Stellar Evolution at Low-Metallicity

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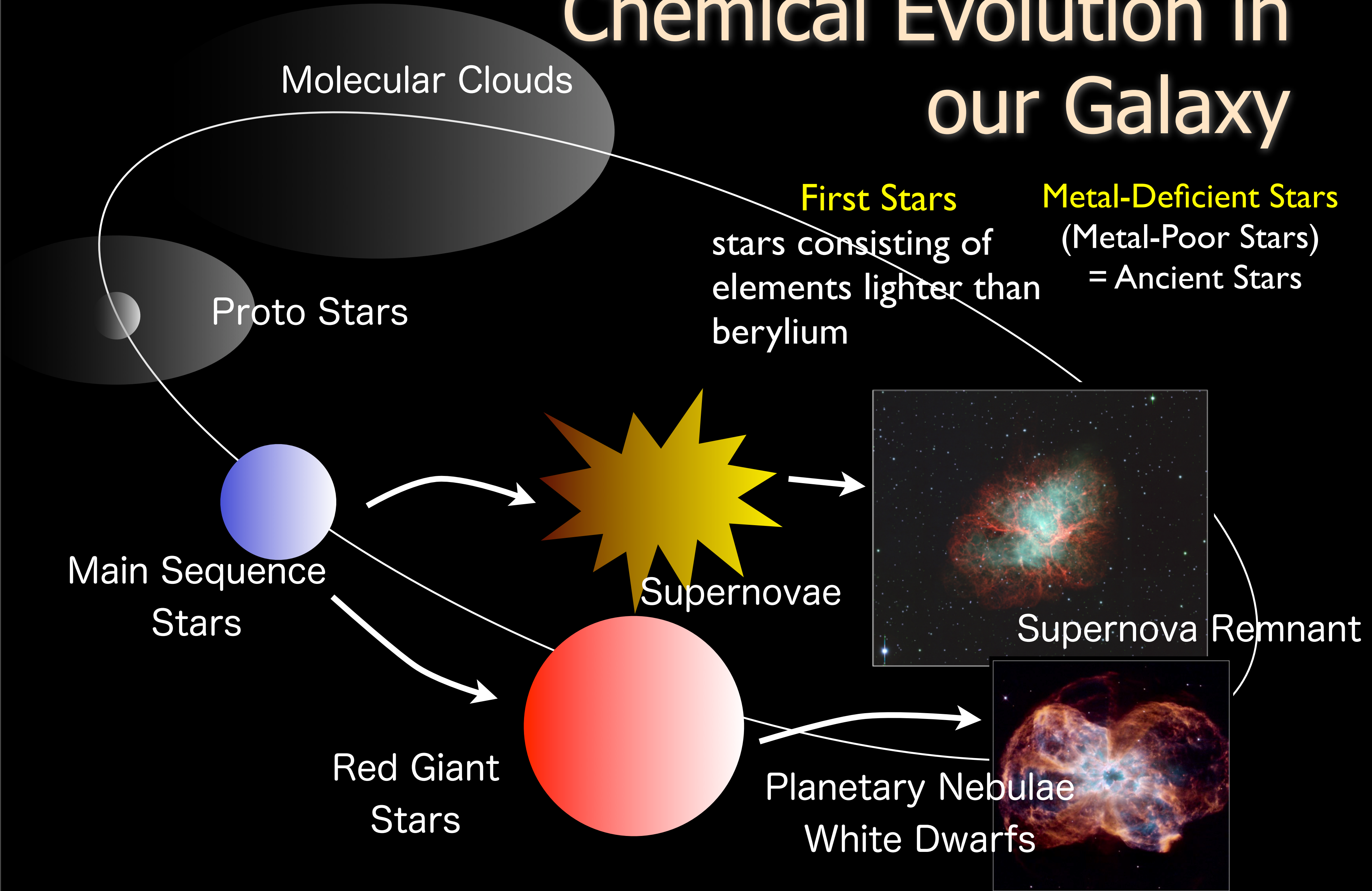
Chemical Evolution in our Galaxy



NGC2440 : from HST
Crab nebula : from Subaru

Metallicity Distribution Function

HE0107-5240 : -5.3

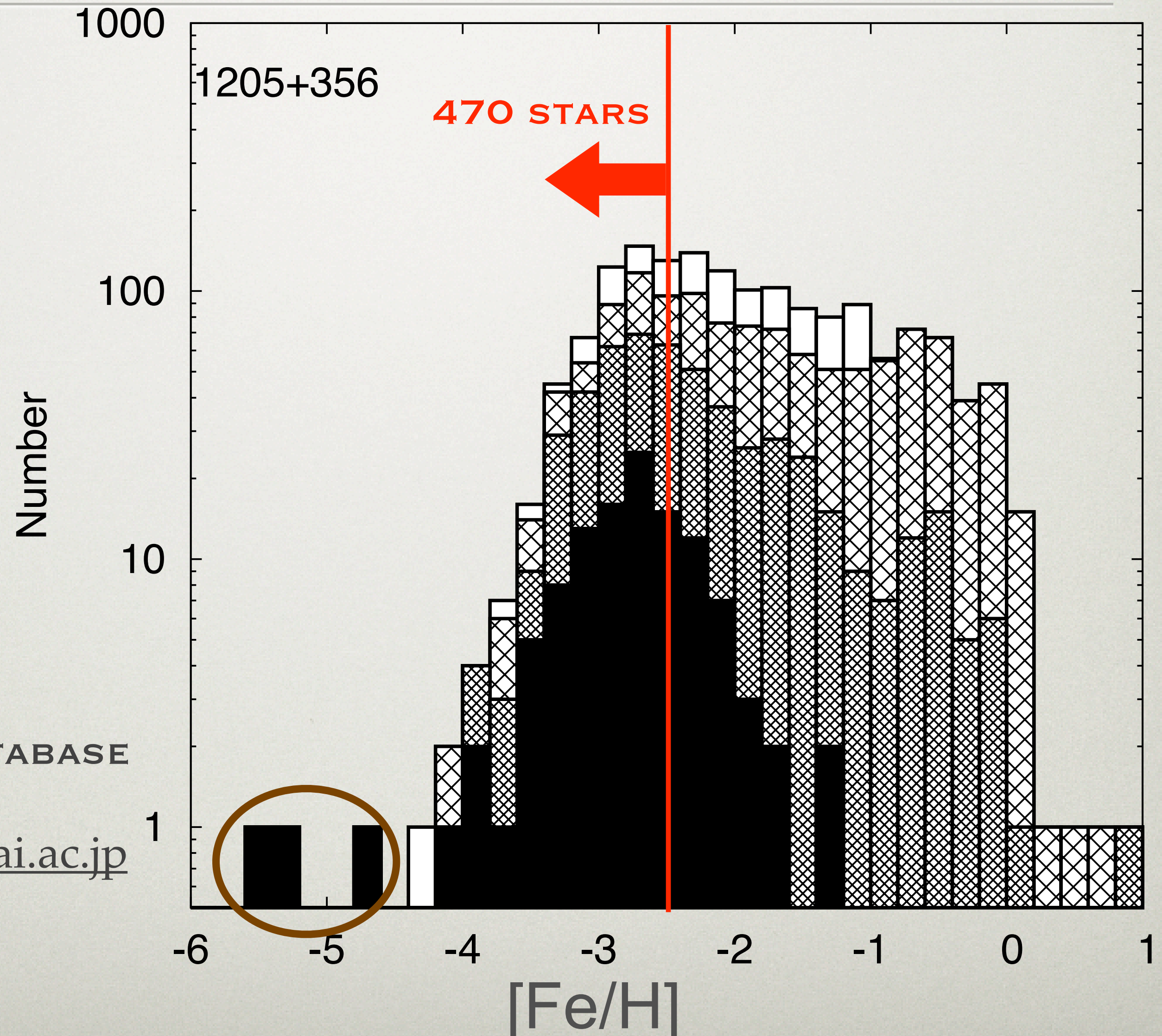
: Christlieb et al. (2002)

HE1327-2326 : -5.4

: Frebel et al.(2005), Aoki et al.(2006)

HE0557-4940 :

-4.8 : Norris et al. (2007)

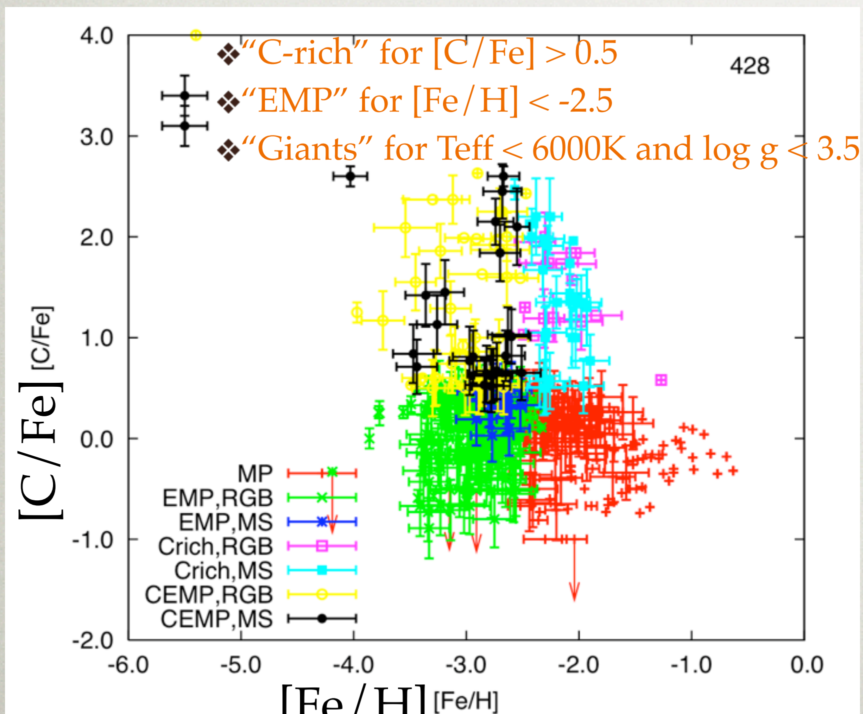


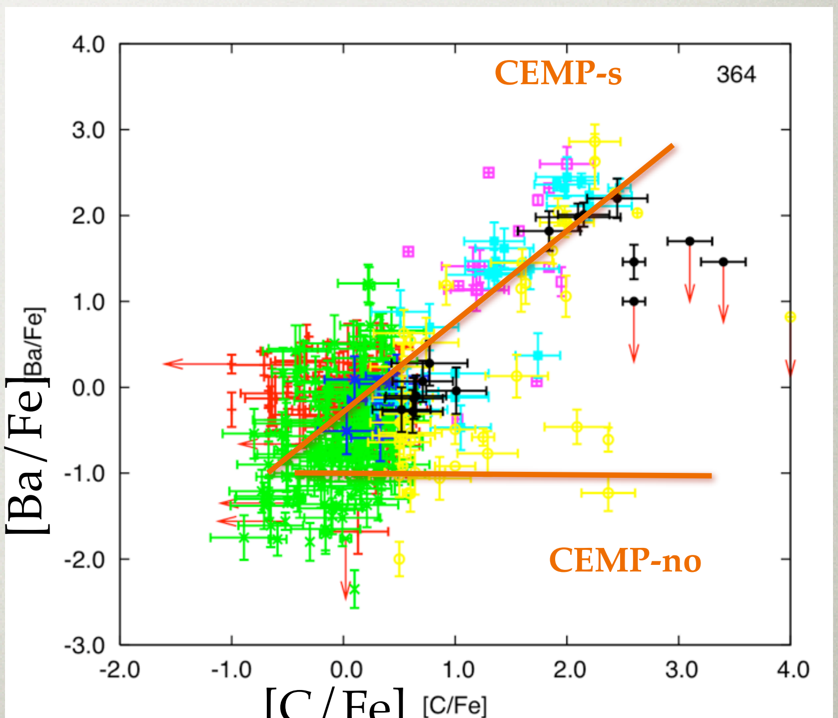
Data from SAGA database (Suda et al. 2008)

http://saga.sci.hokudai.ac.jp

Characteristics of EMP Stars

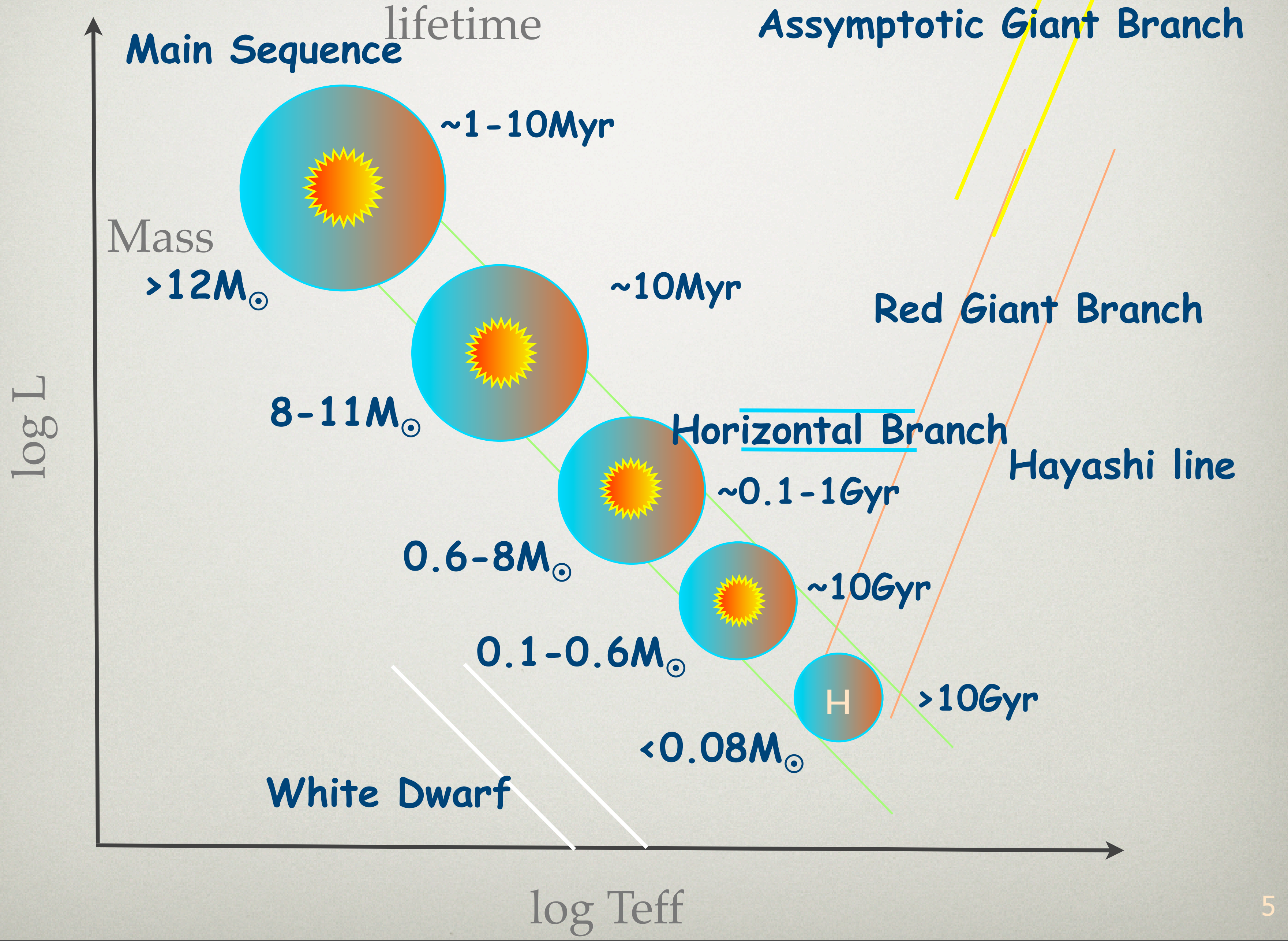
- Large fraction of **carbon rich** stars ([C/Fe] >~ 0.5) (**CEMP** stars) compared with the Population I & II stars
- Two groups of CEMP stars : with/without enhancement of s-process elements (**CEMP-s** and **CEMP-no(s)**, respectively)



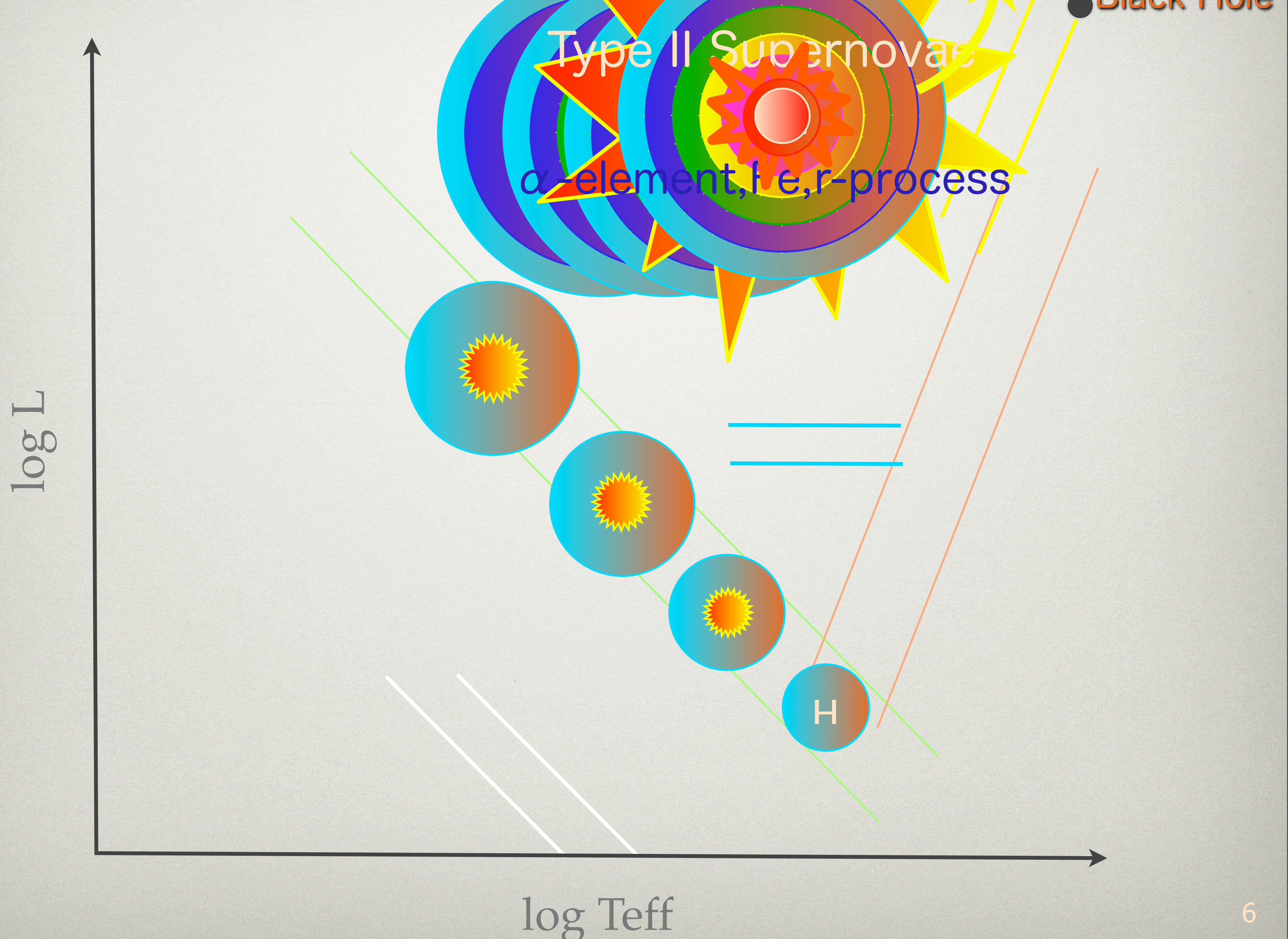


Figures created with SAGA-DB

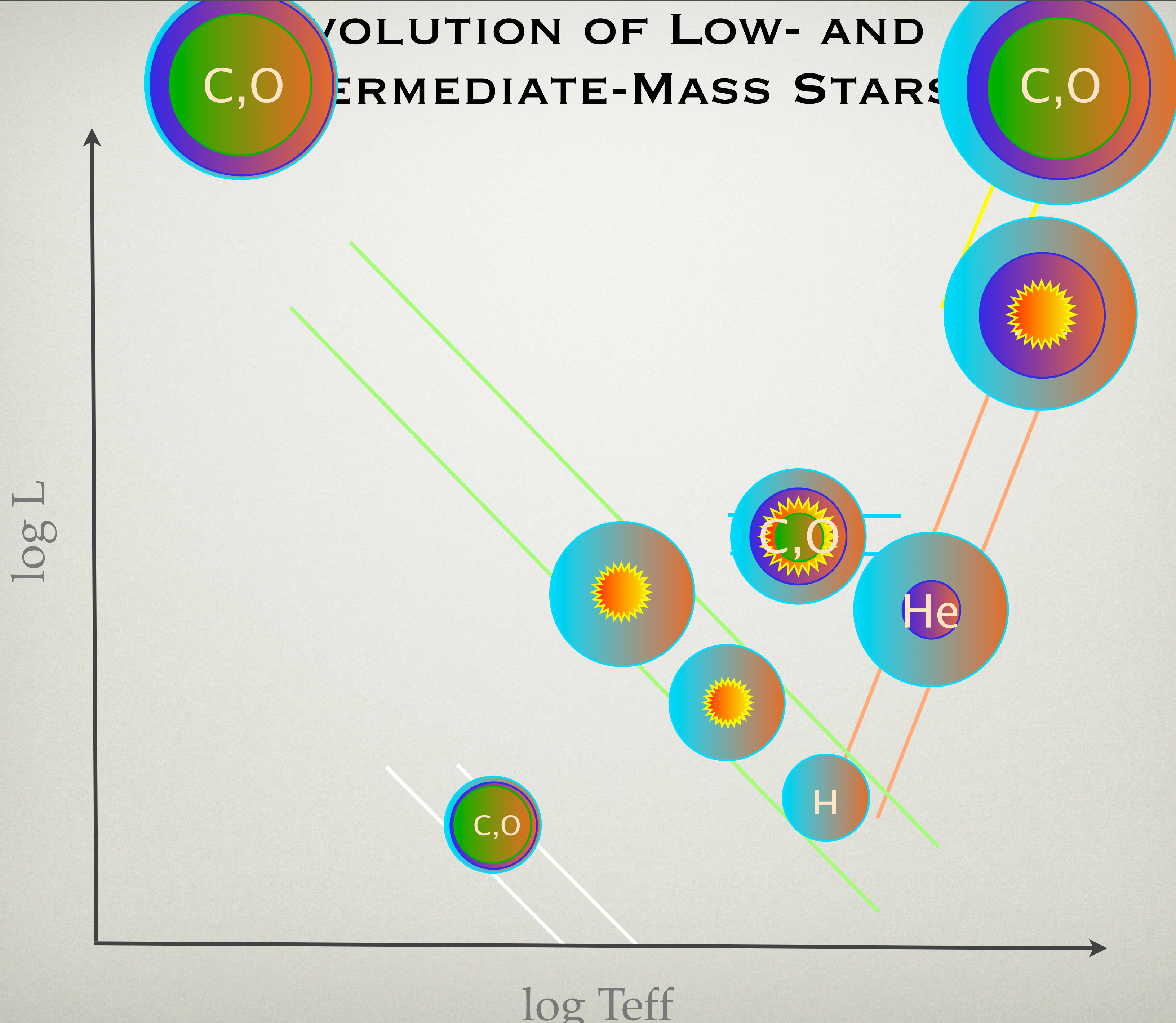
Stellar Structure and Evolution - H-R Diagram



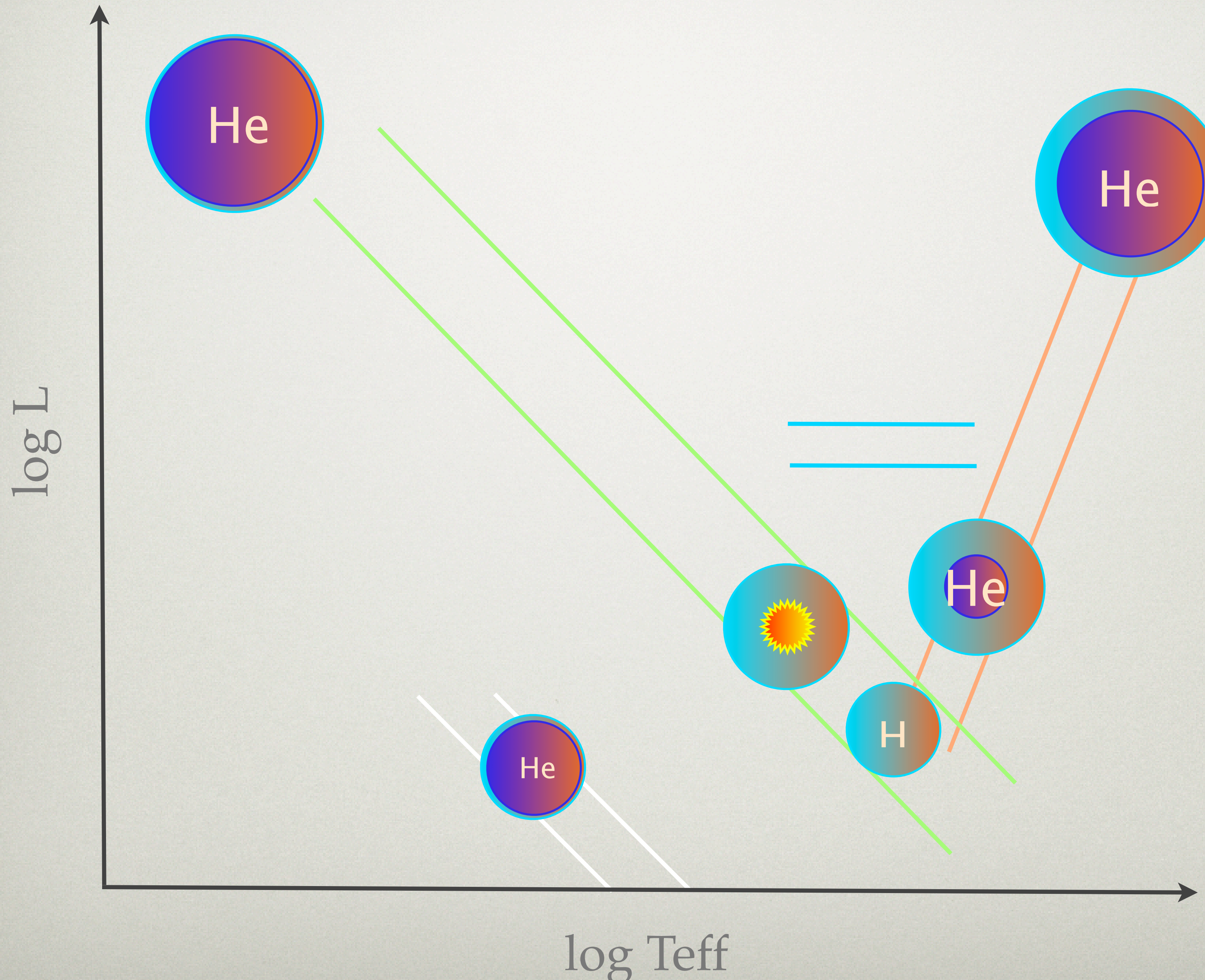
Evolution of Massive Stars

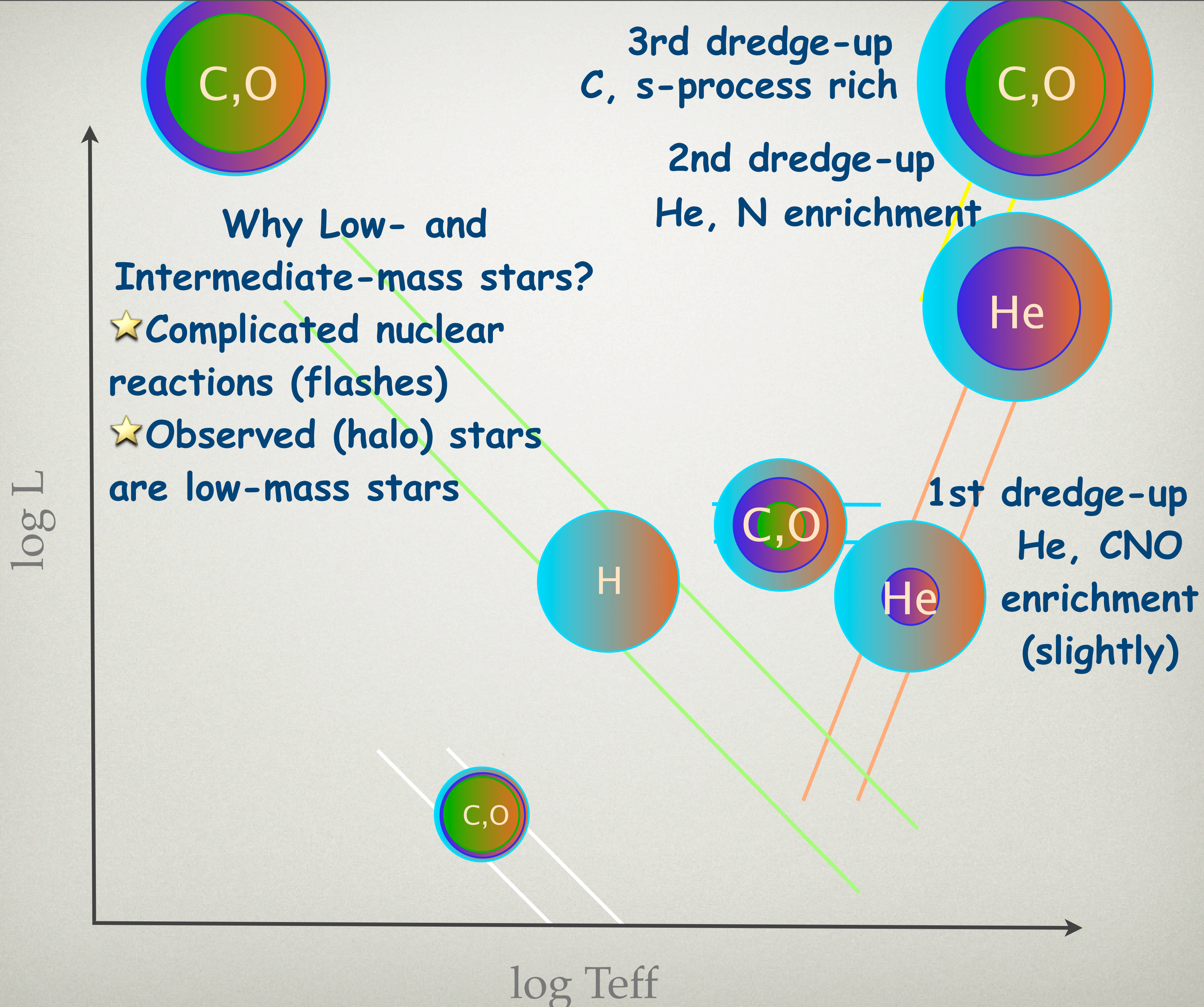


…volution of Low- and …ermediate-Mass Stars



Evolution of Low-Mass Stars




3rd dredge-up
C, s-process rich
C,O
C,O
2nd dredge-up
He, N enrichment
Why Low- and
Intermediate-mass stars?
Complicated nuclear reactions (flashes)
Observed (halo) stars are low-mass stars
He
log L
C,O
H
1st dredge-up
He, CNO enrichment (slightly)
He
C,O
log Teff

Comparisons of Theory with Observations

- 低、中質量の恒星進化理論で観測をどこまで説明できるか。
  - 連星起源説の追求、低金属量星の進化 (Suda et al. 2004, 2007, 2009)
  - 低、中質量AGB星における元素合成 (Nishimura et al. 2009)
- 連星シナリオの枠組みで何が解明できるか。
  - 初期質量関数の推定、化学進化(Komiya et al. 2007, 2009ab, poster session)
  - 大質量星連星の影響(Yamada et al. 2009)

Stellar Evolution at Low-Metallicity

- 初期のZ=0、低質量星の進化計算では特に注目すべき振る舞いは発見されなかった。
    - ~0.8 Msunの計算例: Wagner 74, D’Antona 82, Guenther+83
- $Z_{CNO}<10^{-7}$の低質量星モデルではHe-burning時に水素がHe-burning対流層に混入する。(Hollowell+90, Fujimoto+90)
- 水素混入の結果、爆発的水素燃焼(flash)により表面対流層が内部の物質を汲み上げ、表面のCN組成が劇的に変化する (Helium-Flash Driven Deep Mixing, He-FDDM)。
    - 0.8-1.0 Msunの進化計算例: Hollowell+90, Fujimoto+90, Cassisi+96, Fujimoto+00, Schlattl+00, Weiss+04, Straniero+04, Iwamoto+04, Picardi+04, Campbell+08
    - 2-8 Msunの進化計算例: Fujimoto+00, Chieffi+01, Herwig+03, Iwamoto+04, Campbell+08
    - 水素混入が起こる計算例: Schlattl+01, Suda+04, Suda+07
    - 水素混入が起こらない、あるいは発見できなかった計算例: Weiss+00, Marigo+01, Siess+02, Gil-Pons+05, Gil-Pons+07

Basic Equations for Stellar Structure

- 質量保存（連続の式）

$$\frac{dr}{dM_r} = \frac{1}{4\pi r^2 \rho}$$

- 静水圧平衡

$$\frac{dP}{dM_r} = -\frac{GM_r}{4\pi r^4}$$

- 輻射輸送

$$\frac{dT}{dM_r} = \frac{3\kappa L}{64\pi^2 a c r^4 T^3}$$

- エネルギー保存

$$\frac{dL}{dM_r} = \epsilon_n + \epsilon_g - \epsilon_\nu$$

- 元素合成

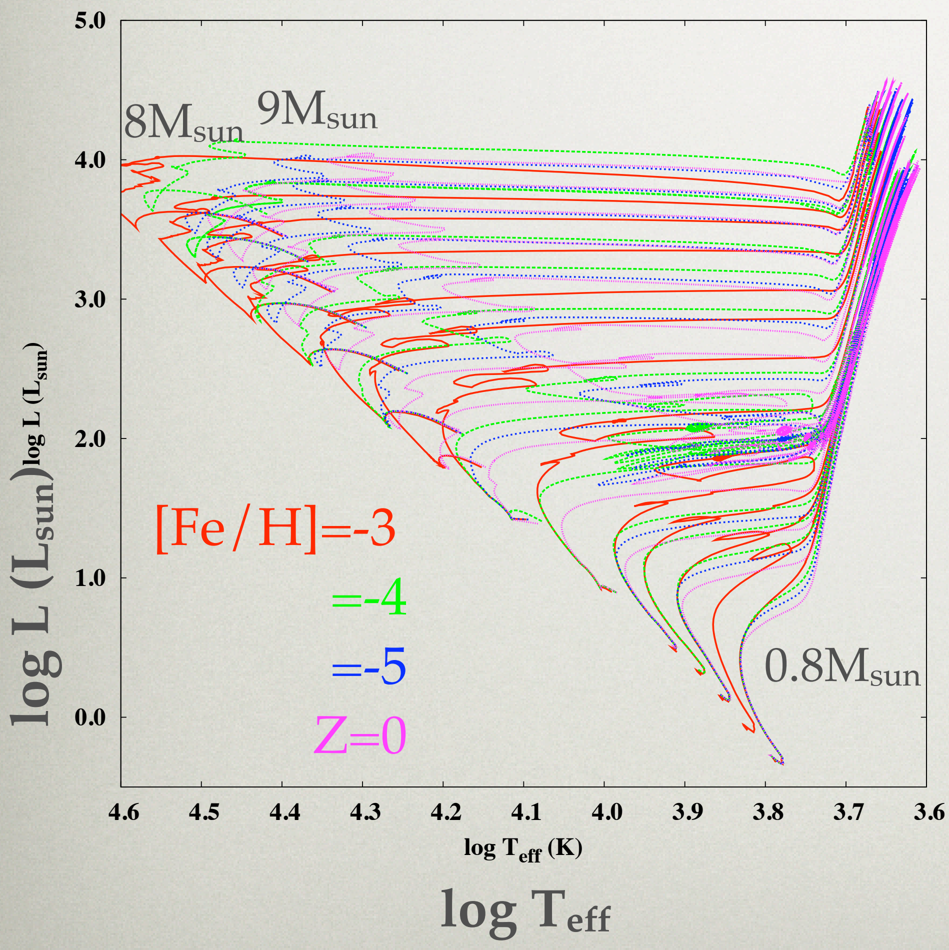
$$\frac{dX_i}{dt} = \frac{\rho}{\mu_e} N_A \langle \sigma v \rangle_{ji} - \frac{\rho}{\mu_e} N_A \langle \sigma v \rangle_{ik}$$

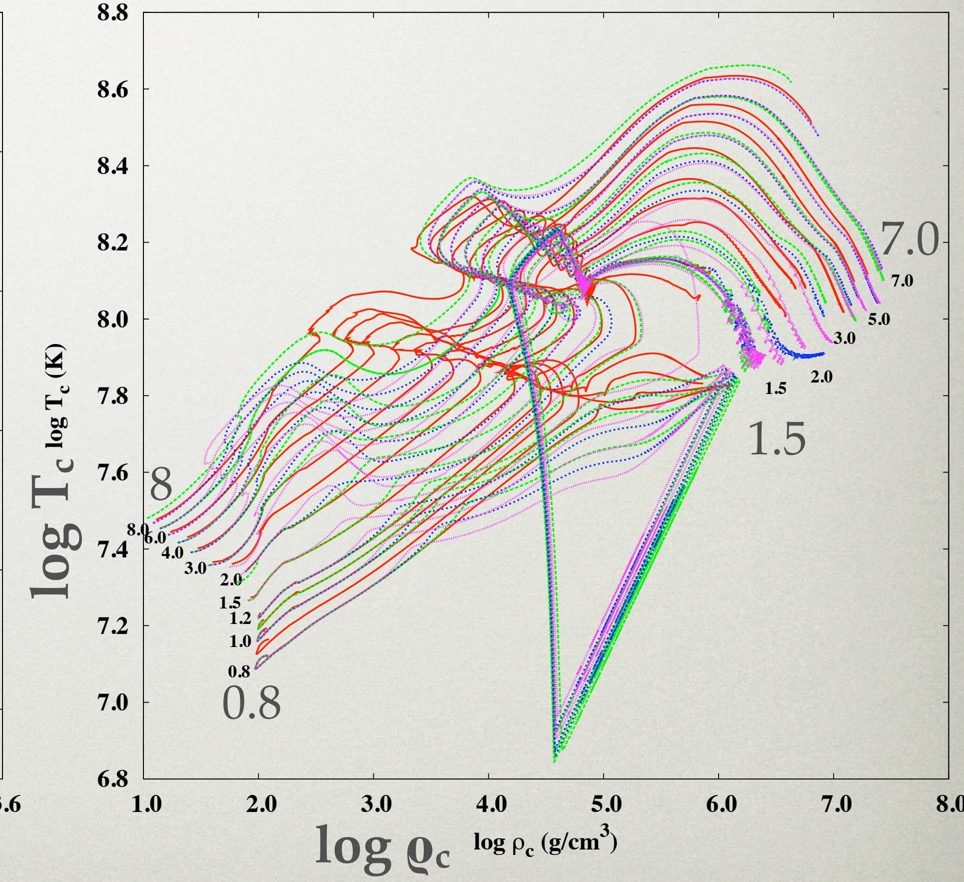
Input Physics

- One-dimensional adaptive mesh
- Thermal convection by Schwartzschild Criterion
  - Mixing parameter α=1.5
  - No overshoot and No semi-convection
- Most up-to-date input physics
  - 9 elements with reaction rate : NACRE
  - radiative and conductive opacities : OPAL, Alexander & Ferguson (1994), Itoh et al. (1983)
  - neutrino cooling processes : Itoh et al. (1996)
- No inclusion of mass loss and extra mixing
  - Proper assumption to follow He-FDDM
    - Mixing timescale = Nuclear timescale となる層まで混ぜる。

see T.S., Fujimoto, Itoh (2007, ApJ)

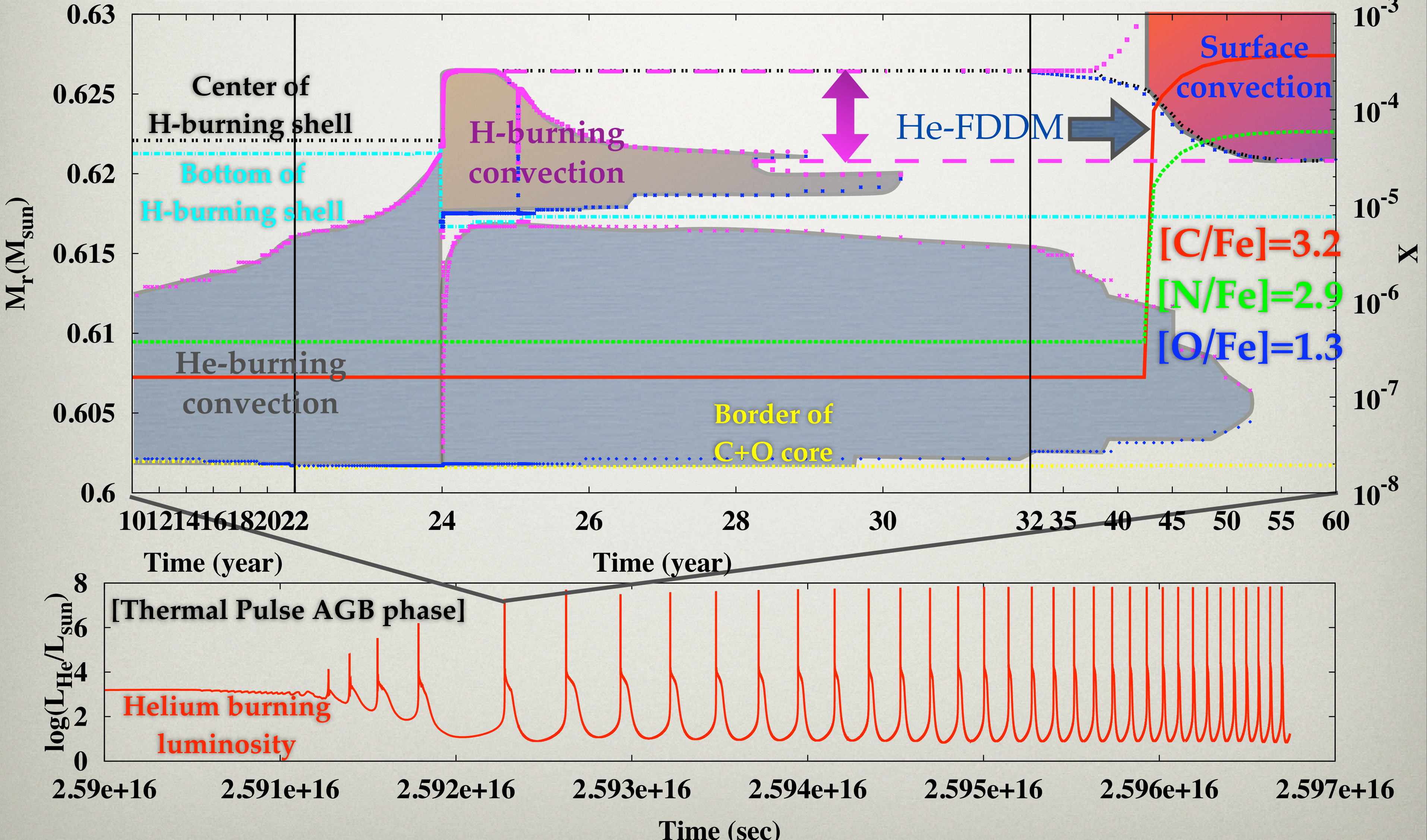
Evolution of EMP Models





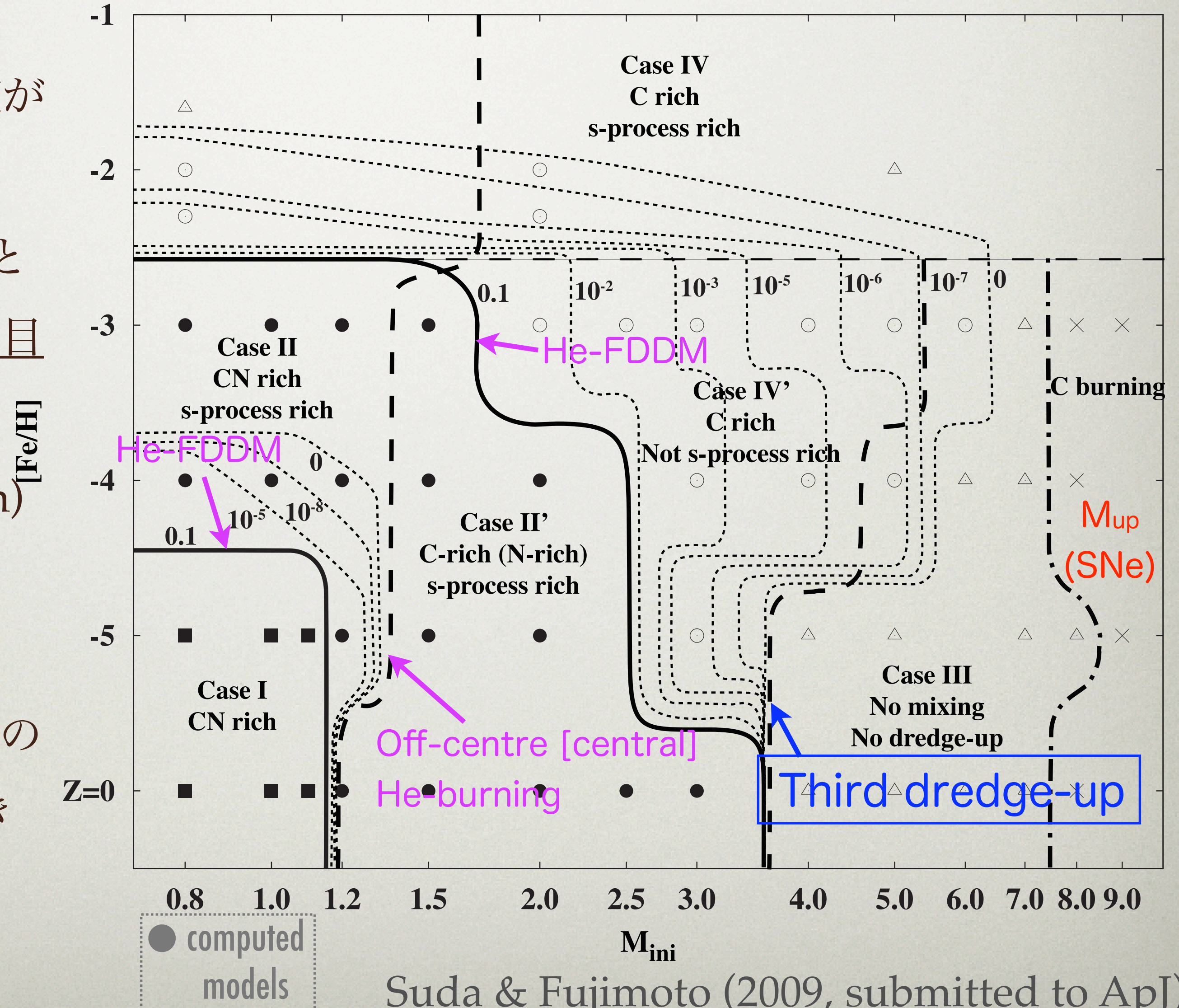
T.S. and Fujimoto (2009)

Model Computations: M=2 M_{sun}, [Fe/H]=-4



Stellar Evolution at [Fe/H] < -3

- [Fe/H]<-2.5でHe-FDDMが起こる。
- 一度He-FDDMが起こると[CNO/H]>-2.5となり二度目のmixingは起こらない。
- AGBと低質量星(0.8Msun)との連星系があればHe-FDDMの証拠を検出可能
- 連星間距離（連星周期）の違いによる組成のばらつき



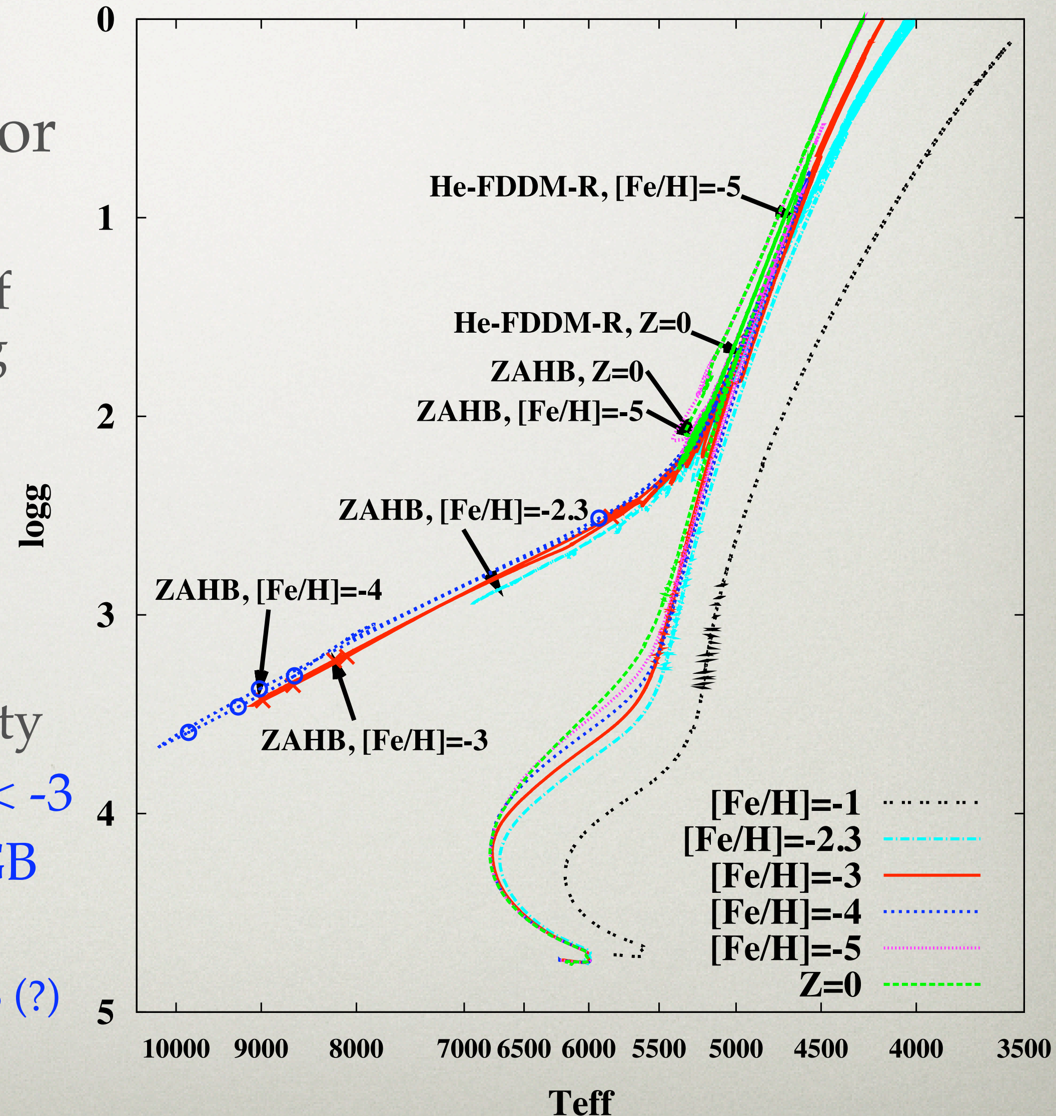
Suda & Fujimoto (2009, submitted to ApJ)

Implications for Observation -
Blue Horizontal Branch Stars

- Bluer horizontal branch for metal-poor stars
  - due to the decrease of entropy in H-burning shell
- ~30 Myr Lifetime at blue HB
  - 1/30 of RGB having comparable luminosity

⭐ 1 BHB star with [Fe/H] < -3 should appear per 30 RGB

☆ Metal-poor dSph (e.g., segue 1, [Fe/H]~-3) consits only of BHB (?)



Conclusion

- EMP starsのモデルを計算した。
  - 0.8-9 Msun, Z=0, -5 < [Fe/H] < -2.3
- He-Flash Driven Deep Mixingによる表面のCN enhancement
- Third dredge-up efficiencyのmass, metallicity依存性
  - Massive, Metal-poorほどTDUが効かなくなる。
- 観測との比較
  - [Fe/H] < -3のBlue Horizontal Branch starsがRGB stars 30個に1個ぐらい見つかるはず。
  - 連星輸送を仮定すると、表面対流による希釈効果が期待されるが、観測では見えない。主系列でmetal diffusionが効いている可能性がある。