The Evolution of Population III Stars

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Outline

1. Introduction (Definitions & Motivation)
2. Formation of Population III stars
3. Nucleosynthesis in Population III stars
4. The Fate of Population III stars
5. Conclusions

What are Population III Stars?

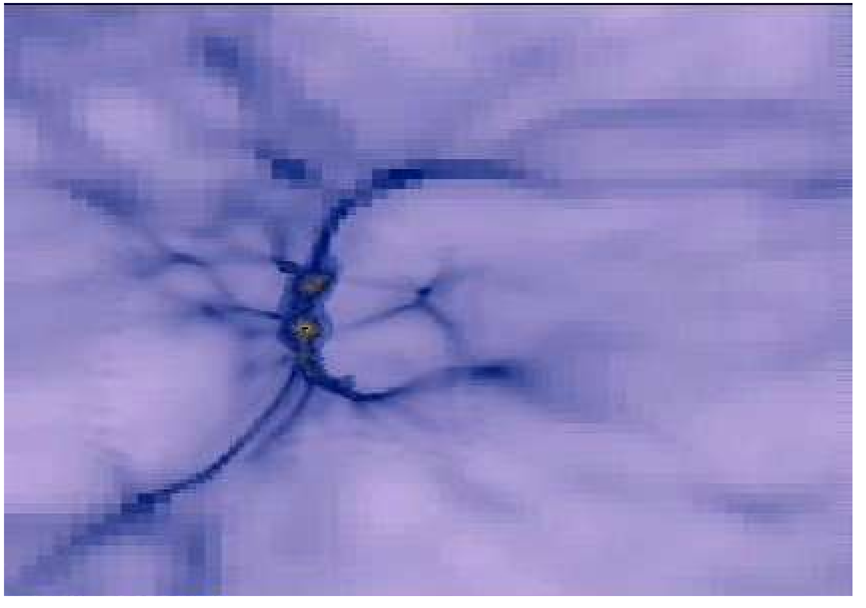
1) Very low metallicity stars ([Fe/H] ~ -2.5)
2) Zero metallicity stars (other than a little Li)
3) Stars formed within 10^6 - 10^7 years of the Big Bang (independent of metallicity)
4) Stars that no longer exist, but affected the environment of the early Universe

Why Study Population III Stars?

- Big Bang metallicities ($z \sim 10^{-12} – 10^{-10}$) → Population II metallicities ($z \sim 10^{-4} – 10^{-3}$)
- How many Pop III SN are needed to make a Pop II star?
- Did Pop III stars reionize the early Universe?
- How do such stars form, live, and die?

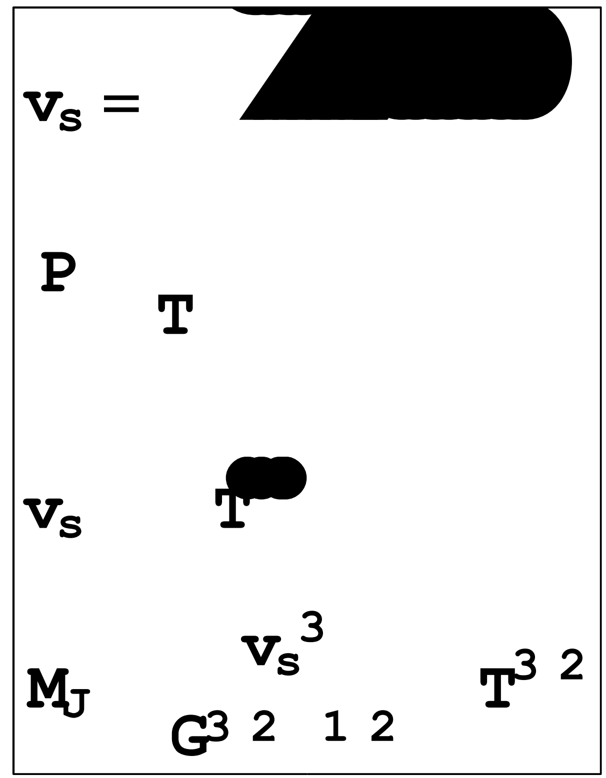
The Origins of Population III Stars

- Form from primordial “molecular” clouds



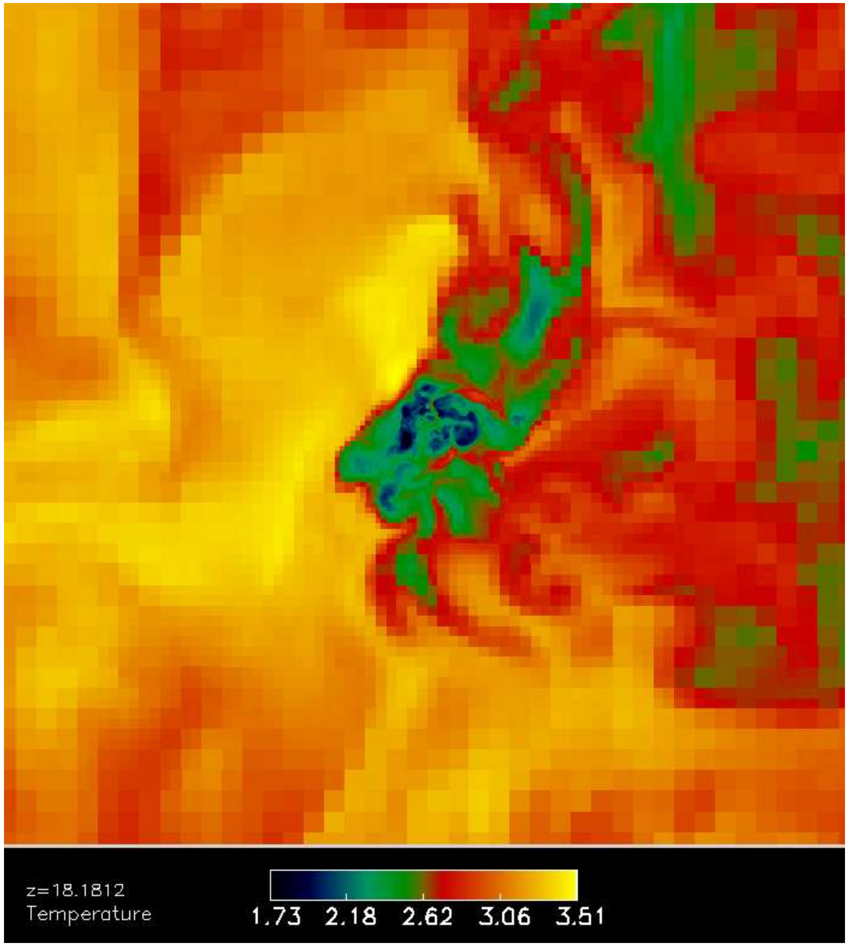
Jeans Mass

- High temperatures -> larger Jeans mass ($M_J \sim T^{3/2}$)
- $T \sim 10^4$ K, $M >> 10^5\ M_o$!
- These stars are huge!
- …or are they?



Molecular Hydrogen Cooling

- Some cooling in the center of the cloud...!
- Temperatures ~300K
- Sets an upper mass limit



Possible Origins of H_2

Charge exchange reaction:

$H^+ + H \rightarrow H_2^+ + h\nu$

$H_2^+ + H \rightarrow H_2 + H^+$

Dissociative attachment reaction:

$e^- + H \rightarrow H^- + h\nu$

$H^- + H \rightarrow H_2 + e^-$

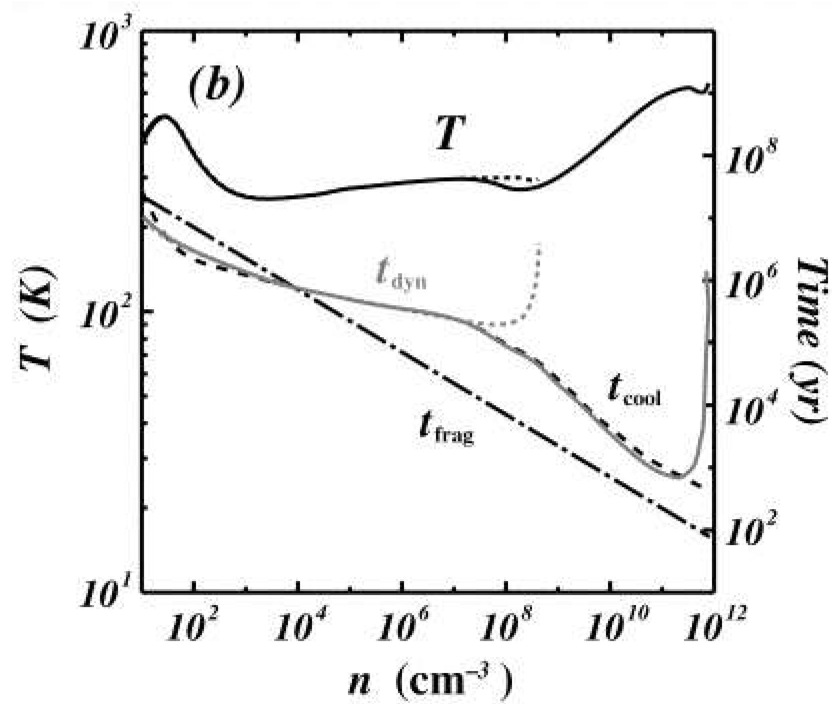
Three-body reactions (at high ρ):

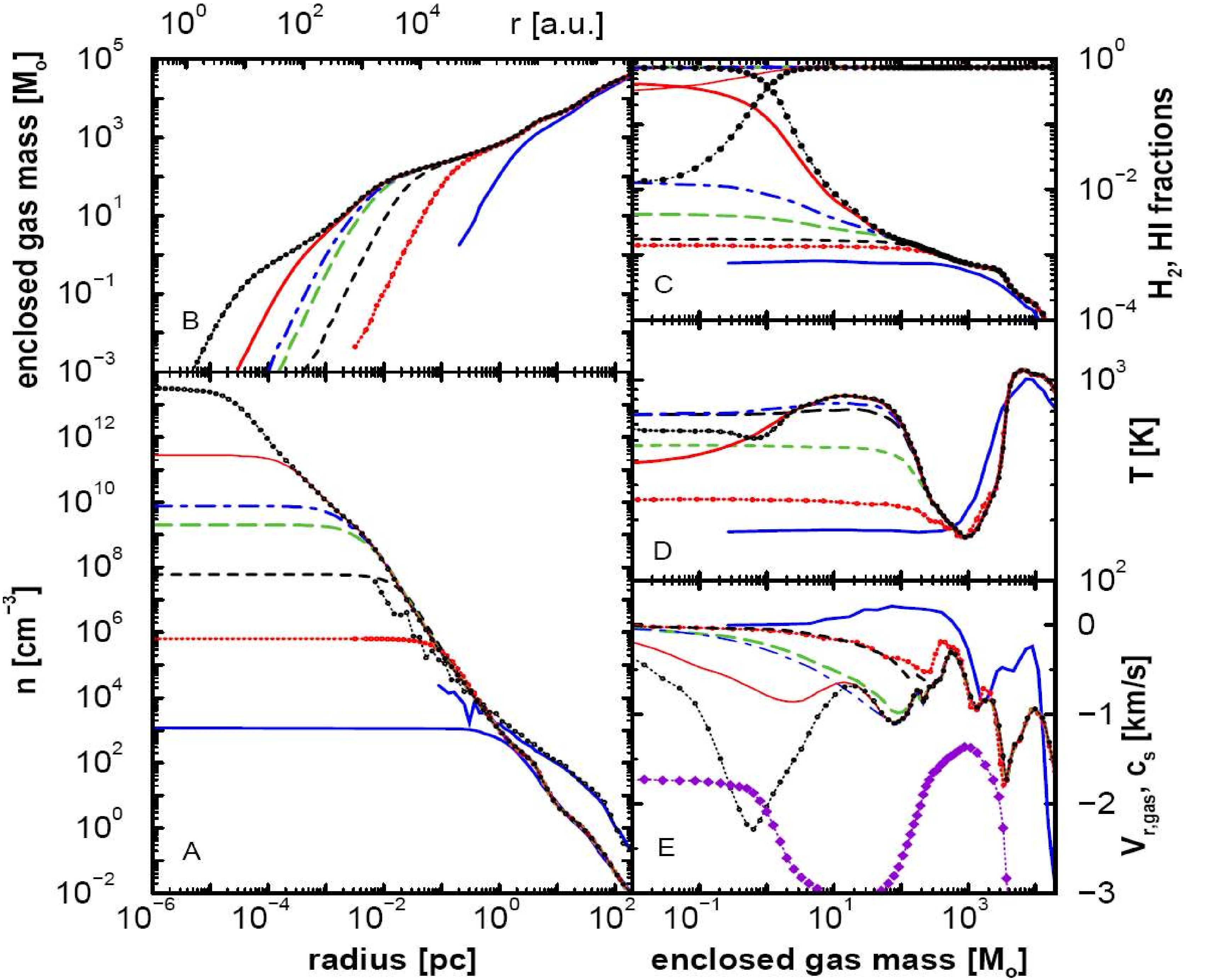
$3\,H \rightarrow H_2 + H$

$2H + H_2 \rightarrow 2H_2$

Molecular Hydrogen Cooling

- As long as $t_{cool} > t_{frag}$, the cloud will not fragment
- Temperature rises and falls with different production rates of H_2





r [a.u.]
enclosed gas mass [Mo]
n [cm^-3]
radius [pc]
H2, HI fractions
T [K]
Vr,gas, cs [km/s]
enclosed gas mass [Mo]
A
B
C
D
E

Molecular H Cooling?

- But H_2 would be destroyed by UV light from other Pop. III objects!
- But H_2 would be protected if it existed inside giant H clouds!

…Further simulations are needed, especially for including opacities

The IMF of Pop. III Stars

- Without dust grains, there is little or no cooling in Population III stars
- There is still no agreement as to the range of initial Pop. III masses
- Somewhere between 0.7 $M_{\odot}$ and 1000 $M_{\odot}$

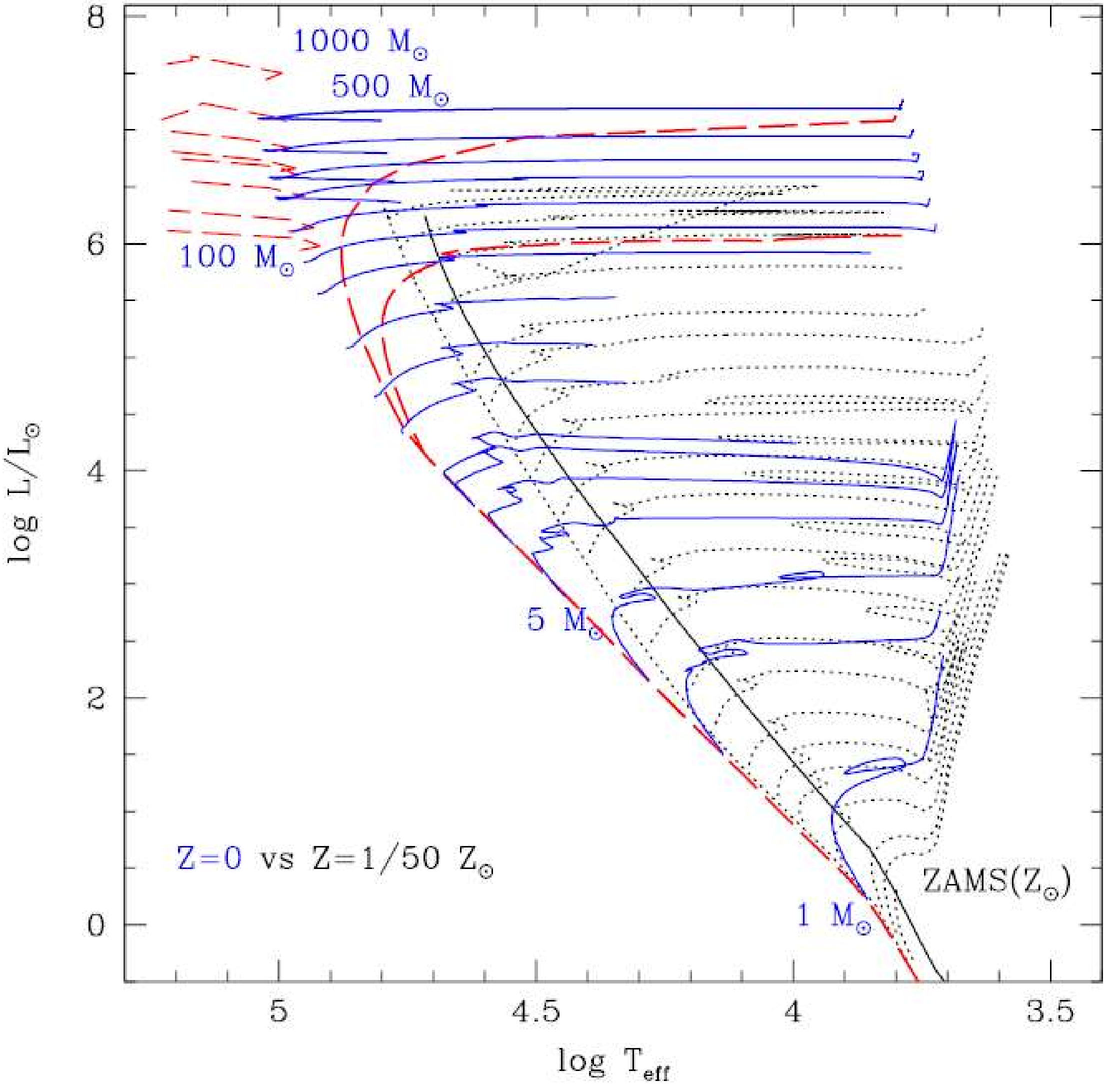
The Primary Structural Difference…

- Stars with a mass fraction of $^{12}C < 10^{-9}$ cannot start the CNO cycle
- The only source of energy is the p-p chain
- The p-p chain has a much lower dependency on temperature, so it acts as a poor thermostat, and the core gets very hot & dense

The Primary Structural Difference…

- When the temperatures get high enough, 3α starts, ^{12}C is formed, and the CNO cycle can begin

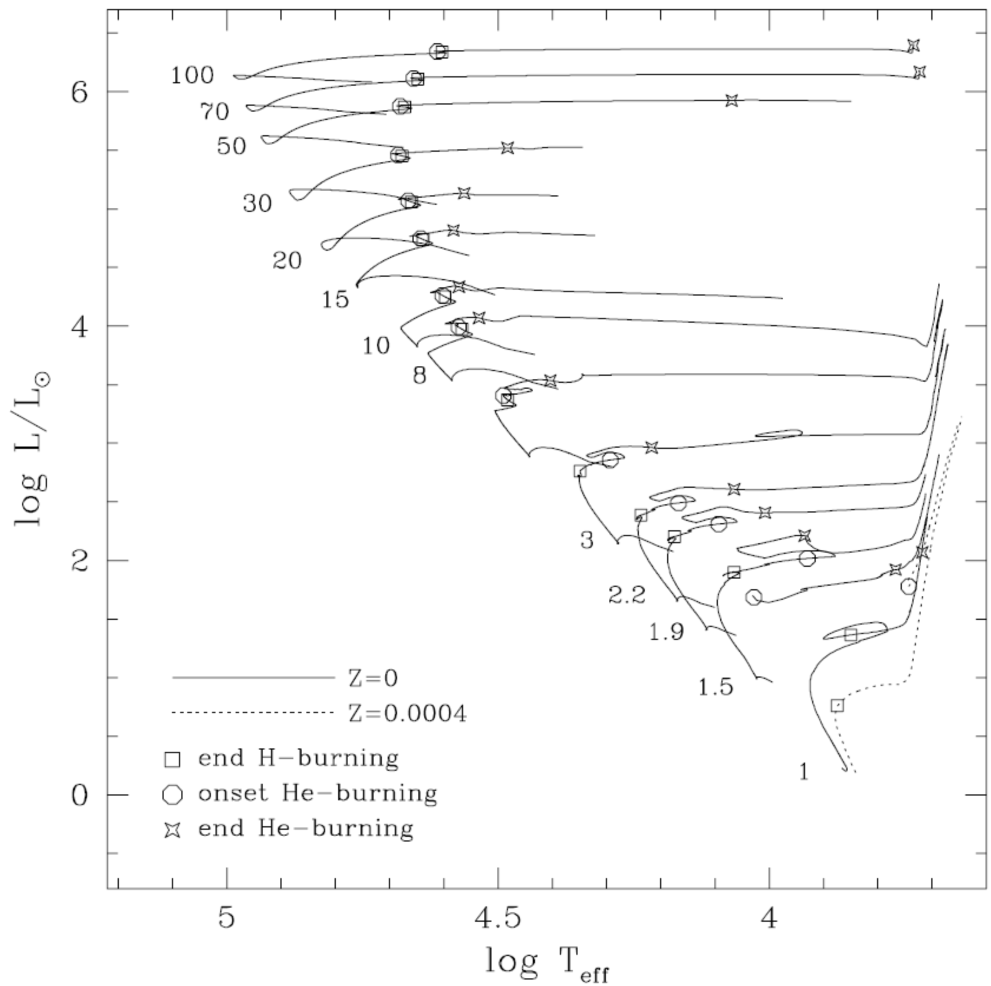
Pop III Evolutionary Tracks



- Pop. III stars are hotter & more luminous than their Pop. II counterparts

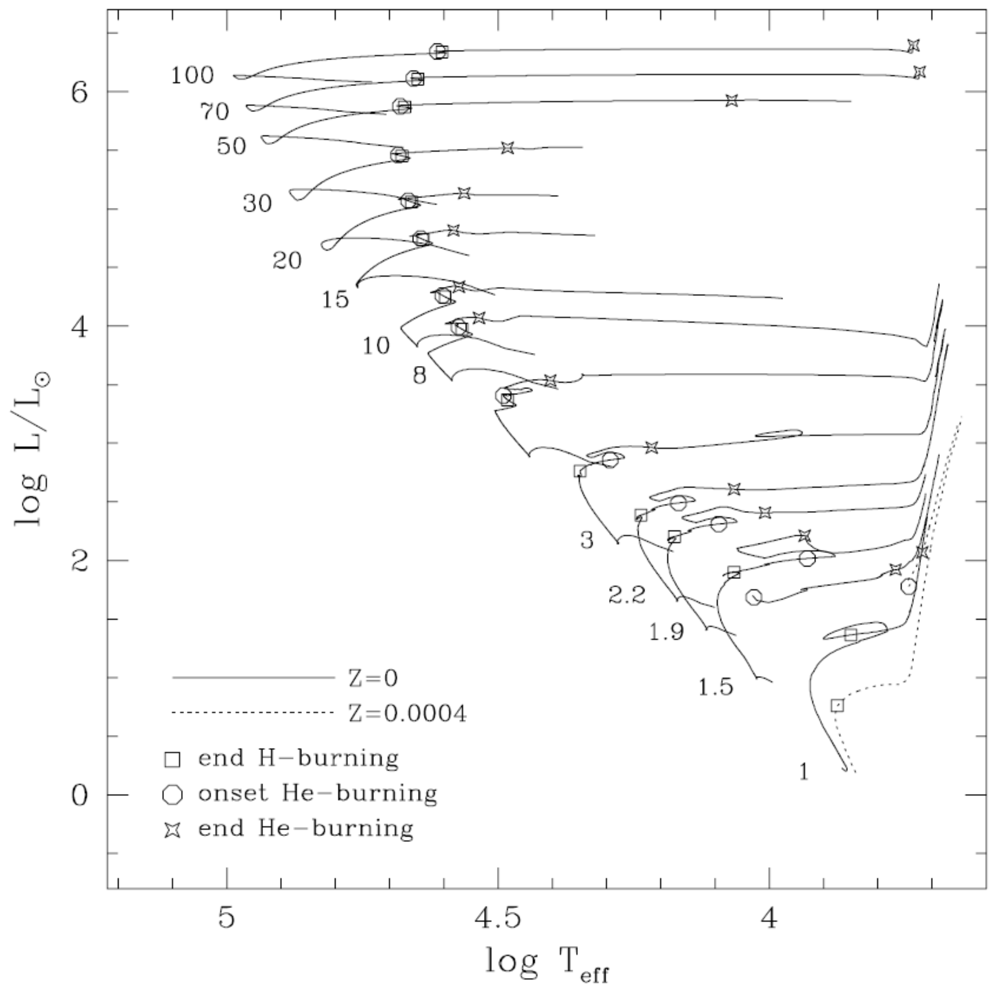
Pop III Evolutionary Tracks

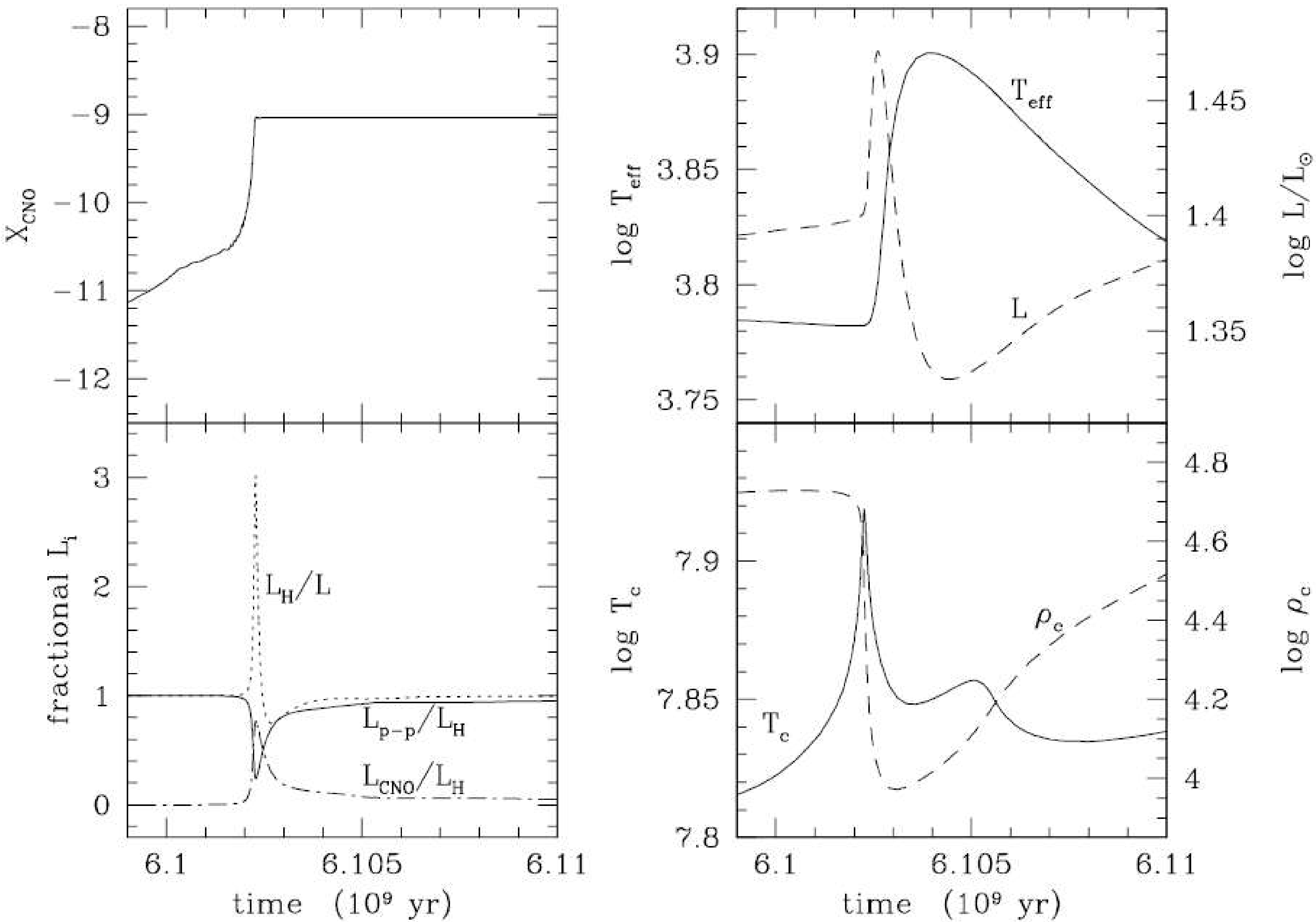
- He burning before the RGB!
- The evolutionary timescale is shorter than the thermal timescale



Pop III Evolutionary Tracks

- Blue loops:
  - As H is exhausted in the core, T & ρ increase
  - 3α process is enhanced
  - CNO cycle kicks in
  - Thermal runaway → H flash
  - Convective core appears, only to disappear once the central H abundance drops to zero.

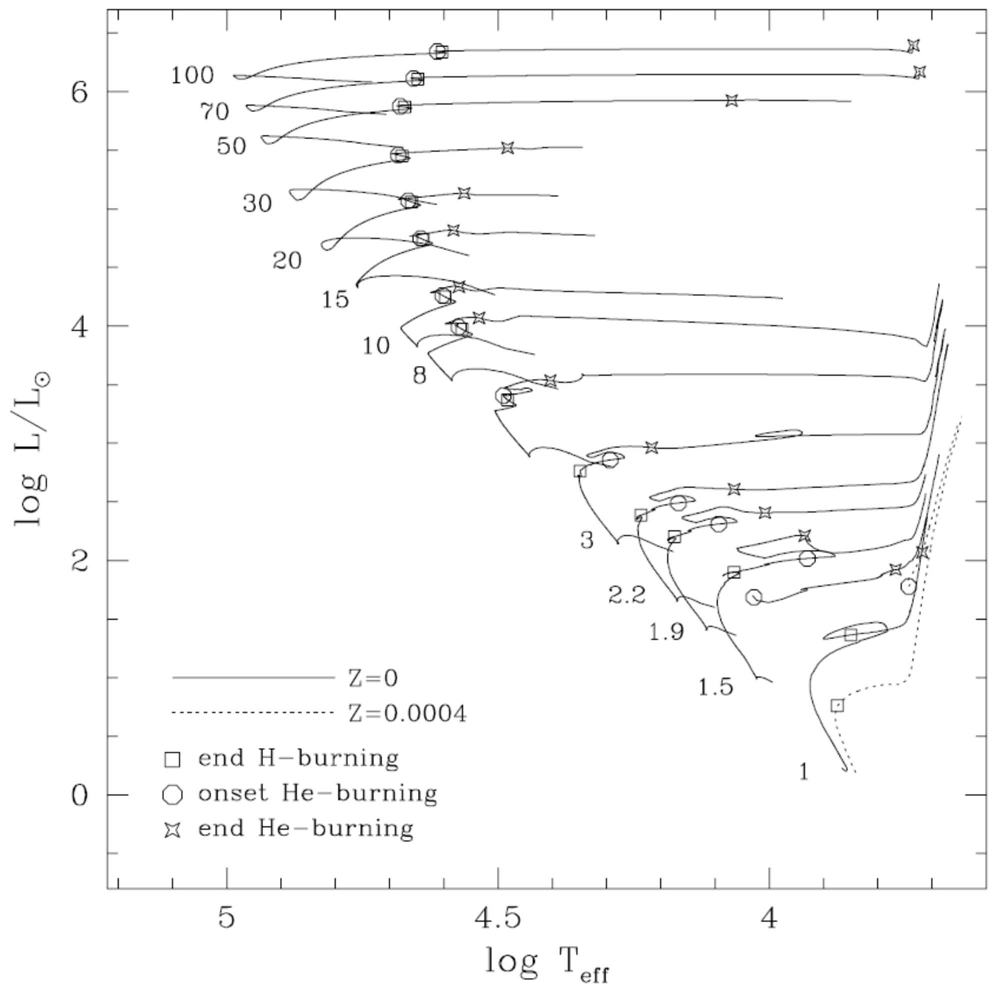




X_{CNO}
−8
−9
−10
−11
−12
fractional L_i
3
2
1
0
L_H/L
L_{p-p}/L_H
L_{CNO}/L_H
6.1
6.105
6.11
time (10⁹ yr)
log T_{eff}
3.9
3.85
3.8
3.75
log $L/L_{\odot}$
1.45
1.4
1.35
T_{eff}
L
log T_c
7.9
7.85
7.8
log ρ_c
4.8
4.6
4.4
4.2
4
ρ_c
T_c
6.1
6.105
6.11
time (10⁹ yr)

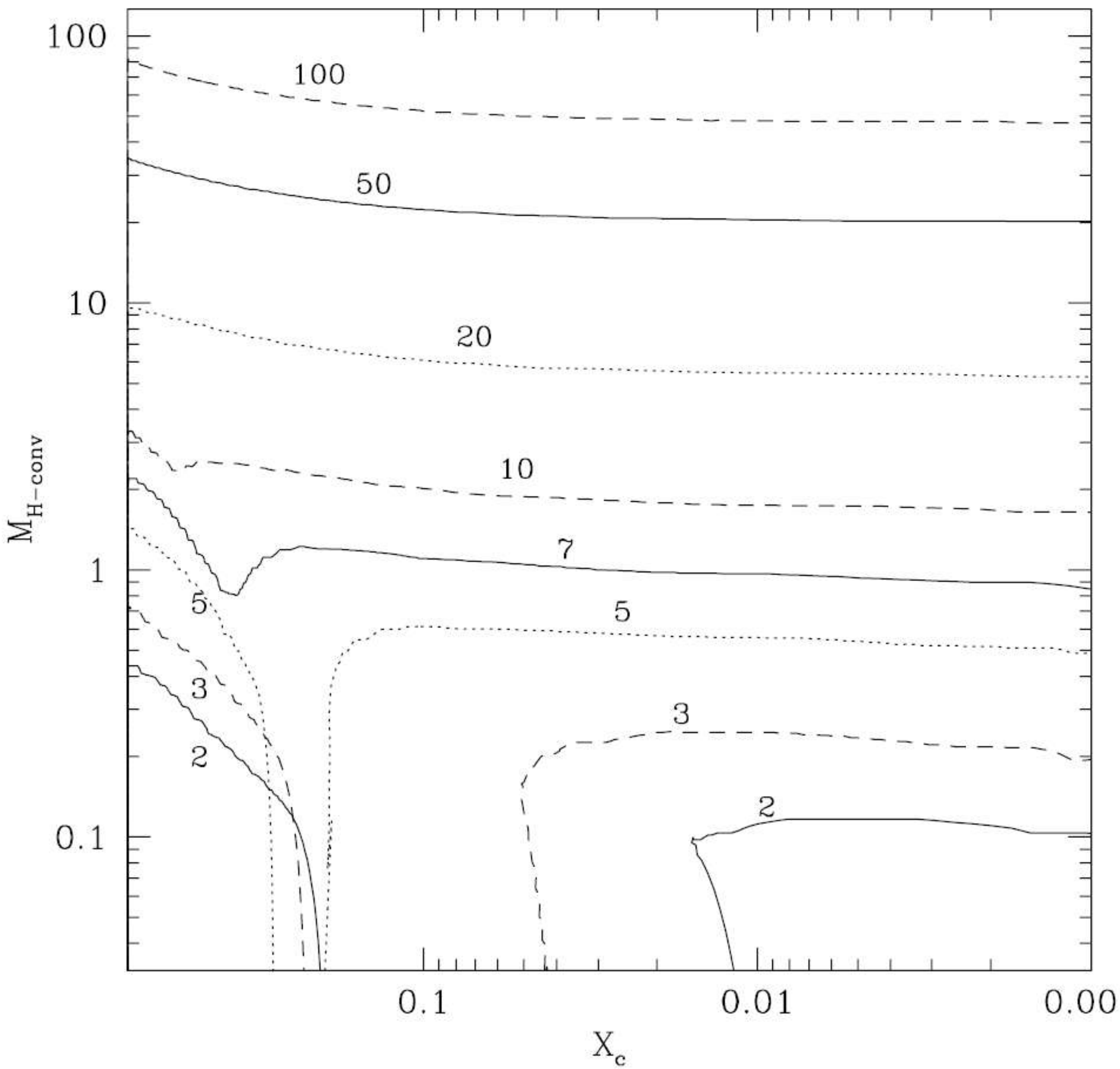
Pop III Evolutionary Tracks

- Pop. III stars begin burning He before they reach the RGB
- No first dredge-up (except in the lowest masses)

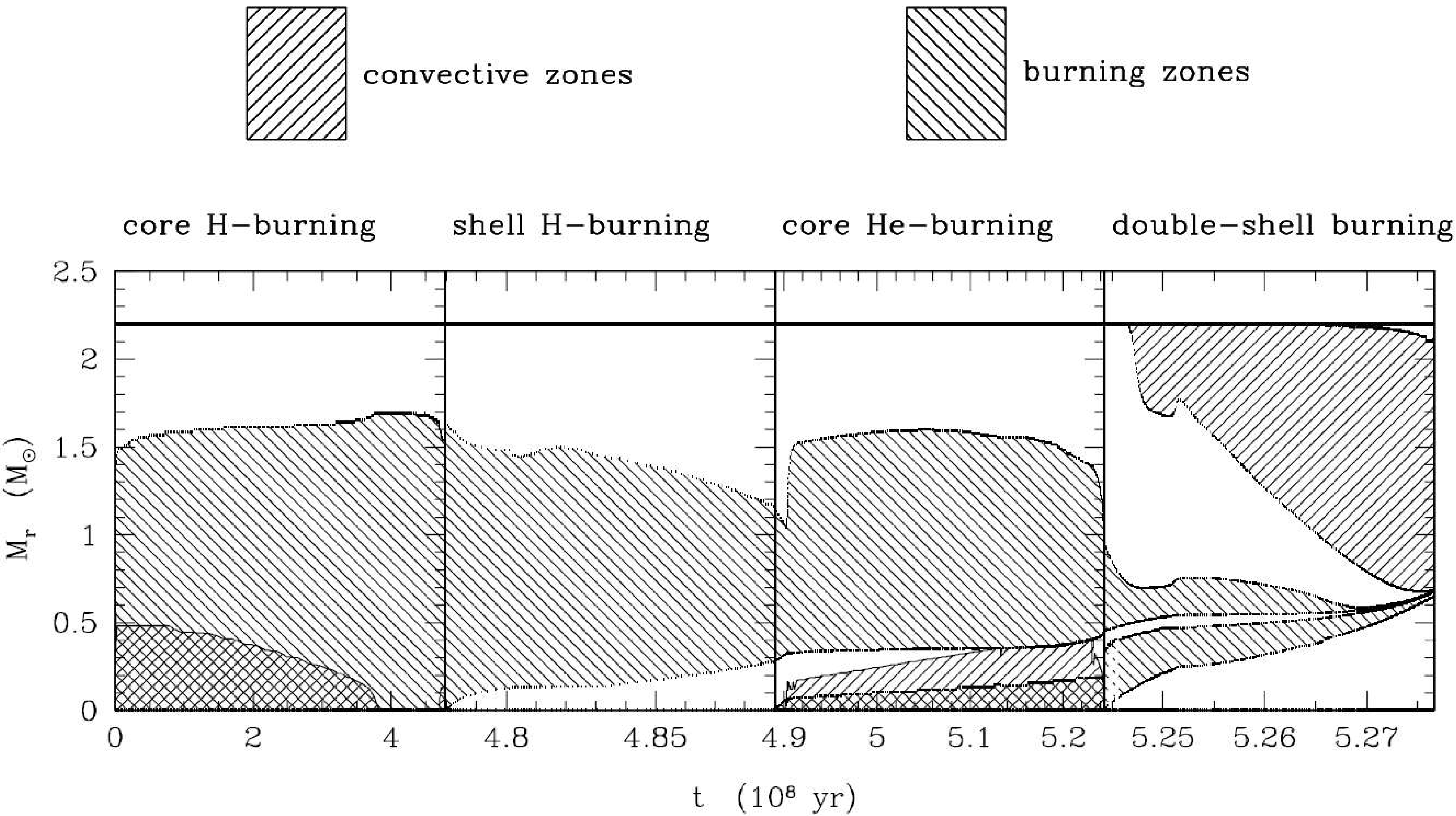


The Primary Structural Difference…

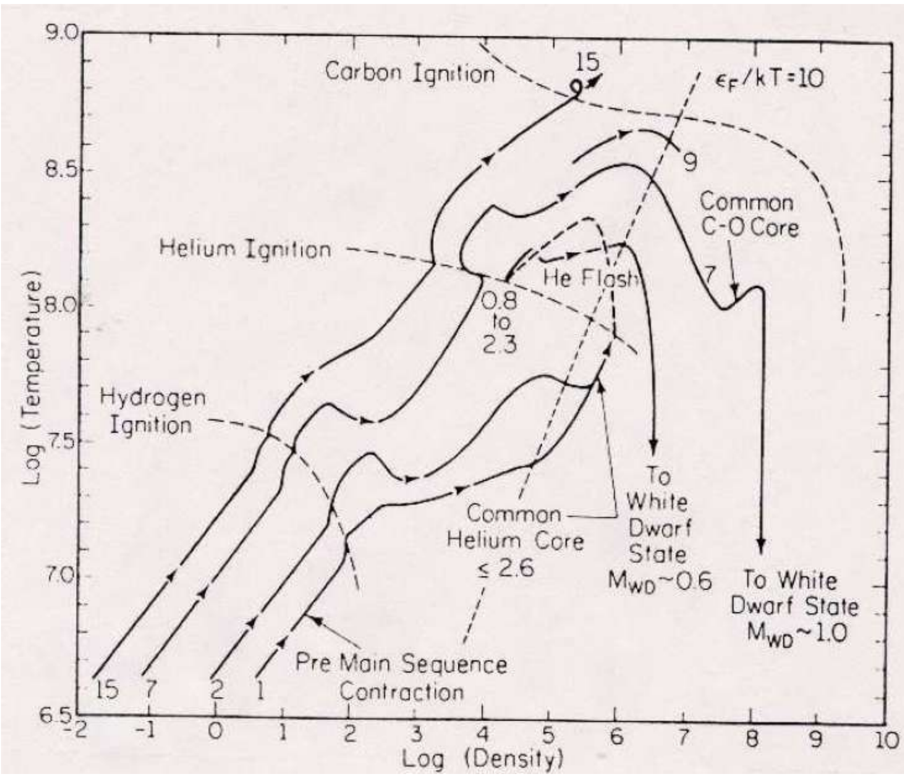
- Highly radiative cores – convection turns on & off in low-mass stars

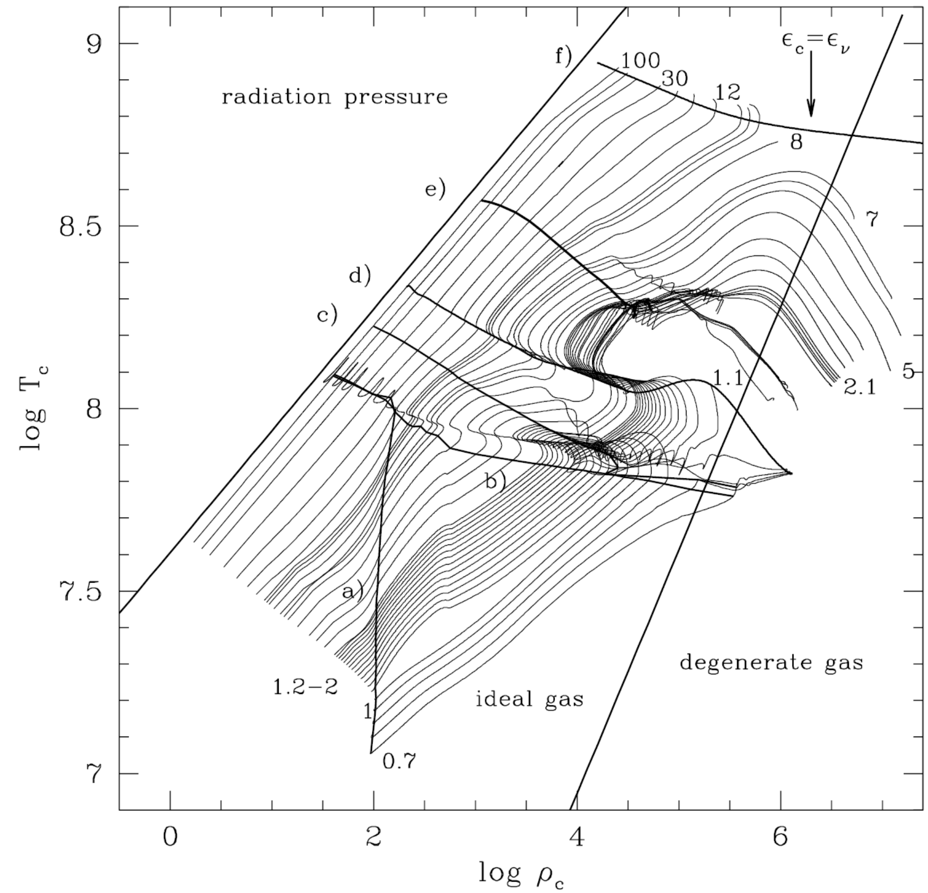


Convection, H, & He Burning



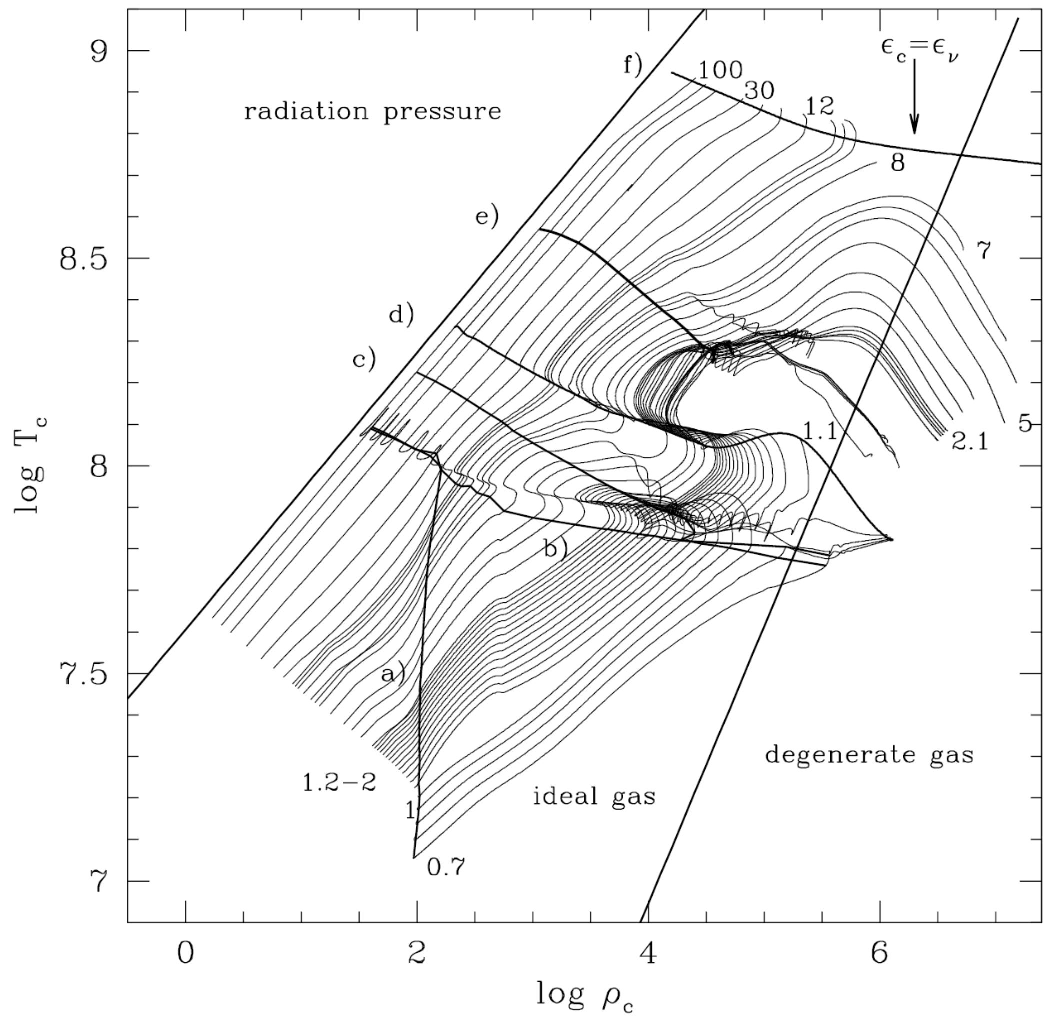
Temperature-Density Evolution





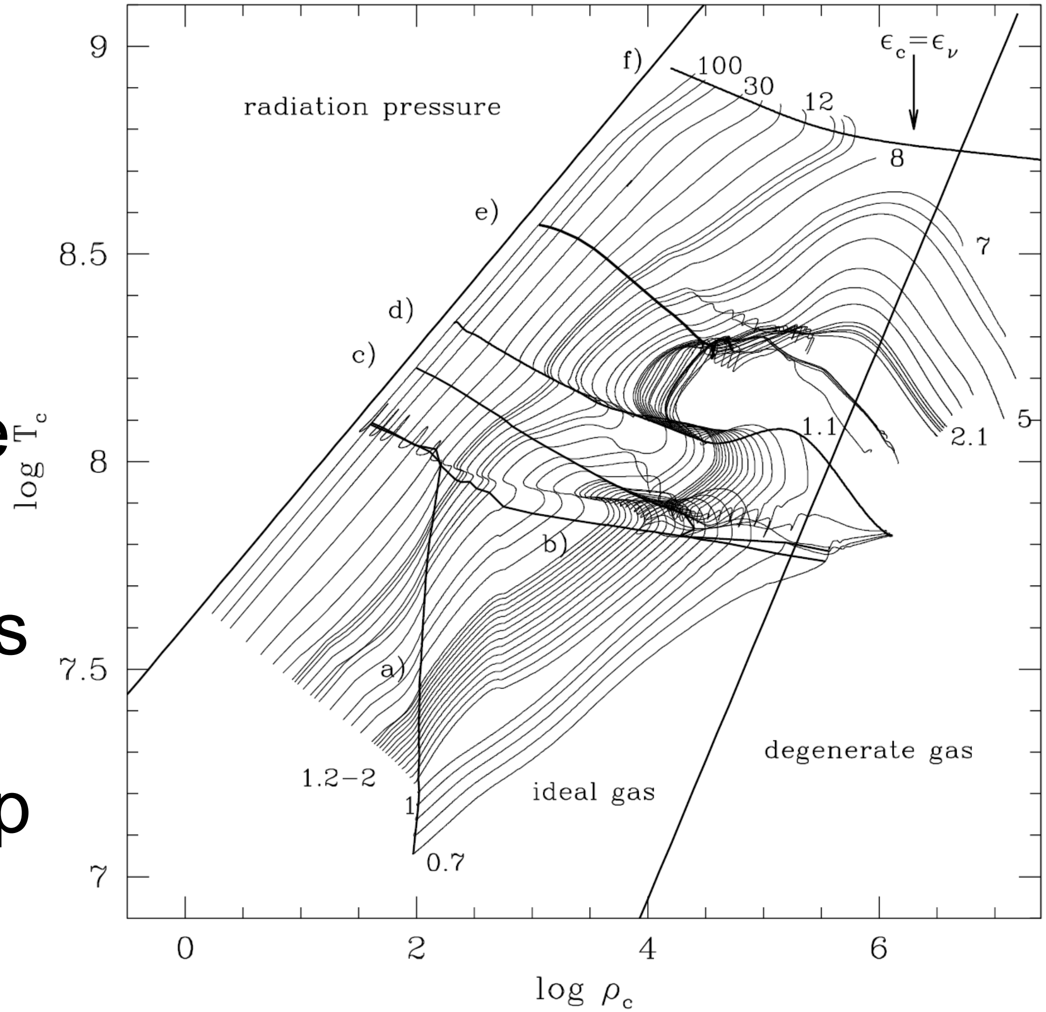
Pop III Nuclear Reactions

a) Onset of H-burning
b) Onset of 3α
c) End of H-burning
d) Onset of He-burning
e) End of core He-burning
f) Energy balance



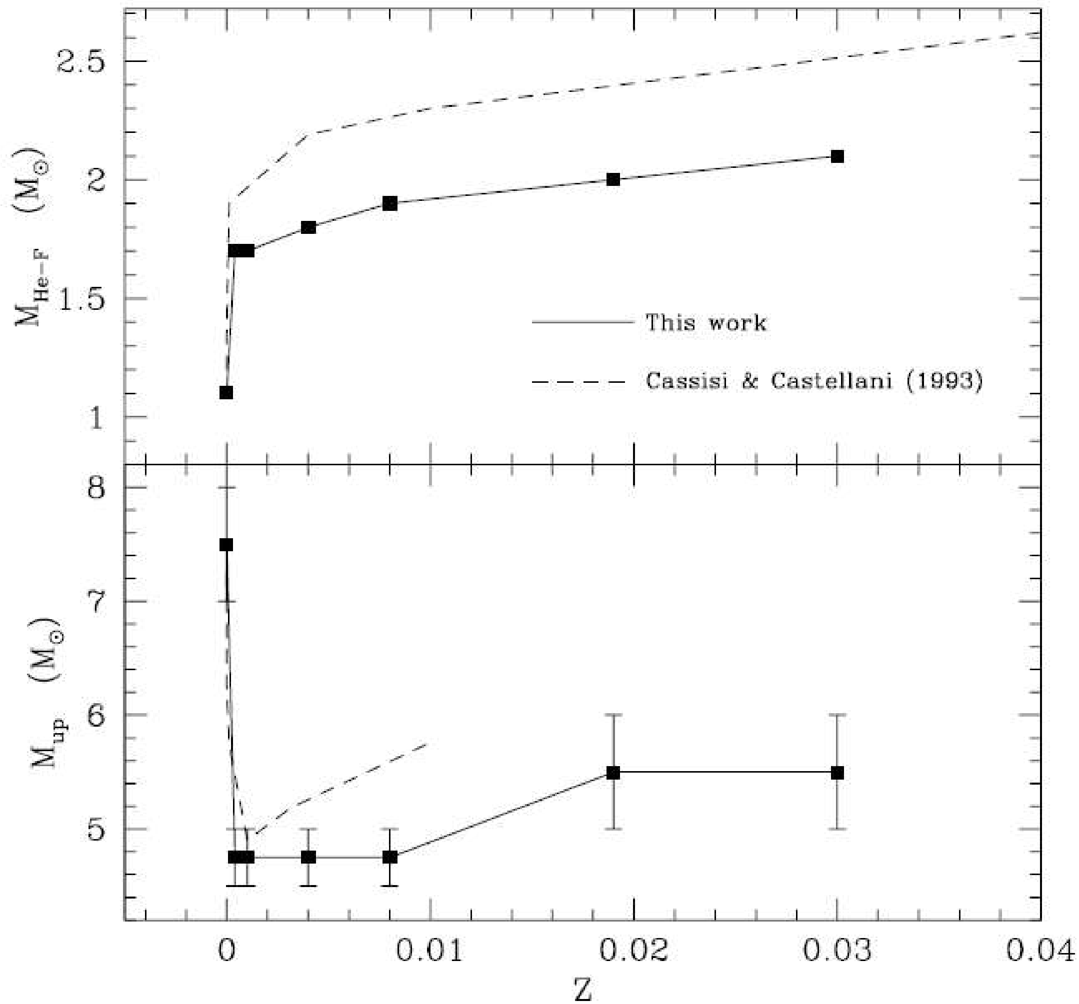
Pop III Nuclear Reactions

- Some stars become degenerate *before* He-ignition
- Easy to see the weak T-dependence of the p-p chain
- More massive stars start the 3α process before TE via the p-p chain



Pop III Nuclear Reactions

- M_{HeF} – Maximum mass star to develop an electron-degenerate core after the MS (~1.1 $M_{☉}$)
- M_{up} – The upper-mass limit for stars to develop an electron-degenerate core after core He burning (~7 $M_{☉}$)

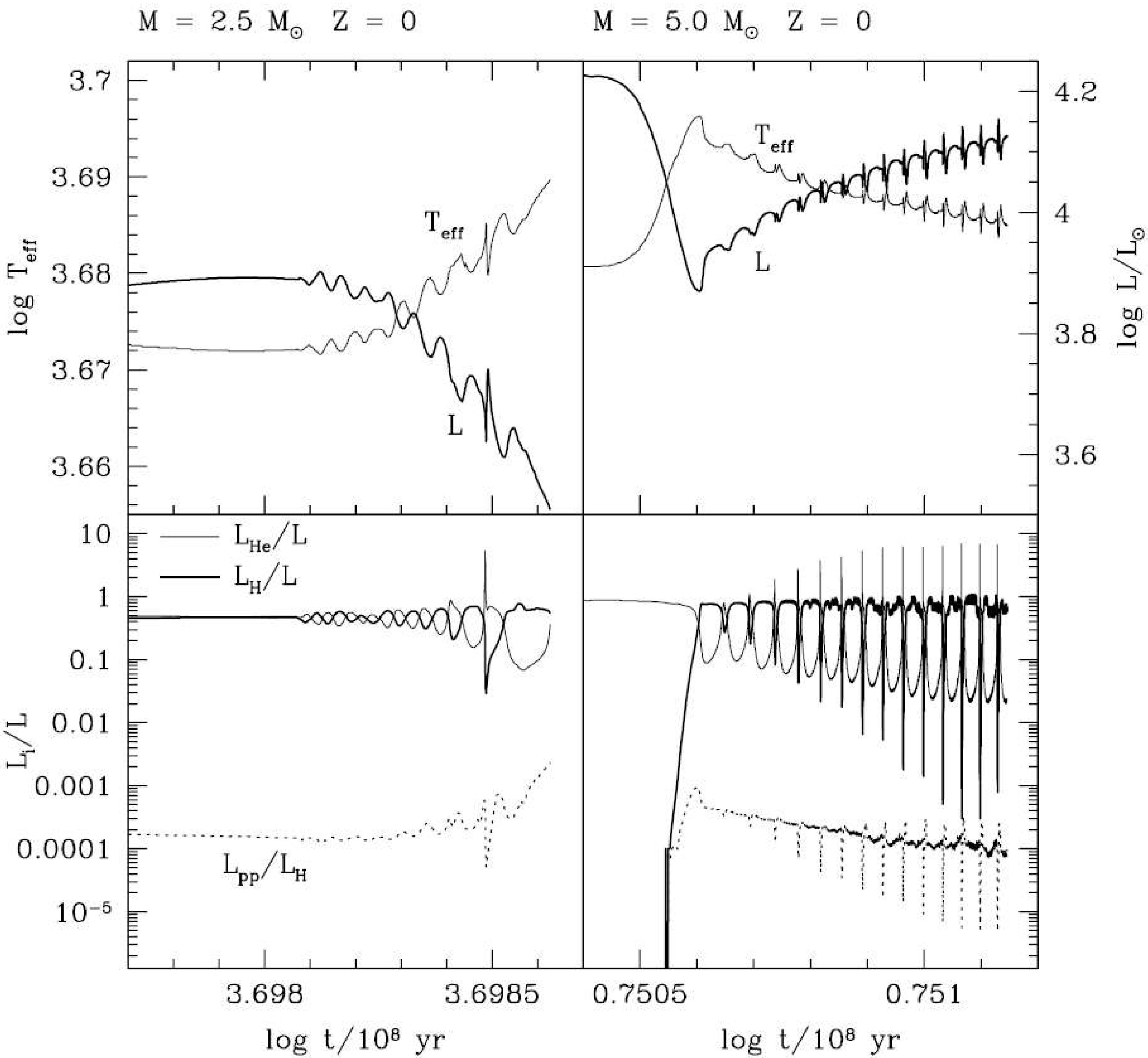


AGB Evolution

- After central He exhaustion, the convective envelope extends inward
- Second dredge-up begins
- Two models from Marigo et al (2001): 2.5 $M_{\odot}$ and 5.0 $M_{\odot}$

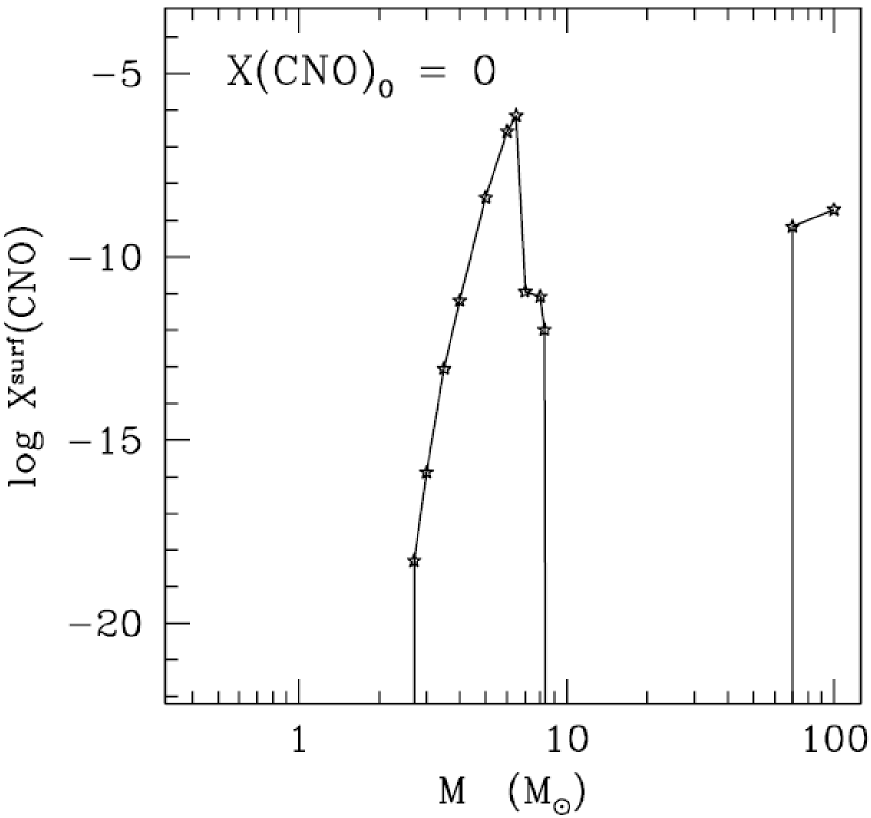
AGB Evolution

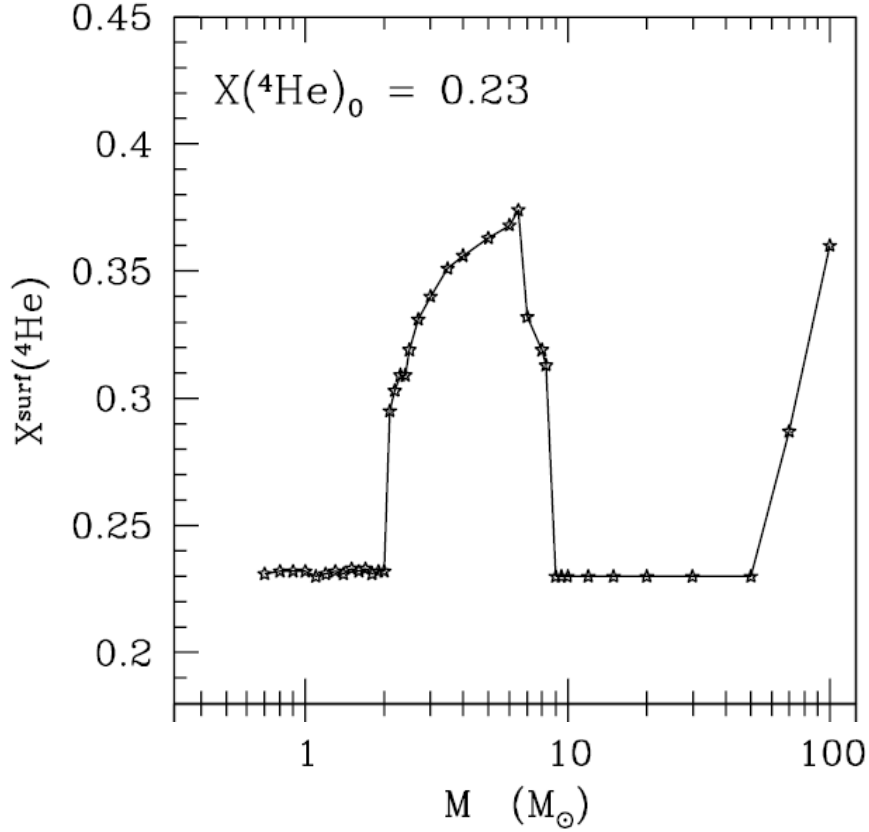
- 2.5 $M_\odot$
  - Convection dredges up He
  - Fluctuations due to alternating H- and He-burning shells
- 5.0 $M_\odot$
  - Convection dredges up CNO elements
  - Fluctuations due to He-shell flashes
  - C continues to be created via the 3α process in the H shell



M = 2.5 M⊙ Z = 0
M = 5.0 M⊙ Z = 0
log Teff
log L/L⊙
Teff
L
LHe/L
LH/L
Li/L
Lpp/LH
log t/10⁸ yr
3.698
3.6985
0.7505
0.751

Final Surface Composition



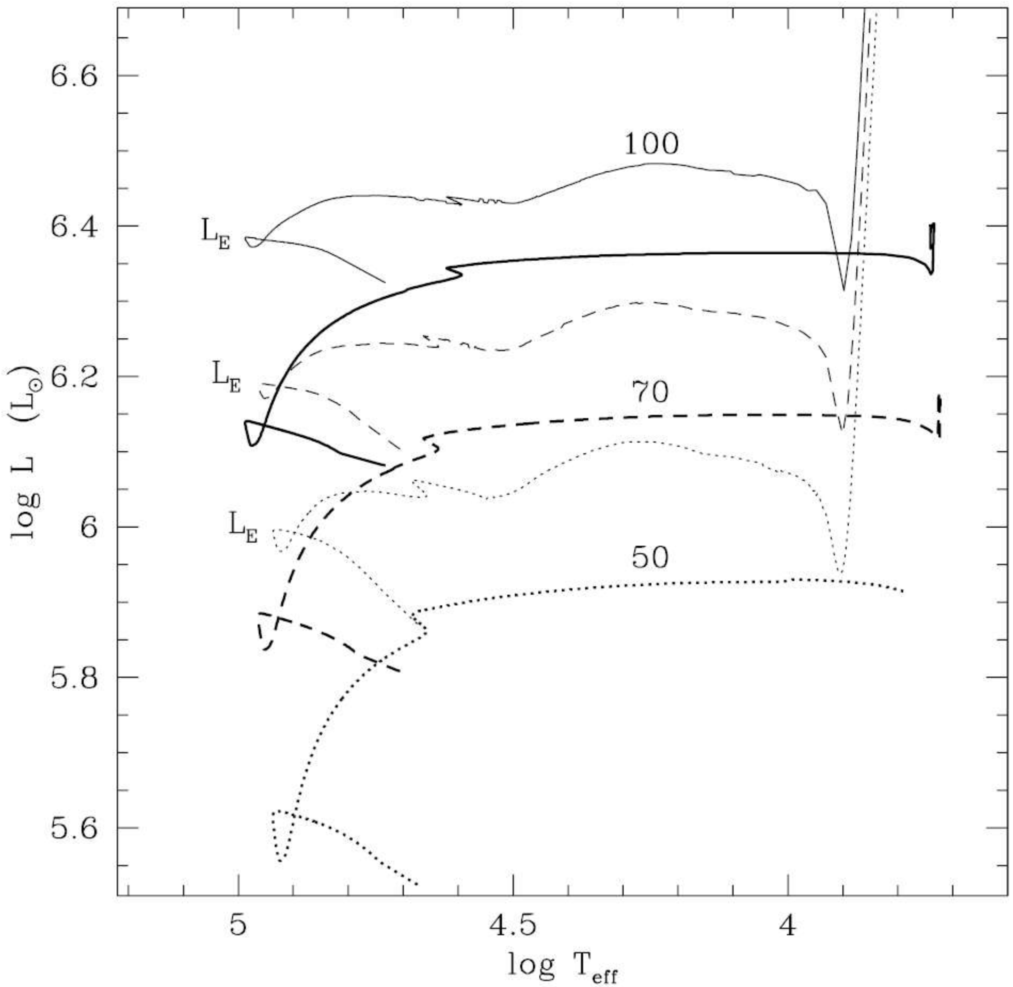


Dredge-up occurs for 2.1 < M < 8 and 70 < M < 100

8.3 < M < 50 stars ignite carbon before the giant branch, so they do not experience dredge-up.

Mass Loss?

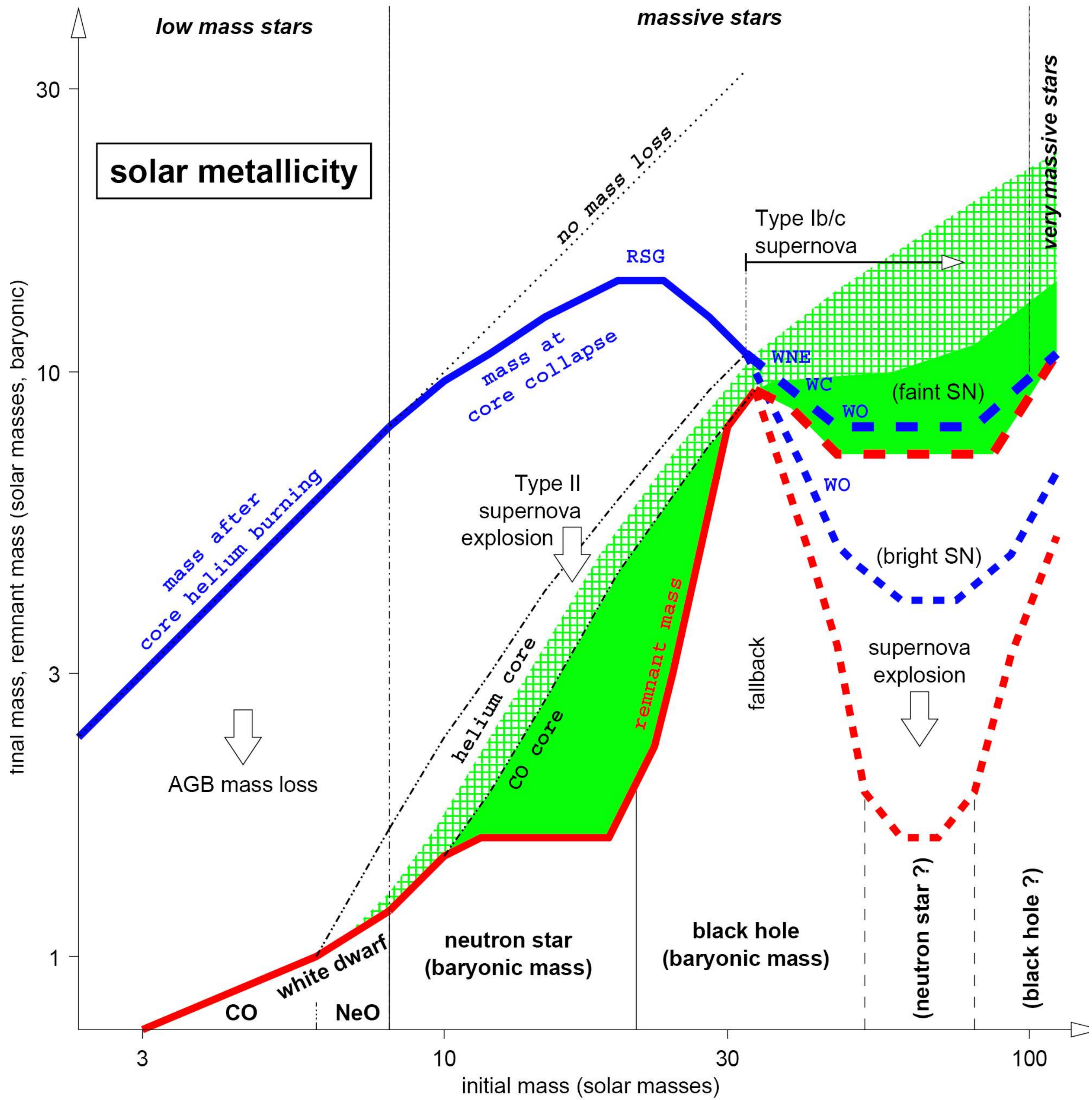
- Super-Eddington Luminosities in High-Mass stars?

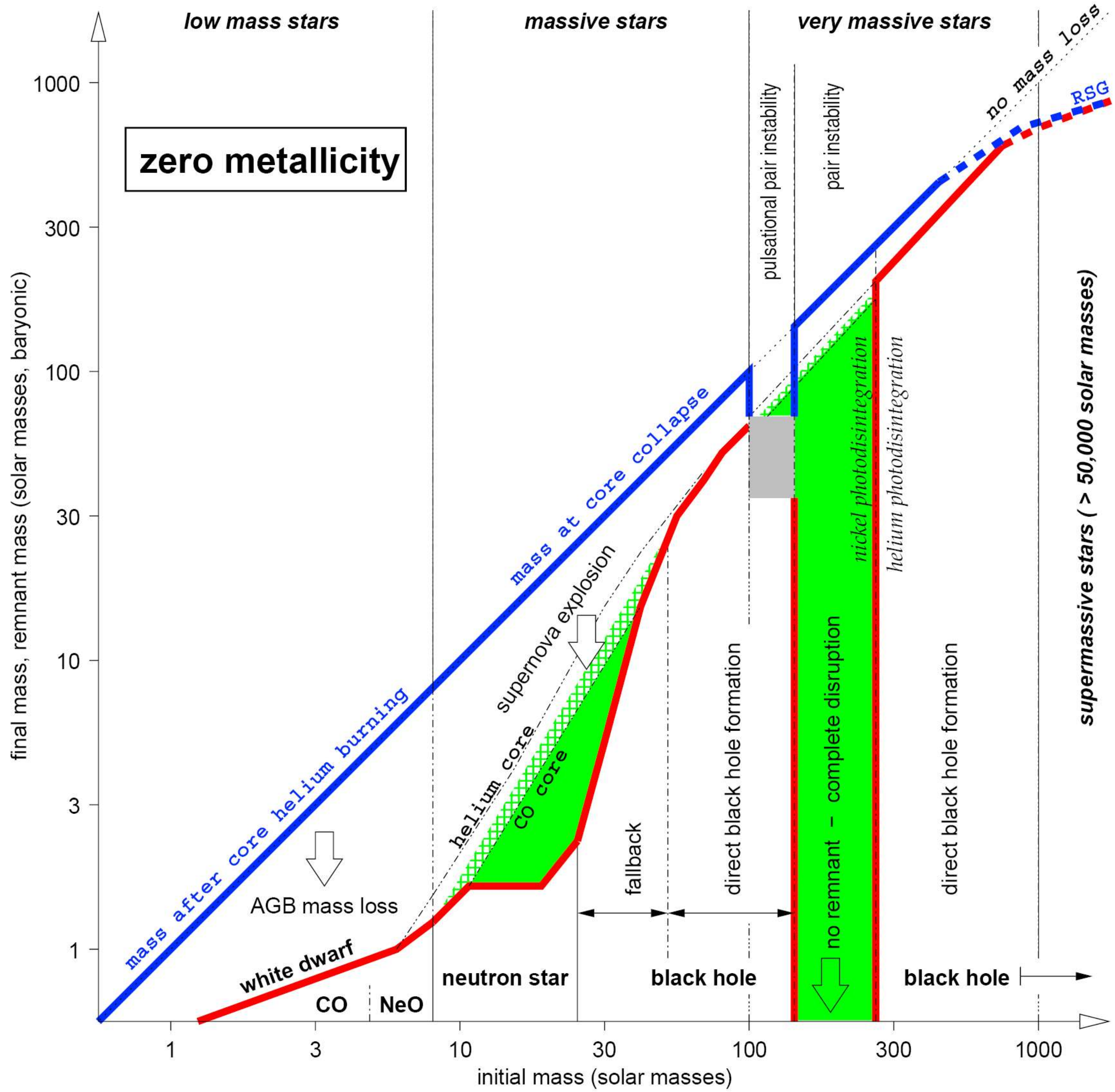


Mass Loss?

- Mass loss via stellar winds is unlikely
  - In massive stars, usually driven by radiation pressure on resonance lines of heavier ions
  - In low-mass stars, usually driven by radiation pressure on dust grains
- Mass loss on the AGB is also unlikely
  - Riemer's mass loss ~ LR/M; the masses are huge and the effective temperatures are high (so R is small)

The Fate of Population III Stars


low mass stars
massive stars
very massive stars
solar metallicity
no mass loss
RSG
mass at
core collapse
mass after
core helium burning
Type Ib/c
supernova
WNE
WC
WO
(faint SN)
WO
(bright SN)
Type II
supernova
explosion
helium core
CO core
remnant mass
fallback
supernova
explosion
AGB mass loss
white dwarf
CO
NeO
neutron star
(baryonic mass)
black hole
(baryonic mass)
(neutron star ?)
(black hole ?)
final mass, remnant mass (solar masses, baryonic)
initial mass (solar masses)
30
10
3
1
3
10
30
100


low mass stars
massive stars
very massive stars
zero metallicity
no mass loss
RSG
1000
300
100
30
10
3
1
final mass, remnant mass (solar masses, baryonic)
mass after core helium burning
mass at core collapse
pulsational pair instability
pair instability
nickel photodisintegration
helium photodisintegration
supermassive stars (> 50,000 solar masses)
supernova explosion
helium core
CO core
AGB mass loss
white dwarf
CO
NeO
fallback
direct black hole formation
no remnant – complete disruption
direct black hole formation
neutron star
black hole
black hole
1
3
10
30
100
300
1000
initial mass (solar masses)

Pair Instability Supernovae

- After He burning, high-mass cores are mostly ^{16}O
- C, Ne start to burn radiatively (no convective core forms)
- By the time the Ne is depleted, the star starts to collapse at 1000 km/s
- Energy from the collapse does not raise the temperature, but creates pairs
- The structural adiabatic index drops below 4/3, and the collapse accelerates

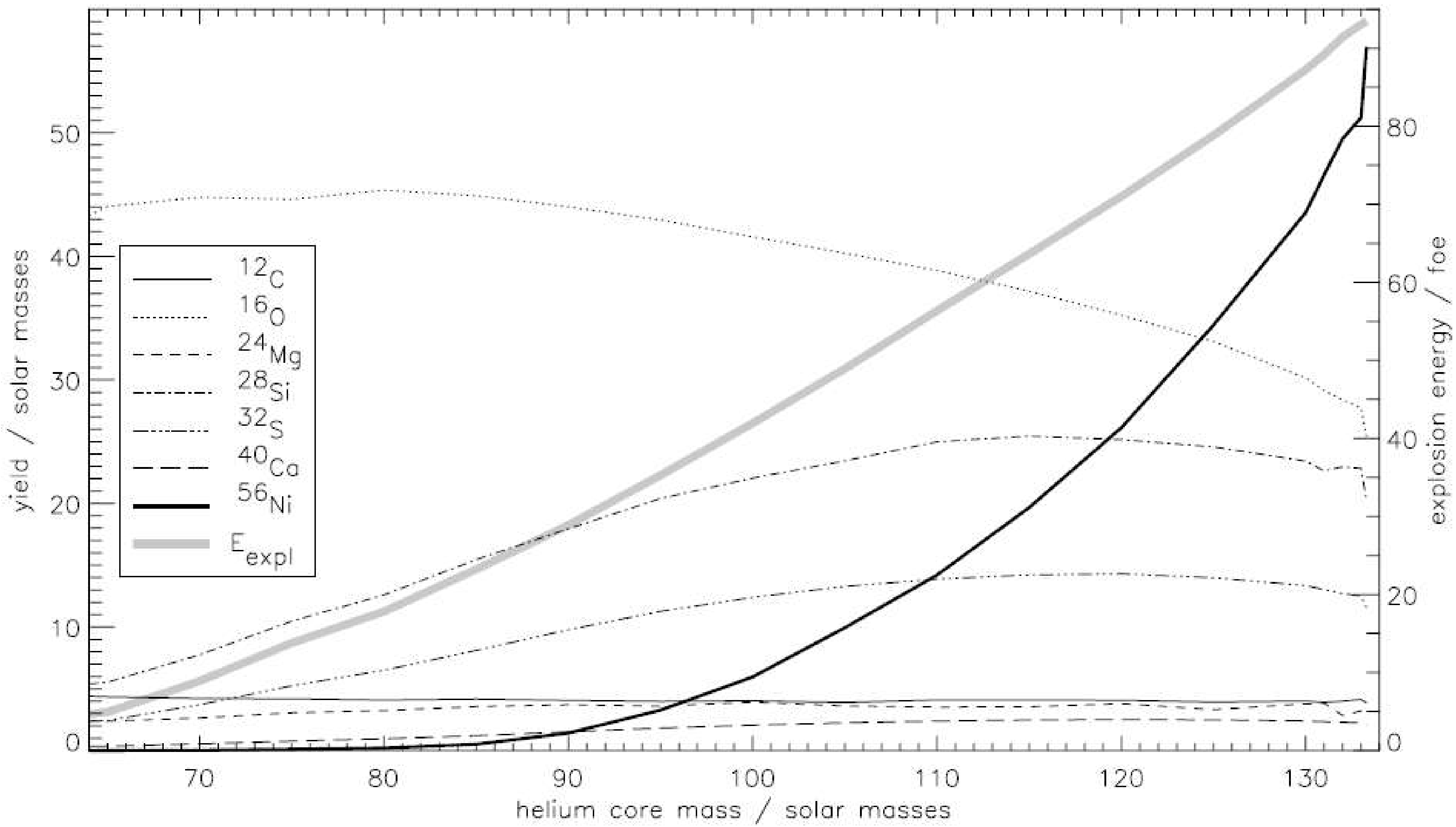
Pair Instability Supernovae

- Explosive oxygen burning occurs, but not until after the star overshoots the temperature and density necessary for TE, so the core rebounds
- These rebounds are extraordinarily energetic – 10^{51} ergs or more!
- The outer layers are ejected
- The star collapses again on a Kelvin-Helmoltz timescale, with no nuclear burning
- Further pulses may be expected

Pair Instability Supernovae

- 40 $M_\odot$ – 65 $M_\odot$: Pulsations continue for years or centuries
- 65 $M_\odot$ – 133 $M_\odot$: The entire star is disrupted by a single pulse
- > 133 $M_\odot$: Collapse to a black hole

Nucleosynthetic Yields



Pair Instability Supernovae - Example

- 63 $M_\odot$ He core:
  - First pulse
    - T = 3.2 x 10^9 K
    - P = 1.5 x 10^6 g cm^{-3}
    - E = 6.5 x 10^{51} ergs
    - ΔM = 12.8 $M_\odot$
  - Second pulse (4800 yrs later)
    - E = 1.3 x 10^{50} ergs
    - ΔM = 2.7 $M_\odot$

Pair Instability Supernovae - Example

- 63 $M_{\odot}$ He core:
  - Third pulse (8 days later)
    - $E = 5.1 \times 10^{50}$ ergs
    - $\Delta M = 2.2\ M_{\odot}$
  - The core contracts, Si burns, the core grows Fe, and collapses from the photodisintigration instability, and becomes a black hole
  - Such supernovae might not be bright (no radioactive elements), unless the puffed-off shells run into each other

Further Uncertainties

- How important is mass loss in Pop. III stars? During which phases of evolution do these stars lose mass?
- What is the IMF of Pop. III stars?
- What is the rate of formation of ^{16}O?
- Computer simulations of opacities

Next time, on Astronomy 534…

- How do we detect these stars or infer their existence?
- Do any of these stars still exist?

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