# Evolution of Metal-Poor Massive Stars
# (低金属大質量星の進化)

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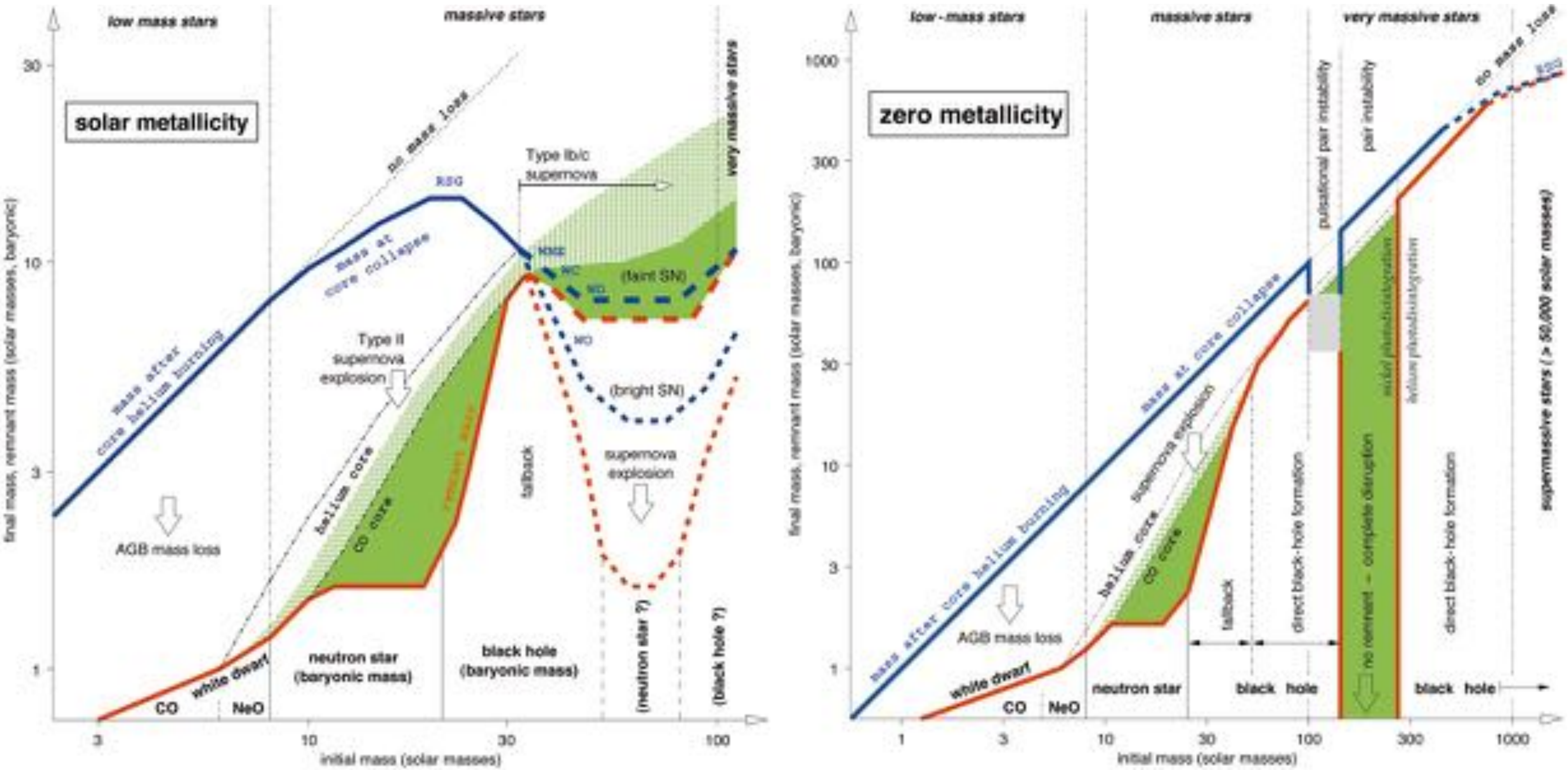
# Final Structures of $Z = Z_\odot$ and 0 Stars




(Woosley et al. 2002)

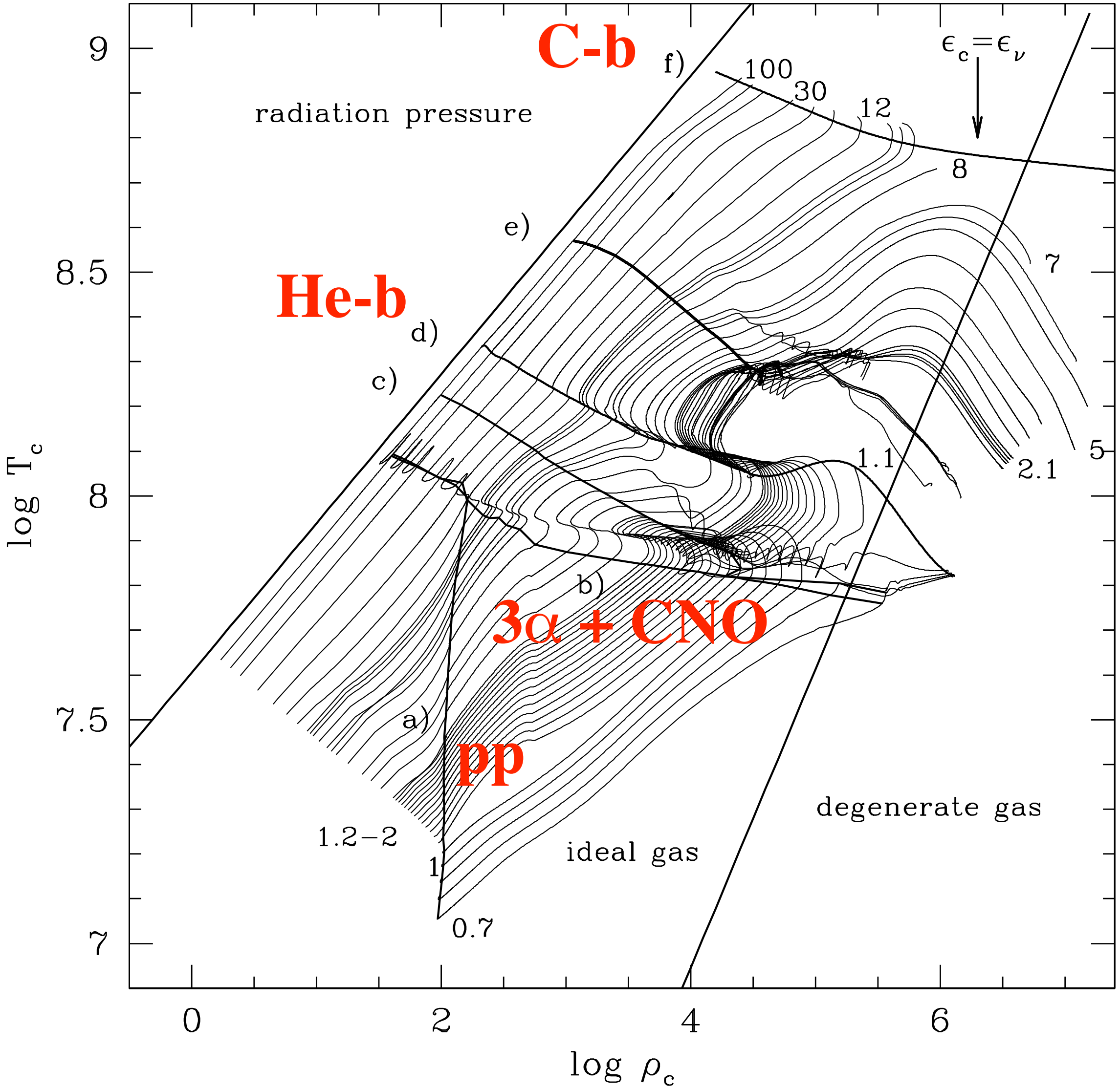
- H and He burnings
- Evolution to red/blue supergiants
- No or less effective mass loss
- Pair instability SNe and pulsational pair-instability

# Evolution of Metal-Poor Massive Stars

- Metal-free ($Z$=0) massive stars
  - H and He burnings
  - Evolution to red/blue supergiants
  - Effect of rotation
    - → Evolution to red/blue supergiants
    - → Production of N and odd-$Z$ elements in H shell burning
    - → Chemically homogeneous evolution
  - Pair instability SNe
- Massive stars with $Z \leqq 10^{-4}$
  - Evolution to red/blue supergiants
  - Current status of our study on metal-poor massive stars

# H and He burnings in $Z$=0 Stars

- Evolution on log $T_C$ - log $\rho_C$ diagram



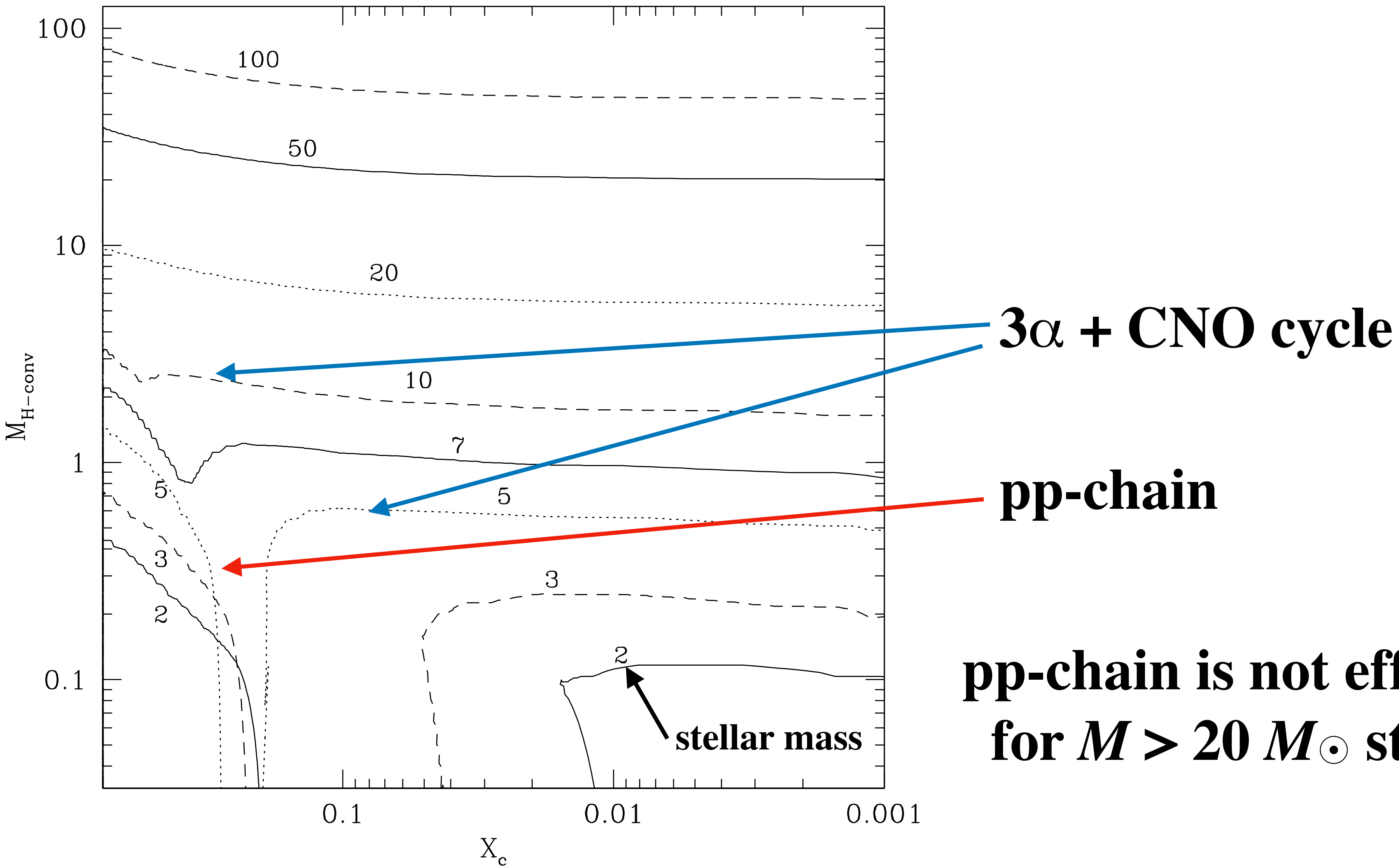

(Marigo et al. 2001)

No CNO elements in $Z$ = 0 stars

- pp-chain
- 3α reaction + CNO cycles

# H and He burnings in $Z$=0 Stars

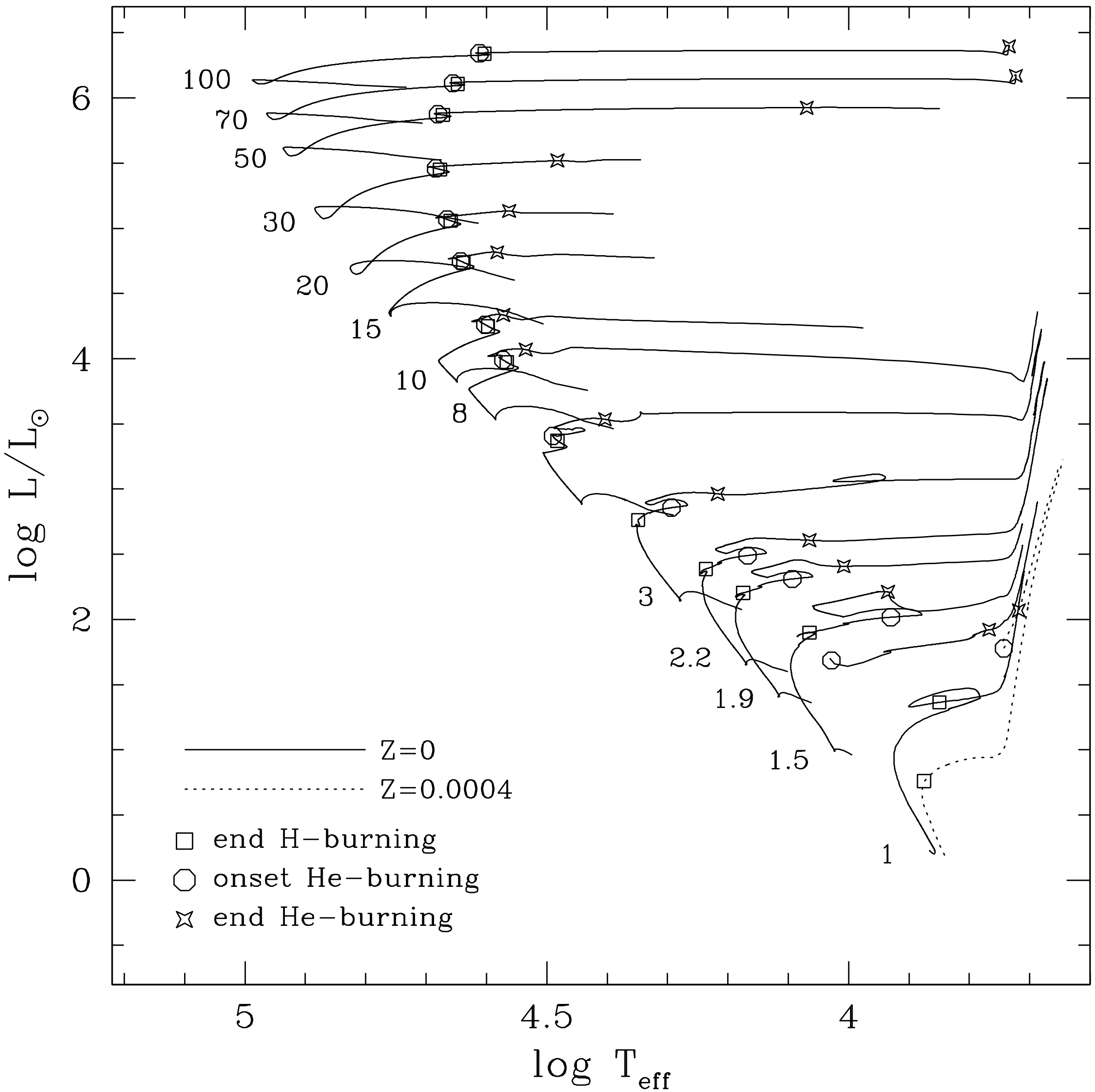
- **Evolution on convective core during H burning**




**pp-chain is not effective for $M$ > 20 $M_\odot$ stars.**

**(Marigo et al. 2001)**

# HR diagram of Z=0 Stars




(Marigo et al. 2001)

- **Blue supergiant**

  **$10 < M < 50\ M_\odot$**

- **Red supergiant**

  **$M < 10\ M_\odot$**

  **after He burning**

  **$M > 50\ M_\odot$**

  **during He burning**

**Fig. 2.** Zero-metal evolutionary tracks (solid lines) for selected initial masses (in $M_\odot$) as indicated. The evolutionary track of the ($1\ M_\odot$, $Z = 0.004$) model, calculated by Girardi et al. (2000), is also shown for comparison (dotted line)

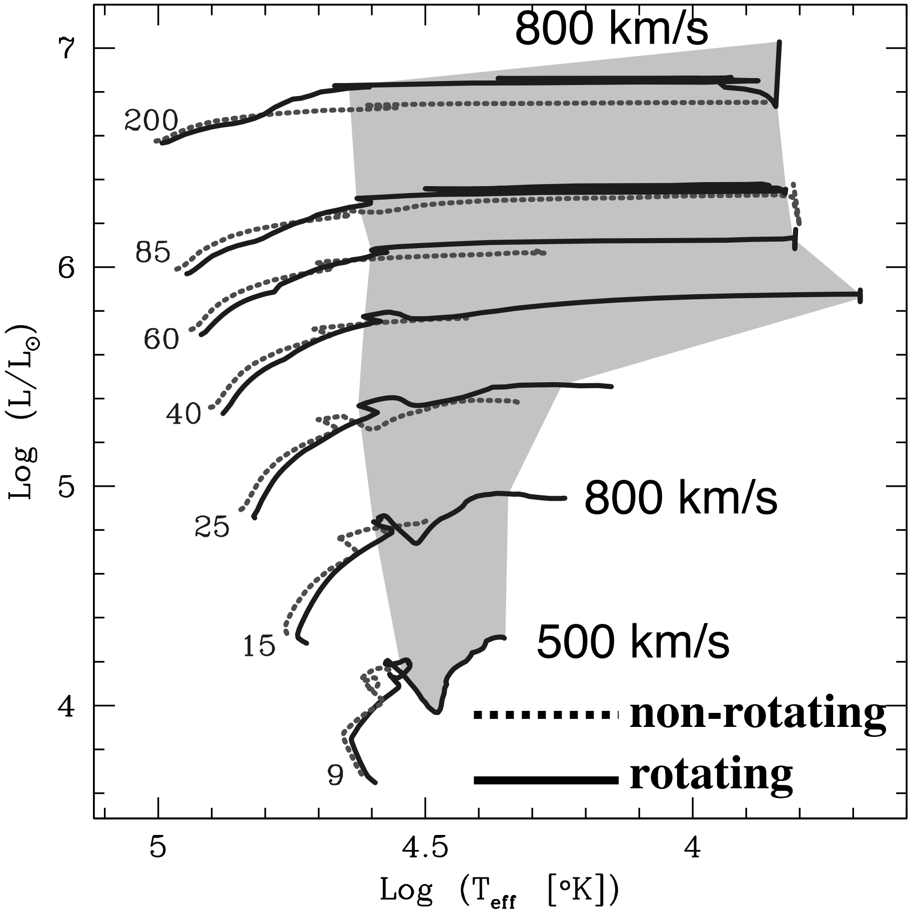
# Effect of Rotation

- Effect of rotation
  - Extra mixing
    - Meridional circulation and horizontal turbulence
      - → (Larger cores)
      - → Favoring red-ward evolution(?), Homogeneous chemical evolution
      - → Strong H shell burning
  - Mass loss

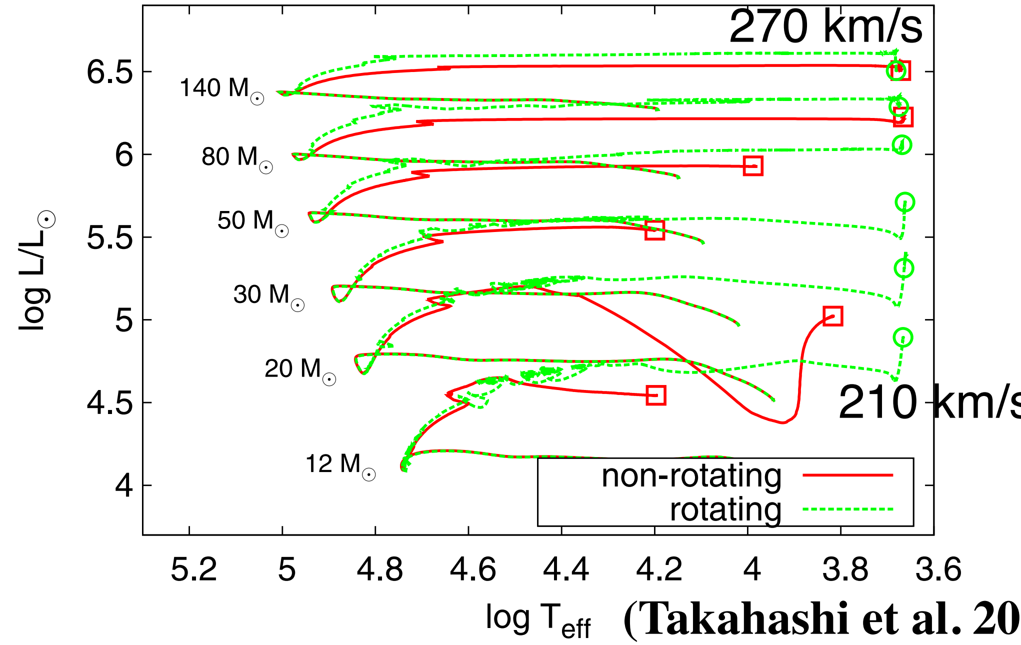
- Different treatment of angular momentum transport
  - Advection → Genec, Franec
  - Diffusion approximation → Kepler, MESA, HOSHI

# Effect of Rotation

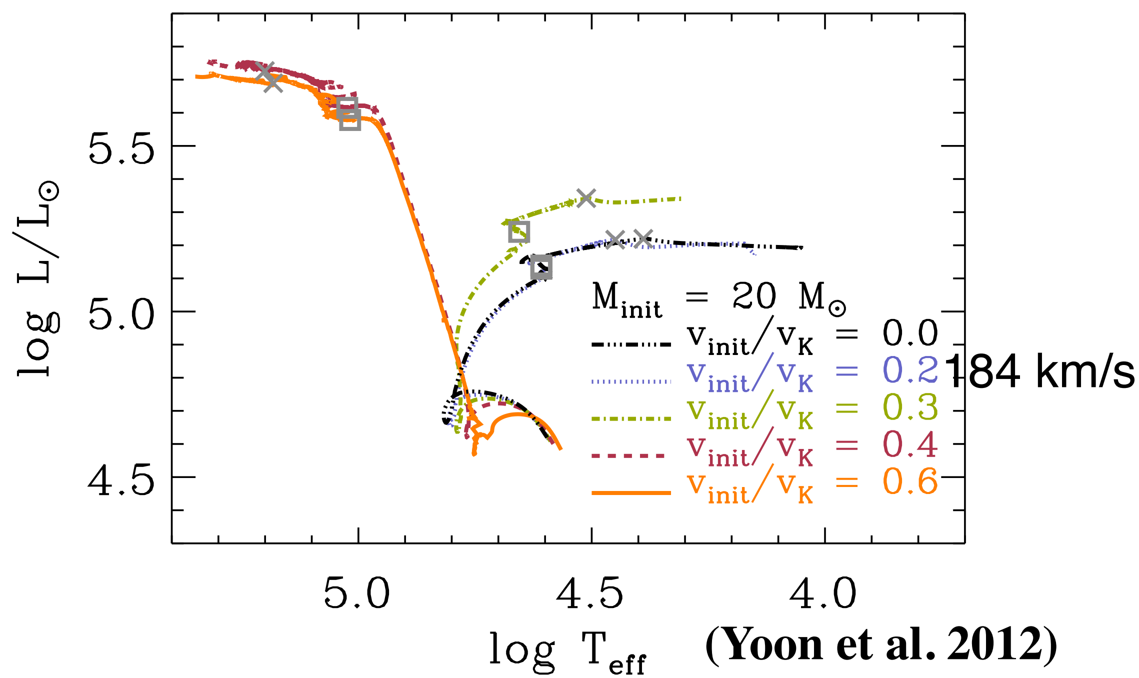
- **HR-diagram**




(Ekström et al. 2008)



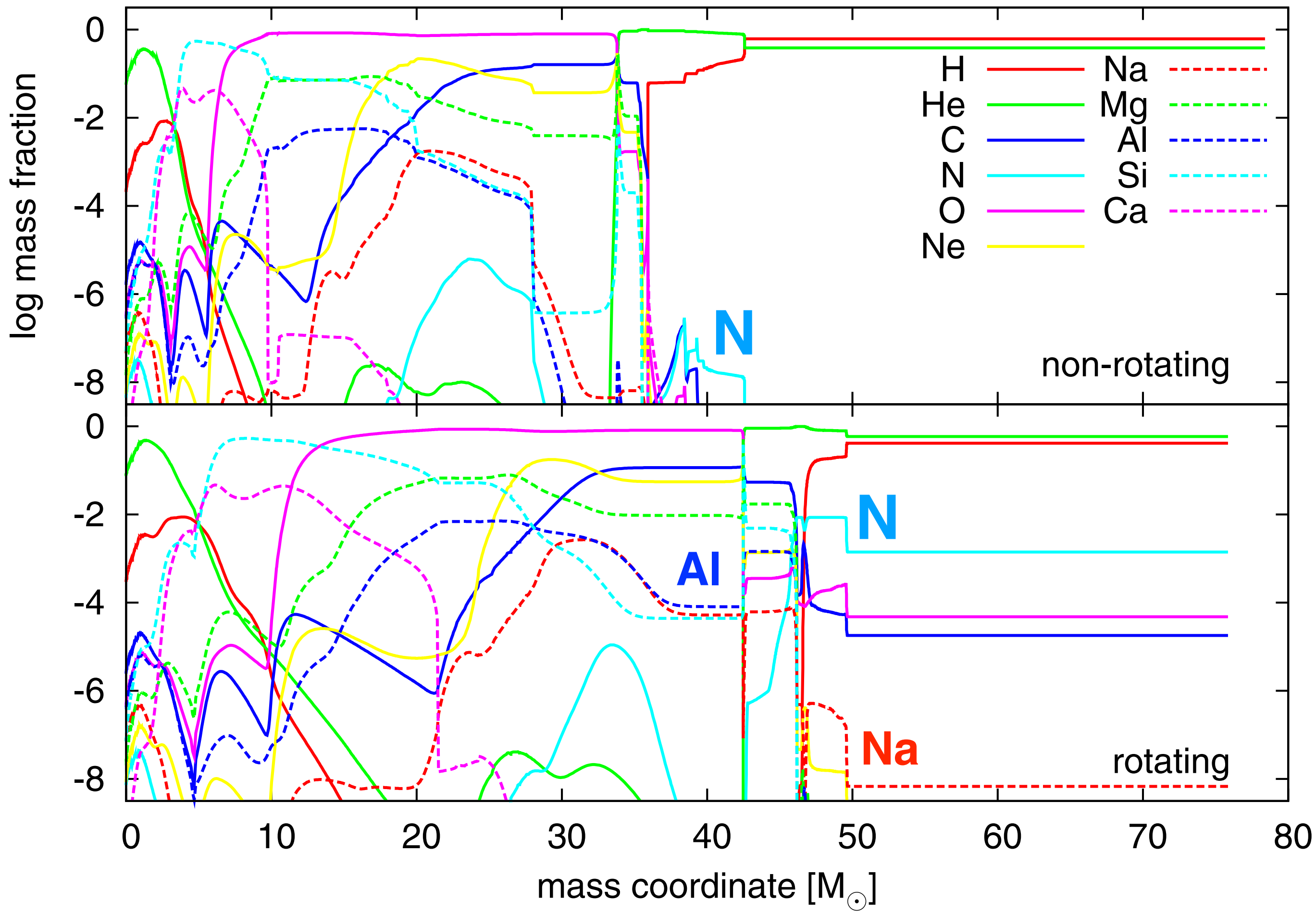

(Takahashi et al. 2014)




(Yoon et al. 2012)

# Effect of Rotation

- Nucleosynthesis through strong H shell and He burnings



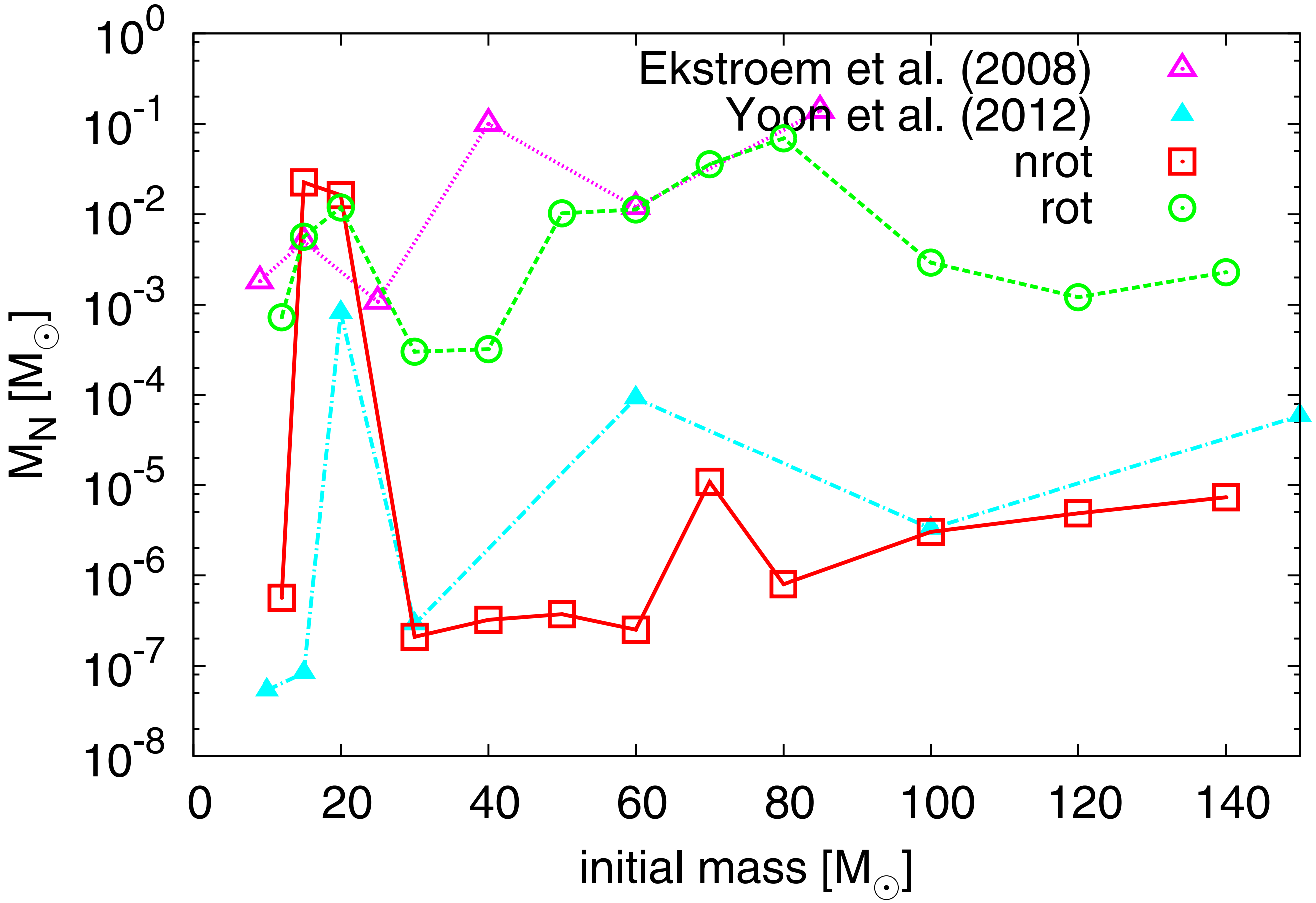

80 $M_\odot$ star

(Takahashi et al. 2014)

- Transport of CNO elements in He core to H shell by rotational mixing
  - → N production by CNO cycle in H shell
  - → Na and Al produced from $^{22}$Ne

# Effect of Rotation

- Nitrogen production is rotating Pop. III stars

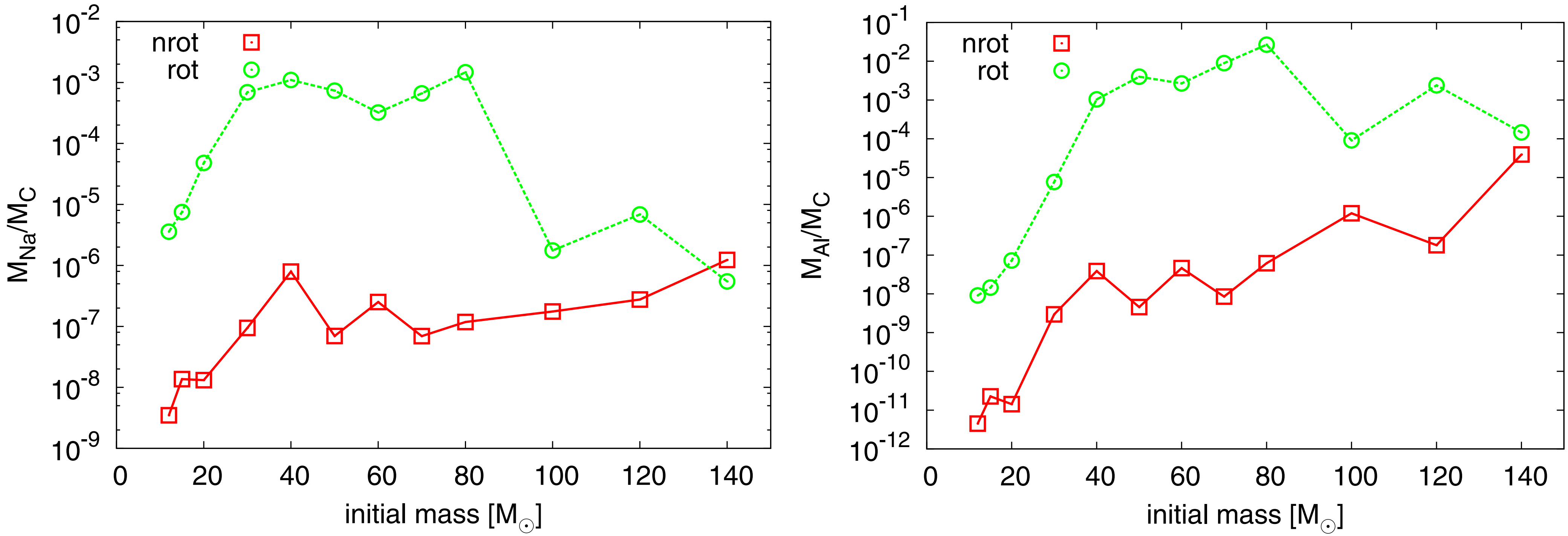



(Takahashi et al. 2014)

- $M_N \sim 10^{-4}$ - 0.1 $M_\odot$ in rotating models for Ekström+08, Takahashi+14
  Rotating models in Yoon+12 indicate less N enhancement.
- Proton ingestion to He shell in C-core burning
  → N production in non-rotating ~20 $M_\odot$ models

# Effect of Rotation

## Na and Al




**(Takahashi et al. 2014)**

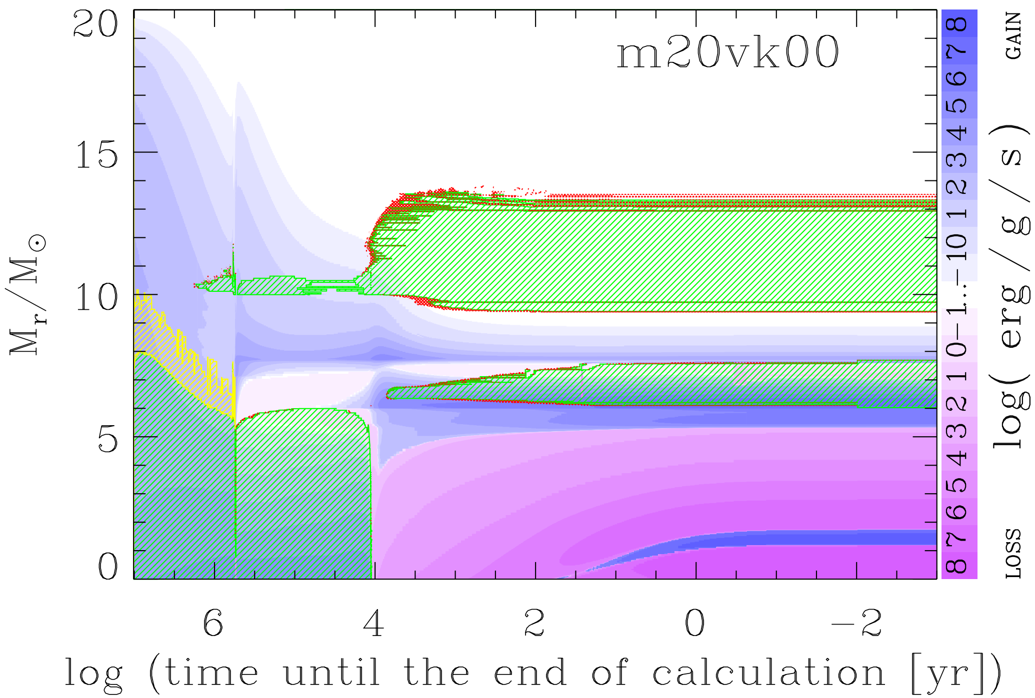
**$^{22}$Ne production:** $^{14}N(\alpha,\gamma)^{18}F(\beta^+)^{18}O(\alpha,\gamma)^{22}Ne$

- **Na** ➡ $^{22}Ne(n,\gamma)^{23}Ne(\beta^-)^{23}Na$
- **Al** ➡ $^{22}Ne(\alpha,n)^{25}Mg(n,\gamma)^{26}Mg(n,\gamma)^{27}Mg(\beta^-)^{27}Al$

# Effect of Rotation

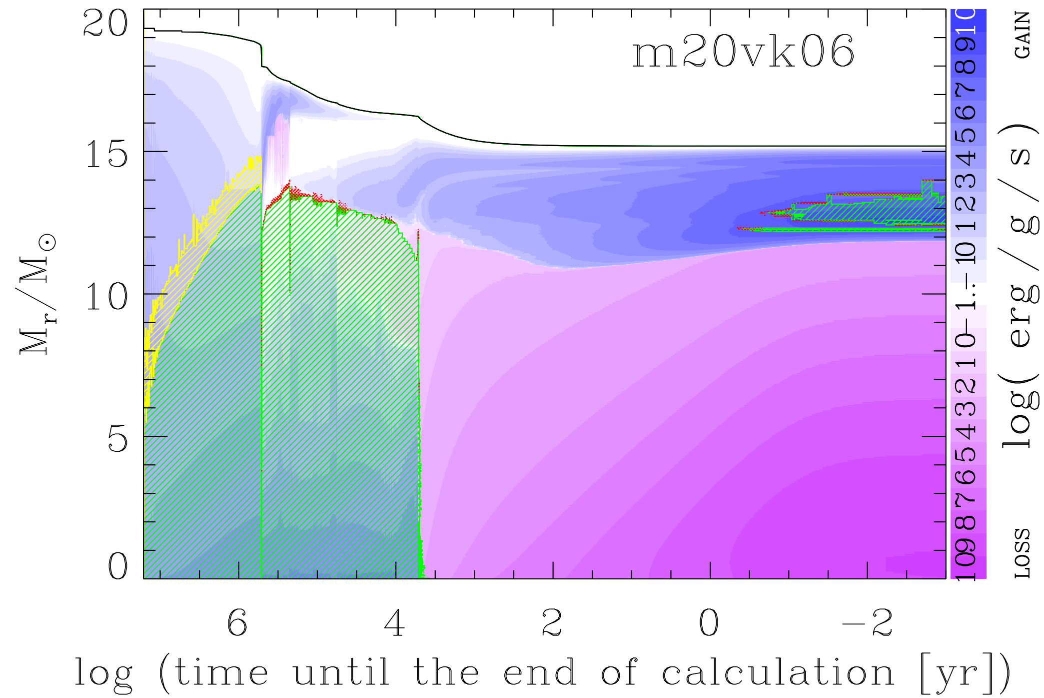
- **Chemically homogeneous evolution (CHE)**

  **Transport by meridional circulation and Spruit-Tayler dynamo**




**20 $M_\odot$ non-rotating**

**Normal evolution (NE)**




**20 $M_\odot$ rotating ($v_i/v_K = 0.6$)**

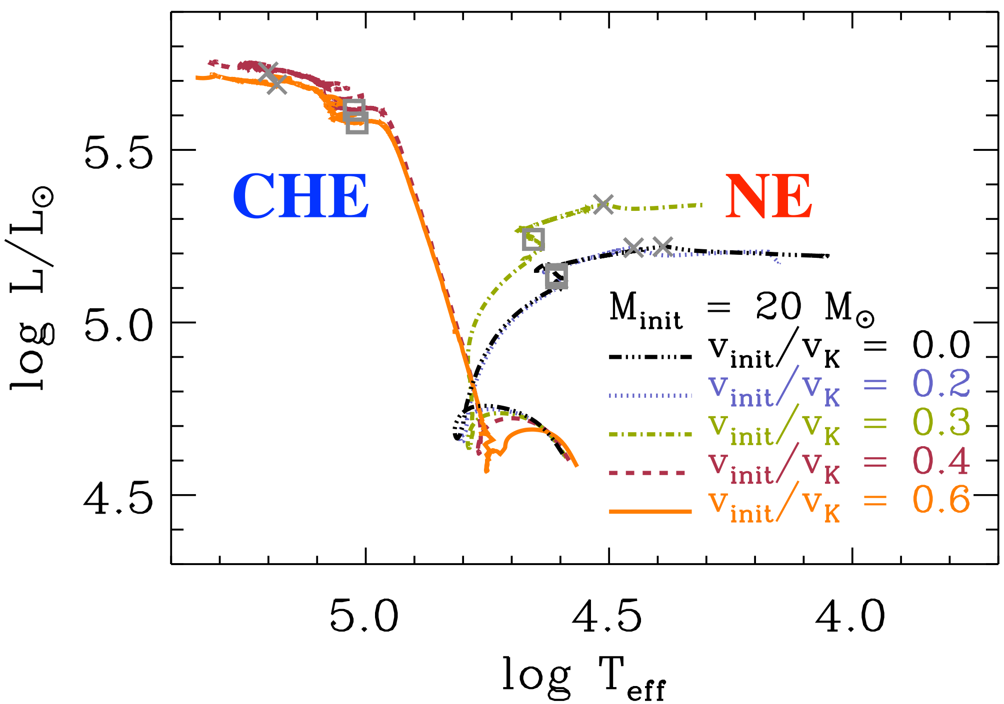
**CHE**

**(Yoon et al. 2012)**

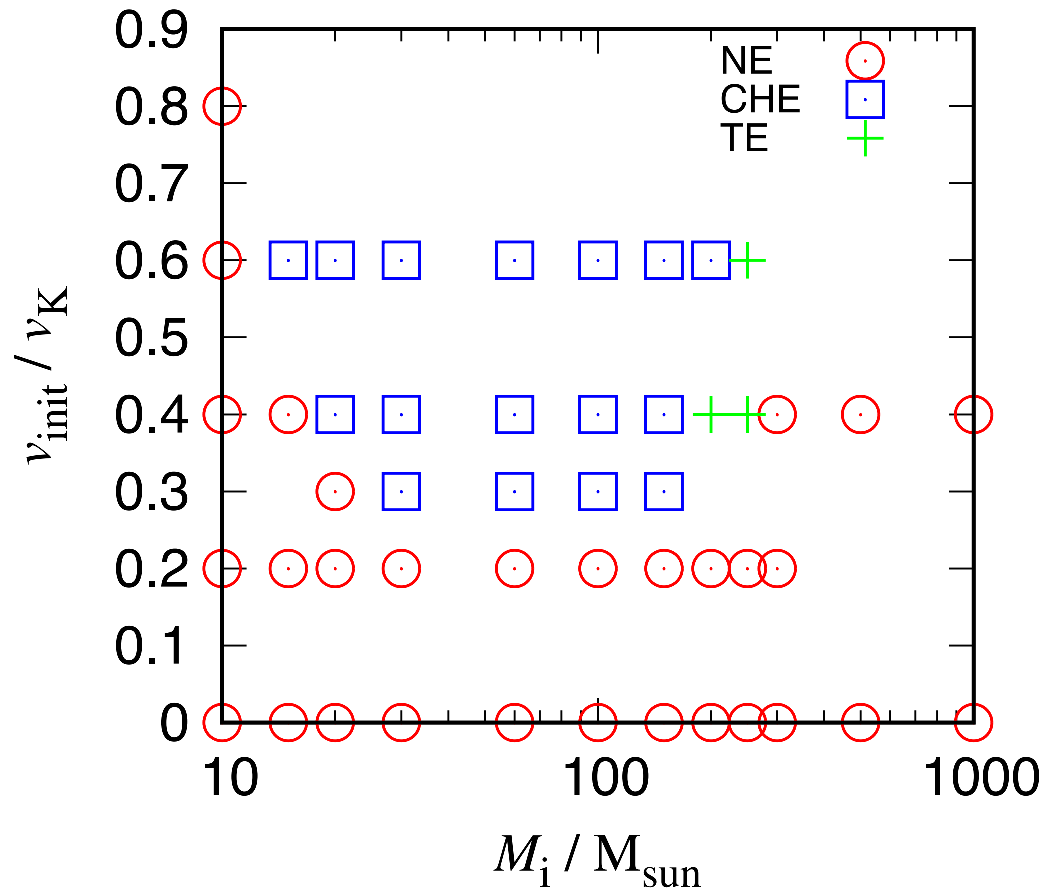
# Effect of Rotation

- **Chemically homogeneous evolution (CHE)**

**HR diagram for 20 $M_\odot$ models**




(Yoon et al. 2012)

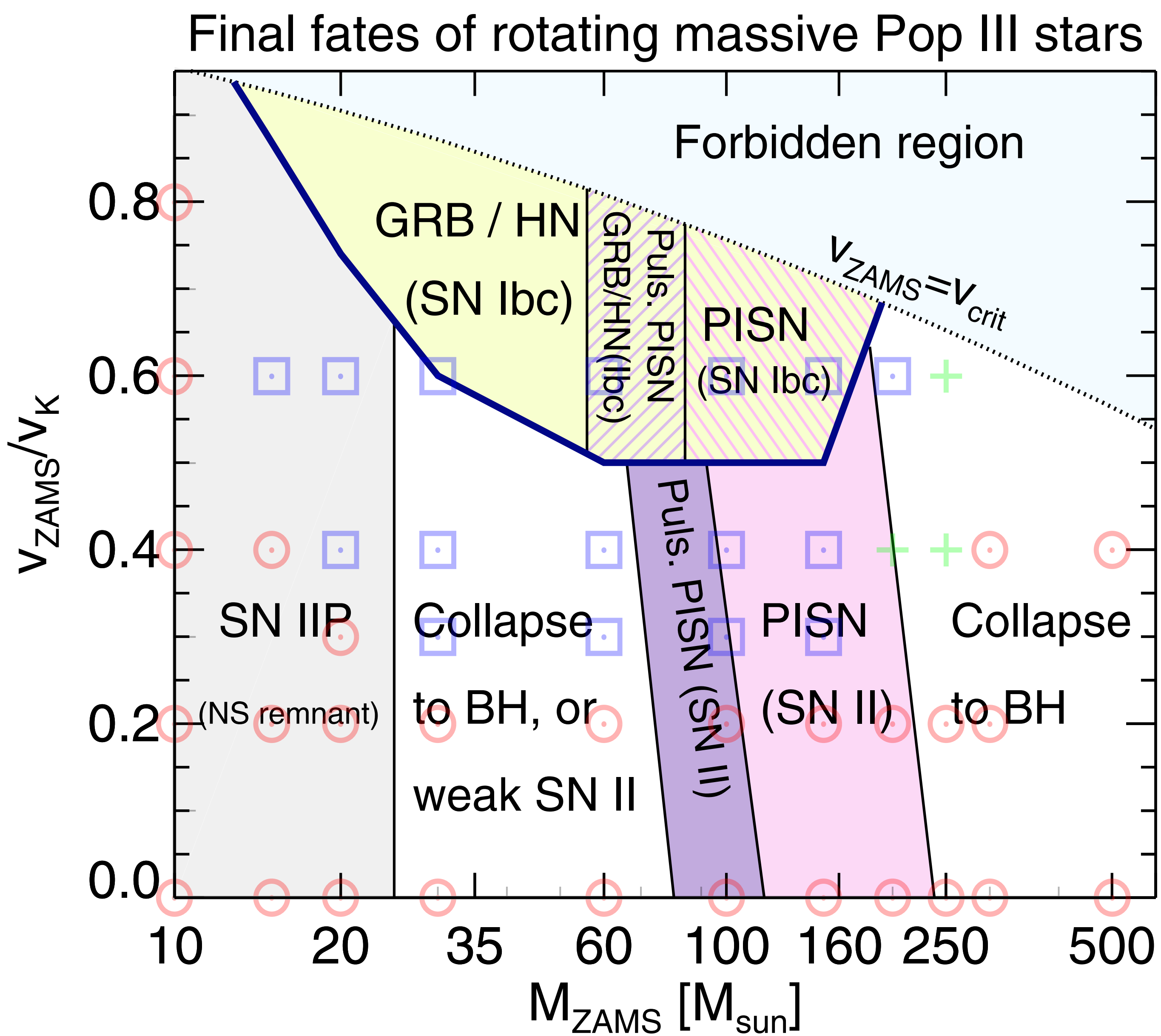



(Data from Yoon et al. 2012)

**TE: Transition evolution**

# Effect of Rotation

- **Final fates** (Yoon et al. 2012)

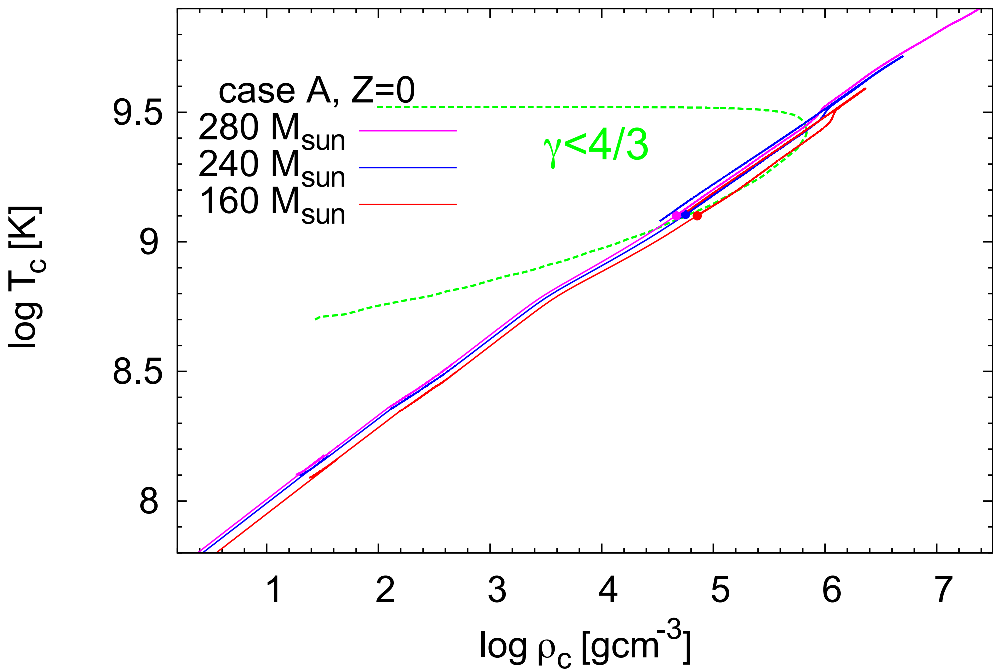


# Pair Instability SNe

- $e^-e^+$ pair production after C burning ➡ Dynamical evolution
  ➡ O and Si burnings for a very short time scale (~ a few minutes)
  ➡ Pair instability supernova!

Mass range ➡ $M_{He} \sim 64 - 133\ M_\odot$ (Heger & Woosley 2002)

$M \sim 145 - 260\ M_\odot$ (Takahashi et al. 2016)



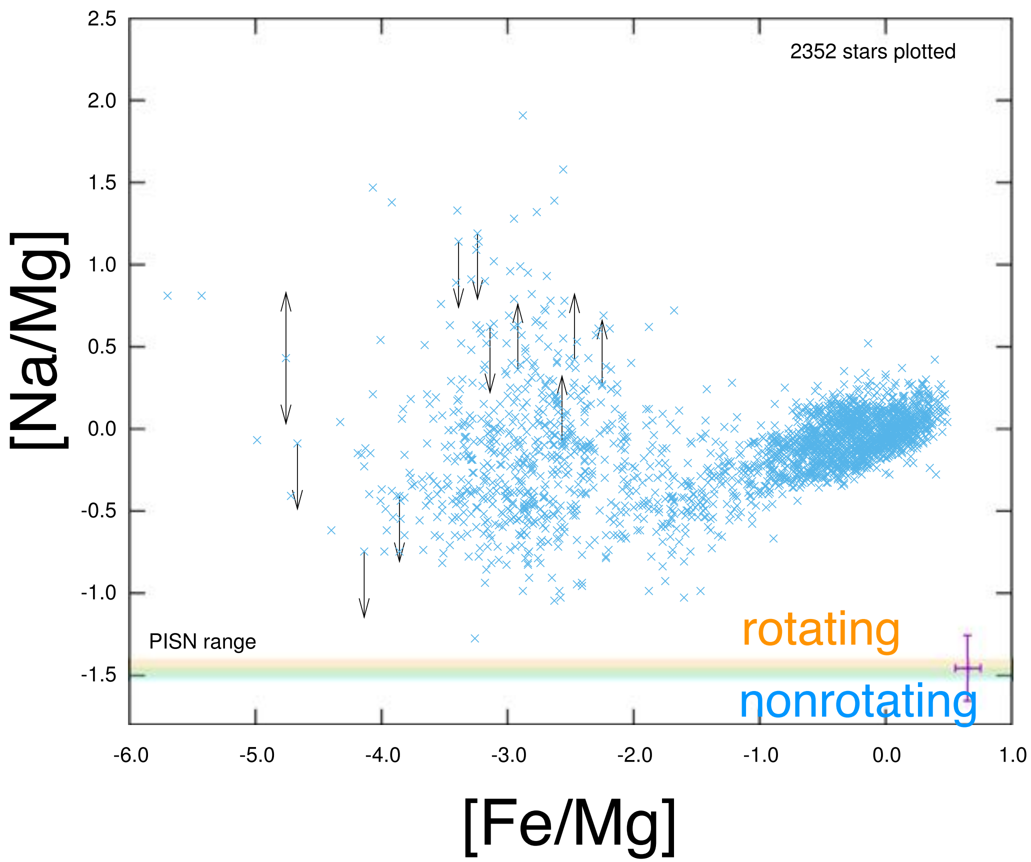

(Takahashi et al. 2016)

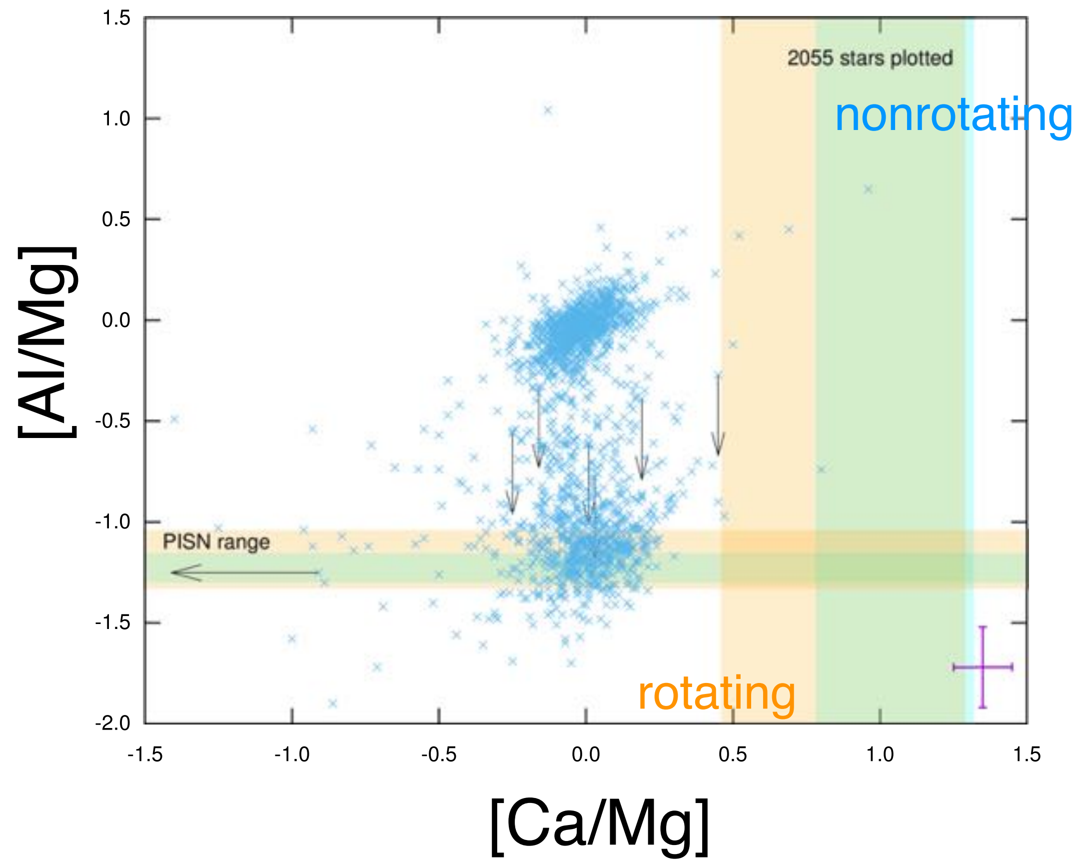
- Pulsational pair instability ➡ Eruptive mass loss
  (Woosley et al. 2007; Yoshida et al. 2016)
  $M_{He} \sim 40 - 64\ M_\odot$ (Heger & Woosley 2002)

# Yields of Pop. III Pair Instability SNe

- **No current observed metal-poor star matches with the PISN abundance.**

(Takahashi et al. 2018)



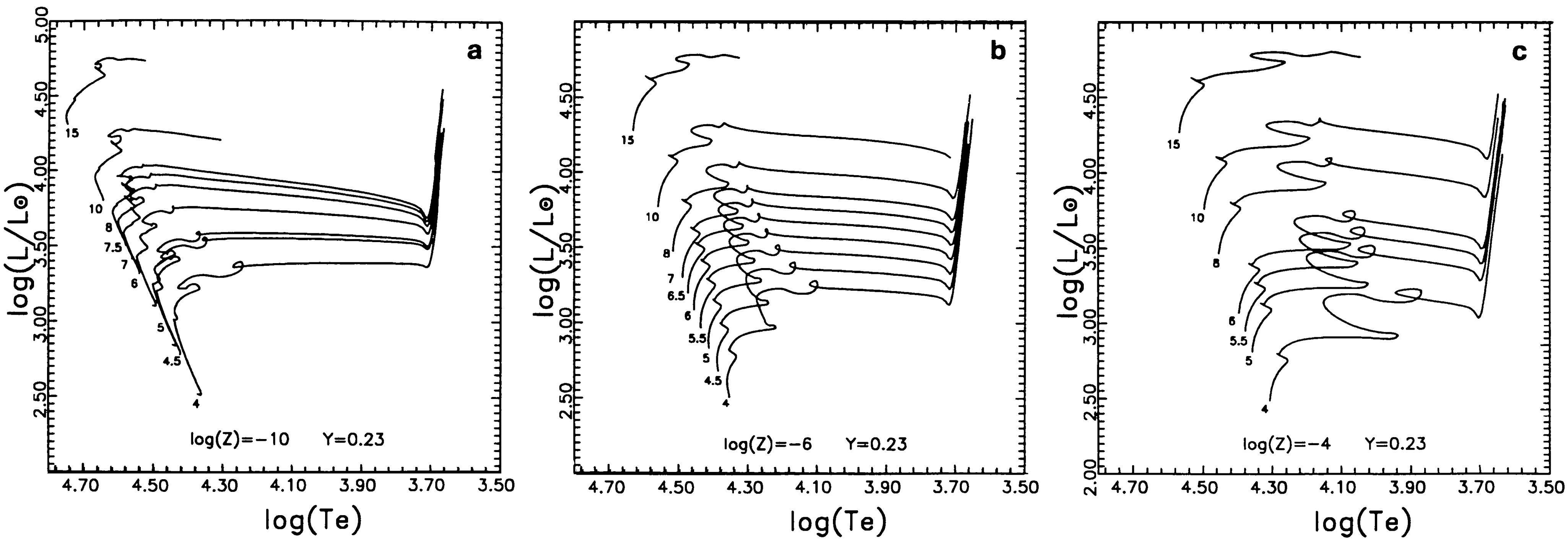

- **No significant difference between rotating and nonrotating models.**

→ **[Na/Mg] ~ -1.5; [Ca/Mg] ~ 0.5 - 1.3**

# Evolution of Metal-Poor Stars

- **Evolution of Z = $10^{-10}$ - $10^{-4}$ stars up to C ignition**

**(Cassisi & Castellani 1993)**




- **Favoring red-ward evolution for higher *Z* massive stars**

**Similar *Z* dependence is also seen in Hirschi (2007).**

# $Z$ Dependence of Massive Star Evolution

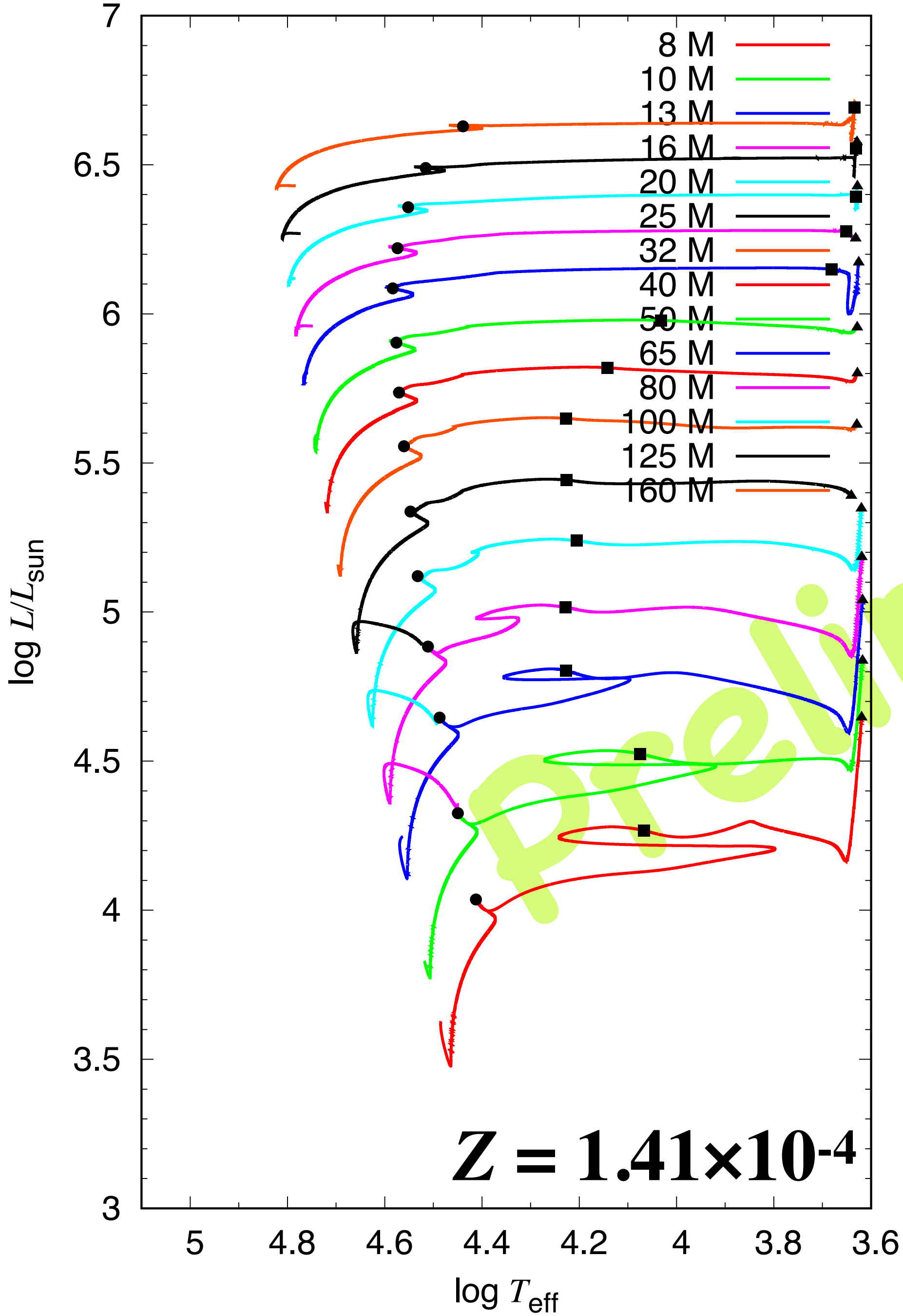
- **Evolution of metal-poor massive stars up to central C-burning**

  (TY, Tanikawa, Kinugawa, Umeda, Takahashi, in prep.)

  - **Stellar evolution code:**
    **HOngo Stellar Hydrodynamics Investigator (HOSHI) code (tentative)**

  - **Initial mass:**
    $M_i$ = 8, 10, 13, 16, 20, 25, 32, 40, 50, 65, 80, 100, 125, 160 $M_\odot$
  - **Metallicity:** $Z = 1.41\times(10^{-10}, 10^{-8}, 10^{-7}, 10^{-6}, 10^{-4})$
  - **Evolution from ZAMS until log $T_C$ = 9.0 [K]**
  - **Calibration of overshoot parameter: similar to Brott et al. (2011)**
  - **No mass loss**

# HR diagram




- $Z = 1.41\times10^{-10}$

  **$10 < M < 50\ M_\odot$ stars**

  ➡ **Blue/yellow supergiant**

- $Z = 1.41\times10^{-8}$ -> $1.41\times10^{-6}$

  ➡ **Toward red supergiant**

**These models will be used for population synthesis.**

# Summary

- Metal-free ($Z$=0) massive stars
  - pp chain and 3α+CNO cycle in H burning
  - Blue supergiants in ~ 10 - 50 $M_\odot$ (depending on overshoot parameter)
  - Effect of rotation
    - ➡ Favoring red-ward evolution
    - ➡ Production of N and odd-$Z$ elements in H shell burning
    - ➡ Chemically homogeneous evolution
  - Pair instability SNe
    - ➡ No current observed metal-poor star having PISN abundance
- Massive stars with $Z \leqq 10^{-4}$
  - Higher $Z$ stars favor red-ward evolution for $Z \sim 10^{-8}$ - $10^{-6}$