ペア不安定型超新星爆発の爆発・Yield計算

高橋亘

東京大学 天文学専攻

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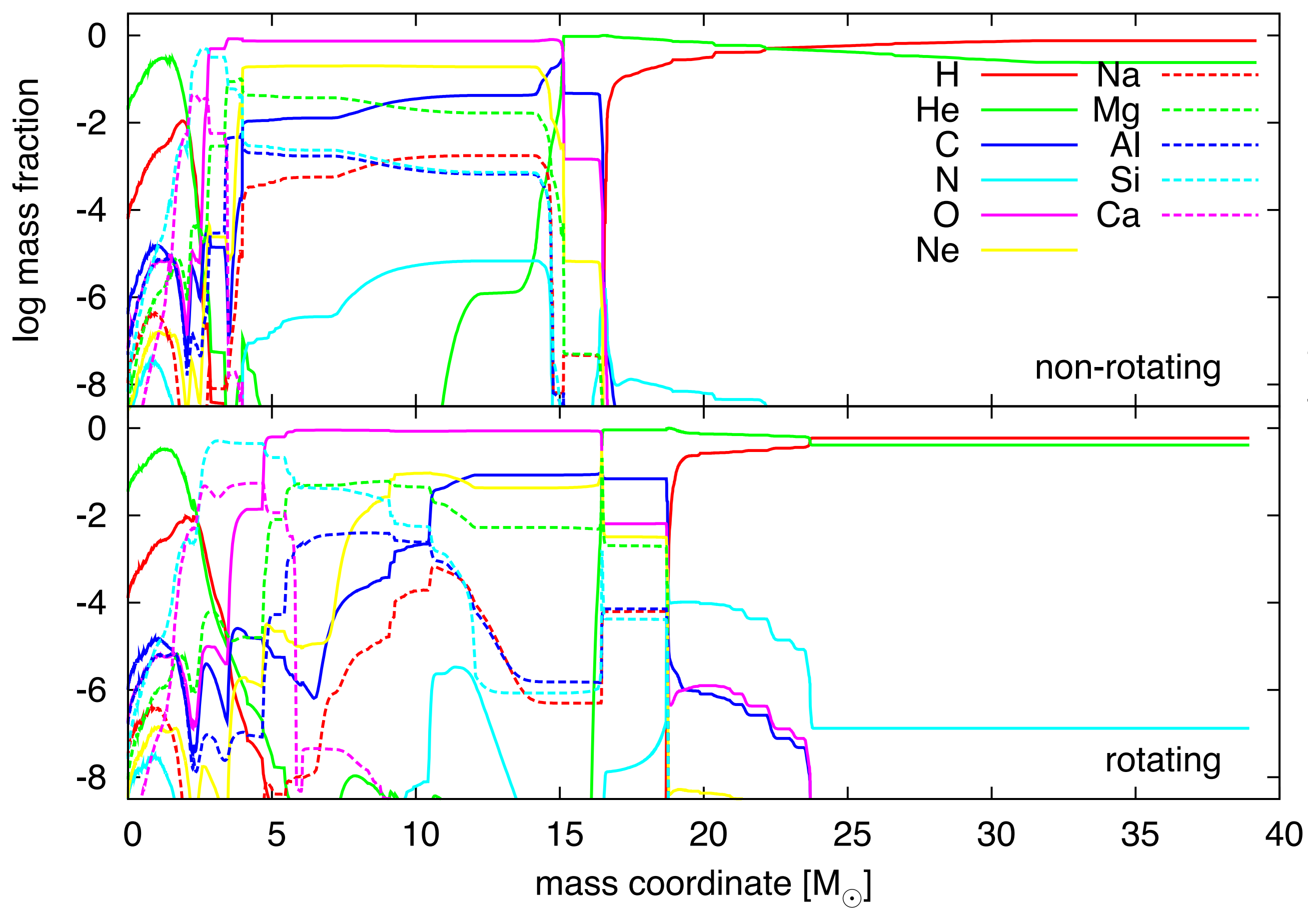
PISN Yield計算

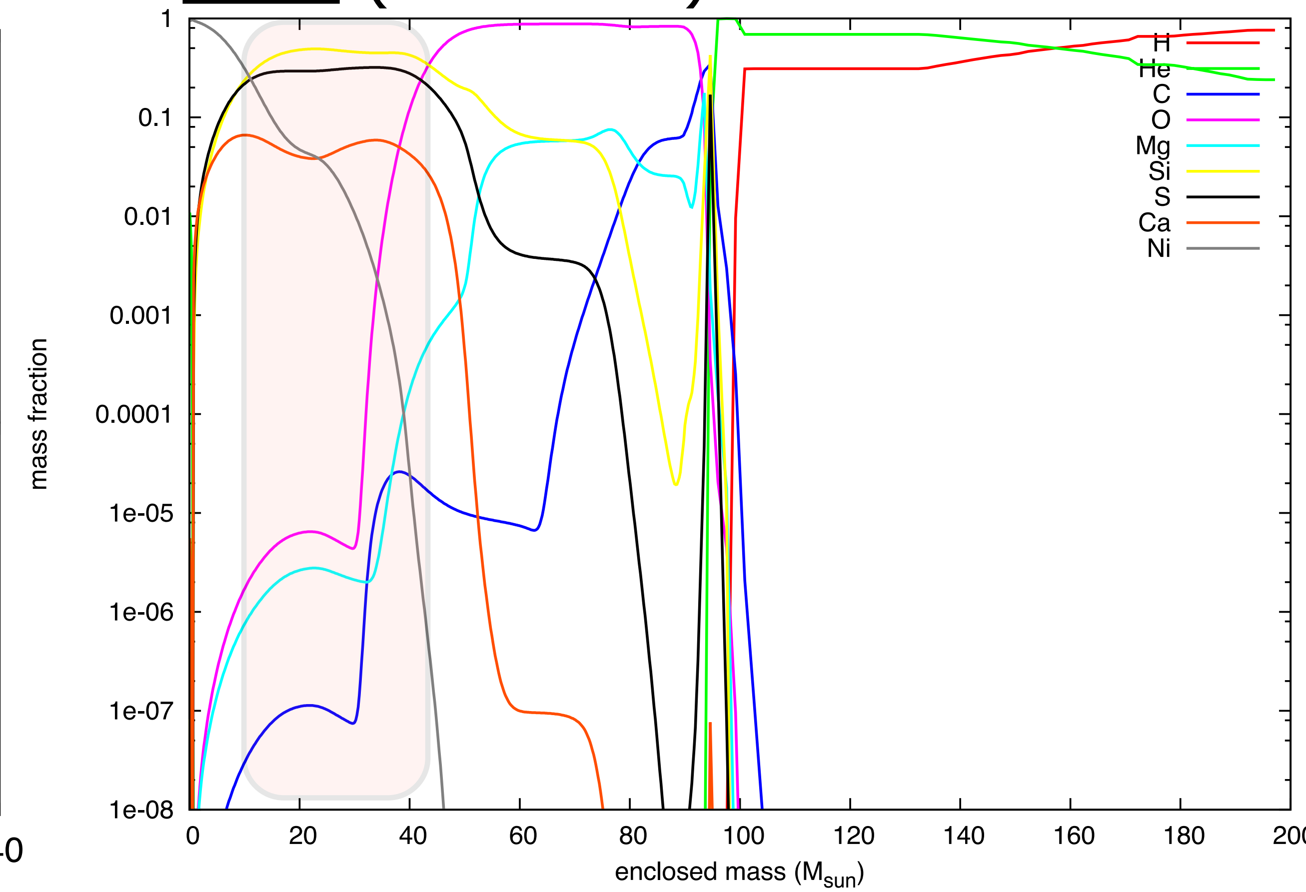
PISNは**爆発的酸素燃焼**によって爆発する。

core entropy rapidly increase due to
explosive nuclear burning of oxygen.

Core collapse (40Msun)

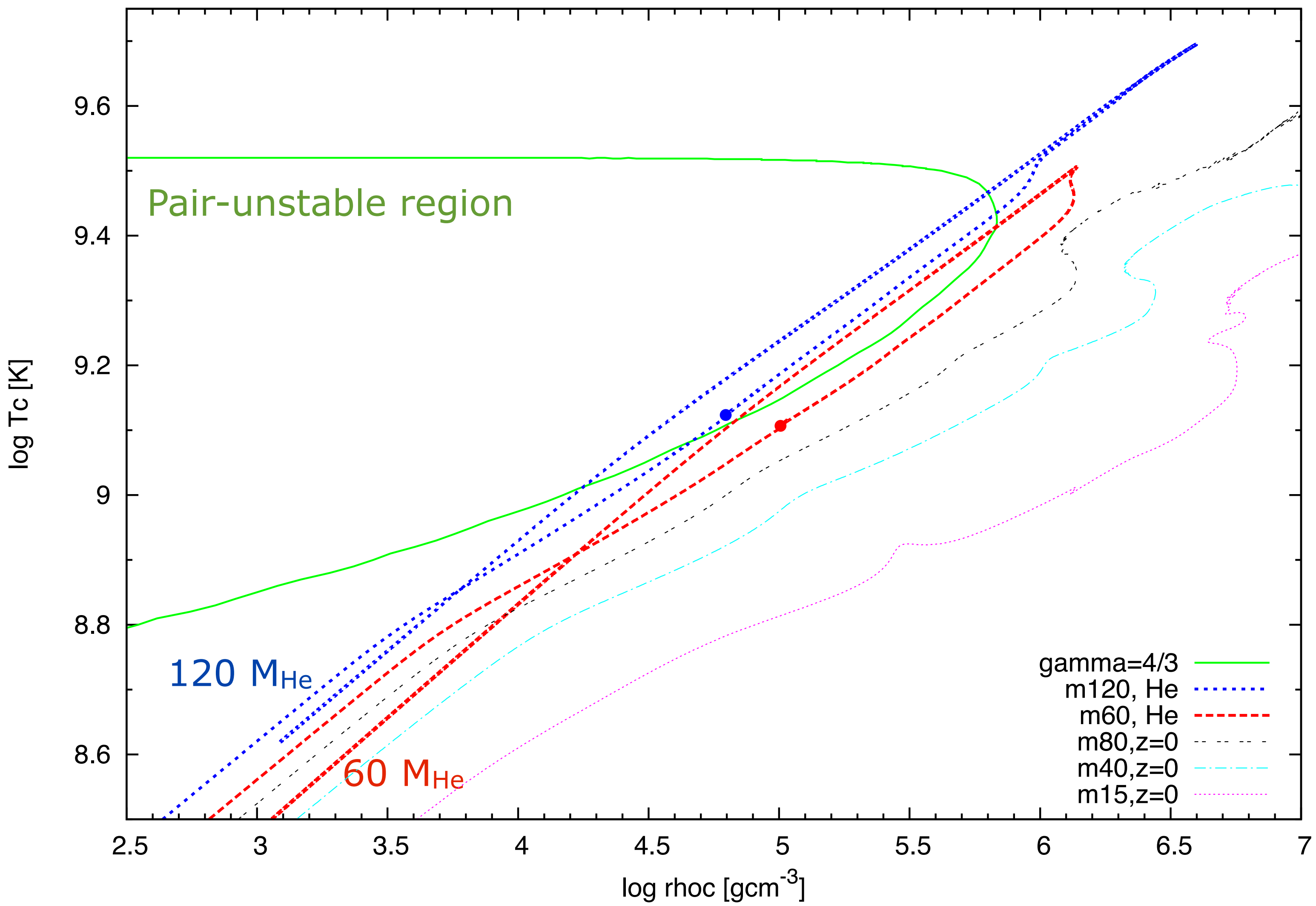


PISN (200Msun)



PISN Yield計算

explosion mechanism:
e^-e^+ pair creation reduces gamma < 4/3



大質量COコア中では **電子-陽電子が対生成** し、星を不安定にする。

PISNになるためには、**COコアが十分大きい**事が必要。

PISNe need very massive CO cores (~60-130 Msun), formed in very massive stars (~150-300 Msun).

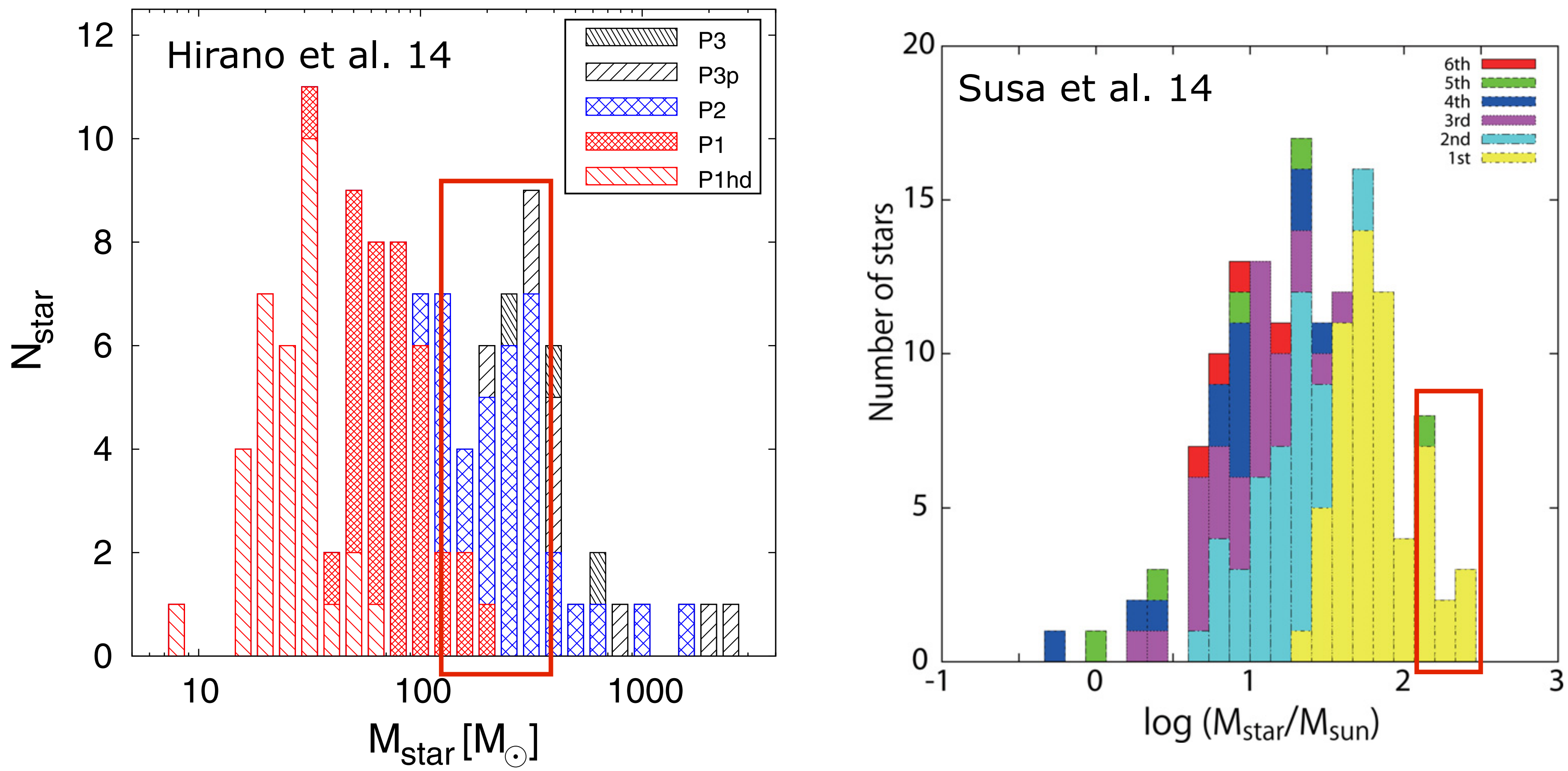
PISN Yield計算

超大質量星は何処にあるか？

Very massive CO cores are favored by low metallicity environments.

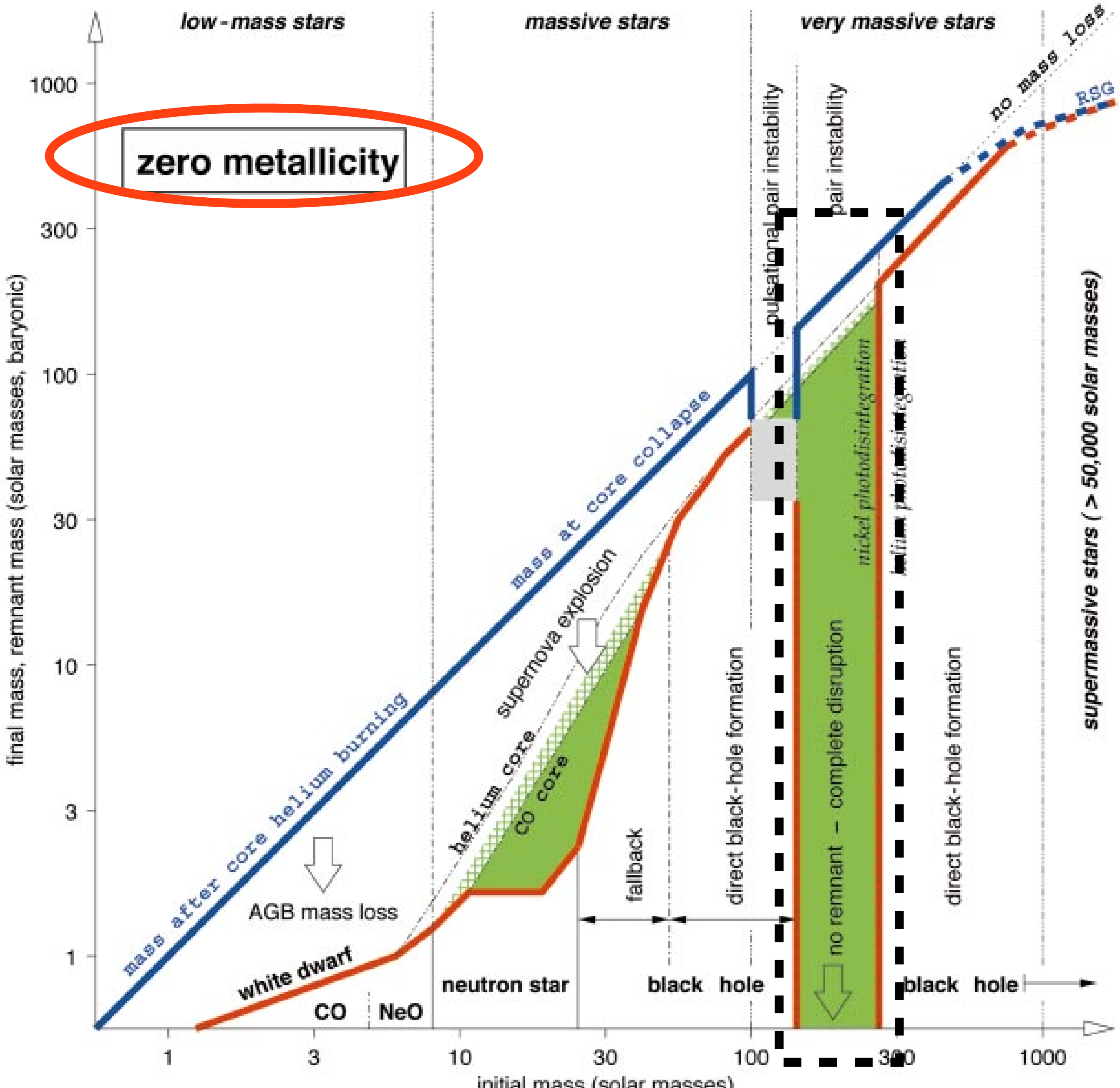
This is because

1. Very massive stars would be formed in the early universe.



PISN Yield計算

超大質量星は何処にあるか？



Woosley, Heger, & Weaver 02

and

2. Wind mass loss during the evolution would be weaker.

初期質量 vs remnant mass の図

青線が爆発前の質量

赤線がremnant mass.

PISNはremnantを残さないで星全体が爆発する。

PISN Yield計算

PISNのYield計算はこれまで初代星にのみ限られていた。

Yields of Pop III PISNe was calculated in
Umeda & Nomoto (02) and Heger & Woosley (02).

NUCLEOSYNTHESIS OF ZINC AND IRON PEAK ELEMENTS IN POPULATION III TYPE II SUPERNOVAE: COMPARISON WITH ABUNDANCES OF VERY METAL POOR HALO STARS

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ABSTRACT

We calculate nucleosynthesis in core collapse explosions of massive Population III stars and compare the results with abundances of metal-poor halo stars to constrain the parameters of Population III supernovae. We focus on iron peak elements, and, in particular, we try to reproduce the large [Zn/Fe] observed in extremely metal-poor stars. The interesting trends of the observed ratios [Zn, Co, Mn, Cr, V/Fe] can be related to the variation of the relative mass of the complete and incomplete Si-burning regions in supernova ejecta. We find that [Zn/Fe] is larger for deeper mass cuts, smaller neutron excess, and larger explosion energies. The large [Zn/Fe] and [O/Fe] observed in the very metal-poor halo stars suggest deep mixing of complete Si-burning material and a significant amount of fallback in Type II supernovae. Furthermore, large explosion energies ($E_{51} \gtrsim 2$ for $M \sim 13\ M_\odot$ and $E_{51} \gtrsim 20$ for $M \gtrsim 20\ M_\odot$) are required to reproduce [Zn/Fe] ~ 0.5. The observed trends of the abundance ratios among the iron peak elements are better explained with this high-energy ("hypernova") model than with the simple "deep" mass cut effect because the overabundance of Ni can be avoided in the hypernova models. We also present the yields of pair instability supernova explosions of $M \simeq 130$–$300\ M_\odot$ stars and discuss that the abundance features of very metal-poor stars cannot be explained by pair instability supernovae.

THE NUCLEOSYNTHETIC SIGNATURE OF POPULATION III

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ABSTRACT

Growing evidence suggests that the first generation of stars may have been quite massive ($\sim$100–300 $M_\odot$). Could these stars have left a distinct nucleosynthetic signature? We explore the nucleosynthesis of helium cores in the mass range $M_{\rm He} = 64$–$133\ M_\odot$, corresponding to main-sequence star masses of approximately 140–260 $M_\odot$. Above $M_{\rm He} = 133\ M_\odot$, without rotation and using current reaction rates, a black hole is formed, and no nucleosynthesis is ejected. For lighter helium core masses, $\sim$40–63 $M_\odot$, violent pulsations occur, induced by the pair instability and accompanied by supernova-like mass ejection, but the star eventually produces a large iron core in hydrostatic equilibrium. It is likely that this core, too, collapses to a black hole, thus cleanly separating the heavy-element nucleosynthesis of pair instability supernovae from those of other masses, both above and below. Indeed, black hole formation is a likely outcome for all Population III stars with main-sequence masses between about 25 and 140 $M_\odot$ ($M_{\rm He} = 9$–$63\ M_\odot$) as well as those above 260 $M_\odot$. Nucleosynthesis in pair instability supernovae varies greatly with the mass of the helium core. This core determines the maximum temperature reached during the bounce. At the upper range of exploding core masses, a maximum of 57 $M_\odot$ of ^{56}Ni is produced, making these the most energetic and the brightest thermonuclear explosions in the universe. Integrating over a distribution of masses, we find that pair instability supernovae produce a roughly solar distribution of nuclei having even nuclear charge (Si, S, Ar, etc.) but are remarkably deficient in producing elements with odd nuclear charge—Na, Al, P, V, Mn, etc. This is because there is no stage of stable post–helium burning to set the neutron excess. Also, essentially no elements heavier than zinc are produced owing to a lack of *s*- and *r*-processes. The Fe/Si ratio is quite sensitive to whether the upper bound on the initial mass function is over 260 $M_\odot$ or somewhere between 140 and 260 $M_\odot$. When the yields of pair instability supernovae are combined with reasonable estimates of the nucleosynthesis of Population III stars from 12 to 40 $M_\odot$, this distinctive pattern of deficient production of odd-Z elements persists. Some possible strategies for testing our predictions are discussed.

PISN Yield計算

目的：

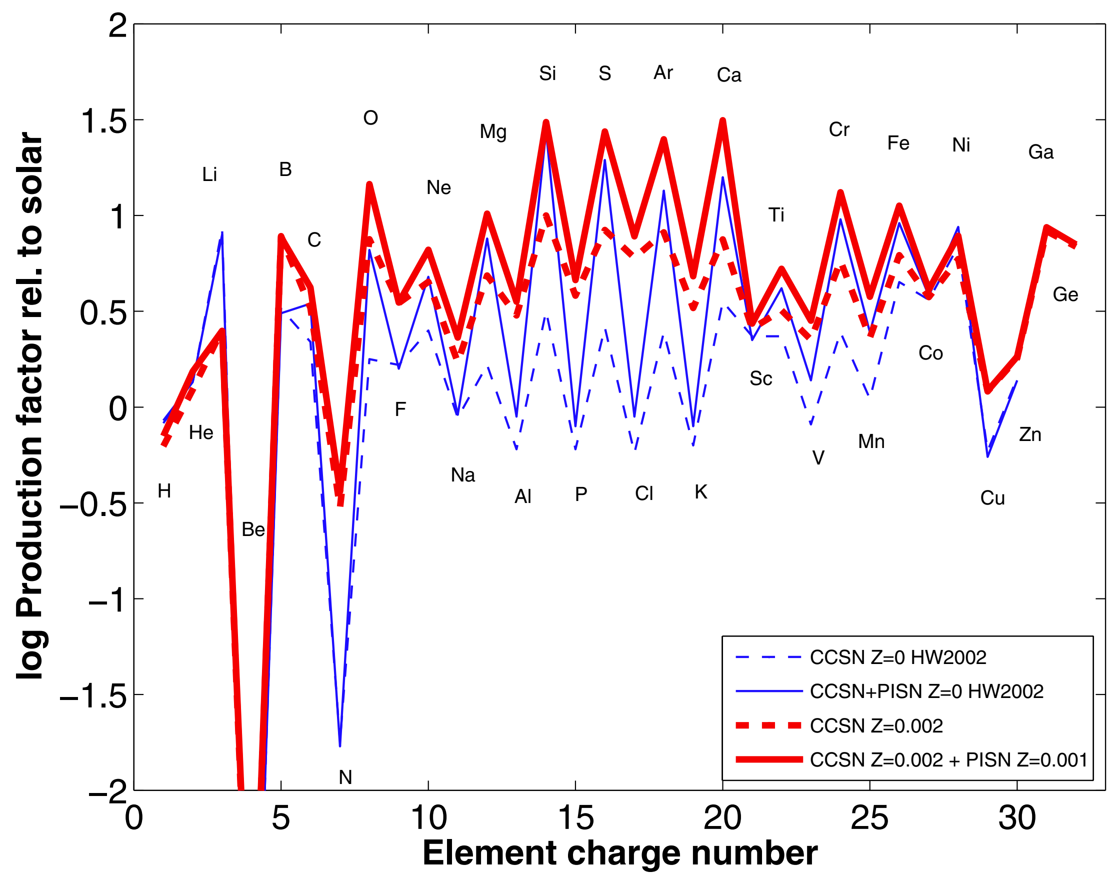
初代星に限らないPISN生成物を
幅広い金属量域で計算する

AIM of this work:

Calculate Yields of PISNe for
wide mass range
& wide metallicity range.

The grid of yields will be useful for
-SLSN light curve estimates
-Chemical evolution
...

Kozyreva et al. 14



PISN Yield計算

Three stages of the calculation.

1. Stellar evolution calculation

Using stellar evolution code (KT+14).
Solve stellar evolution from MS phase up to the ignition of carbon ($\sim T_c=10^{9.1}$K)

2. Explosion calculation

Using implicit hydrodynamical code (Yamada97)
Onset of collapse, oxygen & silicon burning, explosion, and shock propagation are solved

3. Yield calculation

Post process calculation with a large reaction network.

Calculate hydrostatic and hydrodynamic structure of a star.

○ Basic Equations

- mass conservation

$$\frac{dr}{dM} = \frac{1}{4\pi r^2 p}$$

- hydro dynamical structure

$$\frac{dp}{dM} = -\frac{GM}{4\pi r^4} - \frac{M}{4\pi r^2 p}\frac{d^2r}{dt^2}$$

- energy conservation

$$\frac{dL}{dM} = -T\frac{ds}{dt} - \mu'\frac{dn}{dt} + \varepsilon_{nuc} - \varepsilon_{\nu}$$

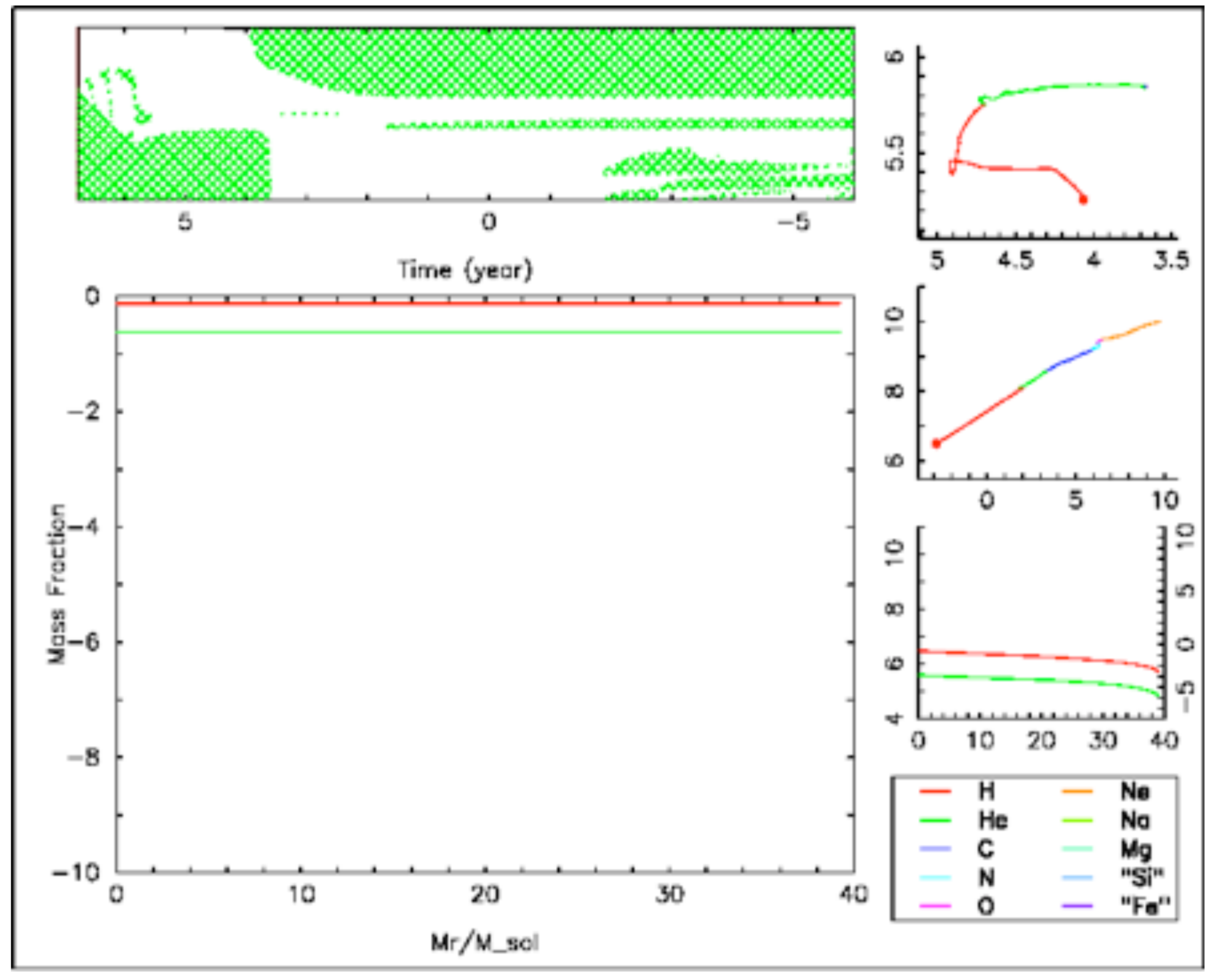
- energy transport

$$\frac{dT}{dM} = -\frac{GMT}{4\pi r^4 p}\left[\nabla_{rad} \text{ or } \nabla_{conv}\right]$$

- composition evolution

$$\frac{dX_i}{dt} = \left[\frac{dX_i}{dt}\right]_{nuc} + \left[\frac{dX_i}{dt}\right]_{mix}, \quad \left[\frac{dX_i}{dt}\right]_{nuc} = f_i(X;T,\rho,Y_n,Y_e),$$

$$\left[\frac{dX_i}{dt}\right]_{mix} = \frac{d}{dM}\left(D\frac{dX_i}{dM}\right)$$



Evolution of a rotating 40 M☉ first star.

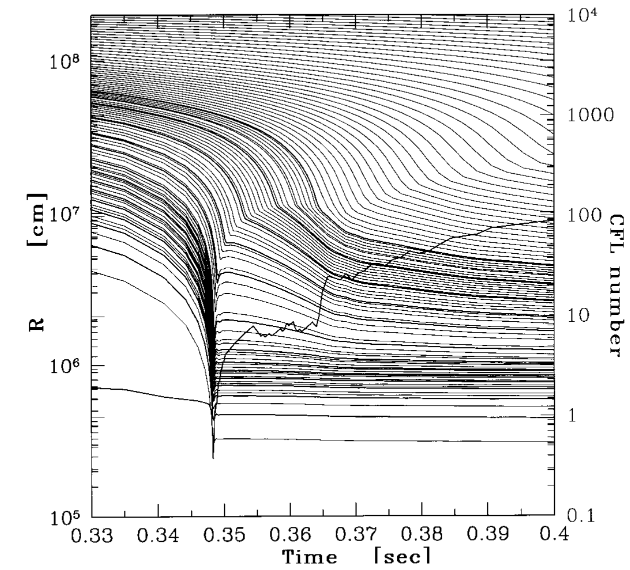
PISN Yield計算

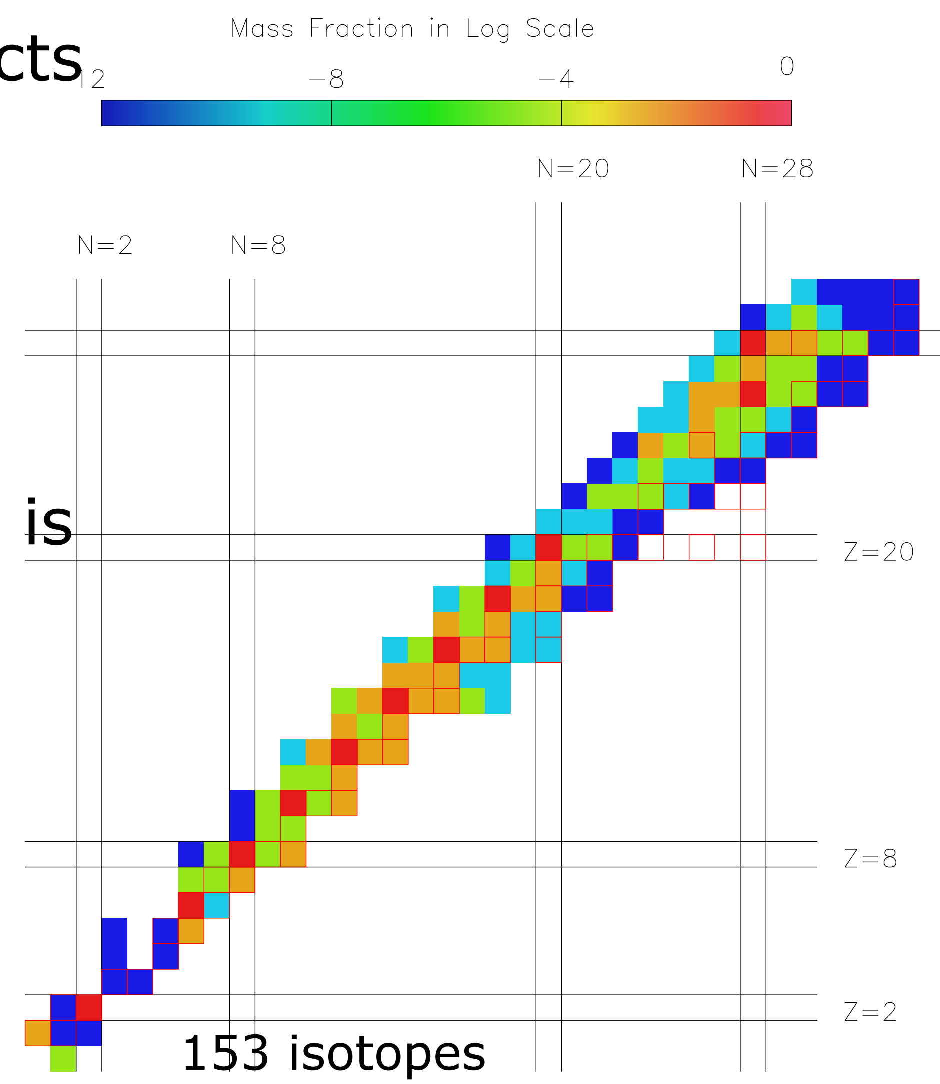
2. Explosion calculation

Implicit hydrodynamical code (Yamada 97, Yamada+99)

-general relativistic hydrodynamical equations
-Shock capture by Roe method
-Boltzmann solver for neutrino transport is equipped,
 but turned off in this work.
  -instead, locally determined neutrino cooling effects
   are installed.

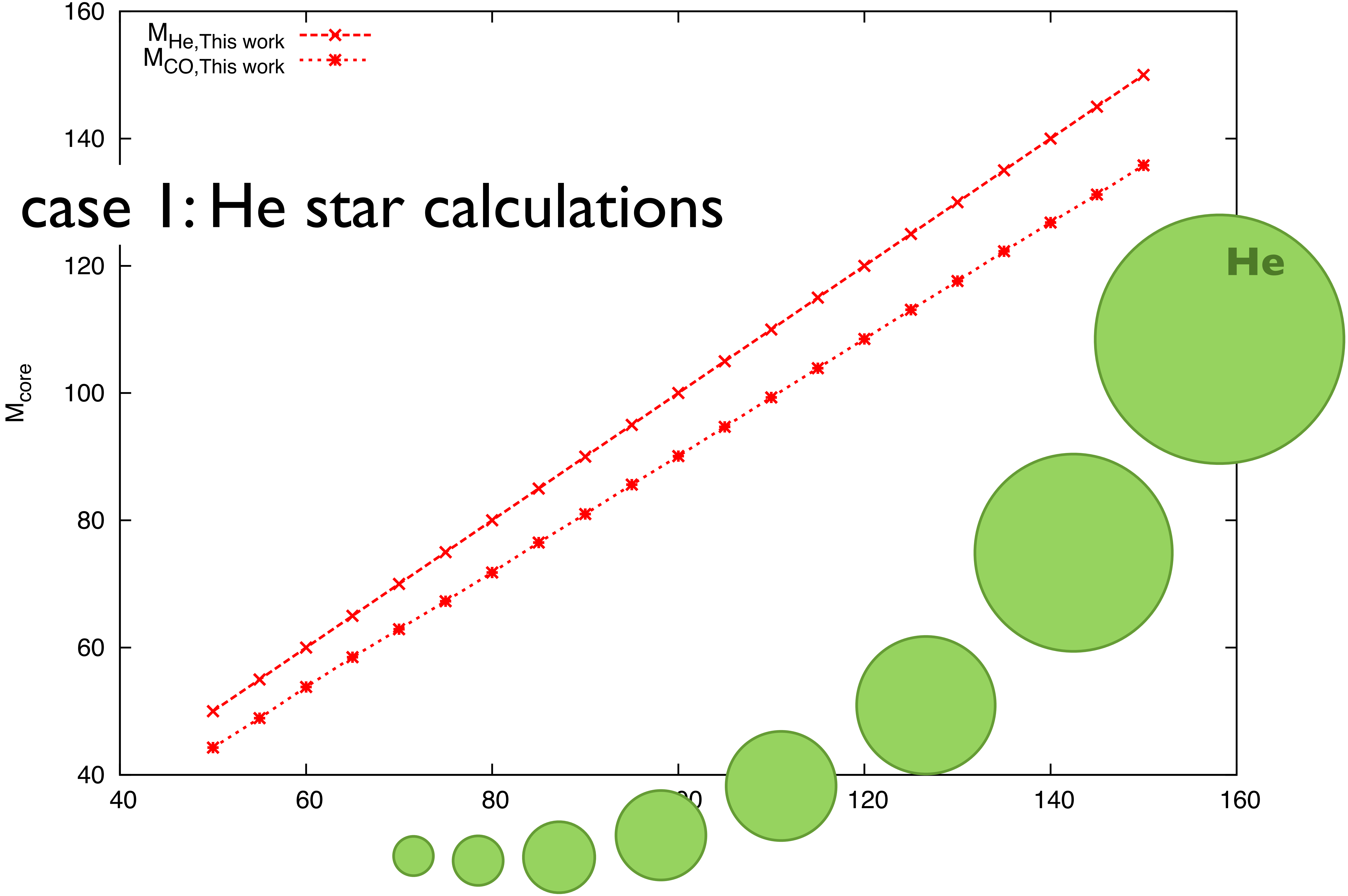
-non-NSE EOS is equipped.
-Nuclear network is newly implemented.
  -Two options, coupled and decoupled with
   hydrodynamical equations. Decoupled treatment is
   used in most cases.





PISN Yield計算

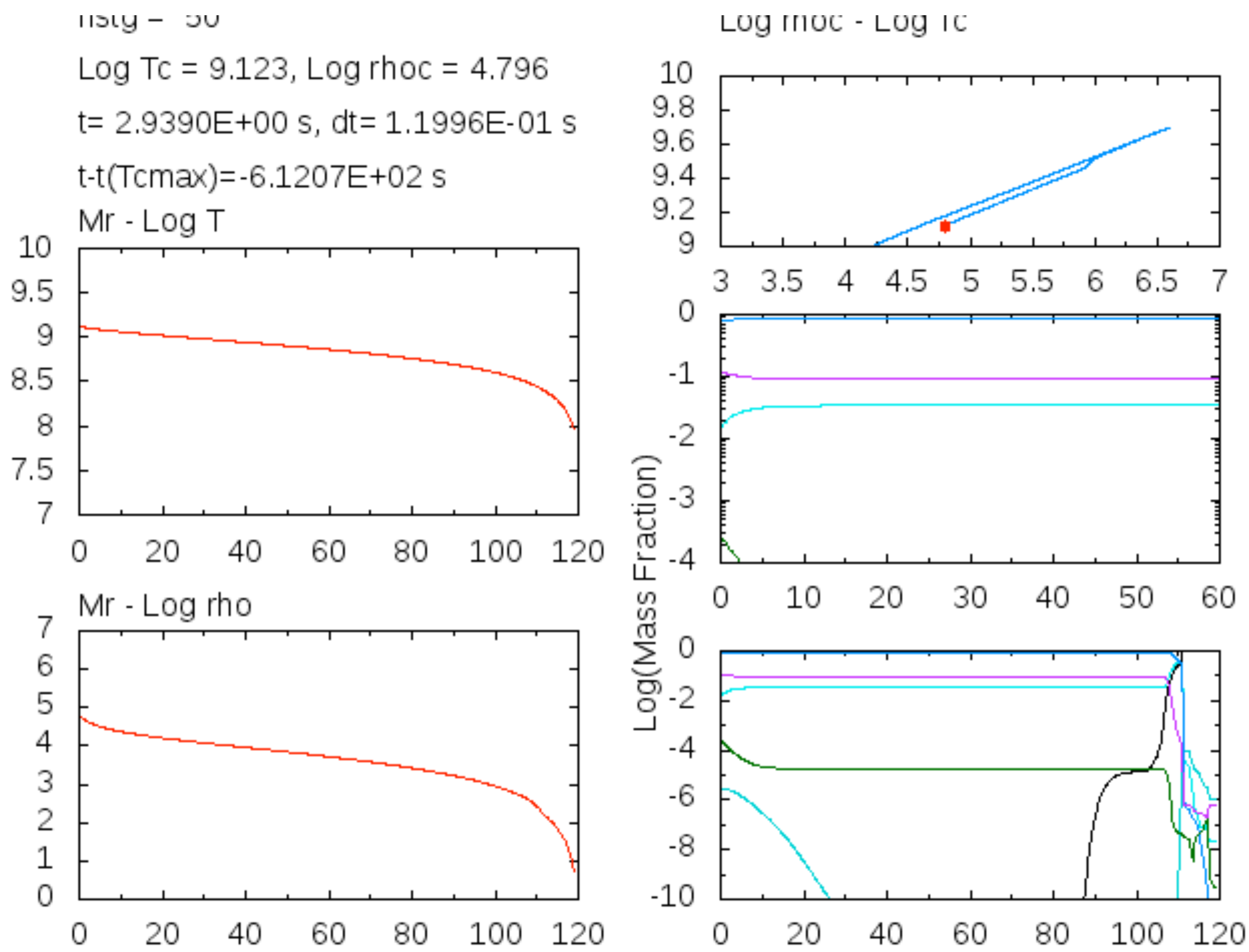
case 1: He star calculations



PISN Yield計算

case1: He stars

Explosion of 120 M_{He}

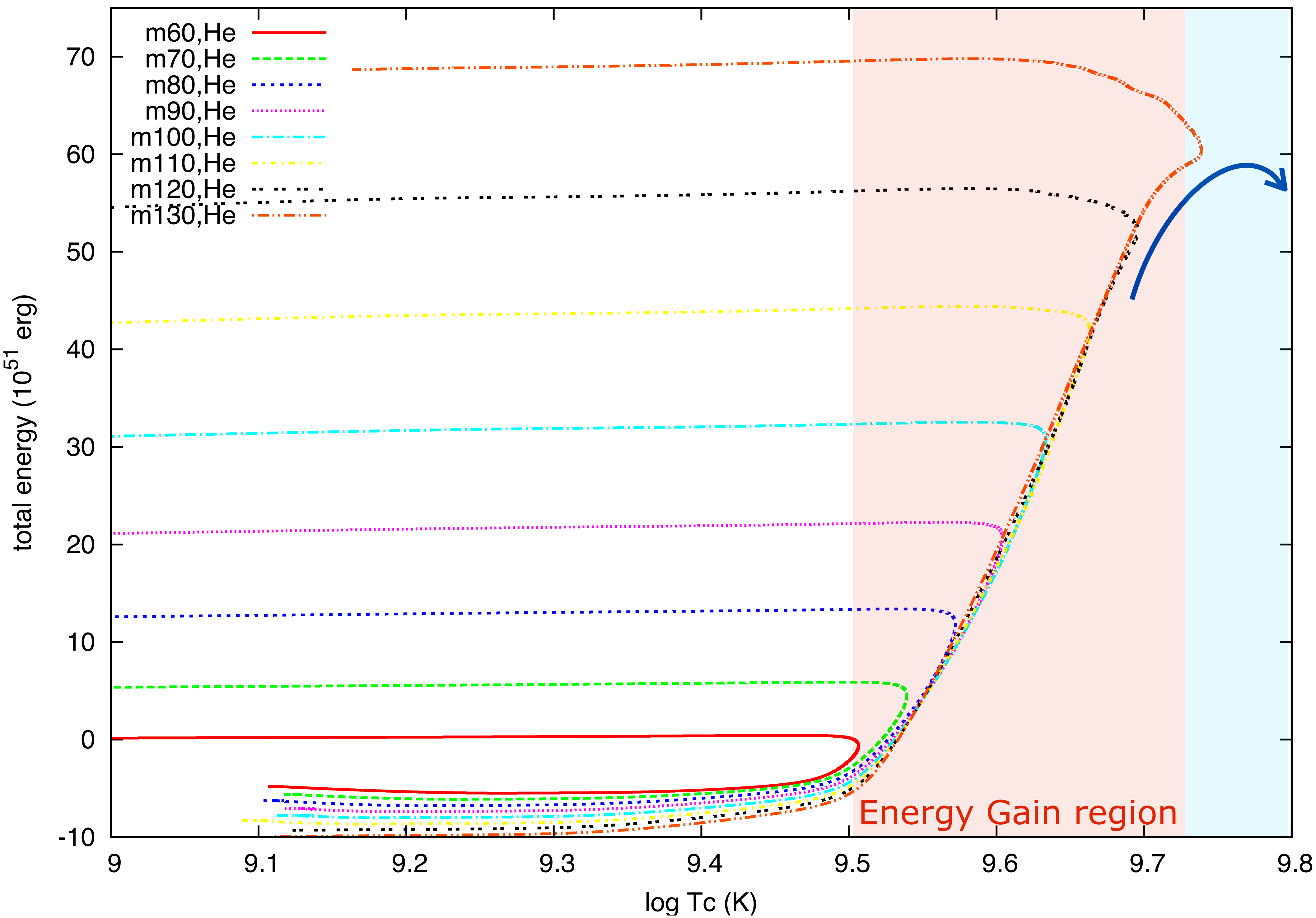


赤：H (水素)
黒：He (ヘリゥム)
紺：O (酸素)
紫：Ne (ネオン)
水：C (炭素)
緑："Si" (シリコン)
茶："Fe" (鉄)

PISN Yield計算

case1: He stars

PISNは**爆発的酸素燃焼**によって爆発する。
鉄族の合成が吸熱反応となり全エネルギーを減少させる。

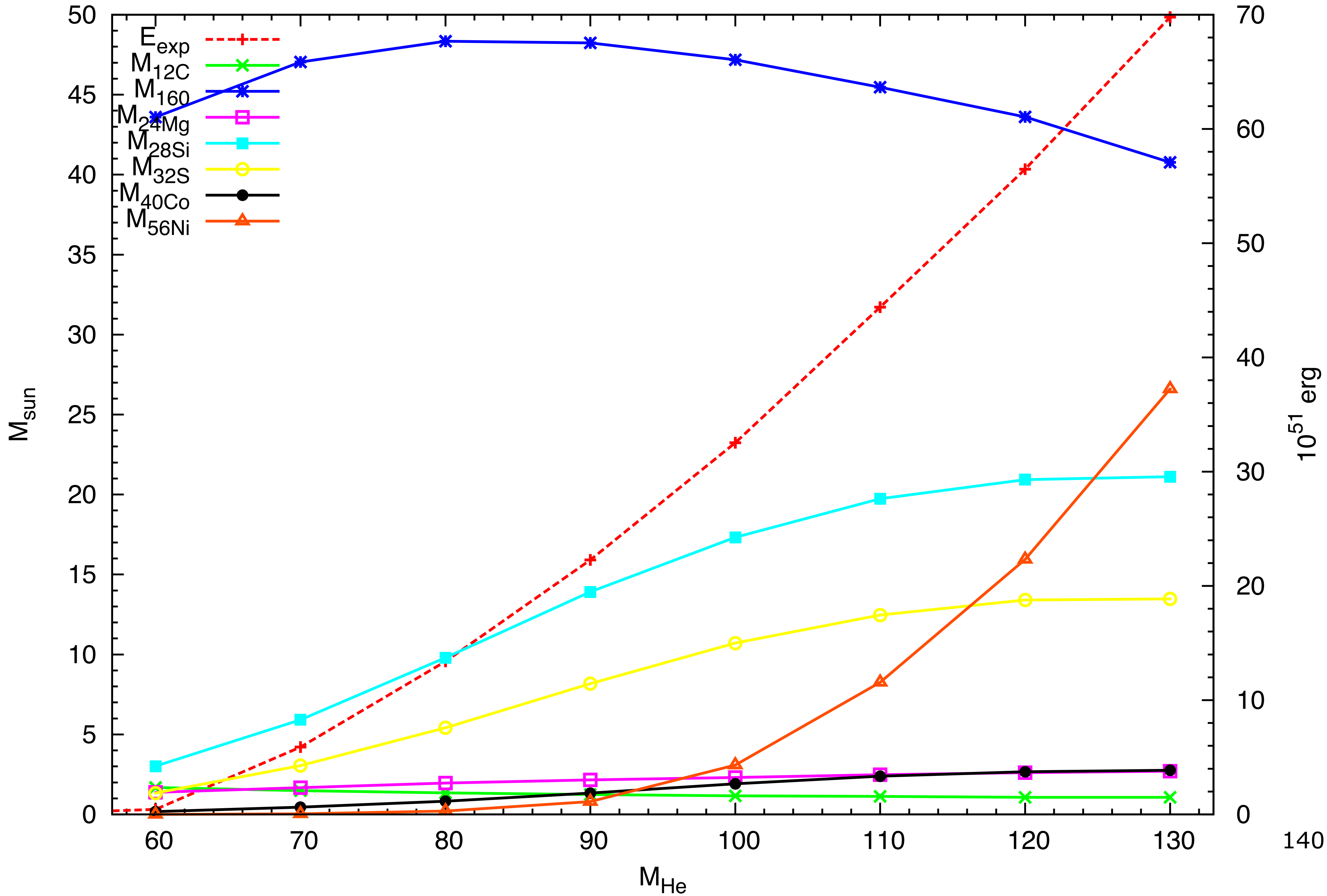


PISN Yield計算

case1: He stars

PISNは **O**, **Si**, **S** を放出する。

Fe (Ni) を合成するのは重いPISN（だけ）

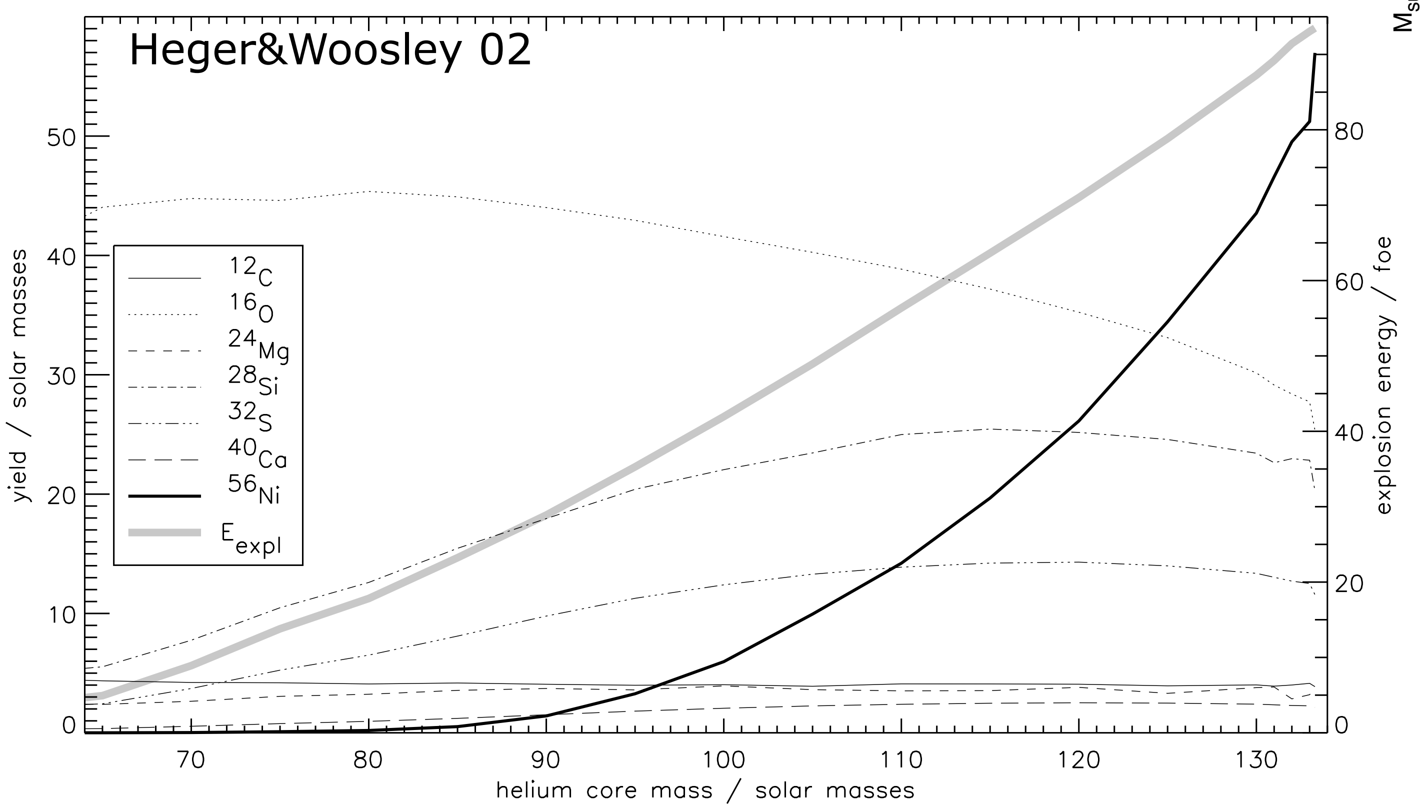


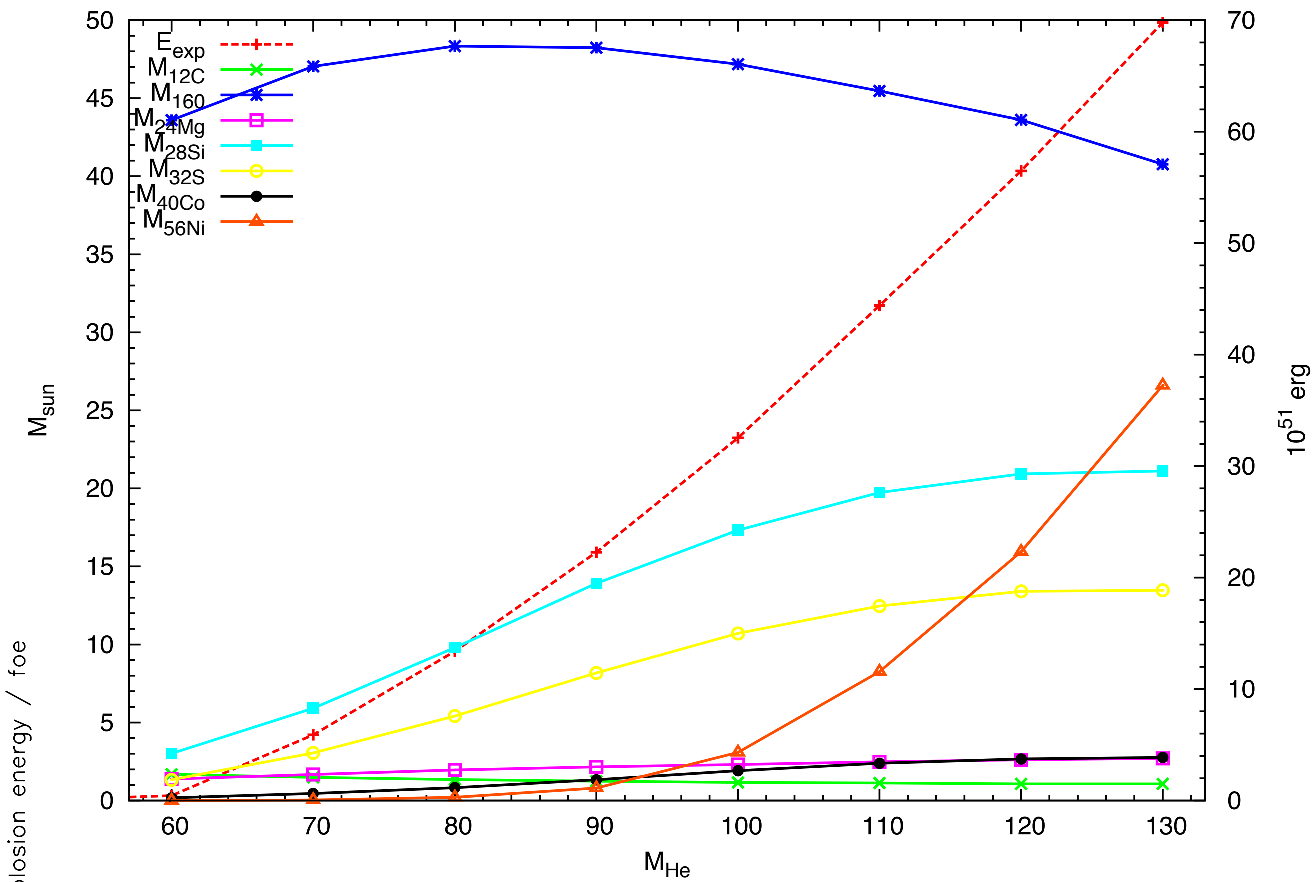
140も飛ぶかも

PISN Yield計算

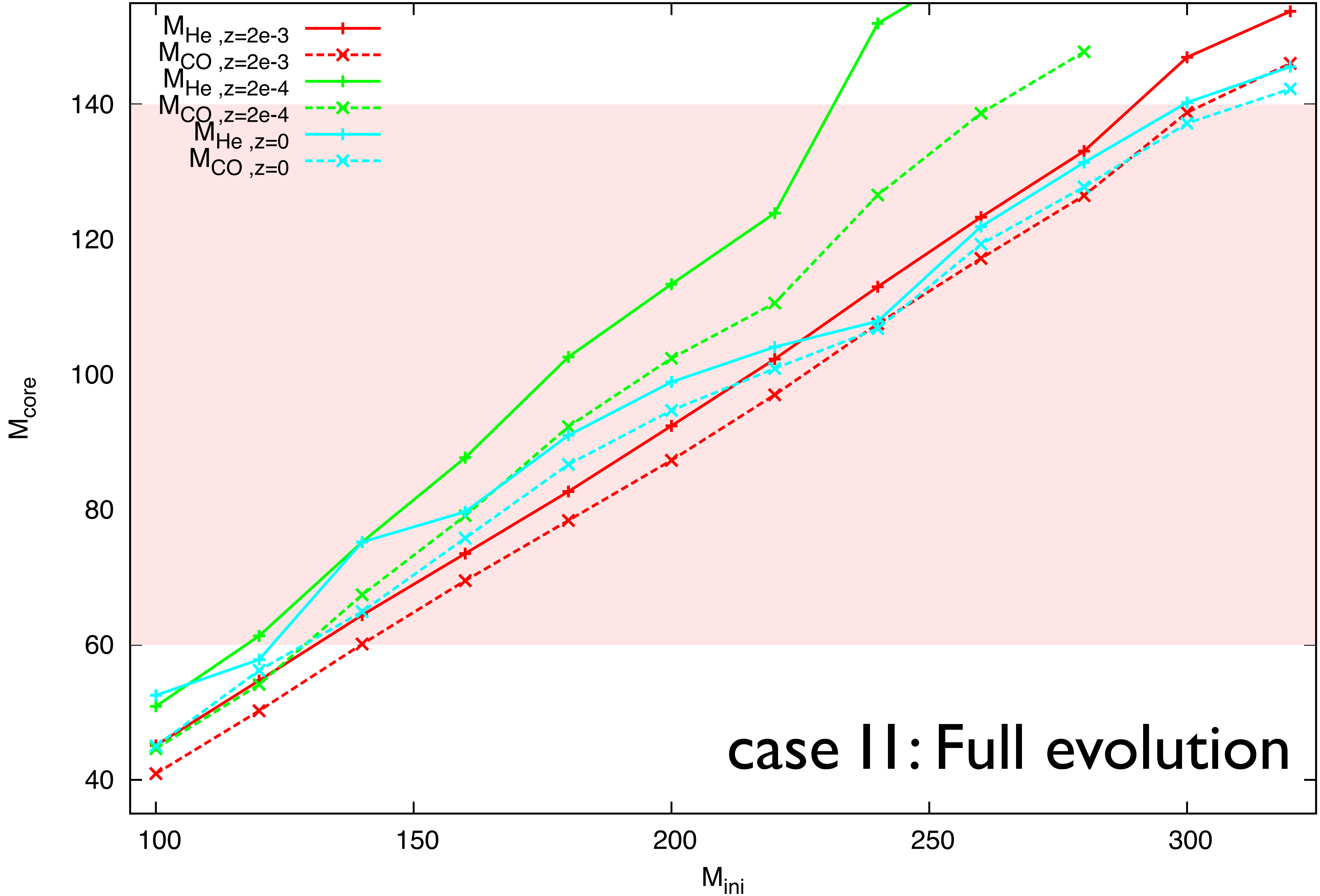
case1: He stars

He星の計算でH&W(02)の結果を確認。
➡ 外層付きの星、メタルのある星ではどうなる？

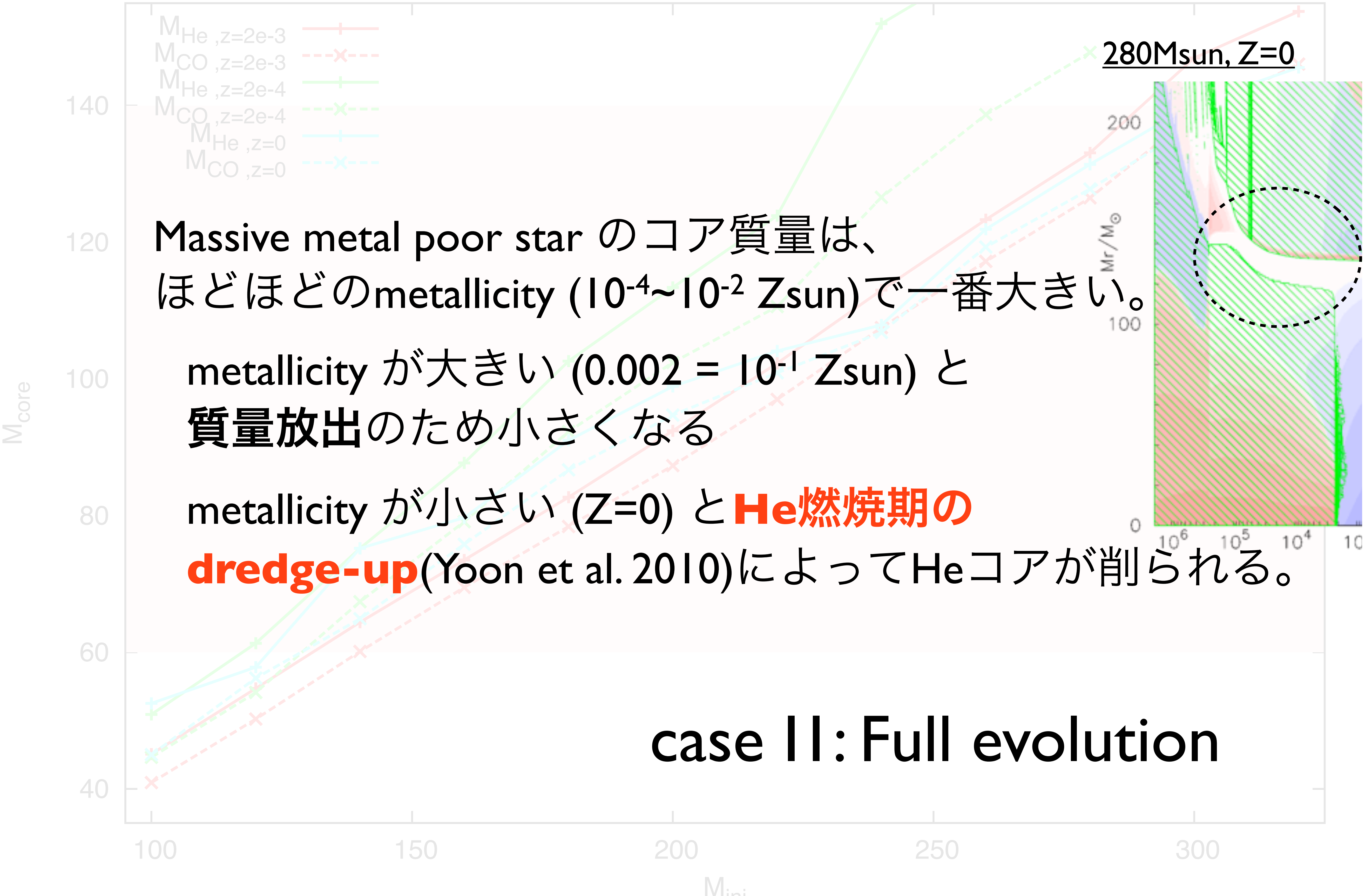




PISN Yield計算



PISN Yield計算



Massive metal poor star のコア質量は、
ほどほどのmetallicity (10^{-4}~10^{-2} Zsun)で一番大きい。

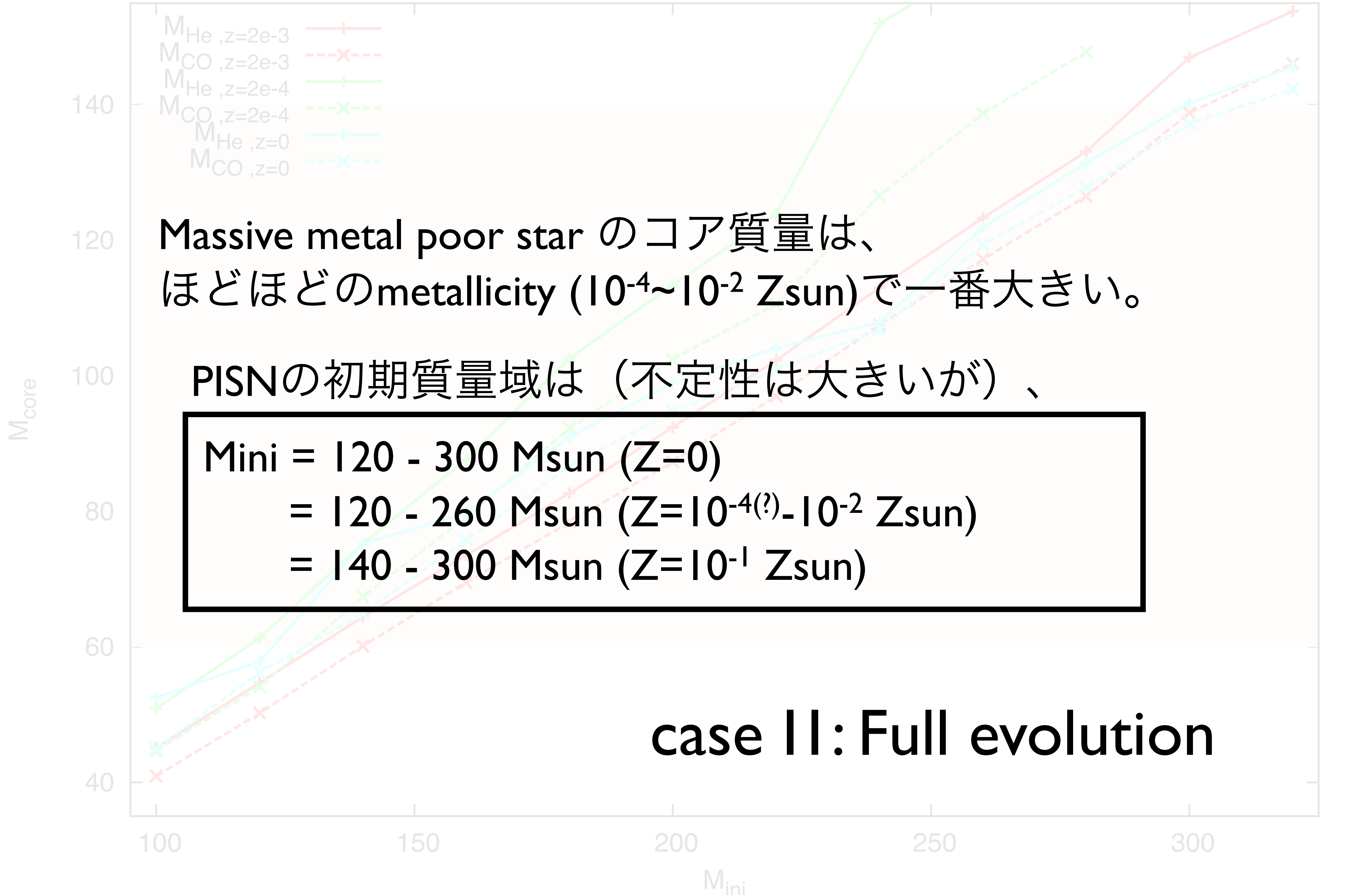
metallicity が大きい (0.002 = 10^{-1} Zsun) と
質量放出のため小さくなる

metallicity が小さい (Z=0) と**He燃焼期の dredge-up**(Yoon et al. 2010)によってHeコアが削られる。

case 11: Full evolution

15年1月18日日曜日

PISN Yield計算



Massive metal poor star のコア質量は、
ほどほどのmetallicity (10^{-4}~10^{-2} Zsun)で一番大きい。

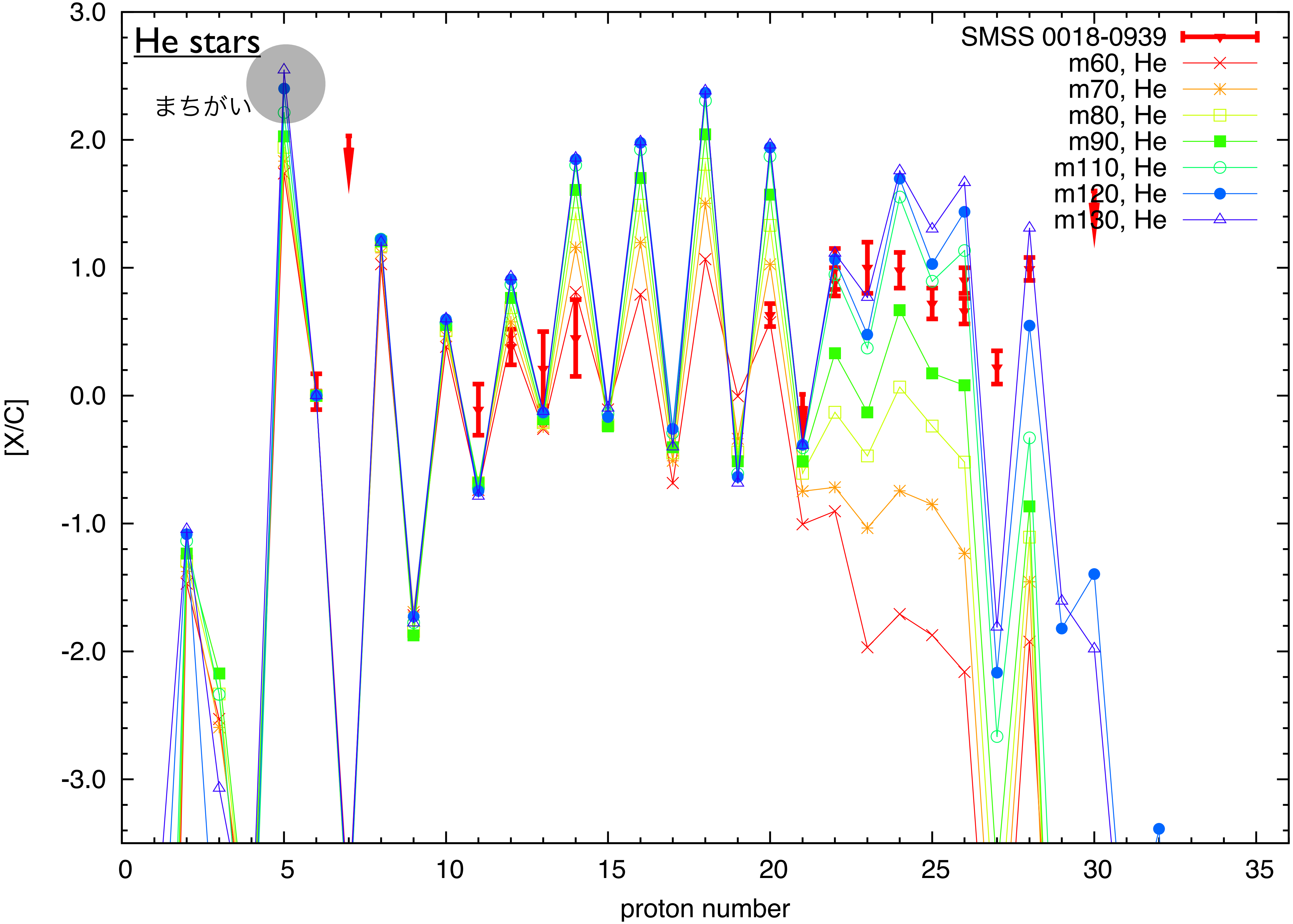
PISNの初期質量域は（不定性は大きいが）、

Mini = 120 - 300 Msun (Z=0)
= 120 - 260 Msun (Z=$10^{-4(?)}$-10^{-2} Zsun)
= 140 - 300 Msun (Z=10^{-1} Zsun)

case II: Full evolution

PISN Yield計算

メタルがあるとPISN組成は変わるのか？



PISN Yield計算

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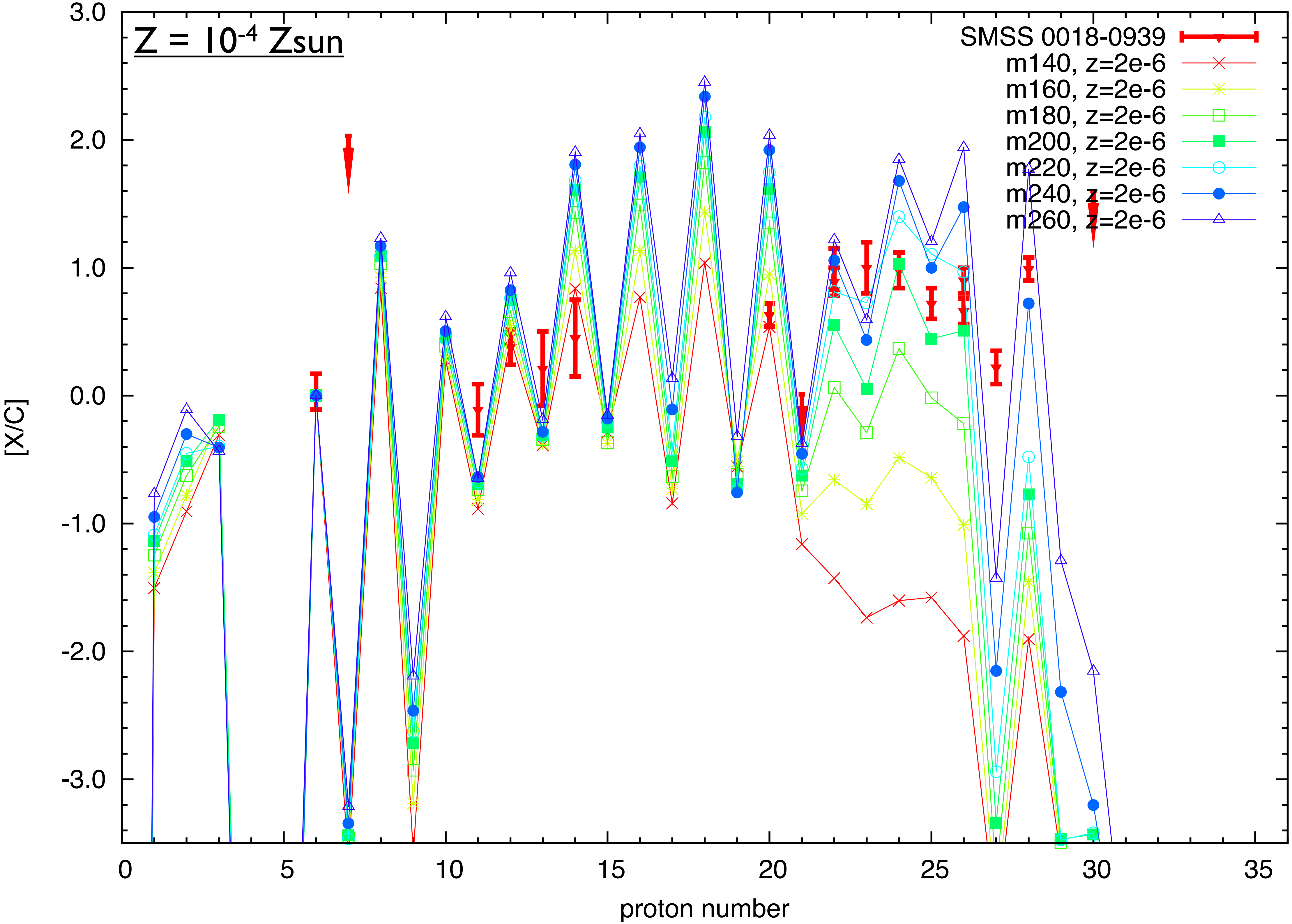

PISN Yield計算

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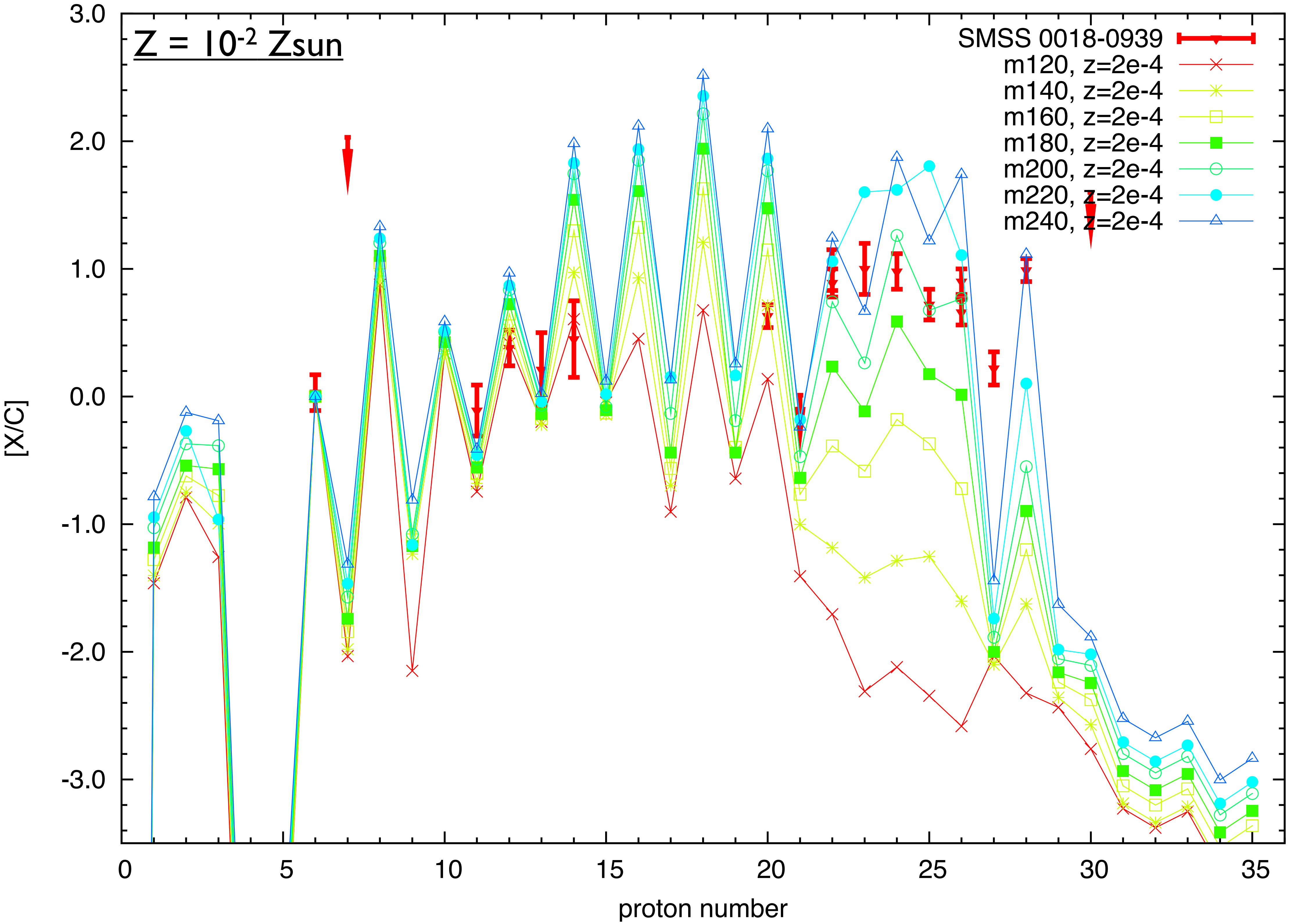


PISN Yield計算

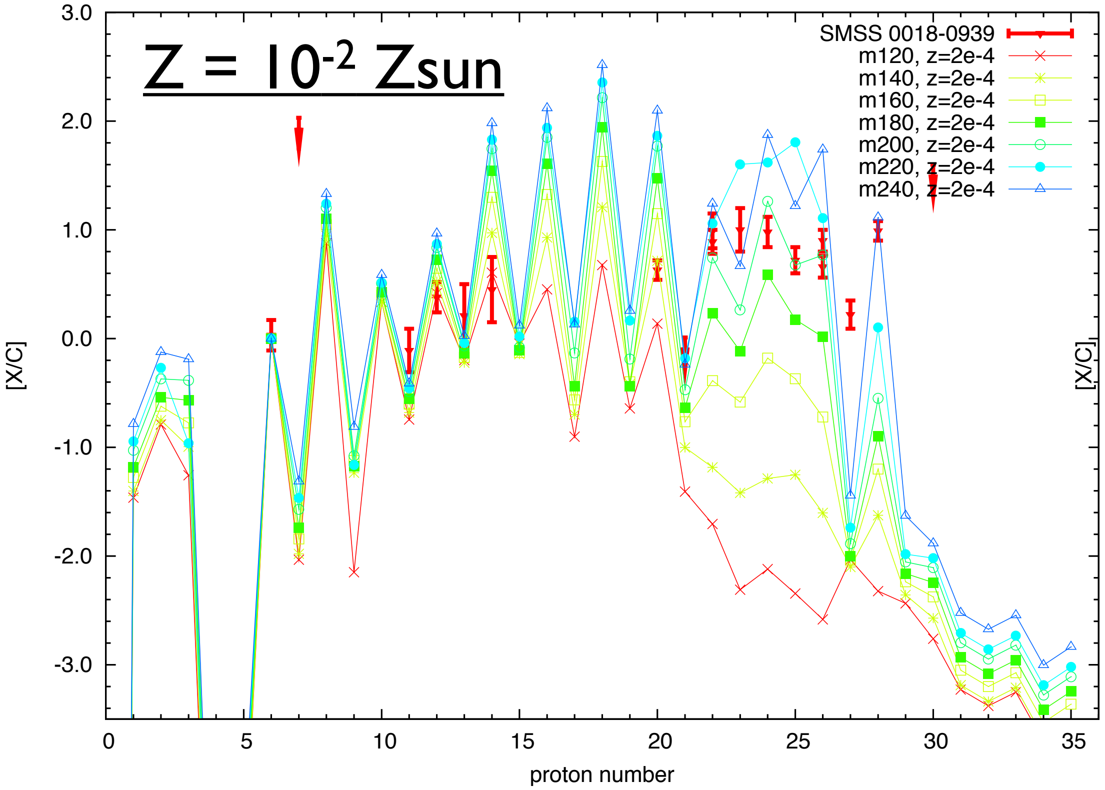
メタルがあるとPISN組成は変わるのか？

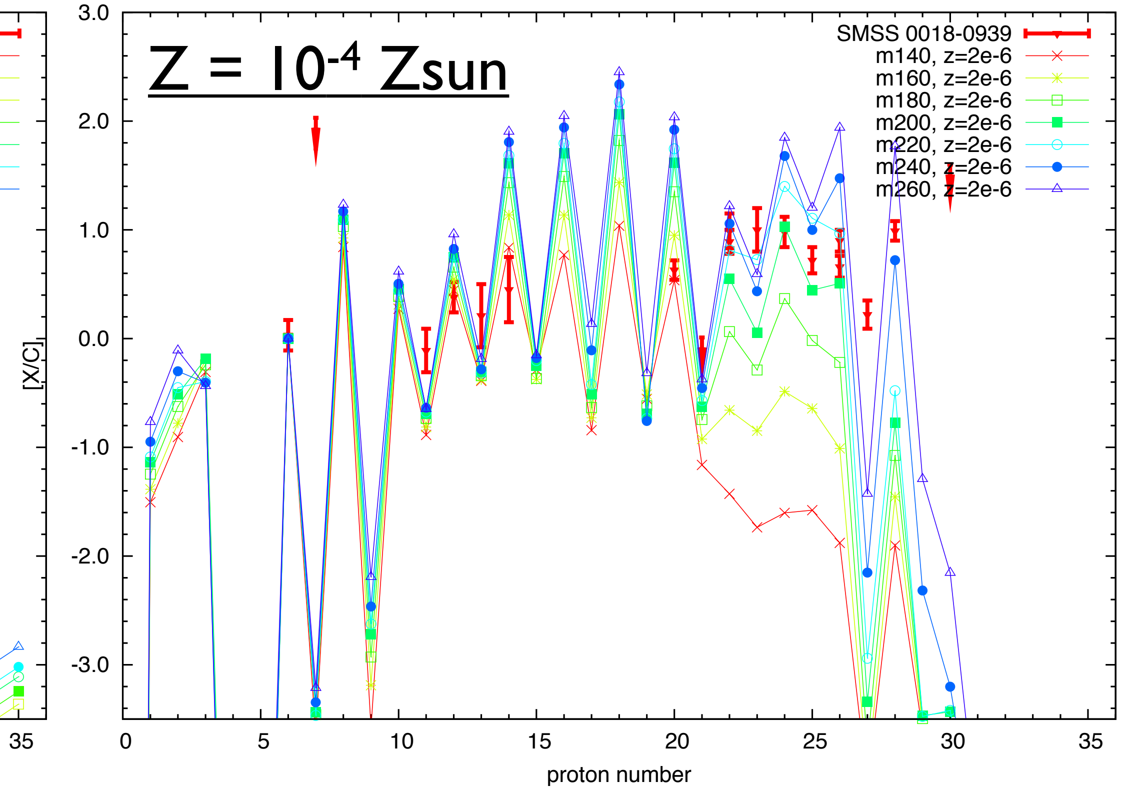
PISN Yiled の Metallicity 依存は**弱い**。

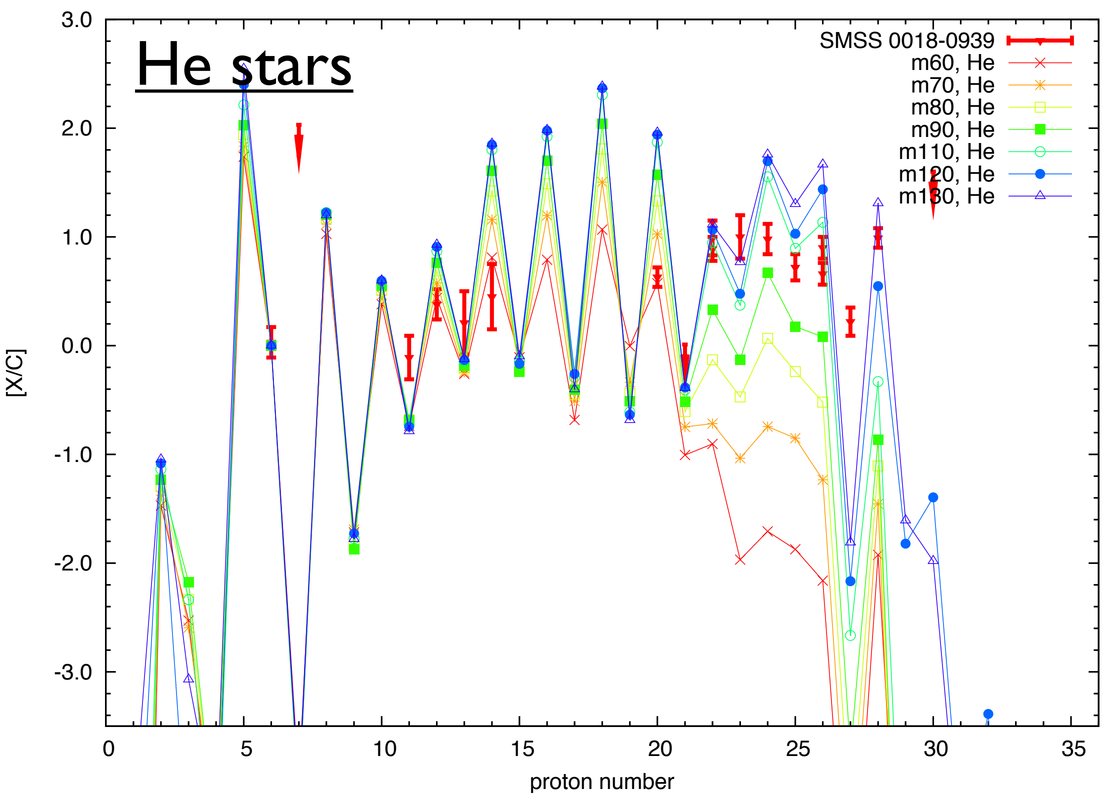
N, Fなどの低質量奇数核種が影響を受けるのみ。

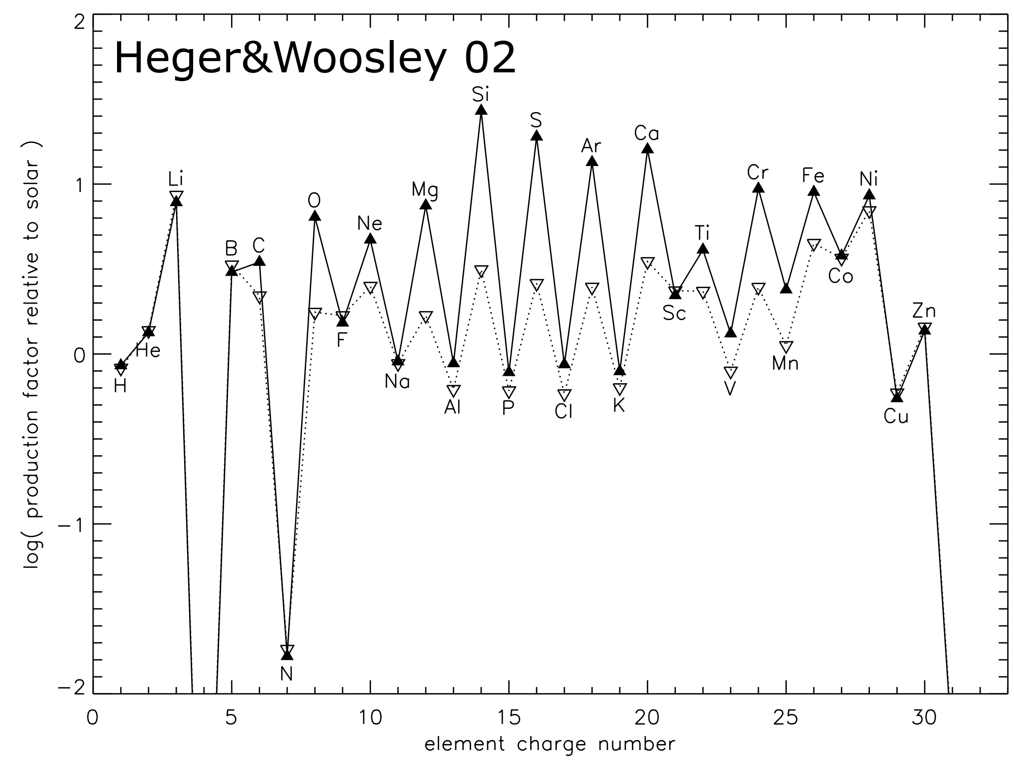
PISN Yield計算

Sc, Coが少ない。









PISN Yield計算

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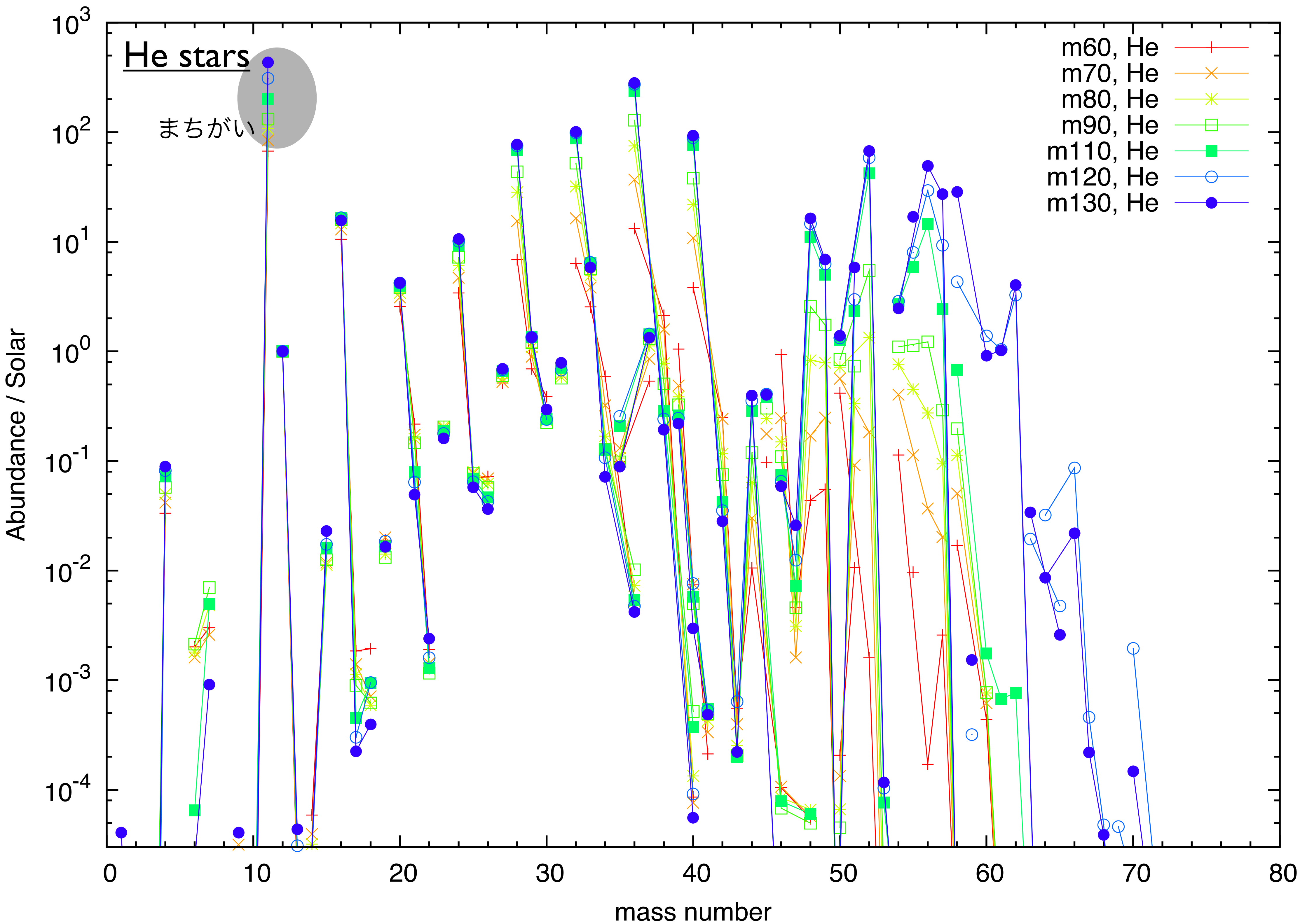

PISN Yield計算

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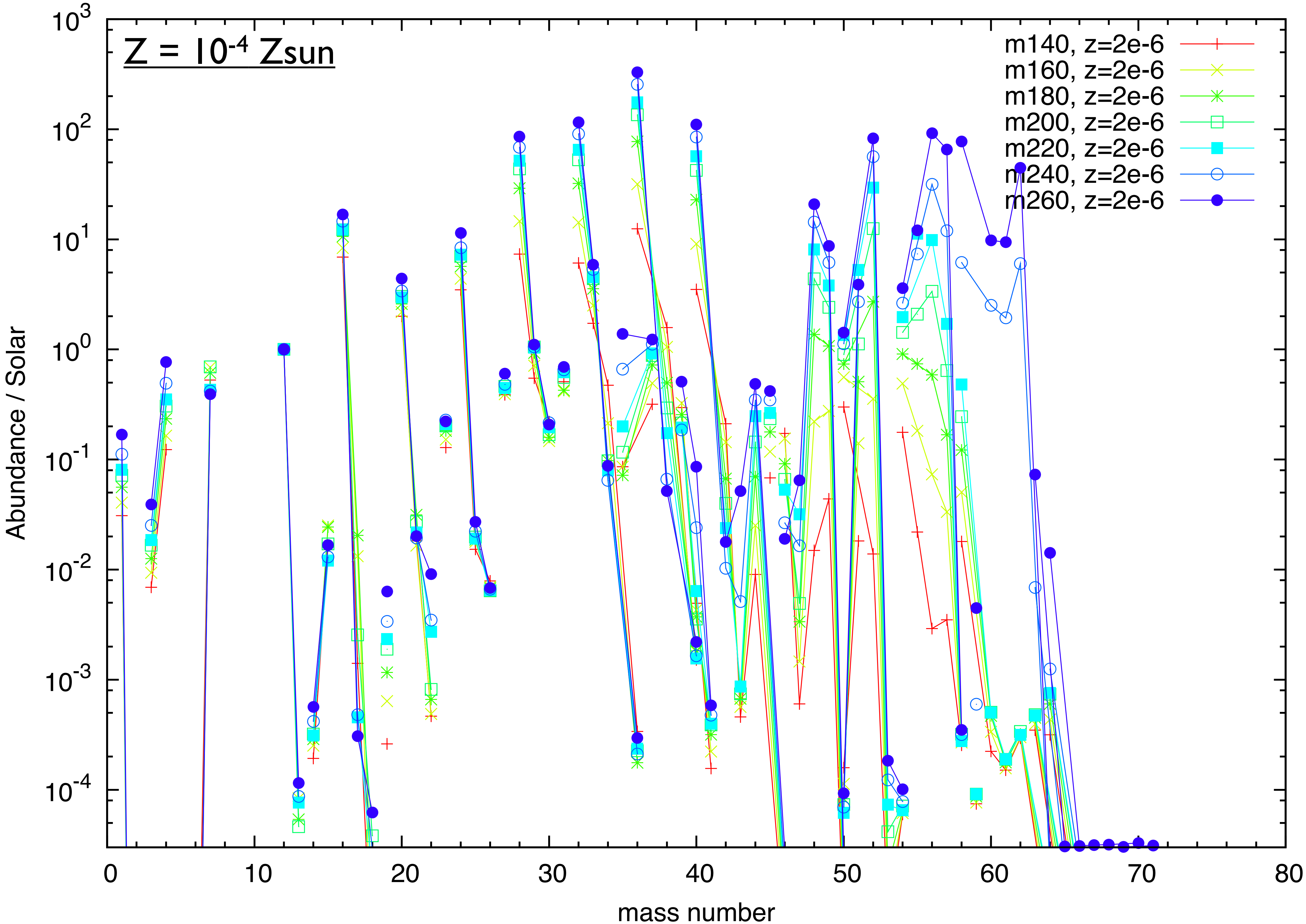
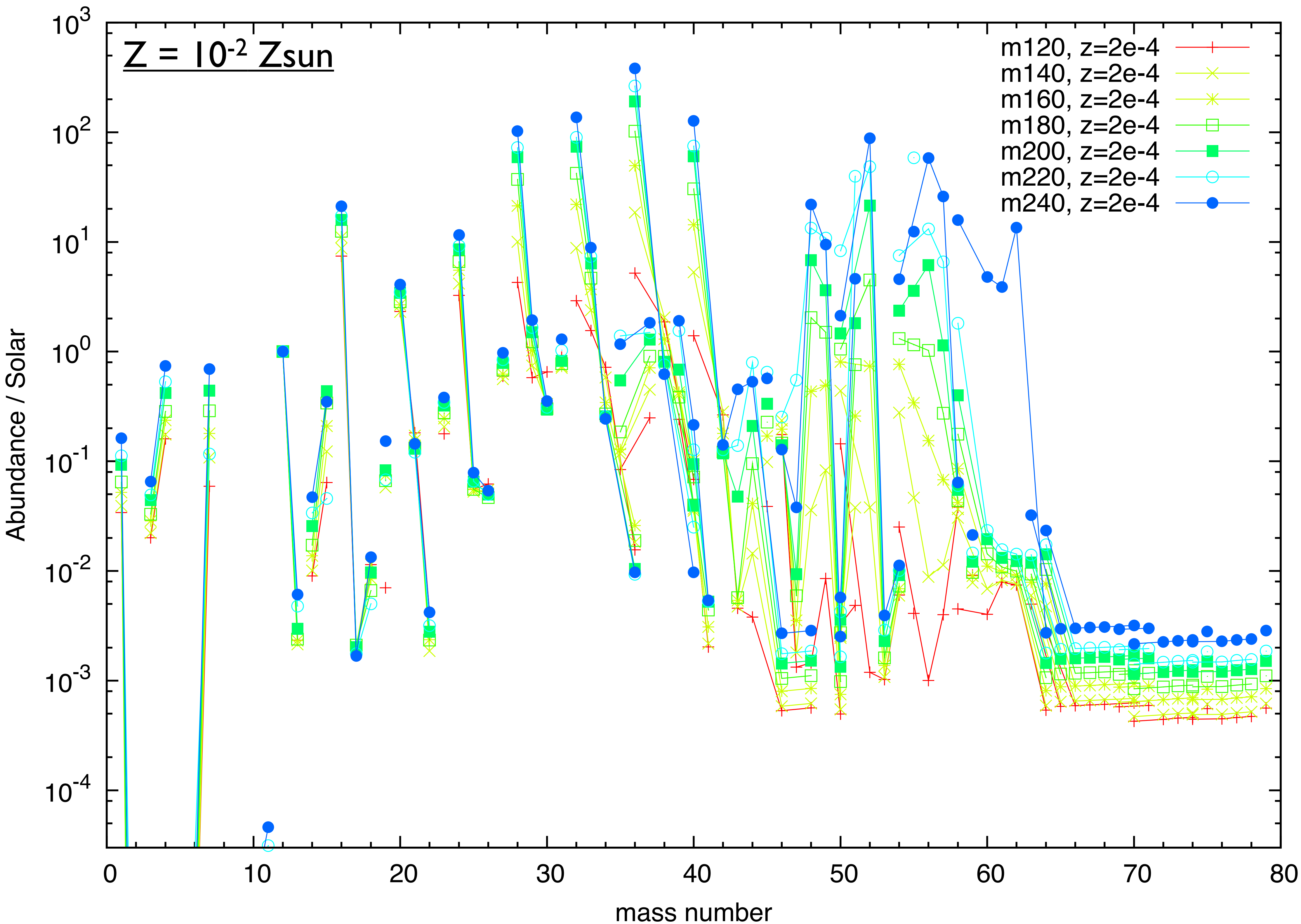


PISN Yield計算

メタルがあるとPISN組成は変わるのか？

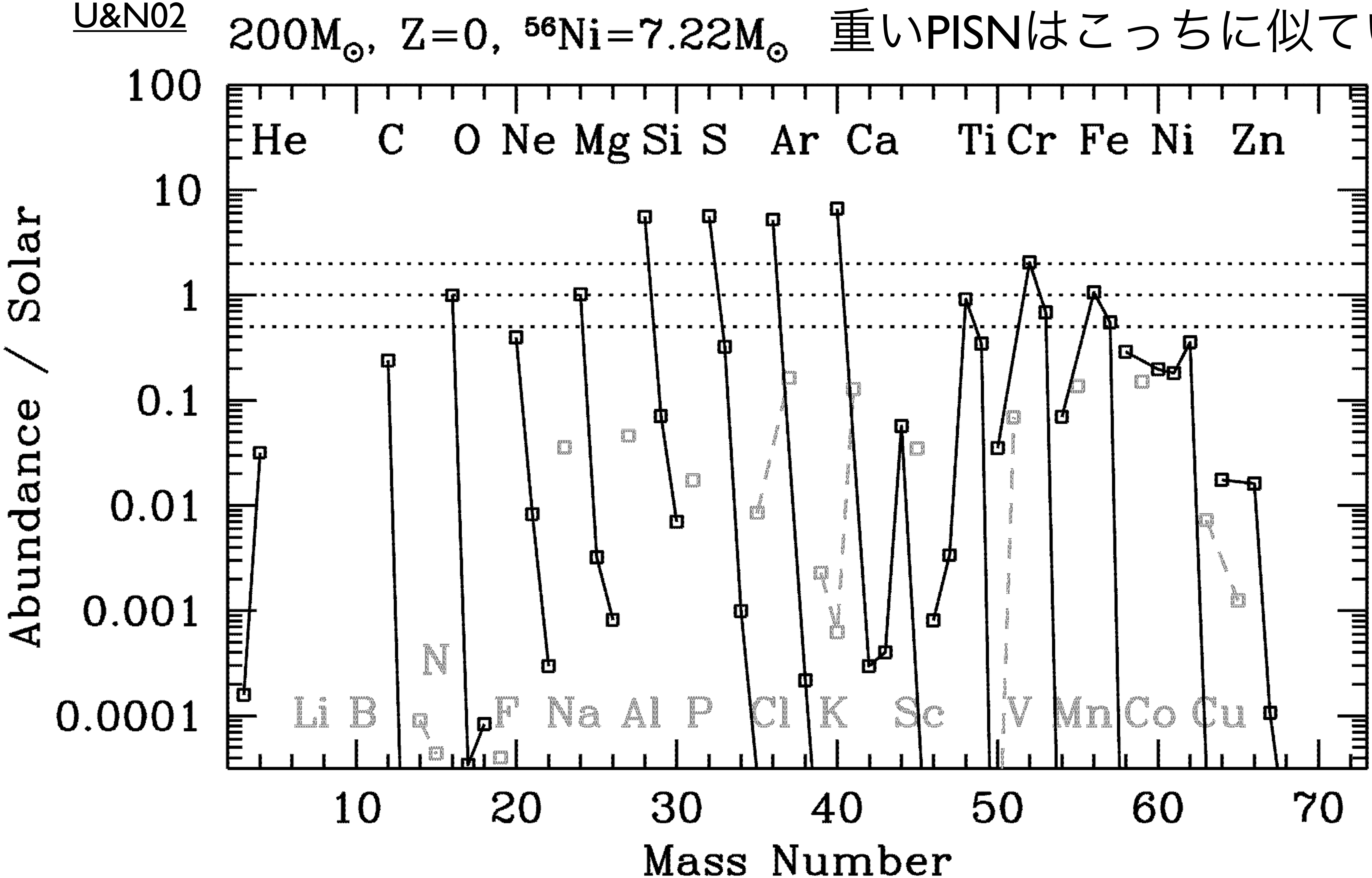


PISN Yield計算

メタルがあるとPISN組成は変わるのか？

U&N02

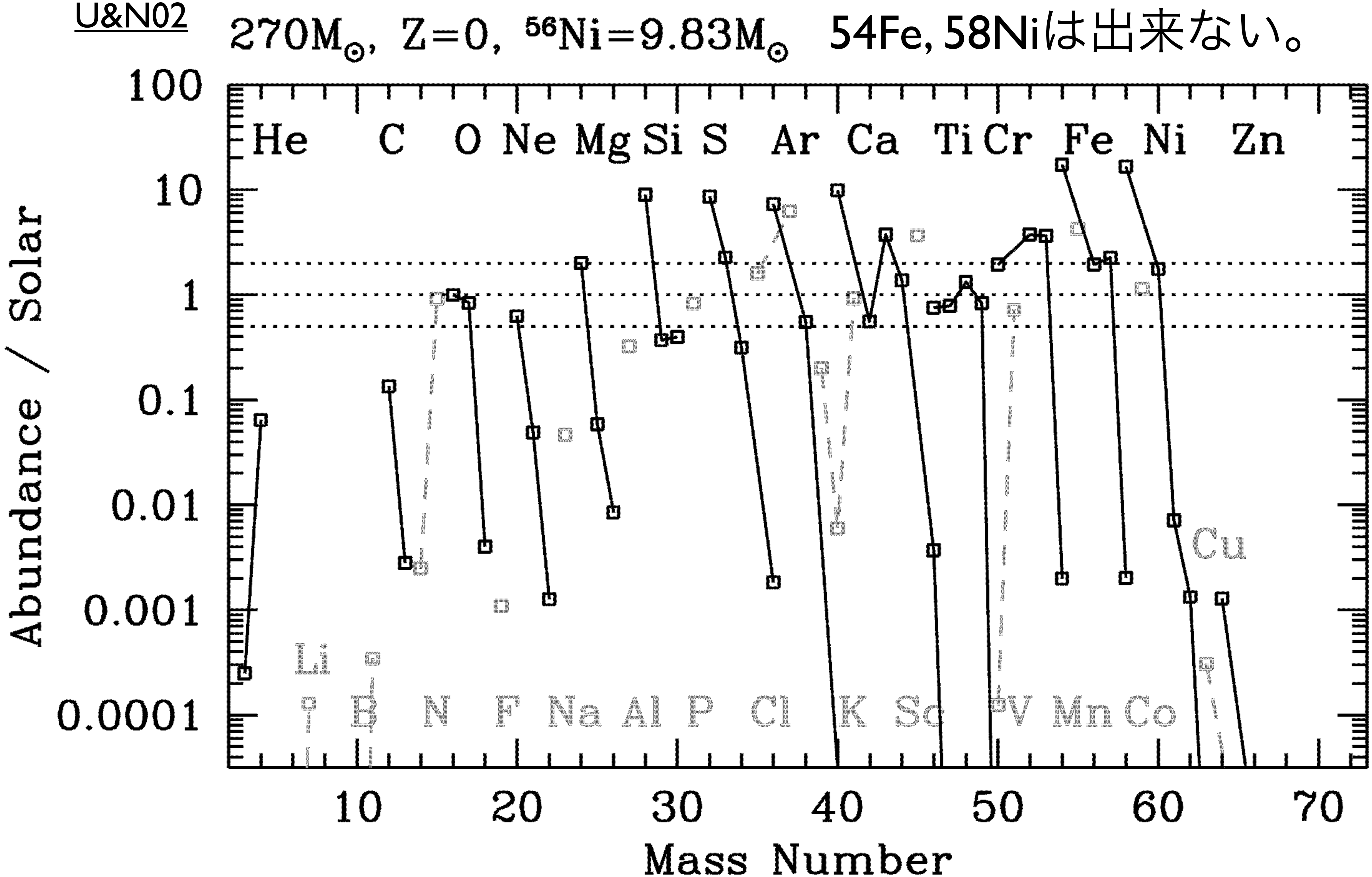
重いPISNはこっちに似ている



PISN Yield計算

メタルがあるとPISN組成は変わるのか？

U&N02　　54Fe, 58Niは出来ない。



PISN Yield計算

=まとめ=

目的：

初代星に限らないPISN生成物を
幅広い金属量域で計算する

結果：

- He星 および non-zero metallicity full star のYield を提供可
- 大抵のPISNの主生成物は**酸素**、次いで**シリコン**。
  鉄をだすのは重いものだけ。
- initial mass range はmetallicityに依る。(mass loss & **D-up**)
- Yield abundance はmetallicityに依らない？