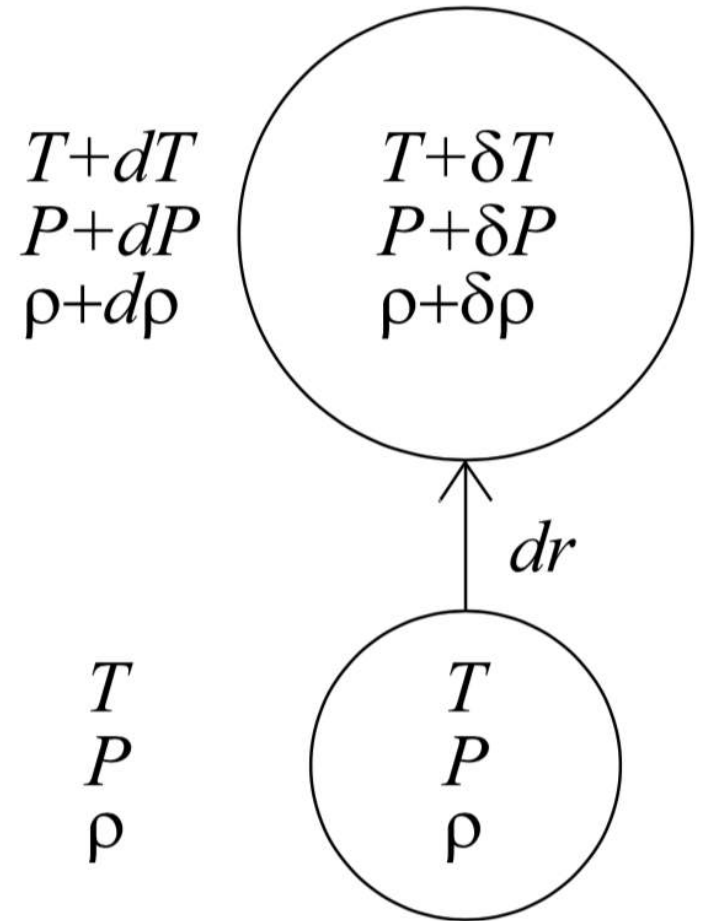# Convection

▸ Hydrodynamic instability that transports mass & heat

▸ Driven by buoyancy

▸ Convectively unstable if mass element displaced upward from equilibrium wants to continue to rise (i.e., less dense than surroundings after coming into P eq.)

$T+dT$
$P+dP$
$\rho+d\rho$

$T+\delta T$
$P+\delta P$
$\rho+\delta\rho$

dr

T
P
ρ

T
P
ρ

Convection criterion

▸ For ideal gas, adiabatic displacement *convectively unstable if*

$$\left|\frac{dT}{dr}\right| > \frac{\gamma - 1}{\gamma} \frac{T}{\rho} \left|\frac{dP}{dr}\right|$$

  i.e., for *T* profile that decreases "fast enough" with *r*

▸ Adiabatic index $\gamma = 1 + \frac{2}{f}; \; f = \#\text{degrees of freedom}$

$$\text{e.g., } f = 3 \text{ (translational) for monatomic gas}$$
$$\Rightarrow \gamma = 5/3$$

▸ As $f \to \infty, \; \gamma \to 1, \; (\gamma - 1)/\gamma \to 0 \Rightarrow$ more prone to convection

  e.g., in cool regions of stars where bound atoms & molecules exist

  (electronic, rotational, vibrational d.o.f.'s)

Places where convection is important, effects

‣ Low-mass stars

‣ Outer layers of intermediate-mass stars (outer 28% of the Sun's radius)

‣ Envelopes of red giants

Convection is very effective at transporting energy so also tends to set in where rapid energy transport is needed, e.g. cores of massive stars $\epsilon \sim T^{18}$

Also *mixes* material at different *r* within convection zones, can bring heavy elements synthesized in core to the surface (e.g., 'dredge up' events during post MS)

Re-arranges stars so that marginally stable within convection zones:

$$\frac{dT}{dr} = \frac{\gamma - 1}{\gamma} \frac{T(r)}{\rho(r)} \frac{dP}{dr}$$

Convection observed as solar granules
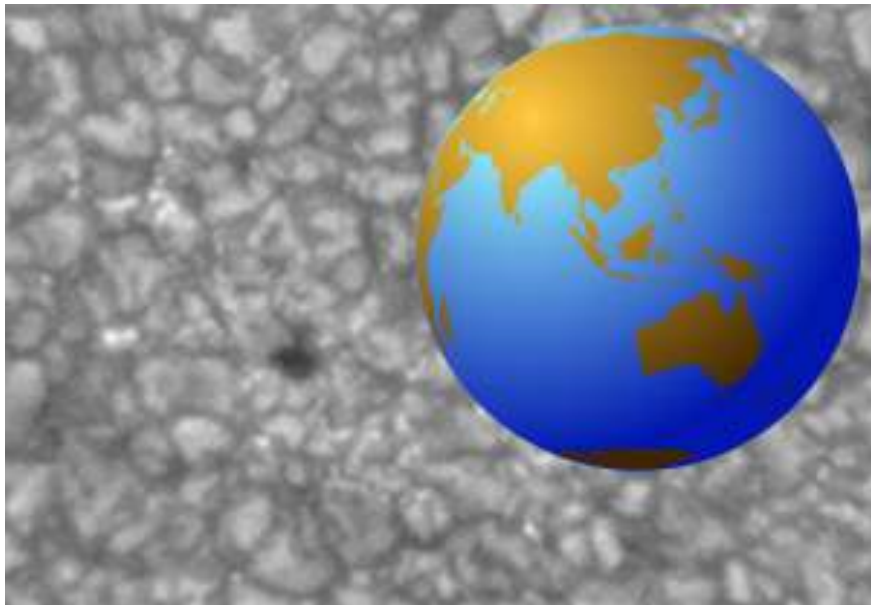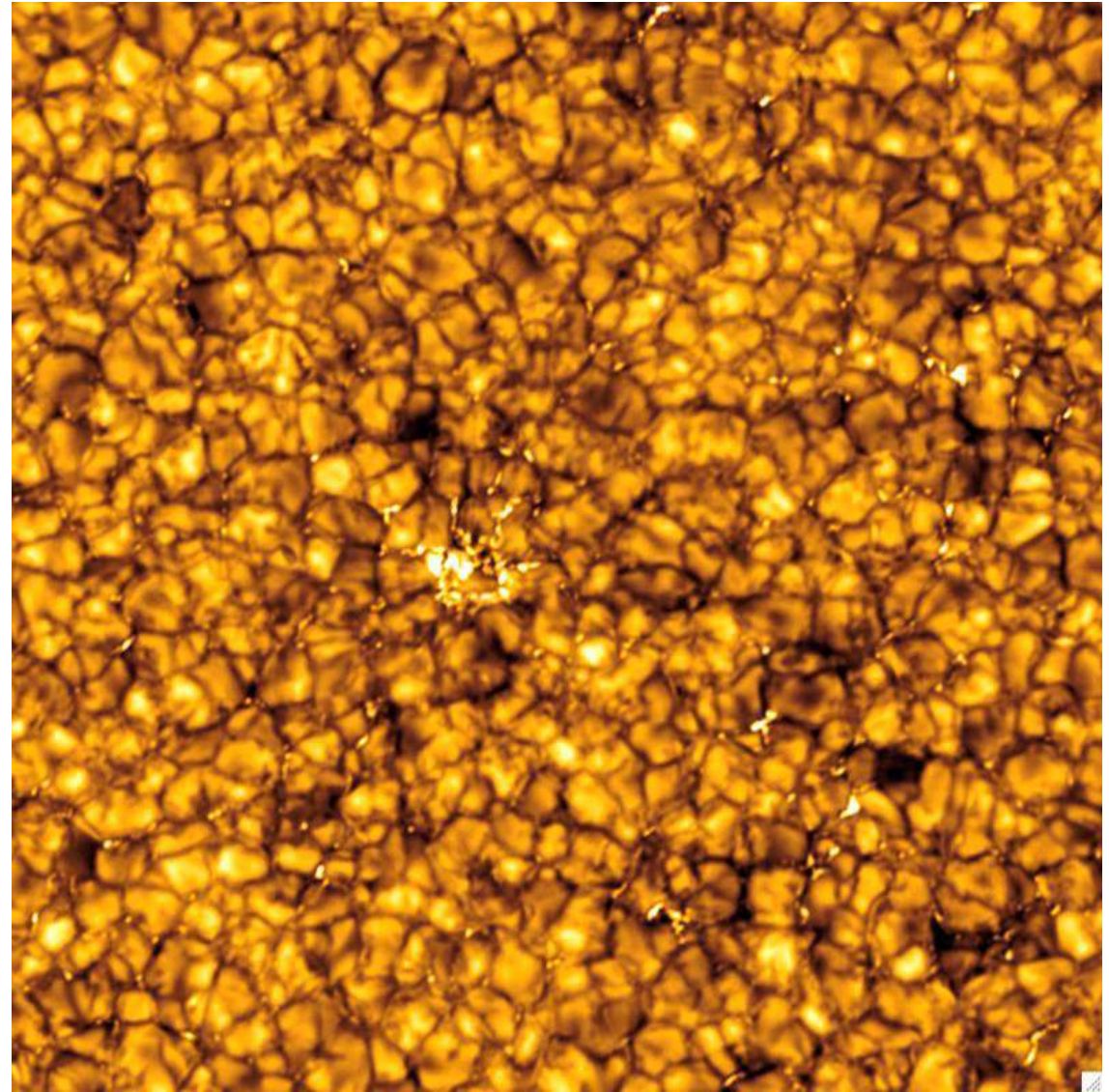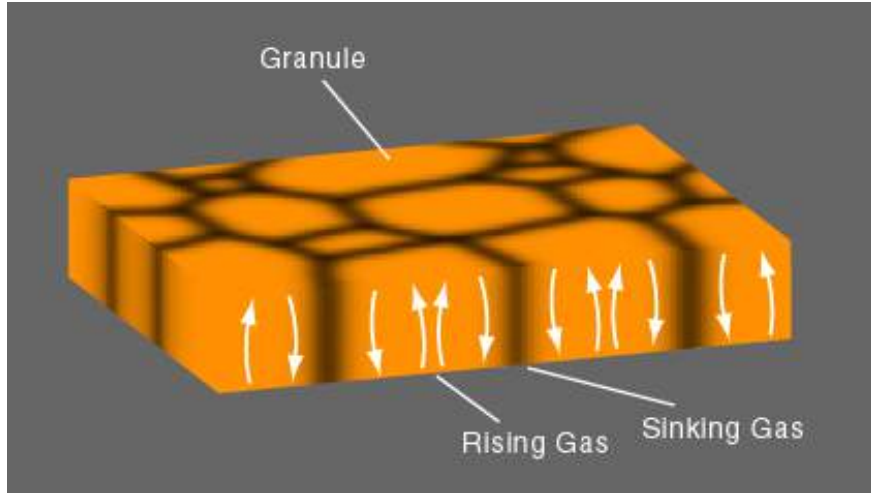
Numerical solutions of the equations of stellar structure — especially important as stars evolve past the main sequence

On post-MS evolution:

"It would thus clearly be safer if we stopped our discussion of stellar evolution here and waited for the results from the big computers, which we may expect in the nearest future. But for those whose curiosity is stronger than their wish for safety we shall go on — fully aware of the risk."

STRUCTURE AND EVOLUTION OF THE STARS

MARTIN SCHWARZSCHILD
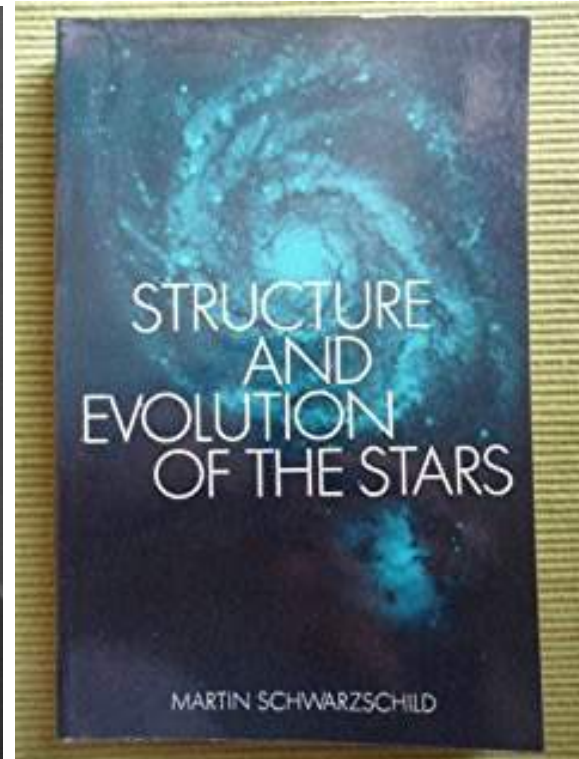
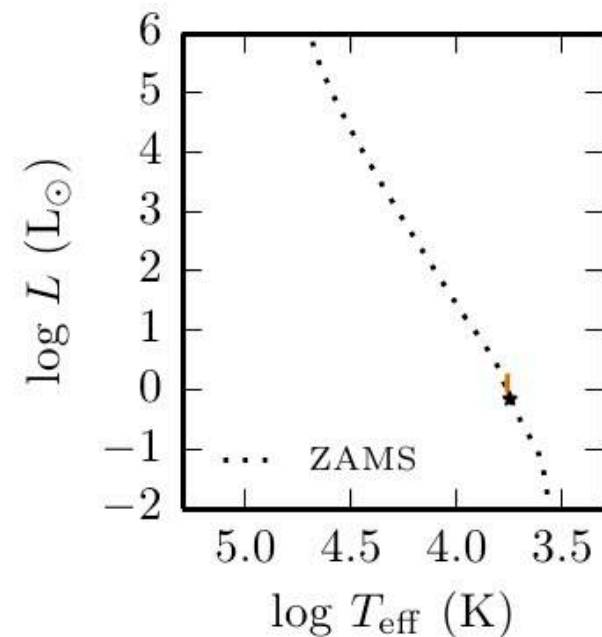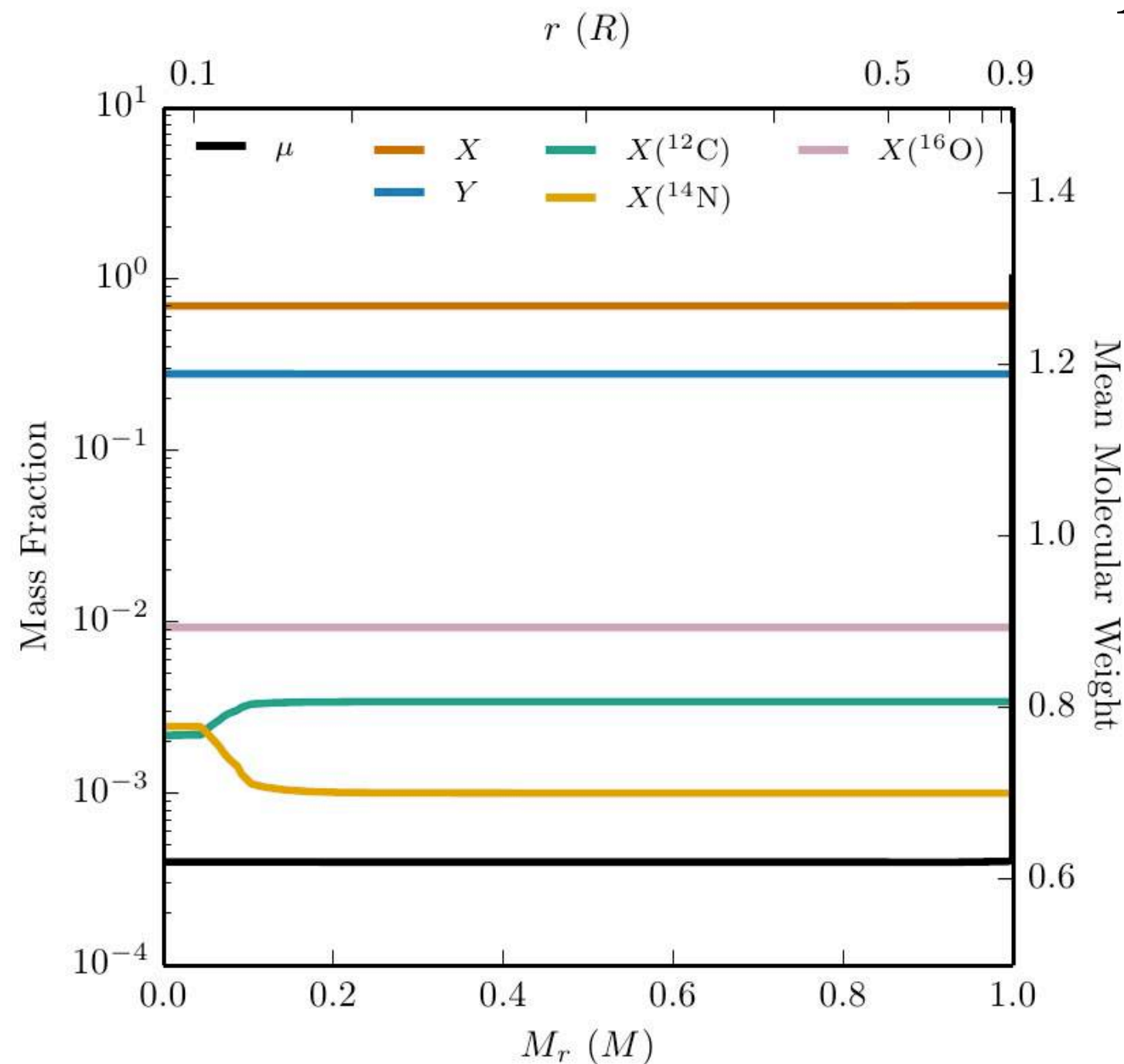- Martin Schwarzschild* in Structure and Evolution of the Stars (1958)

* Son of Karl Schwarzschild (of the Schwarzschild metric describing black holes) and nephew of astrophysicist Robert Emden (of the Lane-Emden equation describing polytropes).

MESA

Modules for Experiments in Stellar Astrophysics
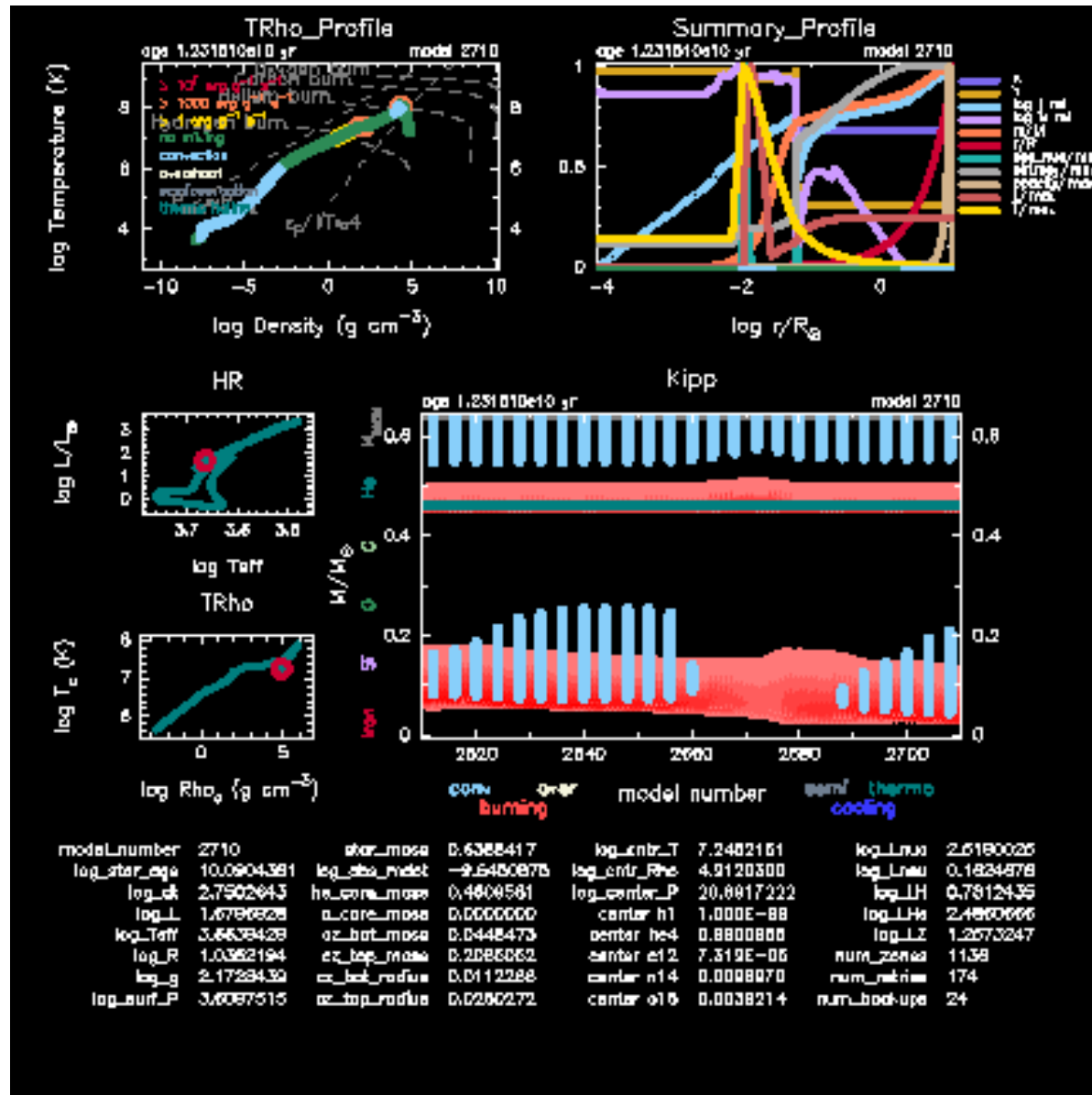
Evolution of 1 M$_{sun}$ star on the main sequence

1 M$_{sun}$ MS — composition

log M (M$_\odot$) : -0.00

log R (R$_\odot$) : -0.05

log L (L$_\odot$) : -0.15

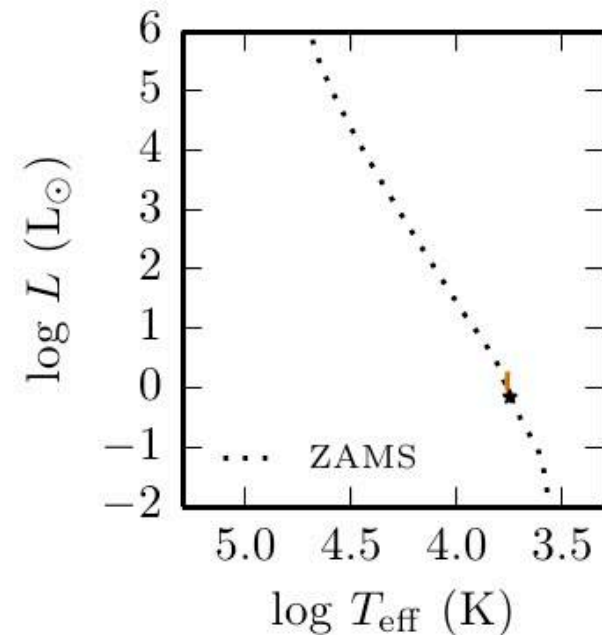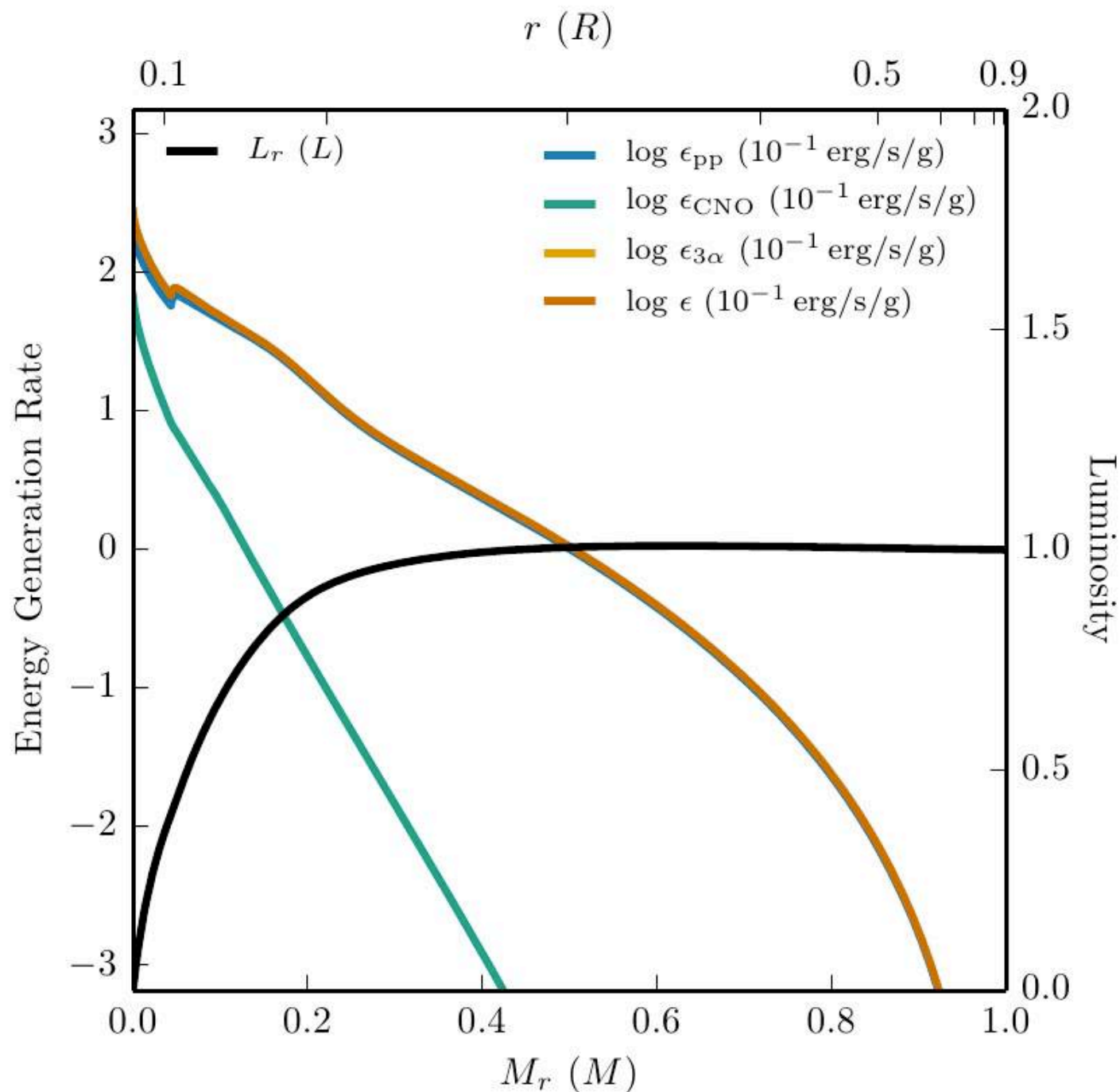log T_{eff} (K) : 3.75

log Age (yr) : 6.90

Phase : Main Seq.

= convection

1 M$_{sun}$ MS — energy gen.

$\log M$ (M$_\odot$) : -0.00

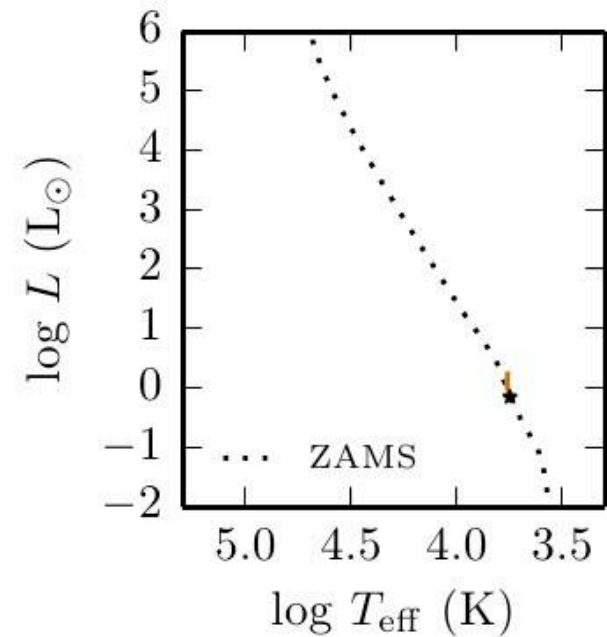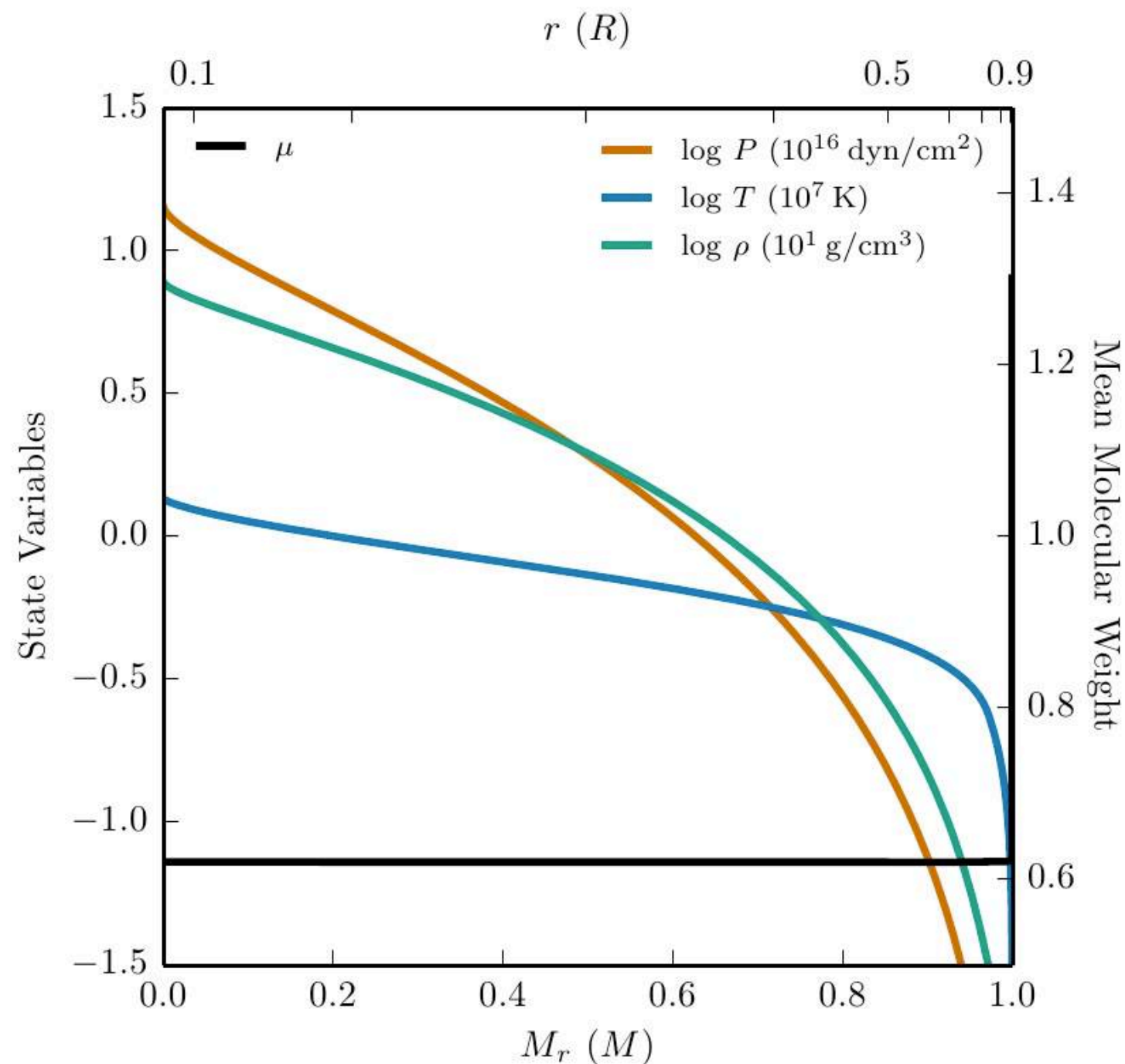$\log R$ (R$_\odot$) : -0.05

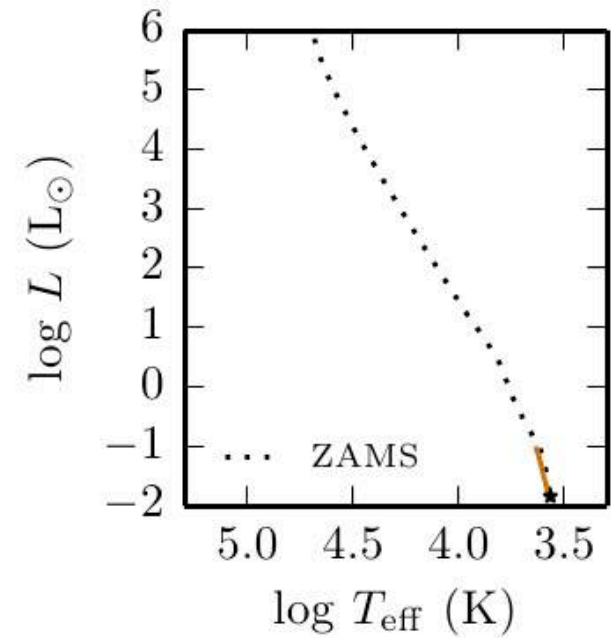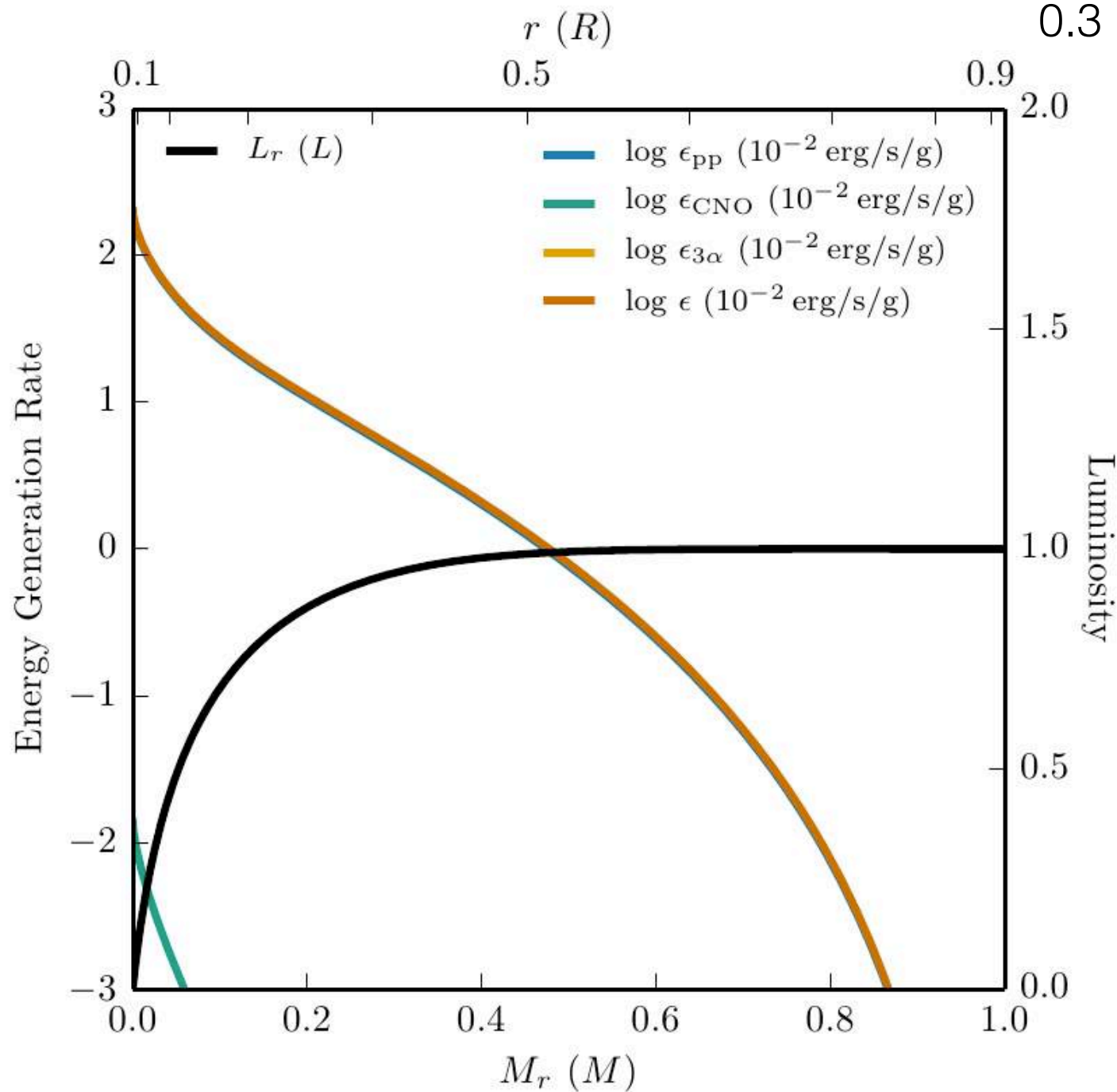$\log L$ (L$_\odot$) : -0.15

$\log T_{\text{eff}}$ (K) : 3.75

$\log$ Age (yr) : 6.90

Phase : Main Seq.

1 M$_{sun}$ MS — profiles

r (R)

$\log P$ $(10^{16}$ dyn/cm$^2)$
$\log T$ $(10^7$ K$)$
$\log \rho$ $(10^1$ g/cm$^3)$

μ

State Variables

Mean Molecular Weight

M_r (M)

$\log L$ $(L_\odot)$

ZAMS

$\log T_{\rm eff}$ (K)

$\log M$ (M$_\odot$) : -0.00

$\log R$ (R$_\odot$) : -0.05

$\log L$ (L$_\odot$) : -0.15

$\log T_{\rm eff}$ (K) : 3.75

$\log$ Age (yr) : 6.90

Phase : Main Seq.

H burn
He burn

Nuclear burning on the main sequence for 0.3, 1, 3, 10 M_{sun} stars

0.3 M$_{sun}$ MS — pp dominates

$\log M$ (M$_\odot$) : -0.52

$\log R$ (R$_\odot$) : -0.53

$\log L$ (L$_\odot$) : -1.84
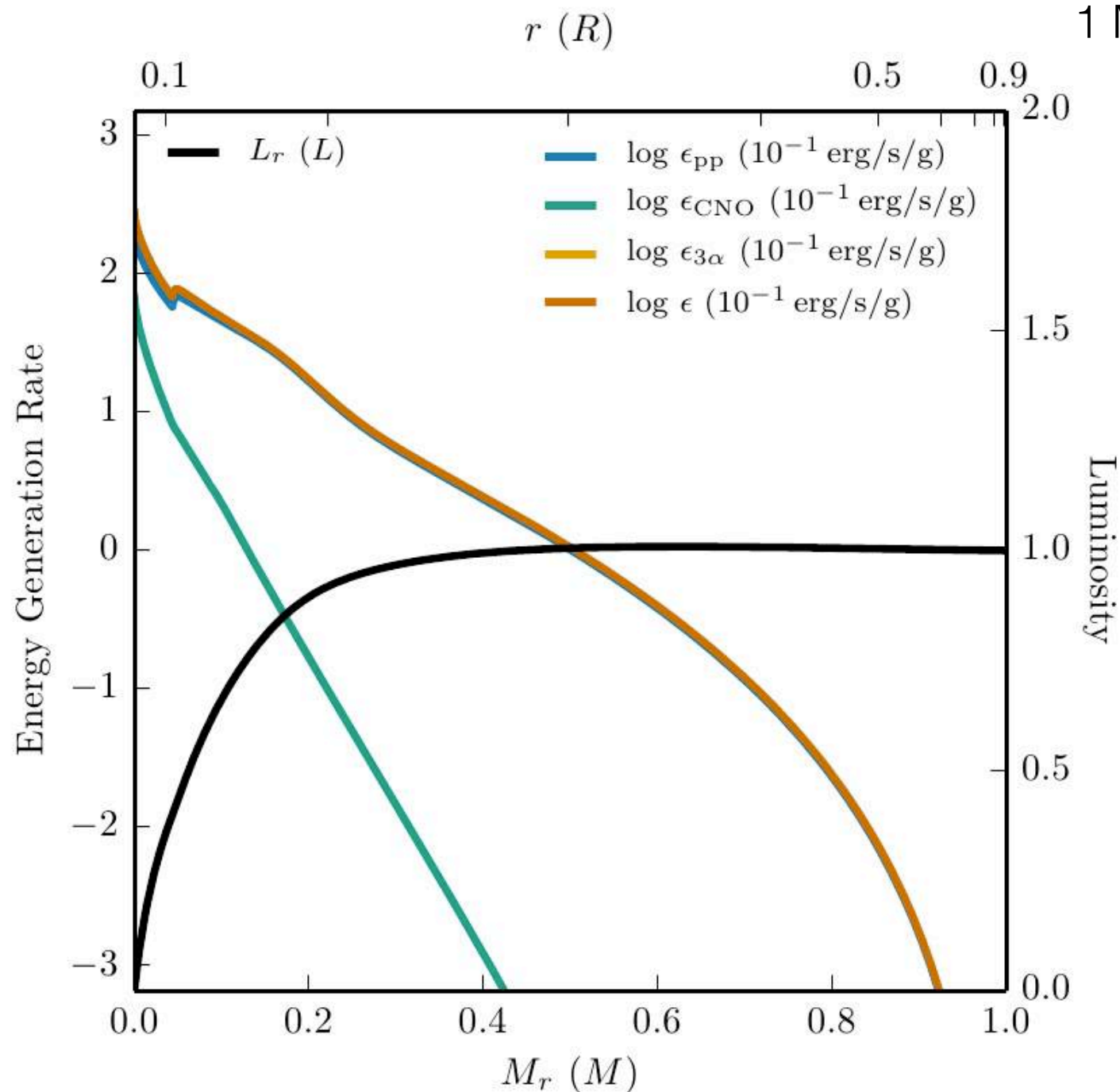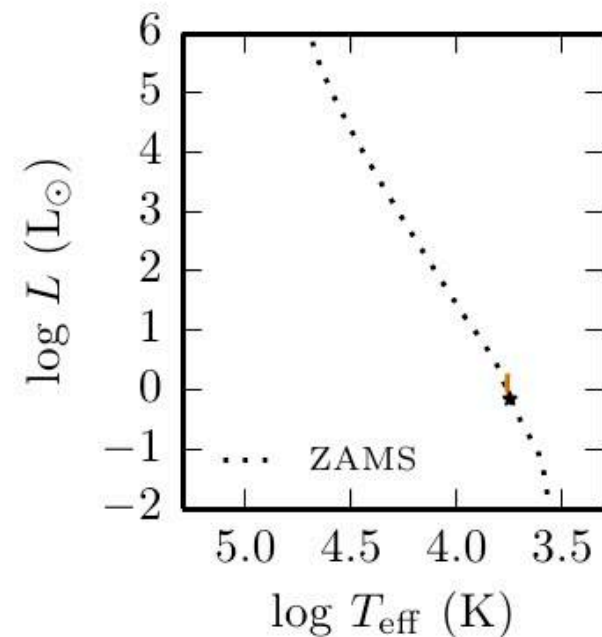
$\log T_{\rm eff}$ (K) : 3.57

$\log$ Age (yr) : 9.53

Phase : Main Seq.

fully convective until $t > 10^{11}$ yr

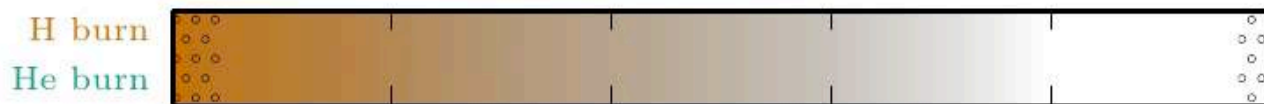1 M$_{sun}$ MS — pp dominates

$\log M\ (\mathrm{M_\odot}) : -0.00$

$\log R\ (\mathrm{R_\odot}) : -0.05$

$\log L\ (\mathrm{L_\odot}) : -0.15$

$\log T_{\mathrm{eff}}\ (\mathrm{K}) : 3.75$

$\log \mathrm{Age}\ (\mathrm{yr}) : 6.90$

Phase : Main Seq.

convective outer envelope
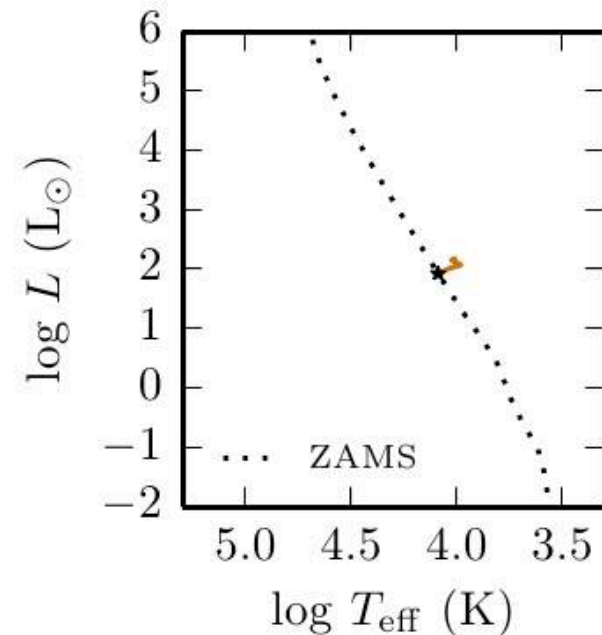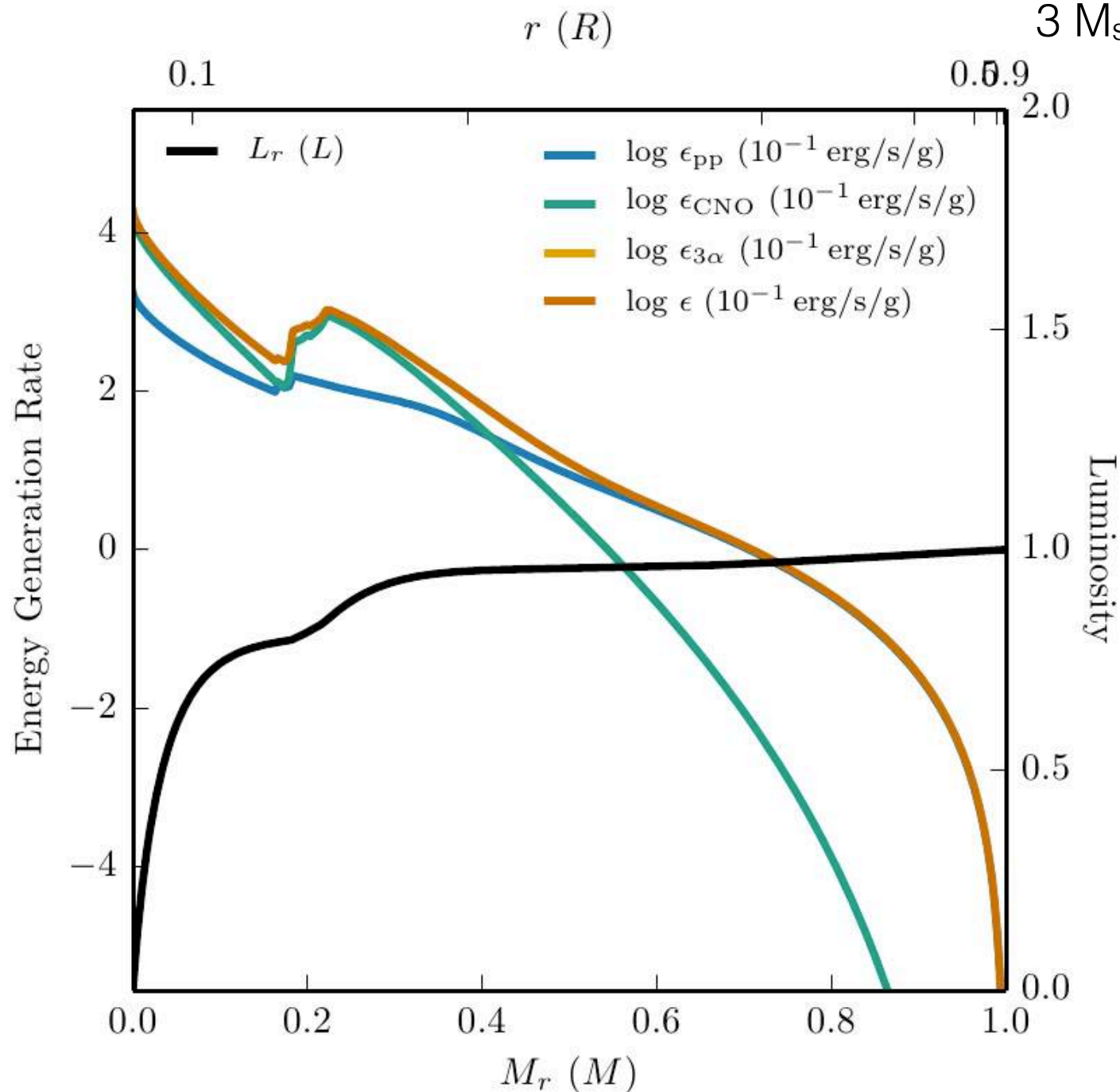
$\log M$ (M$_\odot$) : 0.48

$\log R$ (R$_\odot$) : 0.31

$\log L$ (L$_\odot$) : 1.93

$\log T_{eff}$ (K) : 4.09

$\log$ Age (yr) : 4.49

Phase : Main Seq.

convective core
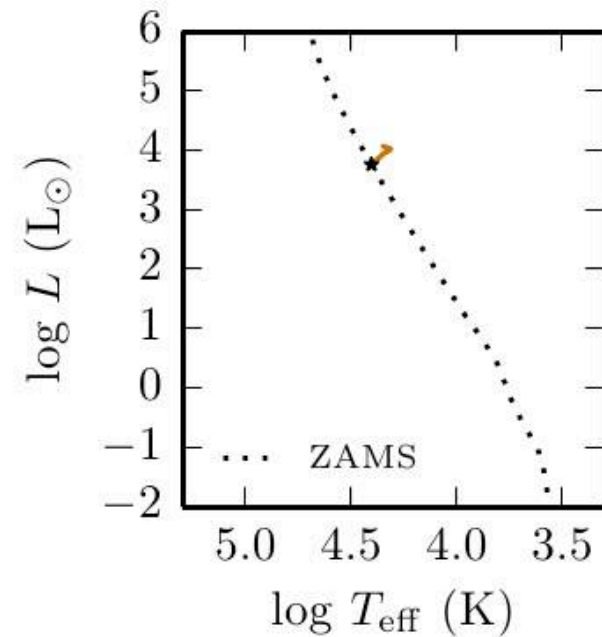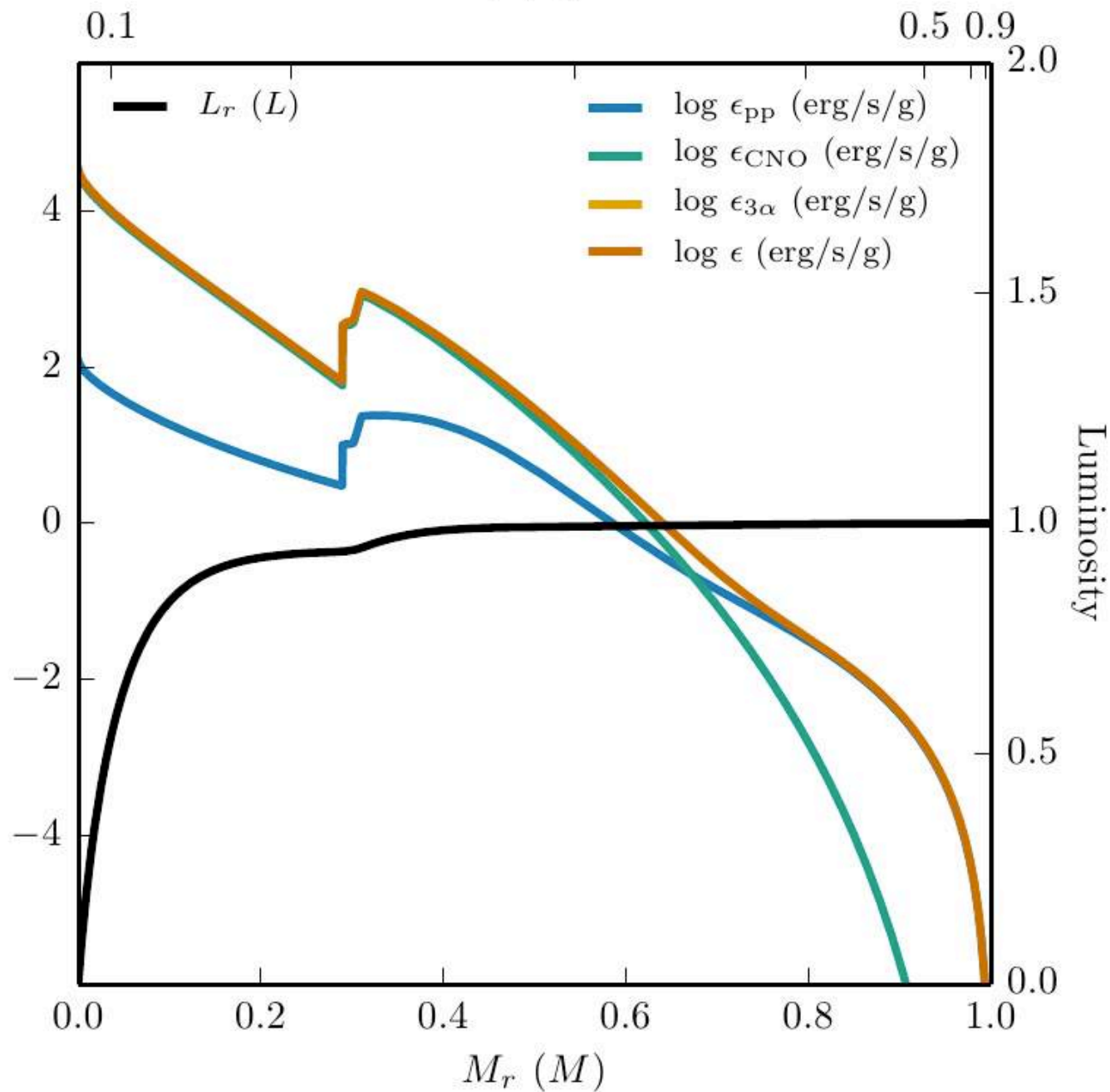
10 M$_{sun}$ MS — CNO dominates

r (R)

L_r (L)

log ϵ_{pp} (erg/s/g)
log ϵ_{CNO} (erg/s/g)
log $\epsilon_{3\alpha}$ (erg/s/g)
log ϵ (erg/s/g)

Energy Generation Rate

M_r (M)

Luminosity

log L (L$_\odot$)

ZAMS

log T_{eff} (K)

log M (M$_\odot$) : 1.00

log R (R$_\odot$) : 0.59

log L (L$_\odot$) : 3.76

log T_{eff} (K) : 4.40

log Age (yr) : 3.50

Phase : Main Seq.

H burn
He burn

convective core