Massive Stars: Evolution, Explosion and Nucleosynthesis

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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
- 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

Presupernova Evolutions

INITIAL MASSES: 13, 15, 20, 25, 30, 40, 60, 80 and 120 $M_\odot$

INITIAL COMPOSITIONS:	[Fe/H]=0 ,	$Z=1.345\ 10^{-2}$	Asplund+ 2009
	[Fe/H]=-1 ,	$Z=3.236\ 10^{-3}$	Scaled solar $Fe/Fe_\odot$=0.1,0.01,0001
	[Fe/H]=-2 ,	$Z=3.236\ 10^{-4}$	except
	[Fe/H]=-3 ,	$Z=3.236\ 10^{-5}$	[C/Fe]=0.18
			[O/Fe]=0.47
			[Mg/Fe]=0.27
			[Si/Fe]=0.37
			[S/Fe]=0.35
			[Ar/Fe]=0.35
			[Ca/Fe]=0.33
			[Ti/Fe]=0.23
			(Cayrel+ 2004 and Spite+ 2005)

INITIAL EQUATORIAL VELOCITIES: 0, 150, 300 km/s

L 2017 Handbook of Supernovae (Springer) – LC 2018 ApJS (Astro-ph)

Presupernova Evolutions

FRANEC - Frascati RAphson Newton Evolutionary Code 6.0

- FULL COUPLING of all EQUATIONS
- INCLUSION OF ROTATION:
  - Shellular Rotation (Meynet & Maeder 1997)
  - Transport of Angular Momentum due to shear instabilities and meridional circulation (Advection/Diffusion equation, Meynet & Maeder 2000)
  - Coupling of Rotation and Mass Loss
- MASS LOSS:
  - OB: Vink et al. 2000,2001
  - RSG: de Jager 1988+Van Loon 2005 (Dust driven wind)
  - WR: Nugis & Lamers 2000
  - Supra Eddington Mass Loss
  - Mechanical mass loss due to rotation
- TWO NUCLEAR NETWORKS:
  - 220 iso (n-^{209}Bi) H/He Burning
  - 338 iso (n- ^{209}Bi) Advanced Burning

$$\frac{\partial P}{\partial M} = -\frac{GM}{4\pi R^4} f_P$$

$$\frac{\partial R}{\partial M} = \frac{1}{4\pi \rho R^2}$$

$$\frac{\partial T}{\partial M} = -\frac{GMT}{4\pi R^2 P} \nabla \frac{f_T}{f_P}$$

$$\frac{\partial L}{\partial M} = \varepsilon_n + \varepsilon_g + \varepsilon_\nu$$

$$\frac{\partial Y_i}{\partial t} = \left(\frac{\partial Y_i}{\partial t}\right)_{\rm nuc} + \frac{\partial}{\partial m}\left[(4\pi\rho r^2)^2 (D_{\rm mix} + D_{\rm semi} + D_{\rm rot}) \left(\frac{\partial X_i}{\partial m}\right)\right]$$

FRANEC 6.0

FULL COUPLING of:

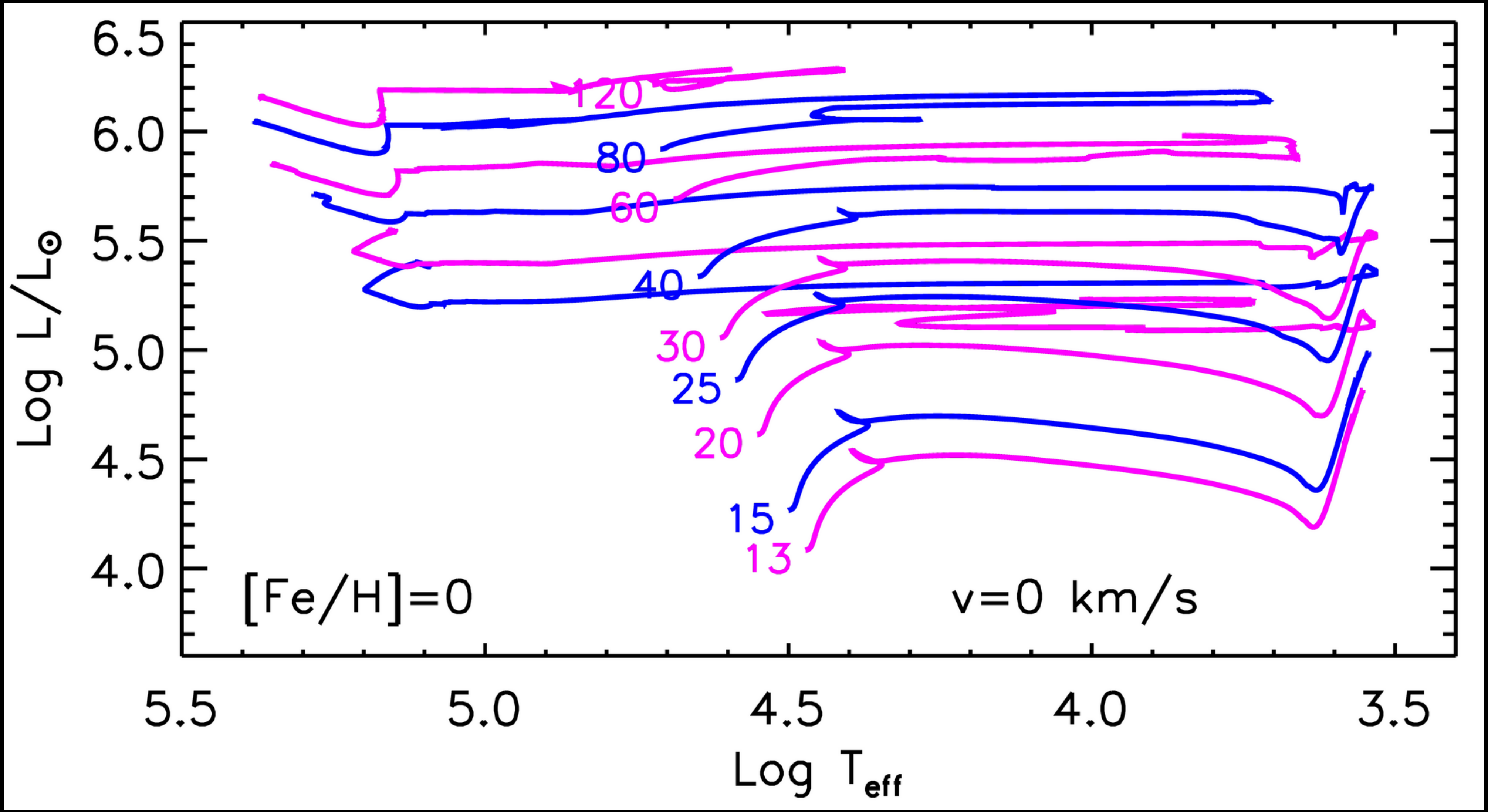
- Physical Structure
- Nuclear Burning
- Chemical Mixing (convection, semiconvection, rotation)

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

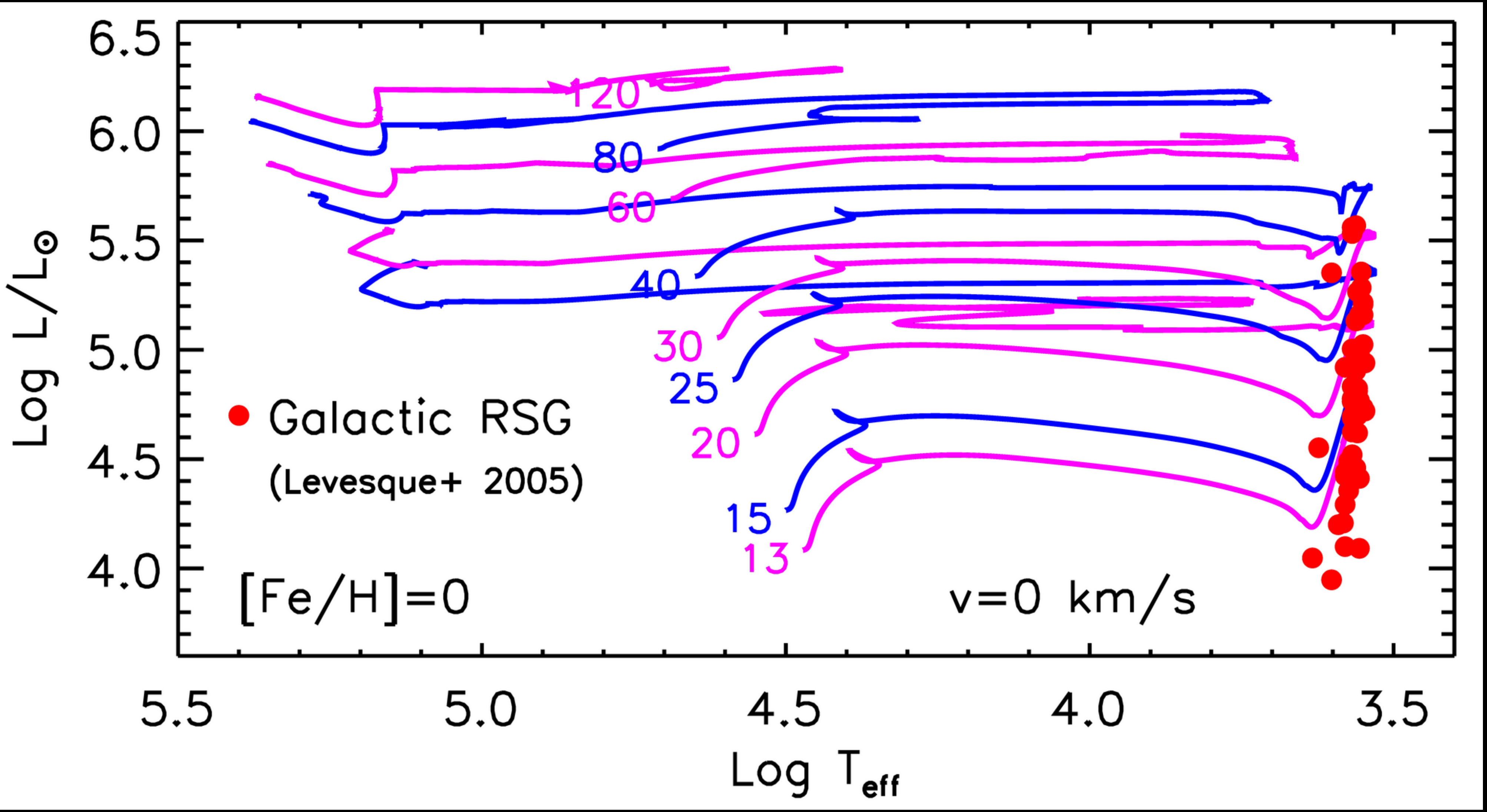
Meridional Circulation — Shear Instabilities

(CL 2013, ApJ, 764, 21 ; LC 2018, ApJS)

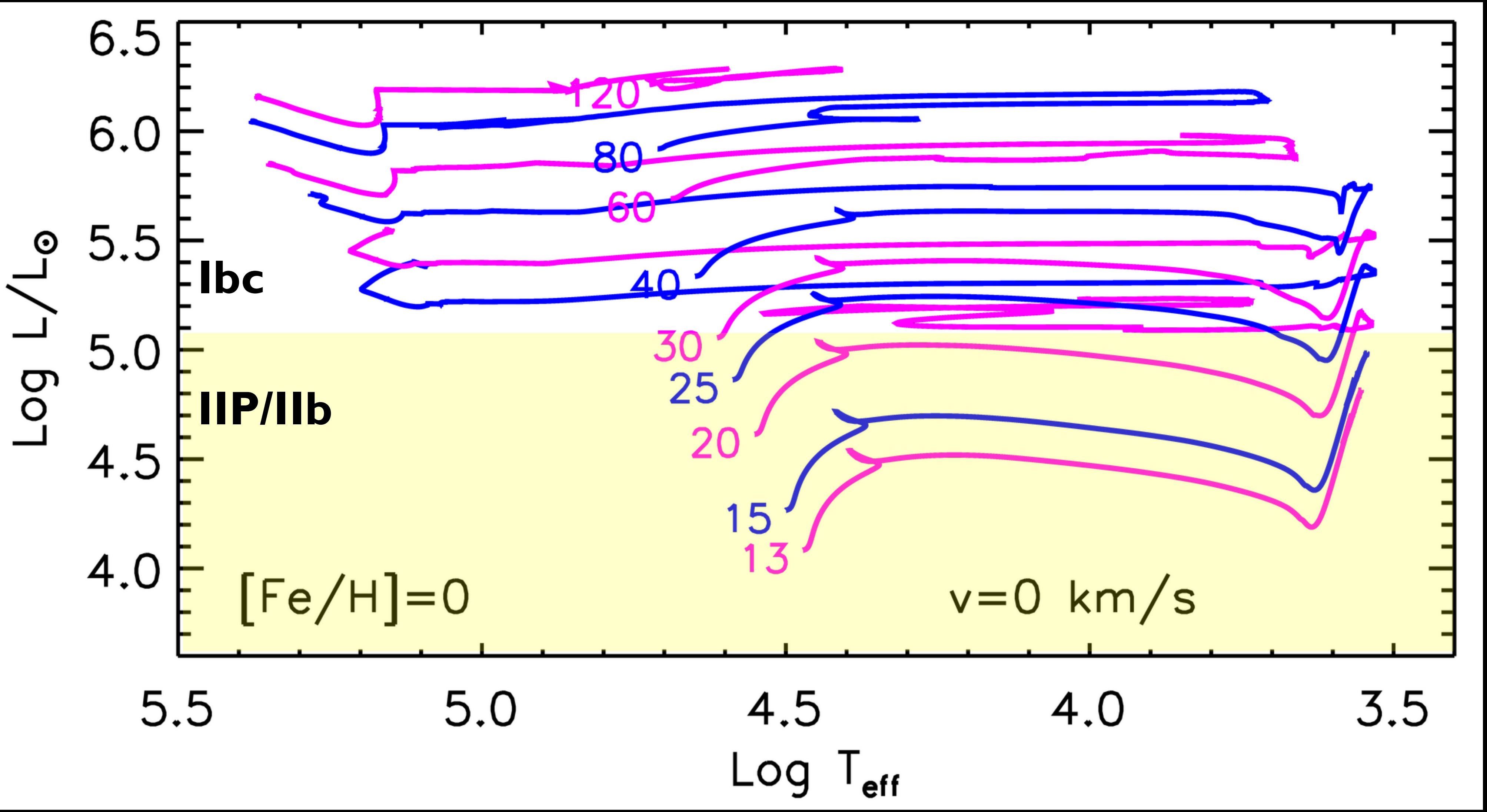
Solar Metallicity non Rotating Models: Presupernova Evolution



Solar Metallicity non Rotating Models: Presupernova Evolution



Solar Metallicity non Rotating Models: Expected Final Fate



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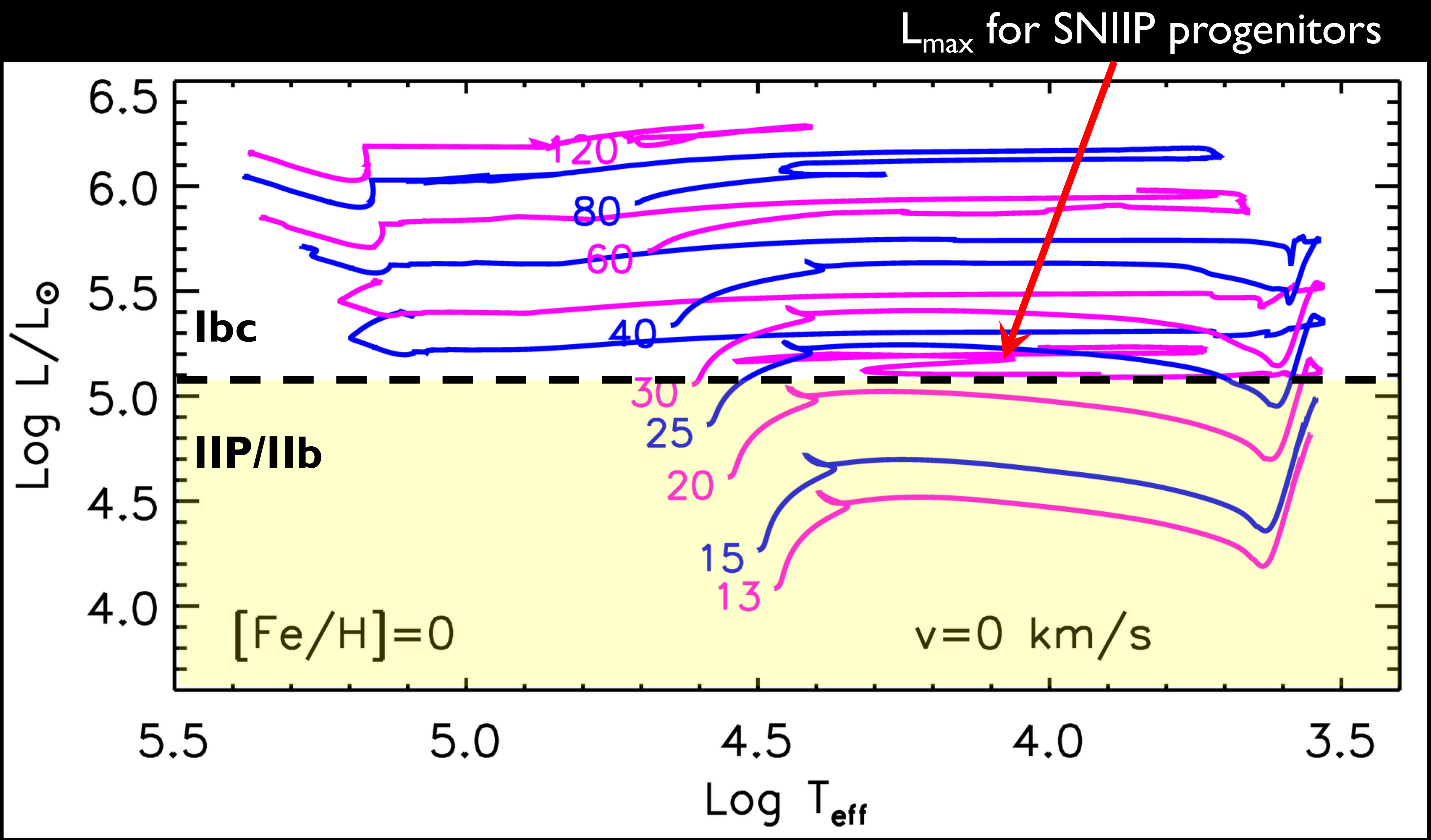
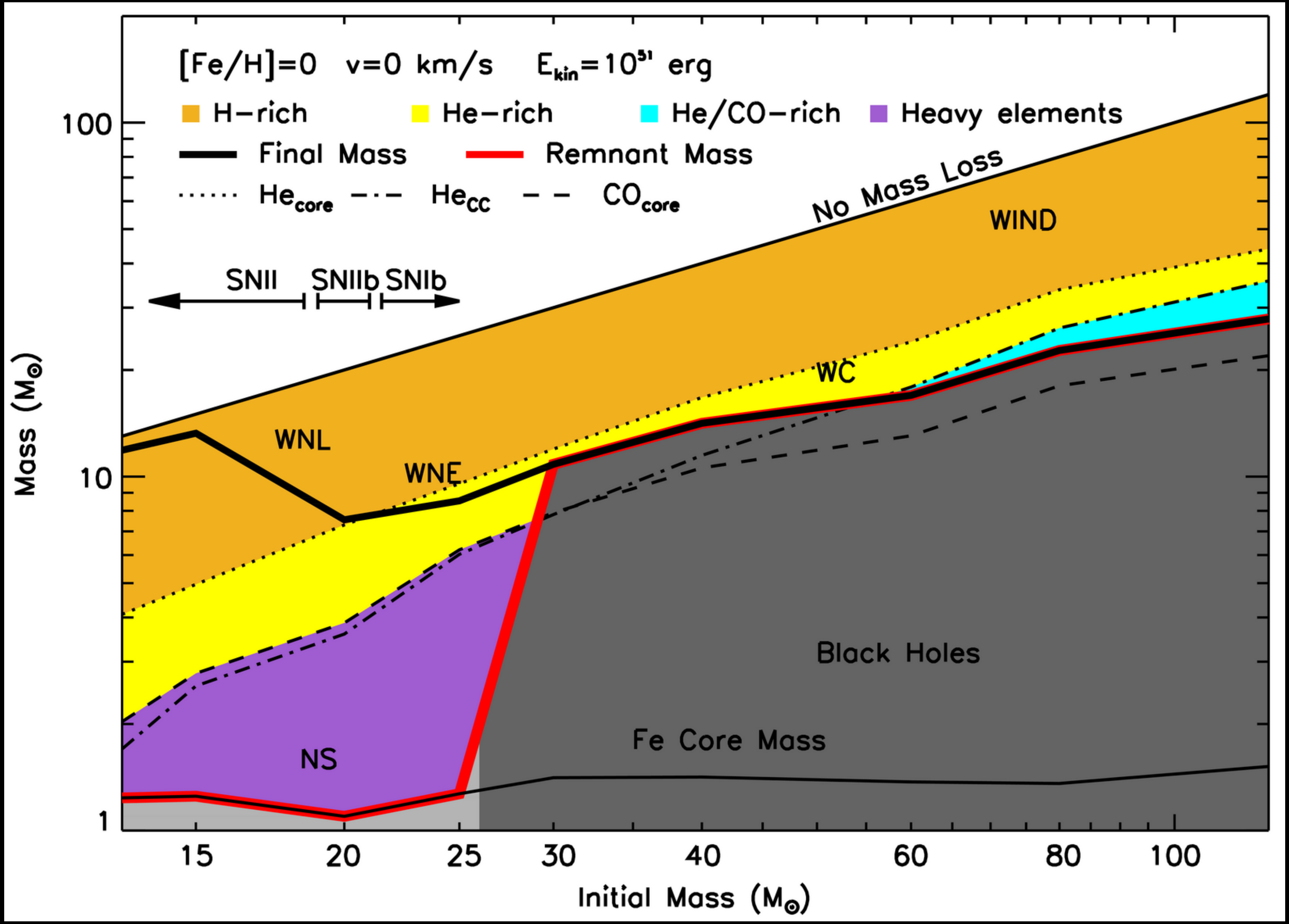


Solar Metallicity non Rotating Models: Nature of the Remnants



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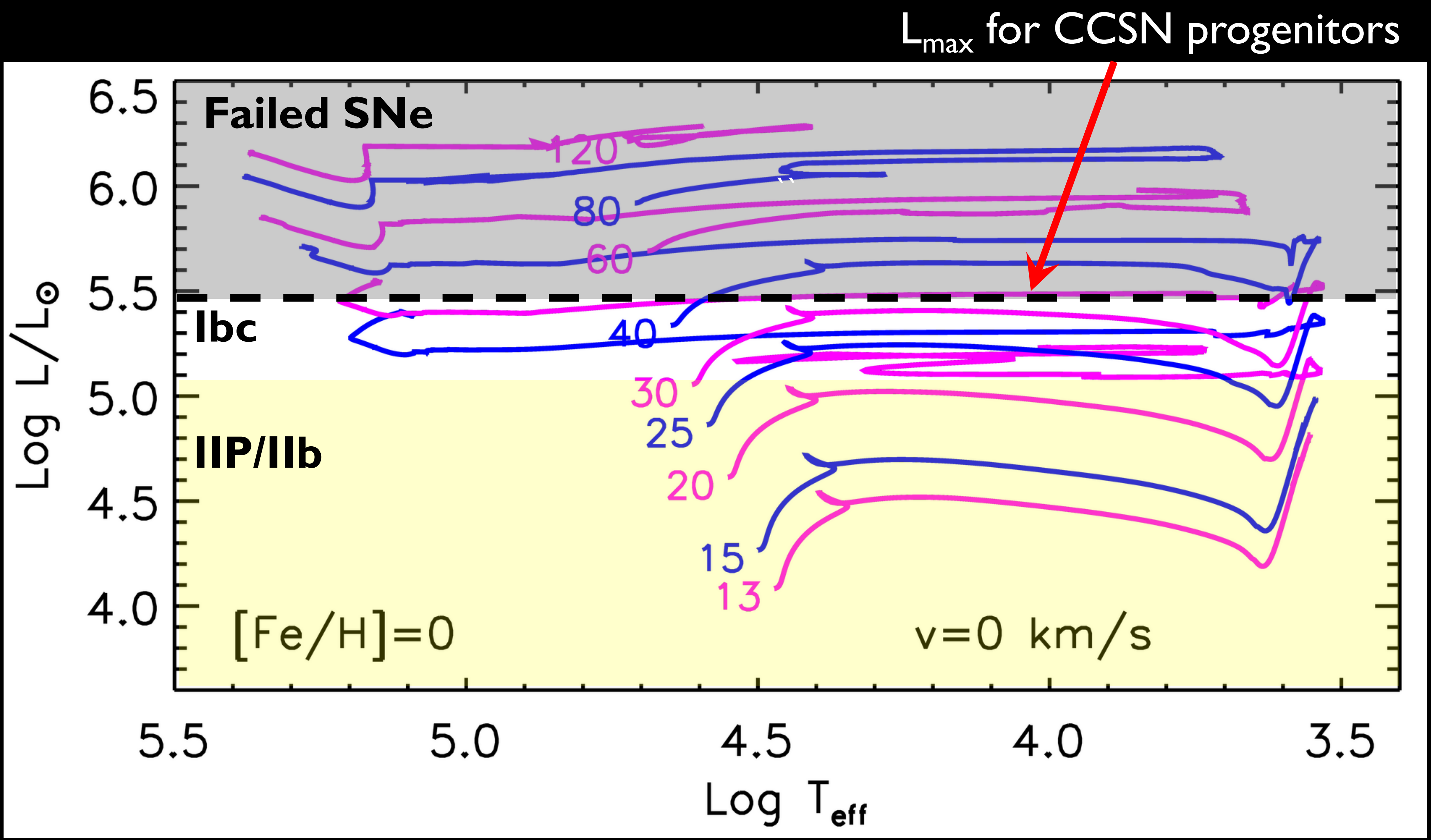

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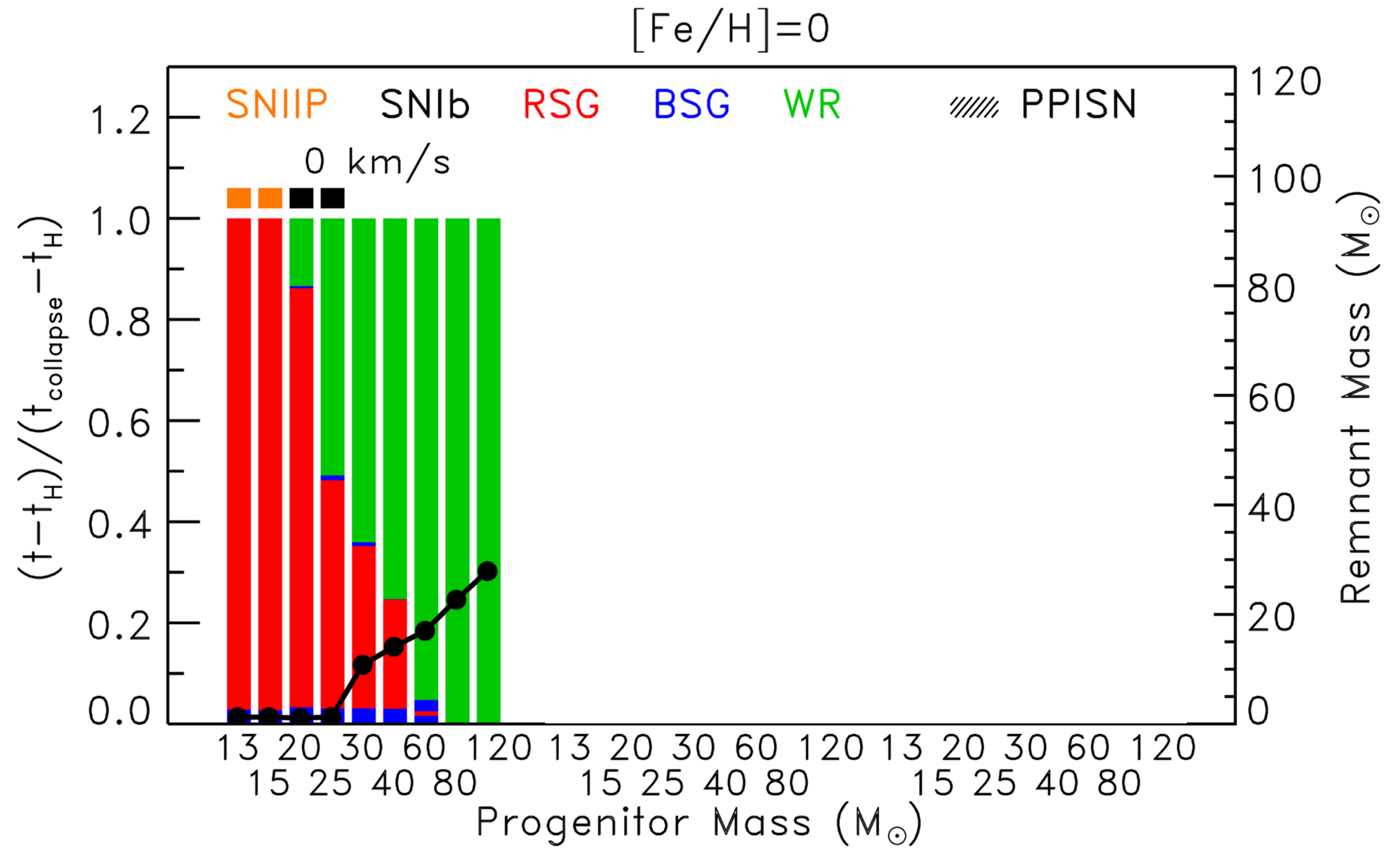
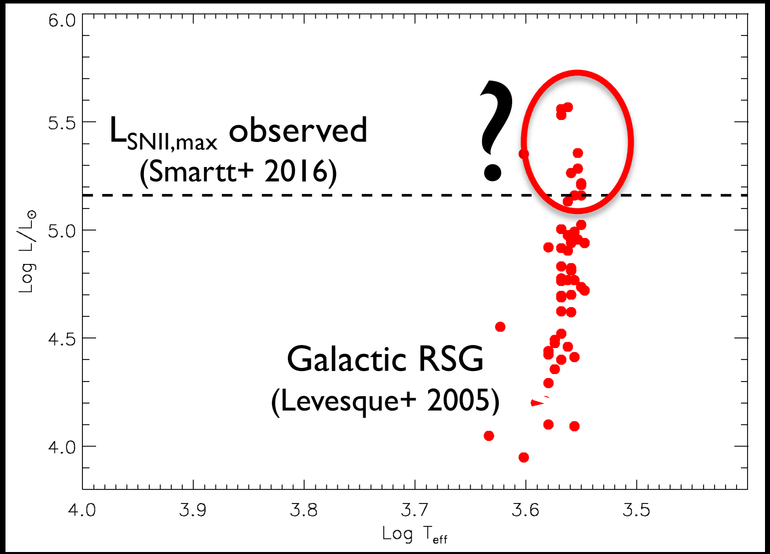


The Progenitors of Core Collapse Supernovae



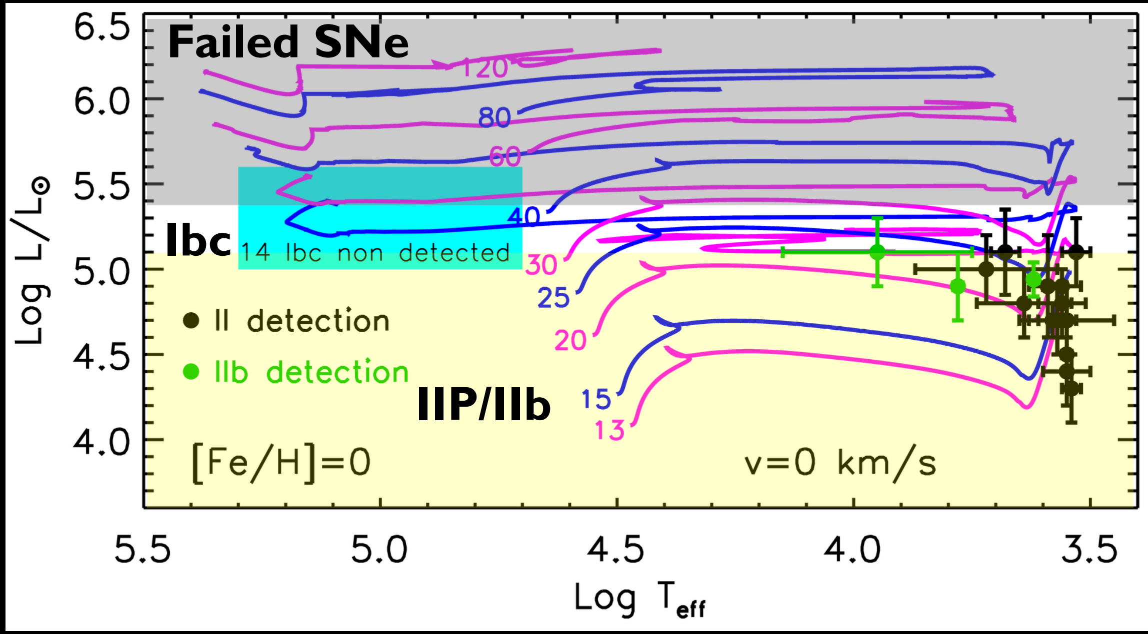
$$\mathrm{Log}(L/L_\odot)_{\mathrm{RSG,max}} = 5.6$$

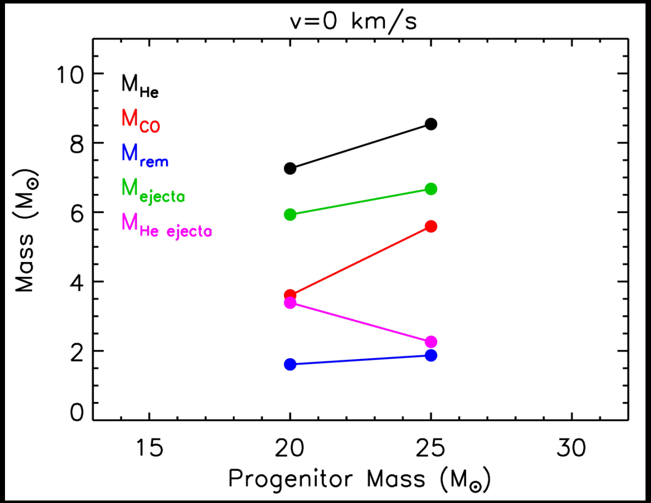
(Levesque+ 2016)

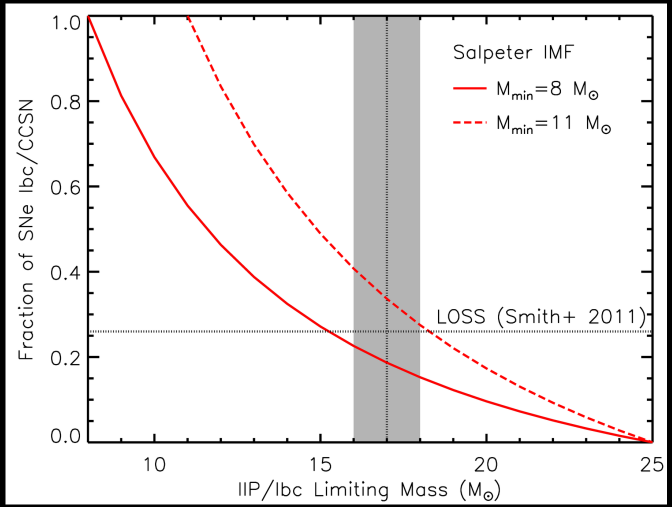
$$\mathrm{Log}(L/L_\odot)_{\mathrm{SN,max}} = 5.1$$

(Smartt+ 2016)

The "RSG Problem" (Smartt+ 2009, 2016)

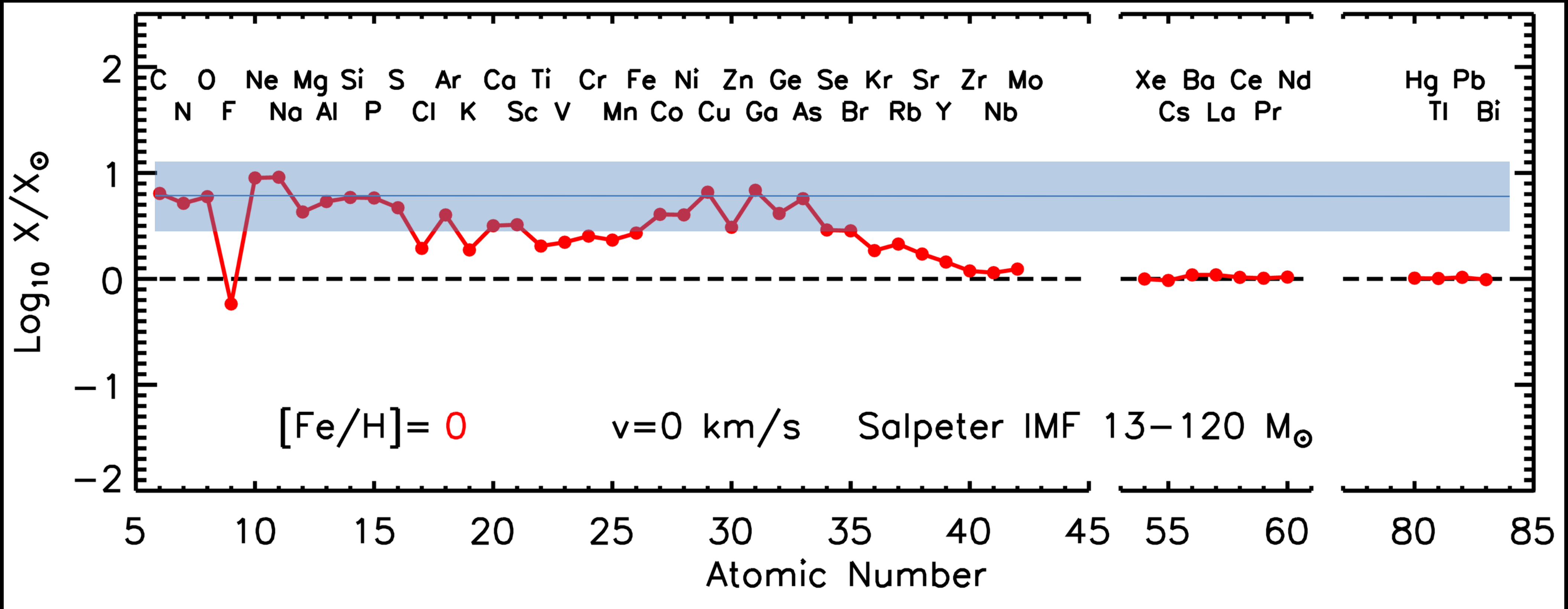






The Red Supergiant Problem can be explained naturally by these models

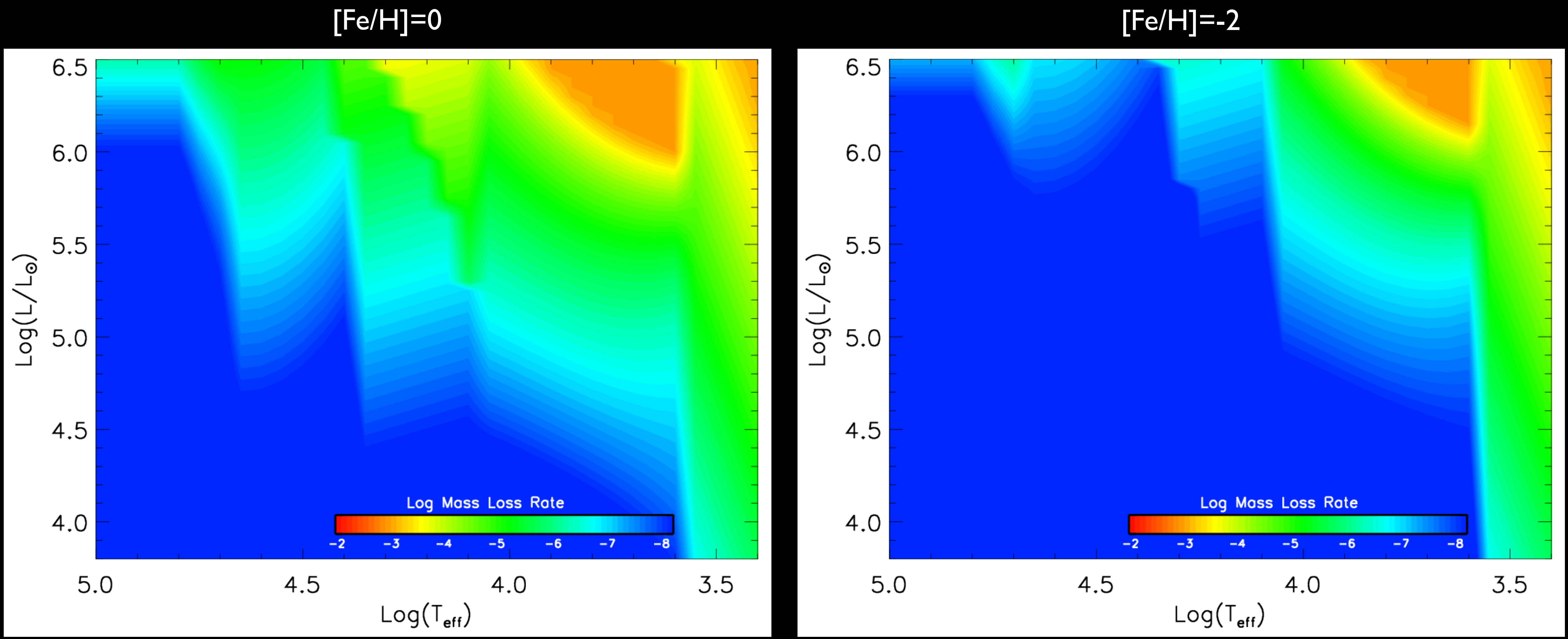
Solar Metallicity non Rotating Models: Composition of the Ejecta



- The elements Ne-Ca (synthesized only by massive stars) are coproduced with O. Some of them underproduced by more than a factor of 2 (Cl K) → other sources
- The iron peak elements Ti-Ni are underproduced compared to O. SNIa fill the gap
- The elements Cu-Zr (weak component, synthesized mainly by massive stars) are coproduced with O. Kr-Rb slightly underproduced → AGB fill the gap
- Elements heavier than Zr (main+strong component produced only by AGB stars) not produced

Low Metallicity non Rotating Models: Presupernova Evolution

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



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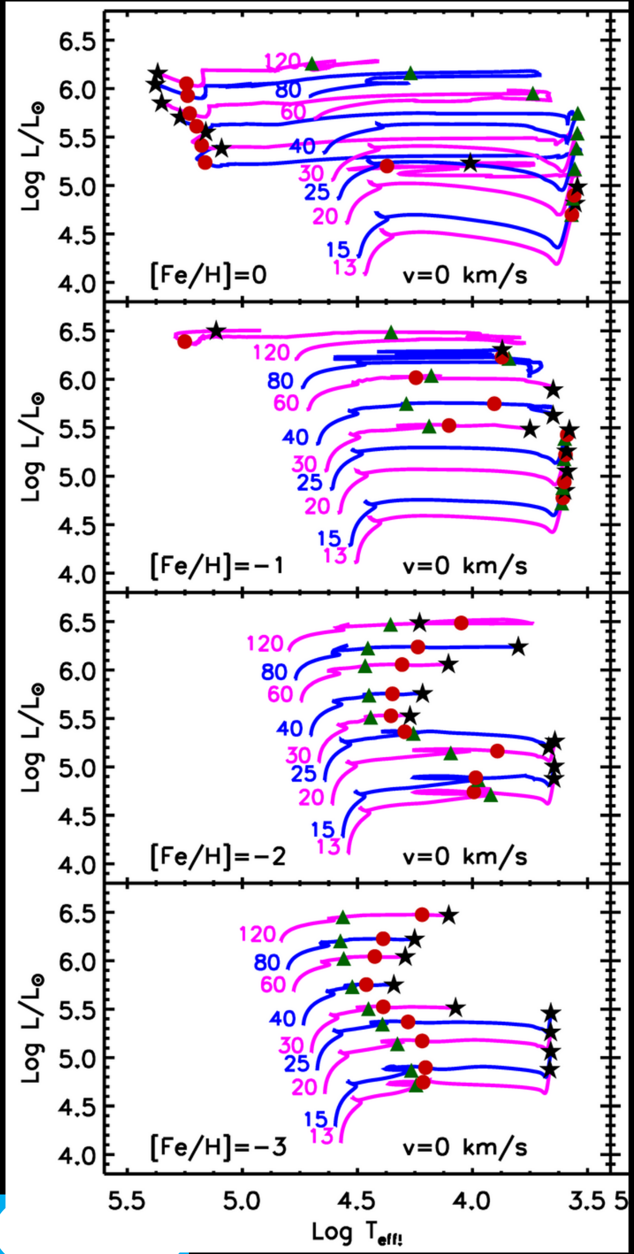
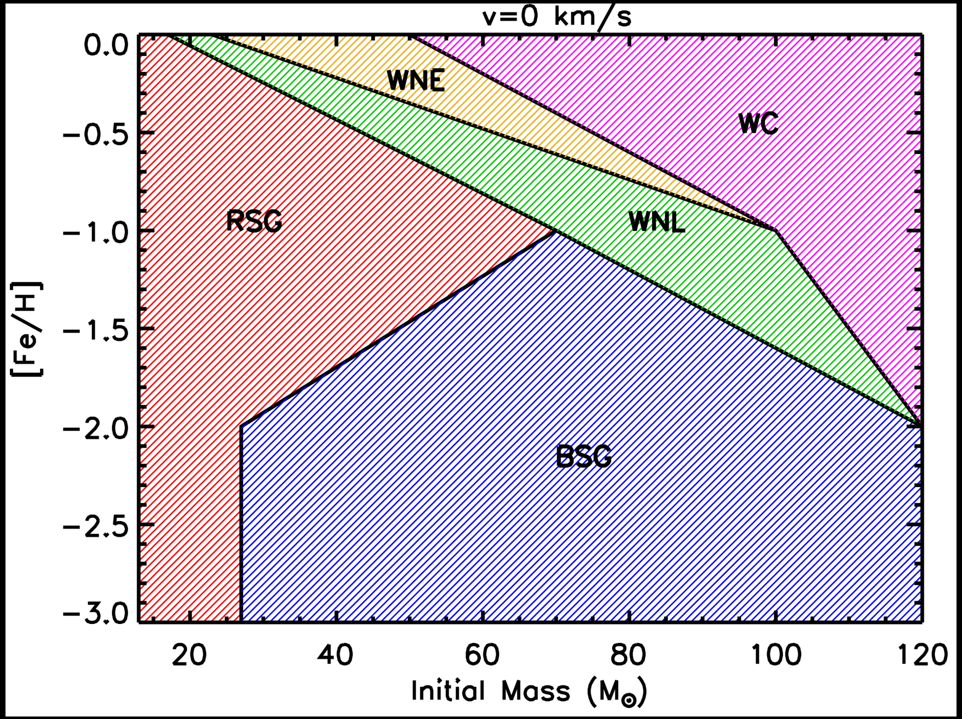
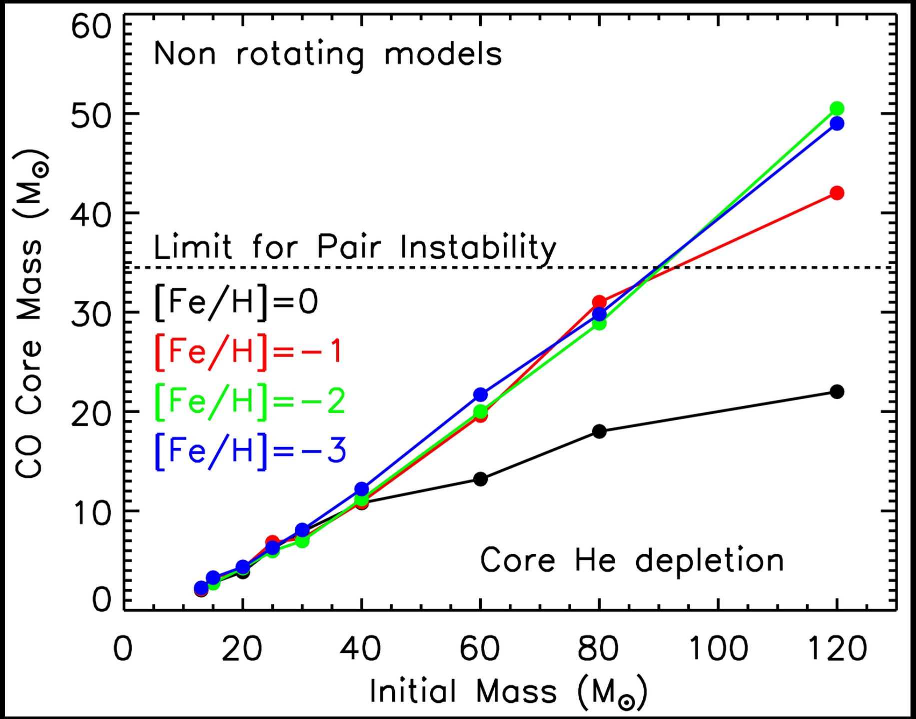




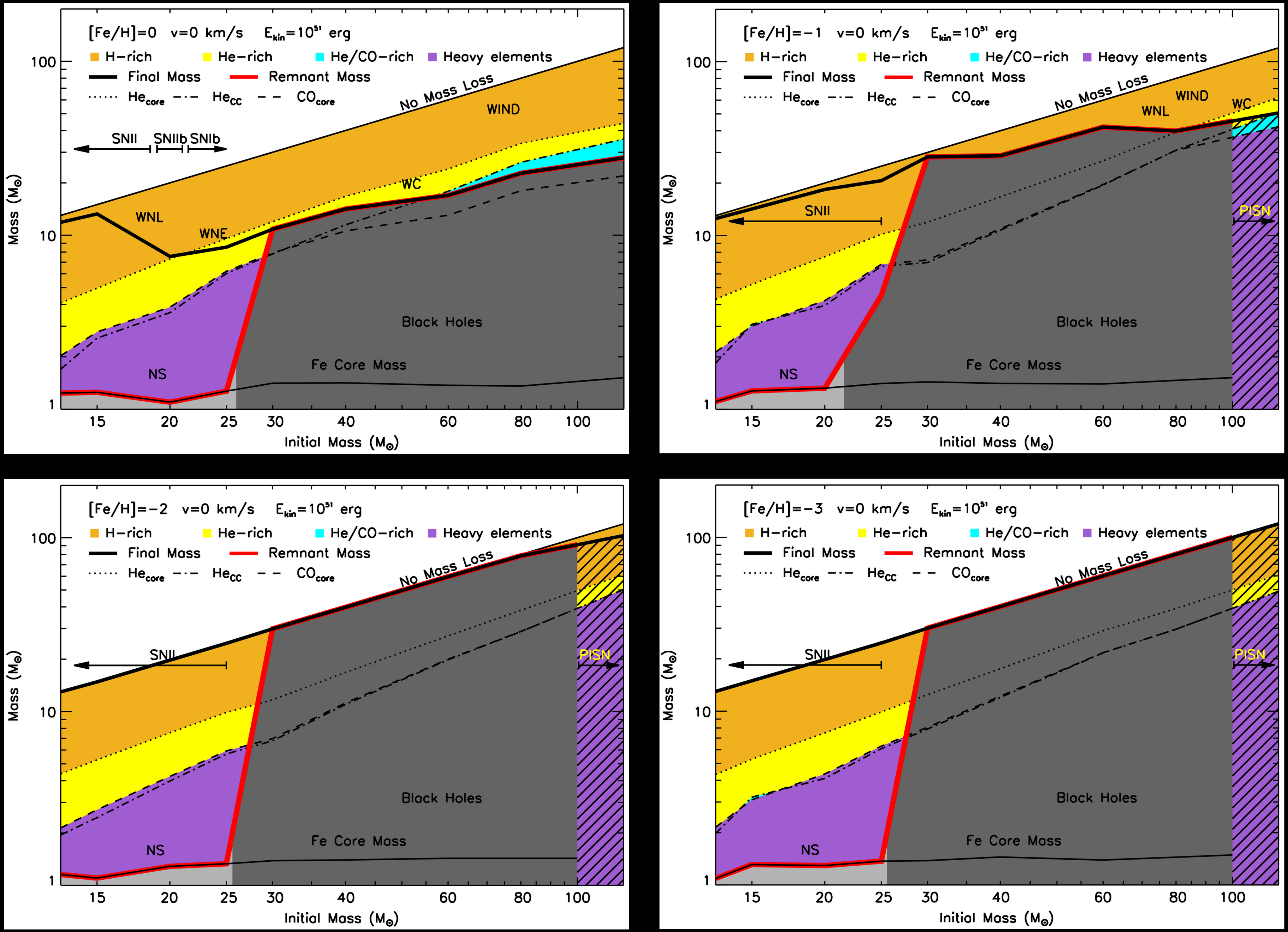


Evolution at ~ constant mass - RSG phase skipped progressively - BSG with H-rich envelope SN

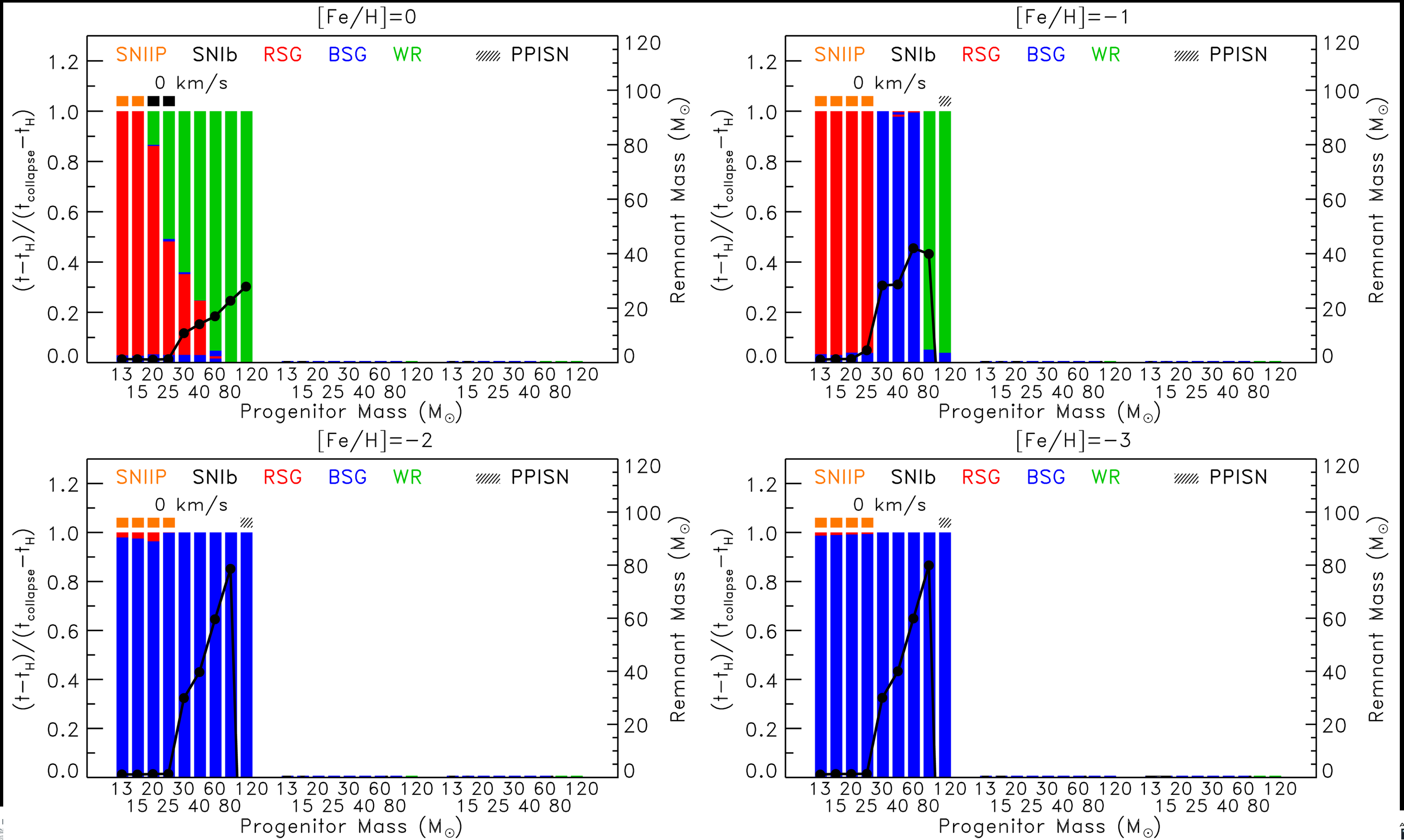
M ≥ 30 $M_\odot$ → CO core increases substantially as the metallicity decreases

Stars with M > 80 $M_\odot$ with [Fe/H] ≤ -1 explode as PISN

Solar Metallicity non Rotating Models: Nature of the Remnants



Non Rotating Models: Presupernova Evolution, Final Fate and Remnants



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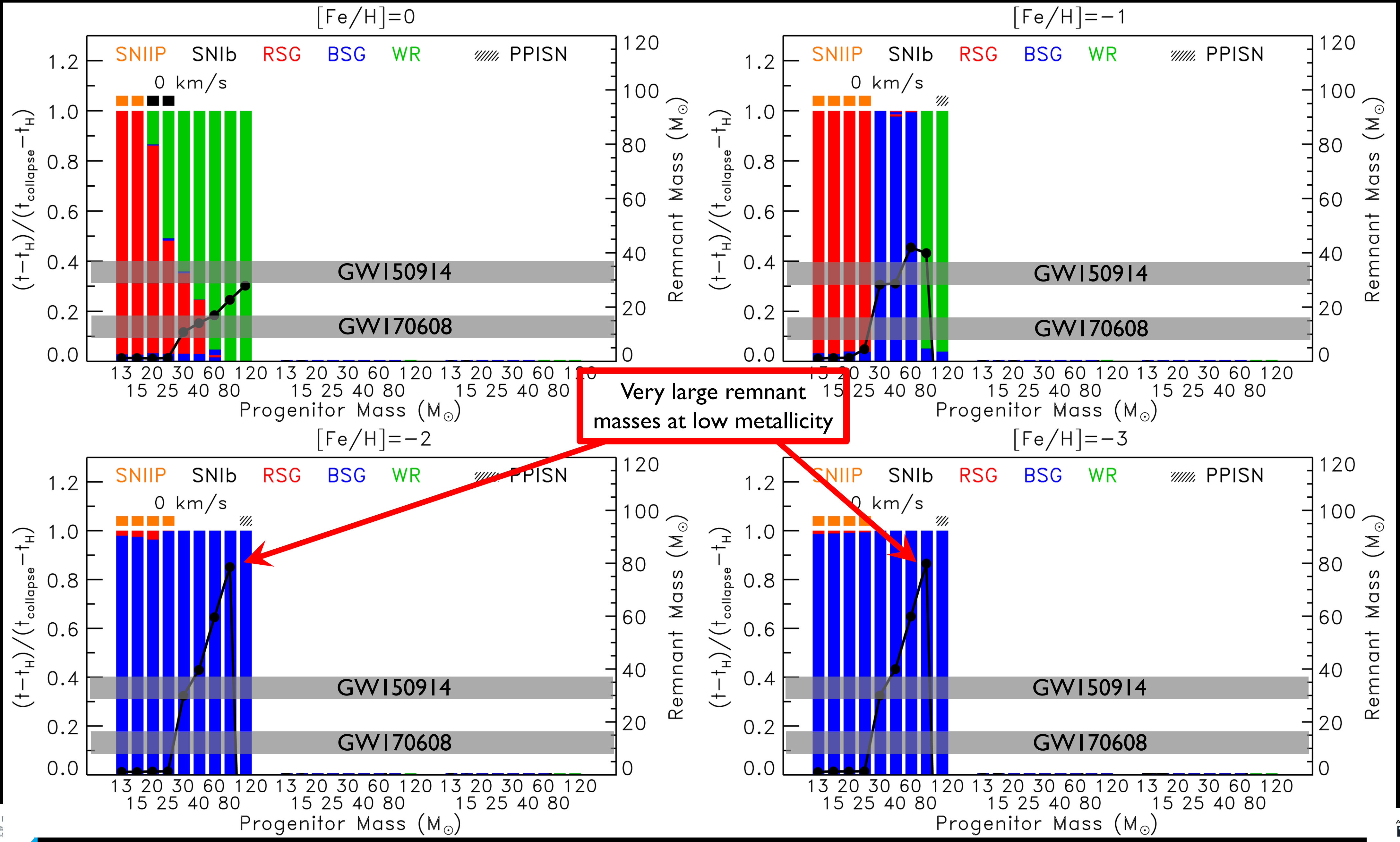
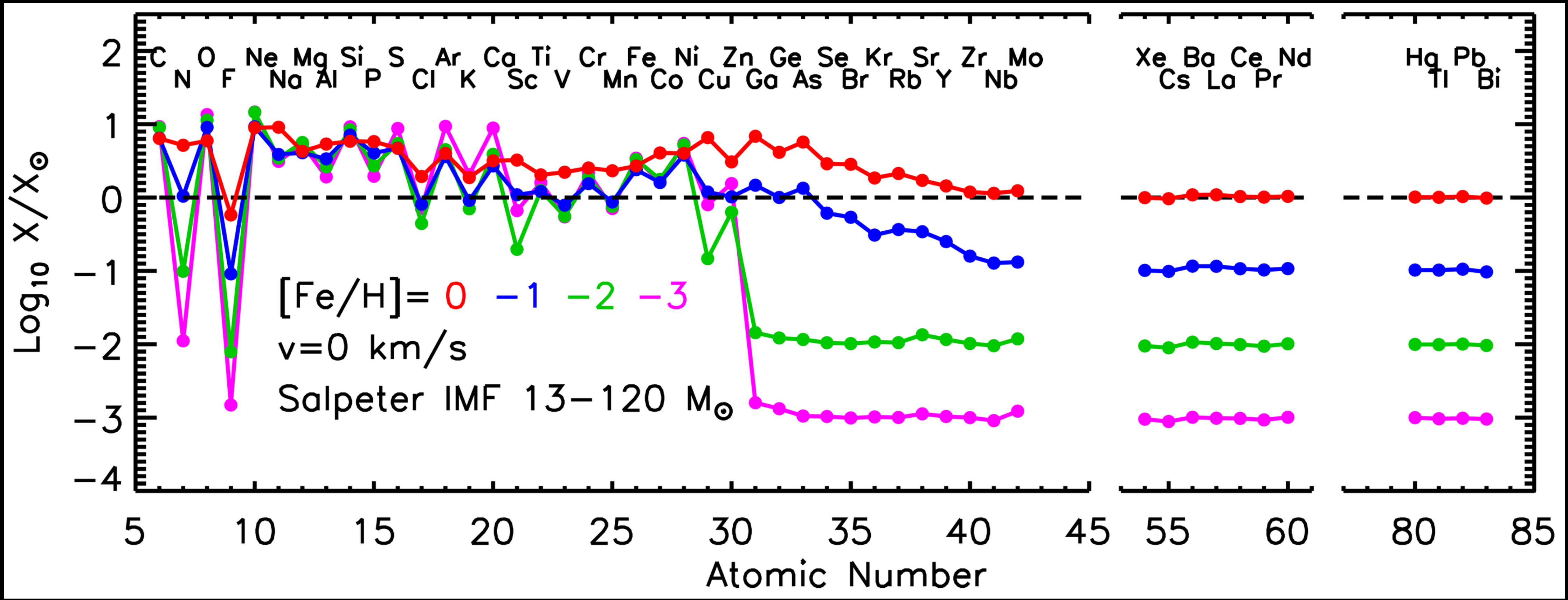


Low Metallicity non Rotating Models: Composition of the Ejecta



- Alpha elements show (as expected) the typical behavior of primary nuclei (negligible dependence on the initial metallicity)
- The odd elements (from N to Sc), on the contrary, show a typical secondary behavior
- All the heavy elements above Fe-peak are produced as secondaries (Zn-Zr start being produced above metallicity [Fe/H]=-1, the others are never produced)

Massive Stars: The Impact of Rotation

Increase of mass loss (Dust Driven Wind – Eddington Limit)

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 237:13 (33pp), 2018 July Limongi & Chieffi

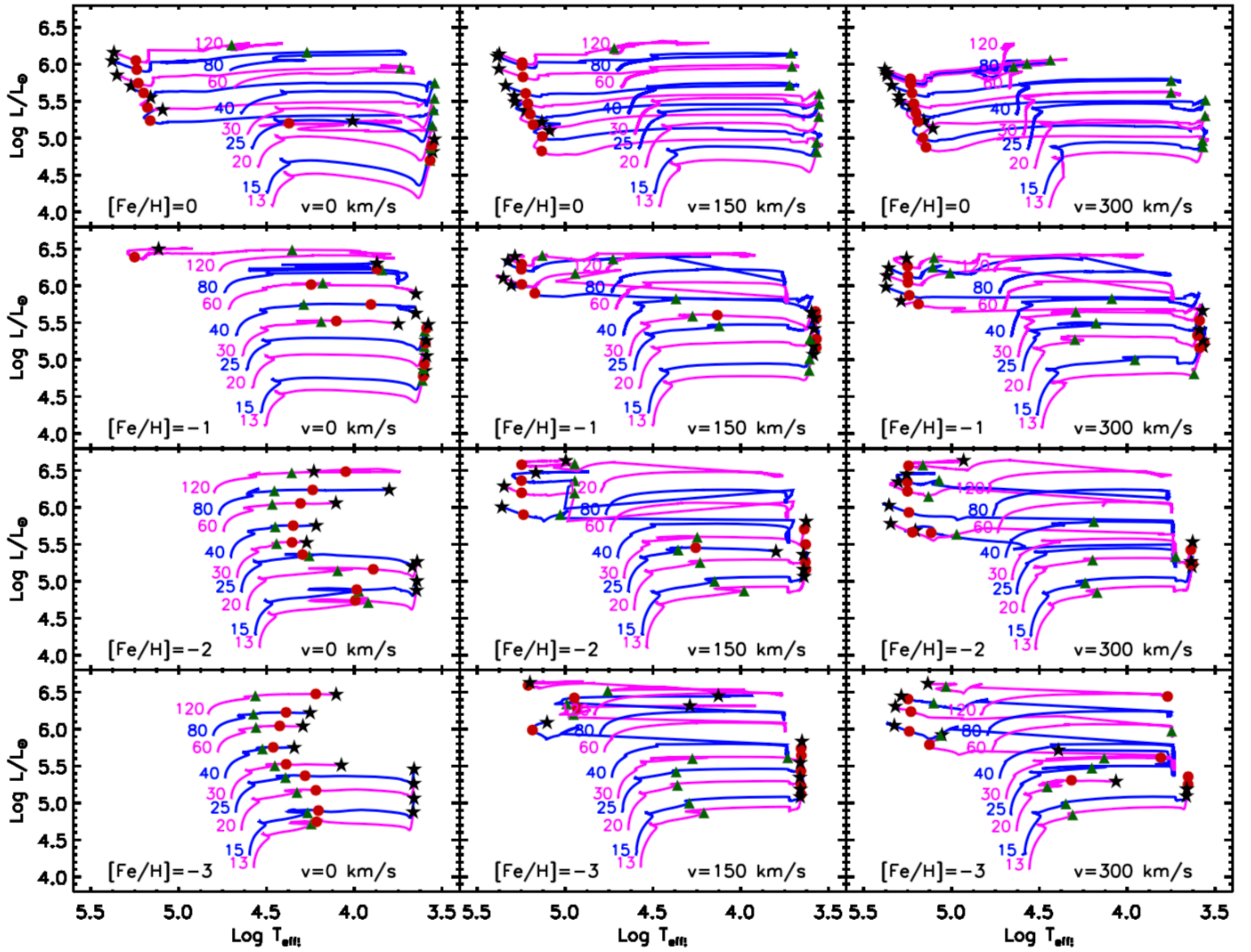


Figure 14. Evolutionary tracks of all our models on the HR diagram. The various symbols mark the central He-ignition (green triangles), the central He-exhaustion (red dots), and the final position at the presupernova stage (black star).

Massive Stars: The Impact of Rotation

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

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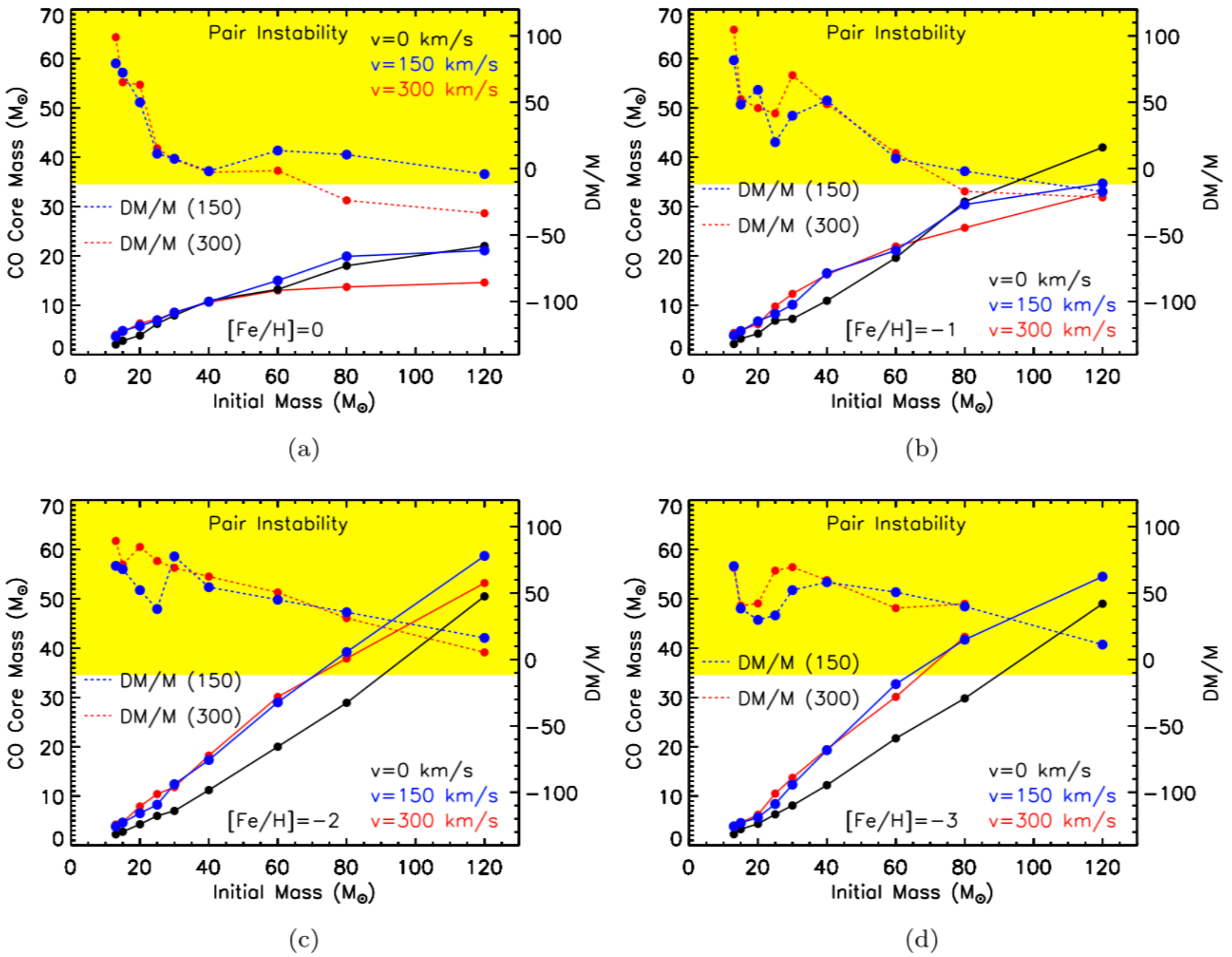
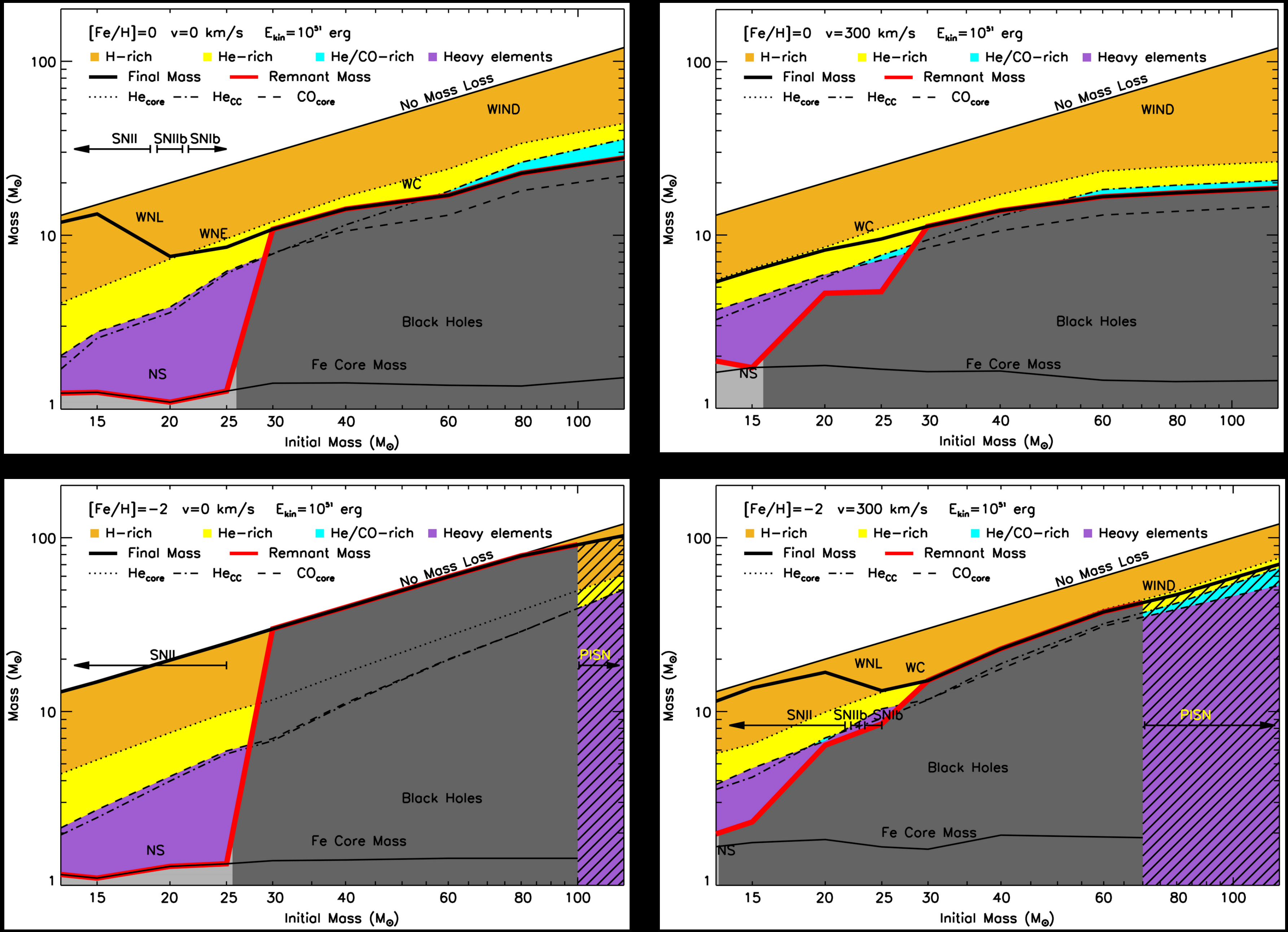
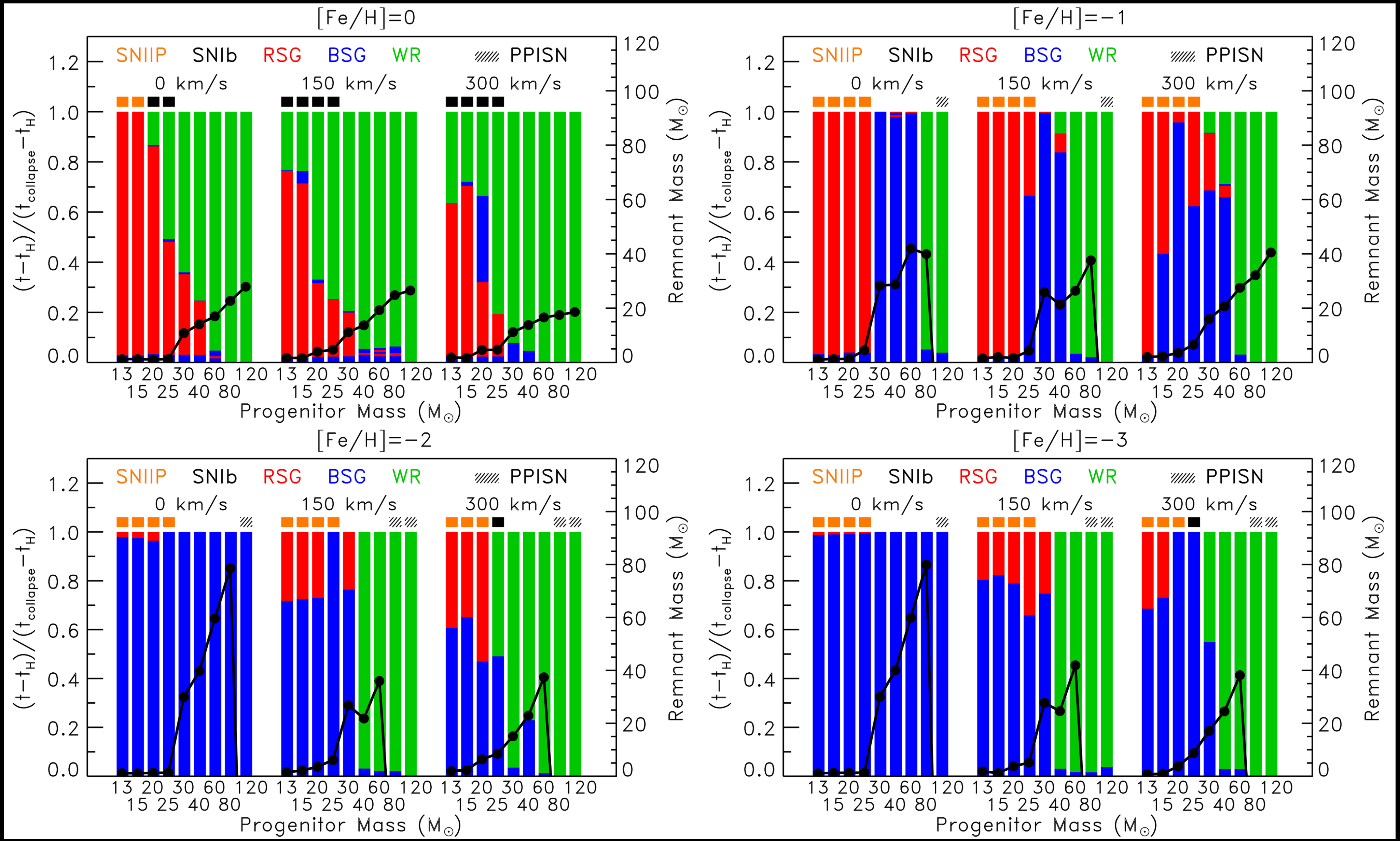


Figure 17. The four panels show, for each initial metallicity, the M_{CO}–M_{INI} relation obtained for the nonrotating (black) and the rotating cases, 150 km s^{-1} (blue) and 300 km s^{-1} (red), as solid lines (left Y-axis). The dashed lines show the per cent difference (DM/M) between rotating and nonrotating M_{CO} (right y-axis).

Low Metallicity Rotating Models: Nature of the Remnants



Massive Stars: Presupernova Evolution, Final Fate and Remnants



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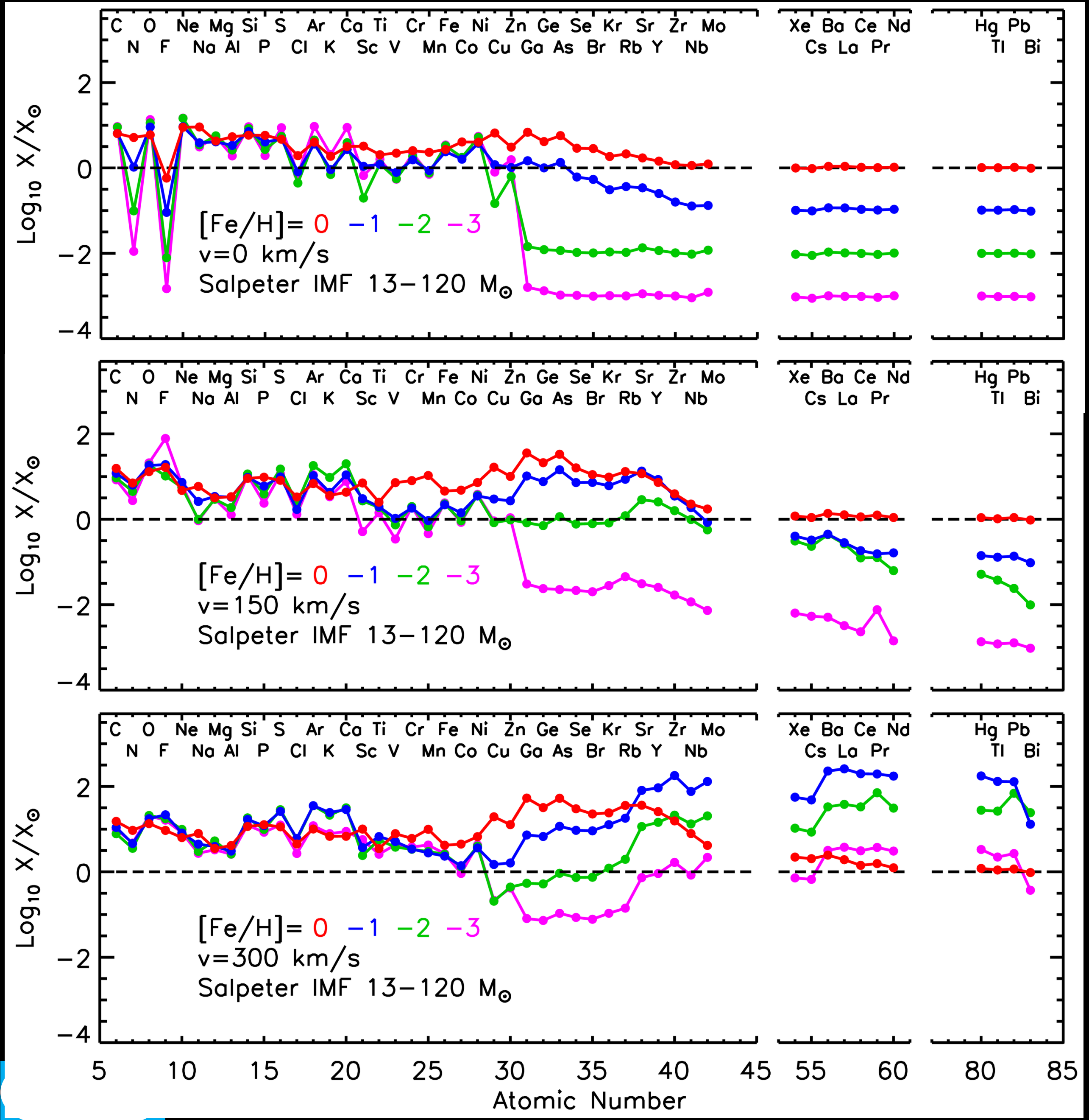
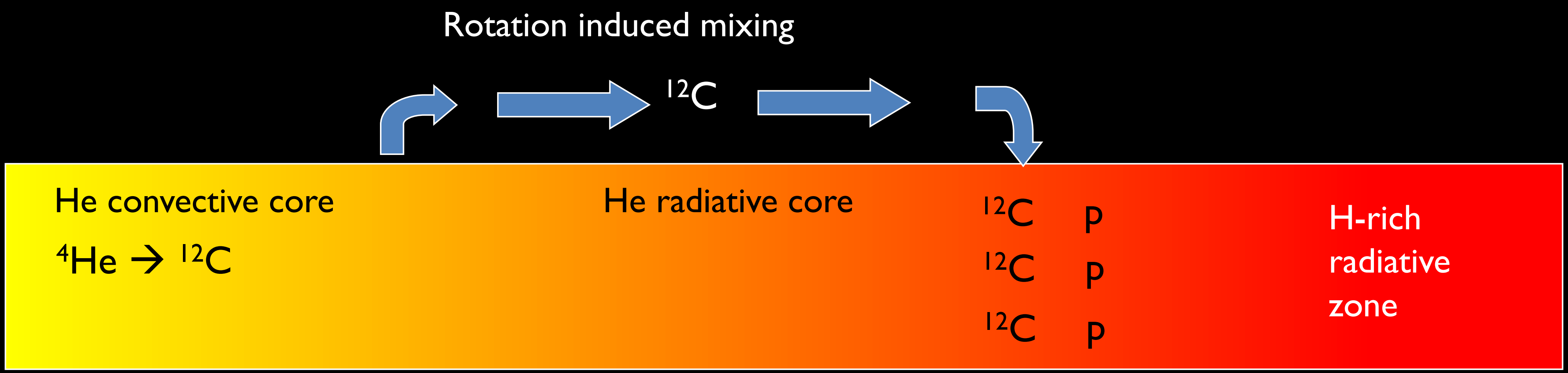
Rotating Models: Composition of the Ejecta



- The trends of N and F with the initial metallicity turn from a typical secondary to a typical primary behavior
- The production of s-process elements is substantially enhanced with increasing the initial rotation velocity
- Large overproduction with respect to O (especially the s-only isotopes) at metallicities -2<[Fe/H]<0
- The yields of almost all the elements are considerably increased in rotating models due to the larger He cores induced by the rotation driven mixing

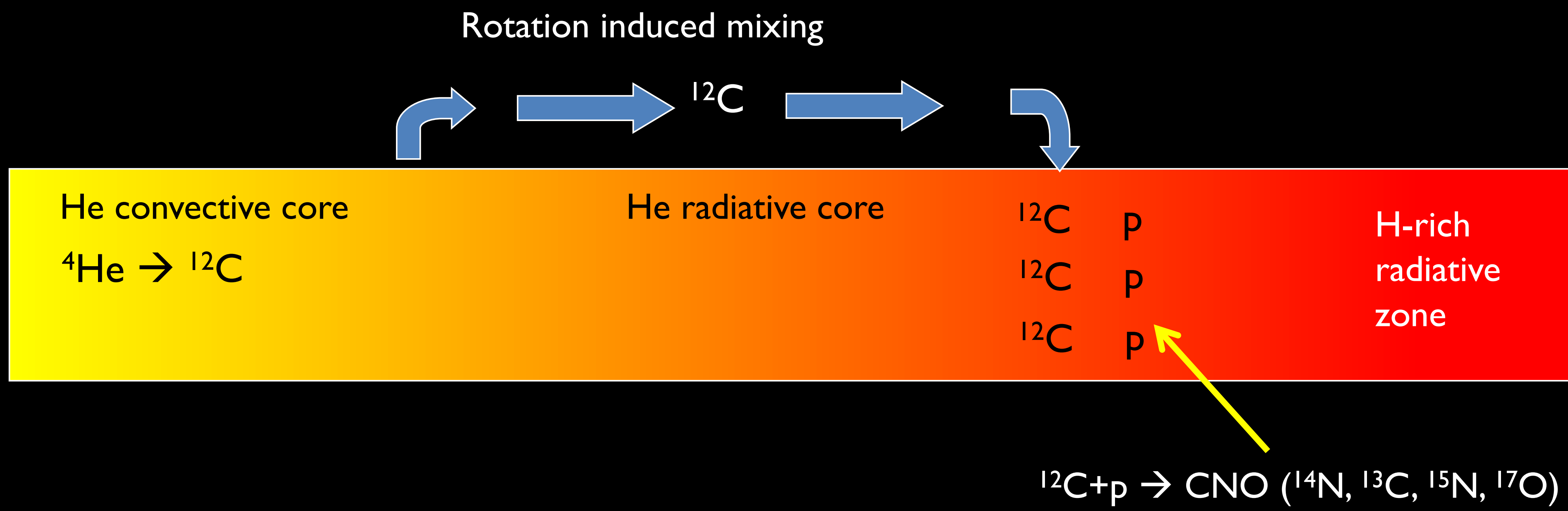
Production of N, F and s-process Elements in Rotating Massive Stars

- ^{12}C synthesized in the He convective core diffuses up to the tail of the H-burning shell



Production of N, F and s-process Elements in Rotating Massive Stars

- ^{12}C synthesized in the He convective core diffuses up to the tail of the H-burning shell
- ^{12}C is converted into CNO nuclei whose abundances are enhanced (the most abundant being ^{14}N)



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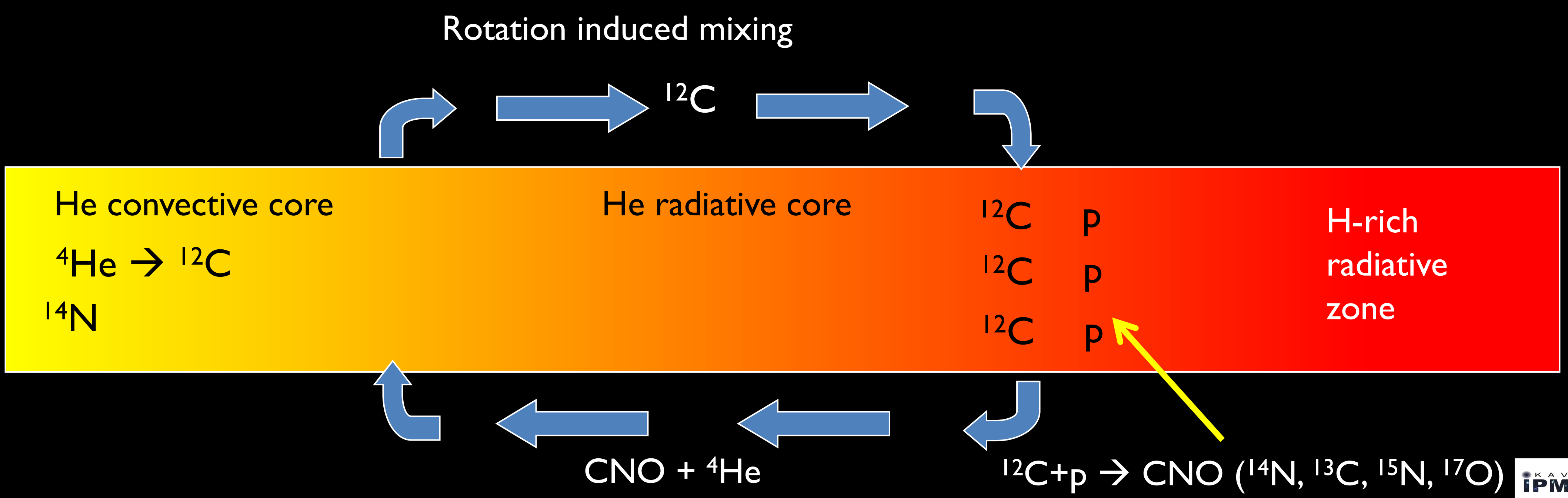

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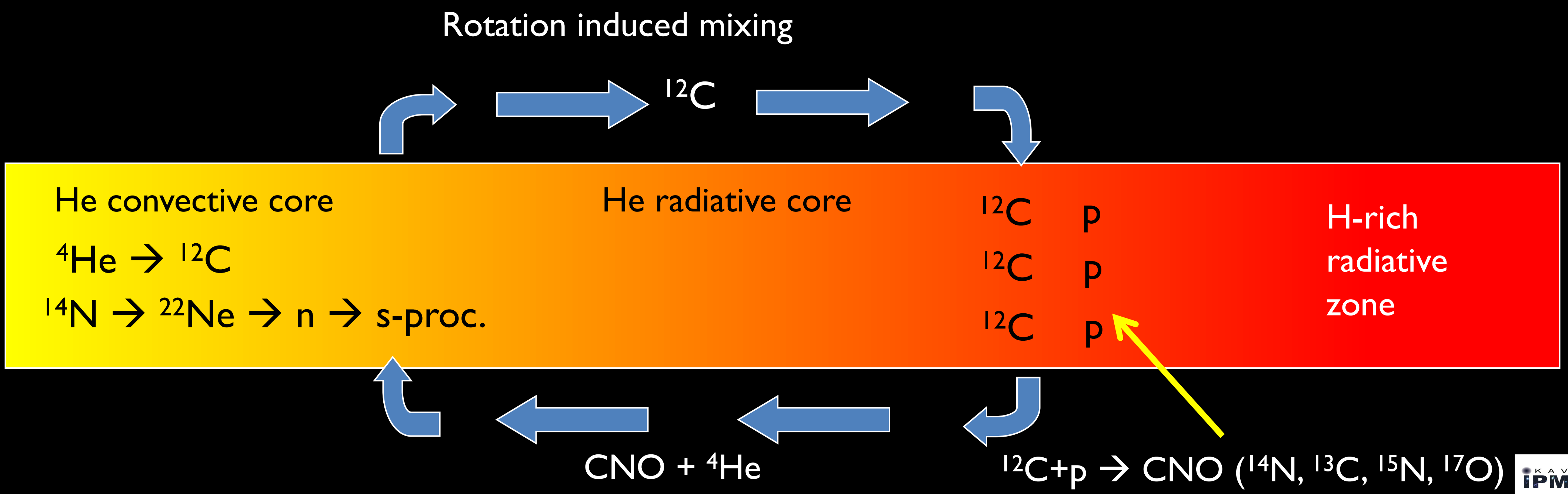
- The ^{14}N that diffused back to the center is quickly converted into ^{22}Ne that becomes an efficient primary neutron source → strong s-process nucleosynthesis activated



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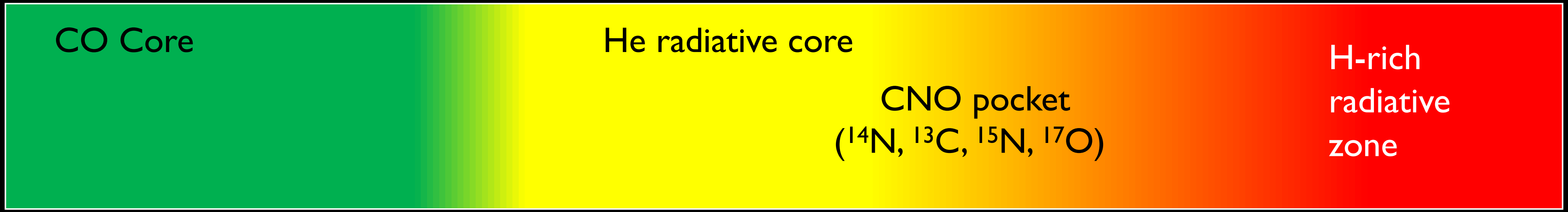
- Formation of a CNO (^{14}N, ^{13}C, ^{15}N, ^{17}O) pocket in the radiative layers of the He core



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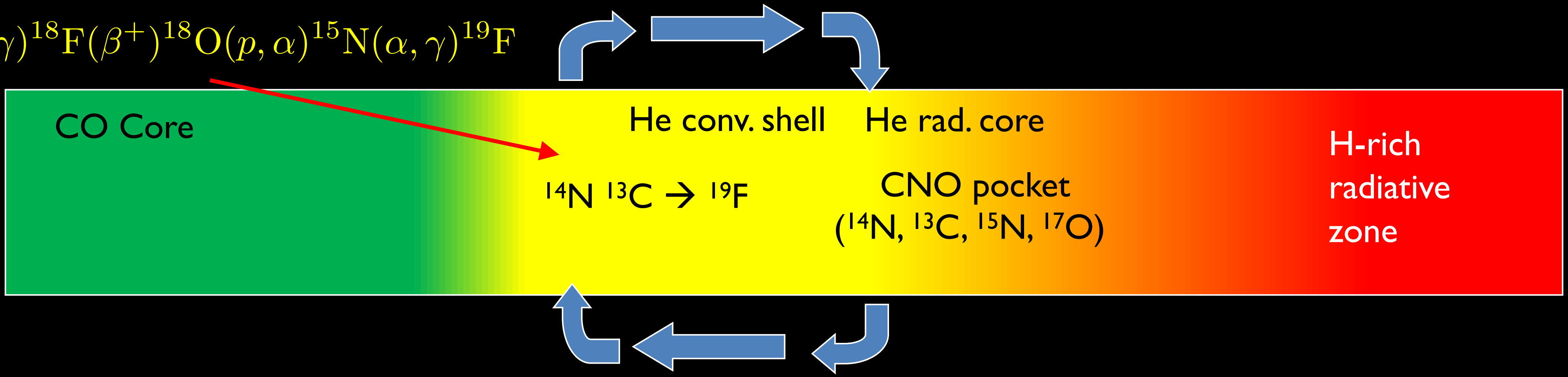
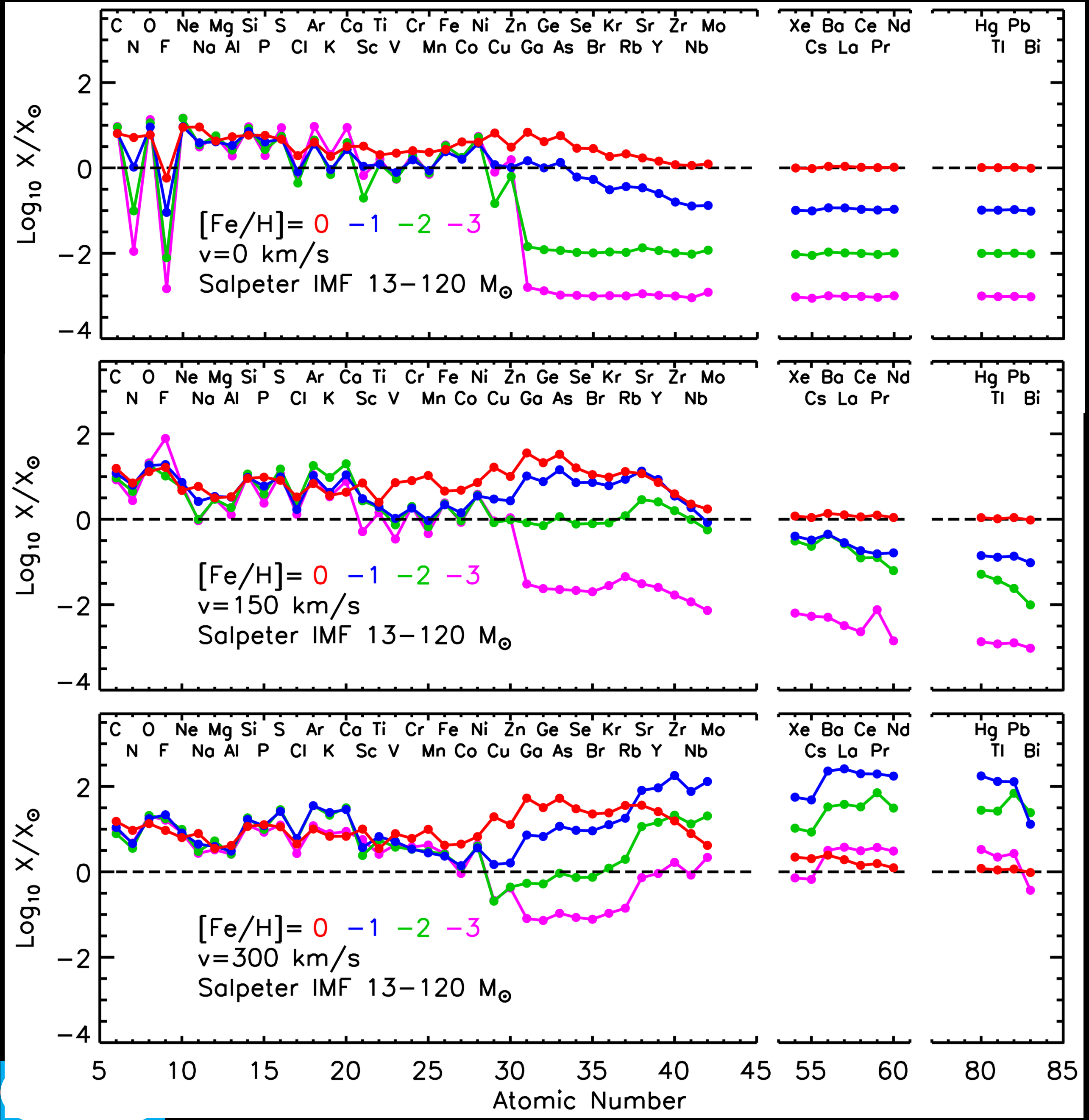
- Formation of a CNO (^{14}N, ^{13}C, ^{15}N, ^{17}O) pocket in the radiative layers of the He core
- The ^{13}C and ^{14}N engulfed by the He convective shell activate a strong ^{19}F production

$^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$ $^{14}\mathrm{N}(n,p)^{14}\mathrm{C}$

$^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^+)^{18}\mathrm{O}(p,\alpha)^{15}\mathrm{N}(\alpha,\gamma)^{19}\mathrm{F}$



Rotating Models: Composition of the Ejecta



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OBSERVATIONAL REQUIREMENTS

- Primary behavior of N (at the lowest metallicities)
- Prevention of an overproduction of the s-only nuclei at metallicities -2<[Fe/H]<-1

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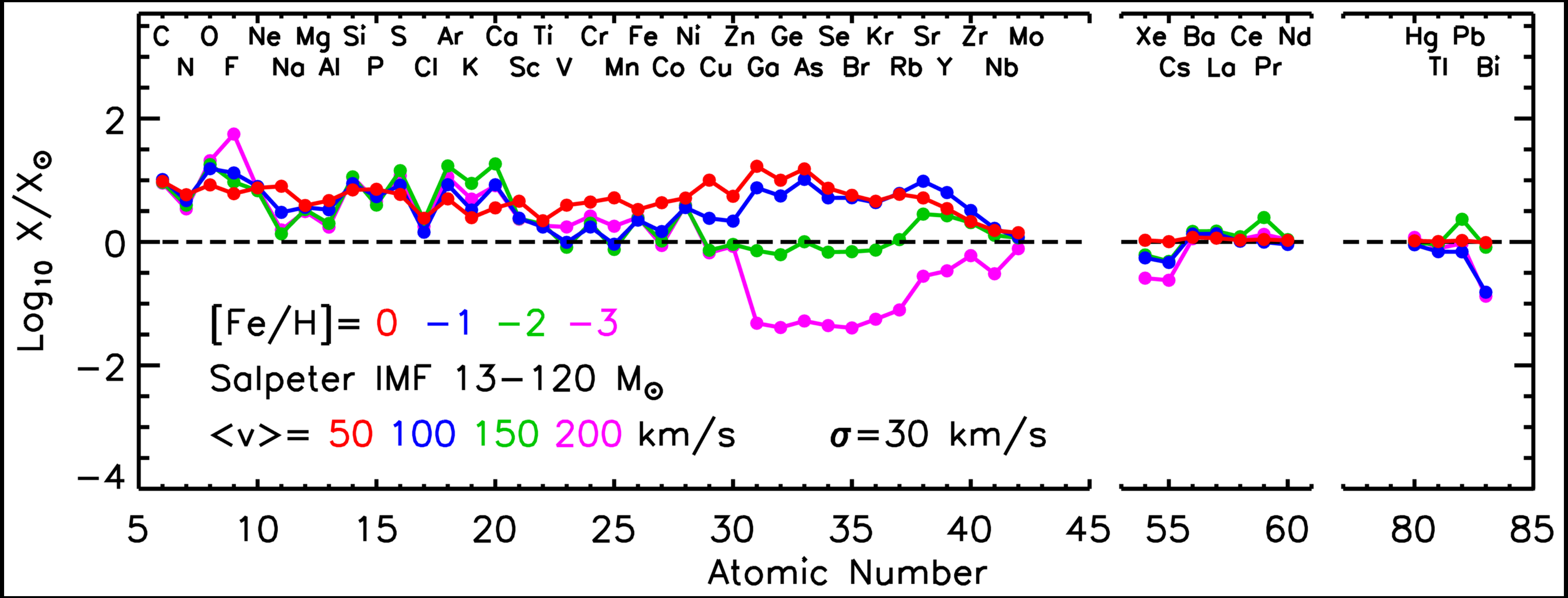
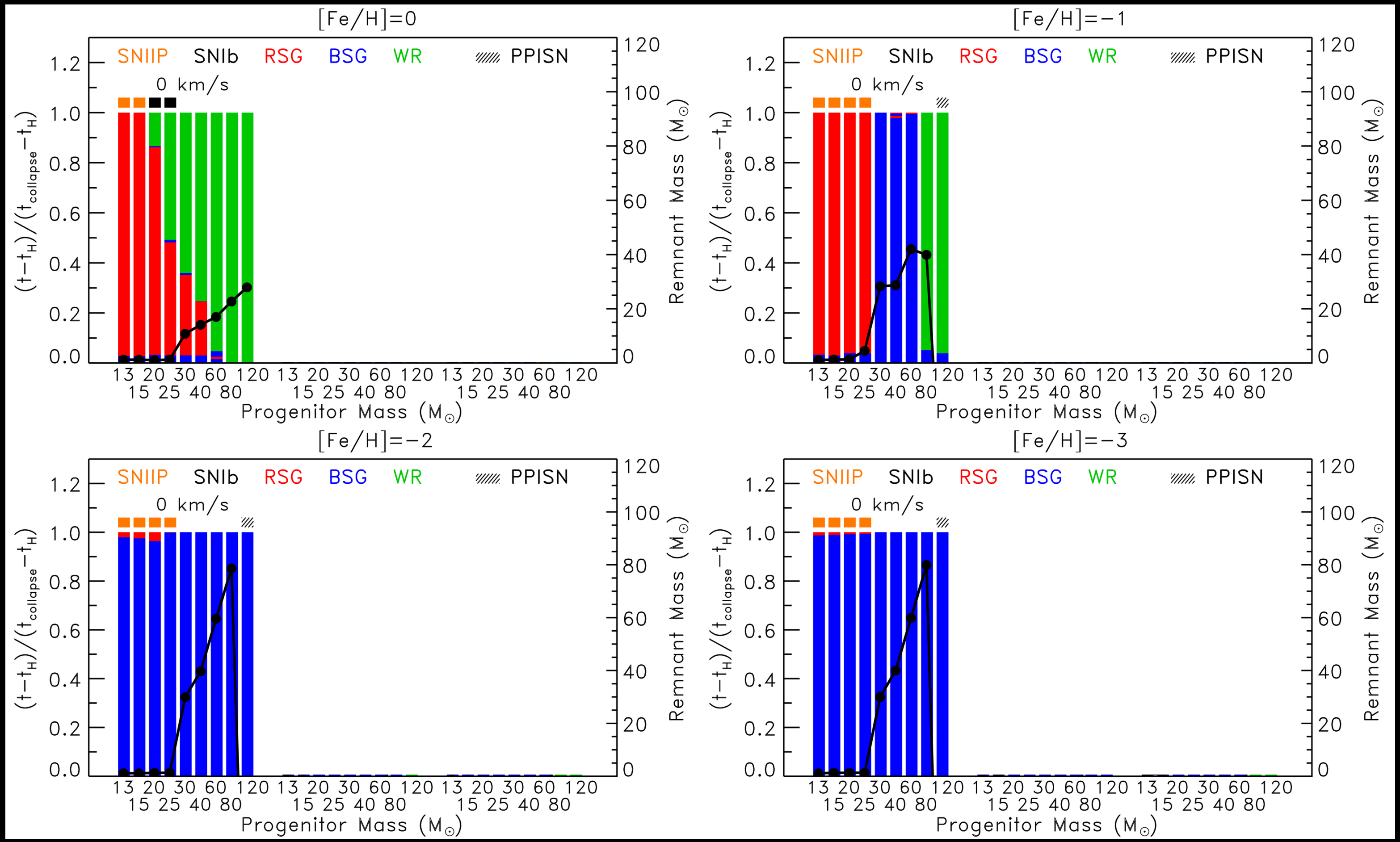
Rotating Models: Composition of the Ejecta

Initial Distribution of Rotation Velocities (IDROV)   Gaussian with $\langle v \rangle$ and σ



- Alpha elements behave as primaries
- N shows a negligible dependence on the initial metallicity (primary)
- Elements between Zn and Zr display a secondary like behavior and always underproduced compared with O. At solar metallicity almost coproduced with O
- Elements heavier than Zr behave like primary elements but their overproduction remains always lower than that of O

Summary and Conclusions

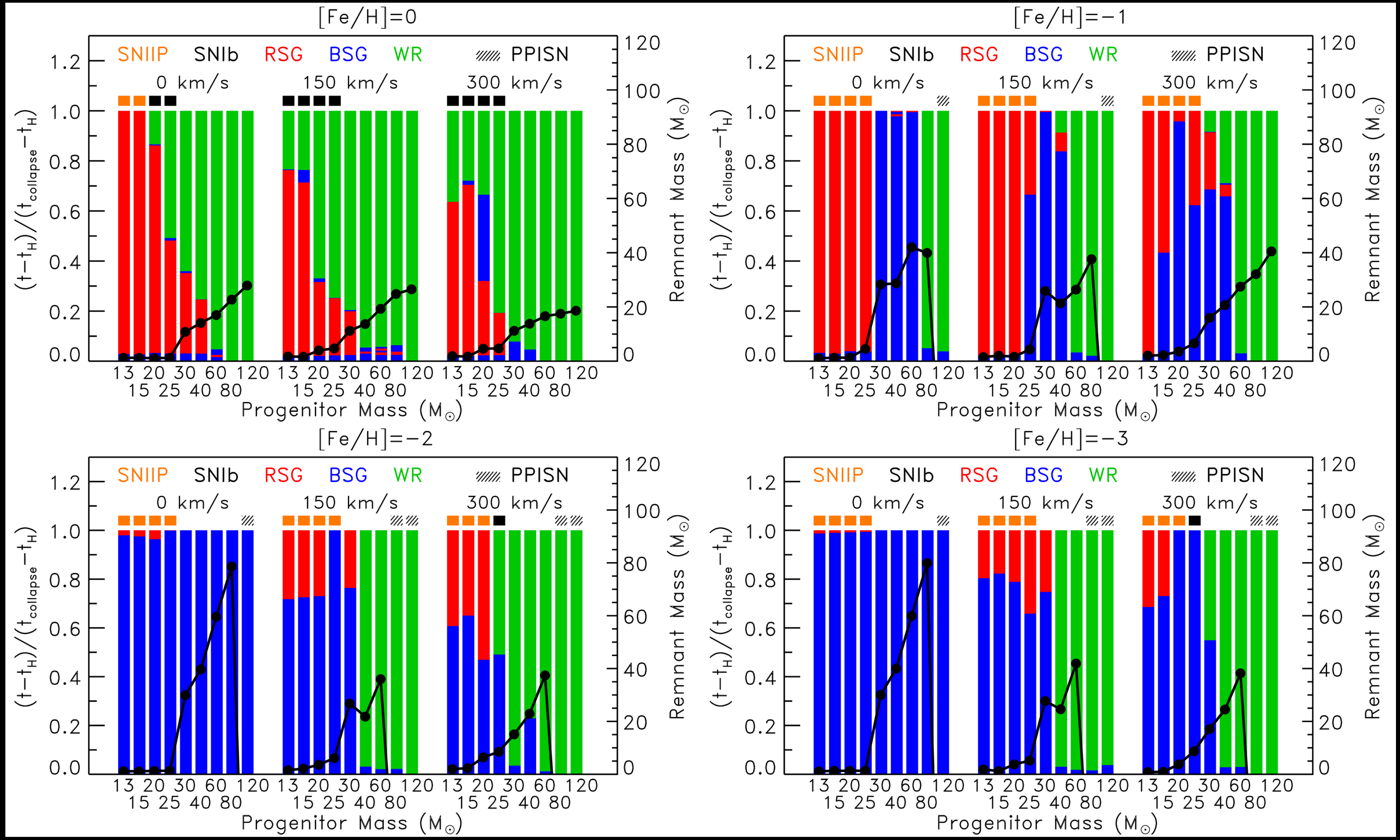


In the NON ROTATING case as the metallicity decreases we find:

- M>25 $M_\odot$ → Failed Supernovae
- Reduction of RSGs and WRs
- No Type Ib SNe expected for [Fe/H]<0
- Reduction of minimum mass for PPISN
- Increase of the remnant masses

All the models and yields available at the website: http://orfeo.iaps.inaf.it

Summary and Conclusions



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With the inclusion of rotation ROTATION we find:

- M>25 $M_\odot$ → Failed Supernovae
- Increase of RSGs and WRs
- Few Type Ib SNe for fast rotators
- Reduction of minimum mass for PPISN
- Decrease of the remnant masses

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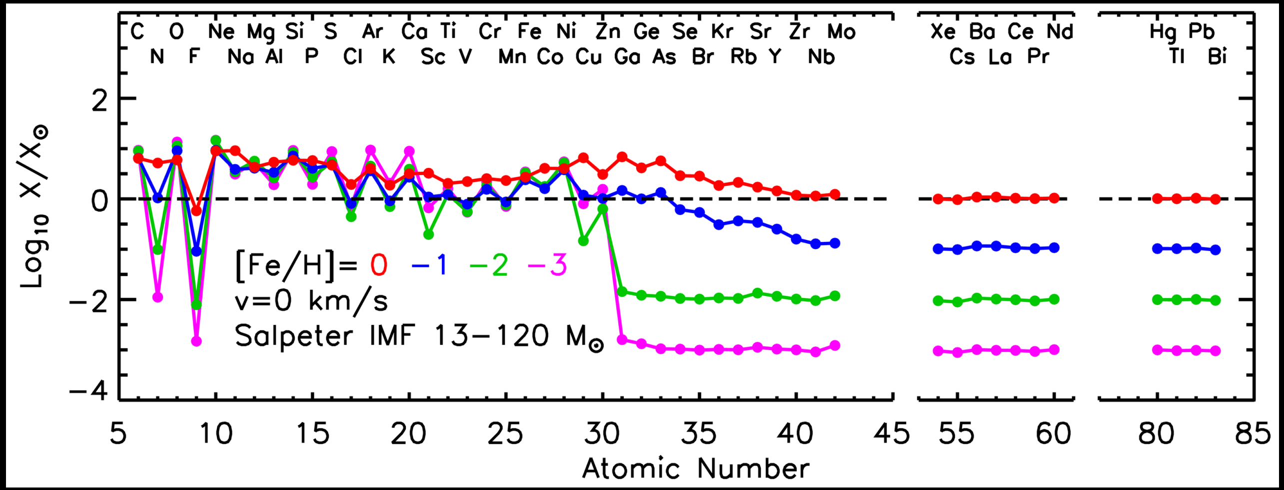
Summary and Conclusions



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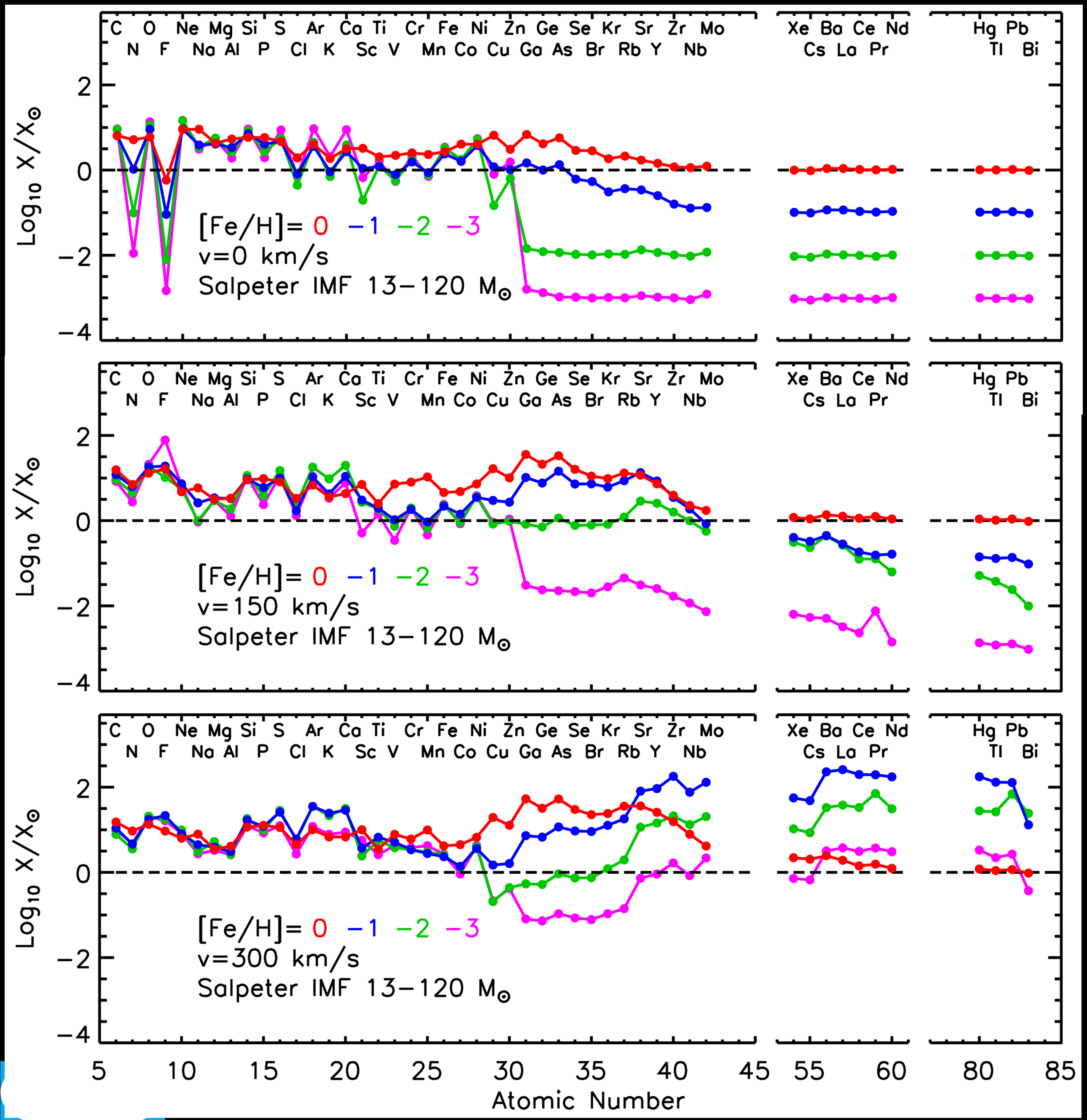

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