Presupernova Evolution of Massive Stars: Current Status and Future Directions

Marco Limongi

INAF – Osservatorio Astronomico di Roma, ITALY

INFN – Sezione di Perugia, ITALY

Kavli IPMU, University of Tokyo, JAPAN

marco.limongi@inaf.it

and

Alessandro Chieffi, INAF – IAPS, Italy

Lorenzo Roberti, INFN-LNS, Italy

Agnese Falla, Sapienza University of Rome, Italy

Ken'ichi Nomoto, IPMU – The University of Tokyo, Japan

Why do we care about Massive Stars?

Massive stars play e fundamental role in the evolution of the Universe

- Produce of most of the heavy elements (especially those necessary to life)
- Light up regions of stellar birth → induce star formation
- Contribute to the production of Neutron Stars and Black Holes
- Constitute a natural laboratory for the study of the physics of neutrinos
- Are the progenitors of long Gamma Ray Bursts
- Are sources of Gravitational Waves (collapse and remnants)

A good knowledge of the evolution of these stars is required in order to shed light on many astrophysical topical subjects

Presupernova Evolutions

$$\frac{\partial P}{\partial m} = -\frac{Gm}{4\pi r^4}$$
$$\frac{\partial r}{\partial m} = \frac{1}{4\pi r^2 \rho}$$
$$\frac{\partial l}{\partial m} = \varepsilon_n + \varepsilon_\nu - c_P \frac{\partial T}{\partial t} + \frac{\delta}{\rho}\frac{\partial P}{\partial t}$$
$$\frac{\partial T}{\partial m} = -\frac{GmT}{4\pi r^2 \rho}\nabla$$
$$\frac{dY_i}{dt} = \sum_j c_i(j)\lambda_j Y_j + \sum_{j,k} c_i(j,k)\rho N_A \langle\sigma v\rangle_{j,k} Y_j Y_k + \sum_{j,k,l} c_i(j,k,l)\rho^2 N_A^2 \langle\sigma v\rangle_{j,k,l} Y_j Y_k Y_l + \frac{\partial}{\partial m}\left[(4\pi r^2\rho)^2 D \frac{\partial Y_i}{\partial m}\right] \quad i = 1, ...N$$
$$\rho\frac{d}{dt}\left(r^2\omega\right) = \frac{1}{5r^2}\frac{\partial}{\partial r}\left(\rho r^4 \omega U\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho D_{\rm shear} r^4 \frac{\partial \omega}{\partial r}\right)$$

Full Coupling of
- Physical Structure Equations
- Chemical Evolution due to Nuclear Burning
- Mixing

Inclusion of Rotation
- Transport of Angular Momentum (Advection/Diffusion)
- Rotation Driven Mixing (Diffusion)
- Coupling Mass Loss - Rotation

340 isotopes Nuclear Network (n-Bi) fully coupled to all the equations

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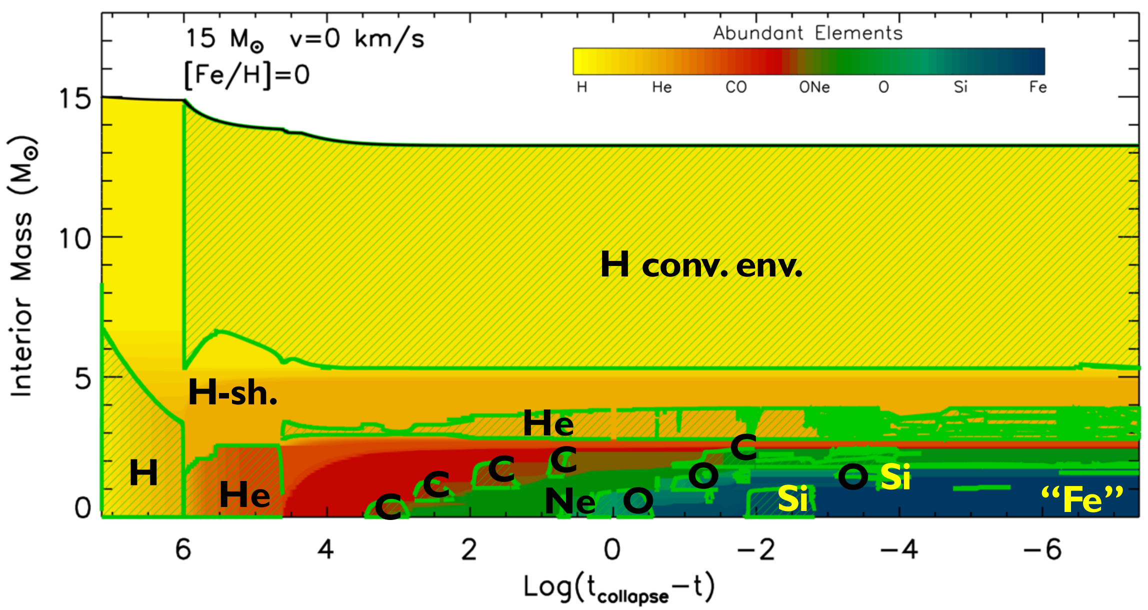
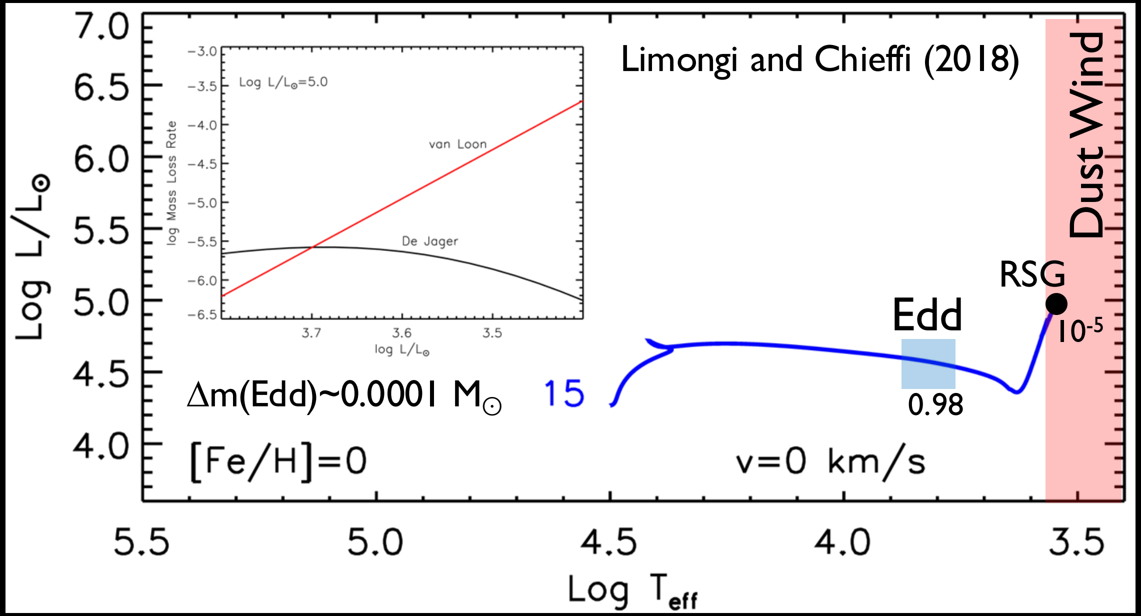
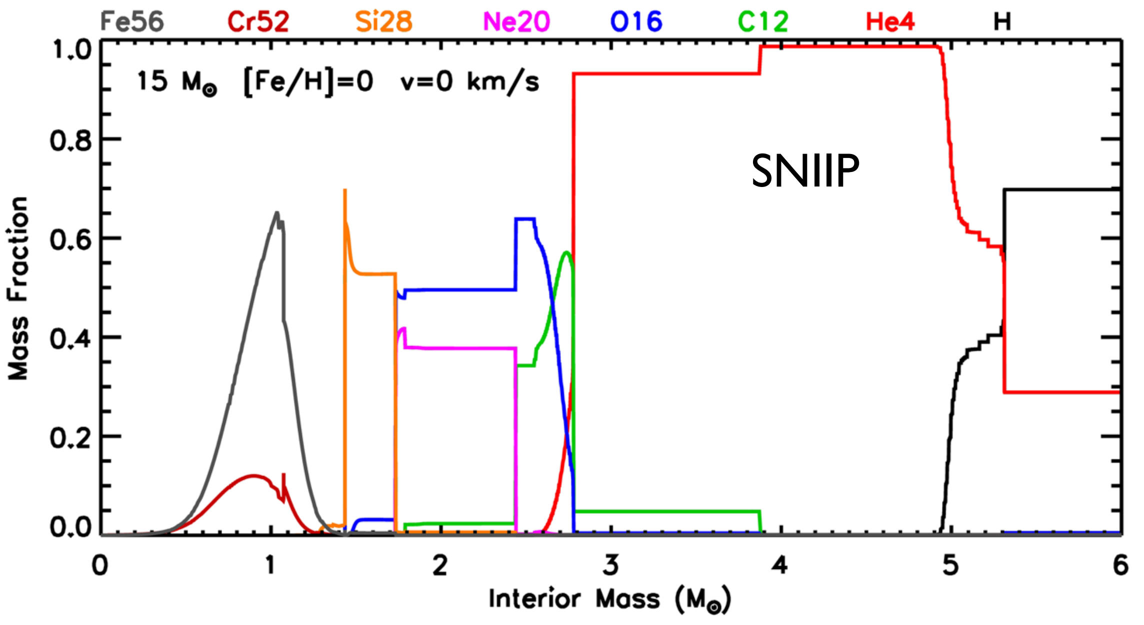
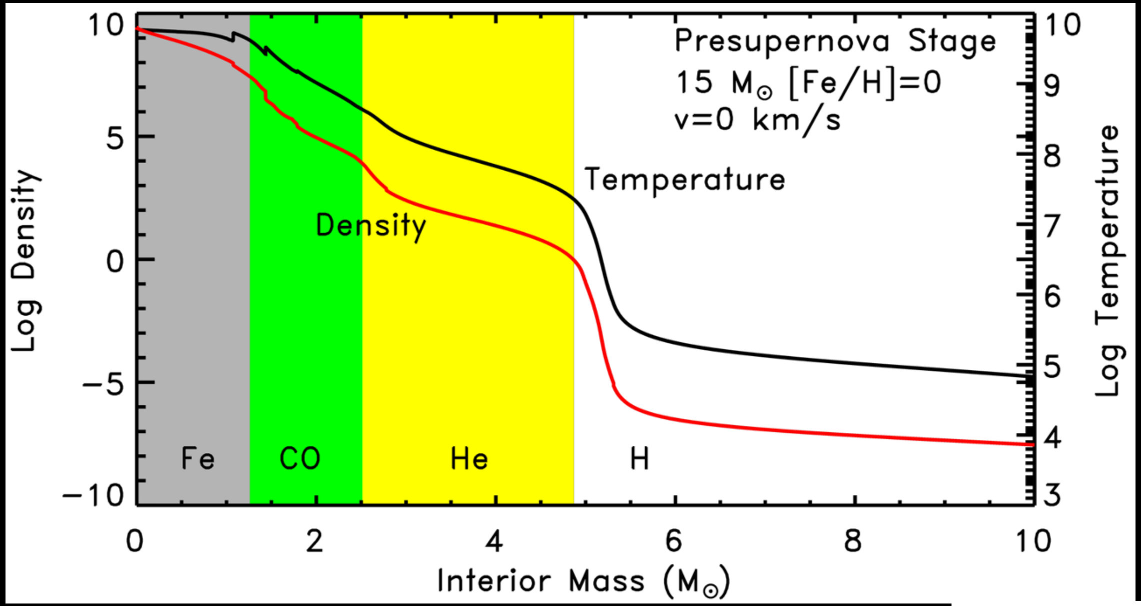
Chieffi & Limongi (2013) – Limongi & Chieffi (2018)

Solar Metallicity non Rotating Models: Presupernova Evolution

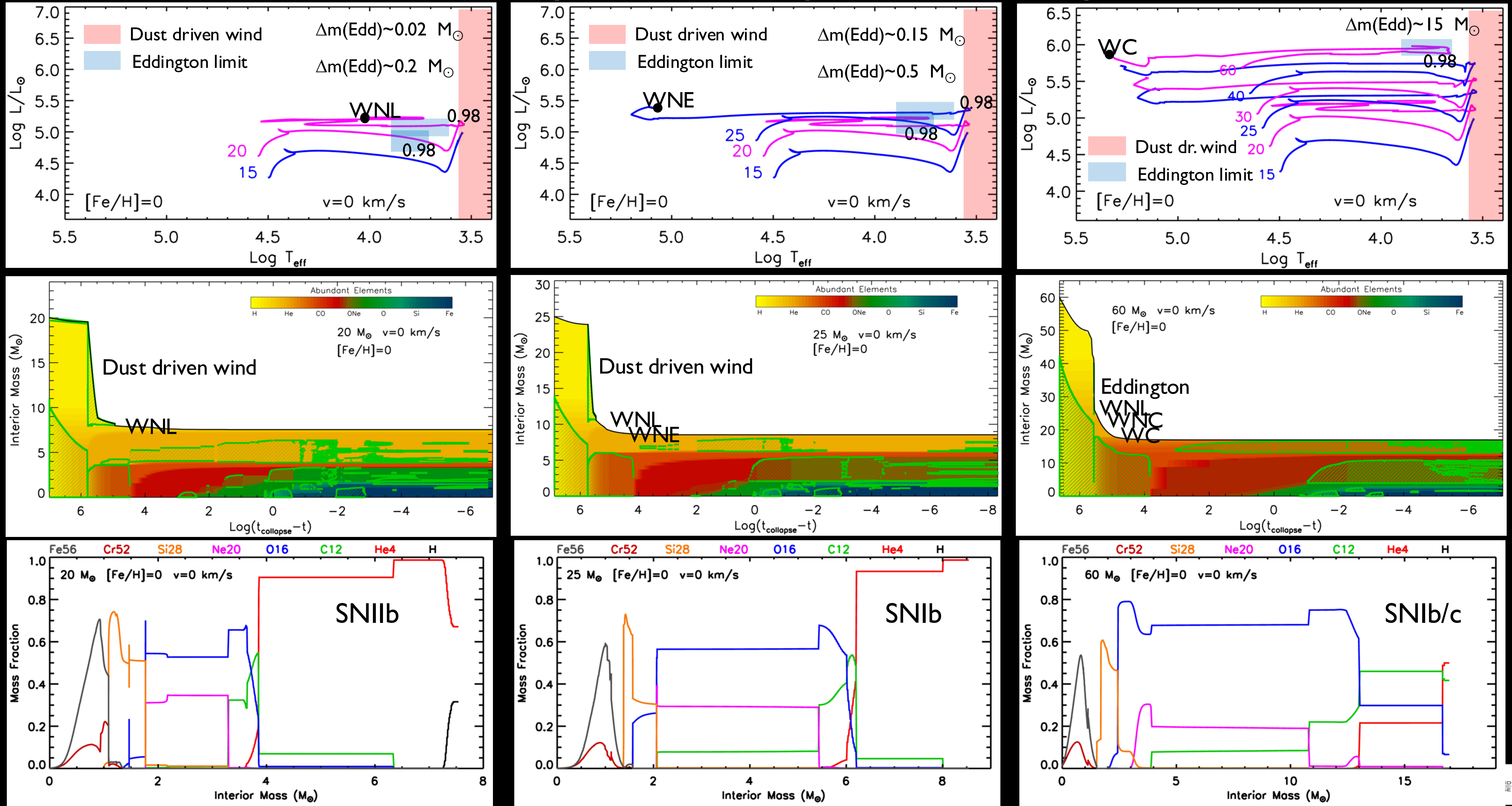








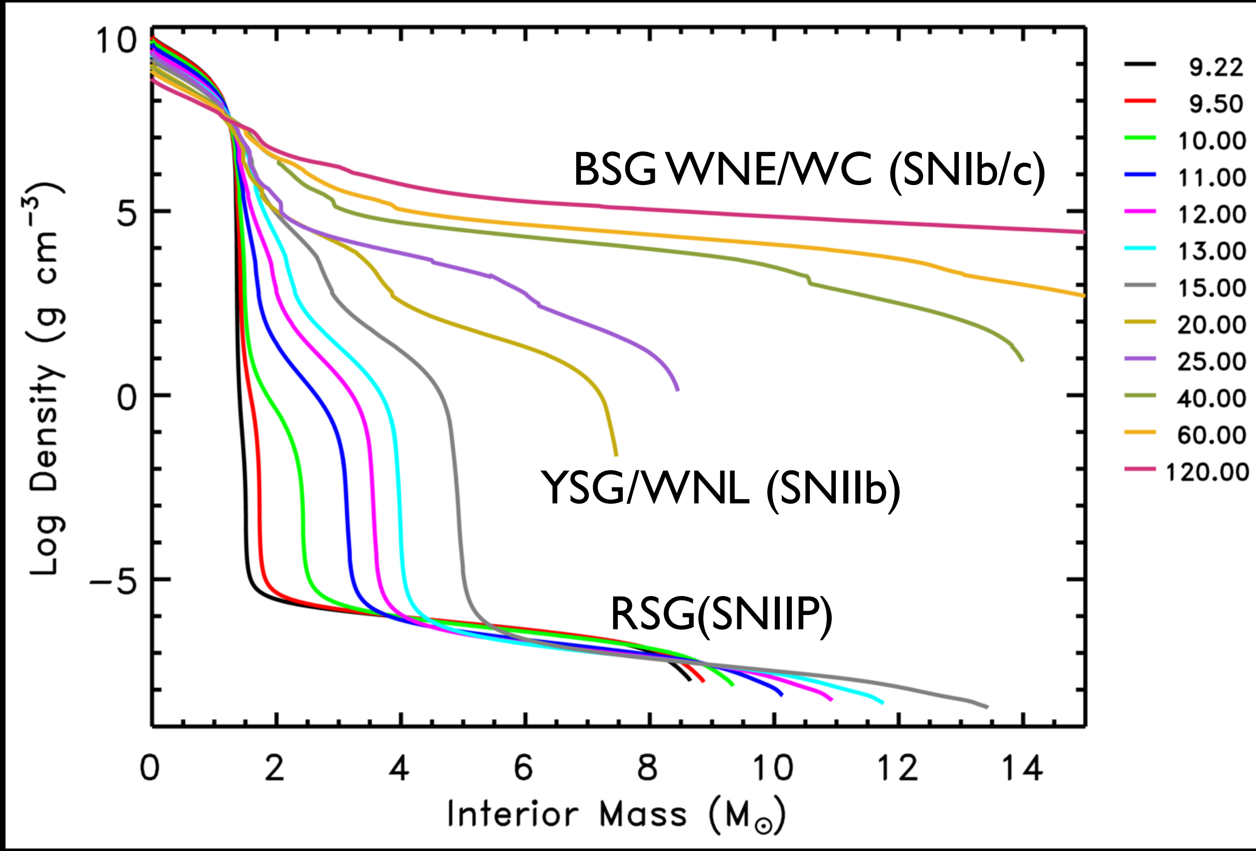
Solar Metallicity non Rotating Models: Presupernova

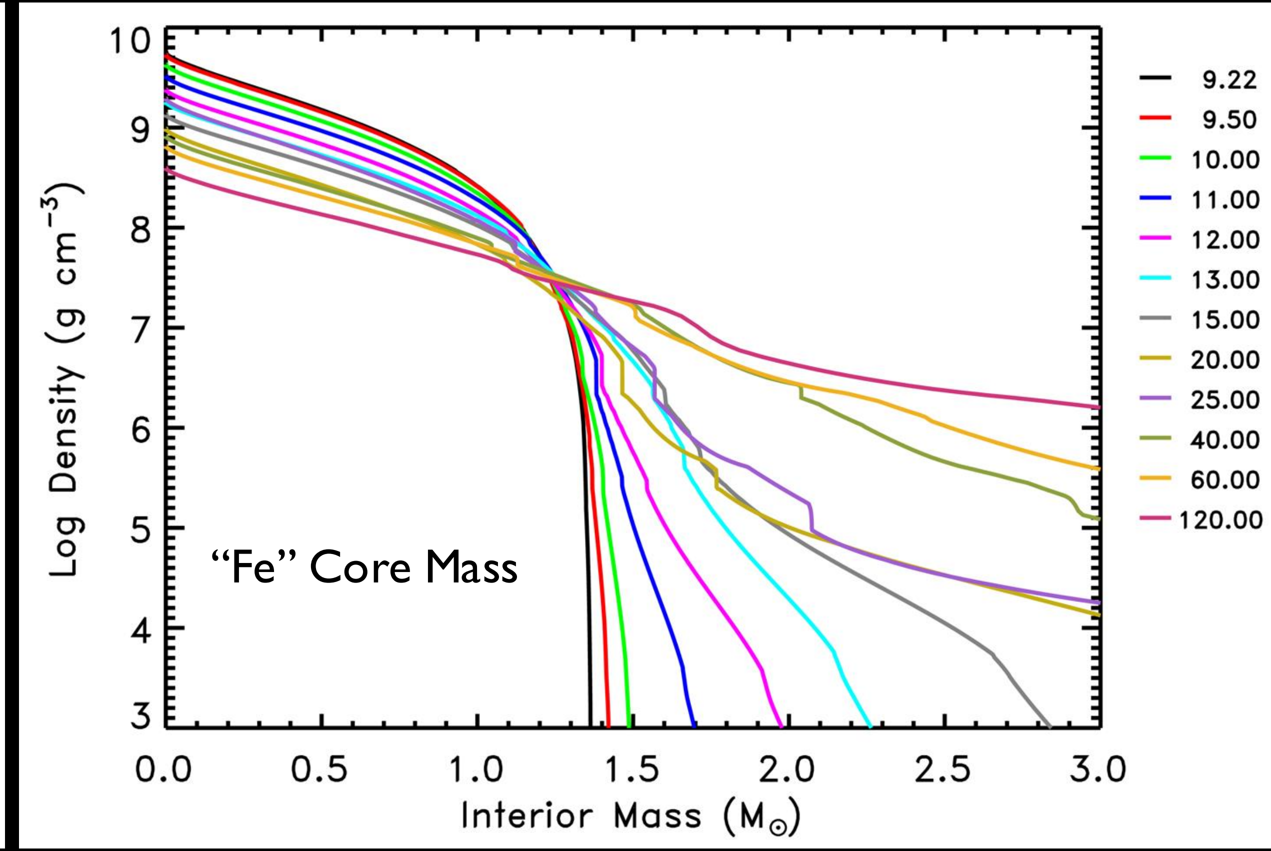


The Presupernova Stars

The complex interplay among the shell nuclear burning and the timing of the convective zones determines in a direct way the final physical and chemical structure

The mass loss history (RSG/WR) determines in a direct way the CCSN type





Models from Limongi and Chieffi (2018) and Limongi+ (2024)

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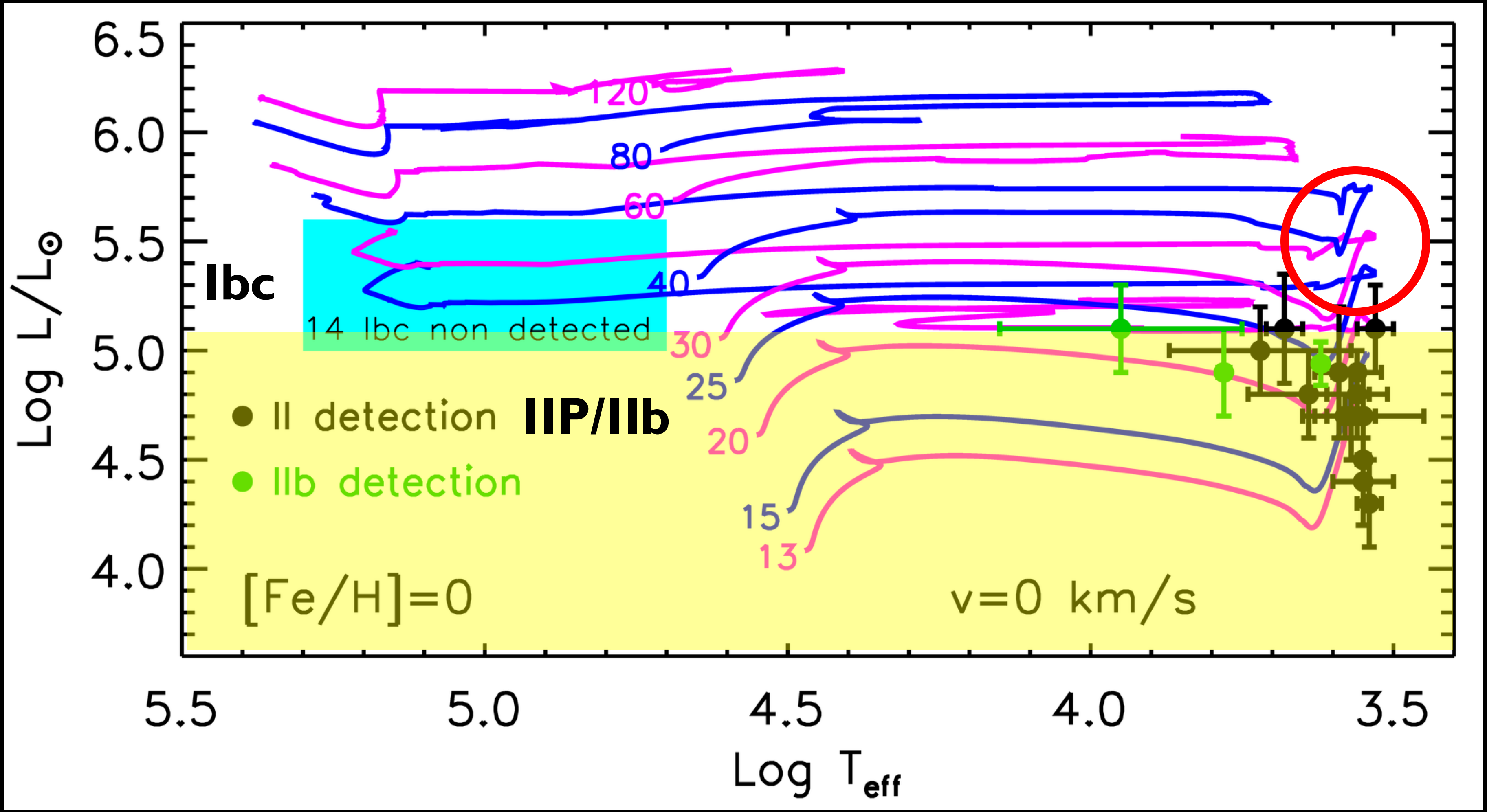
The Progenitors of Core Collapse Supernovae



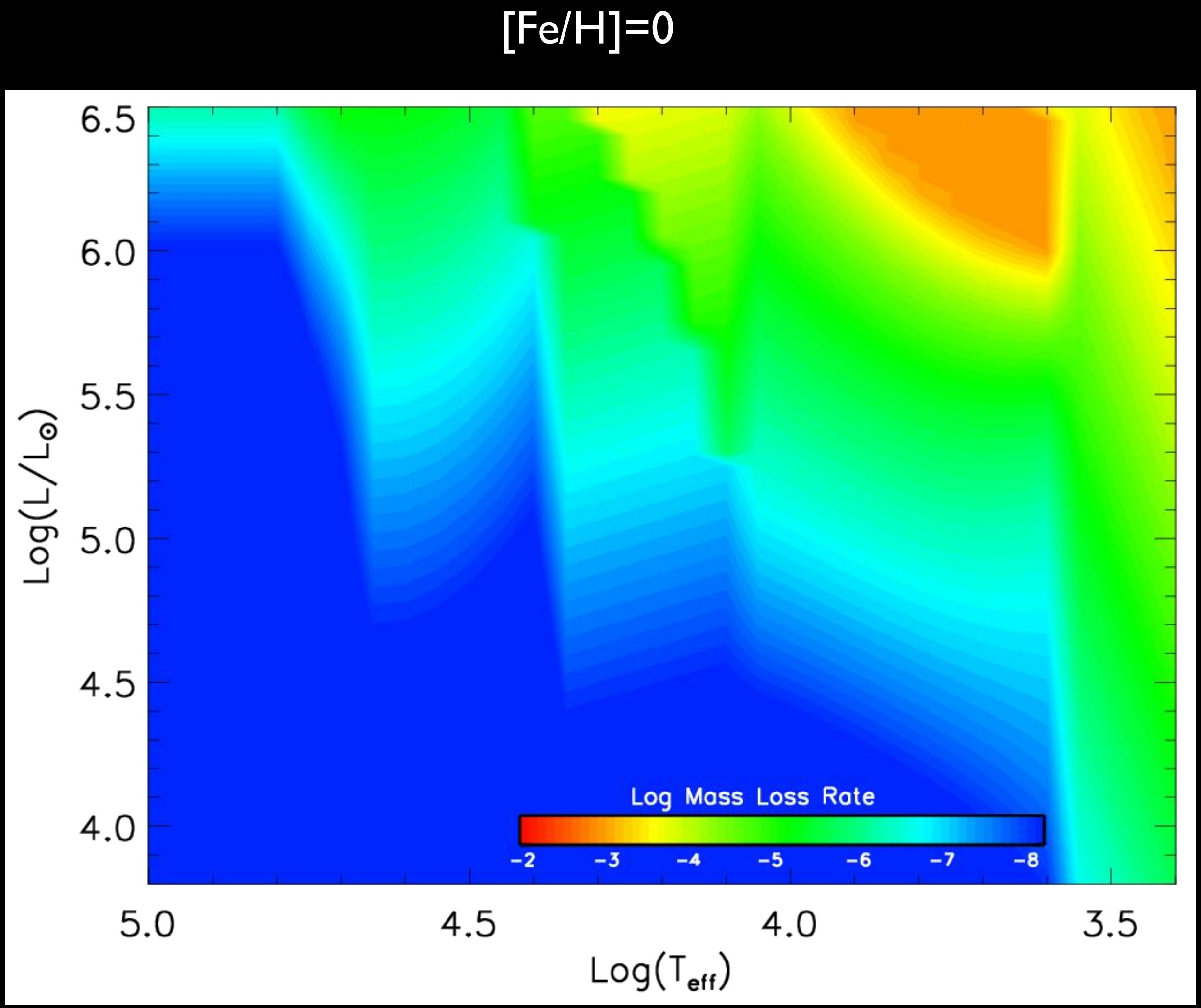
Models from Limongi and Chieffi (2018) Data from Smartt+(2015)

The high luminosity RSGs are predicted but then they explode as SNIbc

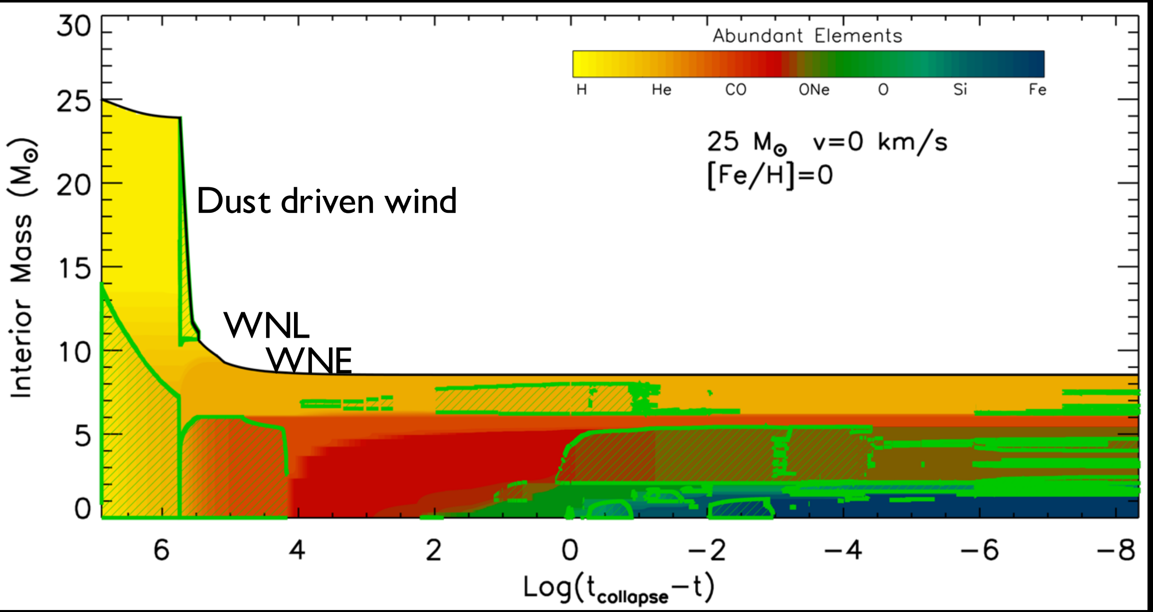
The maximum luminosity of the progenitor of SNIIP agrees with the observations

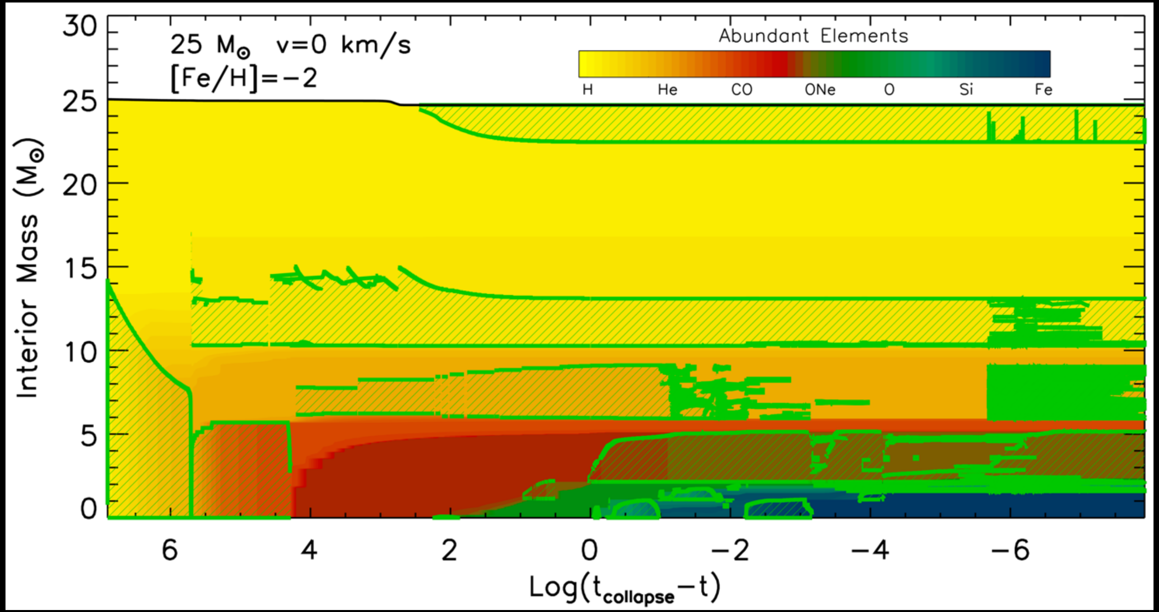
Low Metallicity non Rotating Models: Presupernova Evolution

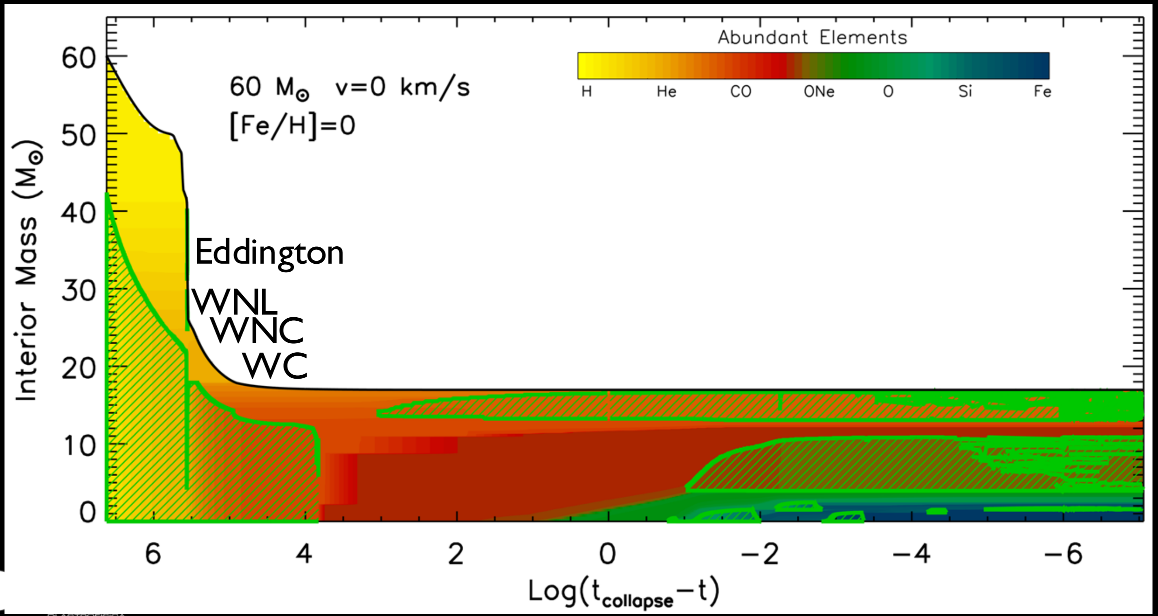
Mass loss reduces dramatically as the metallicity decreases $\dot{M} \sim Z^{0.85}$

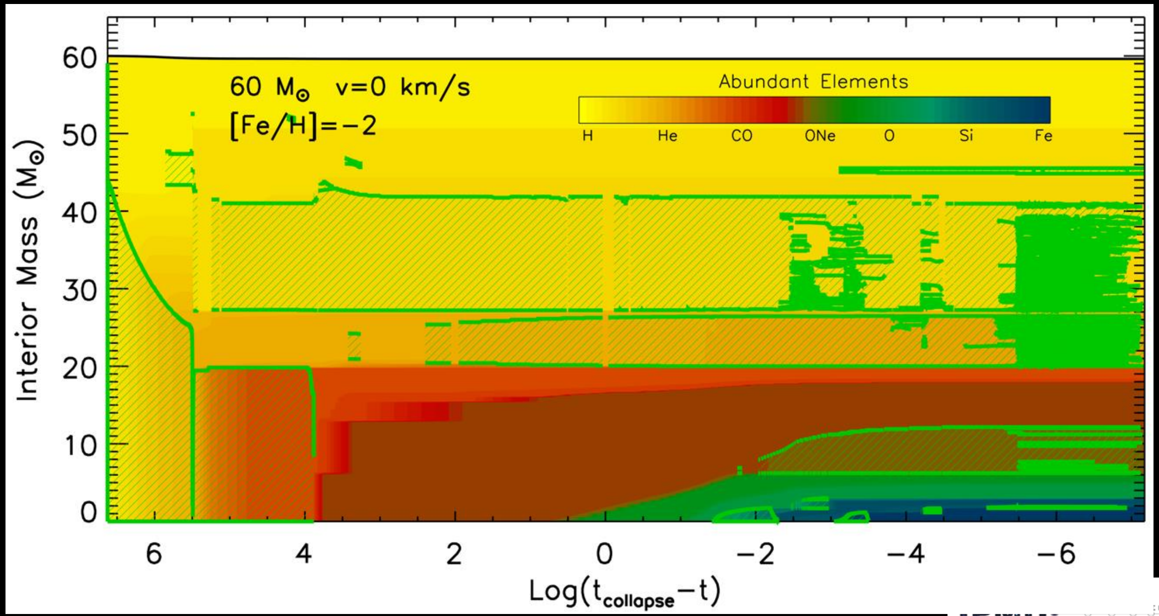


Low Metallicity non Rotating Models: Presupernova Evolution

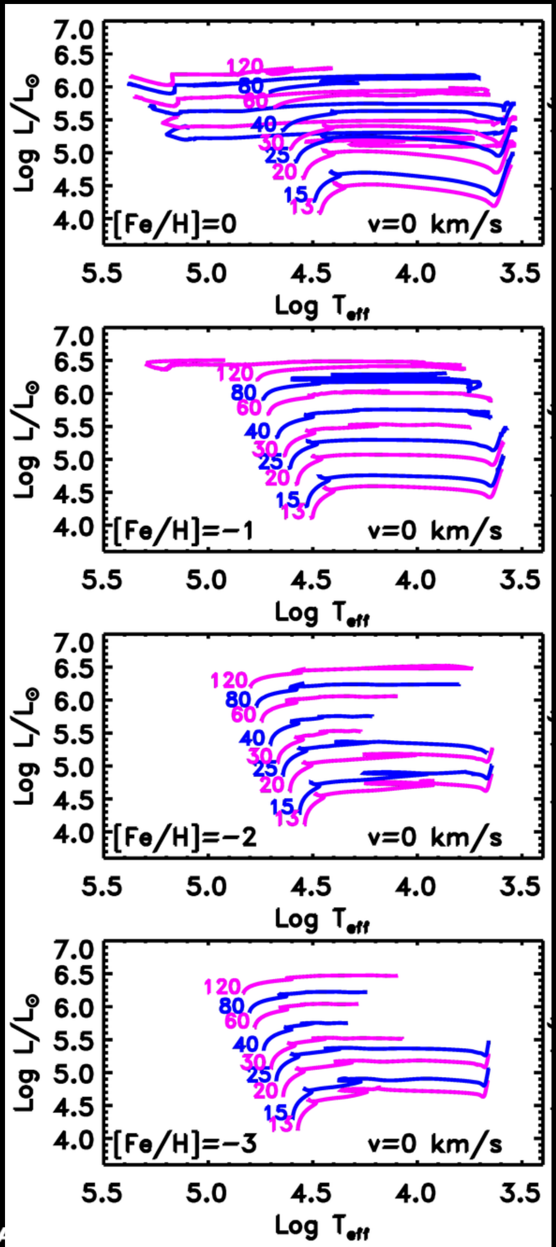




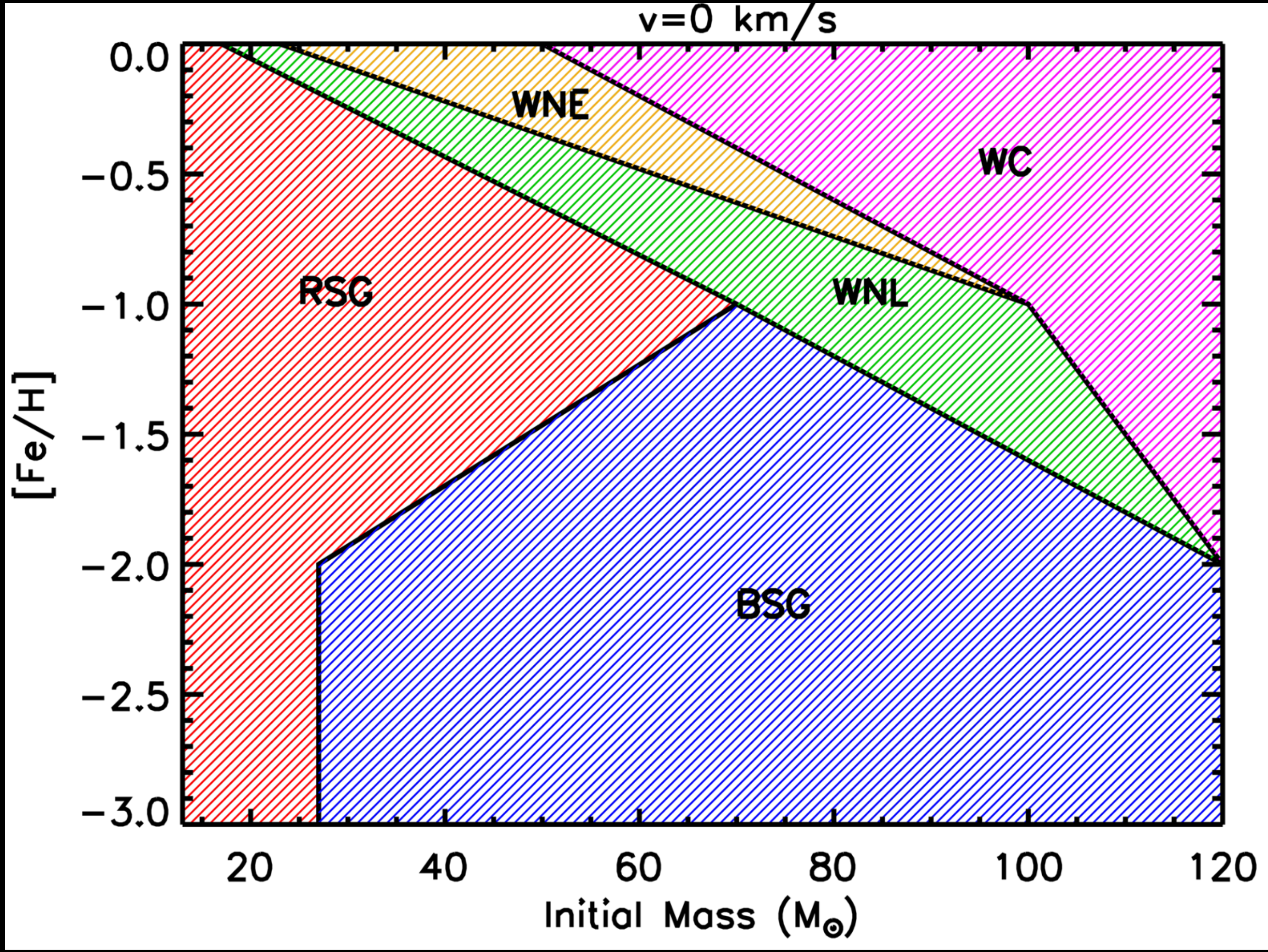




Low Metallicity non Rotating Models: Presupernova Evolution



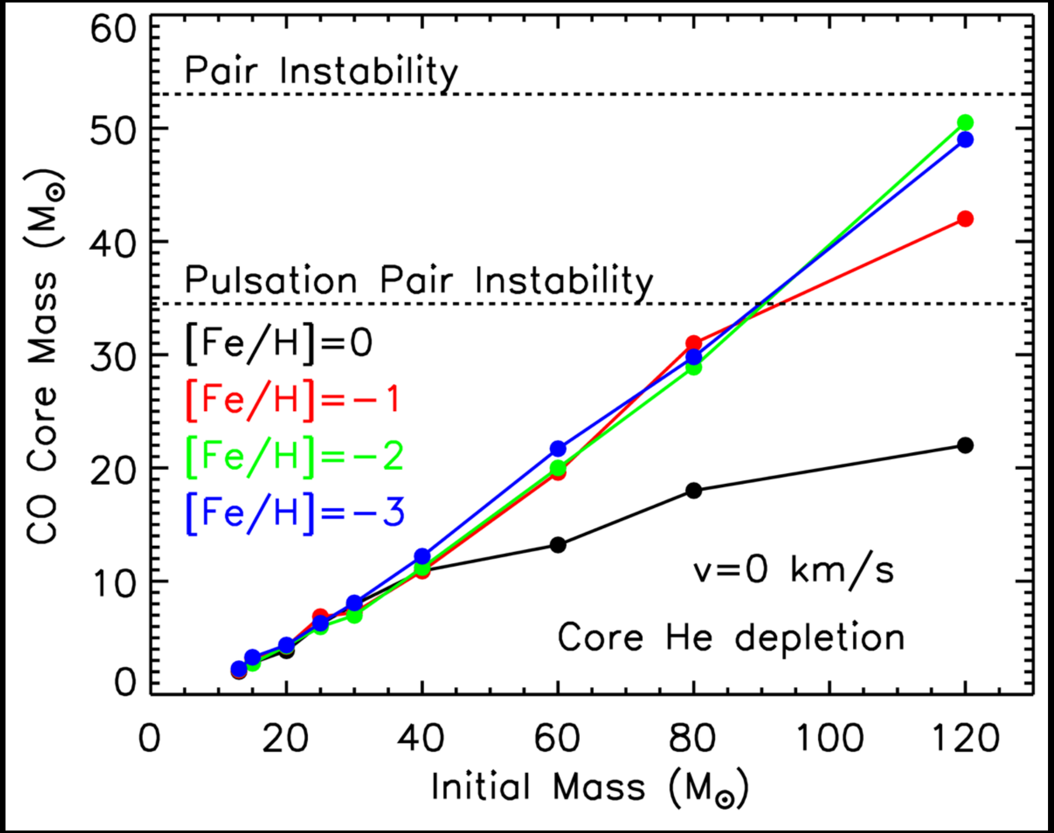
Mass loss progressively reduced - RSG phase progressively skipped - BSG with H-rich envelope SN

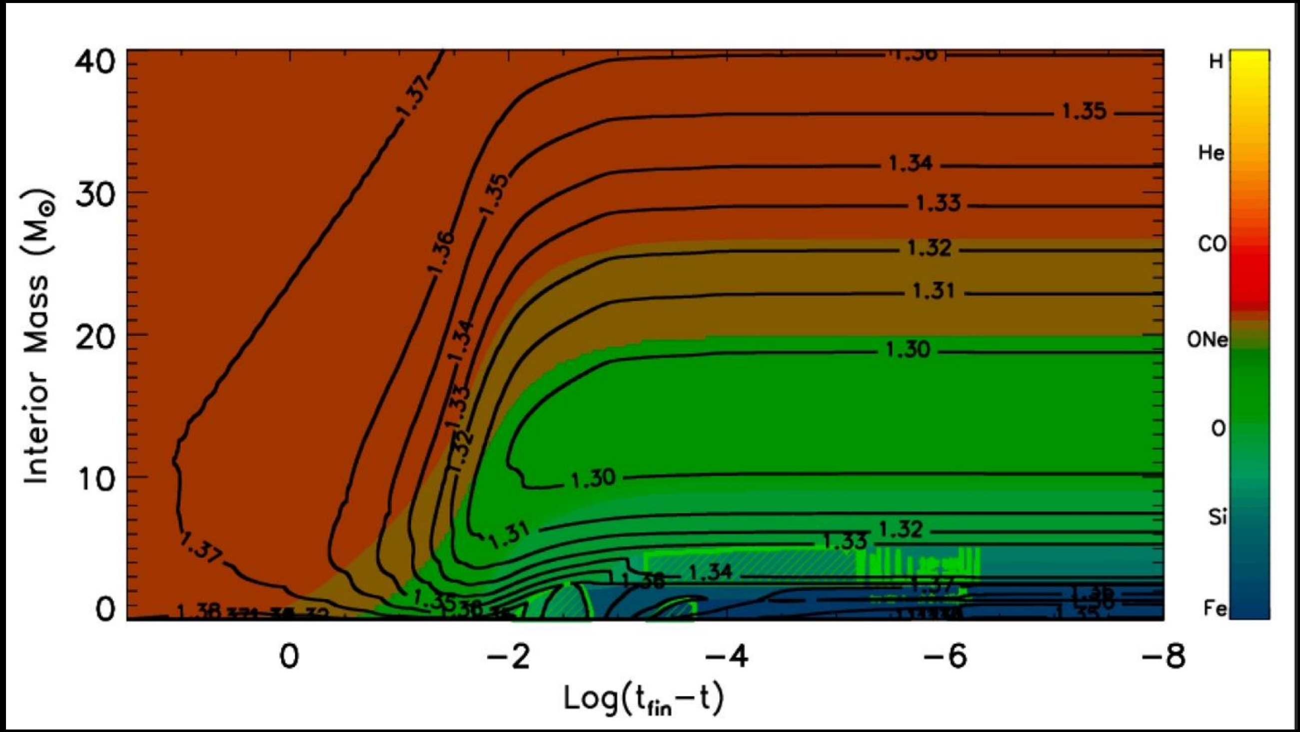


Limongi & Chieffi (2018)

Low Metallicity non Rotating Models: Presupernova Evolution

M ≥ 30 $M_\odot$ → CO core increases substantially as the metallicity decreases





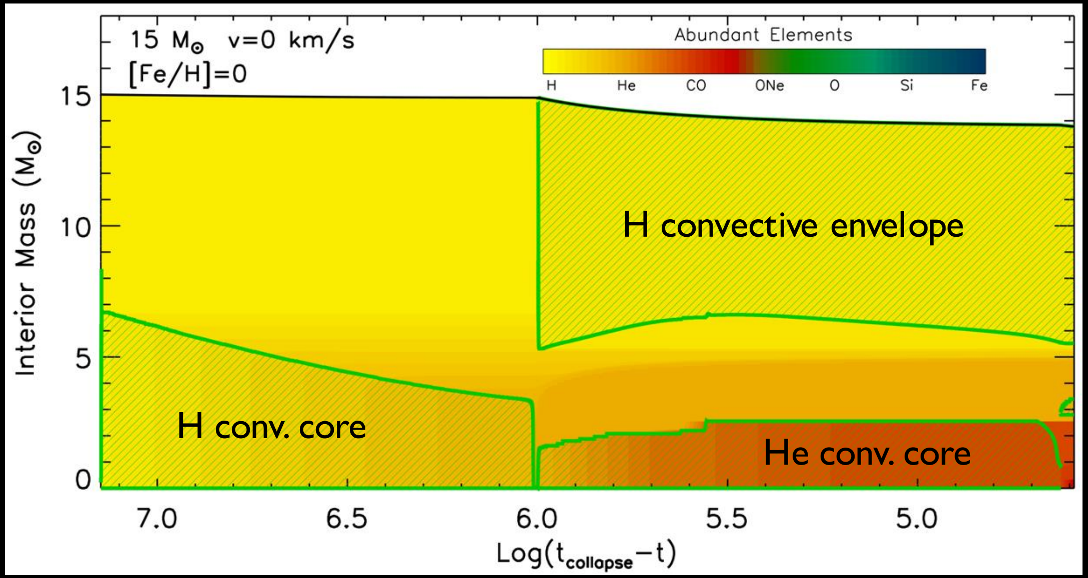
Models from Limongi & Chieffi (2018)

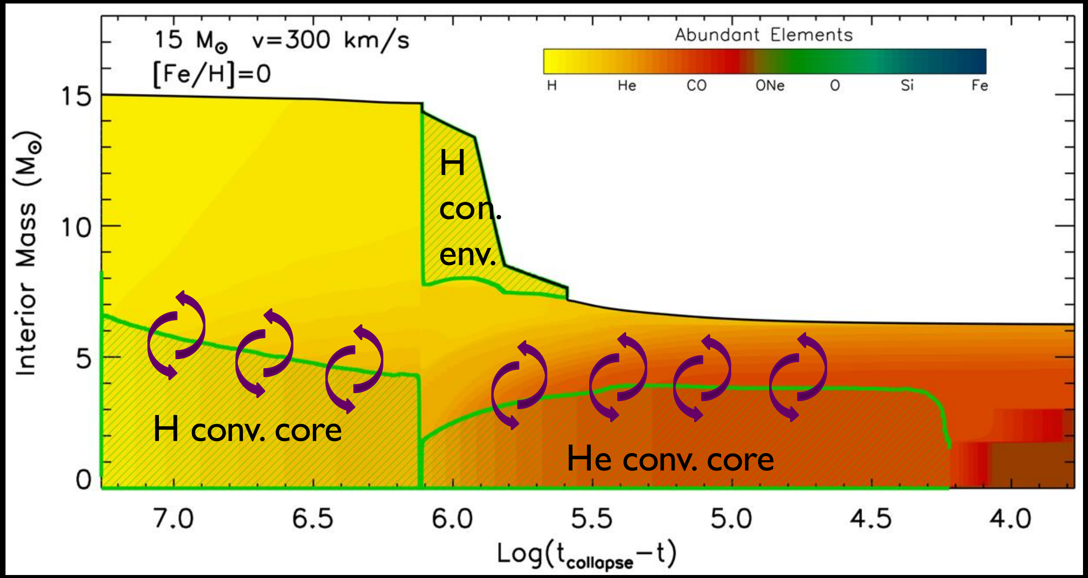
Stars with M > 90 $M_\odot$ with [Fe/H] ≤ -1 enter the Pulsation Pair Instability

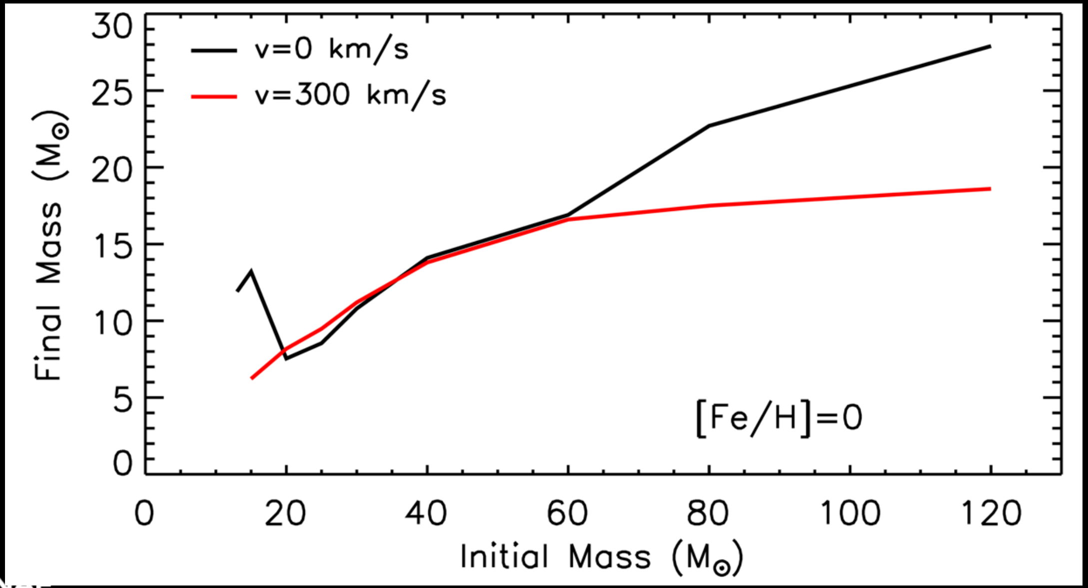
Stars with M > 130-140 $M_\odot$ with [Fe/H] ≤ -1 enter the Pair Instability

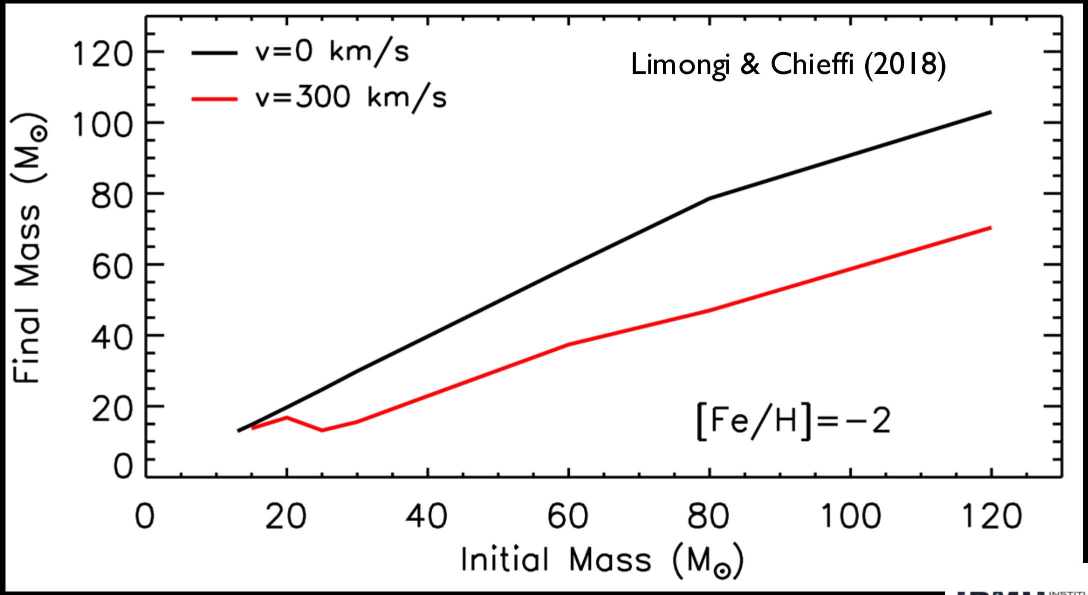
Rotating Models: Presupernova Evolution

Rotation driven mixing → larger cores / lower envelope opacity → higher L / lower T_{eff} → higher mass loss



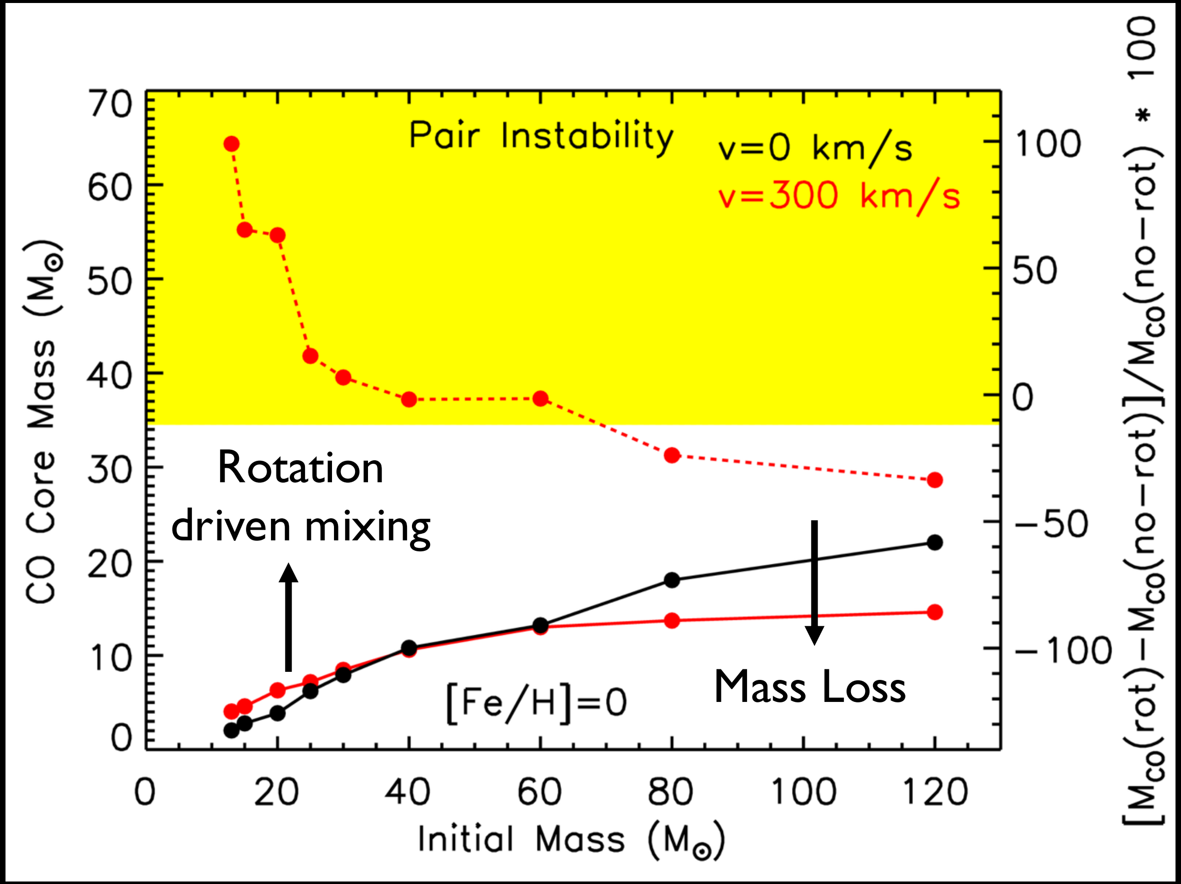


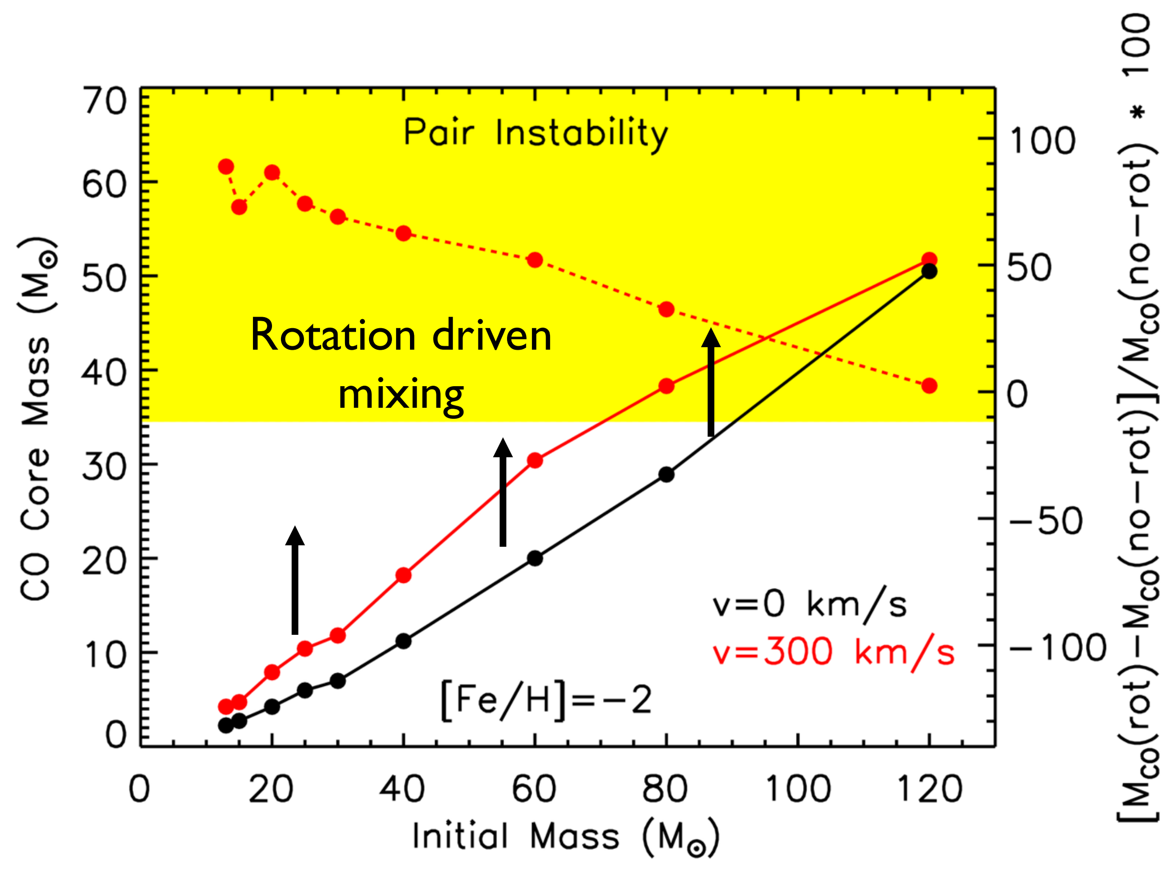




Rotating Models: Presupernova Evolution

Rotating models have larger CO cores because of the effect of rotation driven mixing
In high mass solar metallicity stars, the mass loss dominates and reduces the CO core



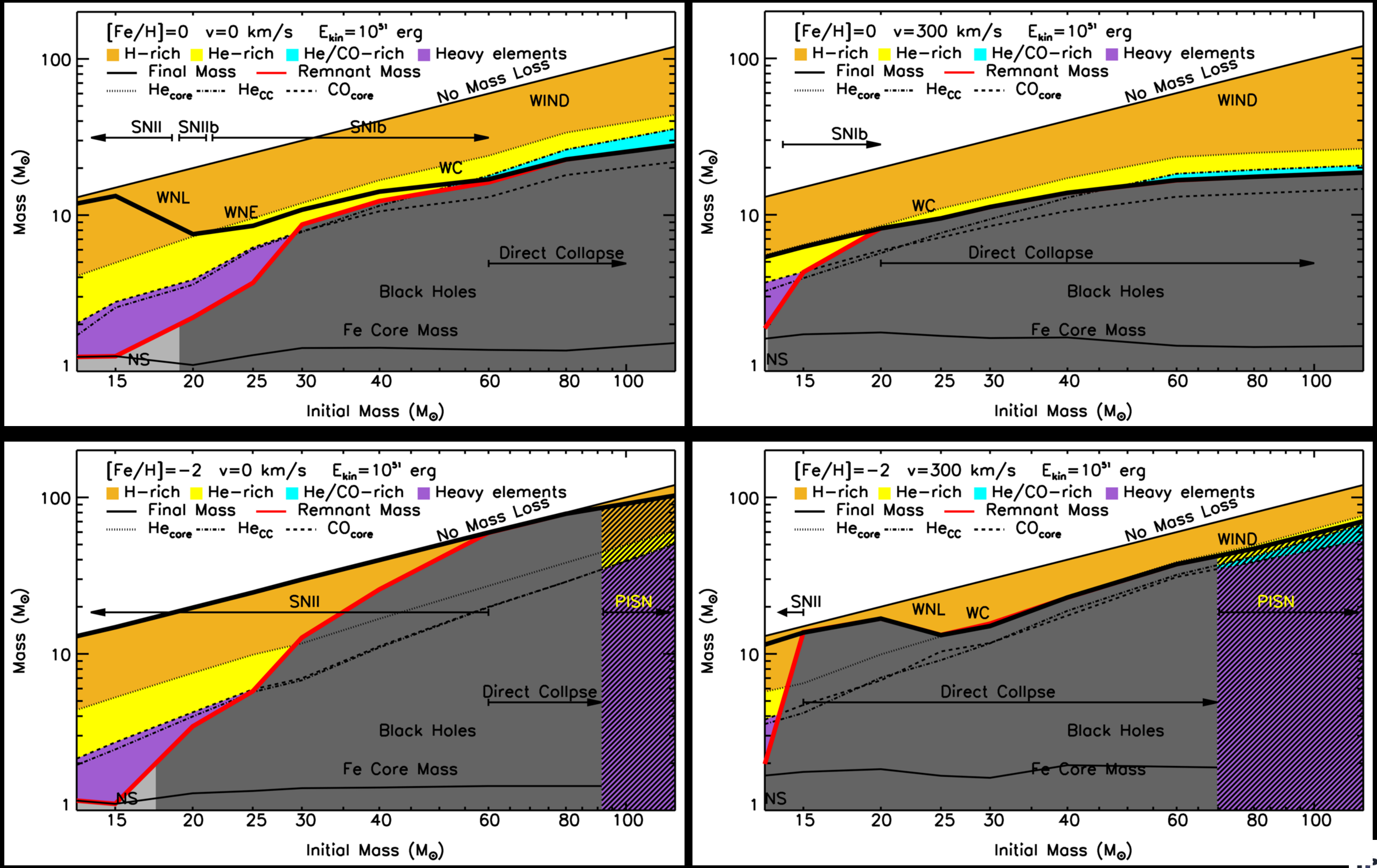


Limongi & Chieffi (2018)

Increase of CO mass (rotation driven mixing) → reduction of PPISN limit

Evolution of Massive Stars: Global Picture

Limongi (2017)



Main Limitations of the Present Stellar Models

Stellar models computed assuming spherical symmetry → main limitations due to the approximated treatment of multi-D phenomena

- Mixing phenomena: these include the transport of any quantity (chemical composition, angular momentum, heat content, magnetic field) over any time scale (convection, semiconvection, diffusion)

- Rotation: makes the star oblate → departure from spherical symmetry

Physical phenomena that strongly influence the evolution of the star

- Mass Loss: this includes all the possible mechanisms (line driven, mechanical due to rotation, dust driven, binary interaction)

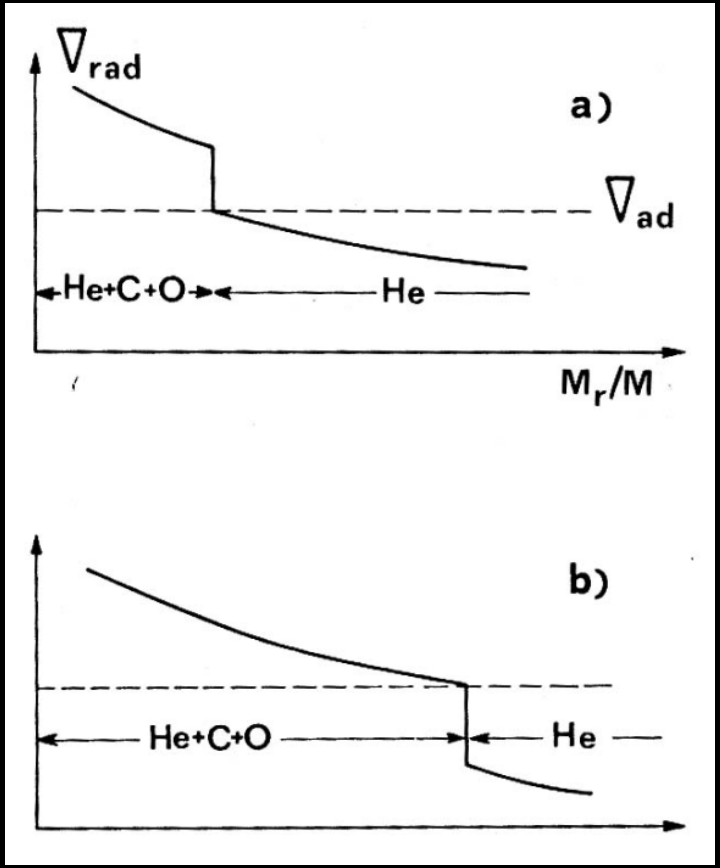
Different theoretical groups follow different approaches and make different assumptions. No one can be clearly preferred to the others

Limitation of the predictive power of the stellar models in all the mass intervals

Convection

Breathing pulses occurring during the late stages of core He burning

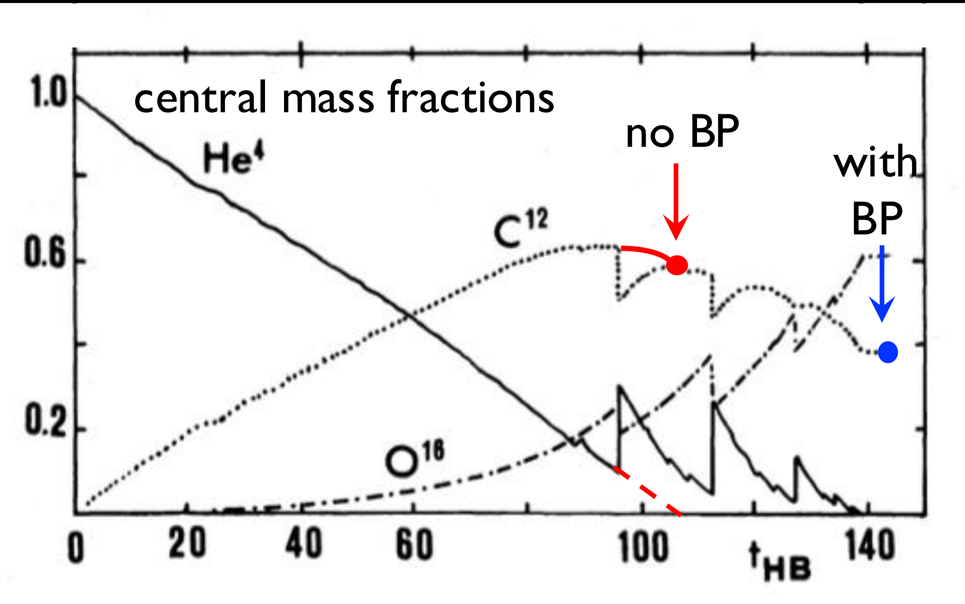
Increase of the Convective Core due to the conversion of He→C+O



Castellani+ (1985)

When He_c<=0.1 the enrichment of core He produced be the increase of the convective core, even by a small amount, drives an enhancement of the nuclear energy generation that in turn drives a phase of progressive increase of the convective core

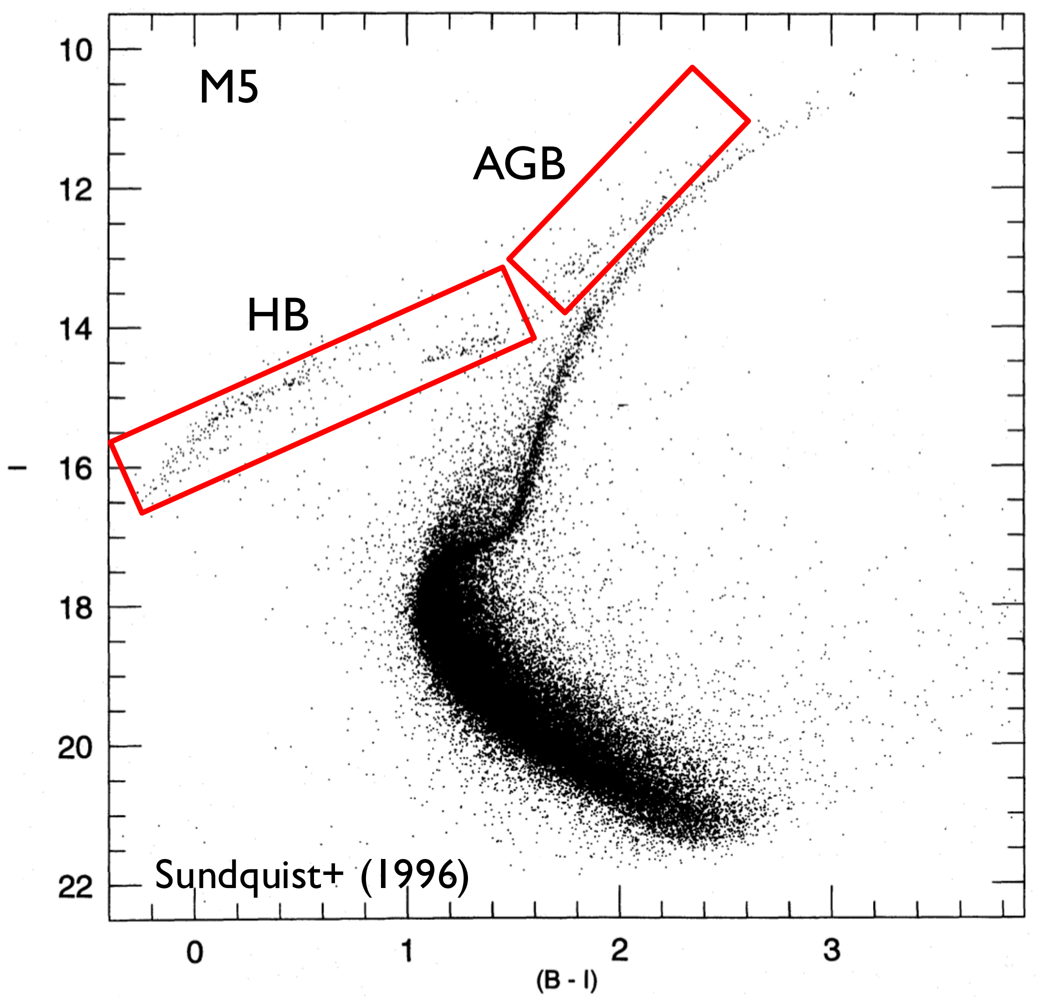
- prolonged core He burning phase
- prolonged conversion of ^{12}C into ^{16}O
- non monotonic (stochastic) ^{12}C at core He depletion vs initial mass



Convection

It is not possible to determine, based on first principles, if this runaway occurs or not in real stars.

$$R_2 = \frac{\text{Number of AGB stars}}{\text{Number of HB stars}}$$ sensitive to the presence/absence of breathing pulses



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The treatment of mixing in core helium burning models – II. Constraints from cluster star counts

Thomas Constantino,[1,2★] Simon W. Campbell,[2,3] John C. Lattanzio[2] and Adam van Duijneveldt[2]

[1] *Physics and Astronomy, University of Exeter, Exeter EX4 4QL, UK*
[2] *Monash Centre for Astrophysics (MoCA), School of Physics and Astronomy, Monash University, VIC 3800, Australia*
[3] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Straße 1, D-85748 Garching bei München, Germany*

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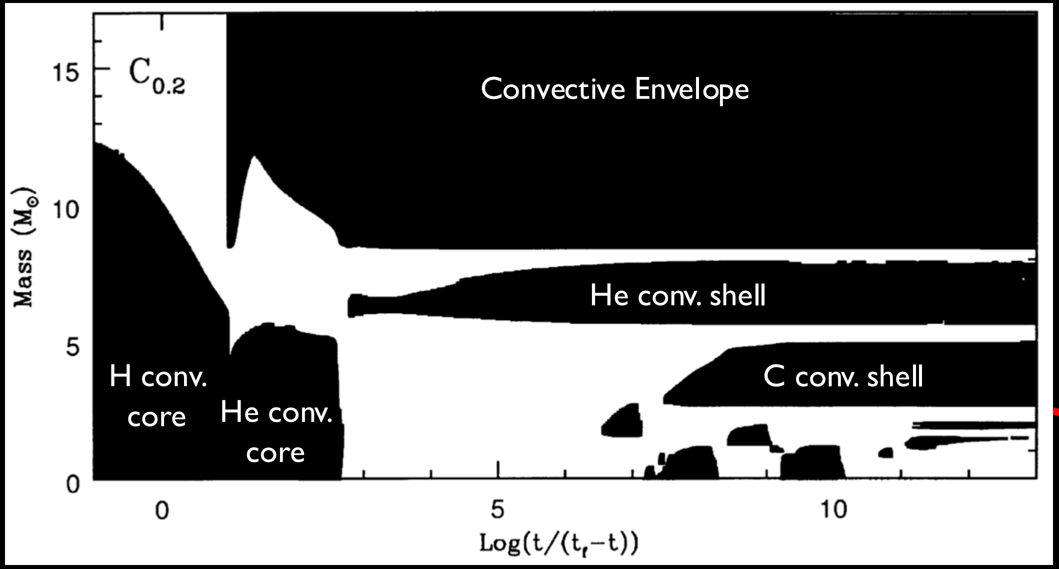
ABSTRACT

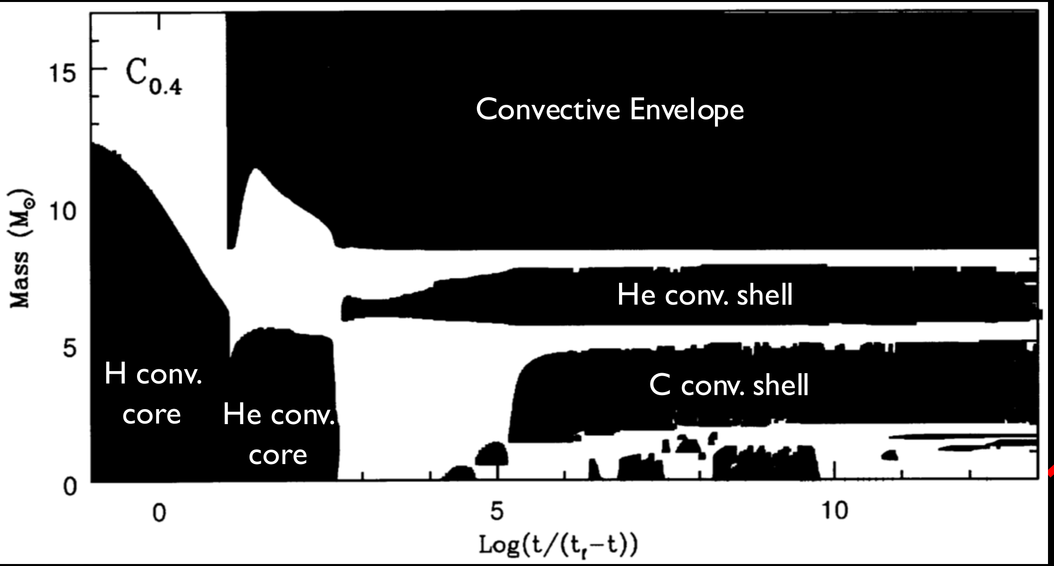
The treatment of convective boundaries during core helium burning is a fundamental problem in stellar evolution calculations. In the first paper of this series, we showed that new asteroseismic observations of these stars imply they have either very large convective cores or semiconvection/partially mixed zones that trap g modes. We probe this mixing by inferring the relative lifetimes of asymptotic giant branch (AGB) and horizontal branch (HB) from R_2, the observed ratio of these stars in recent *HST* photometry of 48 Galactic globular clusters. Our new determinations of R_2 are more self-consistent than those of previous studies and our overall calculation of $R_2 = 0.117 \pm 0.005$ is the most statistically robust now available. We also establish that the luminosity difference between the HB and the AGB clump is $\Delta \log L_{\rm HB}^{\rm AGB} = 0.455 \pm 0.012$. Our results accord with earlier findings that standard models predict a lower R_2 than is observed. We demonstrate that the dominant sources of uncertainty in models are the prescription for mixing and the stochastic effects that can result from its numerical treatment. The luminosity probability density functions that we derive from observations feature a sharp peak near the AGB clump. This constitutes a strong new argument against core breathing pulses, which broaden the predicted width of the peak. We conclude that the two mixing schemes that can match the asteroseismology are capable of matching globular cluster observations, but only if (i) core breathing pulses are avoided in models with a semiconvection/partially mixed zone, or (ii) that models with large convective cores have a particular depth of mixing beneath the Schwarzschild boundary during subsequent early-AGB 'gravonuclear' convection.

Convection

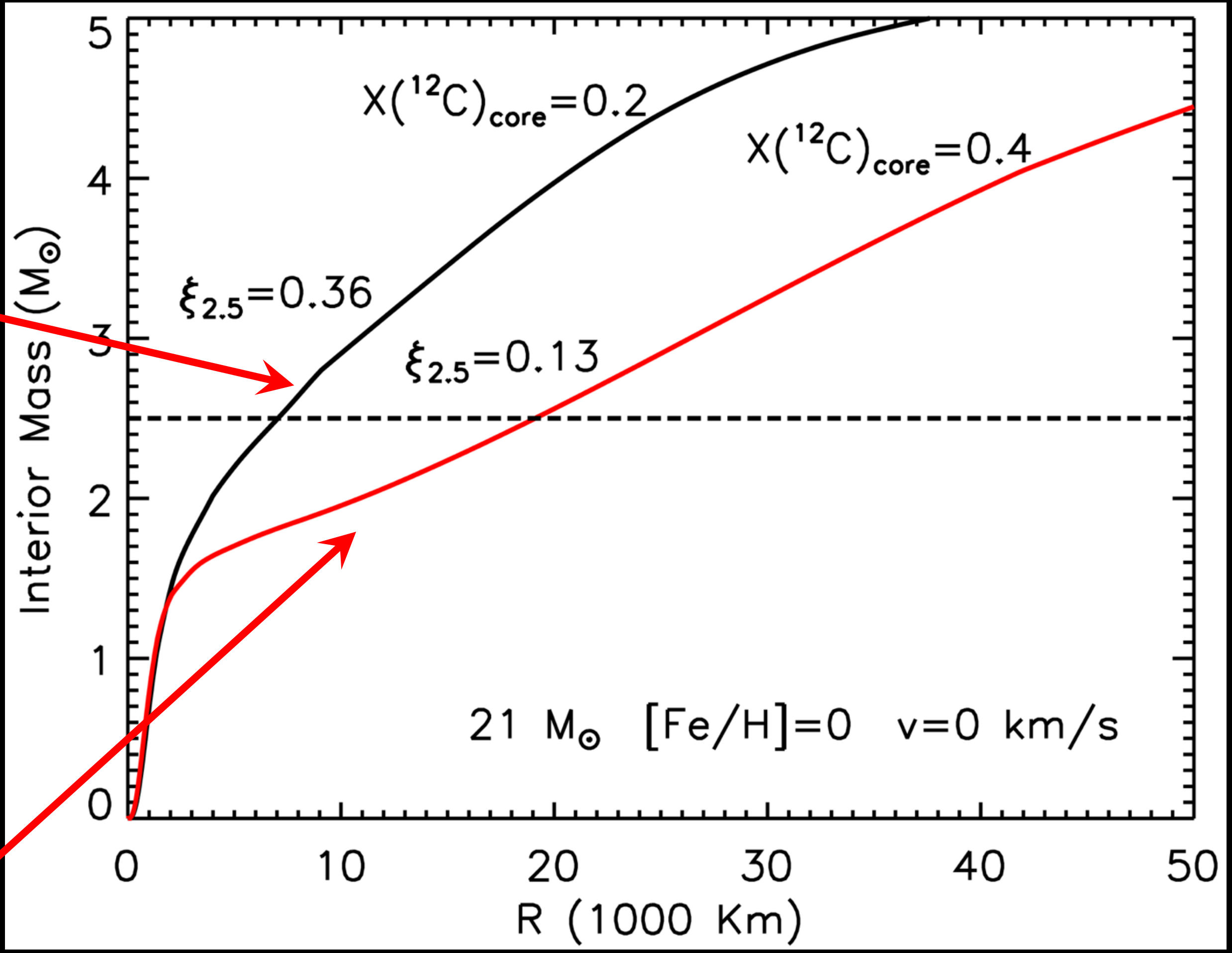
Treatment of BP impacts on ^{12}C at core He depletion → on the efficiency of the C-shell burning

Imbriani+ (2001)



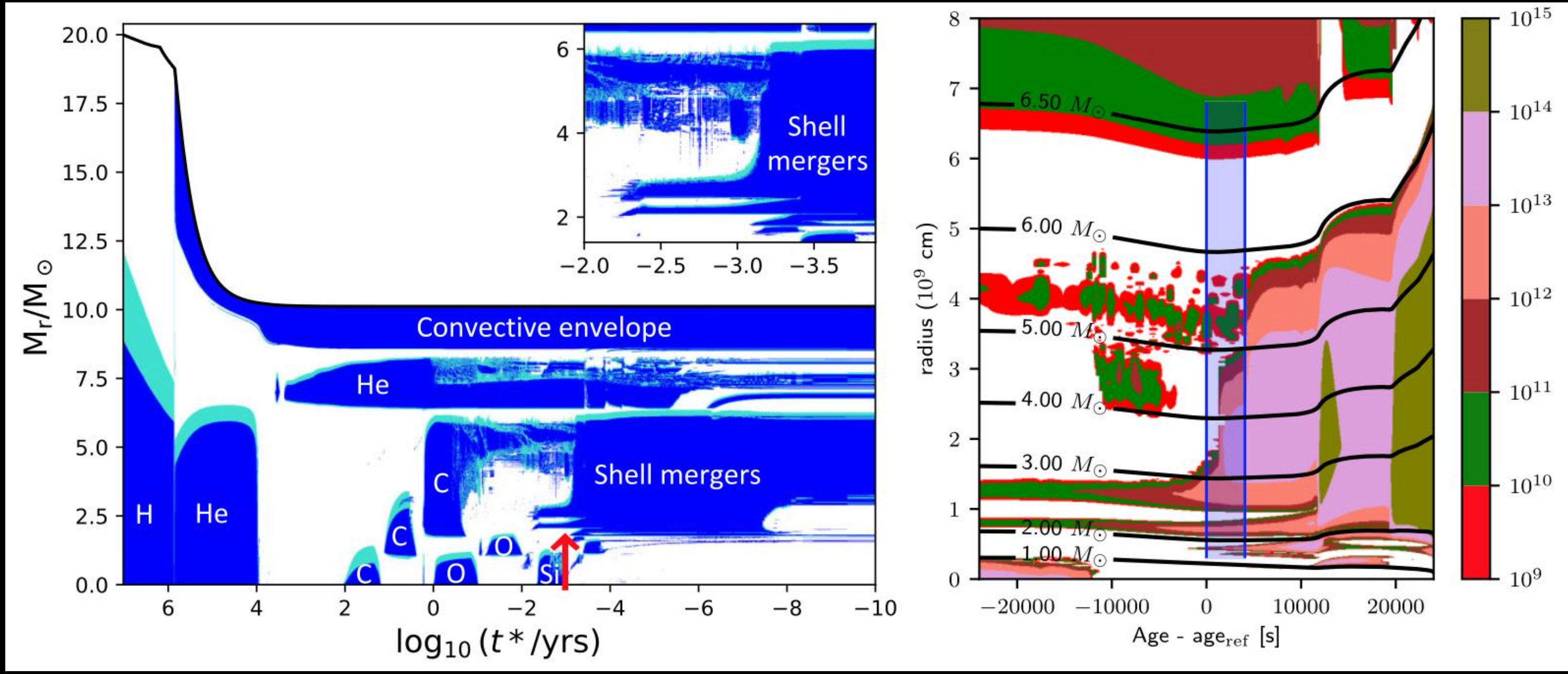


Implications on the compactness at presupernova stage



Convection

Carbon-Oxygen shell merger in massive stars



Rizzuti+ (2024)

- Ingestion of C (and Ne) in the O burning shell during the very late stages of the evolution;
- Formation of an extended (both in mass and radius) mixed convective zone;
- Peculiar nucleosynthesis
- Expansion of the O-C rich layers
- Impact on the compactness and explodability

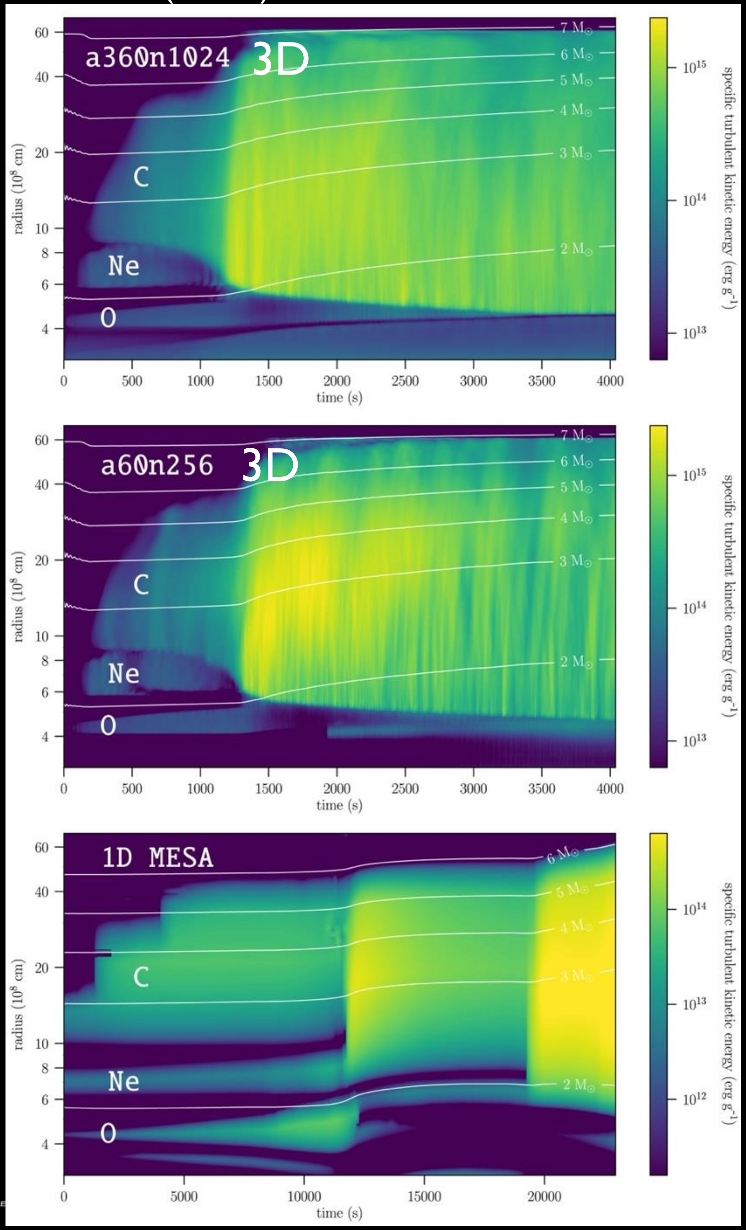
Since it is not found systematically in 1D stellar models of massive stars:

- it is not clear whether shell merging is just a numerical effect of the 1D models, or this phenomenon is also expected to occur in real stars
- it leads to a stochastic behavior of the compactness as a function of the initial mass

Convection

Carbon-Oxygen shell merger in massive stars

Rizzuti+ (2024)

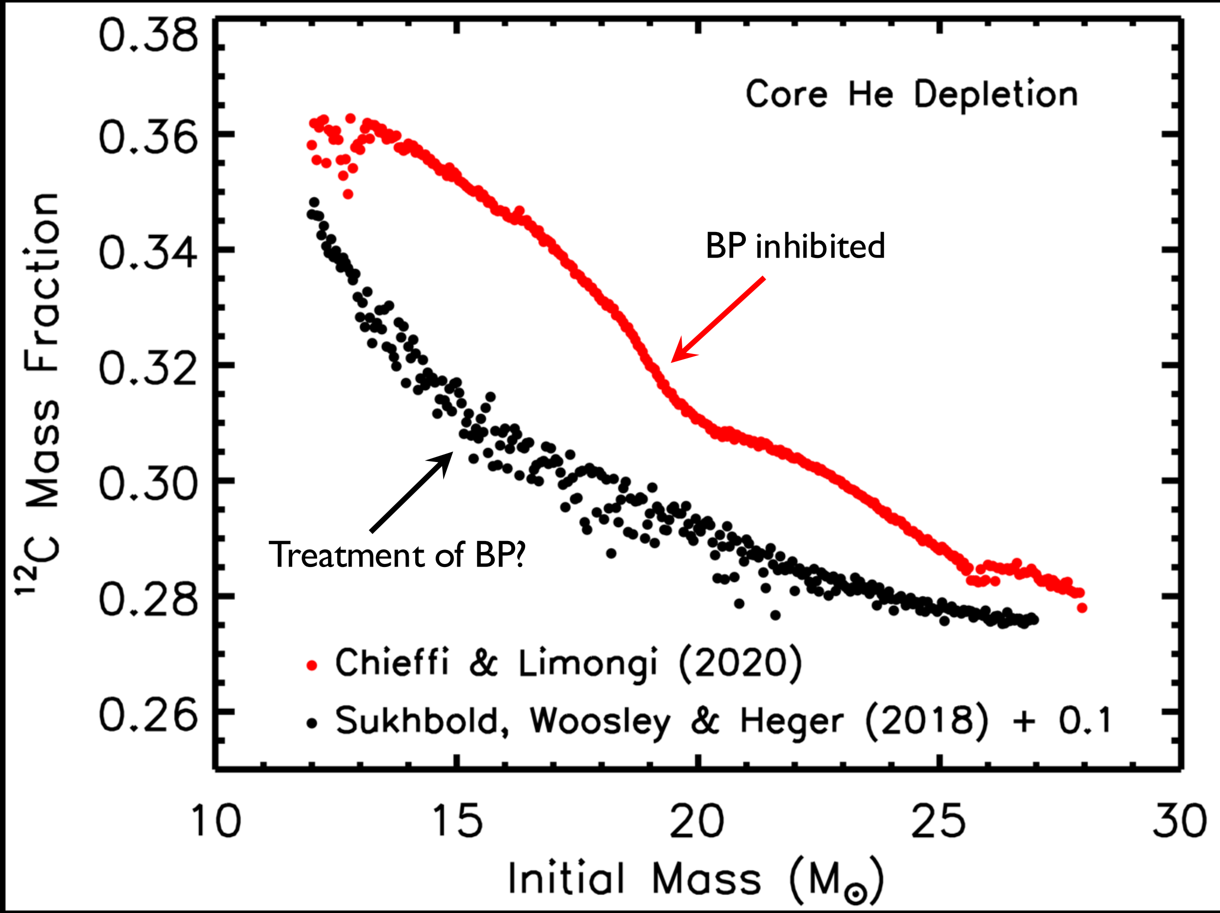


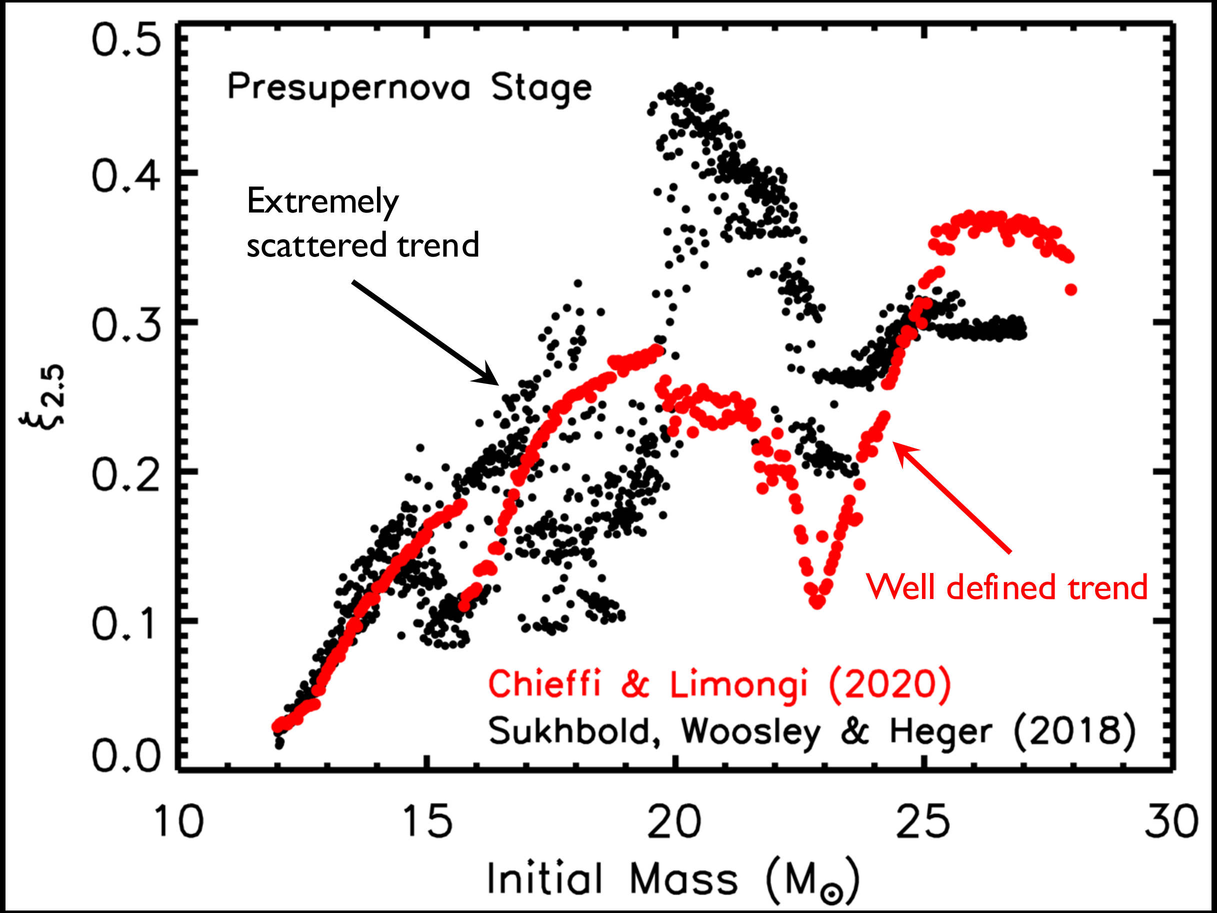
Substantial differences between 3D and 1D models

Limitations due to the very high computational cost required for running multidimensional simulations

- Very small nuclear network (12 iso) adopted for the calculation of the nuclear energy generation that plays a crucial role in this phenomenon
- Not conclusive results because performed on only one progenitor star
- Limited spatial resolution and time scales
- 1D models still remain the main tools for drawing an overview of evolutionary properties of stars in a wide range of initial masses and for predicting and explaining the evolution of stellar populations

The Compactness of Massive Stars





If the relation between the ^{12}C at core He depletion and the Initial Mass is very tight, a well defined, (not scattered) trend of the compactness with the initial mass is obtained

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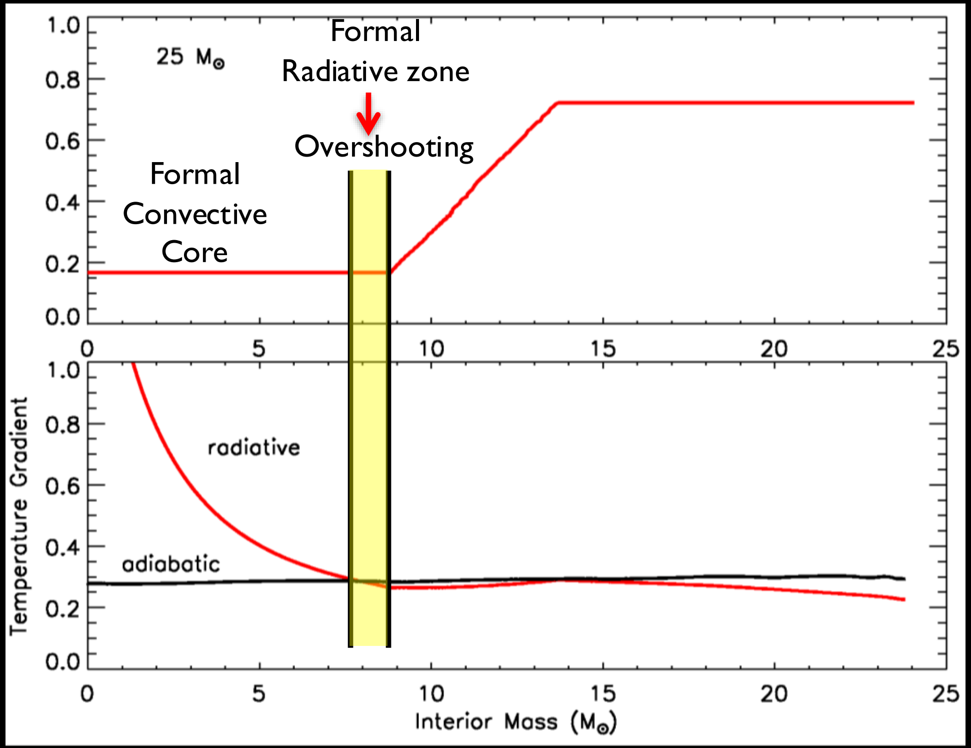
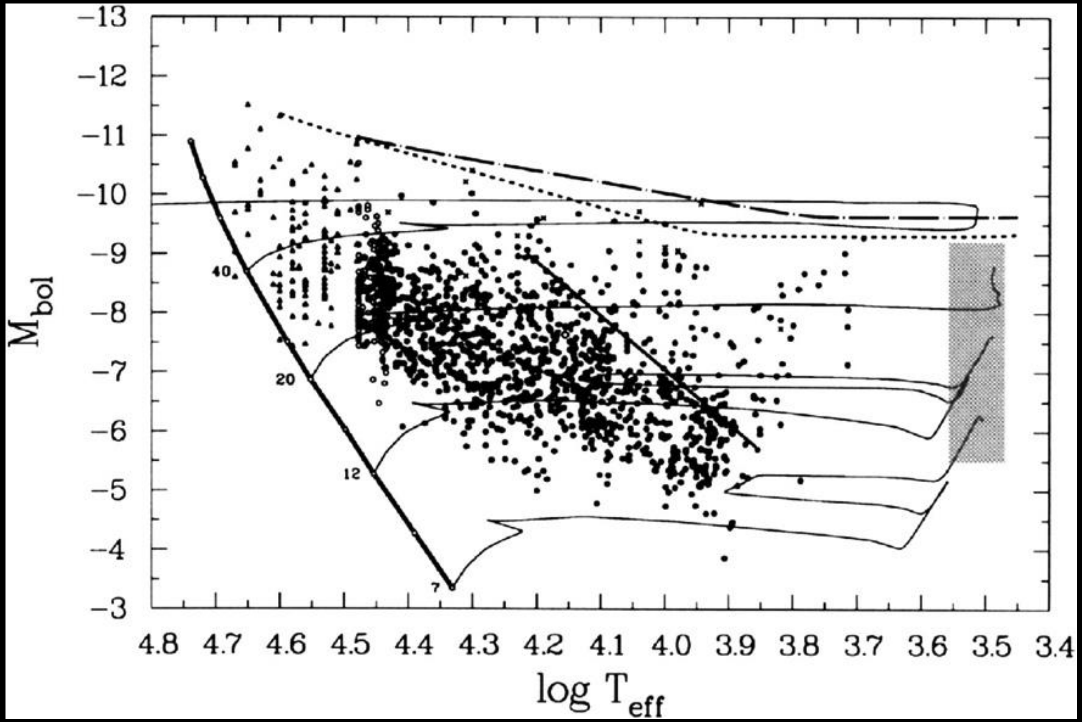
Convection

The overshooting in core H burning was invoked in the '80s in order to explain the main sequence band of bright stars

The convective elements may penetrate (overshoot) into the formally stable radiative zone





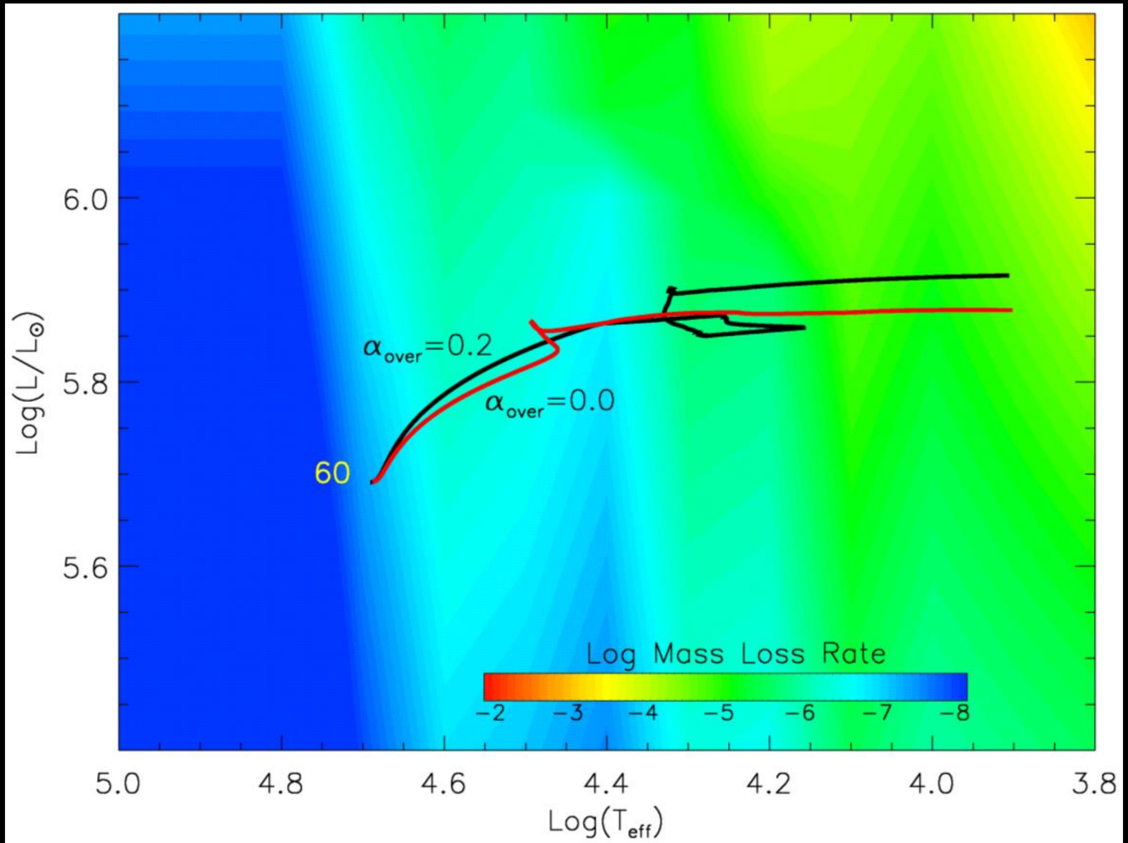
Massey ARA&A, 2003

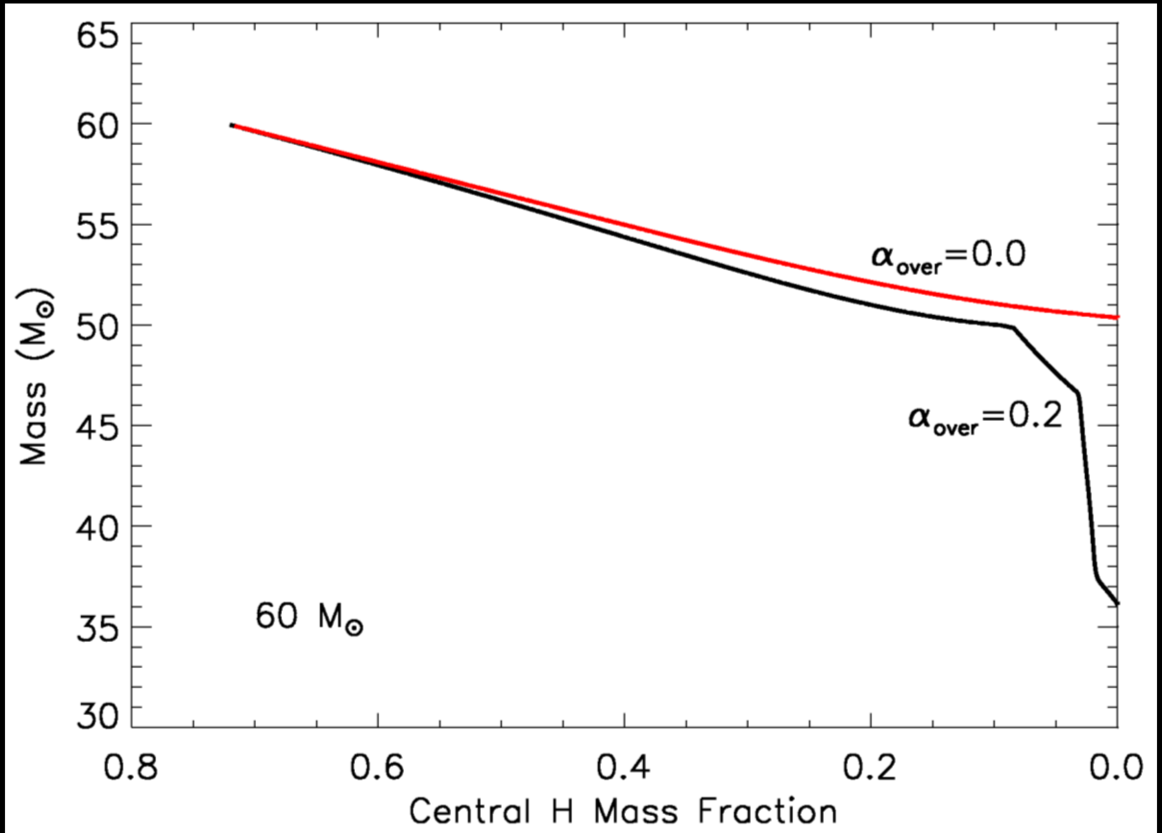
Convective overshoot is formulated with the aid of the Mixing-Length theory
→ it is heavily uncertain

Convection

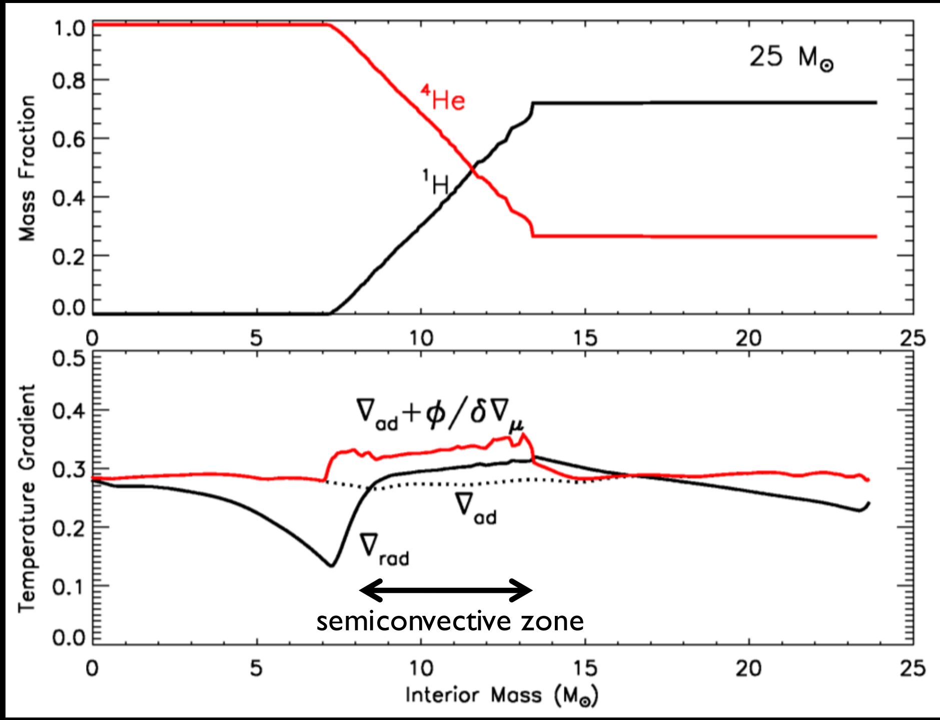
The effect of the overshooting is that
- the evolutionary track is more luminous and more extended to lower effective temperatures
- the core H burning lifetime is significantly higher

Uncertainties on this phenomenon may have dramatic consequences on the final mass
→ on the yields and final fate





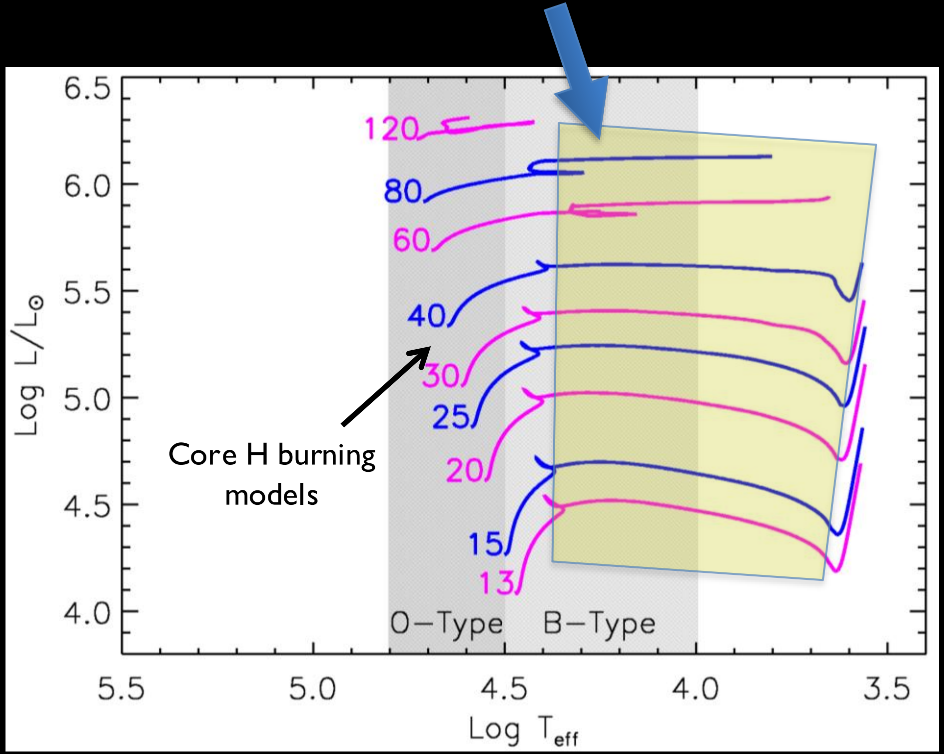
Convection



Unstable (Schwarzschild) $\nabla_{\rm ad} < \nabla_{\rm rad}$

Stable (Ledoux) $\nabla_{\rm ad} < \nabla_{\rm rad} < \nabla_{\rm ad} + \frac{\varphi}{\delta}\nabla_\mu$

The mixing efficiency in the semiconvective zone determines the timescales of the redward evolution after the MS phase



No theory based on first principles can provide the mixing velocity in this zone

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Convection

Fast Mixing

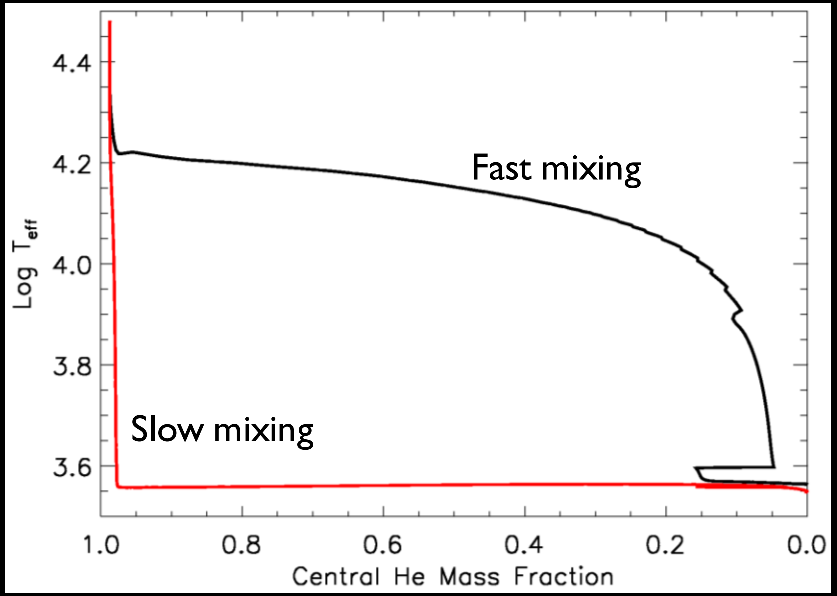
Homogenous mixing → Schwarzschild

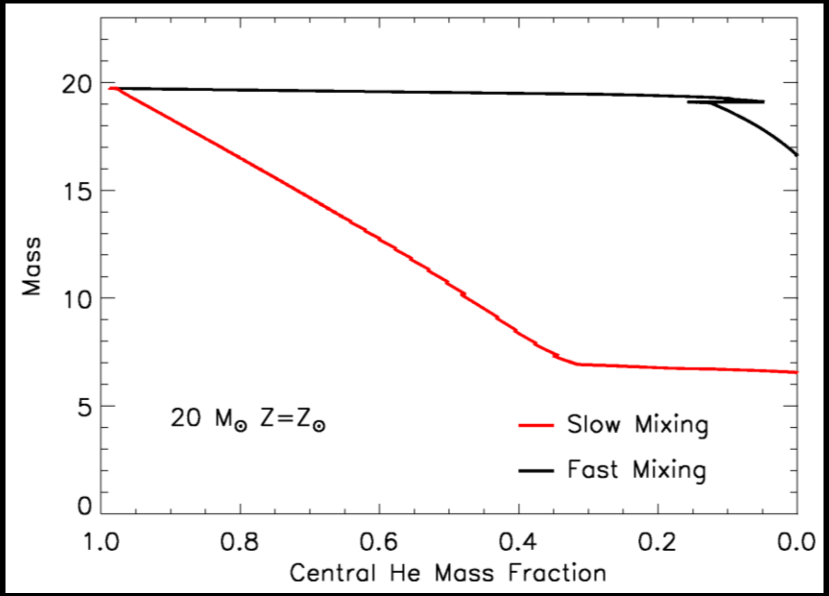
- the redward evolution occurs on nuclear timescales
- the star becomes RSG in an advanced stage of core He burning
- small amount of mass lost
- SNIIP explosion

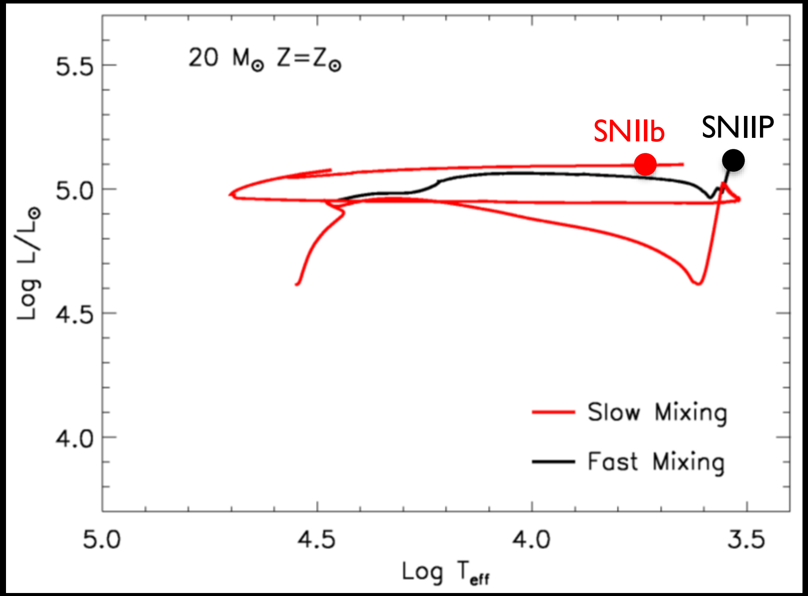
Slow Mixing

No mixing → Ledoux

- the redward evolution occurs on thermodynamic timescales
- the star becomes RSG at the very beginning of core He burning
- large amount of mass lost
- SNIIb/SNIb explosion



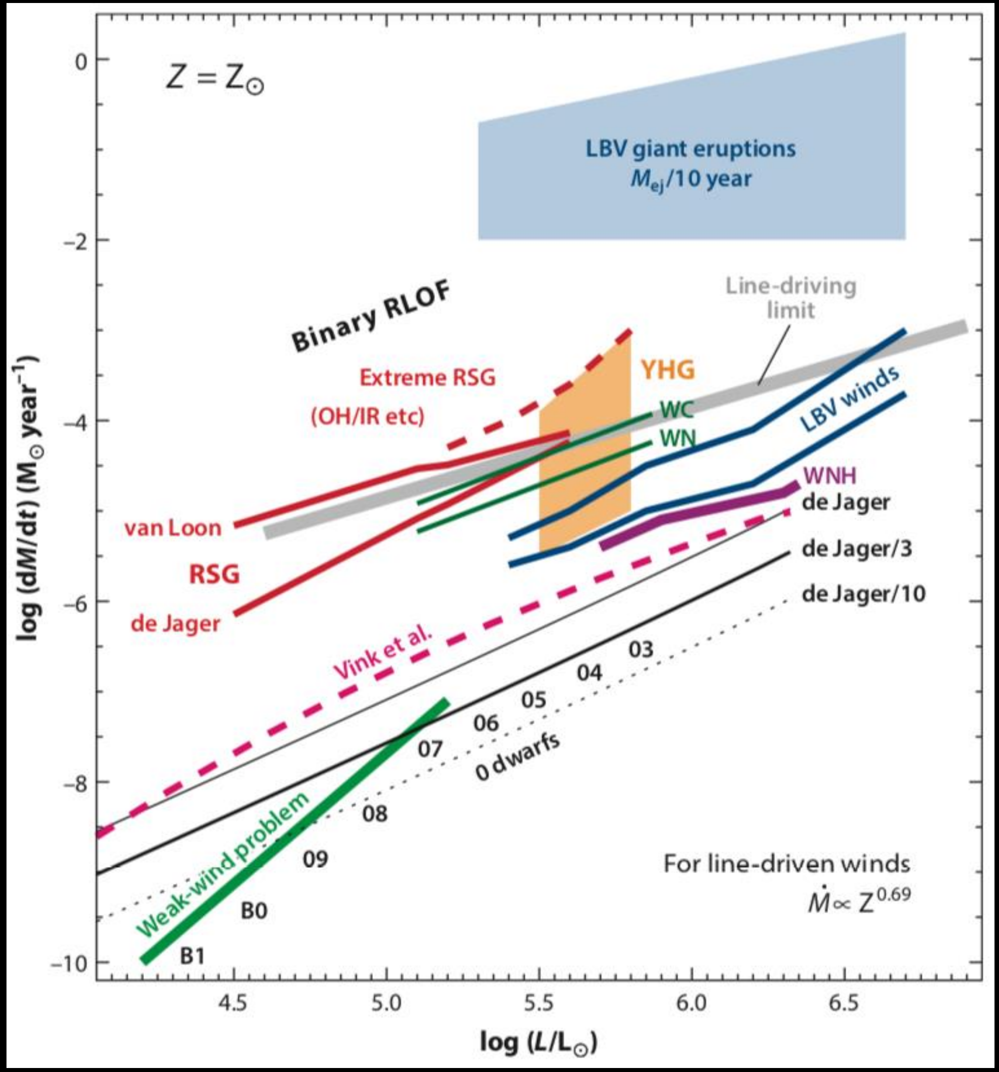




Mass Loss

Mass loss plays a crucial role in the evolution of a massive star (evolutionary path, collective ionizing radiation, UV luminosity, winds, final fate, type of SN, remnant mass)

Different prescriptions for wind mass loss used in the models



Unfortunately….

Mass Loss: Its Effect on the Evolution and Fate of High-Mass Stars

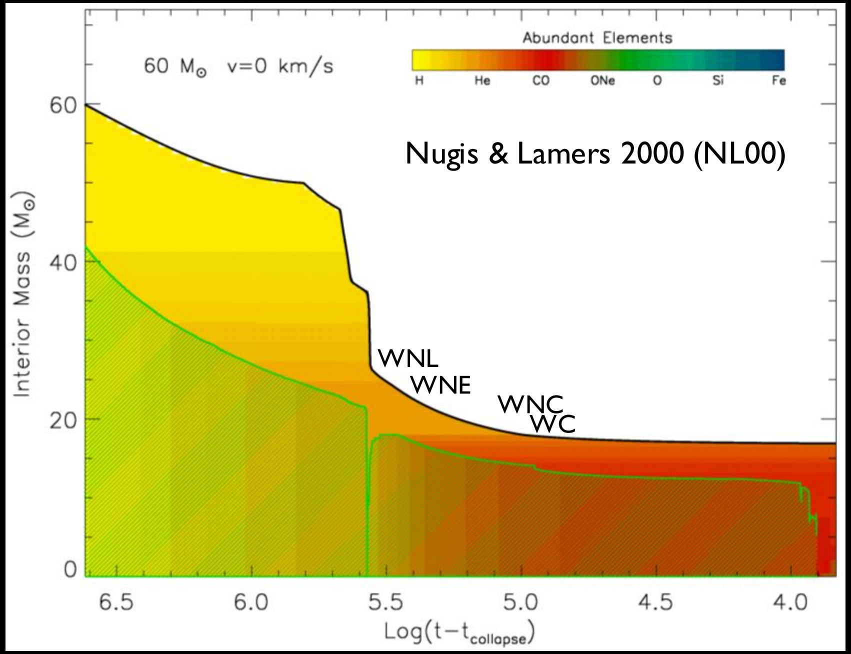
Nathan Smith

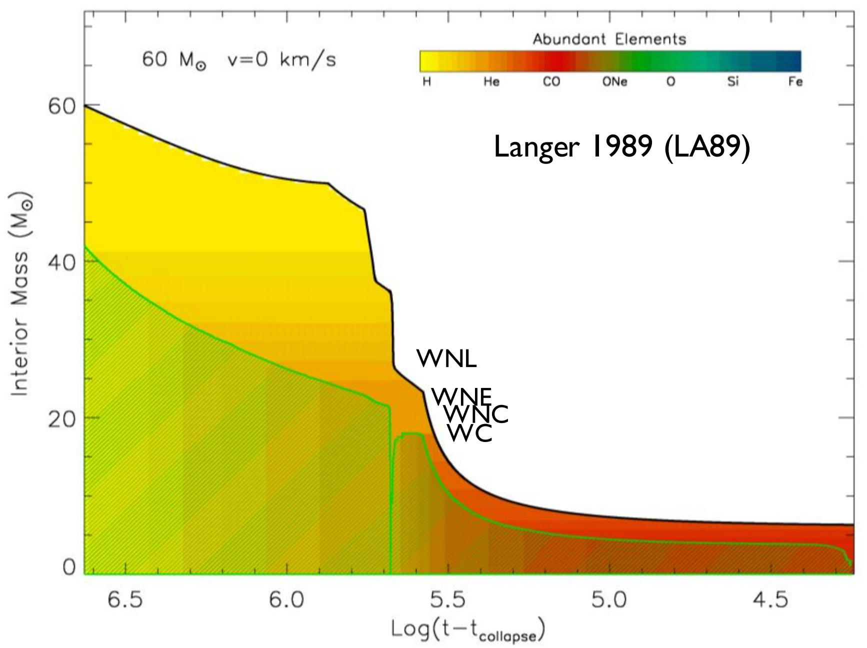
Steward Observatory, University of Arizona, Tucson, Arizona 85721;
email: nathans@as.arizona.edu

……………………………

Although convenient recipes and simple scaling relations to account for the collective effects of mass loss and feedback will always be available, researchers working in these other branches of astronomy should not believe that such recipes are reliable to better than order-of-magnitude levels. Even in the very local Universe, where we have excellent multiwavelength observations, there is still tremendous uncertainty in derived mass-loss rates for massive stars, and so there is large uncertainty in their influence on evolution. This is exacerbated by the predicament that these uncertainties are largest for the most massive and most luminous stars, but these stars also tend to be the most influential. Extrapolating to the early Universe is still quite risky and should always raise eyebrows. This review provides a broad overview of the current understanding of mass loss and its influence on the evolution of massive stars and raises a flag of caution about the uncertainties involved.

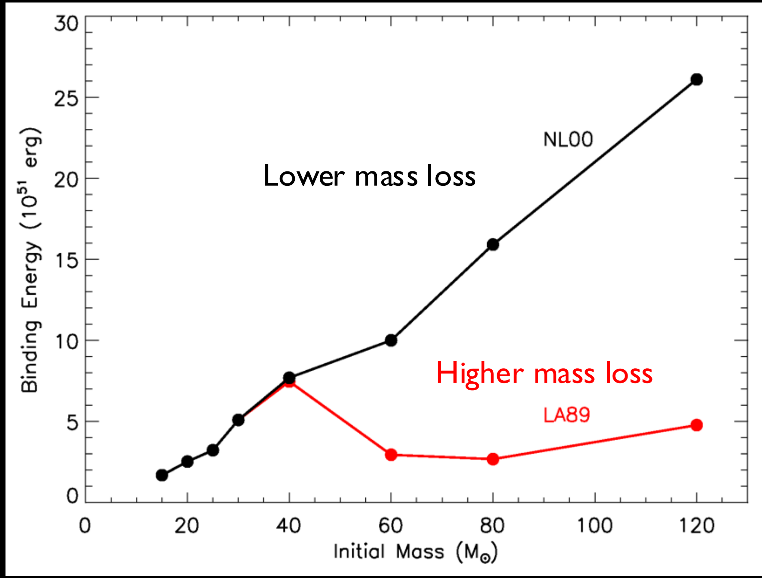
Mass Loss

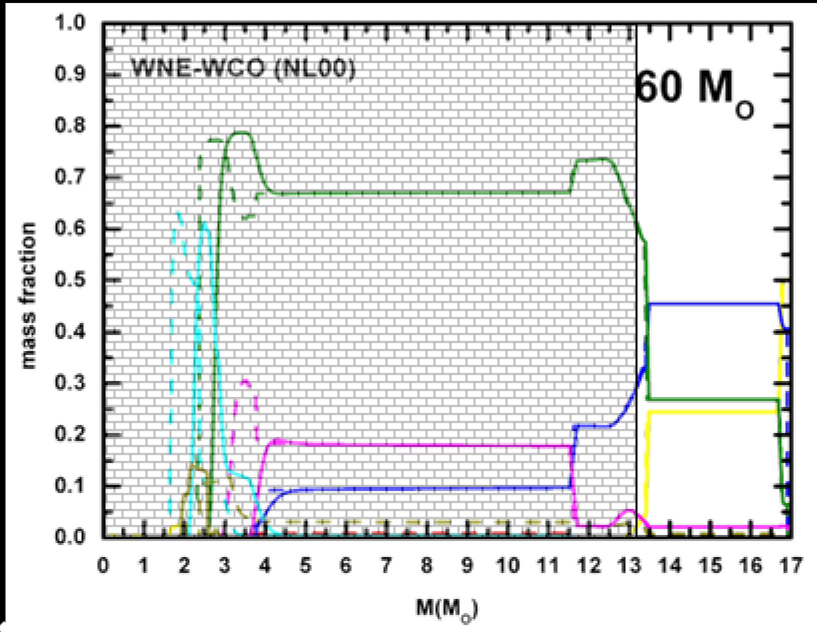


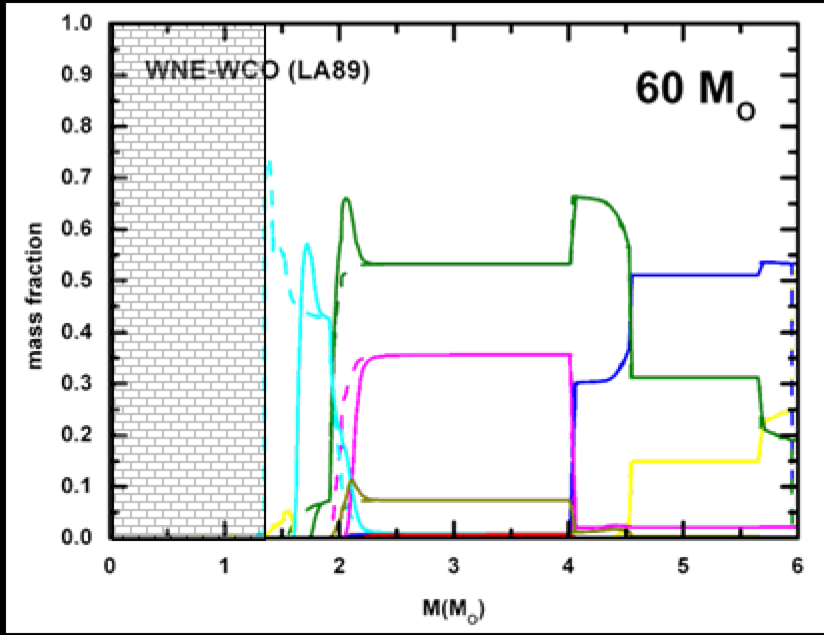


Higher mass loss:

Lower CO core masses → Lower binding energies

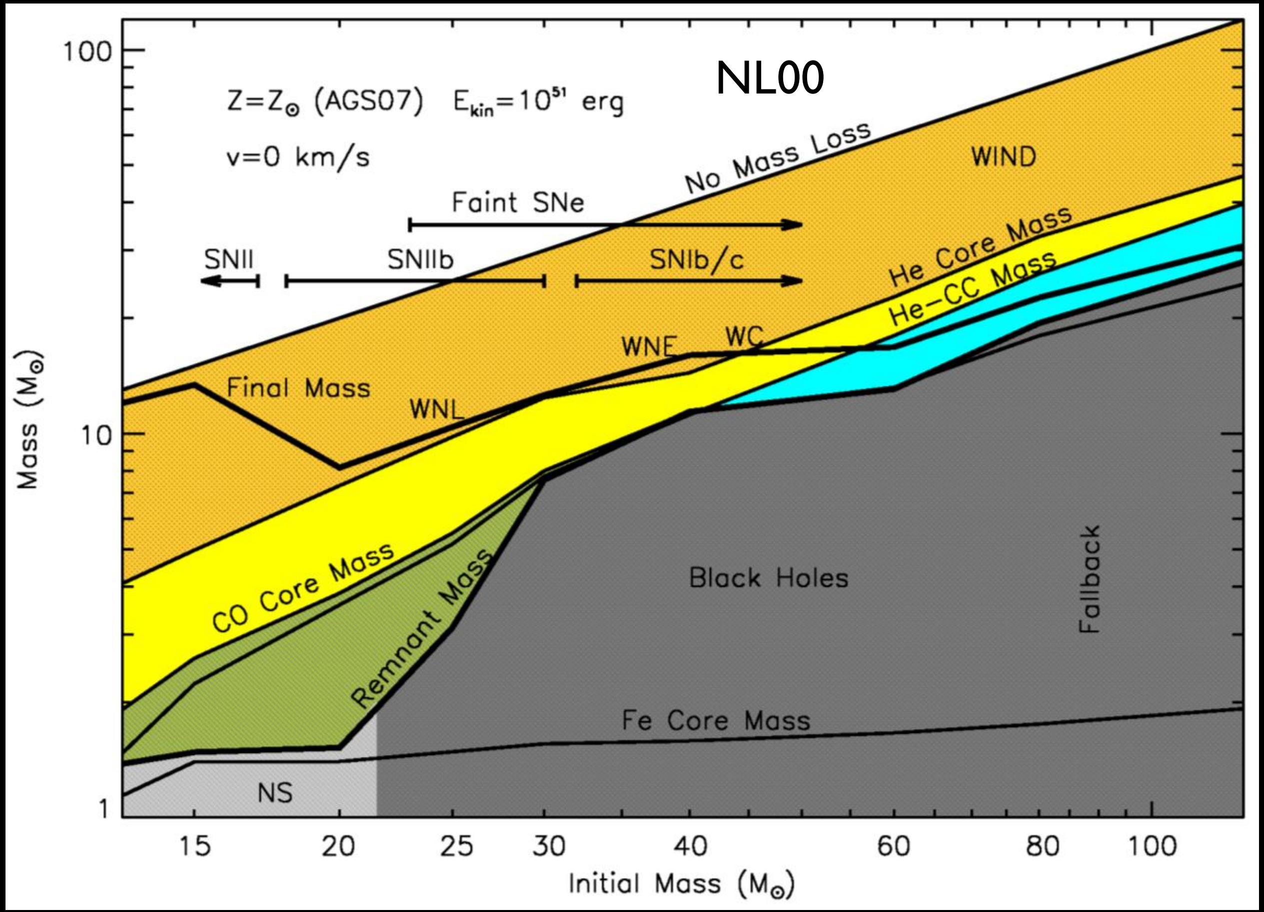


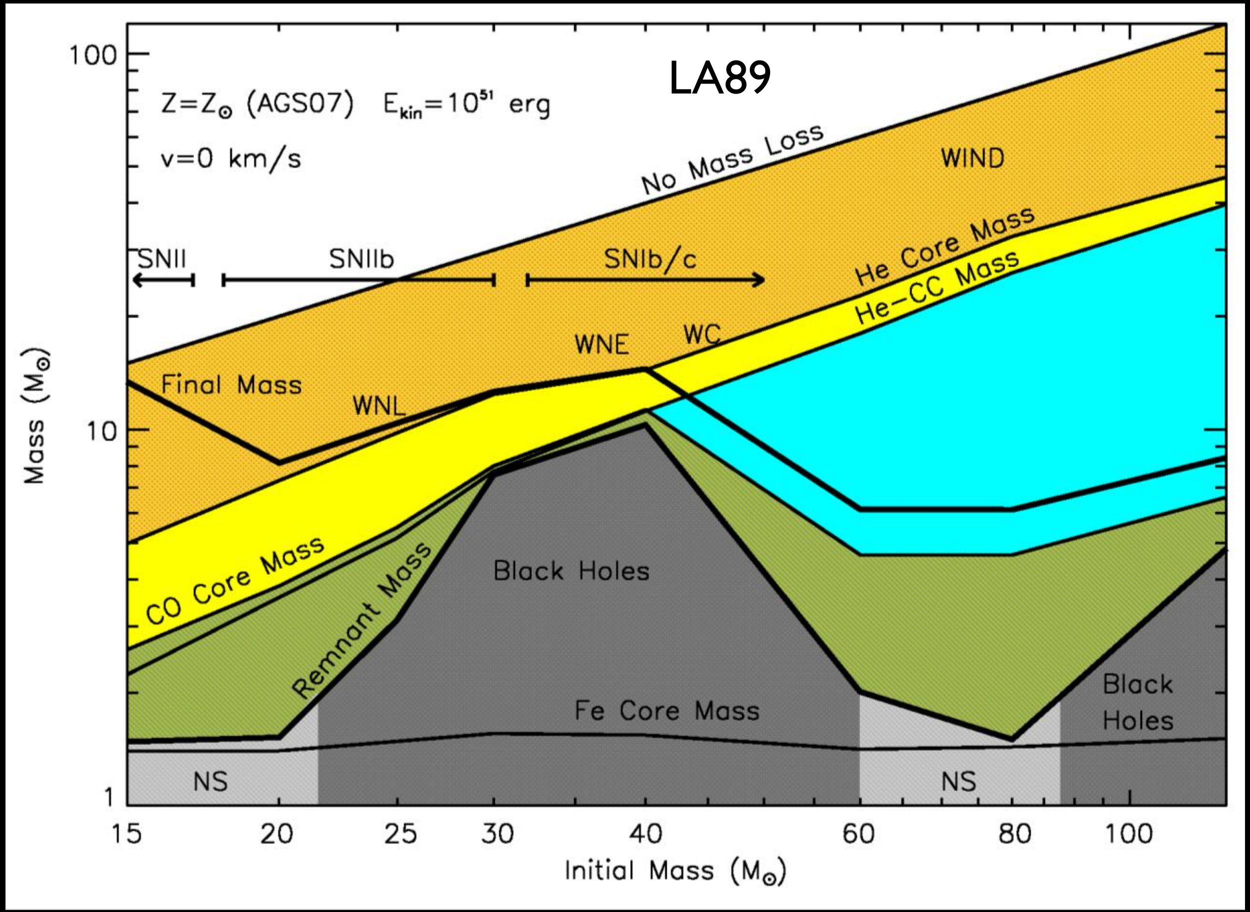




Lower remnant mass

Mass Loss





Completely different expected ratios of NS and BH forming Supernovae by using the two prescriptions for the WR mass loss

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Rotation

The implementation of rotation in a 1D code relies on some necessary assumptions that are natural sources of uncertainties

TRANSPORT OF ANGULAR MOMENTUM:

Advection-Diffusion Equation

$$\rho \frac{d}{dt}\left(r^2\omega\right) = \frac{1}{5r^2}\frac{\partial}{\partial r}\left(\rho r^4 \omega U\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho D_{\rm shear} r^4 \frac{\partial \omega}{\partial r}\right)$$

FRANEC
GENEC

Advection due to meridional circulation

Diffusion due to turbulent shear

Diffusion Equation

$$\rho \frac{d}{dt}\left(r^2\omega\right) = \frac{1}{r^2}\left[\rho r^4 \left(D_{\rm shear} + D_{\rm mc}\right)\frac{\partial \omega}{\partial r}\right]$$

KEPLER
STERN
MESA

TRANSPORT OF CHEMICAL SPECIES:

$$\left(\frac{\partial X_i}{\partial t}\right)_m = \left(\frac{\partial}{\partial m}\right)_t \left[\left(4\pi\rho r^2\right)^2 D \left(\frac{\partial X_i}{\partial m}\right)_t\right]$$

$$D = D_{\rm shear} + D_{\rm mc}$$

FRANEC
GENEC
KEPLER
STERN
MESA

Rotation

Efficiency of the Rotation Driven Mixing

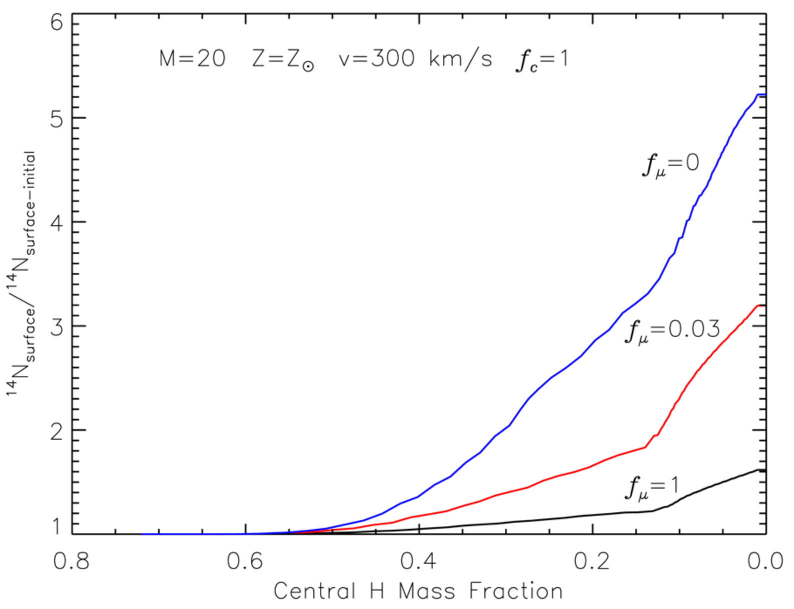
Many prescriptions for $U \quad D_{\rm shear} \quad D_{\rm mc}$ (Kippenhahn 1974, Talon+ 1997, Zahn 1992, Maede, Heger+ 2000)

All the uncertainties in the treatment of rotation may be accounted for essentially by means of one or two free parameters:

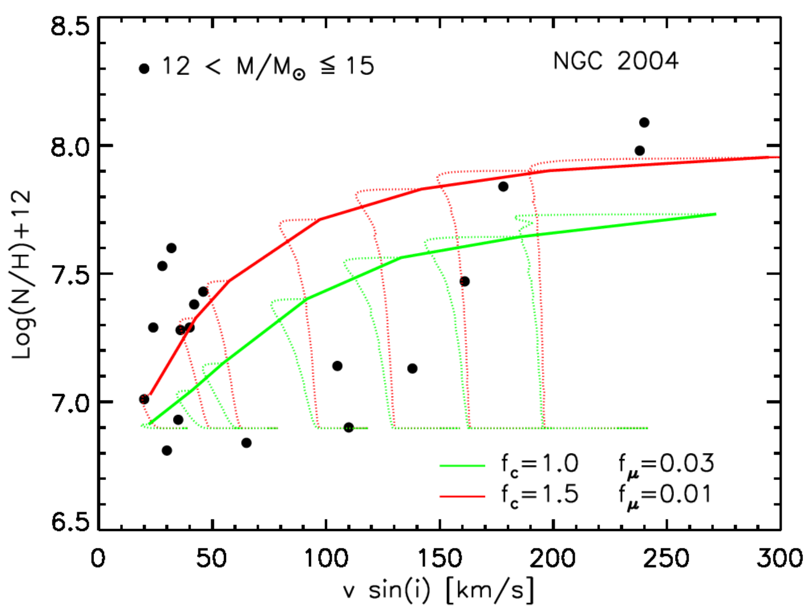
f_c that multiplies the diffusion coefficient adopted for the mixing $\quad D = f_c(D_{\rm shear} + D_{\rm mc})$

f_μ that multiplies the gradient of molecular weight $\quad \nabla_\mu \to f_\mu \nabla_\mu$

Enrichment of nitrogen of order 2-3 in evolved stars of ~10-20 $M_\odot$ with $v_{rot} \simeq 200/300$ km/s (Heger+2000, Chieffi+ 2013)



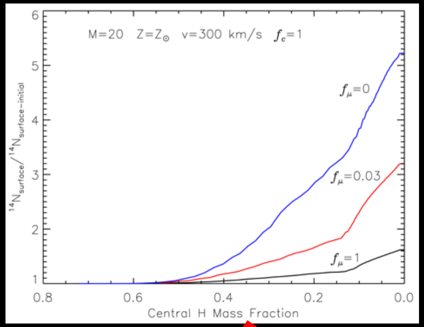
Reproduction of the Hunter diagram (Brott+ 2011, ML+ 2018)

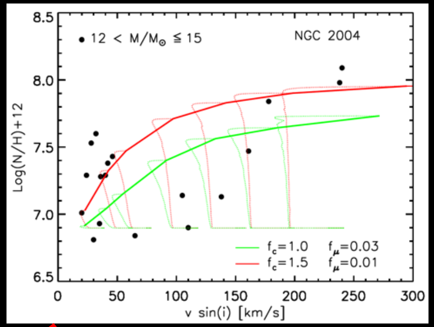


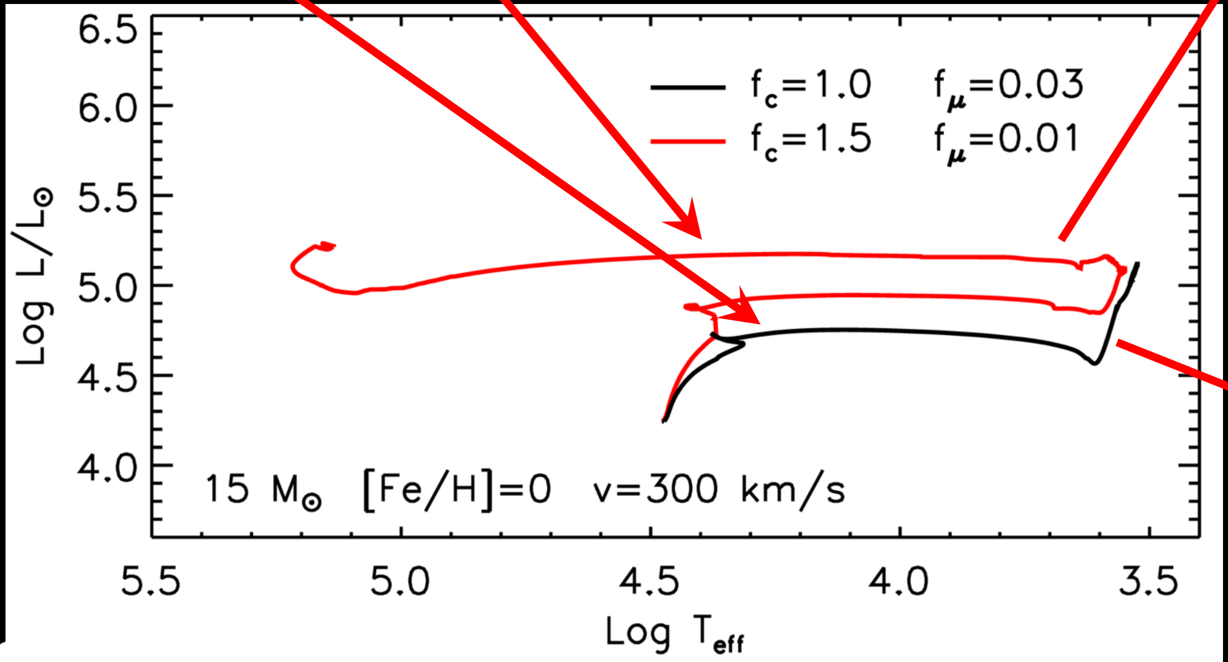
Rotation

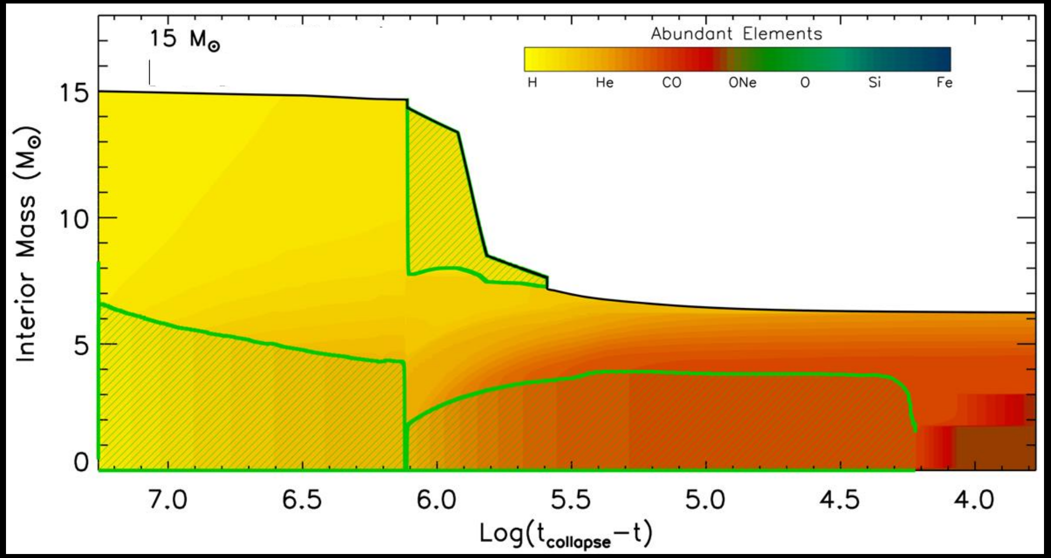
Efficiency of the Rotation Driven Mixing

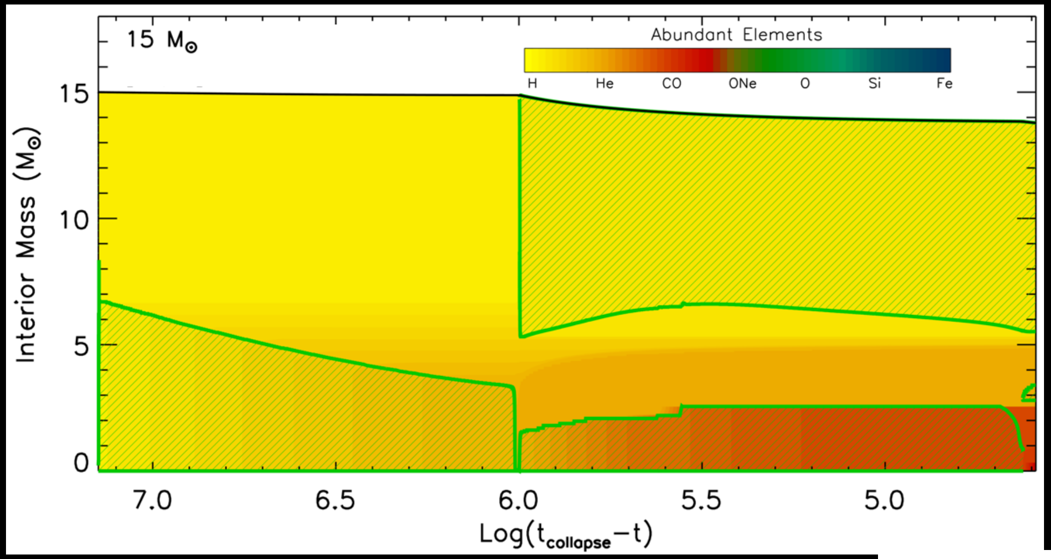
Different calibrations → different evolution properties





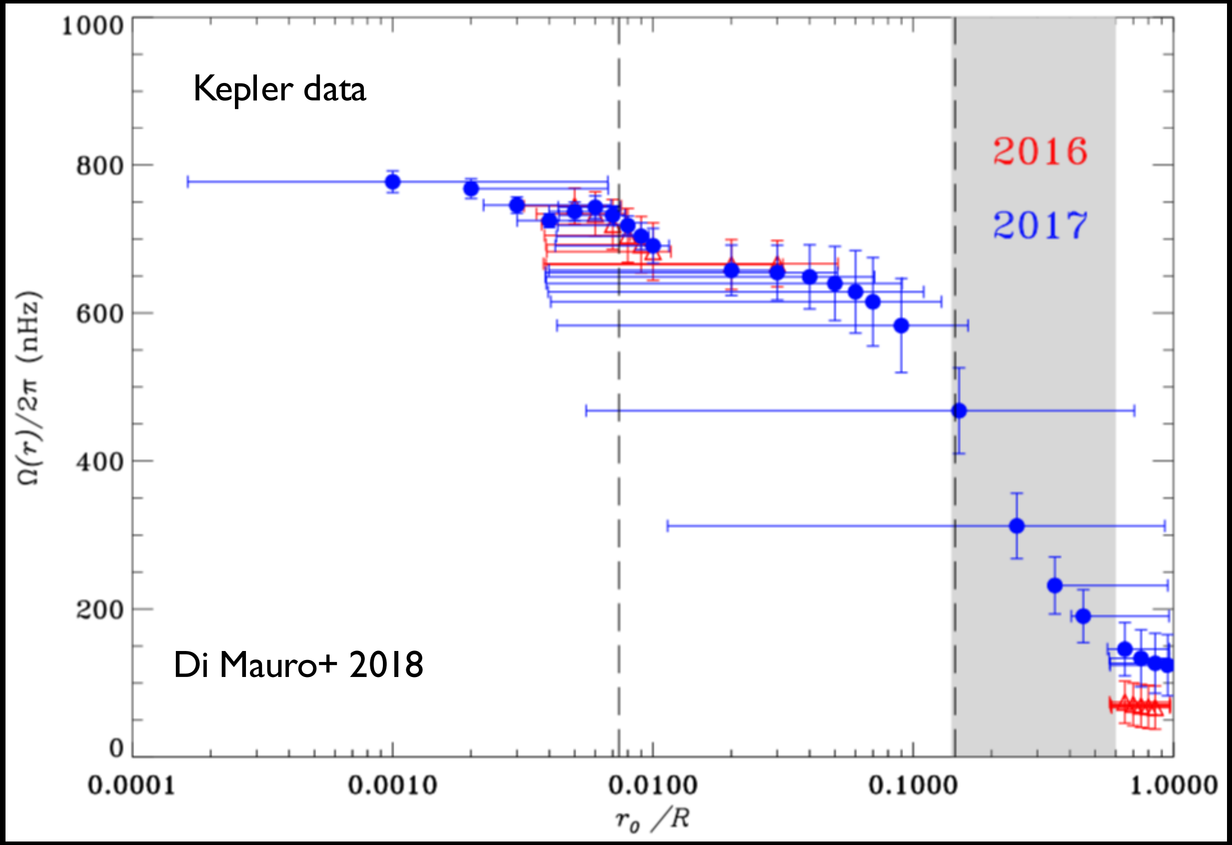


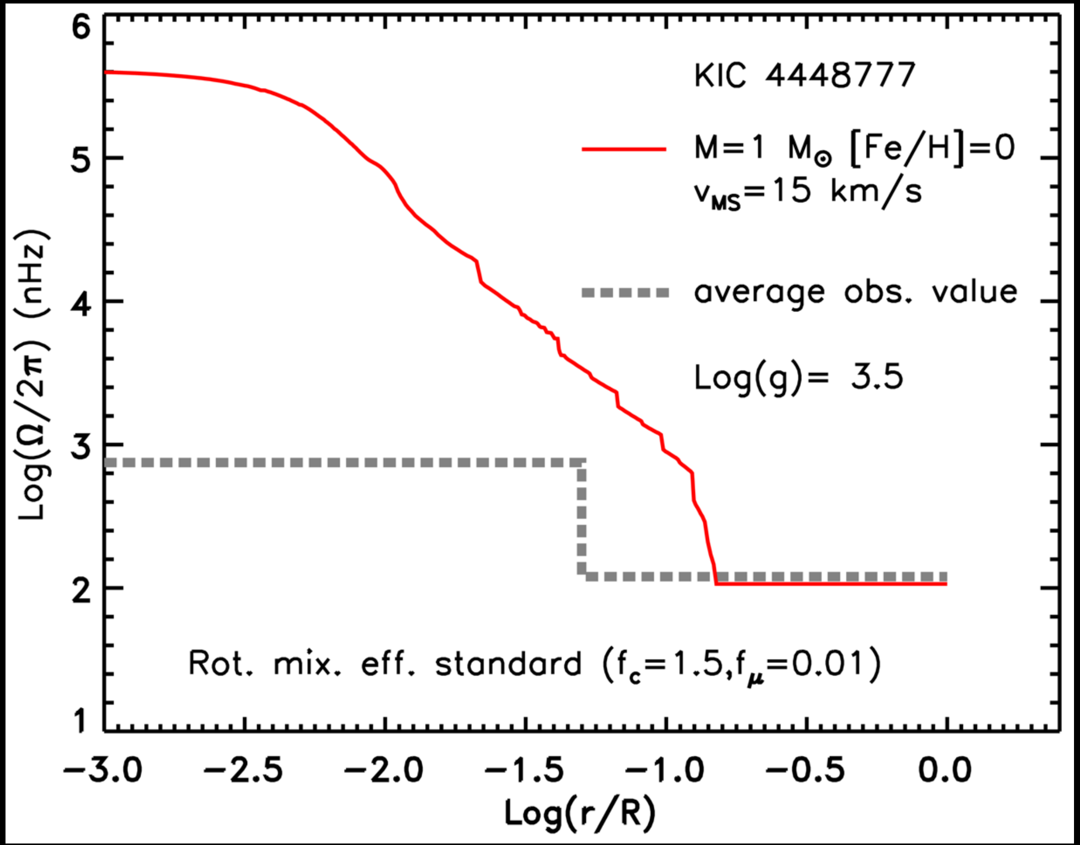




Rotation
Efficiency of the Angular Momentum Transport

Asteroseismology: A powerful tool to test the reliability of rotating models





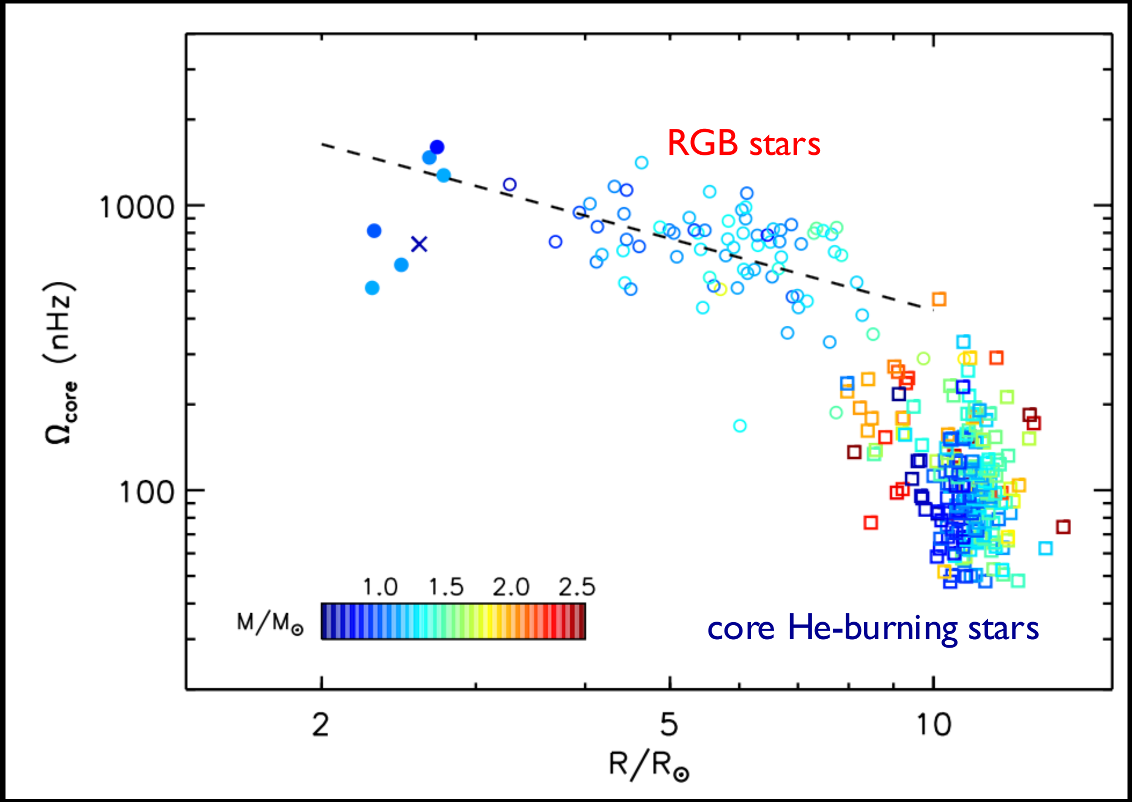
The angular momentum transport must be much more efficient than the one predicted by "calibrated" models

Large discrepancies between the theoretical predictions and the observations

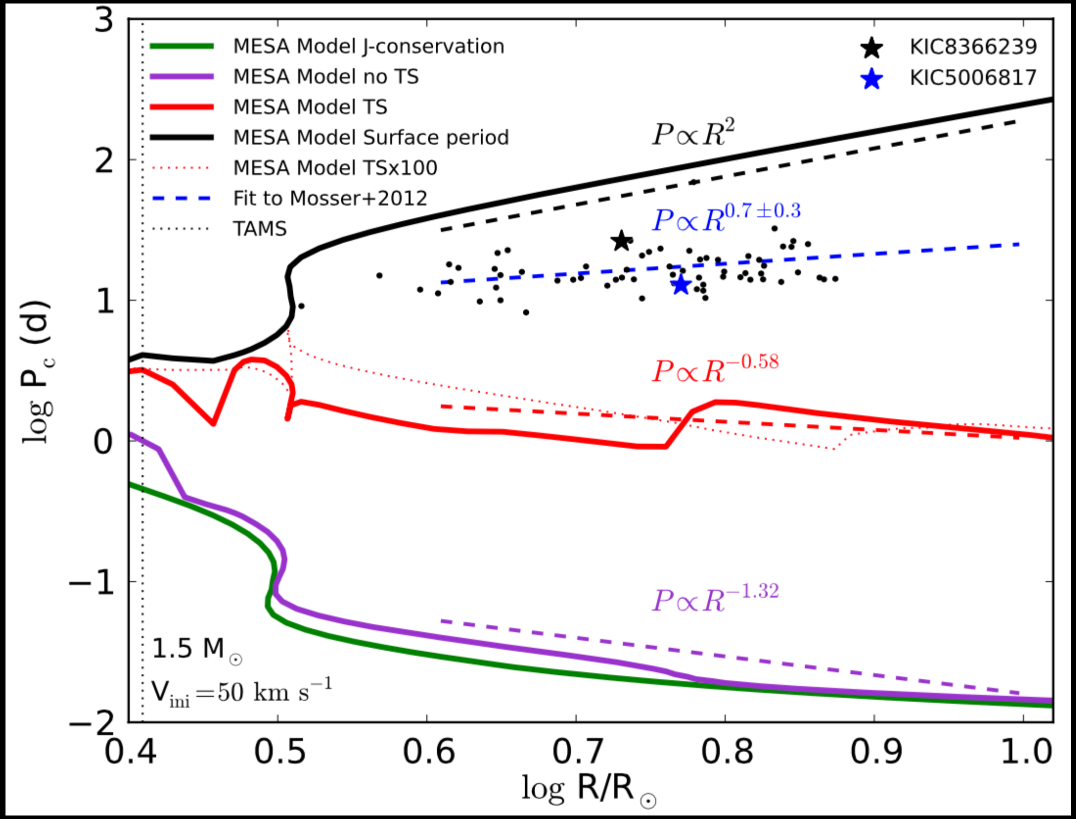
Rotation

Efficiency of the Angular Momentum Transport

This tension between rotating models and observations is confirmed by the large KEPLER sample even with the inclusion in the models of the magnetic fields



Mosser et al. (2013) - Deheuvels et al. (2014)



Cantiello+14

The inclusion of additional PARAMETRIZED input physics (Magnetic field) does not solve the problem

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Future Directions

1D models are simple, fast, accurate enough to explain and predict several observed and galactic properties, but they are not able to account for multidimentional phenomena (convection, rotation, magnetic fields, etc.) → predictive power of current stellar models is still limited

An important step forward would be represented by the development of 3D stellar models, where multidimensional phenomena would be treated based on first principles and where their efficiency would be the natural outcome of the simulations

Performing 3D simulations of stellar evolution is computationally extremely expensive and it is also affected by some limitations

Typical Spatial Scale

Microscopic nuclear reactions → Macroscopic processes like Mass Loss through Stellar Wind

Typical Lifetimes

Billions of years → days, hours and even minutes

Resolving all these scales simultaneously in 3D simulations is impractical due to computational constraints

hours of stellar evolution → millions of core-hours in a supercomputer

Following the Main Sequence phase, even for a Massive Star where this phase lasts few million years is unfeasible

Conclusion: The Path Forward

Transition from 1D to 3D modeling in stellar evolution is a key feature direction

Computational limitations currently restrict the use of 3D models to physical phenomena in stars occurring in a limited spatial scale and over short time scales

Overcoming the computational, physical, and methodological challenges will require new strategies

Possible steps forward:

- 321 models, i.e. use 3D simulations as guidlines for 1D stellar evolution codes (convection, overshooting, various mixing processes)
- Hybrid models, where 1D models are used for early stages and transitioned to 3D for more critical phases (capture the essential physics without the prohibitive computational cost of full-time 3D simulations)