

金属欠乏星で探る 宇宙の星形成と化学進化

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Contents

I. 導入

- 金属欠乏星で探る銀河考古学
- 小・中質量星の進化
- (大質量星の進化)

II. 金属欠乏星の観測

- 最も鉄の少ない星の探査
- 金属欠乏星の化学組成
- 金属欠乏星の起源

III. 金属欠乏星の起源としての連星仮説(1)

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- 炭素過剰金属欠乏星で探る金属欠乏星の初期質量関数
- 銀河系における初期質量関数の変遷

IV. 金属欠乏星の起源としての連星仮説(2)

- 大質量星連星シナリオ
- SPHシミュレーションを用いた超新星爆発と伴星の衝突
- OB型星視線速度変動モニタリングを用いた大質量星連星探査

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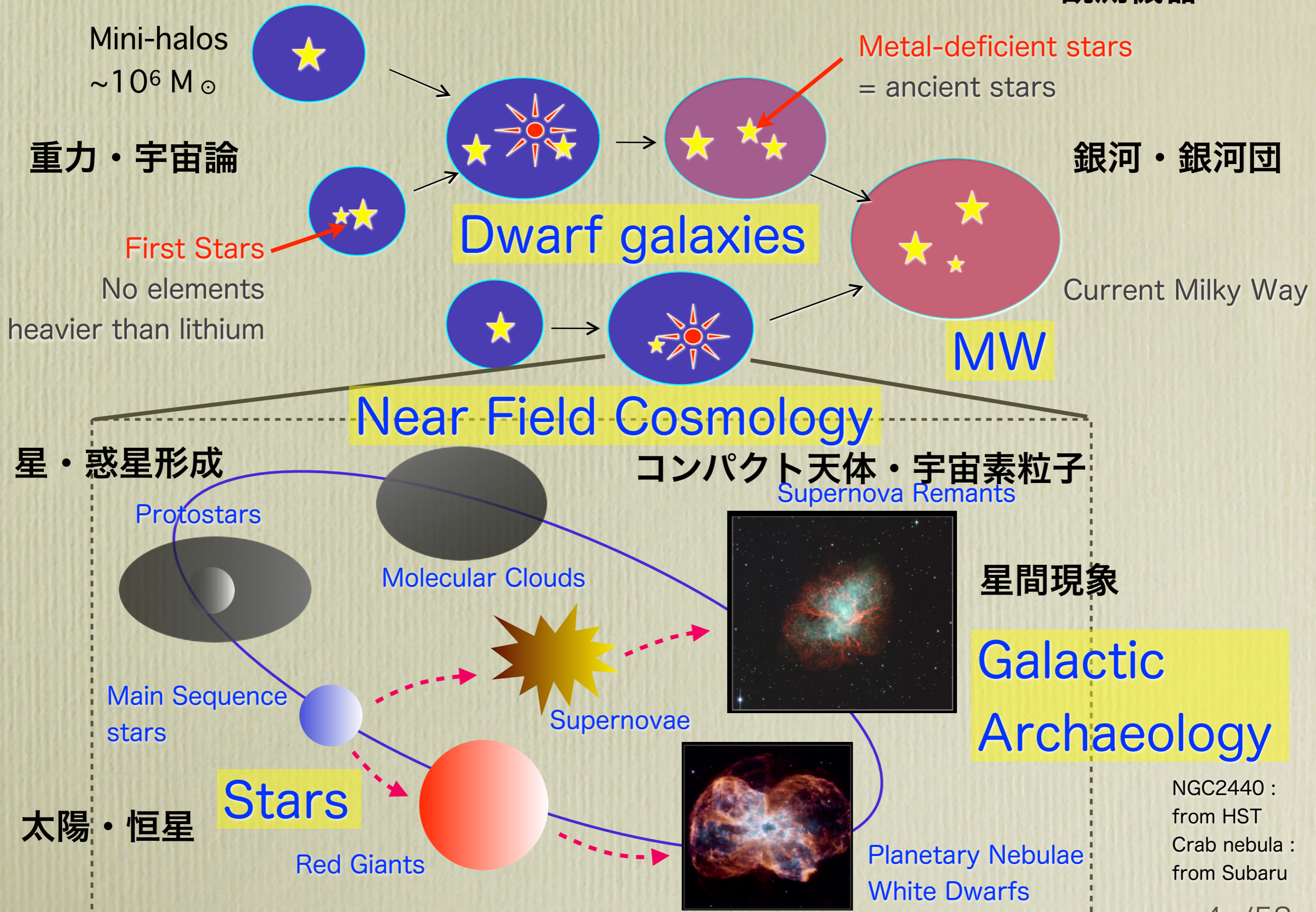
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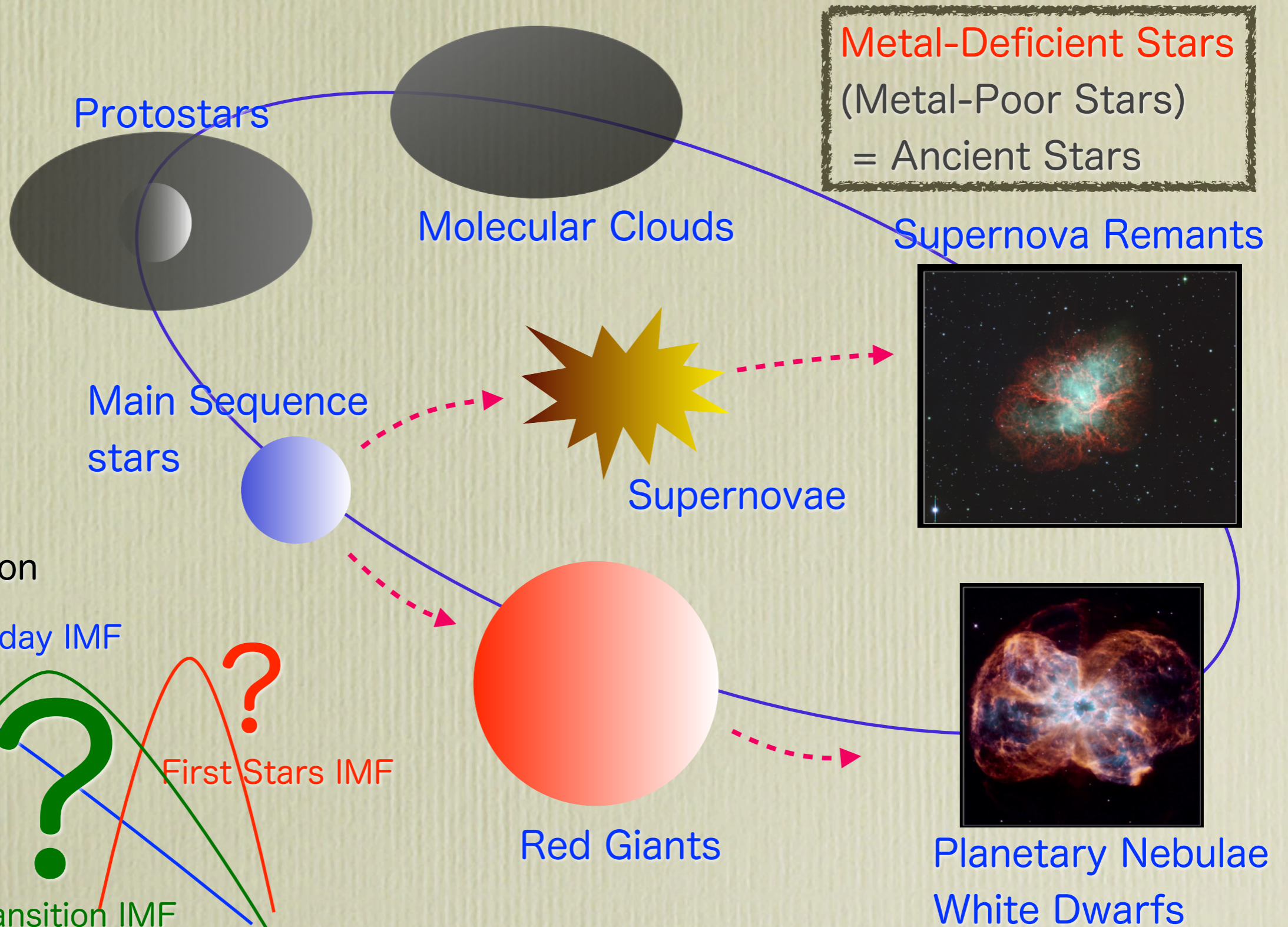
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宇宙の物質循環と化学進化

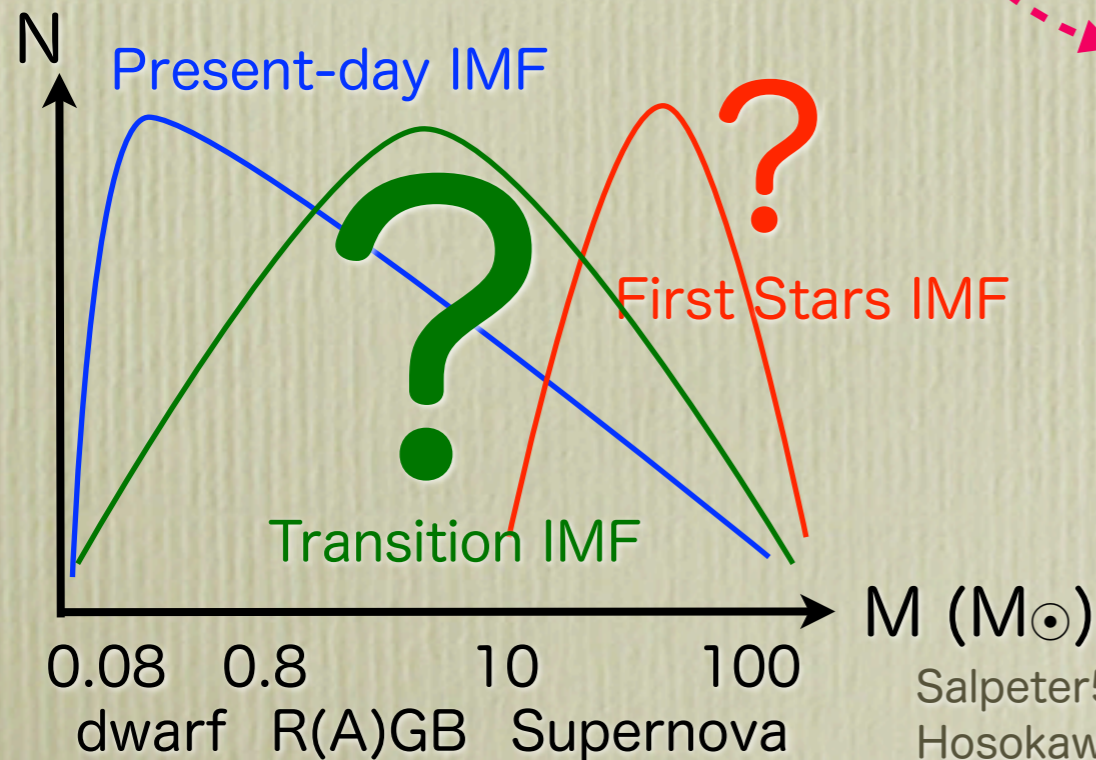
観測機器



Chemical Evolution and Stellar Initial Mass Function



Stellar Initial Mass Function



銀河考古学の主要な問題

- **Can we find the first (Population III) stars in our Galaxy?**
 - formation of low-mass Pop. III stars.
 - detectability of Pop. III survivors.
- **How can we understand the synthesis of elements in stars?**
 - stars with peculiar abundances like
 - carbon-enhanced metal-poor stars
 - stars with unusual abundance patterns for neutron-capture elements
 - stars showing anomalously enhanced/depleted alpha-elements
- **What is the star formation history in the early Galaxy?**
 - initial mass function of Pop. III stars or low-metallicity stars
- **How is our Galaxy formed?**
 - dwarf galaxies in the local group are building blocks of our Galaxy?

恒星の構造と進化を決める基礎方程式

一次元球対称 + 熱対流による物質混合 (回転なし)

- Mass conservation (Eq. of continuity)

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

- Pressure balance

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

- Radiative transfer

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

- Energy conservation

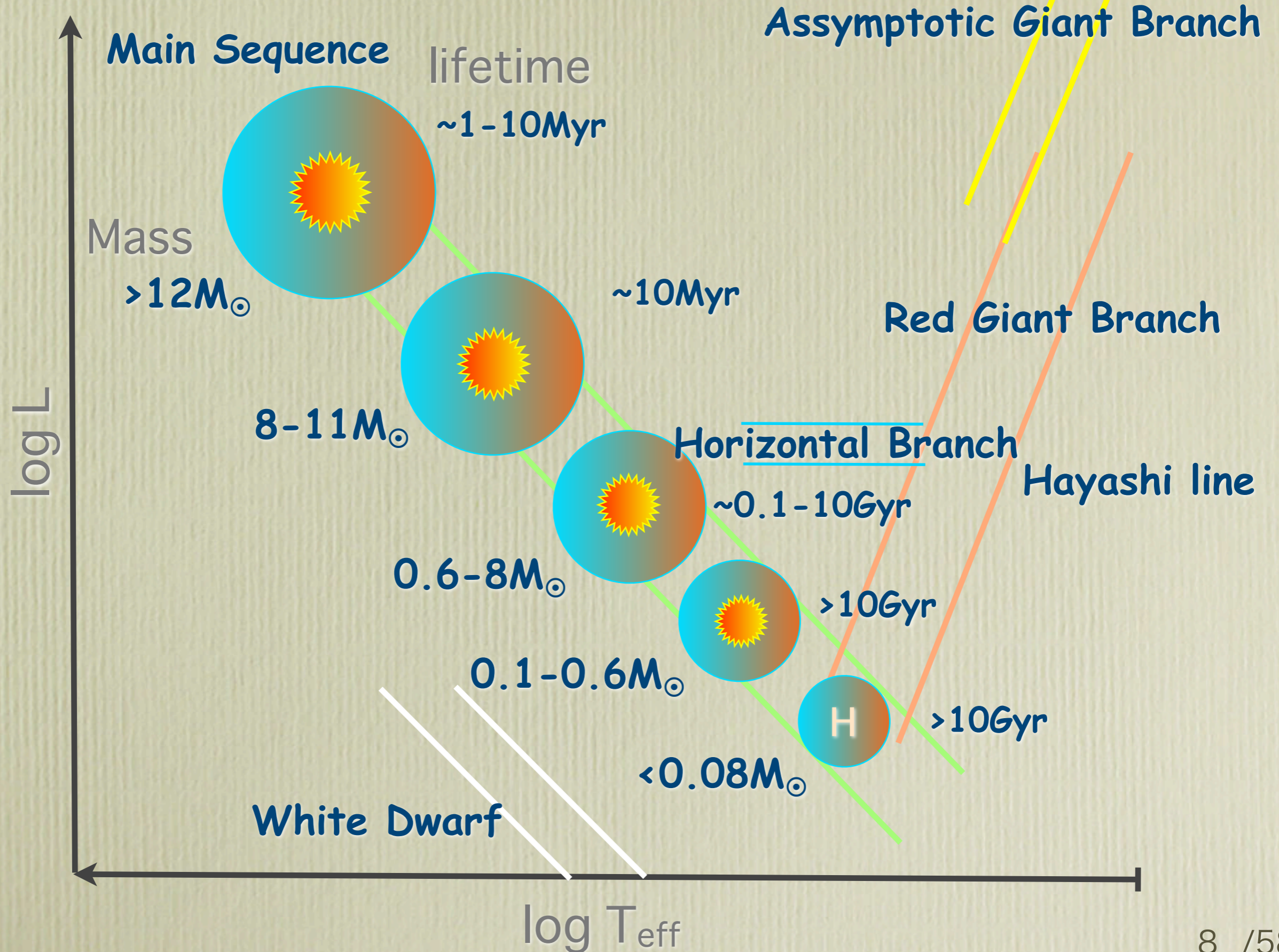
$$\frac{dL}{dM_r} = \epsilon_n + \epsilon_g - \epsilon_\nu$$

- Rate equations

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

Other constituents: Mass loss, Convective overshooting, Convective boundary mixing, etc.

Stellar Structure and Evolution - H-R Diagram

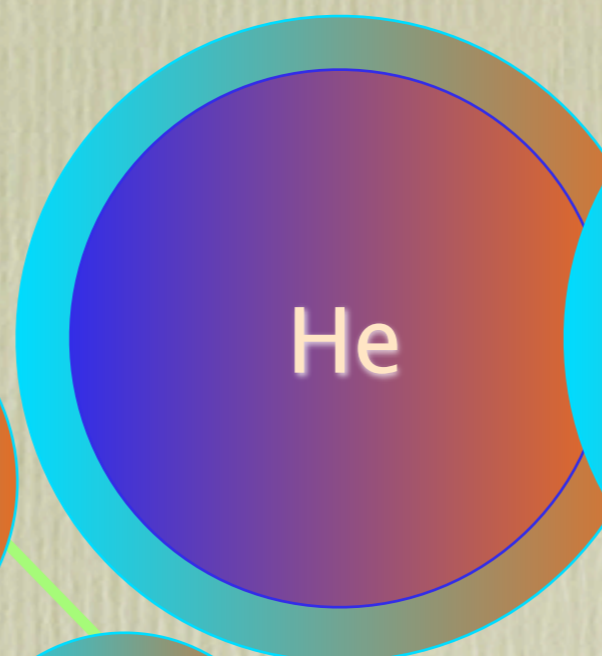


Evolution of Massive Stars

Neutron Star ●
Black Hole ●

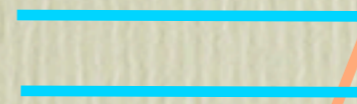
log L

$>12M_{\odot}$



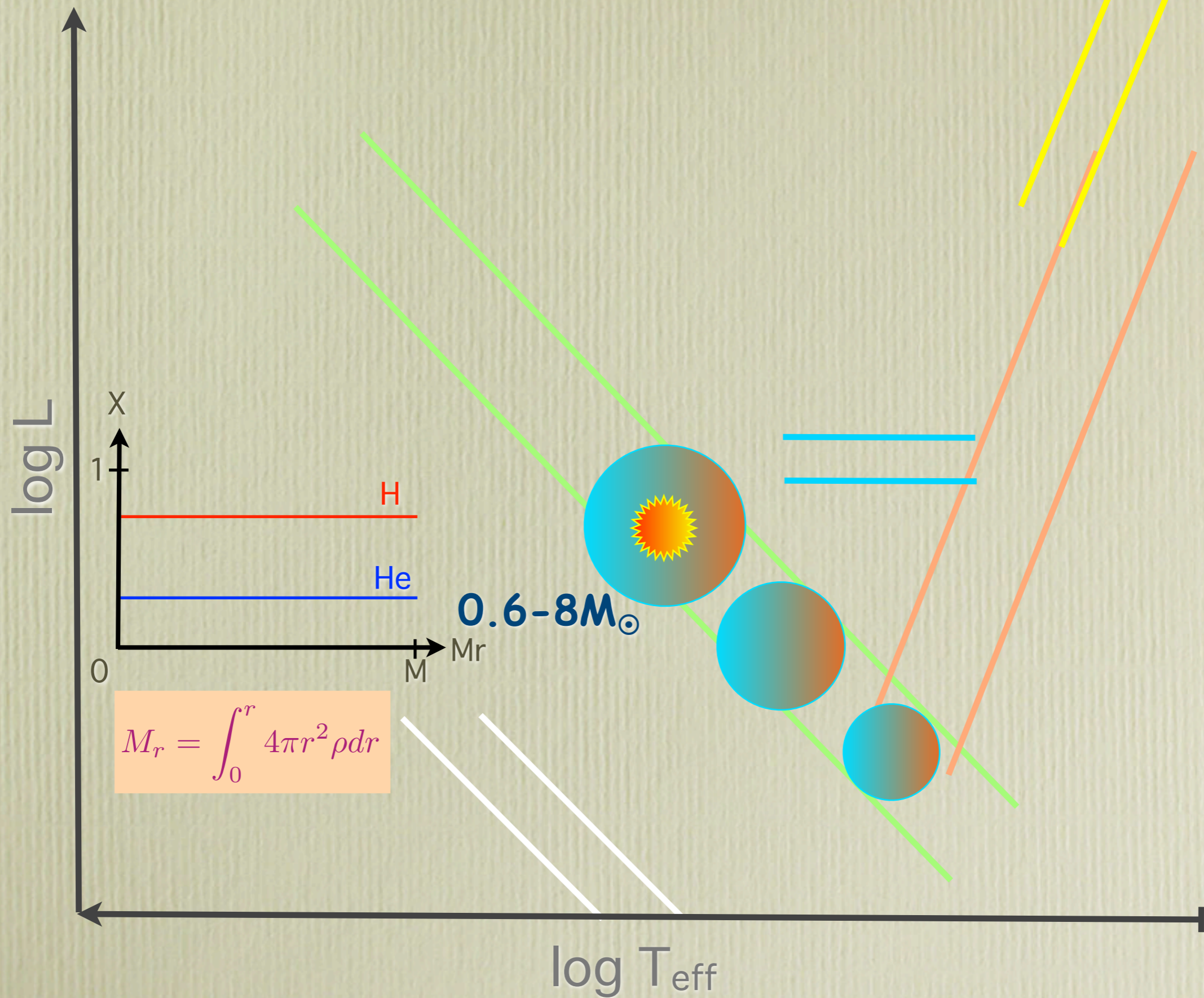
Type II Supernovae

α -element, Fe, (r-process)

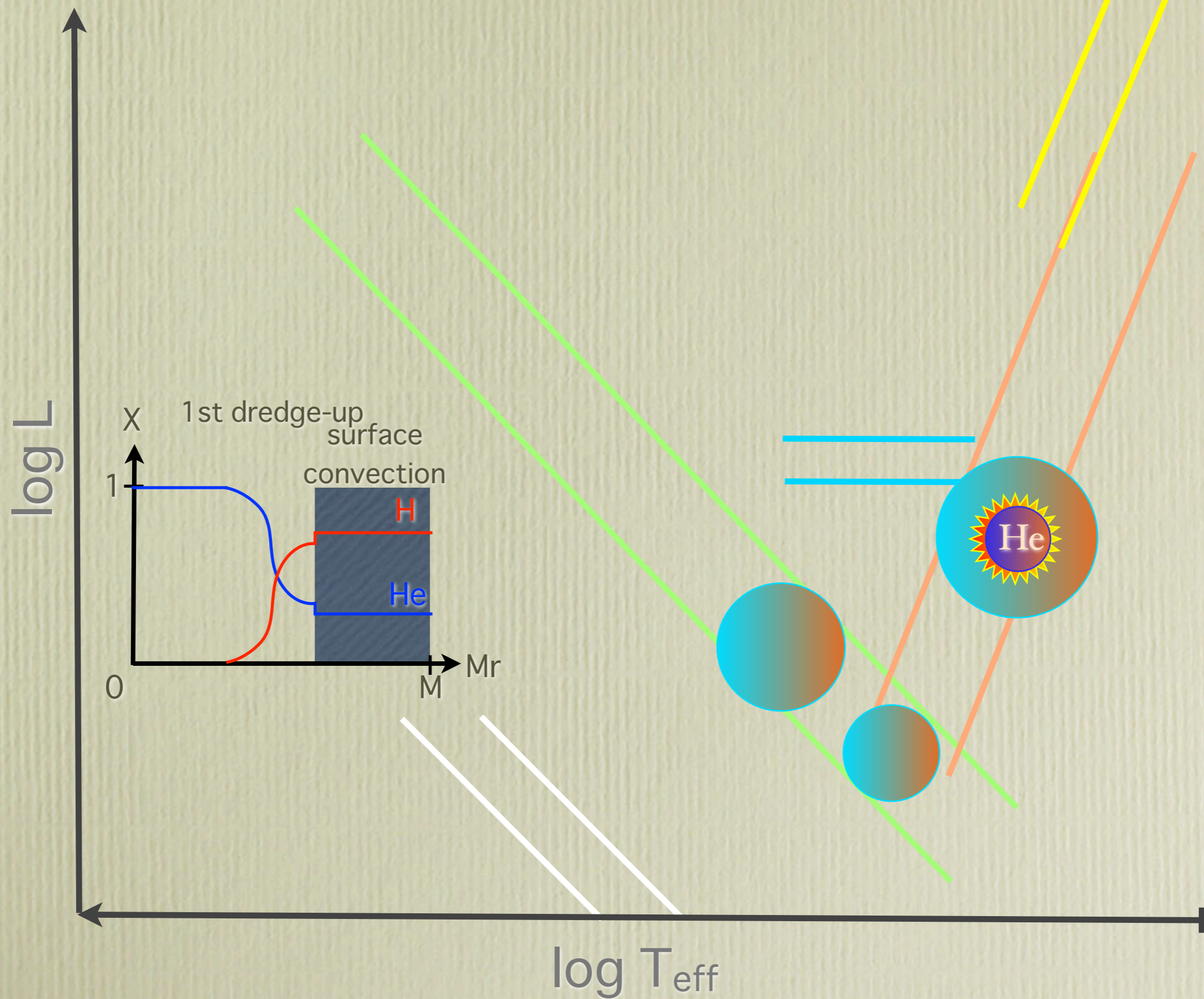


log T_{eff}

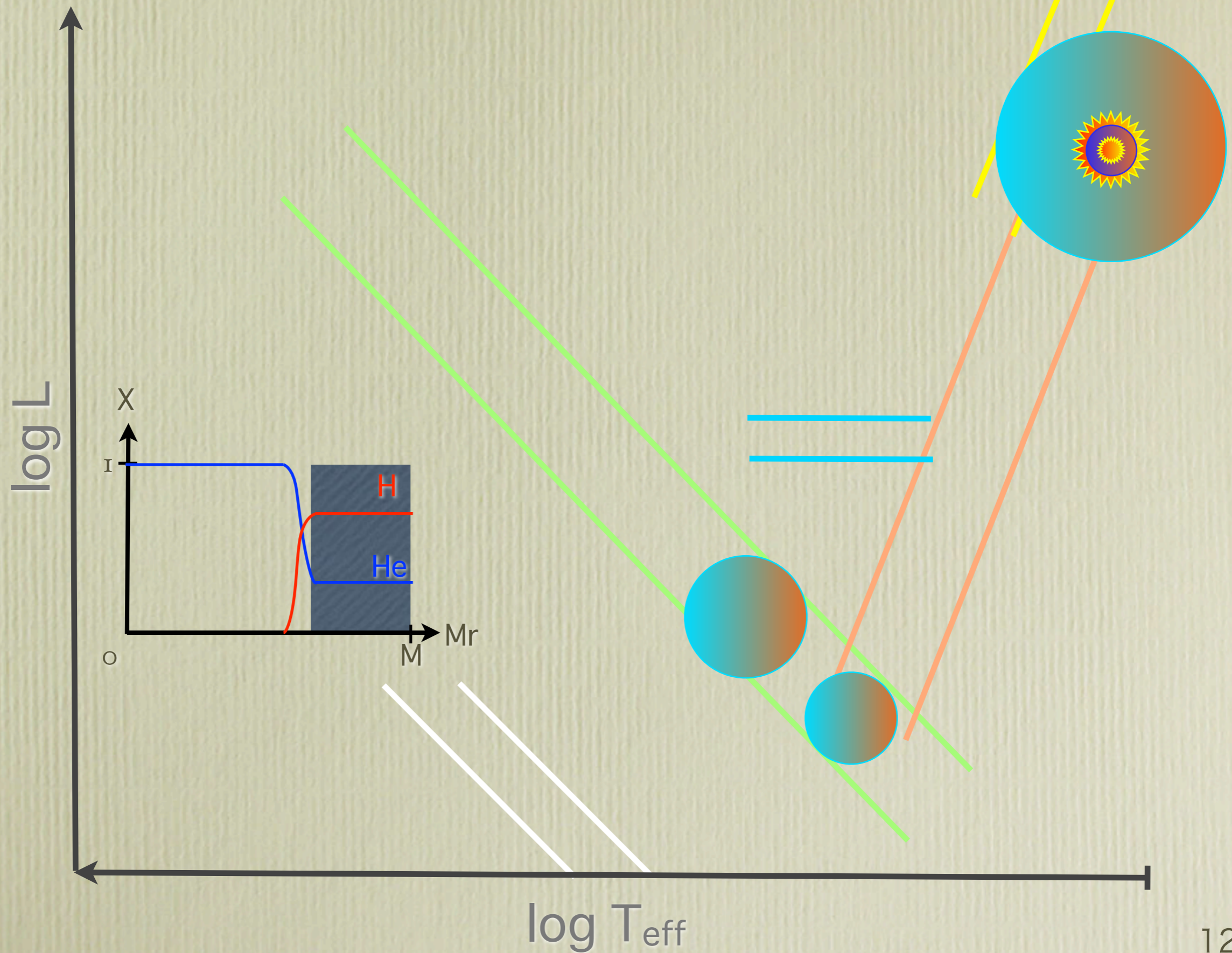
Evolution of Low- and Intermediate-Mass Stars



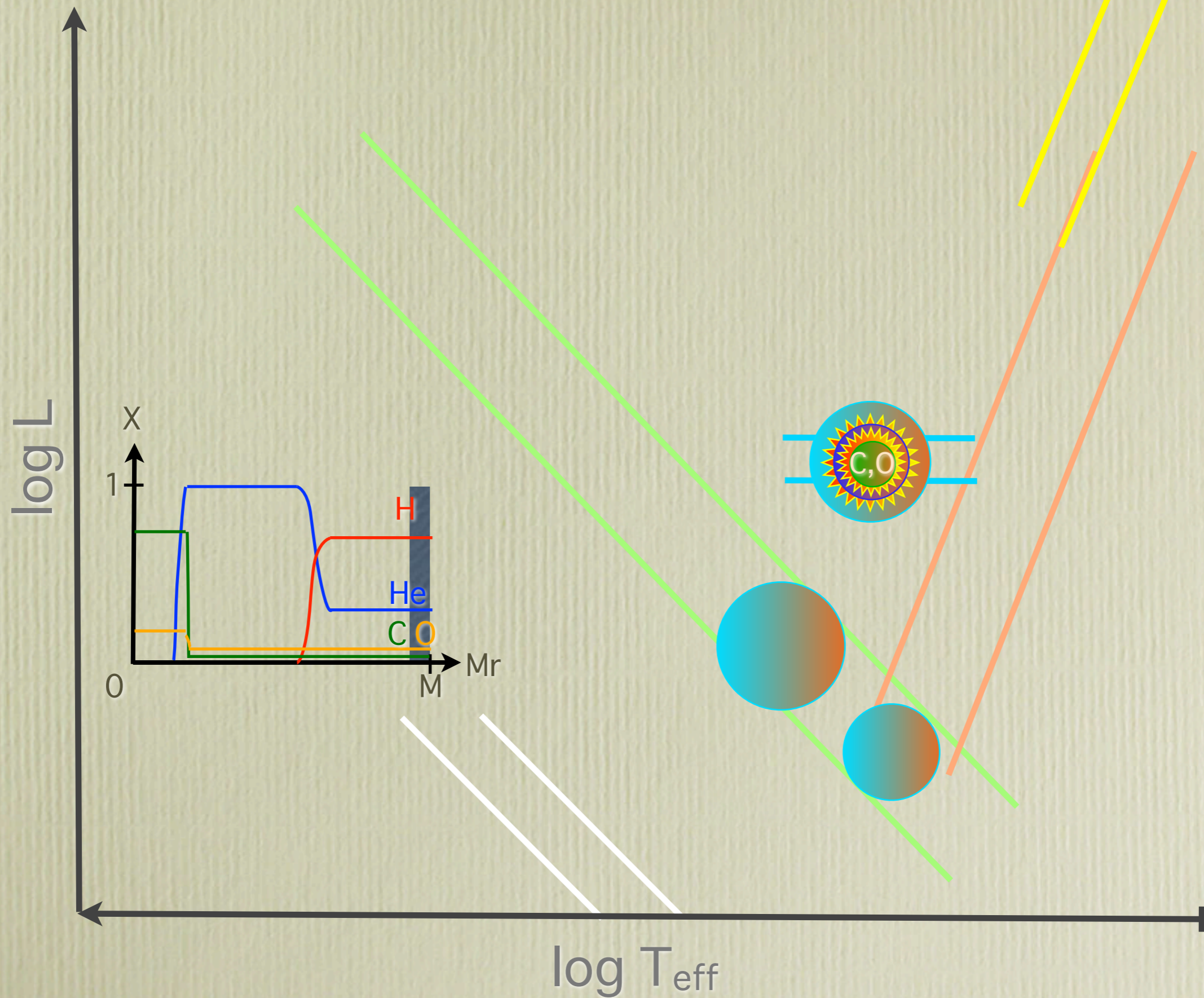
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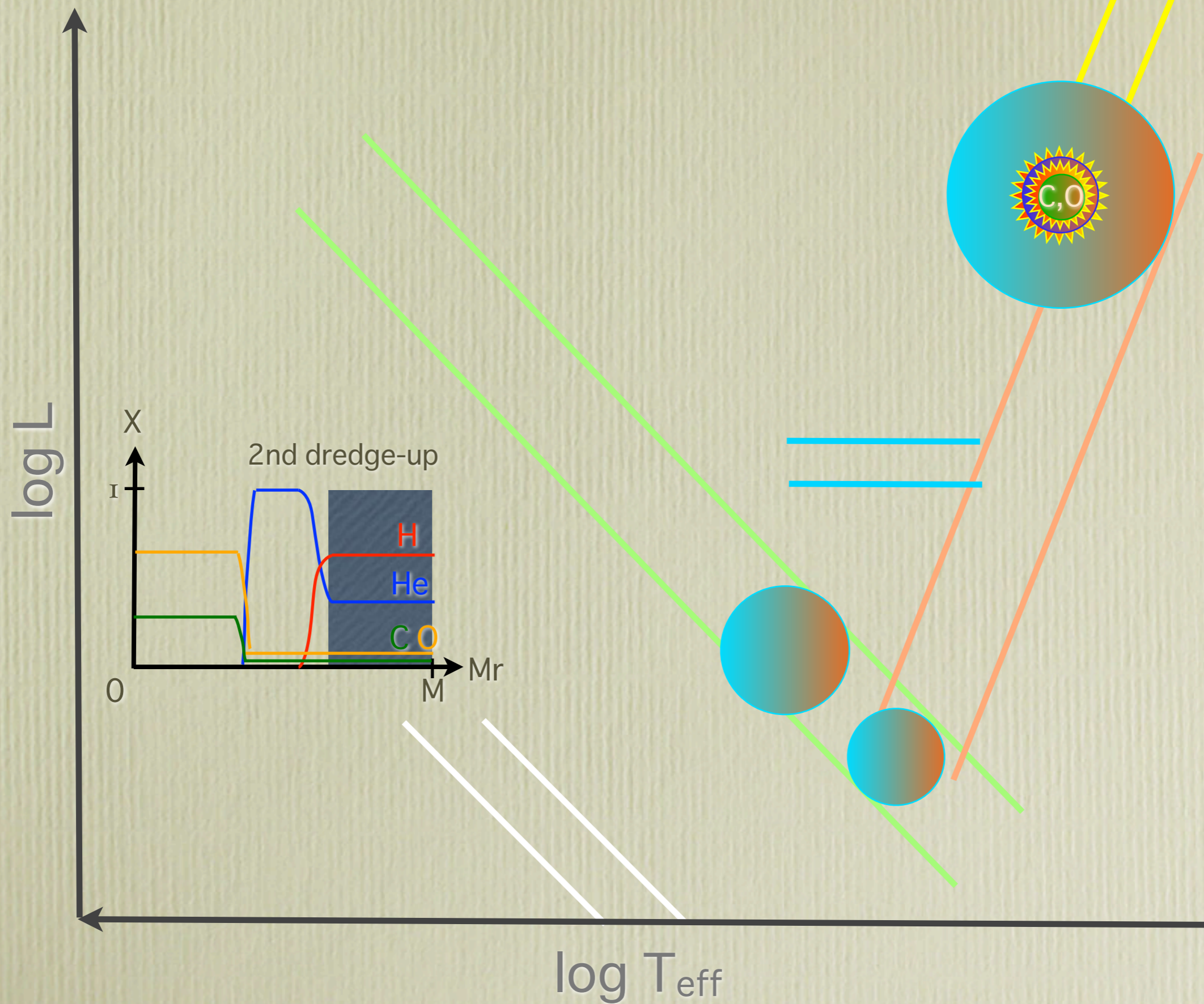
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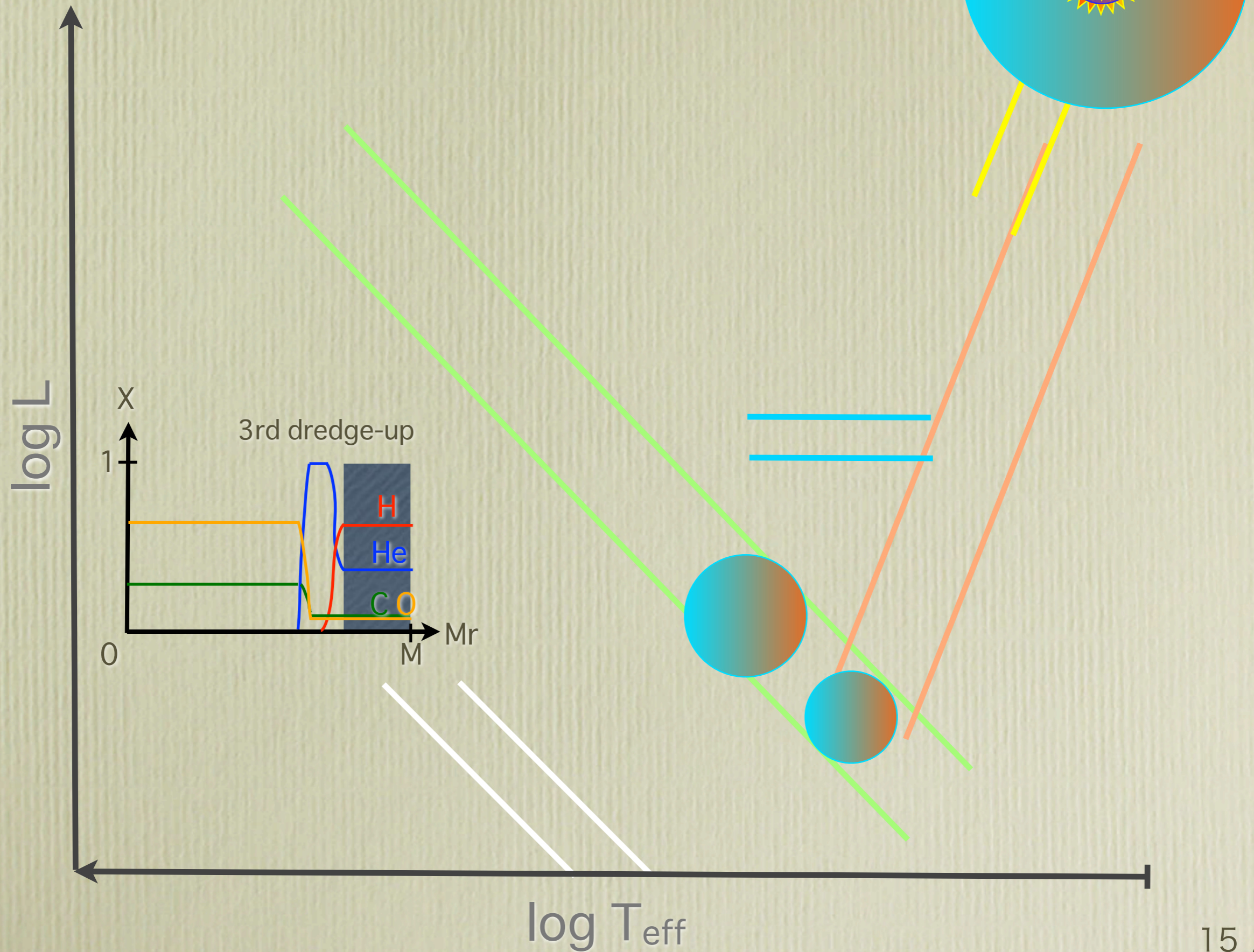
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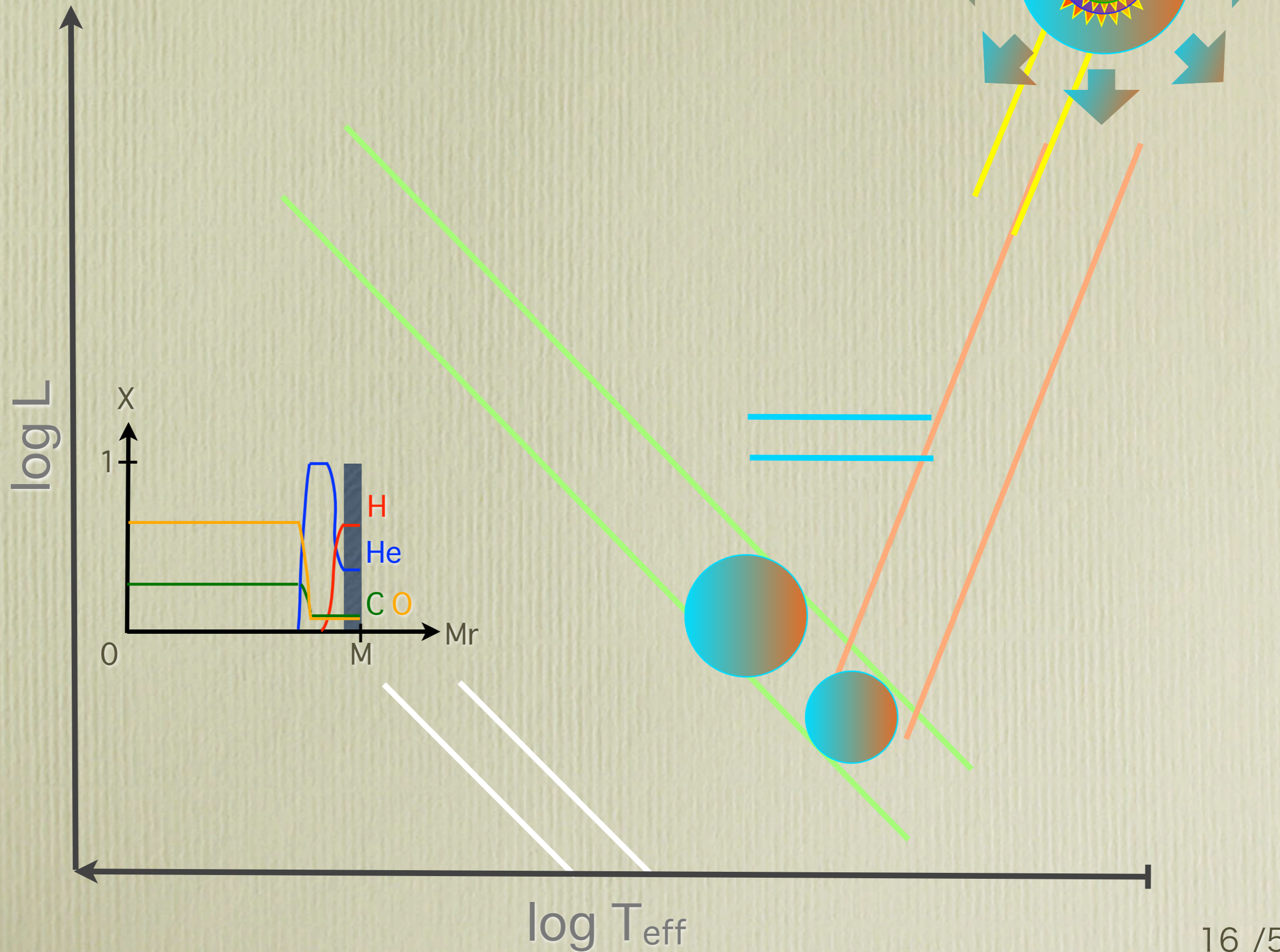
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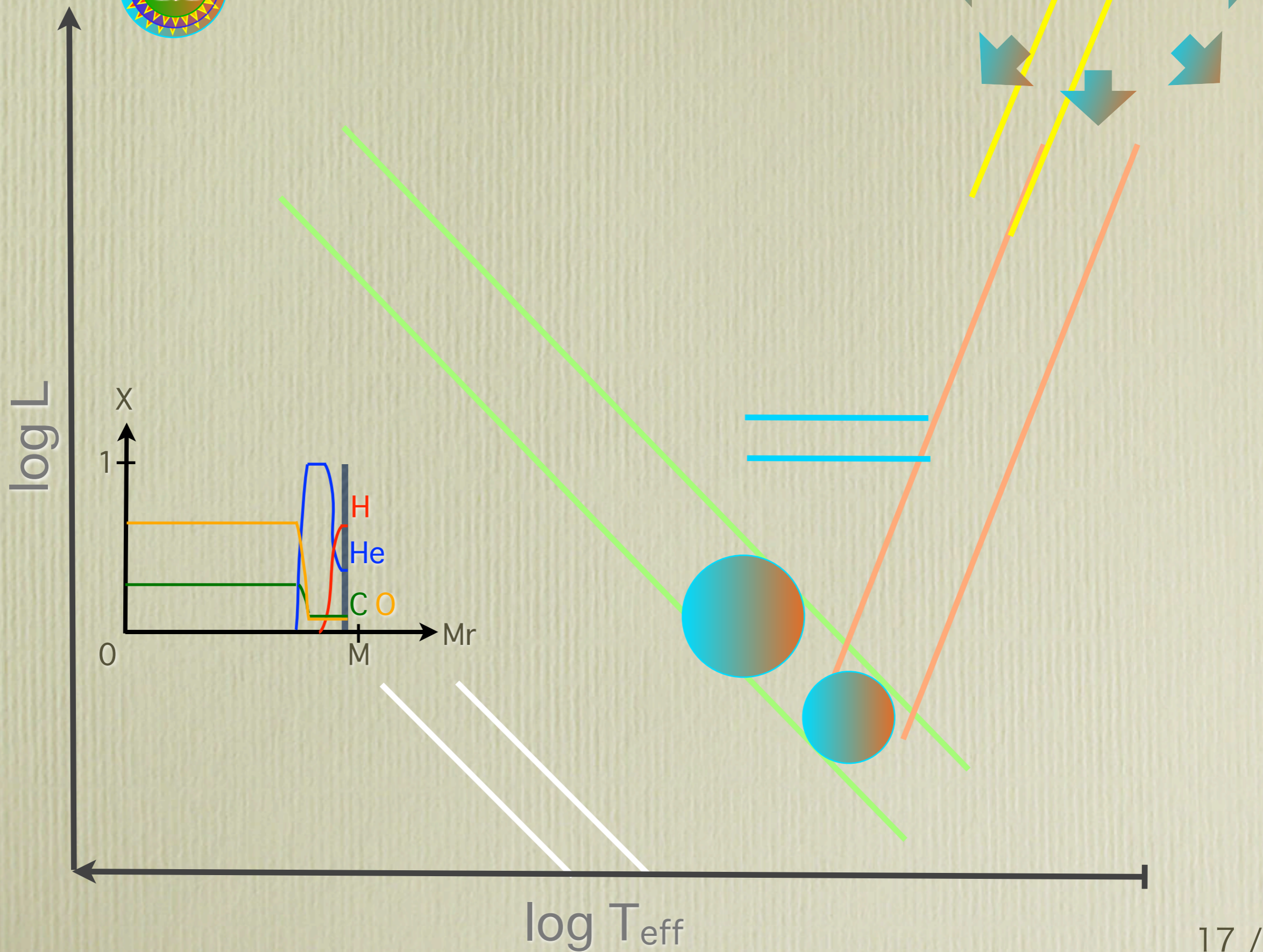
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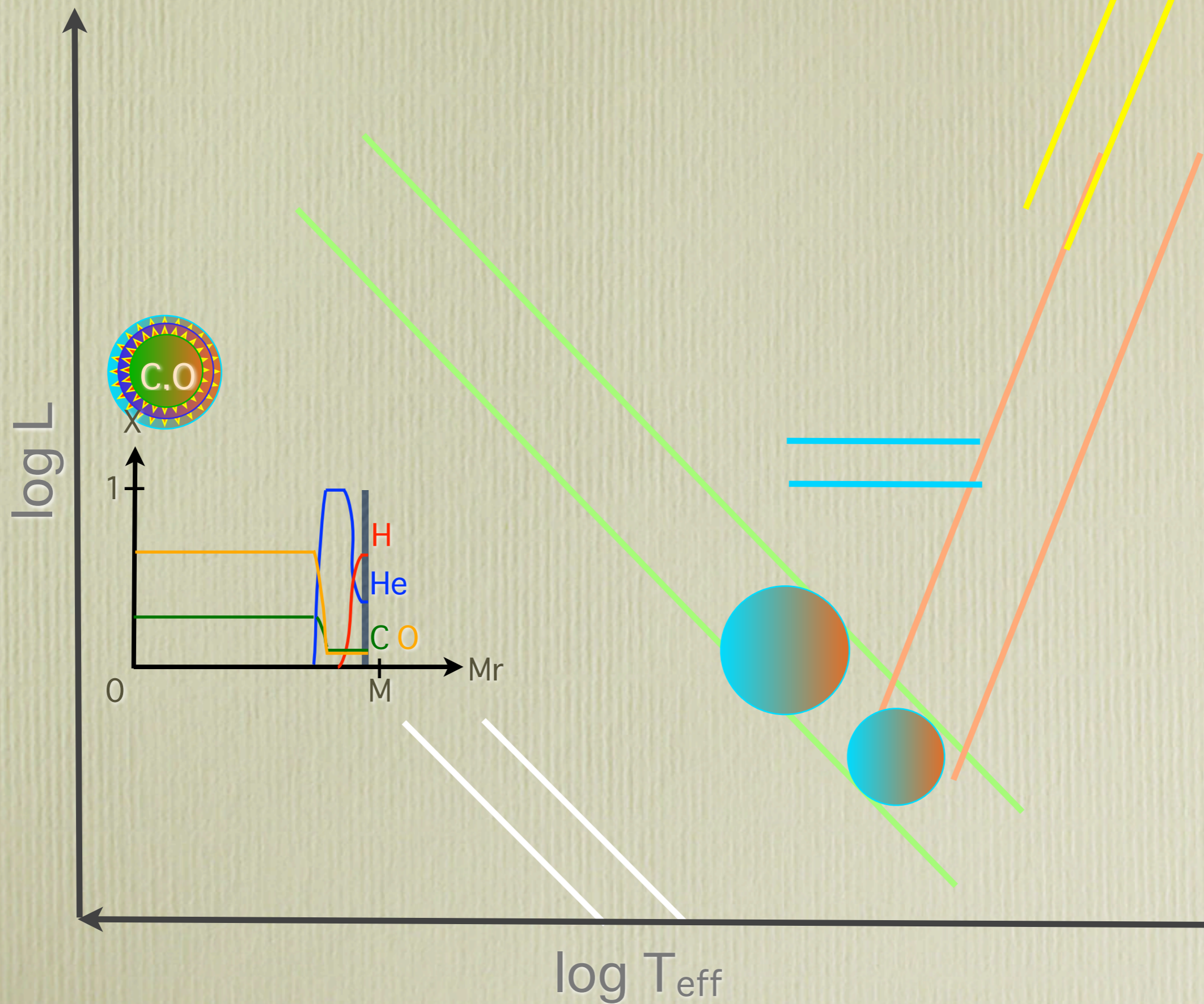
Evolution of Low- and Intermediate-Mass Stars



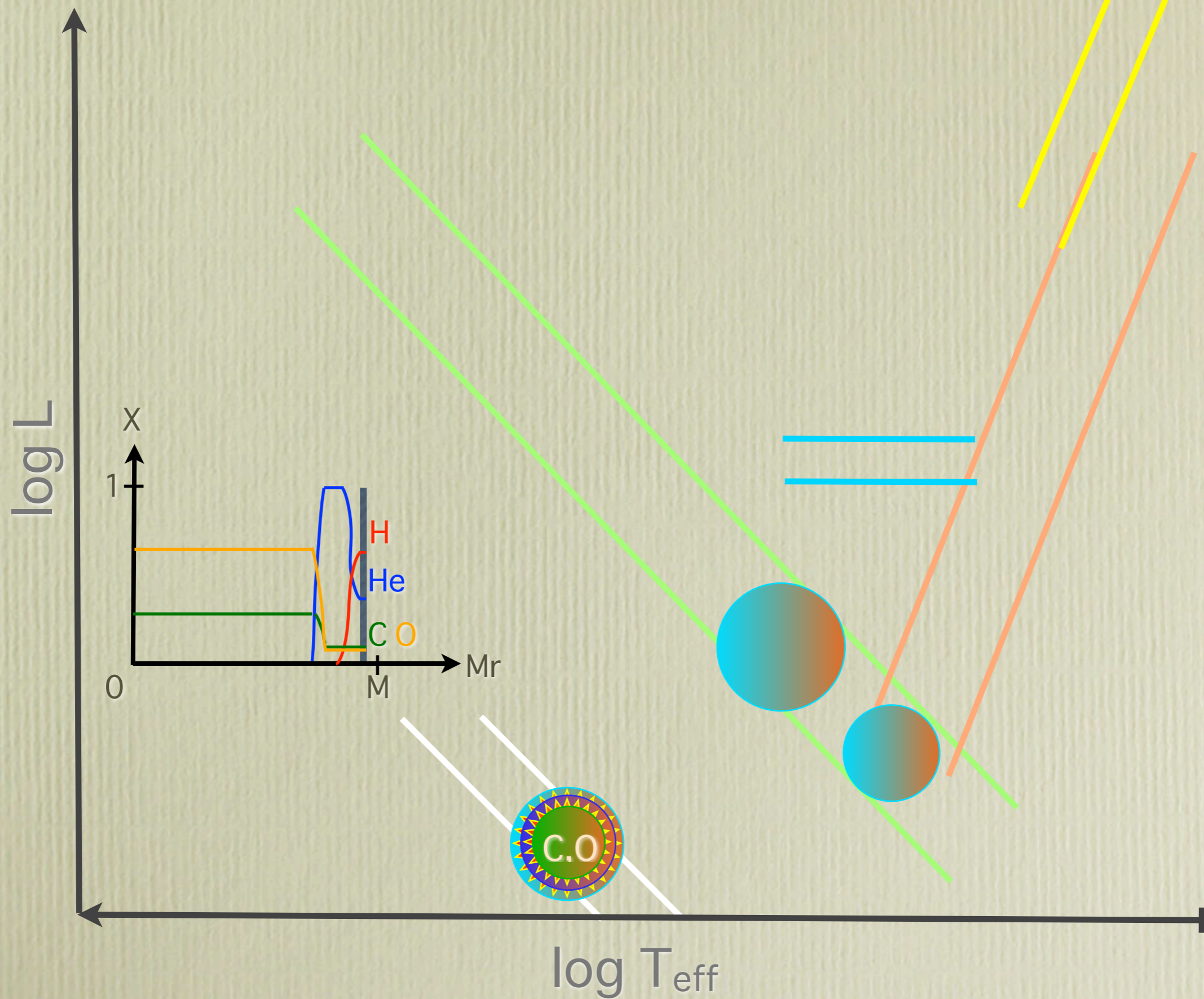
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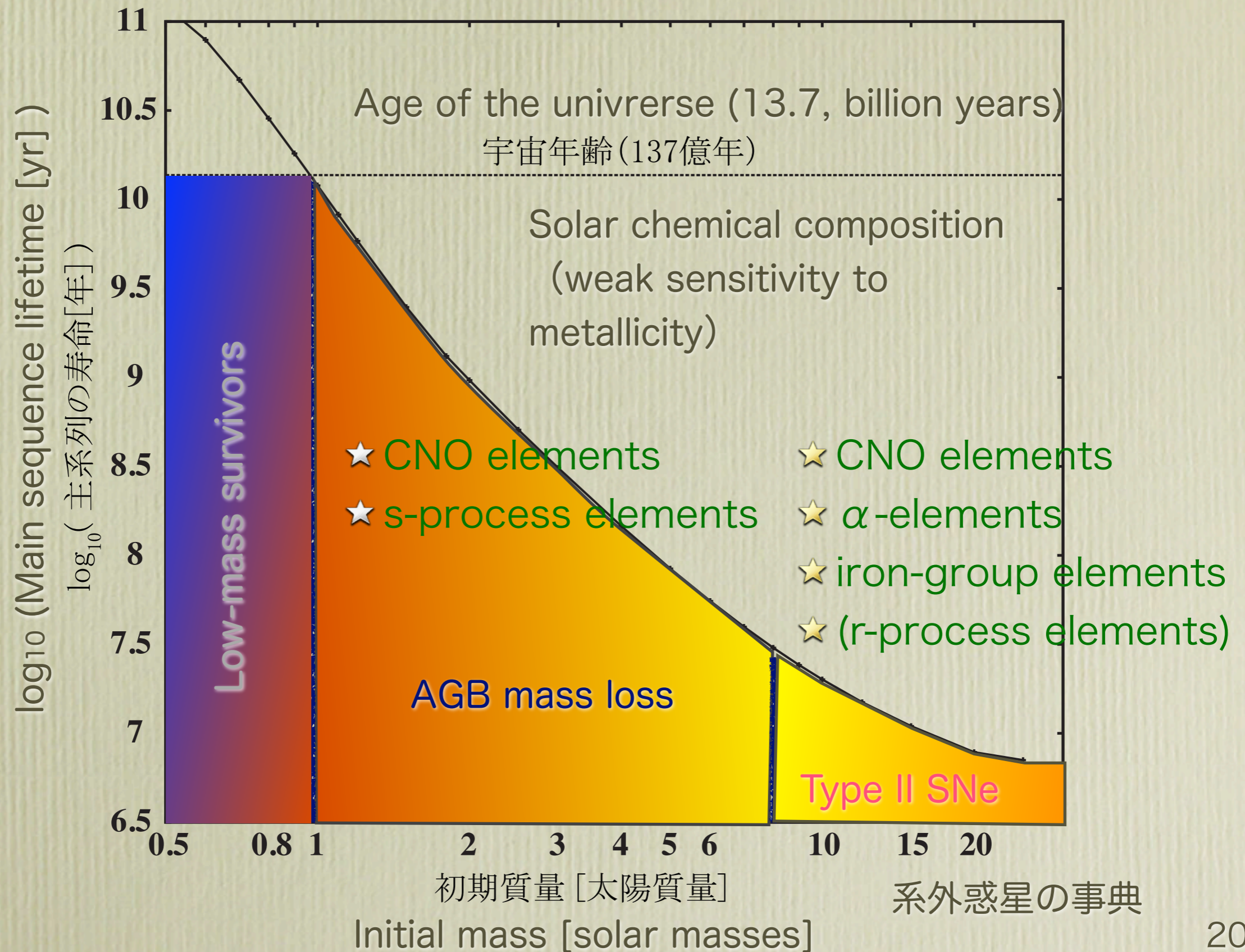
Evolution of Low- and Intermediate-Mass Stars



Evolution of Low- and Intermediate-Mass Stars



Mass - Lifetime relation

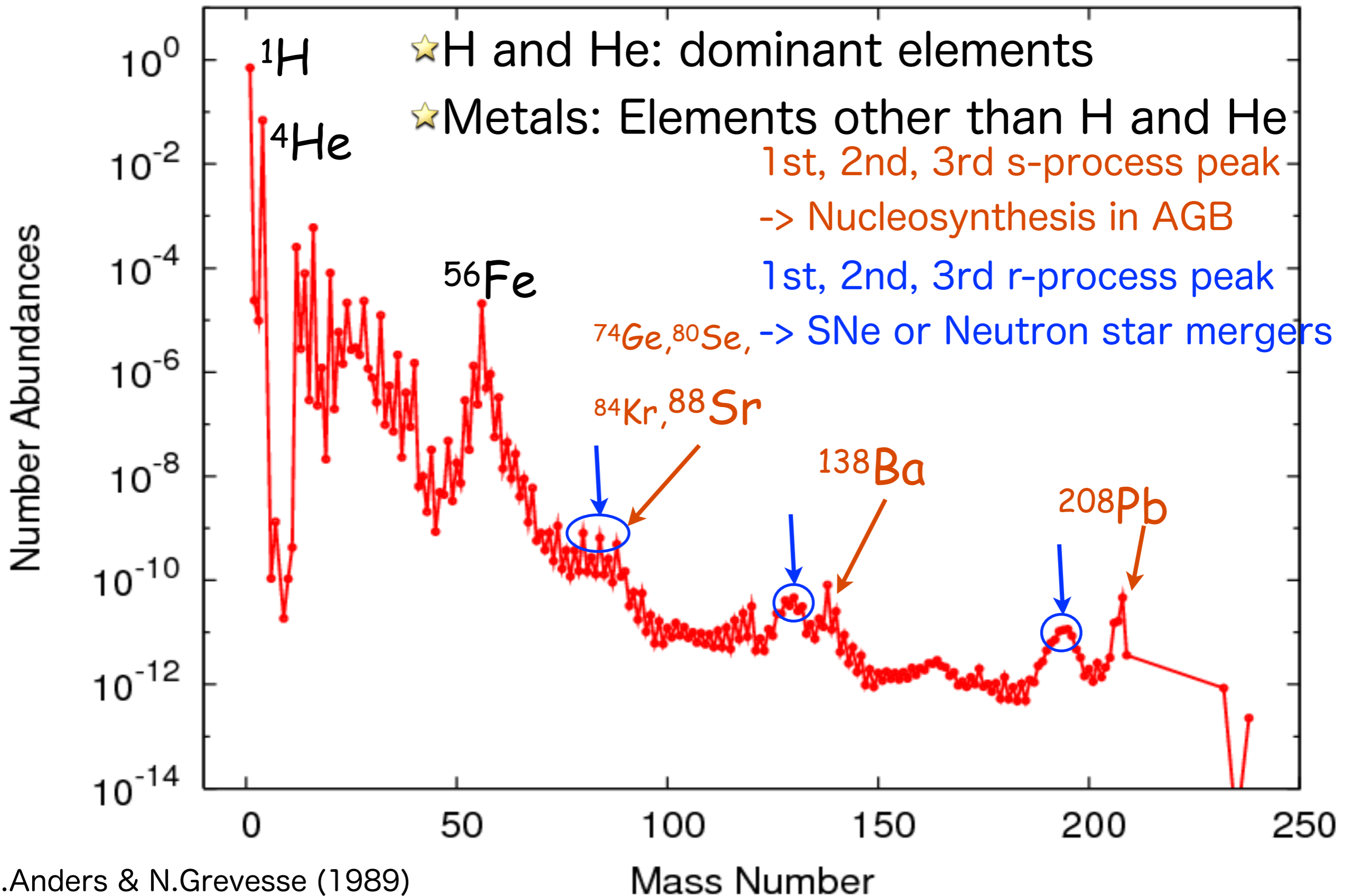


What is important in Galactic Archaeology?

Element Abundances!

- to identify the first stars in the universe
- to compare stellar models with observations
- to constrain star formation history
- to understand the formation and evolution of galaxies

Solar Chemical Composition

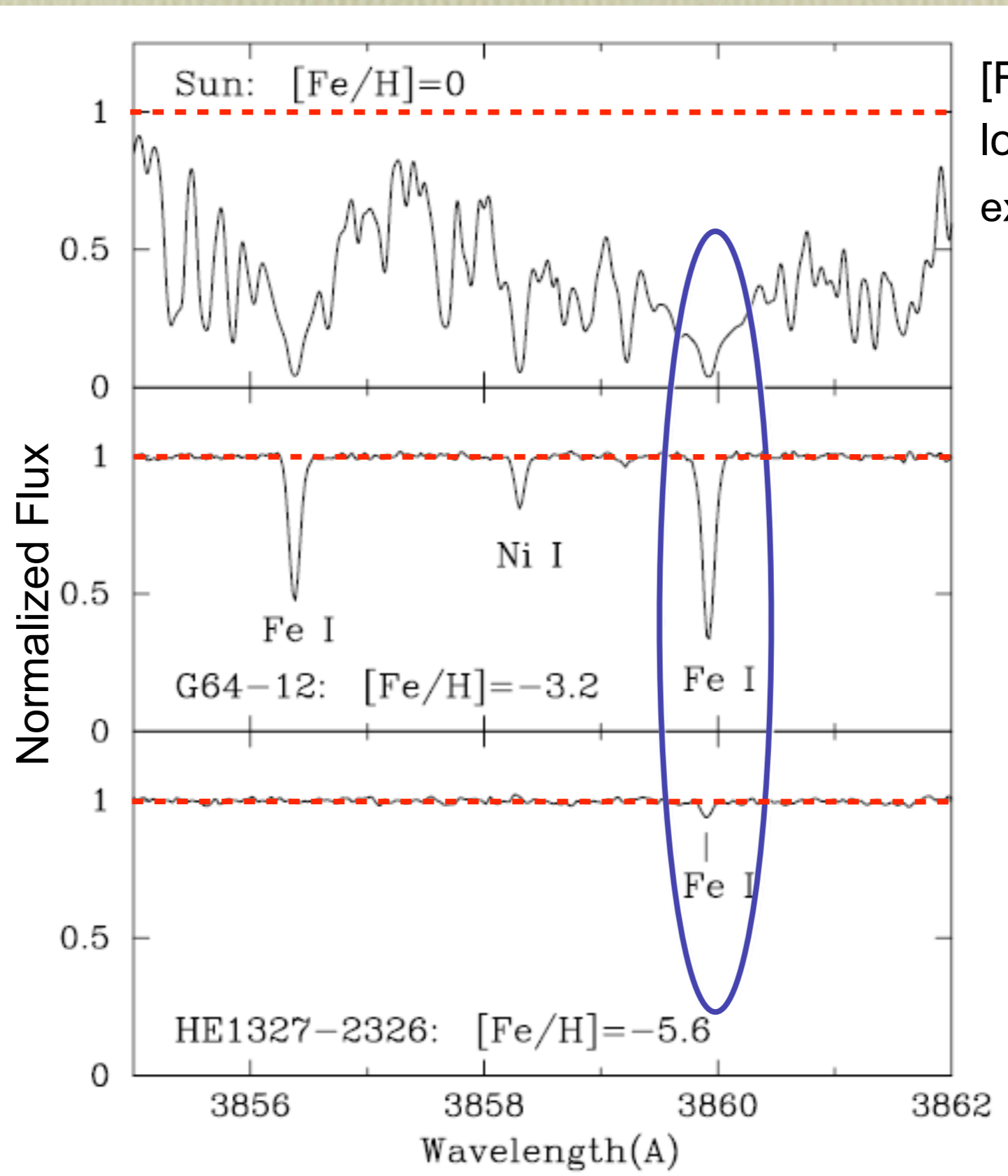


E.Anders & N.Grevesse (1989)

Stellar Spectra

Sun (Disk star)

Extremely
Metal-Poor
stars
(Halo stars)



$$[Fe/H] = \log(X_{Fe}/X_H) - \log(X_{Fe}/X_H)_{\odot}$$

ex) $[Fe/H] = 0$: solar
 $= -\infty$: Pop. III

Summary & Discussion

- 恒星進化の標準理論はほぼ確立されている。
 - 標準理論で説明できない現象はいくつかあり、どれも解決は困難
 - 観測技術の向上によって困難の度合いは増すと予想
- 恒星モデルの予言能力にも関わらず不定性は小さくない。
 - 質量放出
 - 物質混合
- 恒星進化理解のカギとなるのは星の元素組成（と星震学）
 - 星の内部構造（核反応）、物質混合（表面へのくみ上げ）への制限
 - 外部汚染（表面降着、連星間相互作用）の影響

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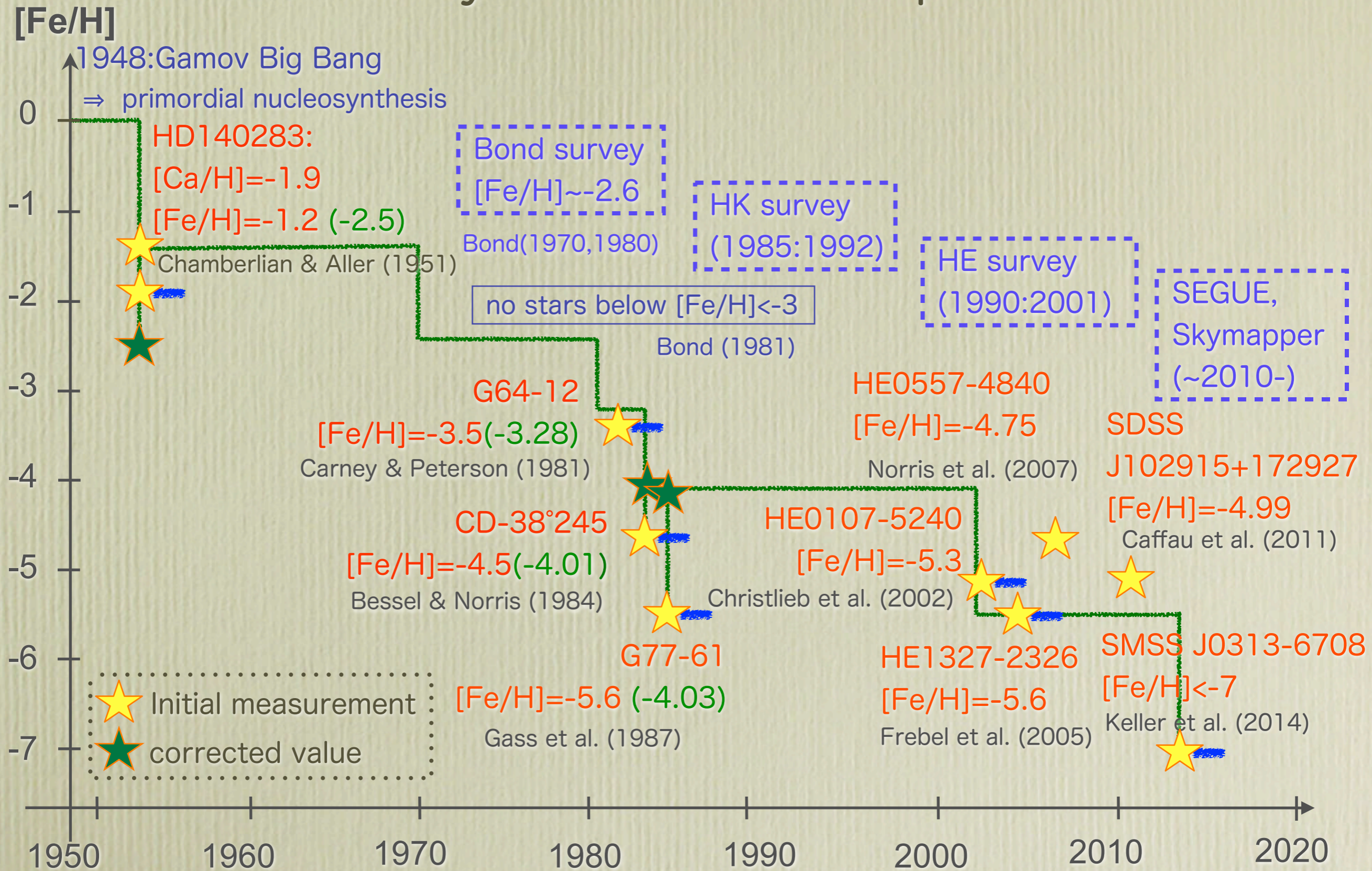
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- Suda et al.
 - PASJ, 60, 1159, 2008
- Suda et al.
 - MNRAS, 412, 843, 2011
- Yamada et al.
 - MNRAS, 436, 1362, 2013
- Suda et al.
 - PASJ, 69, 76, 2017

Formation of the First Stars

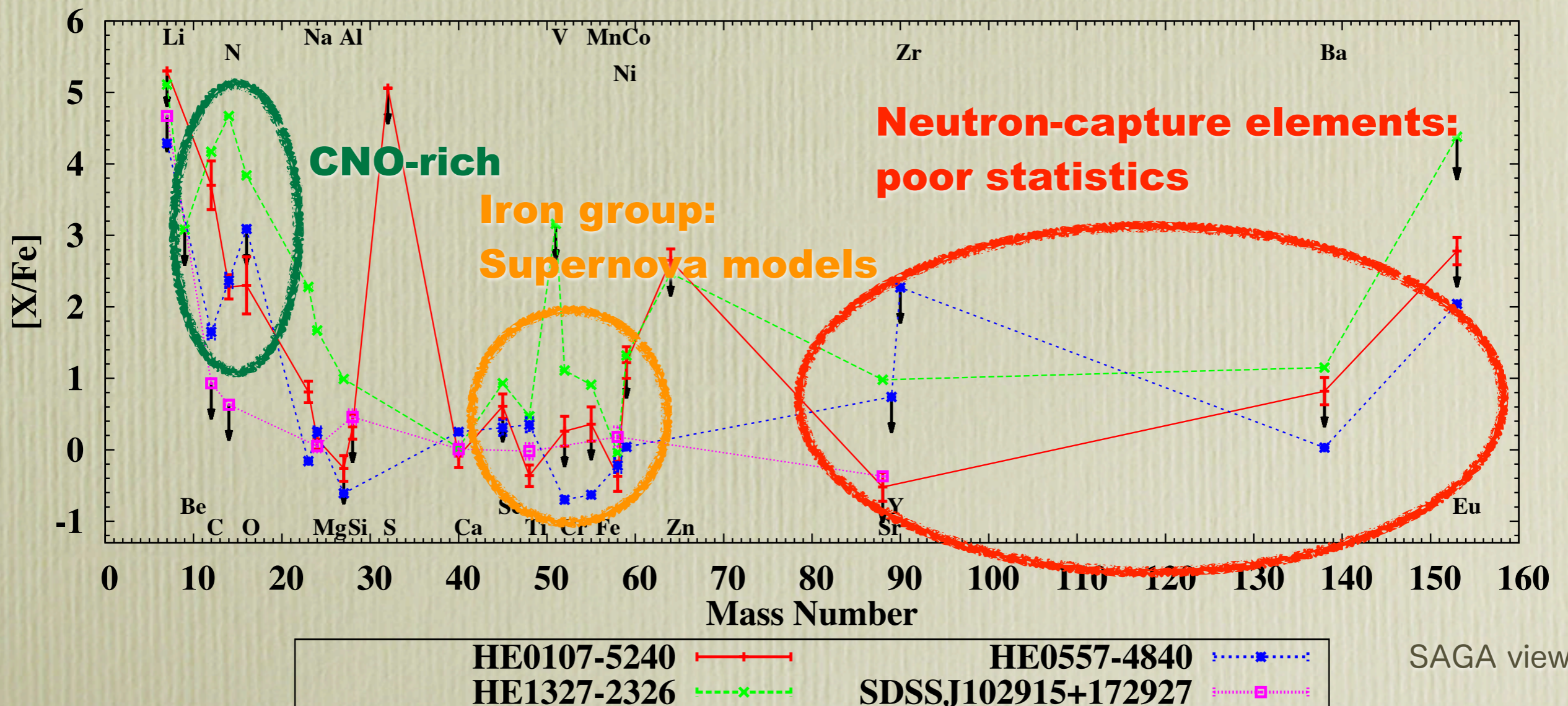
- Typical mass of the first stars
 - $\gg 100 M_{\odot}$ (BH formation, Ohkubo)
 - $\gg 100 M_{\odot}$ (Explode as Pair Instability Supernovae, PISNe: $\sim 260 M_{\odot}$) (Abel, Bromm, Larson, Loeb, Omukai, Inutsuka, Palla, Schneider, Ferrara)
 - $\sim 140 M_{\odot}$ (Photo-evaporation of disks: McKee, Tan)
 - $\gg 10 M_{\odot}$ (Type II SNe dominant: Brian, Norman)
 - $\sim 40 M_{\odot}$ (Cooling by HD molecules; Accretion disk around protostar: Hosokawa, Omukai, Yoshida, Hirano)
 - $\sim 1 M_{\odot}$ (bimodal peak (~ 1 and $>10 M_{\odot}$) IMF: Nakamura, Umemura; Fragmentation of disk: Clark, Greif, Susa)
- Extrinsic factors
 - Low-mass star formation by UV radiation (Omukai, Yoshii)
 - SN-induced star formation (low-mass stars: Salvaterra, Ferrara, Schneider, Machida)

History of Search for Pop. III

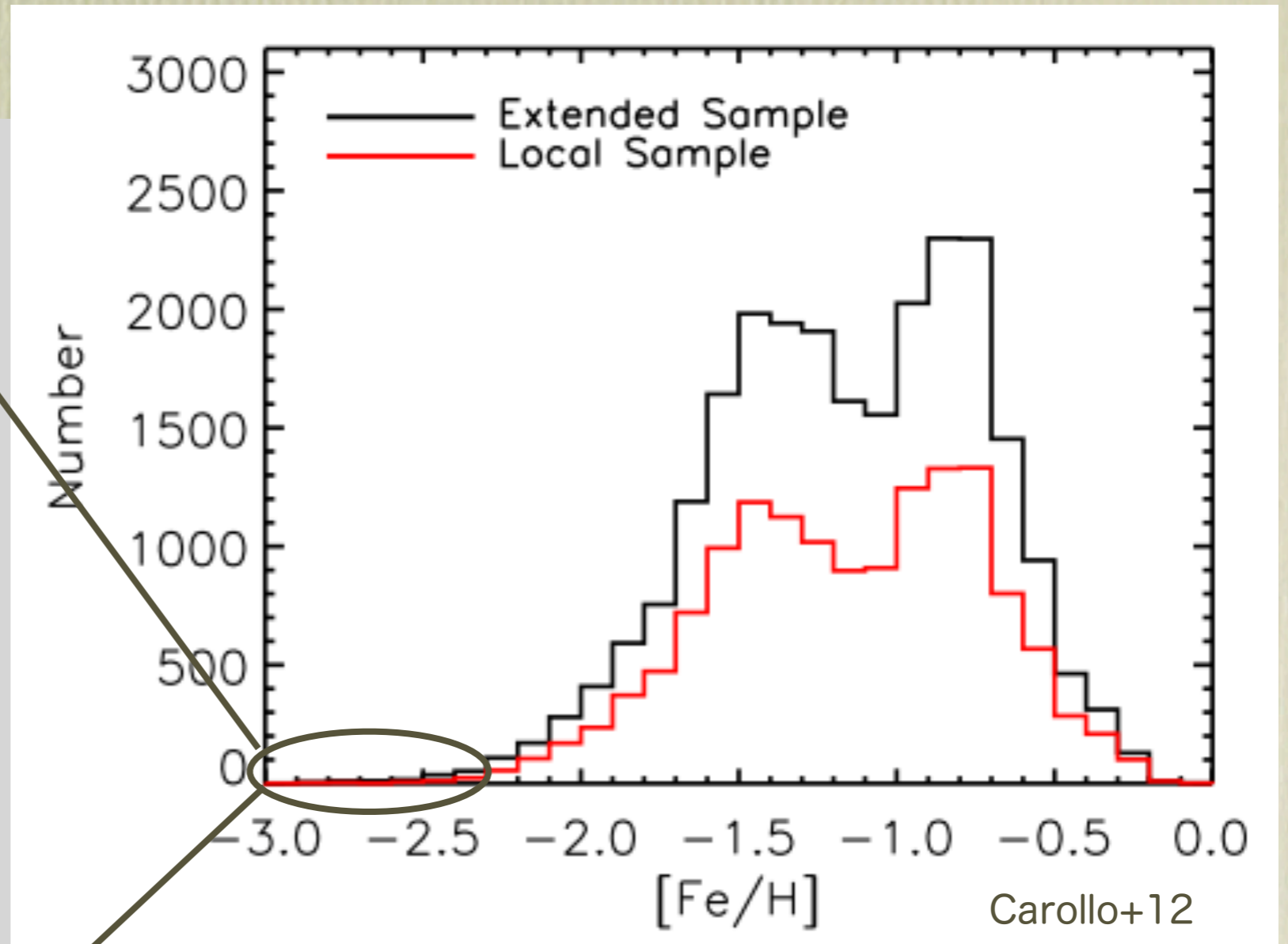
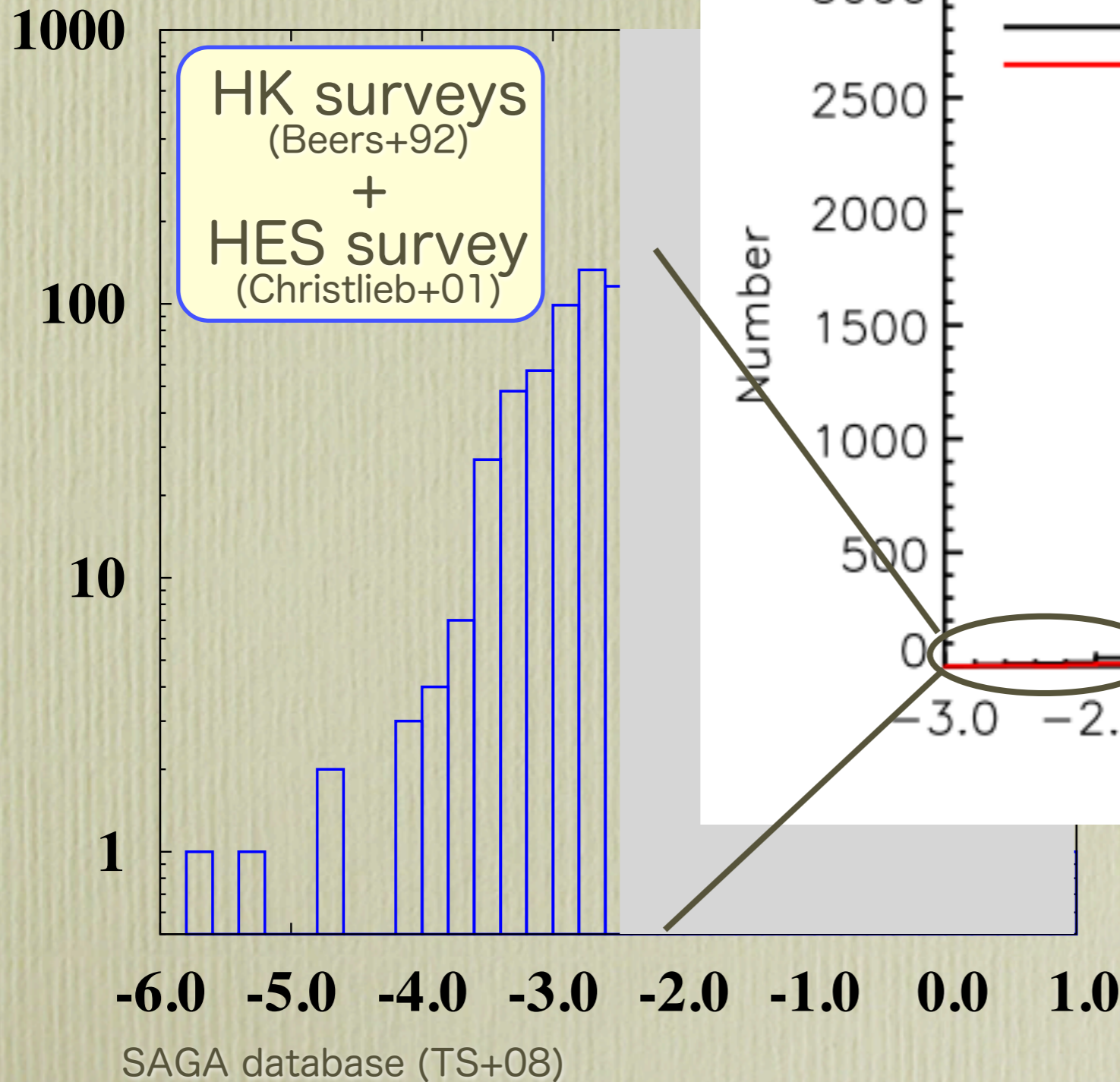


Hyper Metal-Poor Stars

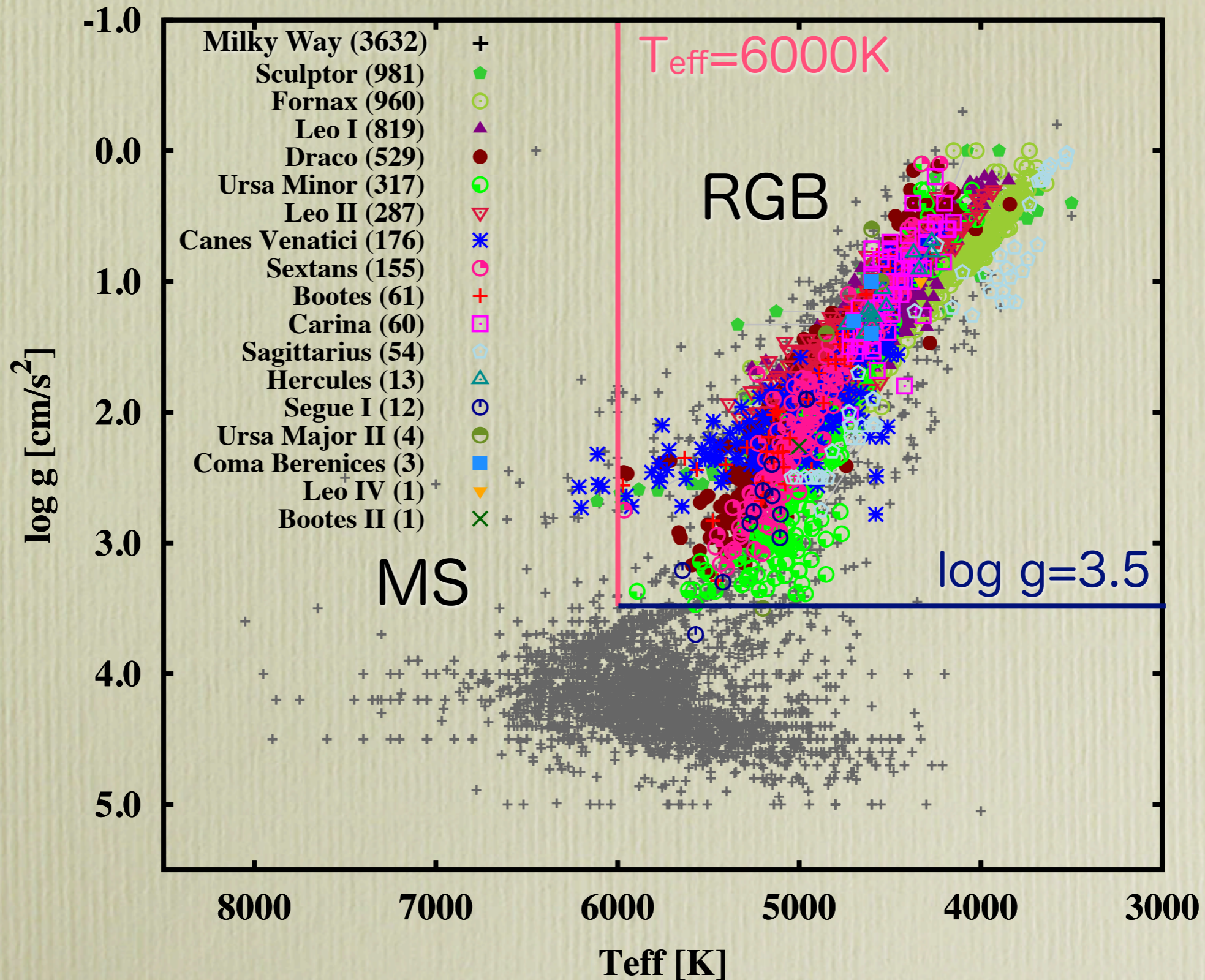
- are considered as the candidates of the first stars
- are related to low-mass star ($\sim 0.8M_{\odot}$) formation
 - What is the minimum metallicity to form low-mass stars?
 - How many low-mass Pop.III stars are formed and how much of them have survived until today?



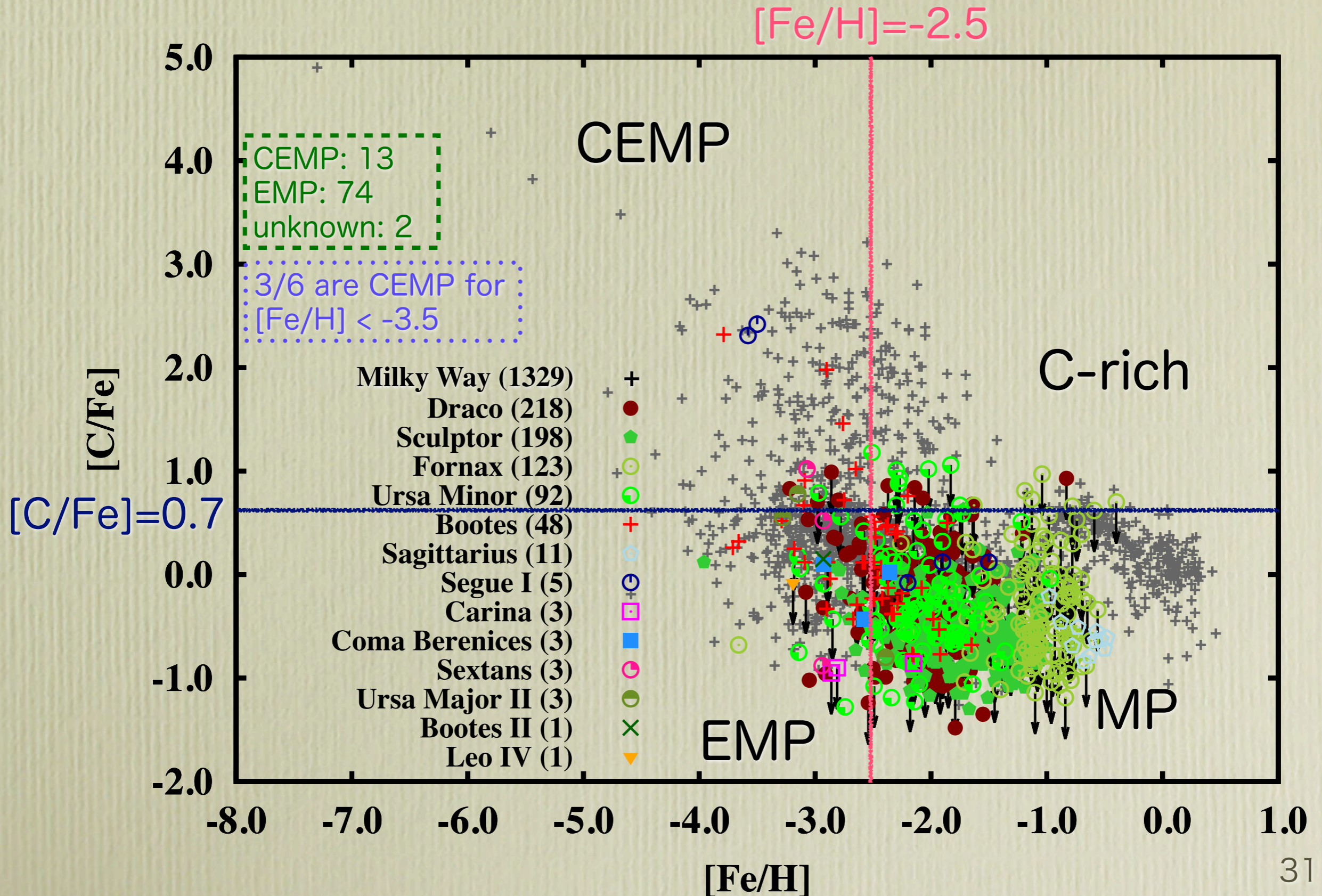
Metallicity Distribution Function



SAGA Sample Stars on H-R Diagram

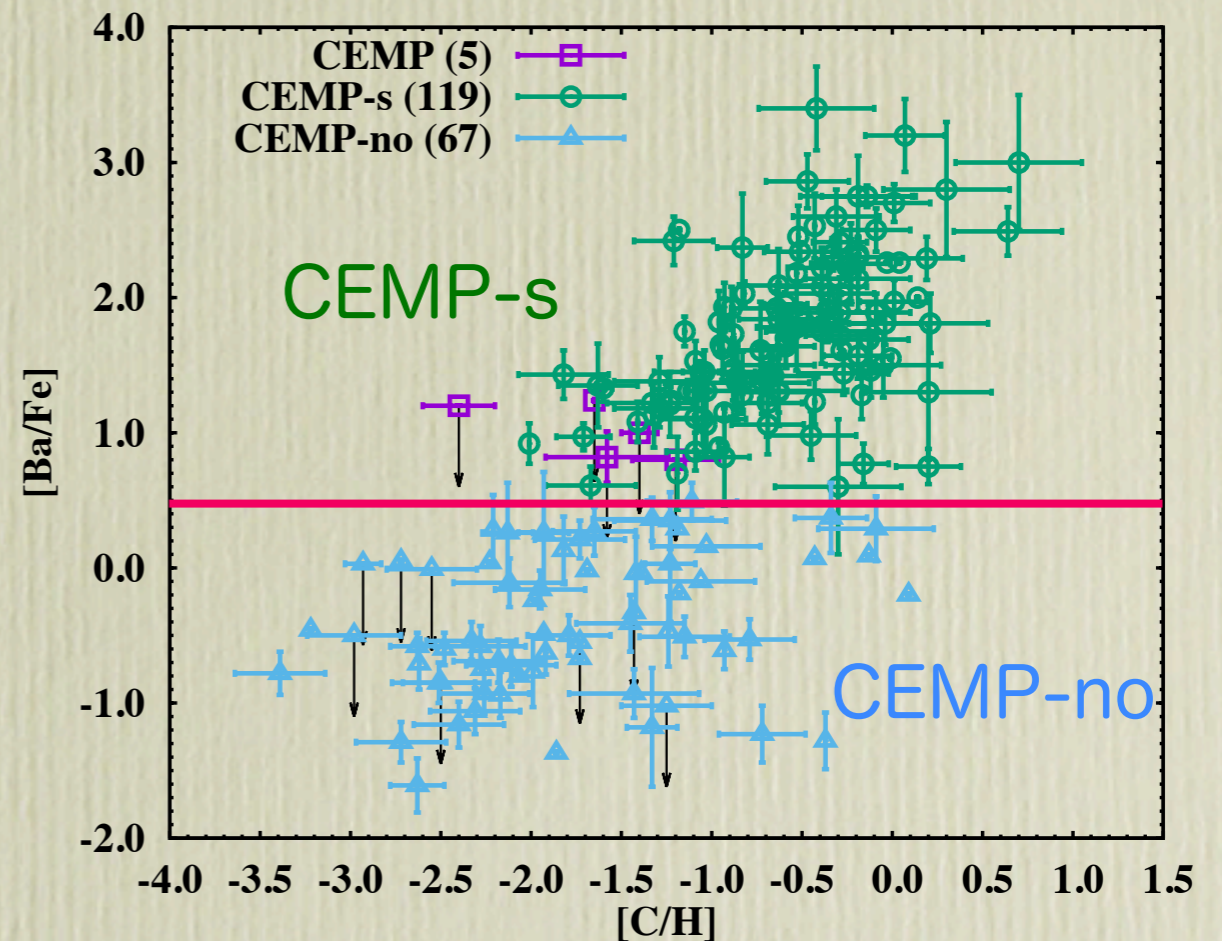
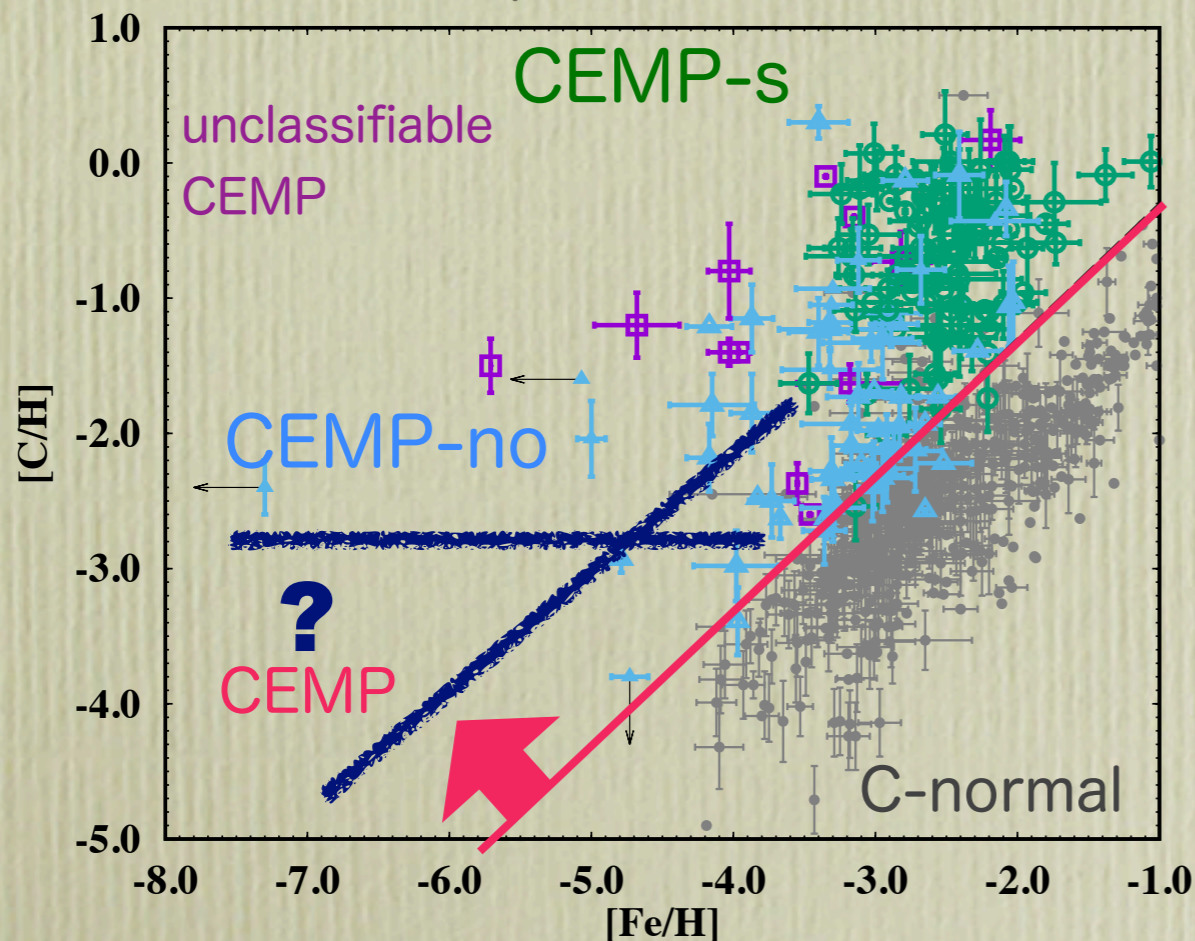


Large Number of Carbon-Enhanced Stars



Properties of Carbon-Enhanced Metal-Poor (CEMP) Stars

- ★ common in Extremely Metal-Poor (EMP) stars
 - ★ > 20 % for $[\text{Fe}/\text{H}] < -2$ with $[\text{C}/\text{Fe}] \geq 0.7$
- ★ divided into subclasses
 - ★ CEMP-s (s-process) $[\text{Ba}/\text{Fe}] \geq 0.5$
 - ★ CEMP-no (no s-process) $[\text{Ba}/\text{Fe}] < 0.5$
 - lower and higher CEMP-no (Bonifacio+15)
 - ★ CEMP-r (r-process), CEMP-r/s (s+r), etc.



See also discussions by Aoki+07, Bonifacio+15, Yoon+16, Matsuno+17, etc.

Summary & Discussion

- 初代星の直接的証拠は見つかっていない。
 - 最も鉄の少ない星は $[\text{Fe}/\text{H}] < -7.1$
 - 8m級地上望遠鏡での検出限界は $[\text{Fe}/\text{H}] \sim -8$
- 金属欠乏星($[\text{Fe}/\text{H}] < -3$)の多くが炭素過剰($[\text{C}/\text{Fe}] \geq 0.7$)を示す。
 - s-process元素(Ba)過剰を示す星(CEMP-s)と示さない星(CEMP-no)に分けられる。
 - $[\text{Fe}/\text{H}]$ が小さいほどCEMP-noの割合が大きい。
 - CEMPは全体の20-30%程度 (ディスク星では~1%)
 - $[\text{Fe}/\text{H}] < -5$ ではすべてCEMP-no
- 鉄と炭素以外にも多くの不思議な元素組成が見られる。
 - 窒素過剰(NEMP)星
 - Na, Mg, Alの過剰、過小を示す星。
 - Li組成の金属量依存性
 - r-process元素の過剰を示す(r-I, r-II)星
 - r-, s-process両方の過剰を示す(CEMP-r/s)星

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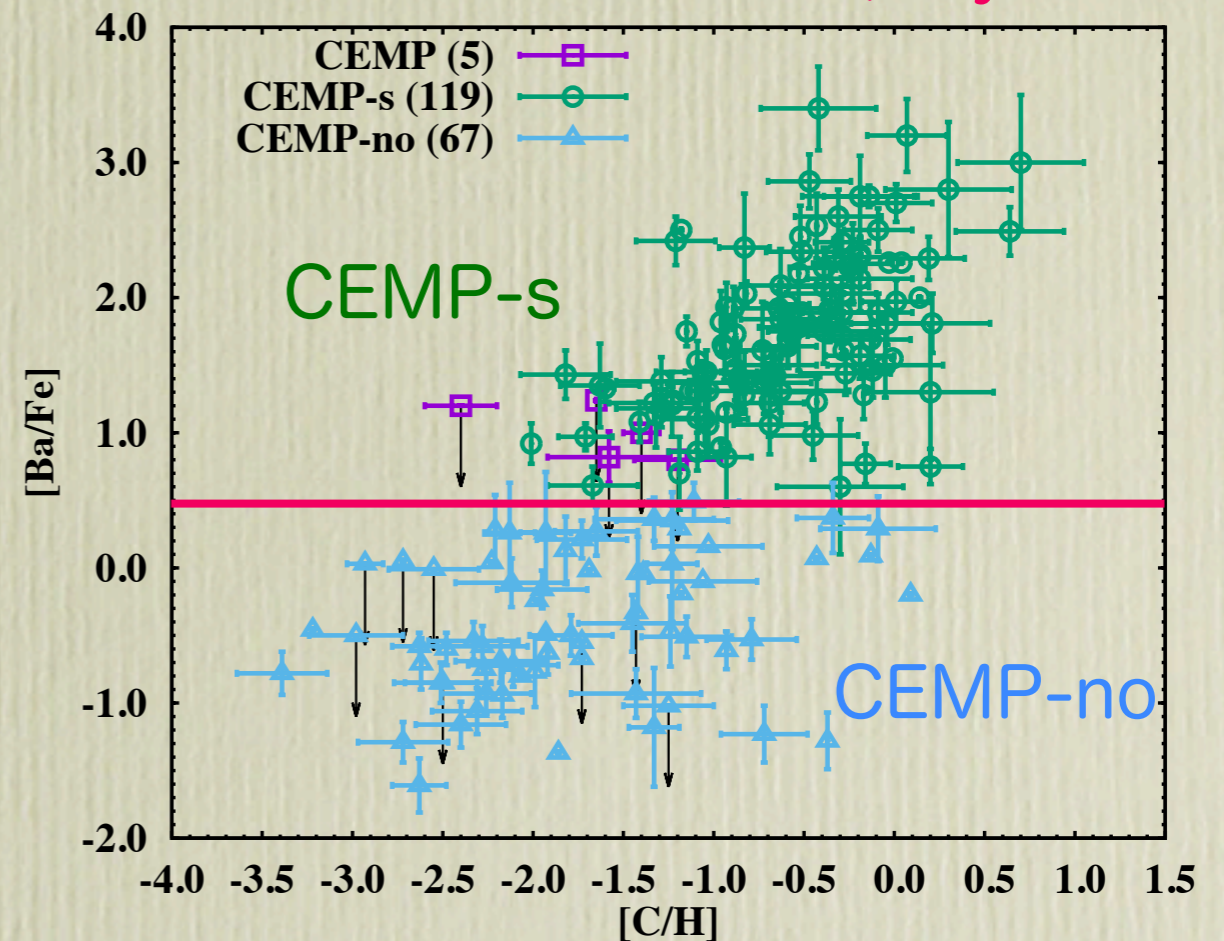
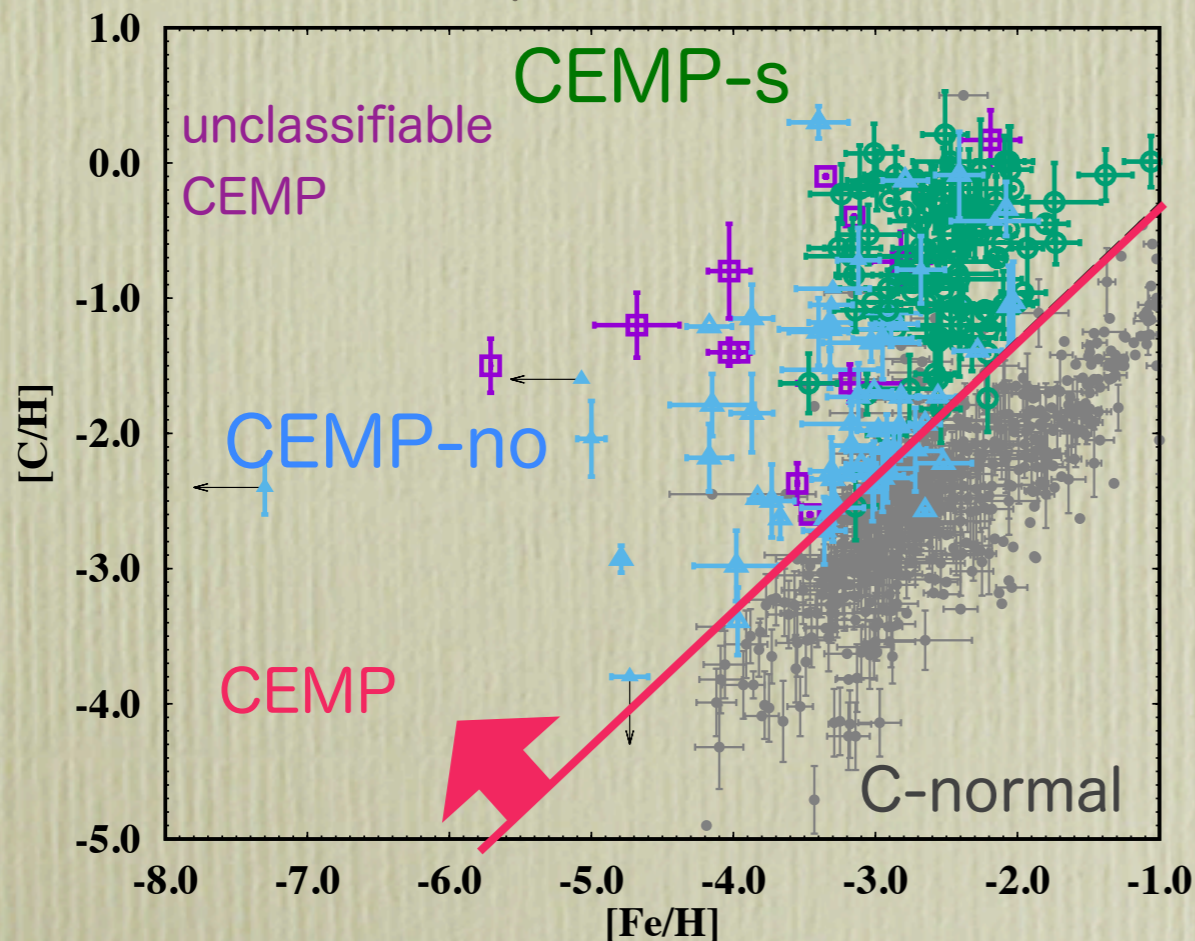
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- Suda et al.
 - ApJ, 611, 476, 2004
- Komiya et al.
 - ApJ, 658, 367, 2007
- Nishimura et al.
 - PASJ, 61, 909, 2008
- Suda & Fujimoto
 - MNRAS, 405, 177, 2010
- Suda et al.
 - MNRAS, 432, L46, 2013
- Lee, Suda, Beers, Stancliffe
 - ApJ, 788, 131, 2014

Origin of Extremely Metal-Poor (EMP) Stars

- ★ common in Extremely Metal-Poor (EMP) stars
 - ★ $> 20\%$ for $[\text{Fe}/\text{H}] < -2$ with $[\text{C}/\text{Fe}] \geq 0.7$
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 - lower and higher CEMP-no (Bonifacio+15)
 - ★ CEMP-r (r-process), CEMP-r/s (s+r), etc.
- Possible origins
- I) CEMP-s and no come from binary mass transfer
 - II) CEMP-no from supernova models (Umeda+02)
 - III) CEMP-no from rotating massive stars (Meynet+06)



See also discussions by Aoki+07, Bonifacio+15, Yoon+16, Matsuno+17, etc.

(炭素過剰) 金属欠乏星の起源

- Mixing and Fallback Supernova Models

Fallback (0.002% ejected)

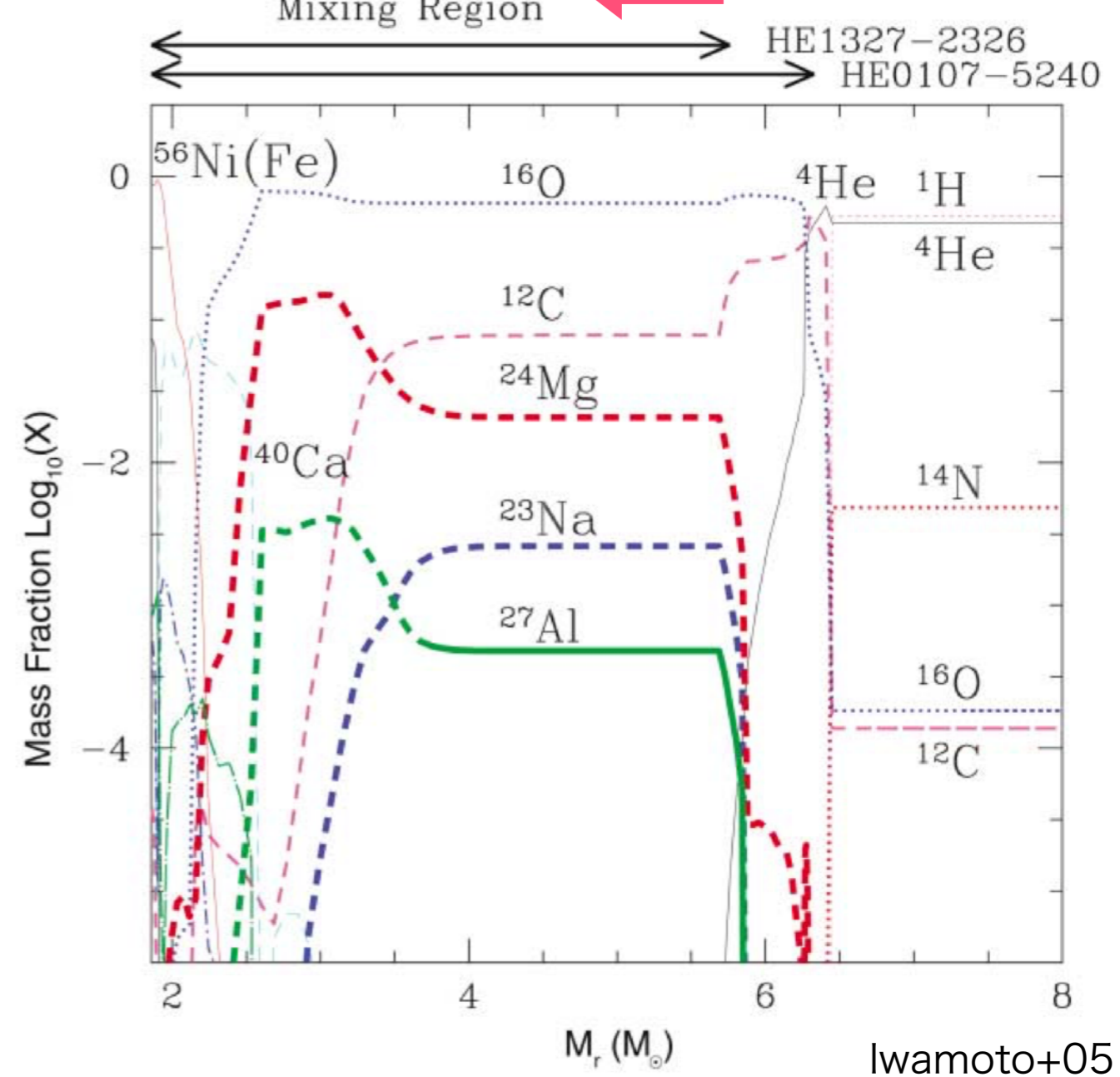
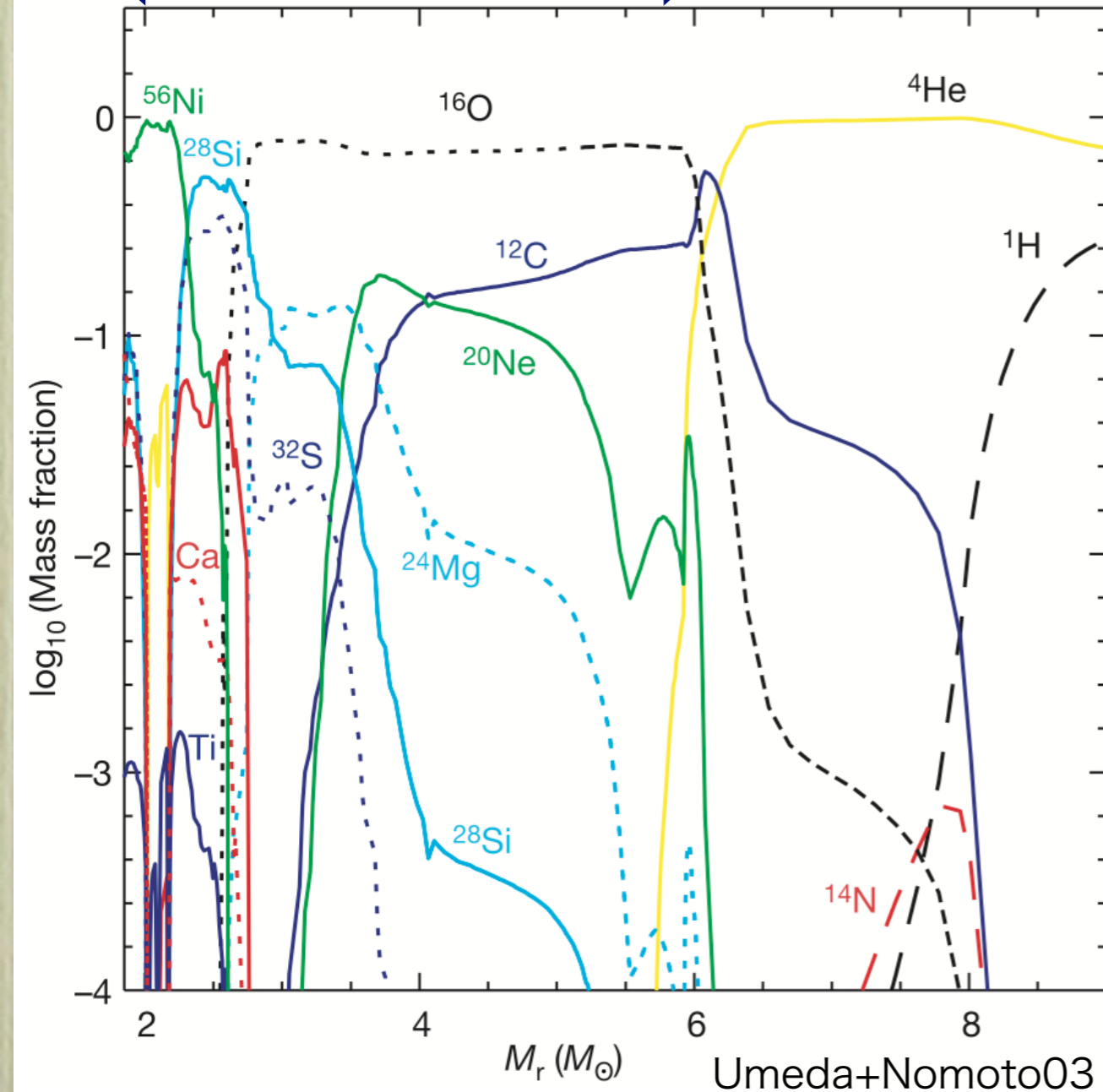
Mixing Region

Fallback (0.012% ejected)

Fallback (0.0087% ejected)

Mixing Region

HE1327-2326
HE0107-5240



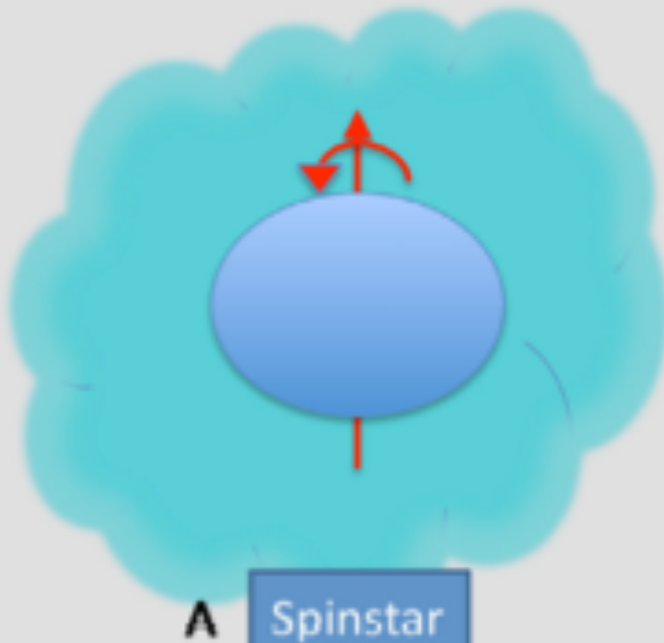
Umeda+03, Iwamoto+05, Tominaga+07, Nomoto+13,
Ishigaki+14, Takahashi+14

faster mixing (HE1327-2326)
x30 larger diffusion coefficient

(炭素過剰) 金属欠乏星の起源

- Fast Rotating Massive Stars

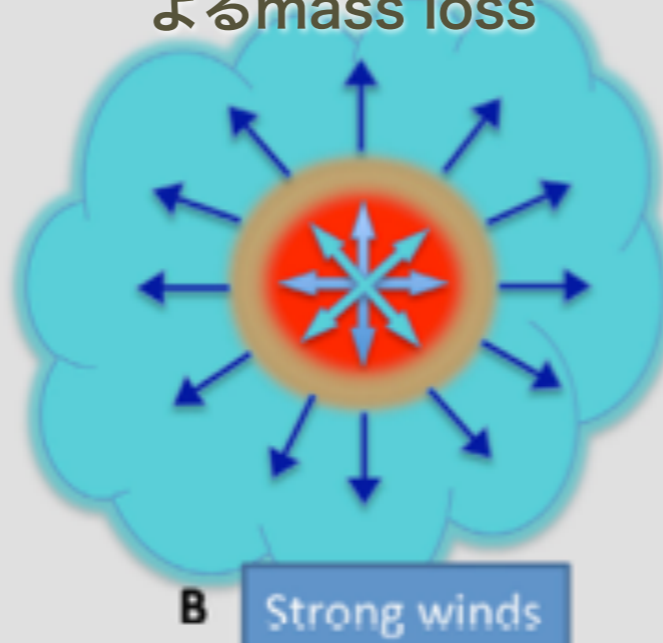
回転による物質混合



A Spinstar

core H-burning

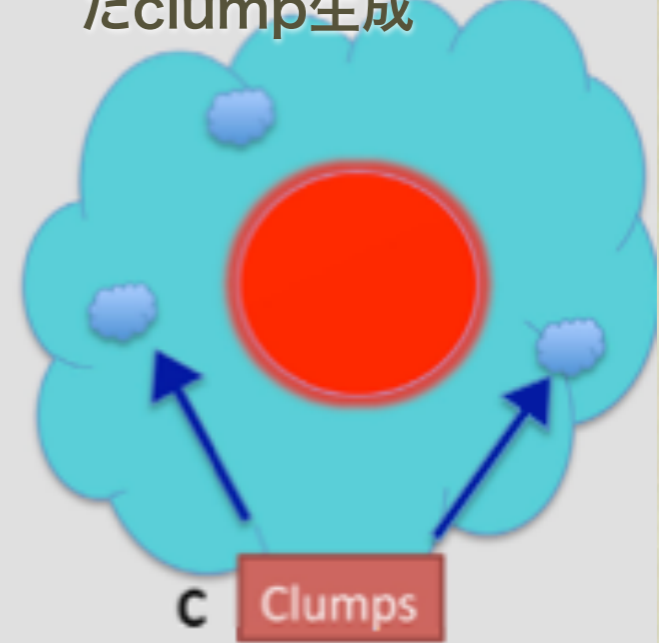
表面のCNO増加によるmass loss



B Strong winds

core He-burning

元素合成を反映したclump生成



C Clumps

wind+ISM -> clumps

爆発しないので
clumpが生き残る。



Future CRUMP
or CEMP star

D1 No SN event

BH without supernova

jet爆発でclumpが
生き残る。



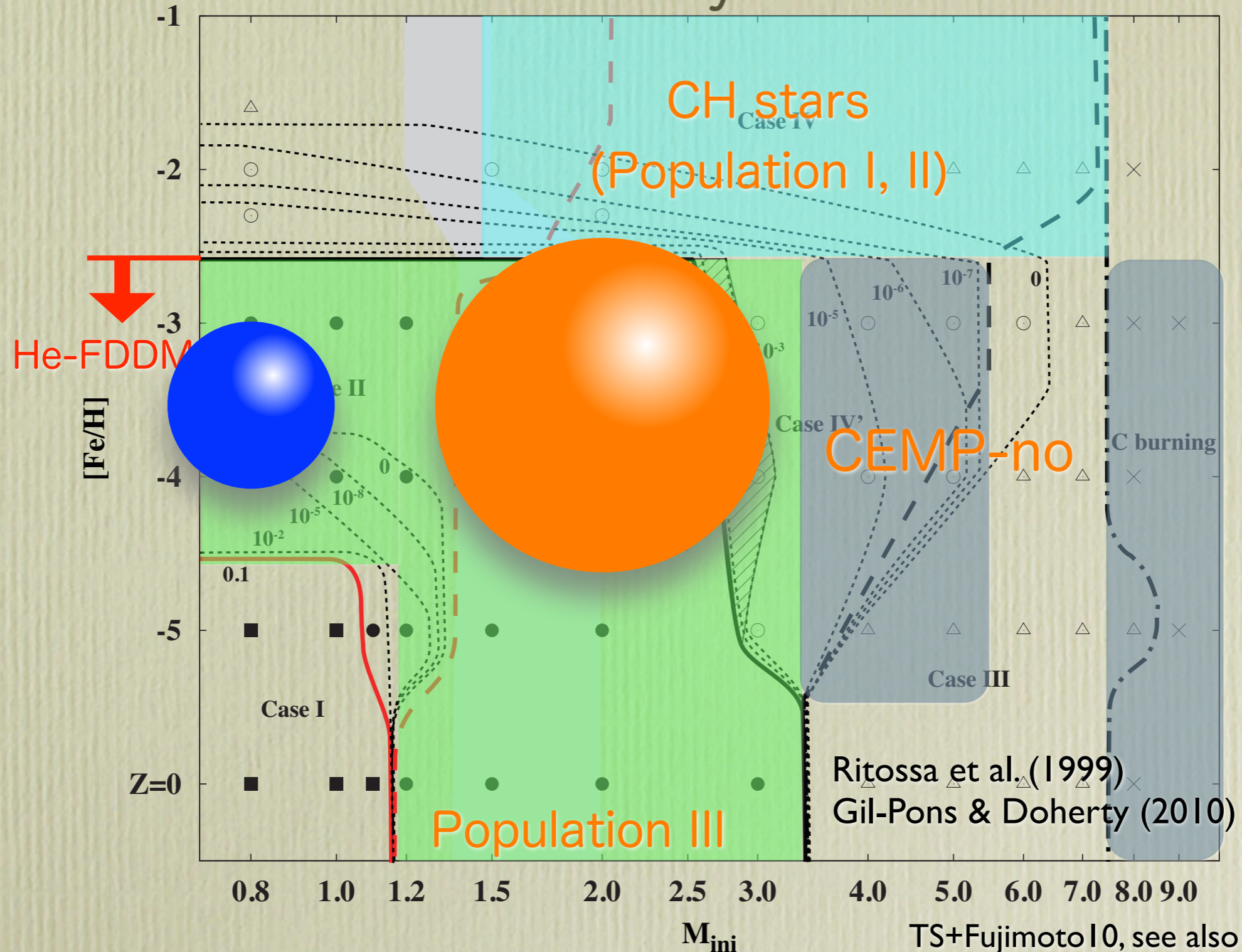
D2 Anisotropic SN explosion

supernova explosion

Meynet+10

(炭素過剰) 金属欠乏星の起源

- Binary Mass Transfer Models

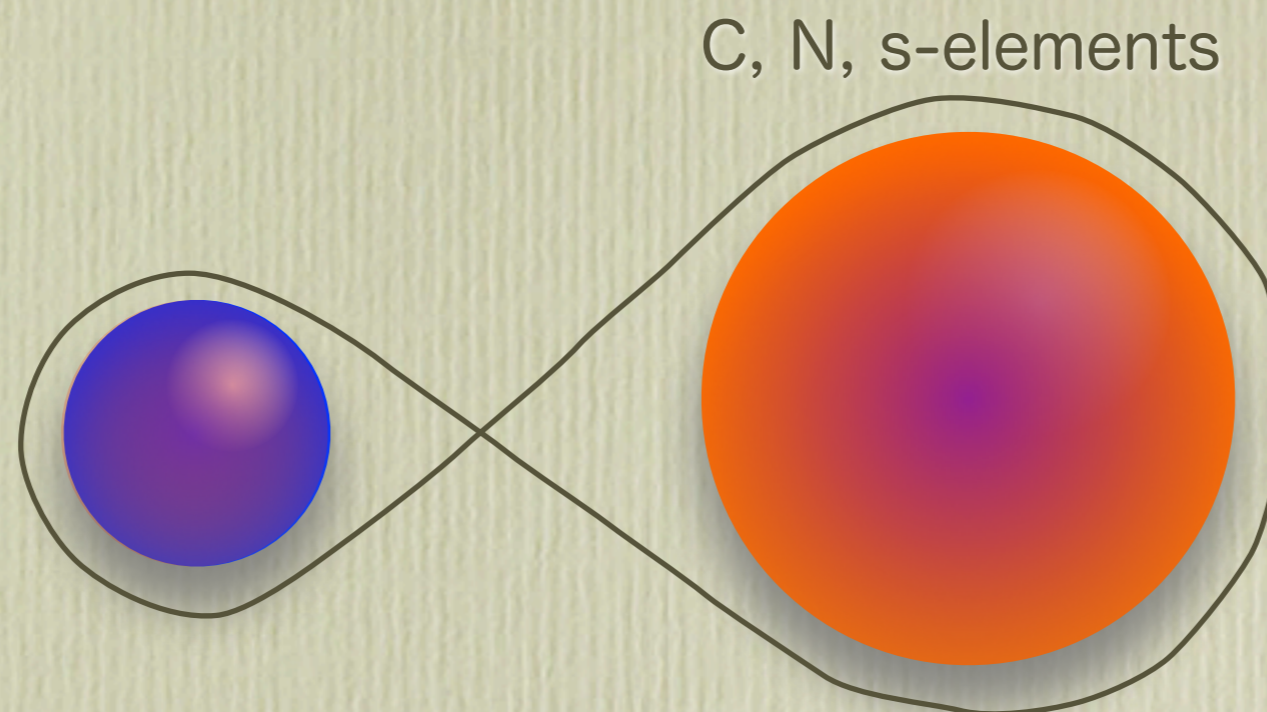


He-Flash Driven Deep Mixing: H-ingestion into the He-flash convective zone
 Fujimoto+90, Hollowell+90, Cassisi+96, Fujimoto+00, Schlattl+02, Suda+04,
 Iwamoto+04, Picardi+04, Herwig+05, Campbell+Lattanzio+08, Lau+09, Cristallo+09,
 Iwamoto09, Campbell+09, Suda+Fujimoto 10

TS+Fujimoto 10, see also Fujimoto+00

(炭素過剰) 金属欠乏星の起源

- Binary Mass Transfer Models



CEMP星の割合が連星パラメーターによって決まる。=>連星種族合成

- ★ 初期質量関数
- ★ 連星の質量比分布
- ★ 連星の周期分布

連星形成=>重力波天体

It is expected that the typical mass of stars are more massive than that expected from the present day IMF (Komiyama+07, Lucatello+06).

(炭素過剰) 金属欠乏星の起源

Mixing and fallback models

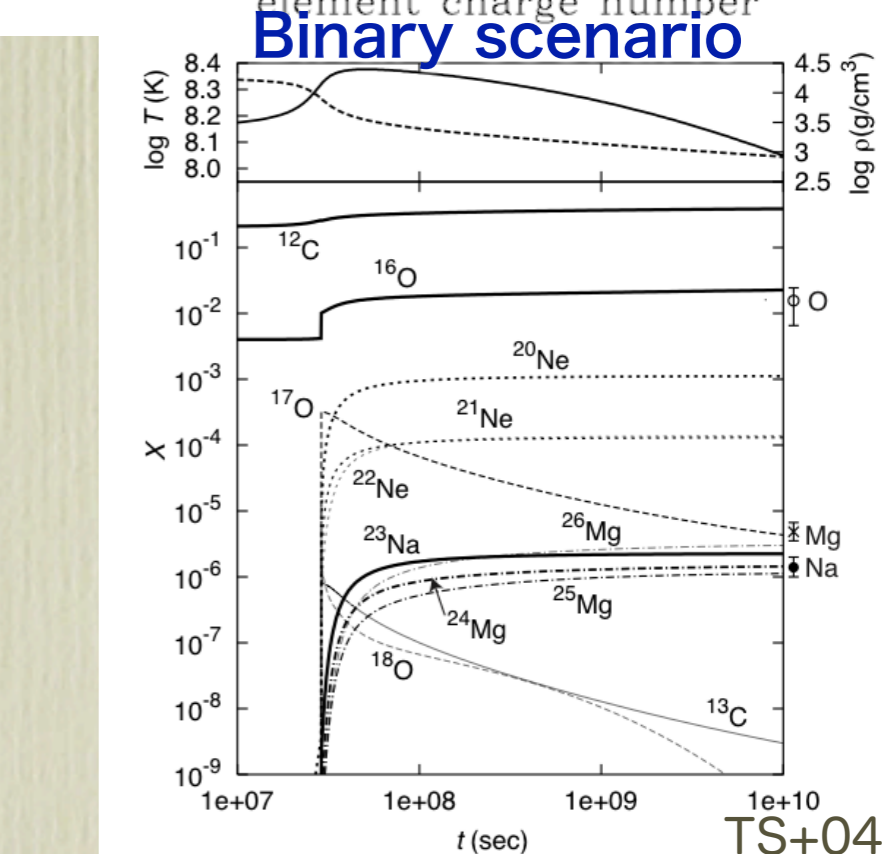
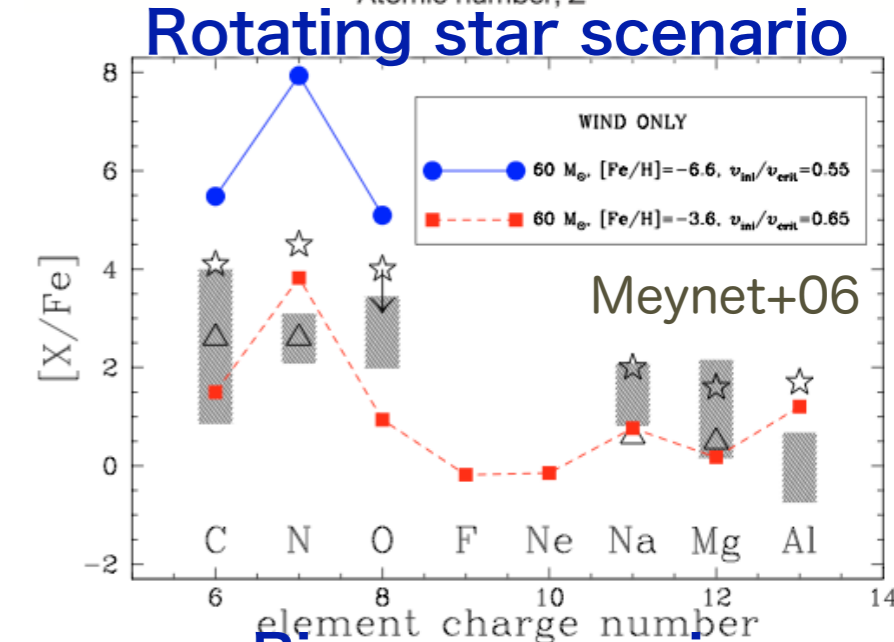
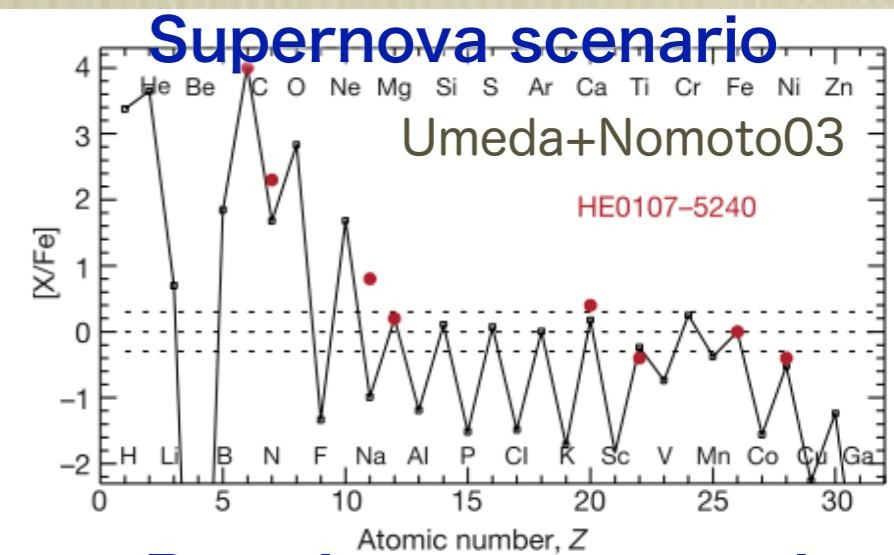
- Mixing regionとfallback parameterを調整することで多くの金属欠乏星の組成パターンを説明可能。(Tominaga+14)
- faint supernovaから次世代の星を作ることができるかどうか議論されている。(Chiaki+16,17)
- すべてのPop. IIIをfaint supernovaと仮定した場合の[C/Fe]と[Fe/H]分布との比較が行われている。(Cooke+Madau14)

Fast rotating massive star (FRMS) models

- すべてのPop.IIIがFRMSだと仮定して化学進化モデルの計算。(Chiappini+06)
- Li組成や $^{12}\text{C}/^{13}\text{C}$ 比を説明するためにmixing parameterを調整。(Choplin+17)

Binary mass transfer models

- 連星モデルから星のIMFを予言。(Komiya+07)
- 金属欠乏AGB星に特有な物質混合(Fujimoto+90,00, Cassisi+96, Schlattl+02, TS+04,07,10, Campbell+08, Iwamoto+04,09, Lau+09, Lugaro+12)
- CEMP(-no)星は連星に属していないという観測結果。(Starkenburg+14, Hansen+16)
 - HE0107-5240では連星周期150年を予言。(TS+04)
- 鉄組成の星間降着は難しい。(Tanaka+17)
 - 星間、銀河間降着によるPop.IIIの表面汚染。(Komiya+16)



IS HE 0107–5240 A PRIMORDIAL STAR? THE CHARACTERISTICS OF EXTREMELY METAL-POOR CARBON-RICH STARS

2004, ApJ, 611, 476

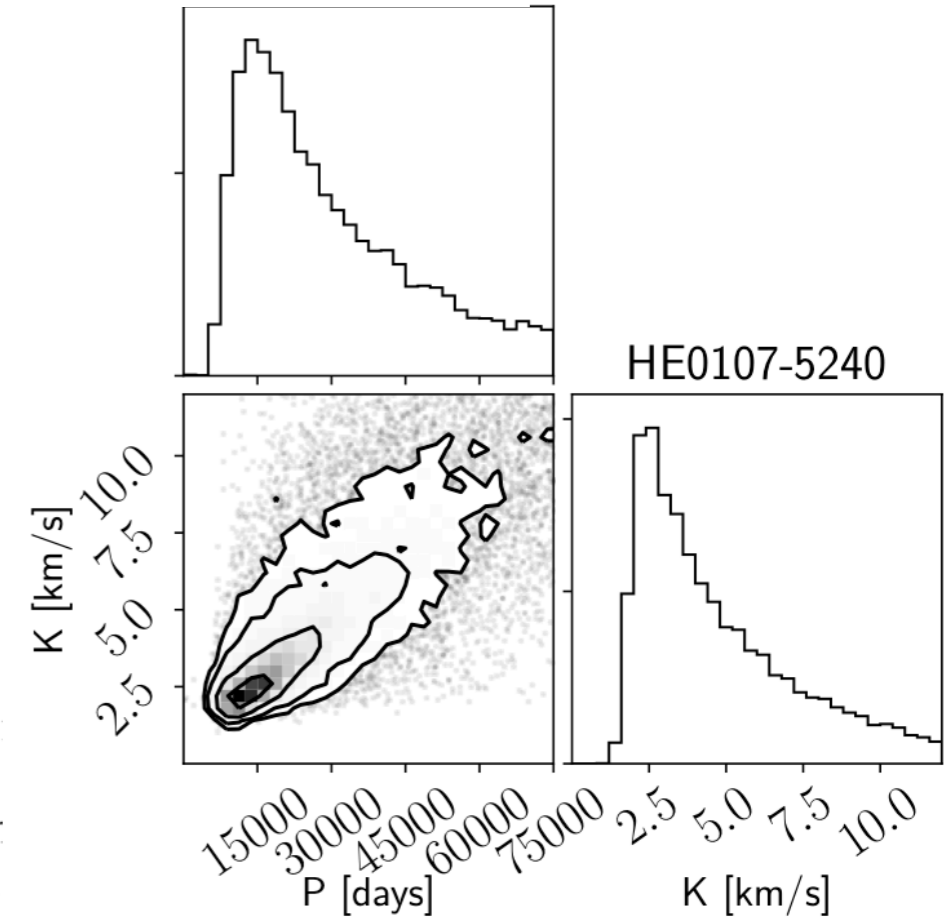
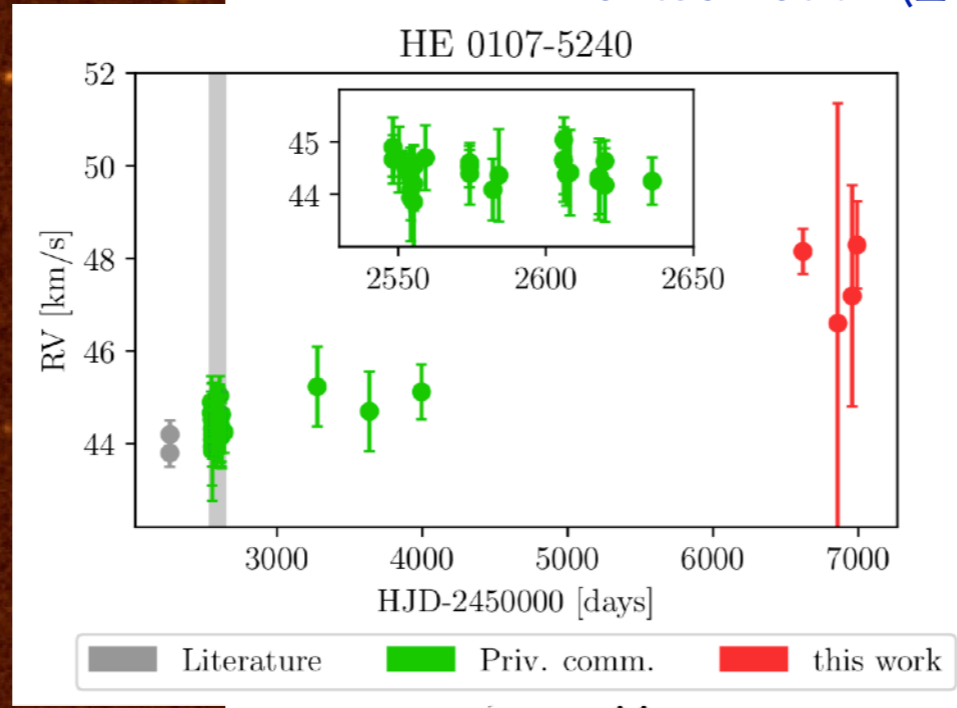
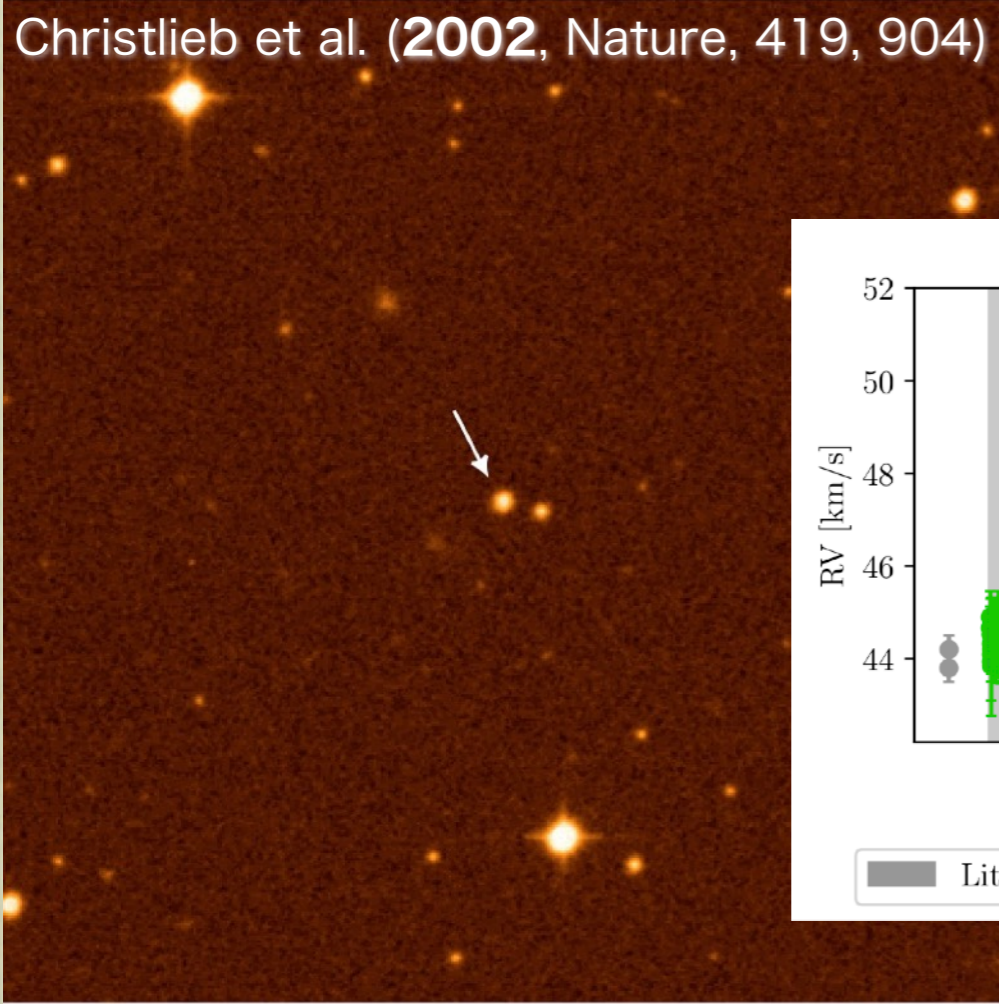
TAKUMA SUDA,¹ MASAYUKI AIKAWA,¹ MASAHIRO N. MACHIDA,^{2,3} AND MASAYUKI Y. FUJIMOTO
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Christlieb et al. (2002, Nature, 419, 904)

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 Received 2004 Febr Arentsen et al. (2019, A&A, 621, A108)



The Very Metal-Deficient Star HE 0107-5240

ESO PR Photo 25a/02 (30 October 2002)

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chemically evolved companion, which ... in the binary, we rely on the results ... Nucleosynthesis in a helium-flash ... ved, allowing us to explain the origin in ... enrichments and to discuss the abundances of *s*-process elements. From th ... that HE 0107–5240 has evolved from a wide binary (of initial separation ~ 20 AU) with a primary of initial mass in the range $1.2\text{--}3 M_{\odot}$. On the assumption that the system now consists of a white dwarf and a red giant, the present binary separation and period are estimated at $\simeq 34$ AU and a period of $\simeq 150$ yr, respectively. We also conclude that the abundance distribution of heavy *s*-process elements may hold the key to a satisfactory understanding of the origin of HE 0107–5240. An enhancement of $[\text{Pb}/\text{Fe}] \simeq 1\text{--}2$ should be observed if HE 0107–5240 is a second-generation star, formed from gas already polluted with iron-group elements. If the enhancement of main-line *s*-process elements is not detected, HE 0107–5240 may be a first-generation secondary in a binary system with a primary of mass less than $2.5 M_{\odot}$, born from gas of primordial composition, produced in the big bang, and subsequently subjected to surface pollution by accretion of gas from the parent cloud metal-enriched by mixing with the ejectum of a supernova.

Parameter Ranges of the IMF

Search for typical mass (M_{md}) consistent with observations. ($\Delta_M = 0.33$)

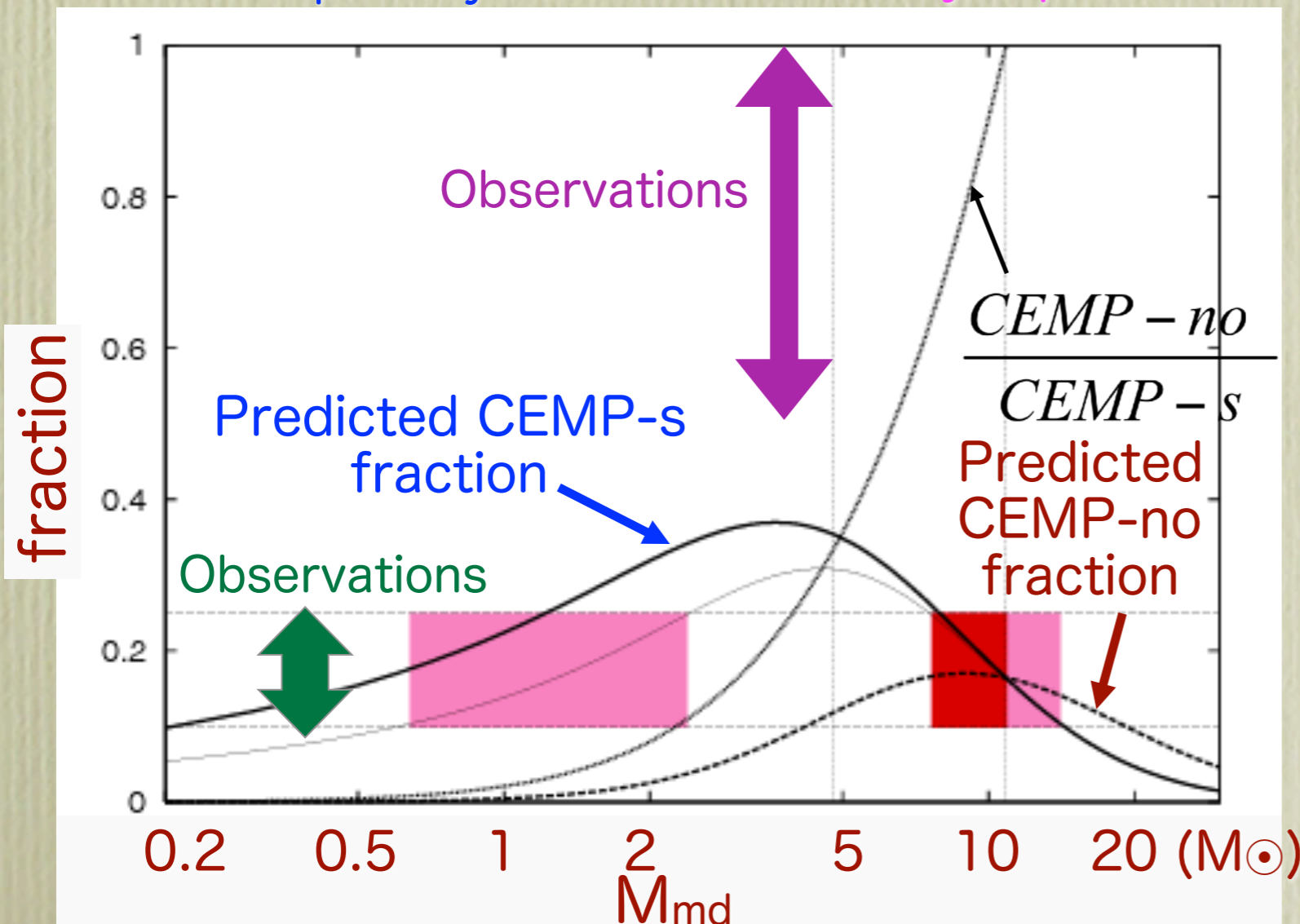
CEMP-s fraction is predicted from

$$\psi_{CEMP-s} = \int_{0.8}^{3.5} \xi(m_1) \frac{n(m_2/m_1)}{m_1} dm_1 \int_{A_{He-FDDM}(M_1)}^{A_M(M_1)} f(A) dA$$

mass range of primary mass ratio distribution distribution of binary separation

log normal IMF

$$\xi(\log m) \propto \exp\left(-\frac{(\log m - \log M_{md})^2}{2 \times \Delta_M^2}\right)$$



Required range of M_{md} to account for CEMP-s fraction

: $\sim 1 M_{\odot}$ and $\sim 10 M_{\odot}$

Required range of M_{md} to account for CEMP-s \sim CEMP-no

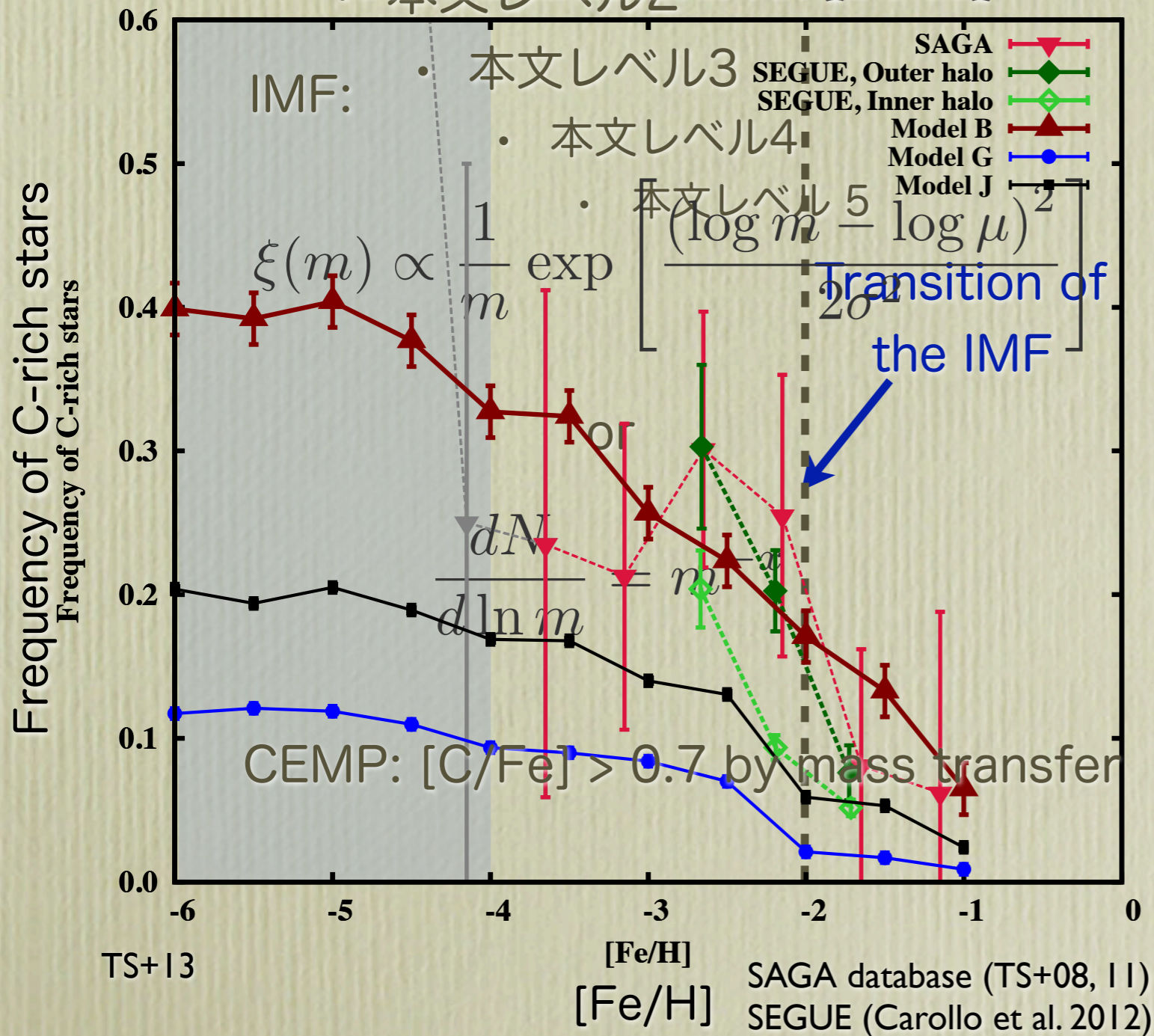
: $\sim 10 M_{\odot}$

High-Mass IMF

Transition to Low-mass IMF

Observations imply high-mass star dominated IMF.

CEMP fraction vs. [Fe/H]



Model	IMF	CEMP/EMP
A	$\mu=5, \sigma=0.6$	0.19
B	(10, 0.4)	0.25
C	(20, 0.45)	0.19
D	(30, 0.5)	0.17
E	(50, 0.6)	0.18
F	(0.79, 0.51)	0.031
G	$x = 1.35$	0.08
H	0.85	0.1
I	0.35	0.12
J	0	0.14

Summary & Discussion

- 炭素過剰金属欠乏(CEMP)星(特にCEMP-no)の起源として3つのシナリオが提示されている。
 - 超新星シナリオ
 - 回転星シナリオ
 - 連星シナリオ
- 連星シナリオから宇宙初期の星の初期質量関数を推測できる。
 - CEMP星をたくさん作るにはたくさんAGB星が必要
 - 大質量星とその連星が多数作られていたはず

Contents

I. 導入

- 金属欠乏星で探る銀河考古学
- 小・中質量星の進化
- (大質量星の進化)

II. 金属欠乏星の観測

- 最も鉄の少ない星の探査
- 金属欠乏星の化学組成
- 金属欠乏星の起源

III. 金属欠乏星の起源としての連星仮説(1)

- 炭素過剰金属欠乏星への進化
- 炭素過剰金属欠乏星で探る金属欠乏星の初期質量関数
- 銀河系における初期質量関数の変遷

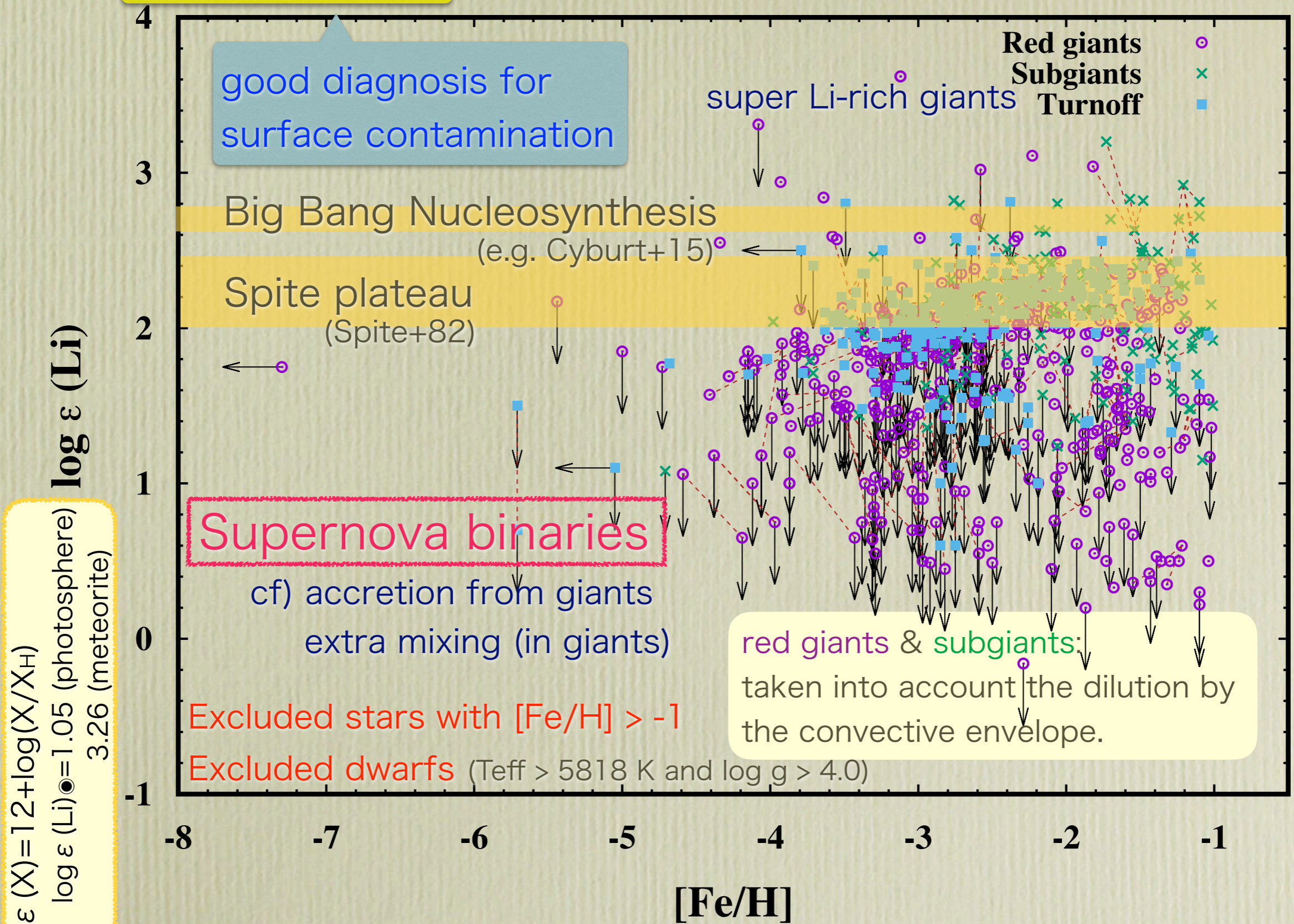
IV. 金属欠乏星の起源としての連星仮説(2)

- 大質量星連星シナリオ
- SPHシミュレーションを用いた超新星爆発と伴星の衝突
- OB型星視線速度変動モニタリングを用いた大質量星連星探査

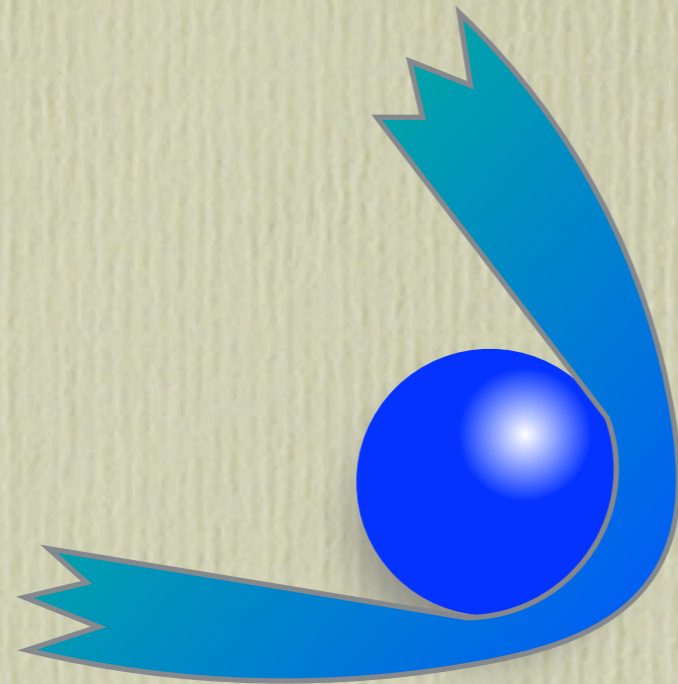
- Moritani et al.
 - Stars and Galaxies, 1, 1, 2018
- Suda et al.
 - in prep.

fragile element
burn at 2.5×10^6 K

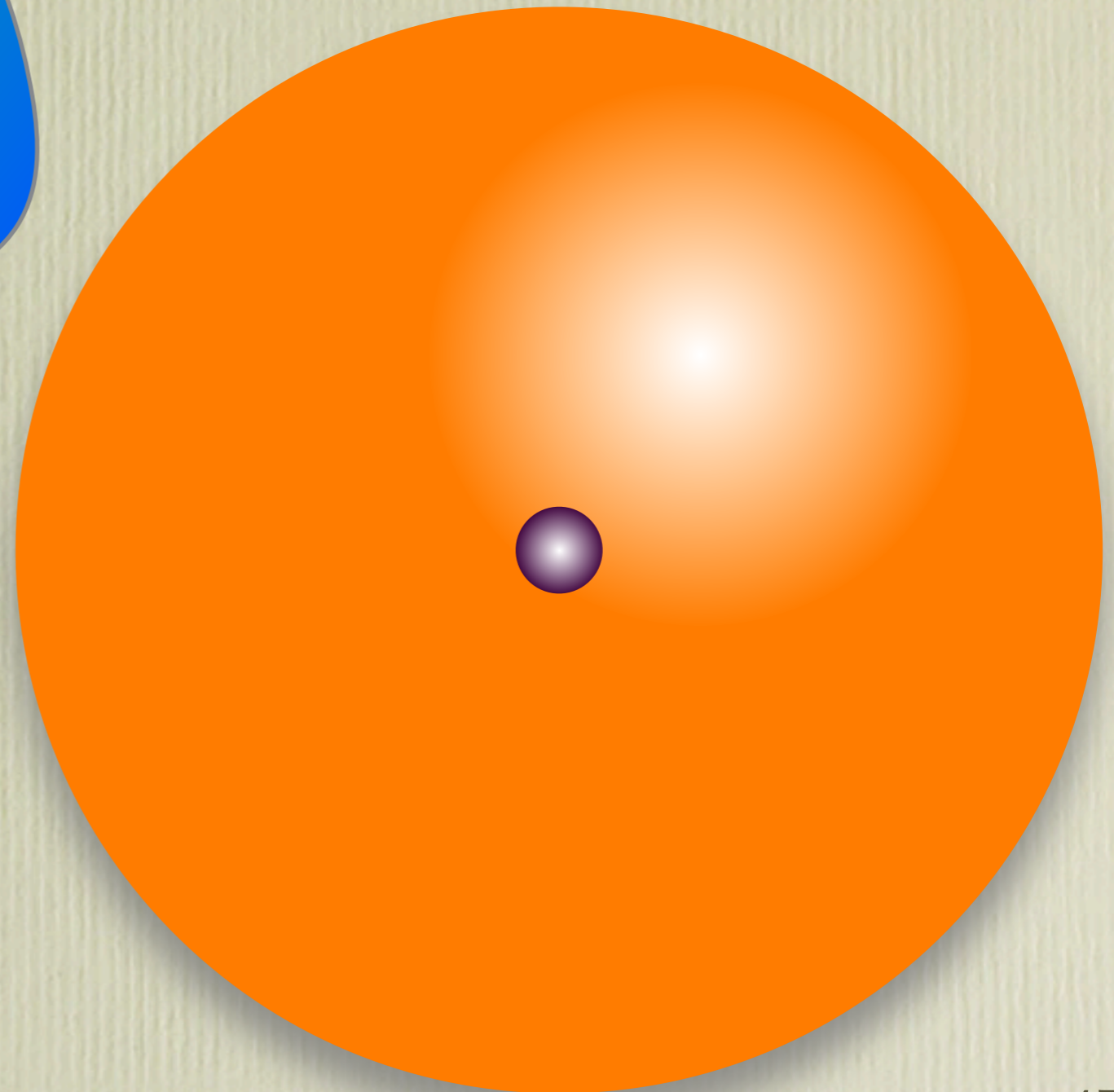
Li Problems



Supernova binary scenario



Massive Pop III star



Low-mass Pop III companion

- ★ Stripping of surface layers
- ★ Accretion of SN ejecta
- ★ Binary separation has to be small enough.
- ★ Evolution to red supergiants ($> \sim 5$ au) will inhibit this scenario (cf. Marigo+01, Heger+10, Kinugawa+14).

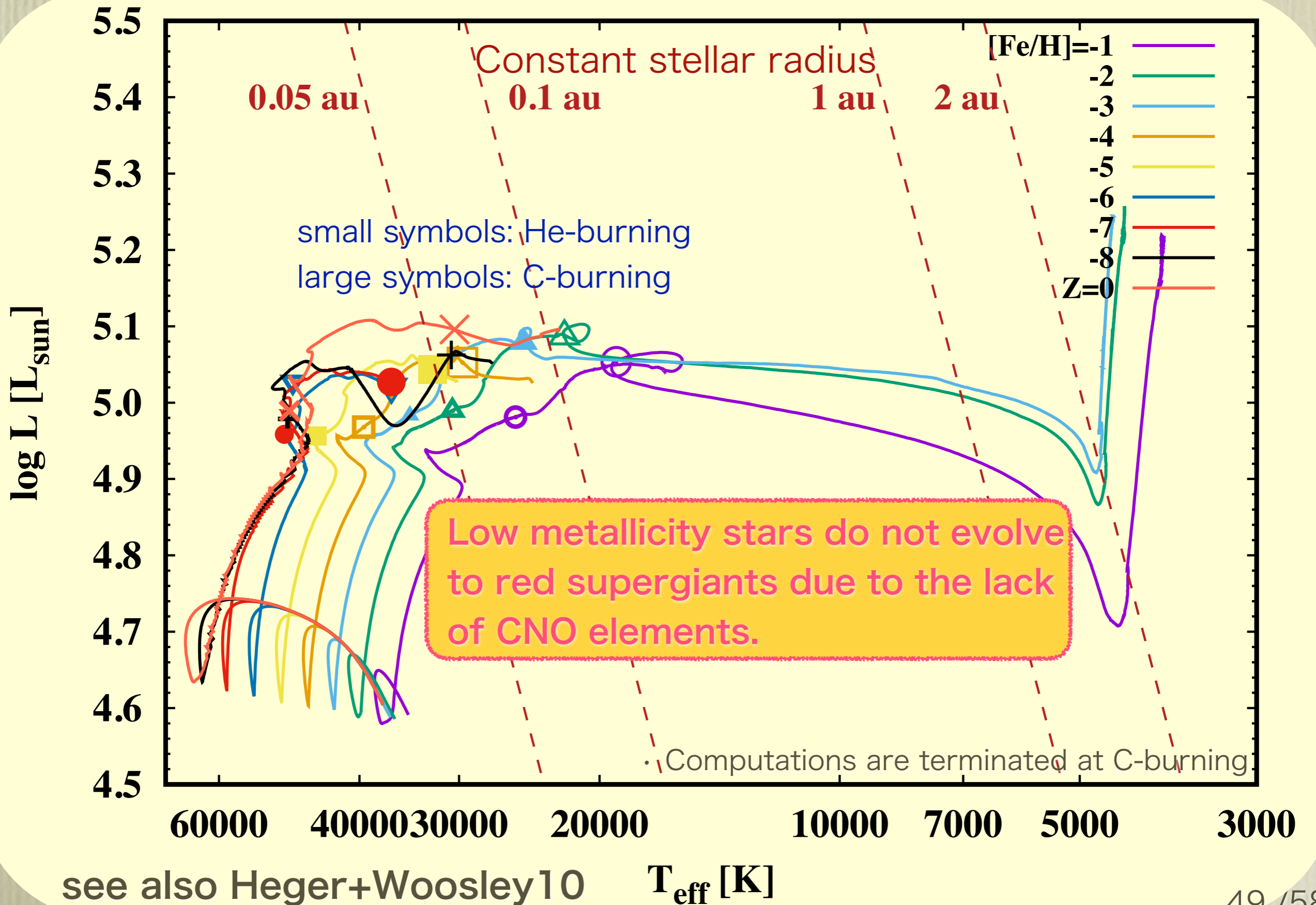
Simulations of SN binary scenario

- Stellar evolution models: 1D hydrostatic (Suda+10)
- Supernova explosion models: SN1987A (Shigeyama+90)
- SPH simulations: ASURA code (Saitoh+08)

- Binary system: $20 M_{\odot} + 0.8 M_{\odot}$
- Separation : ~ 0.05 au ($\sim 10 R_{\odot}$) or ~ 0.1 au ($\sim 20 R_{\odot}$)
- Num. of particles: ejecta: ~ 16 M, companion: ~ 1 M

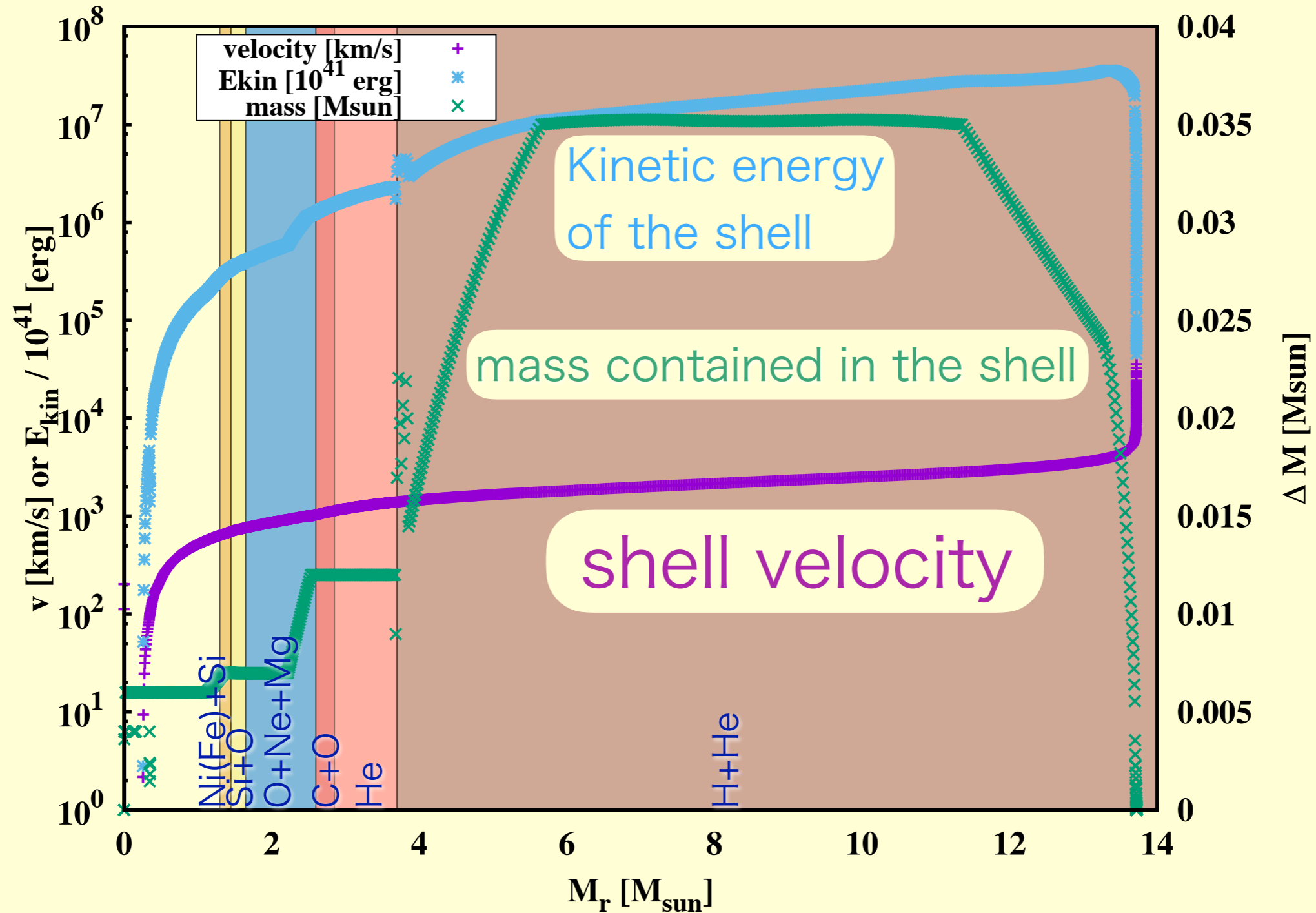
- Previous studies on the stripping by the collisions of supernova ejecta
 - Ia: Marietta+00: PPM
 - Ia: Pakmor+08: GADGET
 - Ia: Pan+12: FLASH
 - II: Hirai+14: yamazakura, massive + massive
 - Ibc: Rimoldi+16: Gadget-2

Evolution of 20 M_⊙ Stars



SN ejecta of H15[_2] models

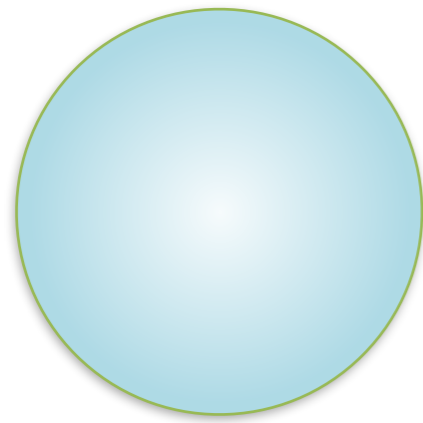
Shigeyama+90 prescription based on Heger+10 models



Configuration with ASURA code



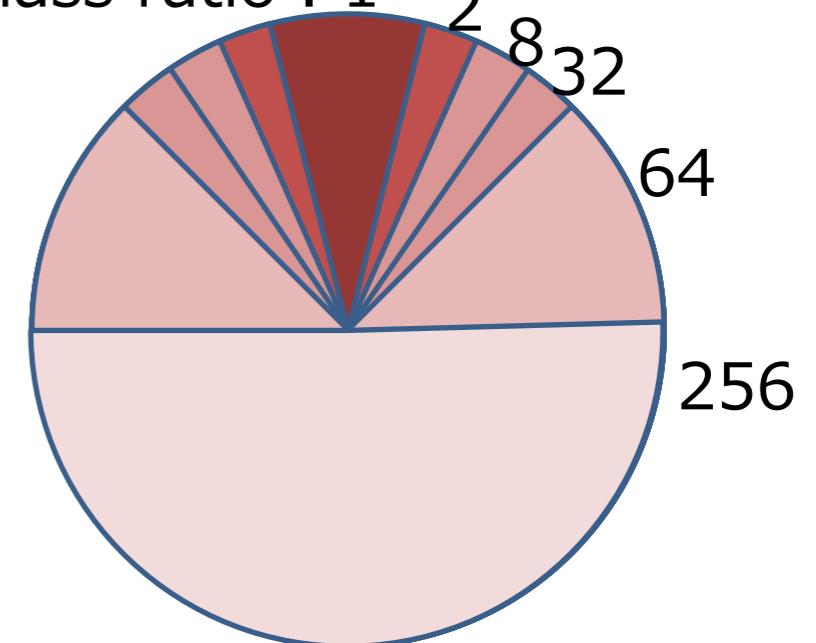
Saitoh+08



- Target: $0.8 M_{\odot}$ with $R=0.64 R_{\odot}$
- Distribution of mass and temperature from $Z = 0$ models
- $N \sim 10^6$ (sink particle in the center)

- Supernova: Heger & Woosley (2010) ($15, 20, 25 M_{\odot}$)
- $N \sim 7 \times 10^6$ (reduced the number of particles for offset collision)

particle mass ratio :





Simulation Result

$M_1 = 15M_{\odot}$

主星質量

$M_2 = 0.8M_{\odot}$

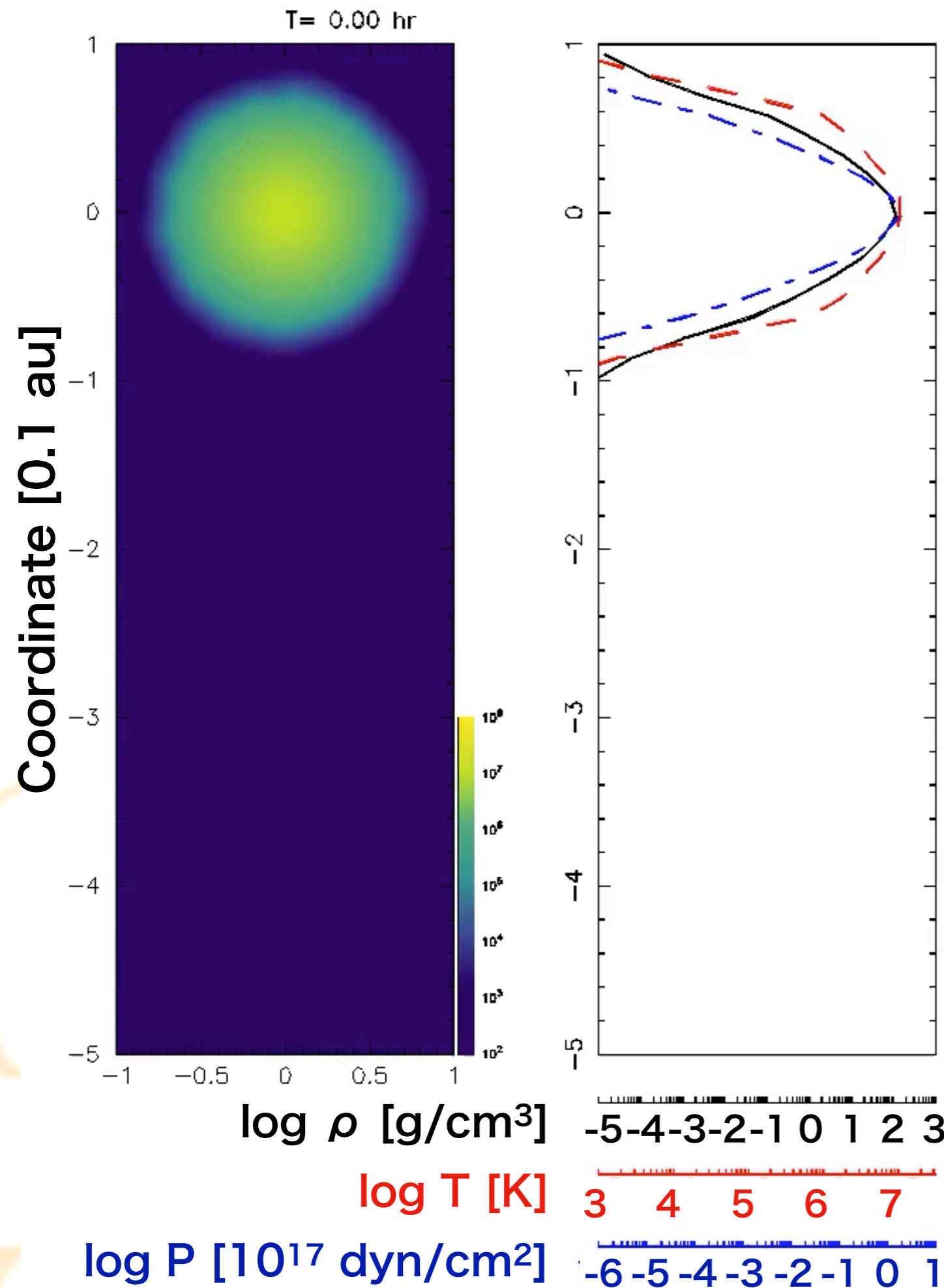
伴星質量

$a = 0.1 \text{ au}$

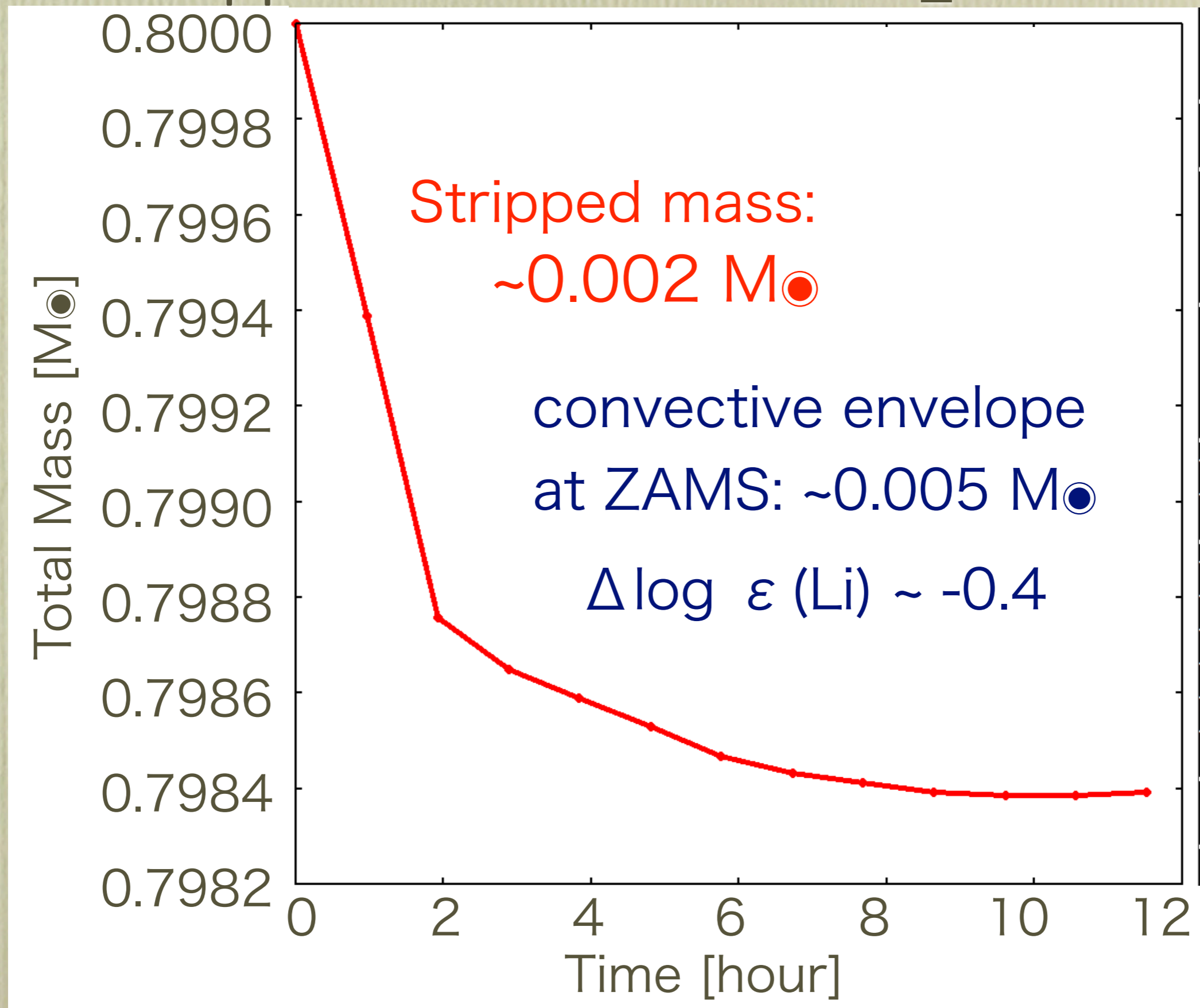
連星間距離

$t = 0-20 \text{ hours}$

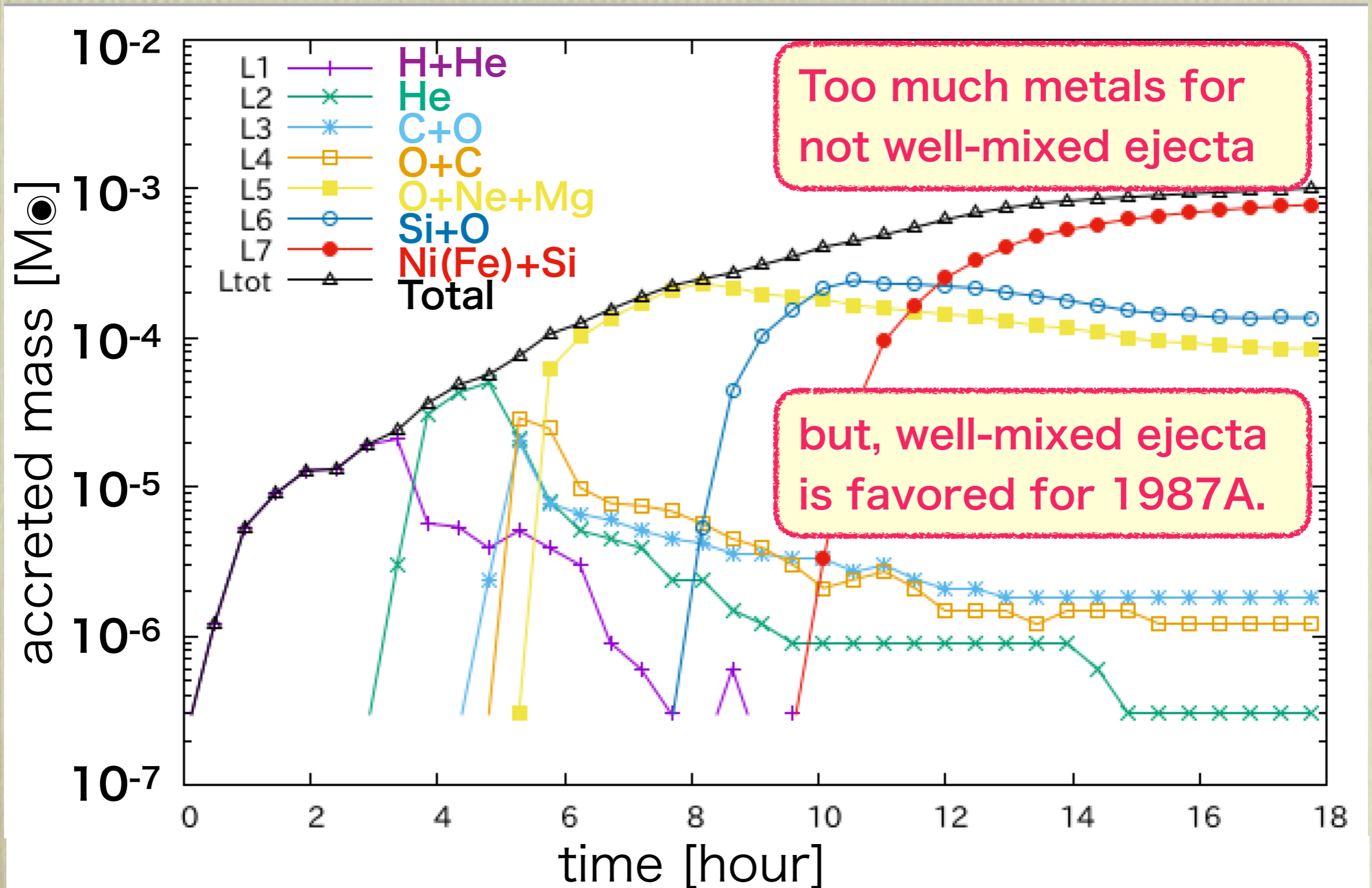
計算時刻



Stripped mass for the H15_2 model

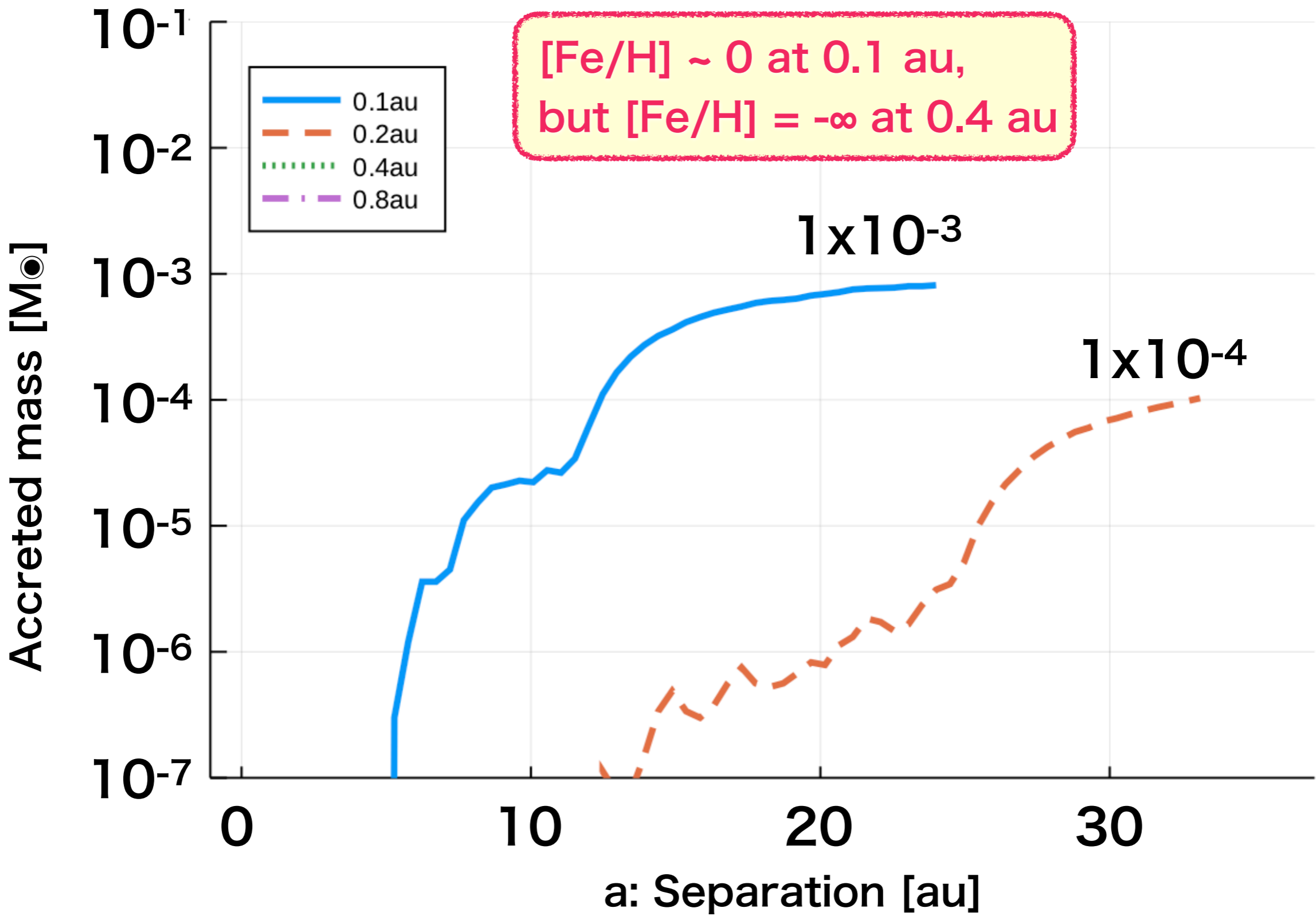


Accretion of ejecta



Preliminary result of

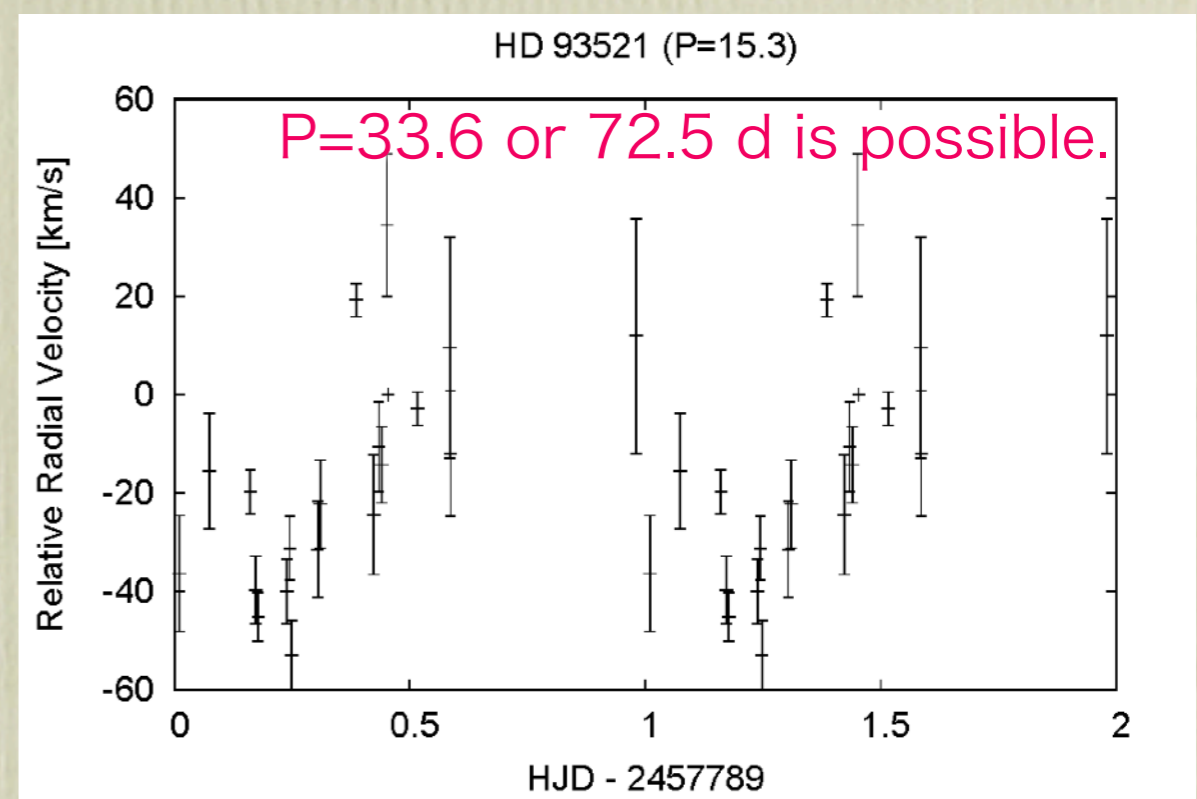
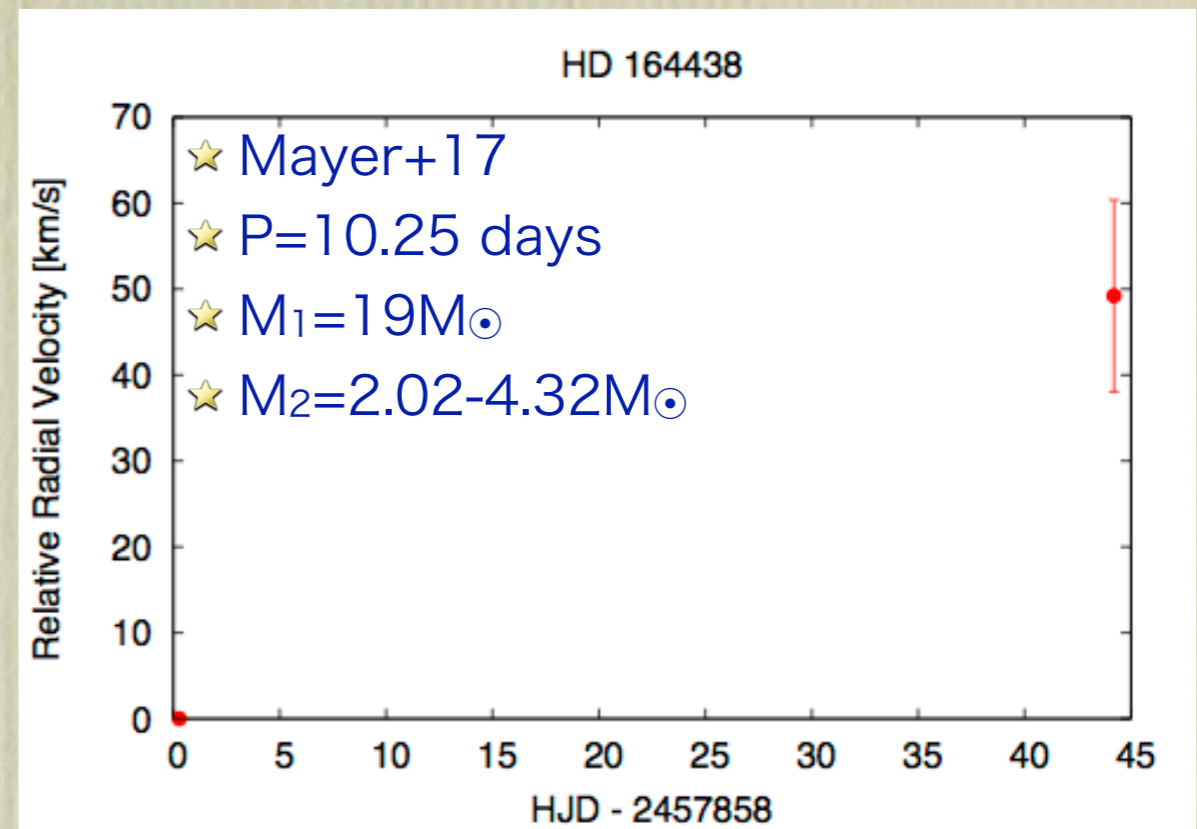
Dependence of accreted mass on separation



Observational Counterparts

- Massive Pop. III stars cannot survive until today.
 - Observational counterparts in nearby OB stars
- Radial velocity monitoring
 - MALLS on Nayuta telescope (Mid Res.)
 - 20 nights (16B-18B) + 3 nights (19A)
 - HIDES on Okayama (High Res.)
 - 17A: 6 nights
 - GAOES on Gunma Obs. (High Res.)
 - 2016/11/12-2017/2/4: 7 nights
- Target: Massive (+Low-mass) stars
 - OB stars from spectroscopic catalog (Skiff, 2009-2016) [64112 stars]
 - Exclude double-lined, eclipse, and visual binaries from >20 references [62940]
- Spectroscopic SB1 [62]
- brighter than 8 mag. [24]
- Dec. > -25° [14] -> 10 stars

preliminary results for radial velocities

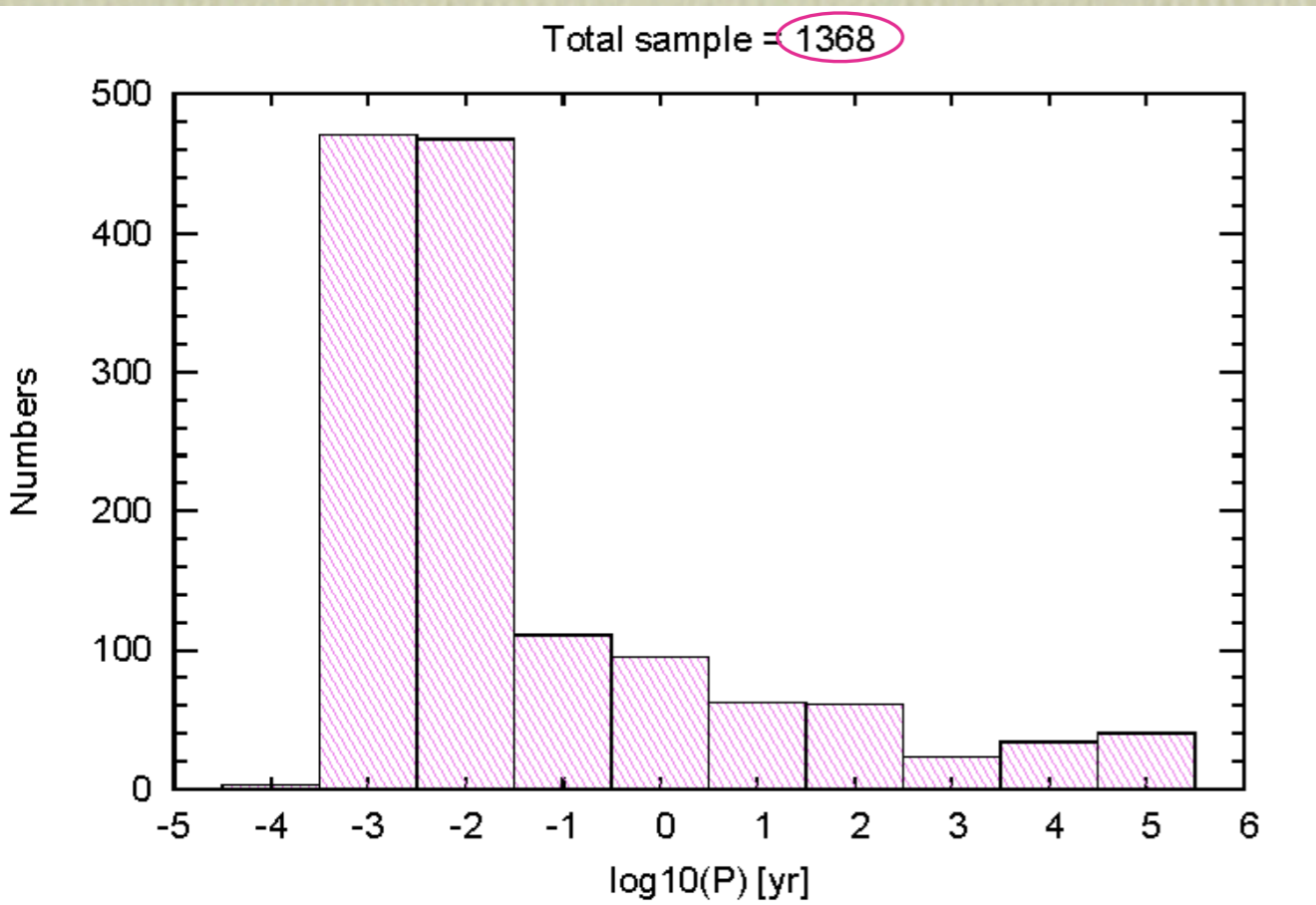


OB star binaries in literature

(excluding X-ray binaries)

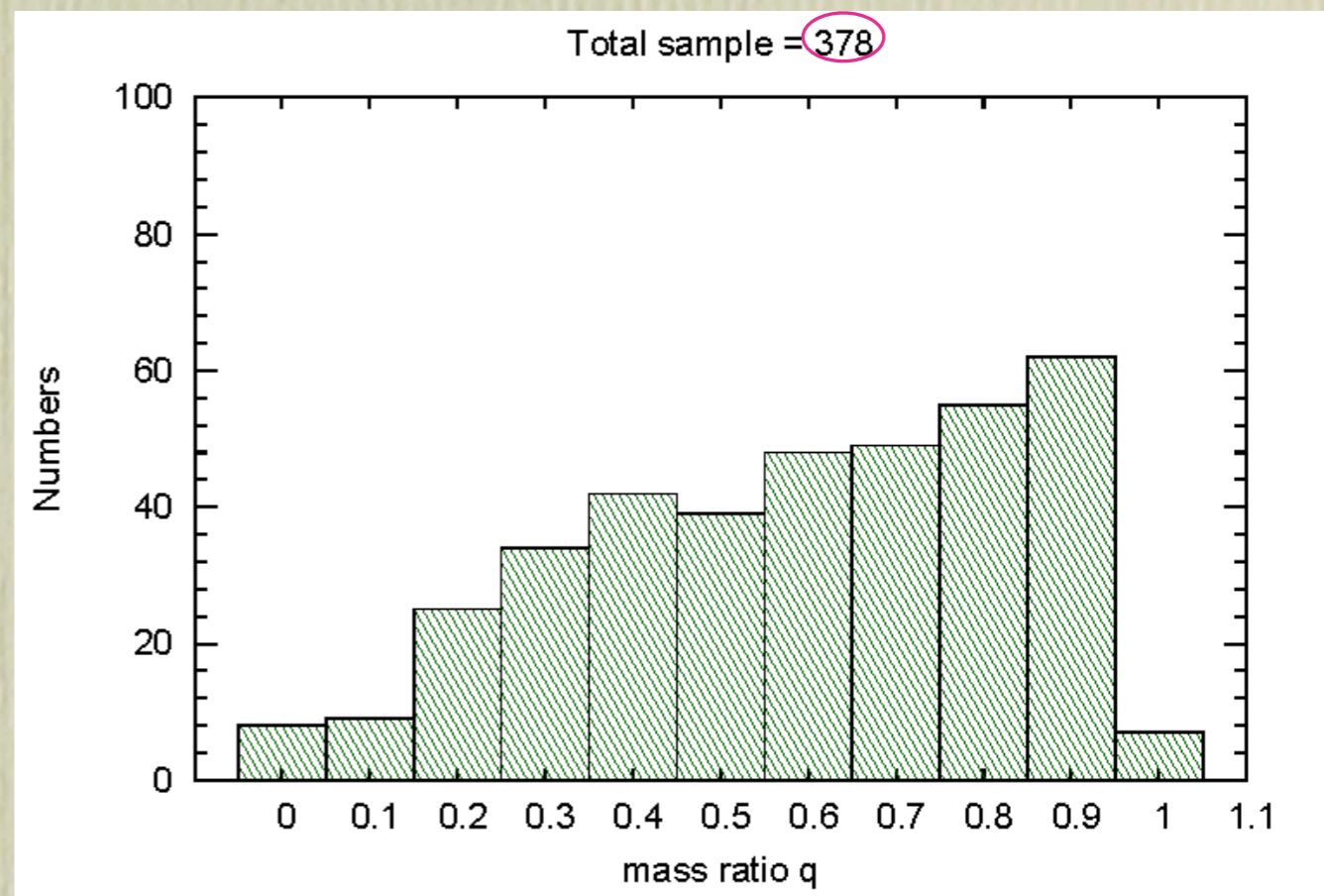
Observational counterparts in solar neighborhood

Orbital periods



* multiple systems are counted separately.

Mass ratios



* Most of them are derived in eclipsing or spectroscopic binaries.

Summary & Discussion

- 金属欠乏星の起源となる4つめのシナリオ、超新星連星シナリオを提案した。
 - 超新星イジェクタの低質量伴星への衝突
- SPHシミュレーションによる伴星の剥離、降着を調べた。
 - 剥離の影響はそれほど大きくない。
 - 降着の影響は大きい、連星間距離への依存性が極めて大きい。
 - 炭素過剰星の起源や他の元素の組成分布との比較が可能になる。
- 対応天体となる大質量星連星の観測を行った。
 - 連星周期を決定できる段階になった。
 - 太陽近傍では連星間距離の短い大質量星連星は存在する。