Stellar Physics and The Chemical Enrichment of the ISM from 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

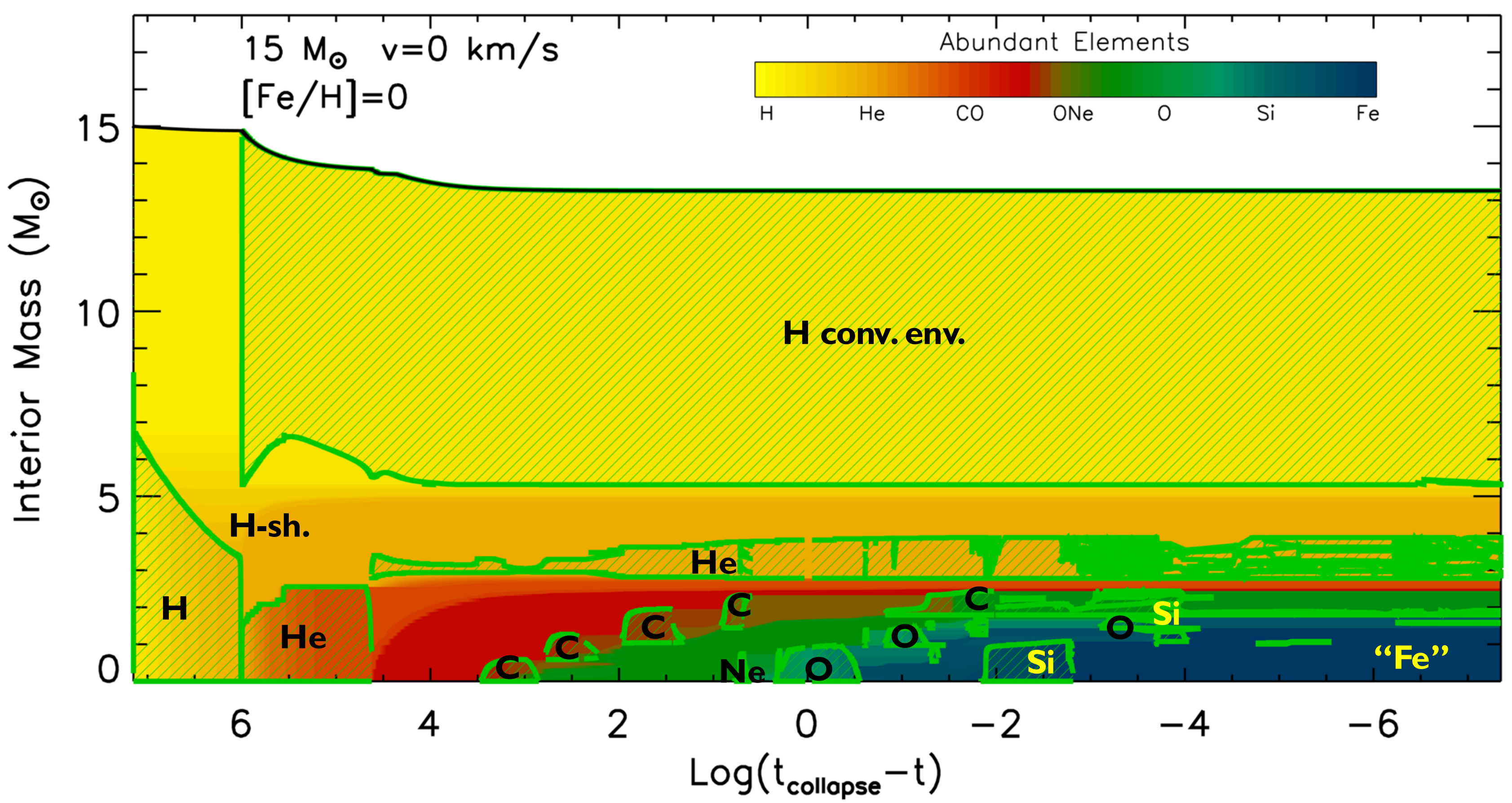
Massive Stars: Distinctive Features

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

$$\boxed{\mathrm{M} \gtrsim 9\ \mathrm{M}_\odot}$$

- 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

Presupernova Evolution of a Massive Star: Chemical and Convective Hystory



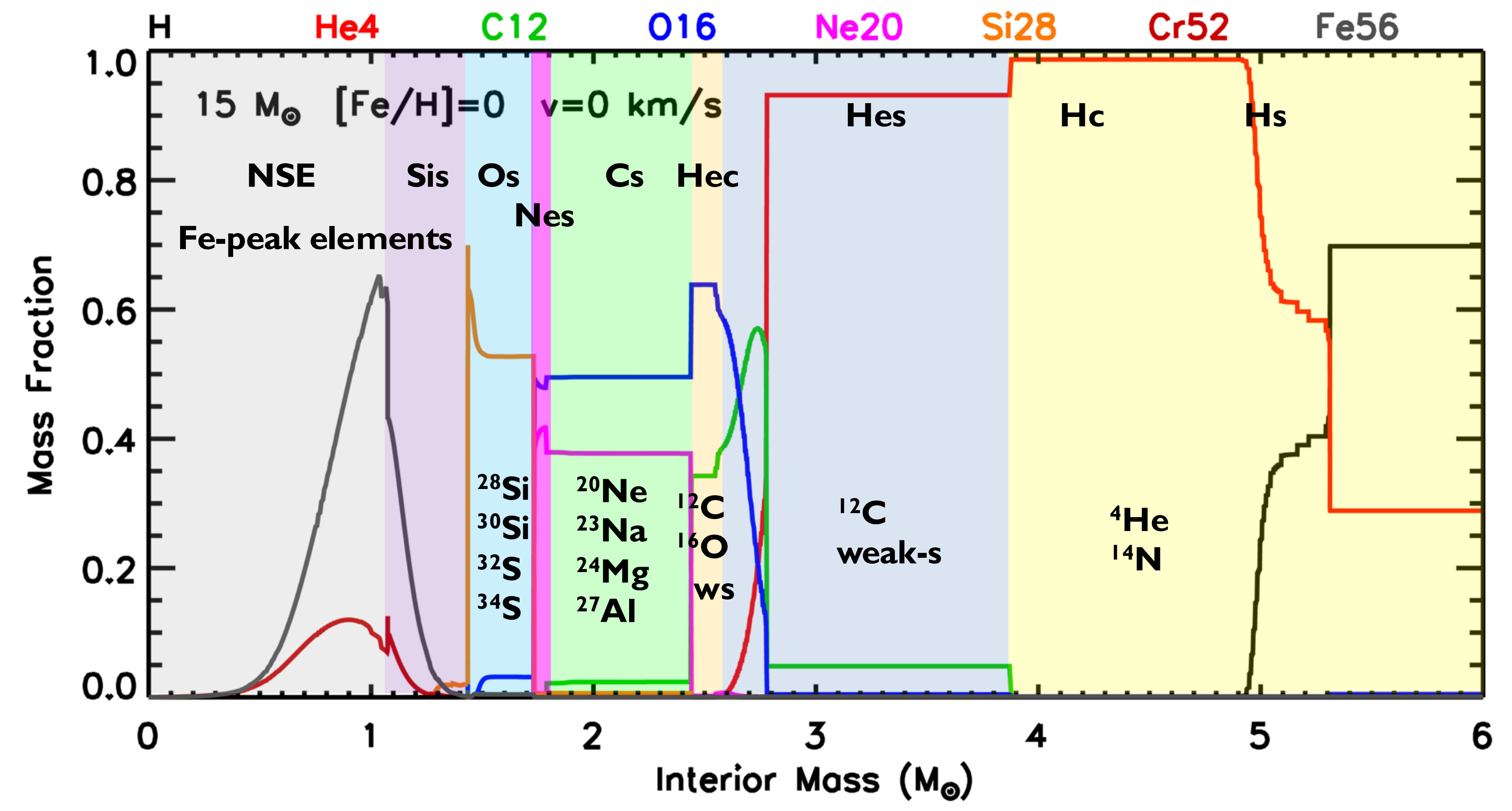
Central burning → formation of a convective core

Central exhaustion → shell burning → convective shell

Local exhaustion → shell burning shifts outward in mass → convective shell

Chemical Stratification @ PreSN Stage

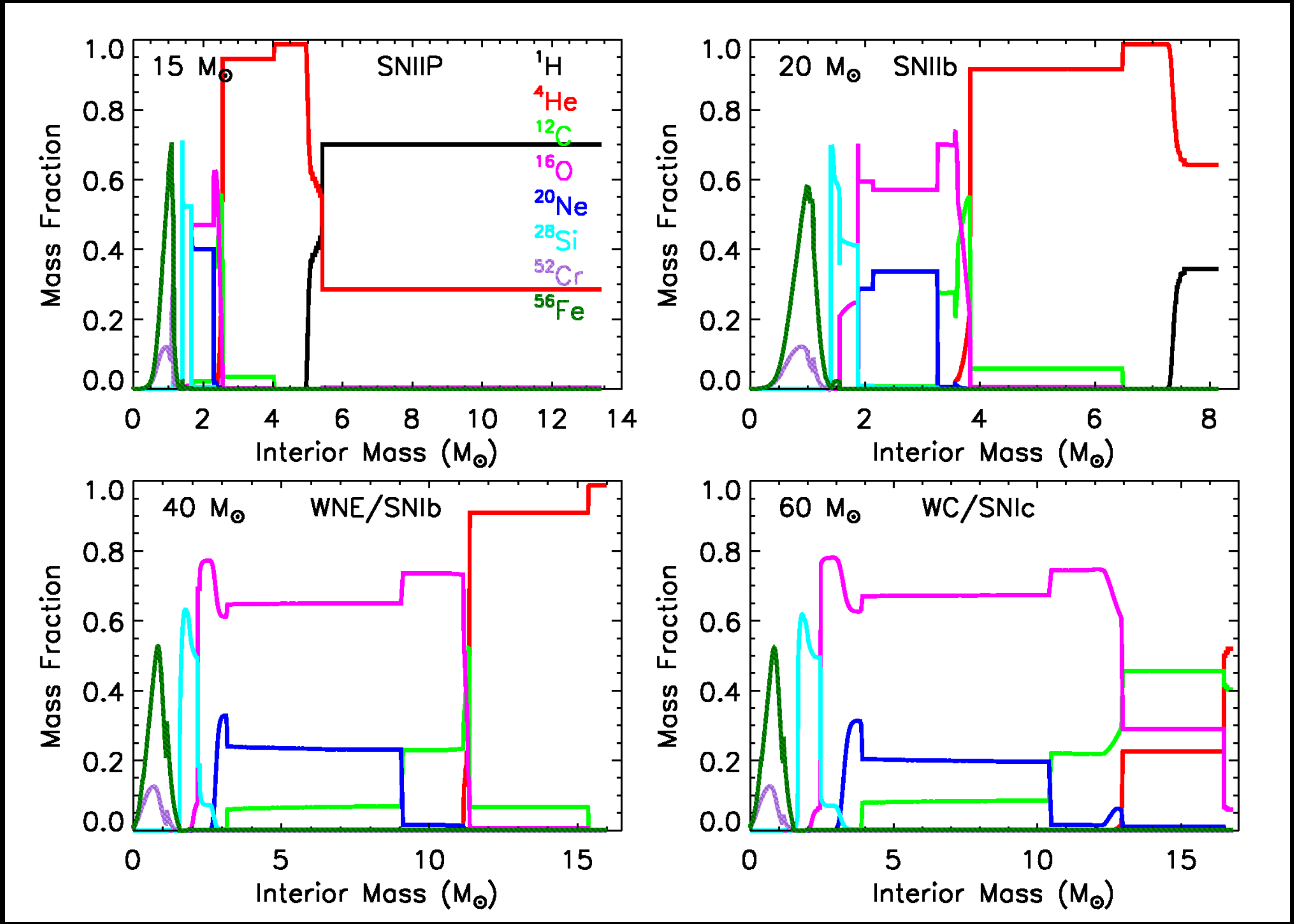
The complex interplay among shell nuclear burning, timing and overlap of the convective zones determines in a direct way the final distribution of the chemical composition and the physical structure of the star @ presupernova stage



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)

Core Collapse Supernova Explosion and Nucleosynthesis

- The Fe core becomes unstable, collapses to nuclear density, rebounces and through a sequence of events a shock wave is launched that drives the explosion of the star

- The propagation of the shock wave through the mantle of the star induces compression and heating → some modification of the chemical composition produced during the hydrostatic burning stages is expected

- Such a modification is called Explosive Nucleosynthesis

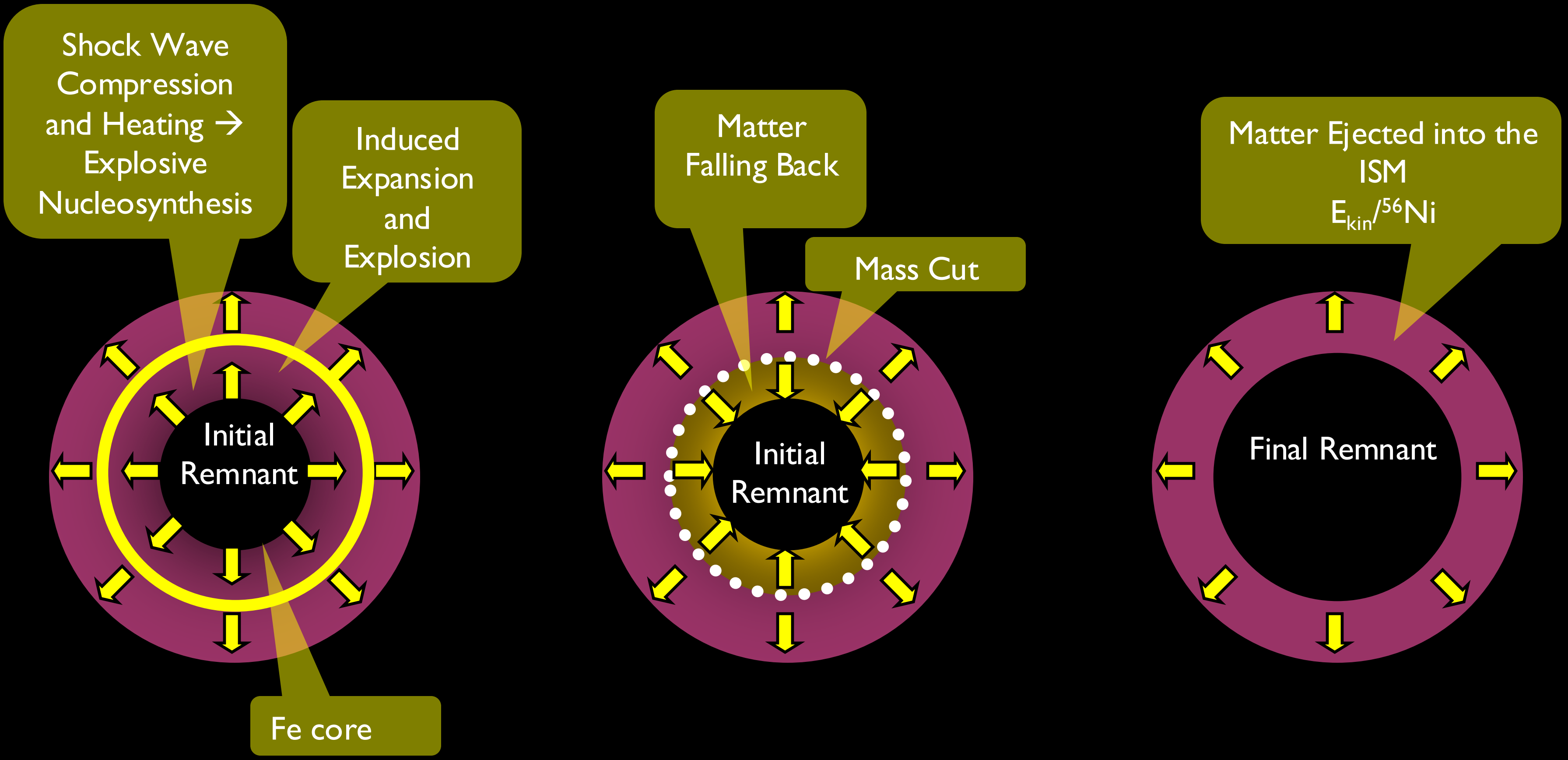
- The modeling of the explosion of the star is mandatory to have information on:
  - The chemical composition of the ejected matter (chemical yields)
  - The initial mass-remnant mass relation

- At present detailed explosive nucleosynthesis calculations for core collapse supernovae are mainly based on artificially induced explosions

Induced Explosion

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)



Shock Wave Compression and Heating → Explosive Nucleosynthesis

Induced Expansion and Explosion

Initial Remnant

Fe core

Matter Falling Back

Mass Cut

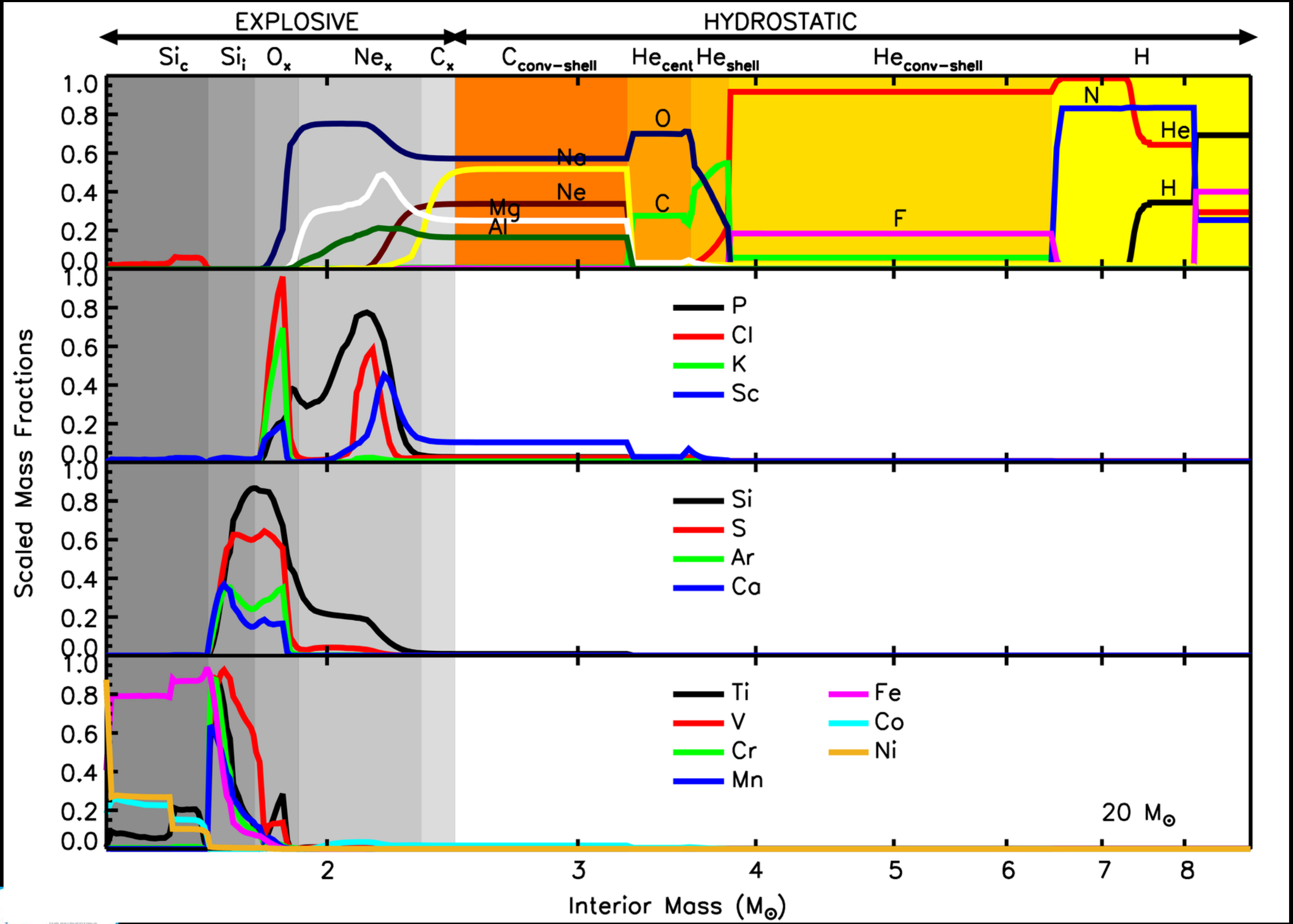
Initial Remnant

Matter Ejected into the ISM

$E_{kin}/^{56}$Ni

Final Remnant

Composition of the Ejecta



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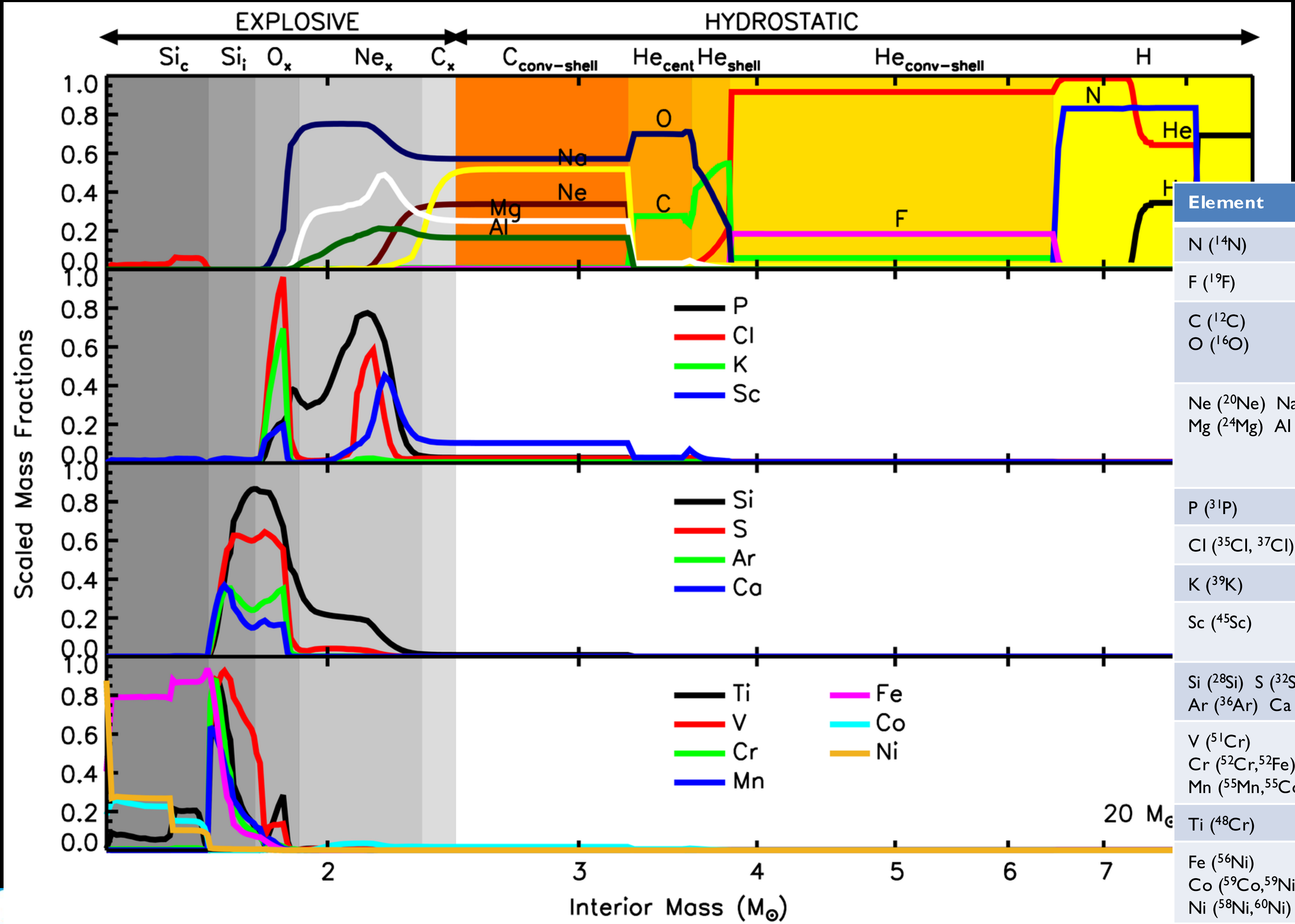
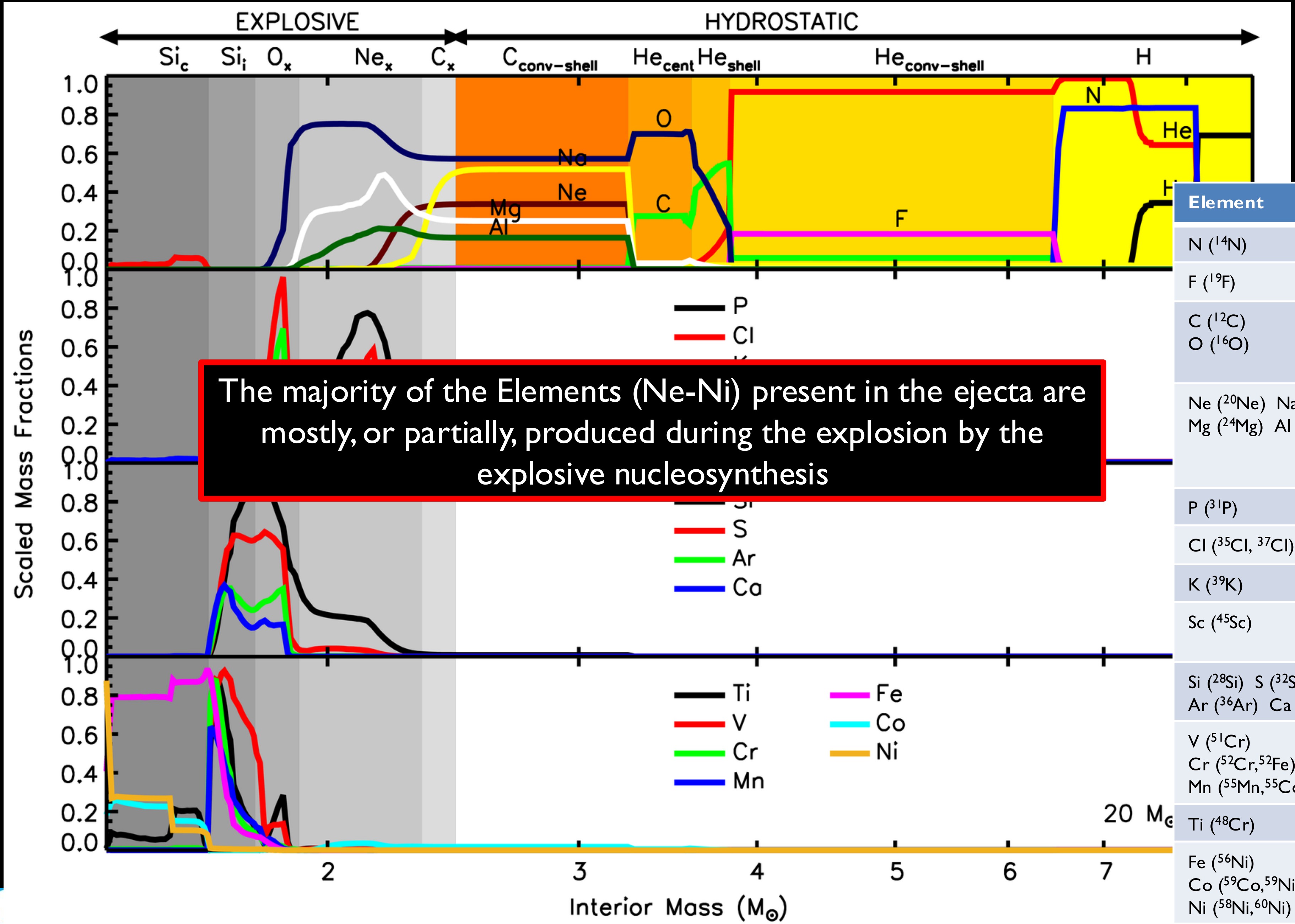


Element	Production Site
N (^{14}N)	Hydrostatic H burning
F (^{19}F)	Hydrostatic He convective shell
C (^{12}C) O (^{16}O)	Hydrostatic core He burning (^{16}O partially modified by Cshell and Ne$_x$)
Ne (^{20}Ne) Na (^{23}Na) Mg (^{24}Mg) Al (^{27}Al)	Hydrostatic C convective shell Partially destroyed by C$_x$ (^{23}Na) and Ne$_x$ (^{20}Ne) Partially produced by Ne$_x$ (^{24}Mg,^{27}Al)
P (^{31}P)	Ne$_x$
Cl (^{35}Cl, ^{37}Cl)	Ne$_x$+O$_x$
K (^{39}K)	O$_x$
Sc (^{45}Sc)	Hydrostatic C convective shell Ne$_x$+O$_x$
Si (^{28}Si) S (^{32}S) Ar (^{36}Ar) Ca (^{40}Ca)	O$_x$+Si$_i$
V (^{51}Cr) Cr (^{52}Cr,^{52}Fe) Mn (^{55}Mn,^{55}Co)	Si$_i$
Ti (^{48}Cr)	O$_x$+Si$_i$+Si$_c$
Fe (^{56}Ni) Co (^{59}Co,^{59}Ni) Ni (^{58}Ni,^{60}Ni)	Si$_c$

Composition of the Ejecta



The majority of the Elements (Ne-Ni) present in the ejecta are mostly, or partially, produced during the explosion by the explosive nucleosynthesis

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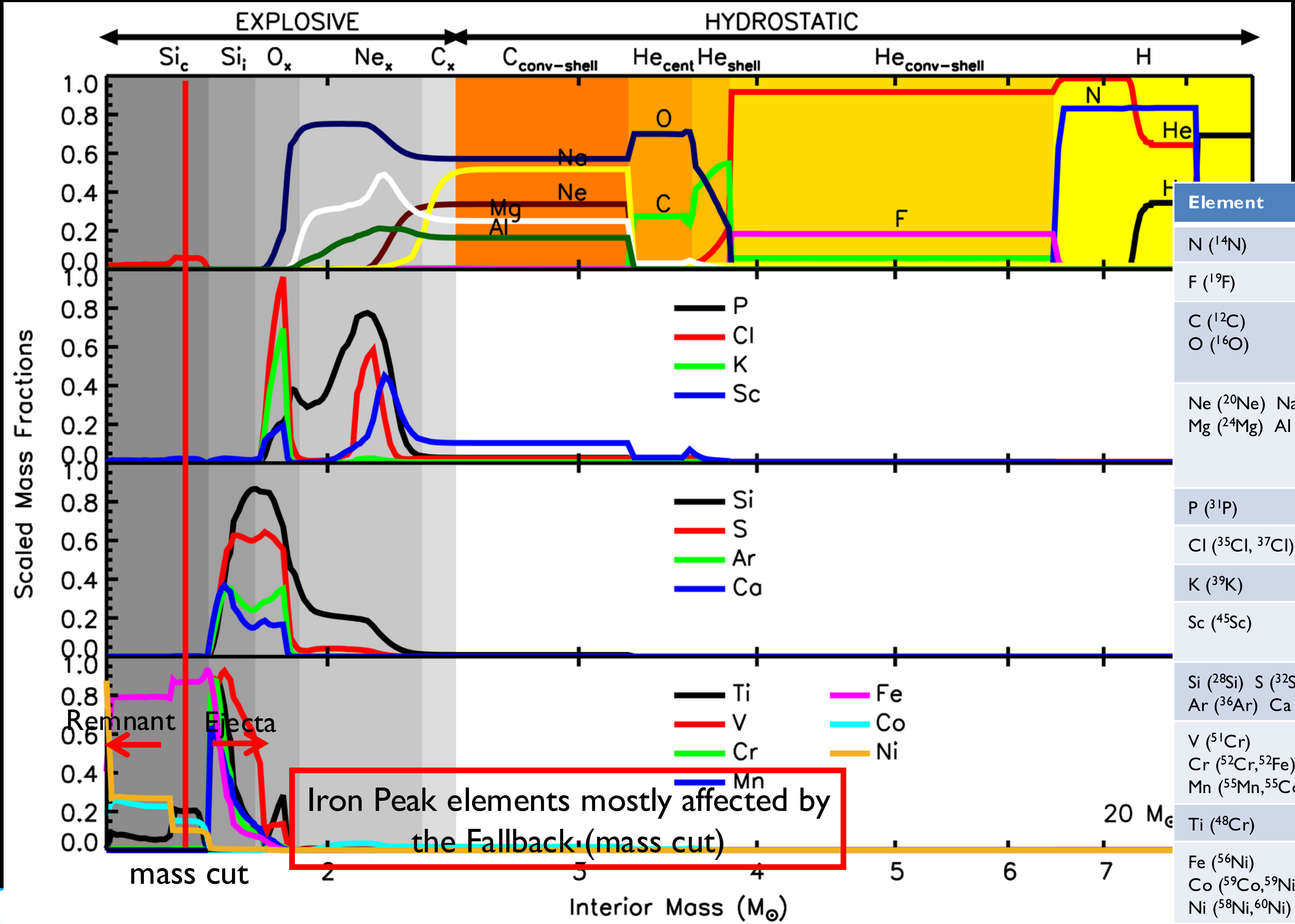
Composition of the Ejecta



Remnant

Ejecta

Iron Peak elements mostly affected by the Fallback (mass cut)

mass cut

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Ti (^{48}Cr)	O_x+Si_i+Si_c
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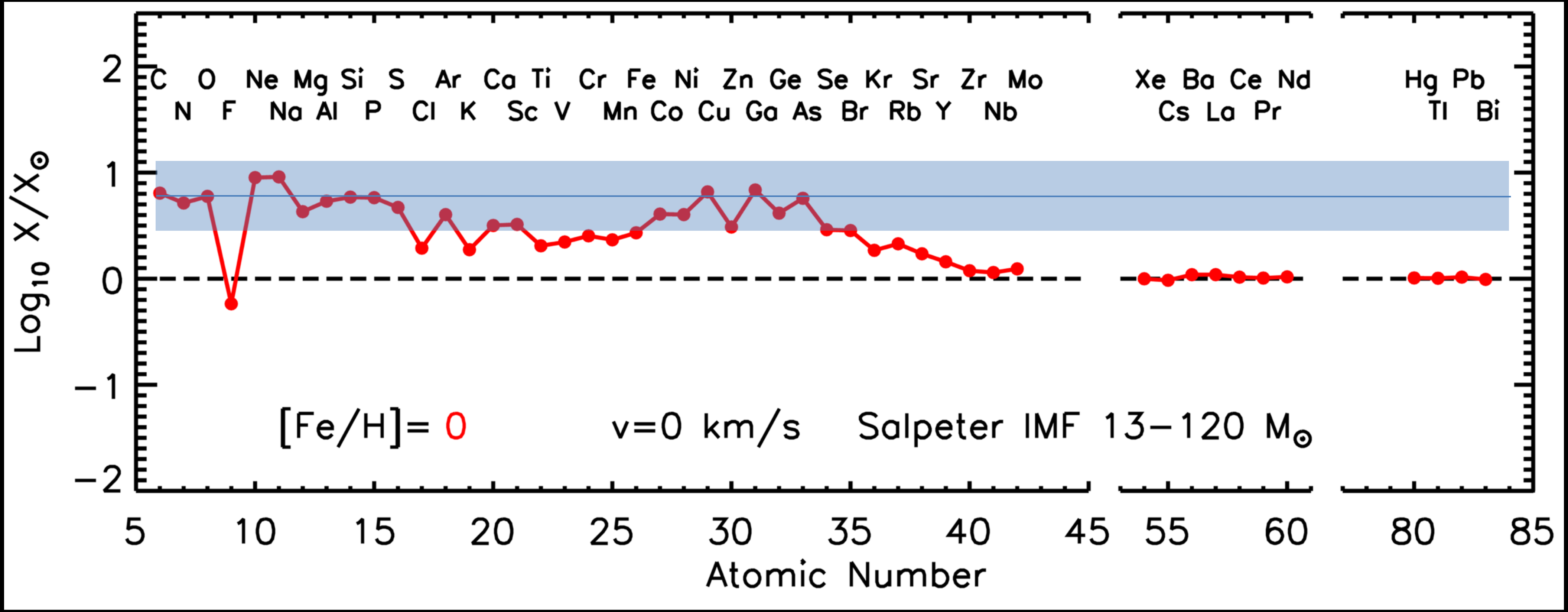
Solar Metallicity non Rotating Models: Composition of the Ejecta

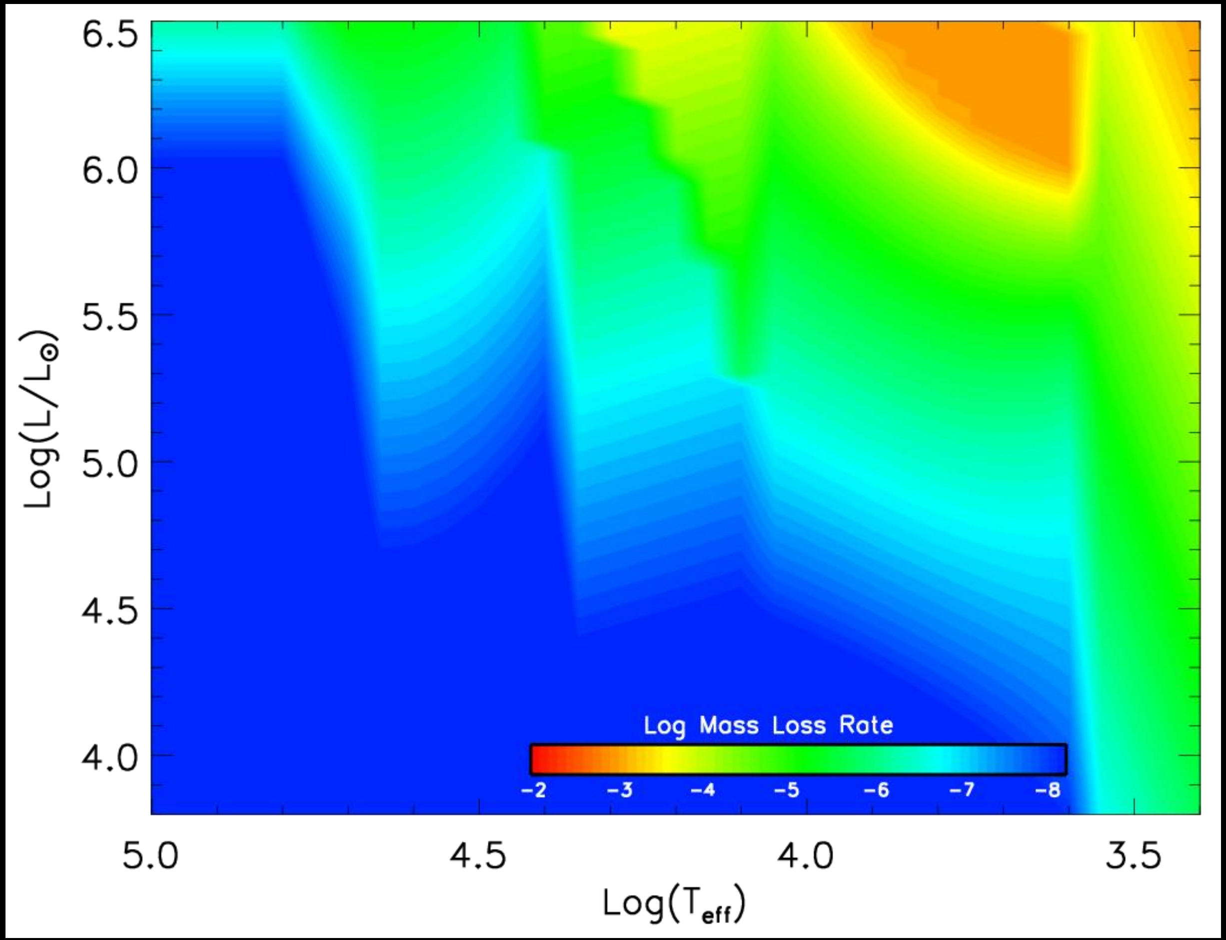


- The elements Ne-Ca (synthesized only by massive stars) are coproduced with O. Some of them underproduced by more than a factor of 2 (Cl K) → other sources
- The iron peak elements Ti-Ni are underproduced compared to O. SNIa fill the gap
- The elements Cu-Zr (weak component, synthesized mainly by massive 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

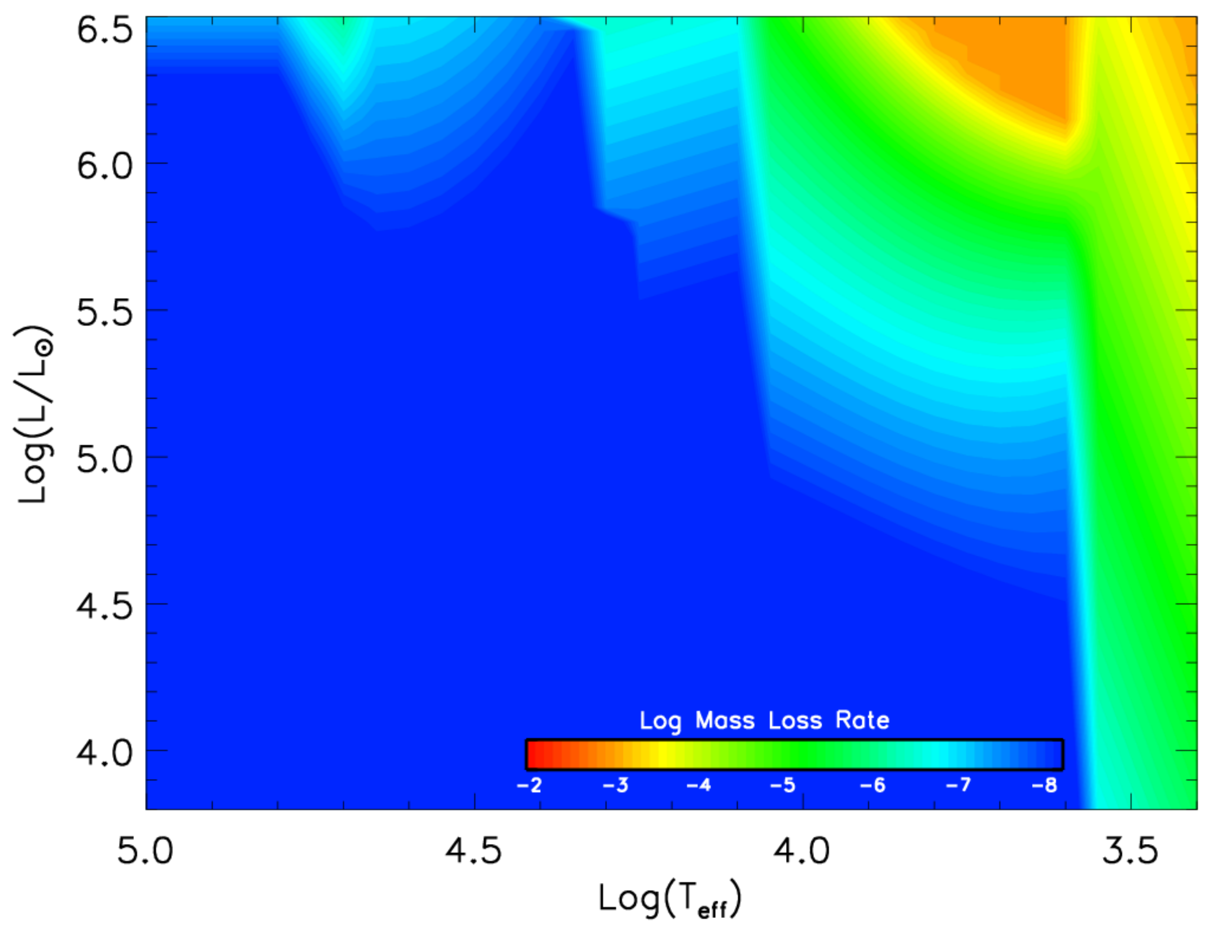
Low Metallicity non Rotating Models: Presupernova Evolution

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

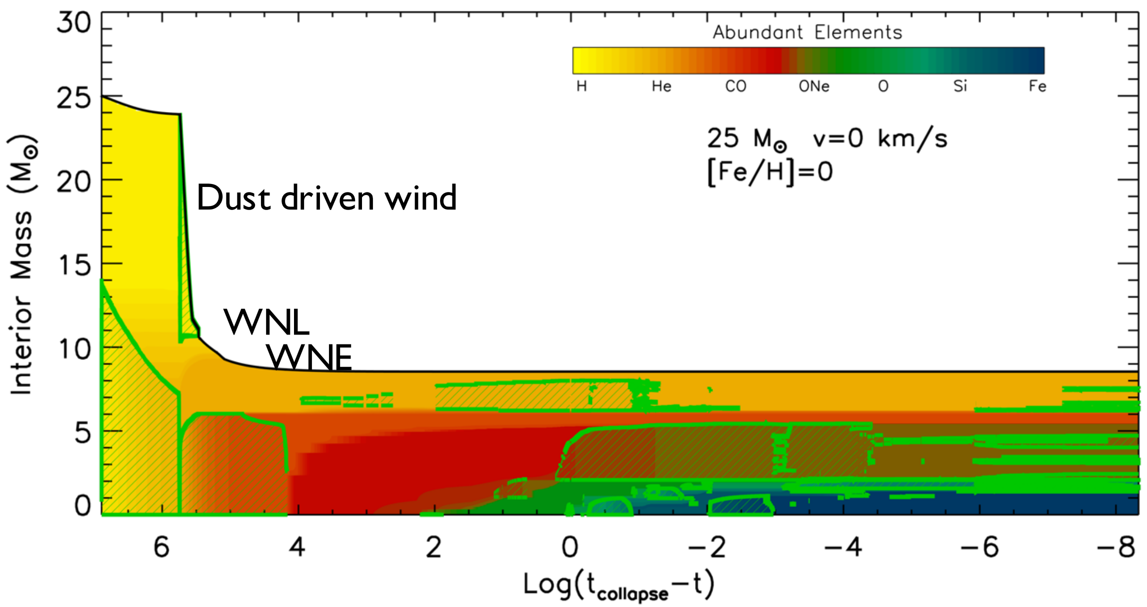
[Fe/H]=0

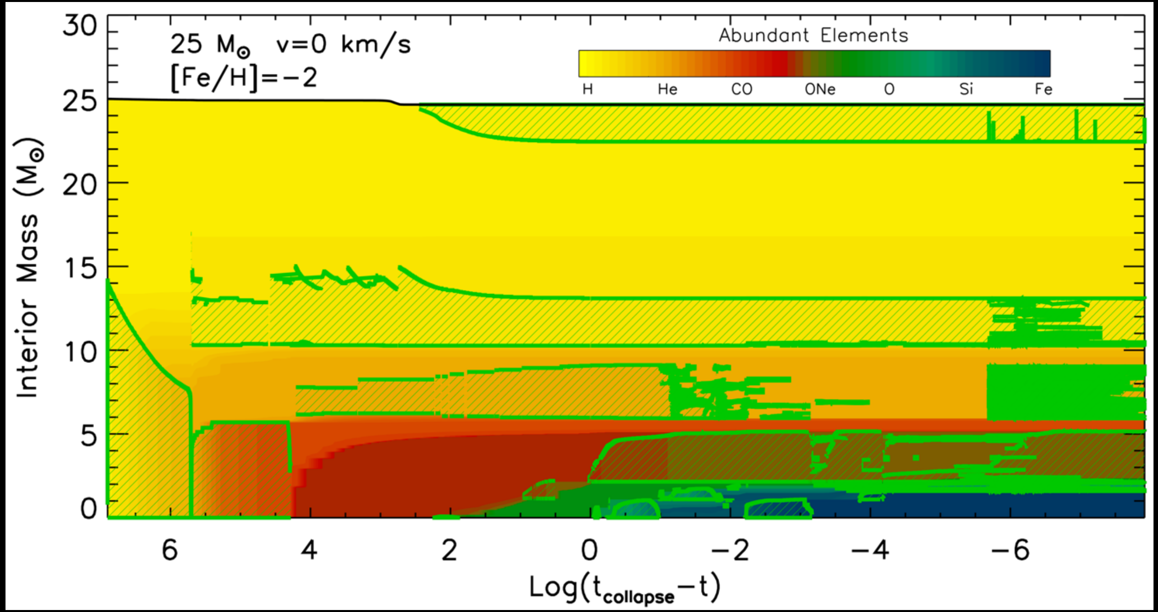


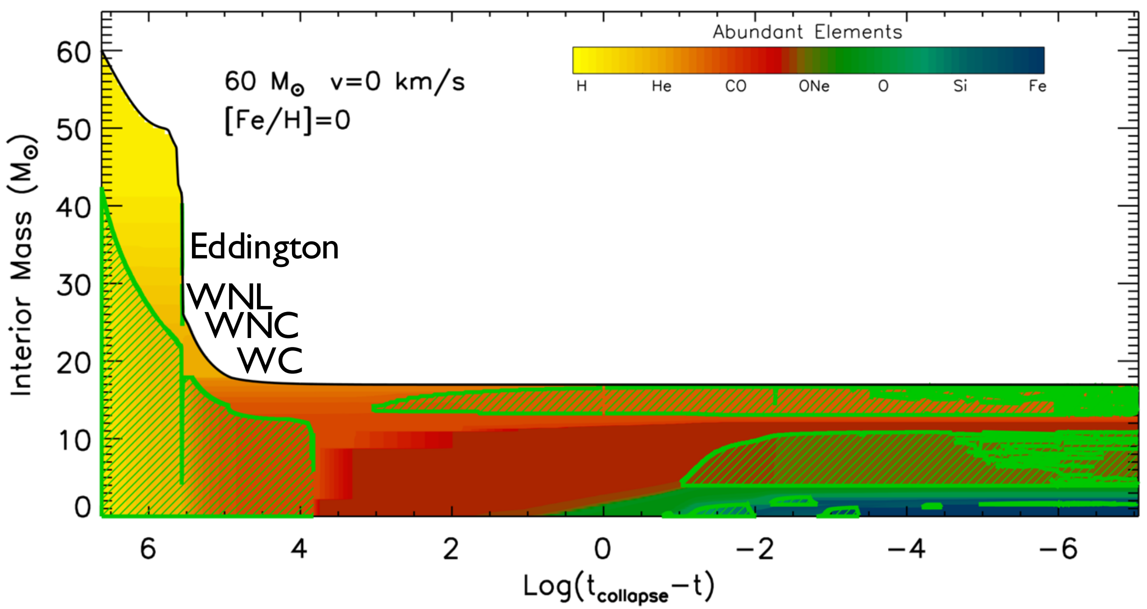
[Fe/H]=-2

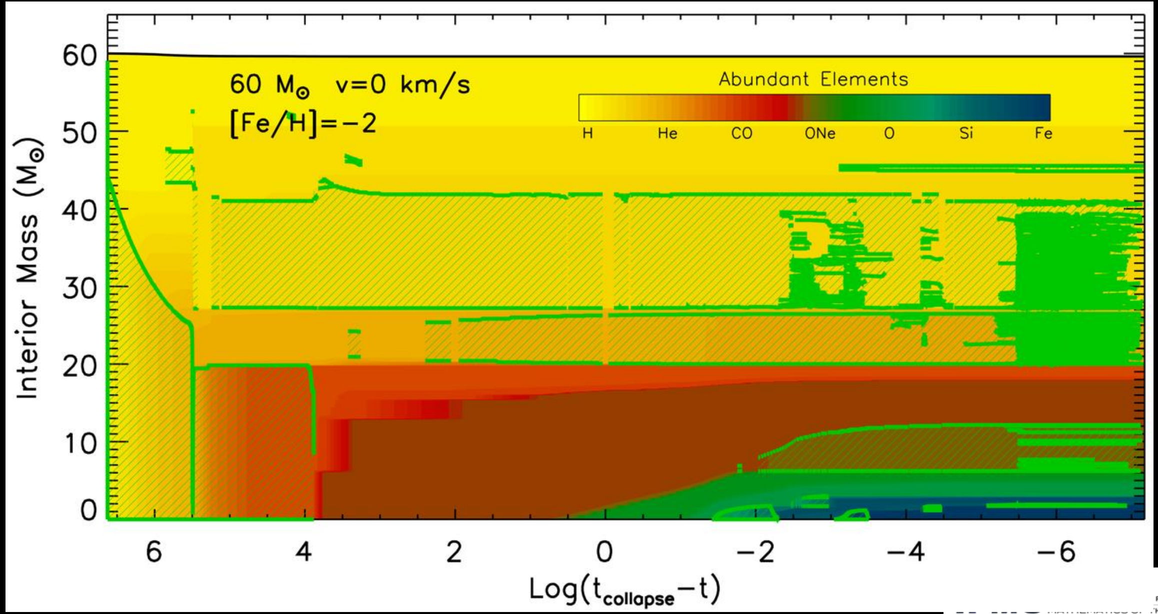


Low Metallicity non Rotating Models: Presupernova Evolution

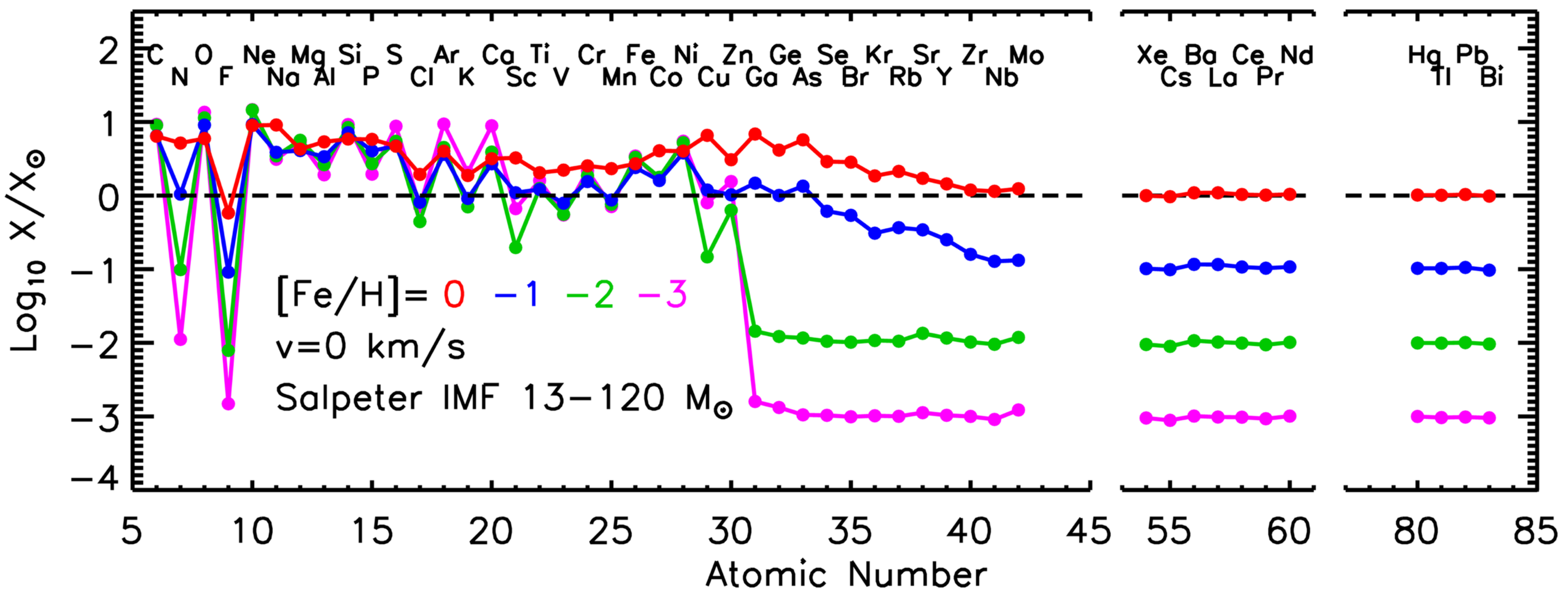








Low Metallicity non Rotating Models: Composition of the Ejecta

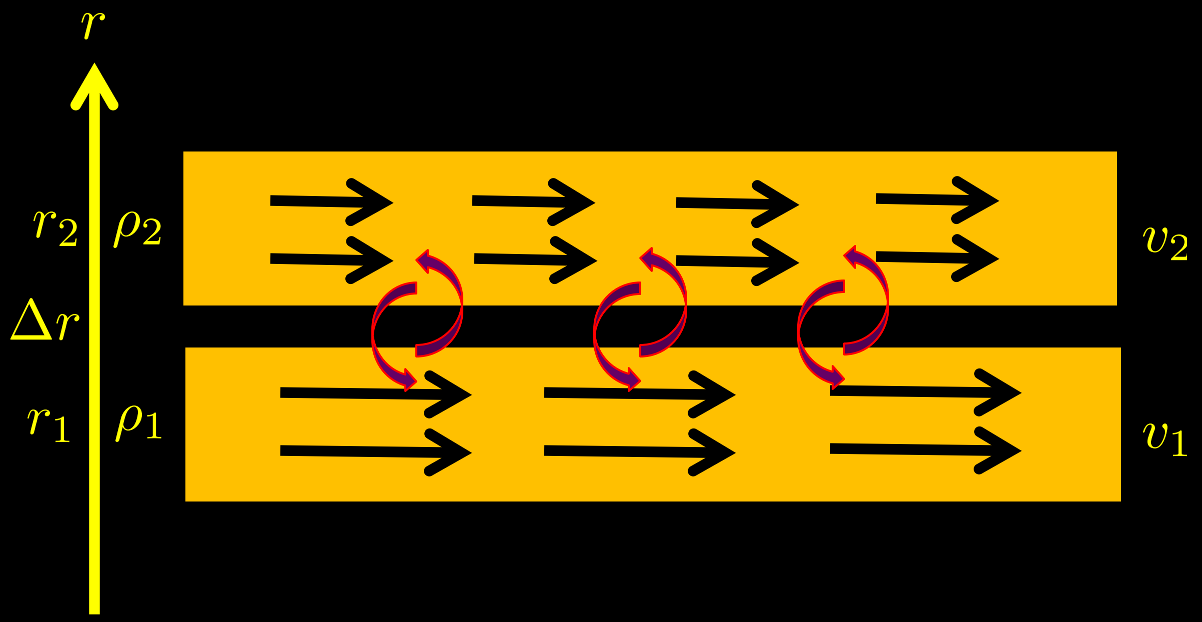


- Alpha elements show (as expected) the typical behavior of primary nuclei (negligible dependence on the initial metallicity)
- The odd elements (from N to Sc), on the contrary, show a typical secondary behavior
- All the heavy elements above Fe-peak are produced as secondaries (Zn-Zr start being produced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

ROTATION DRIVEN INSTABILITIES: TURBULENT SHEAR

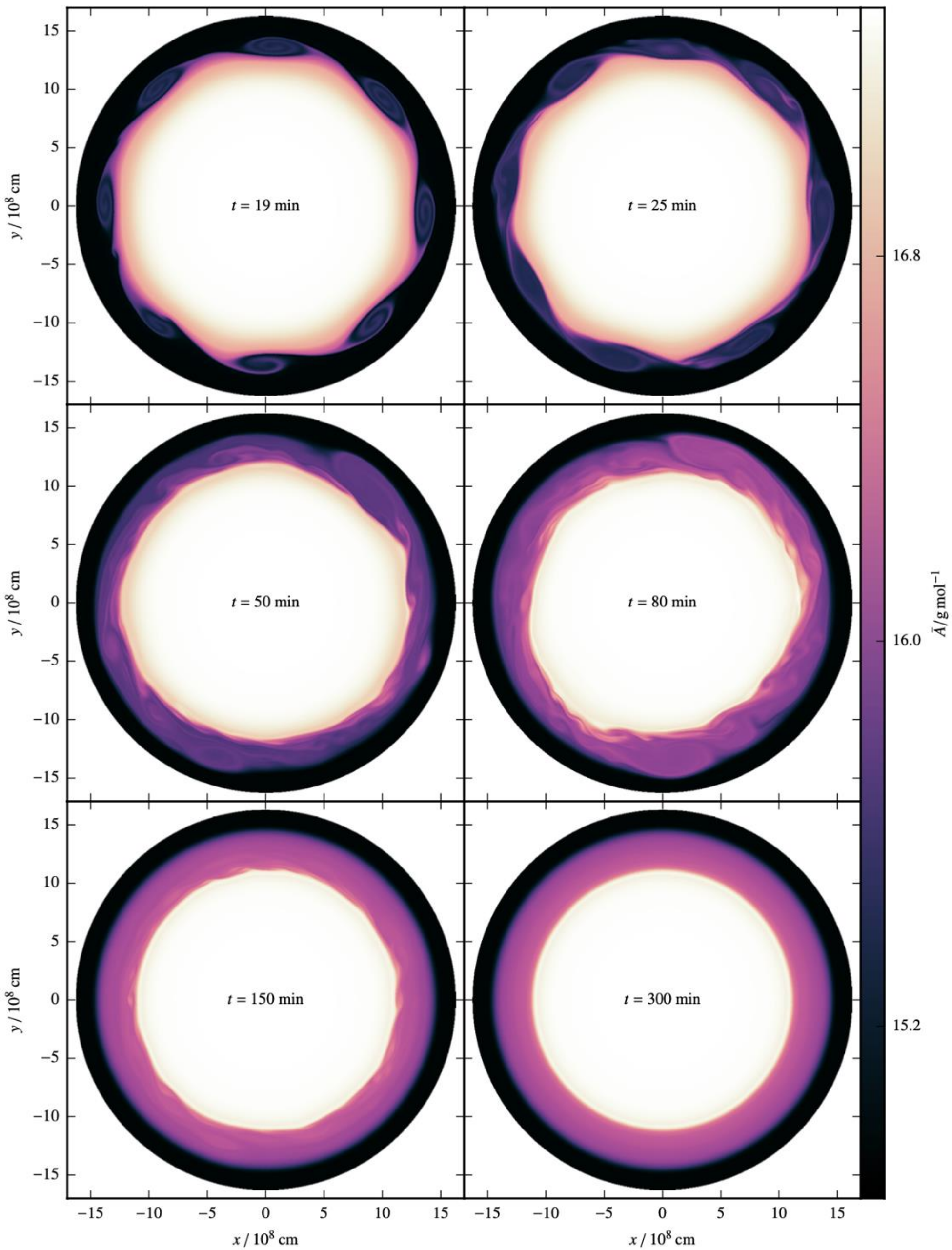
Edelmann+2017

Differential rotation induces chemical mixing



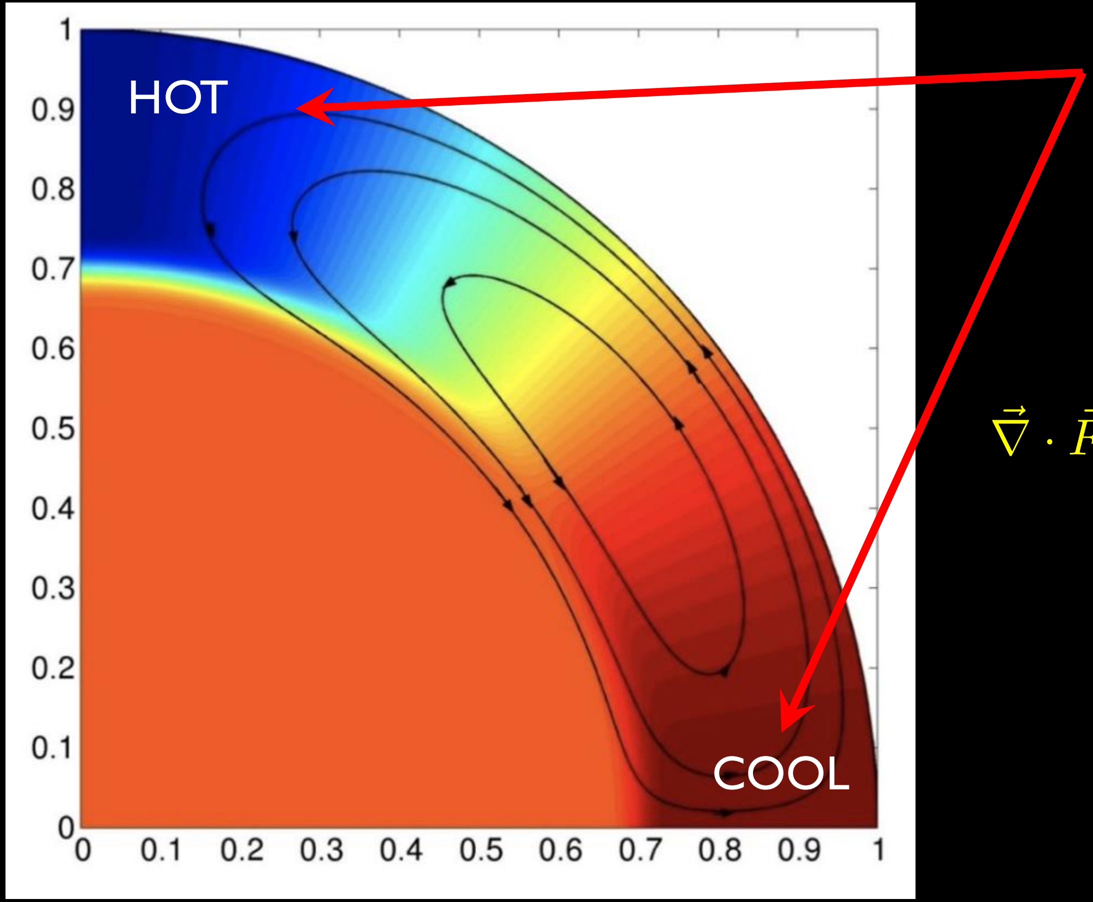
$$\left(\frac{\partial X_i}{\partial t}\right)_m = \left(\frac{\partial}{\partial m}\right)_t \left[(4\pi\rho r^2)^2 D \left(\frac{\partial X_i}{\partial m}\right)_t\right]$$

$$\boxed{D_{\mathrm{shear}} = \frac{1}{3} v l = 2\frac{R\left(\partial\omega/\partial r\right)^2}{N_T^2/\left(K+D_h\right)+N_\mu^2/D_h}}$$



ROTATION DRIVEN INSTABILITIES: MERIDIONAL CIRCULATION

Rotation makes the star oblates



Different heat content between the pole to the equator

Large-scale MERIDIONAL CIRCULATION develops

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

Velocity of meridional circulation

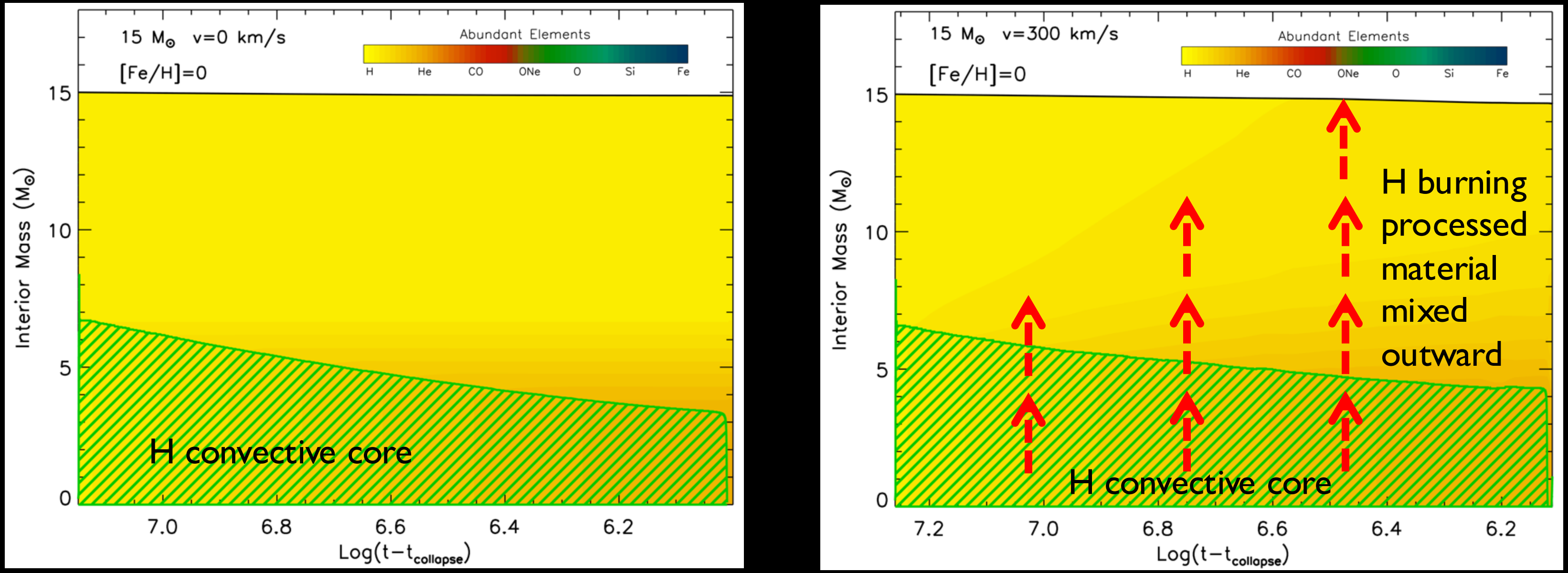
Meridional circulation moves matter through the star and hence it can both transport angular momentum and induce mixing of the chemical composition

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

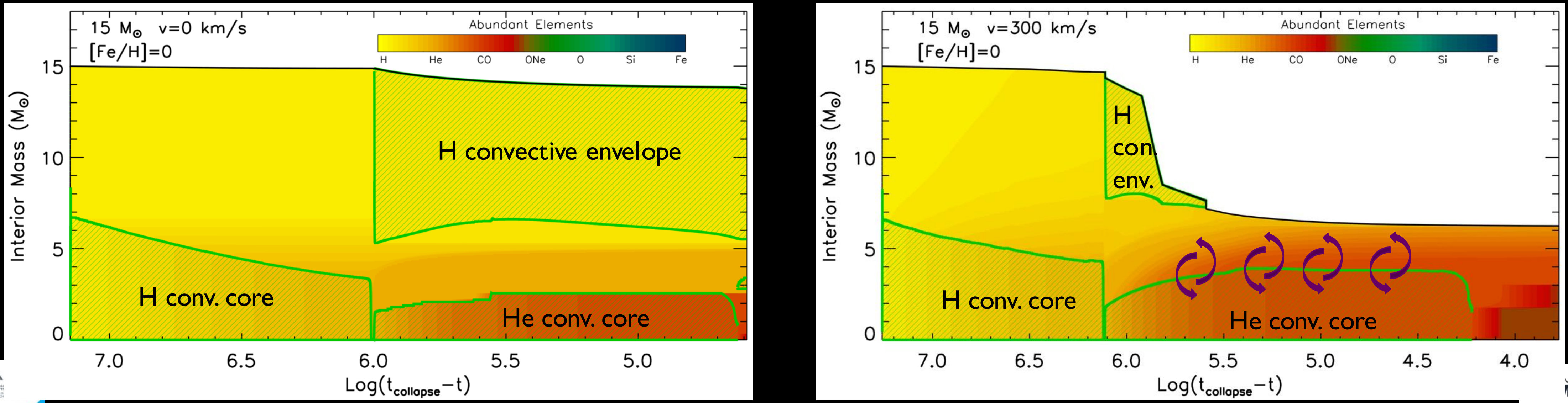
$$\boxed{D_{\rm mc} = \frac{1}{30} r\,|U|}$$

Rotation Driven Mixing in Core H and Core He Burning

Internal evolution: mixing of core H burning products into the H-rich envelope



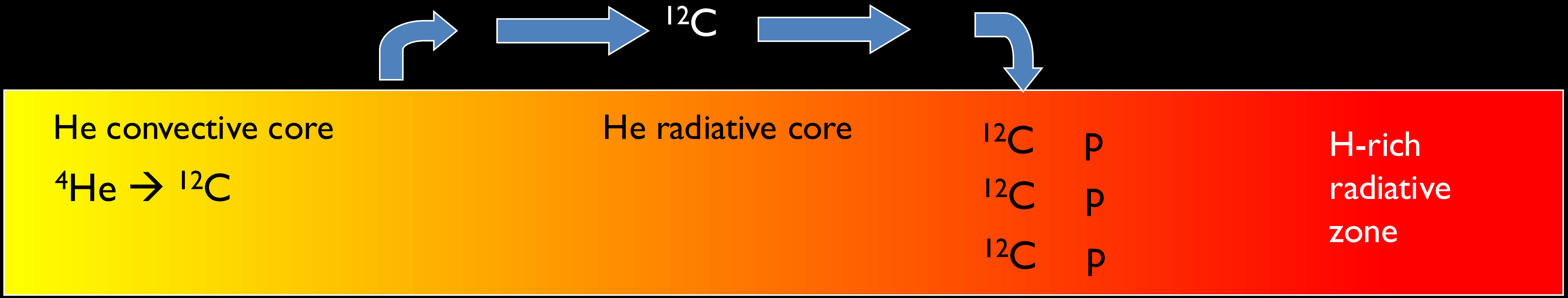
Internal evolution: mixing of core He burning products up to the tail of H-shell



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

Rotation induced mixing



^{12}C

He convective core

$^{4}He \rightarrow {}^{12}C$

He radiative core

^{12}C p

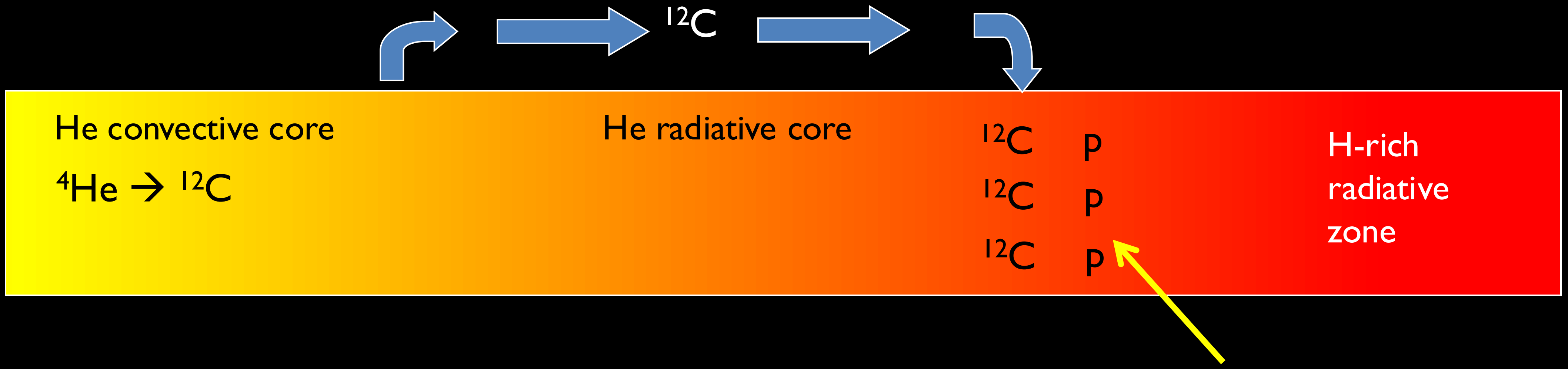
^{12}C p

^{12}C p

H-rich
radiative
zone

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)



Rotation induced mixing

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He convective core

$^{4}He \rightarrow {}^{12}C$

He radiative core

^{12}C p

^{12}C p

^{12}C p

H-rich radiative zone

$^{12}C + p \rightarrow$ CNO (^{14}N, ^{13}C, ^{15}N, ^{17}O)

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

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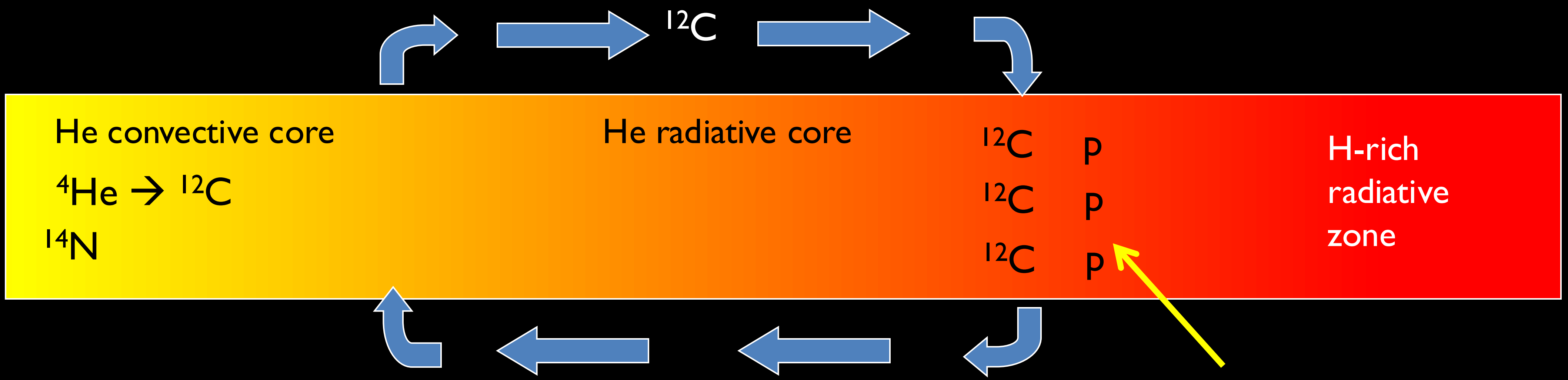
- The fresh CNO nuclei, and in particular ^{14}N, plus fresh He, are brought back toward the center.



Rotation induced mixing

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^{12}C p

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H-rich
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CNO + ^{4}He

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

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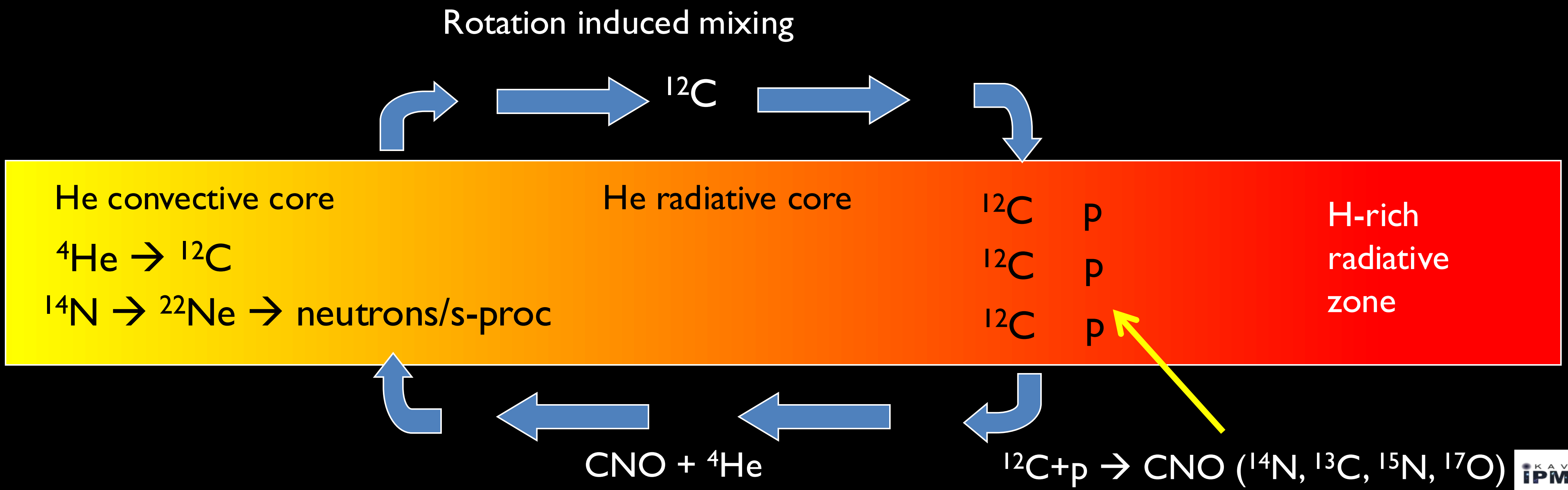
- The fresh CNO nuclei, and in particular ^{14}N, plus fresh He, are brought back toward the center.
- The ^{14}N that diffused back to the center is quickly converted into ^{22}Ne that becomes an efficient primary neutron source → strong s-process nucleosynthesis activated



Rotation induced mixing

^{12}C

He convective core

$^{4}He \rightarrow {}^{12}C$

$^{14}N \rightarrow {}^{22}Ne \rightarrow$ neutrons/s-proc

He radiative core

^{12}C p

^{12}C p

^{12}C p

H-rich radiative zone

CNO + ^{4}He

$^{12}C+p \rightarrow$ CNO (^{14}N, ^{13}C, ^{15}N, ^{17}O)

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

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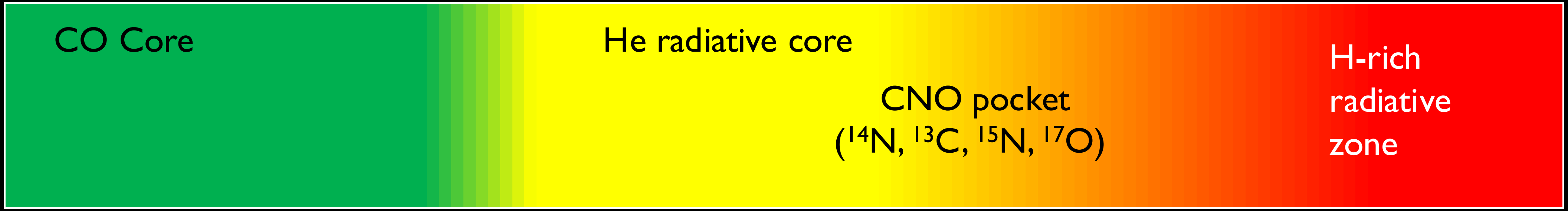

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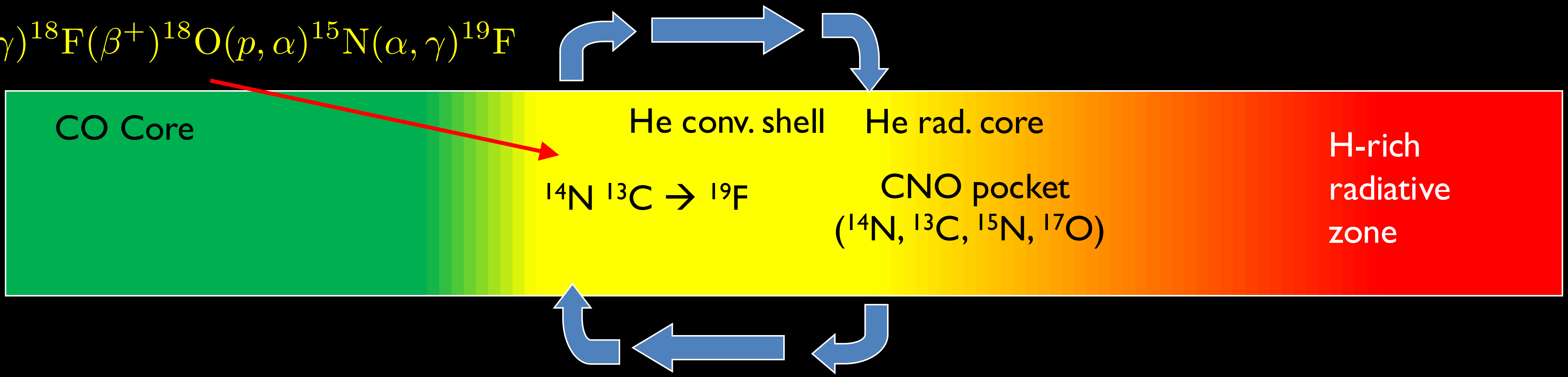
- Formation of a CNO (^{14}N, ^{13}C, ^{15}N, ^{17}O) pocket in the radiative layers of the He core
- The ^{13}C and ^{14}N engulfed by the He convective shell activate a strong ^{19}F production

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

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



CO Core

He conv. shell

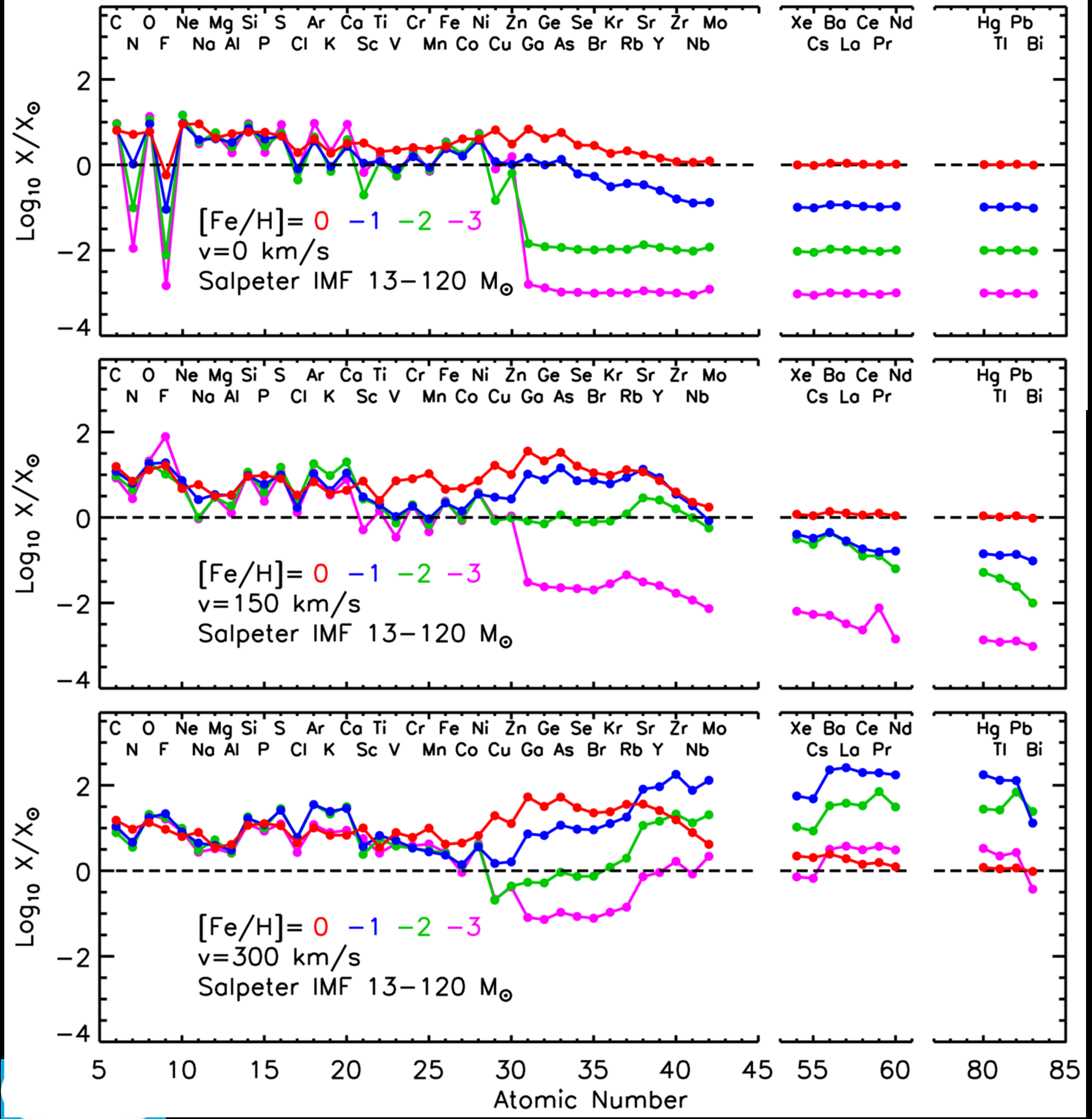
He rad. core

^{14}N ^{13}C → ^{19}F

CNO pocket
(^{14}N, ^{13}C, ^{15}N, ^{17}O)

H-rich
radiative
zone

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

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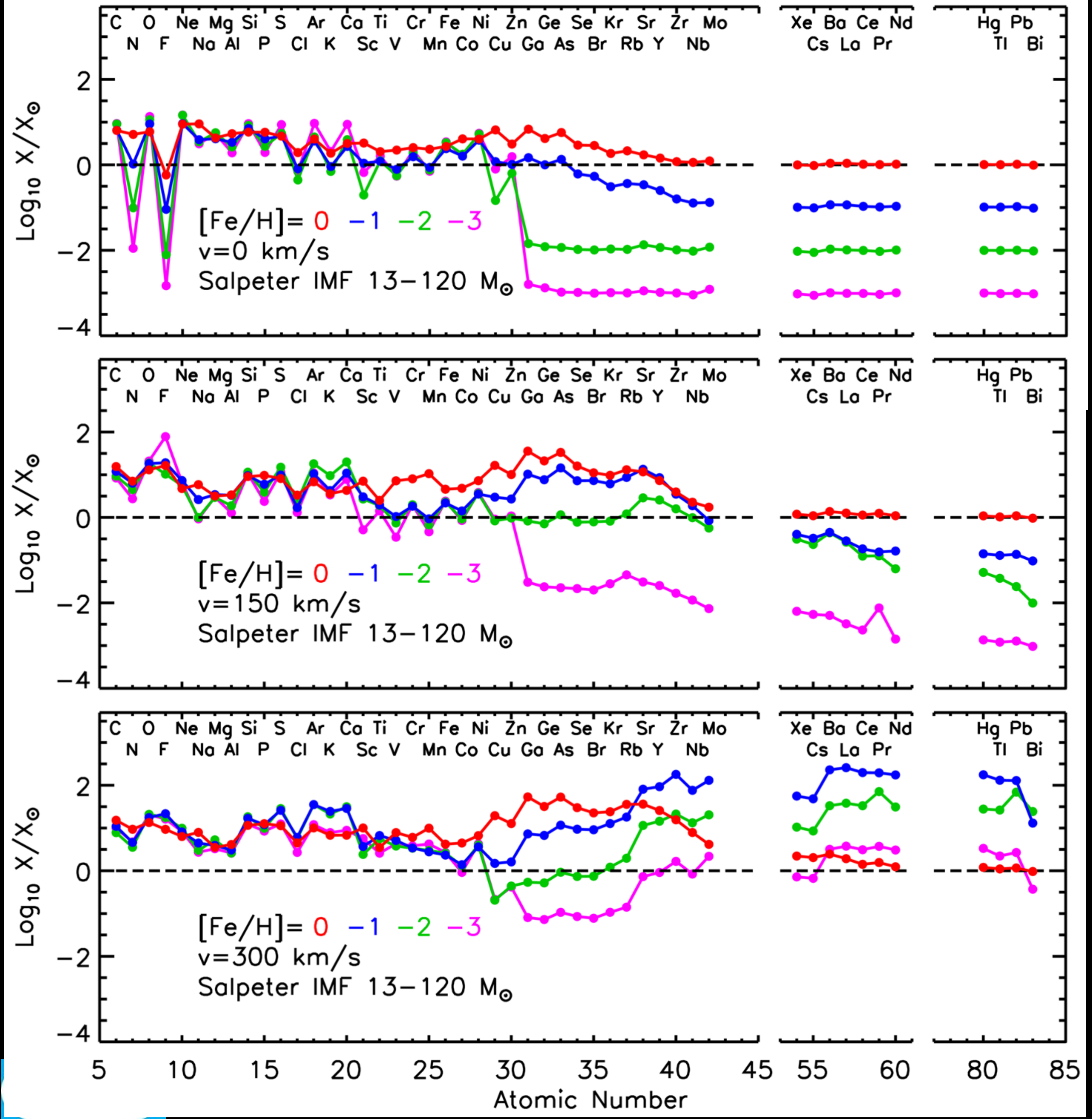

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- The production of s-process elements is substantially enhanced with increasing the initial rotation velocity

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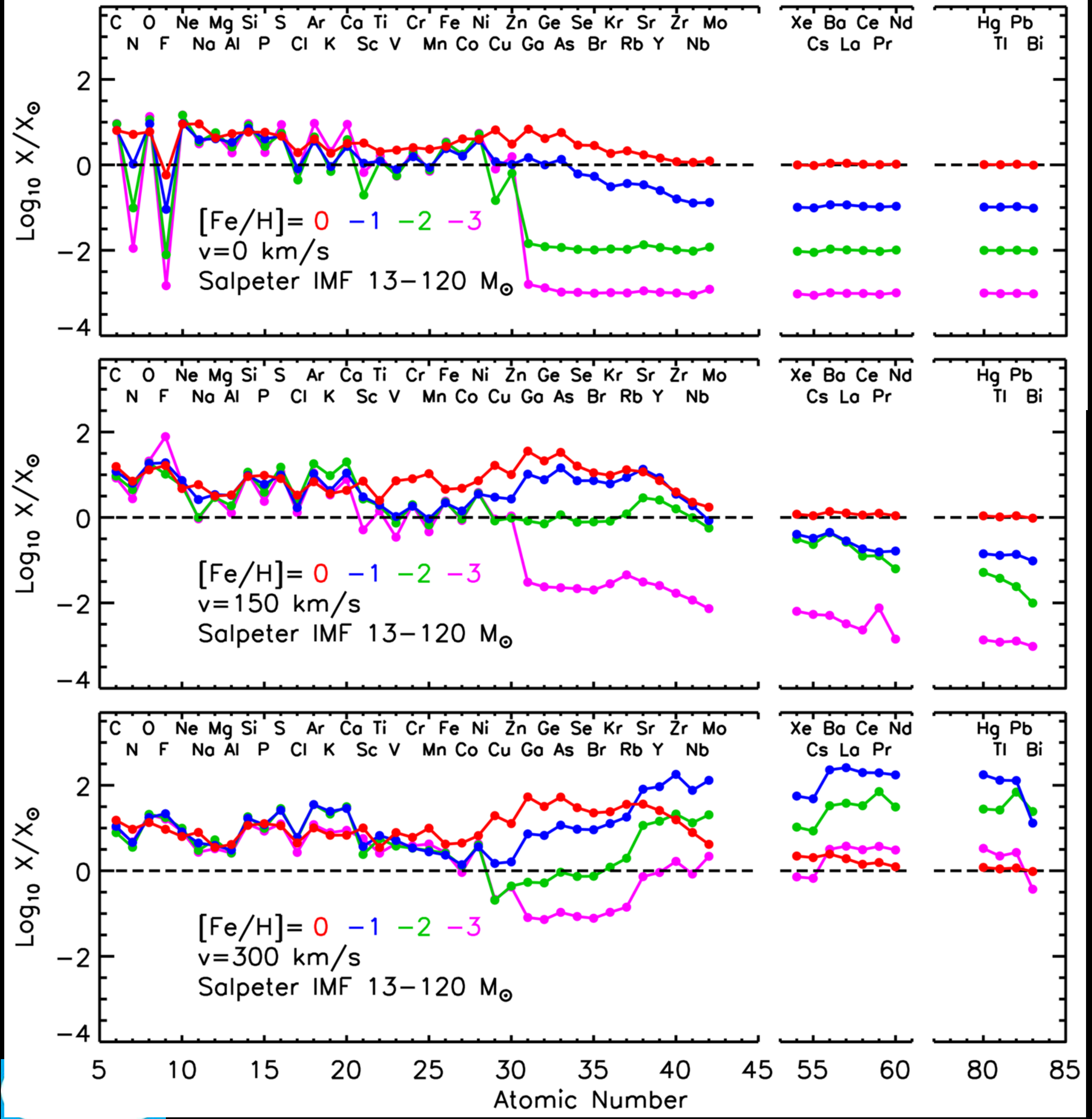

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- Large overproduction with respect to O (especially the s-only isotopes) at metallicities -2<[Fe/H]<0

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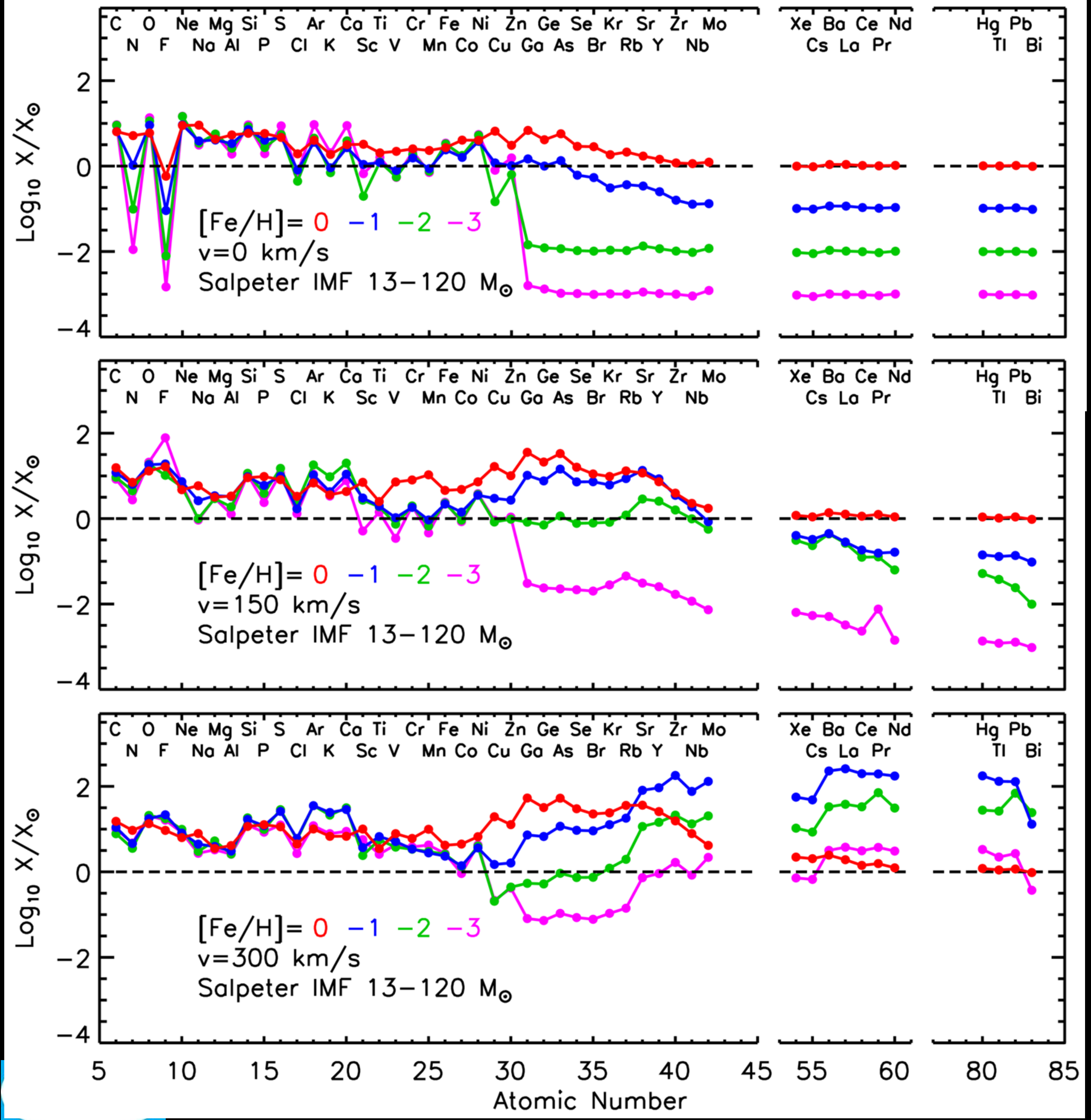

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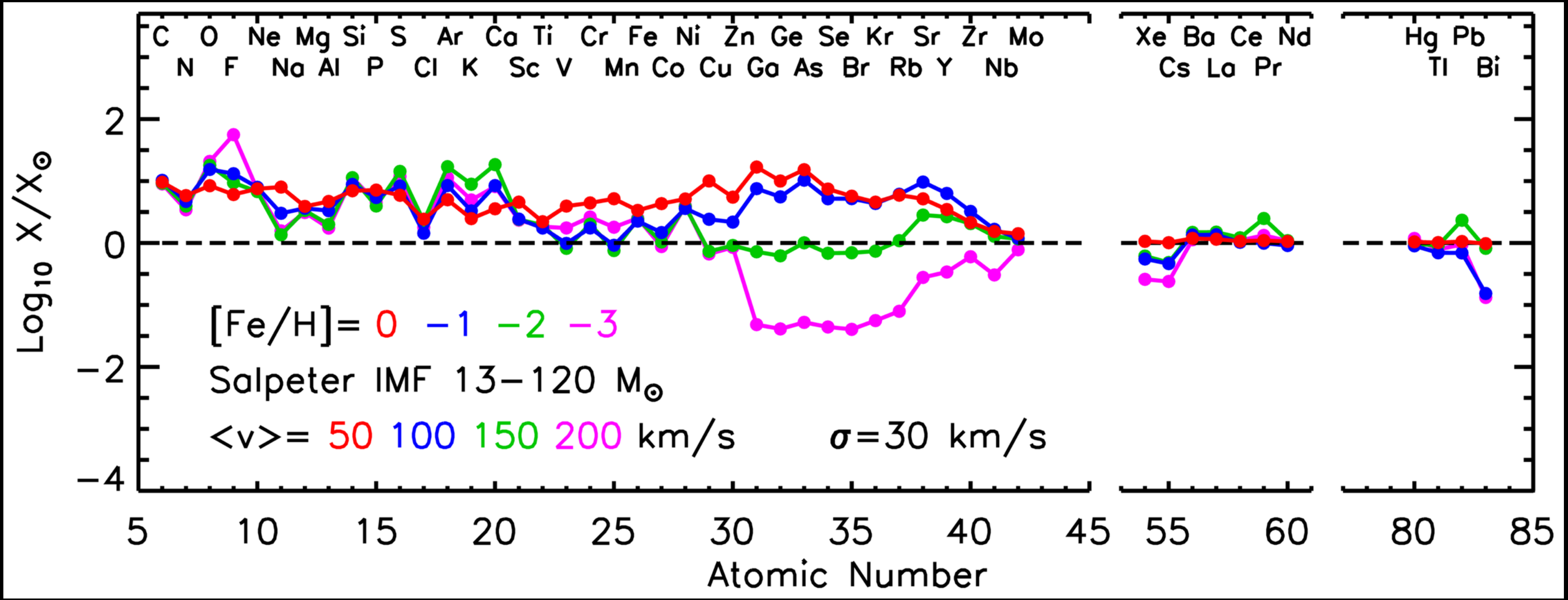
OBSERVATIONAL REQUIREMENTS

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

Rotating Models: Composition of the Ejecta

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



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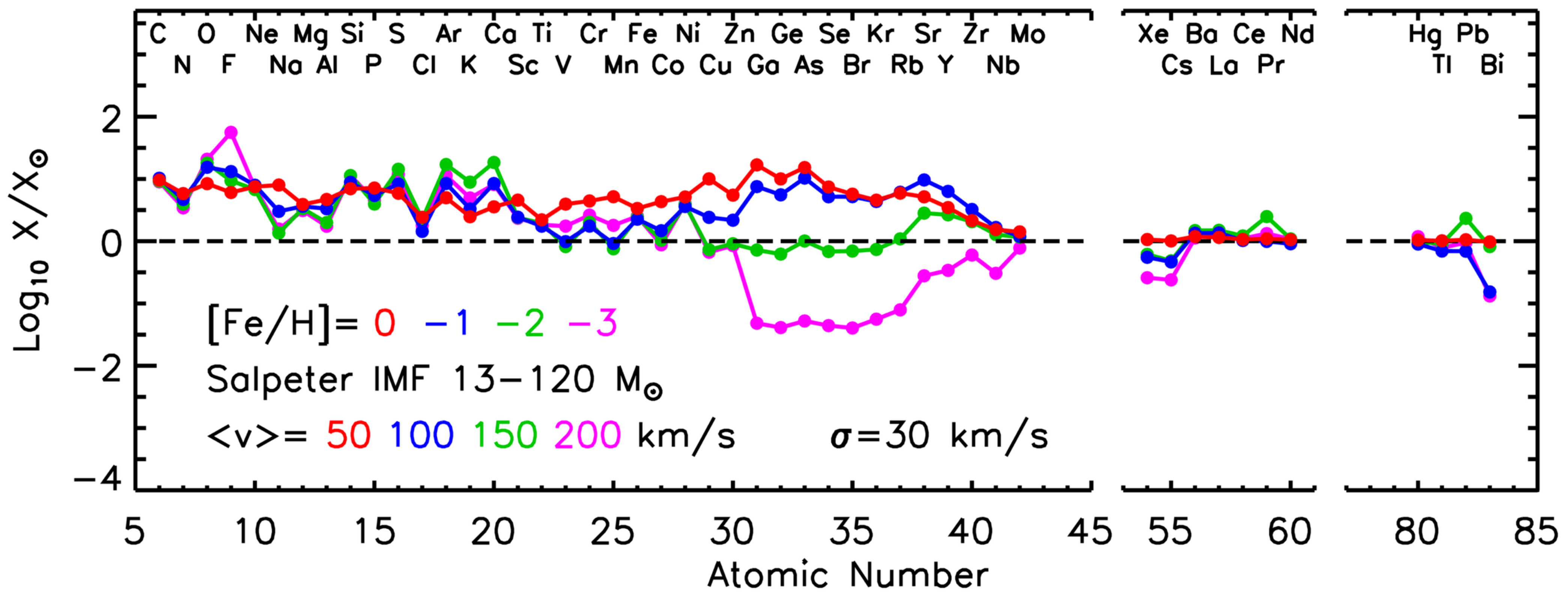
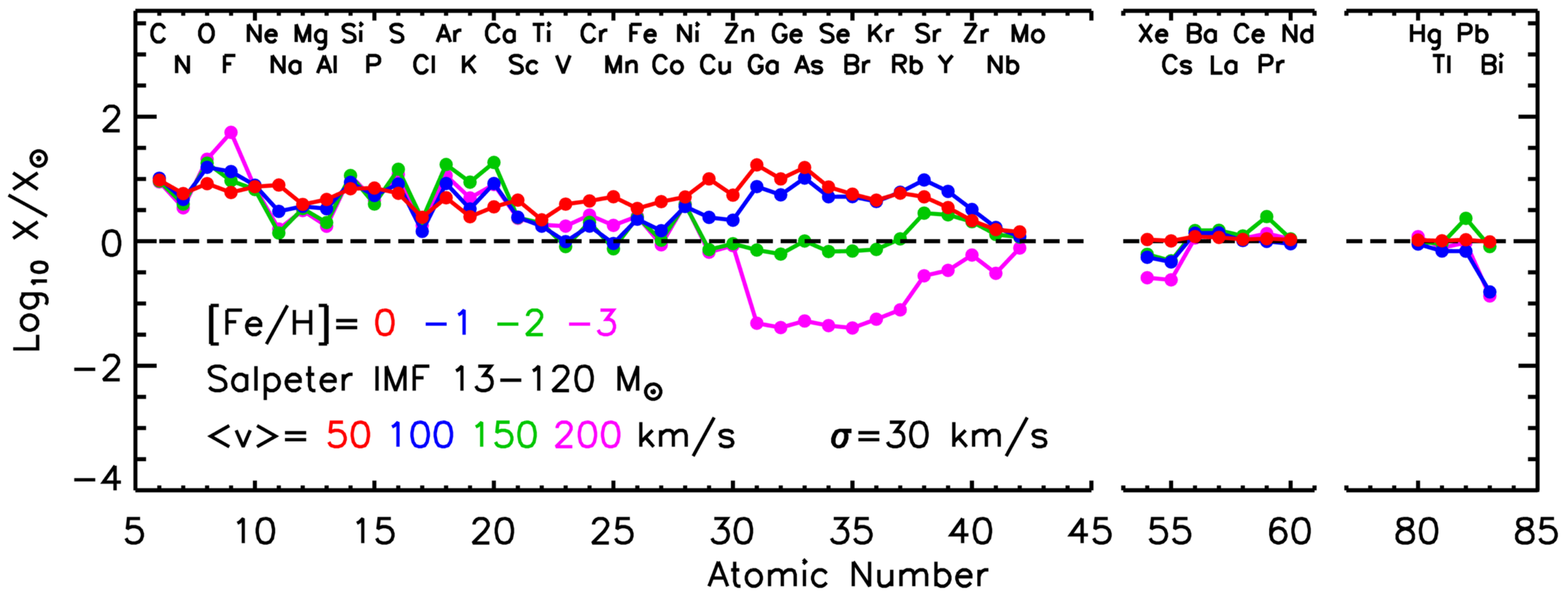


- Alpha elements behave as primaries

Rotating Models: Composition of the Ejecta

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



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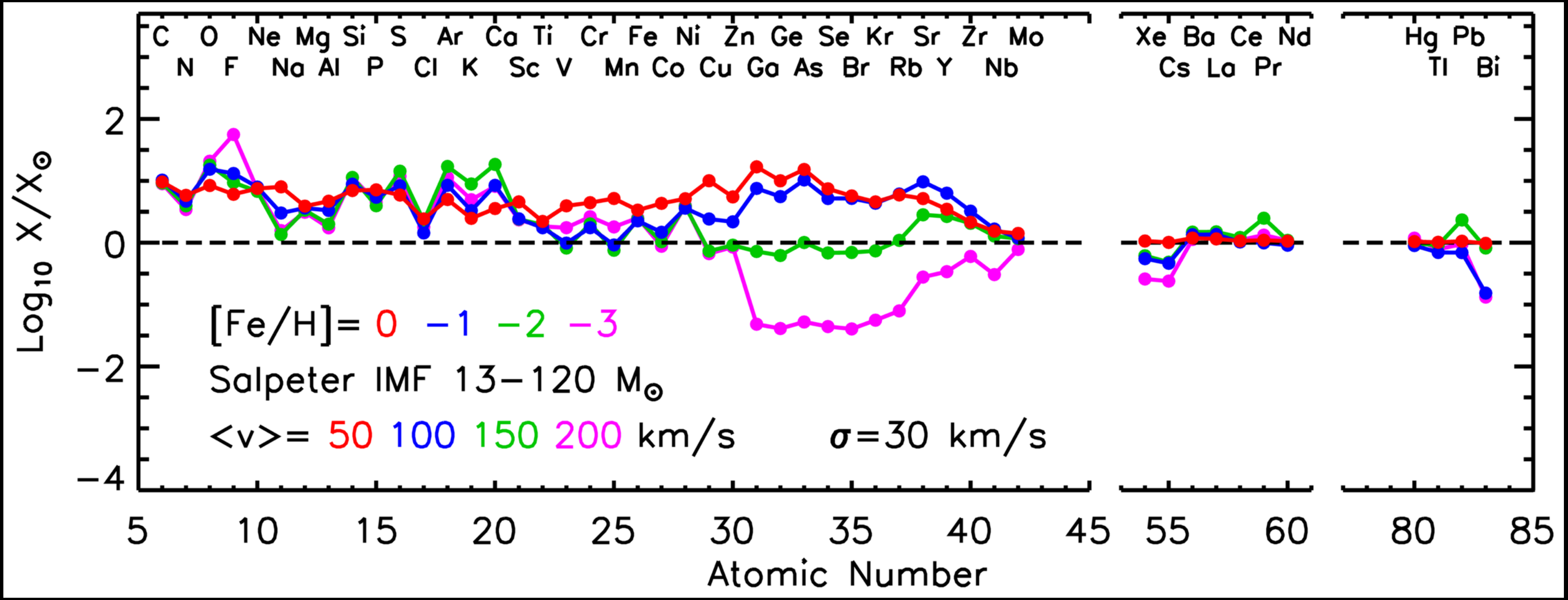

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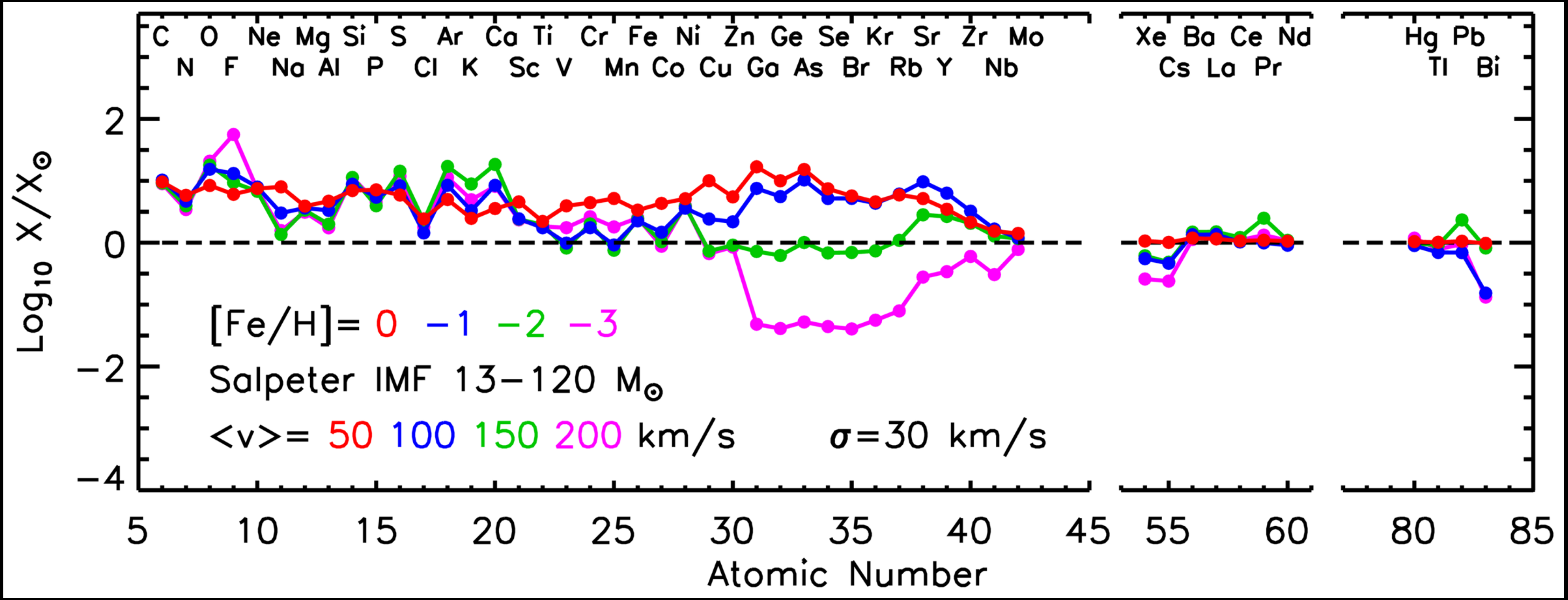
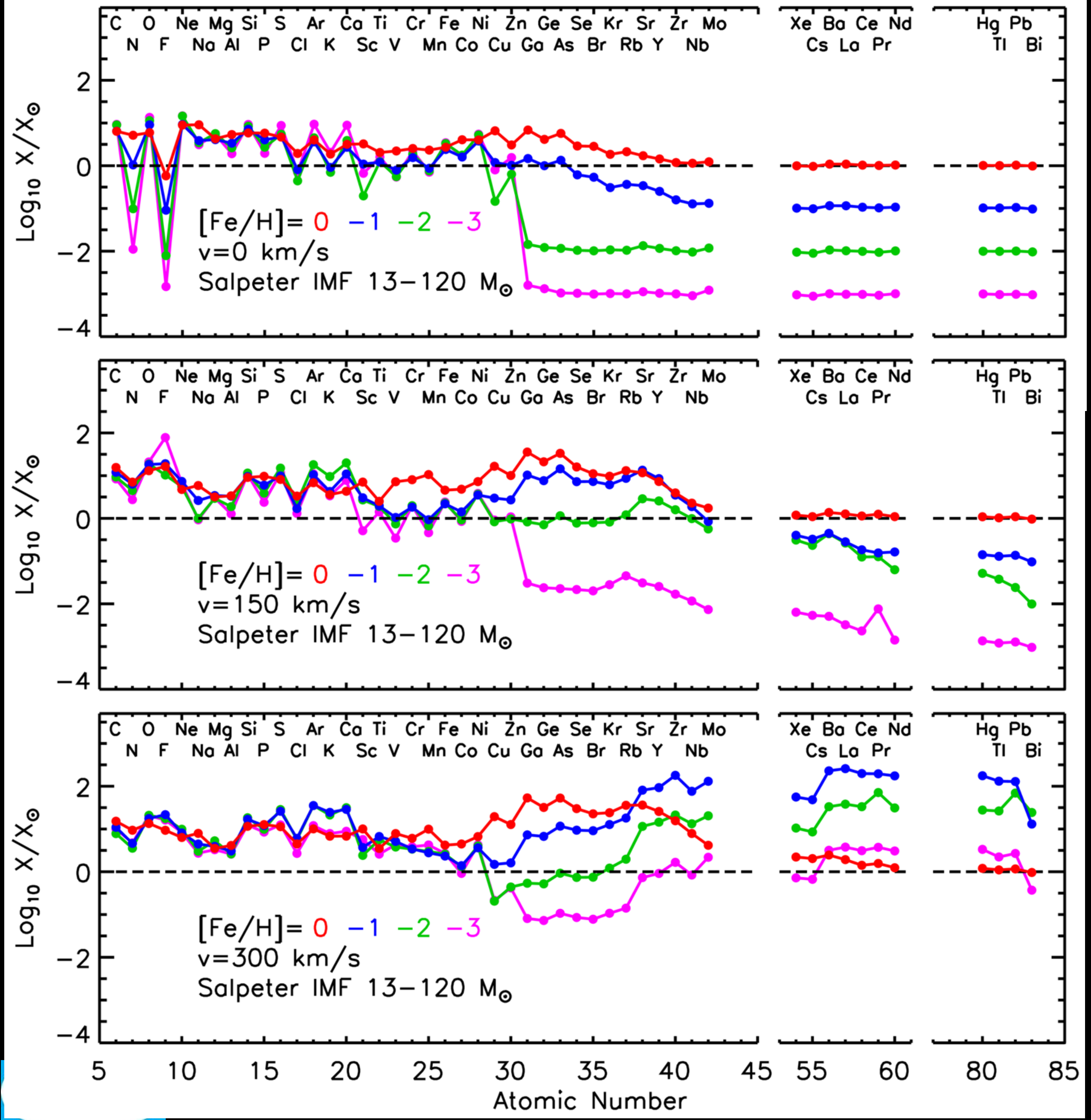


- Alpha elements behave as primaries
- N shows a negligible dependence on the initial metallicity (primary)
- Elements between Zn and Zr display a secondary like behavior and always underproduced compared with O. At solar metallicity almost coproduced with O
- Elements heavier than Zr behave like primary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

Summary and Conclusions



In the NON ROTATING case:

- Alpha elements show 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)

In the ROTATING case:

- 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