HEAVY BLACK HOLE FORMATION FROM MASSIVE STARS

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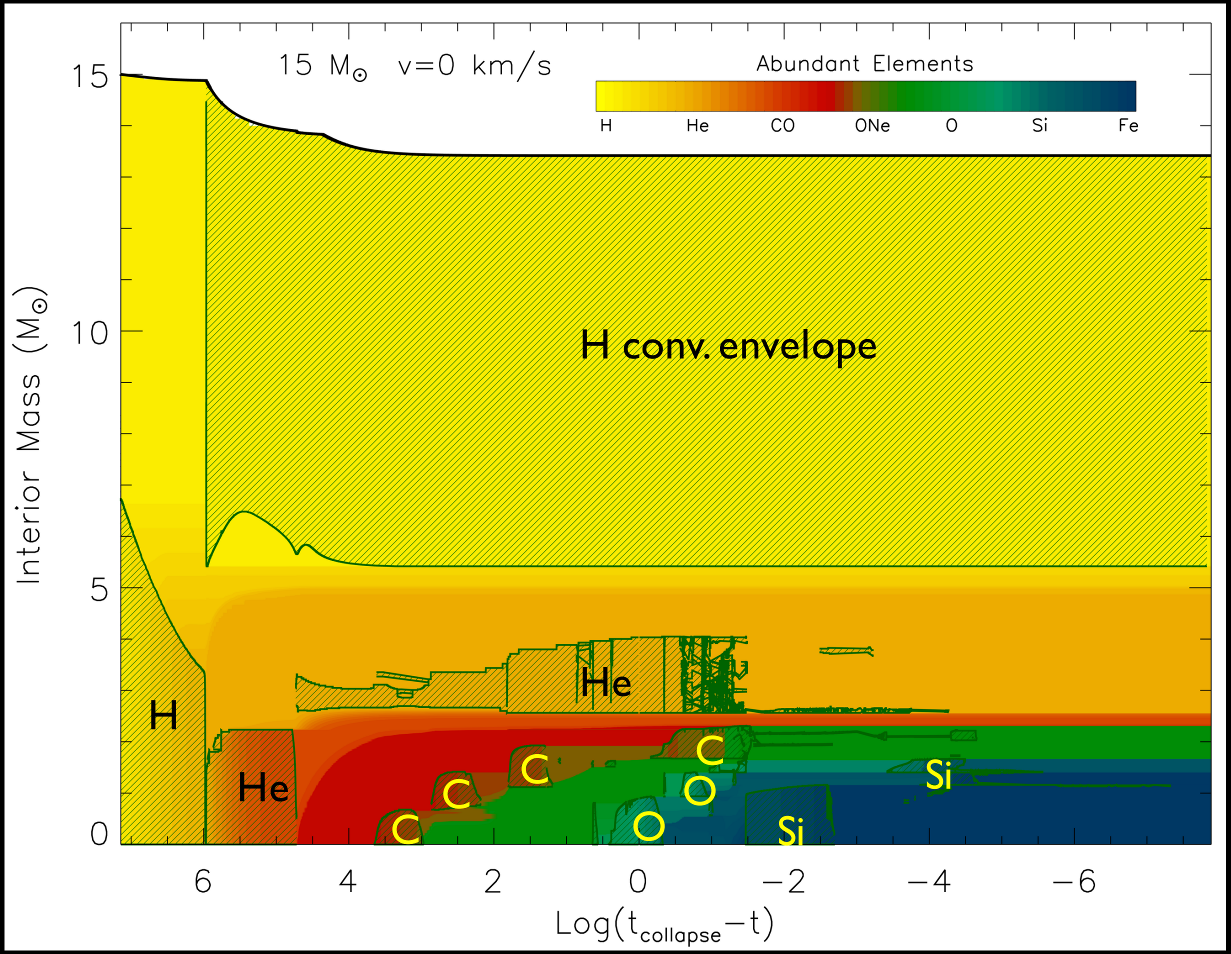
Outline

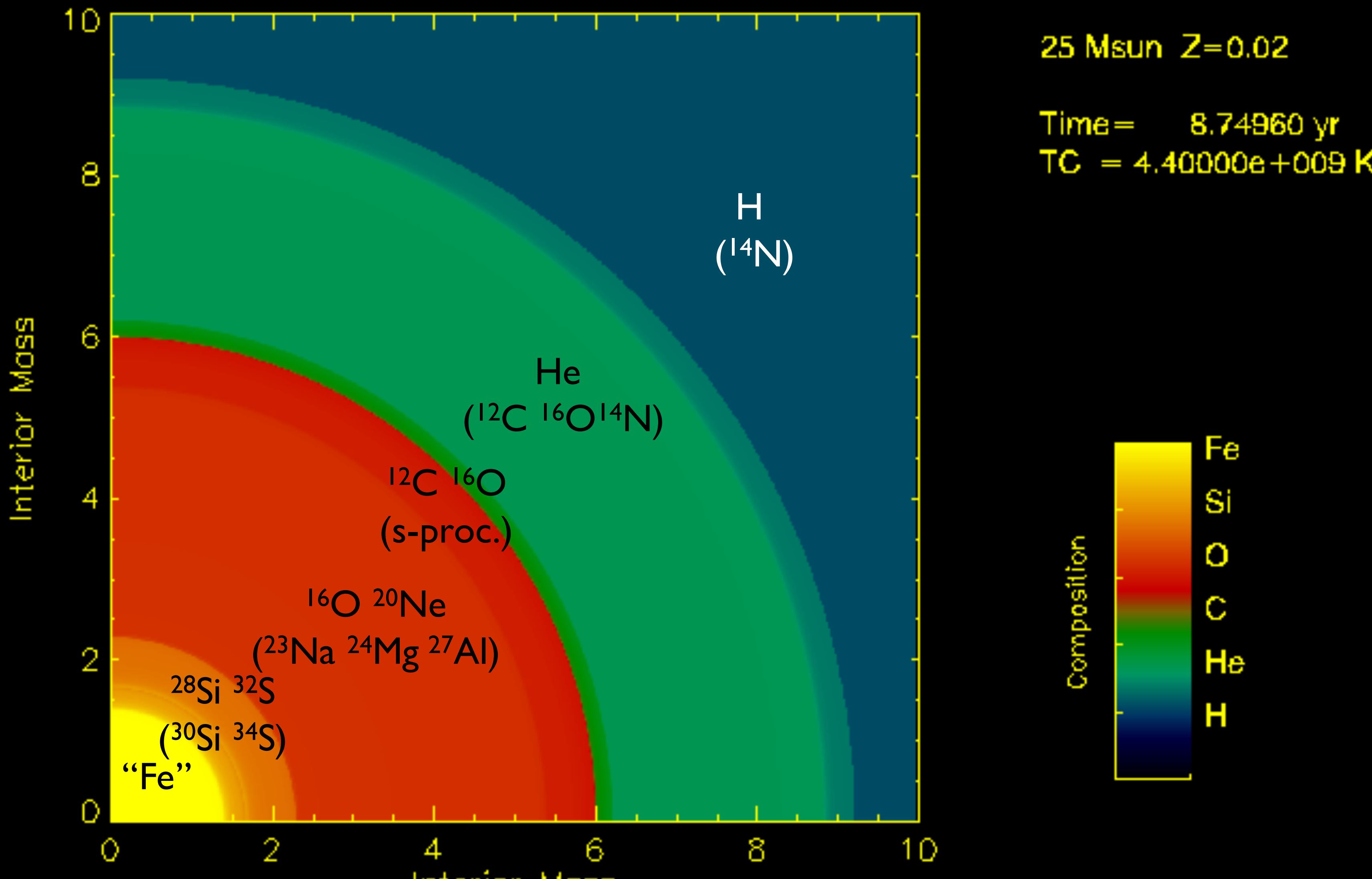
- Gravitational waves from GW150914 due to pair of merging massive BH
- The understanding of BH formation as the result of stellar evolution is crucial
- Which is the evolutionary path toward the formation of a "stellar" Black Hole?
- Which is the robustness of the theoretical Initial Mass-Remnant Mass relation?
- How the final remnant depends on the initial properties of the star (Metallicity, Stellar Rotation)?

Presupernova Evolution of a typical Massive Star
Convective Hystory



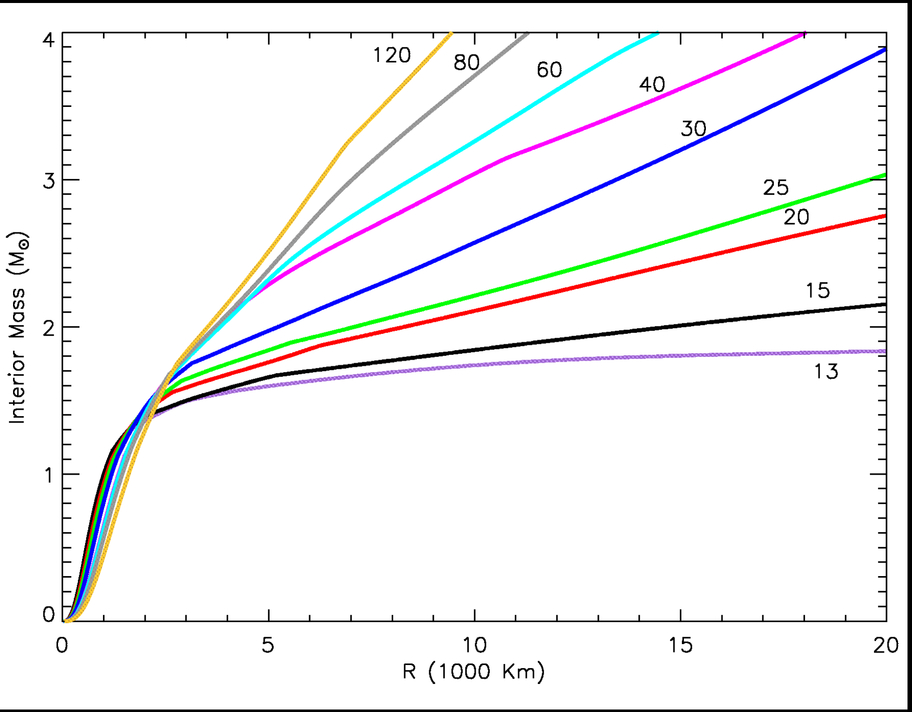
Chemical Structure at Presupernova Stage

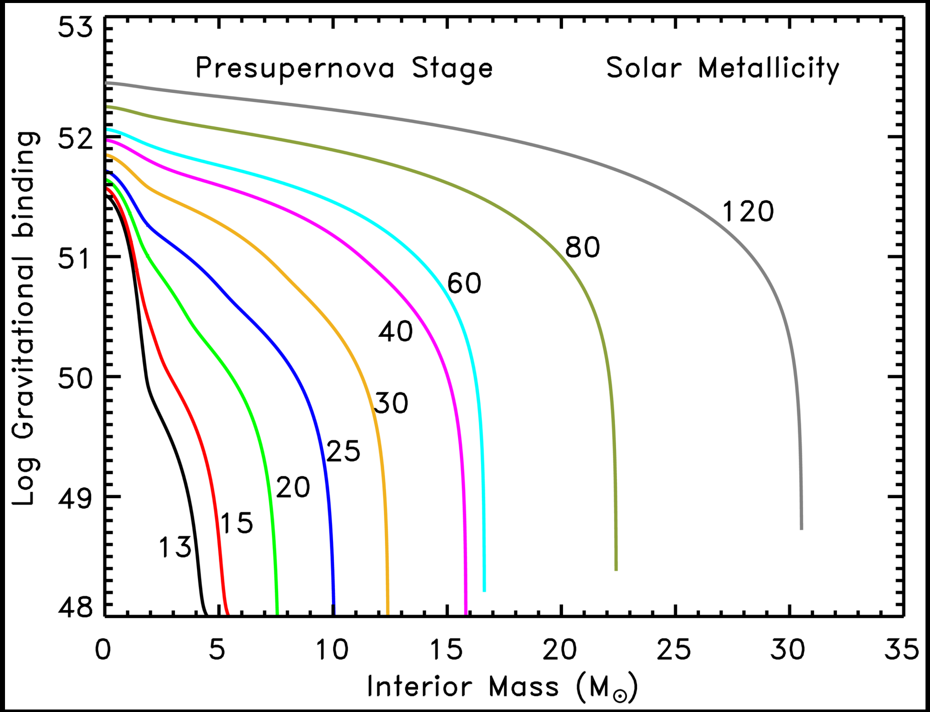
The complex interplay among the shell nuclear burning, the timing and overlap of the convective zones determines in a direct way the final distribution of the chemical composition



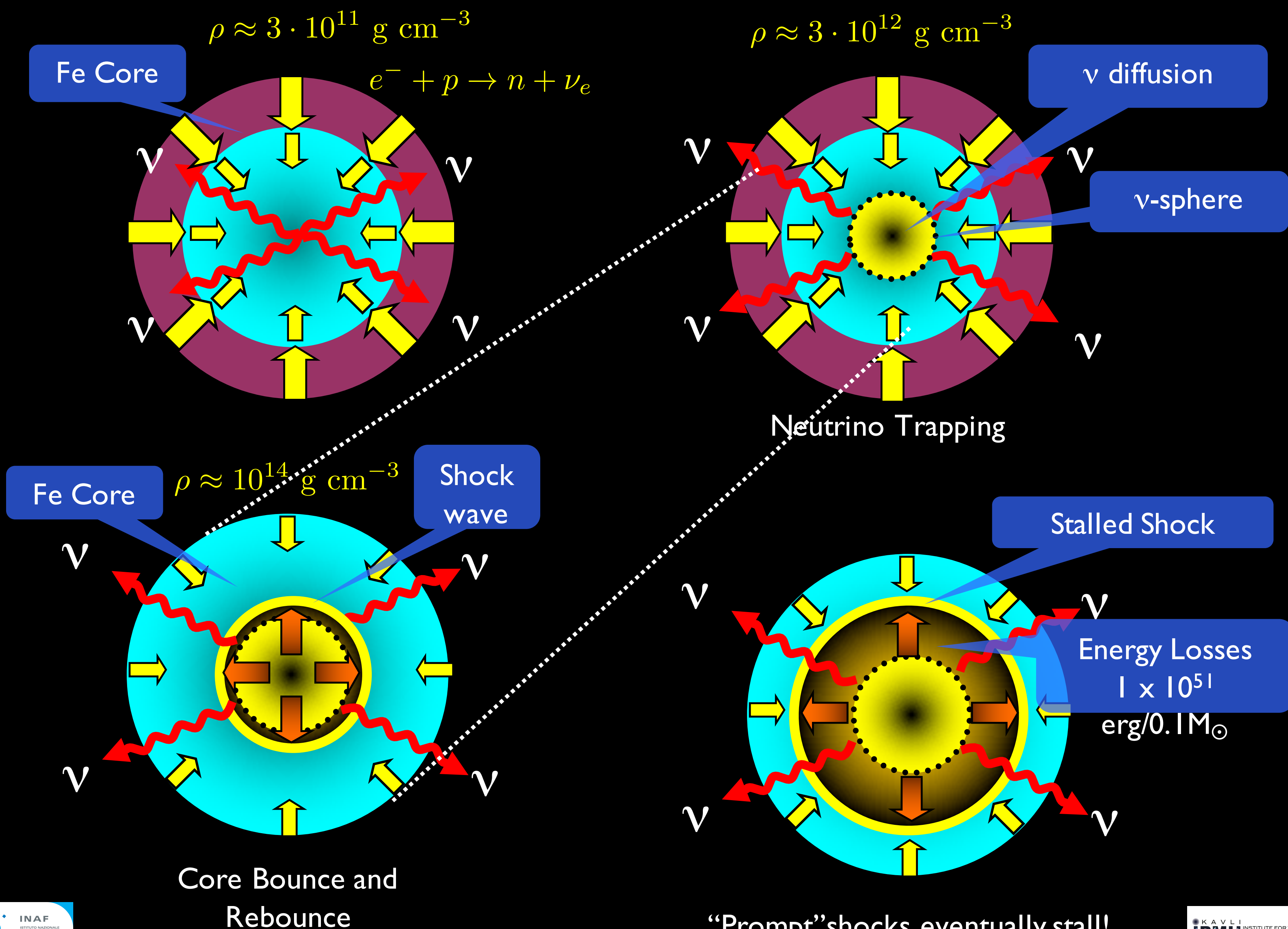
Physical Structure at Presupernova Stage

and the density distribution as well





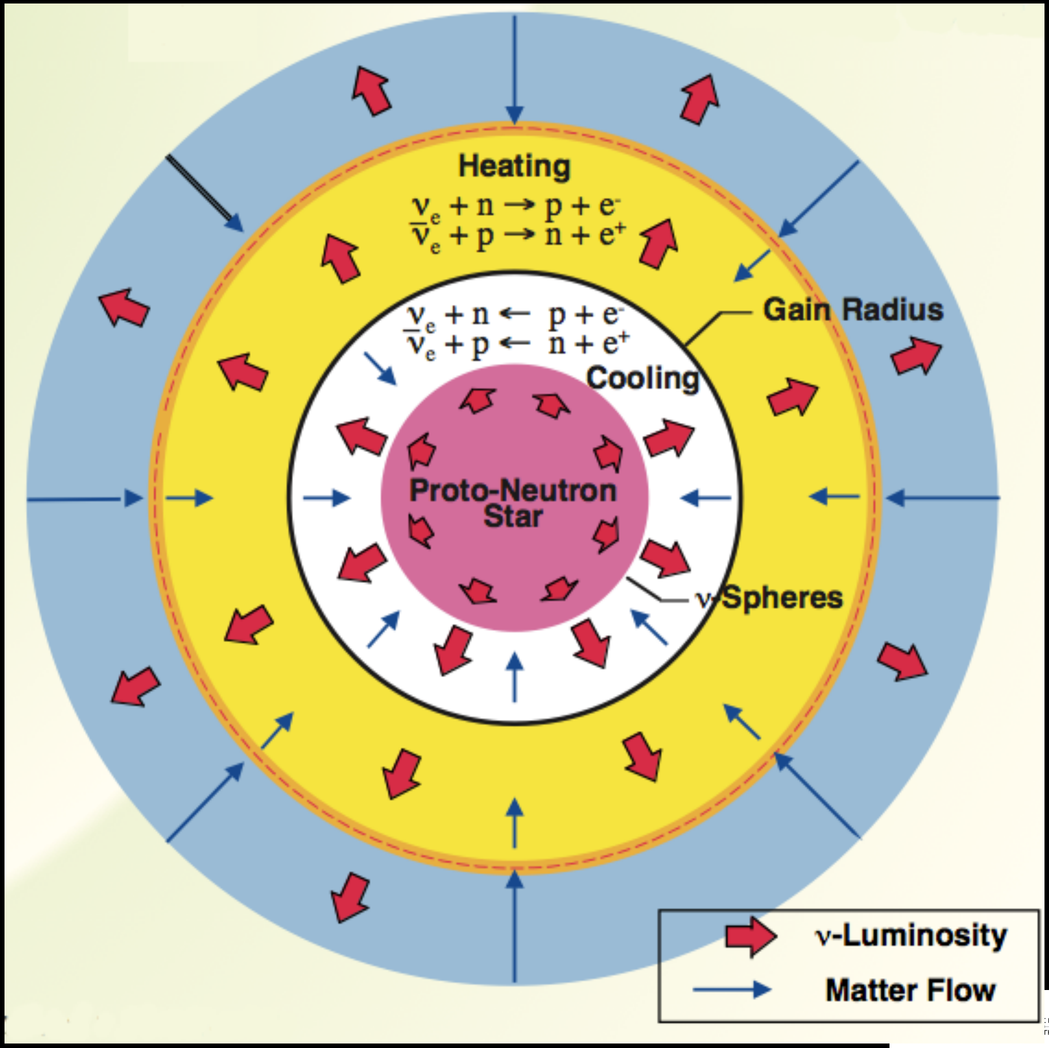
Core Evolution Toward the Explosion



Core Collapse Supernova Mechanism

Between the neutrinosphere and the shock, the material both heats and cools by electron neutrino and antineutrino emission and absorption.

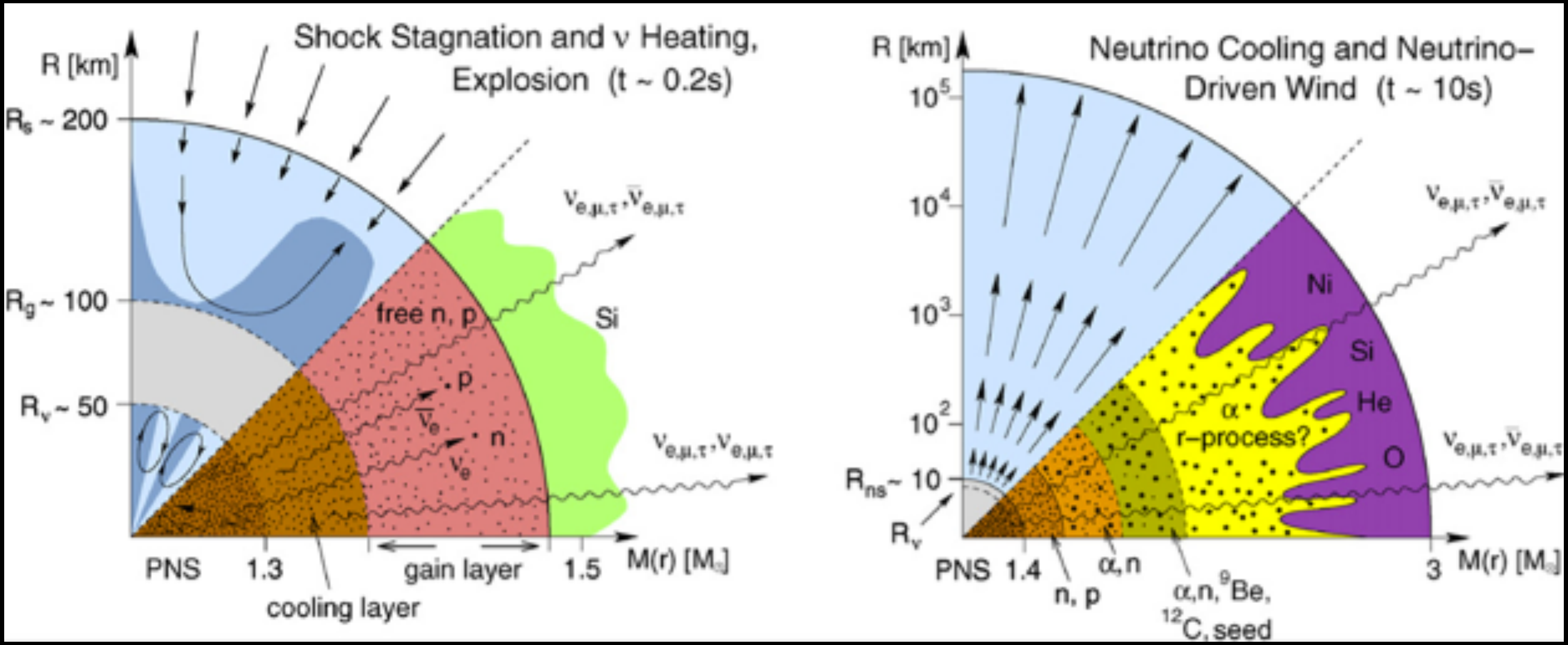
The neutrino heating and cooling have different radial profiles → consequently, this region splits into a net cooling region and a net heating region, separated by a gain radius at which heating and cooling balance.



Mezzacappa, 2005

Core Collapse Supernova Mechanism

The persistent neutrino energy deposition behind the shock keeps the pressure high in this region and drives the shock outwards again, eventually leading to a supernova explosion.



Janka+ 2007

Core Collapse Supernova Mechanism

Remember: The canonical explosion energy of a supernova is less than one percent of the total gravitational binding energy lost by the nascent neutron star in neutrinos.

This mechanism requires that few percent of the radiated neutrino energy (or 10–20% of the energy of electron neutrinos and antineutrinos) are converted to thermal energy of nucleons, leptons, and photons.

The success of the delayed supernova mechanism turned out to be sensitive to a complex interplay of neutrino heating, mass accretion through the shock, and mass accretion through the gain radius.

After ~3 decades of research the paradigm of the neutrino driven wind explosion mechanism is widely accepted

BUT

The most recent and detailed simulations of core collapse SN explosions show that:

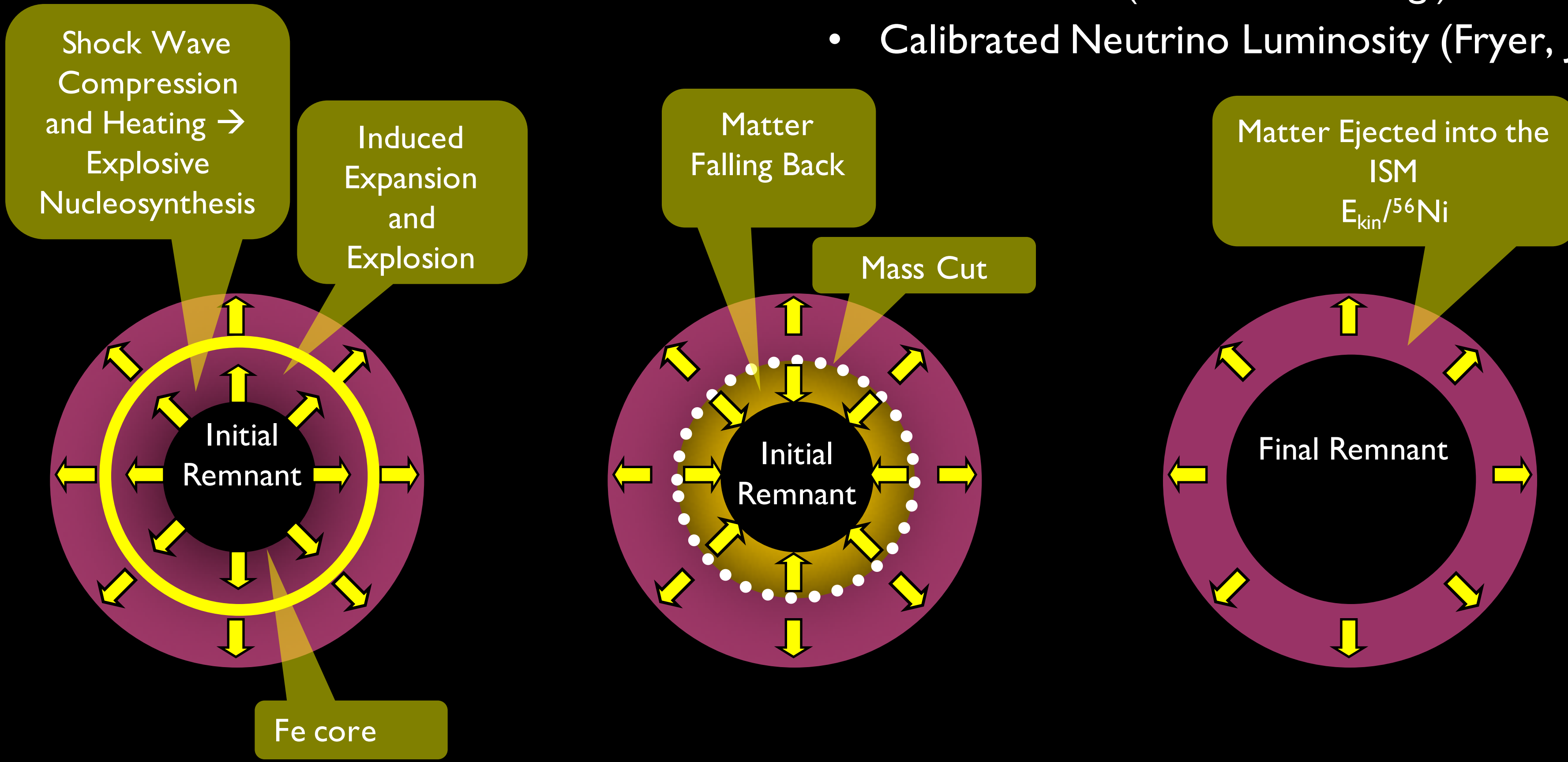
- the shock still stalls → No explosion is obtained
- the energy of the explosion is a factor of 3 to 10 lower than usually observed

Work is underway by all the theoretical groups to better understand the problem and we may expect progresses in the next future

Induced Explosion and Fallback

Different ways of inducing the explosion →

- Piston (Woosley, Weaver and coll.)
- Thermal Bomb (Nomoto, Umeda and coll.)
- Kinetic Bomb (Chieffi & Limongi)
- Calibrated Neutrino Luminosity (Fryer, Janka)



FB depends on the Binding Energy of the mantle: the higher is the binding energy the higher is the mass of the remnant

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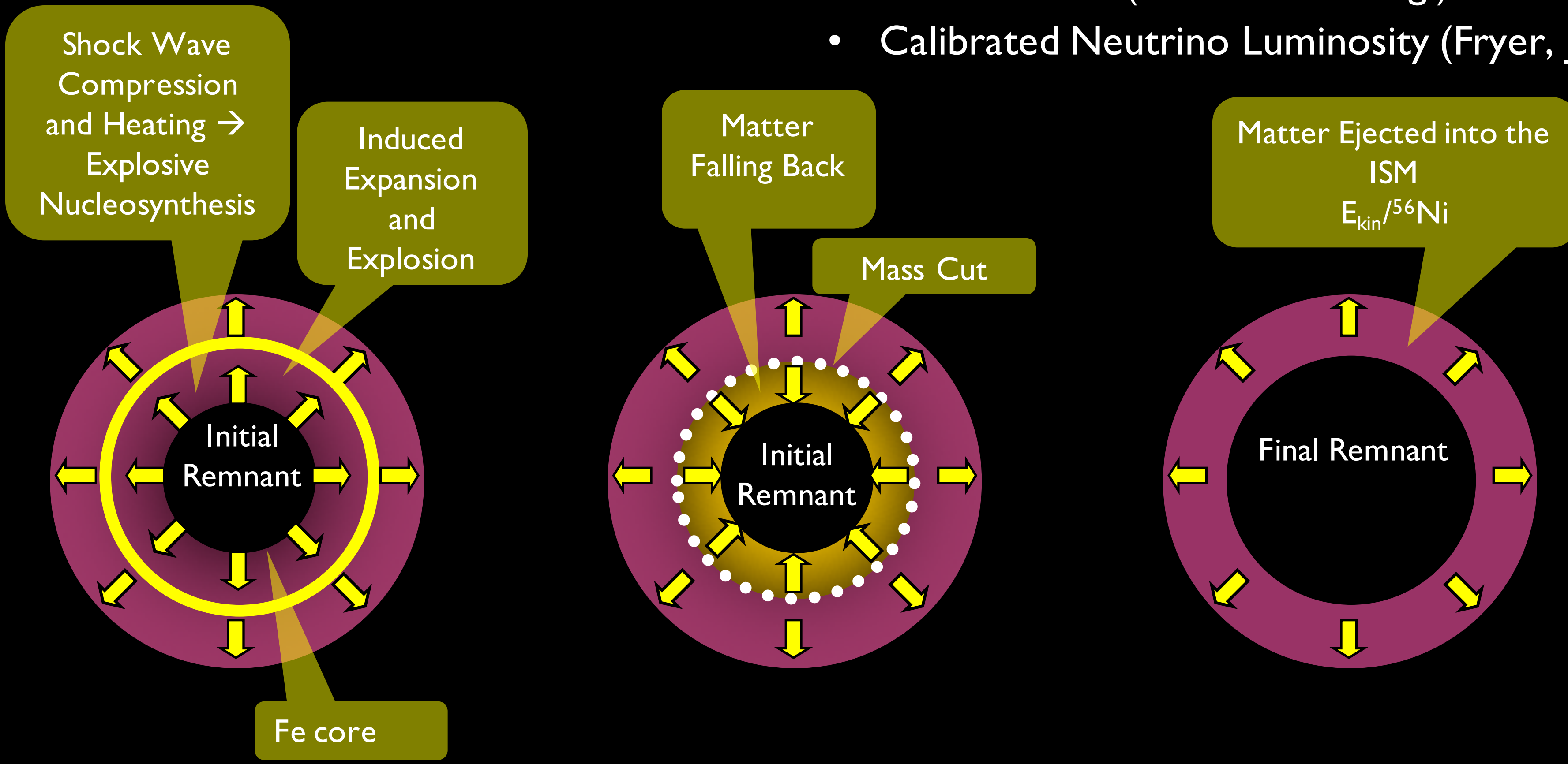
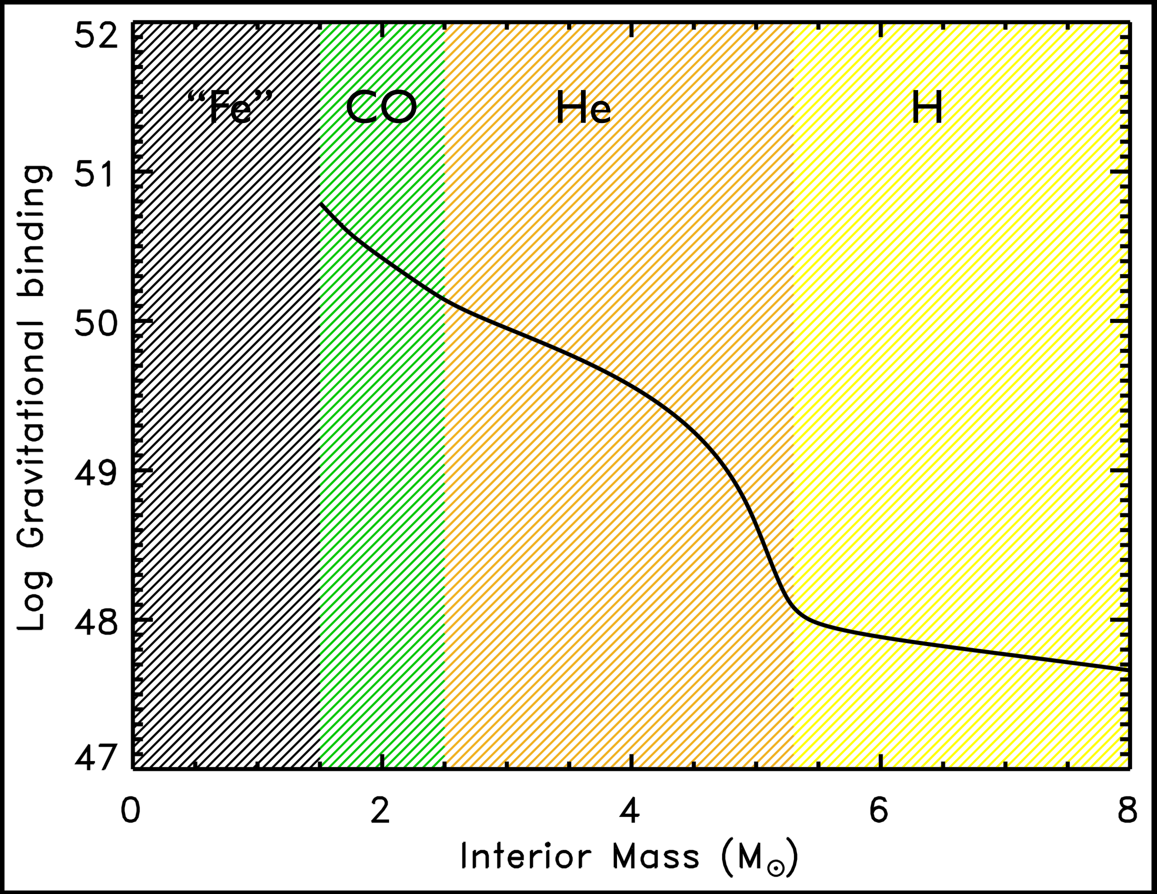


FB depends also on the Explosion Energy: the higher is the explosion energy the lower is the mass of the remnant

Binding Energy the Presupernova Star

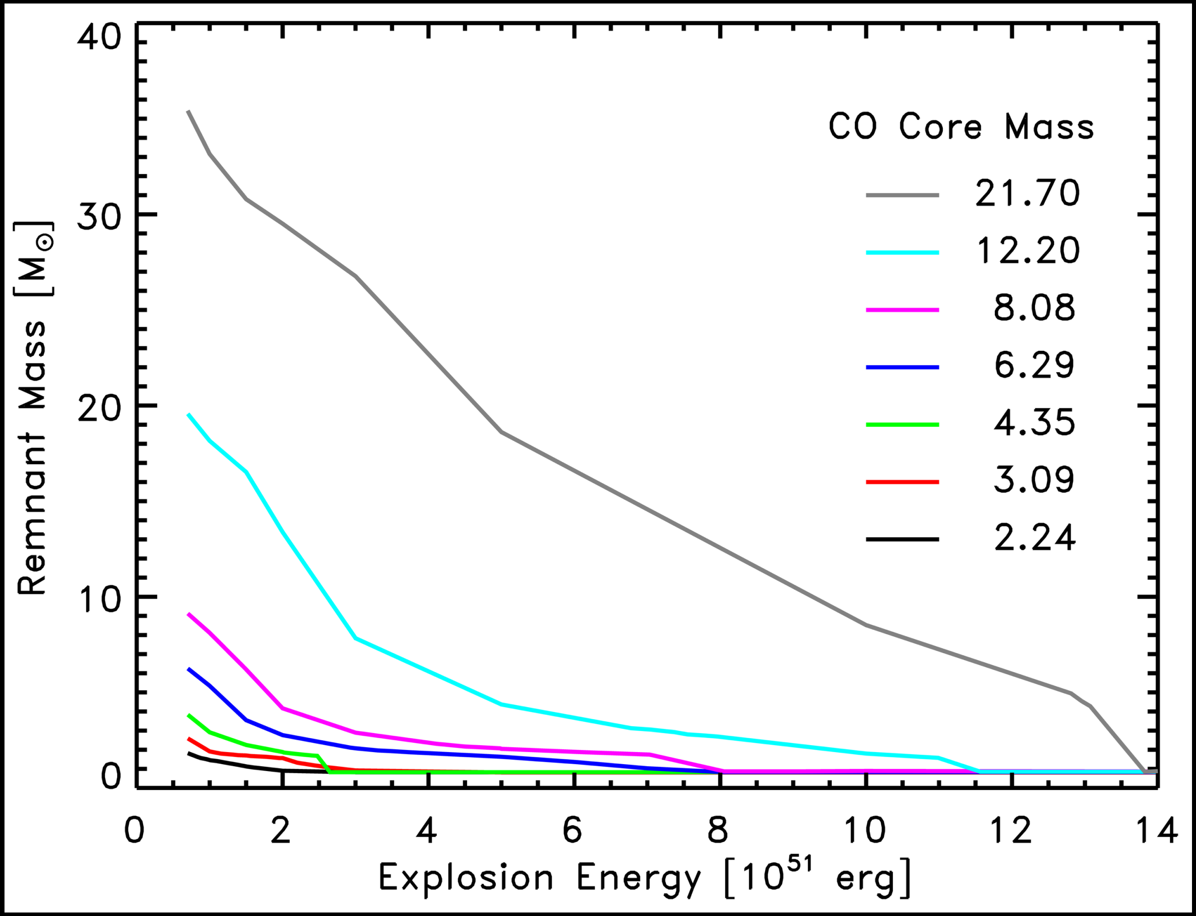


Most of the binding energy is contained within the CO core

$$E_{bind} \propto M_{CO}$$

Binding Energy the Presupernova Star

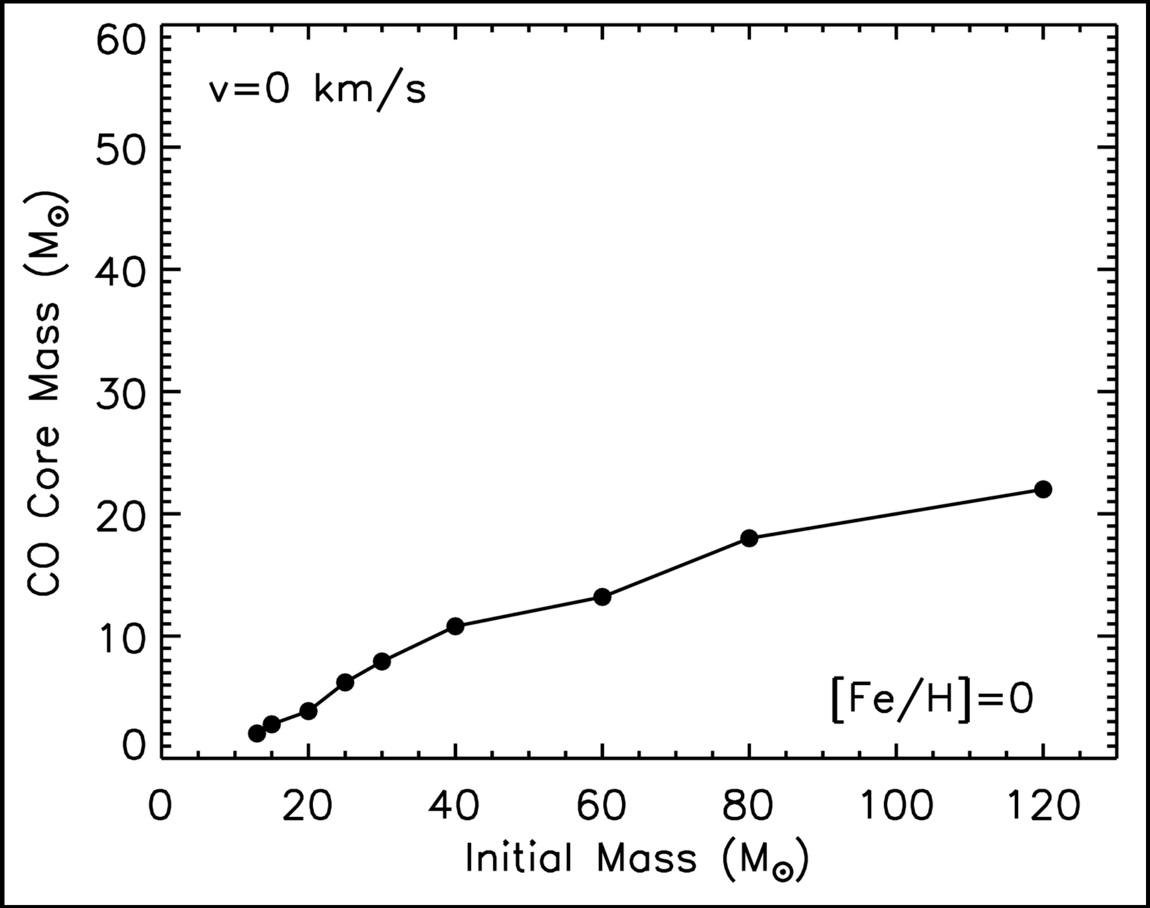
$$M_{remnant} = f(M_{CO},\ E_{expl})$$



$$M_{CO} = f(M,\ Z,\ v)$$

Binding Energy the Presupernova Star

Dependence of the CO core mass on the INITIAL MASS



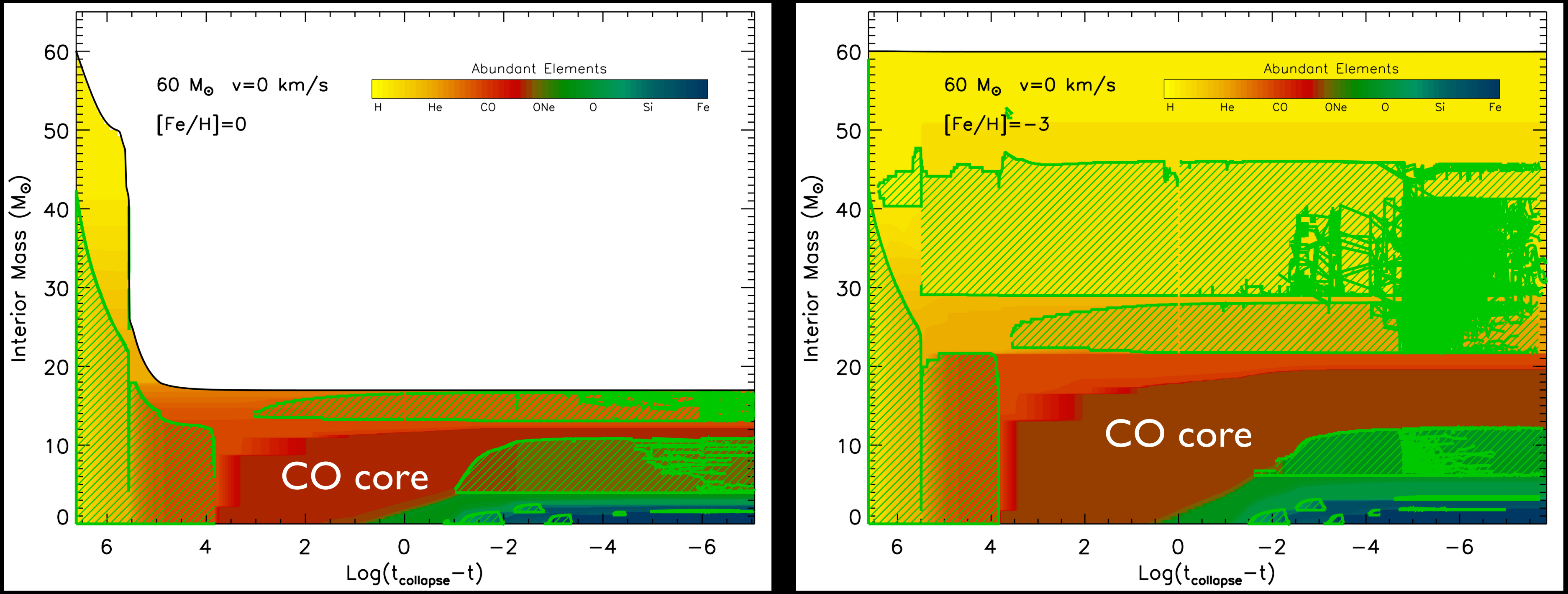
CO core mass increases with the Initial Mass

Binding Energy in the Presupernova Star

Dependence of the CO core mass on the INITIAL METALLICITY

Mainly due to reduction of the Mass Loss with the Metallicity

$$\dot{M} \propto Z^{0.85}$$



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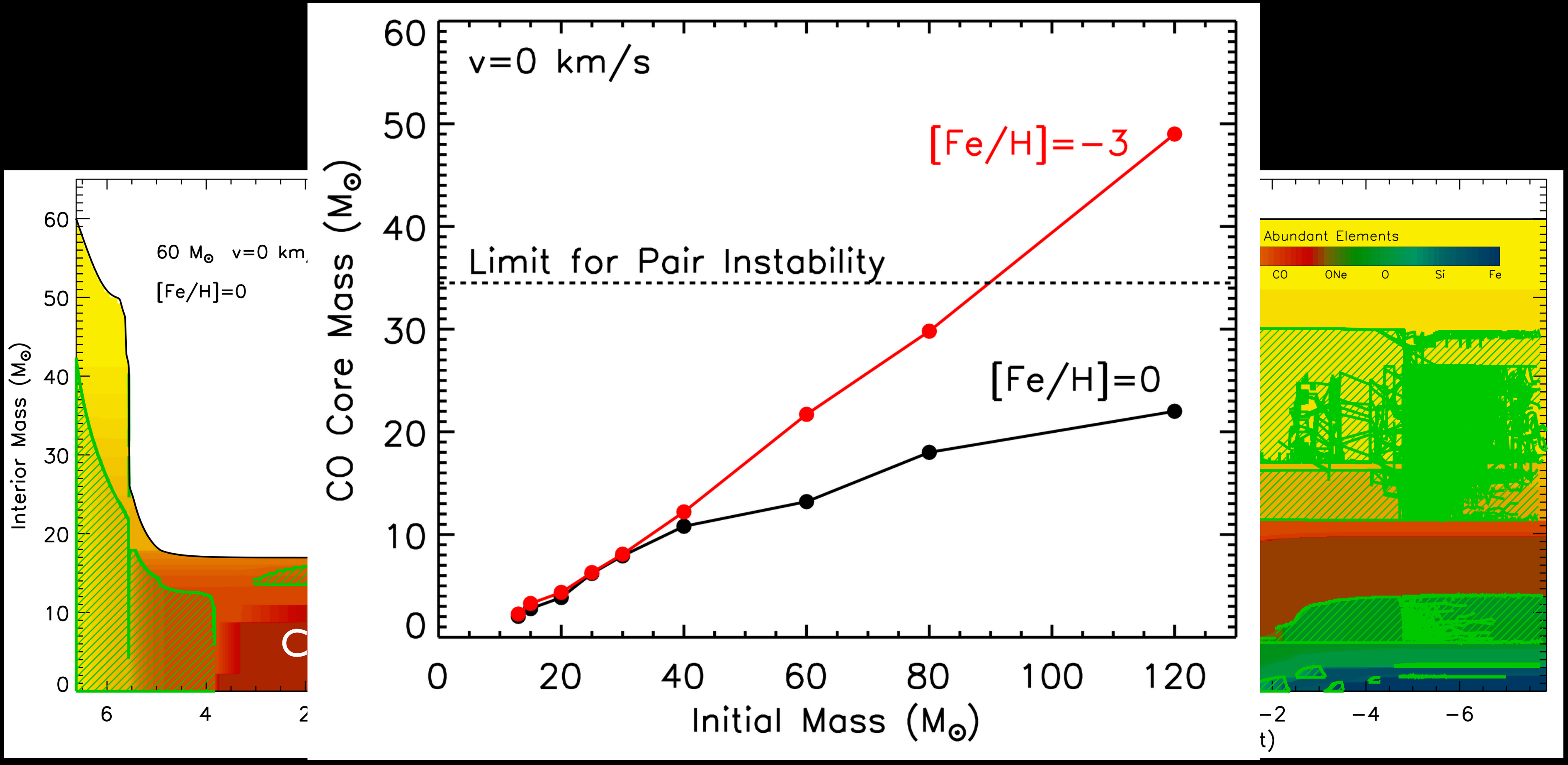


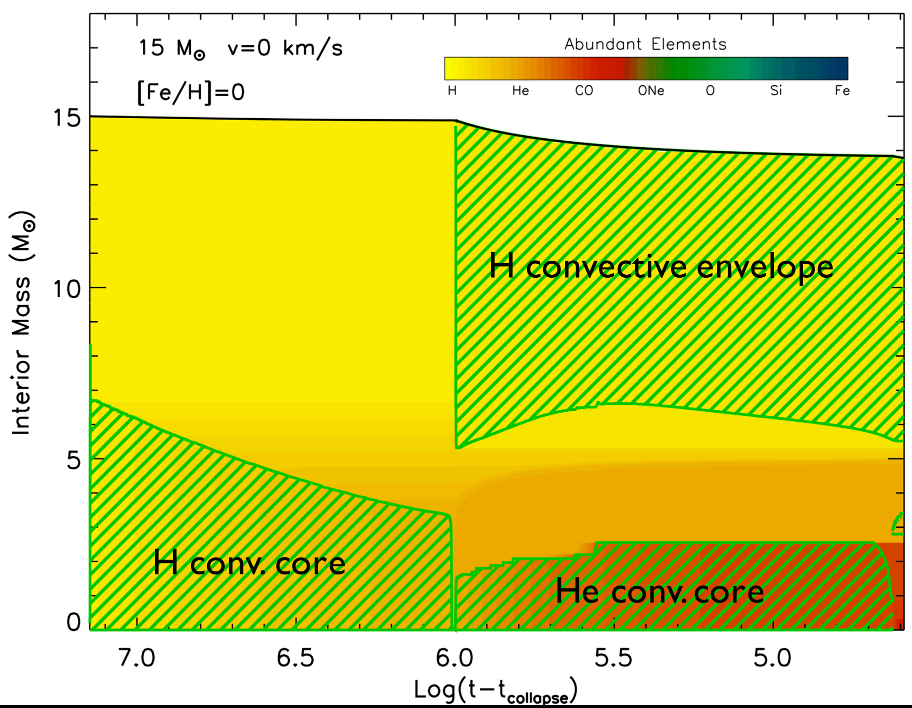
CO core mass increases as the metallicity decreases

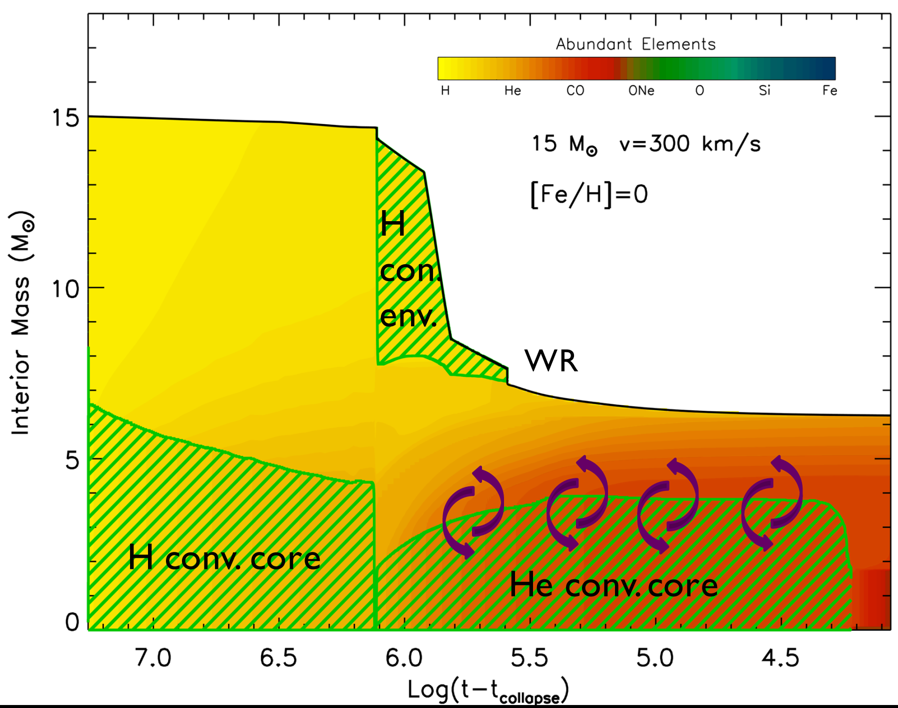
Binding Energy in the Presupernova Star

Dependence of the CO core mass on the INITIAL ROTATION VELOCITY

Rotation driven instabilities (meridional circulation+shear turbulence)
→ increase of the CO core mass

Chieffi & ML 2013





CO core mass increases as the initial rotation velocity increases

This effect increases as the metallicity decreases
because lower metallicities stars are more compact

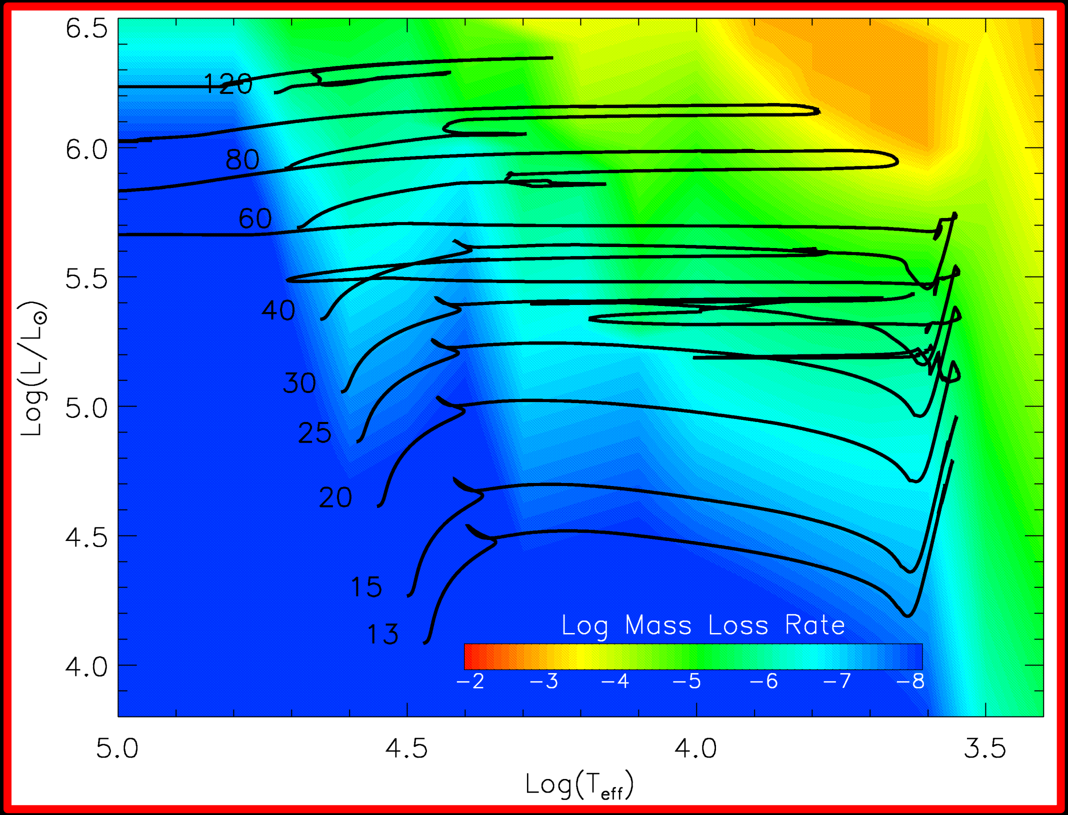
$$\tau_{diff} \sim \frac{\Delta R^2}{D}$$

Binding Energy in the Presupernova Star

Dependence of the CO core mass on the INITIAL ROTATION VELOCITY

Rotating models are in general brighter, redder and live more than the non rotating ones

Mass Loss is higher for higher L and lower T_{eff}



Binding Energy in the Presupernova Star

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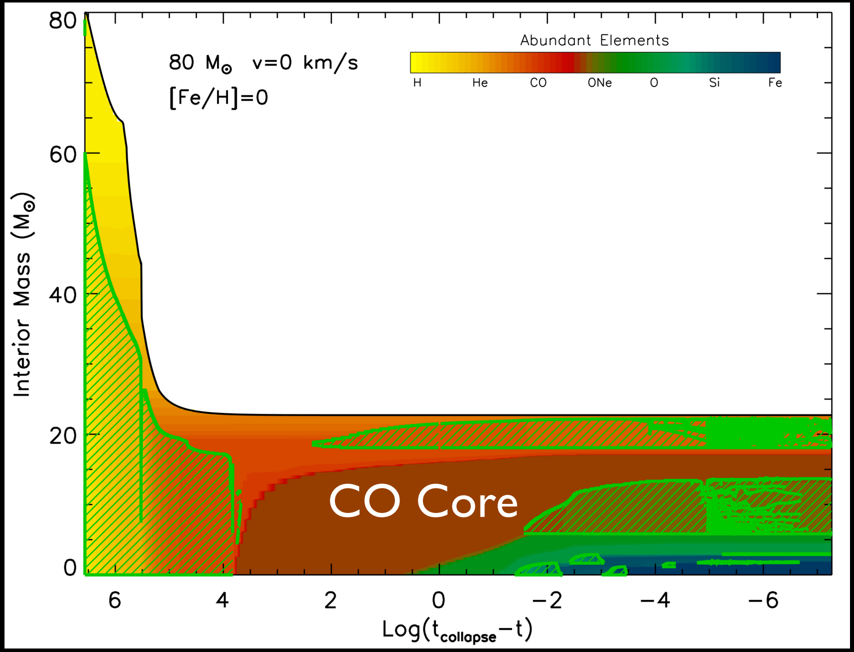
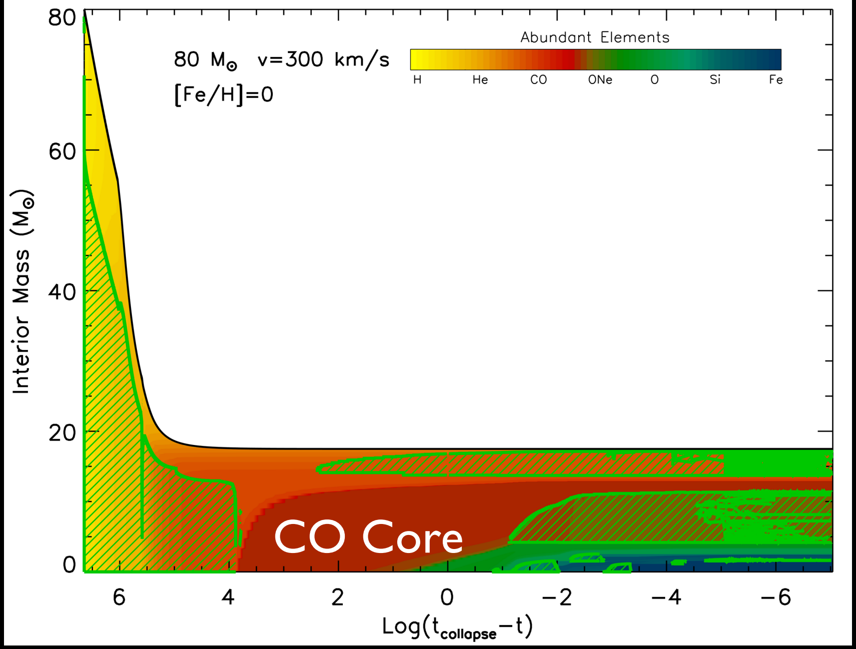


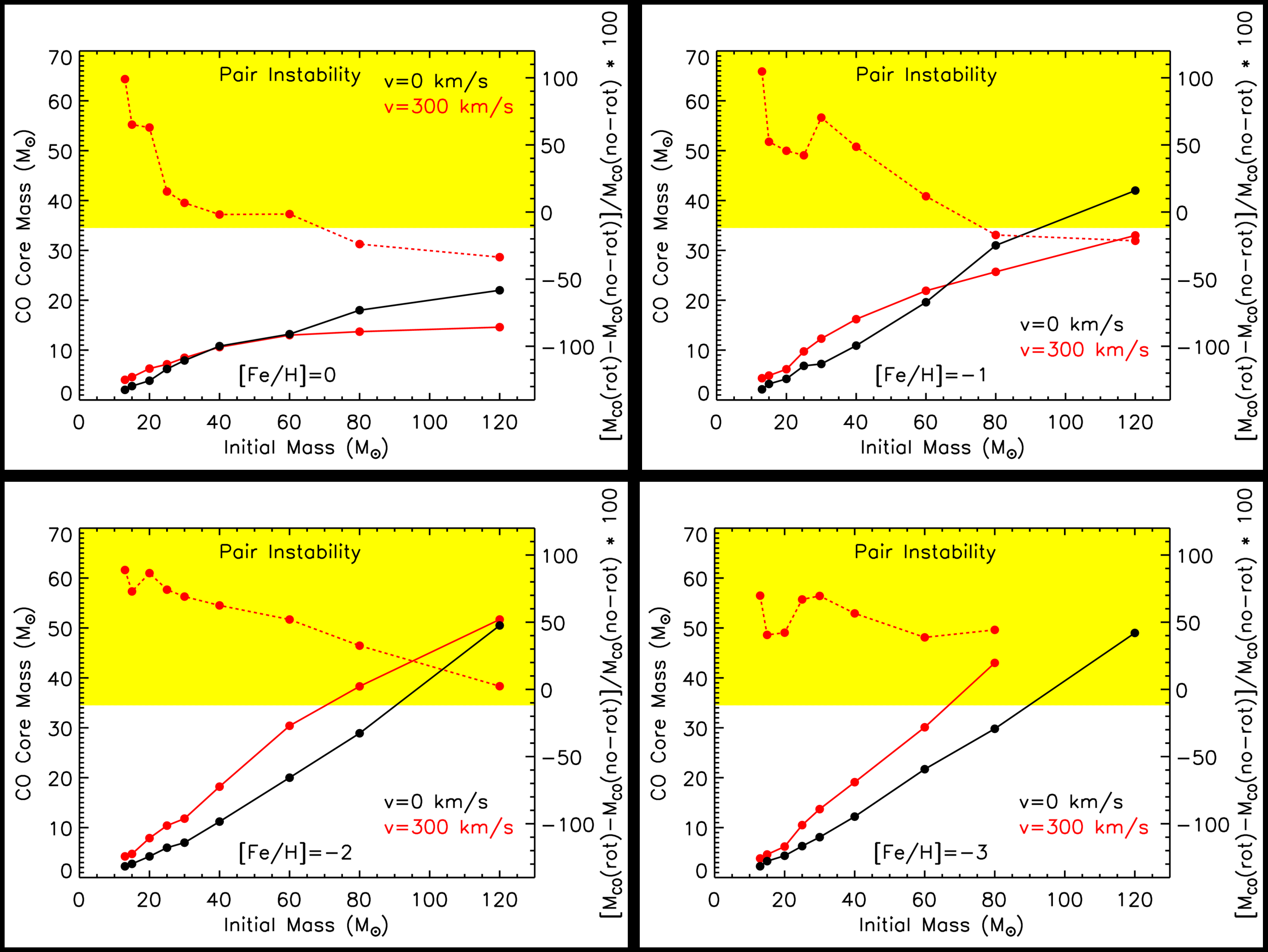


ML & Chieffi 2016

CO core mass may even decrease as the initial rotation velocity increases

Binding Energy in the Presupernova Star

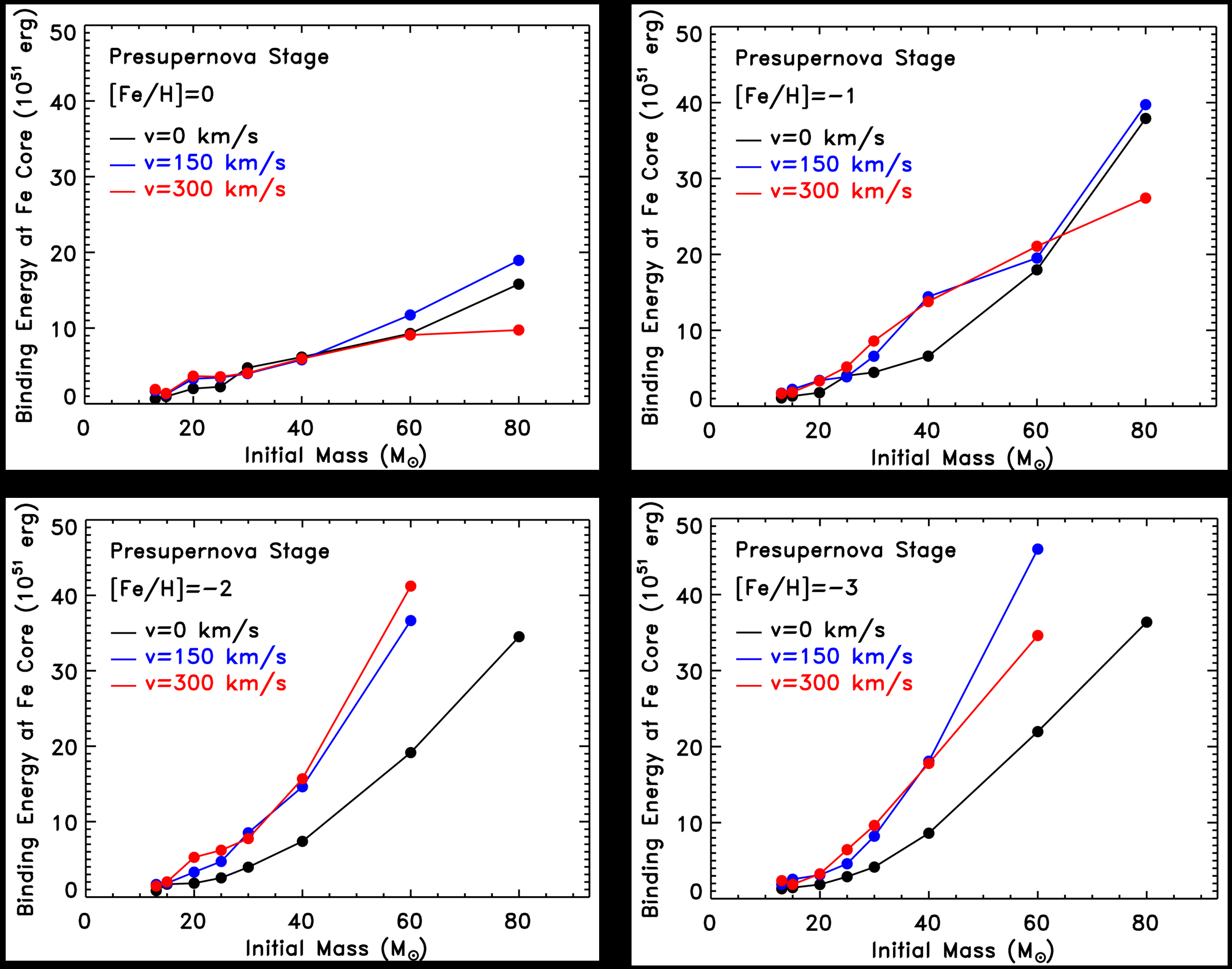
The CO core mass is sensitive to the complex interplay between Metallicity and Rotation
In general it increases with decreasing the metallicity and with increasing the initial velocity



ML & Chieffi 2016

Binding Energy in the Presupernova Star

The binding energy follows the same behavior



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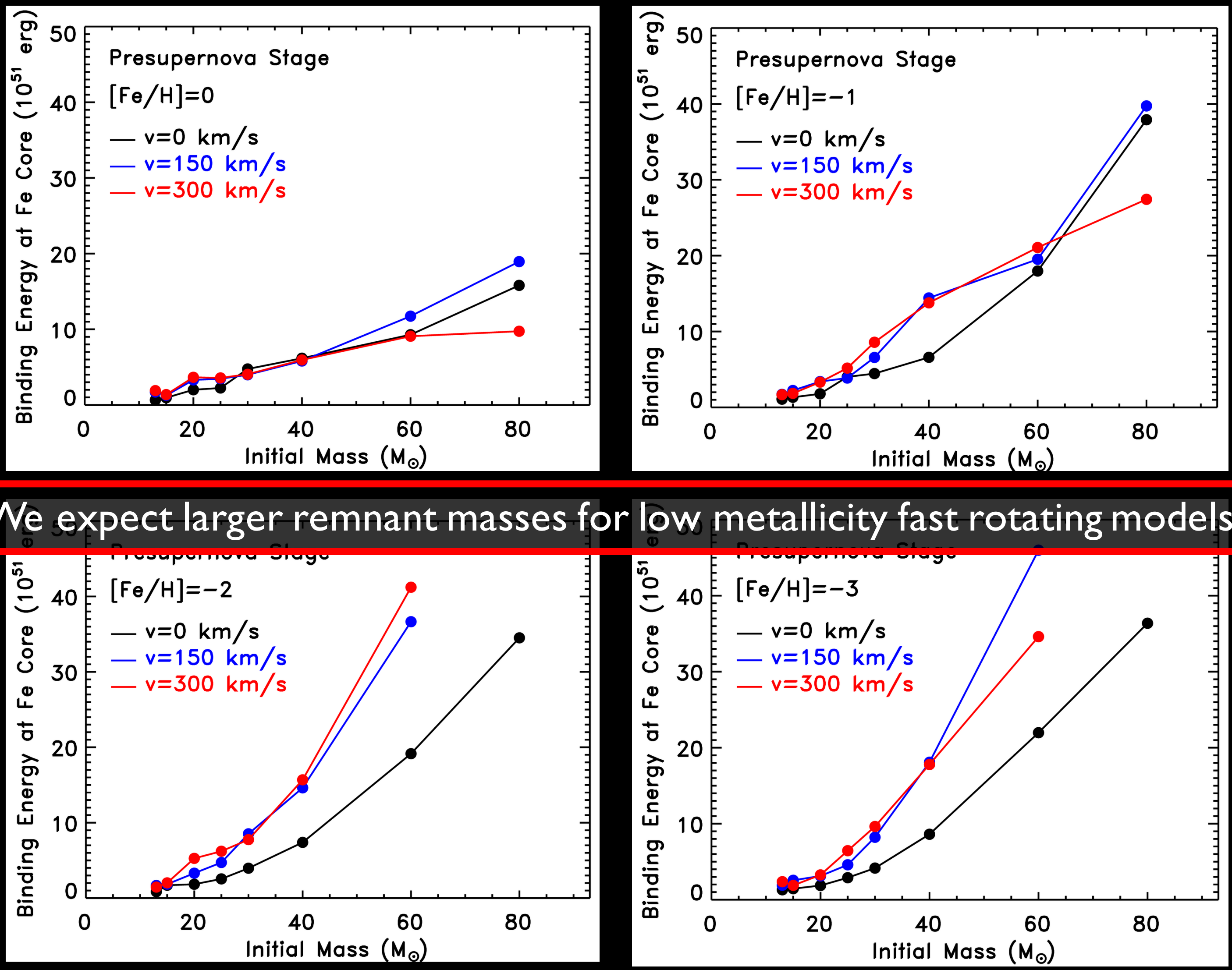
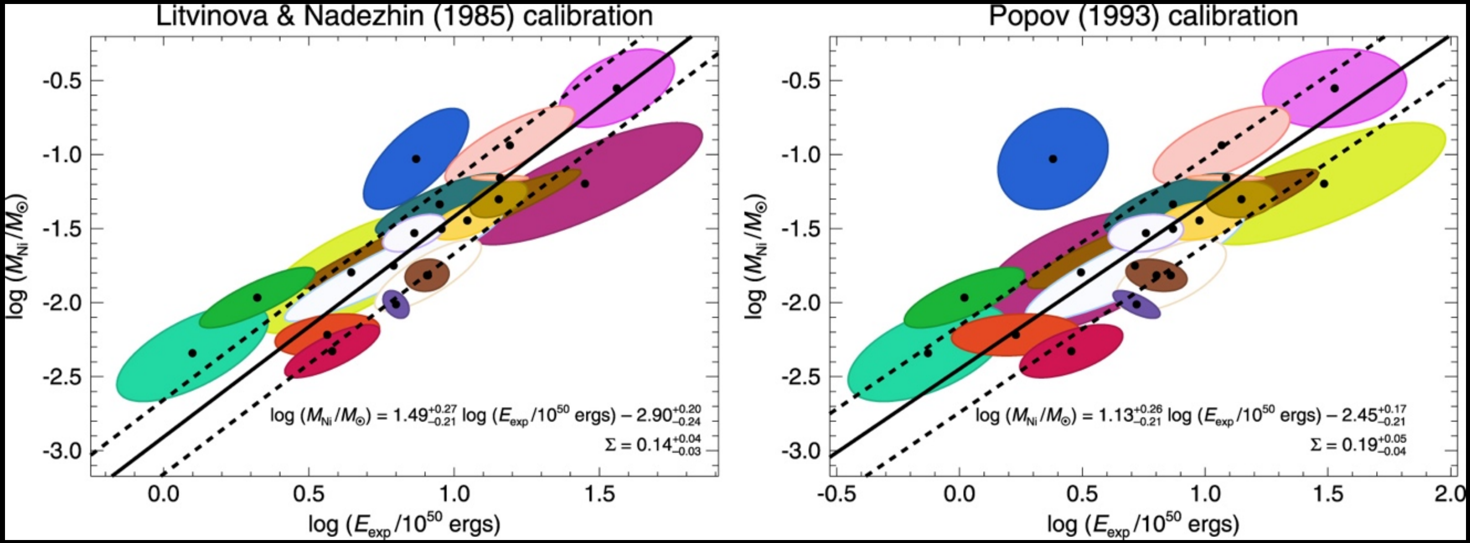


We expect larger remnant masses for low metallicity fast rotating models

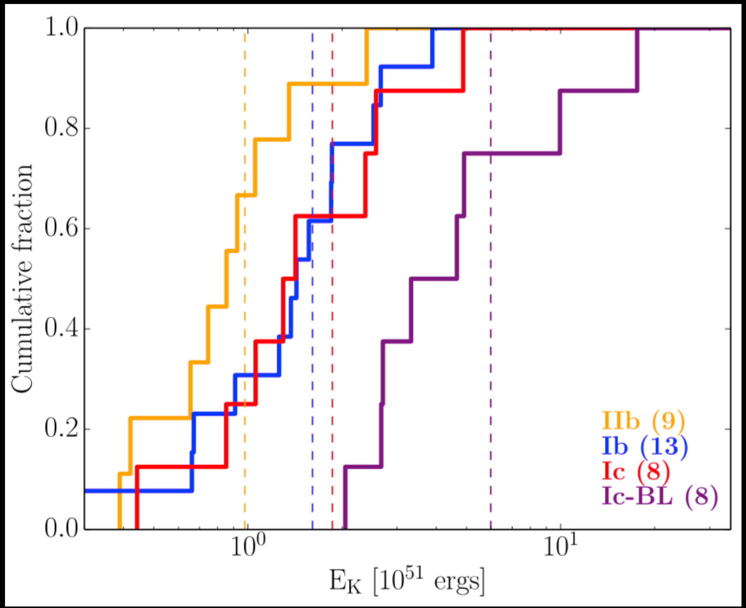
CCSN Explosion Energies

SNII-P



Pejcha & Prieto (2015)

Stripped Envelope CCSNe



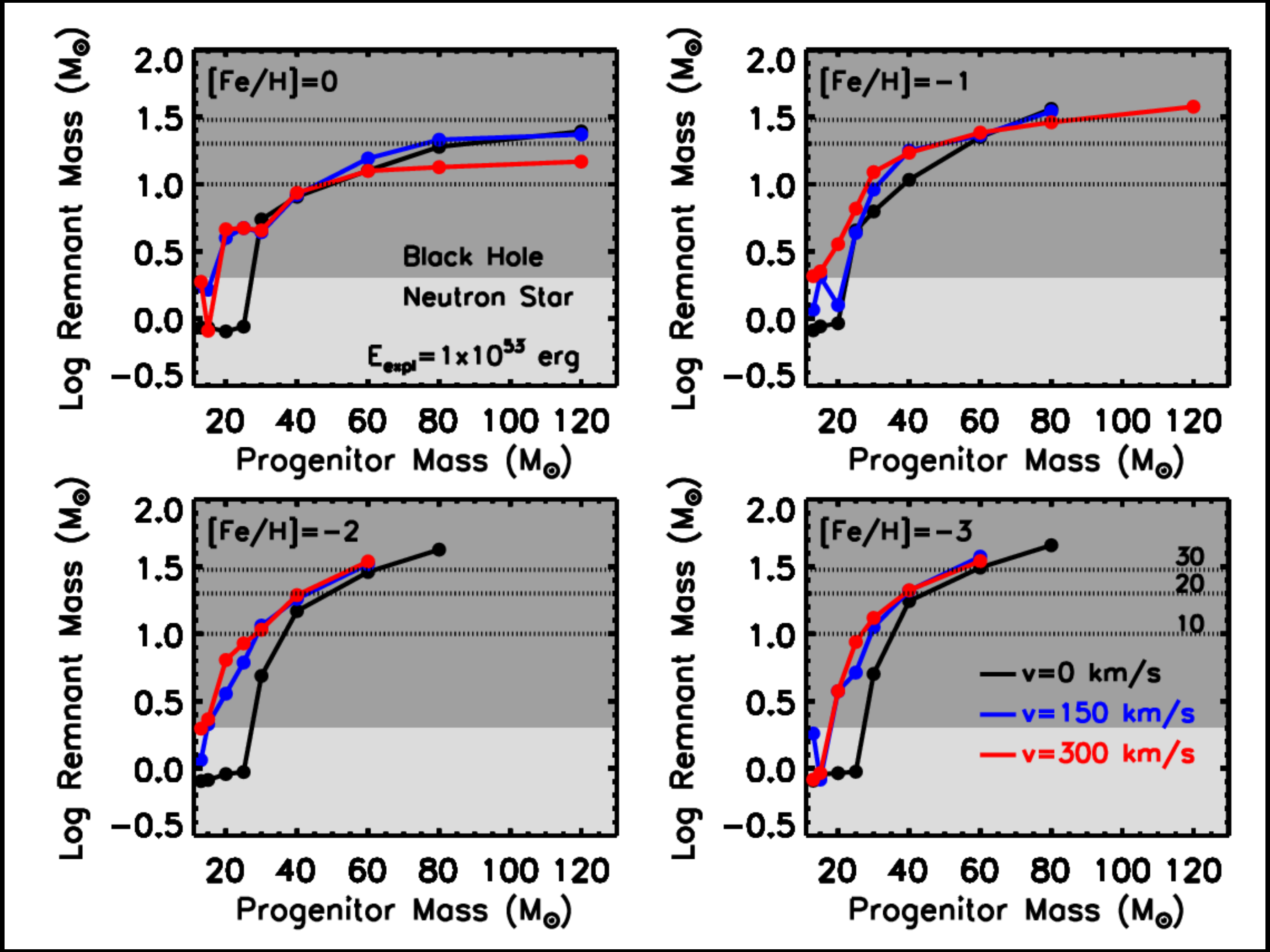
Lyman+ (2016)

$$E_{expl}^{CCSNe} \lesssim 3 \cdot 10^{51} \text{ erg}$$

$$\langle E_{expl}^{CCSNe} \rangle \sim 10^{51} \text{ erg}$$

The Remnant Mass-Initial Mass relation

Hydrodynamic simulations in the framework of the kinetic bomb model

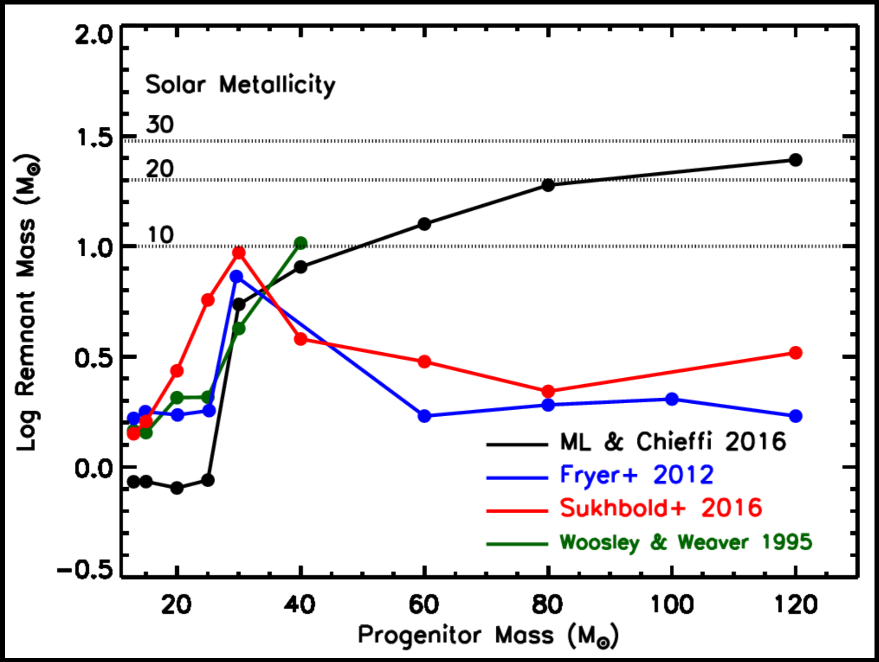


ML & Chieffi 2016, Marassi+ 2016

Sources of Uncertainties

Lack of self-consistent hydrodynamical models for core collapse supernova explosion → current theoretical predictions for the Initial Mass-Remnant Mass relation are based on artificially induced explosions → they are highly uncertain

No systematic study on the differences coming out from the various approaches starting from the same presupernova models is available in literature yet



All these results MUST be taken with caution

Sources of Uncertainties

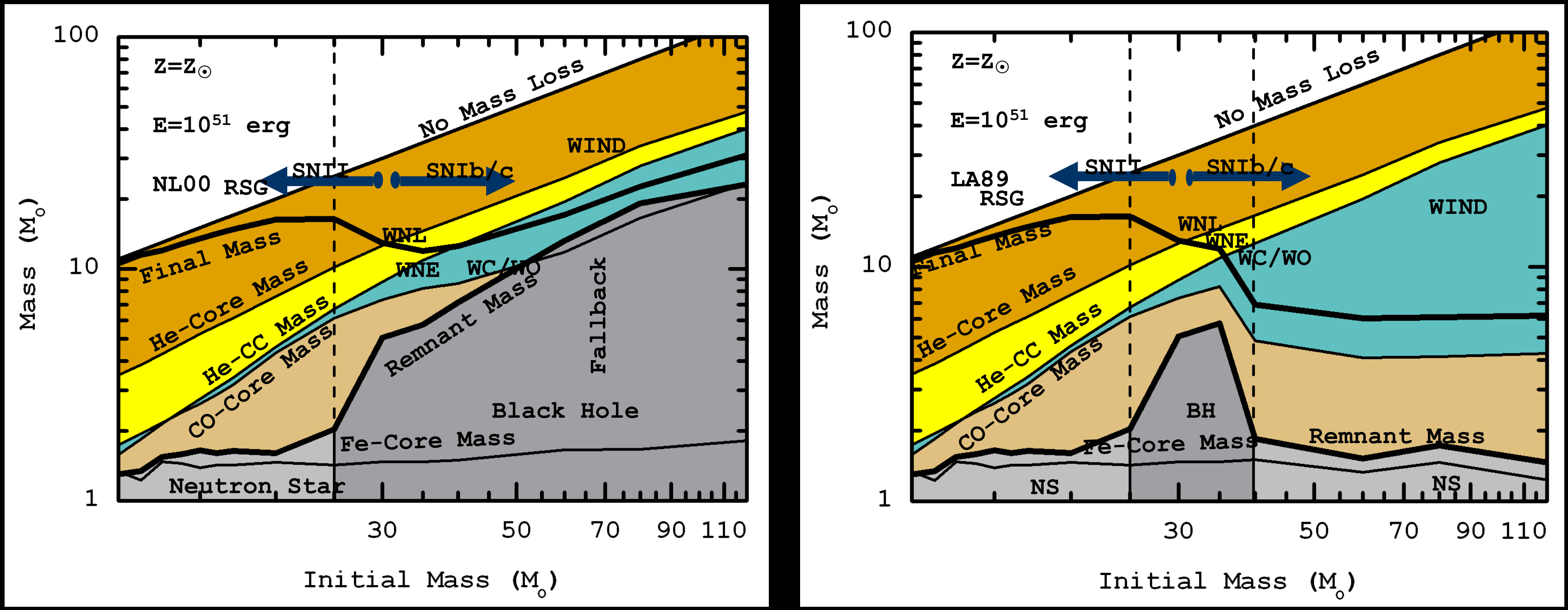
Different prescriptions for mass loss during the presupernova evolution may alter, even significantly, the final Initial Mass-Remnant Mass relation

$$\dot{M}_{WR} = 10^{-11} \left(\frac{L}{L_\odot}\right)^{1.29} Y^{1.7} Z^{0.5} \ \mathrm{M_\odot \ yr^{-1}}$$

Nugis & Lamers (2000)

$$\dot{M}_{WR} = 10^{-7} \left(\frac{M}{M_\odot}\right)^{2.5} \ \mathrm{M_\odot \ yr^{-1}}$$

Langer (1989)



ML & Chieffi (2008)

Summary and Conclusions

GW150914 demonstrated that binary systems formed by two massive BHs exist

In principle BHs with masses M_{BH}>30 $M_{\odot}$ can be the "natural" result of the normal explosions (E_{kin}< 3 x 10^{51} erg) of stars with masses M_{BH}>40 $M_{\odot}$ and with metallicities [Fe/H]<-1

BUT

These results MUST be taken with caution because of the high uncertainties in the calculation of the Remnant Masses

@INAF We have a long tradition and a top level experties in the computation of the presupernova evolution of massive stars.

We urgently need to increases our knowledge on the hydrodynamic simulations of the core collapse and bounce and postexplosion fallback