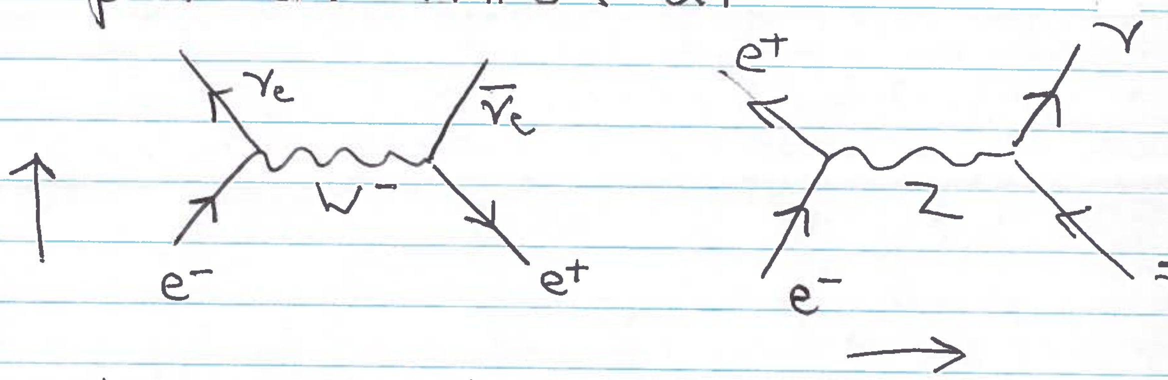
- NB: $S \propto \frac{T^3}{\rho}$ (radiation) ; $S \propto \frac{T^{3/2}}{\rho}$ (ideal-gas)
  so entropy increases with mass

- Perfect gas equation of state is good mostly but need to consider Coulomb corrections after helium burning.

- Electron scattering and also conduction


log T_c [Kelvin]
10.0
9.5
9.0
8.5
8.0
7.5
log ρ_c [g/cm^3]
0
2
4
6
8
10
Fe
Si
O
C
He
H
25 $M_\odot$
15 $M_\odot$
$\rho_c \propto T_c^3$

- Neutrino losses: high T, low ρ
  - pair annihilation $\propto T^9$



- each successive burning stage
  (1) Requires high T
  (2) Releases less energy per mass
  (3) Suffers larger neutrino losses
  (4) Lasts shorter periods of time
  Silicon burning lasts about one day

- treatment of convection is crucial as burning layers are convective
  - semi-convection because large composition gradients
  - overshoot can merge burning layers
  - diffusion

- high-mass stars suffer high-mass loss rates
  - $L \sim L_{edd}$: $L_{edd} = 3.2 \times 10^4 L_\odot (M/M_\odot)$
  - binarity (usually after H depletion)
  - Wolf-Rayet stars ; helium stars ($35 M_\odot$ and up)

- A star spends 90% of its life in H-burning and 10% (almost) in He-burning so nearly all stars are observed in these stages (except SN progenitors)

- Hydrogen burning through CNO cycle (25 MeV / helium, slightly less than for low-mass stars) $4.22 \cdot 10^{18}$ erg/g

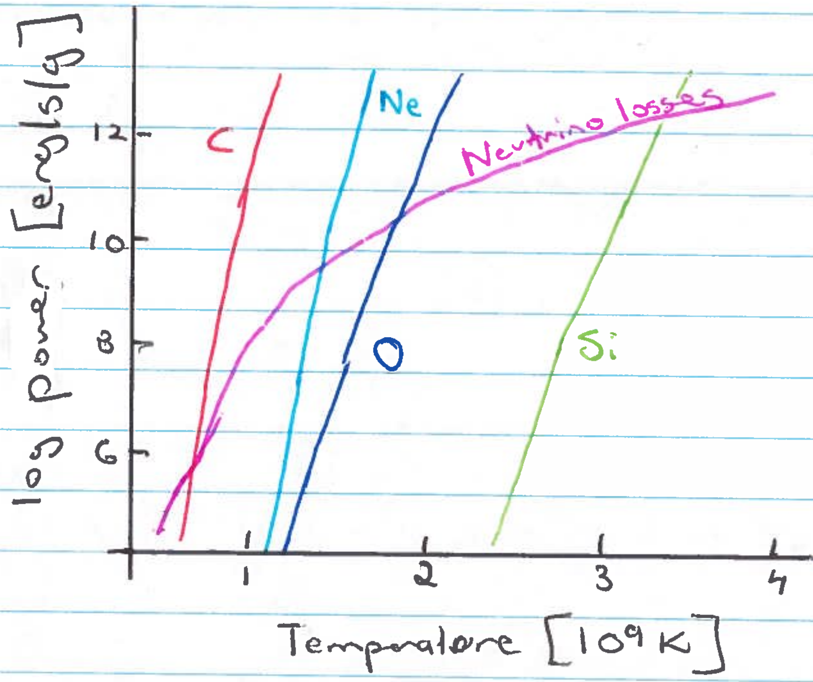
- Helium burning
  - first, $^{14}N(\alpha,\gamma)^{18}F(\beta^+ \nu)^{18}O$ 10^{16} erg/g (convective nitrogen burning!) at the end of He-burning $^{18}O \rightarrow {}^{22}Ne$ which is a neutron source

  - next, triple-α which is well understood

  - But $^{12}C(\alpha,\gamma)^{16}O$ is important as it determines C/O ratio and the structure of the pesupernova star

- $5.85 * 2.86 \, X(^{16}O) \times 10^{17}$ erg/g much less than H-burning
- helium burning stars lie near a boundary between two stable solutions
  (1) Red convective envelope
  (2) Blue radiative envelope

• Advanced burning stages



C	$4 \cdot 10^{17}$ erg/g
Ne	$1.1 \cdot 10^{17}$ erg/g
O	$5 \cdot 10^{17}$ erg/g
Si	$2 \cdot 10^{17}$ erg/g

- basically neutrino-mediated Kelvin-Helmholtz contraction of the carbon-oxygen core

- if the star still has a hydrogen envelope (red supergiant), τ_{KH} at the surface is 10,000 yr so the surface properties don't change until the SN.

- Except for 8-11 $M_\odot$ each massive star ignites new fuel in the centre.

- Carbon and oxygen burning proceed as binary reactions; others by photodisintegration

Silicon burning and NSE

- Do not have $^{28}Si + ^{28}Si \rightarrow ^{56}Ni$ because the Coulomb barrier is too large
- Rather have $^{28}Si(\gamma,\alpha)^{24}Mg(\gamma,\alpha)^{20}Ne(\gamma,\alpha)$ $^{16}O(\gamma,\alpha)^{12}C(\gamma,2\alpha)\alpha$

  establishing an equilibrium approximately
- Also have protons and neutrons

  $^{28}Si(\alpha,\gamma)^{32}S(\gamma,p)^{31}P(\gamma,p)^{30}Si(\gamma,n)^{29}Si(\gamma,n)^{28}Si$
- Alpha particles, protons and neutrons add onto ^{28}Si gradually increasing $\langle A \rangle$
- Above ^{24}Mg have quasi equilibrium

$$Y(^AZ) = C(^AZ, \rho, T_9)\, Y(^{28}Si)\, Y_\alpha^{\delta_\alpha} Y_n^{\delta_n} Y_p^{\delta_p}$$

$$Y_\alpha = (\rho N_A)^3\, C_\alpha(T_9)\, Y_n^2 Y_p^2$$

  C are thermodynamic factors

- All species above ^{24}Mg determined by ρ, T_9, $Y(^{28}Si)$, $\eta = \frac{(N-Z)}{A}$
- For small η, basically assume two ^{28}Si melt and form one ^{56}Ni

  $\simeq 1.9 \times 10^{17}\, X(^{28}Si)$ erg/g

- Toward the end of Si burning all reactions reach equilibrium with triple-α last!
  - three parameters determine all quantities T, ρ and $(N-Z)/A$
  - all strong + electromagnetic reactions in equilibrium
  - For small η and low temperature ^{56}Ni is favoured (remember basically adding α to ^{28}Si)
  - But for $\eta \approx 0.07$, most bound ^{56}Fe
  - Most bound overall is ^{62}Ni: $\eta = 0.096$
- As temperature increases lighter nuclei are favoured, absorbing energy

$$^{56}Fe \rightarrow 13\,{}^{4}He + 4n - 1.7 \cdot 10^{18}\,\text{erg/s}$$

- Also higher energy levels of the nuclei become an important sink of energy.
- Below about $8 M_\odot$ carbon does not ignite
- Above about $11 M_\odot$, carbon + neon ignite non-degenerately

• Between 8 and 11 $M_\odot$

- off-center ignition of carbon & neon
- degeneracy important (like helium flash)
- thermally pulsing He-shell
- strong winds
- perhaps no supernova → O-Ne WD

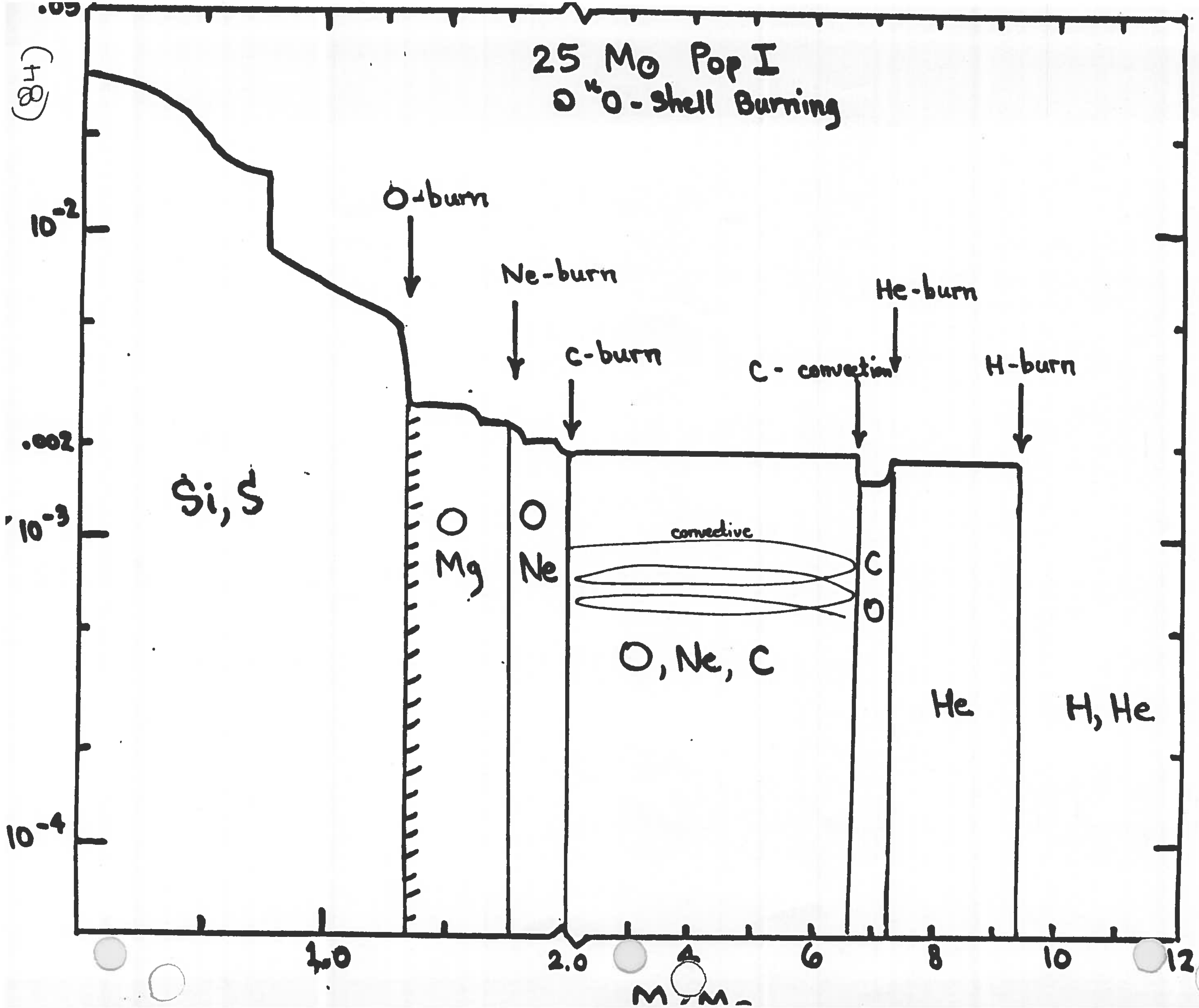
- Alternately, some found at 9-10 $M_\odot$
  Neon doesn't burn stably
- Core grows to M_{CH} → e capture on Neon at $5 \cdot 10^9$ g/cm^3
- burns to NSE → ν powered SN + NS

Above 11 $M_\odot$ to 100 $M_\odot$

- all these stars complete all the advanced burning stages including Si-burning in hydrostatic equilibrium

- more massive stars have higher entropy

- successive burning stages cause the core to lose entropy
  - although nuclear reactions generate entropy and energy they are also precisely balanced by neutrino losses
  - convection transports entropy outward
- weak interactions during Si-burning increase neutron excess; the core reaches "equilibrium" $Y_e(\rho, T)$



25 M⊙ Pop I
^{16}O-Shell Burning
O-burn
Ne-burn
C-burn
C-convection
He-burn
H-burn
Si, S
O
Mg
O
Ne
convective
O, Ne, C
C
O
He
H, He
.05
10^{-2}
.002
10^{-3}
10^{-4}
1.0
2.0
4
6
8
10
12