Progenitors of Supernovae and GRBs

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Contents

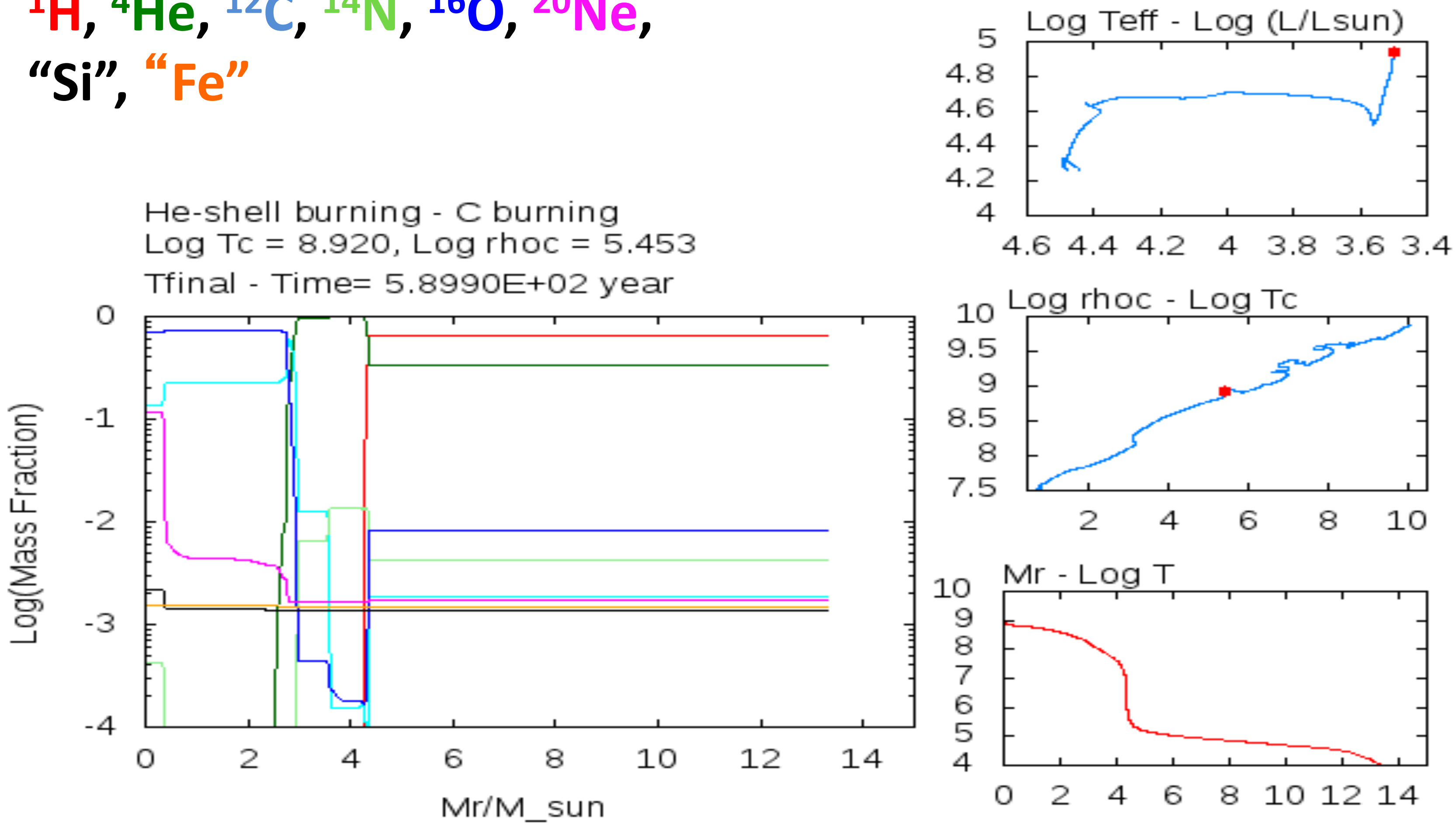
Introduction: SN progenitors

Stellar Mass and Fate (without Mass-loss)

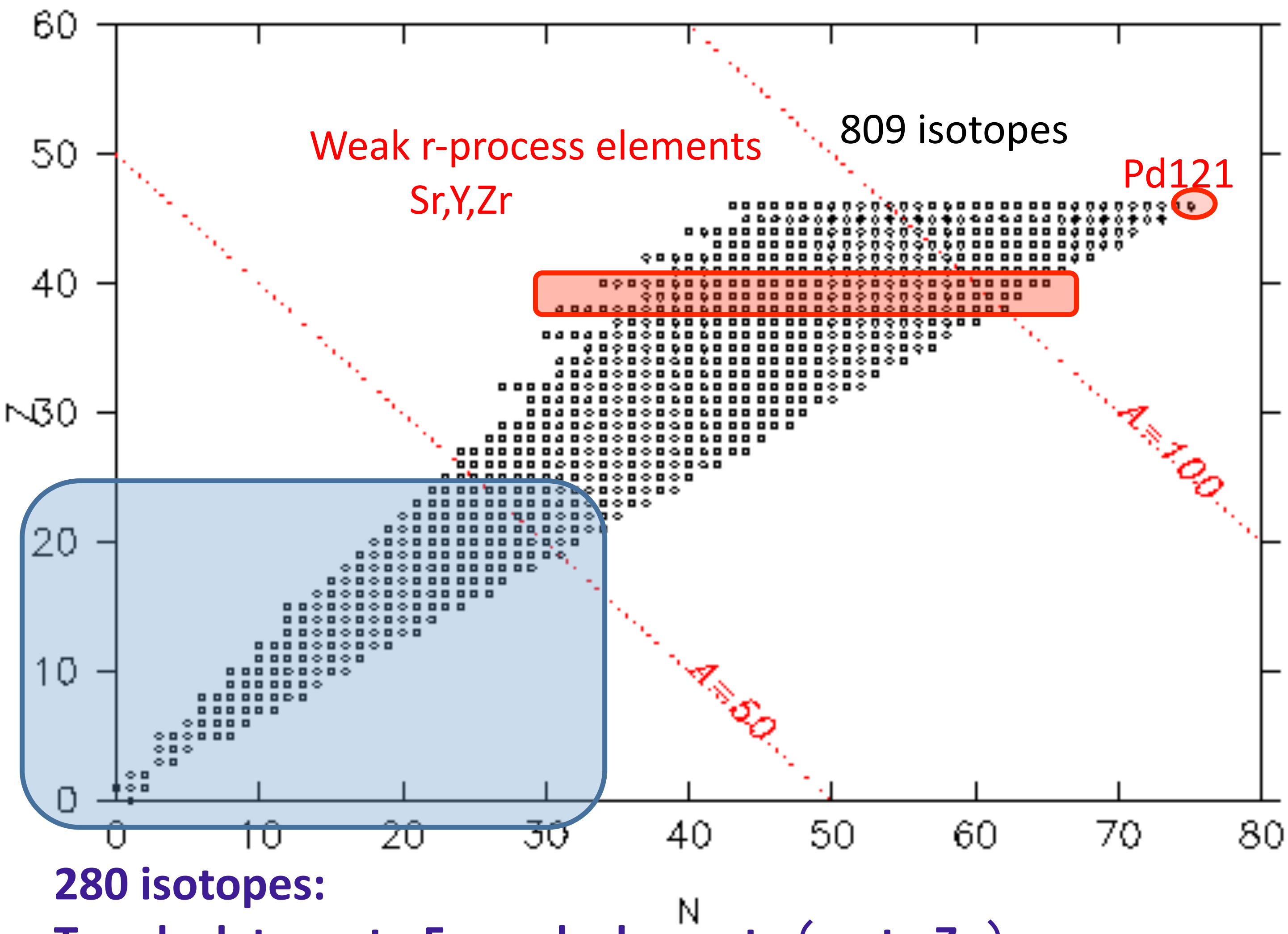
- **$M < 8\ M_\odot$ + binary : SNe Ia**
- **$\sim 8 - 140 M_\odot$: Fe Core collapse (SNe)**
- **$\sim 140 - 300 M_\odot$: e^+-e^- Pair Instability SNe**
- **$> \sim 300 M_\odot$: Fe core collapse**

Evolution of a massive 15$M_\odot$ *star: surface and interior*

^{1}H, ^{4}He, ^{12}C, ^{14}N, ^{16}O, ^{20}Ne, "Si", "Fe"



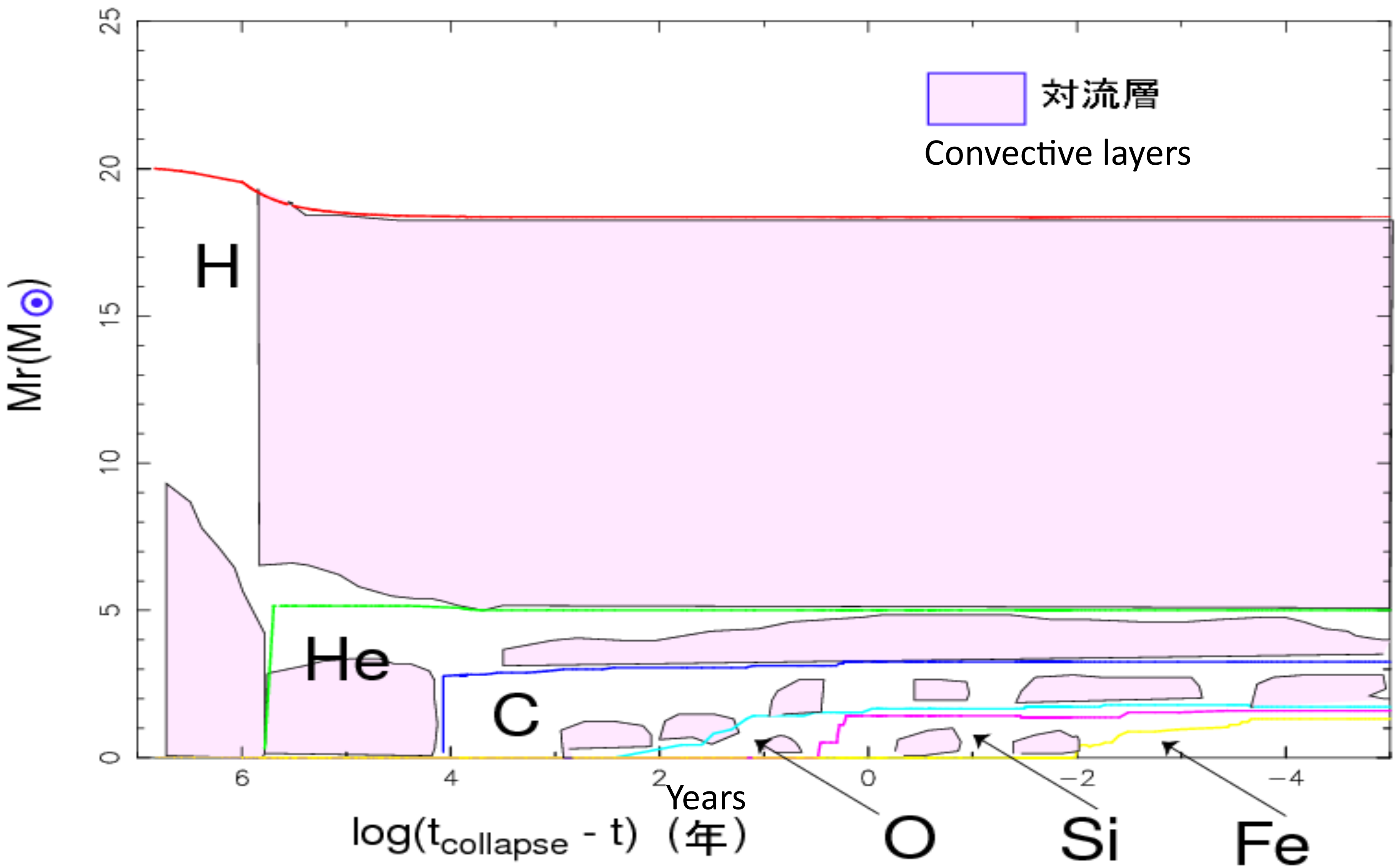
Nucleosynthesis calculations : nuclear reaction networks



For r-process
~ 5000 isotopes

280 isotopes:
To calculate up to Fe peak elements（up to Zn）

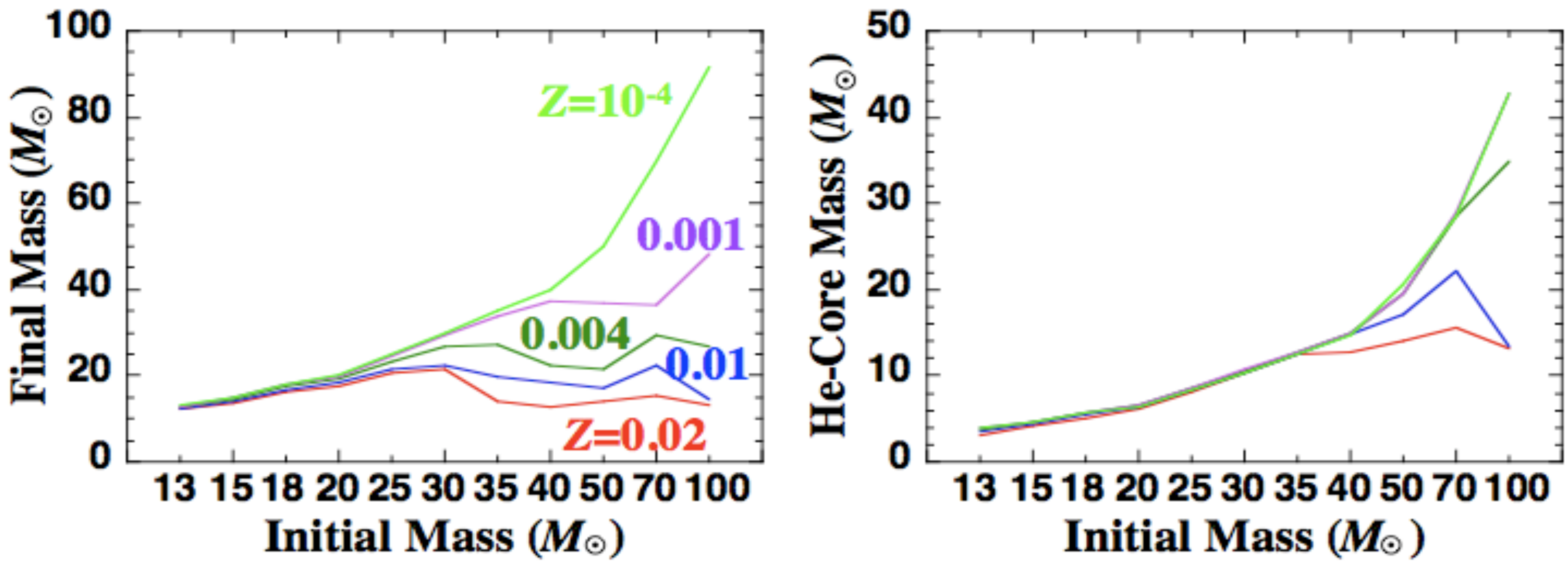
Evolution of inner composition and the location of convective layers (20$M_\odot$, Z=0.02 model)



"Standard" mass loss for non-rotating stars

(Yoshida＆Umeda 2010)

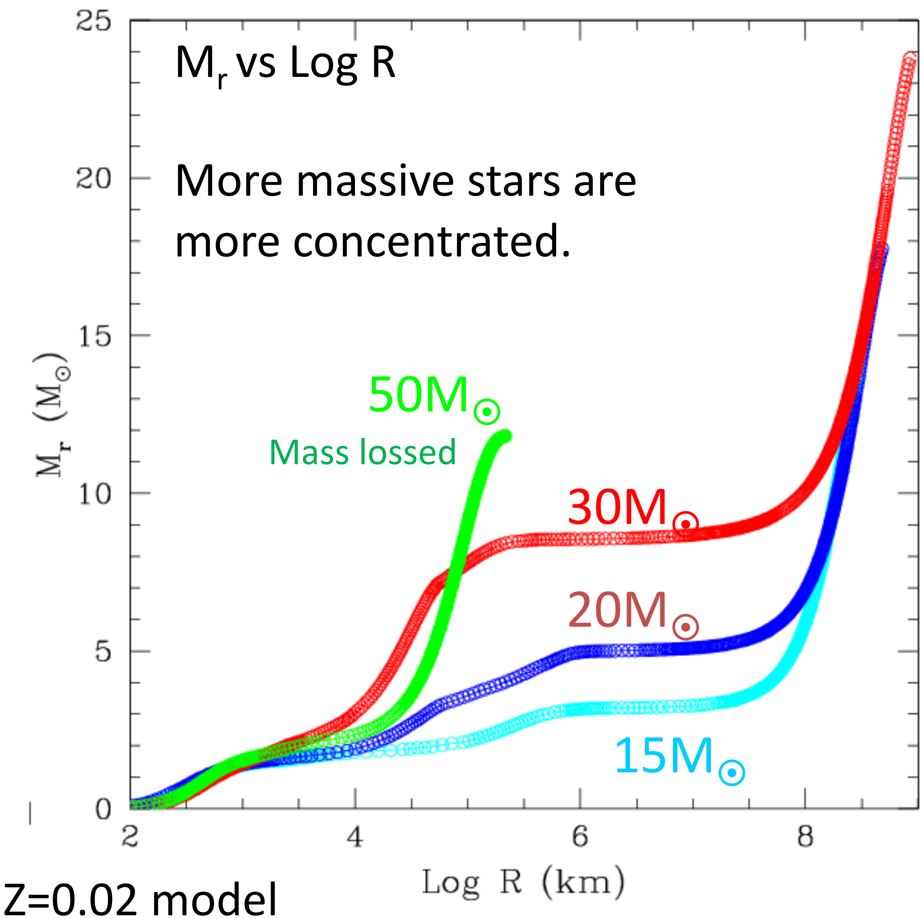
- **Mass loss rate**
  - **OB stars** → **Vink et al. (2001)** $\propto Z^{0.85}$
  - **Red giant branch** → **de Jager et al. (1988)** $\propto Z^{0.5}$ 依存性を追加 (e.g. Kudritzki and Puls 2000)
  - **Wolf-Rayet stars** → **Nugis & Lamers (2000)** $\propto Z^{0.47}$

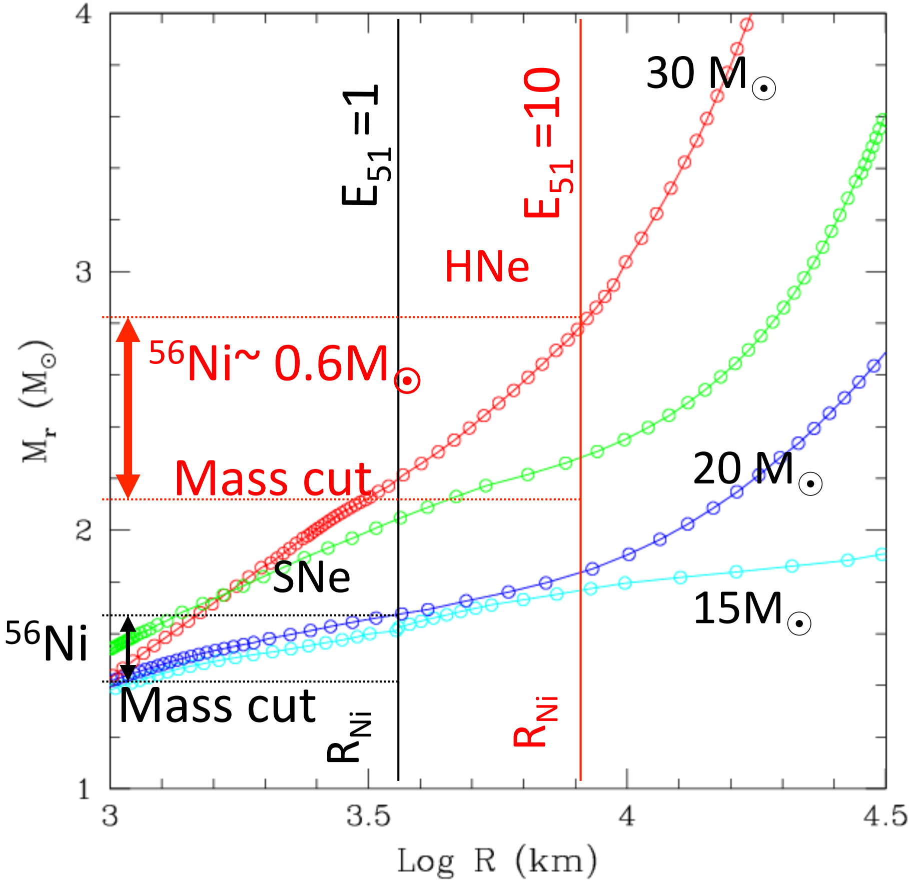


Progenitor's density distribution and ^{56}Ni production

$E=4\pi R^3 a T^4/3$ (radiation dominant)

($T>5\cdot10^9$K for ^{56}Ni production) $R_{Ni} \sim 3700 E_{51}^{1/3}$ (km)





Z=0.02 model

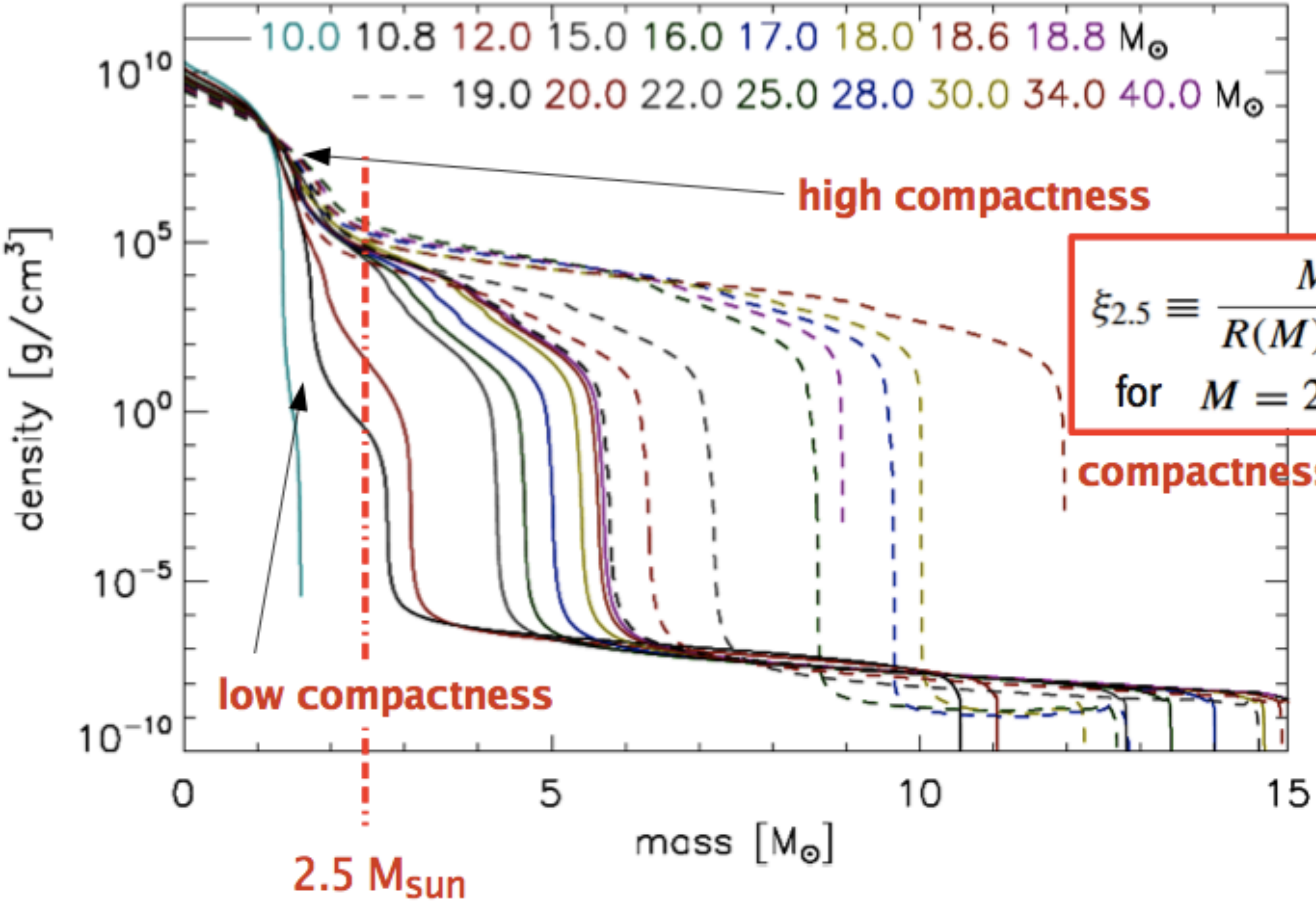
Compactness parameter and explosion

- Definition: $\xi_{2.5} = (M/M_{\odot})/(R(M)/1000\ \text{km})$ for $M=2.5M_{\odot}$@core bounce (O'connor & Ott (2011): $\xi_{2.5} <\ \sim 0.45$ for explosion)
- It is popular now
- Free fall time: $t_{ff}\,(@2.5M_{\odot}) = 0.241\ \xi_{2.5}^{-1.5}$ sec
- In general, if $\xi_{2.5}$ is larger free fall time is fast and harder to explode
- Typically more massive progenitors have larger $\xi_{2.5}$
  - But this is not monotonic function of M

- Later studies (e.g., Ugliano et al 2012) showed that there is no clear critical value $\xi_{2.5}$ for a successful (failed) explosion.

Compactness parameter and explosion

Progenitor models from Woosley, Heger, & Weaver (RMP 2002)



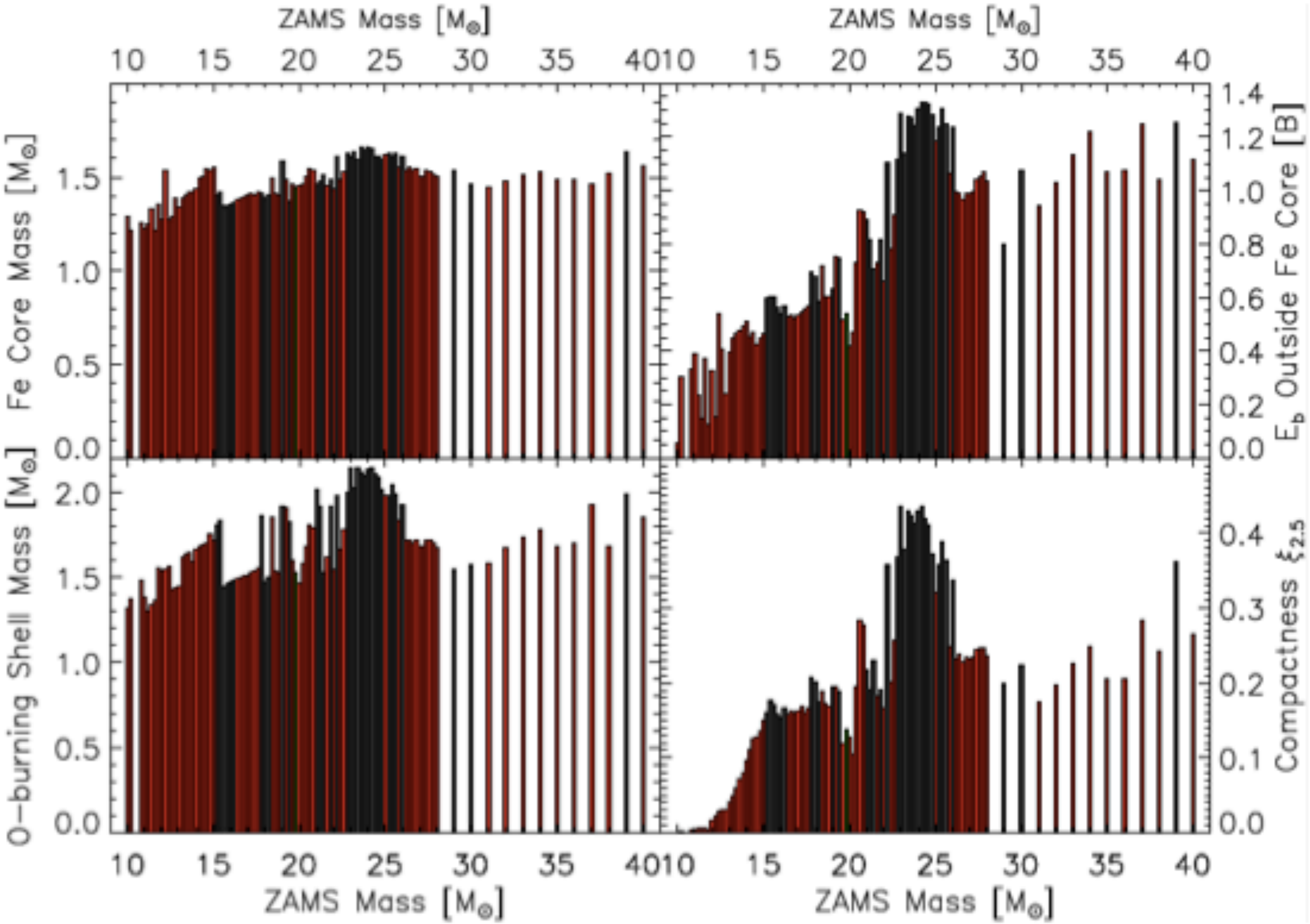
$$\xi_{2.5} \equiv \frac{M/M_\odot}{R(M)/1000\,\mathrm{km}}$$

for $M = 2.5\ M_\odot$

O'Connor & Ott, ApJ 730:70 (2011)

Compactness parameter and explosion

Nonmonotonic Progenitor Properties



Grey = BH formation cases

(Ugliano, THJ, Marek, Arcones, ApJ 757, 69 (2012))

Compactness parameter and explosion

- Typically more massive progenitors have larger $\xi_{2.5}$
  - But this is not monotonic function of M
  - Shell C-burning is important for the compactness
    - Larger X(C) ➡ convective shell burning ➡ smaller $\xi_{2.5}$
    - X(C) in the C-shell depends on M, C(a,g)O rate, and the behavior of convection during the core He burning.
- Later studies (e.g., Ugliano et al 2012: 1D explosion model) showed that there is no clear critical value $\xi_{2.5}$ for a successful (failed) explosion.
- It is even not clear if $\xi_{2.5}$ is so useful to discuss the successful explosion (though it is quite popular right now) .

  (Using M_{core}, dM/dt, M(Fe), M(PNS) instead are probably not much different.

Rotating stellar models

- Necessity (?): several facts can't be explained with single non-rotating stellar models
  - Surface abundance of rotating massive stars
    - N/C,O ratios – can be explained by rotational mixing
  - BSG/RSG ratio
  - Spreads in the HR diagram of clusters

  - However, most of these problems may also be explained with binary stellar models (but probably the enhancement of N is difficult).

Rotating stellar models

•Usually, three effects are treated in 1(.5)-dimensional stellar evolution calculations. Rotation profiles are assumed to be shelluler (タマネギ状) (Zahn 92).

1) Deformation by centrifugal force (遠心力)
2) Matter mixing by rotationally induced instabilities
3) Enhancement on mass-loss

Grids of stellar models with rotation II. : WR populations and supernovae/GRB progenitor at Z = 0.014 C. Georgy et al. 2012

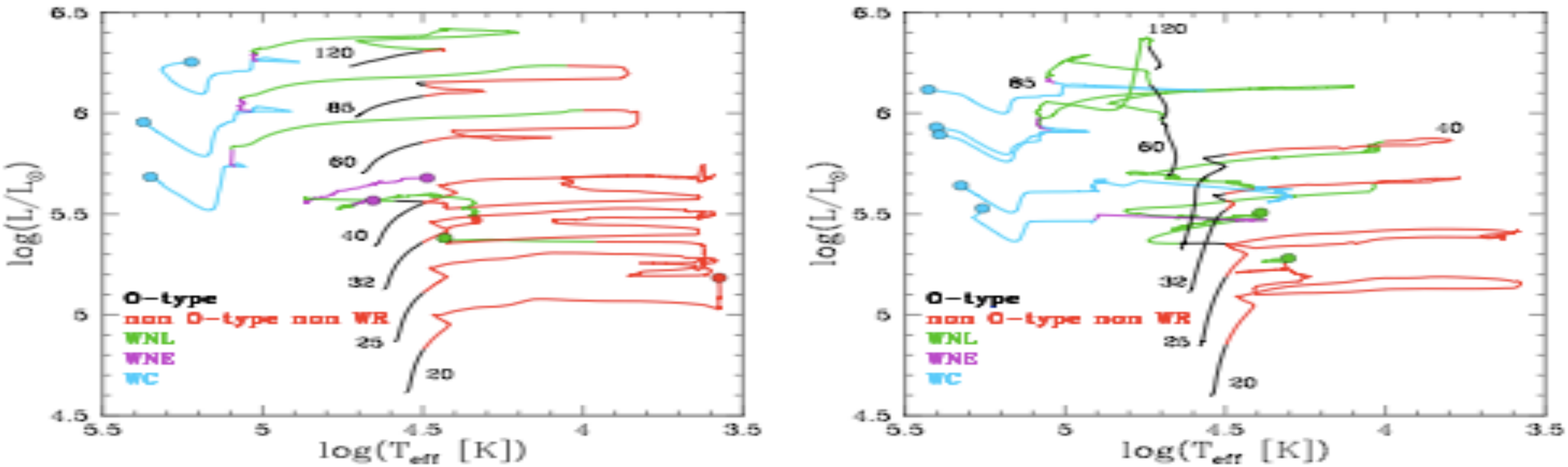


Fig. 1. HRD of the massive models from 20 to 120 $M_\odot$ with the different types/phases marked in colours (O-type: blue; neither O-type nor WR: red; WNL: green; WNE: purple; WC: cyan). *Left:* Non-rotating models. *Right:* Rotating models. We plotted the effective temperature at the surface of the hydrostatic core. The endpoints of the tracks are indicated by a circle.

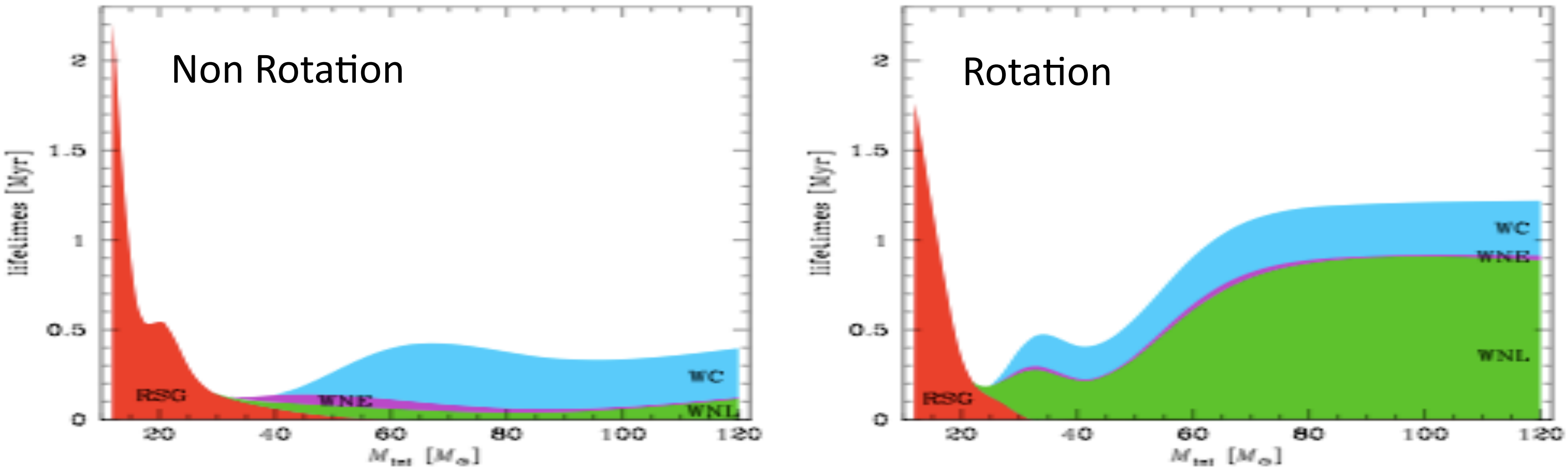
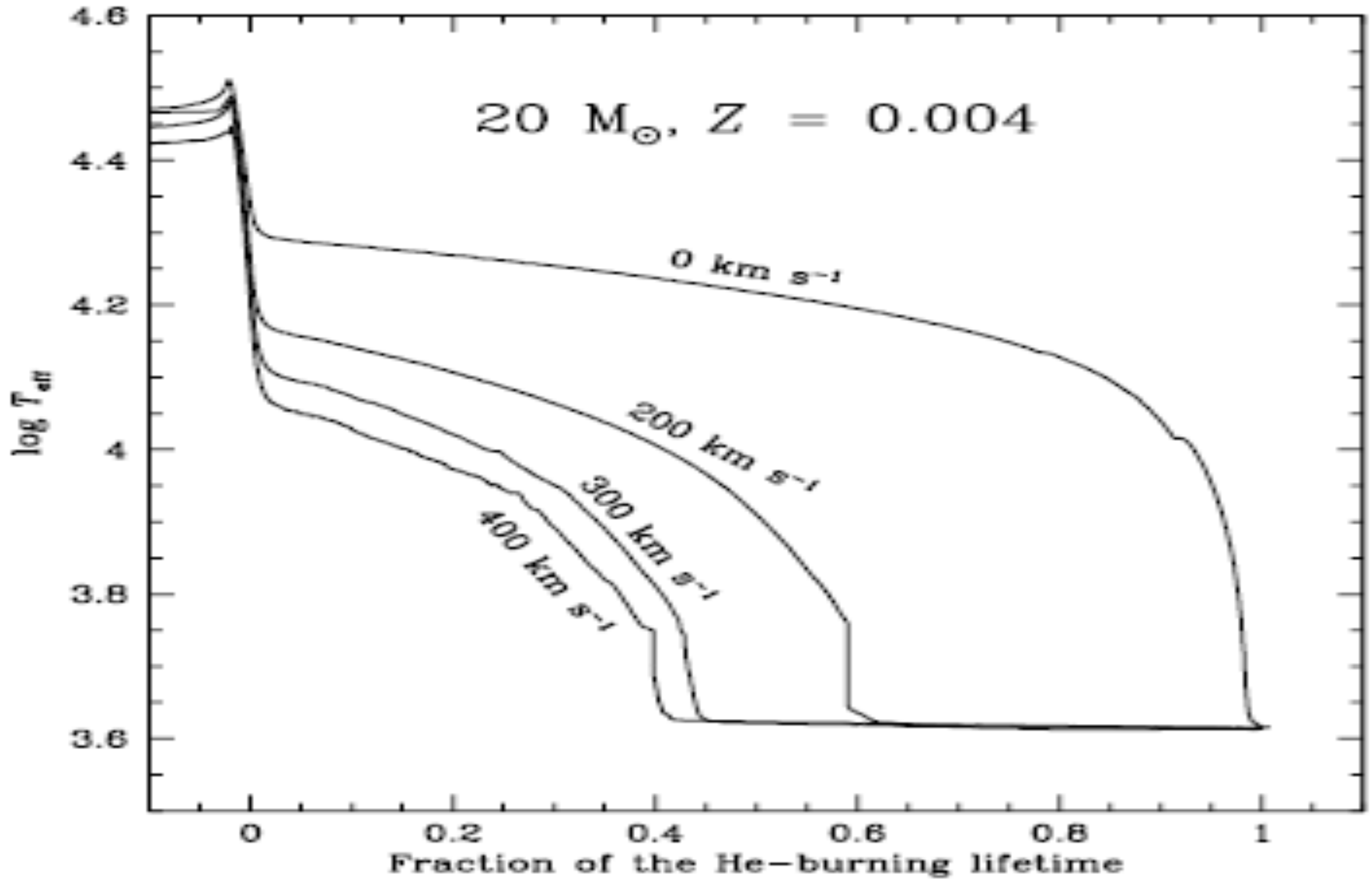


Fig. 2. Lifetimes in the RSG phase (defined as stars with $\log(T_{eff}/K) < 3.66$, see Eldridge et al. 2008) and in the different phases of WR stars. *Left:* Non-rotating models. *Right:* Rotating models.

Massive star rotation & B/R ratio



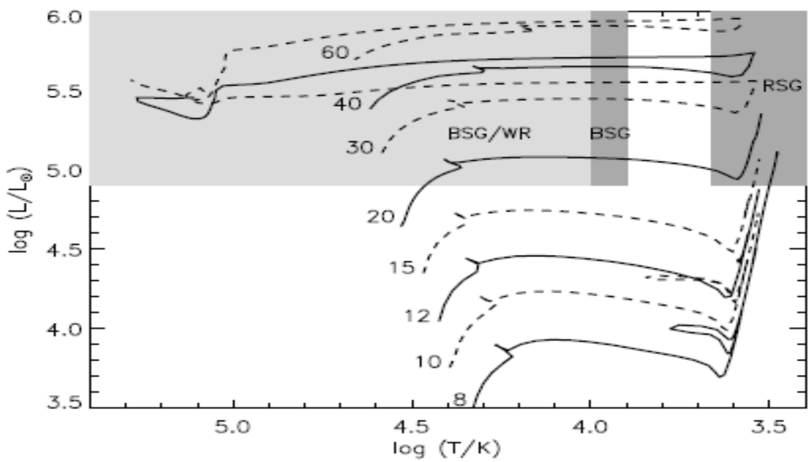
M_{ini}	B/R $v_{ini} = 0$	B/R $v_{ini} = 300$
25	63	0.30
20	47	0.43
15	5.0	0.24
12	20.6	85
9	2.7	0.10

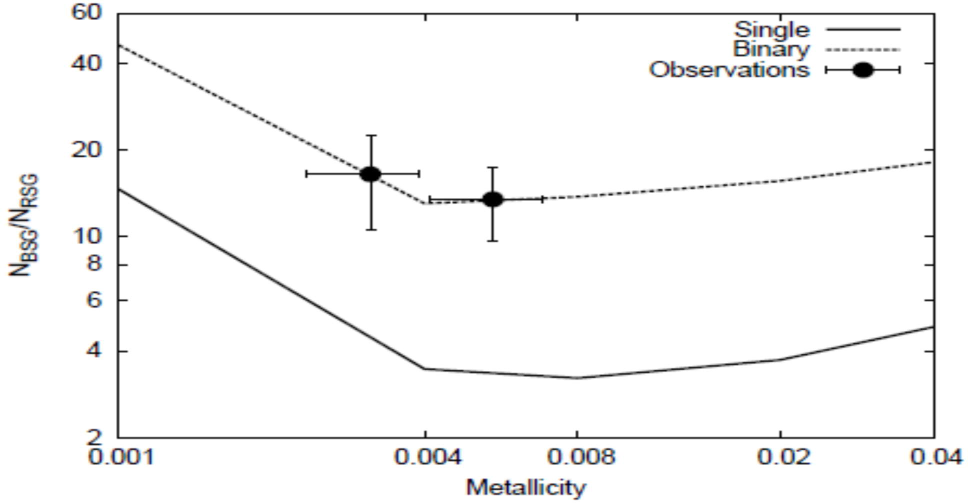
Observed value
0.5~0.8
(SMC, Z=0.004)

Maeder & Meynet (2001)

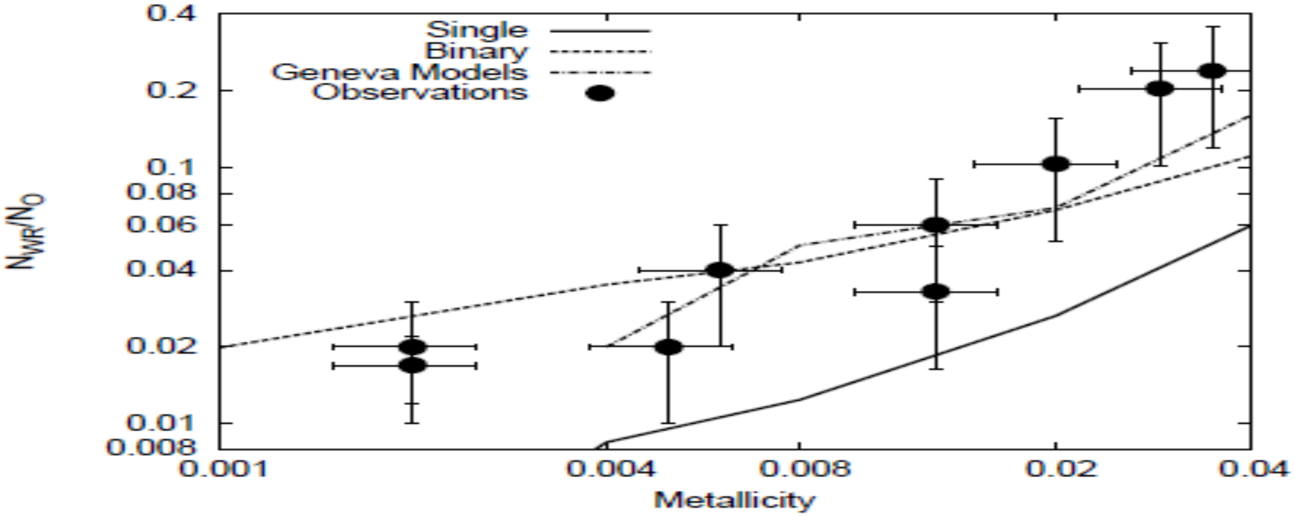
Binary model

Eldridge et al. 2008





BSG/RSG



←WR/O

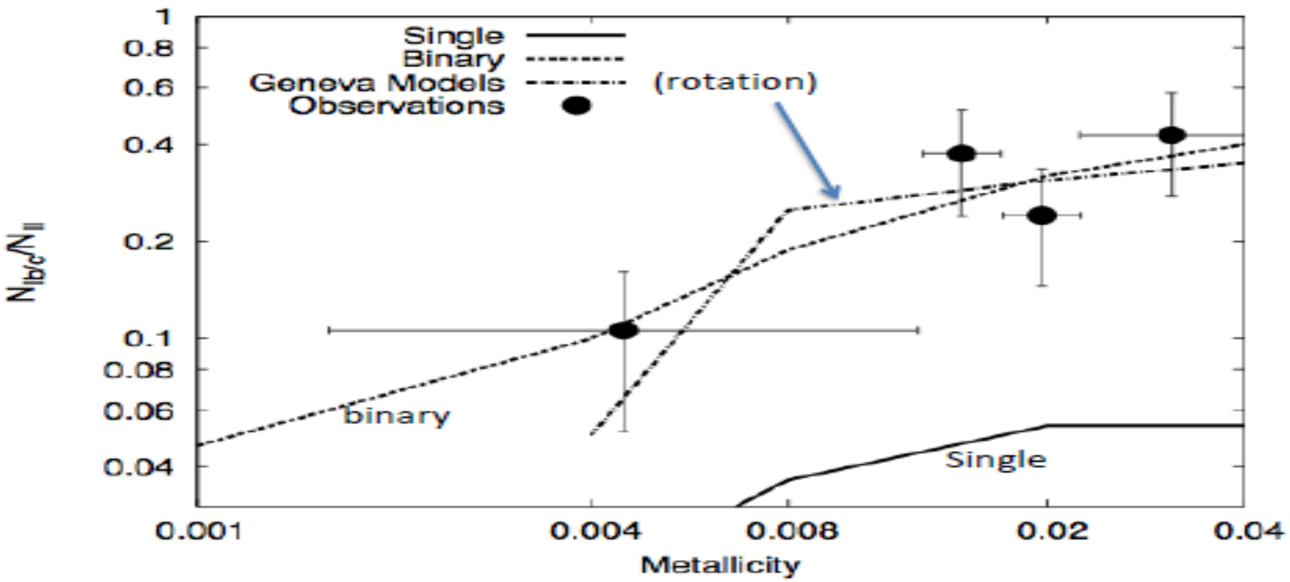
WC/WN ratio also OK

Binary model

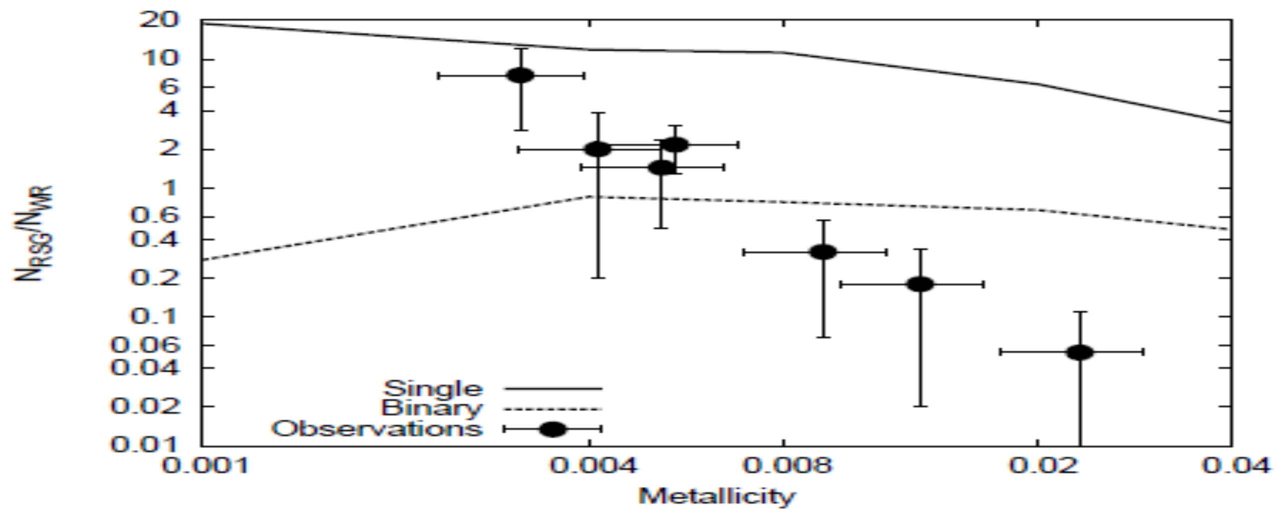
Rotating single star or Binary interaction ?

SN Ib/c / SN II ratio is OK

Eldridge et al. 2009



but
RSG/WR
is not good



Rotating stellar models

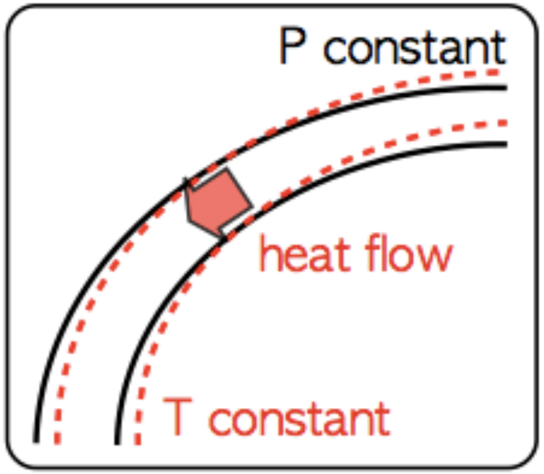
- It is not clear at this moment if currently used formalisms (parameters) for rotating stars represent true stars.
  - Binary effects have to be considered properly
- However, still it should be better than using single-star non rotating models.

- We have to be careful about several uncertainties (as well as convection and mass-loss) :
  - The amount of matter mixing
  - Angular momentum transfer
    - Effects of magnetic field (Spruit-Taylor dynamo)
  - Very limited observational constraints about these

Matter mixing by rotationally induced instabilities

In a rotating stellar matter, several instabilities are considered to grow;

a) Eddington-Sweet Circulation (Meridional circulation)
Temperature-constant surfaces do not coincide with pressure-constant surfaces in a rotating star.
Consequently, large-scale circulation develop.



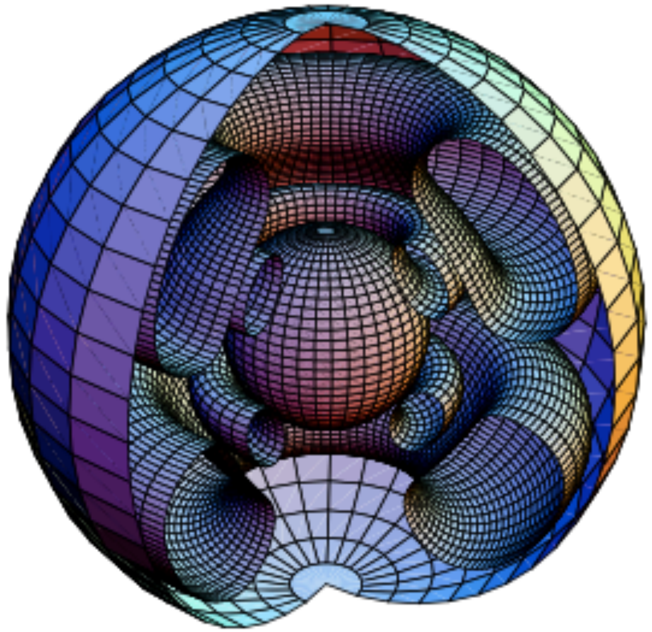
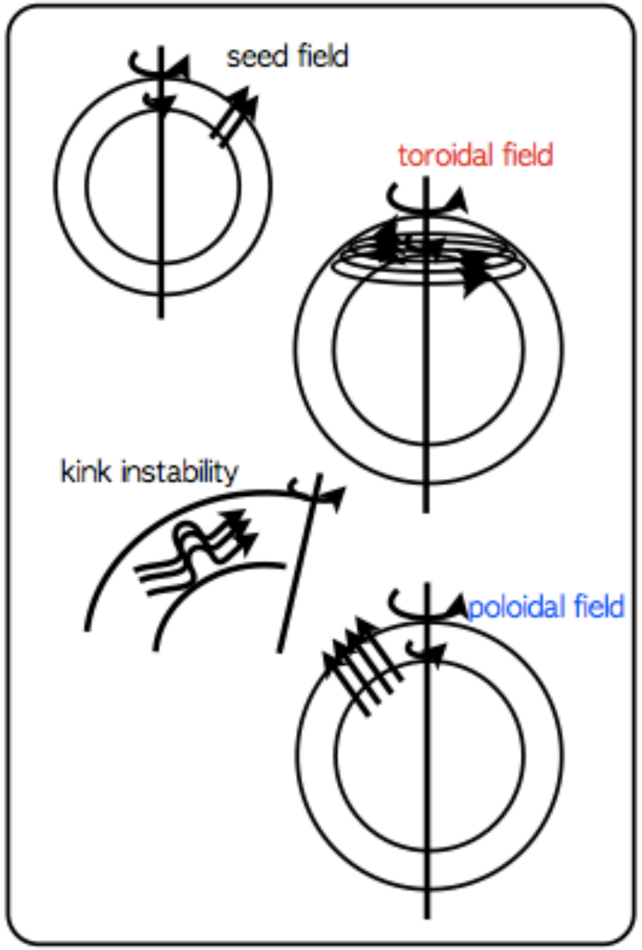


Fig. 1. Stream lines of meridional circulation in a rotating 20 $M_\odot$ model with solar metallicity and v_{ini} = 300 km s^{-1} at the beginning of the H-burning phase (see text). The streamlines are in the meridian plane. In the upper hemisphere on the right section, matter is turning counterclockwise along the outer stream line and clockwise along the inner one. The outer sphere is the star surface and has a radius equal to 5.2 $R_\odot$. The inner sphere is the outer boundary of the convective core. It has a radius of 1.7 $R_\odot$.

(Stream line, Meynet & Maeder 02)

b) Spruit-Tayler dynamo (Spruit 99, 02)

Differential rotation can amplify seed magnetic field since the field are frozen-in to the plasma. This creates a toroidal magnetic field. The amplified toroidal field is affected by kink-type instability, generating poloidal component. The next toroidal field can be produced by the stretching of the poloidal field.



Formulation of our code (Takahashi, Umeda, Yoshida 2014, ApJ, in press)

Matter mixing by rotationally induced instabilities

Many other instabilities are taken into account in stellar evolution codes. However, the way to account for may be too primitive.

Most of the rotation induced mixing are approximated to diffusion process. Diffusion coefficients are calculated by an order-of-magnitude estimation.

$$\left(\frac{\partial \omega}{\partial t}\right)_m = \frac{1}{i}\left(\frac{\partial}{\partial m}\right)_t \left[(4\pi r^2 \rho)^2 i \nu \left(\frac{\partial \omega}{\partial m}\right)_t\right] - \frac{2\omega}{r}\left(\frac{\partial r}{\partial t}\right)_m \left(\frac{1}{2}\frac{d\ln i}{d\ln r}\right)$$

$$\left(\frac{\partial X_n}{\partial t}\right)_m = \left(\frac{\partial}{\partial m}\right)_t \left[(4\pi r^2 \rho)^2 D \left(\frac{\partial X_n}{\partial m}\right)_t\right] + \left(\frac{dX_n}{dt}\right)_{\rm nuc}$$

Spruit-Taylor term

$$\nu = D_{conv} + D_{ES} + D_{DS} + D_{SS} + D_{SH} + D_{GSF} + \nu_{ST}$$

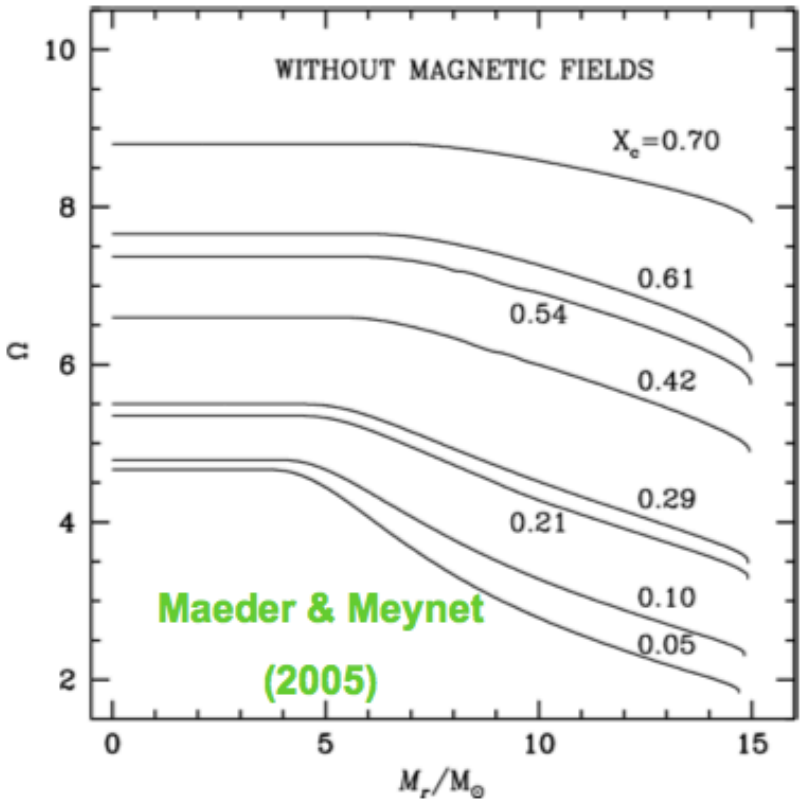
$$D = D_{conv} + f_c \times (D_{ES} + D_{DS} + D_{SS} + D_{SH} + D_{GSF}) + D_{ST}.$$

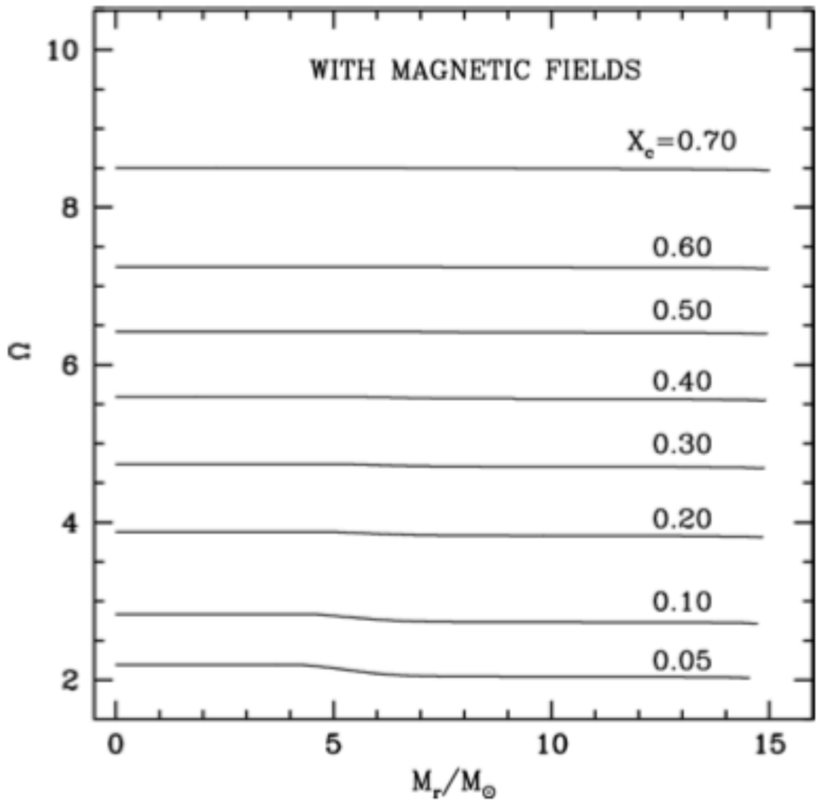
(Heger+00, Heger+05)

Rotation, CHE & GRB progenitors

the works by Yoon et al. are famous in this subject

Models of rotating massive stars (Yoon 2006)





Non-magnetic models

The core keeps large amounts of angular momentum (Heger, Langer, Woosley 00; Hirschi, Meynet & Maeder 05)

Magnetic models (with Spruit – Tayler dynamo; Spruit 2000)

The core loses a lot of angular momenta (Heger, Woosley & Spruit 05; Maeder & Meynet 05)

Role of magnetic torques in J-transport (Yoon 2006)

Models with B-fields are more consistent with observed spin rates of stellar remnants and some other aspects.

	Observations	Models without B-fields	Models with B-fields (Spruit-Talyer dynamo)
Young NS spin	15 – 150 ms	< 1ms (Heger et al.00; Hirschi et al. 05)	4 – 15 ms (Heger et al. 05; Ott et al. 06)
WD spin	< 10 km/s	~ 150 km/s (Langer et al. 98)	< 10 km/s (Suijs et al. 05)
Sun	Rigid rotation in the core	Differential rotation	Rigidly rotating core (Eggenberger et al. 05)
R_{GRB}/ R_{SNIbc}	0.01 – 0.001 GRBs are rare!	Too high!	Difficult to make GRBs from normal type of evolution

Models of rotating massive stars (Yoon 2006)

(Meynet, Maeder, Hirschi, Heger, Langer, Woosley, Yoon)

Without B-fields

- Eddington Sweet Circulations/ Shear instability
- Strongly differential rotation throughout the evolution
- At low Z, mixing is dominated by the shear instability during the giant phase.
- Strong mass loss (and thus WR star formation) is possible due to the surface enrichment of CNO elements during the giant phase

With B-fields

- Magnetic torques (Spruit 00)
- Nearly rigid rotation on main sequence
- Weak differential rotation during the giant phase
- Mixing is dominated by ES circulations.
- Chemically homogeneous evolution with very high initial J?

Evolution of “metal poor” massive stars
(with B-fields)

(Yoon 2006)

- Less mass loss : Mdot ~ $Z^{0.69 - 0.86}$ (talk by J. Vink)
  - Good for keeping angular momentum
    (but the core is still spun down by magnetic torques)
  - Bad for making Wolf-Rayet stars

- Keep more angular momentum => more chemical mixing?

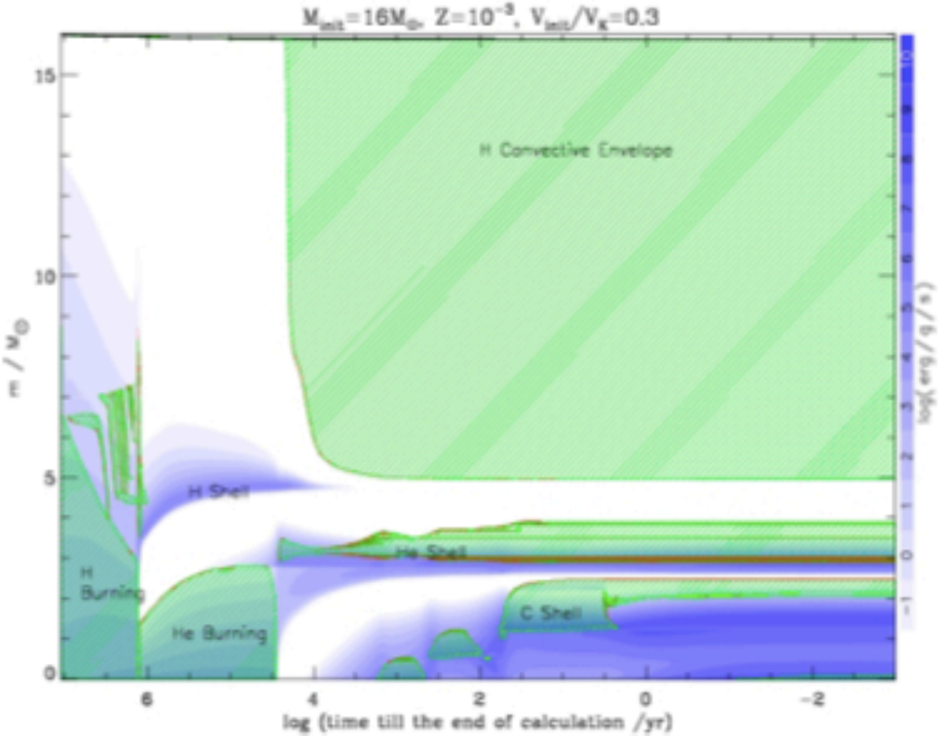
$$t_{ED} \sim t_{th}/[\Omega/\Omega_k]$$

Quasi-chemically homogeneous evolution

(Yoon 2006)

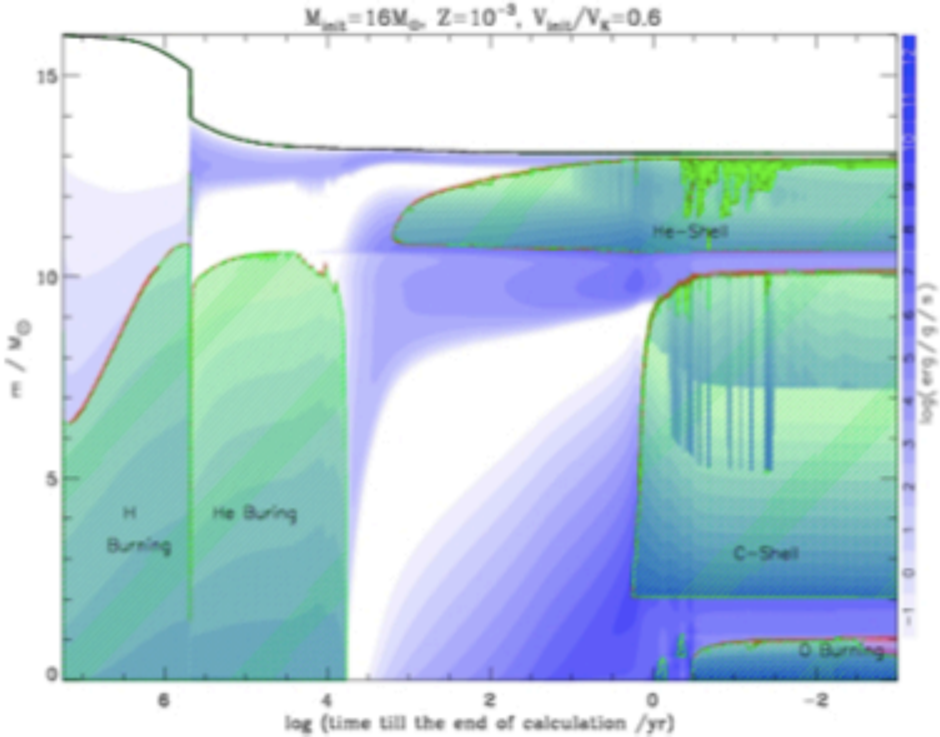
Minit = 16 Msun, Z = 0.001

$t_{MS} < t_{mix}$



Vinit/VK = 0.3.

$t_{MS} > t_{mix}$



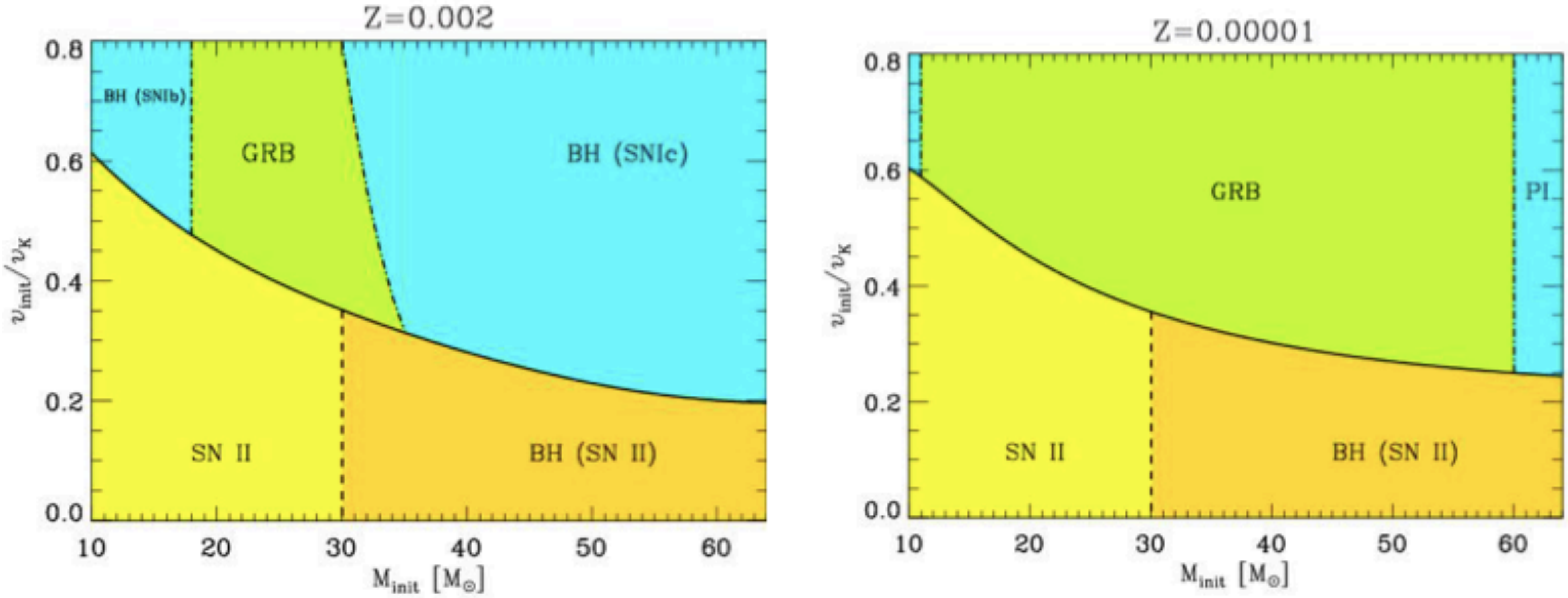
Vinit/VK = 0.6

Yoon & Langer (05, 06); Woosley & Heger (06)

Evolution of massive stars at low metallicity

(Yoon 2006)

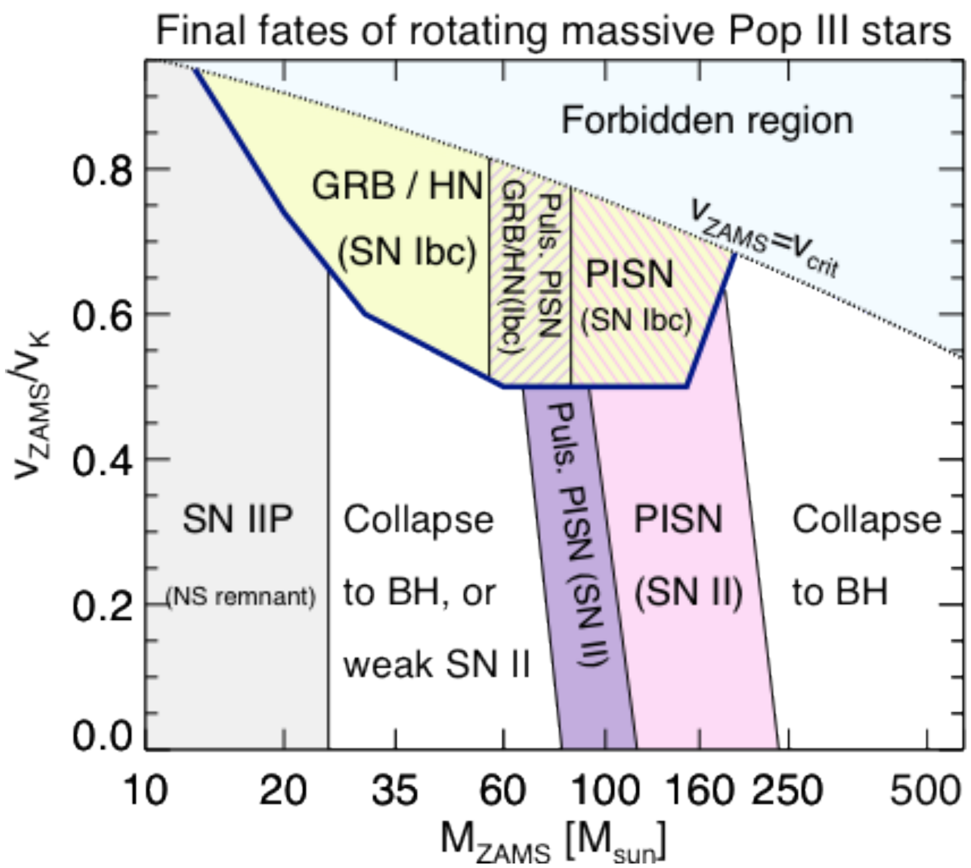
Final Fate = f (M, Z, Vrot) !!



Yoon, Langer & Norman 2006 A&A 460, 199

Pop III Rotating Models

Yoon et al. 2012 (10-1000 M_{sun}, $v_{rot,0}$ = ~1500 km/sec)



Stellar fates are investigated in the work. Fast rotators are suggested to evolve chemically homogeneously, resulting to yield GRBs and PISNe from a less massive region.

Rotation, CHE & GRB progenitors

- Alternative model to the CHE is a binary star (merging of two stars) model. Currently there are no strong evidences that most GRBs are inconsistent with the CHE theory.
- Magnetic field effects (Spruit-Taylor dynamo) are important and critical for the GRB progenitor models, however, there is (almost) no observational evidences for these effects.
    - If CHE (Yoon) model for GRBs are consistent with observations, it may support the ST dynamo theory.
    - It should be important to investigate other kind of magnetic field and angular momentum transfer models.

Our work on rotating stellar models

- With Takashi Yoshida (now in Kyoto Univ.) and Koh Takahashi (U-Tokyo), we have been working on developing a stellar evolution code with rotation.
- First paper just accepted: K.Takahashi, H.Umeda & T.Yoshida, ApJ
- The formulation of the code is similar to Yoon et al. & Heger et al., and the angular momentum transfer is treated diffusiverly. (c.f., Geneva codes)
- The parametric settings are mostly same as Yoon et al. 2012, however, not exactly the same.

- What can we do with the new rotation code?
  - I will briefly explain the contents of the Takahashi et al. 2014.

Formulation of our code (Takahashi, Umeda, Yoshida 2014, ApJ, in press)

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Spruit-Taylor term

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$$D = D_{conv} + f_c \times (D_{ES} + D_{DS} + D_{SS} + D_{SH} + D_{GSF}) + D_{ST}.$$

(Heger+00, Heger+05)

Stellar Yields of Rotating First Stars:

Yields of Weak Supernovae and Abundances of Carbon-enhanced Hyper Metal Poor Stars

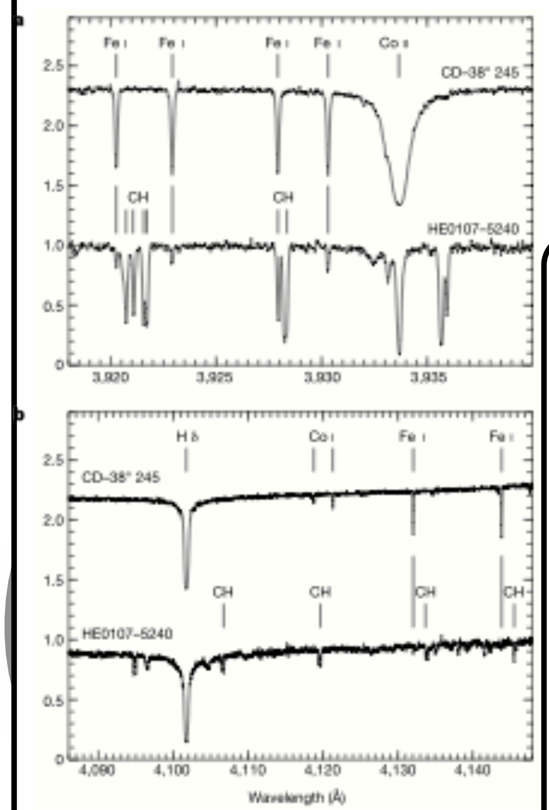
ApJ accepted, arXiv: 1406.5305

Koh Takahashi[1], Hideyuki Umeda[1], Takashi Yoshida[2]
[1]Department of Astronomy, The University of Tokyo
[2]Yukawa Institute for Theoretical Physics, Kyoto University

These stars are all CEMP stars.

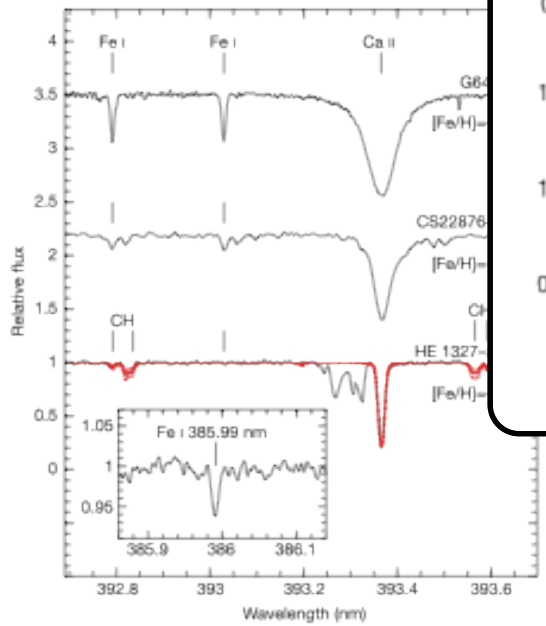
Metal poor stars will have the information about the first stars in their abundances. Using this information … s of the first star …

Christlieb+02



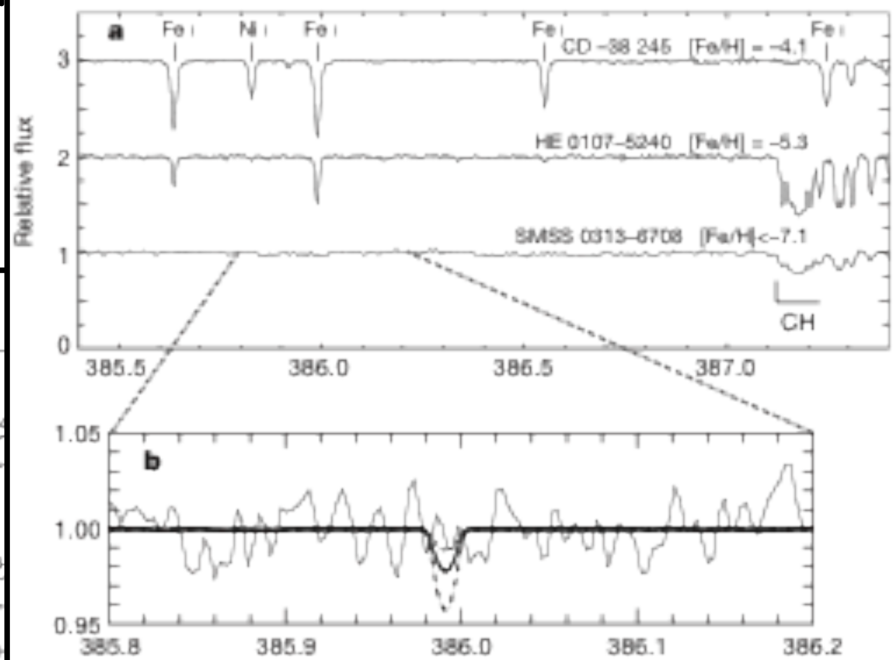
HE 0107-5240
([Fe/H]=-5.3)

Frebel+05

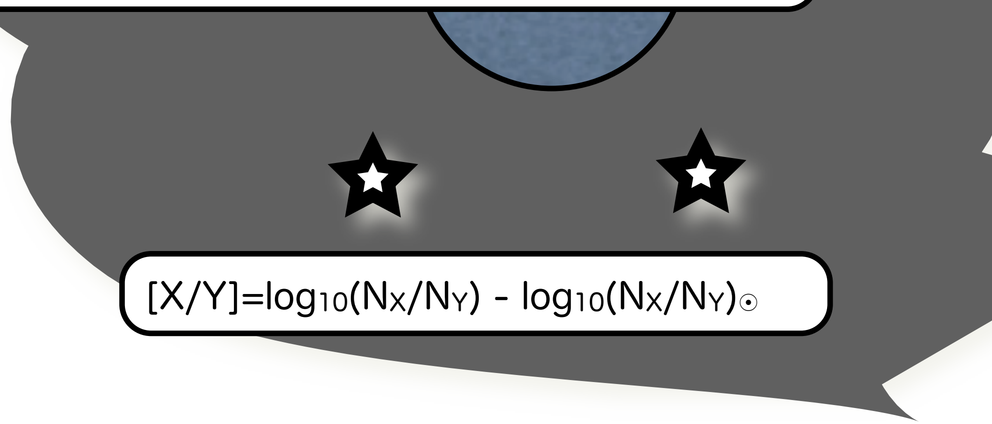


HE 1327-2326
([Fe/H]=-5.7)

Keller+14



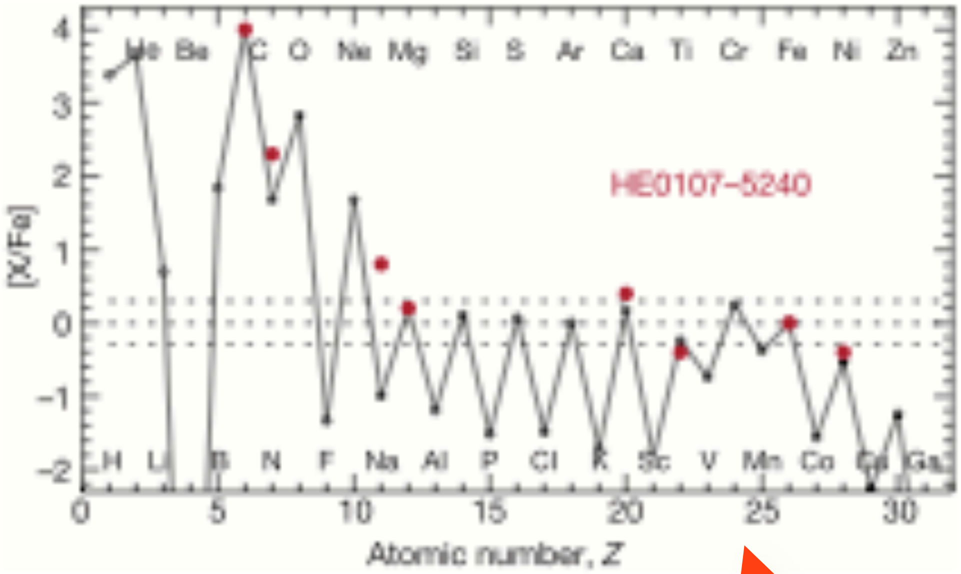
SMSS 0313-6708 ([Fe/H]<-7.1)



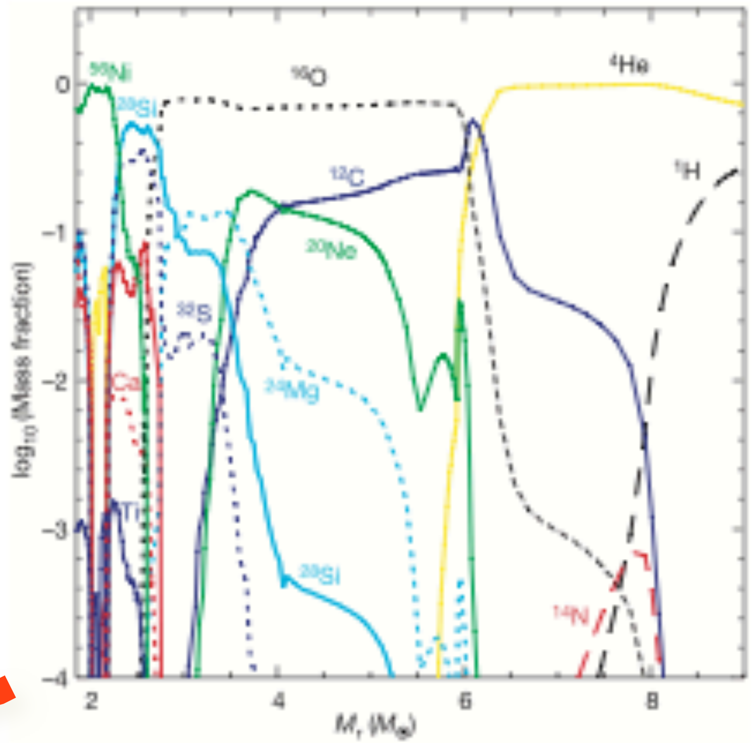
$[X/Y]=\log_{10}(N_X/N_Y) - \log_{10}(N_X/N_Y)_\odot$

Abundance Profiling

Umeda & Nomoto (03)



Abundance distribution by an evolution calculation

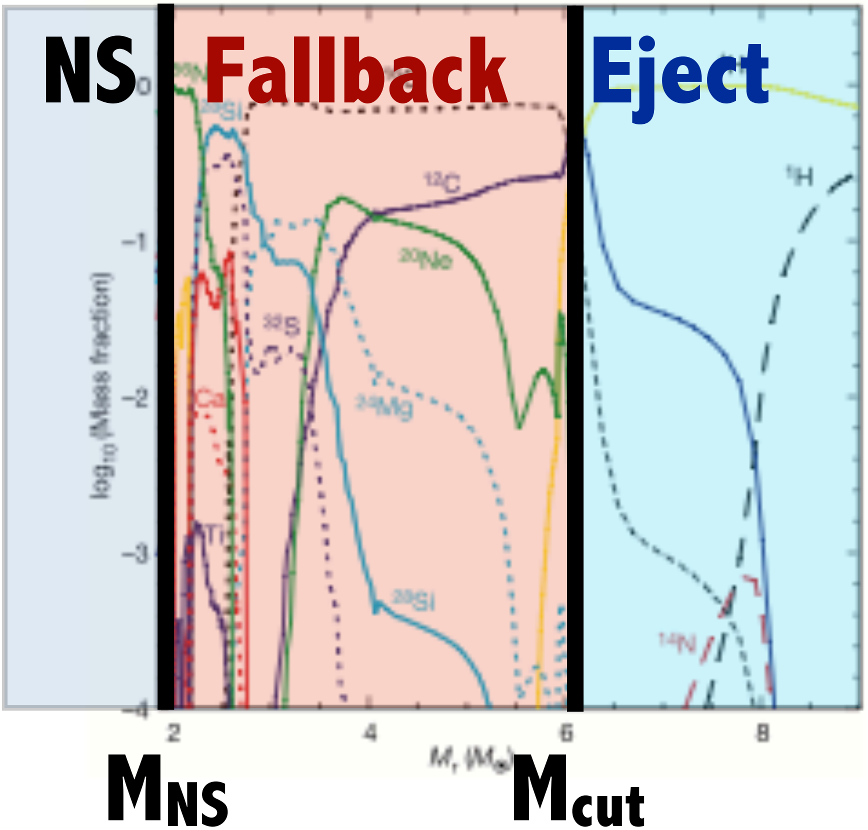


The Mixing-fallback Model

By doing abundance matching with a theoretical yield to observations, supernova explosion mechanism has been constrained.

However, no abundance properties has been known to constrain the initial parameters of the first stars, because of the degeneracy in the explosive yields.

Mixing fallback model



There are (mainly) four parameters.

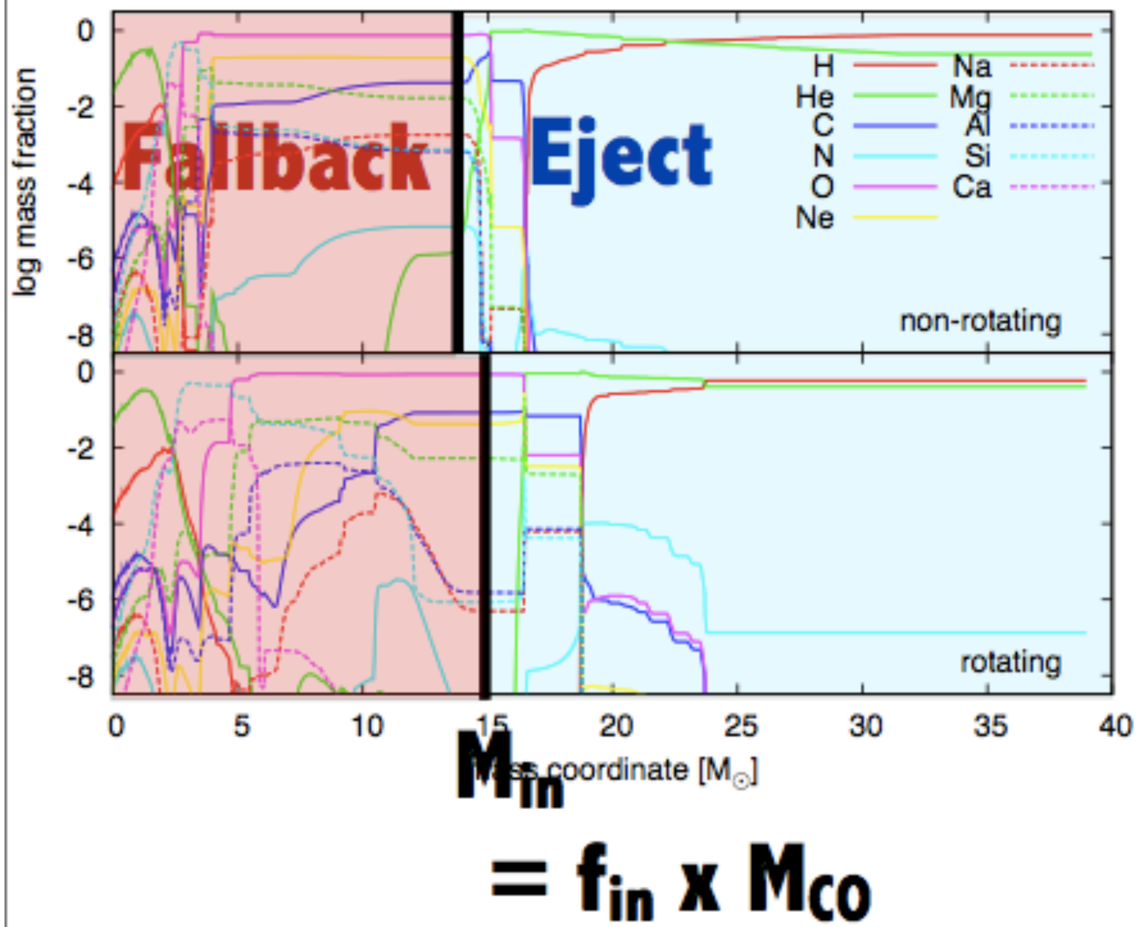
Three M&F parameters
- NS Mass: M_{NS}
- Mass cut: M_{cut}
- Escape fraction: f

and Explosion energy: E_{exp}.

CEMP stars:
Large fallback
➡ weak explosion

Supernova Yields from "Weak Supernovae"

Takahashi et al. 2014



Two assumptions are;

1. Only gravitationally weakly bound outer distributed matter is ejected by the explosion.
2. Shock wave is too weak to modify the outer distributed matter by the explosive nucleosynthesis.

Then the "explosive" yields can be calculated by a simple integration,

$$M_i(M_{in}) = \int_{M_{in}}^{M_{\rm surface}} X_i(M)dM$$

Supernova Yields from "Weak Supernovae"

Thus our stellar yields have three parameters,

1. M_{ini}: Initial mass
2. V_{rot}: Stellar rotation
3. M_{in} : Inner boundary of the ejection. Or $f_{in} = M_{in}/M_{CO}$

Point:

The weak supernova yields depend on the initial mass and stellar rotation of the progenitor, since the initial parameters affect the abundance distribution in helium layers and hydrogen envelopes.

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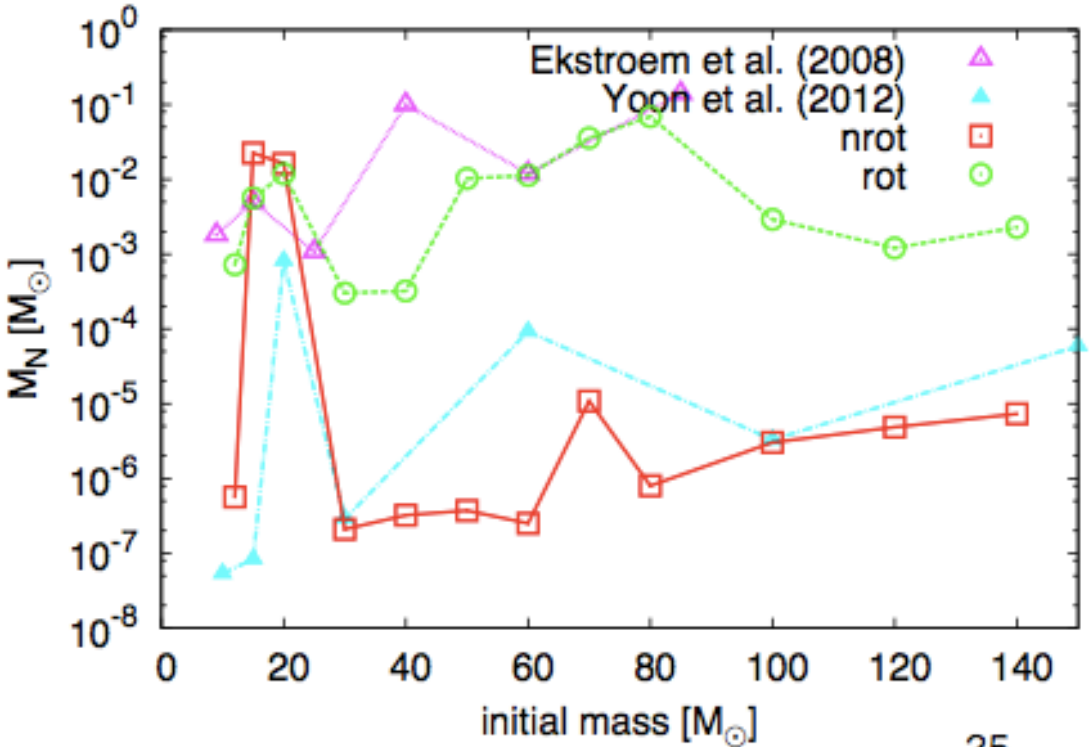
2. Nitrogen

Rotating models show enhancement in the nitrogen production. This is due to efficient rotationally induced mixing during the core helium burning phase.

Example of an rotation yield and comparison with other codes



For $M_{in} = M_{CO}$

Results of the abundance profiling

SMSS 0310-6708
mass range: 50-80 Msun
rotation : only non-rotating models
f_{in} : 0.96+-0.04 (for 60 Msun)

HE 1327-2326
mass range: 15-40 Msun
rotation : both rotating and non-rotating models
f_{in} : 0.96+-0.01 (for non-rot 20 Msun)

HE 0107-5240
mass range: 30-40 Msun
rotation : only rotating models
f_{in} : 1.07+-0.06 (for 30 Msun)

Concluding Remarks

- We have finally published a paper about rotating stellar models.
- Now we can calculate rotating progenitor models for SNe and GRBs (if we have enough man power).
  - For example we have confirmed that CHE (necessary for GRB progenitors) may occur under various conditions.
    - However, it is difficult to justify the parameter used because of lack of observations.
  - It won't be so interesting if we simply repeat similar calculations with other groups' (i.e., Yoon et al's work).

  - So I strongly welcome collaborations with other groups if you have any good ideas.