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Evolution of the most massive AGB star as a progenitor for ECSNe

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Abstract

The most massive asymptotic giant branch (AGB) star can form a critical mass ONe core at its center and core collapse of such a critical ONe core ends up as an electron capture supernova (ECSN).

In this talk, I will present evolutionary properties of the most massive AGB star as a progenitor system of ECSNe.

Abstract

The model of ECSNe has plenty of important suggestions on both observation and theory. Explosion properties which can be inferred by considering the pre-explosion structure of an AGB star provide a possible explanation for some low-energetic supernovae (e.g. SN2005cs)and also a part of type IIn supernovae (e.g. SN2008S). Several authors discuss that the Crab supernova, SN1054, can be a likely candidate of ECSN as well. As for theory,ECSN model is the only exception for which a one dimensional simulation can model a successful explosion a priori. However, there had been only one evolutionary calculation for ECSN, done by Nomoto in 1987, and thus a modern progenitor calculation as a basis of theoretical investigation is strongly demanded. Recently, we have accomplished a progenitor calculation for ECSN for the first time in twenty six years and updated a pre-explosion structure of the model. Evolutionary sequences for this massive AGB star, which is located at (Abridged.)

Abstract

What I want to say…

Abstract

1. ECSN : interesting object

Abstract

2. only 1 progenitor calculation

Abstract

3. New calculation is needed

Abstract

4. We have done it.

Abstract

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EVOLUTION OF PROGENITORS FOR ELECTRON CAPTURE SUPERNOVAE

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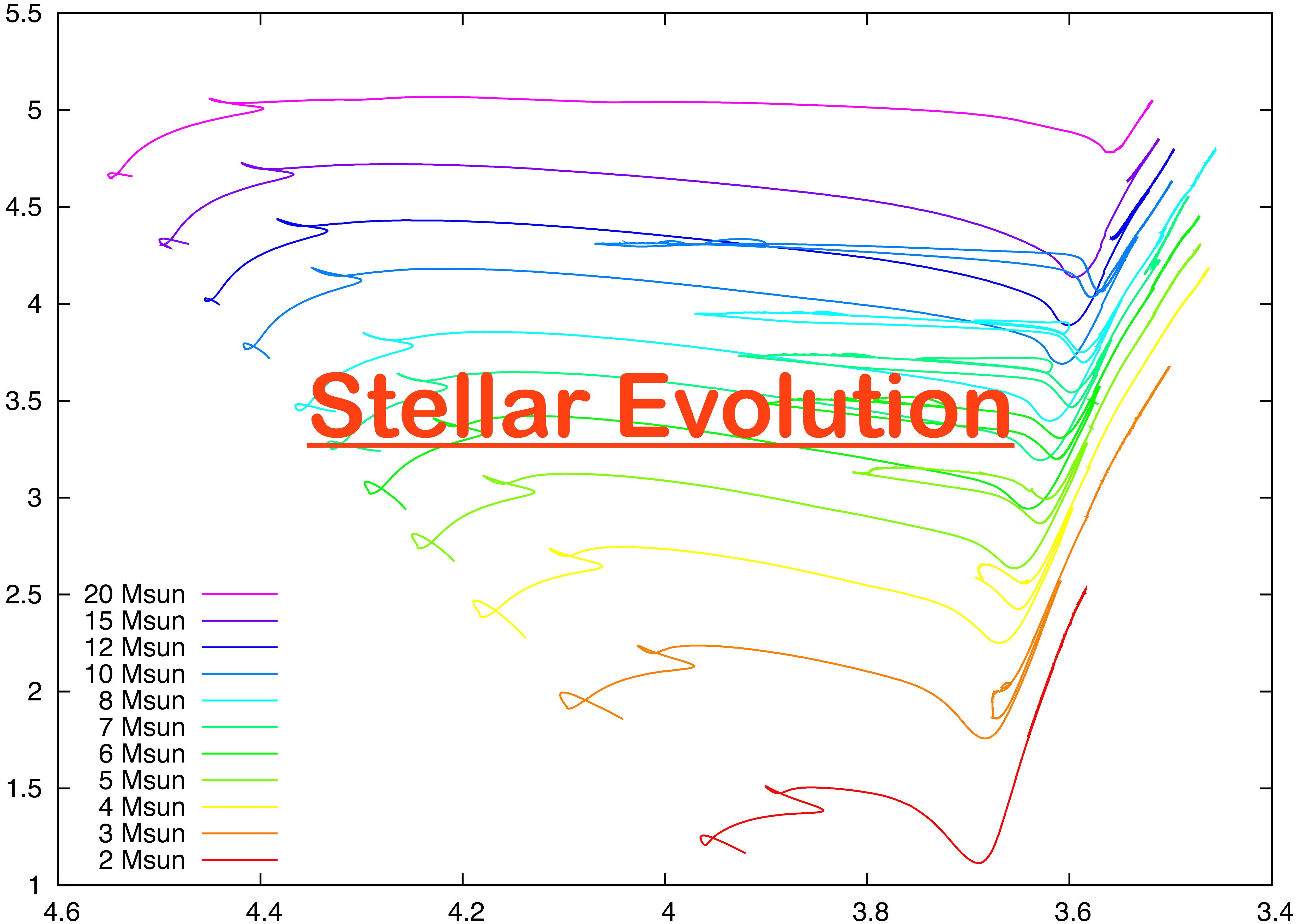
ABSTRACT

We provide progenitor models for electron capture supernovae (ECSNe) with detailed evolutionary calculation. We include minor electron capture nuclei using a large nuclear reaction network with updated reaction rates. For electron capture, the Coulomb correction of rates is treated and the contribution from neutron-rich isotopes is taken into account in each nuclear statistical equilibrium (NSE) composition. We calculate the evolution of the most massive super asymptotic giant branch stars and show that these stars undergo off-center carbon burning and form ONe cores at the center. These cores become heavier up to the critical mass of 1.367 $M_\odot$ and keep contracting even after the initiation of O+Ne deflagration. Inclusion of minor electron capture nuclei causes convective URCA cooling during the contraction phase, but the effect on the progenitor evolution is small. On the other hand, electron capture by neutron-rich isotopes in the NSE region has a more significant effect. We discuss the uniqueness of the critical core mass for ECSNe and the effect of wind mass loss on the plausibility of our models for ECSN progenitors.

Key words: nuclear reactions, nucleosynthesis, abundances – stars: evolution – stars: interiors – supernovae: general

Online-only material: color figures

Stellar Evolution



Stellar Evolution

○ Basic Equations

- mass conservation

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

- momentum conservation

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

- energy conservation

$$\frac{dL}{dM} = -T\frac{ds}{dt} - \mu\frac{dn}{dt} + \varepsilon_{nuc} - \varepsilon_{\nu} + \varepsilon_{ec}$$

- energy transport

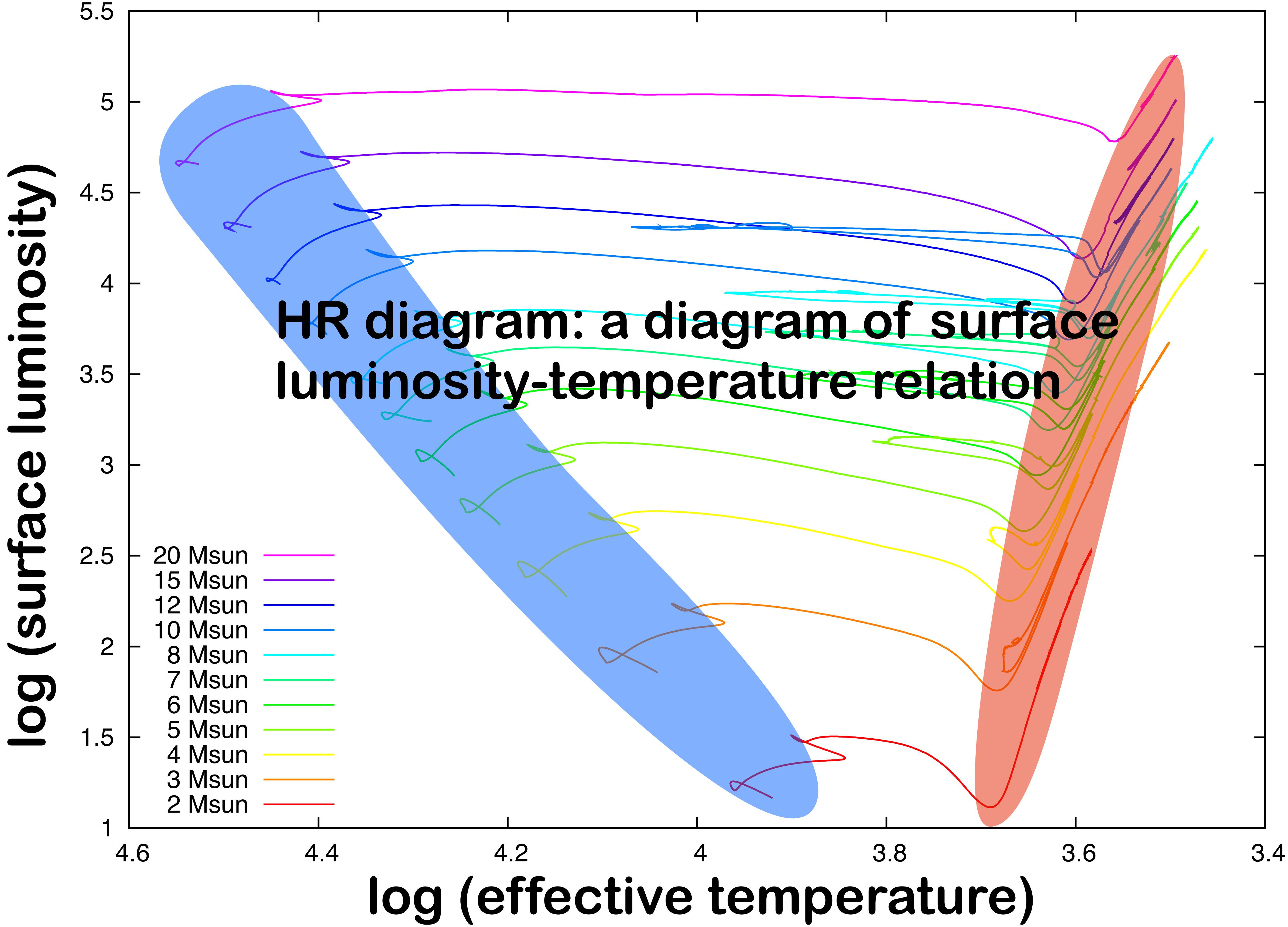
$$\frac{dT}{dM} = -\frac{GMT}{4\pi r^4 \rho}[\nabla_{rad} \text{ or } \nabla_{conv}]$$

+ nuclear reaction network

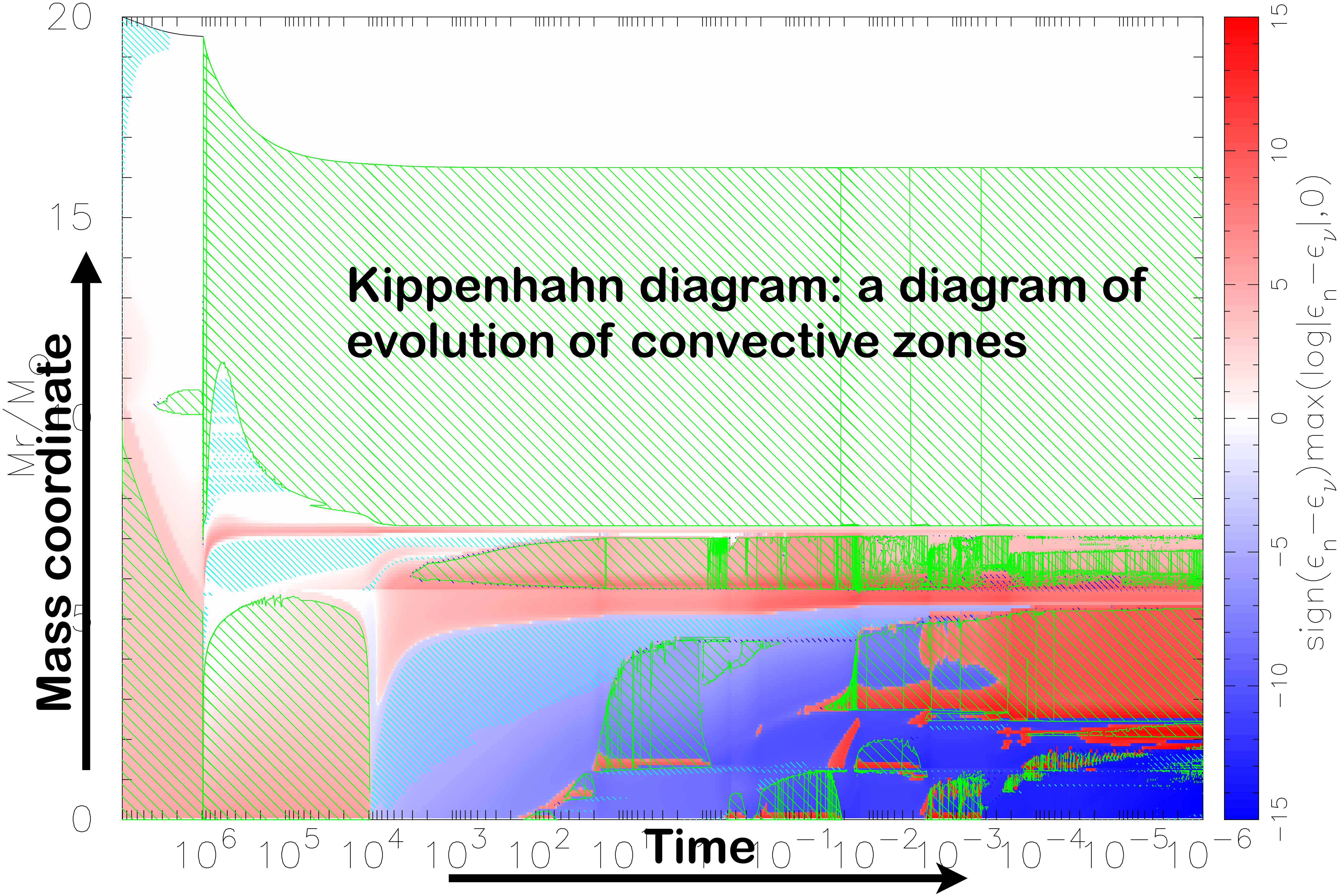
most stellar evolutionary calculations solve these equations iteratively.

then we get evolving structure as a solution.

Stellar Evolution



Stellar Evolution



Stellar Evolution

Massive stars ($M \gtrsim 10\ M_{sun}$)

AIM: to get a pre-explosion structure of a core-collapse supernova

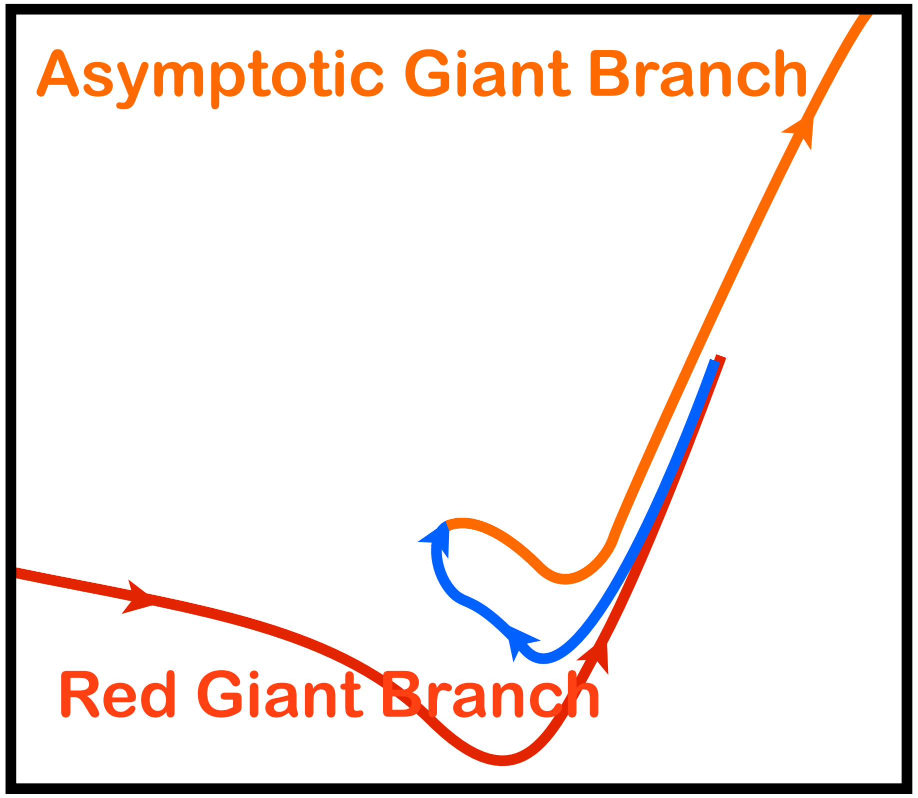
INITIAL MASS

8 10 20 200

Stellar Evolution

Intermediate mass stars (M ~ 2-10 M_{sun})

evolve as asymptotic giant branch (AGB) stars
AIM: s-process nucleosynthesis, dust formation, etc.



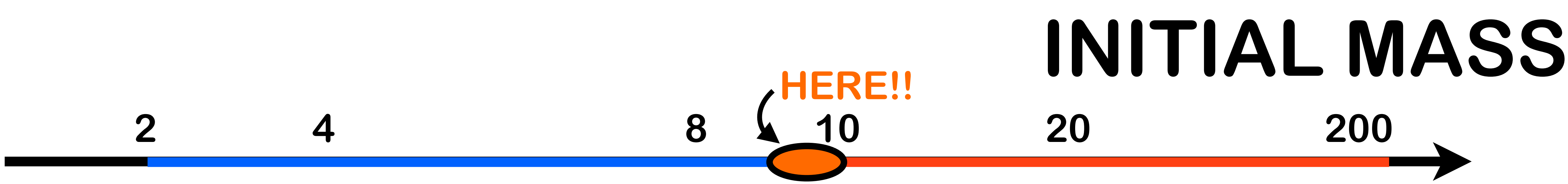
INITIAL MASS

Stellar Evolution

ECSN progenitor
(M ~ 10 M_{sun})

is massive AGB stars,
so, it is from the mass range of...

- the most massive intermediate-mass star
- the least massive massive star



Stellar Evolution

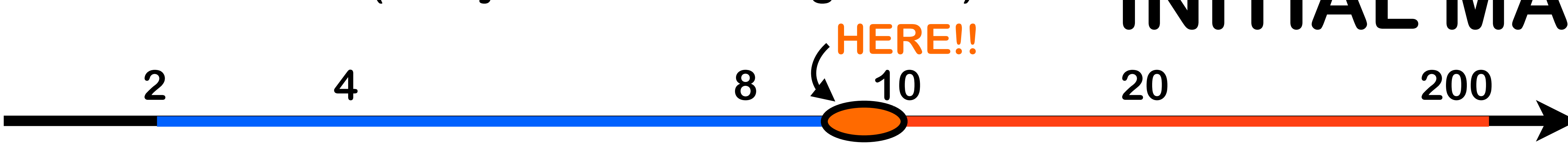
It means that

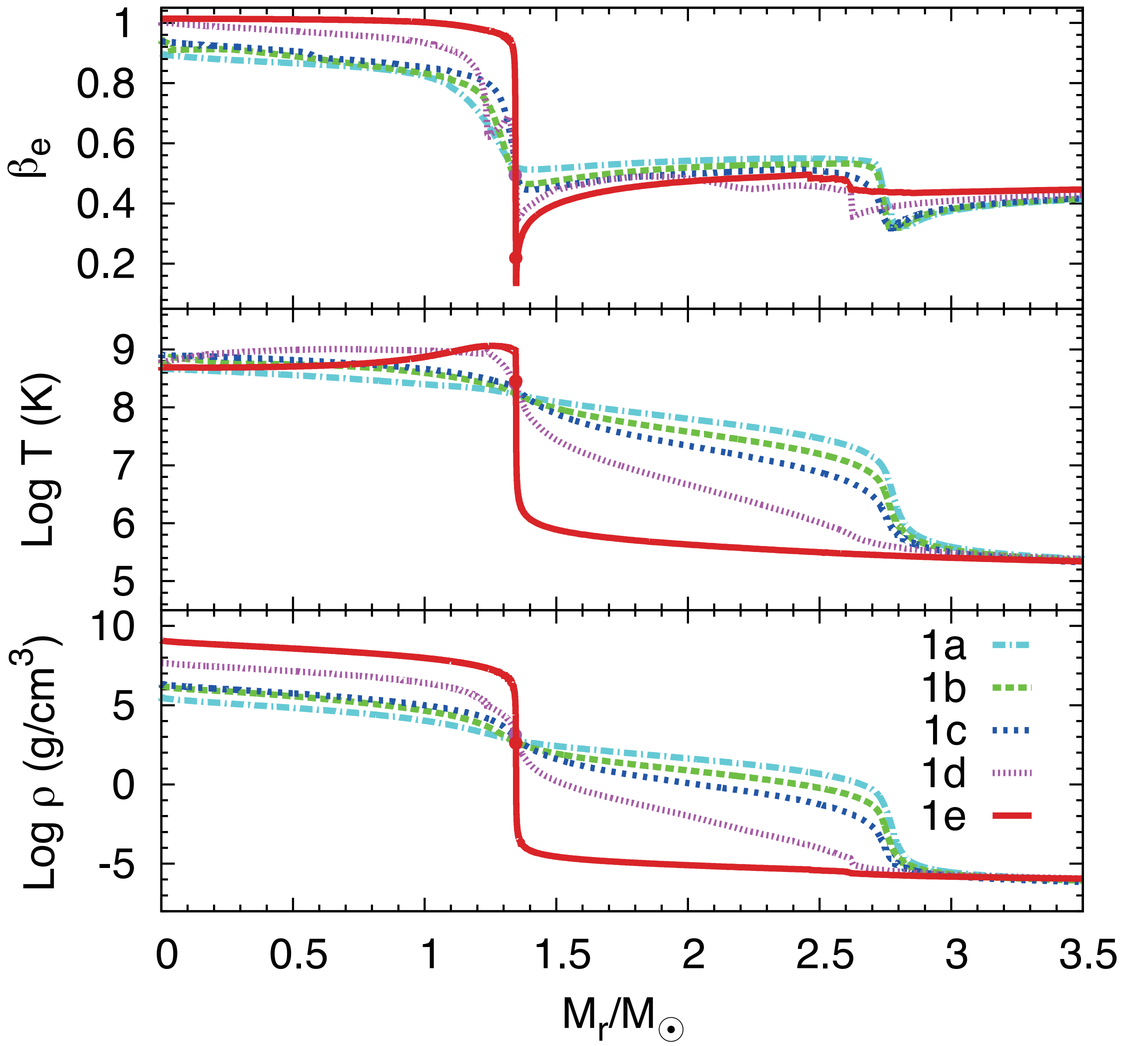
Progenitor evolution of ECSN is quite distinct from other (both massive and intermediate mass) stars.

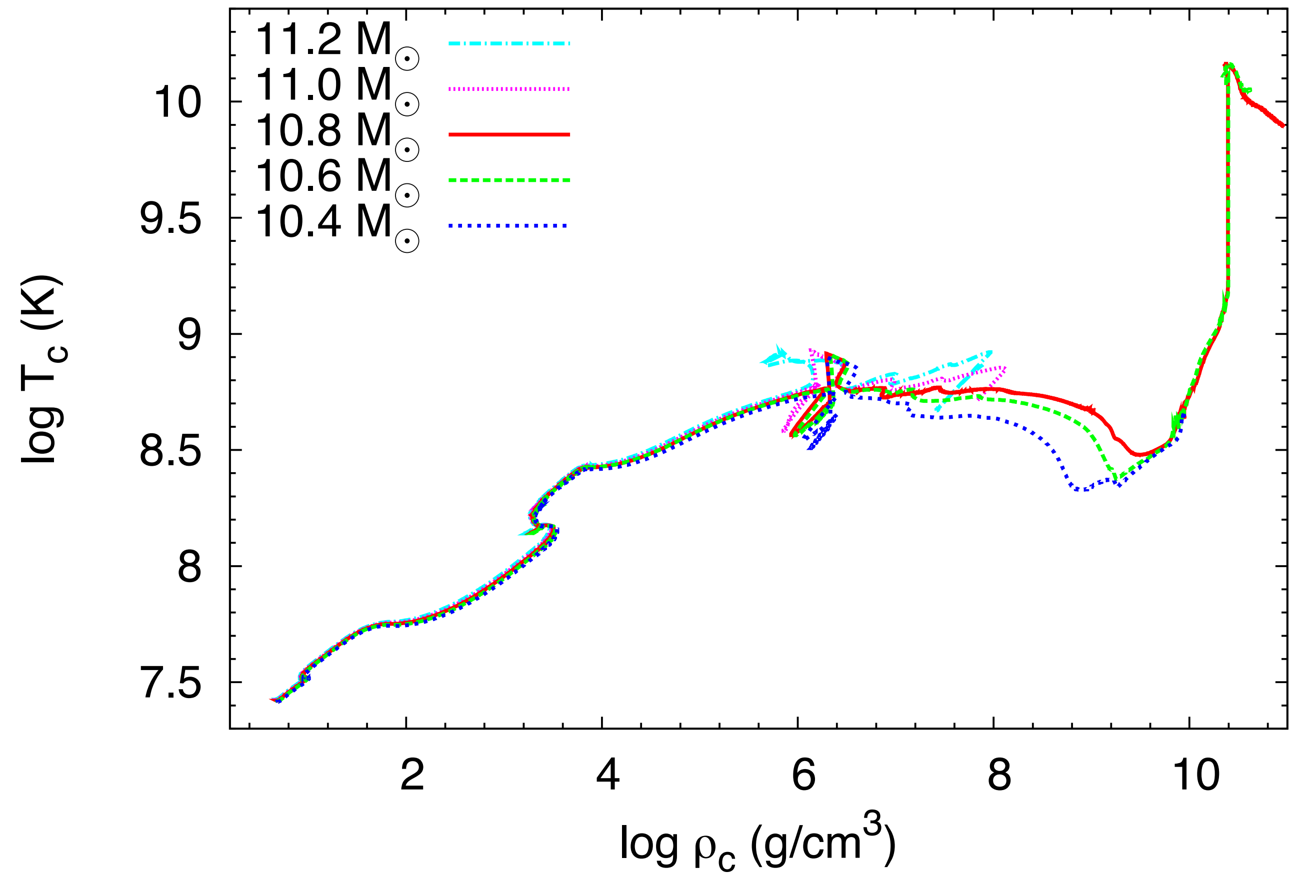
- we should treat some particular physics

(Or it just has been neglected)

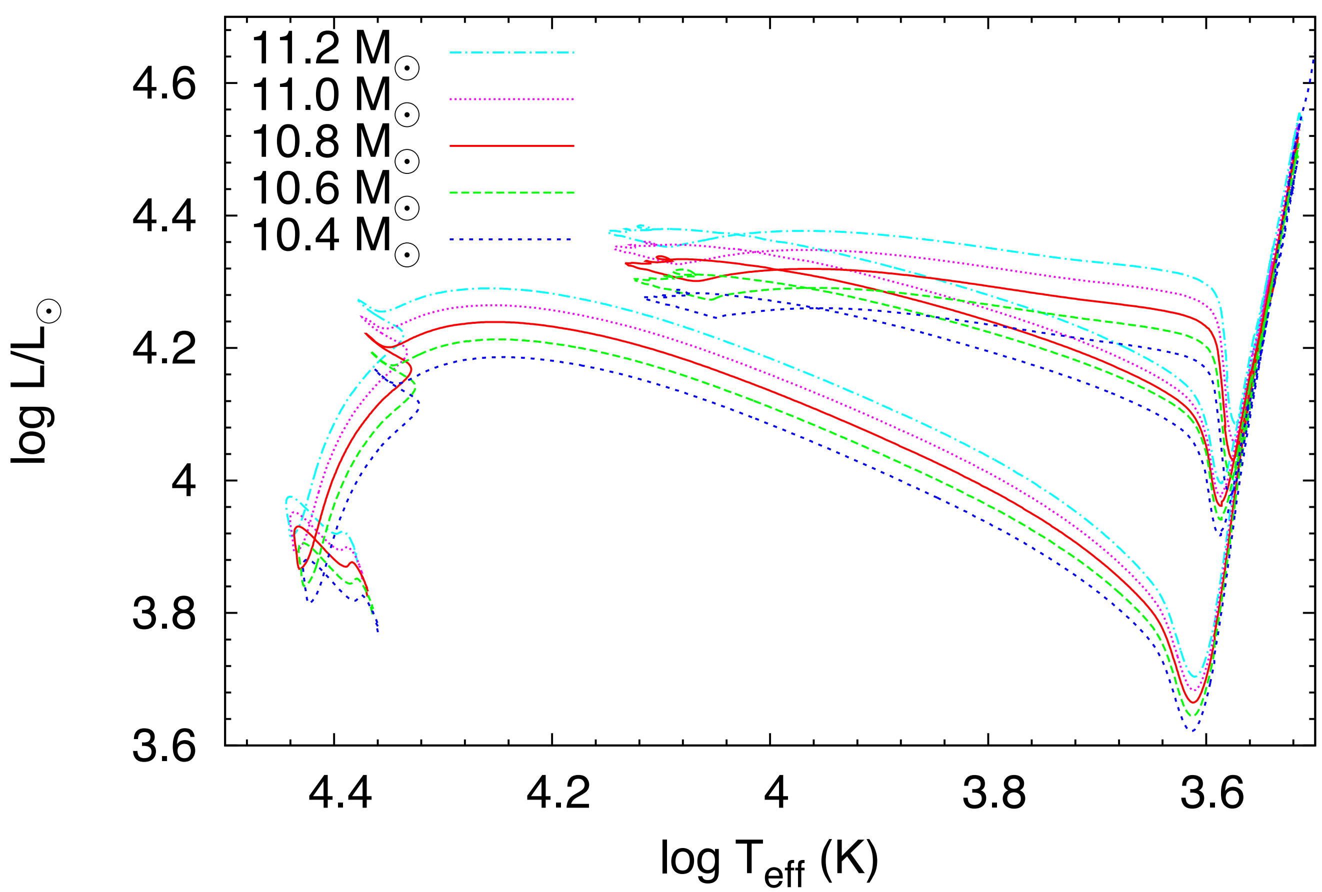
INITIAL MASS

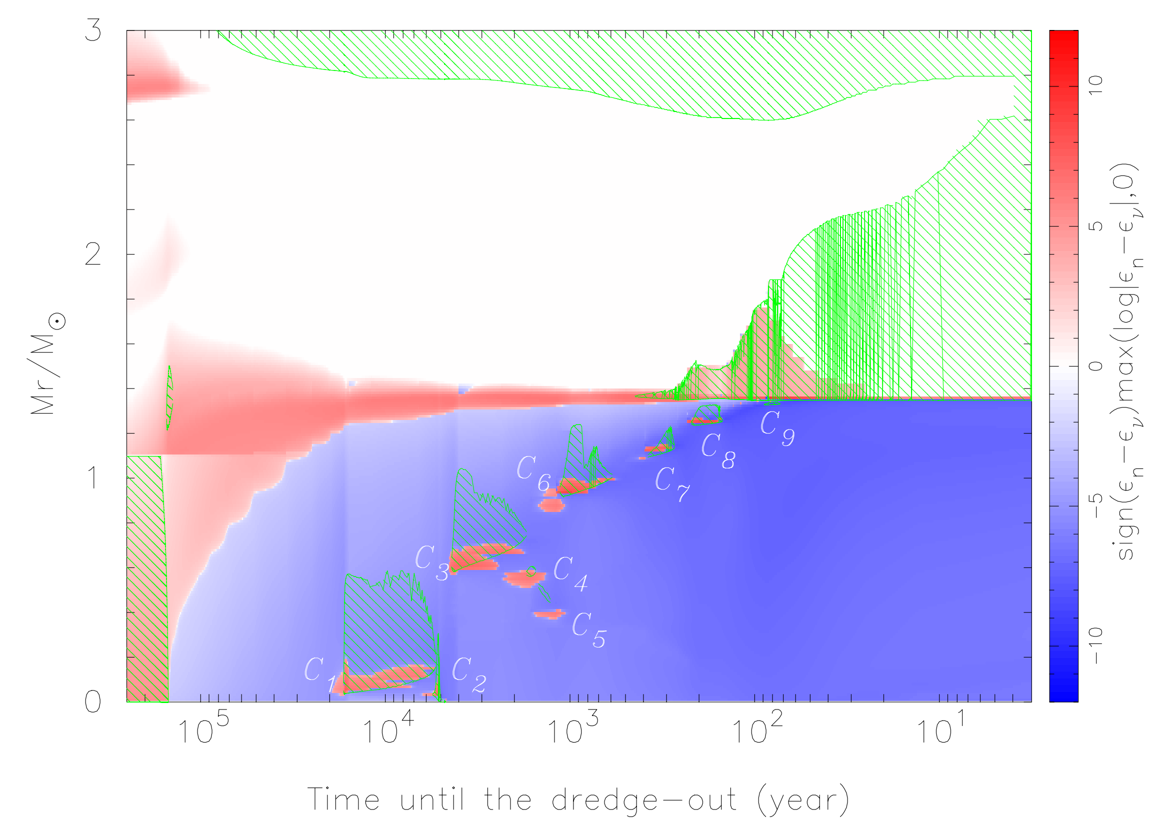






SAGB evolution



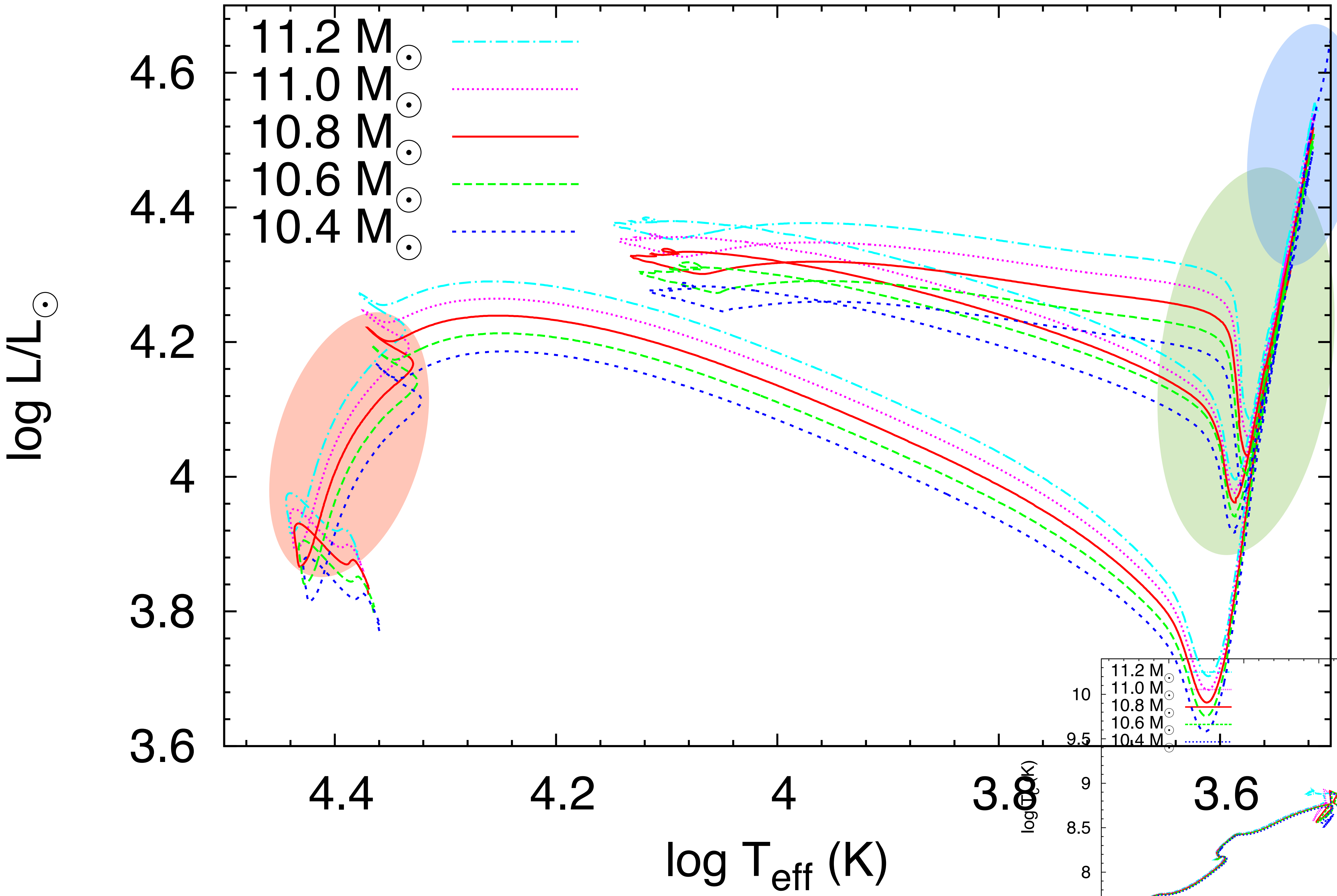


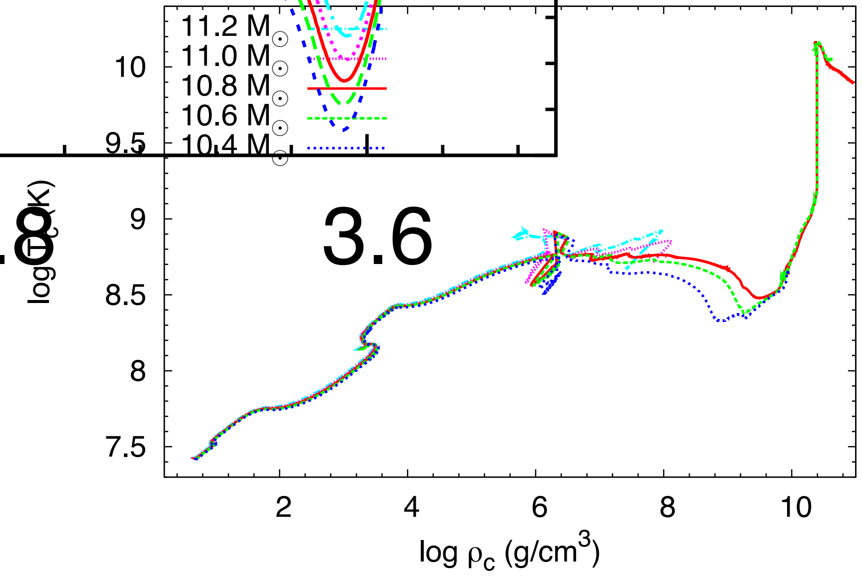
SAGB Evolution

- What is the particularity?
- Qualitative expectation of ECSN properties

SAGB Evolution

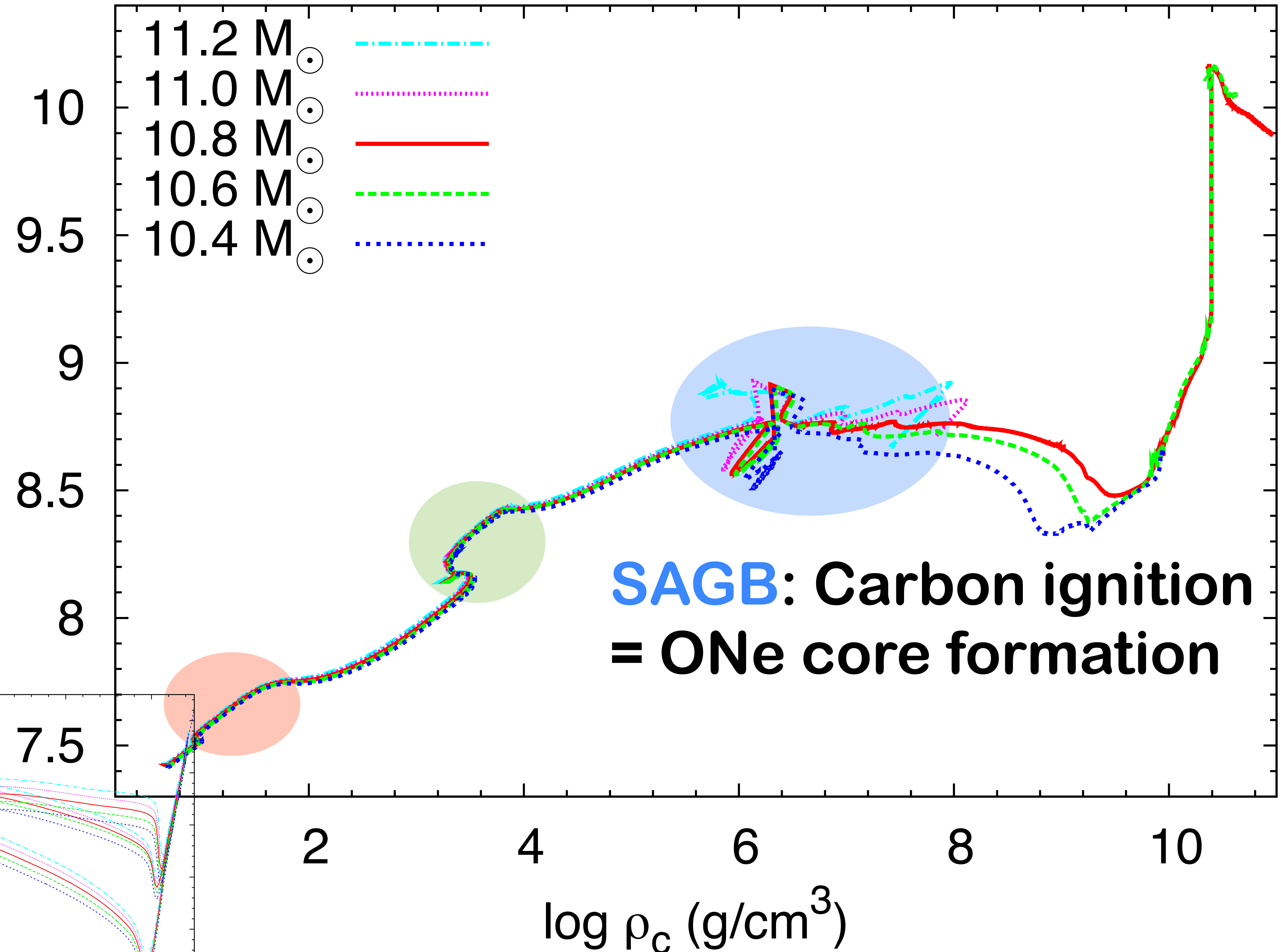
HR diagram: a diagram of surface luminosity-temperature relation

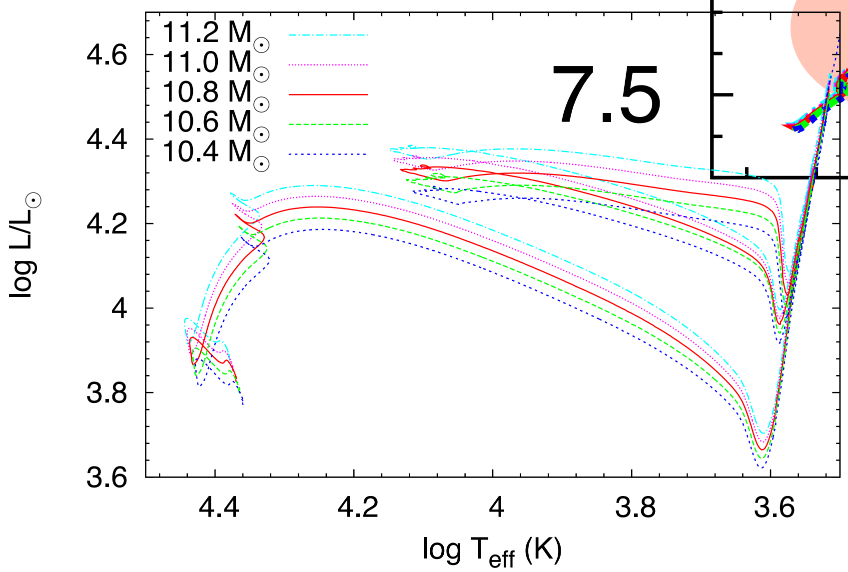




SAGB Evolution

ρ_c-T_c diagram: a diagram of central density-temperature relation

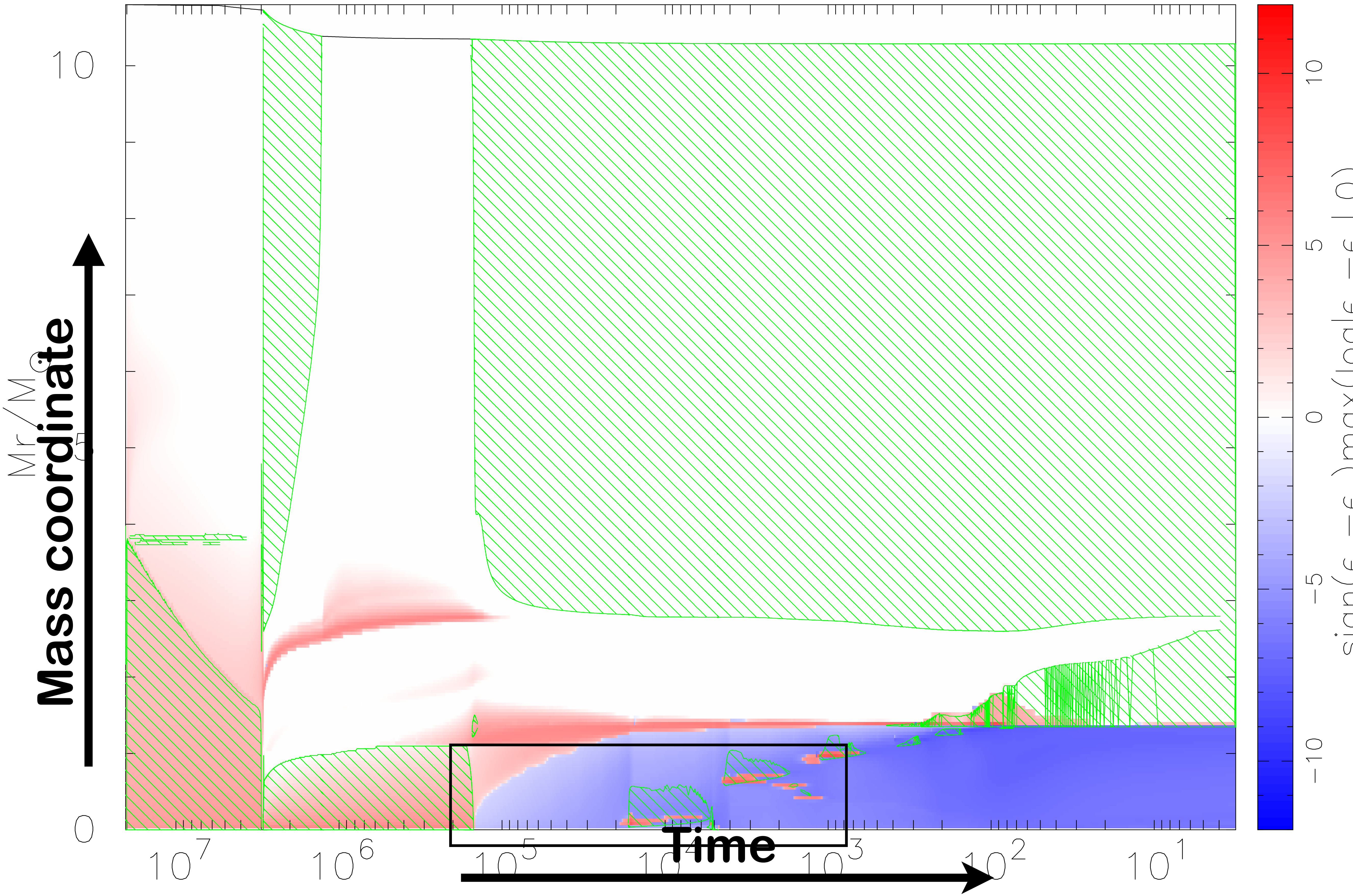




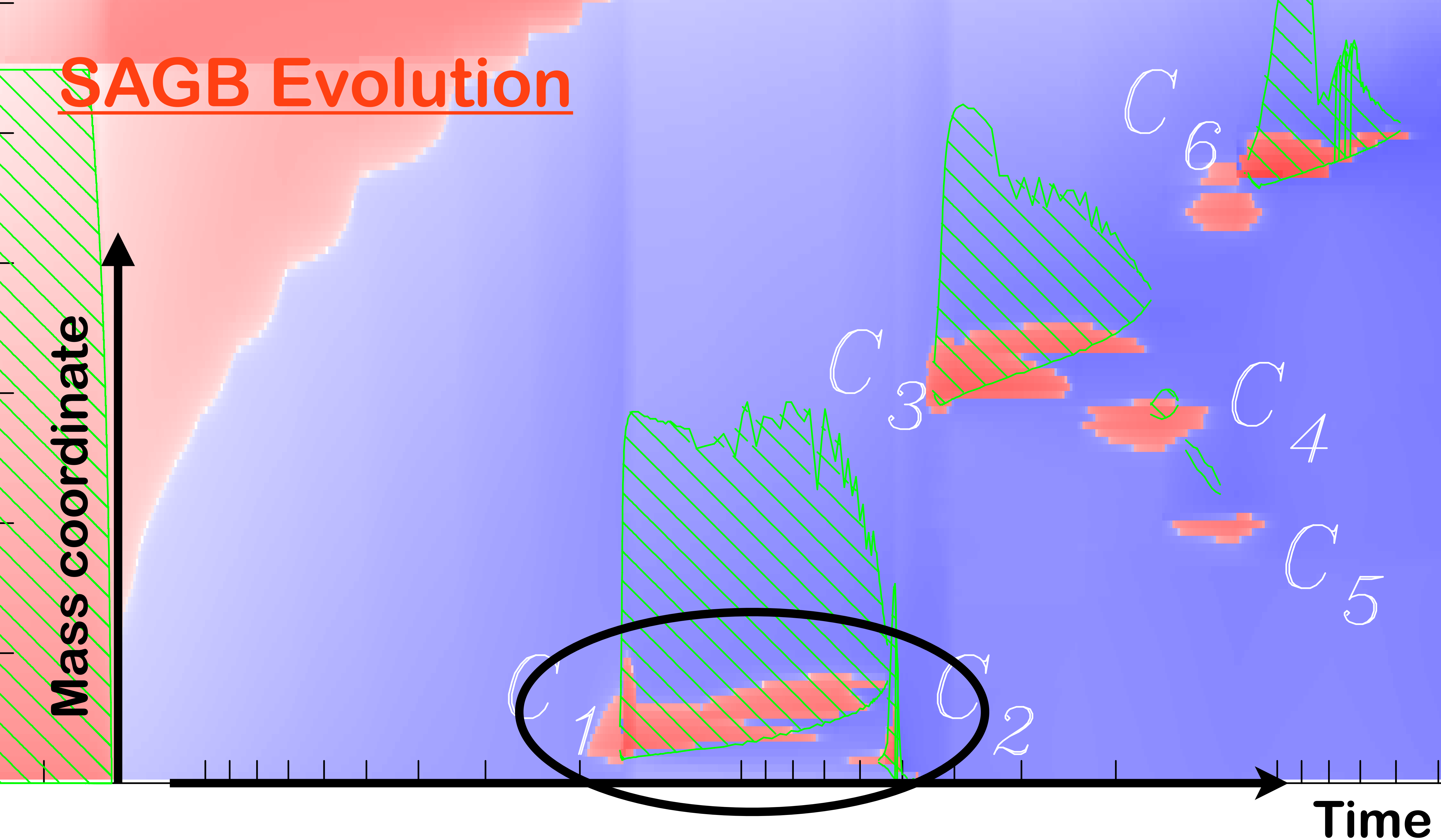
SAGB: Carbon ignition = ONe core formation

SAGB Evolution

Kippenhahn diagram: a diagram evolution of convective zones



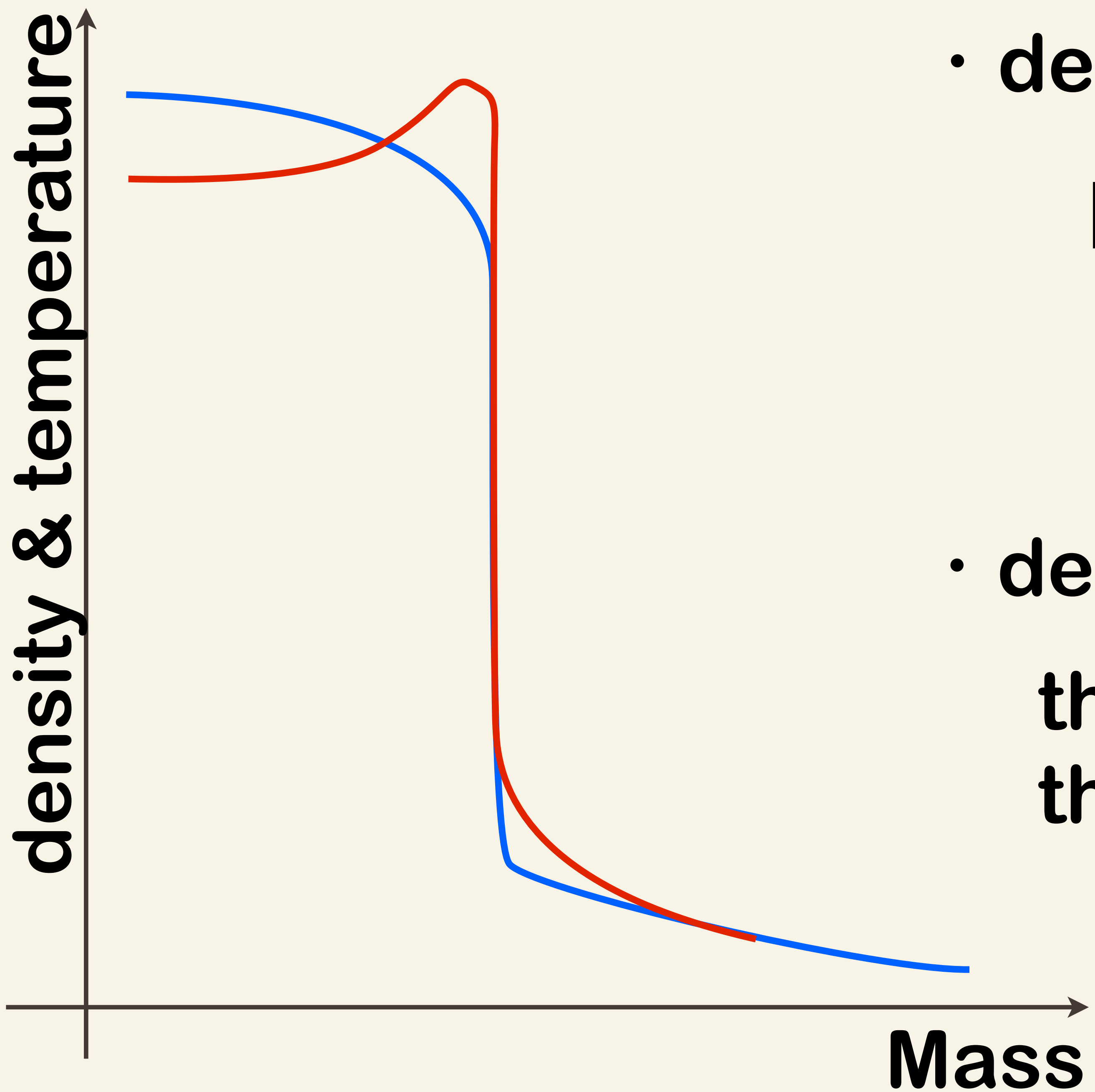
SAGB Evolution



Carbon ignites off-centrally

- temperature inversion due to degeneracy of electrons

Degeneracy of electrons



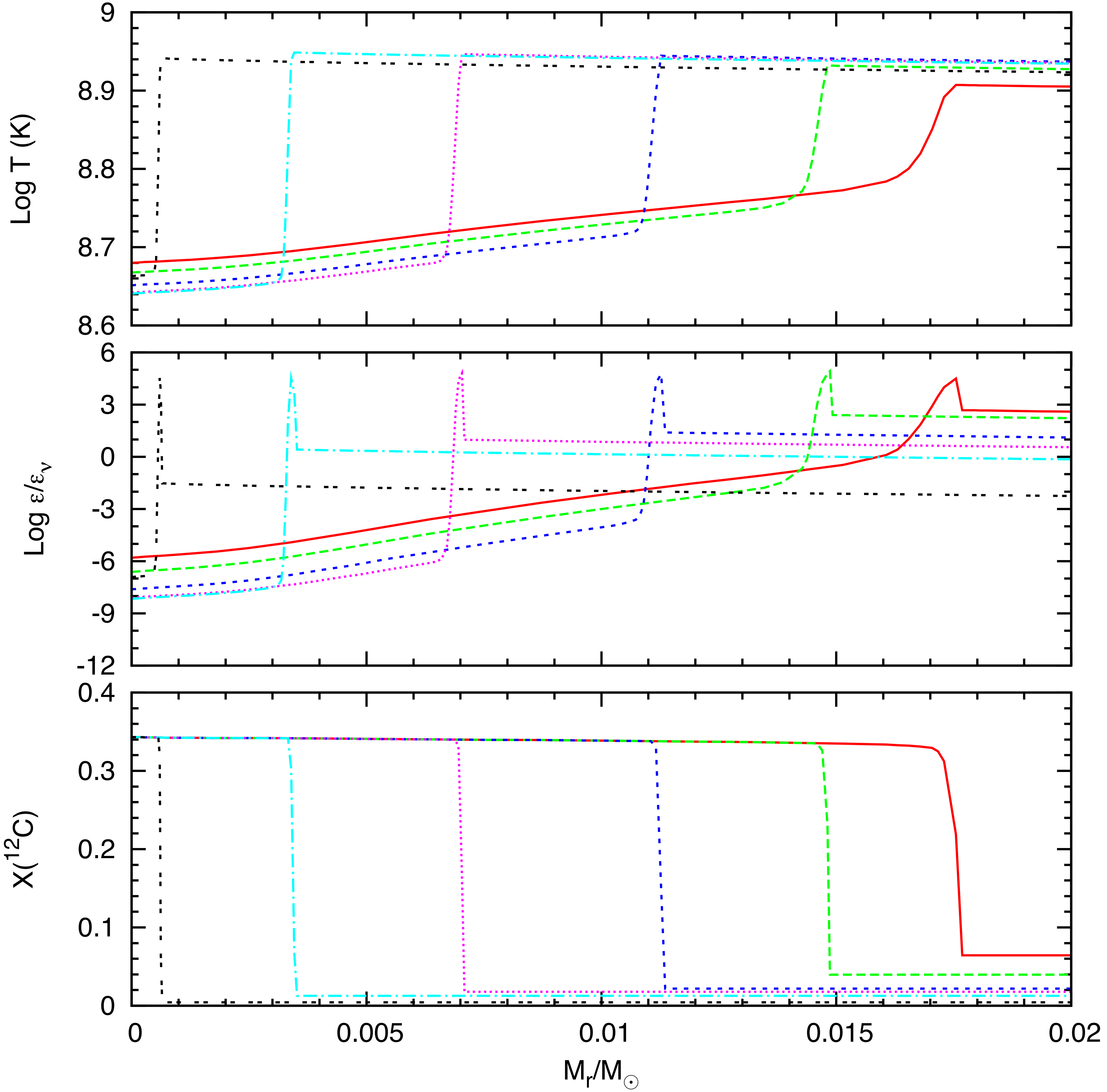
- degenerate electrons

$$p_e = \frac{1}{3}\int \frac{p_\varepsilon v_\varepsilon}{\exp(\frac{\varepsilon-\mu}{kT})+1} d\varepsilon$$
$$= p_e(\rho Y_e)$$

- decoupling of

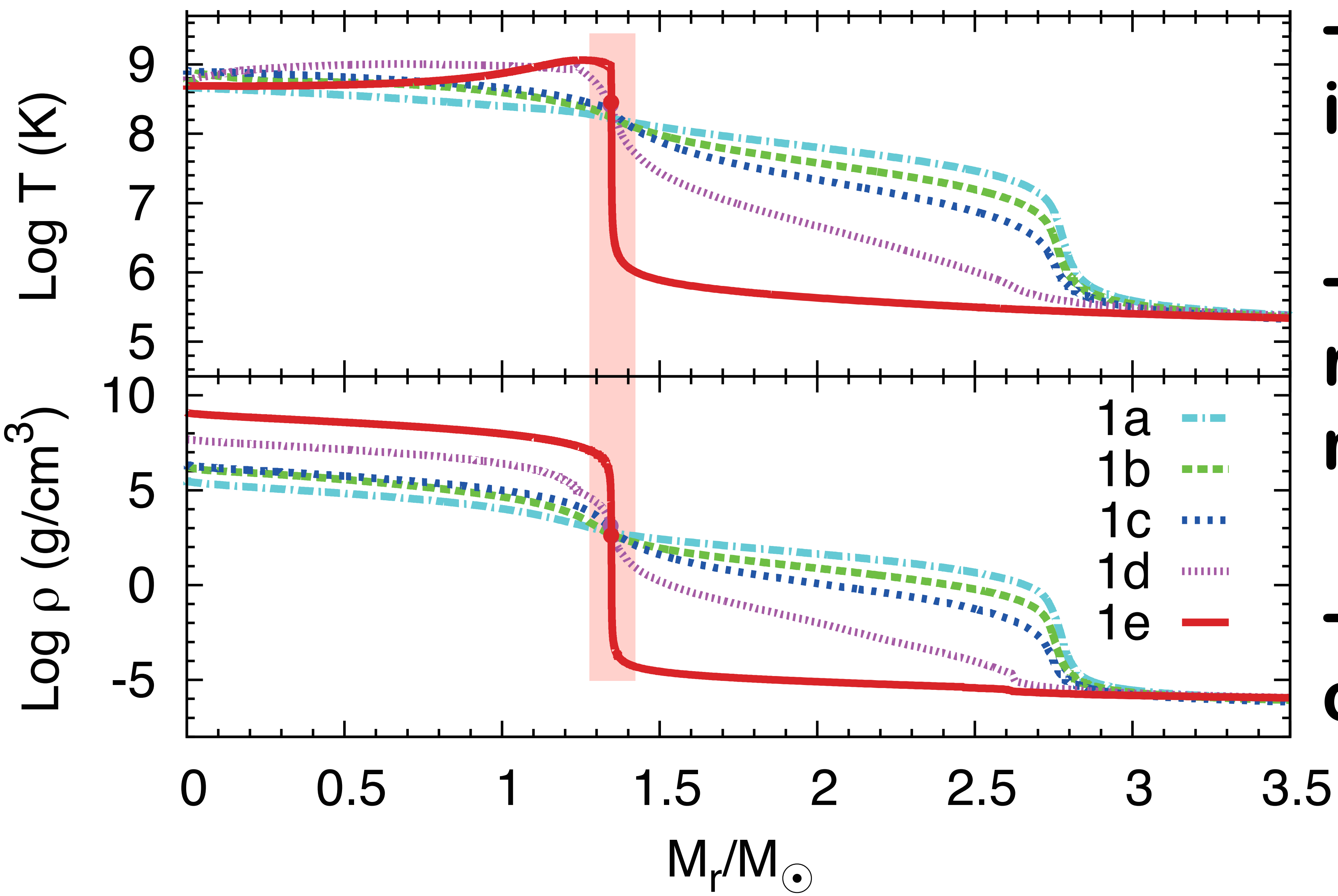
  the **dynamical** structure
  the **thermal** structure

SAGB Evolution



- following flame propagation needs high resolution

SAGB Evolution



- degenerate core is compact

- surrounding region becomes much hotter

- energetic reaction occurs at the edge

- Energetic shell burning results in a highly contrasting structure

- A ~1.37 Msun ONe core with diffuse H+He envelope

SAGB Evolution

What comes next?

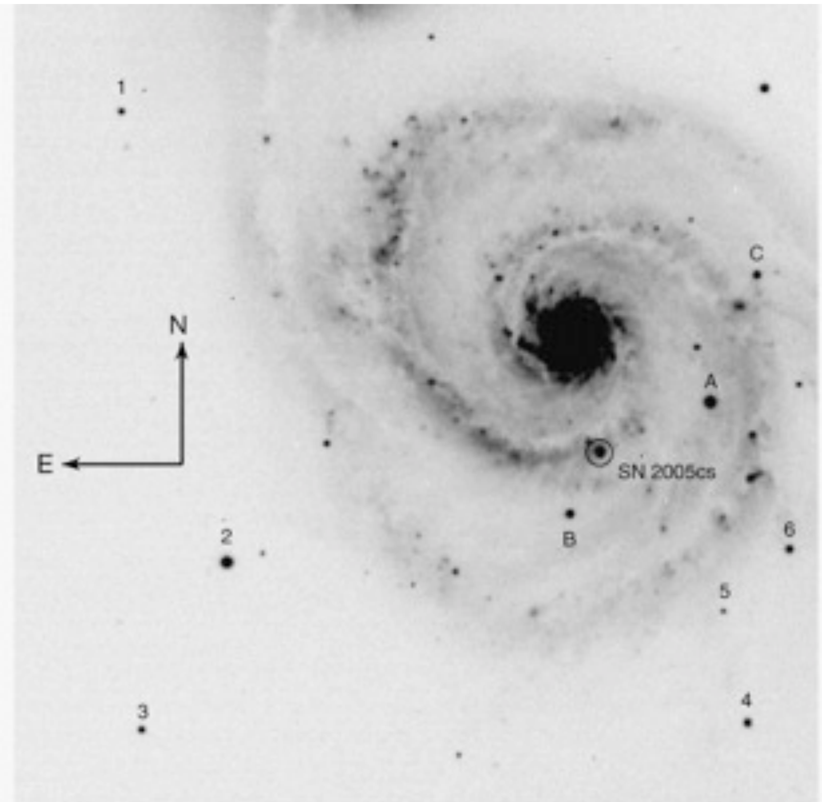
- The core becomes heavier up to the critical mass.
- OR loses its whole envelope by intense mass loss.

Short summary

(the answer for the first question)

- SAGB star is an AGB star with an ONe core.
- Electron degeneracy permit carbon ignites off-centrally.
- Energetic shell burning occur around the degenerate core.
- A SAGB star has a contrasting structure.

ECSN candidates ?



Pastorello A et al. MNRAS 2006;370:1752-1762

- SN 2005cs (SN IIP) may be an ECSN
  - subluminous and subenergetic SN
  - the most less massive core

- SN 2008S (SN IIn) may be an ECSN
  - the progenitor star of ~10 Msun
  - surrounded by dense CSM
  - the large mass loss

SN 2008S (Botticella et al. 2009)

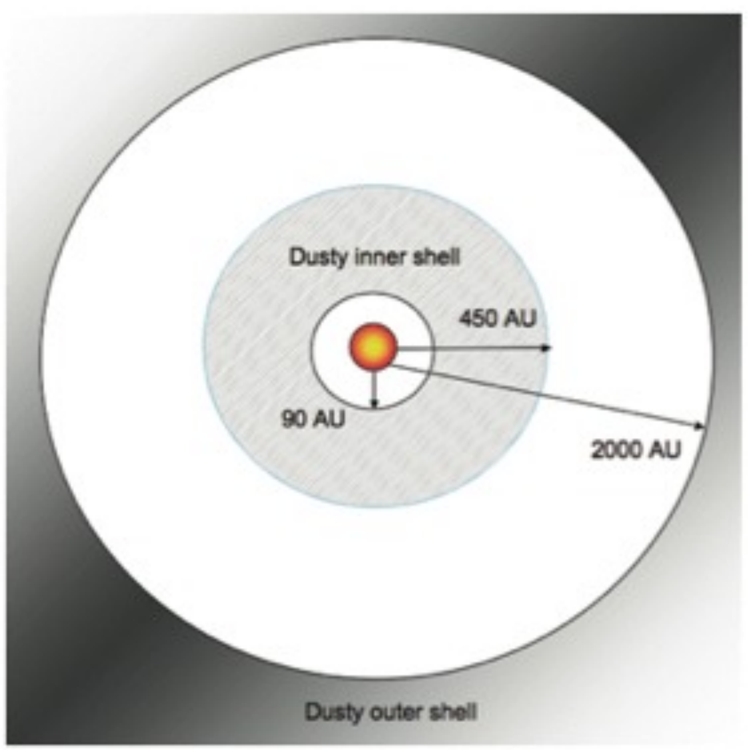
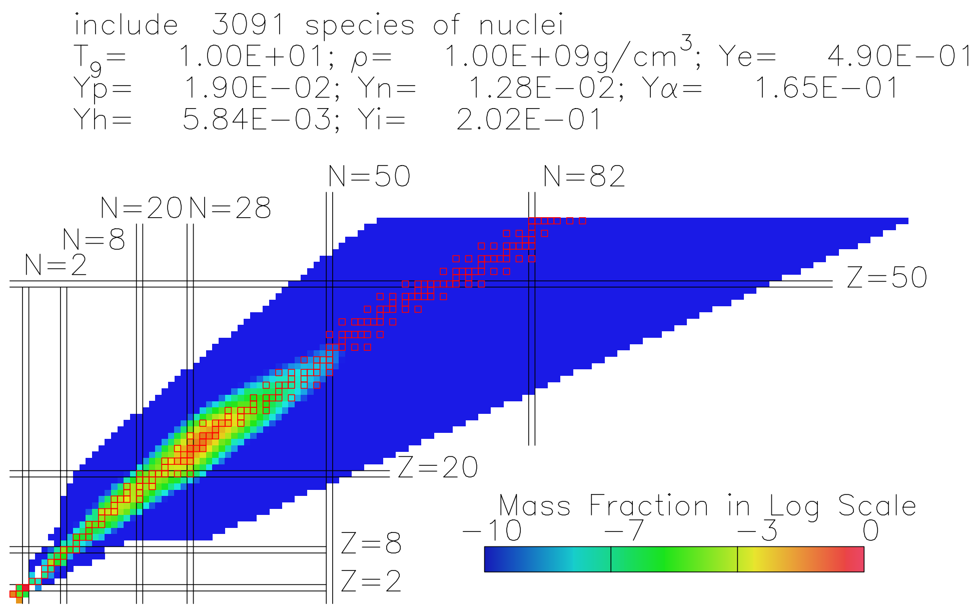
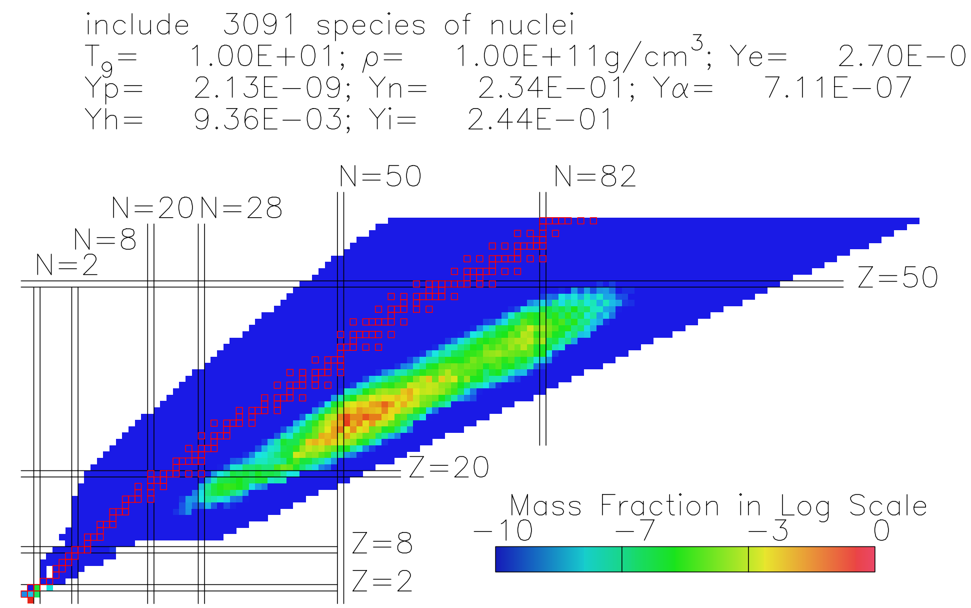


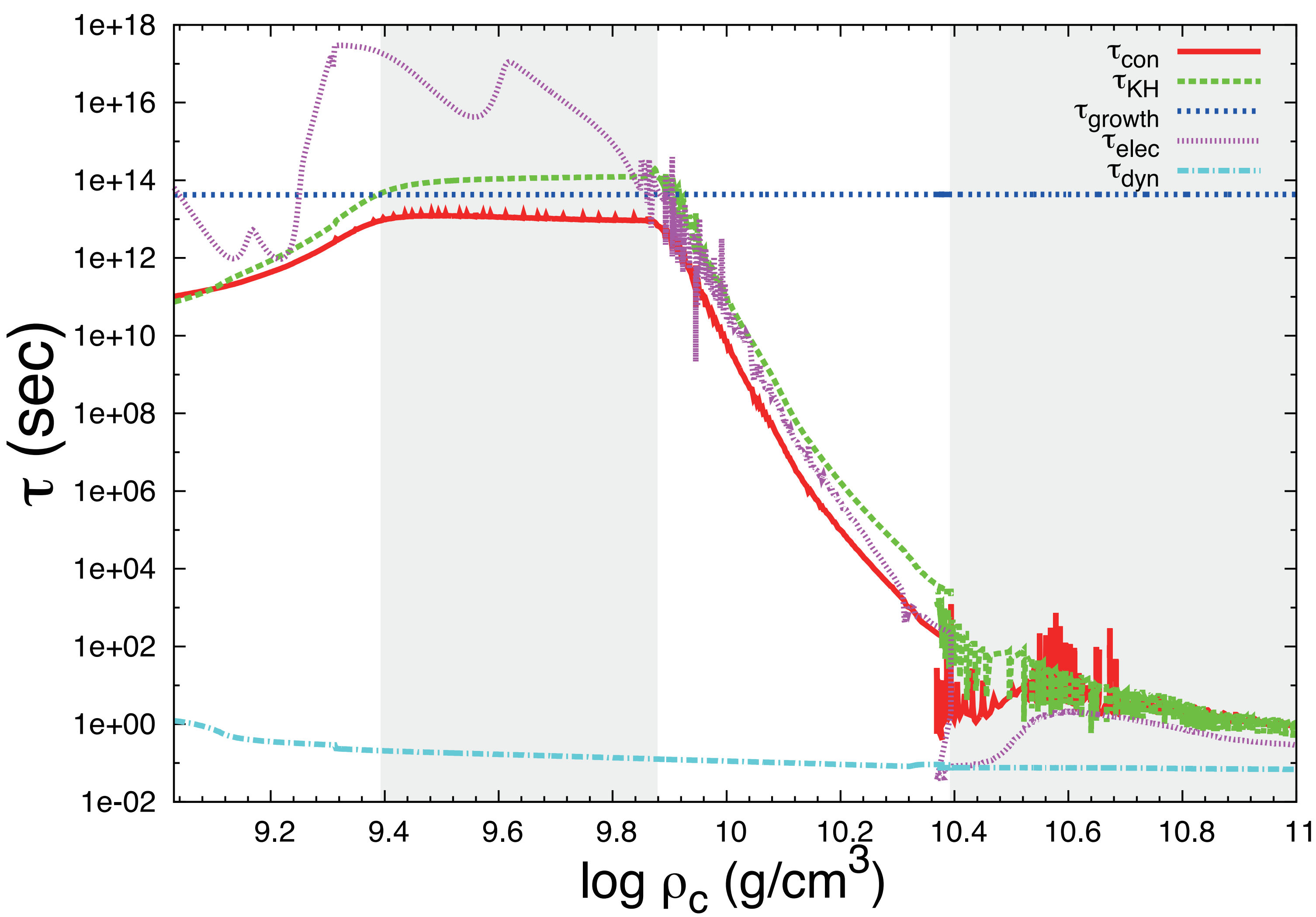
Figure 20. Schematic illustration of the pre-explosion geometry of SN 2008S.

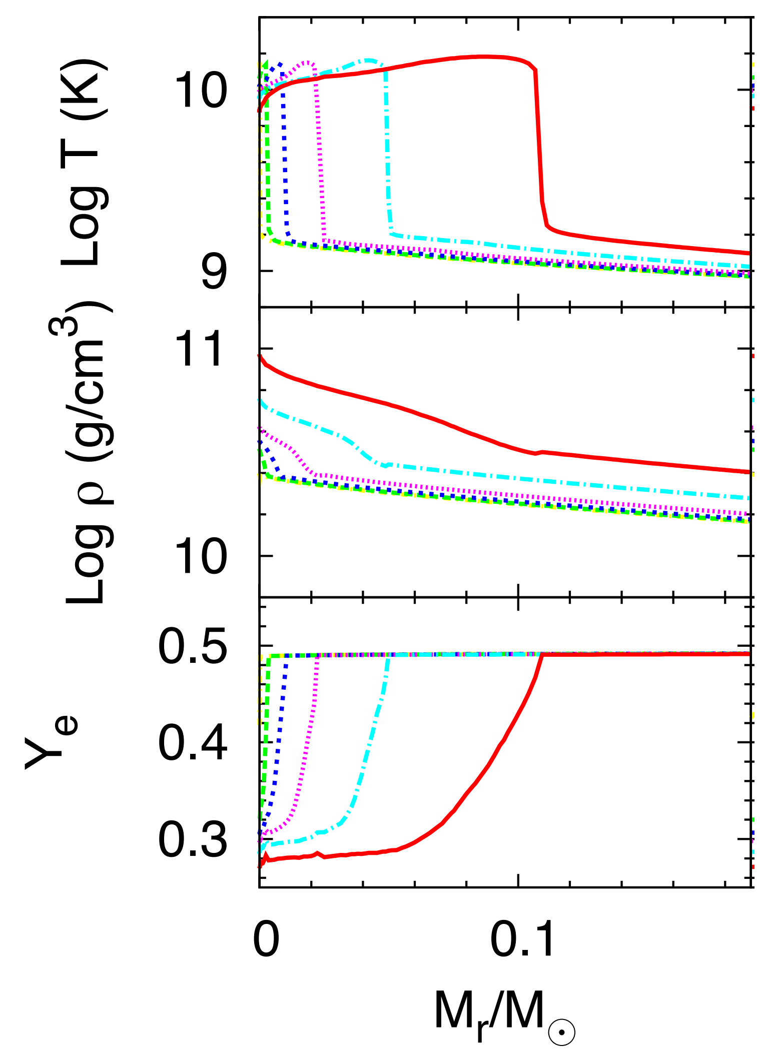
- ECSN can explain the Crab
  - small explosion energy (~0.1 foe)
  - large X(He), small X(O)
  - Not have any substructure





Until core collapse





Until core collapse

Critical mass objects

- CO WD -> Thermonuclear explosion
- Fe core -> Core collapse
- ONe core -> Core collapse (or AIC)

Until core collapse

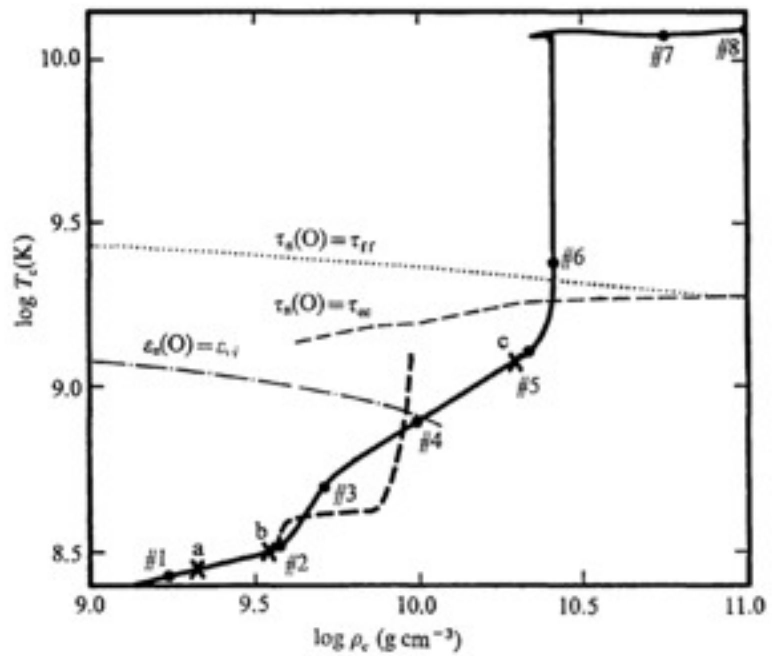


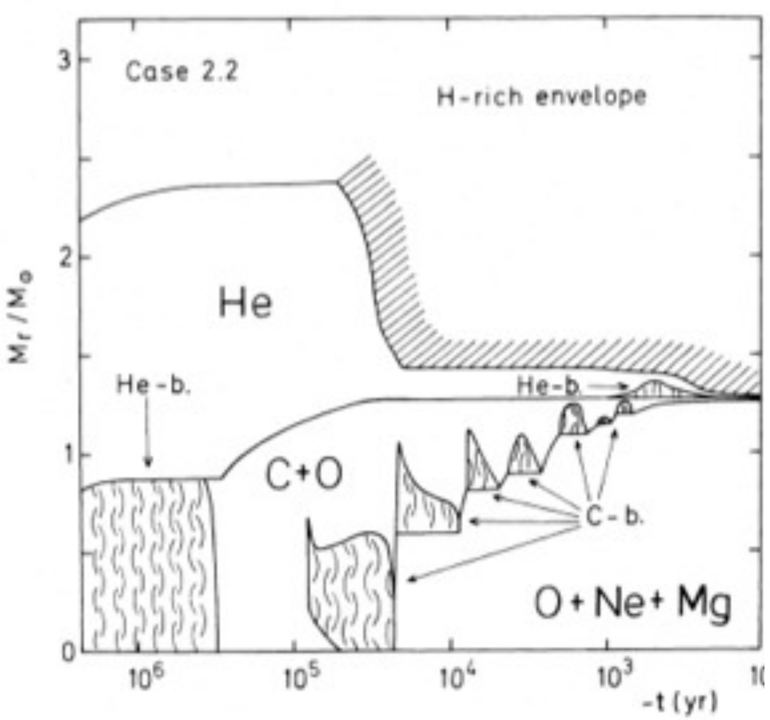
Fig. 5. Evolutionary change in the central temperature and the central density. See the text for stages a, b, and c. If the occurrence of the convective core were neglected, it would run as indicated by the thick dashed curve. Thin lines are concerned with the conditions for oxygen burning (see the text for detail).

(Miyaji et al. 1980)

Evolution of the critical mass ONe core was firstly solved by Miyaji et al. in 1980.

In 1987, Nomoto showed that such ONe core collapse can happen in a star which have a He core of ~2.2 Msun.

(Nomoto 1987)



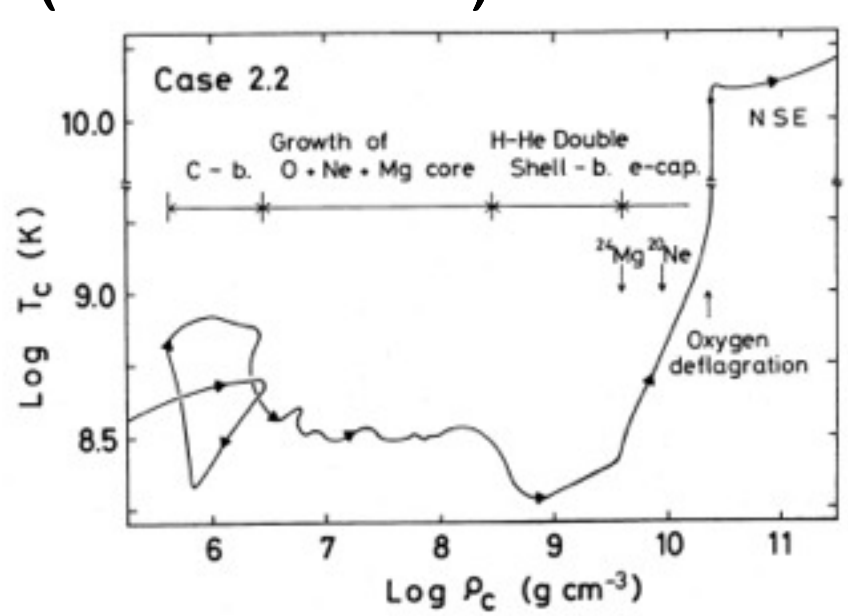
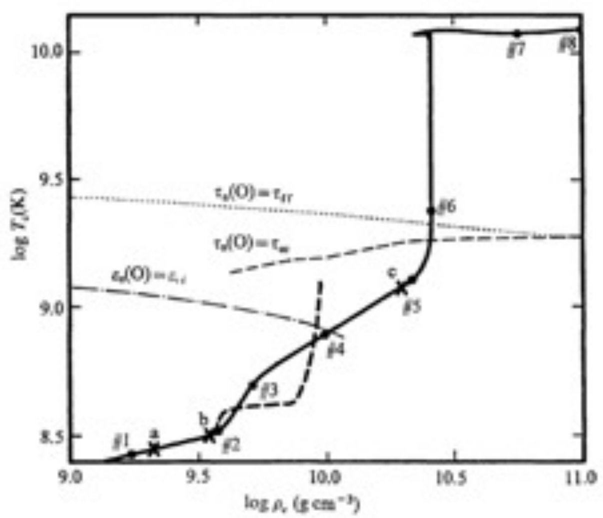


FIG. 4.—Evolutionary track in the central density and temperature diagram

Until core collapse



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(Miyaji et al. 1980)

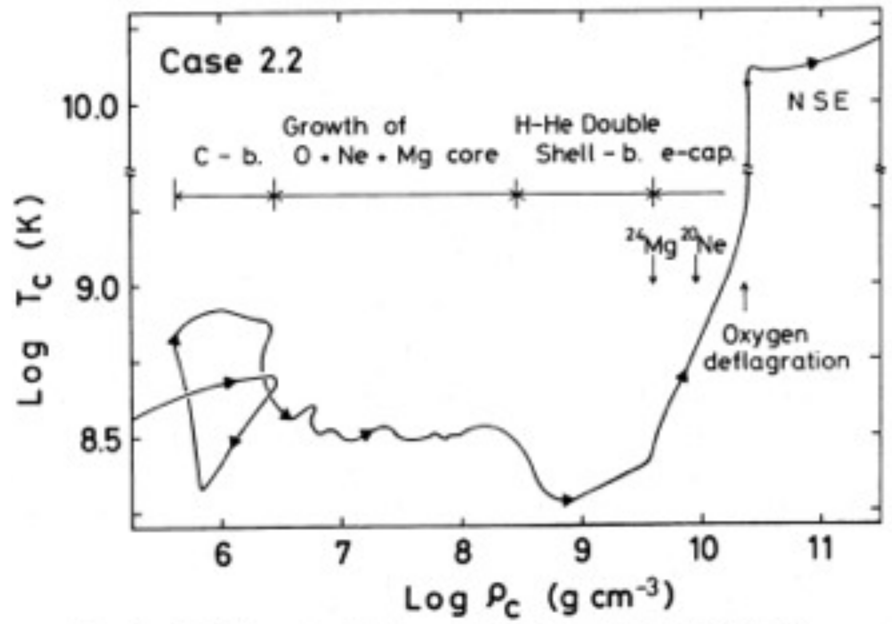
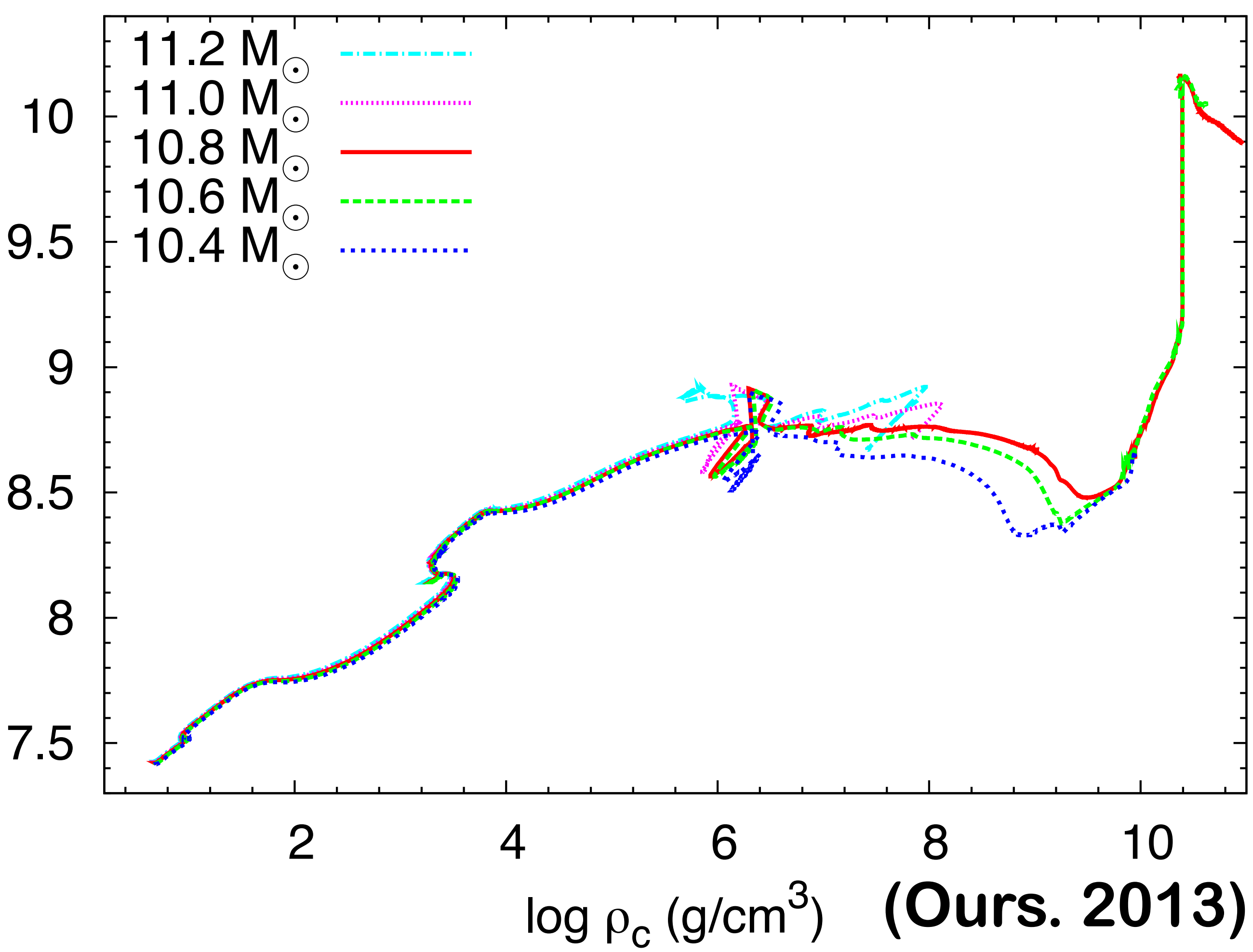


FIG. 4.—Evolutionary track in the central density and temperature diagram

(Nomoto 1987)

We have calculated the collapse of an ONe core after 26 years absence of other works.



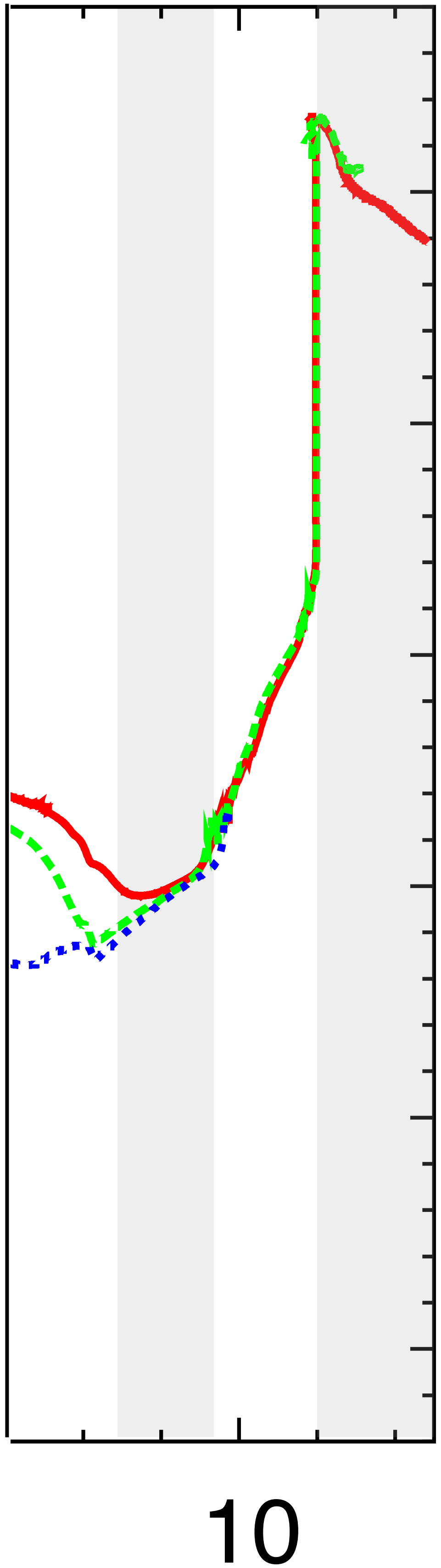
(Ours. 2013)

Our result shows generally good agreements with previous works.

Until core collapse

- How does the core end up as core collapse?
- What physics is important?

Until core collapse

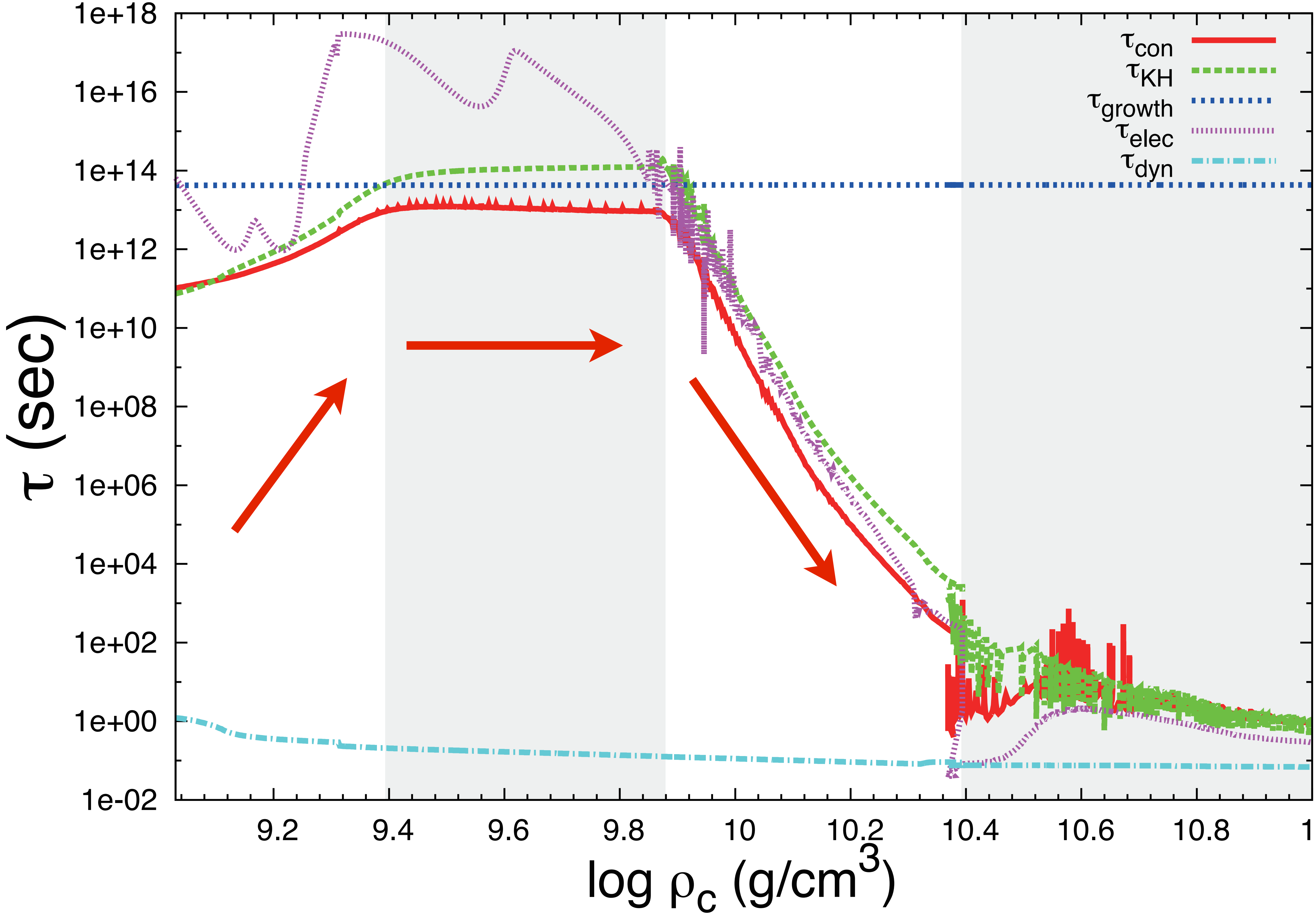


Core contraction can be divided into 4 sub-phases.

1. ν cooling phase
2. core growth phase
3. electron capture phase
4. deflagration phase

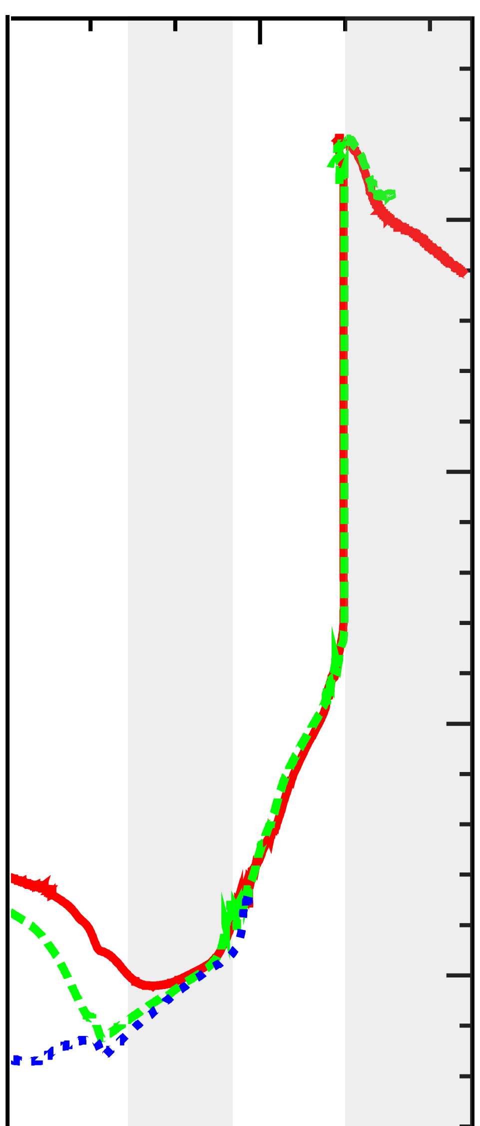
Until core collapse

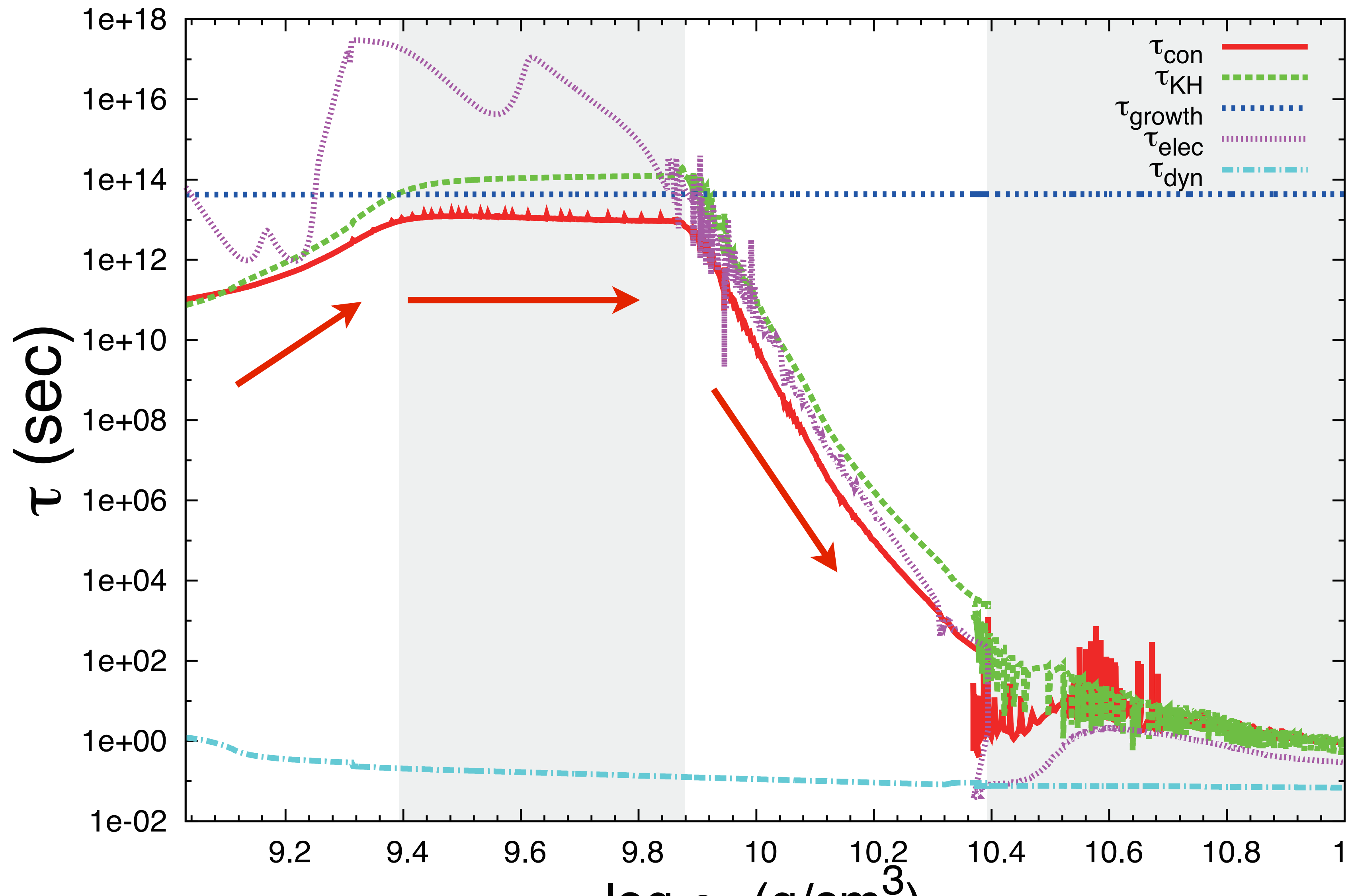
diagram of Evolutionary timescales



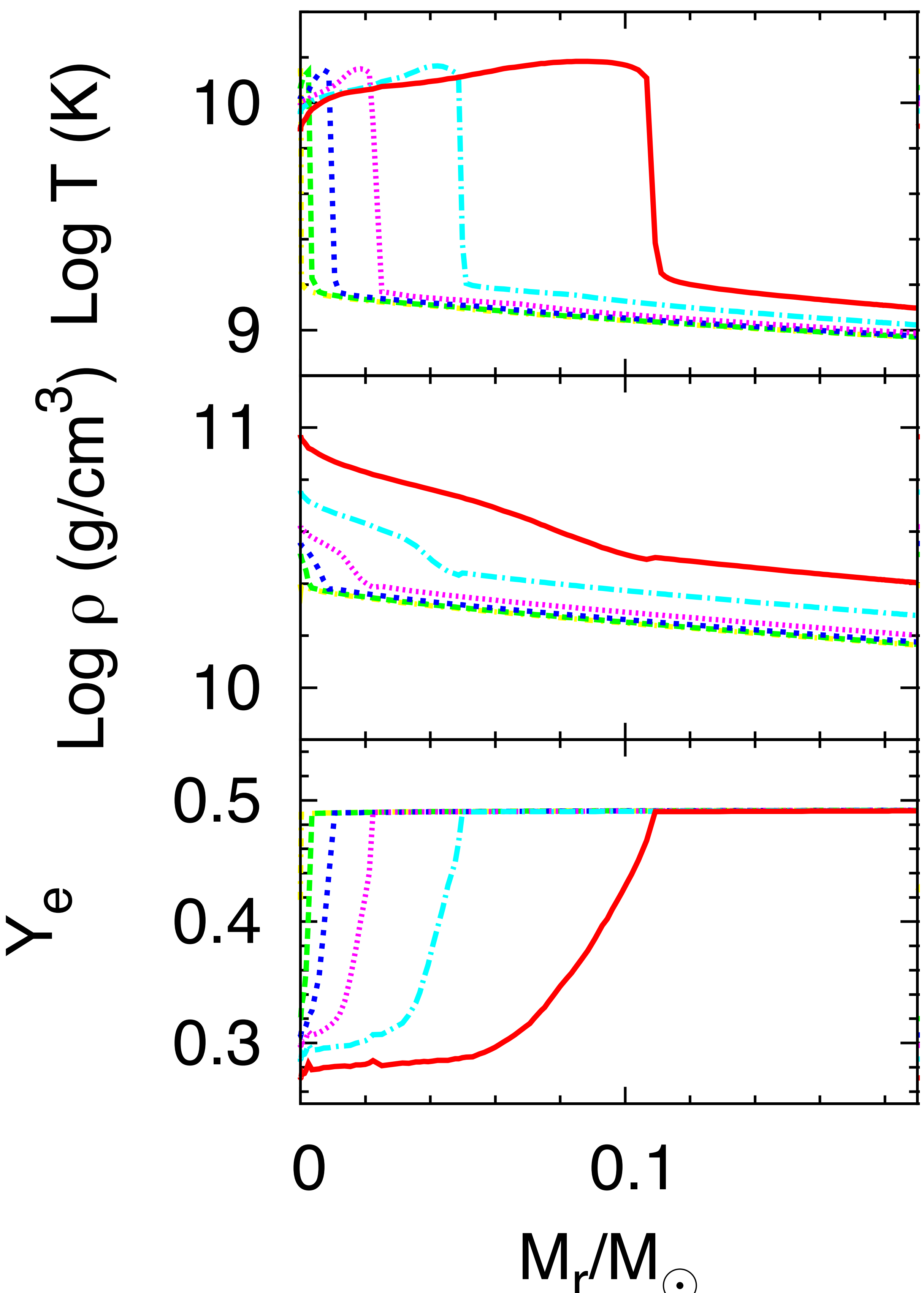
Until core collapse

- ν cooling phase (↗) : self-regulating
- core growth phase (→) : constant
- electron capture phase (↘) : self-enhancing
- deflagration phase : complicated





Until core collapse



- O+Ne burning causes deflagration in the degenerate core.

- convective energy transport is solved.

- **NSE** is achieved behind the deflagration front.

- in the NSE region, intense electron capture reduces Ye.

- Ye reduction cause core contraction.

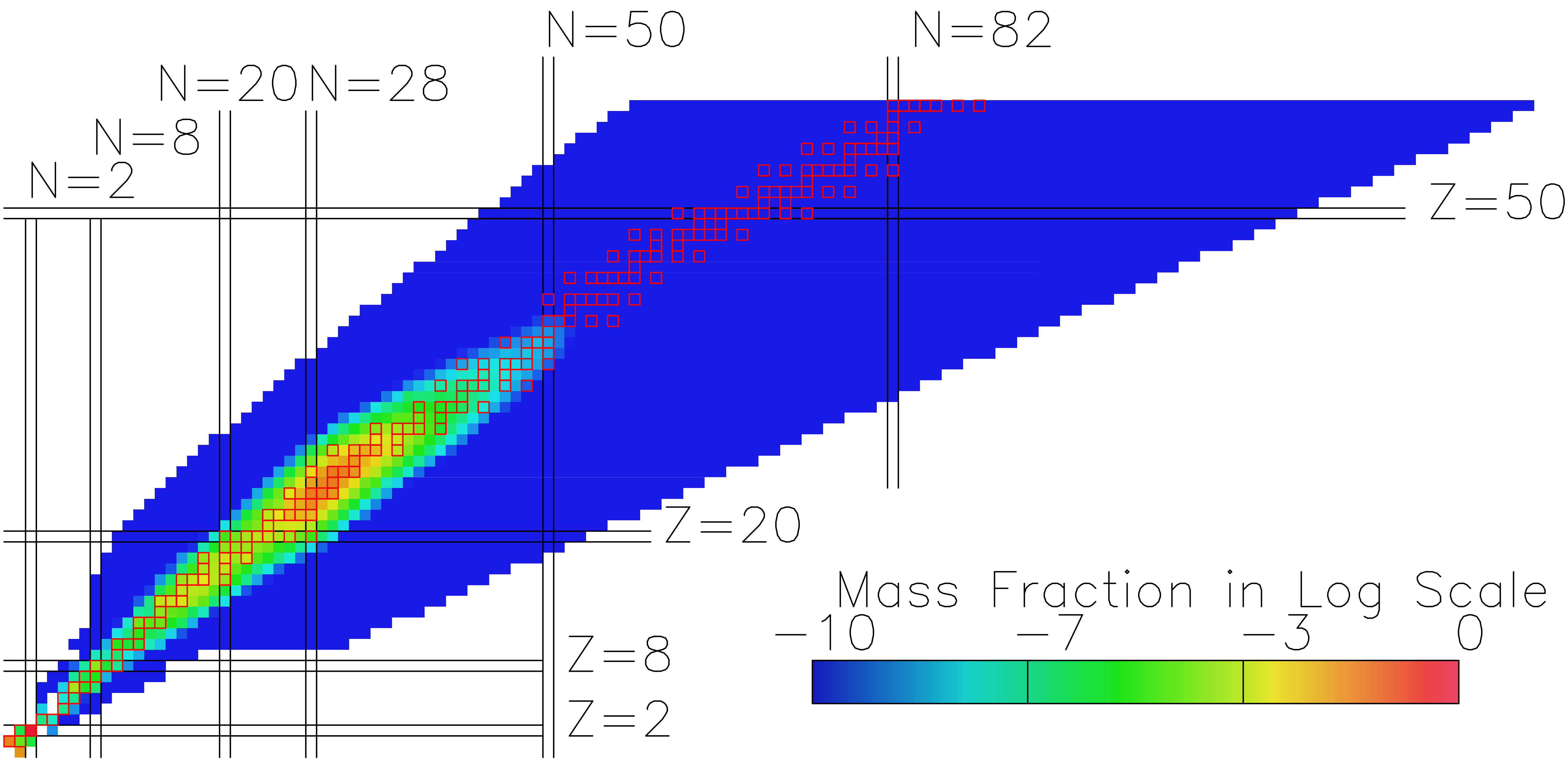
Nuclear Statistical Equilibrium

include 3091 species of nuclei

$T_9 =$ 1.00E+01; $\rho =$ 1.00E+09g/cm^3; $Ye =$ 4.90E-

$Yp =$ 1.90E-02; $Yn =$ 1.28E-02; $Y\alpha =$ 1.65E-01

$Yh =$ 5.84E-03; $Yi =$ 2.02E-01



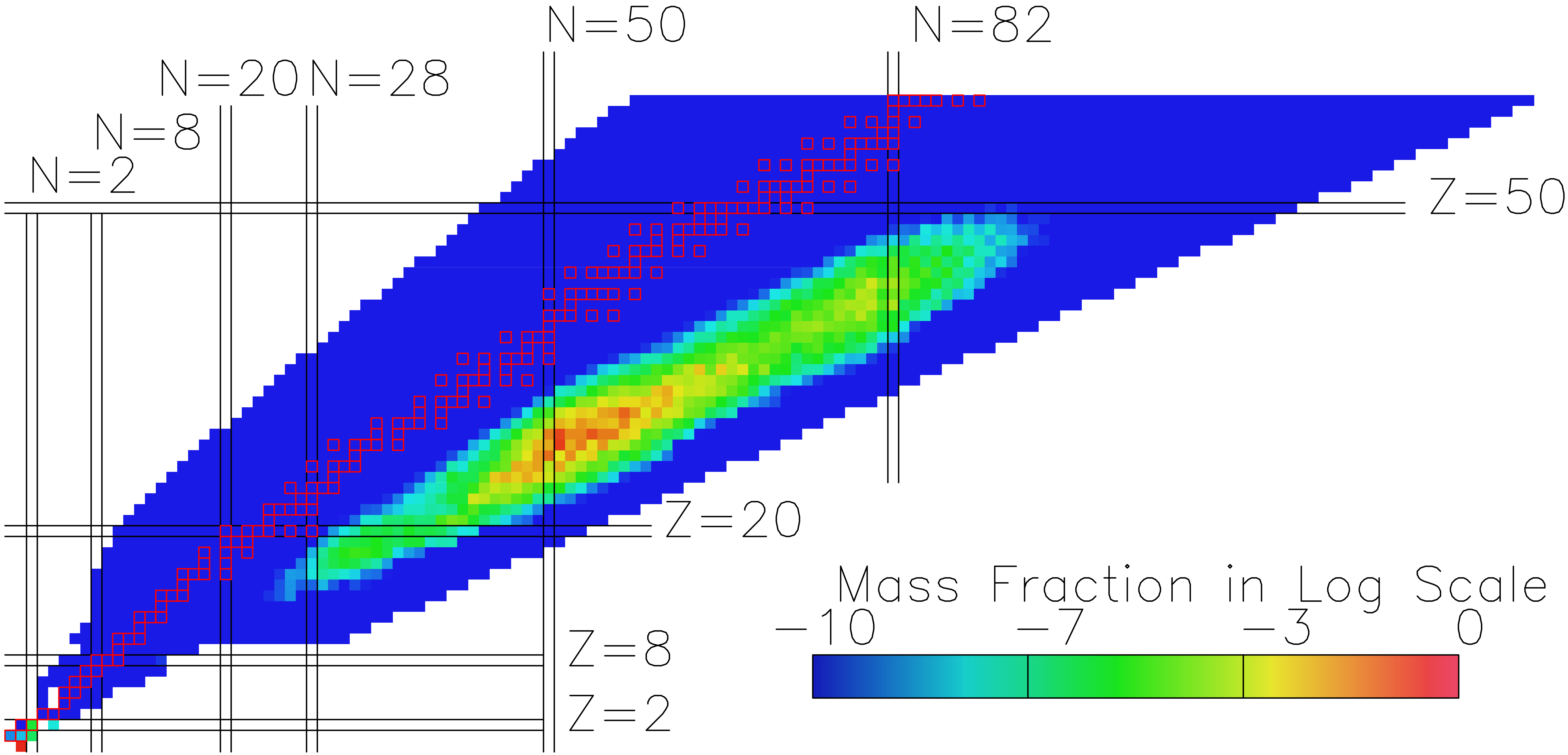
Nuclear Statistical Equilibrium

include 3091 species of nuclei

T_9= 1.00E+01; ρ= 1.00E+11g/cm^3; Ye= 2.70E-

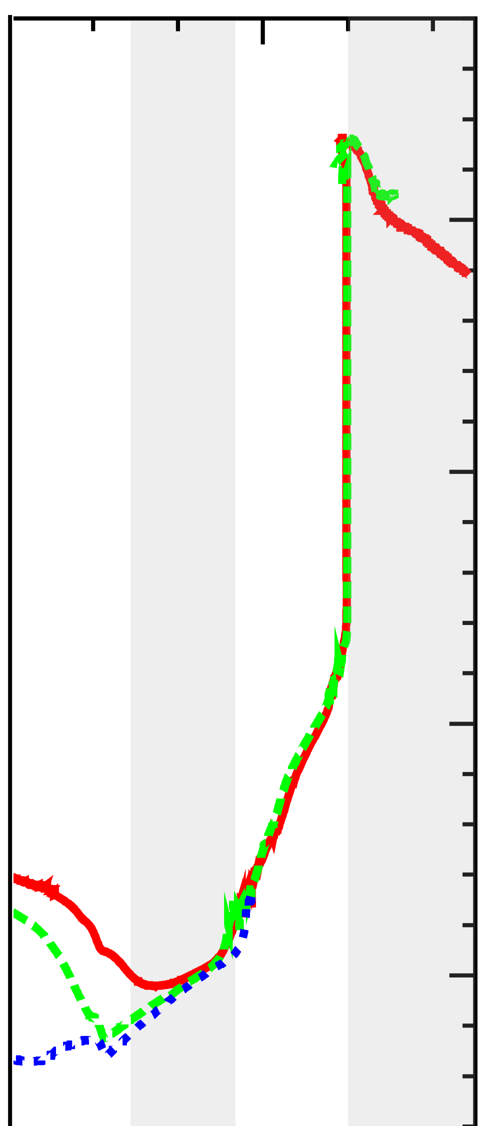
Yp= 2.13E-09; Yn= 2.34E-01; Yα= 7.11E-07

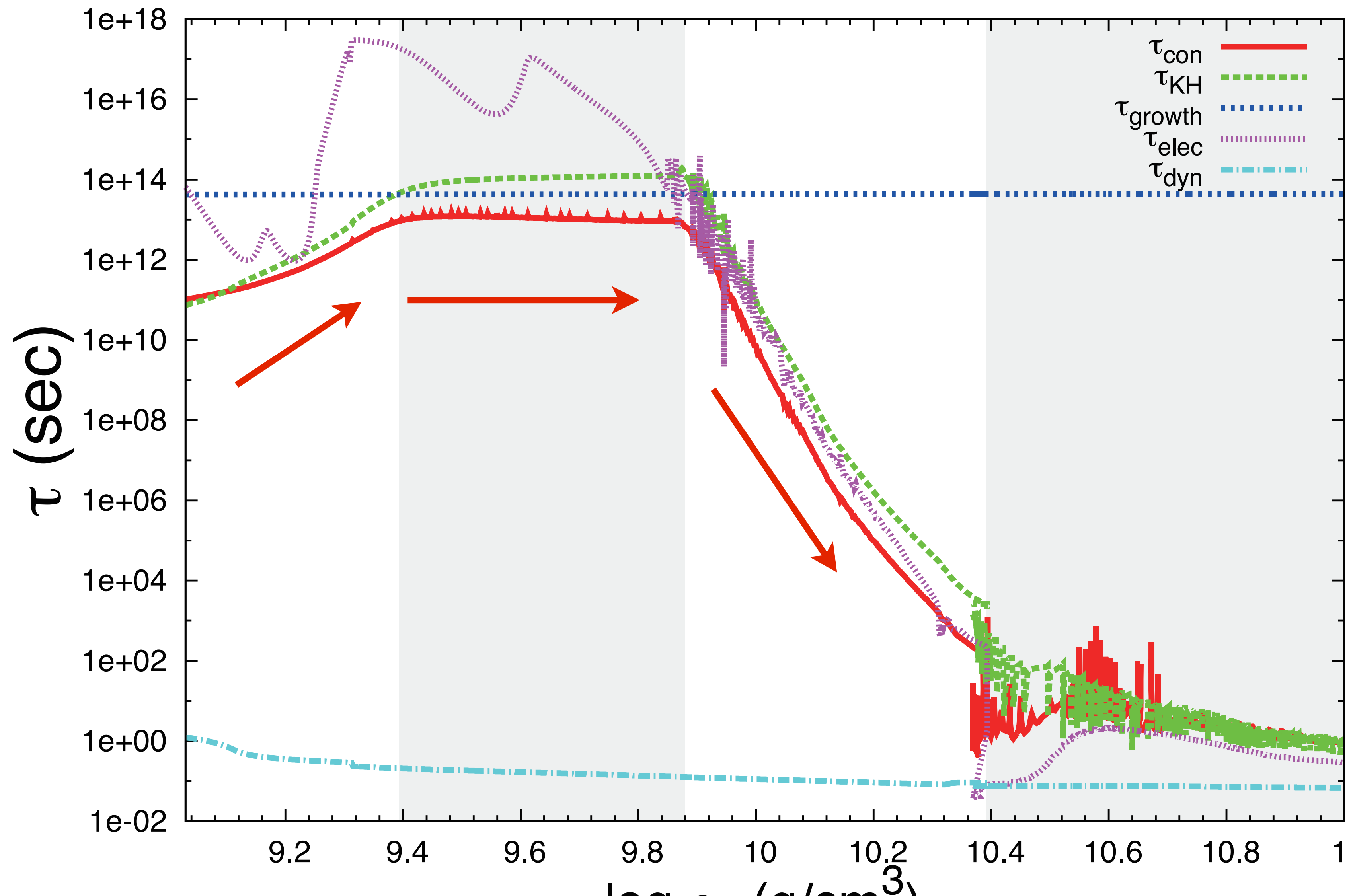
Yh= 9.36E-03; Yi= 2.44E-01



Until core collapse

- deflagration phase
  - propagation of the burning front
  - electron capture reaction in the NSE region
    - reduction of Ye
    - reduction of energy





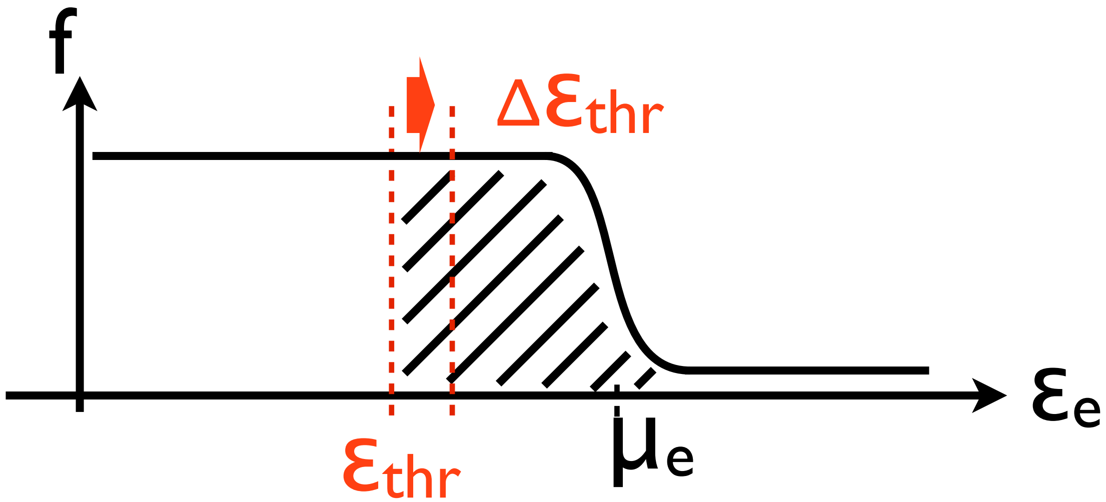
Until core collapse

Short summary 2

- Contraction of an ONe core has 4 sub-phases.
  - self-regulating ν-cooling phase
  - core mass growth phase
  - self-enhancing electron capture phase
  - deflagration phase

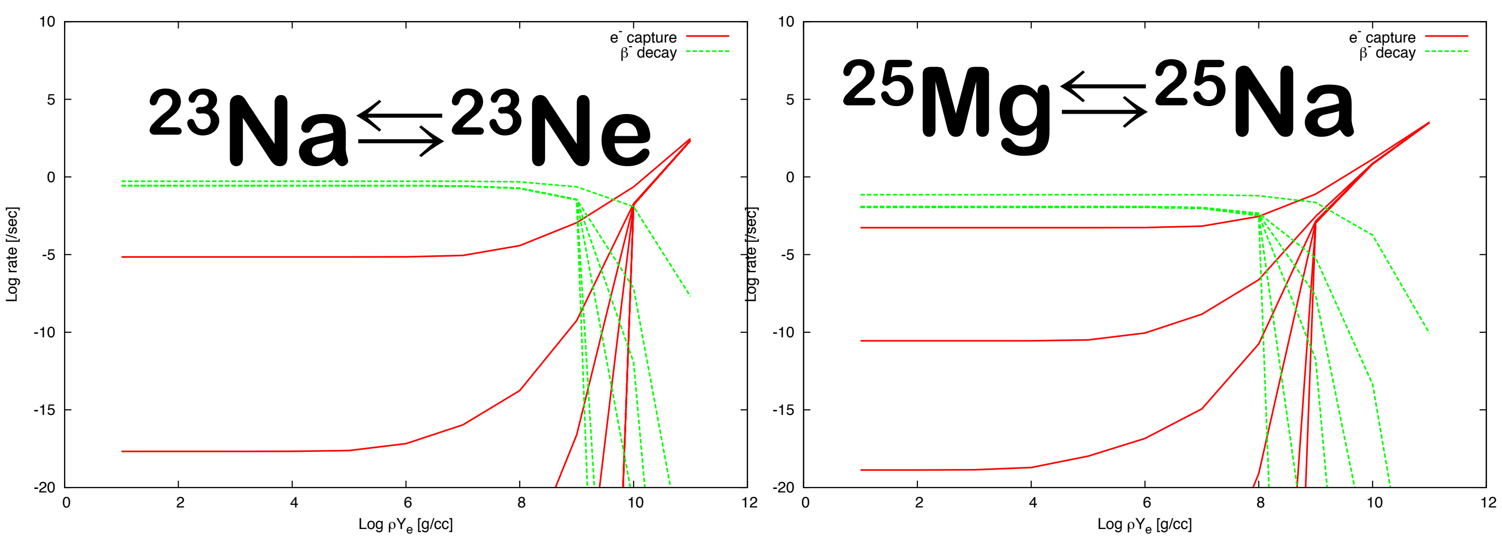
- Deflagration phase is much complicated.
  - propagation of the flame front
  - electron capture in the NSE region

- Core collapse is finally induced by electron capture in the NSE region.

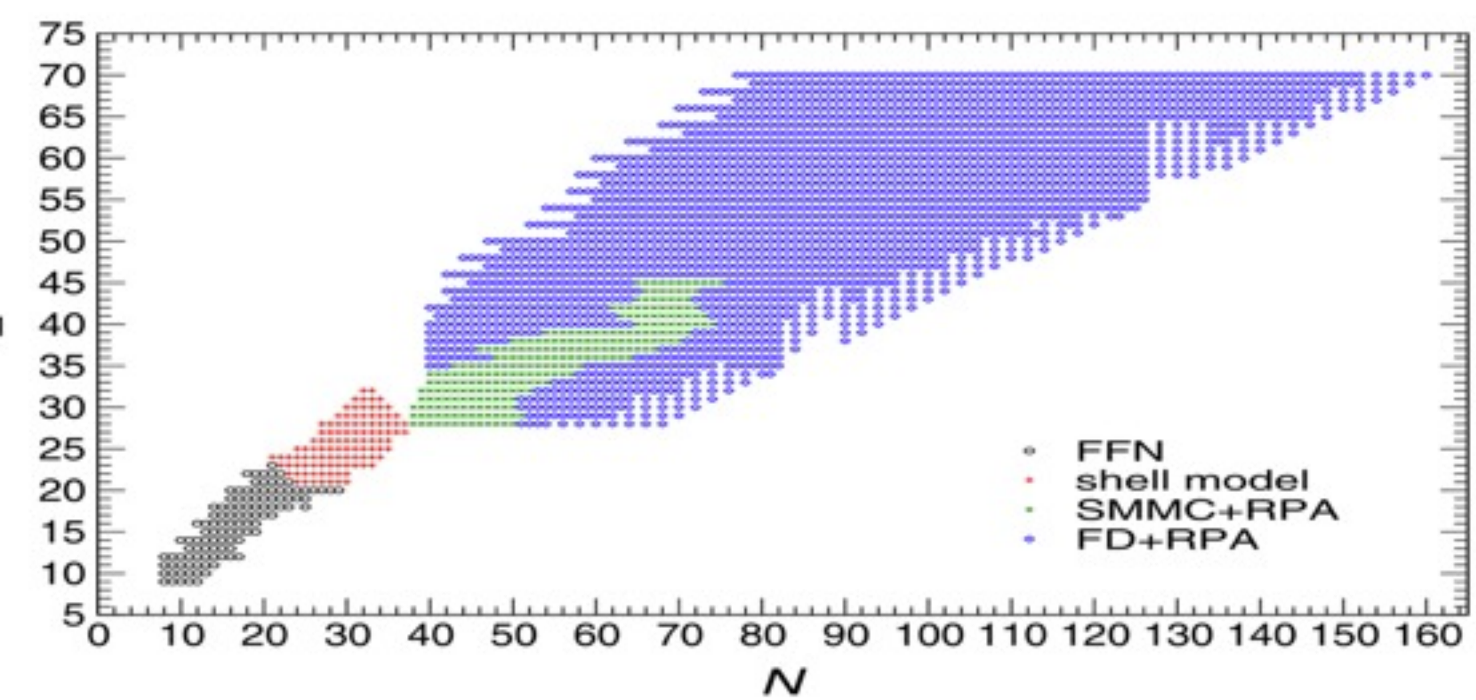


f
Δε_thr
ε_e
ε_thr
μ_e

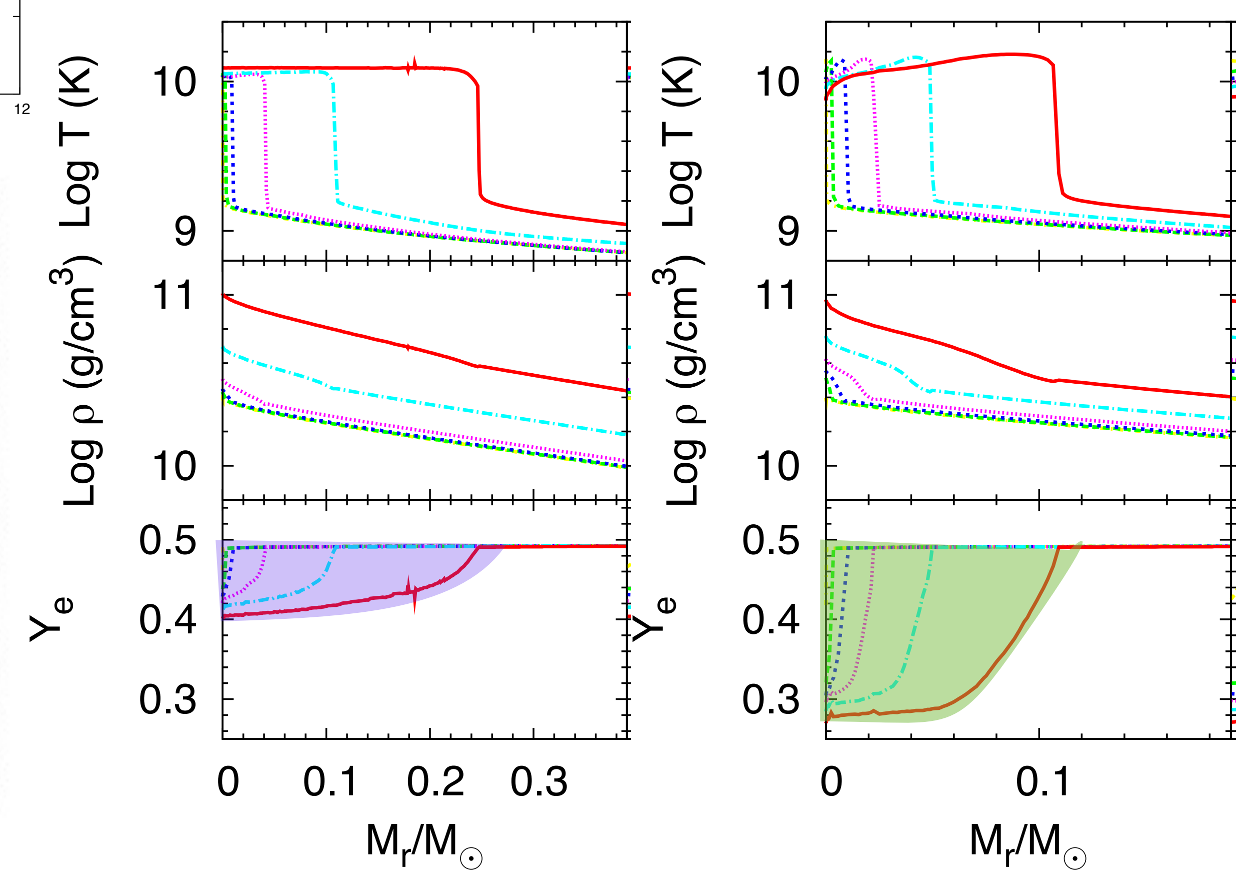
New physics



23Na⇆23Ne
25Mg⇆25Na
e- capture
β- decay
Log rate [/sec]
Log ρYe [g/cc]



FFN
shell model
SMMC+RPA
FD+RPA
N



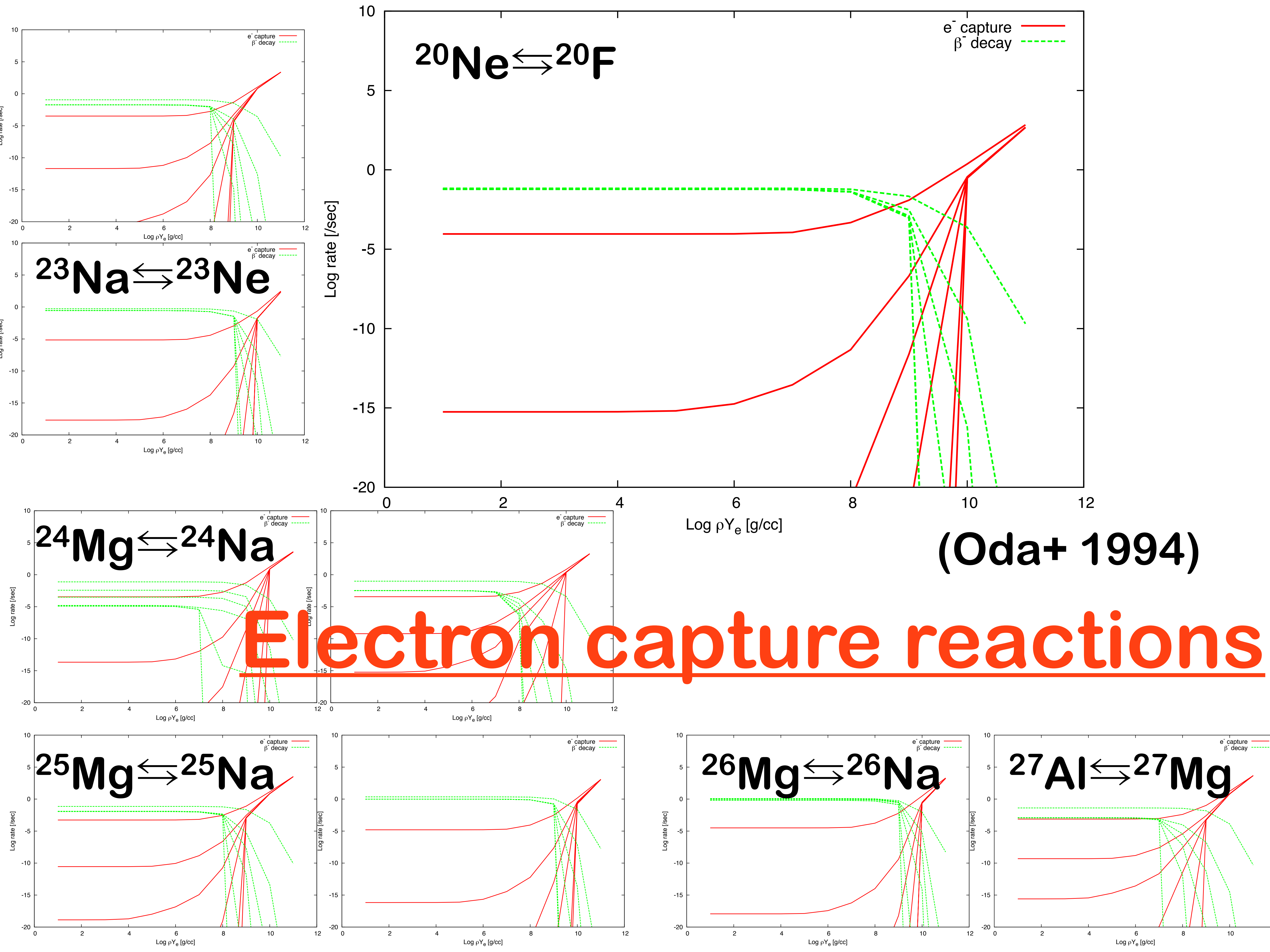
Log T (K)
Log ρ (g/cm3)
Ye
Mr/M⊙

New physics

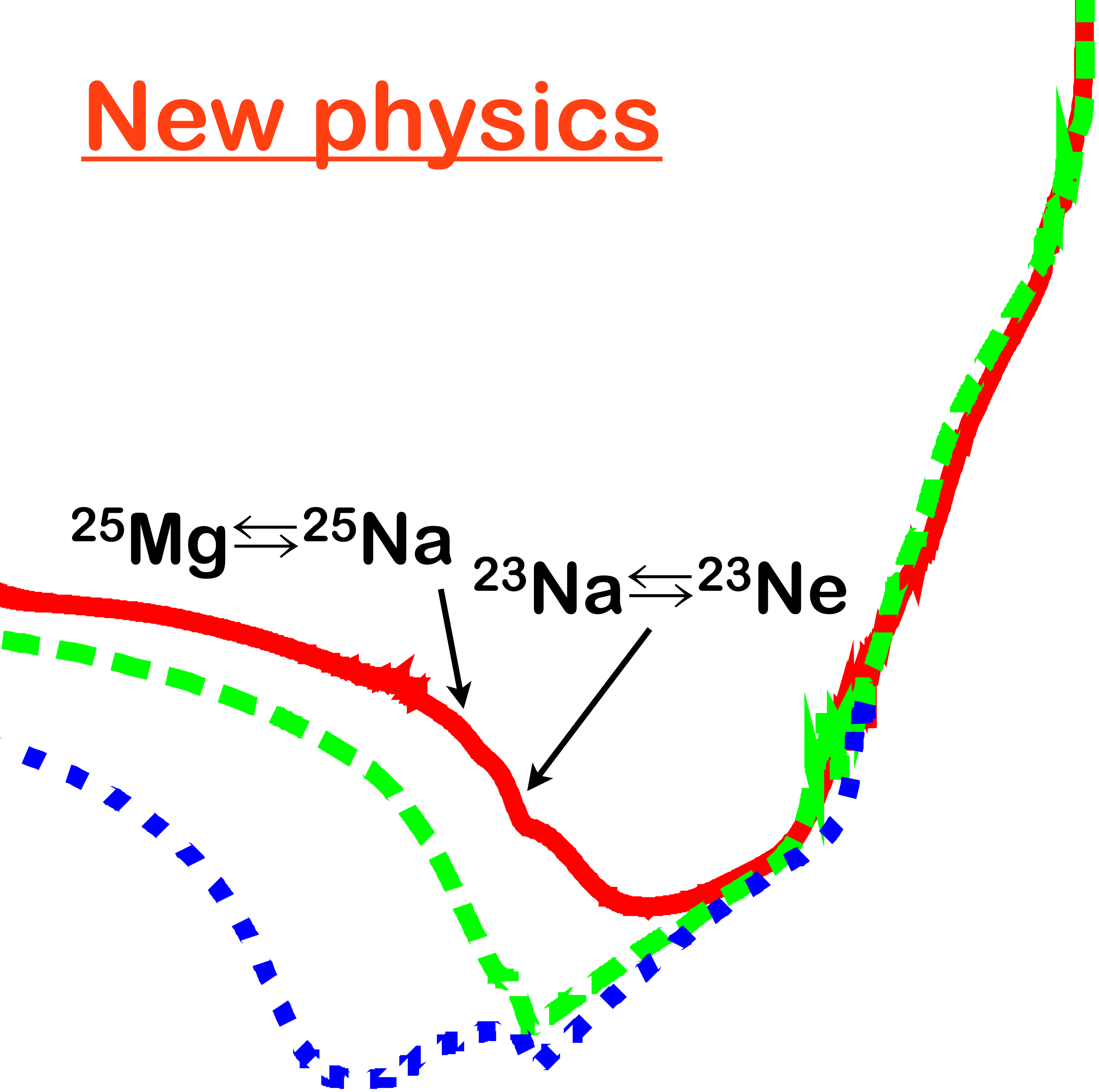
Importance of improved input physics is investigated.

- electron capture by odd proton number isotopes
- the Coulomb correction on the electron capture rates
- electron capture by neutron-rich isotopes in NSE compositions

Electron capture reactions



New physics



The effect can be seen.
But less important.
- **small mass fraction**
- **endothermic reaction**

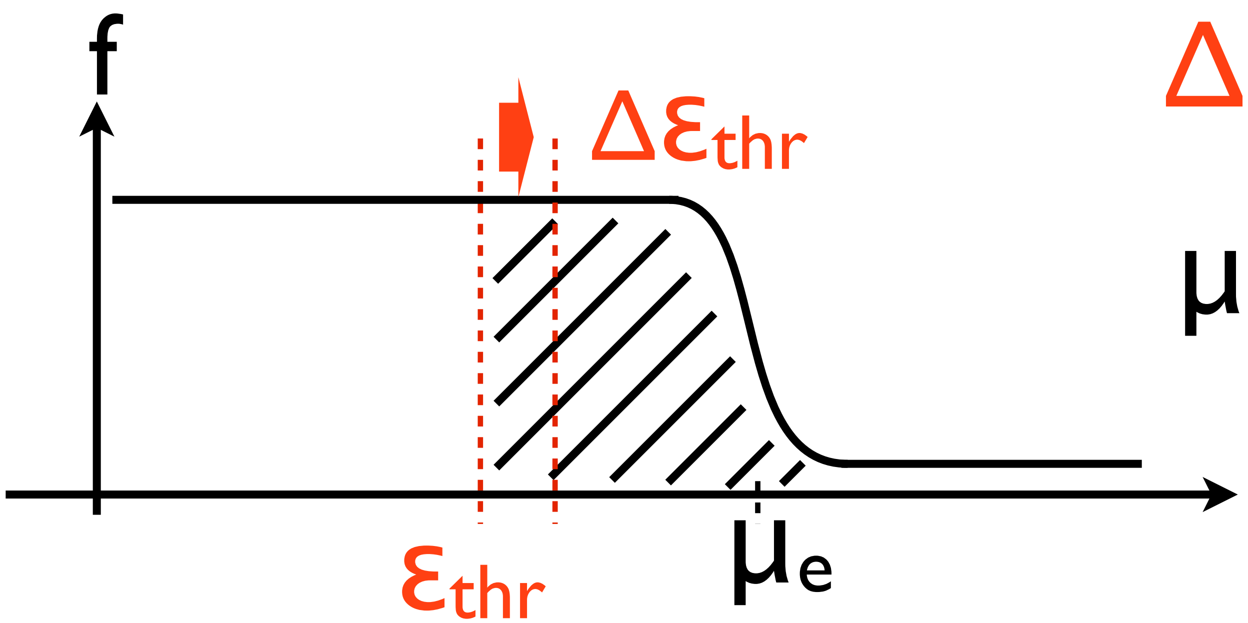
Table 2

Central Mass Fractions of the 14 Most Abundant Isotopes at the End of the Core Carbon Burning Phase

^{16}O	^{20}Ne	^{24}Mg	^{23}Na	^{25}Mg	^{26}Mg	^{27}Al
4.783×10^{-1}	4.074×10^{-1}	4.255×10^{-2}	3.217×10^{-2}	1.451×10^{-2}	7.952×10^{-3}	7.245×10^{-3}
^{22}Ne	^{28}Si	^{12}C	^{21}Ne	^{30}Si	^{29}Si	^{32}S
2.836×10^{-3}	2.330×10^{-3}	1.277×10^{-3}	8.384×10^{-4}	3.621×10^{-4}	3.362×10^{-4}	1.463×10^{-4}

The Coulomb correction for electron capture rates

$$\lambda_{ec} = \frac{1}{\pi^2\hbar^2}\sum\int_{\varepsilon_{thr}+\Delta\varepsilon_{thr}}^{\infty} p_e^2\,\sigma_{ec}\,f(\varepsilon_e-\mu_e)\,d\varepsilon_e$$

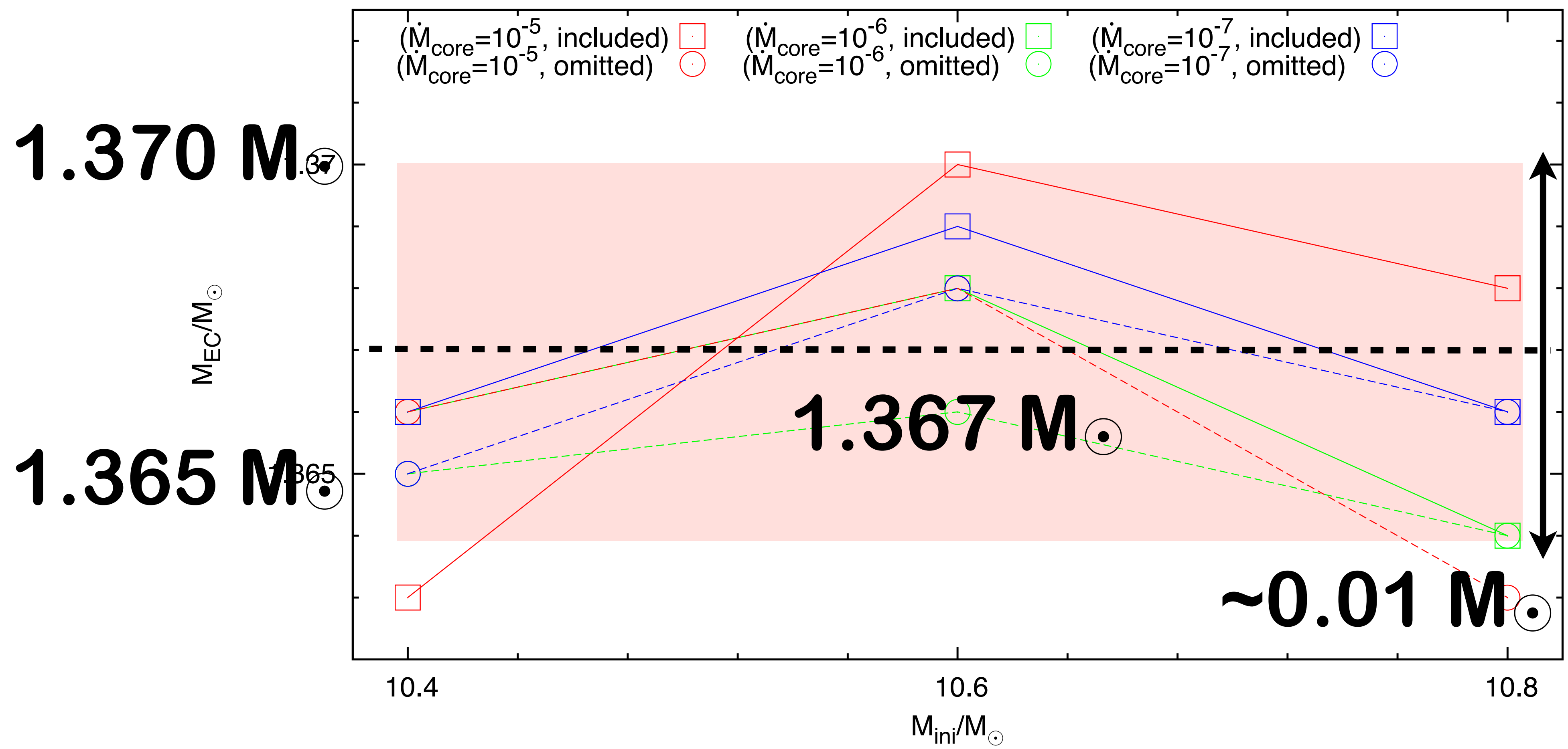


$$\Delta\varepsilon_{thr} = \mu_{ion}(Z-1)-\mu_{ion}(Z)$$

$$\mu_{ion}(Z) = -kT\left(\frac{\bar{Z}}{Z}\right)\left\{\Gamma_z\left[0.9+c_1\left(\frac{\bar{Z}}{Z}\right)^{1/3}+c_2\left(\frac{\bar{Z}}{Z}\right)^{2/3}\right] + \left[d_0+d_1\left(\frac{\bar{Z}}{Z}\right)^{1/3}\right]\right\}$$

(Couch & Loumos 1974; DeWitt et al. 1973)

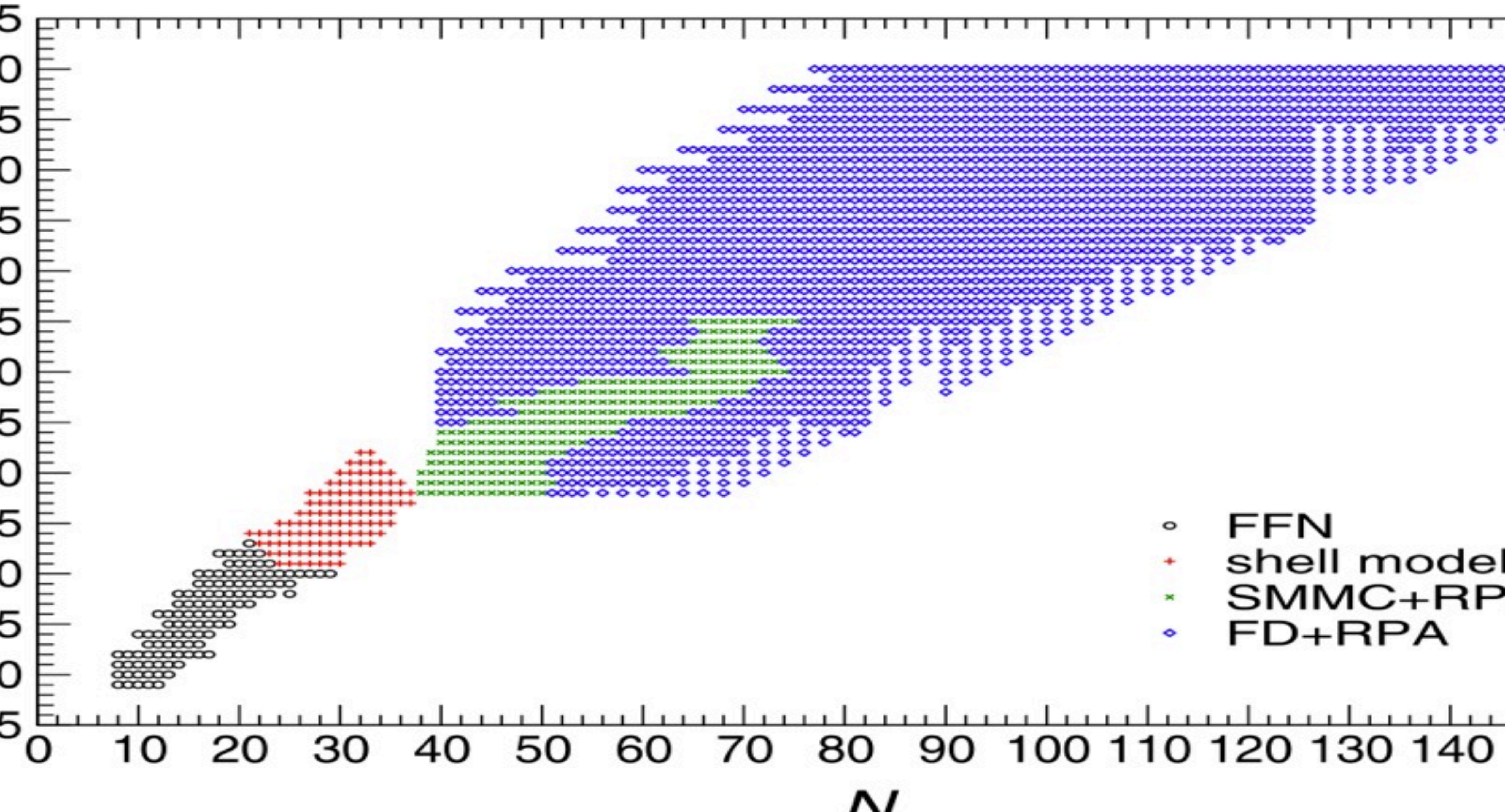
New physics



- ONe core evolution is independent from parameters (3 M_{ZAMS} & 3 $\dot{M}_{core}$)
- **Extremely degenerate ONe core** should have a unique structure

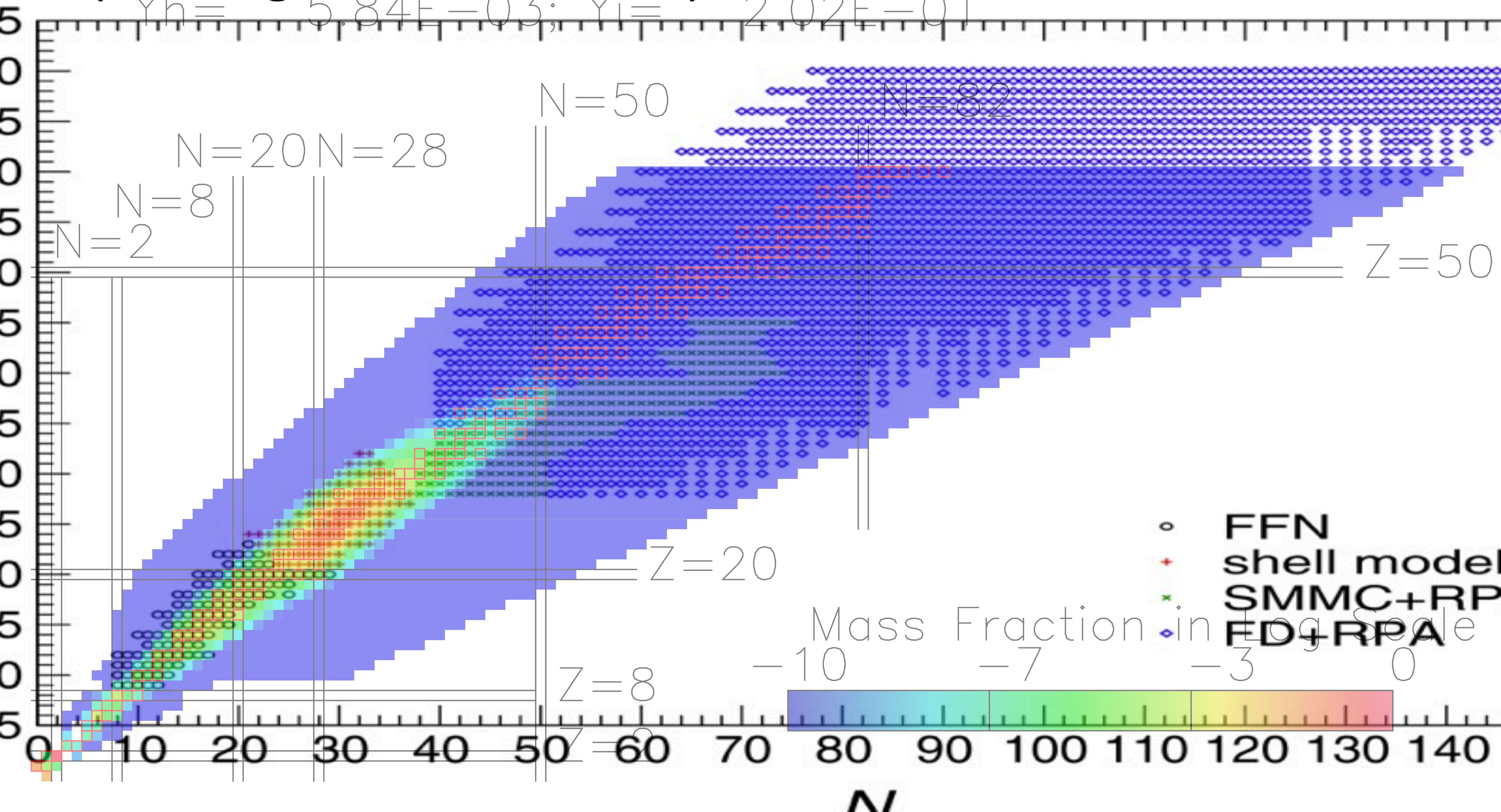
New physics

- electron capture by neutron-rich isotopes in NSE compositions (Juodagalvis et al. 2010)



New physics

- electron capture by neutron-rich isotopes in NSE compositions (Juodagalvis et al. 2010)



New physics

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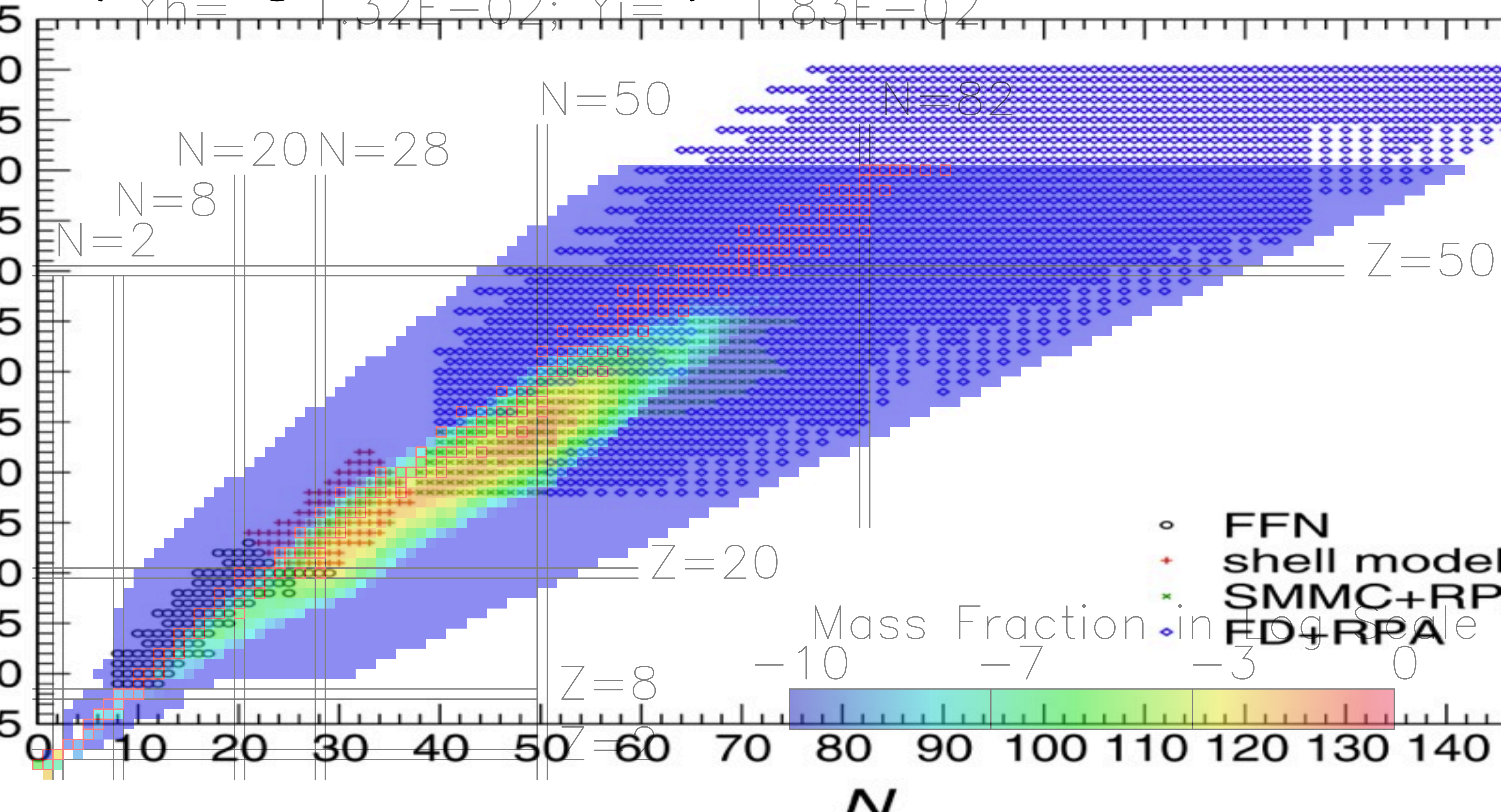
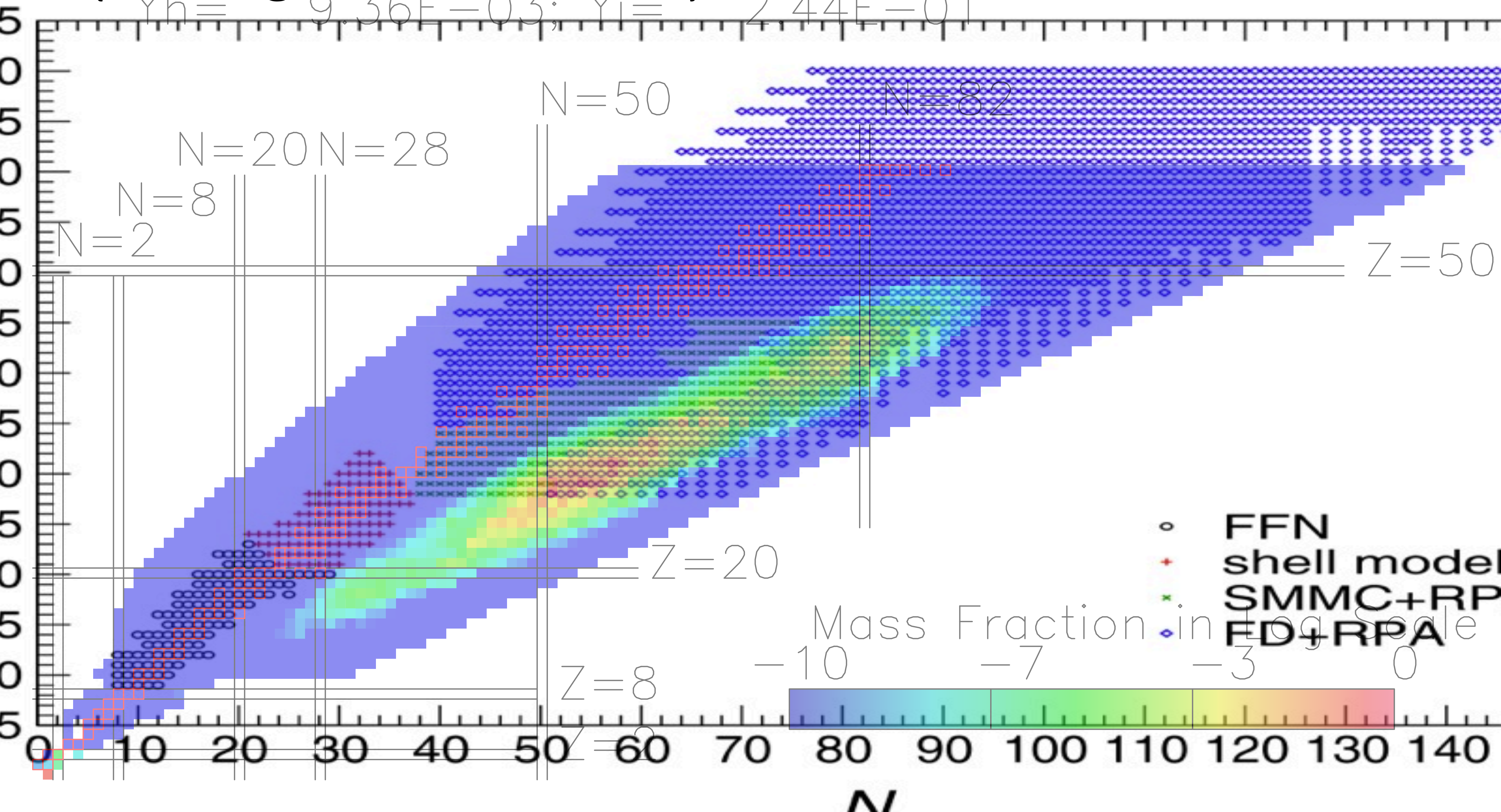
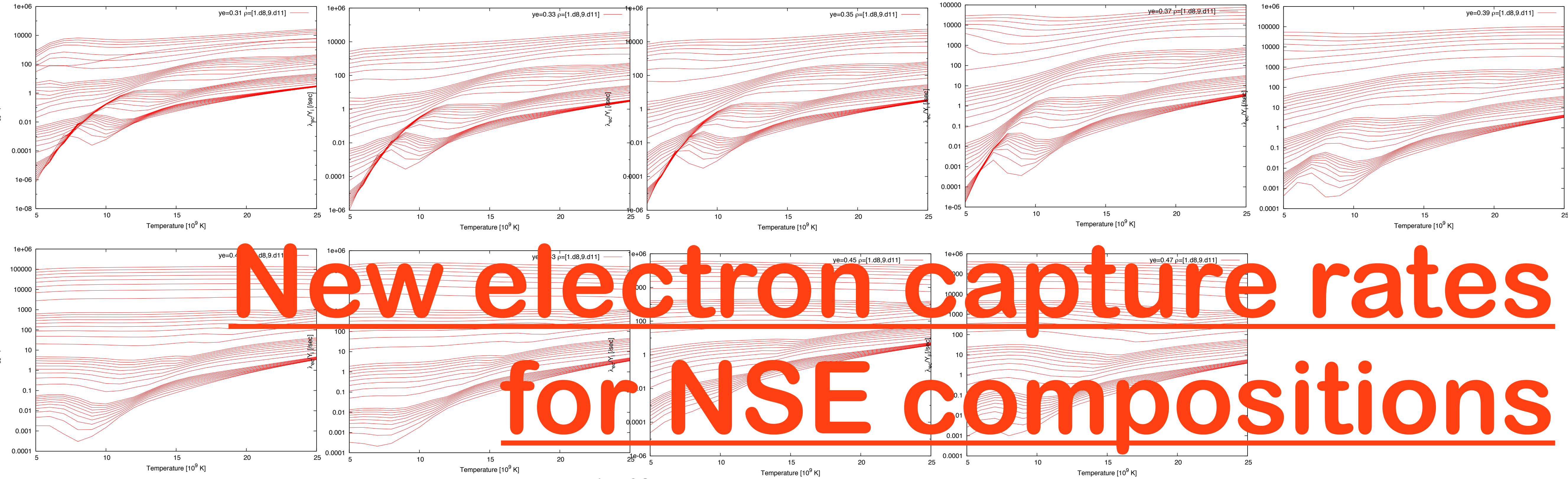


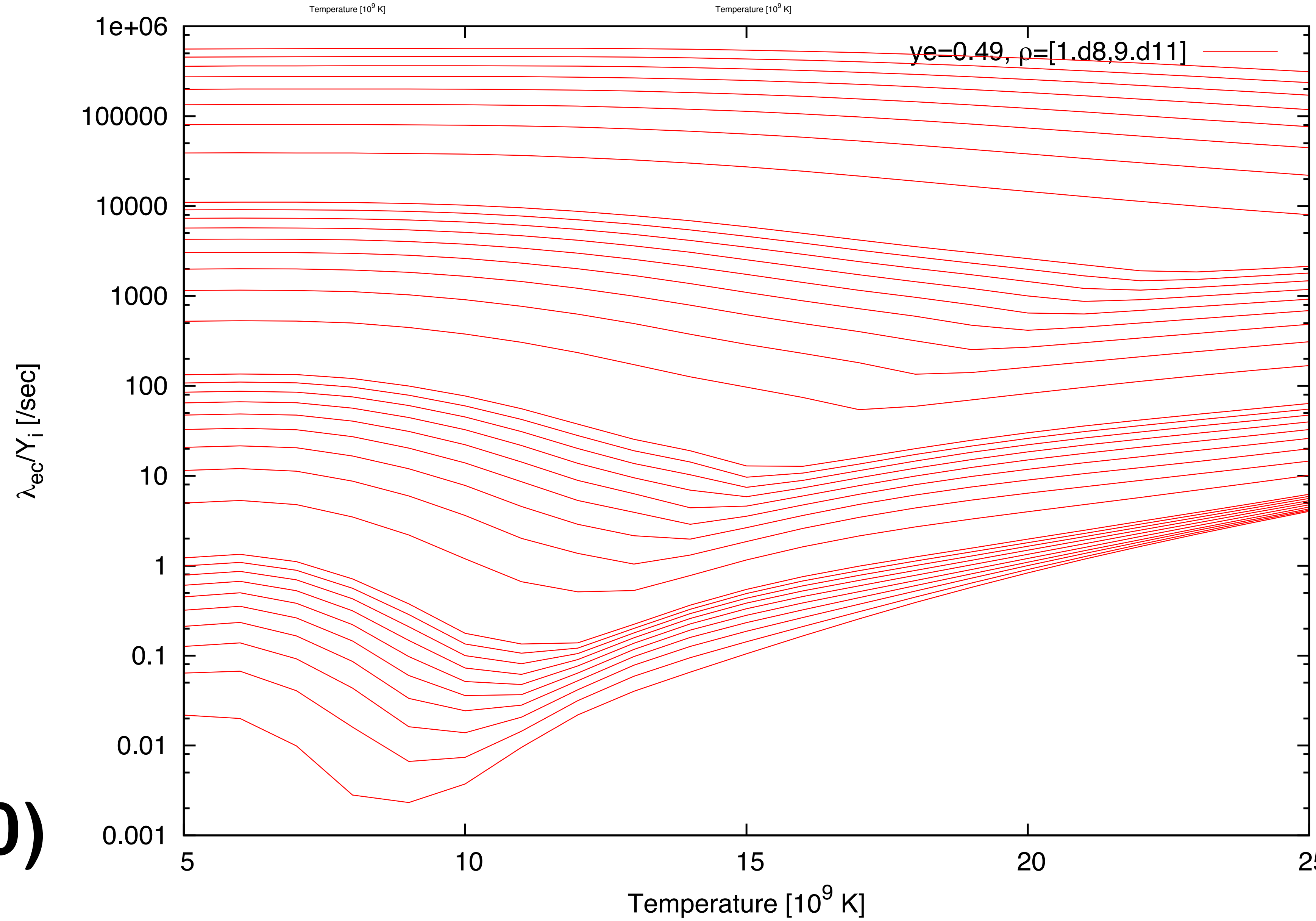
New physics

- electron capture by neutron-rich isotopes in NSE compositions (Juodagalvis et al. 2010)



New electron capture rates for NSE compositions



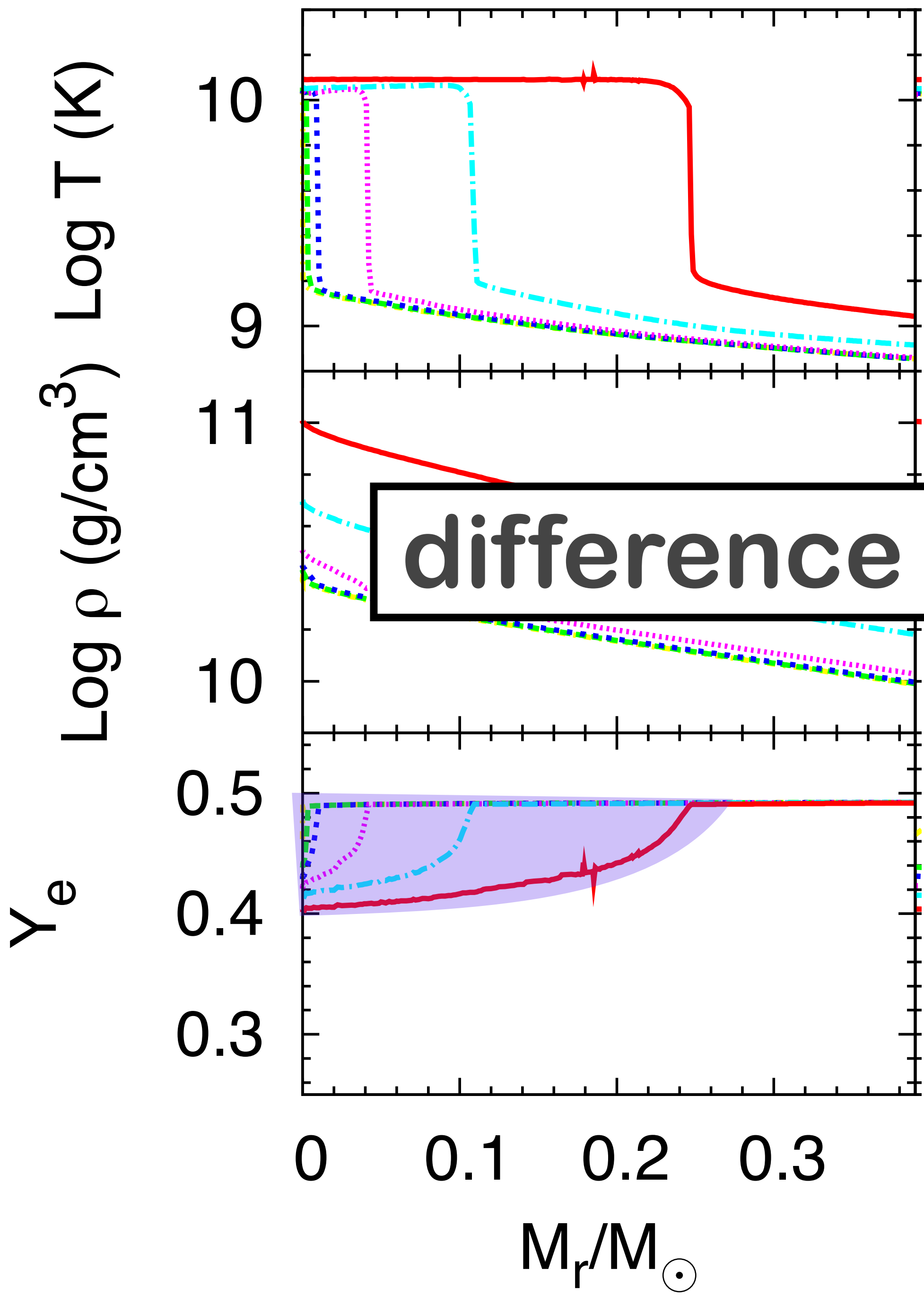


- electron capture by **neutron-rich isotopes**

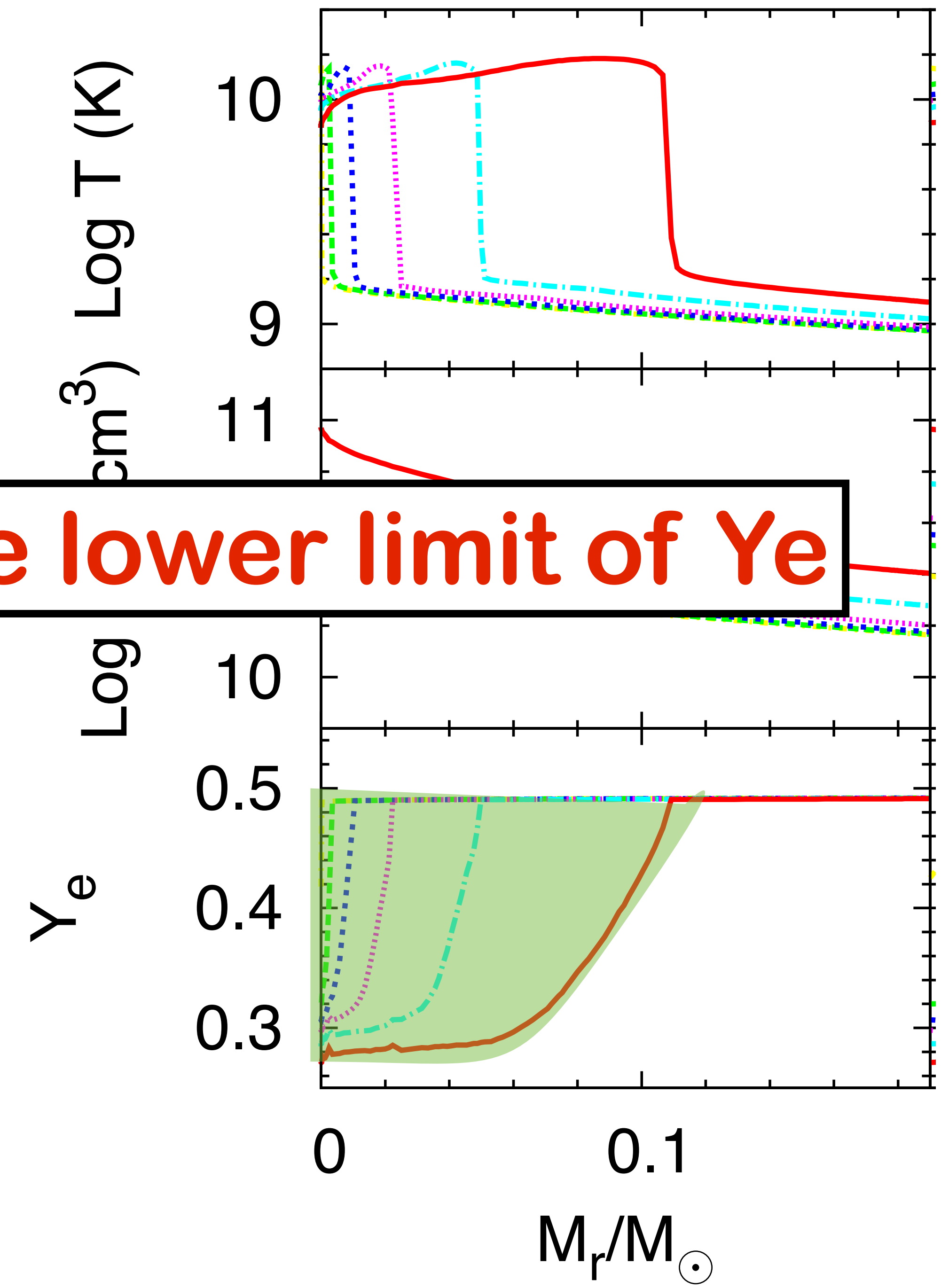
(Juodagalvis+ 2010)

New physics

only by free-protons



by protons + n-rich isotopes



difference in the lower limit of Ye

Until core collapse

Short summary 3

- odd proton number isotopes
  -> minor (convective URCA?)
- the Coulomb correction
  -> minor
- neutron-rich isotopes
  -> important

Conclusion

- ECSNe arise from the most massive SAGB stars.
- In the star, a highly degenerate ONe core forms.
- Some robust properties of ECSN can be expected from the SAGB structure.

- Core evolution can be divided into 4 sub-phases.
- Deflagration phase is much complicated.
- Core collapse is finally induced by electron capture in the NSE region.

- Electron capture by odd proton number nuclei and the Coulomb correction on the rates have minor effect.
- Electron capture by neutron-rich isotopes in NSE compositions should be treated.

Evolution of the most massive AGB star as a progenitor for ECSNe

The End

Thank you for your attention!

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