Presupernova Evolution and Explosion of Massive Stars

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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 sources of Gravitational Waves (collapse and remnants)

- Are the progenitors of long Gamma Ray Bursts

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

Massive Stars

Massive stars (M>9 M$_\odot$) go through all the nuclear burning stages in a non-degenerate environment and eventually explode as Core Collapse Supernovae
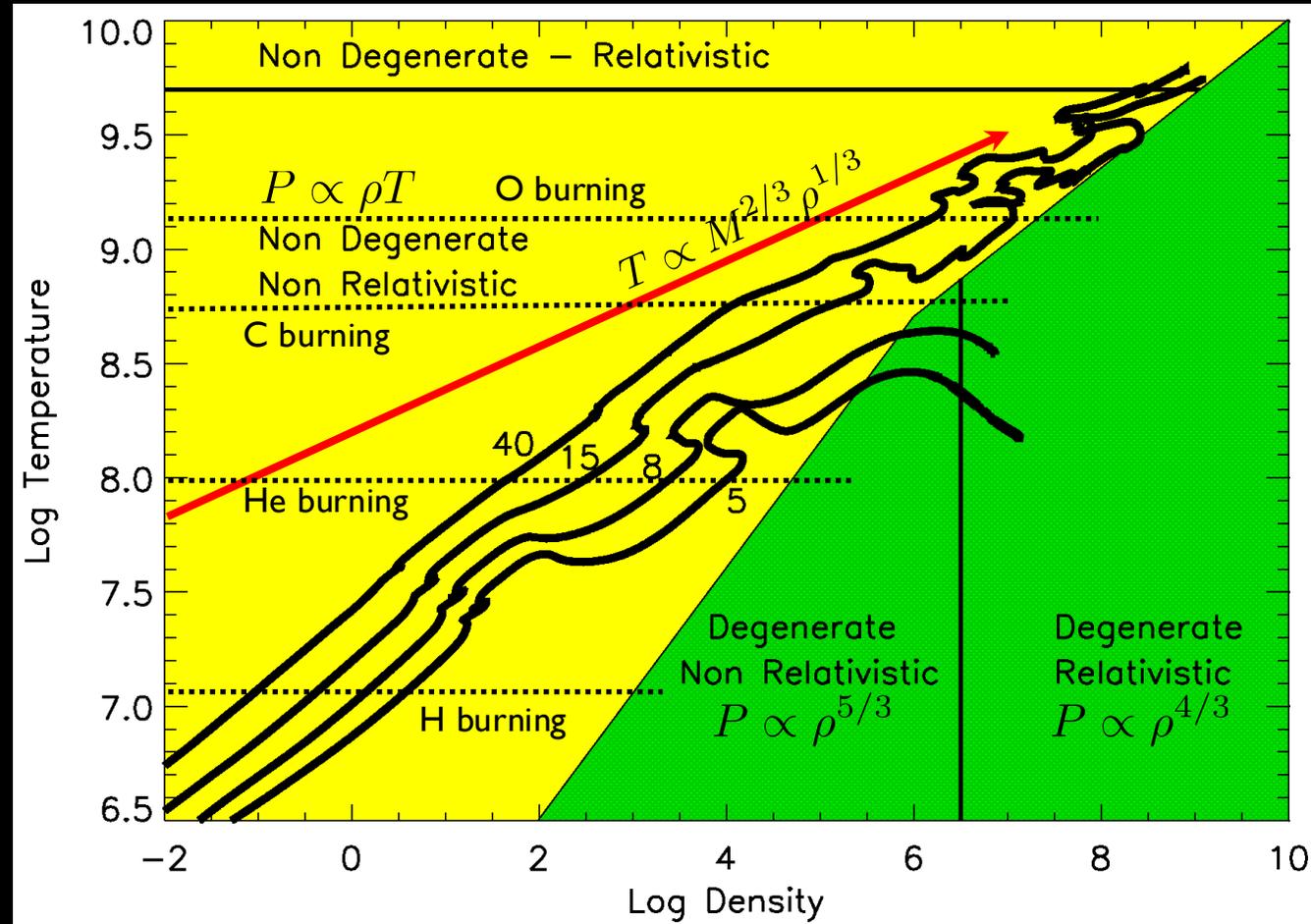
# Massive Stars: Distinctive Features

Massive Stars = A star in which the central temperature and density increase in such a way that degeneracy never takes place

$$M \gtrsim 9 \, M_{\odot}$$

- High temperatures are achieved that all the nuclear burning, from H to Si, go to completion and eventually a Fe core is formed → production of all the elements with 4<Z<38

- Strong neutrino emission from pairs production → dramatic reduction of the nuclear burning lifetimes

- Strong Mass Loss

- Chaotic evolution of the interior with formation of several and overlapping convective zones

- Fe core becomes unstable, collapses to nuclear density, rebounces and launches a shock wave that drives the explosion of the star → Massive stars are the progenitors of Core Collapse Supernovae

Solar Metallicity non Rotating Models: Presupernova Evolution
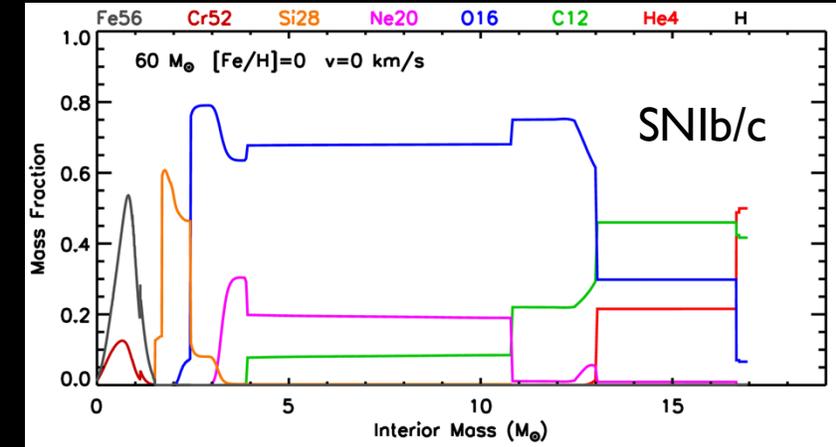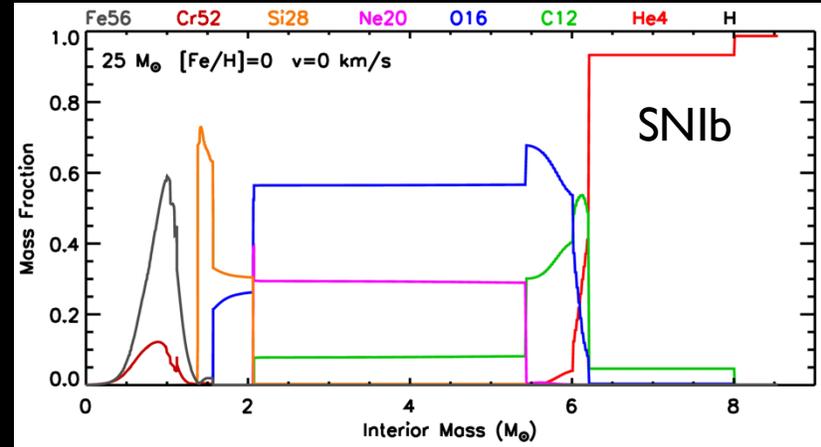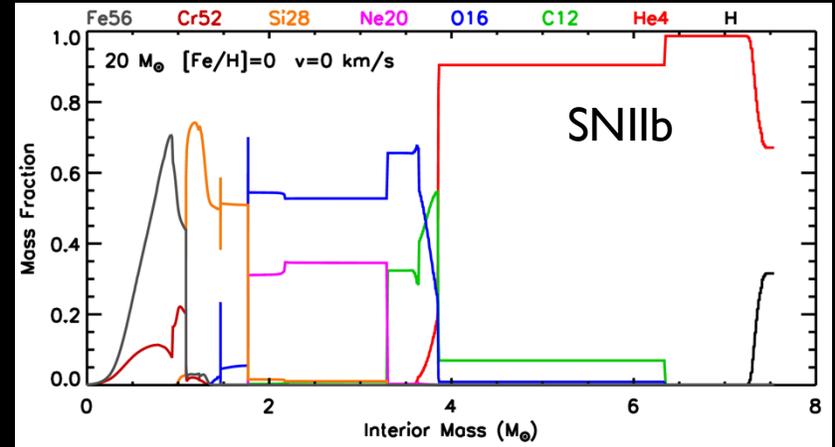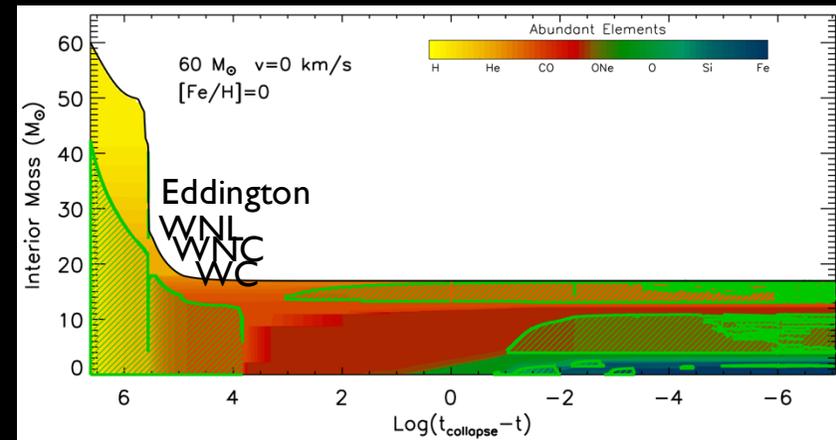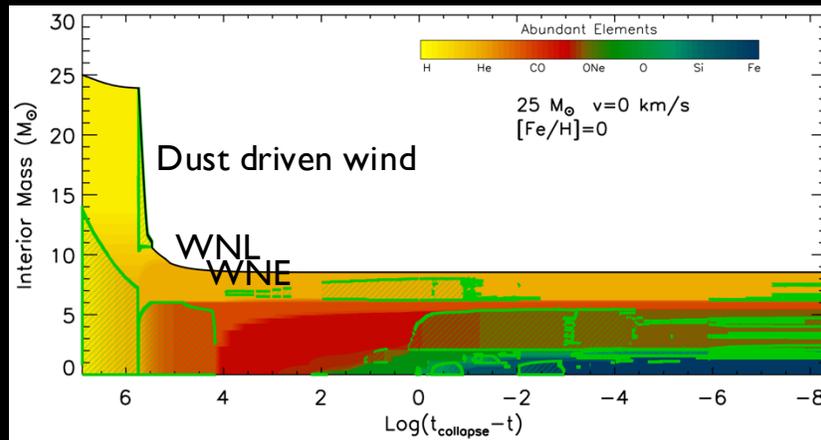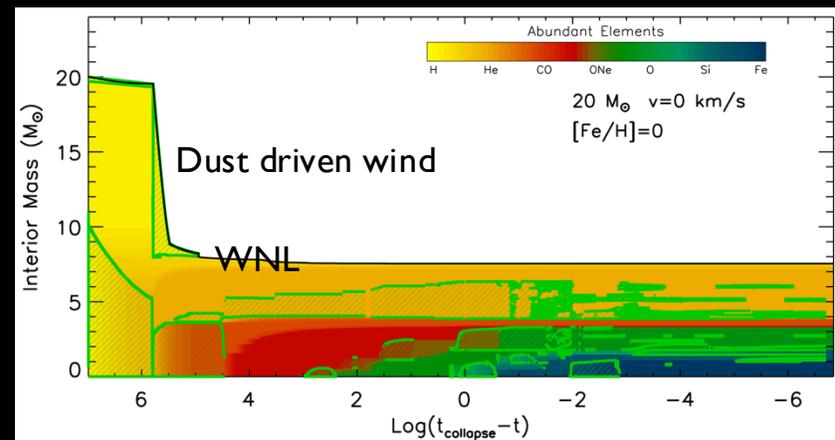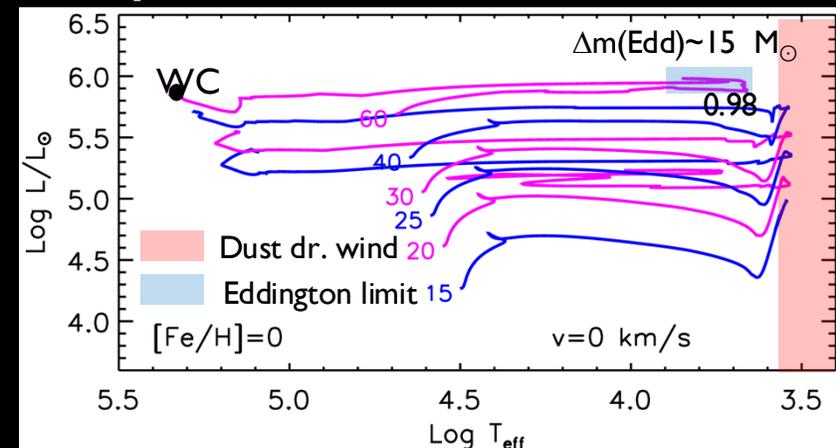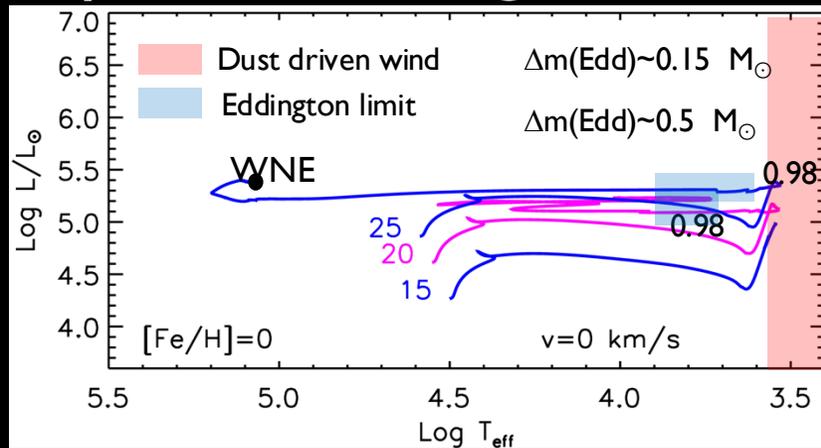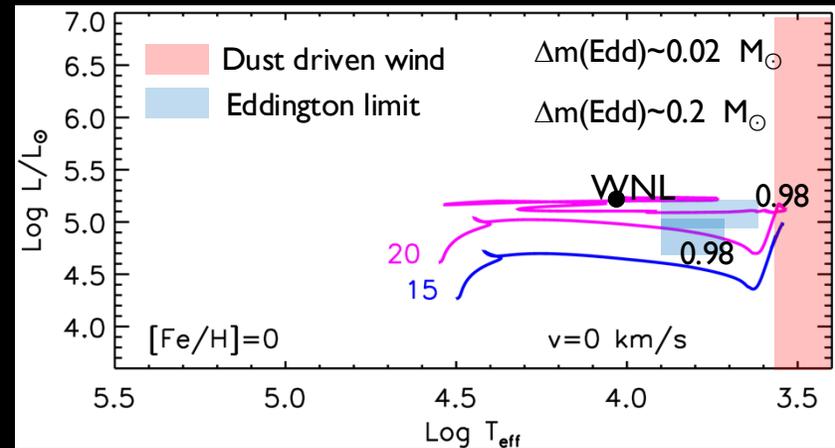
The lower end of Massive Stars
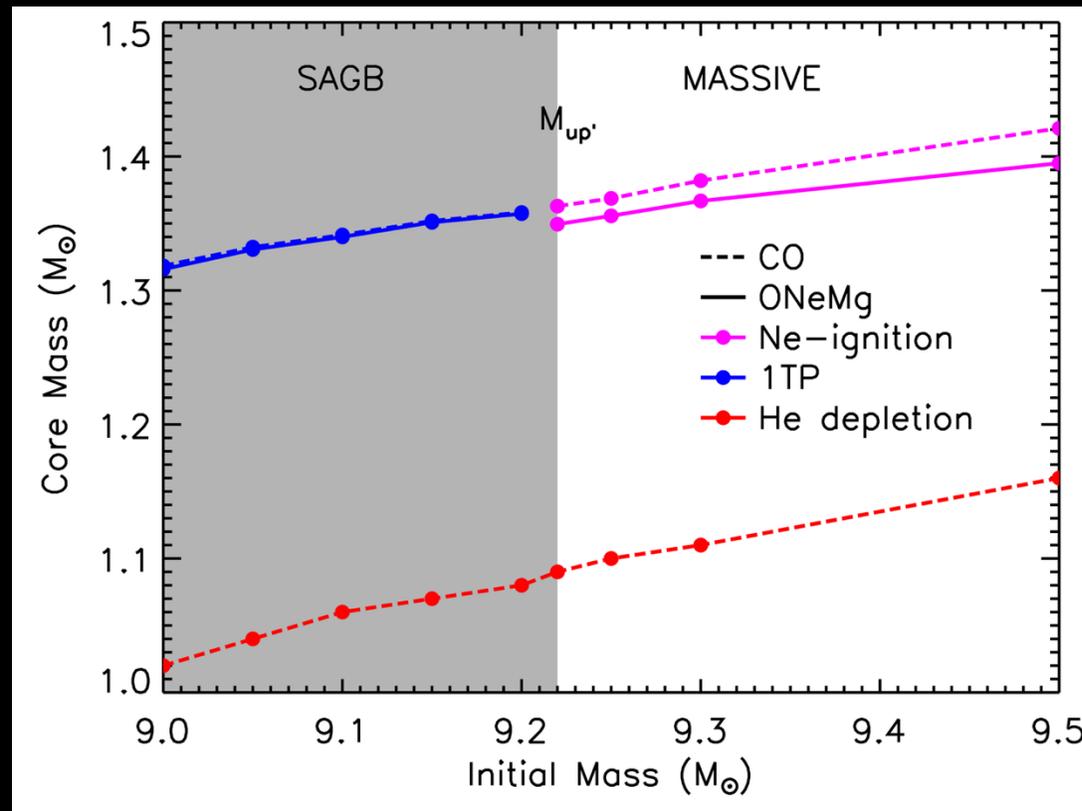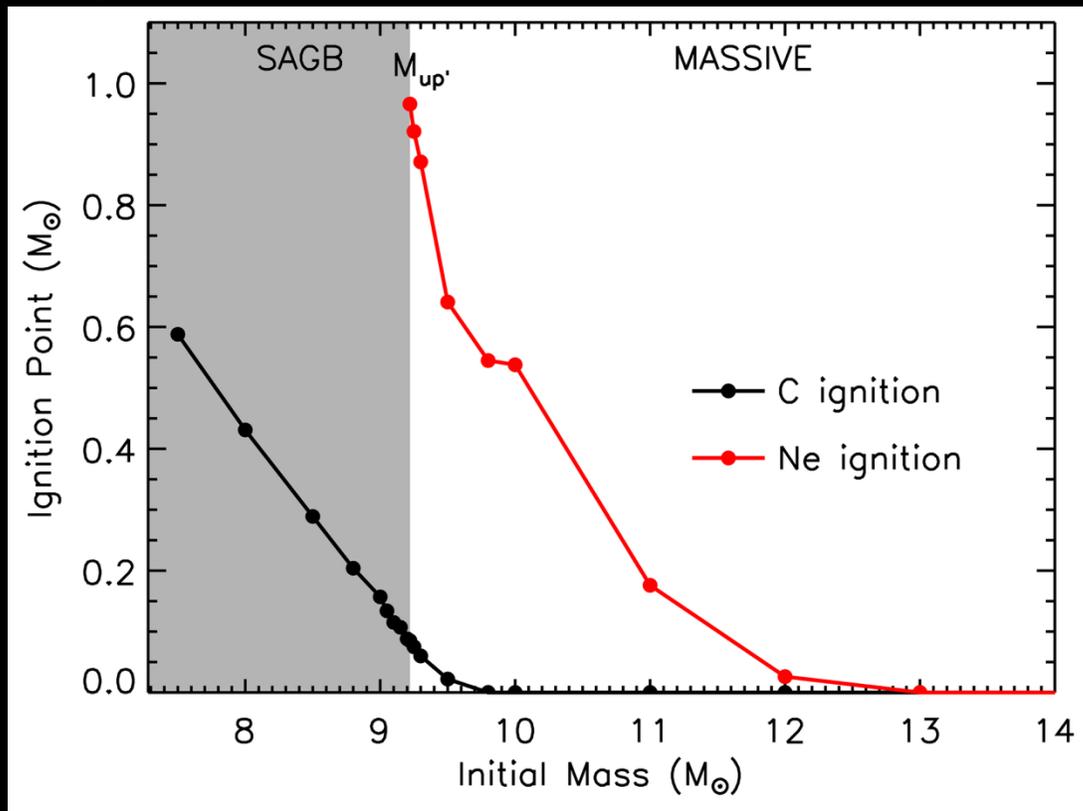
In stars with M < 9.22 $M_\odot$ the temperature does not reach the threshold value for the ignition of Ne burning

The 9.22 $M_\odot$ is the lower limit of Massive Stars

Off-center Ne-ignition in stars with $9.22 \leq M/M_\odot \leq 12$

Minimum CO core for Ne-ignition $M_{CO}=1.363\ M_\odot$ - $M_{ONe}=1.349\ M_\odot$
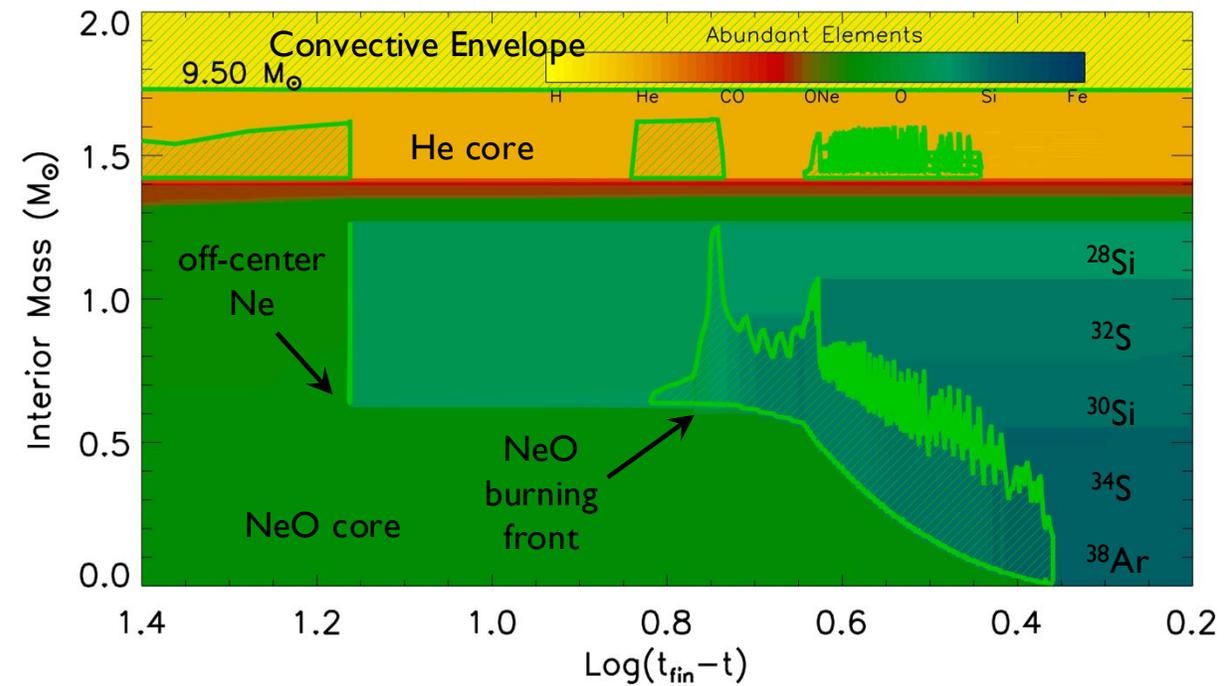
Limongi+ (2024)

The lower end of Massive Stars

Ne ignition in a degenerate environment induces a progressive increase of T and L

A convective zone is formed

Temperature increases to the threshold value for O ignition

Limongi+2024
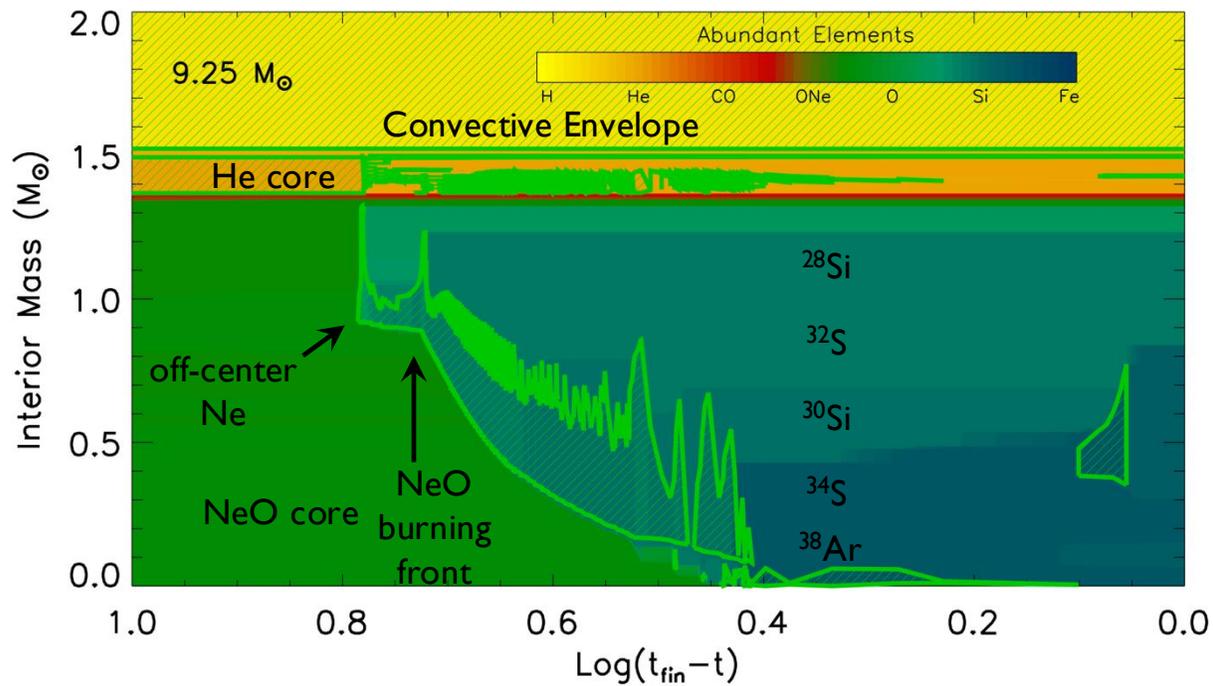
Because of the efficient electron captures, the main products of the off-center Ne/O burning within the convective shell are ^{34}S, ^{28}Si, ^{30}Si and ^{32}S

The efficiency of the electron captures, however, decreases as the initial mass of the star increases

The lower end of Massive Stars

At variance with off- center C burning, no hybrid core is formed as a result of the off- center Ne ignition. All of the stars that ignite off-center Ne burning form an O-depleted core; i.e., in all of these models, the ONe burning front reaches the center

Chemical composition of the O-exhausted core strongly depends on the initial mass

Limongi+ (2024)
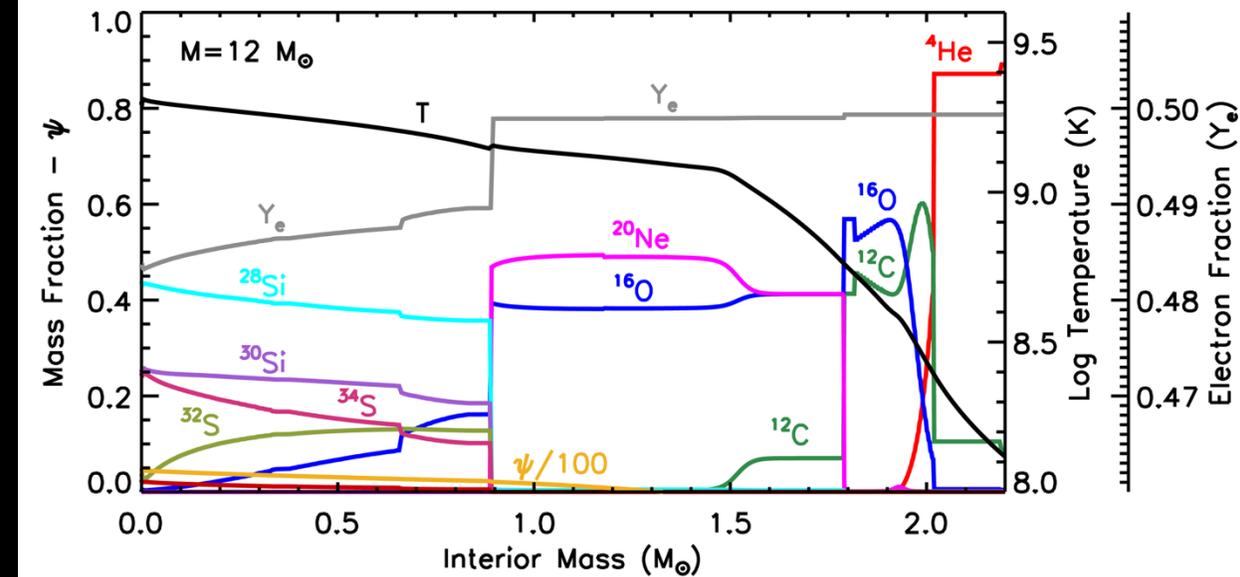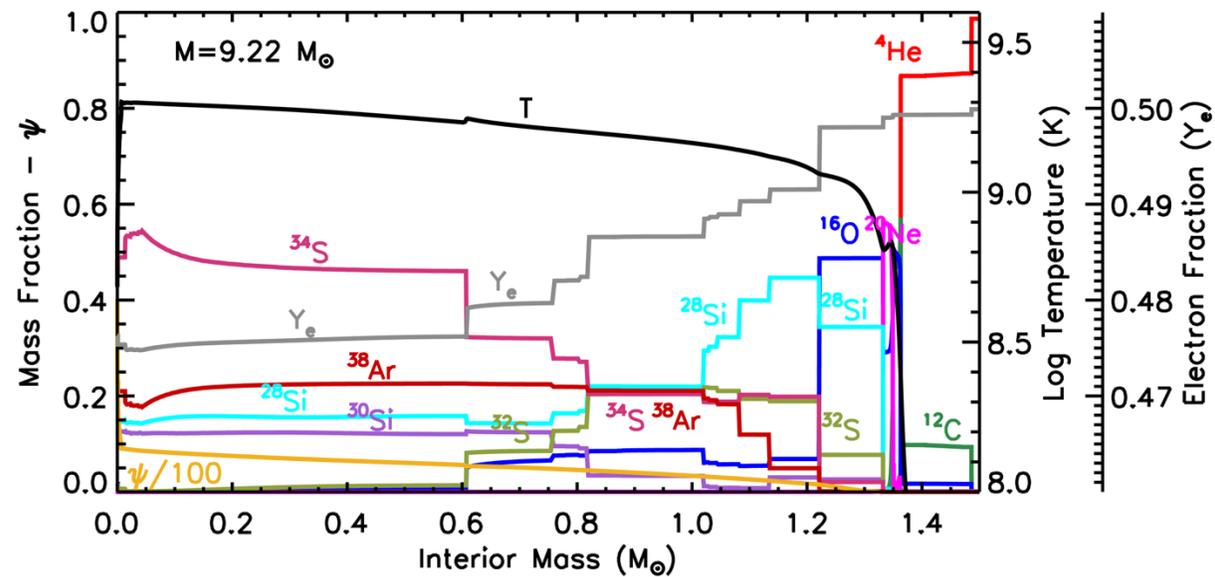
The lower end of Massive Stars

All the stars that ignite NeO, ignite also Si burning (off-center or centrally), form a "Fe" core and explode as CCSNe
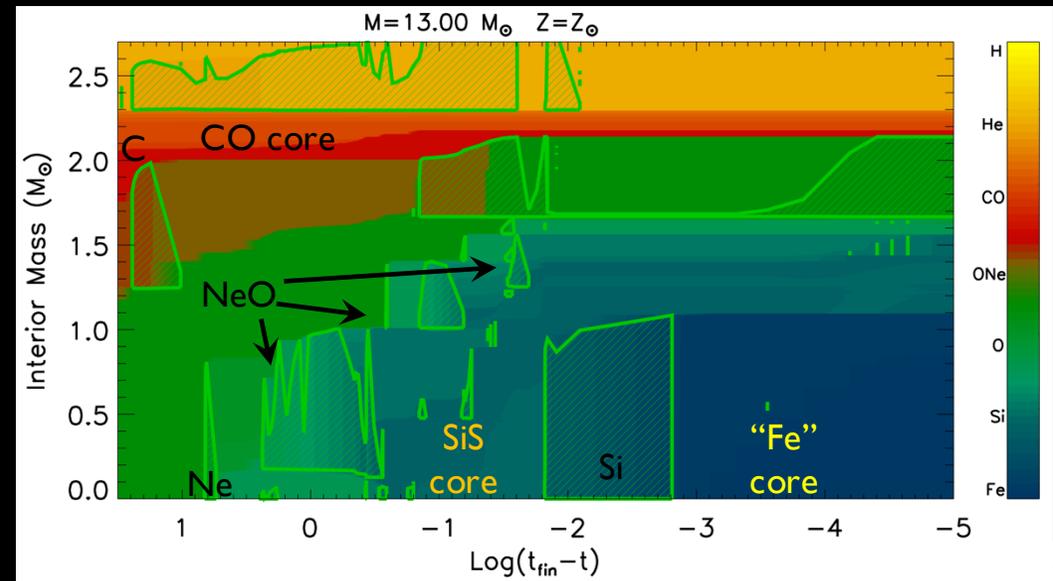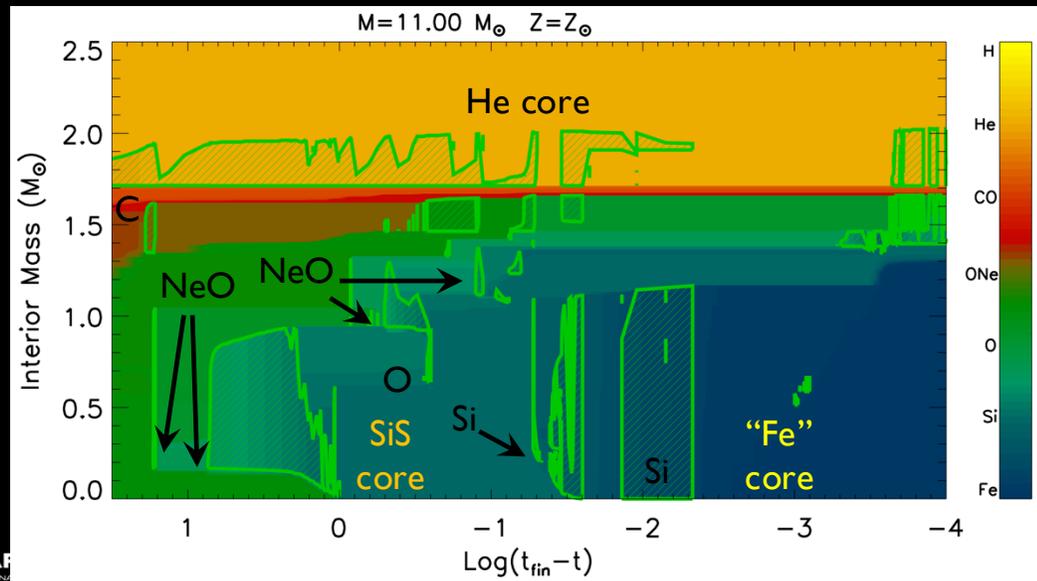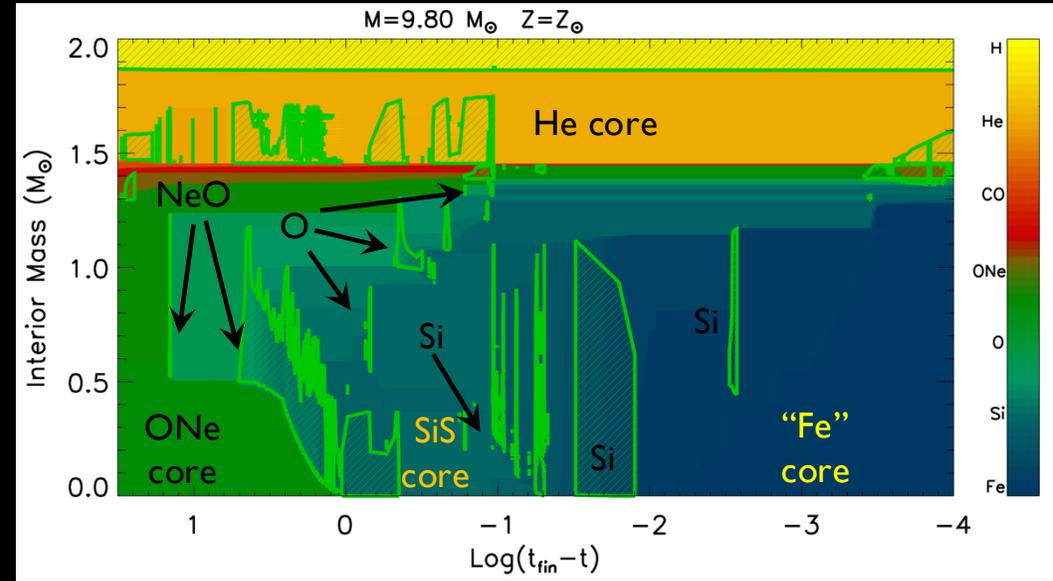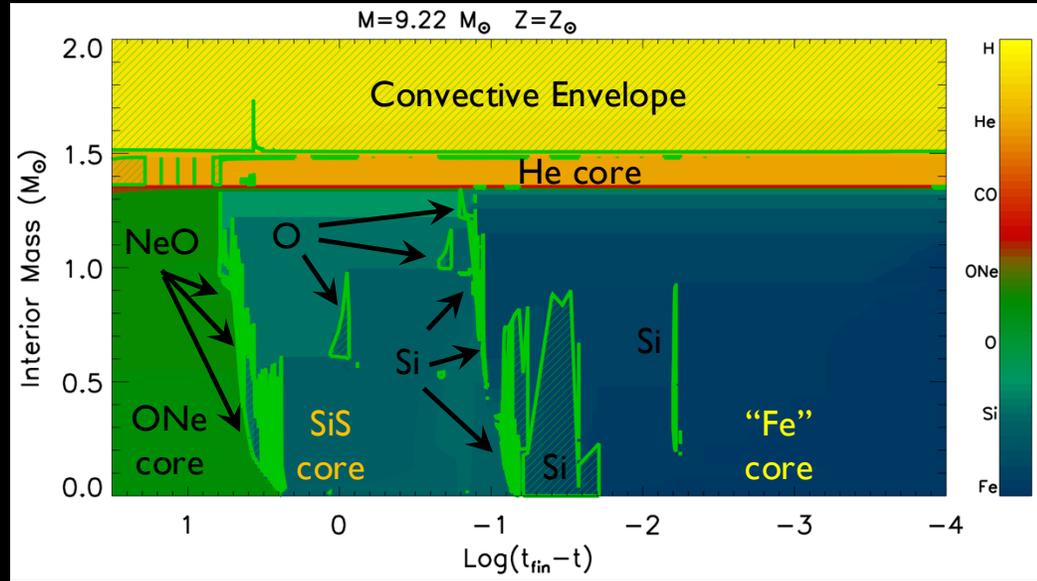
The Presupernova Stars

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)

Open question: The compactness of massive stars @ presupernova stage

- Following core Si burning a Fe core is formed that becomes unstable, collapses, reaches the nuclear densities, re-bounces and produces a shock wave that is powered by the neutrino energy deposition and that ultimately drives the explosion of the star

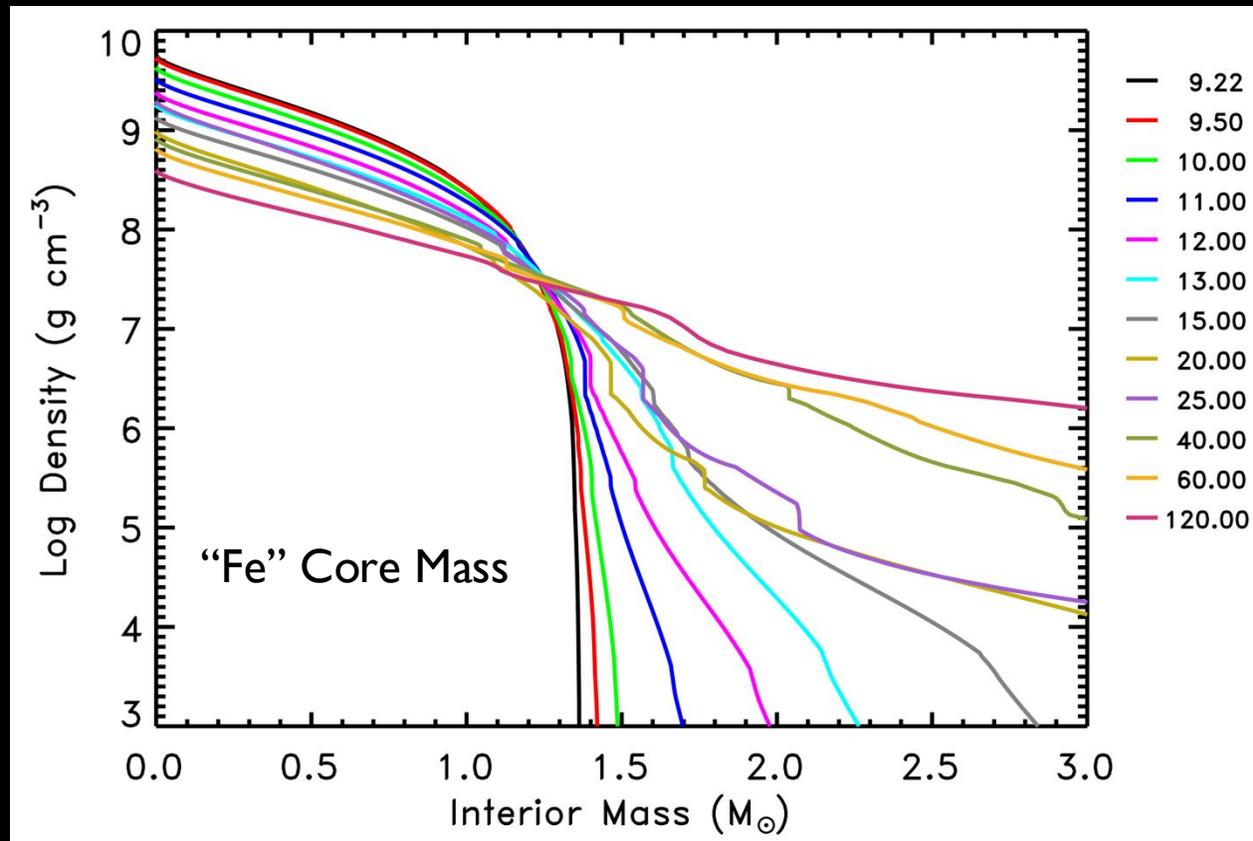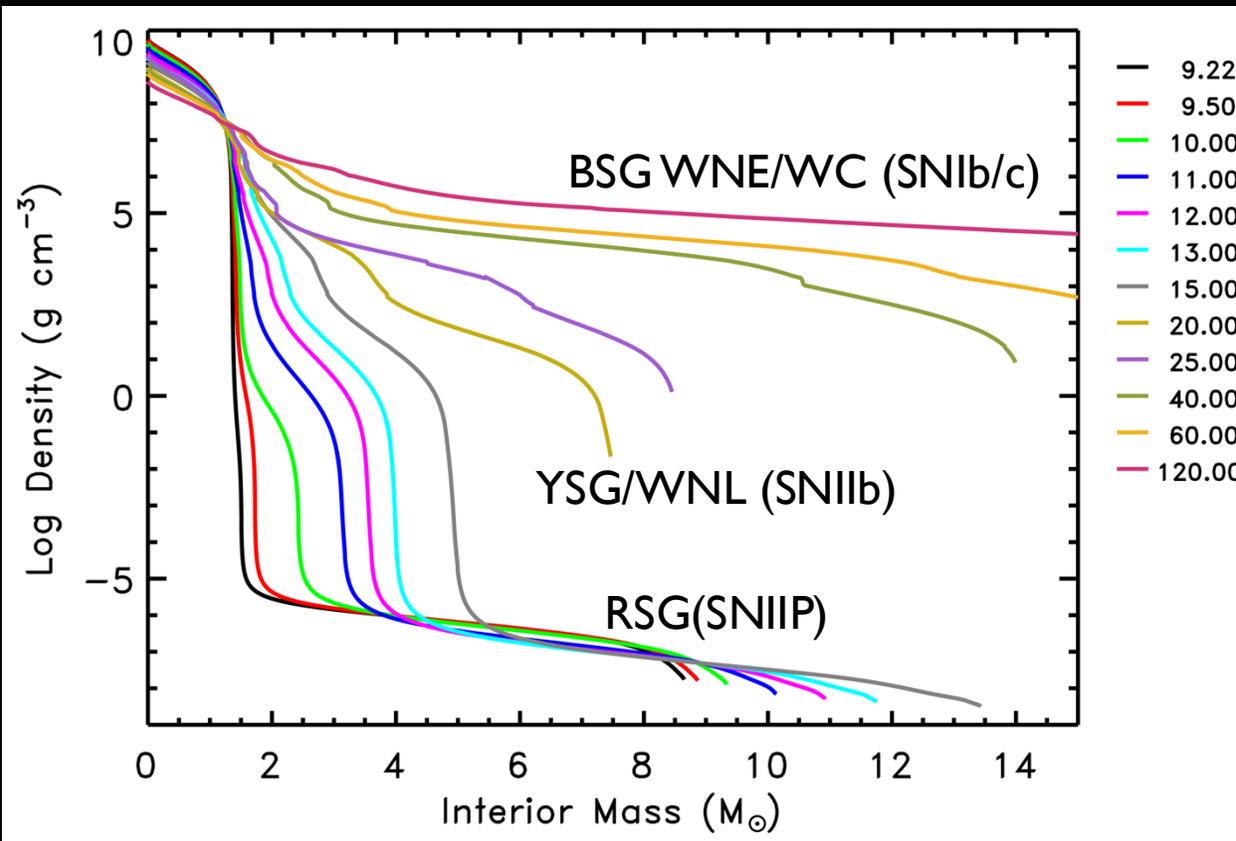- Few self consistent 3D models with the most sophisticated treatment of hydrodynamic and neutrino transport can obtain the explosion of a massive star

- Even in the most favorable case, the explosion is followed for few seconds because of the tremendous demand of computer time

- Increasing interest in the last years in the Compactness Parameter (O'Connor & Ott 2011) in order to predict the explodability of a massive star without making any hydrodynamical simulation of the explosion

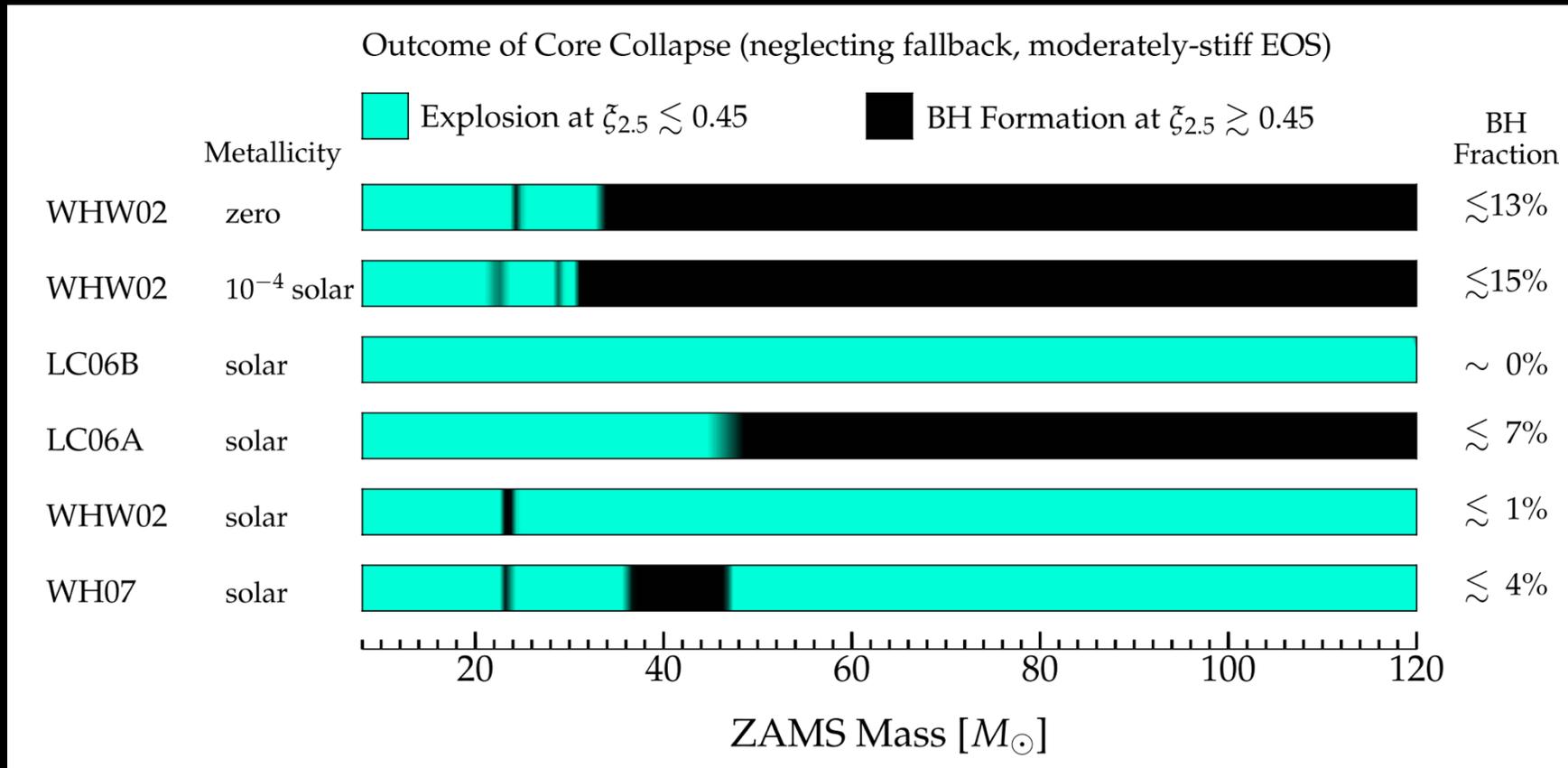$$\xi_M = \frac{m/M_\odot}{r(m)/1000 \text{ km}}$$

The Compactness of Massive Stars

- Basic idea: the larger is the compactness parameter the harder is to explode the star

where the compactness must be evaluated?

which is the critical value for the explosion?

O'Connor & Ott (2011)

Outcome of Core Collapse (neglecting fallback, moderately-stiff EOS)

Explosion at $\xi_{2.5} \lesssim 0.45$ BH Formation at $\xi_{2.5} \gtrsim 0.45$

	Metallicity		BH Fraction
WHW02	zero		$\lesssim 13\%$
WHW02	10^{-4} solar		$\lesssim 15\%$
LC06B	solar		$\sim 0\%$
LC06A	solar		$\lesssim 7\%$
WHW02	solar		$\lesssim 1\%$
WH07	solar		$\lesssim 4\%$

ZAMS Mass [$M_\odot$]

The Compactness of Massive Stars

The use of the compactness paramater has been criticized by various groups that claimed that this is not the only property of a massive star that can be used to infer the explodability (e.g., Perego+ 2015, Ertl+ 2016, Ebinger+ 2020, Ertl+ 2020, Burrows+ 2020)

Other critieria of explodability based on different properties of the core have been proposed (see, e.g., Ertl+ 2016, Boccioli+ 2023) on the basis of 1D hydrodynamical simulations

State-of-the-art 3D simulations have shown that further research must be conducted in order to find an effective explodability criterion (Burrows+ 2020)

Regardless of the explodability problem, the compactness of a massive star is a fundamental properties that certainly plays a pivotal role in the explosion of the star

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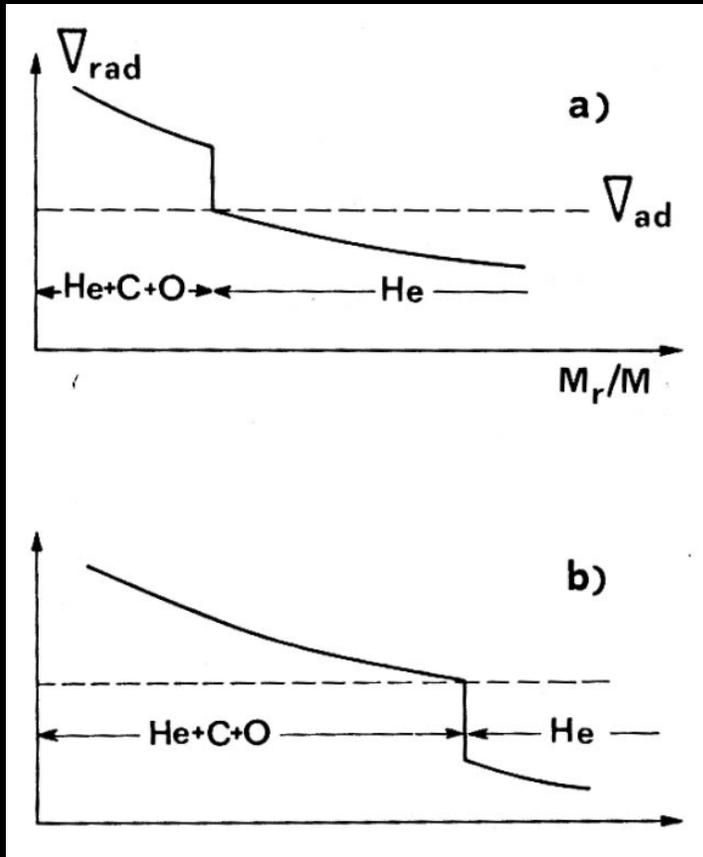
When $He_c <= 0.1$ the enrichment of core He produced be the increase of the convective core, even by a small amount, drives an enhancement of the nuclear energy generation that in turn drives a phase of progressive increase of the convective core

- prolonged core He burning phase

- prolonged conversion of ^{12}C into ^{16}O

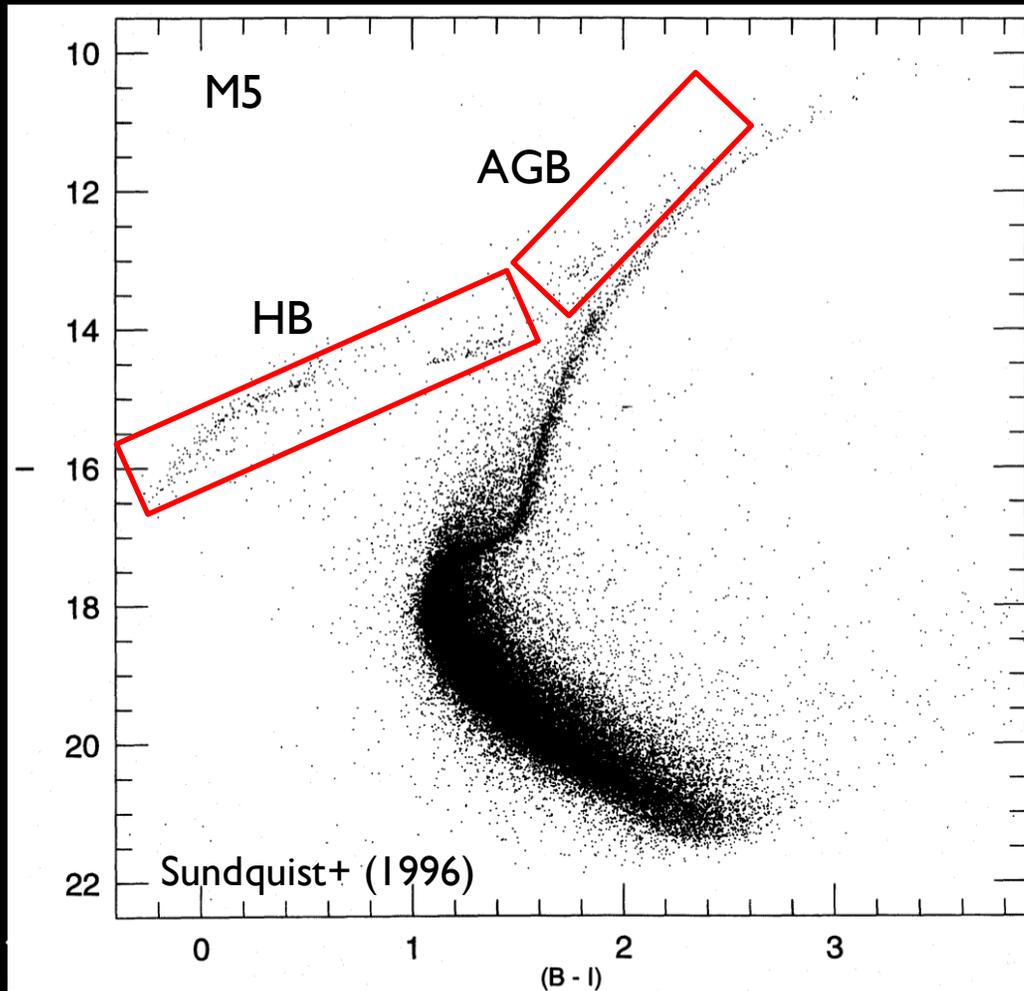- non monotonic (stochastic) ^{12}C at core He depletion vs initial mass
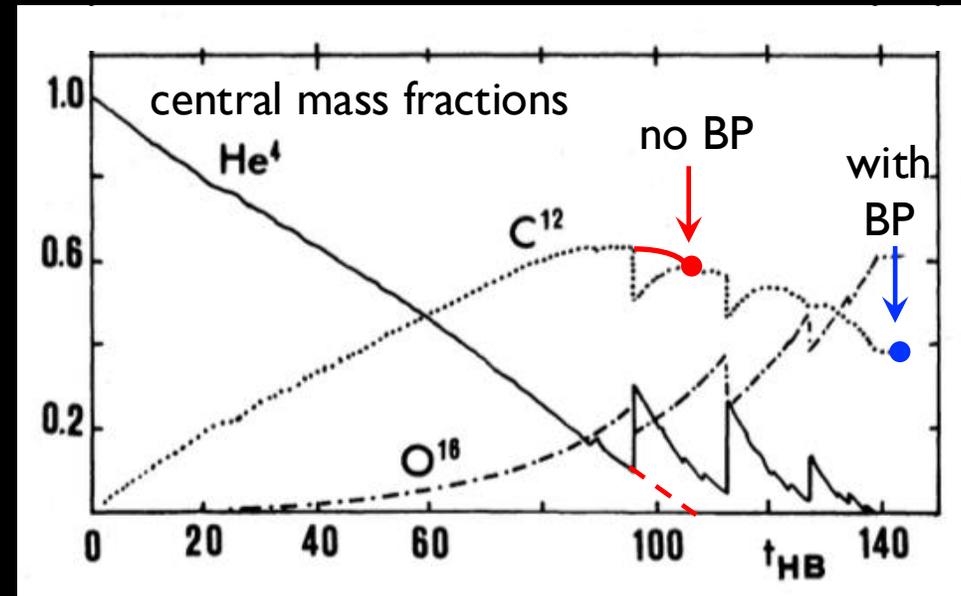
Convection

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

M5

AGB

HB

Sundquist+ (1996)

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]

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[2] Monash Centre for Astrophysics (MoCA), School of Physics and Astronomy, Monash University, VIC 3800, Australia
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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 $\Delta \log L_{\mathrm{HB}}^{\mathrm{AGB}} = 0.455 \pm 0.012$. 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, and (ii) that models with large convective cores have a particular depth of mixing beneath the Schwarzschild boundary during subsequent early-AGB 'gravonuclear' convection.
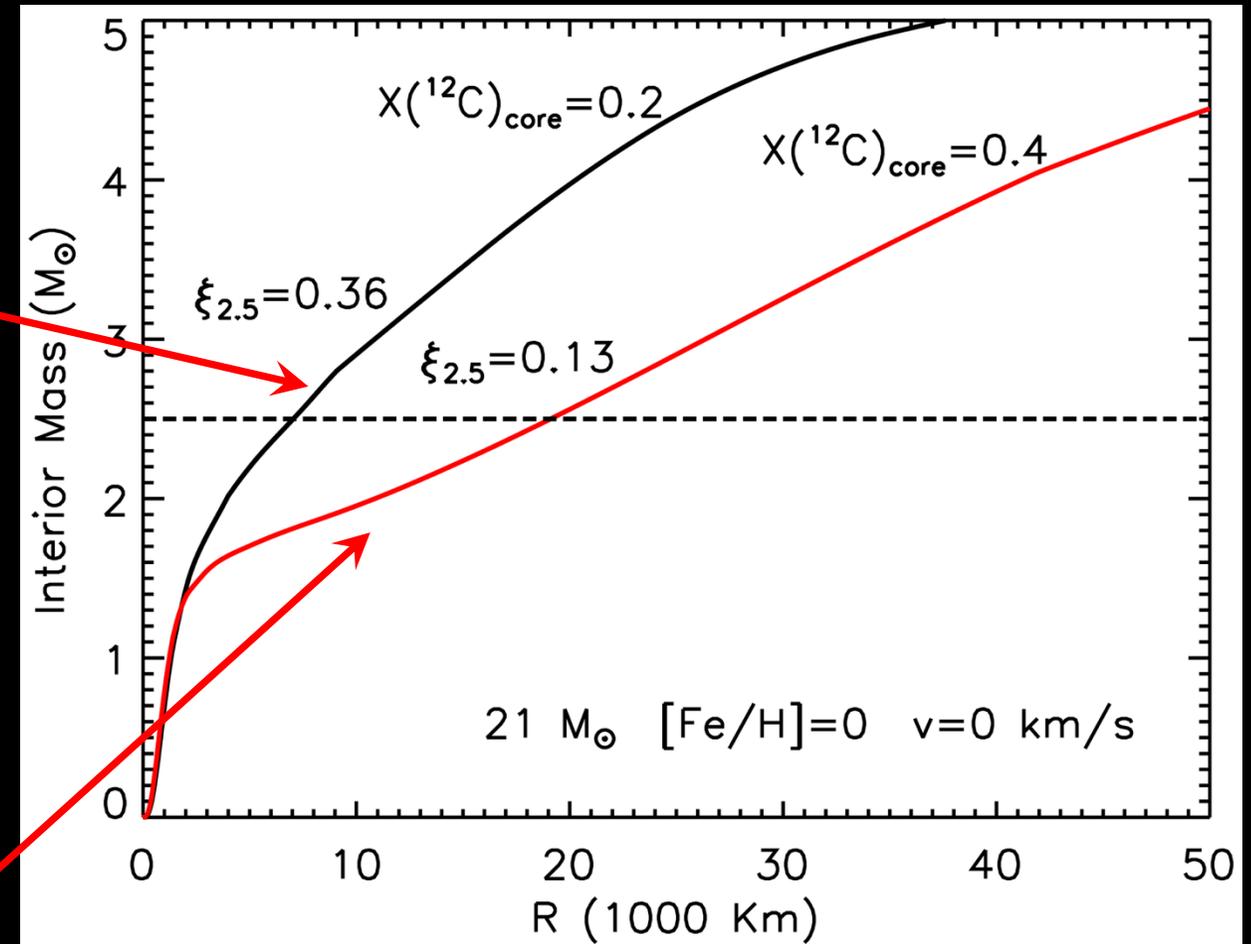
Convection

Treatment of BP impacts on ^{12}C at core He depletion → on the efficiency of the C-shell burning
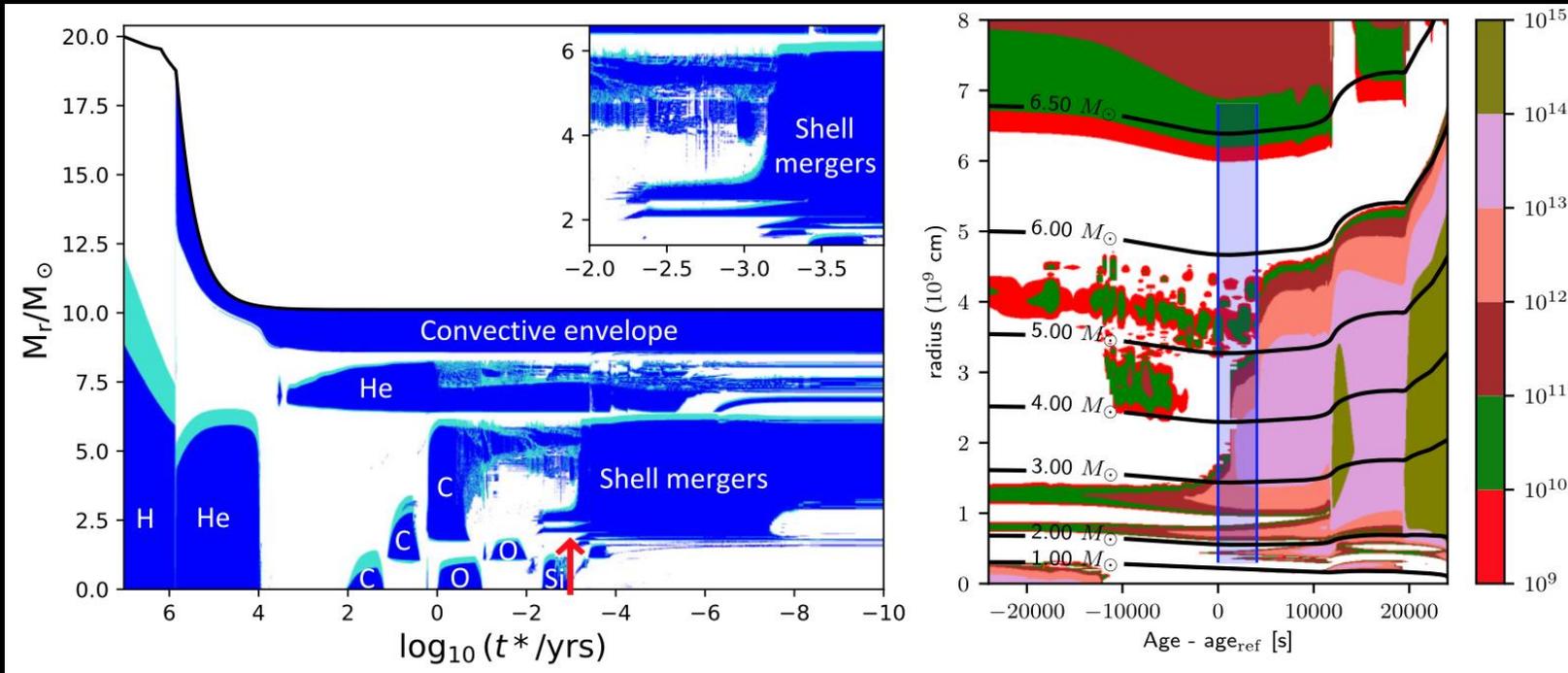
Imbriani+ (2001)
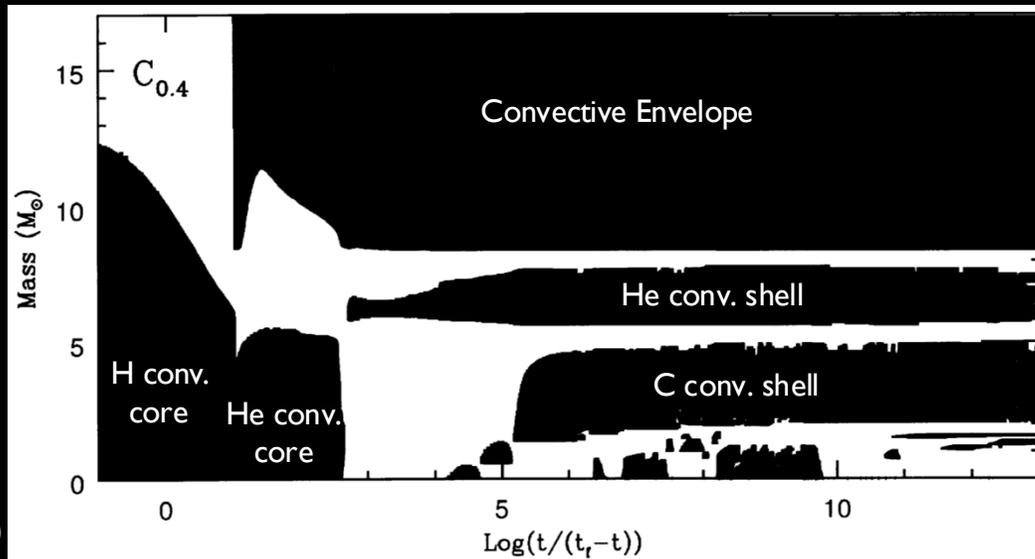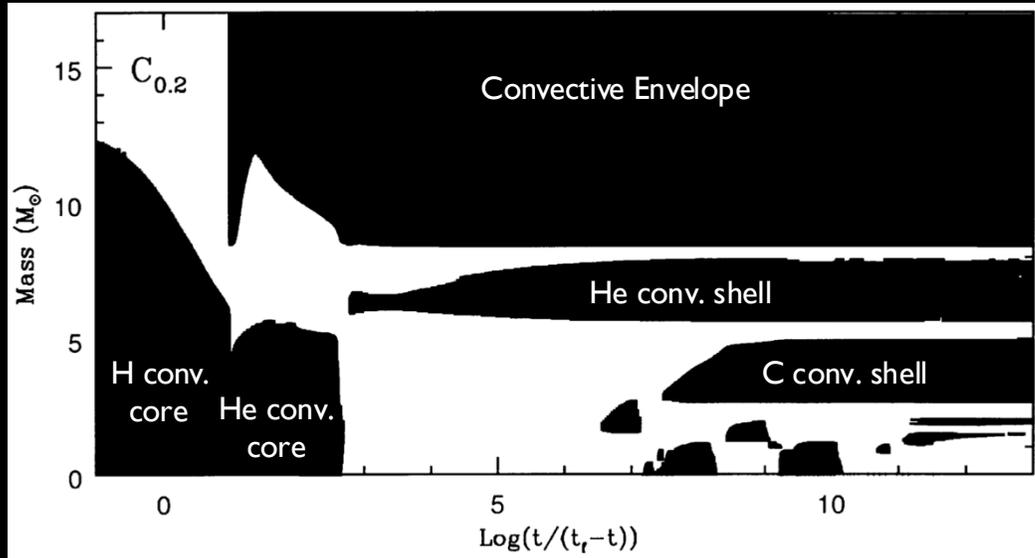
Convection

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)
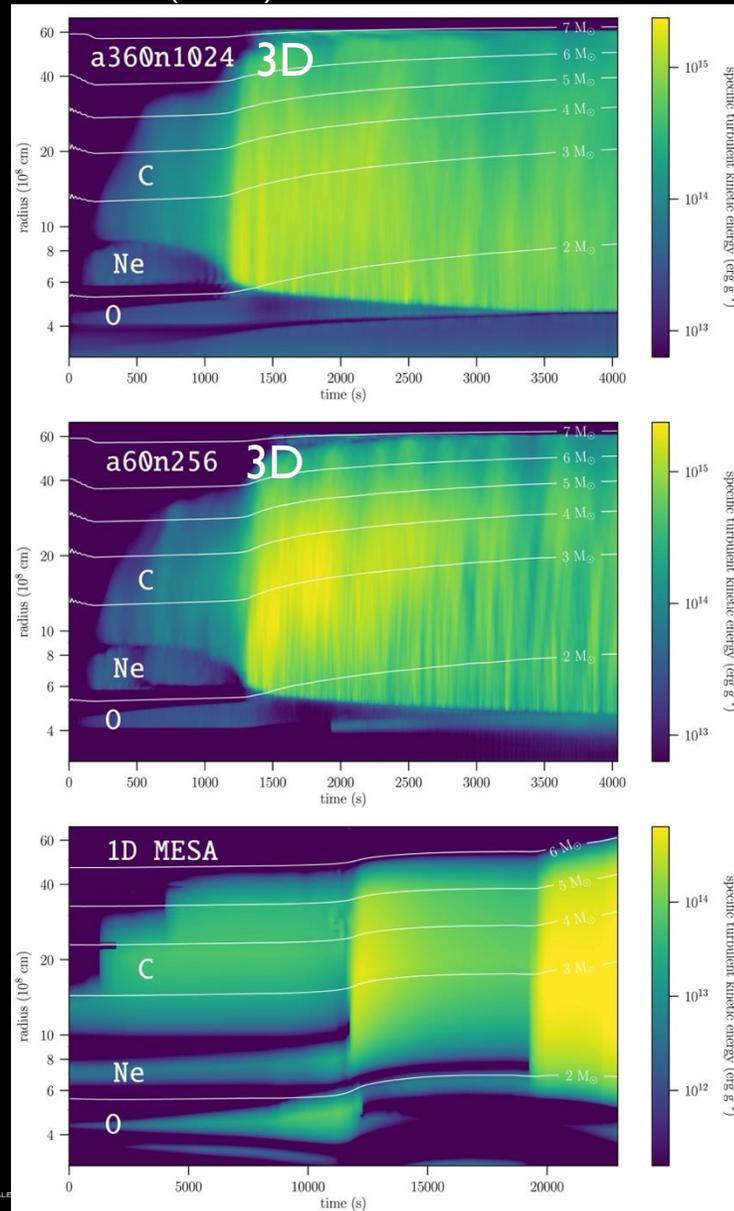
Substantial differences between 3D and 1D models

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

- Detailed study of the evolution of massive stars with a very fine step in mass ($\Delta M = 0.01 M_\odot$) (Sukhbold+2014, Sukhbold+2018) and a more sophisticated criterion for explodability (Ertl+ 2016)
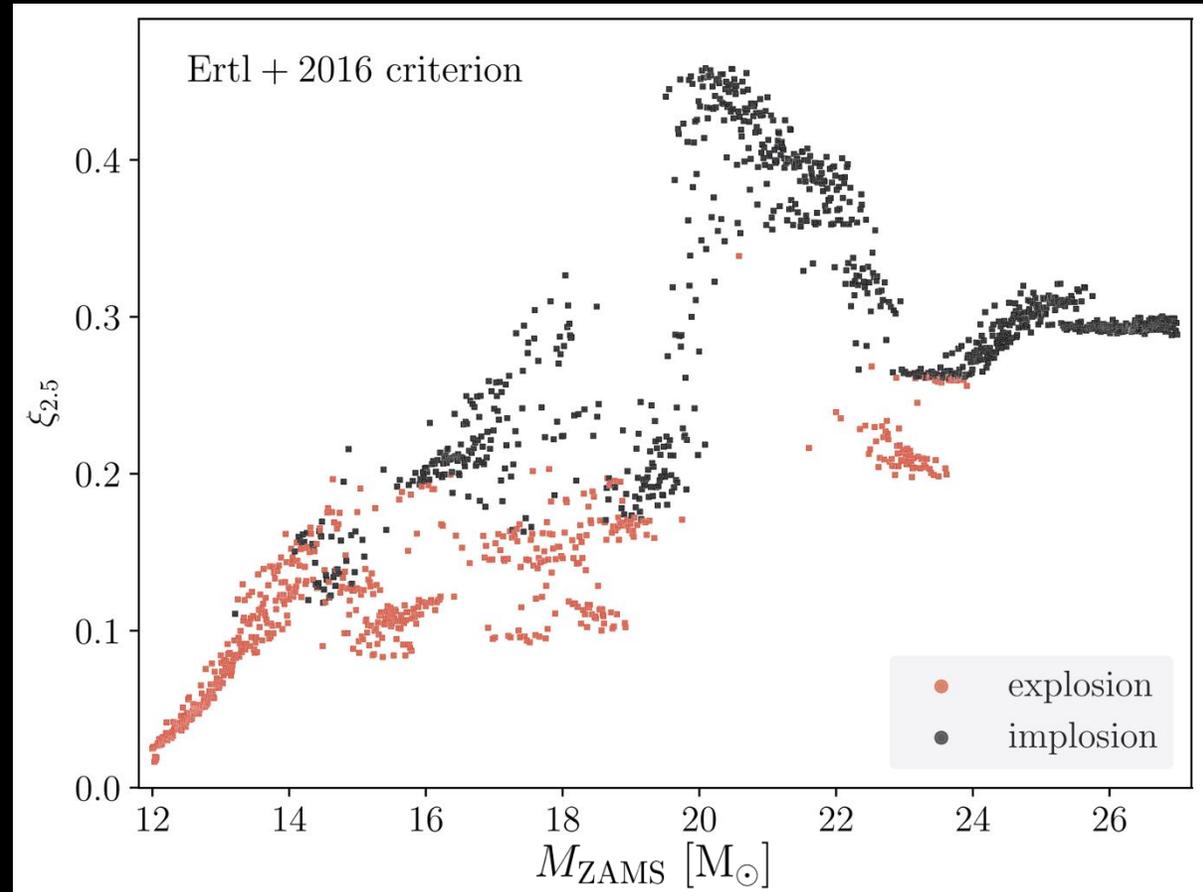
Sukhbold+(2018)

$\xi_{2.5}$ is extremely scattered as a function of the initial mass

extremely small changes in the initial mass may lead to an explosion or to a direct collapse to BH

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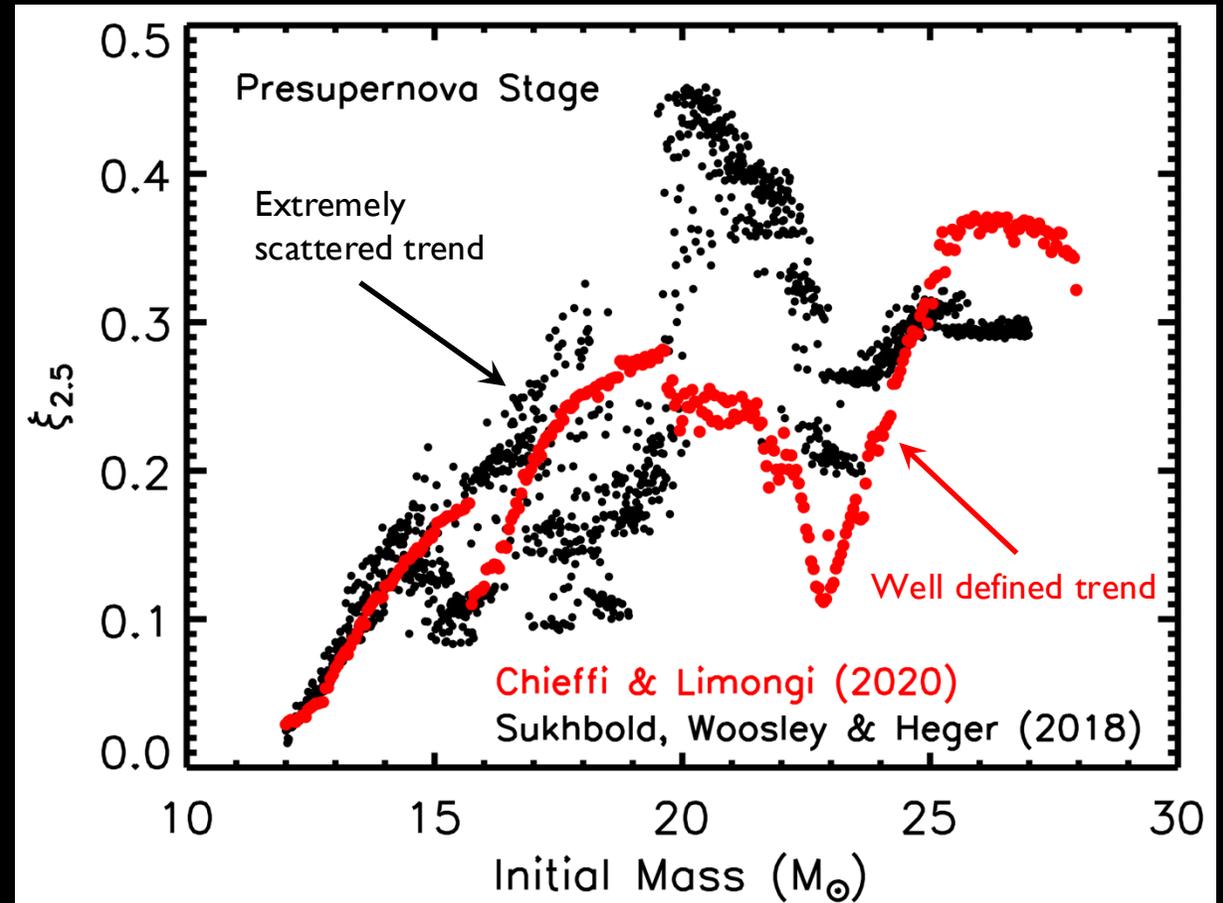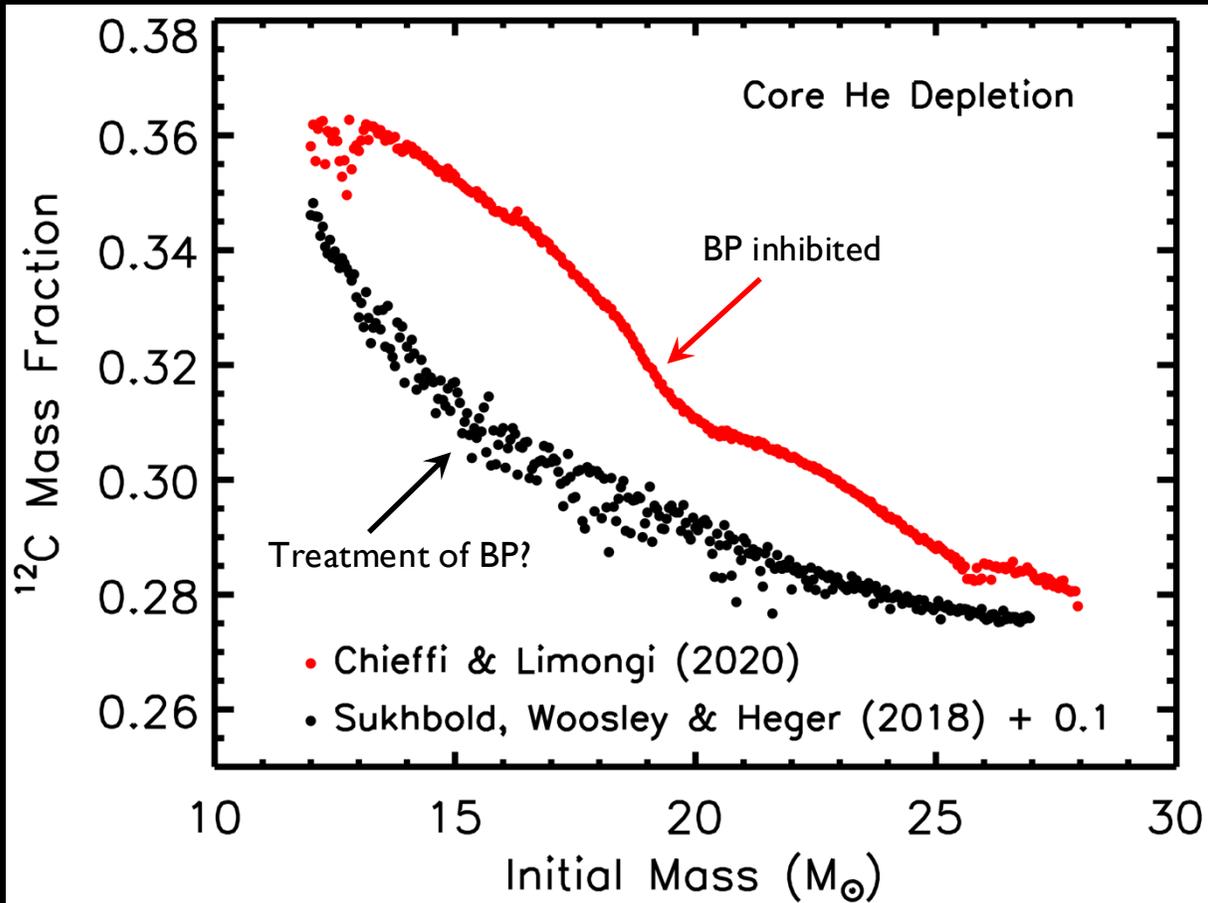
If the relation between the ^{12}C at core He depletion and the Initial Mass is very tight, a well defined, (not scattered) trend of the compactness with the initial mass is obtained

Open Question: The nature of the remnant after the explosion

- Which is the masses of the remnants as a function of the initial mass, metallicity and rotation velocity?

- Which is the maximum BH that can be formed after the explosion?

Fundamental questions in the context of the Gravitational Waves
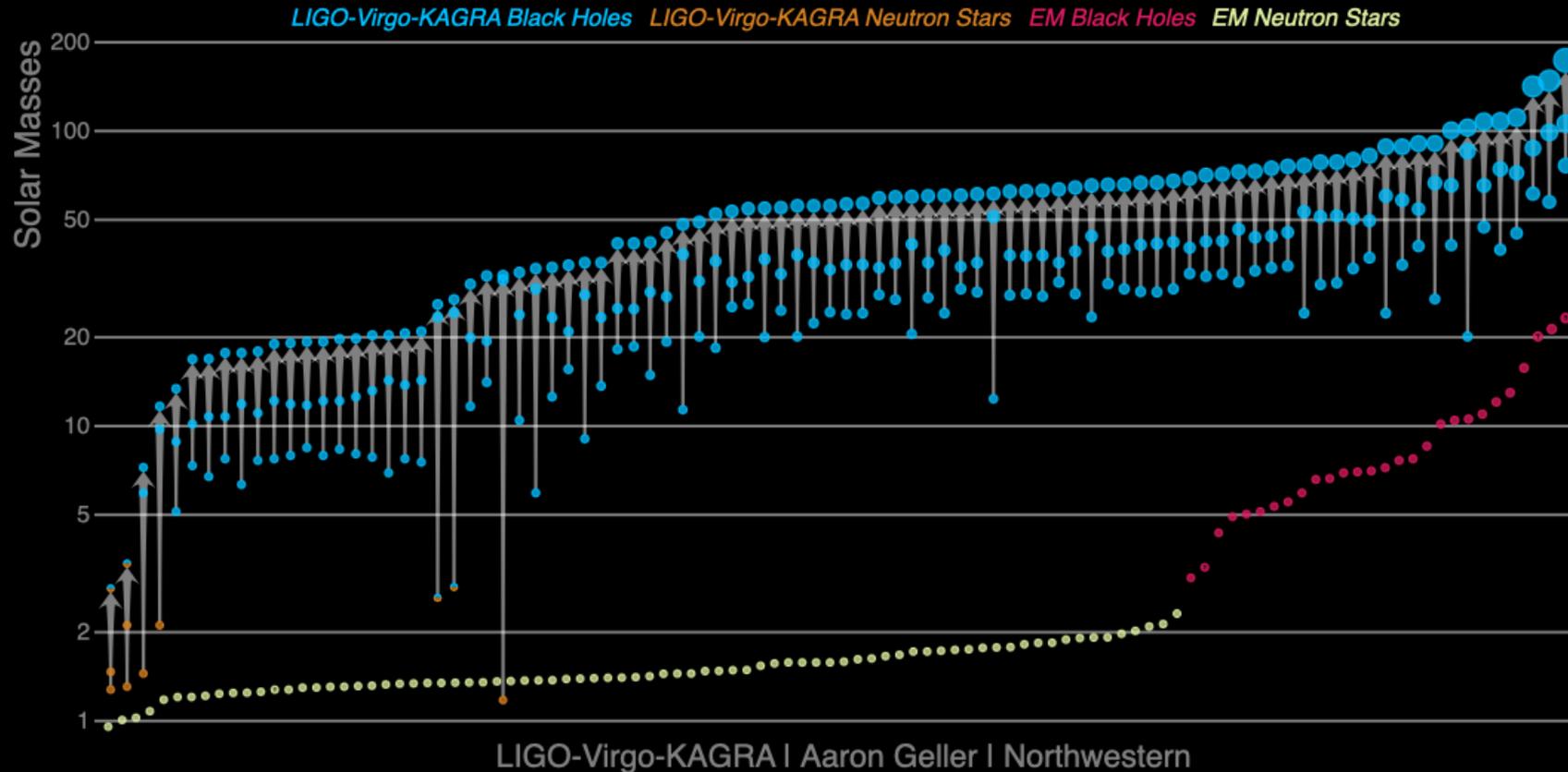
Open Question: The nature of the remnant after the explosion

- Which is the masses of the remnants as a function of the initial mass, metallicity and rotation velocity?

- Which is the maximum BH that can be formed after the explosion?

Assuming that above a critical initial mass the star directly collapses to a BH, the questions are:

- Which is the maximum initial mass that directly collapses to a BH?

- Which is its total mass at the time of the collapse?

- Which are the conditions to form stellar BH of mass ~90-100 $M_{\odot}$?

Open Question: The nature of the remnant after the explosion
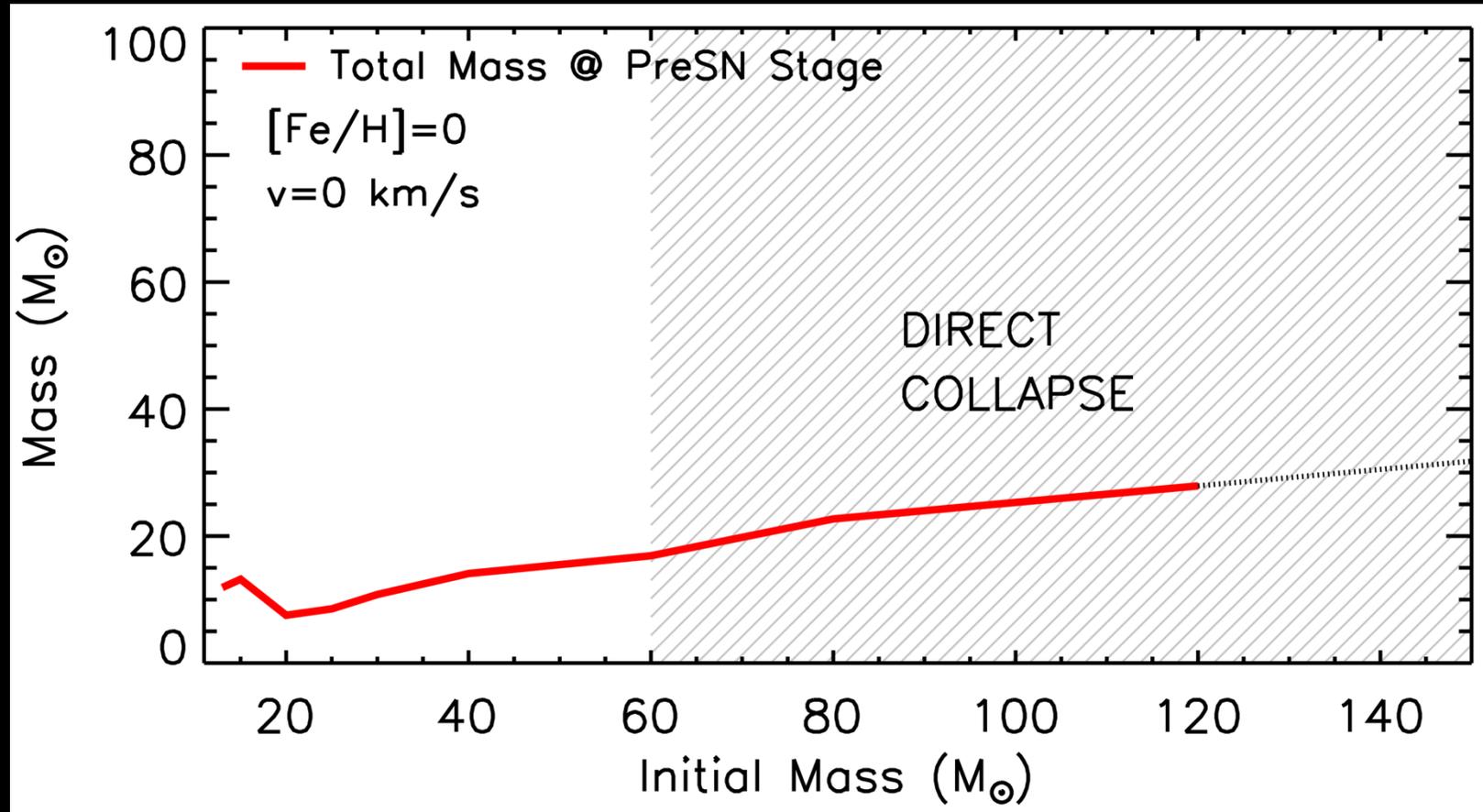
Models from Limongi & Chieffi (2018)

At Solar Metallicity the mass loss is efficient enough to reduce significantly the total mass of the star

It is unlikely to form BH more massive than ~40 $M_\odot$

Low Metallicity non Rotating Models: Presupernova Evolution

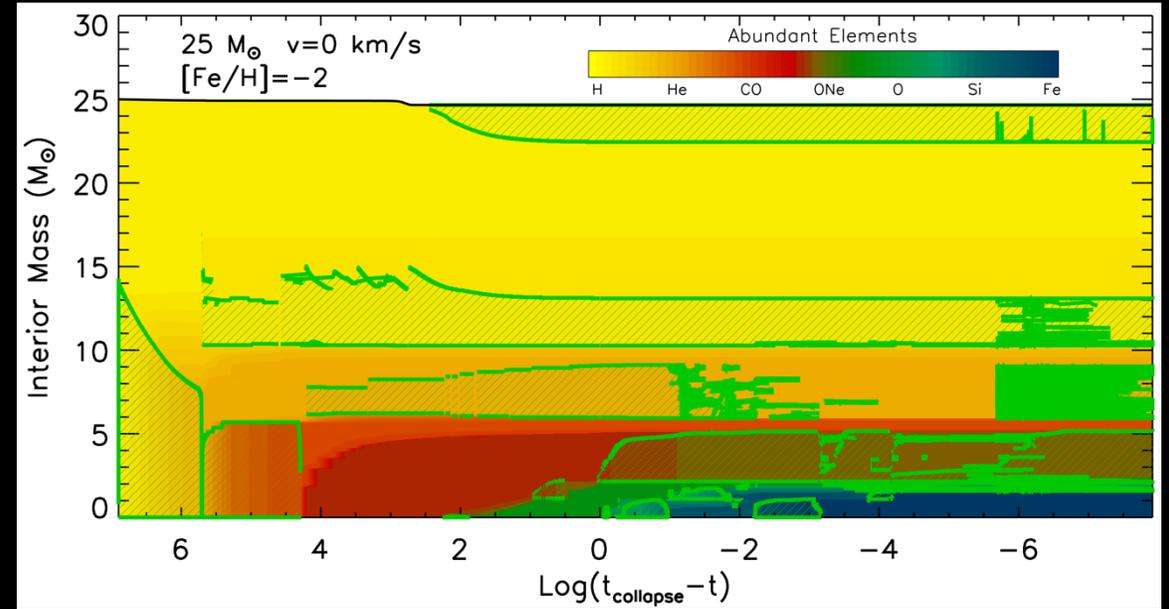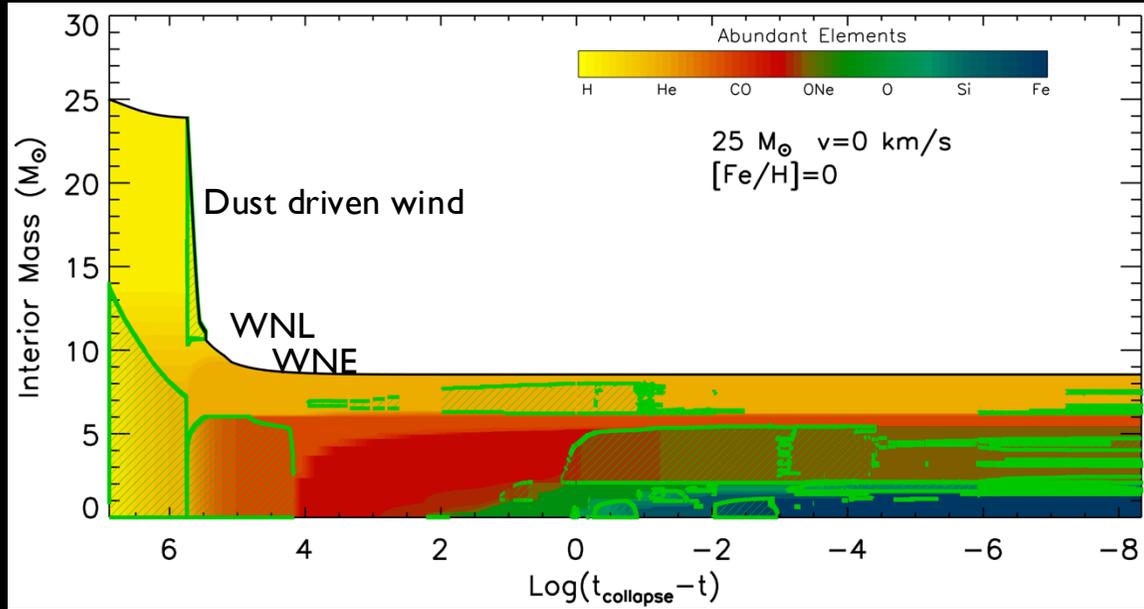Mass loss reduces dramatically as the metallicity decreases $\quad \dot{M} \sim (Z/Z_\odot)^{0.85}$
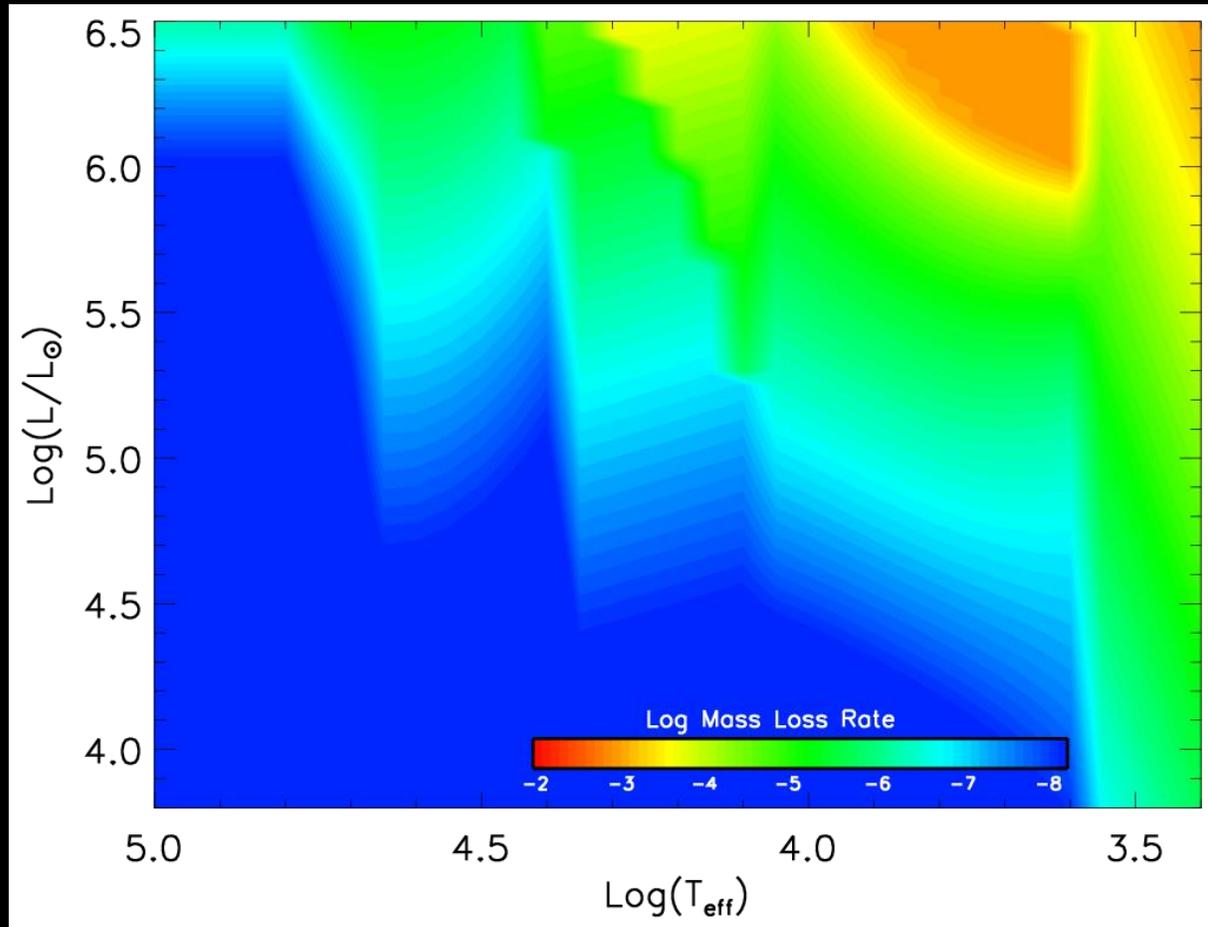
[Fe/H]=0   [Fe/H]=-2
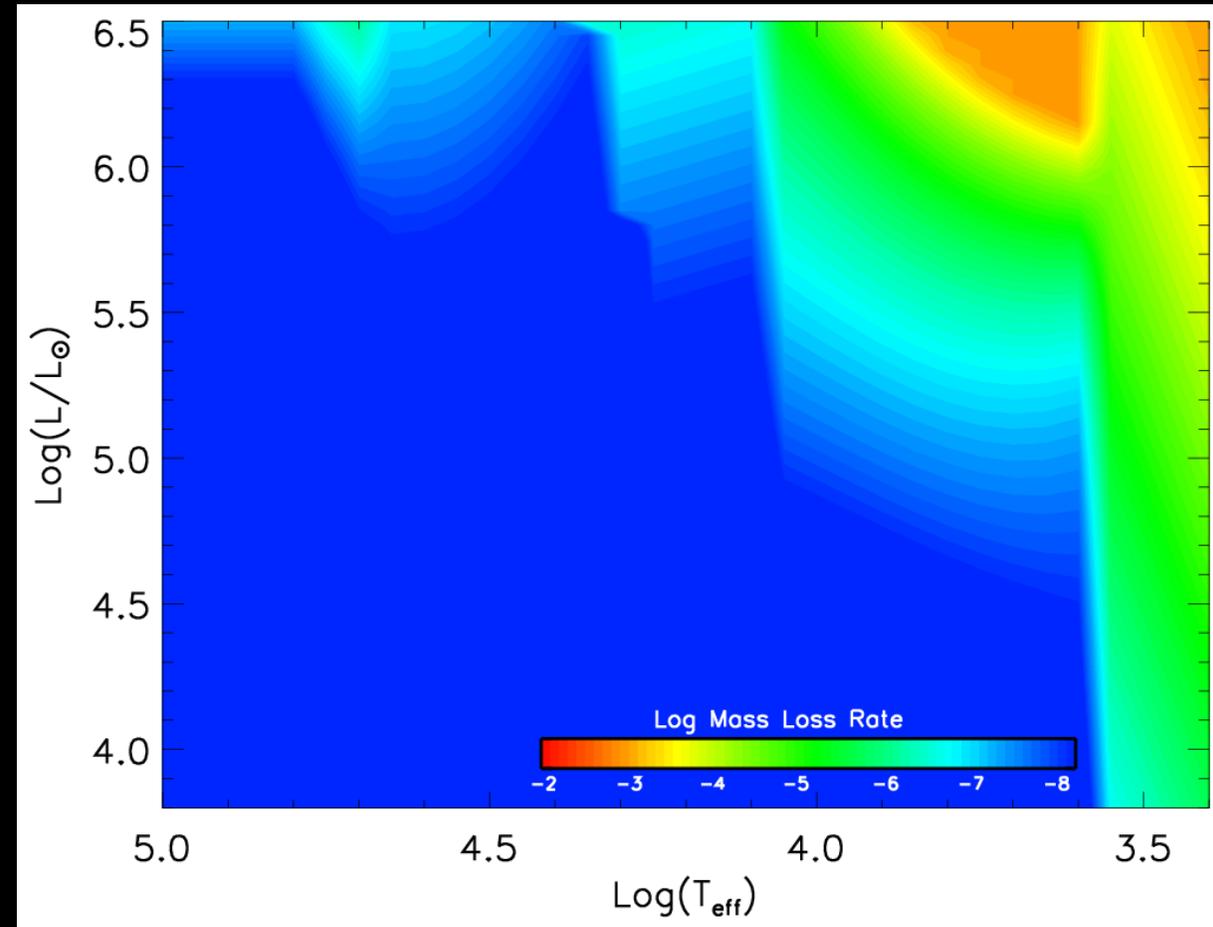
[Fe/H] = Log(Fe/H) - Log(Fe/H)$_\odot$

Low Metallicity non Rotating Models: Presupernova Evolution
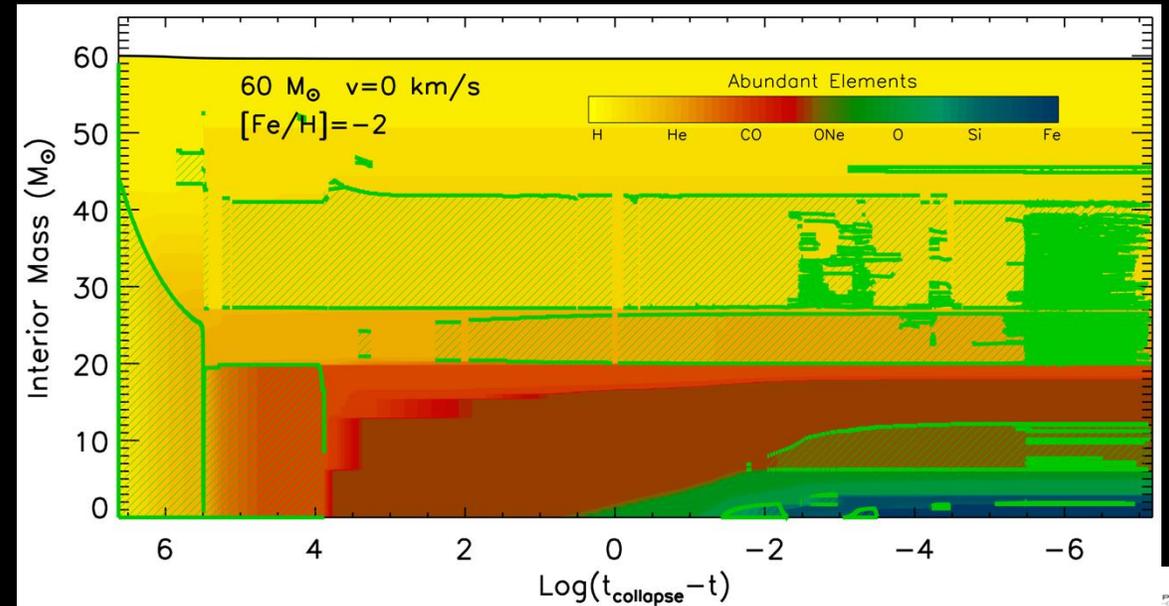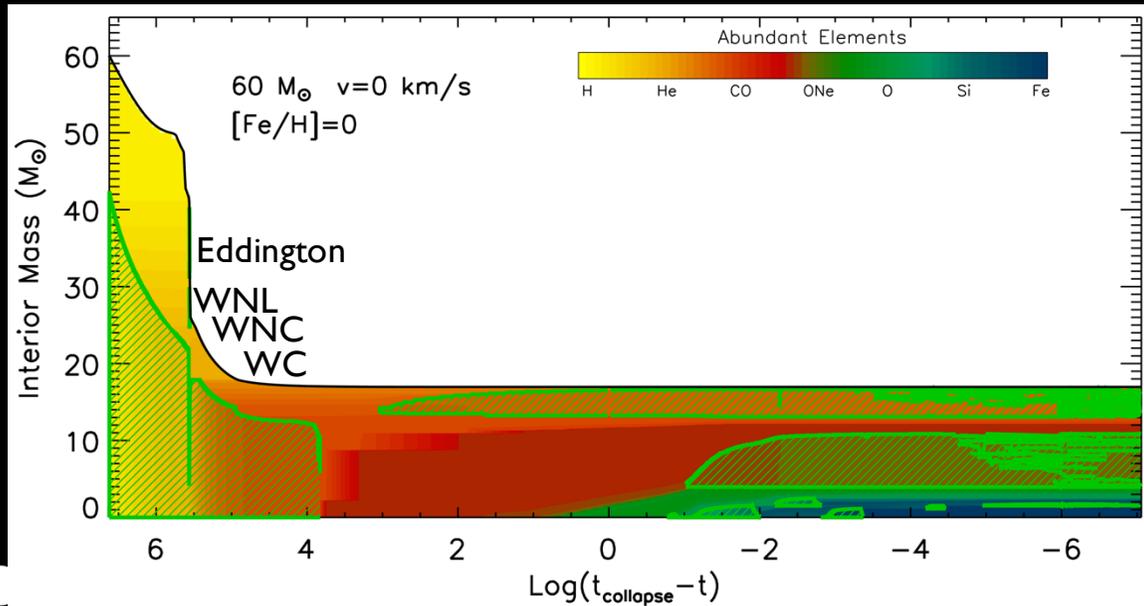
Low Metallicity non Rotating Models: Presupernova Evolution

M ≥ 30 M$_\odot$ → CO core increases substantially as the metallicity decreases
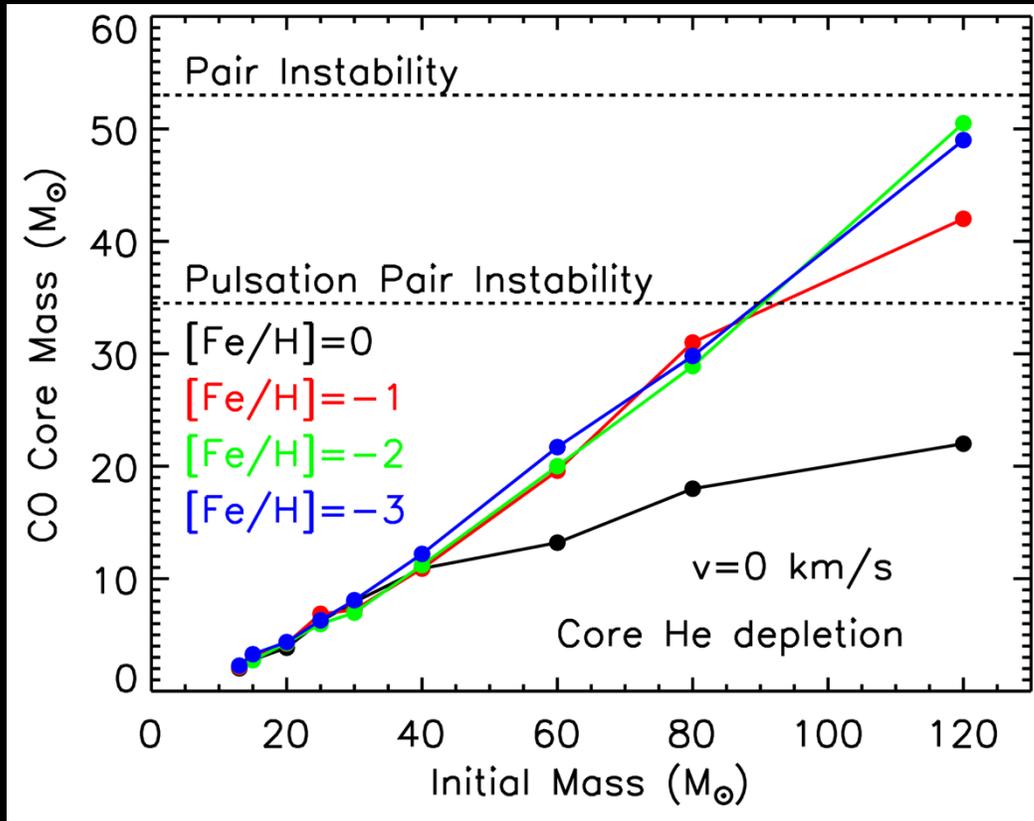
Models from Limongi & Chieffi (2018)
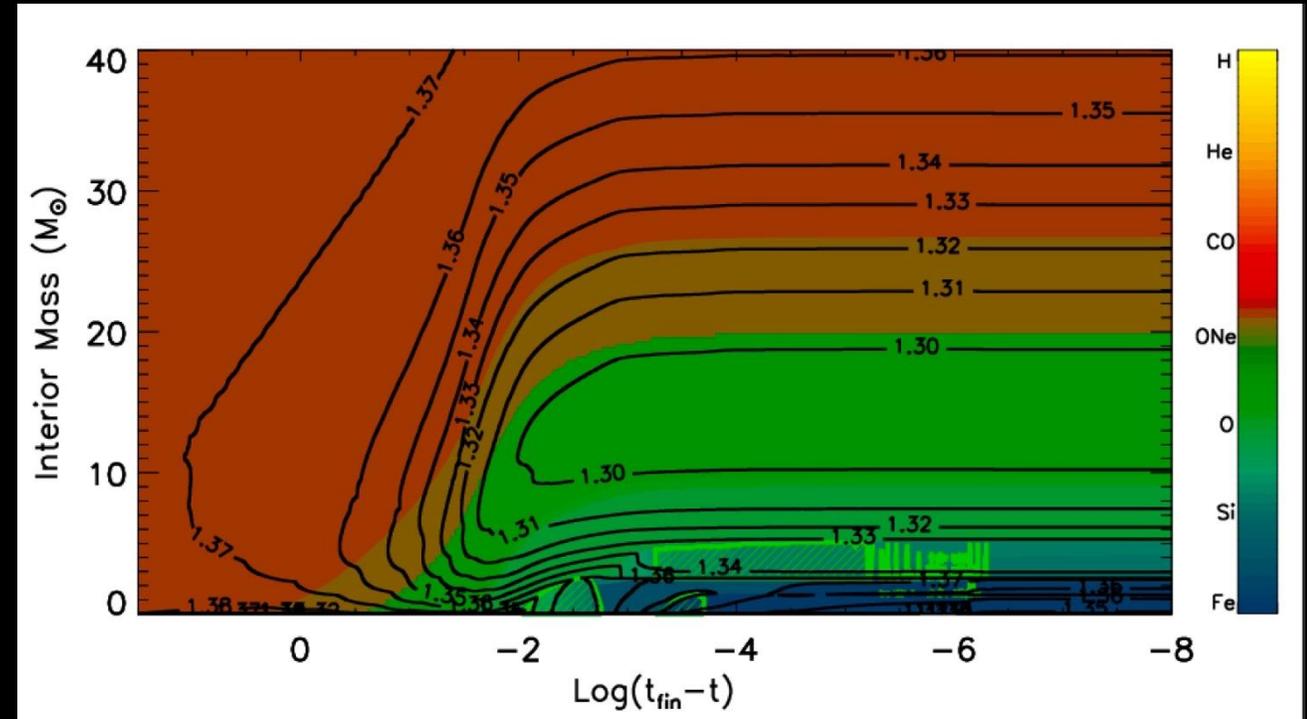
Stars with M > 90 M$_\odot$ with [Fe/H] ≤ -1 enter the Pulsation Pair Instability

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

Non Rotating Models: Nature of the Remnants
The Maximum mass of the BH

DIRECT COLLAPSE

The star collapses directly to a BH

The mass of the BH coincides with the mass of the star at the presupernova stage

PULSATION PAIR INSTABILIY
PPISN

The star enters the Pulsation Pair Instability

Undergoes mass ejection induced by the PPI

Collapses to a BH

The mass of the Black Hole depends on how much mass is lost before collapse

PAIR INSTABILIY
PISN

The star enters the Pair Instability
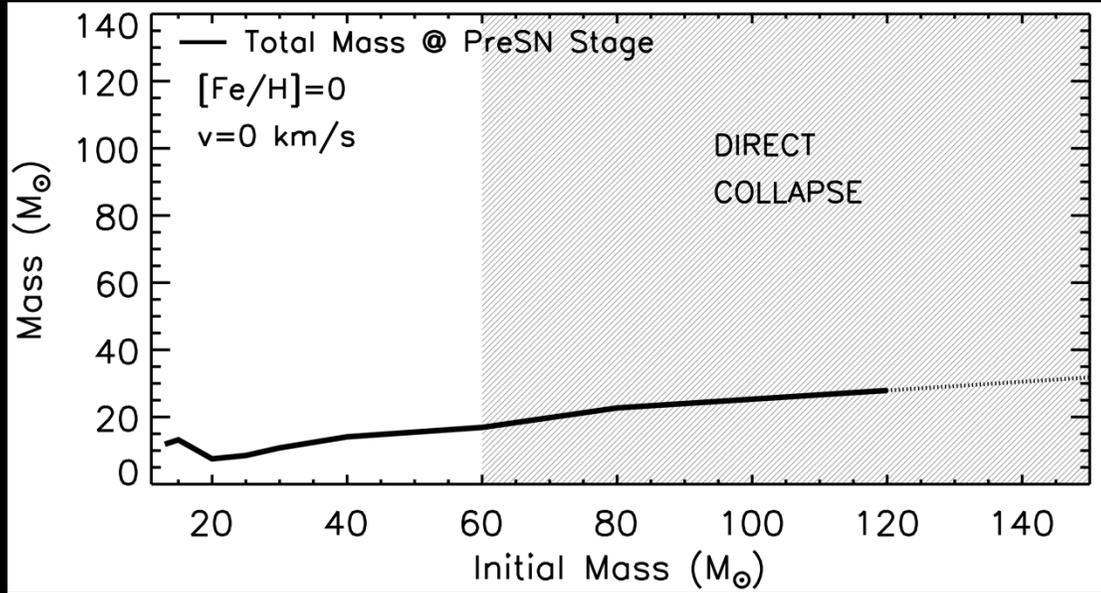
Explosive O burning release enough energy to completely disrupt the star

No remnant is left

M_{max}^{DC} Initial Mass M_{PISN}

The fate of the stars that enter the PPI should be known

Non Rotating Models: Nature of the Remnants

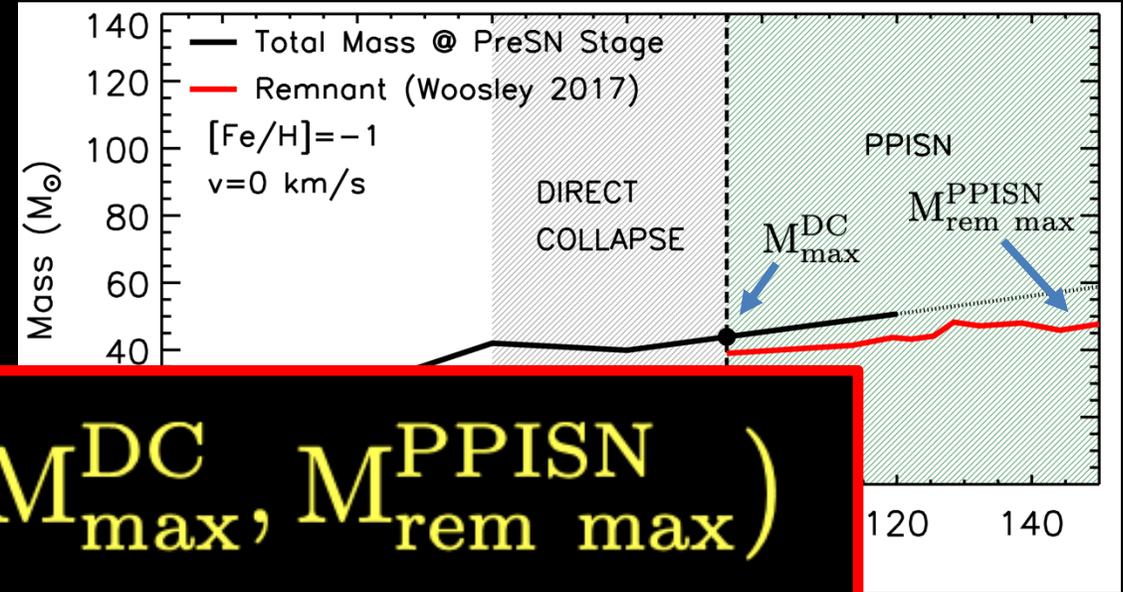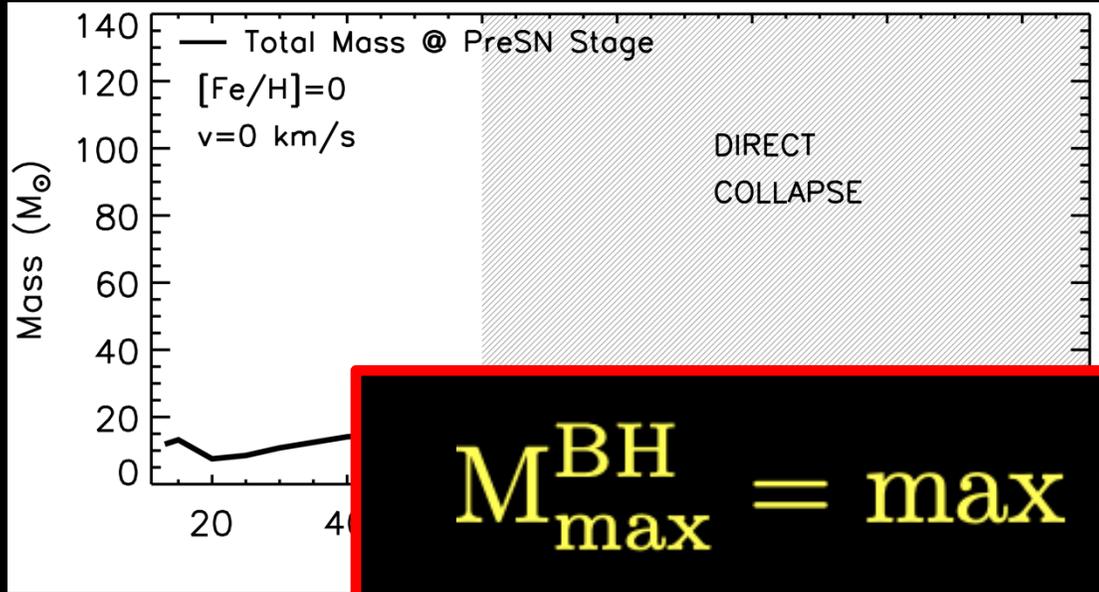## What is the maximum mass of the BH that can be formed?

Models from Limongi & Chieffi (2018)
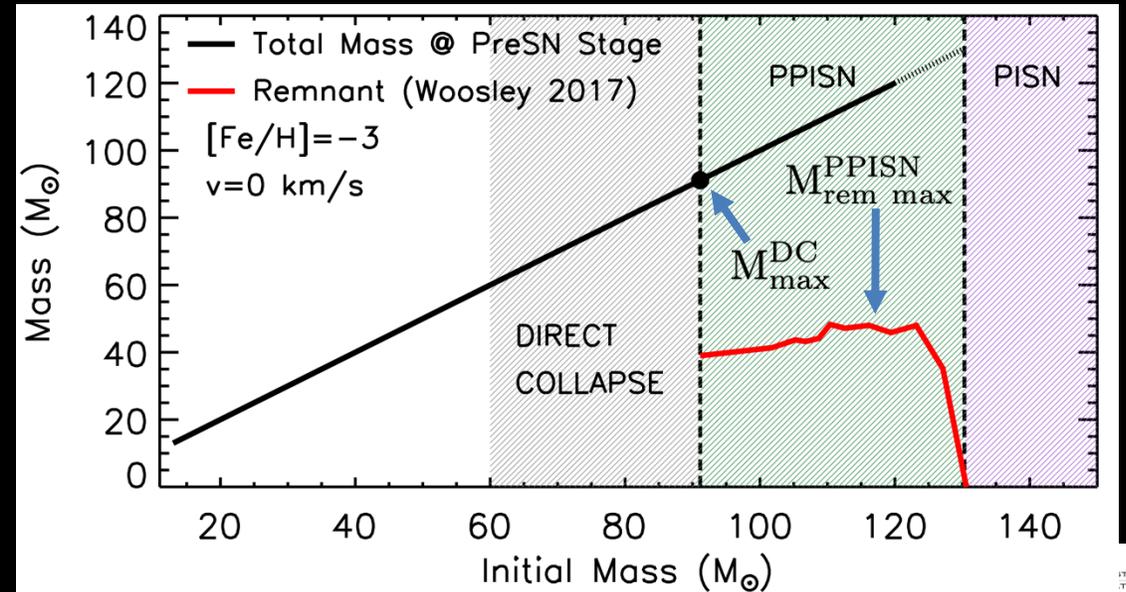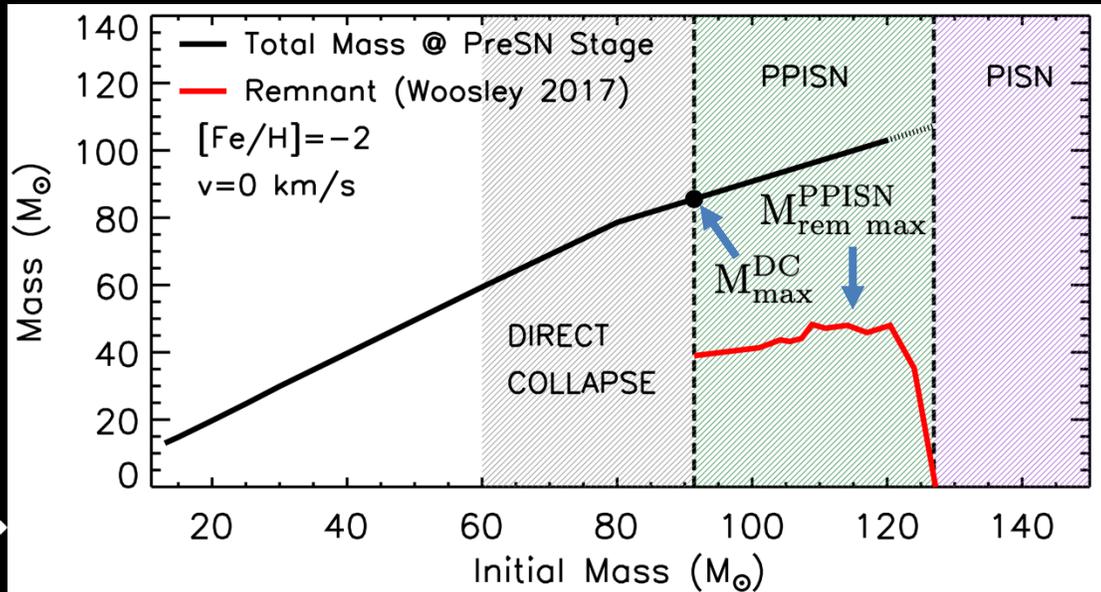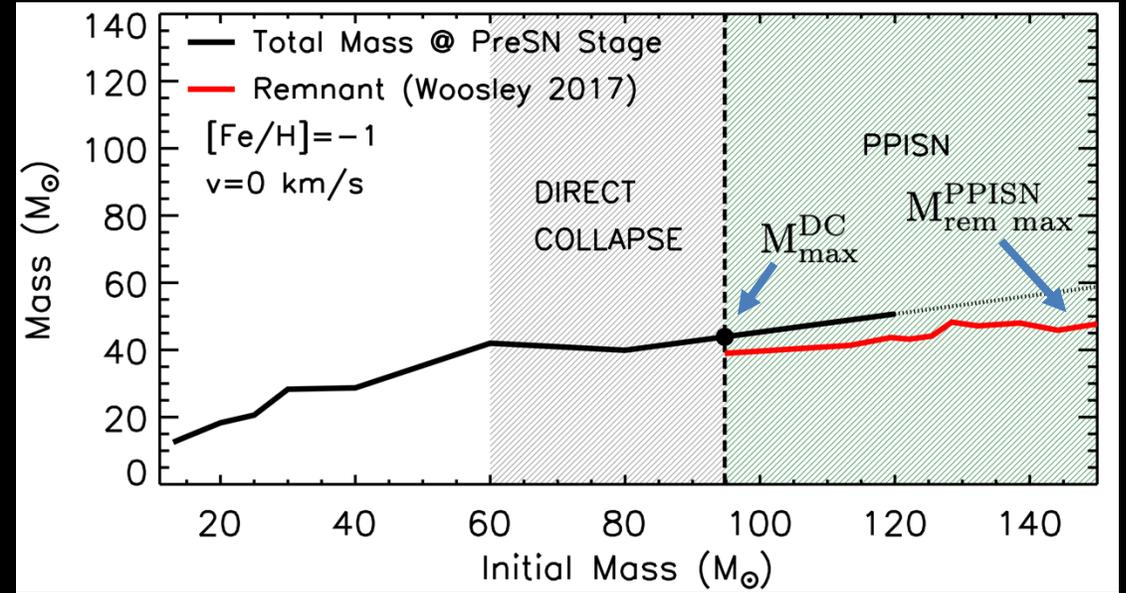
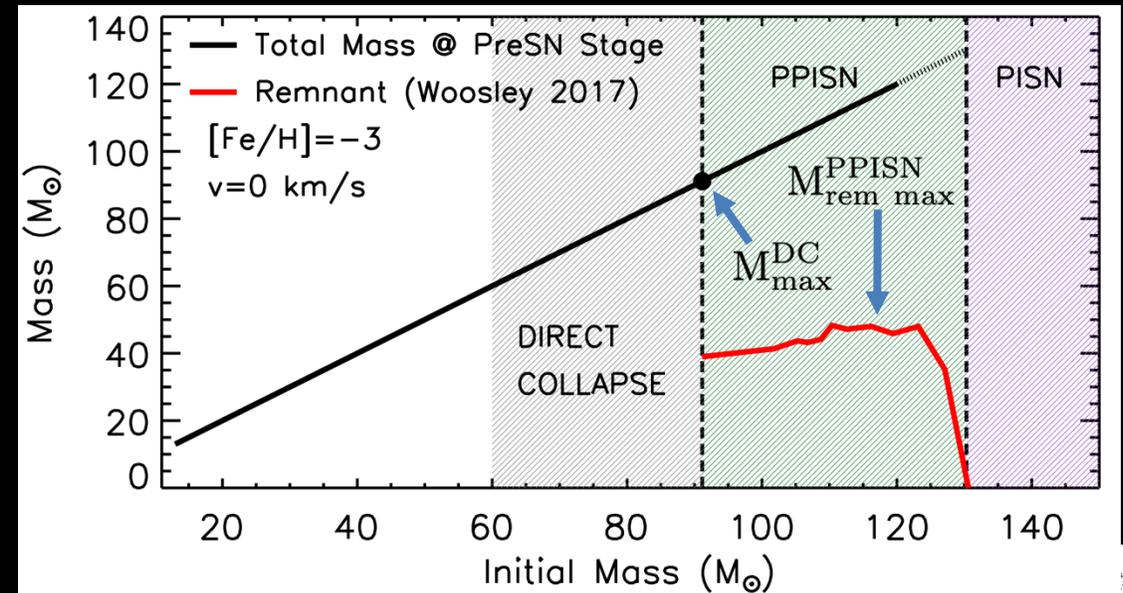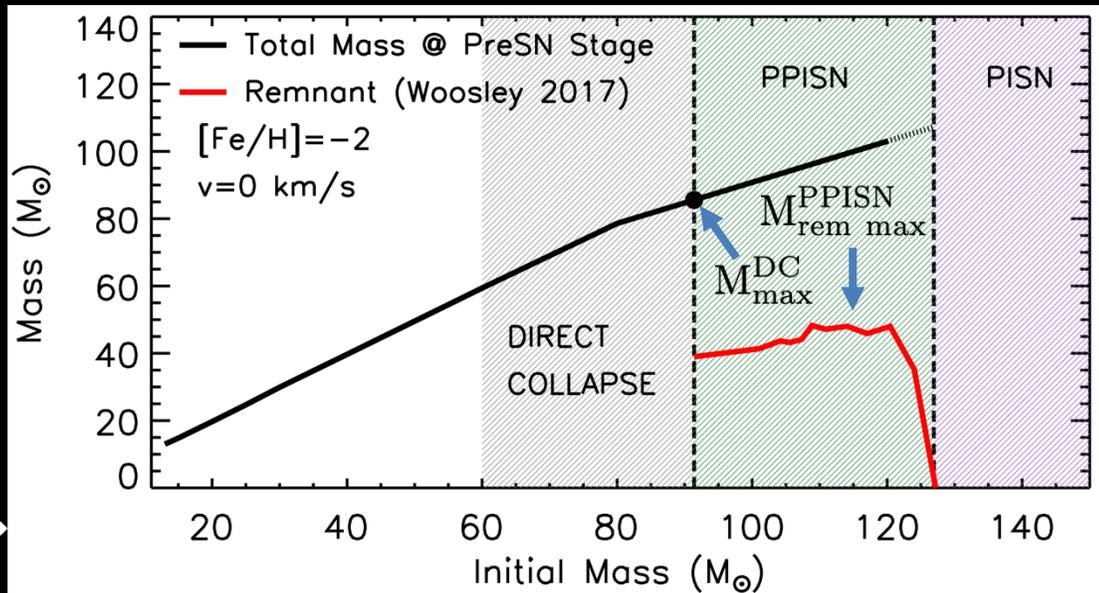# Non Rotating Models: Nature of the Remnants

What is the maximum mass of the BH that can be formed?
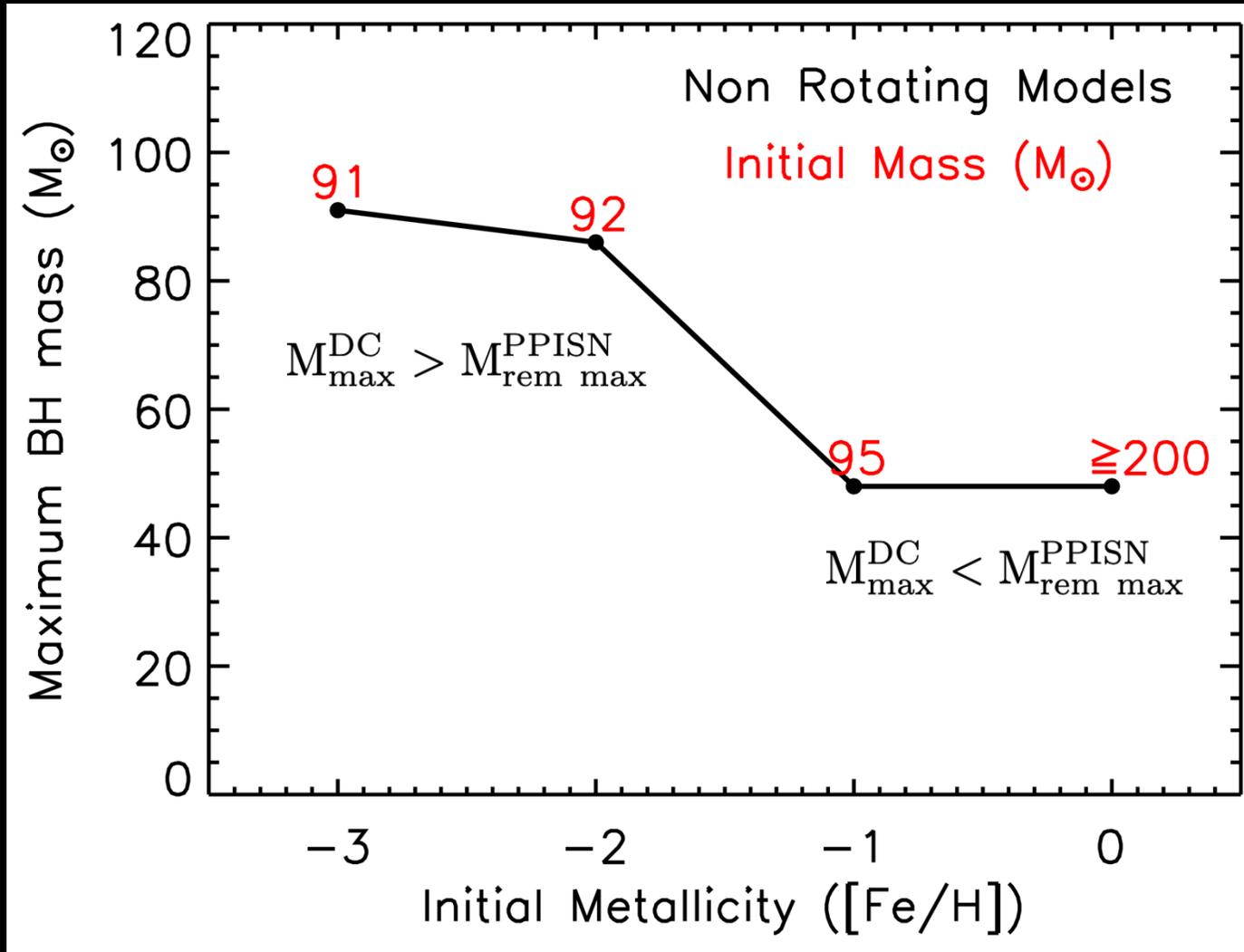
Models from Limongi & Chieffi (2018)

$$M_{max}^{BH} = \max\left(M_{max}^{DC}, M_{rem\ max}^{PPISN}\right)$$

Top-left panel: Total Mass @ PreSN Stage, [Fe/H]=0, v=0 km/s, DIRECT COLLAPSE. Mass (M$_\odot$) vs Initial Mass.

Top-right panel: Total Mass @ PreSN Stage, Remnant (Woosley 2017), [Fe/H]=−1, v=0 km/s, DIRECT COLLAPSE, PPISN, M_{max}^{DC}, $M_{rem\ max}^{PPISN}$.

Bottom-left panel: Total Mass @ PreSN Stage, Remnant (Woosley 2017), [Fe/H]=−2, v=0 km/s, DIRECT COLLAPSE, PPISN, PISN, $M_{rem\ max}^{PPISN}$, M_{max}^{DC}.

Bottom-right panel: Total Mass @ PreSN Stage, Remnant (Woosley 2017), [Fe/H]=−3, v=0 km/s, DIRECT COLLAPSE, PPISN, PISN, $M_{rem\ max}^{PPISN}$, M_{max}^{DC}.

Non Rotating Models: Nature of the Remnants

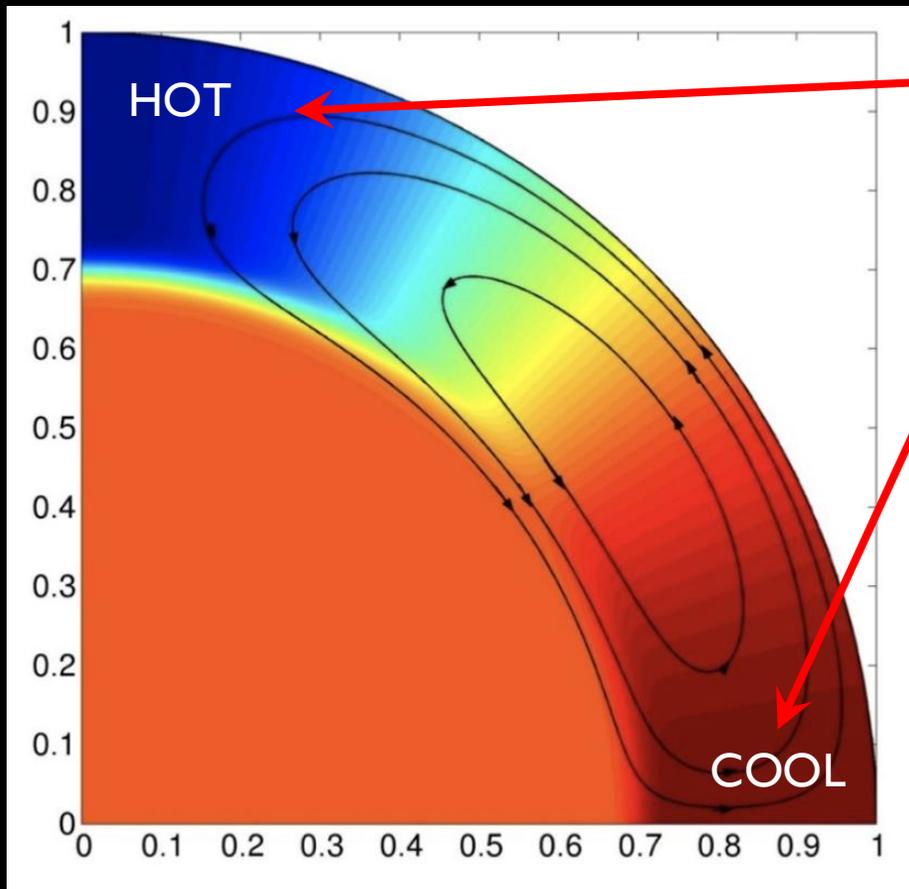What is the maximum mass of the BH that can be formed?

Remnant Masses
The effect of rotation

Rotation Driven Instabilities – Meridional Circulation

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

Rotation makes the star oblate

HOT

COOL

Different heat content between the pole and the equator
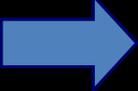
Large-scale MERIDIONAL CIRCULATION develops

$$\vec{\nabla} \cdot \vec{F}_{\mathrm{rad}}(r, \vartheta, \varphi) = \rho \varepsilon_{\mathrm{nuc}} - c_P \rho \frac{\partial T}{\partial t} + \delta \frac{\partial P}{\partial t} - \vec{U} \cdot (c_P \rho \vec{\nabla} T - \delta \vec{\nabla} P)$$

Velocity of meridional circulation

Meridional circulation moves matter through the star and hence it can both transport angular momentum and induce mixing of the chemical composition

Rotation Driven Instabilities – Turbulent Shear

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

Meridional Circulation ➡️ Increase the gradient of angular velocity
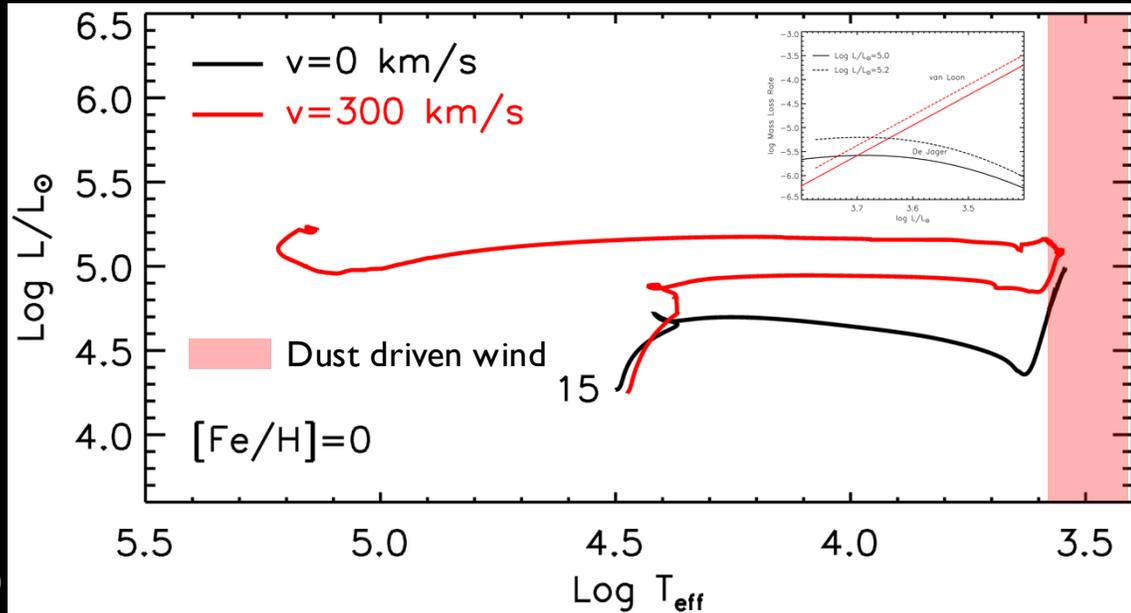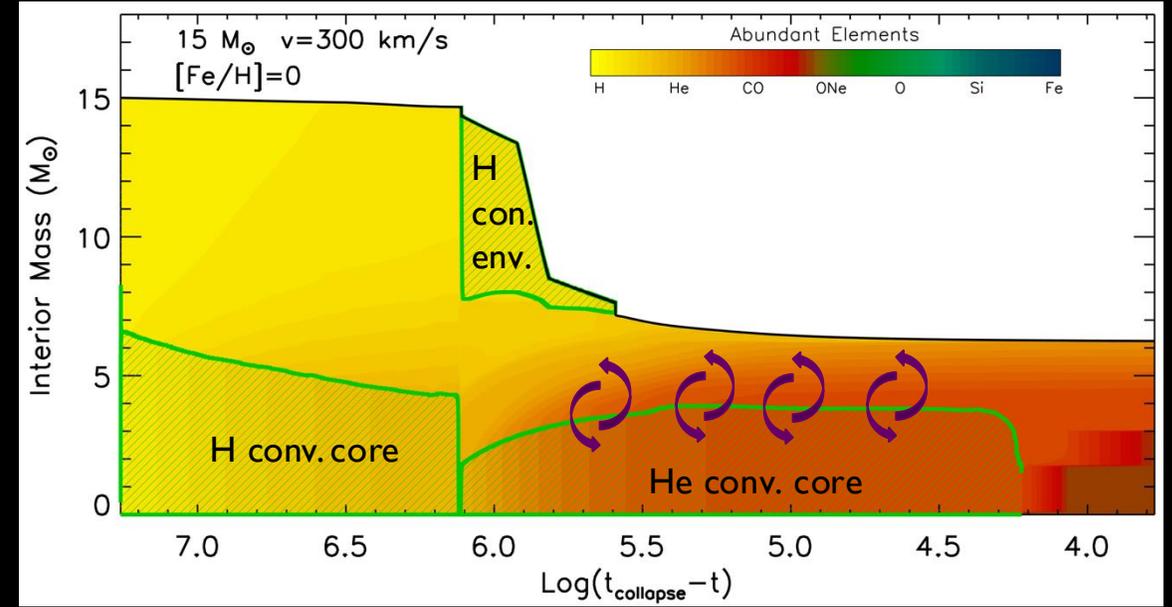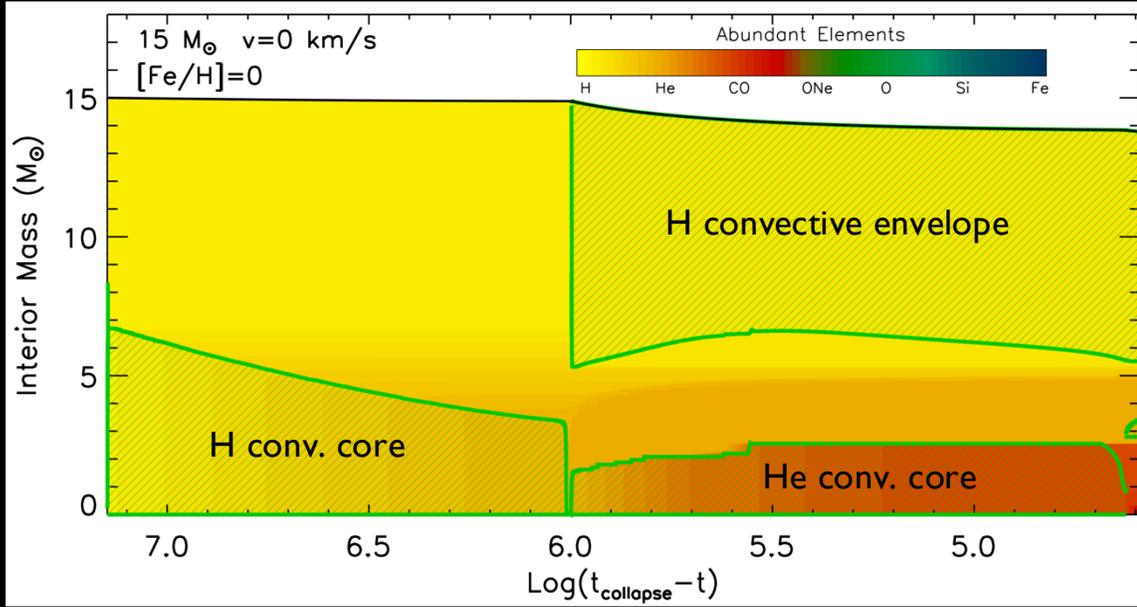
Differential rotation induces chemical mixing and angular momentum transport due to the shear instabilities
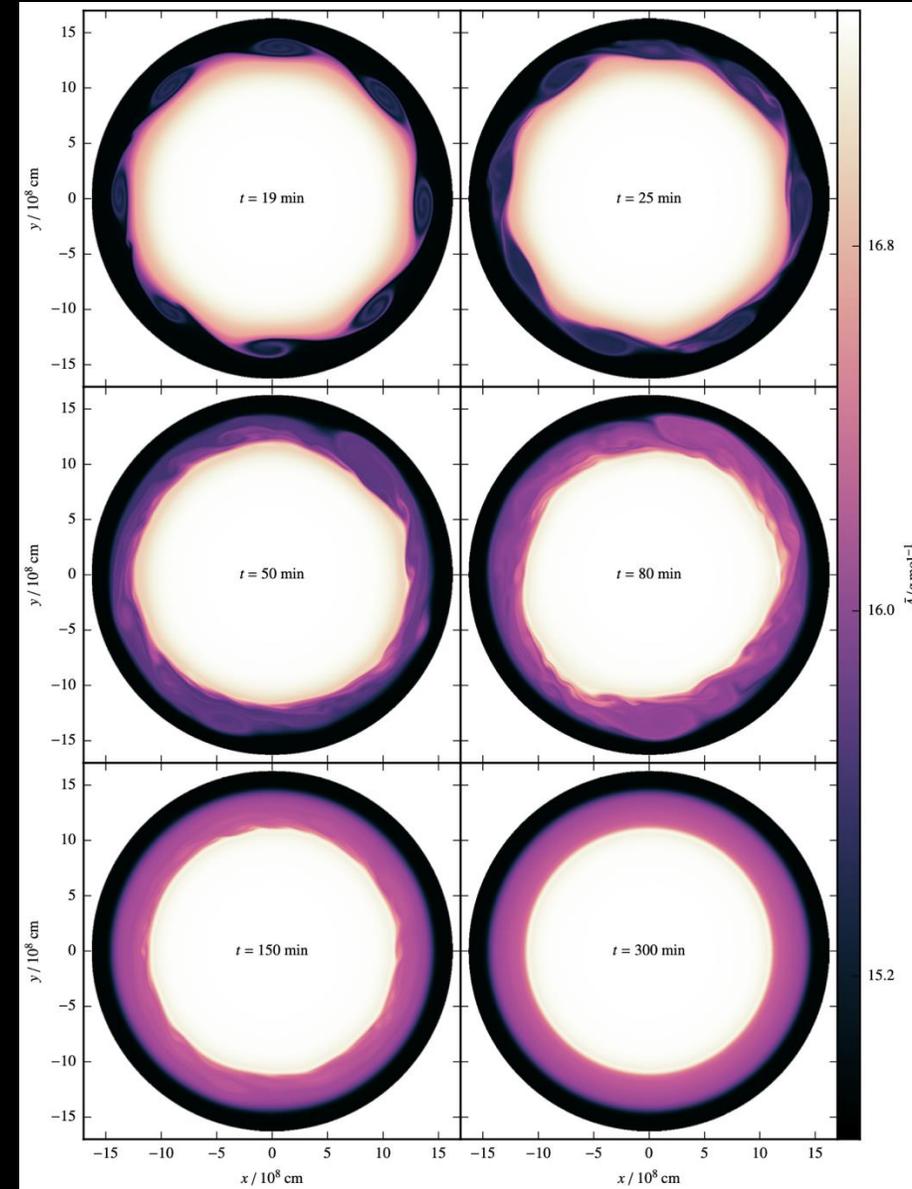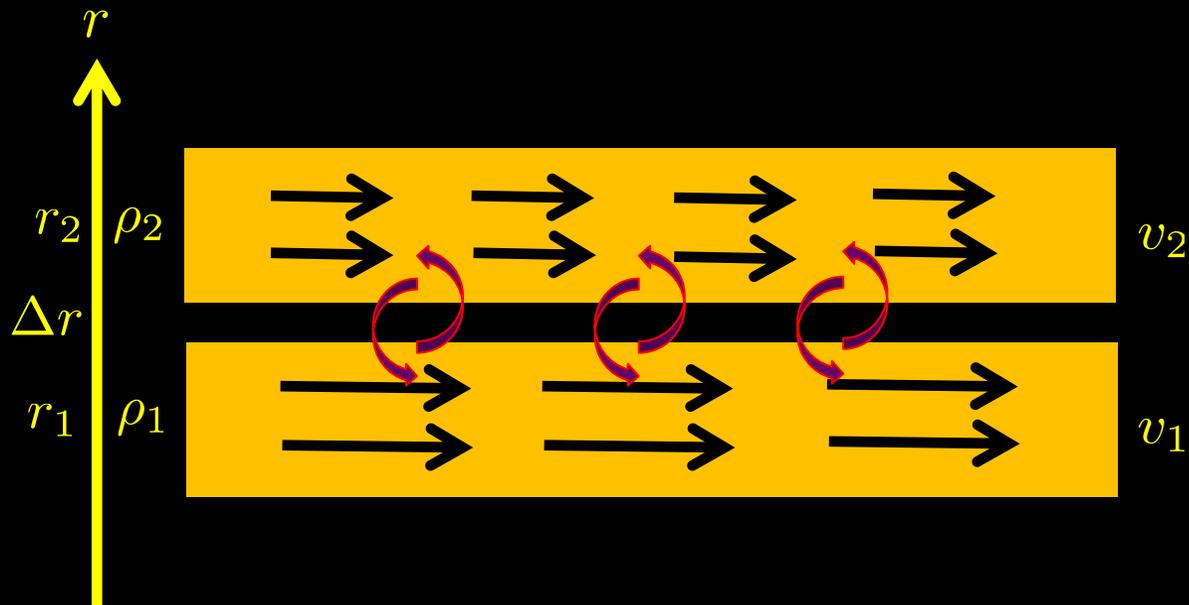
Edelmann+2017

Rotating Models: Presupernova Evolution

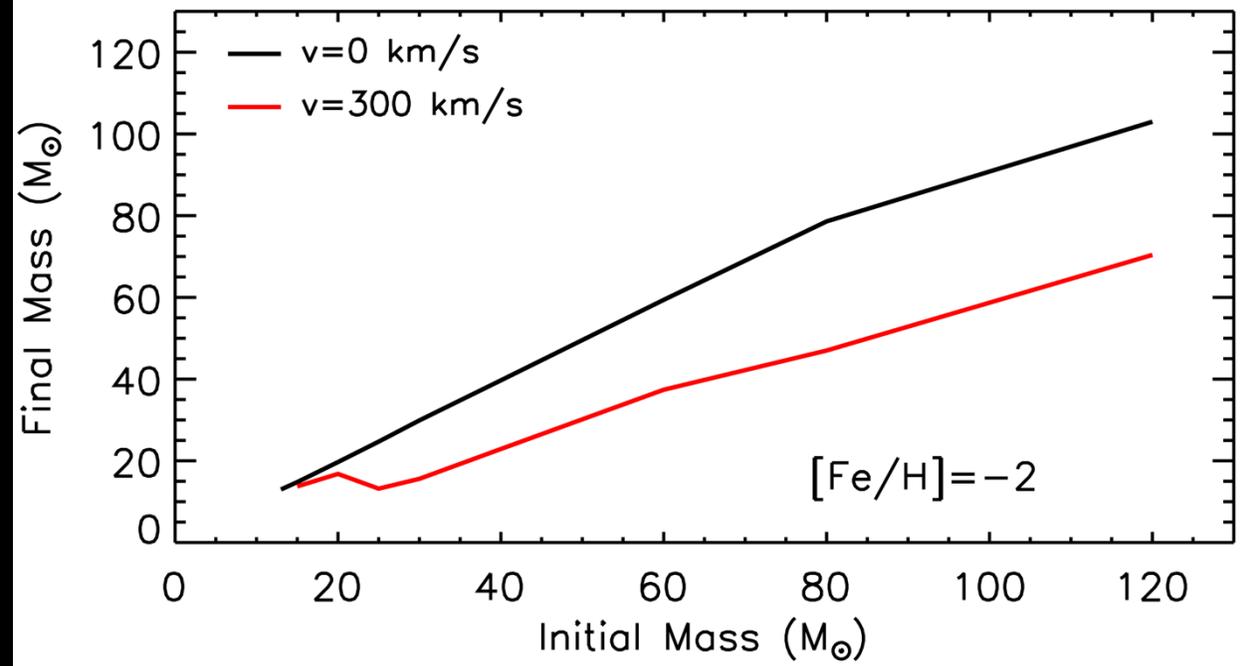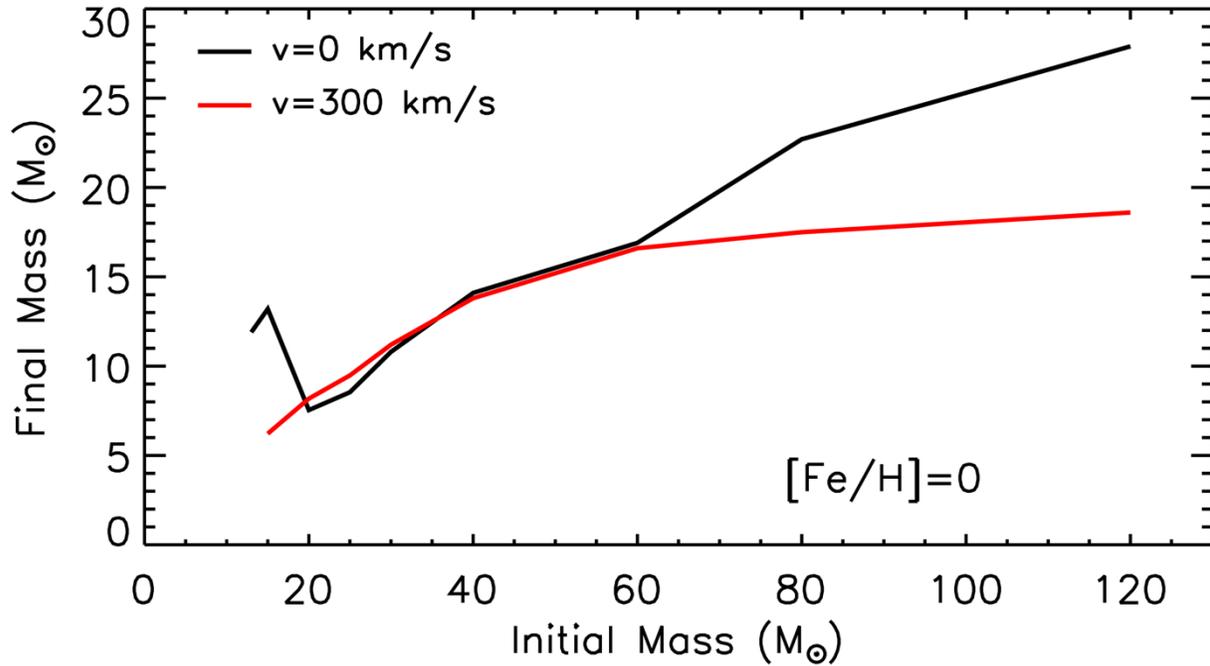Models from Limongi & Chieffi (2018)

Rotation driven mixing implies

Larger cores → Higher L → Stronger mass loss

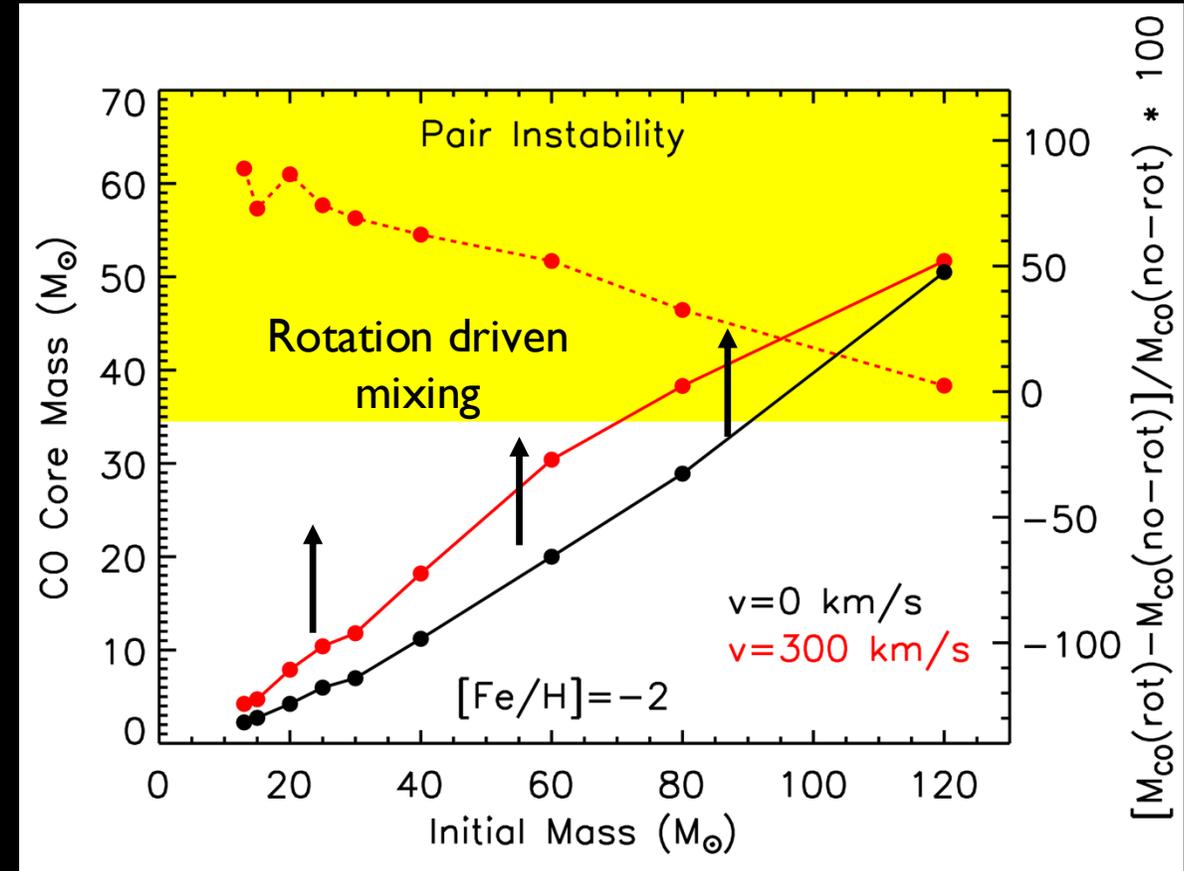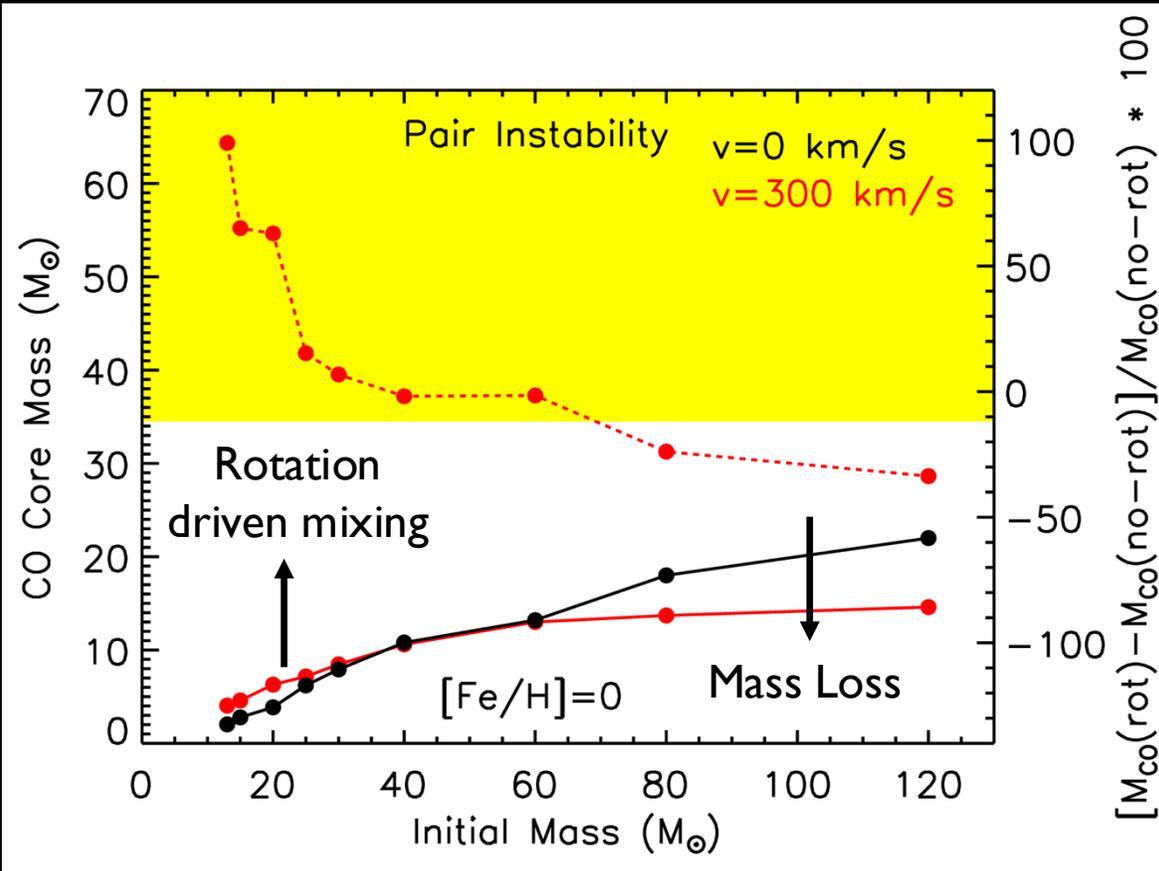# Rotating Models: Presupernova Evolution

Rotating models lose more mass than their nonrotating counterparts

Models from Limongi & Chieffi (2018)

Rotating Models: Presupernova Evolution

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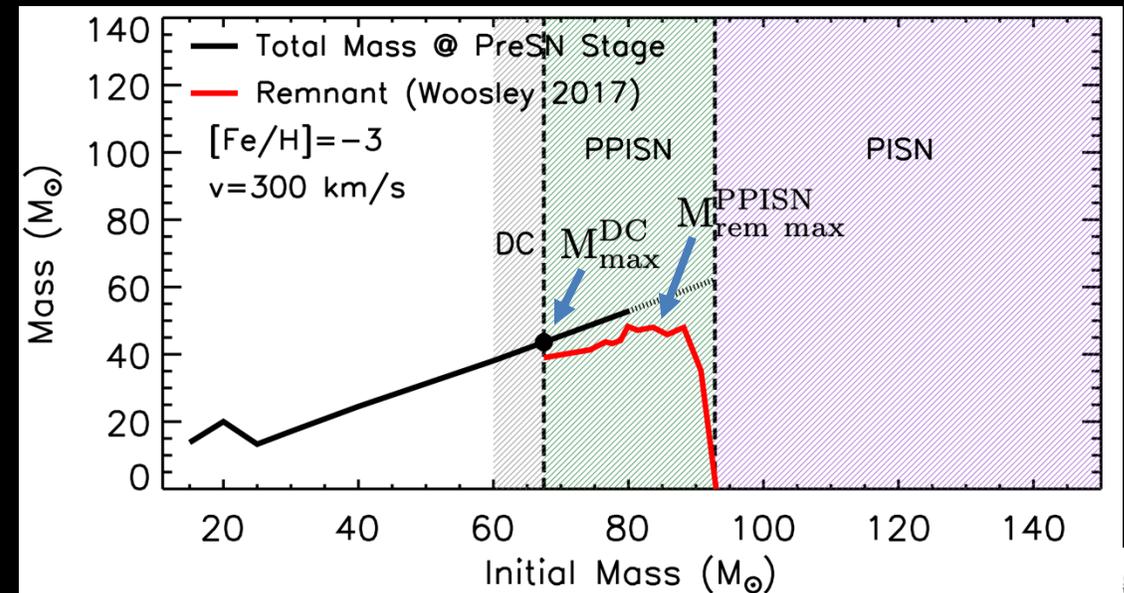In high mass solar metallicity stars, the mass loss dominates and reduces the CO core
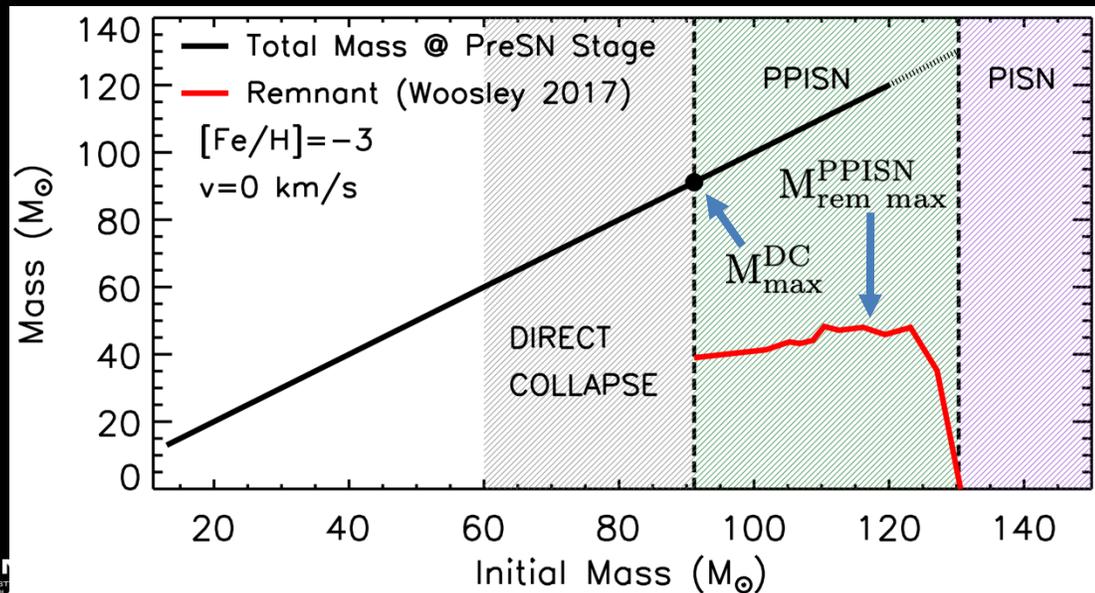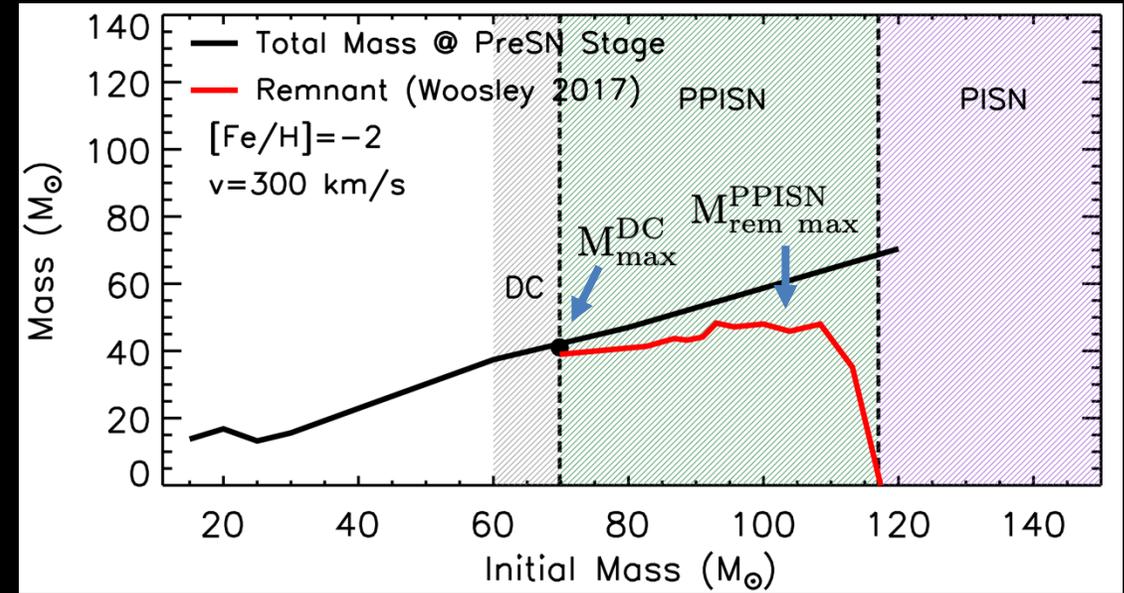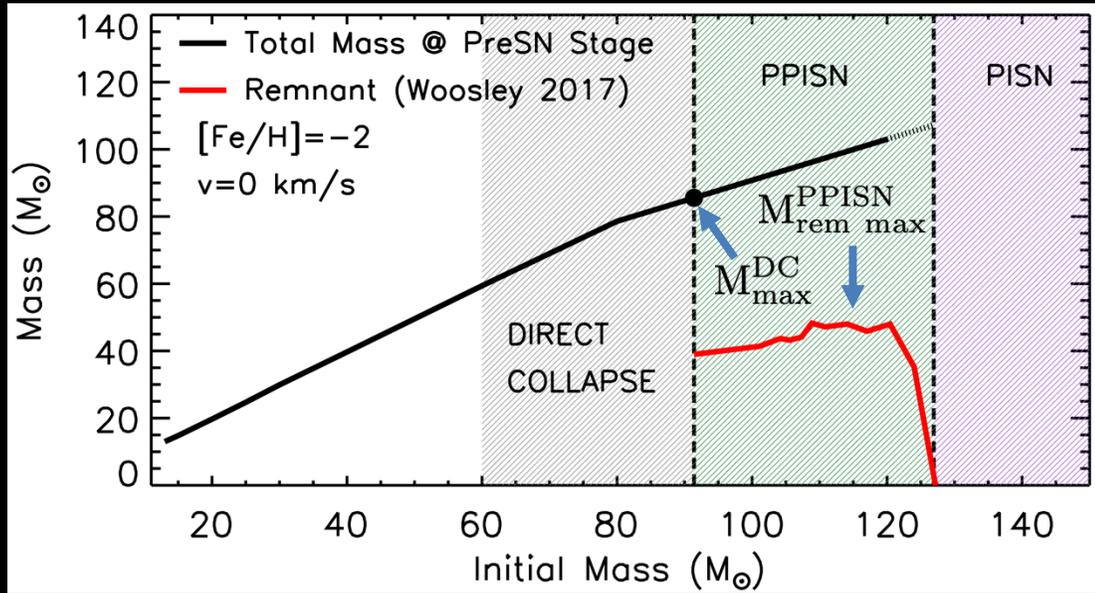

Models from Limongi & Chieffi (2018)

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

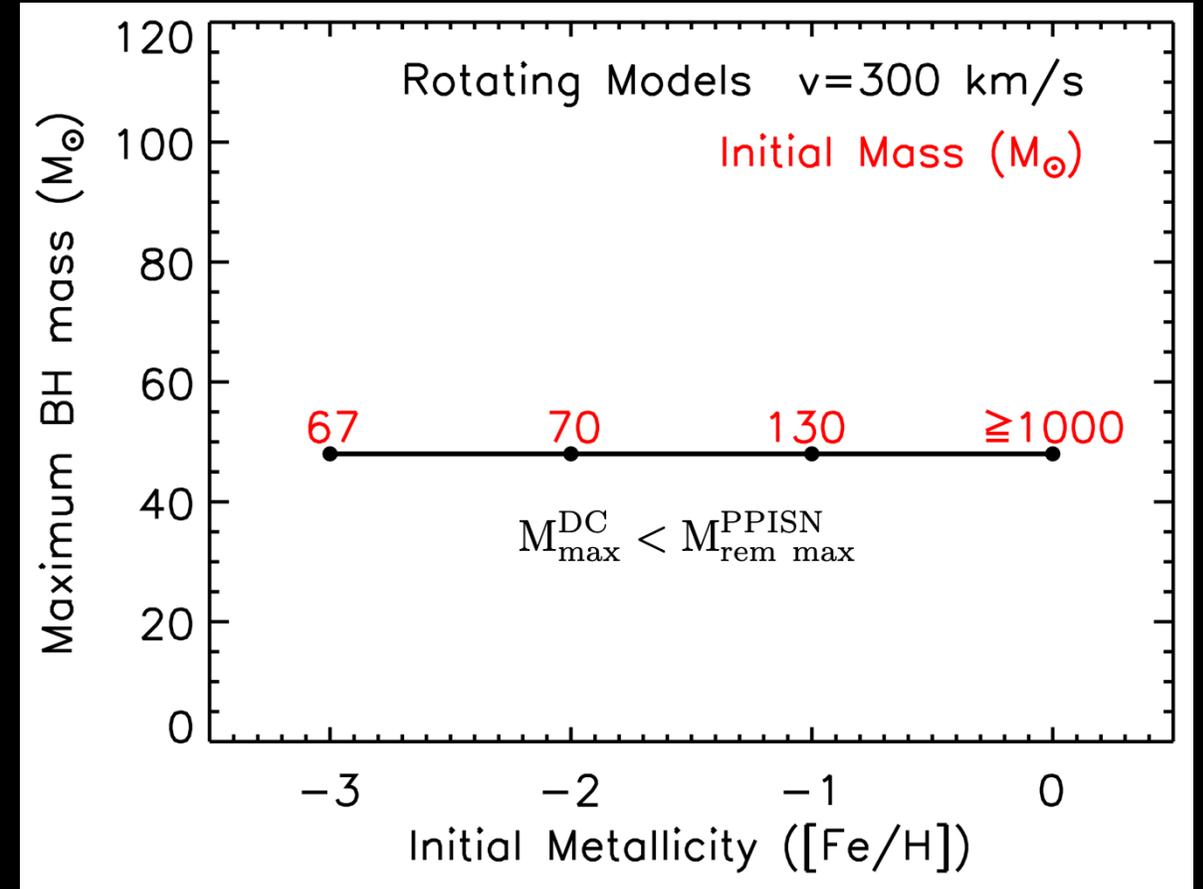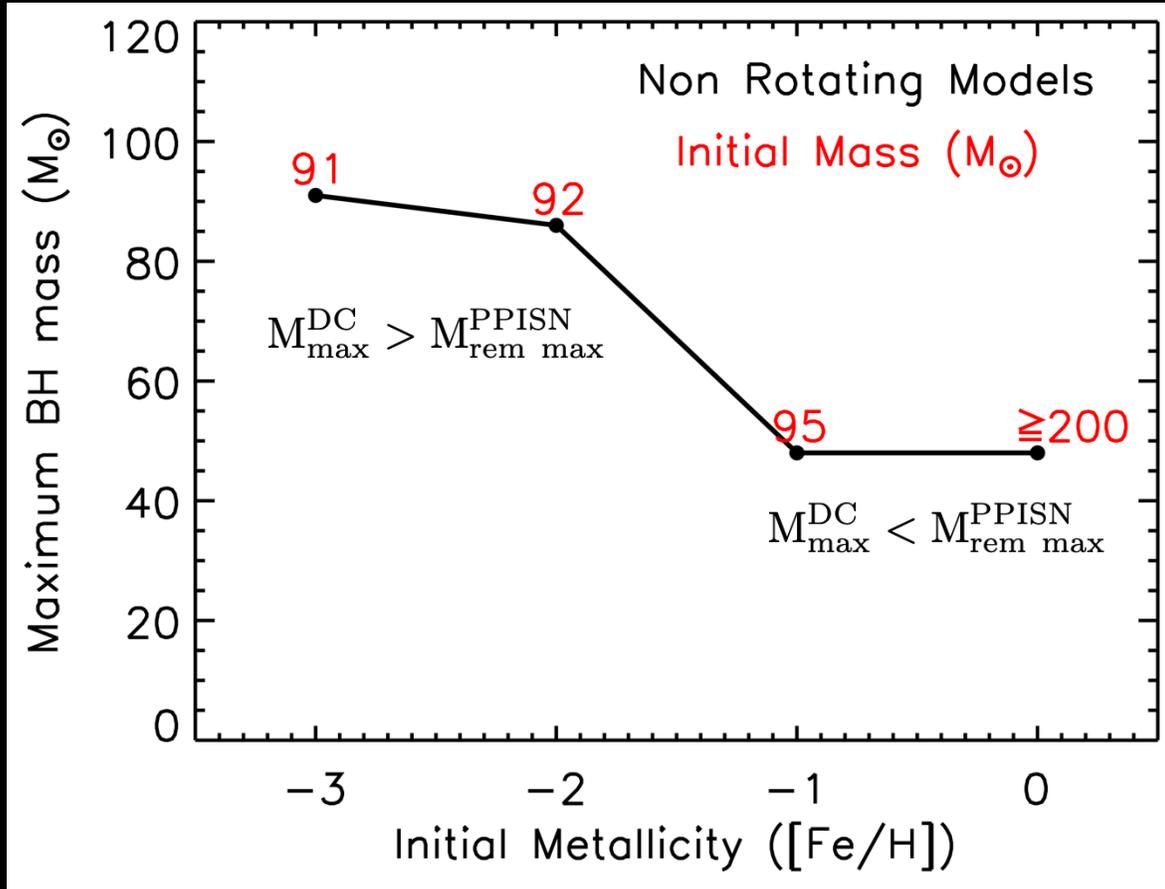# Rotating Models: Nature of the Remnants

What is the maximum mass of the BH that can be formed?

Models from Limongi & Chieffi (2018)

Rotating and non Rotating Models: Nature of the Remnants

The inclusion of rotation reduces the maximum mass of the BH that can be formed

Summary and Conclusions

The high scatter behavior of the compactness parameter that produces the so called "highlands of explodability" is mainly due to the inaccuracy with which both the core He- and shell C-burning are computed

A proper determination of the ^{12}C left by core He burning produces a well defined, non monotonic and non scattered, trend of the compactness parameter as a function of the initial mass

The maximum mass of a stellar BH, produced by a direct collapse, increases with decreasing the metallicity because of the strong reduction of the mass loss efficiency

Stellar BHs with masses as high as ~100 $M_\odot$ can be formed by low metallicity stars

Rotation implies larger CO cores and smaller final masses

Stellar BHs from rotating stars have masses not larger than ~50 $M_\odot$

All the models presented are available for download at orfeo.iaps.inaf.it or orfeo.oa-roma.inaf.it and on request