# Evolution of Galaxies:
## Review of Stellar Evolution

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http://astro.u-strasbg.fr/~koppen/JKHome.html

Star = self-gravitating ball of gas powered by thermonuclear fusion

# Star formation

- Complicated, poorly understood
- Happens in dense, dusty, cool, molecular clouds
- Basic mechanism: Jeans-instability: a self-gravitating gas sphere will collapse if

$$E_{thermal} < E_{grav}$$

$$M/m\ kT < G\ M^2/R$$

$$M > M_{jeans} = \left(\frac{kT}{Gm}\right)^{3/2} \left(\frac{4\pi\rho}{3}\right)^{-1/2}$$

$$= 1000\ M_{sun} \left(\frac{T}{10K}\right)^{3/2} \left(\frac{\rho}{10^{-24}\ g/cm3}\right)^{-1/2}$$

# Star formation

- Time scale for initial collapse: free-fall time scale: $\tau_{ff} \sim 1/\sqrt{G\rho}$

➔Denser clumps will collapse faster than the rest ➔ fragmentation

- Collapse is
  - Resisted by magn.field, turbulence, rotation
  - Assisted by external pressure (SN shock, spiral arm)

# Basic problem of star formation

## How to get rid of angular momentum?

| | M/Msun | Radius | V [km/s] | M*R*V |
|---|---|---|---|---|
| IS cloud | >1 | 1pc = 3 E16 m | <0.1 | 3 E 15 |
| Solar rotation | 1 | 7 E 8 m | 2 | 1.5 E 9 |
| Jupiter orbit | 0.001 | 7 E 11 m | 13 | 9 E 9 |
| Saturn orbit | 0.0003 | 14 E 11 m | 10 | 4 E 9 |

Helpful: -- formation of planet system (?!)

-- stellar winds, bipolar molecular outflows, jets

# Time scales (Sun)

- Free fall: 1 hr
- Sound wave crossing time = response to pressure imbalance: $R/c_s \sim 1$hr
- Kelvin-Helmholtz = lifetime of a collapsing star: $E_g/L = GM^2/RL \sim 10^7$ yrs shorter than age of Earth
  - gravitational contraction is NOT main energy source
  - if no other energy sources, star evolves with this timescale
- Nuclear burning: $\sim 10^{10}$ yrs

freefall = sound << KH << nuclear

➔ Stars evolve in hydrostatic equilibrium

# Static stellar structure

- Assumptions:
  - Single star
  - No magnetic fields
  - No rotation
  - No stellar winds

  (Single star, No magnetic fields, No rotation:) Gravity only
  ➔ Spherically symmetric (1D)

- Conservation of Mass, Momentum, Energy

# Conservation of Mass

Define mass coordinate: mass within sphere of radius r

$$M_r = \frac{4\pi}{3}\int_0^r \rho(r')dr'$$

{ conservation of nuclear species (abundance $\varepsilon_i$ by mass) and with reactions A+B →C and rate coefficients $R_{AB,C}$

$$\varepsilon_i \sum_k \sum_l \varepsilon_k R_{ik,l} = \sum_k \sum_l \varepsilon_k \varepsilon_l R_{kl,i}$$

consumption = synthesis }

# Conservation of momentum

Hydrostatic equilibrium:

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

Pressure $p = p_{thermal} + p_{radiative}$

$\approx aT^4/3$

# Conservation of Energy

- Energy production

Luminosity of sphere r → $$\frac{dL_r}{dr} = 4\pi\, r^2\, \rho\;\; e$$ ← Energy production rate

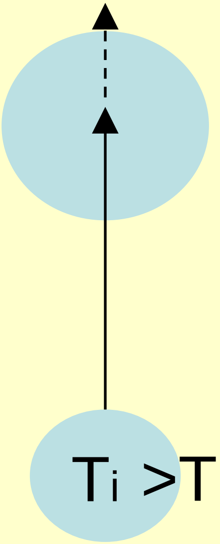
- Energy transport
  - By radiation (interior is highly opaque ➔ diffusion approximation):

$$\frac{dT}{dr} = -\frac{3}{16\pi\sigma c}\,\frac{\kappa\rho}{T^3}\,\frac{L_r}{4\pi r^2}$$

# Energy transport: convection

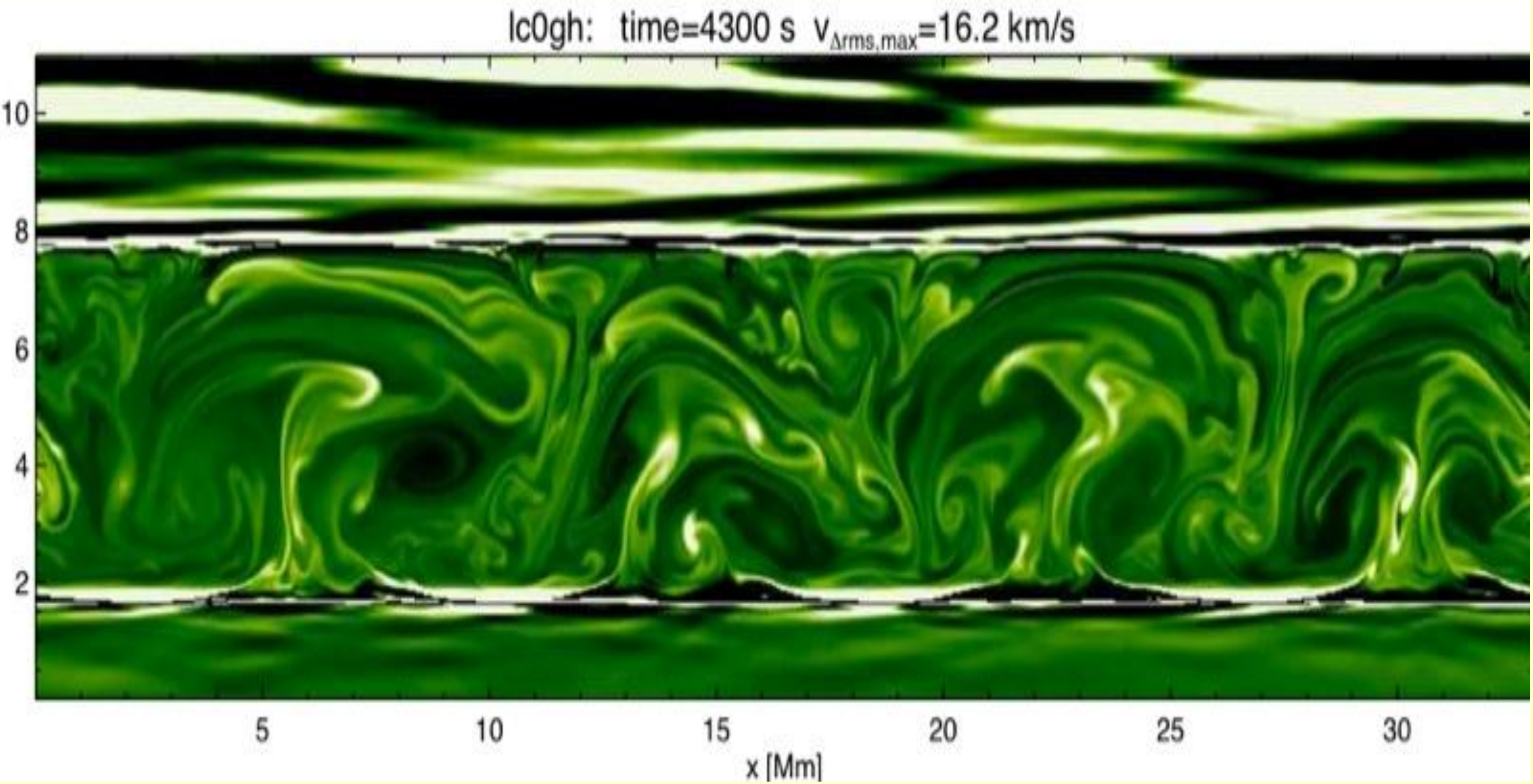
- occurs when layers become dynamically unstable (Schwarzschild criterion for chem.homog.): if $\left.\frac{\partial \ln T}{\partial \ln p}\right|_{\text{rad}} < \left.\frac{\partial \ln T}{\partial \ln p}\right|_{\text{adiab.}} = \frac{\gamma - 1}{\gamma}$

$$\frac{dT}{dr} = -\frac{\gamma - 1}{\gamma} \frac{T}{p} \frac{dp}{dr} \qquad \text{with } \gamma = \frac{c_P}{c_V}$$




- Convection is linked with transport of matter in the unstable regions: Mixing; hot uprising material can overshoot
- Physically consistent description NOT available (use recipes obtained from numerical simulations …

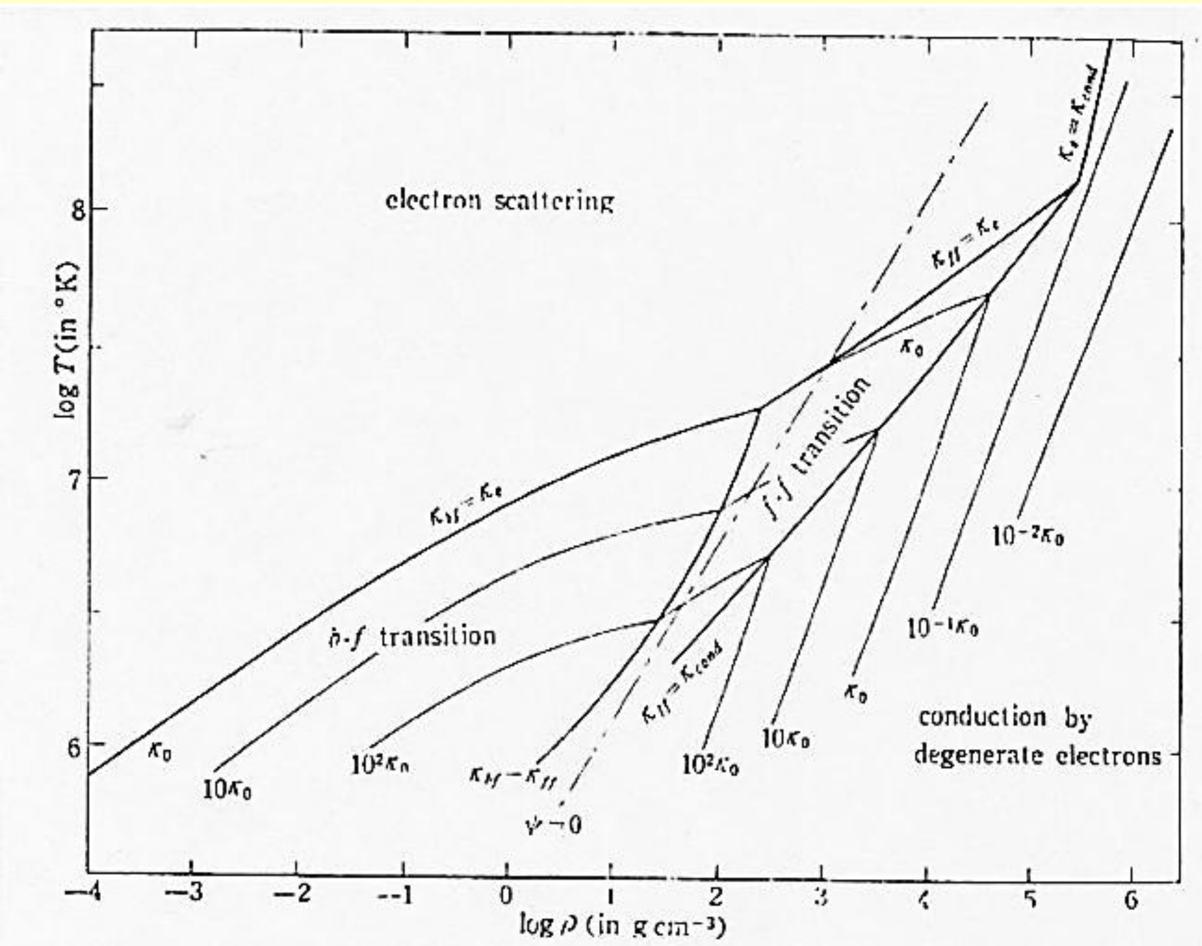
# Convection: simulation

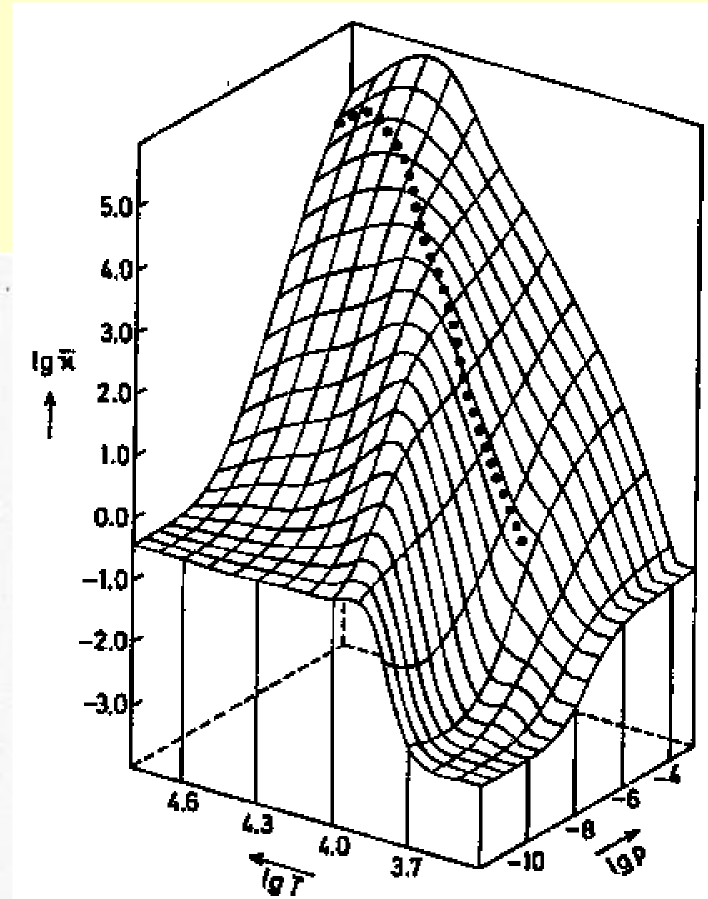


# Stellar Structure equations

- Properties of the material
  - Equation of state (EOS) $p(\rho, T, \varepsilon)$
  - Opacity (LosAlamos, OPAL, ..) $\kappa(\rho, T, \varepsilon)$
  - Energy production $e(\rho, T, \varepsilon)$
- Boundary conditions
  - Centre: $Mr(0) = 0$, $Lr(0) = 0$
  - Surface: $T(R) \approx 0$, $p(R) \approx 0$ (= stellar atm.)
- All these equation fully describe the internal structure of a star
- Stellar evolution: sequence of static models with different composition due to nuclear processes

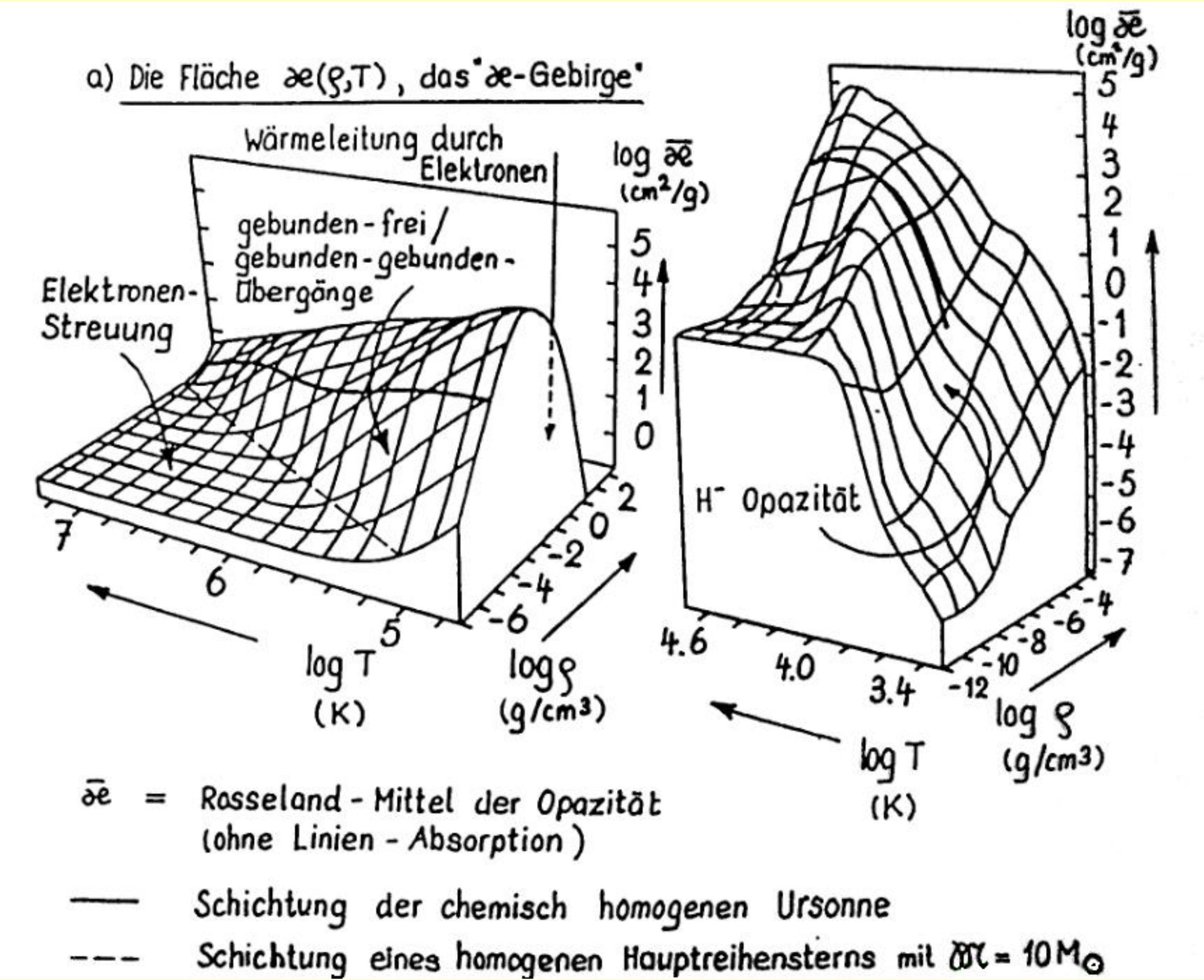
# Opacity 'mountain'




▪ ▪ ▪ outer layers of sun

# Opacity 'mountain'

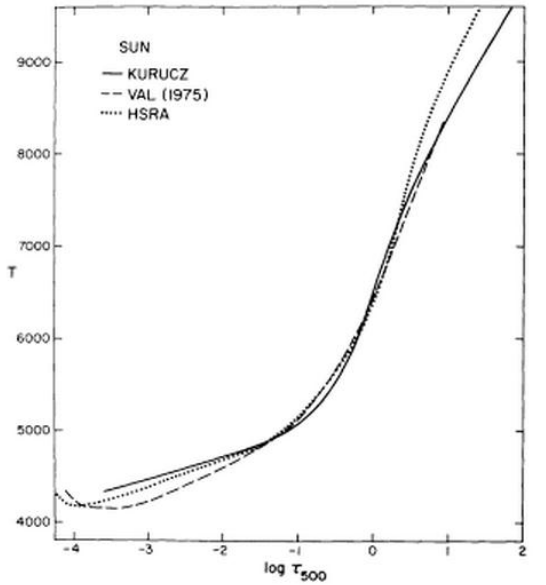


# Solar atmosphere model

TABLE 4.—There are 140 solar abundance models, 72 1/10 solar abundance models, and 72 1/100 solar abundance models listed two per page. The heading for each model gives the effective temperature, log surface gravity, log metal abundance relative to solar, and whether the model is convective plus radiative or purely radiative. The 40 depths actually used in the computation are listed, roughly equally spaced in log $\tau_{Ross}$ from $-4.5$ to 2.0 in steps of $\frac{1}{6}$. Owing to scaling from model to model and to radical temperature corrections, this spacing is not always maintained. To compress the tables, all the variables except temperature are given as logs. The units are cgs for all variables. The columns are mass per unit area, Rosseland optical depth, continuum optical depth at 500 nm, geometric height, temperature, pressure, electron number density, atom number density, mass density, Rosseland mass absorption coefficient, continuum mass absorption coefficient at 500 nm, radiation pressure, radiative acceleration, and the fraction of flux carried by convection. The first values of $\tau_{Ross}$, $\tau_{500}$, and $x$ are defined to be 0. Depths with no convection are listed with 0 convection fraction.

TEFF 5770. LOG G 4.44 LOG ABUND .00 CONVECTIVE

| | MASS | TAU ROSS | TAU 500 | X | T | P | NE | NA | RHO | KAPPA ROSS | KAPPA 500 | P RAD | ACC RAD | CONV FRAC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | -1.49997 | 0.0000 | 0.0000 | 0.0000 | 3054.4 | 2.9400 | 10.0976 | 15.3150 | -8.3418 | -2.2859 | -2.2276 | .1716 | -.7501 | -16.2348 |
| 2 | -1.36788 | -3.6538 | -3.5954 | 6.4024 | 4329.1 | 3.0722 | 11.2206 | 15.2958 | -8.3611 | -2.2859 | -2.2276 | .1719 | -1.2426 | -22.7006 |
| 3 | -1.28746 | -3.5671 | -3.5094 | 6.6398 | 4349.8 | 3.1526 | 11.2953 | 15.3740 | -8.2828 | -2.2167 | -2.1650 | .1721 | -1.2367 | 0.0000 |
| 4 | -1.23190 | -3.5001 | -3.4435 | 6.7508 | 4357.6 | 3.2082 | 11.3452 | 15.4288 | -8.2280 | -2.1698 | -2.1210 | .1722 | -1.2077 | 0.0000 |
| 5 | -1.18463 | -3.4387 | -3.3837 | 6.8272 | 4393.3 | 3.2553 | 11.3941 | 15.4724 | -8.1845 | -2.1268 | -2.0864 | .1723 | -1.2132 | 0.0000 |
| 6 | -1.12900 | -3.3619 | -3.3093 | 6.9030 | 4395.2 | 3.3109 | 11.4426 | 15.5278 | -8.1290 | -2.0802 | -2.0413 | .1725 | -1.1935 | 0.0000 |
| 7 | -1.06680 | -3.2707 | -3.2214 | 6.9748 | 4427.8 | 3.3733 | 11.5039 | 15.5870 | -8.0699 | -2.0252 | -1.9934 | .1727 | -1.1746 | 0.0000 |
| 8 | -.99779 | -3.1638 | -3.1188 | 7.0430 | 4447.8 | 3.4422 | 11.5680 | 15.6539 | -8.0029 | -1.9658 | -1.9386 | .1730 | -1.1572 | 0.0000 |
| 9 | -.92358 | -3.0435 | -3.0035 | 7.1064 | 4476.2 | 3.5164 | 11.6383 | 15.7254 | -7.9315 | -1.9014 | -1.8801 | .1734 | -1.1350 | 0.0000 |
| 10 | -.84501 | -2.9113 | -2.8768 | 7.1651 | 4504.3 | 3.5949 | 11.7122 | 15.8012 | -7.8556 | -1.8336 | -1.8176 | .1739 | -1.1099 | 0.0000 |
| 11 | -.76302 | -2.7693 | -2.7407 | 7.2192 | 4535.2 | 3.6770 | 11.7896 | 15.8803 | -7.7766 | -1.7625 | -1.7523 | .1746 | -1.0816 | 0.0000 |
| 12 | -.67862 | -2.6199 | -2.5974 | 7.2690 | 4566.9 | 3.7614 | 11.8691 | 15.9617 | -7.6952 | -1.6897 | -1.6848 | .1755 | -1.0499 | 0.0000 |
| 13 | -.59256 | -2.4653 | -2.4487 | 7.3148 | 4599.9 | 3.8474 | 11.9501 | 16.0446 | -7.6123 | -1.6158 | -1.6157 | .1768 | -1.0146 | 0.0000 |
| 14 | -.50563 | -2.3074 | -2.2966 | 7.3569 | 4634.3 | 3.9343 | 12.0322 | 16.1283 | -7.5286 | -1.5406 | -1.5458 | .1784 | -.9731 | 0.0000 |
| 15 | -.41827 | -2.1473 | -2.1424 | 7.3958 | 4670.7 | 4.0216 | 12.1149 | 16.2121 | -7.4447 | -1.4642 | -1.4755 | .1807 | -.9245 | 0.0000 |
| 16 | -.33063 | -1.9855 | -1.9866 | 7.4319 | 4709.4 | 4.1092 | 12.1984 | 16.2962 | -7.3607 | -1.3874 | -1.4049 | .1838 | -.8735 | 0.0000 |
| 17 | -.24272 | -1.8224 | -1.8295 | 7.4656 | 4751.2 | 4.1973 | 12.2826 | 16.3804 | -7.2765 | -1.3103 | -1.3341 | .1880 | -.8199 | 0.0000 |
| 18 | -.15450 | -1.6581 | -1.6714 | 7.4972 | 4797.4 | 4.2856 | 12.3681 | 16.4645 | -7.1924 | -1.2326 | -1.2630 | .1938 | -.7637 | 0.0000 |
| 19 | -.06584 | -1.4924 | -1.5122 | 7.5271 | 4850.1 | 4.3742 | 12.4556 | 16.5484 | -7.1085 | -1.1542 | -1.1915 | .2019 | -.7058 | 0.0000 |
| 20 | .02281 | -1.3262 | -1.3527 | 7.5554 | 4911.0 | 4.4628 | 12.5449 | 16.6316 | -7.0253 | -1.0755 | -1.1200 | .2130 | -.6461 | 0.0000 |
| 21 | .11131 | -1.1598 | -1.1931 | 7.5823 | 4982.8 | 4.5513 | 12.6371 | 16.7138 | -6.9431 | -.9961 | -1.0482 | .2281 | -.5847 | 0.0000 |
| 22 | .19922 | -.9940 | -1.0344 | 7.6078 | 5069.0 | 4.6392 | 12.7325 | 16.7942 | -6.8627 | -.9169 | -.9765 | .2485 | -.5217 | 0.0000 |
| 23 | .28649 | -.8286 | -.8763 | 7.6322 | 5174.0 | 4.7265 | 12.8330 | 16.8726 | -6.7843 | -.8362 | -.9037 | .2757 | -.4564 | 0.0000 |
| 24 | .37336 | -.6626 | -.7176 | 7.6557 | 5304.1 | 4.8134 | 12.9434 | 16.9487 | -6.7082 | -.7515 | -.8258 | .3116 | -.3863 | 0.0000 |
| 25 | .45895 | -.4955 | -.5576 | 7.6782 | 5467.3 | 4.8989 | 13.0715 | 17.0211 | -6.6358 | -.6556 | -.7359 | .3584 | -.3029 | 0.0000 |
| 26 | .53989 | -.3283 | -.3973 | 7.6992 | 5675.4 | 4.9799 | 13.2322 | 17.0858 | -6.5711 | -.5321 | -.6200 | .4177 | -.1885 | 0.0000 |
| 27 | .61227 | -.1594 | -.2361 | 7.7179 | 5934.0 | 5.0523 | 13.4408 | 17.1388 | -6.5181 | -.3636 | -.4622 | .4926 | -.0185 | 0.0000 |
| 28 | .66993 | .0105 | -.0749 | 7.7329 | 6300.7 | 5.1099 | 13.7384 | 17.1703 | -6.4866 | -.1224 | -.2305 | .5842 | .2127 | -2.2884 |
| 29 | .71069 | .1769 | .0840 | 7.7440 | 6722.8 | 5.1508 | 14.0697 | 17.1828 | -6.4741 | .1443 | .0328 | .6836 | .4255 | -.9992 |
| 30 | .74213 | .3447 | .2442 | 7.7528 | 7085.6 | 5.1821 | 14.3377 | 17.1911 | -6.4658 | .3727 | .2496 | .7798 | .5485 | -.5526 |
| 31 | .76878 | .5130 | .4026 | 7.7605 | 7403.8 | 5.2087 | 14.5567 | 17.1982 | -6.4587 | .5695 | .4297 | .8660 | .5992 | -.3146 |
| 32 | .79286 | .6798 | .5580 | 7.7676 | 7691.3 | 5.2327 | 14.7419 | 17.2052 | -6.4517 | .7385 | .5853 | .9388 | .6017 | -.1906 |
| 33 | .81608 | .8463 | .7130 | 7.7747 | 7955.8 | 5.2560 | 14.9027 | 17.2131 | -6.4437 | .8870 | .7235 | 1.0012 | .5885 | -.1214 |
| 34 | .83937 | 1.0125 | .8688 | 7.7818 | 8209.4 | 5.2794 | 15.0488 | 17.2222 | -6.4347 | 1.0220 | .8523 | 1.0569 | .5708 | -.0790 |
| 35 | .86323 | 1.1786 | 1.0254 | 7.7893 | 8450.9 | 5.3032 | 15.1816 | 17.2324 | -6.4245 | 1.1511 | .9724 | 1.1078 | .5507 | -.0596 |
| 36 | .88811 | 1.3459 | 1.1830 | 7.7972 | 8686.0 | 5.3282 | 15.3051 | 17.2443 | -6.4125 | 1.2765 | 1.0873 | 1.1560 | .5354 | -.0343 |
| 37 | .91397 | 1.5123 | 1.3398 | 7.8055 | 8916.3 | 5.3539 | 15.4213 | 17.2574 | -6.3995 | 1.3957 | 1.1982 | 1.2015 | .5104 | -.0348 |
| 38 | .94139 | 1.6788 | 1.4975 | 7.8143 | 9136.9 | 5.3815 | 15.5288 | 17.2729 | -6.3840 | 1.5068 | 1.3032 | 1.2451 | .4854 | -.0118 |
| 39 | .97057 | 1.8458 | 1.6569 | 7.8239 | 9369.1 | 5.4106 | 15.6371 | 17.2893 | -6.3676 | 1.6192 | 1.4118 | 1.2874 | .4573 | -.0231 |
| 40 | 1.00167 | 2.0113 | 1.8166 | 7.8340 | 9578.8 | 5.4417 | 15.7333 | 17.3089 | -6.3479 | 1.7174 | 1.5097 | 1.3300 | .4612 | -.0016 |




Kurucz 1979

# Models depend on mass

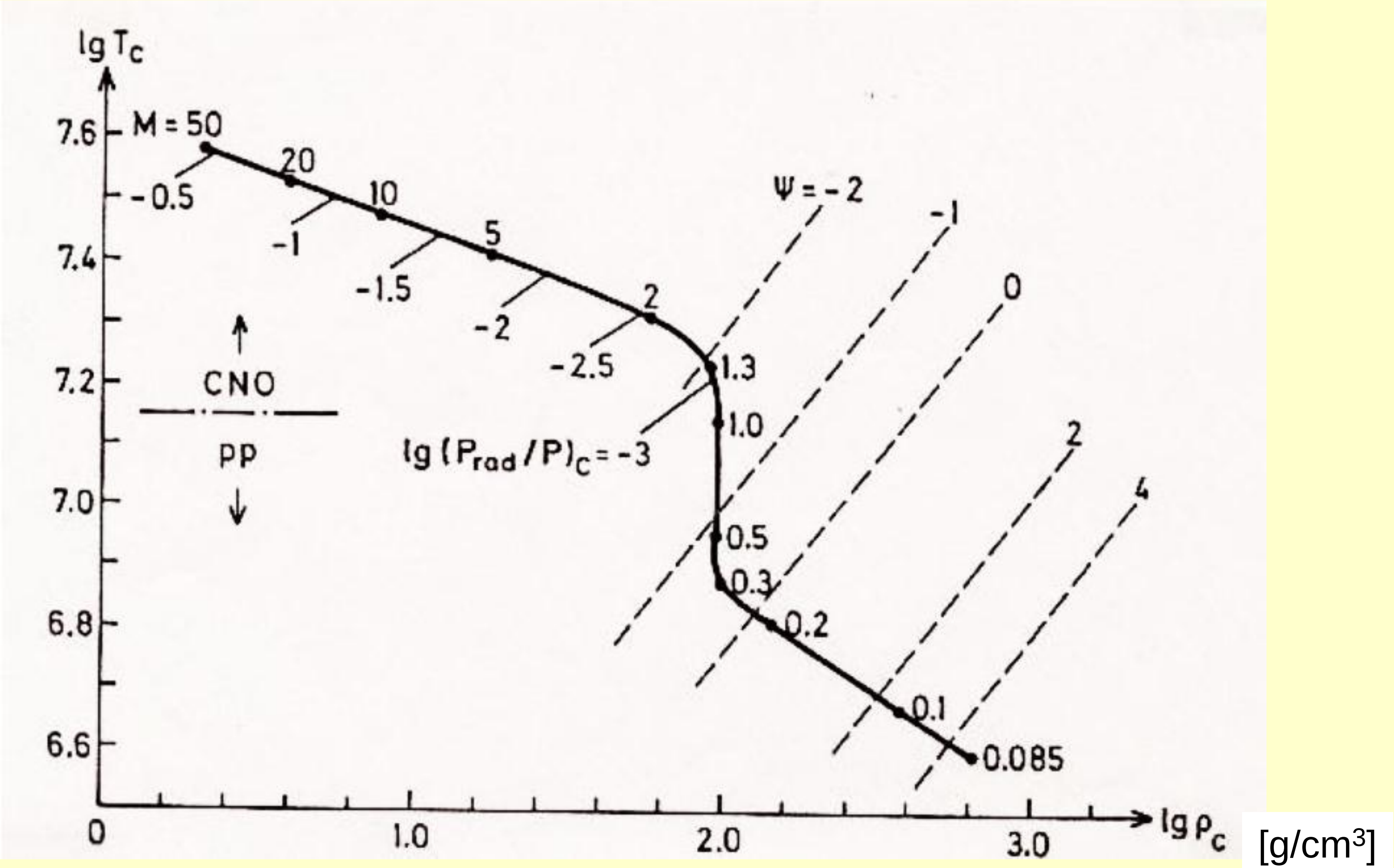
- 100 $M_{sun}$ < M: radiation pressure → instabilities
- 0.08 < M < 100: hydrogen burning in the centre: **Main Sequence** $\rho_c = 2 \ldots 10^3$ g/cm$^3$ $<\rho> \sim 1$
- 0.001 < M < 0.08: $e^{--}$ gas degenerate in centre: no hydrogen fusion (low T): **brown dwarf**

  $\rho_c = 10 \ldots 10^3$ $<\rho> = 100$
- M < 0.001: $e^-$ degenerate, solid core, **Jupiter**-like $\rho_c \sim 10$ $<\rho> = 1$

For comparison

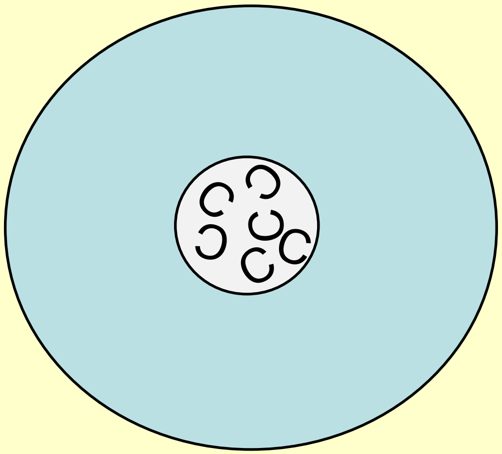
- White dwarf $<\rho> \sim 10^6$
- Neutron star $<\rho> \sim 10^{13} \ldots 10^{15}$
- Black hole $<\rho> \sim 10^{17}$

# MS stars: conditions at centre



# Main sequence stars

## M > 1.5 Msun

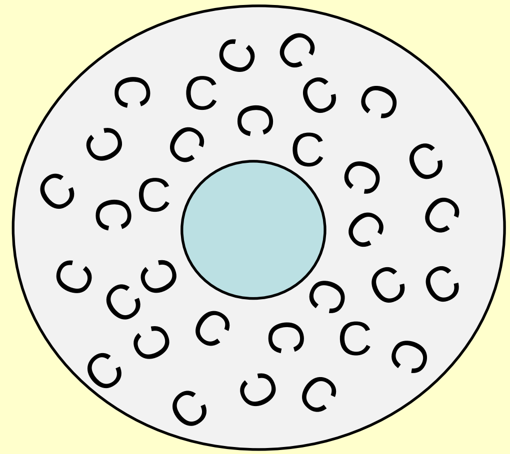


Convective core = always
well mixed
Radiative envelope

CNO cycle: strongly conc.
to centre

M > 20 Msun radiation.pressure

## M < 1.5 Msun



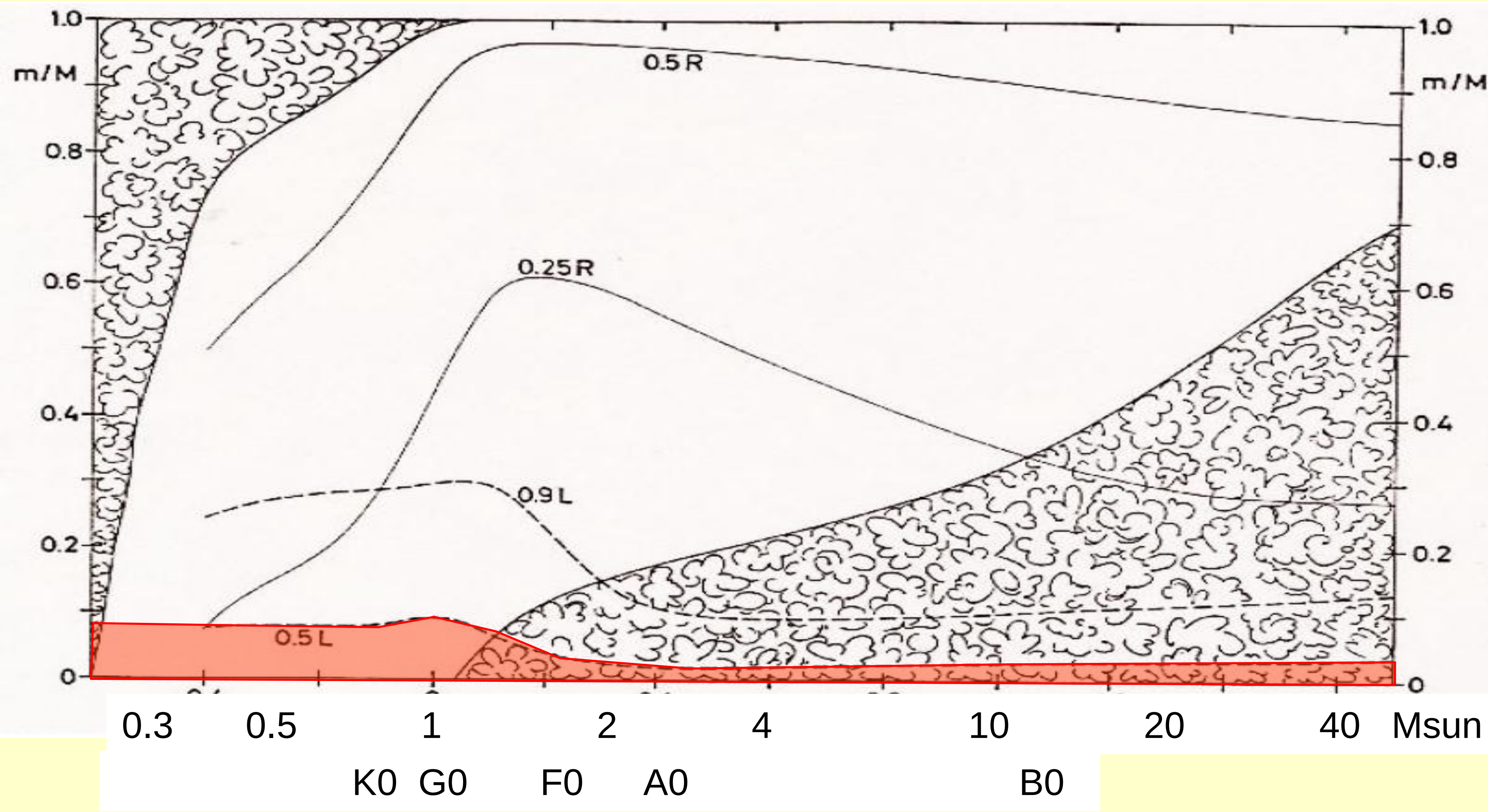
Radiative core

Convective envelope
M<0.3 fully convective

pp chains: low conc. to centre

radiation pressure unimportant

# Main sequence (solar compos.)



# Lifetime on the Main Sequence

- $\tau_{MS} = \frac{M_H}{|\dot{M}_H|} \propto \frac{M_*}{L_*} \propto \frac{M_*}{{M_*}^3} \propto {M_*}^{-2}$

  more accurate (from Geneva models)

  $$\tau_{MS} = \begin{cases} (3 + M^{-1.6})\ \text{Myr} & \text{for } M > 10\ \text{Msun} \\ 10\ \text{Gyr}/M^3 & \text{for } M < 10\ \text{Msun} \end{cases}$$

- Massive stars leave the main sequence earlier than less massive ones. Evolution after burnout is fast ➔ the turn-off mass is a unique function of the age of a stellar population
- Measures ages in absolute terms (nuclear rates)

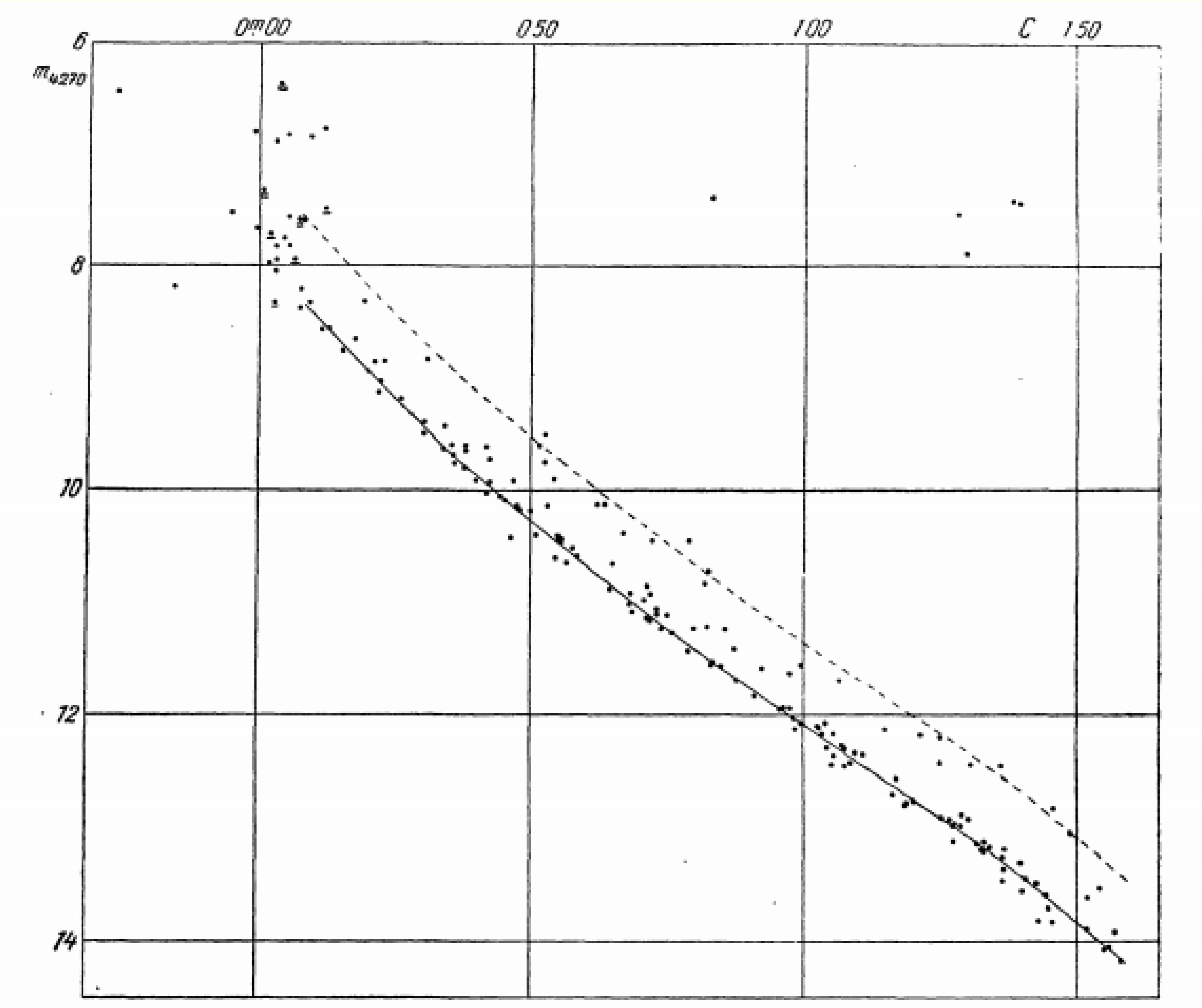
# Table of main sequence

| M/Msun | $t_{MS}$ (Gyr) | Log L | Mv | Teff | B-V | SpT |
|---|---|---|---|---|---|---|
| 0.15 | | -2.5 | 14.2 | 3020 | 1.80 | M7 |
| 0.25 | | -2.0 | 12.0 | 3311 | 1.60 | M5 |
| 0.4 | | -1.4 | 10.0 | 3715 | 1.48 | M1 |
| 0.6 | | -0.9 | 7.6 | 4365 | 1.18 | K5 |
| 0.8 | 25 | -0.4 | 6.0 | 5011 | 0.88 | K1 |
| 0.9 | 15 | -0.2 | 5.4 | 5370 | 0.76 | G8 |
| 1 | 10 | 0 | 4.9 | 5754 | 0.64 | G2 |
| 1.1 | 6.4 | 0.2 | 4.3 | 6166 | 0.56 | F8 |
| 1.2 | 4.5 | 0.4 | 3.7 | 6607 | 0.47 | F6 |
| 1.3 | 3.2 | 0.5 | 3.5 | 6918 | 0.42 | F5 |
| 1.4 | 2.5 | 0.7 | 3.0 | 7244 | 0.36 | F2 |
| 1.5 | 2.0 | 0.8 | 2.8 | 7586 | 0.30 | F0 |

# Table of main sequence (II)

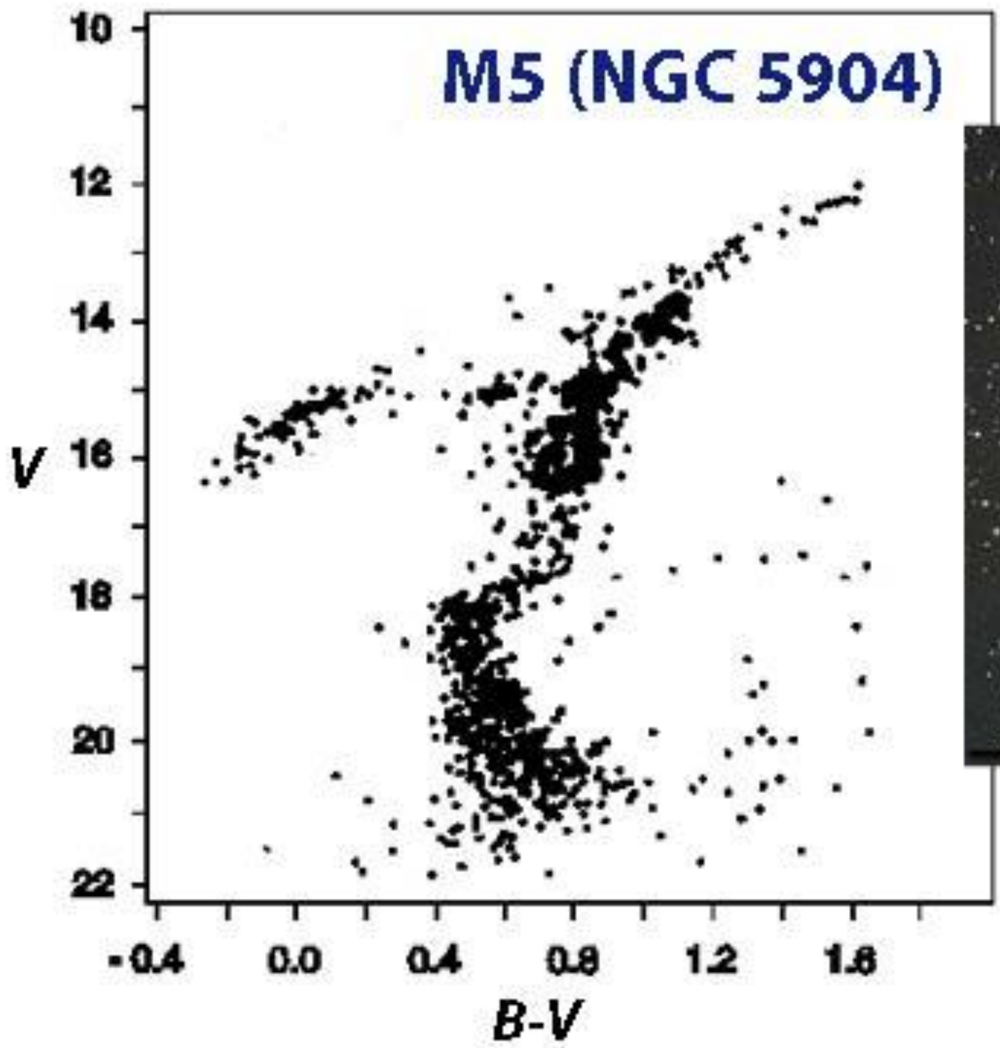
| M/Msun | $t_{MS}$ (Gyr) | Log L | Mv | Teff | B-V | SpT |
|---|---|---|---|---|---|---|
| 2 | 0.75 | 1.3 | 1.4 | 9550 | 0 | A0 |
| 3 | 0.25 | 2.1 | -0.2 | 12600 | -0.12 | B7 |
| 4 | 0.12 | 2.6 | -0.6 | 15100 | -0.17 | B5 |
| 6 | 0.05 | 3.2 | -1.5 | 20000 | -0.22 | B3 |
| 8 | 0.03 | 3.6 | -2.2 | 22400 | -0.25 | B1 |
| 10 | 0.02 | 3.9 | -2.7 | 25000 | -0.27 | |
| 15 | 0.01 | 4.4 | -3.7 | 28000 | -0.29 | |
| 20 | 0.008 | 4.7 | -4.3 | 30200 | -0.30 | B0 |
| 30 | 0.006 | 5.1 | -5.1 | 32400 | -0.31 | O9.5 |
| 40 | 0.004 | 5.4 | -5.7 | 33900 | -0.31 | O9 |
| 60 | 0.003 | 5.7 | -6.2 | 38000 | -0.32 | O5 |

# CMD open cluster: Praesepe

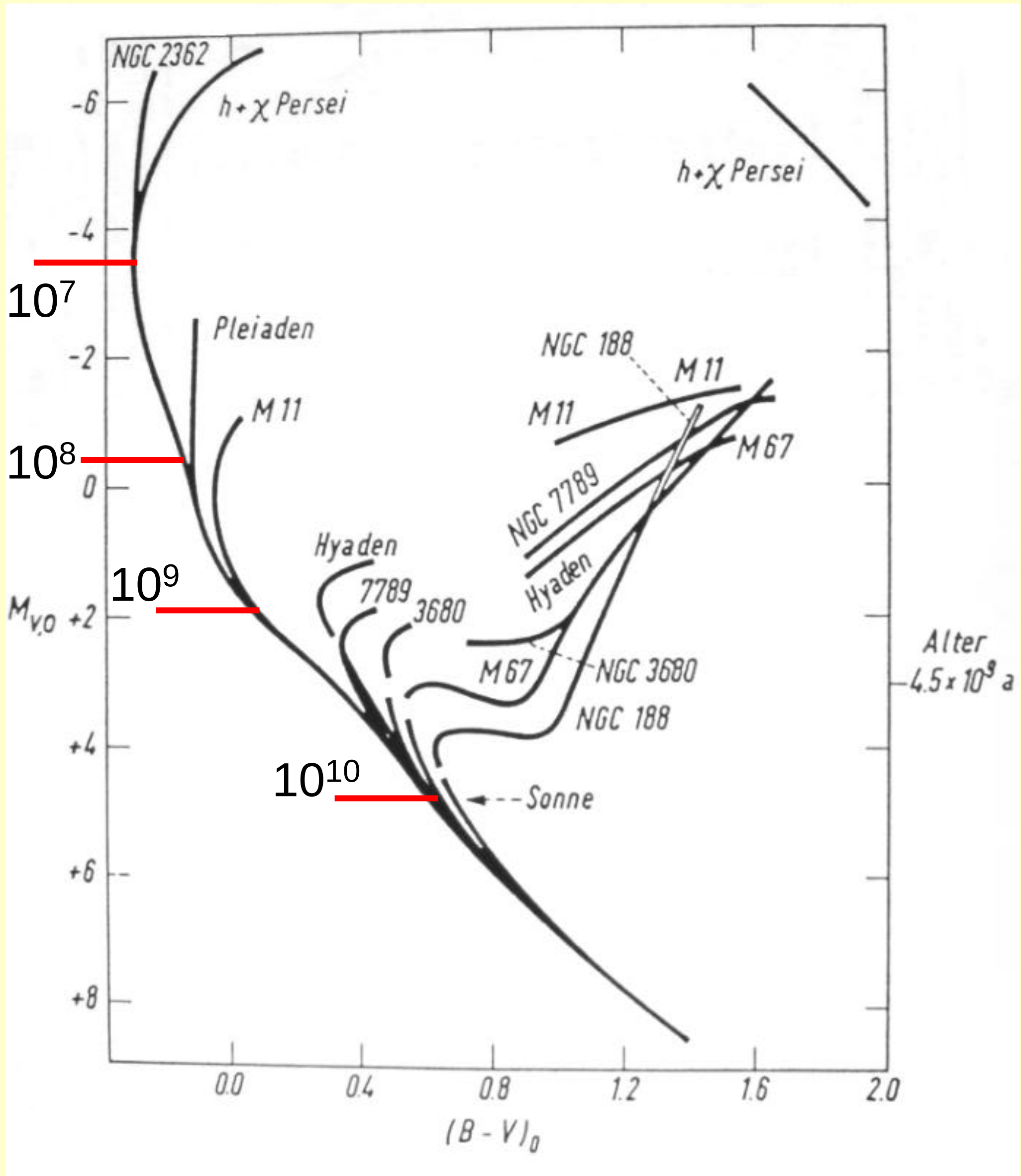



Haffner 1937

# CMD globular cluster



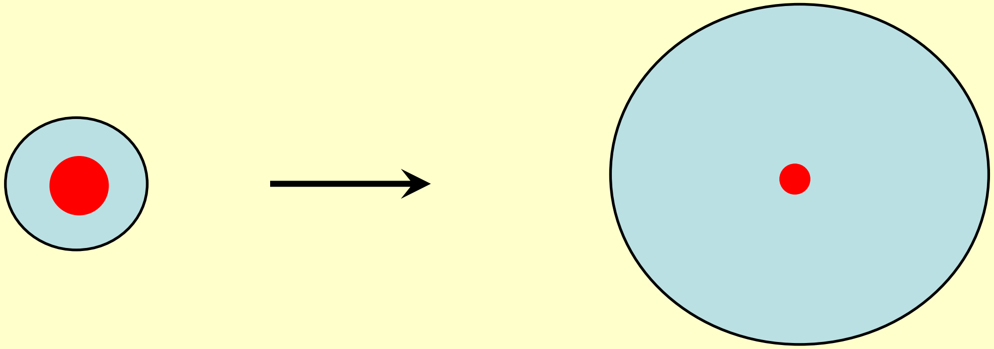

# CMD of clusters of different ages



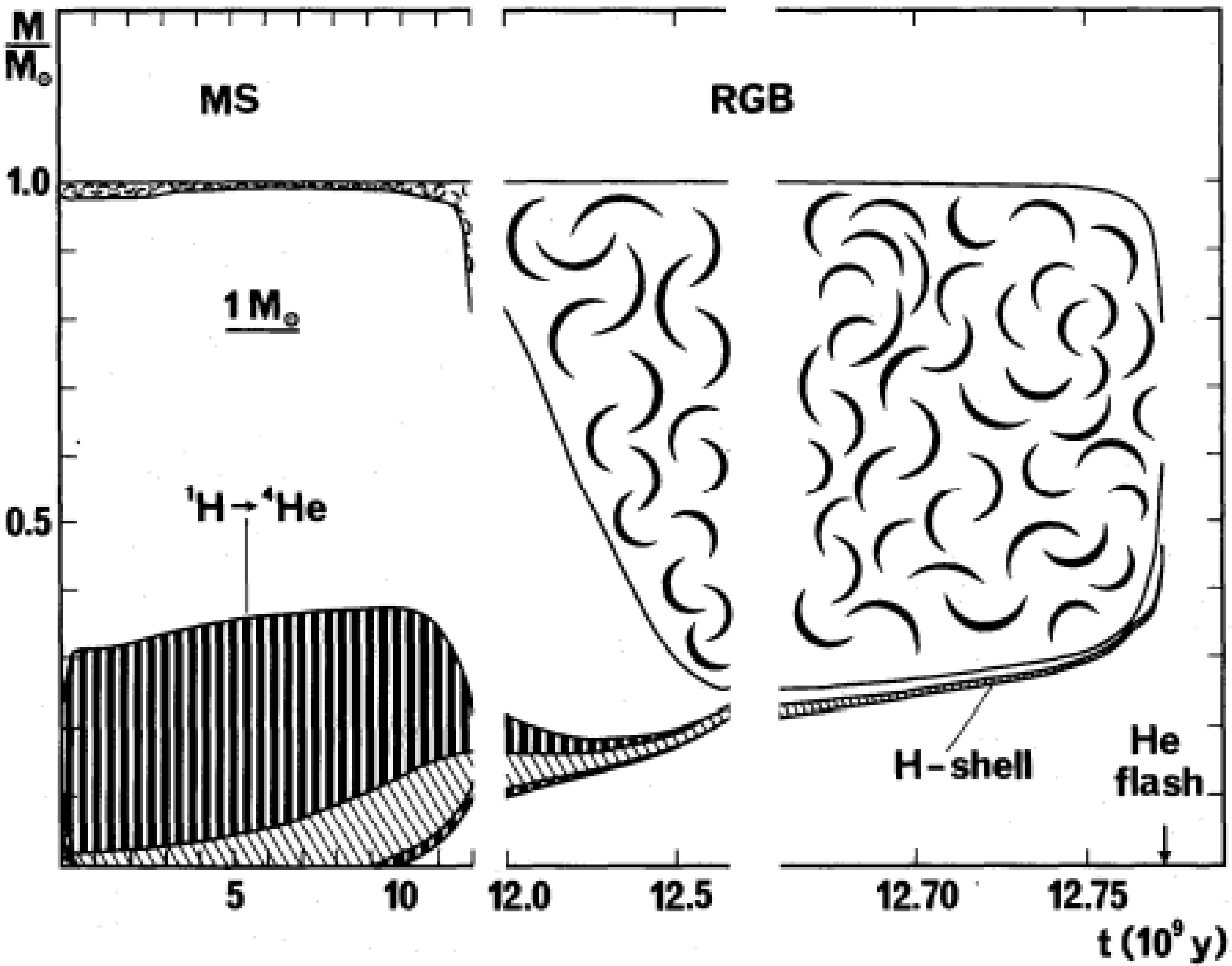

After Eggen & Sandage 1962

# Situation at end of Main Sequence

- Hydrogen exhausted in the centre
- Hydrogen burns in a shell around He-core which eats itself outward
- Gravity ➔ contraction of core + expansion of envelope (found by numerical sims.)



# Solar evolution




Maeder 1989

# Contraction of the core

Consider homologous contraction of gas sphere (R,p,ρ,T with M=const):

- $\rho \propto MR^{-3}$ ➔ $\dot{\rho}/\rho = -3\,\dot{R}/R$
- $\frac{dp}{dr} = -\frac{Gm\rho}{r^2}$ and $\frac{dm}{dr} = 4\pi r^2 \rho$ give $\frac{dp}{dm} = -\frac{Gm}{4\pi r^4}$ so $\frac{p}{M} \approx \frac{M}{R^4}$ ➔ $\dot{p}/p = -4\,\dot{R}/R$
- general EOS $\rho \propto p^{\alpha}\, T^{-\beta}$ ➔ $\frac{\dot{\rho}}{\rho} = \alpha\frac{\dot{p}}{p} - \beta\frac{\dot{T}}{T}$
- ➔ $\frac{\dot{T}}{T} = -\frac{4\alpha - 3}{\beta}\frac{\dot{R}}{R}$

# Contraction of the core …

- Perfect gas ($\alpha = \beta = 1$):

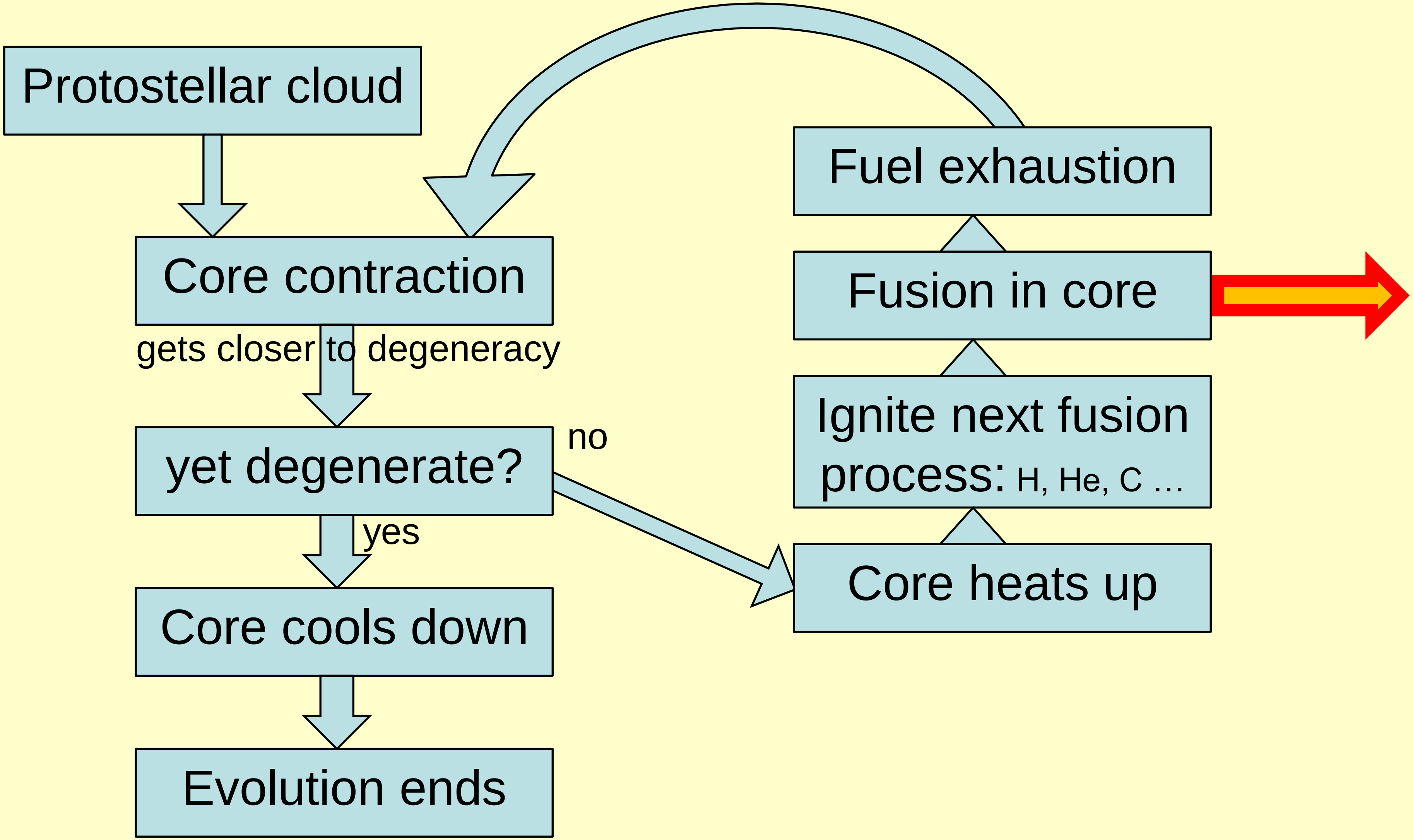
$$\frac{\dot{T}}{T} = -\frac{\dot{R}}{R}$$ contraction ➔ core heats up

- Completely degenerate gas (non rel.)
  $\alpha = 3/5$ $0<\beta<<1$:

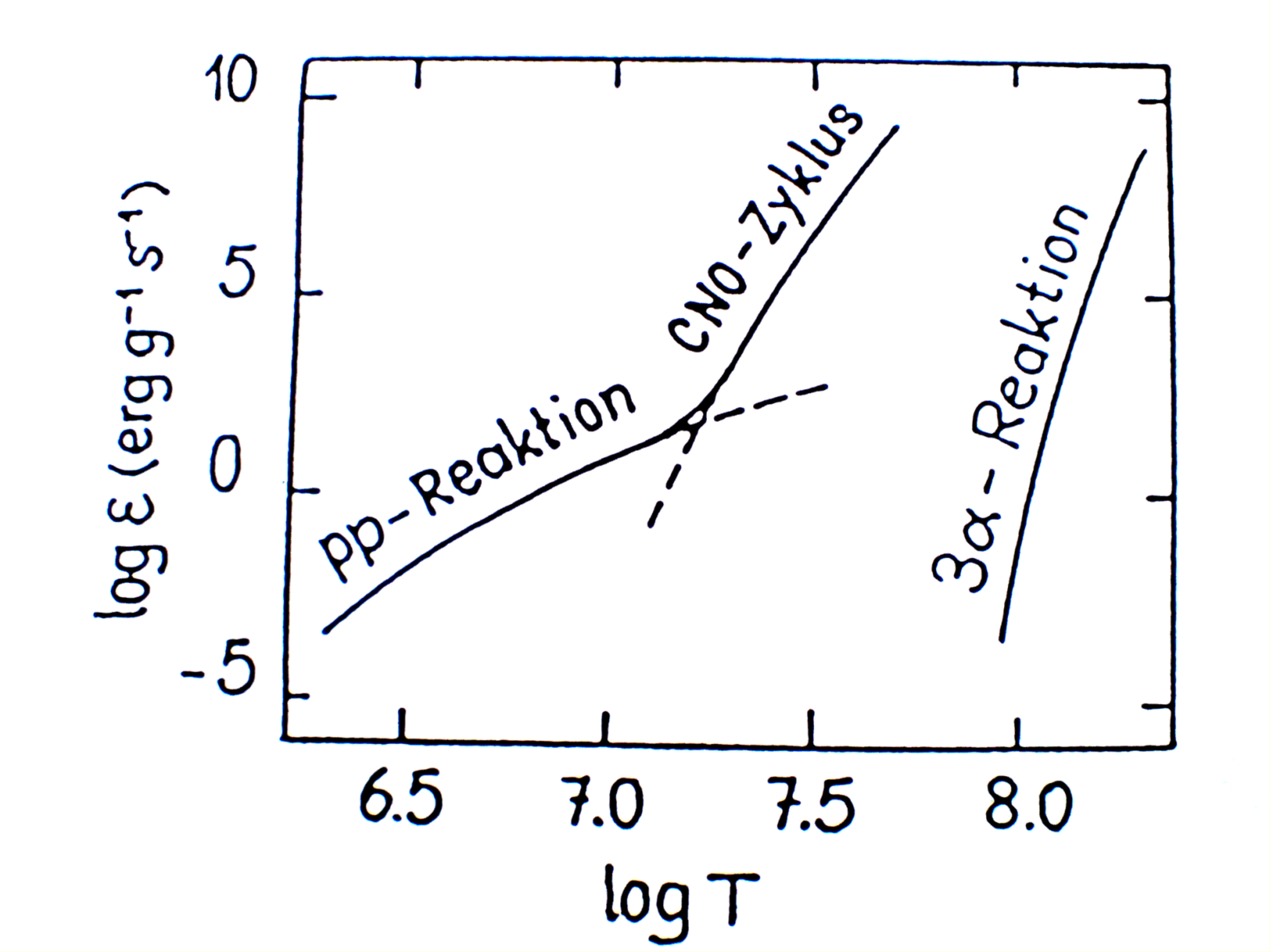
$$\frac{\dot{T}}{T} = +\frac{3}{5\beta}\frac{\dot{R}}{R}$$ contraction ➔ core cools down

{This condition is already reached at some value of $\psi \sim \ln E_f/kT$, long before complete degeneracy!}

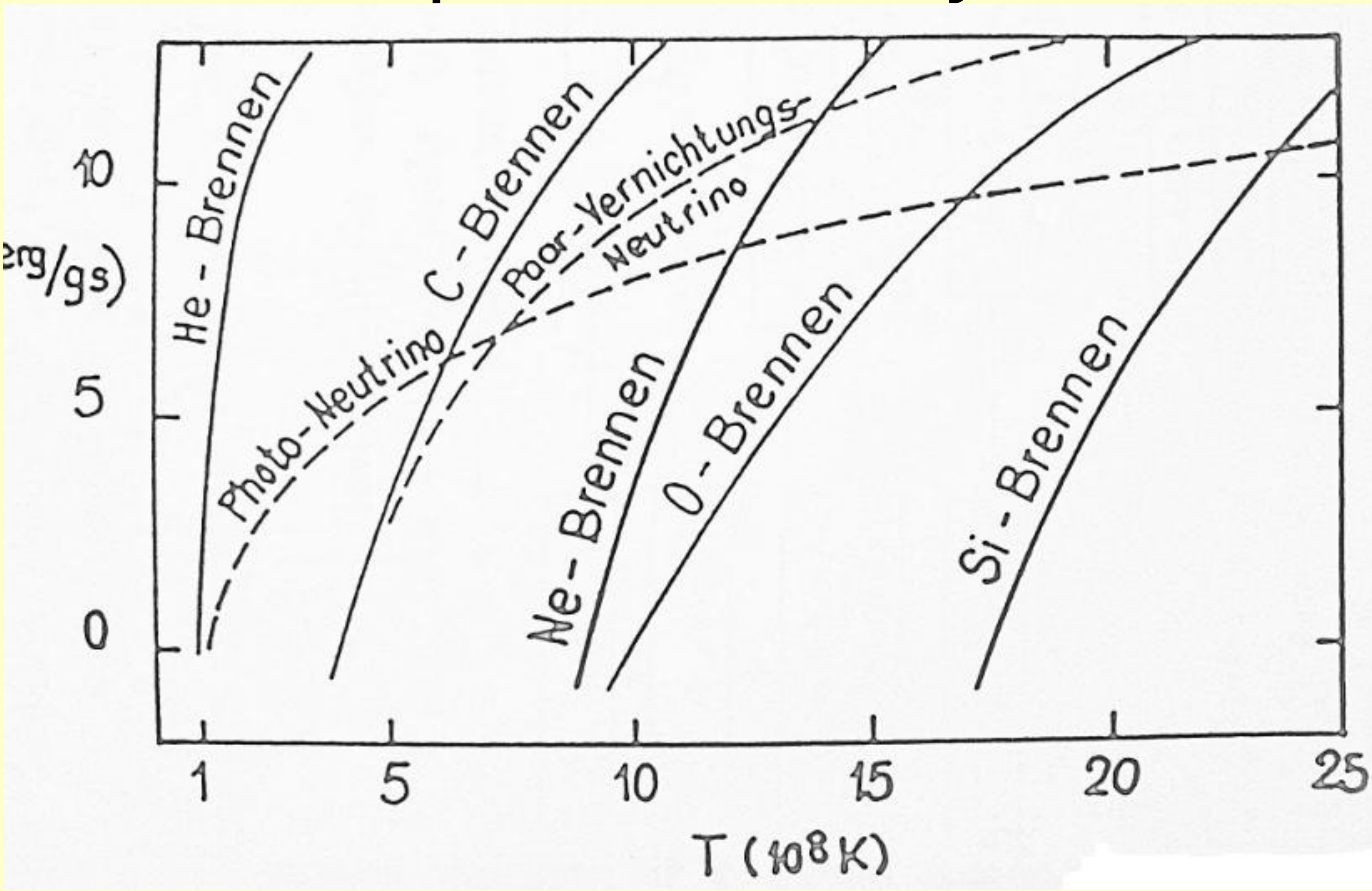
# Behaviour of the central region:



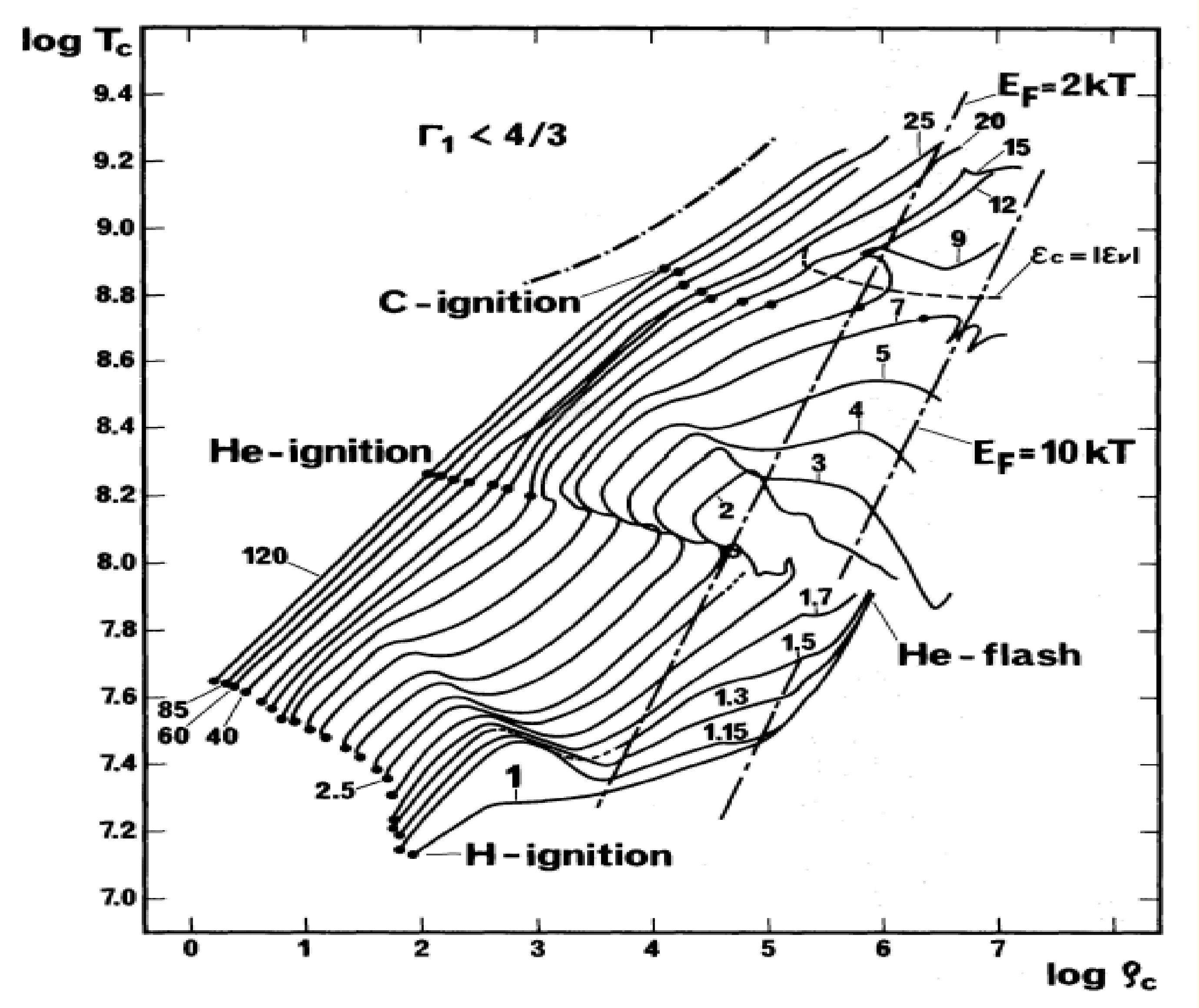
# The H,He-burning processes



# Fusion processes beyond He



# Situation in the core



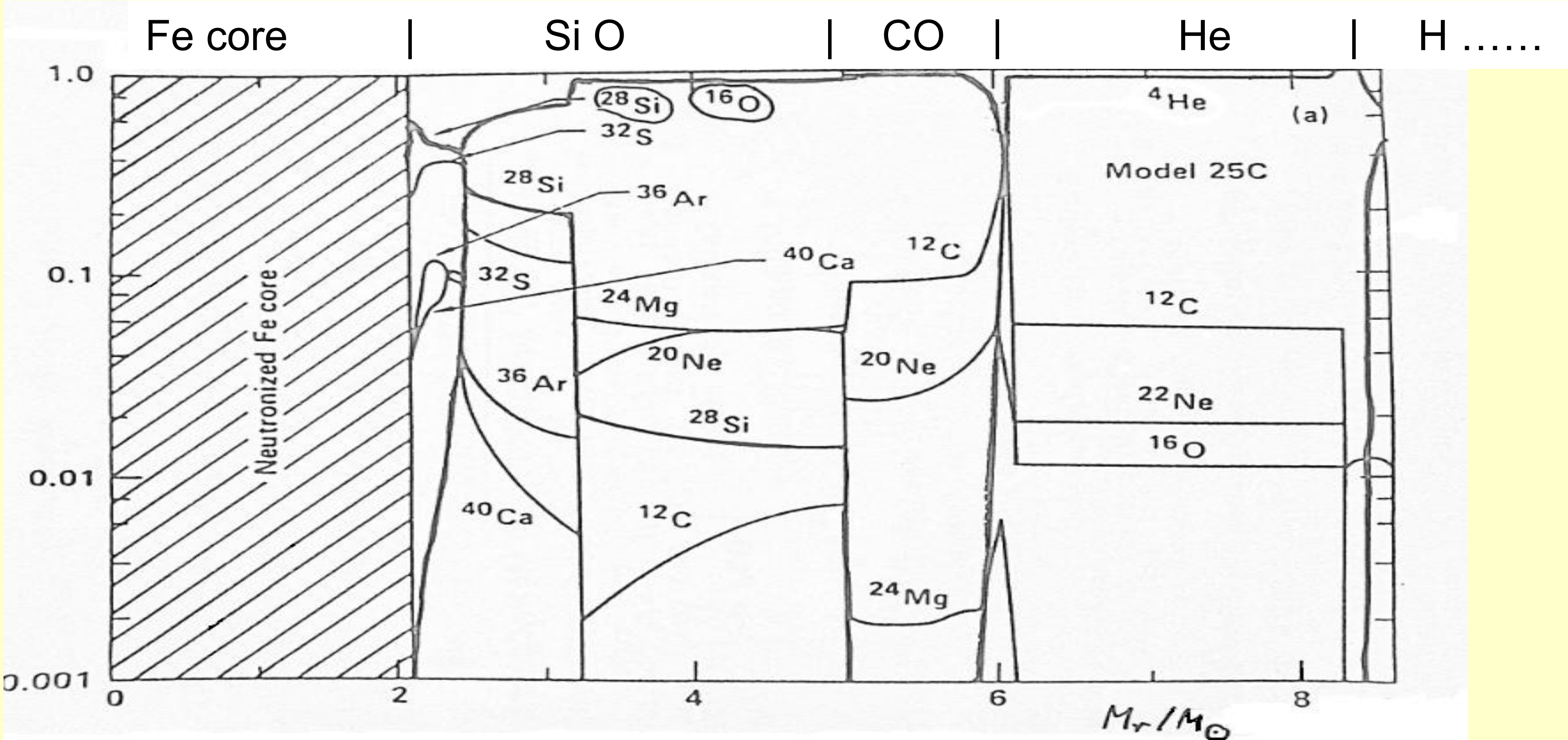

The smaller its mass, the closer a star is to degeneracy, the fewer burning phases it has:

| | |
|---|---|
| M < 0.08 | no H burning |
| M < 2 | no He burn. |
| M < 9 | no CO burn. |

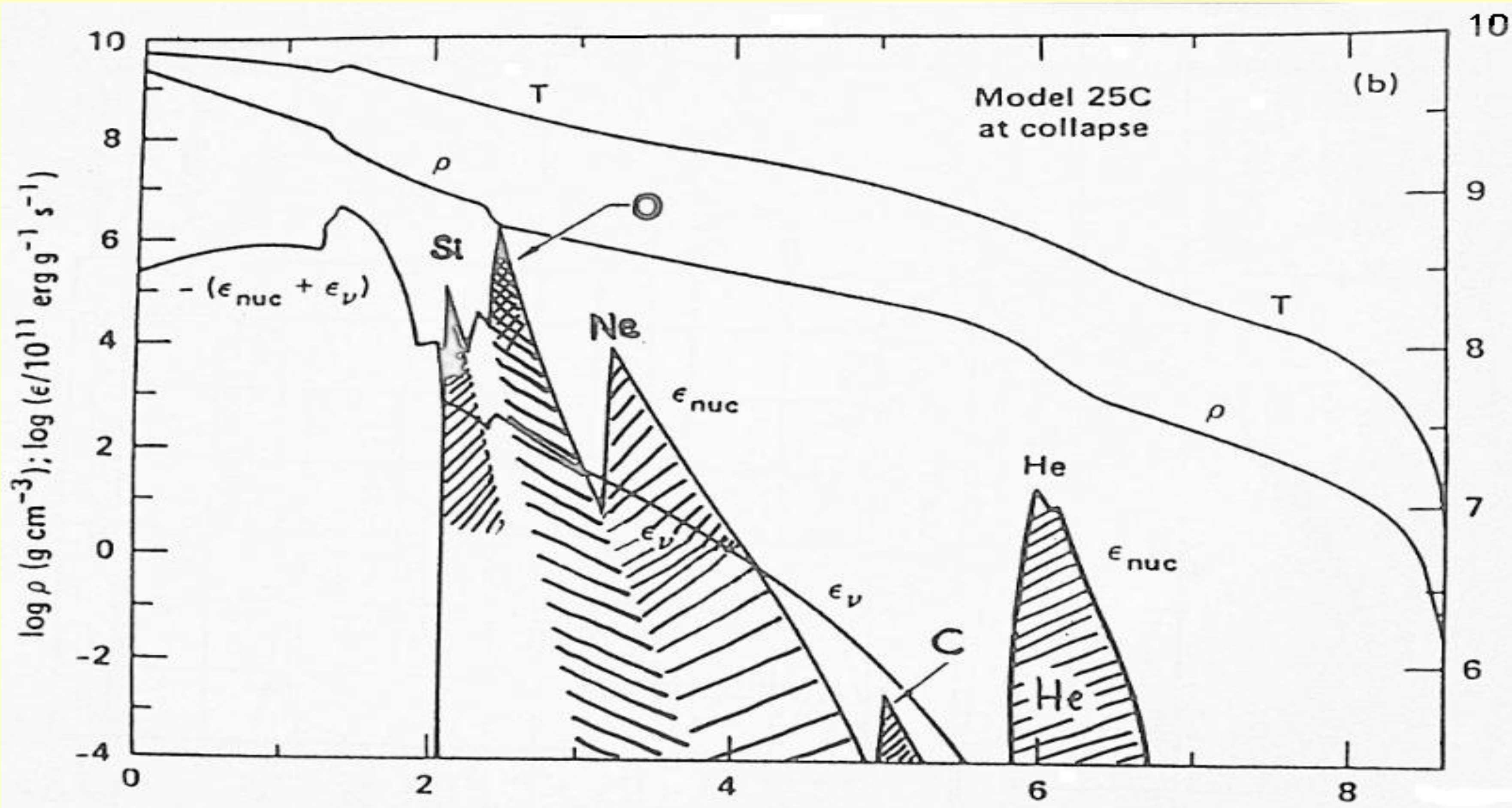
Maeder 1989

# Massive stars (M >10 $M_{sun}$)

- Do all burning phases (H, He, … Si→Fe)
- Onion-shell structure + shell sources



# Shell sources in M=25 Msun



# Massive stars: final fate

After end of Si→Fe burning:

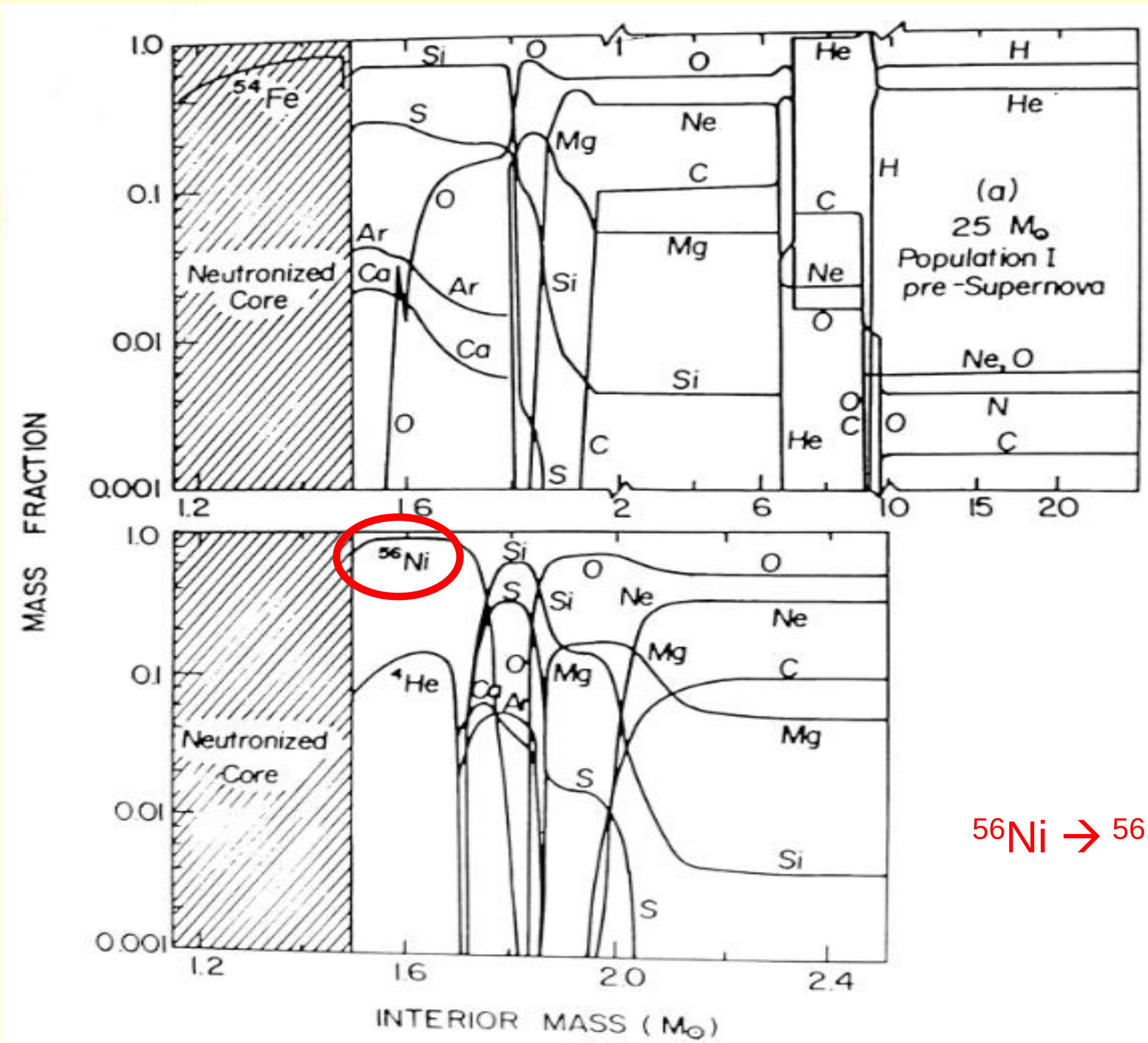
- Collapse of Fe core
- Collapse of envelope

} 0.3 s { $\rho \sim 10^{11}$, $\tau_{FF} \sim 0.04$ s

→ kinetic energy $10^{51}$ erg

- Bouncing of envelope at centre: shock wave thru envelope → compresssion → ignition of fusion reactions
- = supernova explosion
  - Rapidly expanding envelope
  - Explosive nucleosynthesis in envelope
  - Collapse of core: neutron star/black hole

# Explosive fusion



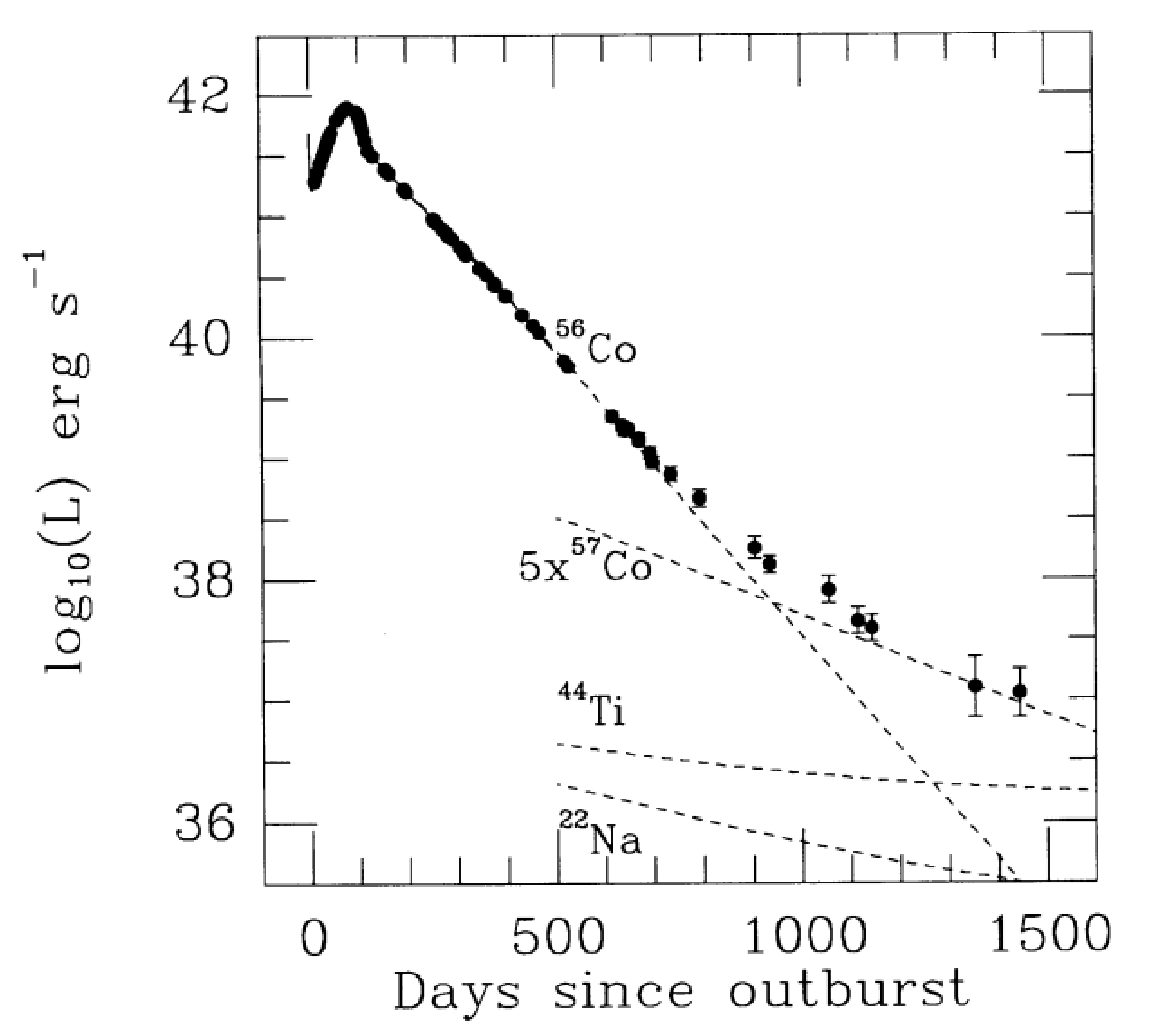

before

after

$^{56}$Ni → $^{56}$Co  half-life 6d

Woosley+Weaver 1982

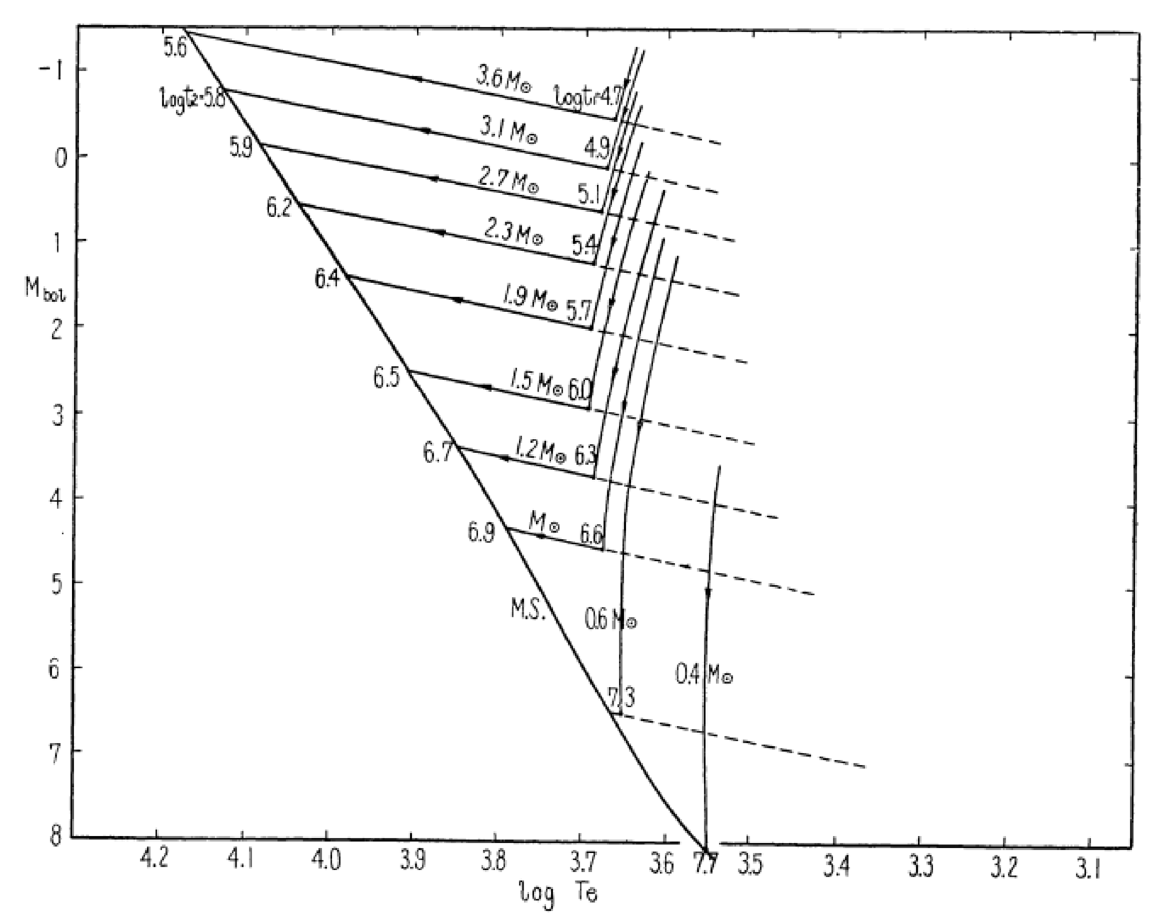
# Light curve of SN1987A




$^{56}Co \rightarrow {}^{56}Fe$ half-life 77d

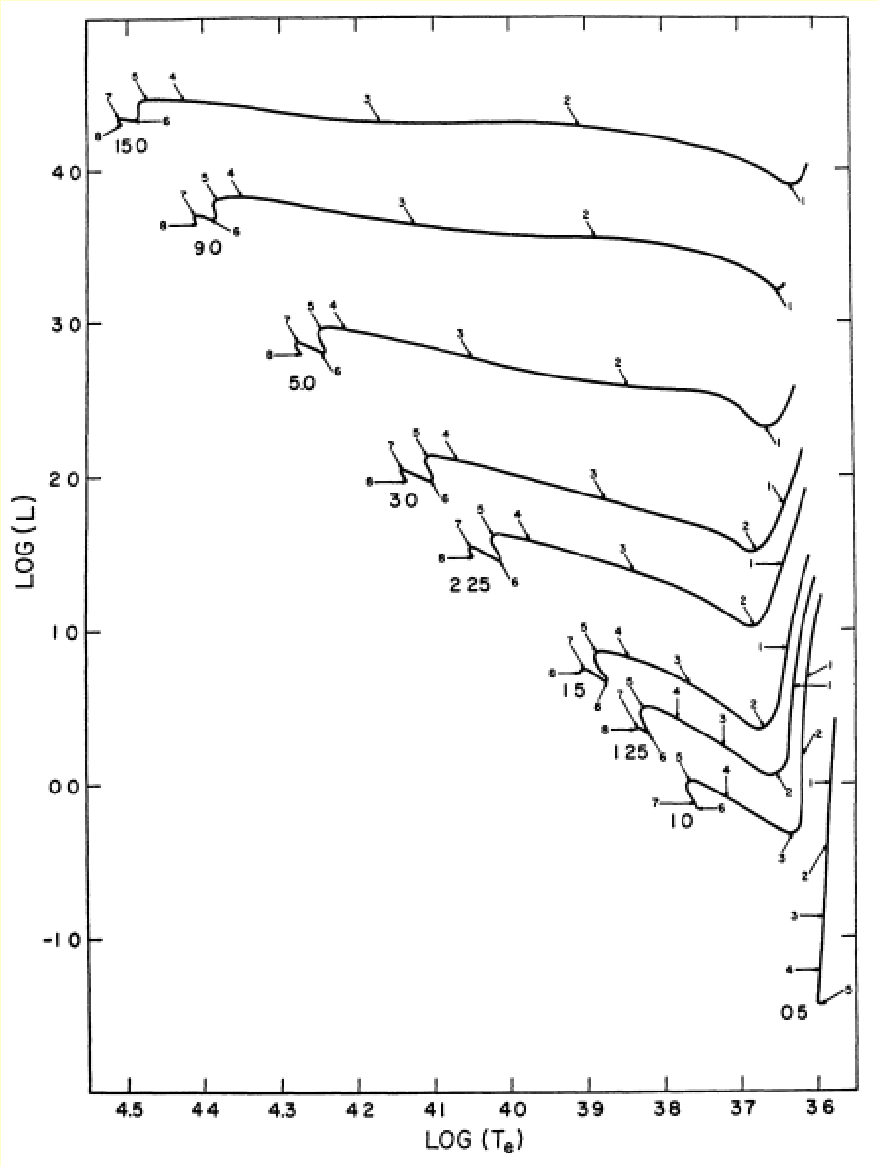
# Hayashi line/tracks

- Locus in the HR diagram of all completely convective, hydrostatic stars of the same mass and composition
- The low-T limit of hydrostatic stars: Any star cooler will evolve within ~100 d towards HL ➔ stars can exist below HL for transitory phases only
- Examples
  - Protostellar collapse
  - HL is limit for giants




Hayashi 1961

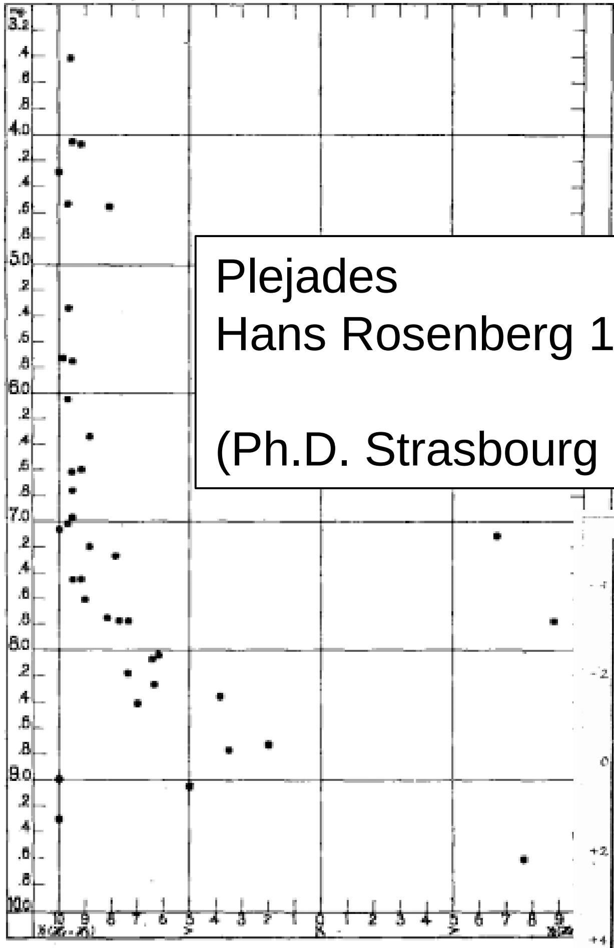
# Protostellar evolution tracks




Iben 1965

# Evolution after Main Sequence

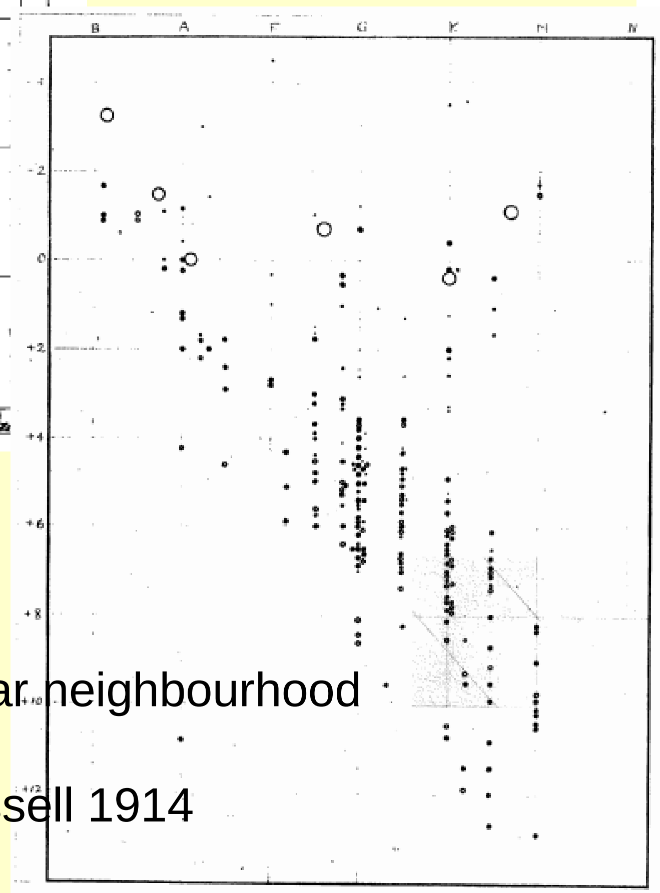
# first HRDs



Plejades
Hans Rosenberg 1910

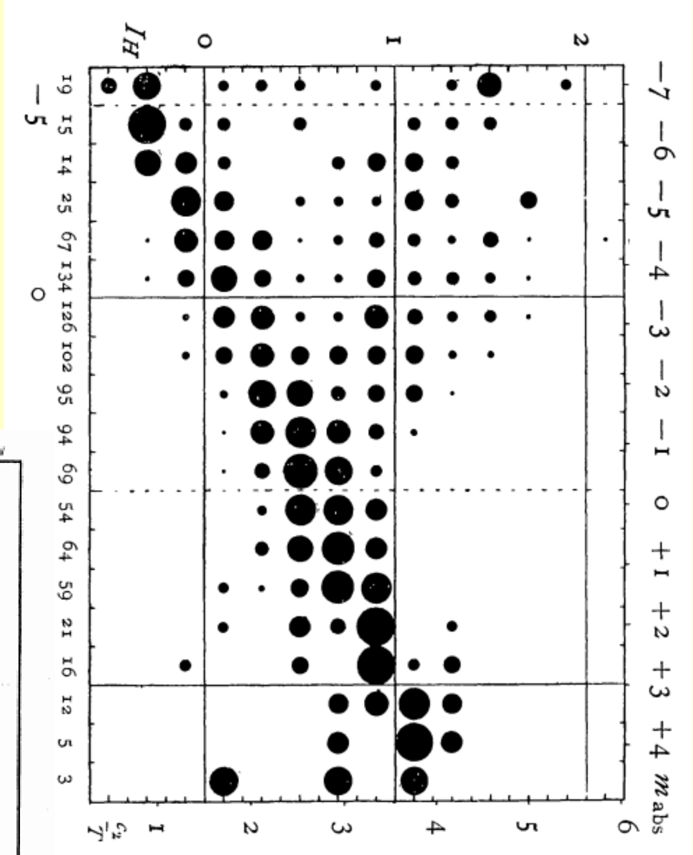
(Ph.D. Strasbourg 1902)

ratio CaII K / Hδ+Hζ →



Solar neighbourhood

Russell 1914

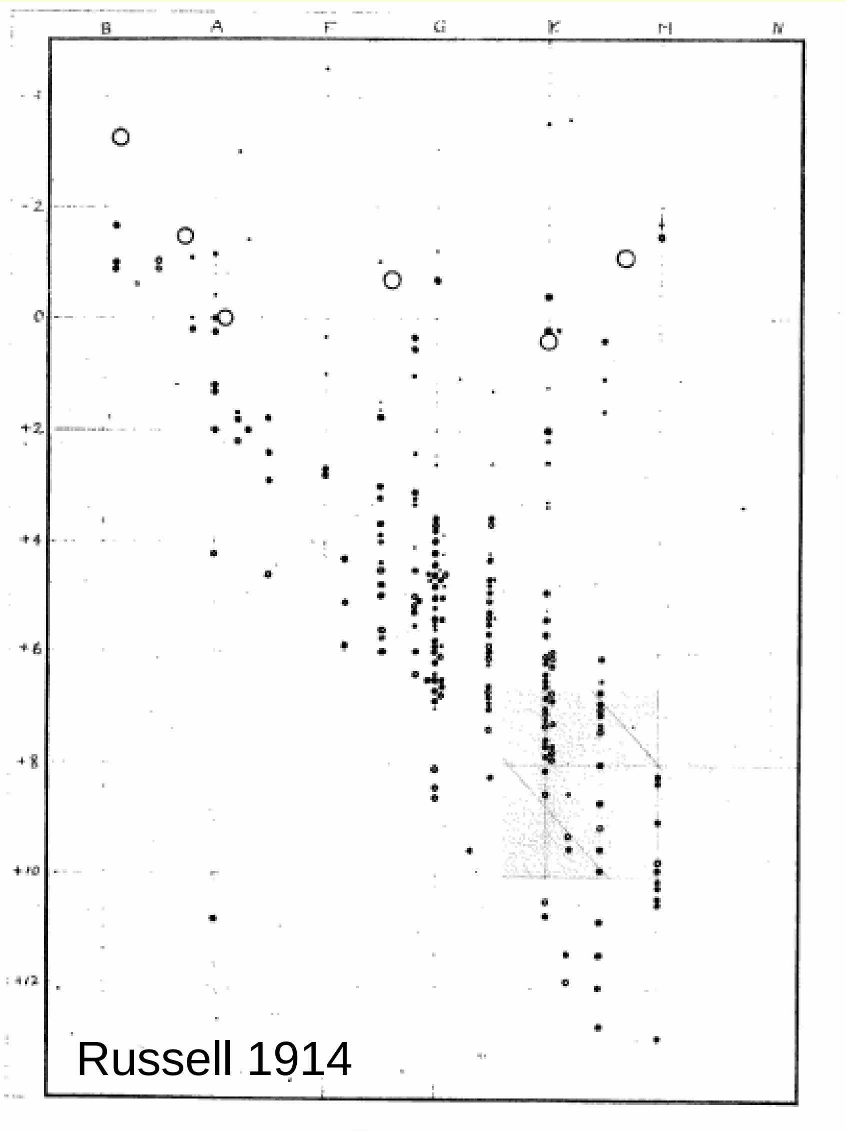


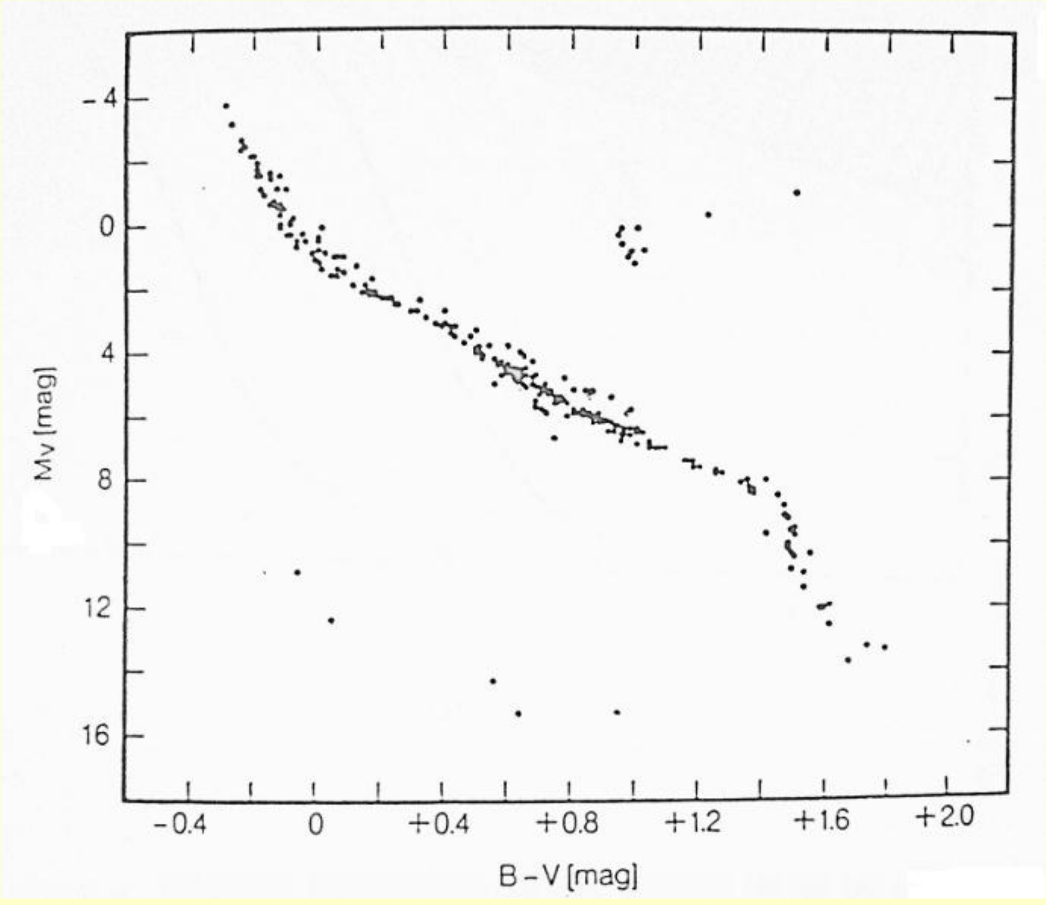
Colour index →

Solar neighbourhood

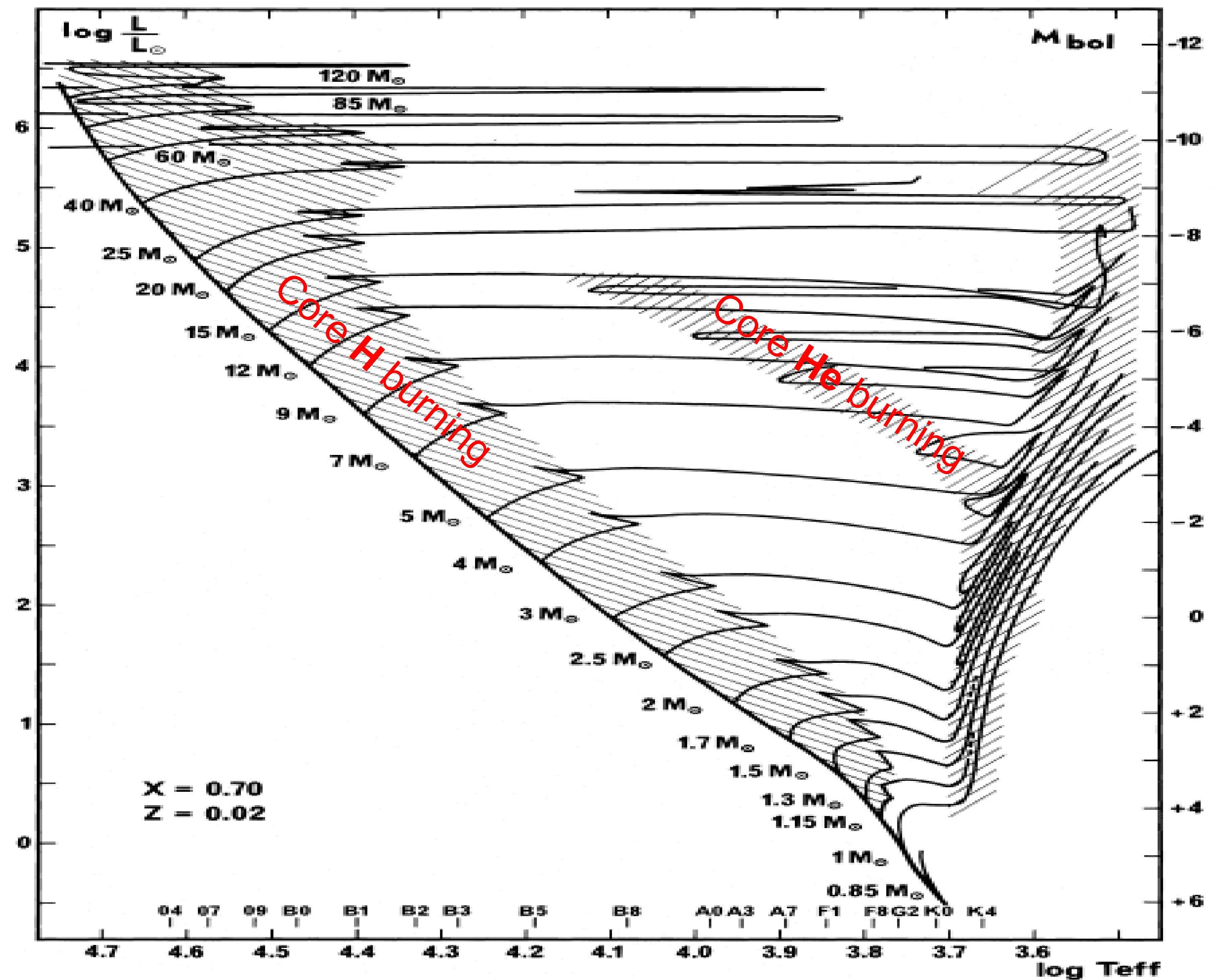
Hertzsprung 1922

# HRD and CMD solar nh'd



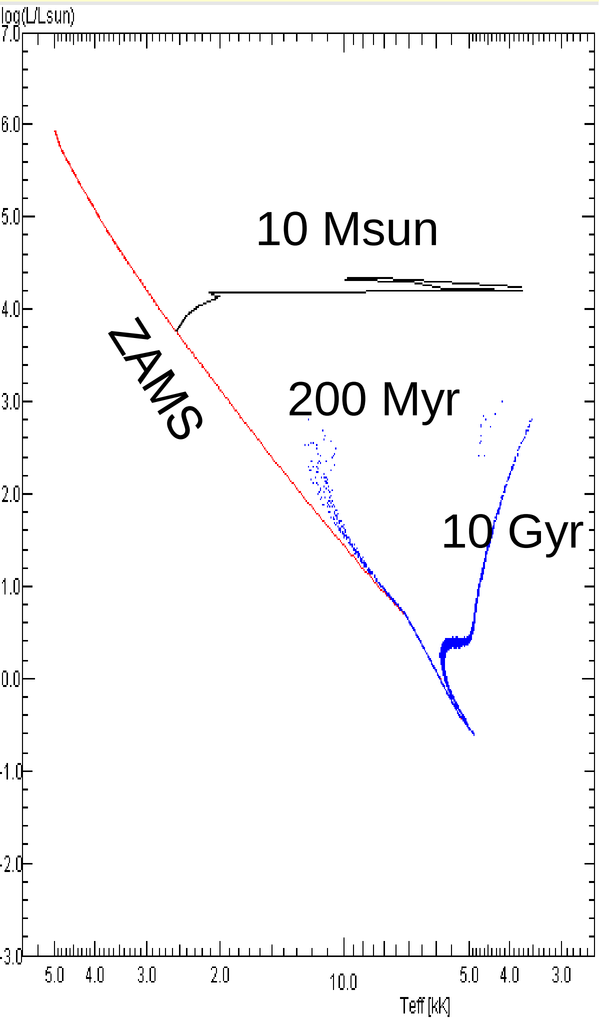
# HRD evolutionary tracks



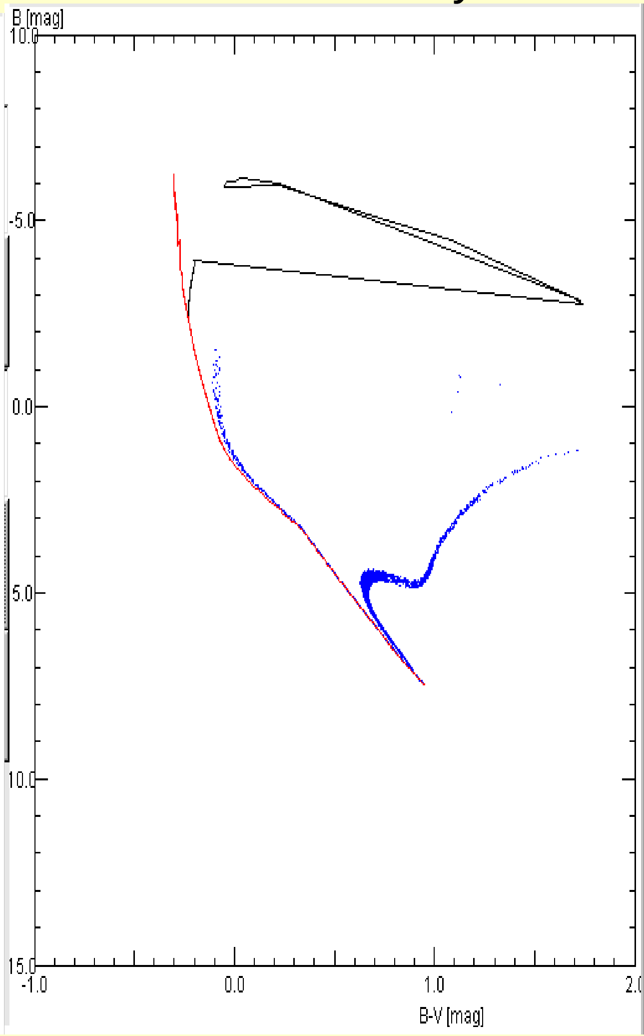

Maeder 1989

# HRD – CMD – HRD

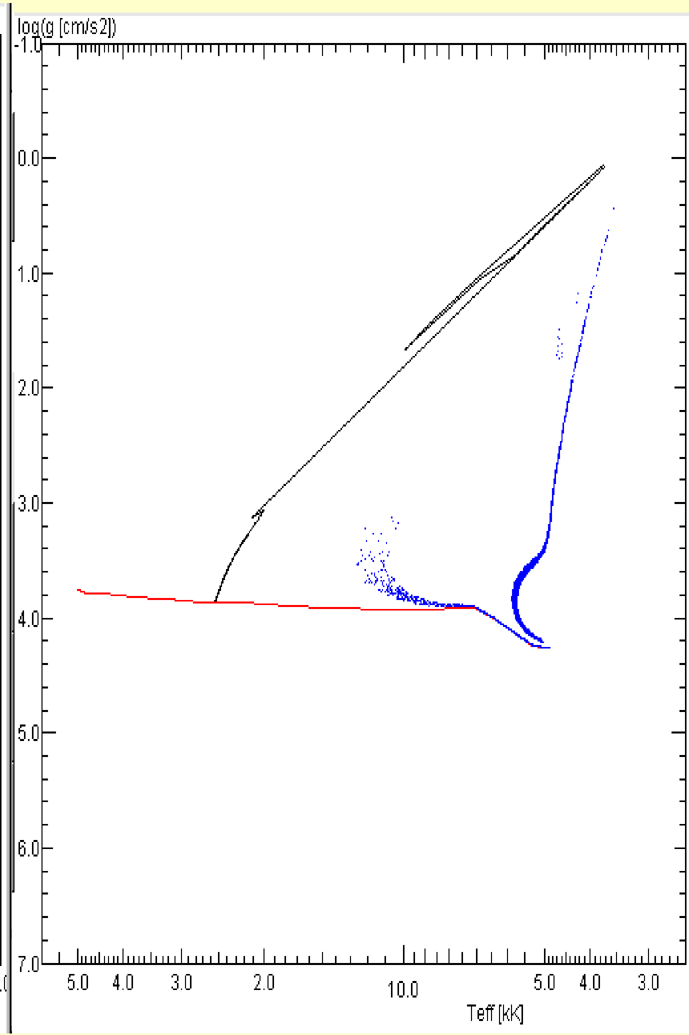
Theory



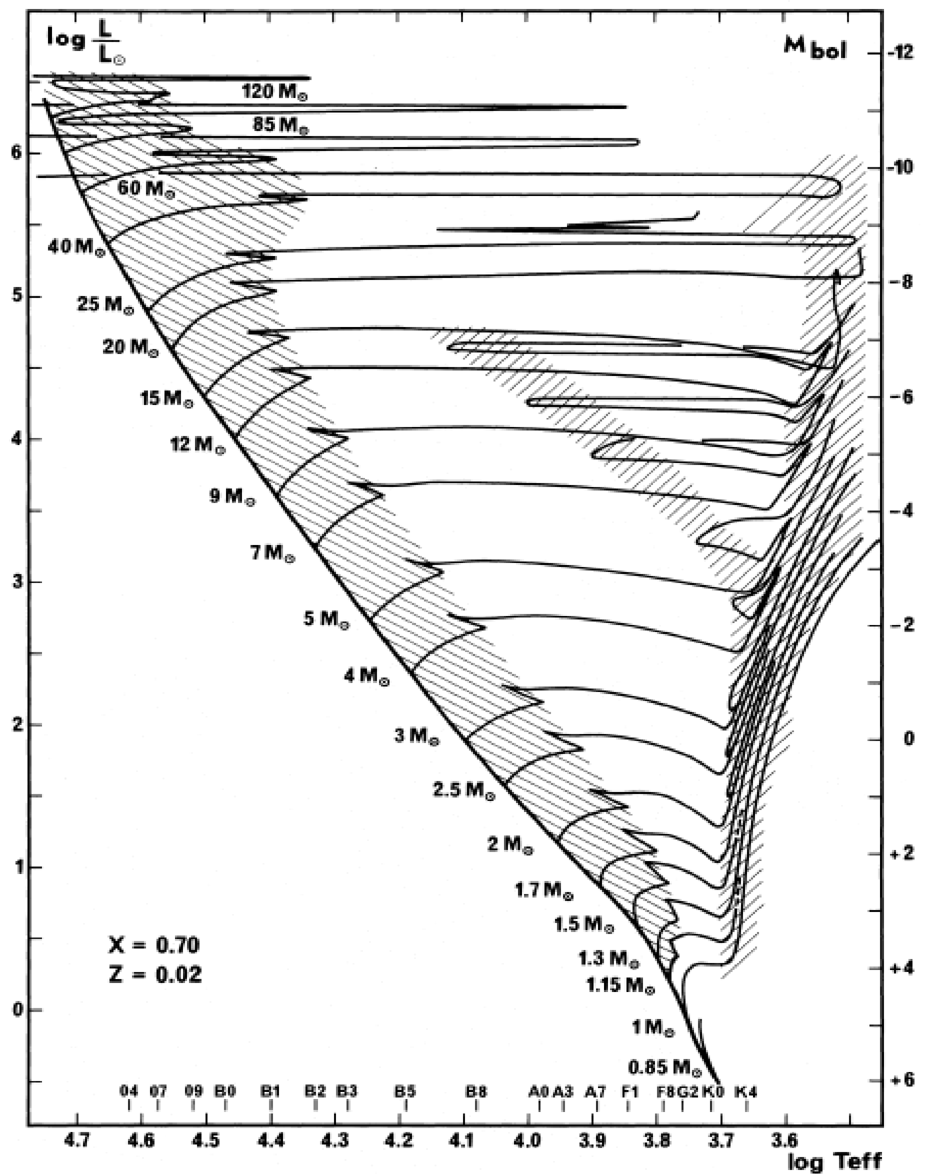

Photometry

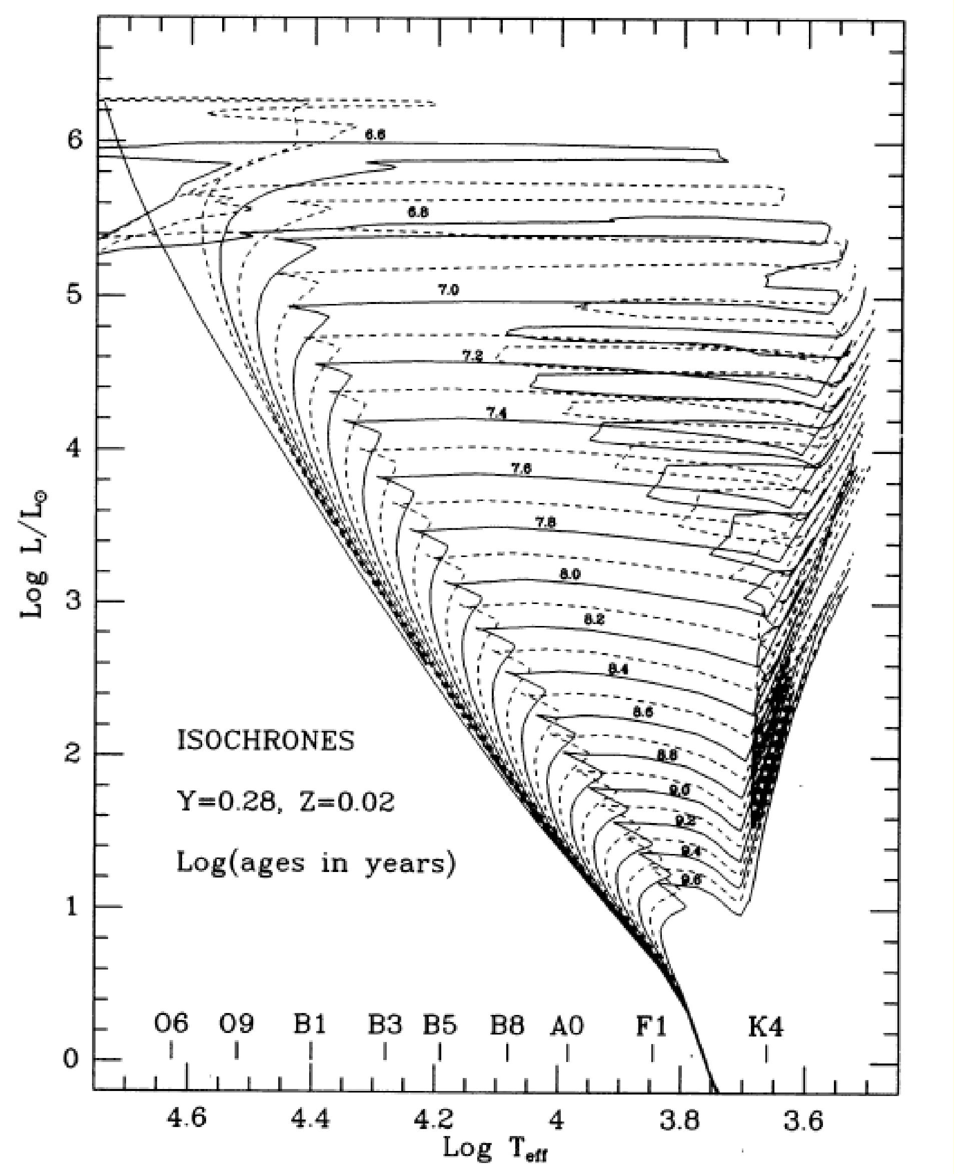



Spectroscopy



# Evol.tracks & isochrones



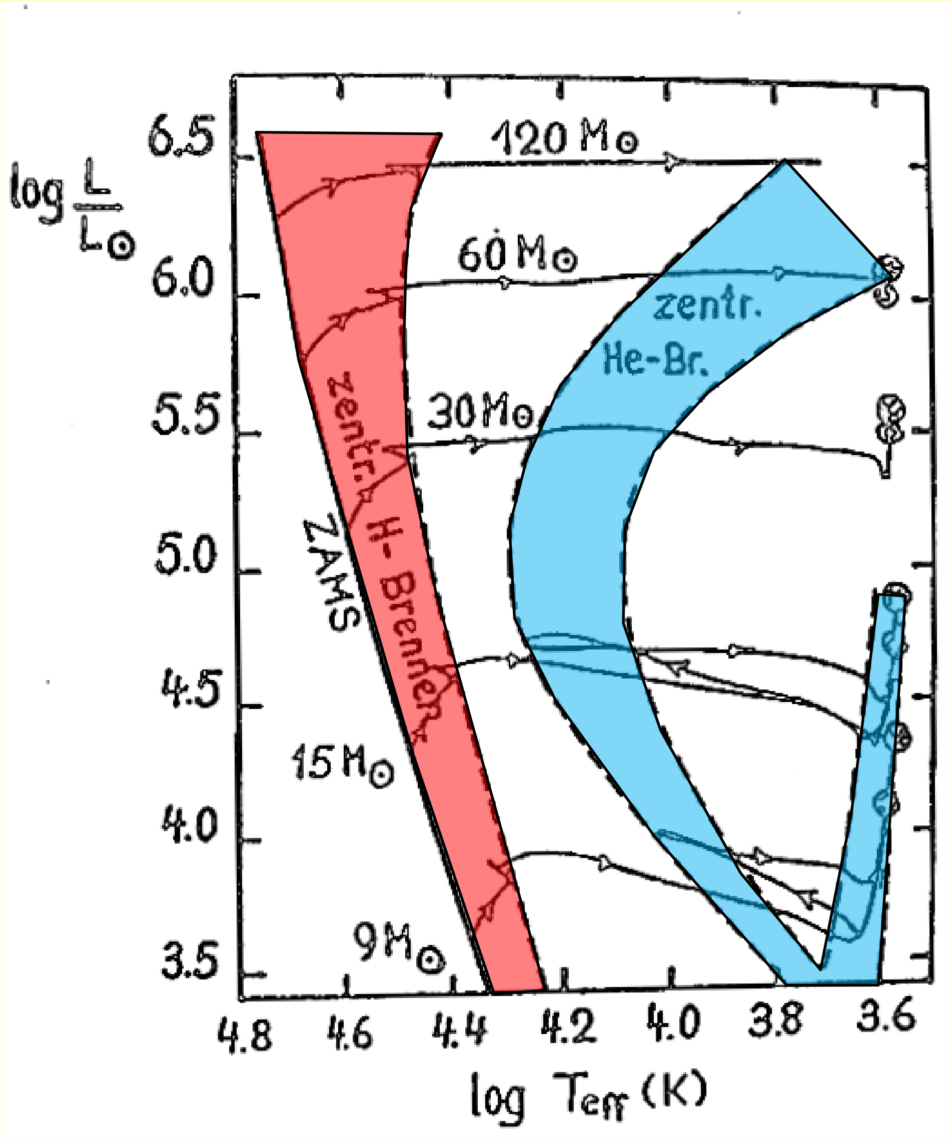



# Evolution: massive stars

- rapid evolution to the ‘right’ in the HRD
- Further burning phases are short
  - He: ~10 … 20% of MS-lifetime
  - C: ~100 yrs
- Strong stellar winds (driven by radiation pressure of hot+luminous stellar atmosph.) modify evolution strongly:

  $|\dot{M}| \approx 10^{-6}$ $M_{sun}$/yr $\tau_{MS}$ ~ 3..10 Myr ➔ star loses 3 … 10 $M_{sun}$
- Rotation

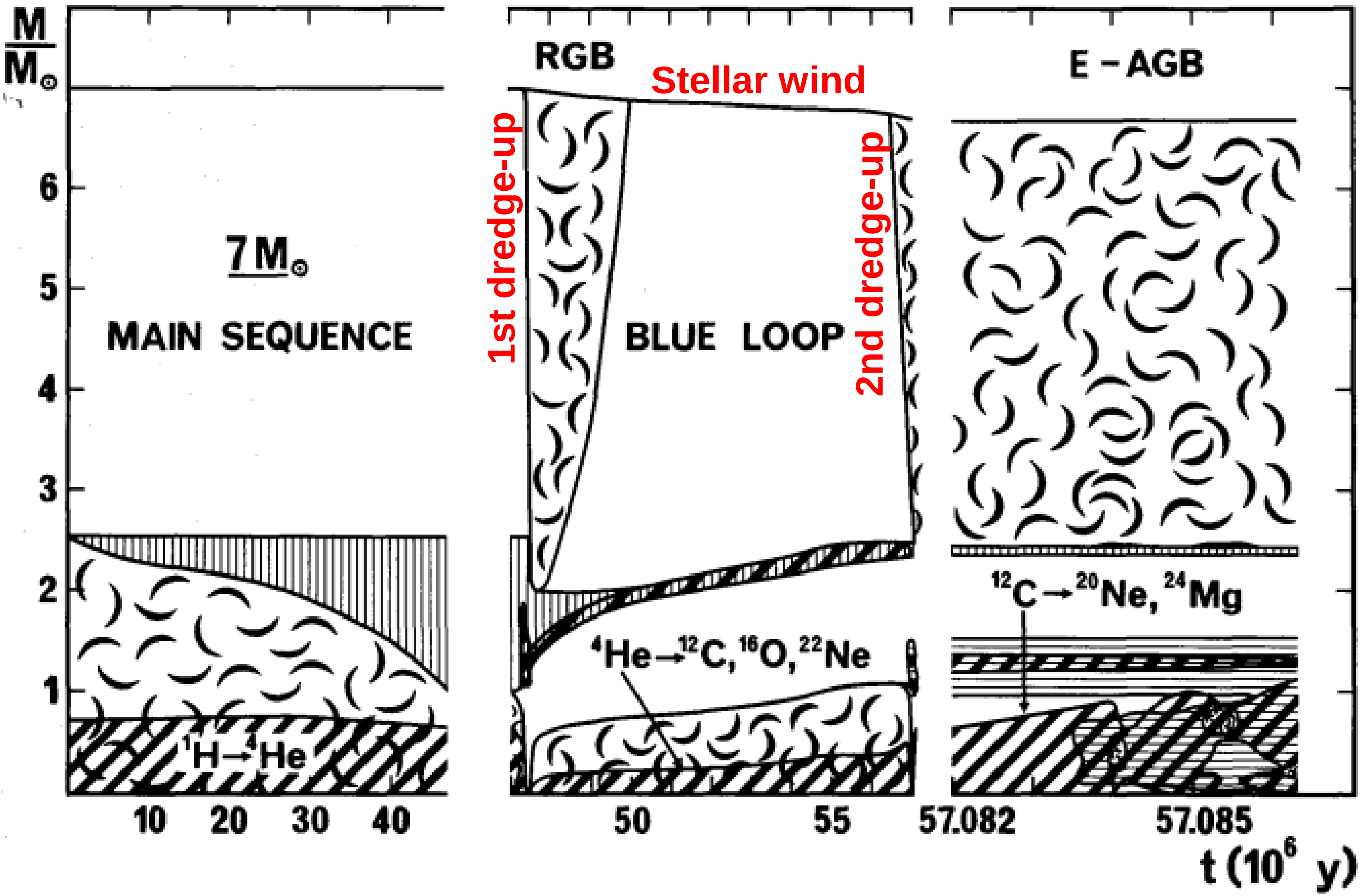
# Evolution: massive stars



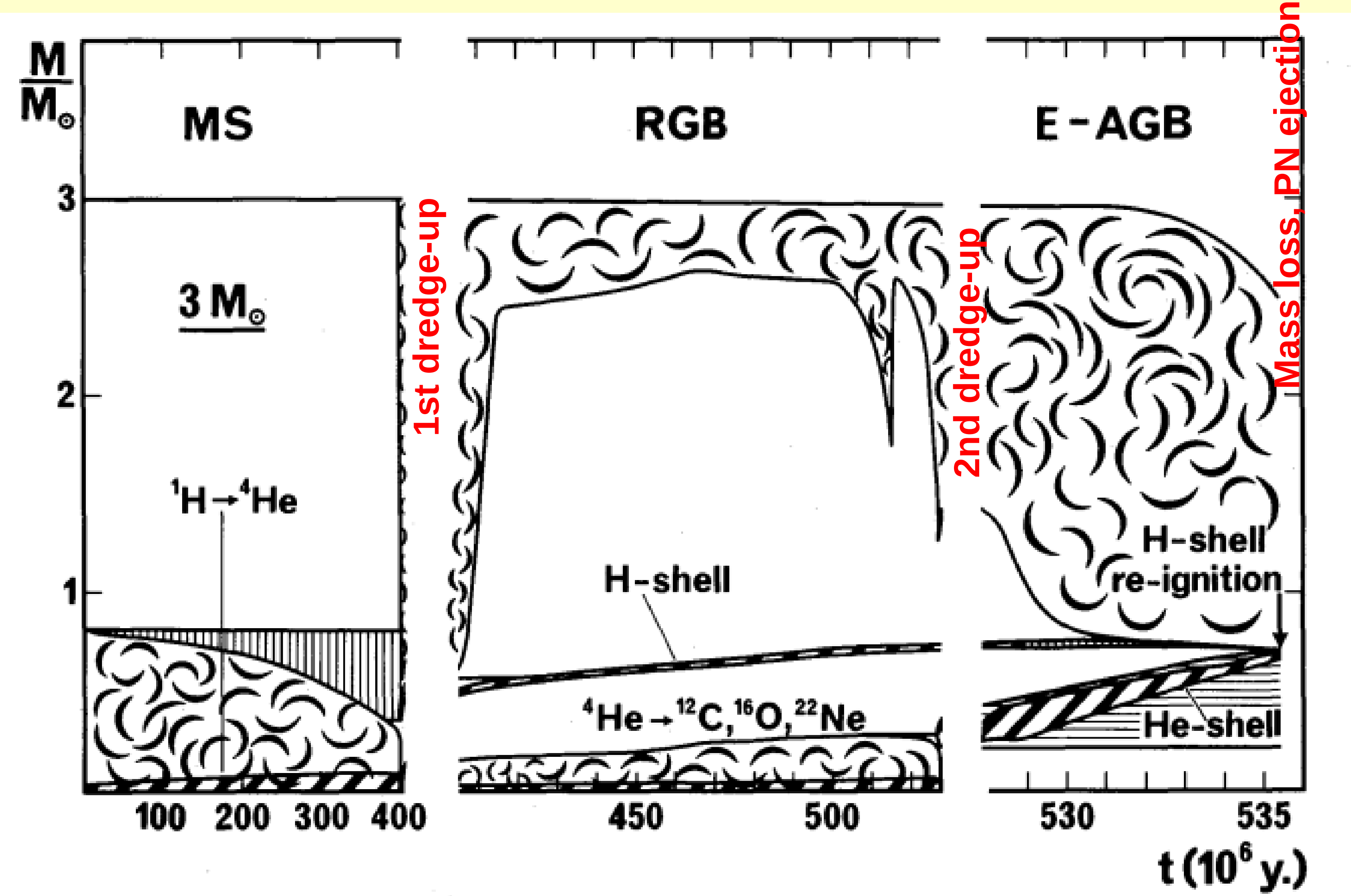
# Intermediate mass stars (3..8 Msun)

- Core H exhaustion: core contracts & envelope expands
- Shell H burning
  - convection zone comes down (1st dredge-up)
  - move to Hayashi line = RGB
- Ascend on RGB
  - Mass loss (high L → radiatively driven wind)
  - At tip: core He-burning ignites

# Evolution of 7 Msun star



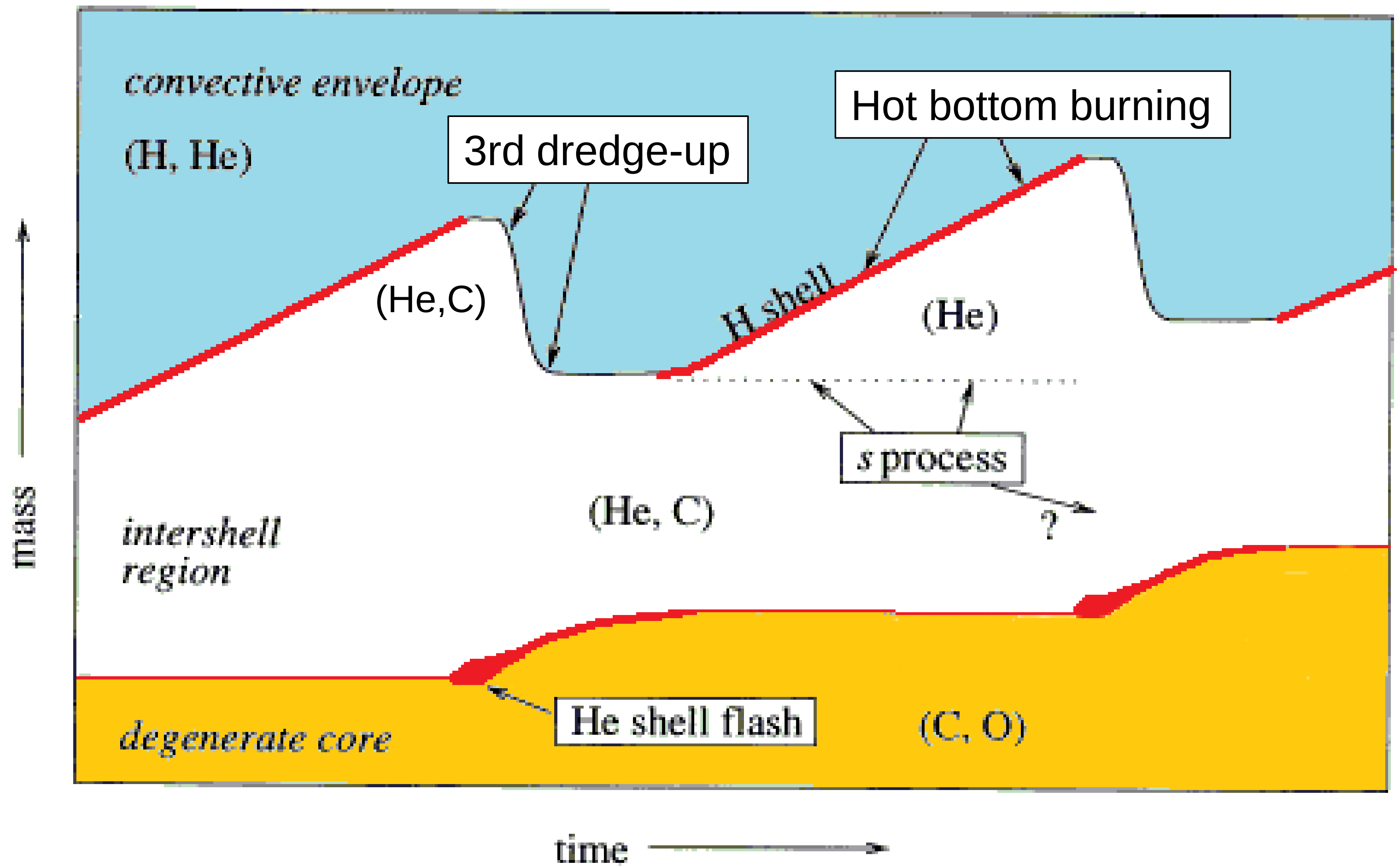
# Evolution of 3 Msun star



# Intermediate mass stars (3..8 Msun)

- Core expands & envelope contracts: **Blue Loop**
- back to Hayashi line = AGB
- Ascend on AGB
  - convection zone comes down (2nd dredge-up): brings down fresh hydrogen ➔ reignition of H-burning shell
  - mass loss
  - thermal pulses (TP) = instability of He-shell (shell flashes)

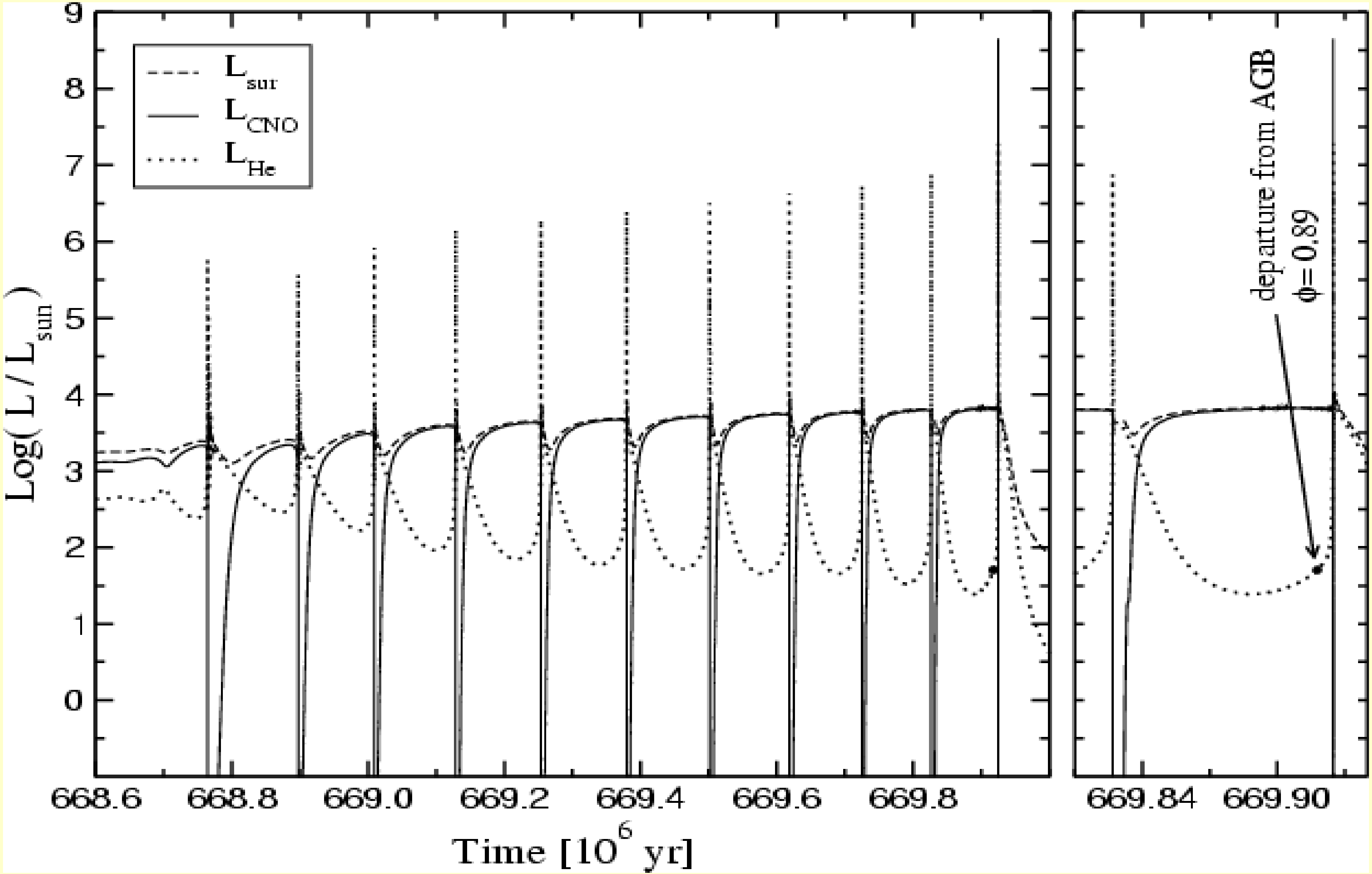
# Thermal pulses




after Pols et al. 2001

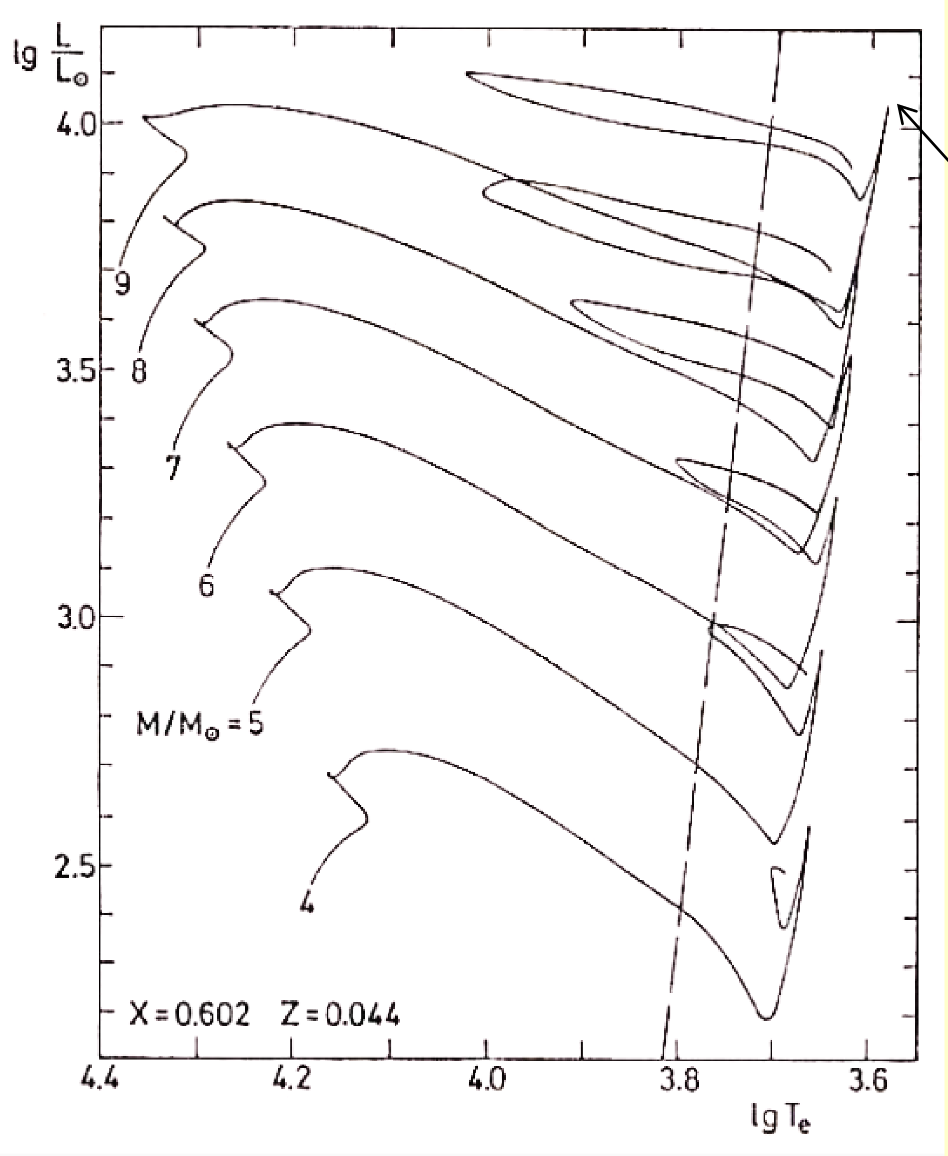
# Thermal pulses

(duration 10..100 yr, period $10^3..10^5$ yr)




Pols et al. 2001

# IMS evolutionary tracks




Ignition of central He-burning

Blue loops

# IMS evolution

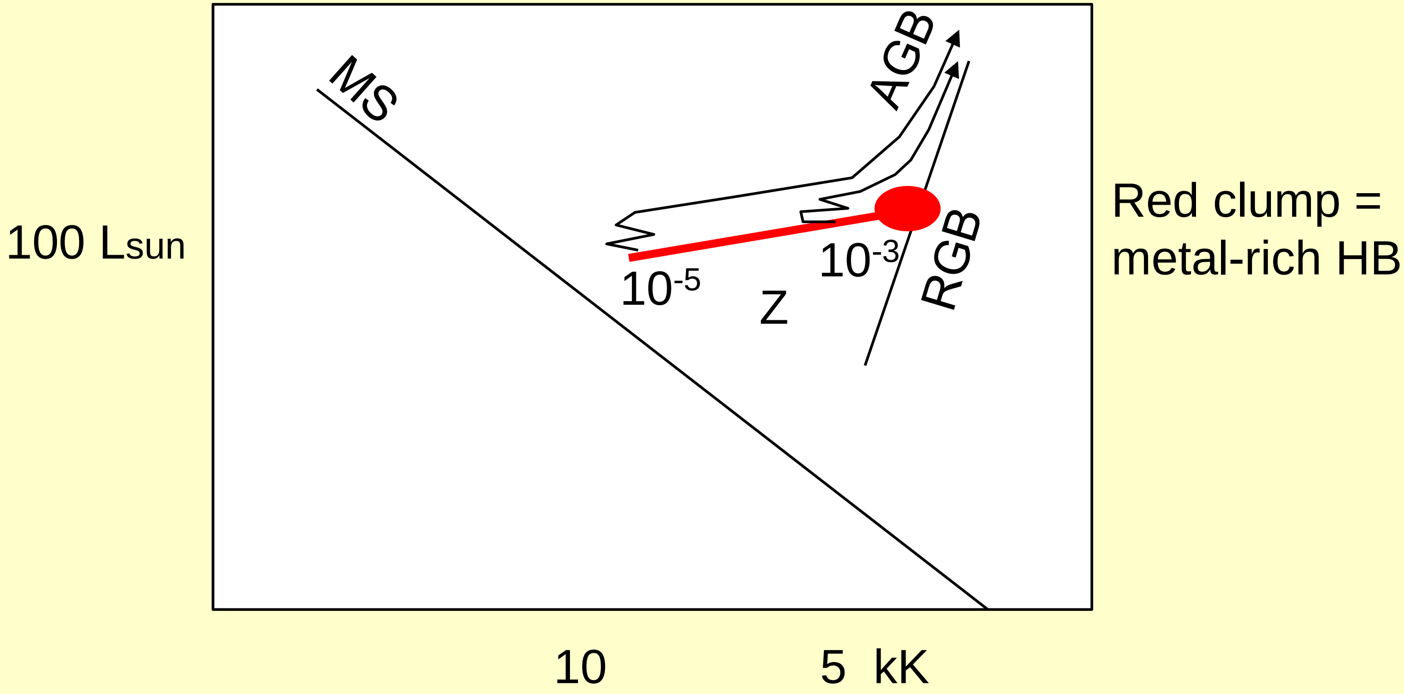
- Above ~5 Msun: Hot bottom burning: hot enough for CNO cycle → $^{12}C$ → $^{14}N$
- Final fate:
  - Short strong wind or expulsion of outer envelope → planetary nebula
  - Remnant star (CO core + $10^{-3}$ Msun H envelope) contracts at constant luminosity (core mass-luminosity relation) → T ~ $10^5$ K and ionizes nebula
  - Shell sources extinguish after ~30000 yr
  - Remnant star (= white dwarf) cools out ($\tau$ ~10 Gyr)

# Low mass stars (0.08 .. 3 $M_{sun}$)

- After core H exhaustion to Hayashi Line = RGB
- Ascend on RGB: at the tip if $M_{He} > 0.45\ M_{sun}$ ignition of He:
  - Degen.matter cannot compensate heat input by expansion ➔ T increases ➔ burning increases: thermonuclear runaway = **core He-flash** (timescale ~hours)
  - T increases until degeneracy is overcome: He burns steadily
  - He-burning shell eats down into core (~$10^5$ yrs) ➔ core He-burning (**Horizontal branch**)

# Horizontal Branch stars

- Position depends on chemical composition and on 2nd parameter (age, core mass …)

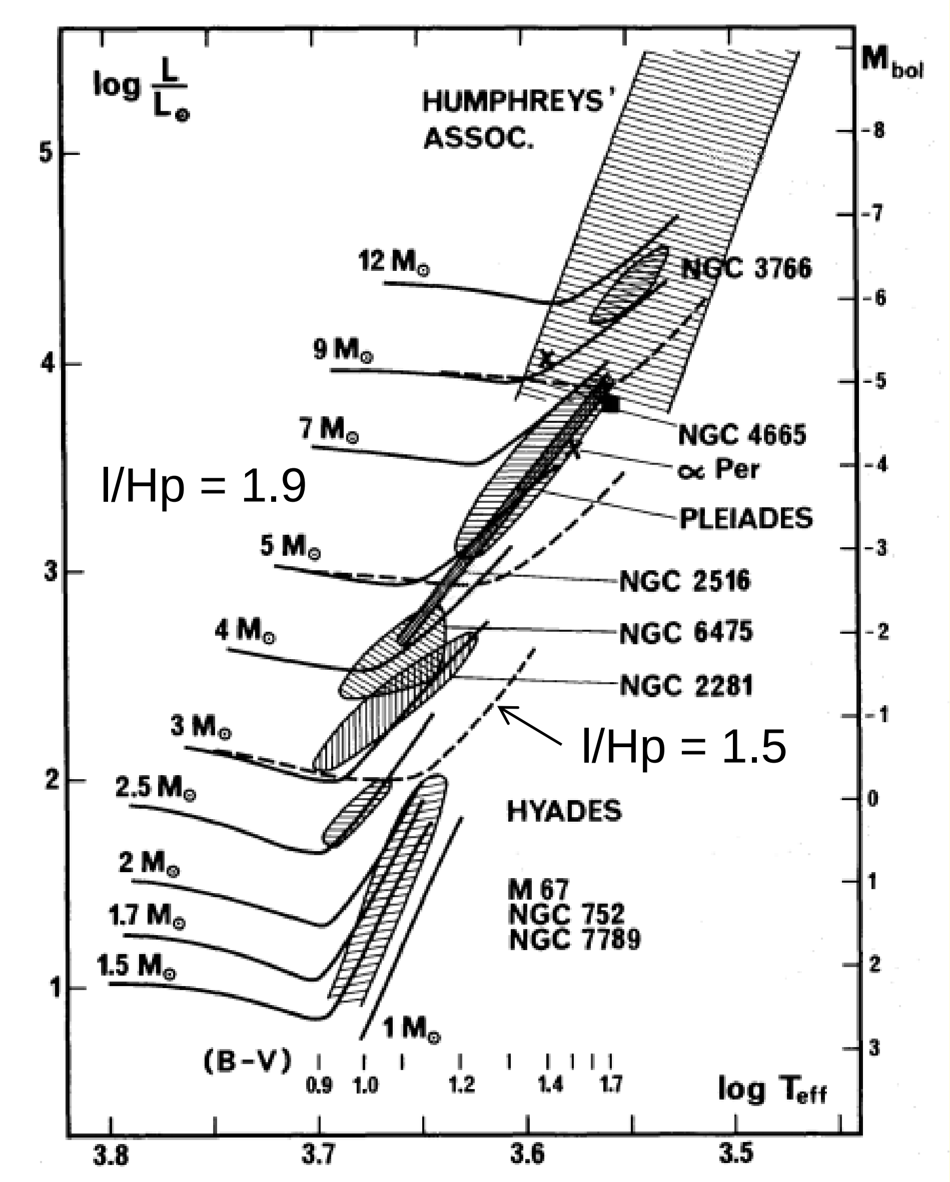



- Exhaustion of core He supply → AGB (but without 2nd and 3rd dredge-ups)

# Problems & difficulties

- Opacities:
  - need absorption cross sections from all levels of all ions of all elements (OPACITY Project)
  - Summation over all relevant levels
- Energy production rates: 1982 rate for $^{12}C(\alpha,\gamma)^{14}N$ increased by factor 3..5
- Equation of state: difficult at high T and $\rho$ (missing energy levels, atoms change structure due to vicinity of other atoms)

# • convection




No physical theory available

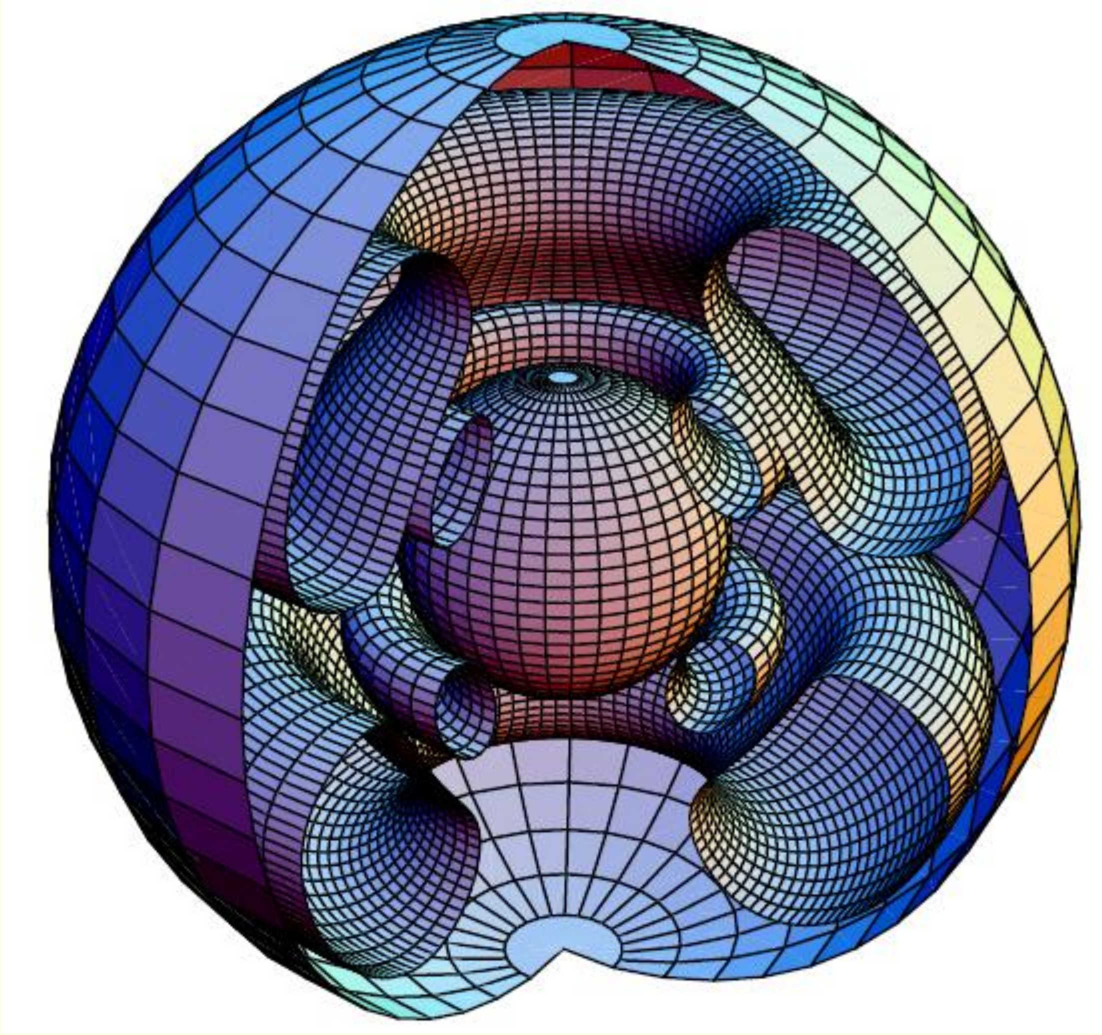
Use simple approaches (mixing length 'theory') and adjust their fudge parameters (mixing length l/Hp)

Use formulae derived from numerical simulations of convection (now possible in 3D)

# Problems & difficulties

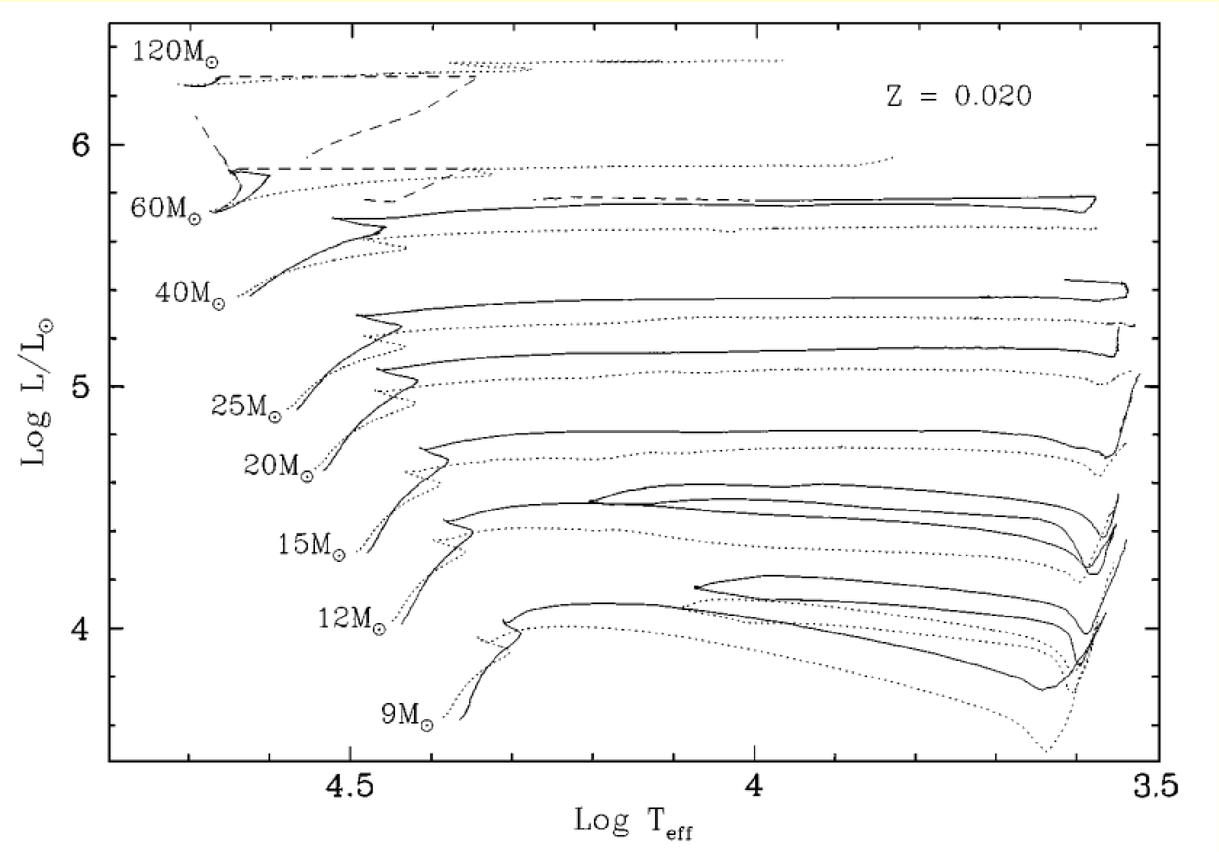
- Stellar winds (recipes from observations or theory)
- Dynamical phases (He-flash, TP, PN, **SN**)
- Double stars (mass transfer, SN Ia)

# • Rotation



- 3D models necessary; now possible
- Large scale mixing effects (Meridional circulation, various instabilities, …)

Meynet+Maeder 2002

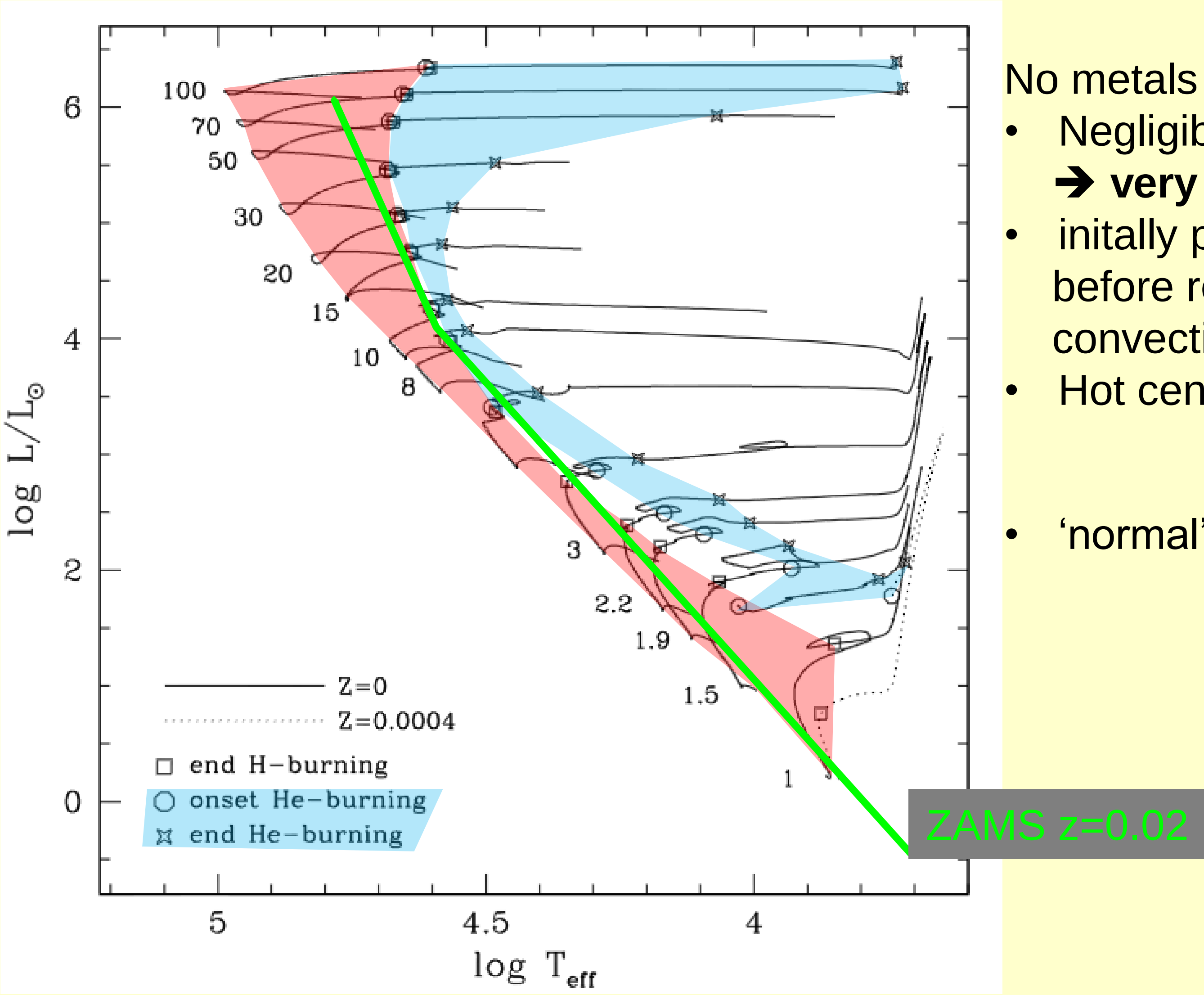



….. non-rotating
___ rotating (300 km/s)

- Consequences of internal mixing
  - Slightly longer MS life times (20…30%)
  - Nucleosynthesis (‘primary N’ in very fast rotators … cf. later!)

Meynet+Maeder 2002

# Zero-metallicity stars (**Pop. III**)




Marigo 2001

No metals ➔

- Negligible radiation pressure
  ➔ **very massive stars** >100 Msun
- initally pp-chains, He3α sets in before reaching RGB, CNO cycle, convective core.
- Hot centre+low opacity: high $T_{eff}$
- ‘normal’ lifetimes ($L \propto M$)