MASSIVE STARS: PRESUPERNOVA EVOLUTION, EXPLOSION AND NUCLEOSYNTHESIS

Marco Limongi
INAF – Osservatorio Astronomico di Roma, ITALY
Kavli IPMU, University of Tokyo, JAPAN
marco.limongi@oa-roma.inaf.it

in collaboration with

Alessandro Chieffi
INAF – Istituto di Astrofisica e Planetologia Spaziali, Italy
CSPA, Monash Univesity, Australia
alessandro.chieffi@iasf-roma.inaf.it

WHY ARE MASSIVE STARS IMPORTANT IN THE GLOBAL EVOLUTION OF OUR UNIVERSE?

Light up regions of stellar birth → induce star formation

Production of most of the elements (those necessary to life)

Mixing (winds and radiation) of the ISM

Production of neutron stars and black holes

Cosmology (PopIII):

Reionization of the Universe at $z>5$

Massive Remnants (Black Holes) → AGN progenitors

Pregalactic Chemical Enrichment

High Energy Astrophysics:

Production of long-lived radioactive isotopes:
(^{26}Al, ^{56}Co, ^{57}Co, ^{44}Ti, ^{60}Fe)

GRB progenitors

The understanding of these stars, is crucial for the interpretation of many astrophysical events

OBSERVATIONAL CONSTRAINTS

- CMD/HR diagrams of Young Populations and OB associations (location of RSG, BSG/RSG) in MW, LMC, SMC
- Relative number of O-type and WR stars and WR/WNE/WNL/WCO stars (mass limits for the formation of the various WR stars)
- Number ratio of Type II and Type Ibc SNe (mass limits for the formation of the various kind of SNe)
- Luminosities of WR stars
- Mass distribution and Periods of young Pulsars
- Progenitor Masses of Core Collapse Supernovae
- Surface composition of Galactic and Magellanic Cloud B-type stars
- γ-rays from the decay of ^{26}Al, ^{60}Fe and ^{44}Ti in the Galaxy
- Abundance pattern in Extremely Metal Poor Stars (EMPS)
- SNIbc/GRB number ratios
- Observed abundances

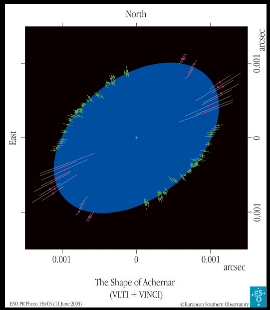
Global properties of a generation of massive stars are required to constrain the models

INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

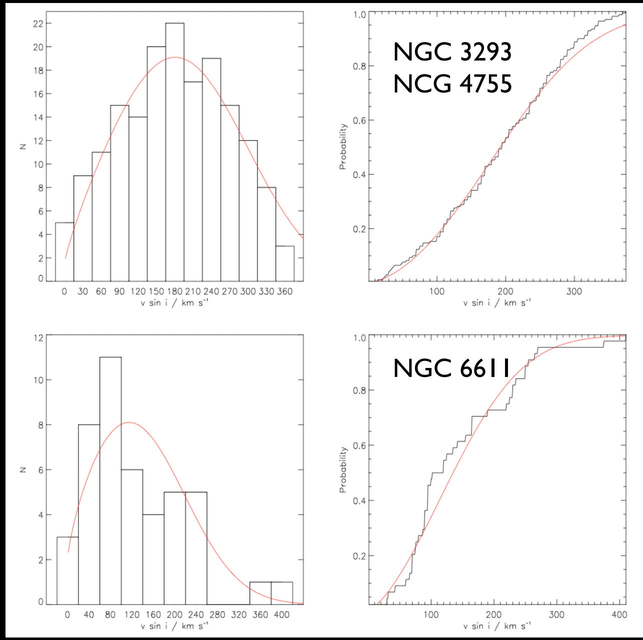
ROTATION IN STELLAR MODELS: IS IT REALLY NEEDED?

Why should we include rotation in the calculation of stellar models?
Why should we complicate our life?

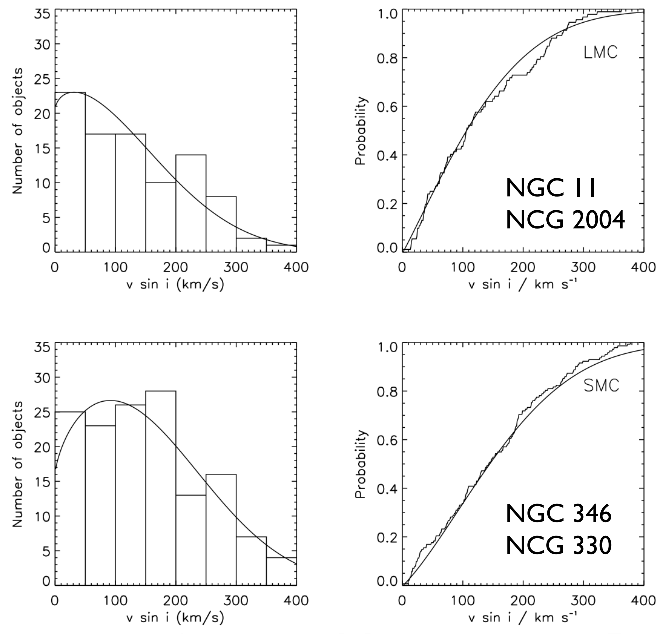


….simply because stars rotate!

VLT-FLAMES survey of massive stars

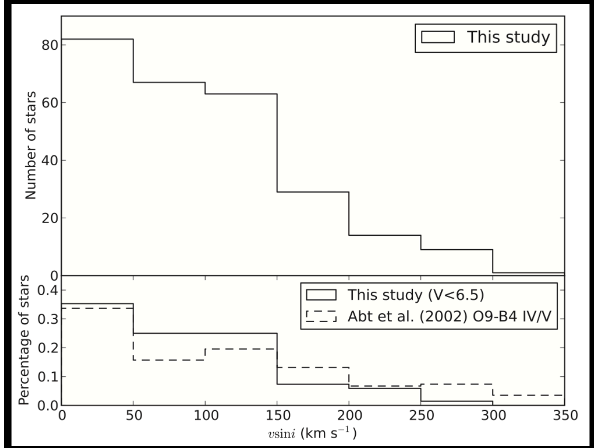


Dufton+ 2006



Hunter+ 2008

266 O and B type stars in galactic clusters, associations and field

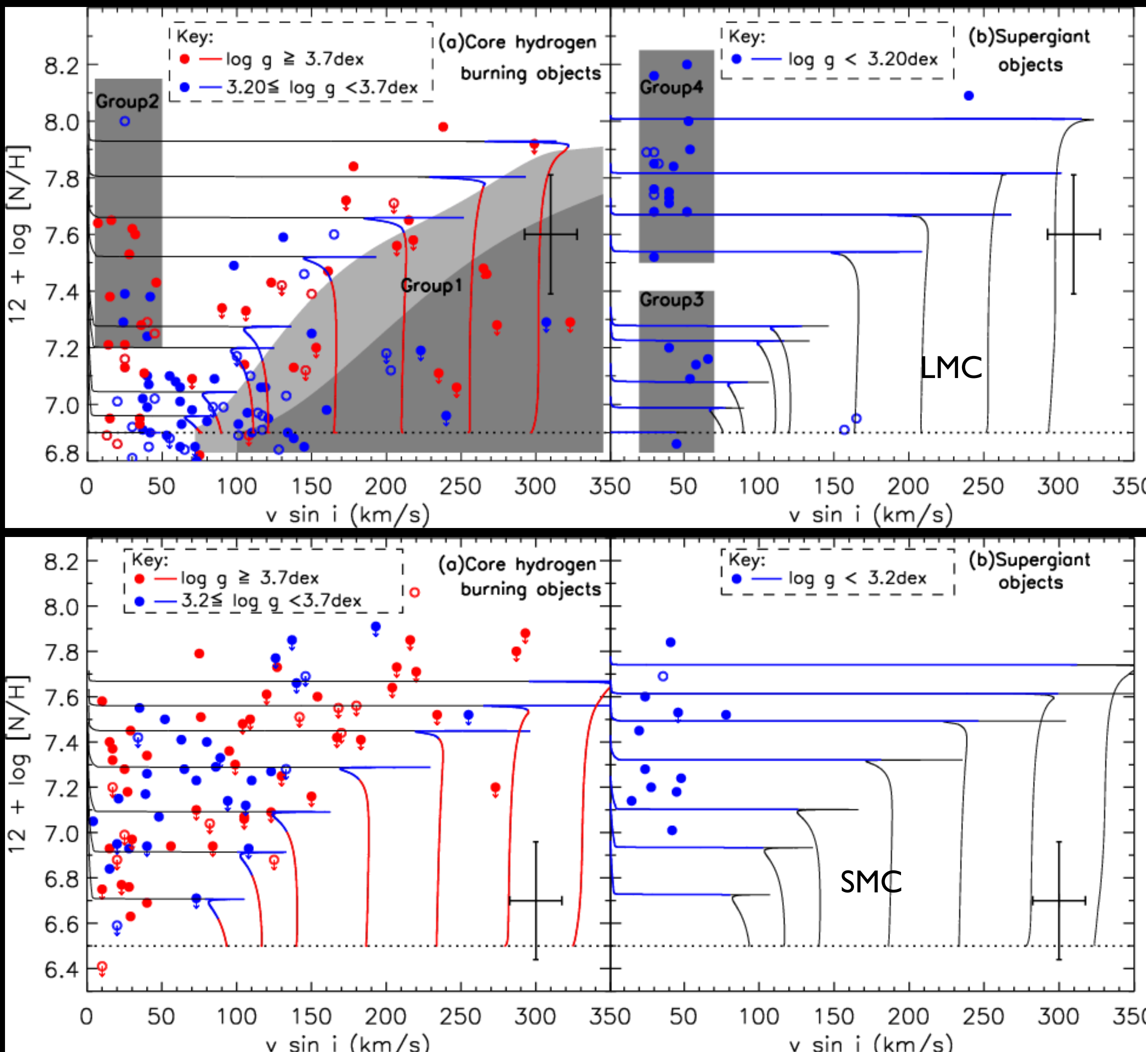


Bragança+ 2012

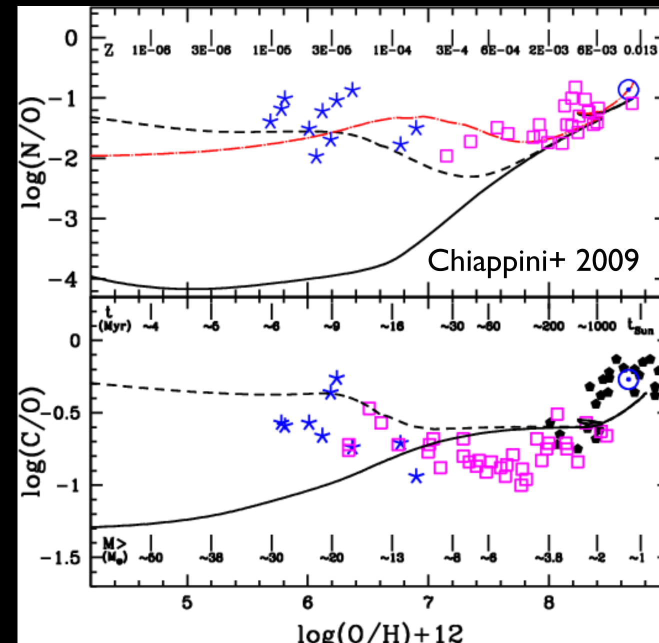
hence its inclusion will help us to better understand them and the world out there

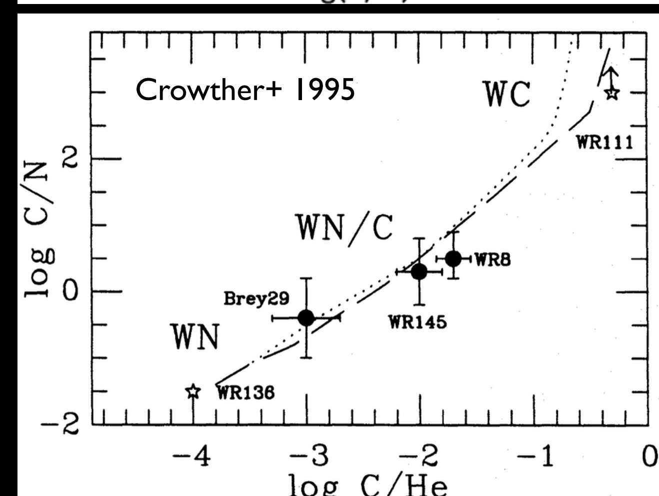
A FEW CHALLENGES IN MASSIVE STAR EVOLUTION

Some observational evidences cannot be interpreted in terms of "classical" models



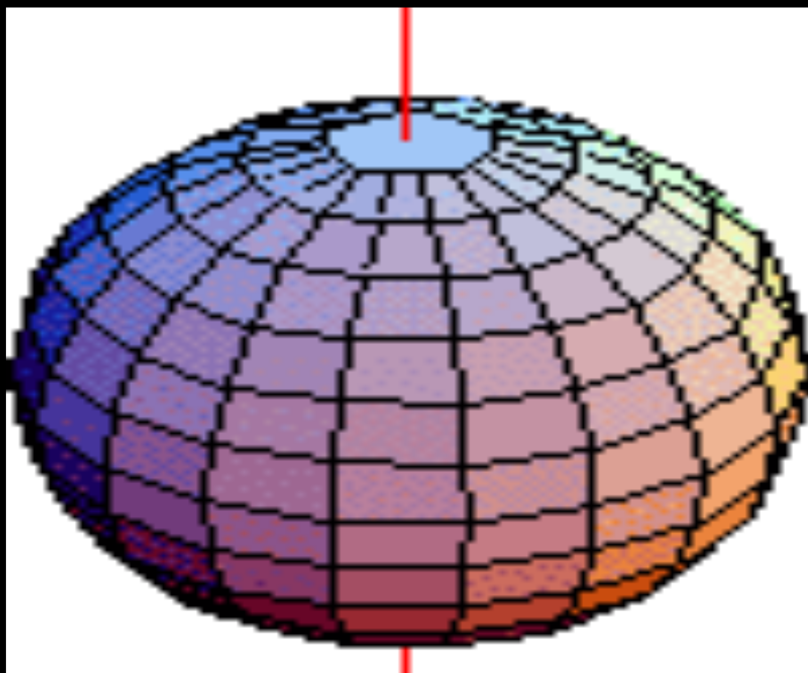
Hunter+ 2009

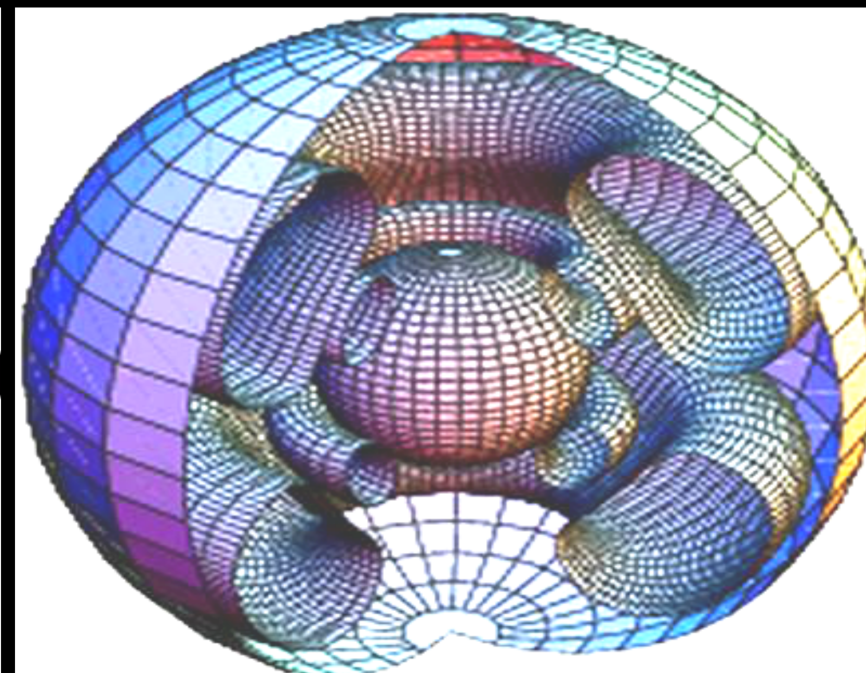




THE PHYSICS OF ROTATION

Rotation is clearly a multidimensional effect → in order to correctly take into account this phenomenon a 2D or even a 3D stellar evolution code should be required





Courtesy of A. Maeder & G. Meynet

THE EQUATION OF STELLAR STRUCTURES

By means of few proper assumptions it is possible to simulate the mechanical and thermal distortions induced by rotation in a 1D code (see Kippenhahn & Thomas 1970)

in this case the equations for the stellar structure may be written on equipotentials as (Kippenhahn & Thomas 1970) :

$$\frac{dP}{dM_\Psi} = -\frac{GM_\Psi}{4\pi r_\Psi^4} f_P$$

$$\frac{dr_\Psi}{dM_\Psi} = \frac{1}{4\pi r_\Psi^2 \rho_\Psi}$$

$$\frac{dlnT_\Psi}{dlnP_\Psi} = -\frac{3\kappa_\Psi L_\Psi P_\Psi}{16\pi acGT_\Psi^4 M_\Psi} \nabla \frac{f_T}{f_P}$$

$$\frac{dL_\Psi}{dM_\Psi} = \varepsilon_\Psi$$

r_Ψ radius of the sphere having the same volume of the equipotential

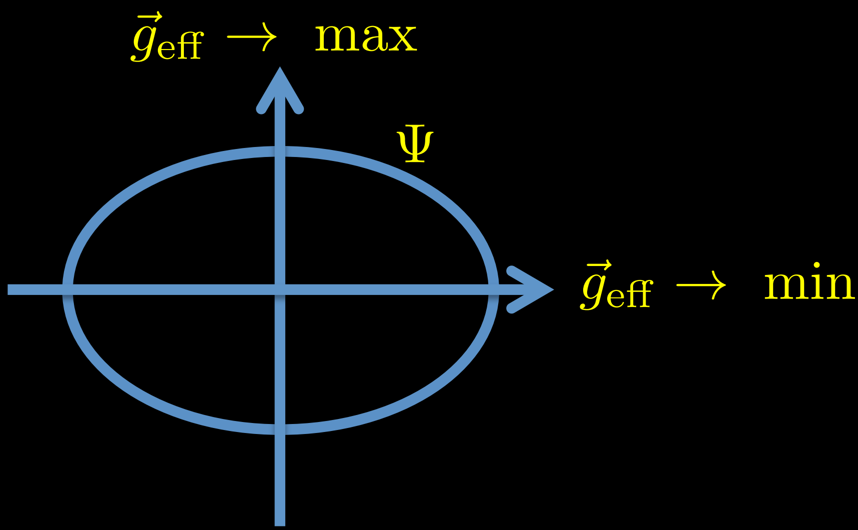
$$V_\Psi = \frac{4}{3}\pi r_\Psi^3$$

M_Ψ mass enclosed inside the equipotential

They keep the same form they have in spherical symmetry except for correction factors that are determined ones the shape of the equipotentials S_Ψ are known

$$f_P = \frac{4\pi r_\Psi^4}{GM_\Psi S_\Psi \langle g_{\mathrm{eff}}^{-1}\rangle} \qquad f_T = \frac{16\pi^2 r_\Psi^4}{S_\Psi^2 \langle g_{\mathrm{eff}}^{-1}\rangle \langle g_{\mathrm{eff}}\rangle}$$

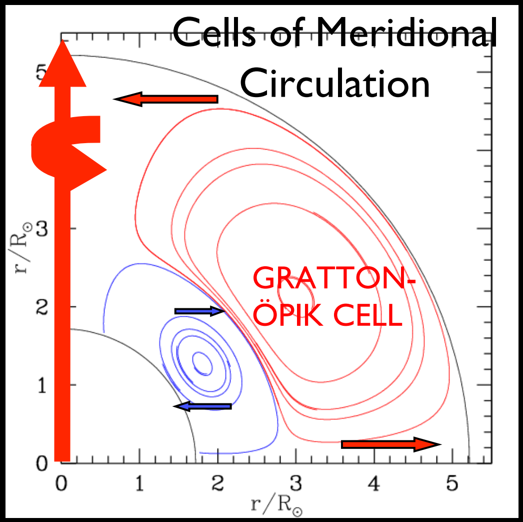
ROTATION DRIVEN INSTABILITIES: MERIDIONAL CIRCULATION



Von Zeipel (1924) was the first one to notice that these two equations cannot be simultaneously fulfilled in radiative equilibrium

$$\vec{F}_\Psi(r,\vartheta,\varphi) = f(\Psi)\vec{g}_{\rm eff}$$

$$\vec{\nabla}\cdot\vec{F}_\Psi(r,\vartheta,\varphi) = \varepsilon_\Psi$$



courtesy of G. Meynet

In order to balance the variation of the radiative flux along the equipotential, a large-scale MERIDIONAL CIRCULATION develops

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

ROTATION DRIVEN INSTABILITIES: MERIDIONAL CIRCULATION

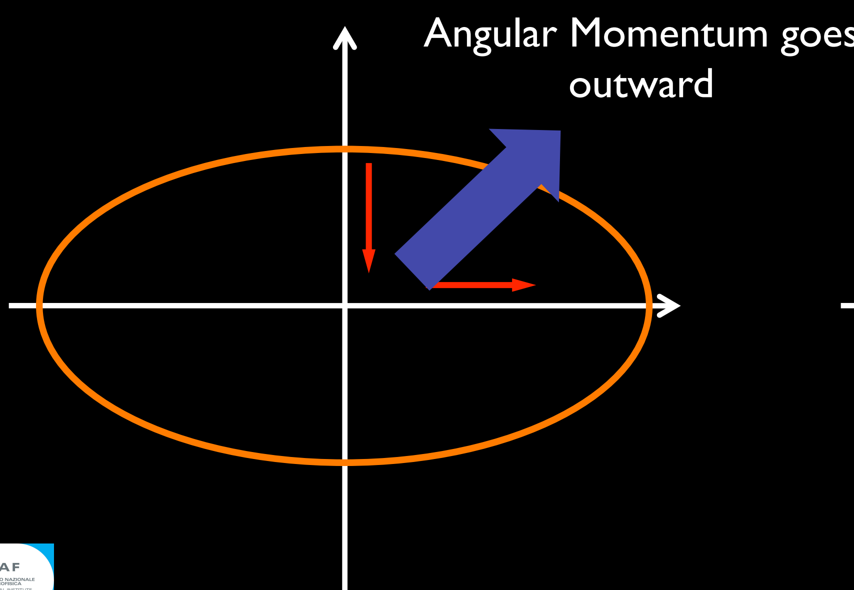
$$\vec{\nabla} \cdot \vec{F}_{\mathrm{rad}}(r, \vartheta, \varphi) = \rho \varepsilon_{\mathrm{nuc}} - c_P \rho \frac{\partial T}{\partial t} + \delta \frac{\partial P}{\partial t} - \vec{U} \cdot (c_P \rho \vec{\nabla} T - \delta \vec{\nabla} P)$$

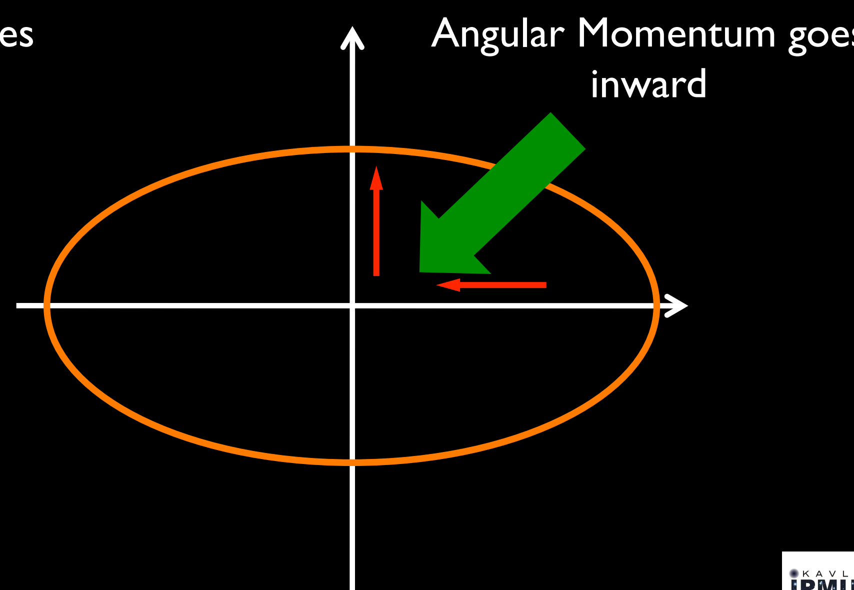
Meridional circulation moves matter through the star and hence it is responsible for both the angular momentum transport and the mixing of the chemical composition

The prescription (sign) for the velocity of the meridional circulation is crucial

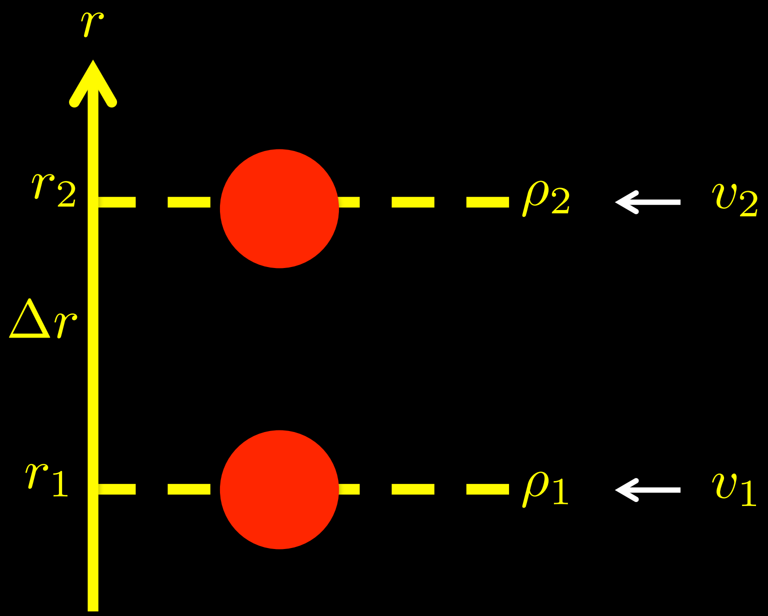
$$U = \frac{P}{\rho g C_P T [\nabla_{\mathrm{ad}} - \nabla + (\varphi/\delta)\nabla_\mu]} \left\{ \frac{L}{M} \left[\frac{8}{3} \frac{\omega^2 r^3}{GM} \left(1 - \frac{\omega^2}{2\pi G \rho} - \frac{\bar{\varepsilon} + \varepsilon_g}{\varepsilon_m} \right) + \right. \right.$$
$$\left. \left. - \frac{\rho_m}{\rho} \left(\frac{r}{3} \frac{d}{dr} A - 2 \frac{H_T}{r} \left(1 + \frac{D_h}{K} \right) \frac{\Theta}{\delta} + \frac{2}{3} \Theta \right) - \frac{\bar{\varepsilon} + \varepsilon_g}{\varepsilon_m} \left(A + f_\varepsilon \varepsilon_T \frac{\Theta}{\delta} + (1 - f_\varepsilon) \Theta \right) - \frac{\omega^2}{2\pi G \rho} \Theta \right] + \frac{C_P T}{\delta} \frac{\partial \Theta}{\partial t} \right\}$$

Maeder & Zahn (1998)





ROTATION DRIVEN INSTABILITIES: TURBULENT SHEAR



Restoring force $f = -g \dfrac{\partial \rho}{\partial r} \Delta r \Delta V$

Energy $E_{\mathrm{restoring}} = f \cdot \Delta r$

Differentially rotating layers

$$E_{\mathrm{turbulent}} = \Delta M \left(\Delta v\right)^2 = \rho \Delta v \left(\frac{\partial v}{\partial r} \Delta r \right)^2$$

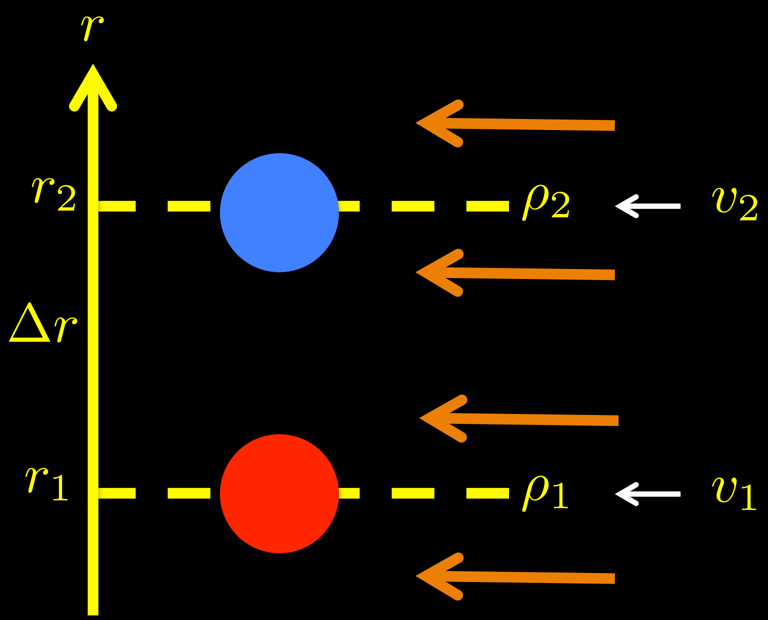
$$R = \frac{E_{\mathrm{restoring}}}{E_{\mathrm{turbulent}}} = \frac{g}{\rho} \frac{\partial \rho}{\partial r} \left(\frac{\partial r}{\partial v} \right)^2 = \left(N_T^2 + N_\mu^2\right) \left(\frac{\partial \ln r}{\partial \omega} \right)^2$$

Richardson number

$$N_T^2 = \frac{g\delta}{H_P} \left(\nabla_{\mathrm{ad}} - \nabla_{\mathrm{rad}}\right) \qquad N_\mu^2 = \frac{g\delta}{H_P} \left(\frac{\varphi}{\delta} \nabla_\mu \right)$$

$$R < \frac{1}{4}$$ → **Dynamical Shear**

ROTATION DRIVEN INSTABILITIES: TURBULENT SHEAR



Thermal losses reduce the restoring force

Horizontal currents reduce both the restoring force and the mean molecular weight gradient

$$N_T^2 \rightarrow \frac{\Gamma_T}{\Gamma_T + 1} N_T^2 \qquad N_\mu^2 \rightarrow \frac{\Gamma_\mu}{\Gamma_\mu + 1} N_\mu^2$$

$$\Gamma_T = \frac{vl}{6\left(K + D_h\right)} \qquad \Gamma_\mu = \frac{vl}{6D_h}$$

K Thermal diffusivity

D_h Turbulent horizontal diffusivity

$$R = \left(N_T^2 + N_\mu^2\right)\left(\frac{\partial \ln r}{\partial \omega}\right)^2 \Rightarrow R = \left(\frac{\Gamma_T}{\Gamma_T + 1} N_T^2 + \frac{\Gamma_\mu}{\Gamma_m u + 1} N_\mu^2\right)\left(\frac{\partial \ln r}{\partial \omega}\right)^2$$

$$R < \frac{1}{4} \rightarrow$$ **Secular Shear**

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

TRANSPORT OF THE ANGULAR MOMENTUM

ADVECTION-DIFFUSION EQUATION

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

Advection due to meridional circulation

Diffusion due to turbulent shear

The adoption of the U provided by Maeder & Zahn 1998 leads to a fourth order equation (U contains third order derivatives of ω) → a system of 4 ODE must be solved by means of a relaxation technique

TRANSPORT OF THE CHEMICAL SPECIES

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

Diffusion coefficients due to meridional circulation and shear turbulent mixing

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

$$D_{\rm shear} = \frac{8}{5}\frac{R_i (r d\omega/dr)^2}{N_T^2/(k+D_h) + N_\mu^2/Dh}$$

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

INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Presupernova Evolution of Rotating and Non Rotating Massive Stars @ Various Metallicities

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 et al. 2009

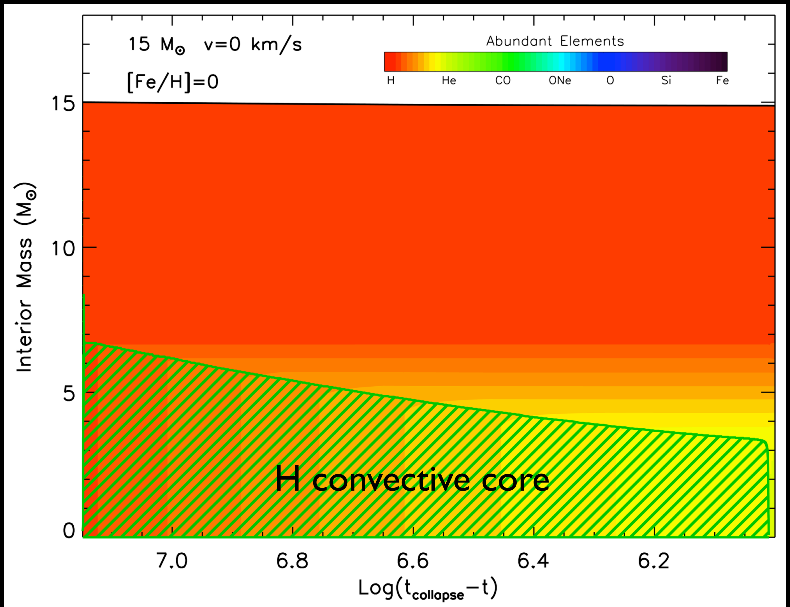
[Fe/H]=-1, Z=3.236 10^{-3}
[Fe/H]=-2, Z=3.236 10^{-4}
[Fe/H]=-3, Z=3.236 10^{-5}

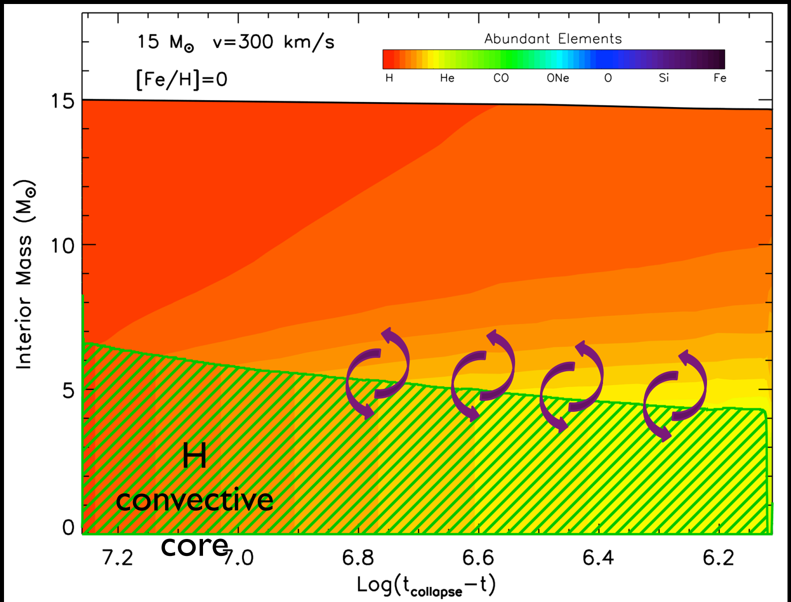
Scaled solar $Fe/Fe_{\odot}$=0.1,0.01,0001
except
[C/Fe]=0.18
[O/Fe]=0.47
[Mg/Fe]=0.27
[Si/Fe]=0.37
[S/Fe]=0.35
[Ar/Fe]=0.35
[Ca/Fe]=0.33
[Ti/Fe]=0.23
(Cayrel+ 2004 and Spite+ 2005)

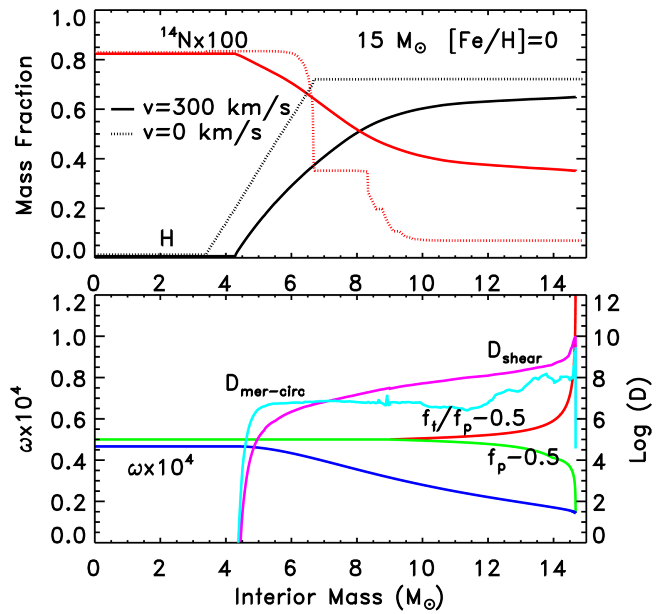
INITIAL EQUATORIAL VELOCITIES: 0, 150, 300 km/s

MASSIVE STAR MODELS with [Fe/H]=0: CORE H BURNING

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



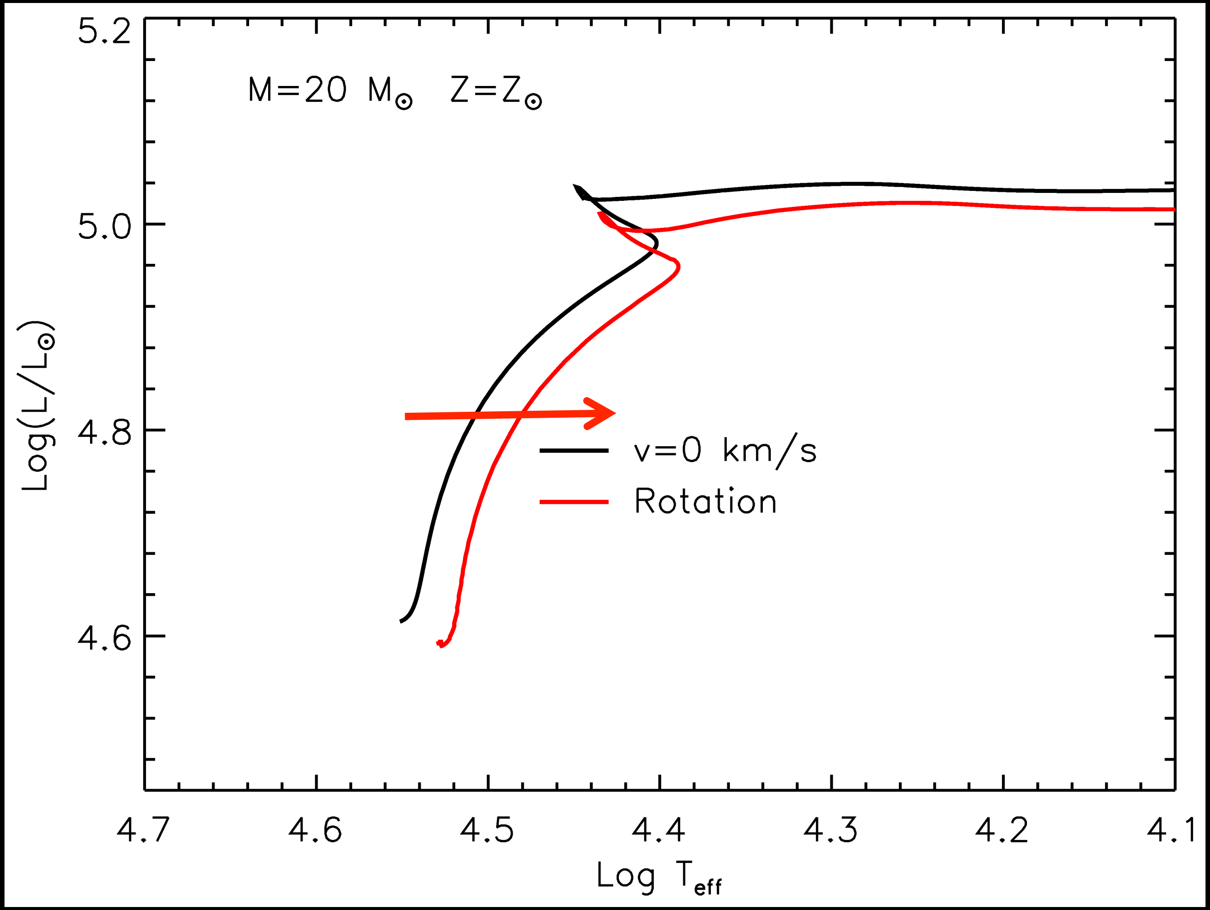




- Increase of the H burning lifetime
- Increase of the He core mass
- Enrichment of the surface ^{14}N

MASSIVE STAR MODELS with [Fe/H]=0: CORE H BURNING

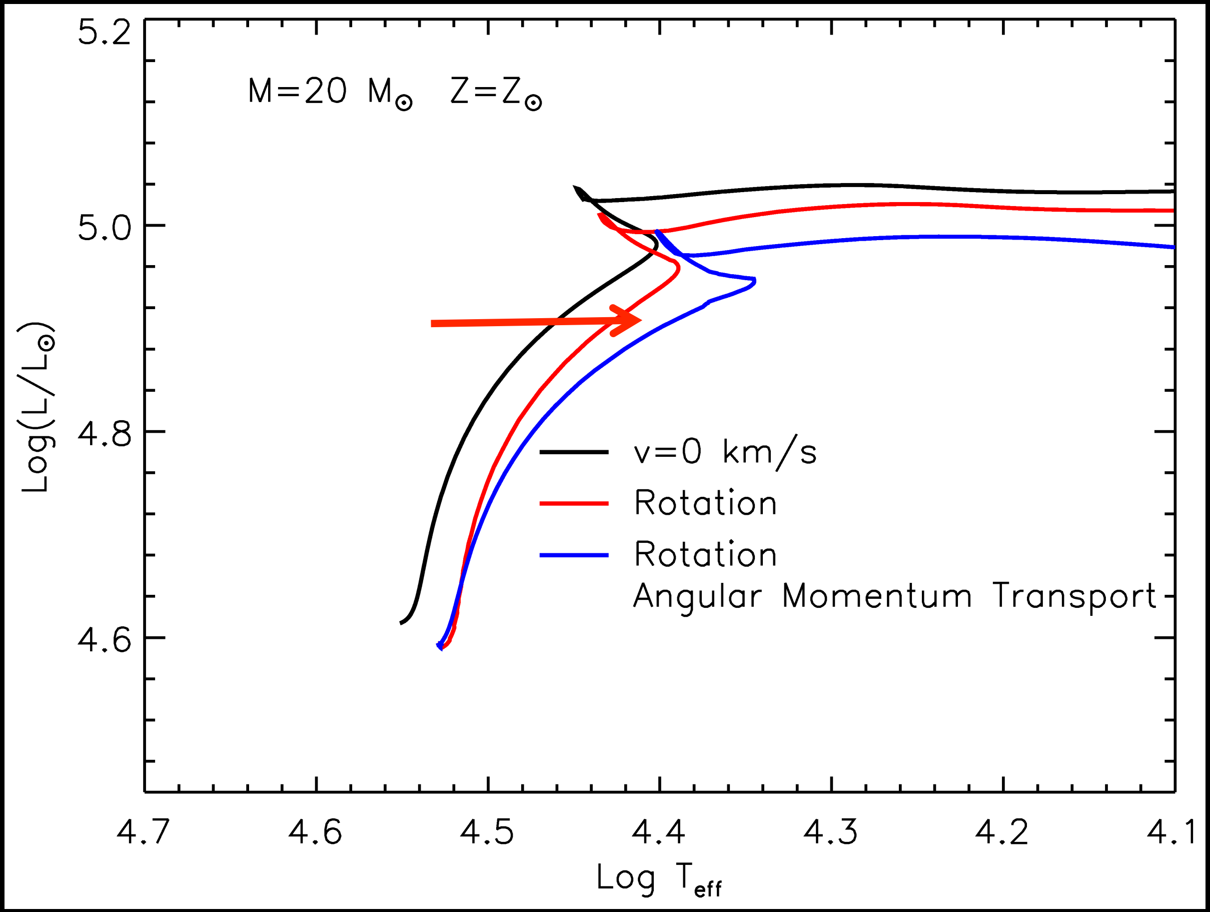
Evolutionary track in the HR diagram



The effective gravity is reduced → the star is less luminous and more expanded

MASSIVE STAR MODELS with [Fe/H]=0: CORE H BURNING

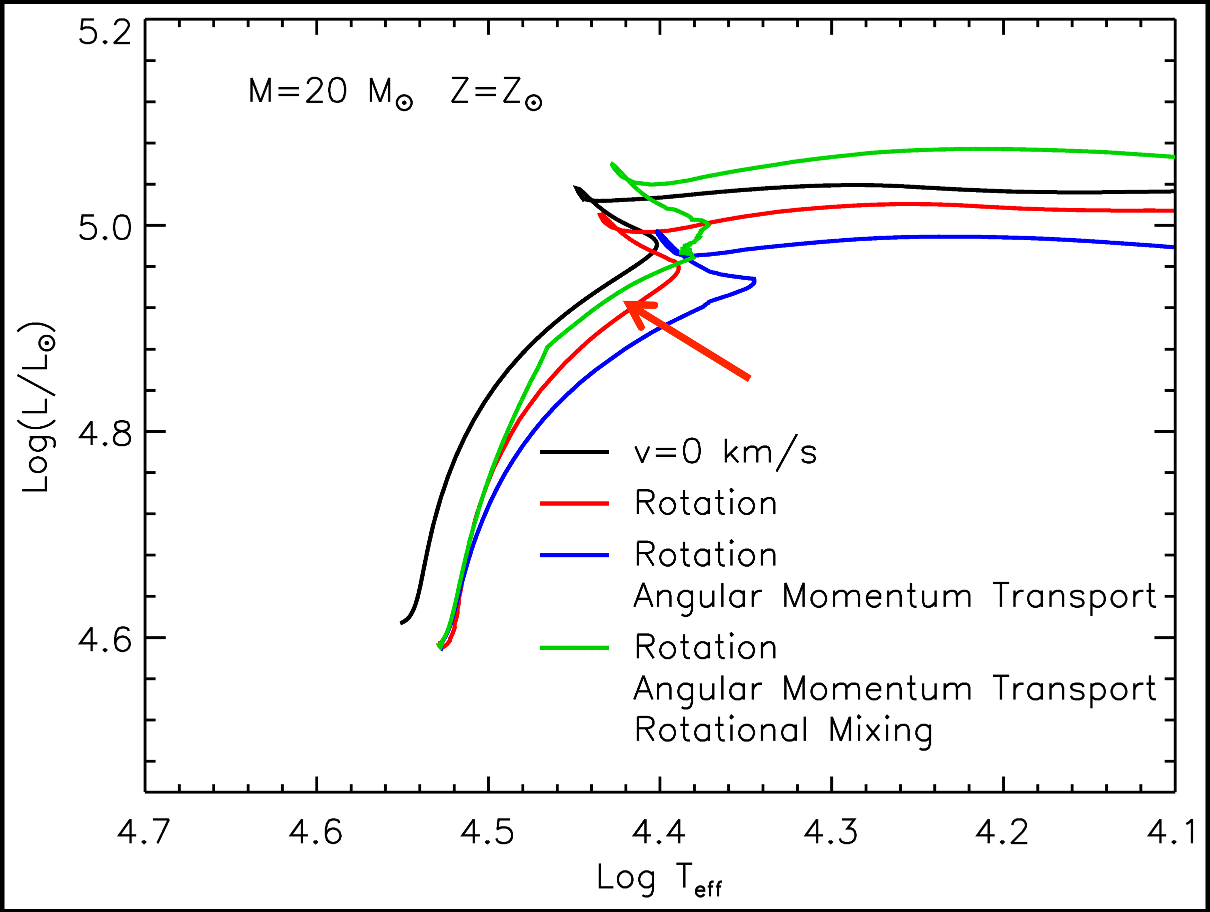
Evolutionary track in the HR diagram



The angular momentum transport increases the angular velocity of the surface
→ reduces even more the effective gravity

MASSIVE STAR MODELS with [Fe/H]=0: CORE H BURNING

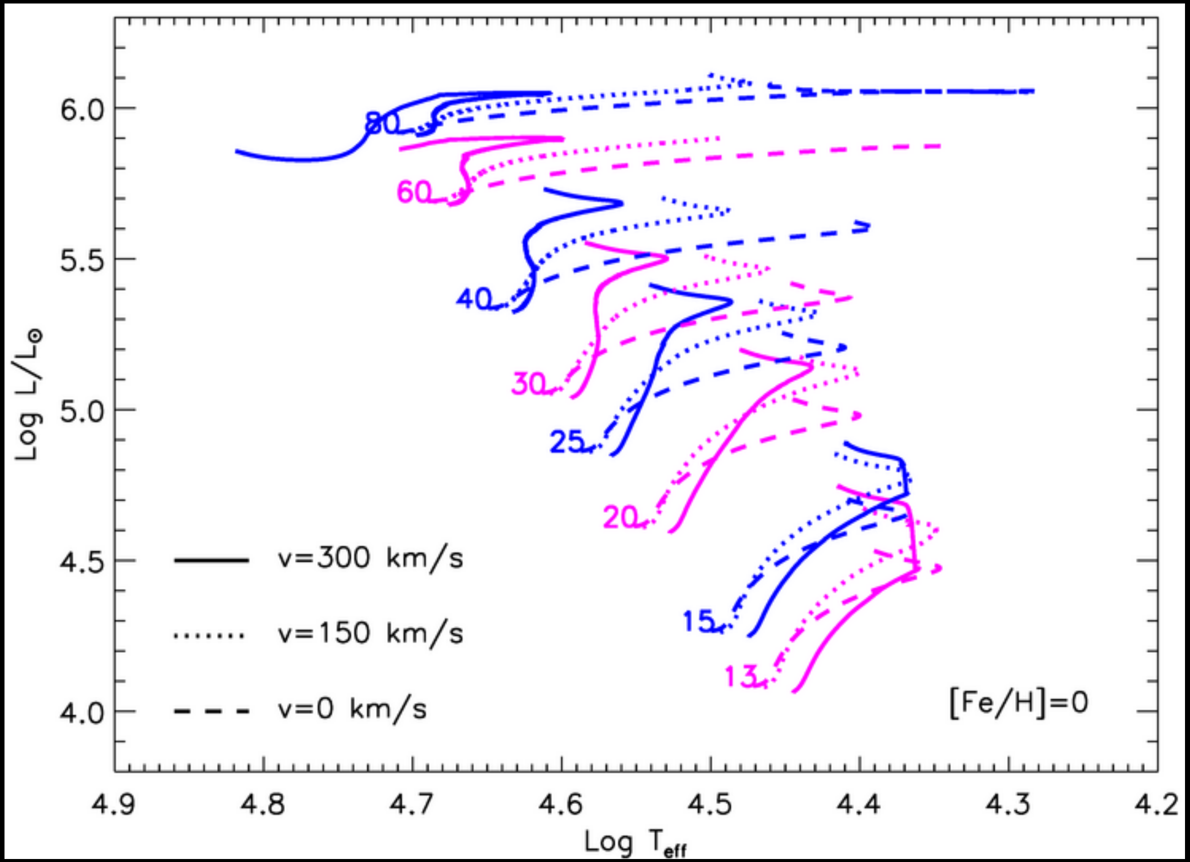
Evolutionary track in the HR diagram



The rotational mixing increases the mean molecular weight on average → simulate the effect of the overshooting and makes the star more compact

MASSIVE STAR MODELS with [Fe/H]=0: CORE H BURNING

Evolutionary track: **Angular Momentum Transport Redward Evolution** vs **Rotational Mixing Blueward Evolution**

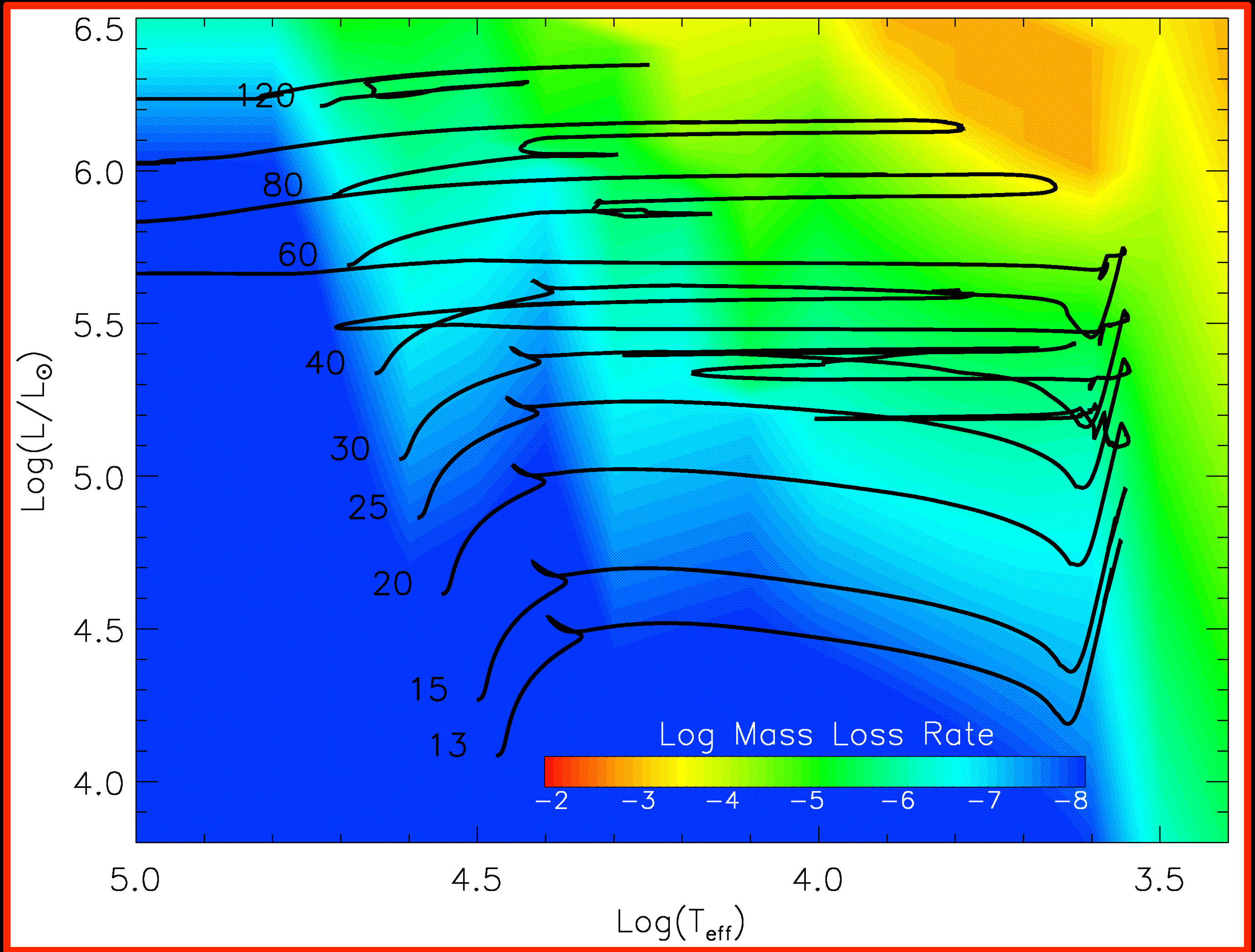


For v=300 km/s angular momentum transport works initially, than rotational mixing drives the evolution in the HR diagram

MASSIVE STAR MODELS with [Fe/H]=0: CORE H BURNING

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

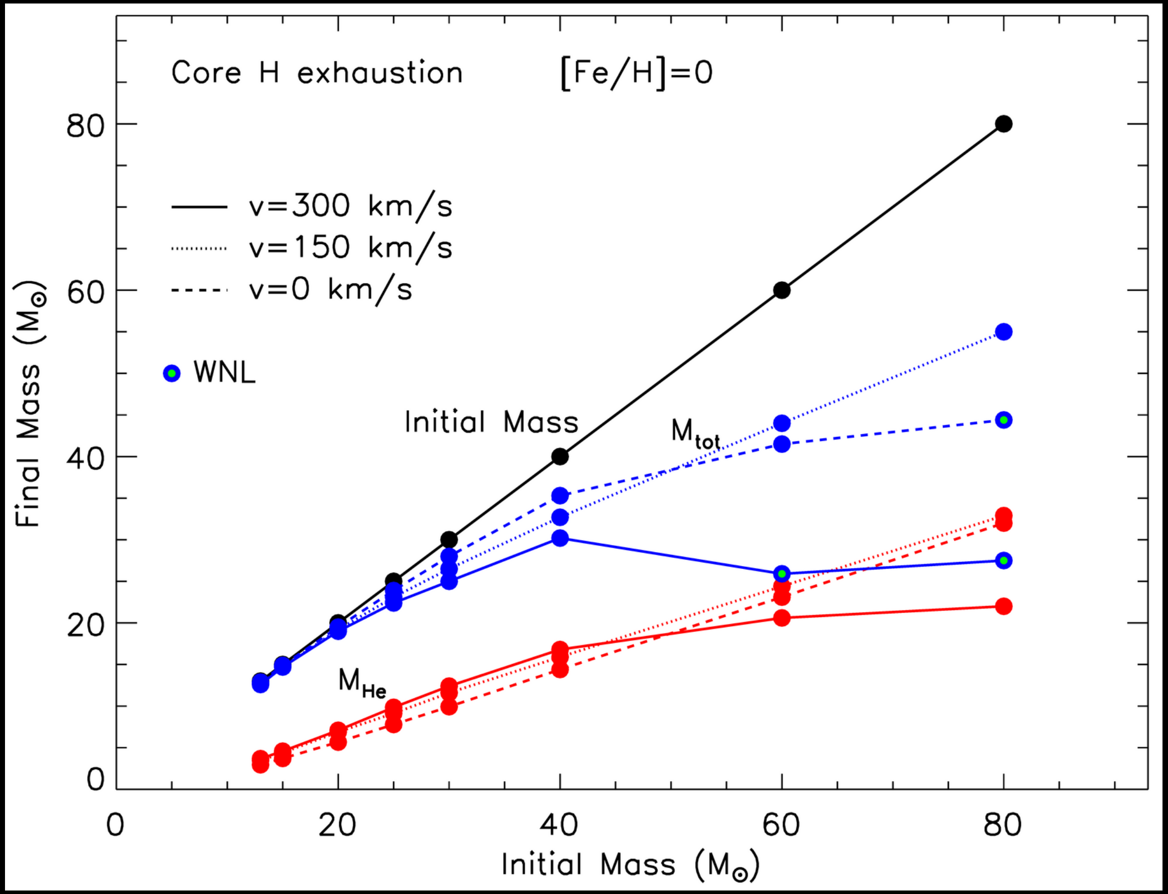
Mass Loss is higher for higher L and lower T_{eff}



MASSIVE STAR MODELS with [Fe/H]=0: CORE H BURNING

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

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

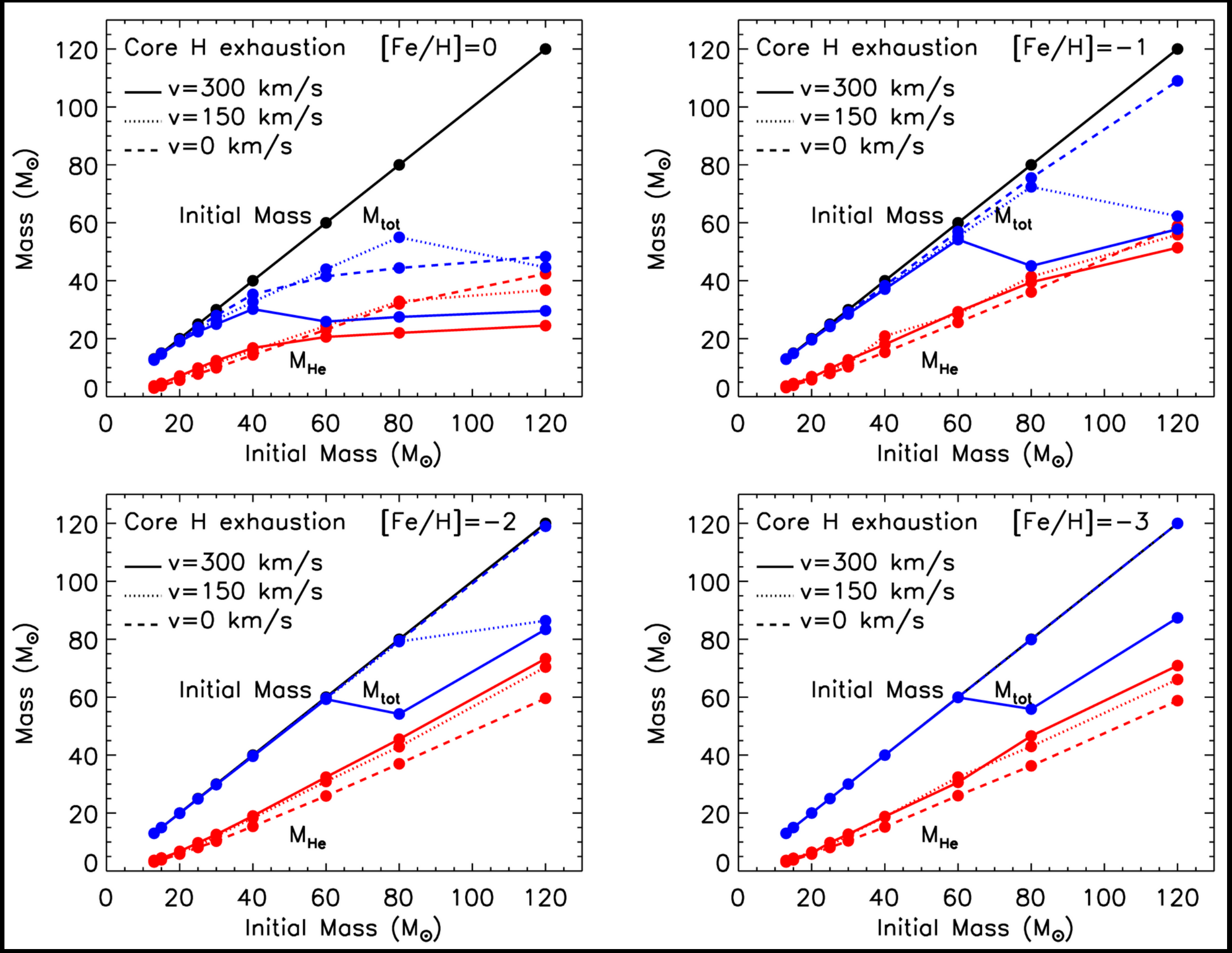


- Smaller masses, larger He core masses → Smaller envelope masses
- Higher mean molecular weight in the envelope (more compact structures)

ROTATING MODELS: CORE H BURNING @ VARIOUS METALLICITIES

Decreasing the metallicity → Increase of Rotation Induced Mixing $\tau_{diff} \sim \frac{\Delta R^2}{D}$

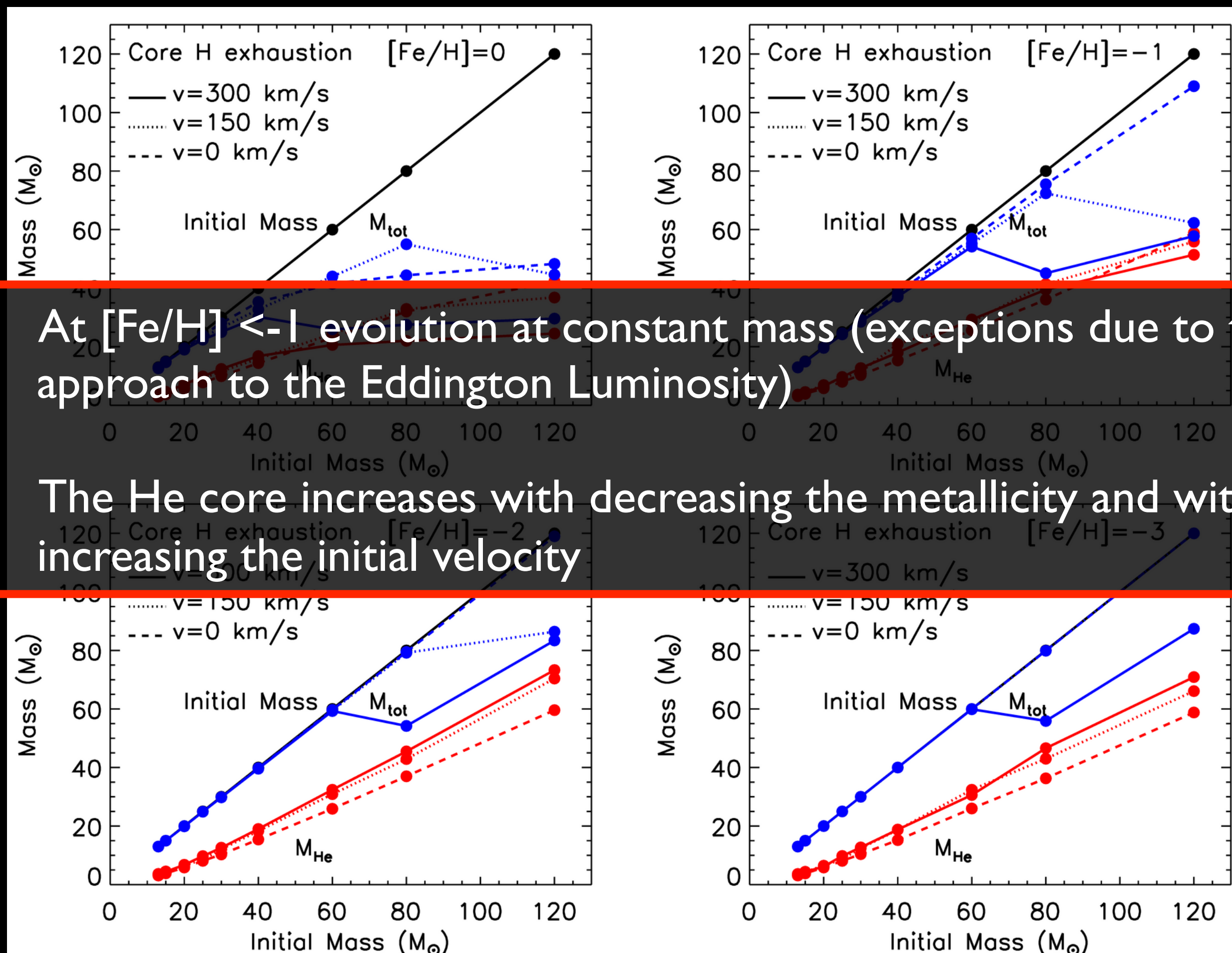
→ Decrease of Mass Loss efficiency $\dot{M} \sim Z^{0.85}$



ROTATING MODELS: CORE H BURNING @ VARIOUS METALLICITIES

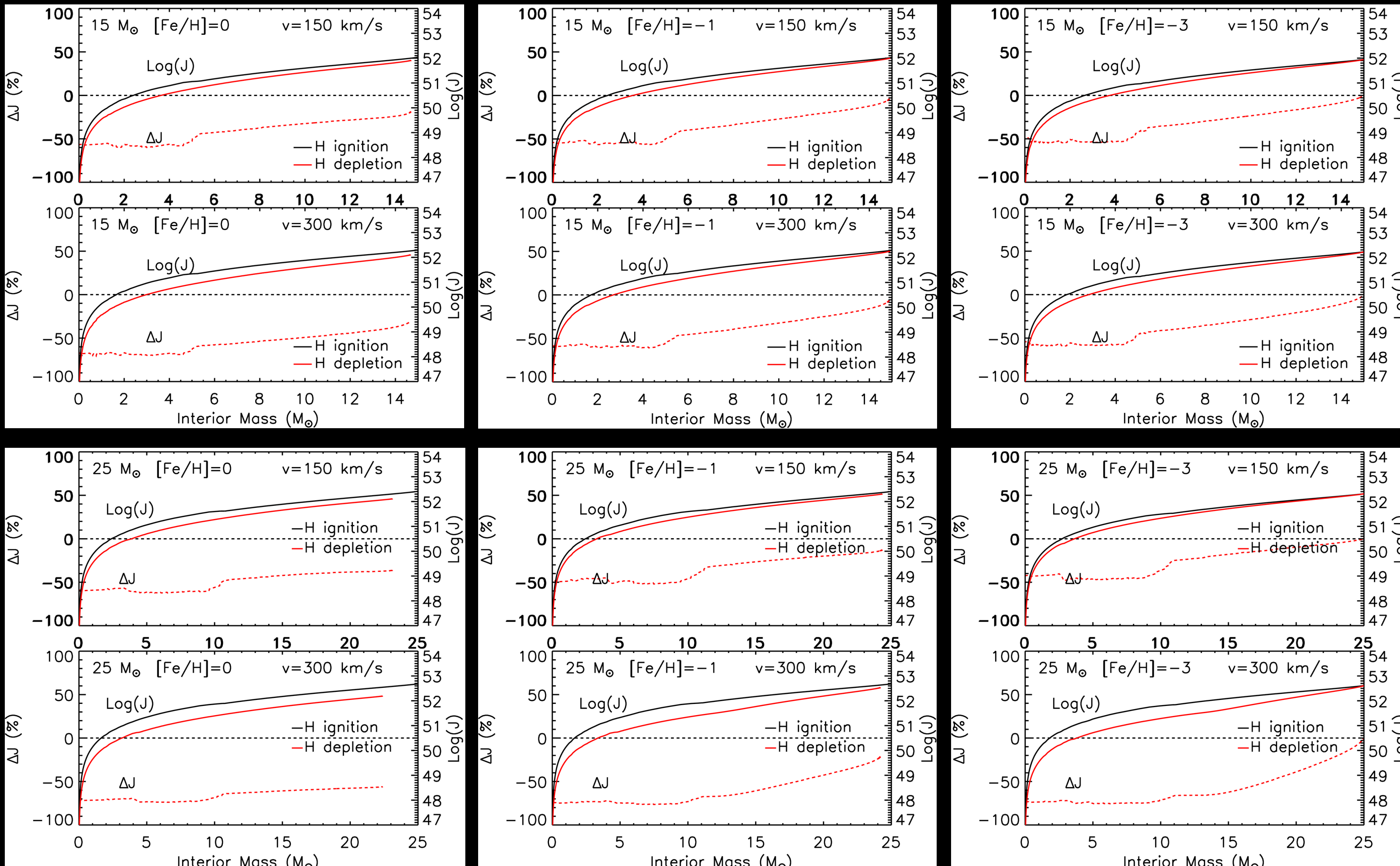
Decreasing the metallicity

- Increase of Rotation Induced Mixing $\tau_{diff} \sim \frac{\Delta R^2}{D}$
- Decrease of Mass Loss efficiency $\dot{M} \sim Z^{0.85}$



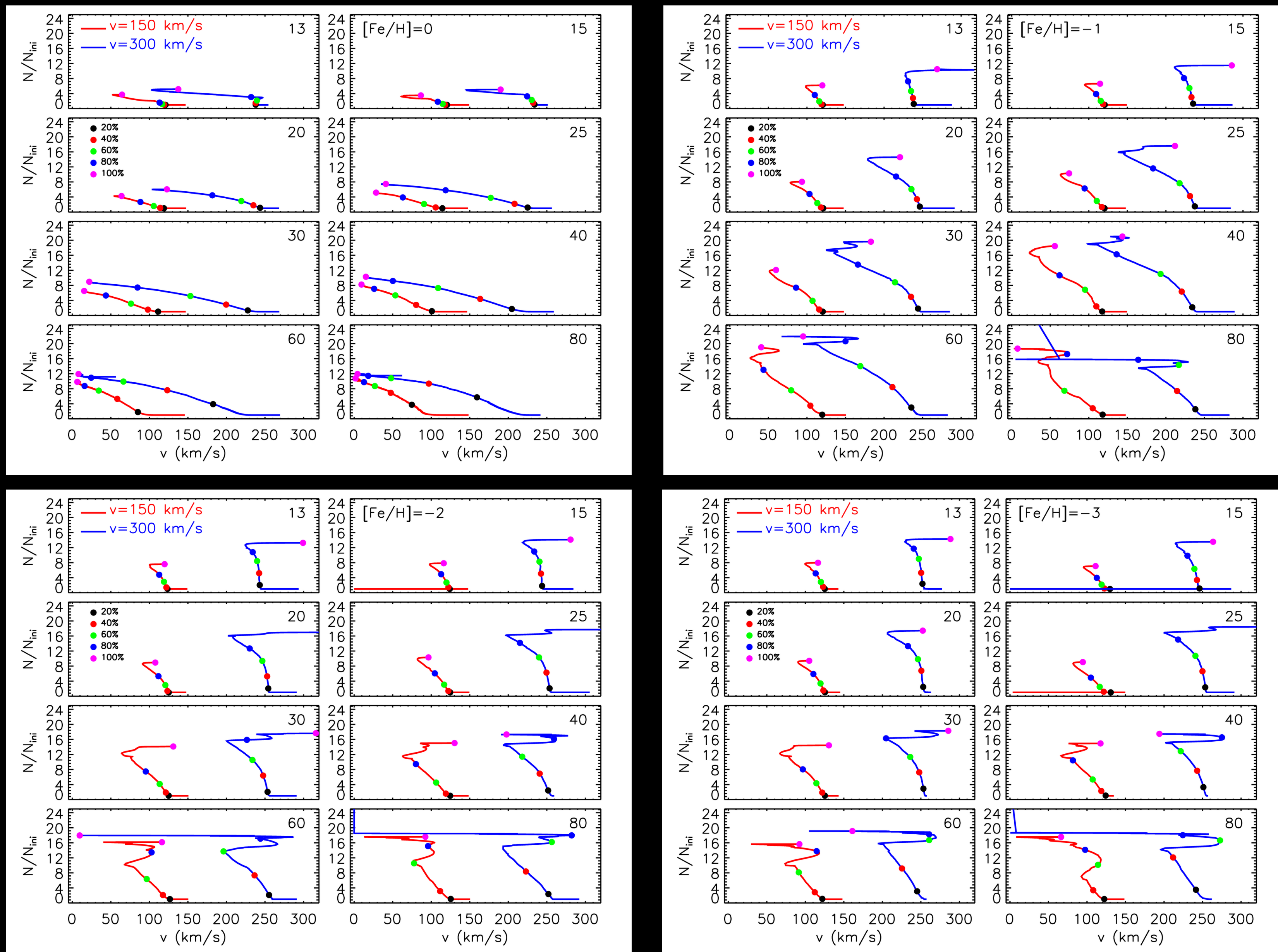
- At [Fe/H] <-1 evolution at constant mass (exceptions due to the approach to the Eddington Luminosity)
- The He core increases with decreasing the metallicity and with increasing the initial velocity

ROTATING MODELS: CORE H BURNING @ VARIOUS METALLICITIES



- Efficiency of the angular momentum transport in the interior essentially independent of the initial metallicity (convection)
- Total angular momentum essentially constant at lower metallicities due to the strong reduction of the stellar wind

ROTATING MODELS: CORE H BURNING @ VARIOUS METALLICITIES

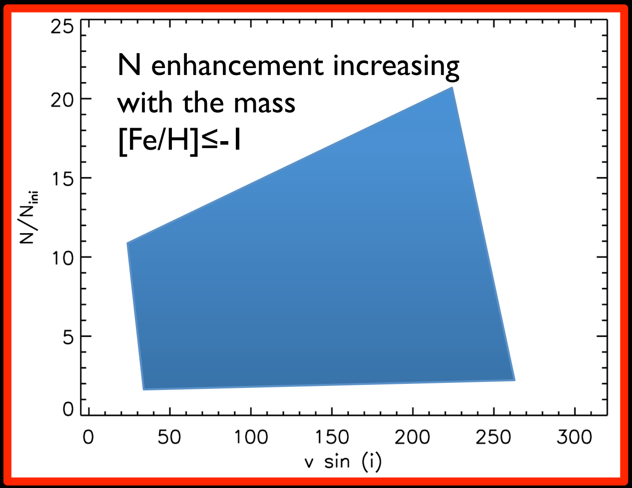


INAF

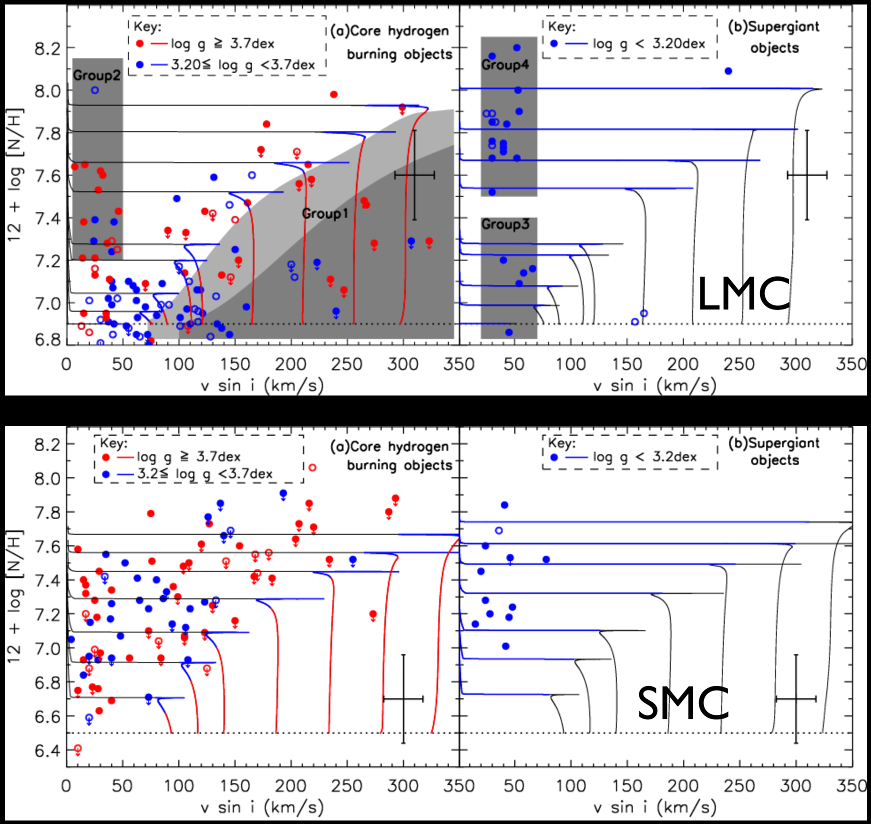
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

ROTATING MODELS: CORE H BURNING @ VARIOUS METALLICITIES

VLT-FLAMES survey of Massive Stars (Hunter+ 2009)

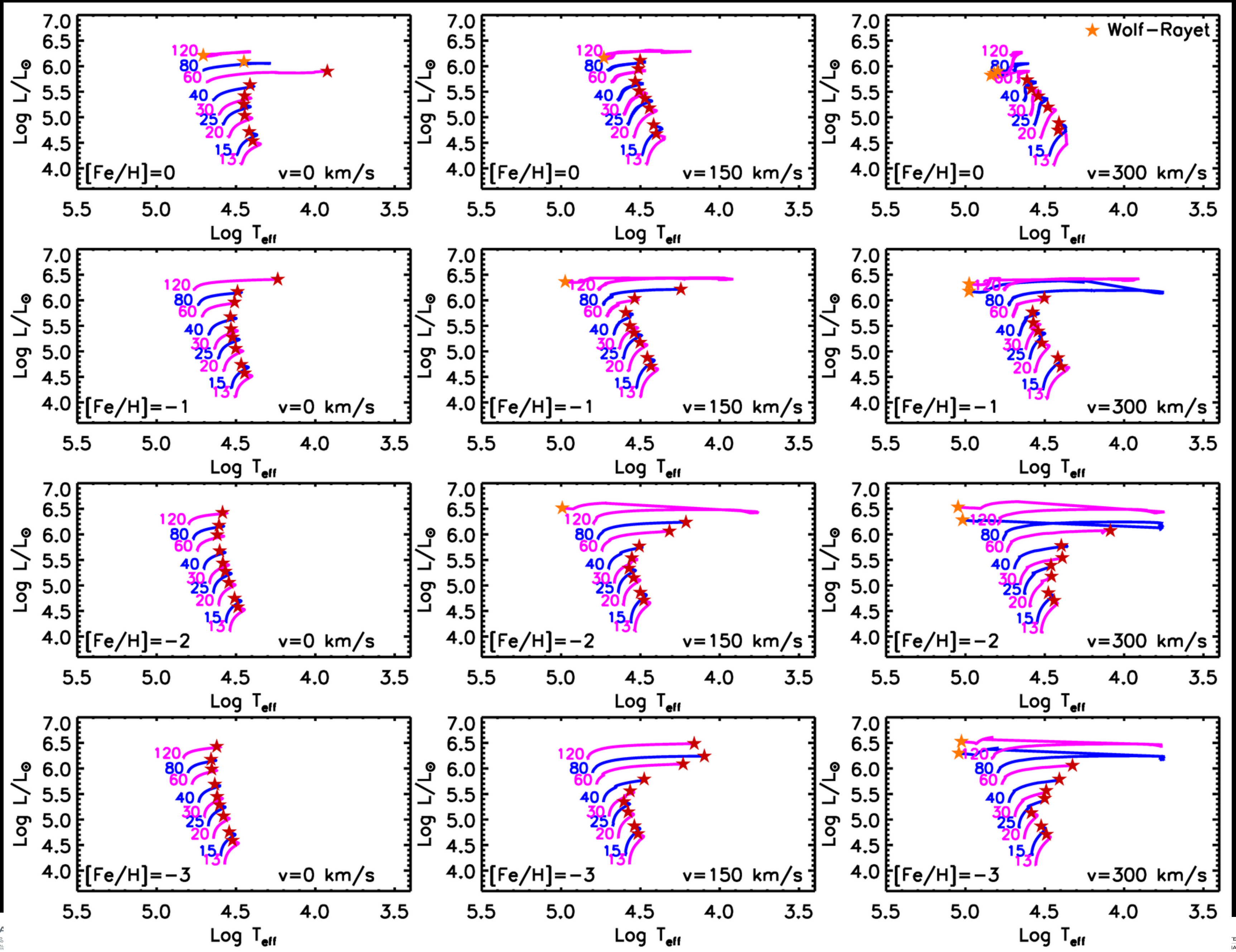


?

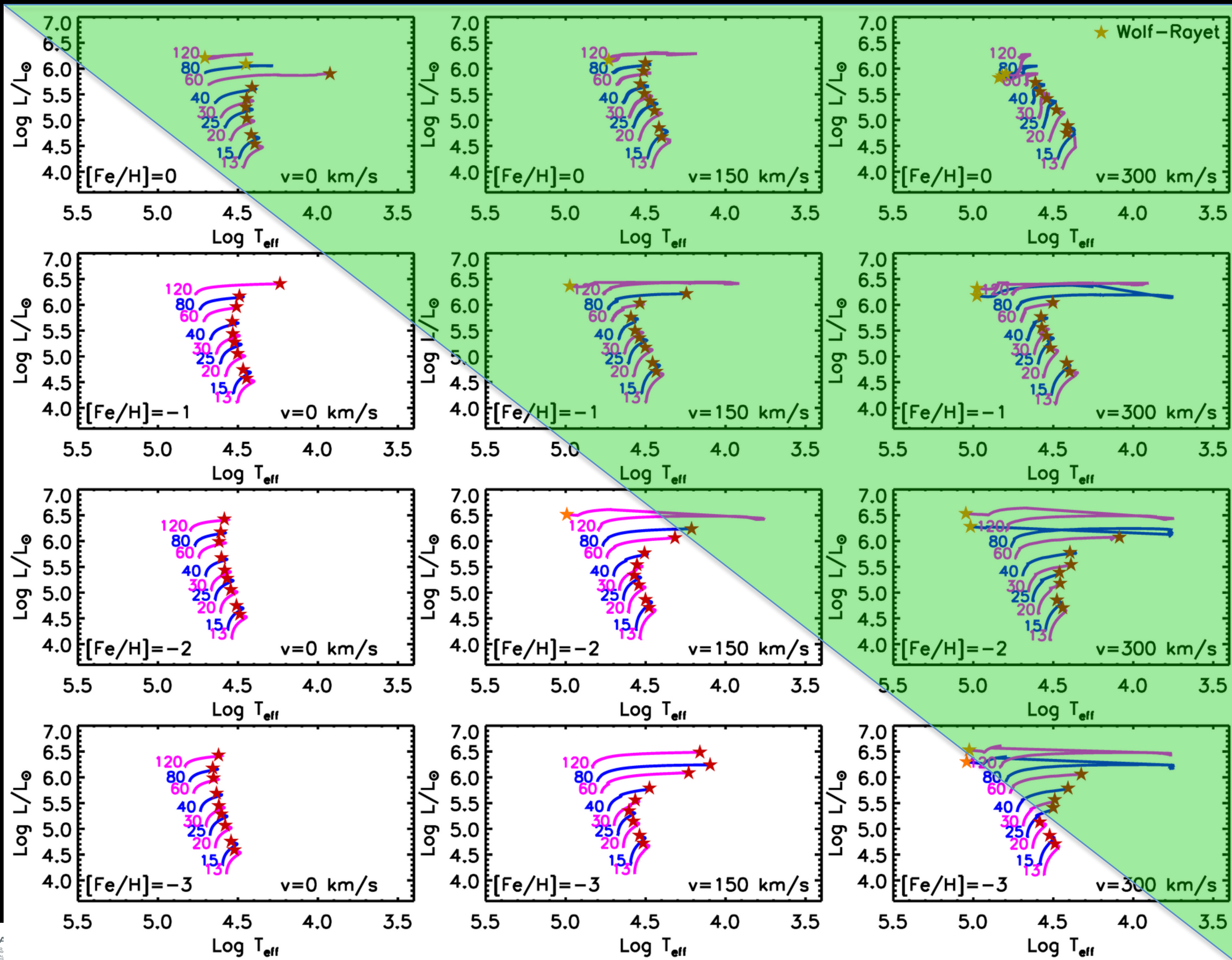


Hunter+ 2009

Configuration @ Core H Depletion

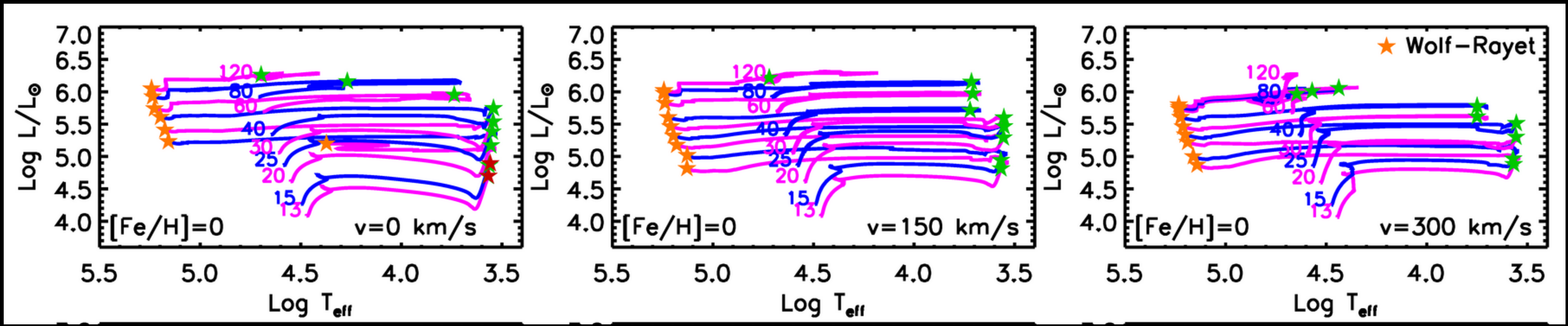


Configuration @ Core H Depletion



Core He Burning: Solar Metallicity Models

After core H depletion, all the solar metallicity models (except the most massive and the most rapidly rotating) evolve toward a RSG configuration



During the following evolution (core He burning)

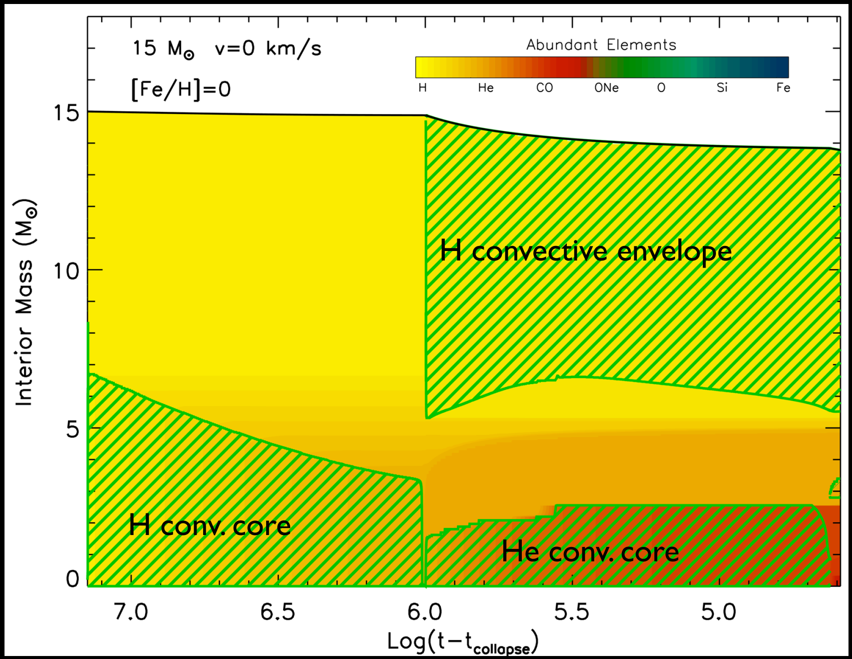
- The more luminous models reach the Eddington limit → lose most of the H-rich envelope and evolve toward a BSG configuration

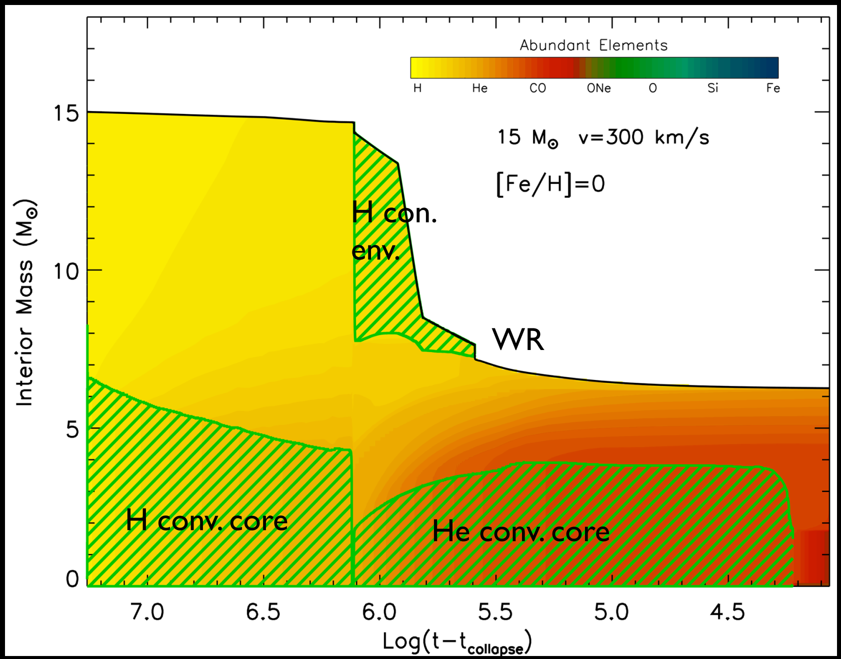
- The low luminous models become cool enough that dust driven wind becomes very efficient. The central He mass fraction at which this occurs determines how much mass is lost during core He burning and weather the star evolves to a BSG (WR) configuration

Core He Burning: Mass Loss

This model enters the dust production region at the very end of core He burning → a very small amount of mass is lost during this phase → the star remains a RSG

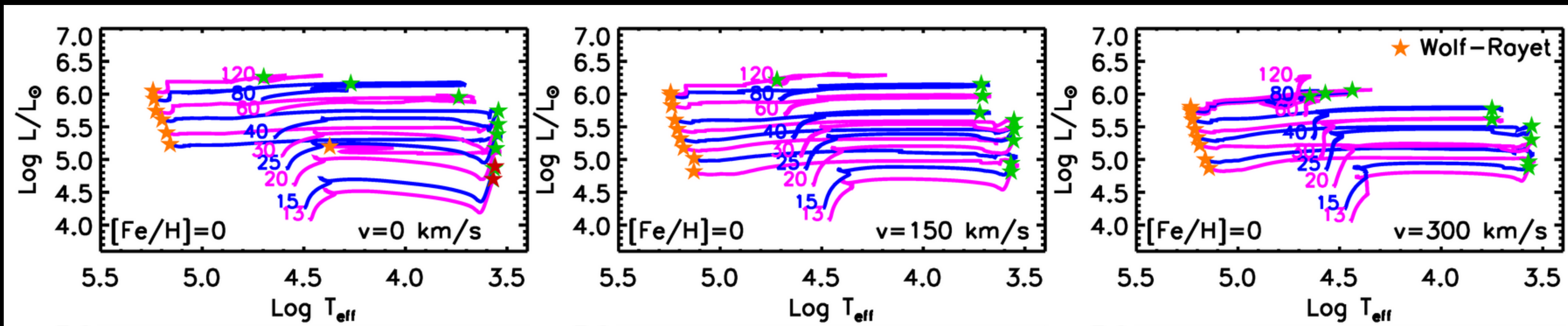
This model enters the dust production region at an early stage of core He burning → all the H-rich envelope is lost during this phase → the star evolves to a BSG (WR) configuration





Core He Depletion: Solar Metallicity Models

Configuration @ He depletion



M ≥ 20 M$_\odot$ → WR

M ≤ 15 M$_\odot$ → RSG

M ≥ 13 M$_\odot$ → WR

M ≥ 13 M$_\odot$ → WR

WR : $Log_{10}(T_{eff}) > 4.0$

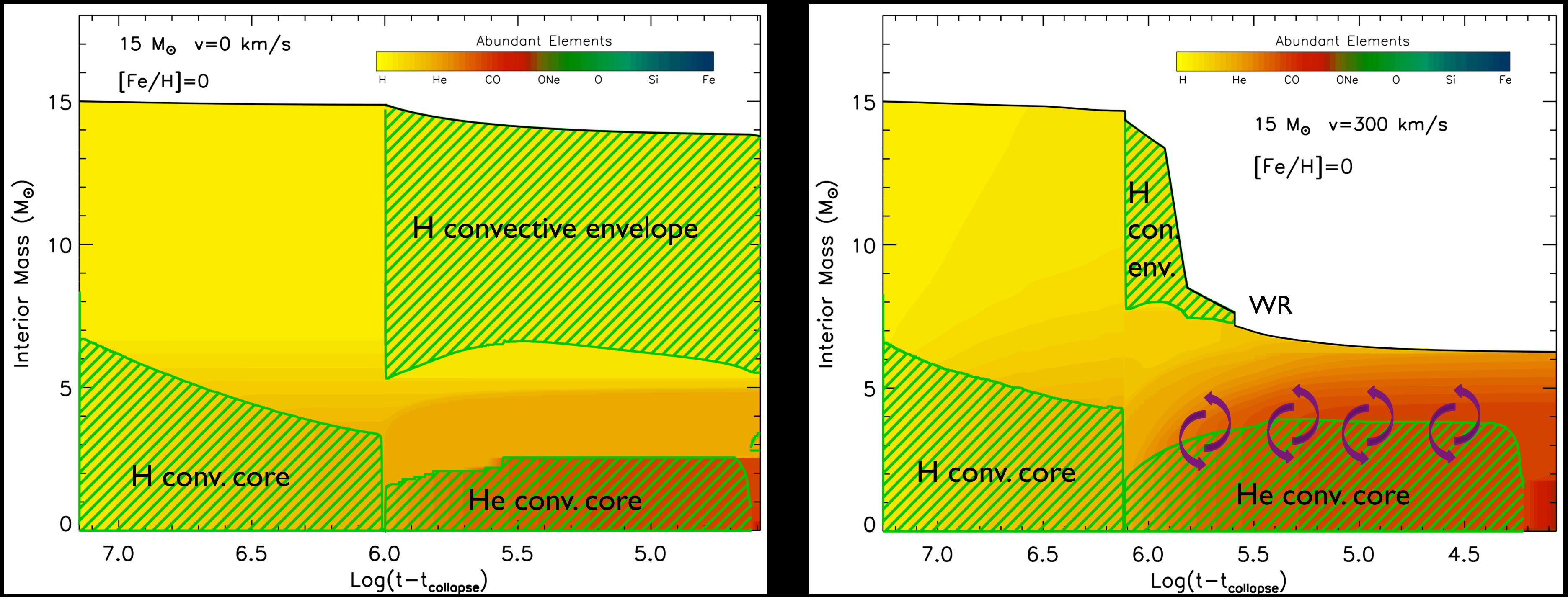
- WNL: $10^{-5} < H_{sup} < 0.4$ (H burning, CNO, products)
- WNE: $H_{sup} < 10^{-5}$ (No H)
- WNC: 0.1 < X(C)/X(N) < 10 (both H and He burning products, N and C)
- WC: [X(C)+X(O)]/X(He) < 1 (He burning products)
- WO: [X(C)+X(O)]/X(He) ≥ 1 (He burning products)

INAF Istituto Nazionale di Astrofisica National Institute for Astrophysics

Kavli IPMU Institute for the Physics and Mathematics of the Universe

ROTATING MODELS with [Fe/H]=0: CORE He BURNING

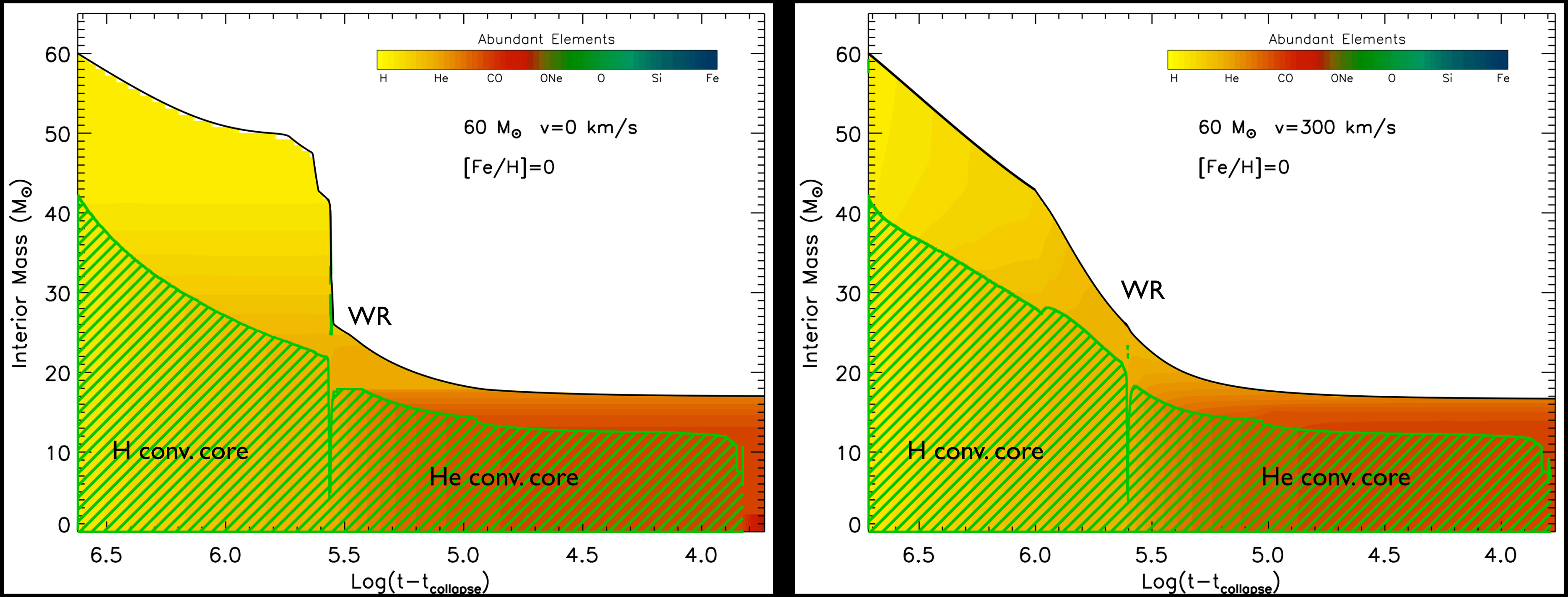
M<40 $M_\odot$: Rotational mixing dominates



- Rotation induced mixing beyond the He convective core
  - Reduced μ-gradient barrier → larger convective cores
  - Larger CO cores
  - Continuous inward mixing of fresh ^{4}He fuel → Lower ^{12}C left over at core He depletion

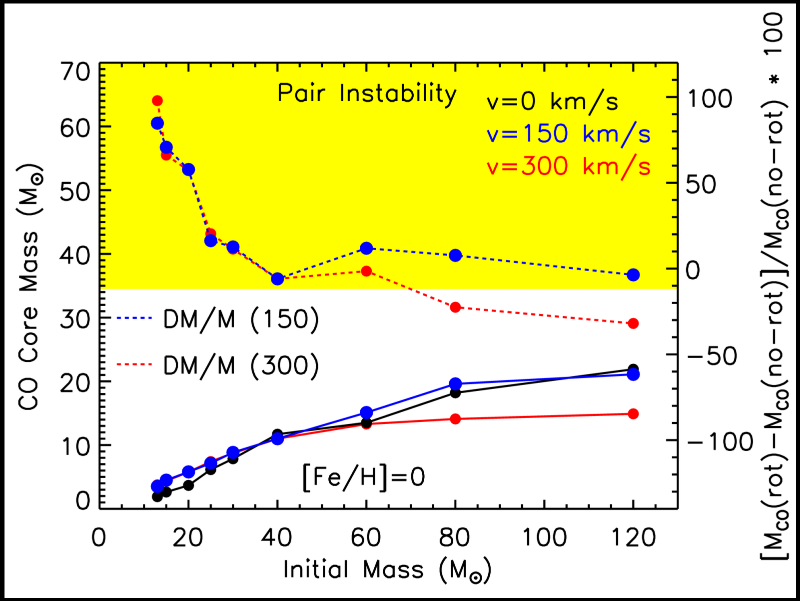
ROTATING MODELS with [Fe/H]=0: CORE He BURNING

M≥40 $M_\odot$: Mass loss dominates

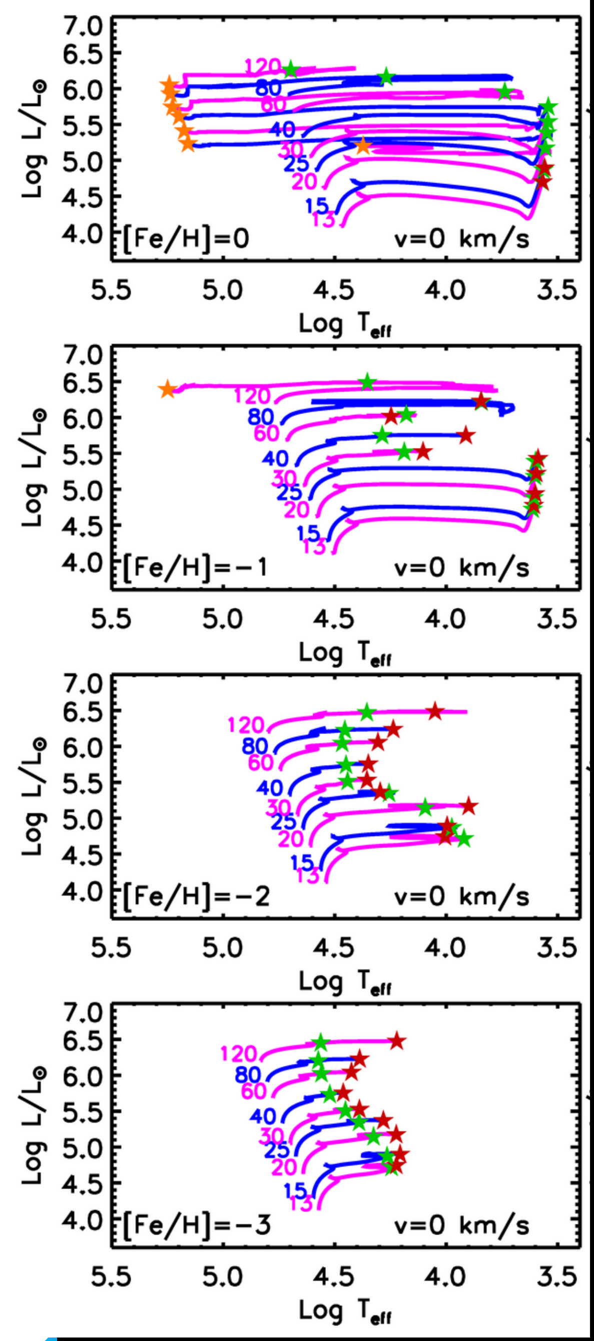


- Mass Loss uncovers the He core at the beginning of Core He burning
  - He convective core progressively recedes in mass and leaves a region of variable He
  - No room for rotational mixing to operate
  - Similar CO cores in rotating and non rotating stars

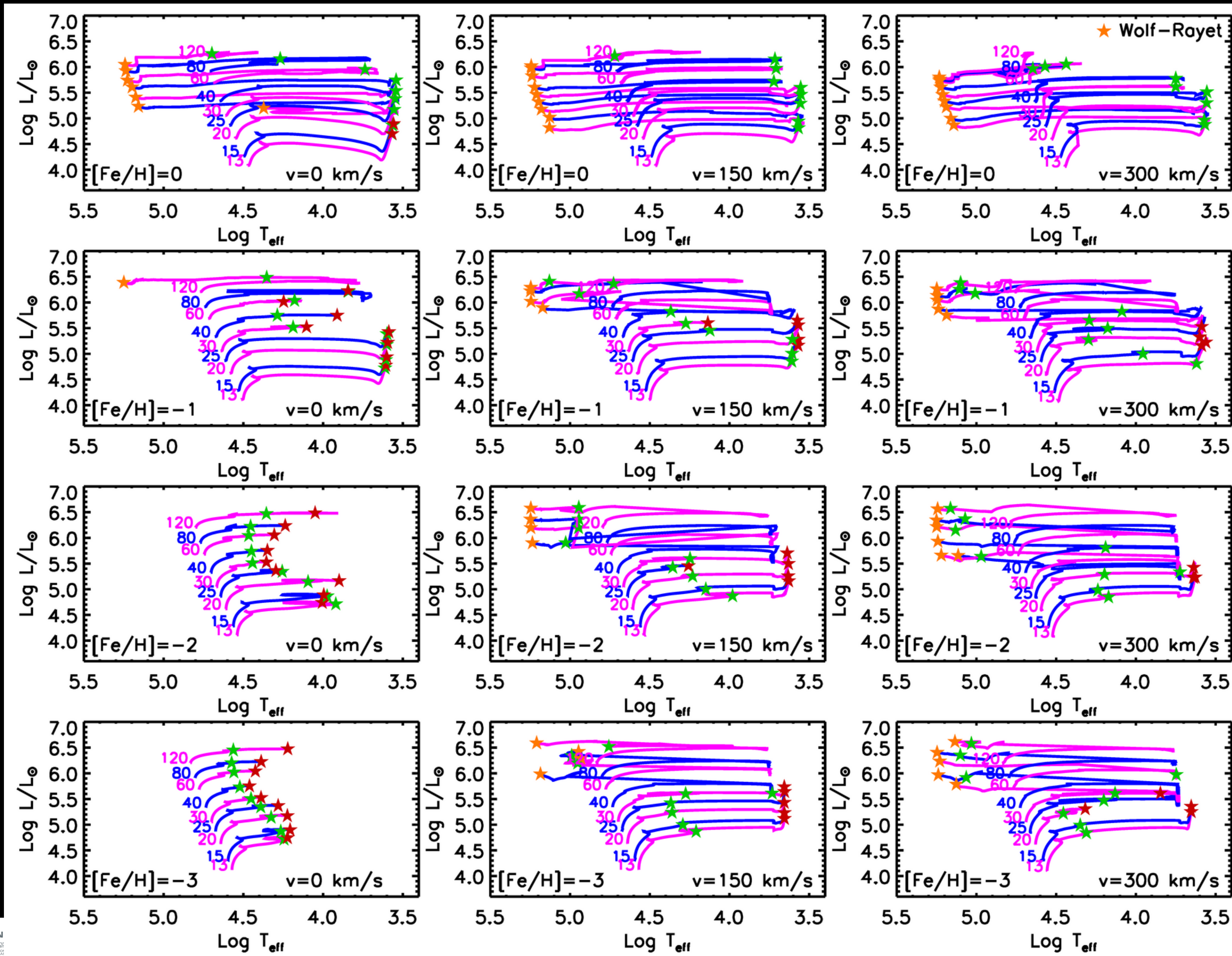
CO Core Mass @ Core He Depletion



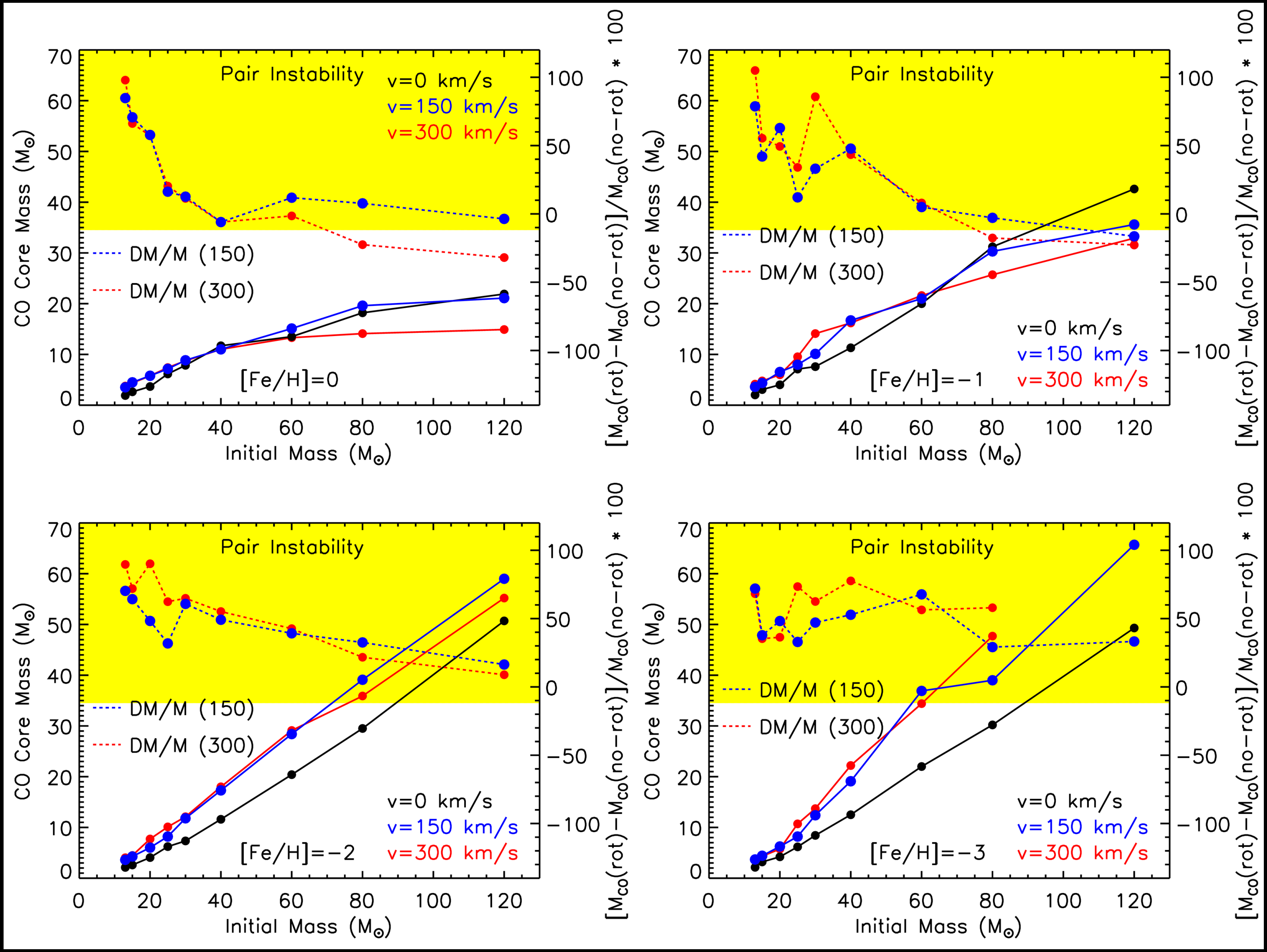
Core He Depletion: Low Metallicity Models



Core He Depletion: Low Metallicity Models



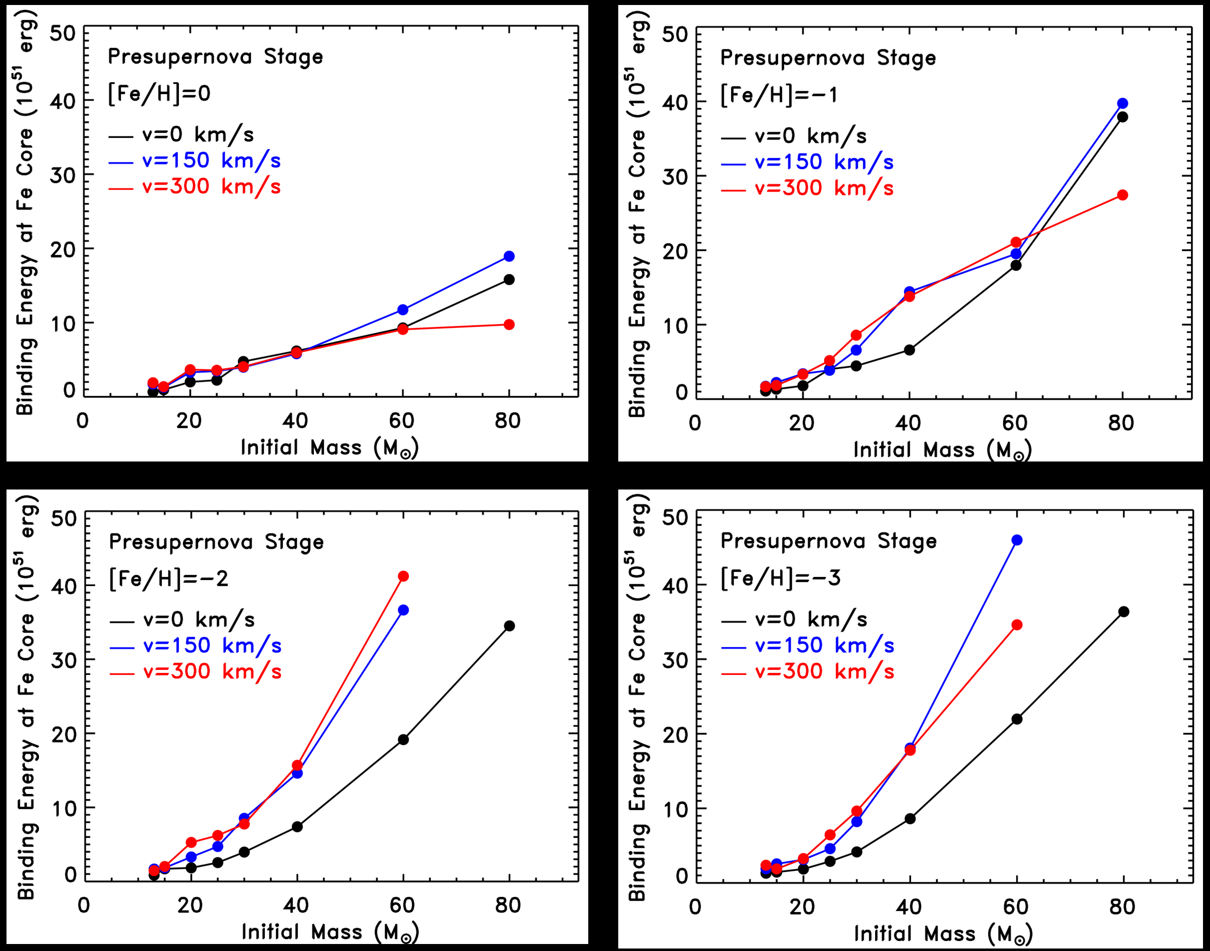
CO Core Mass @ Core He Depletion



ADVANCED BURNING STAGES: INTERNAL EVOLUTION OF ROTATING AND NON ROTATING STARS @ VARIOUS Z

The CO core mass increases with decreasing the metallicity and with increasing the initial velocity

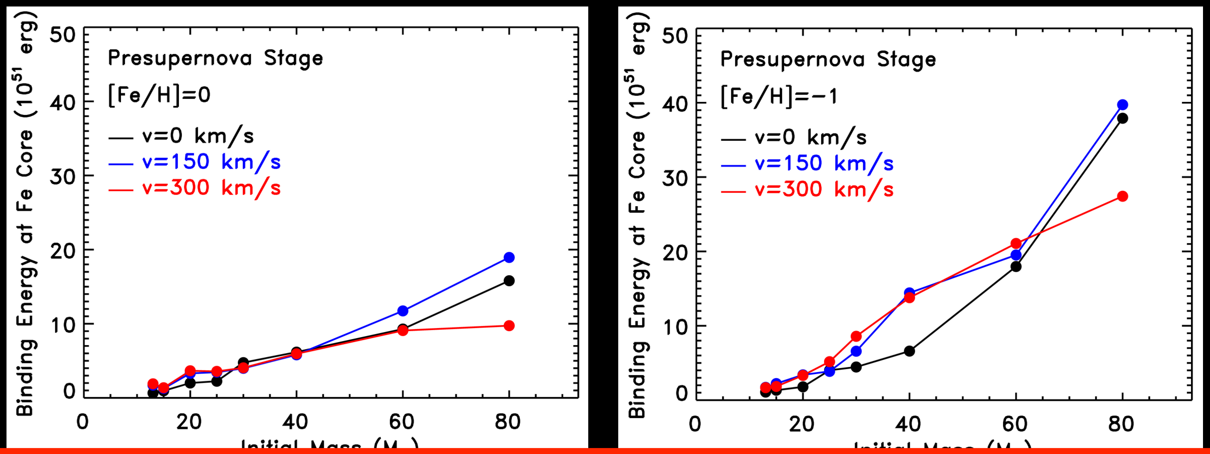
Larger CO at core He depletion → Stronger contraction of the CO core



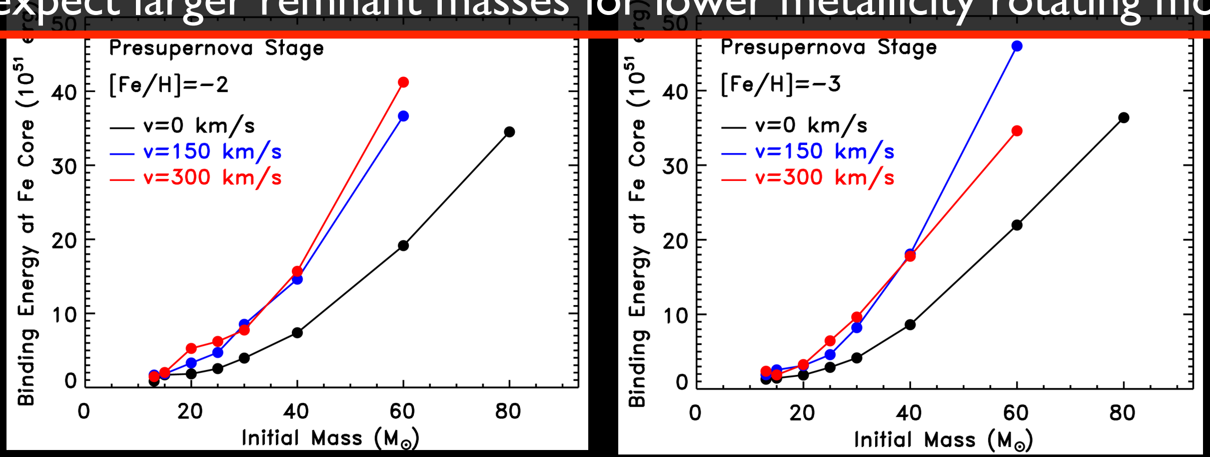
ADVANCED BURNING STAGES: INTERNAL EVOLUTION OF ROTATING AND NON ROTATING STARS @ VARIOUS Z

The CO core mass increases with decreasing the metallicity and with increasing the initial velocity

Larger CO at core He depletion → Stronger contraction of the CO core



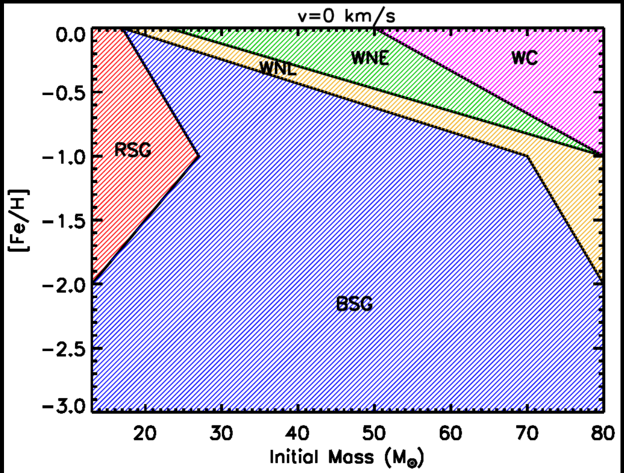
We expect larger remnant masses for lower metallicity rotating models



Some Predictions Still To Be Verified

Due to the dramatic speed up of the advanced evolutionary stages the location of the star in the HR diagram does not change significantly during these phases

RSG = Red Supergiant (extended) SN Progenitor
BSG = Blue Supergiant (compact) SN Progenitor
WX = Wolf-Rayet (compact) SN Progenitor with no or very little H



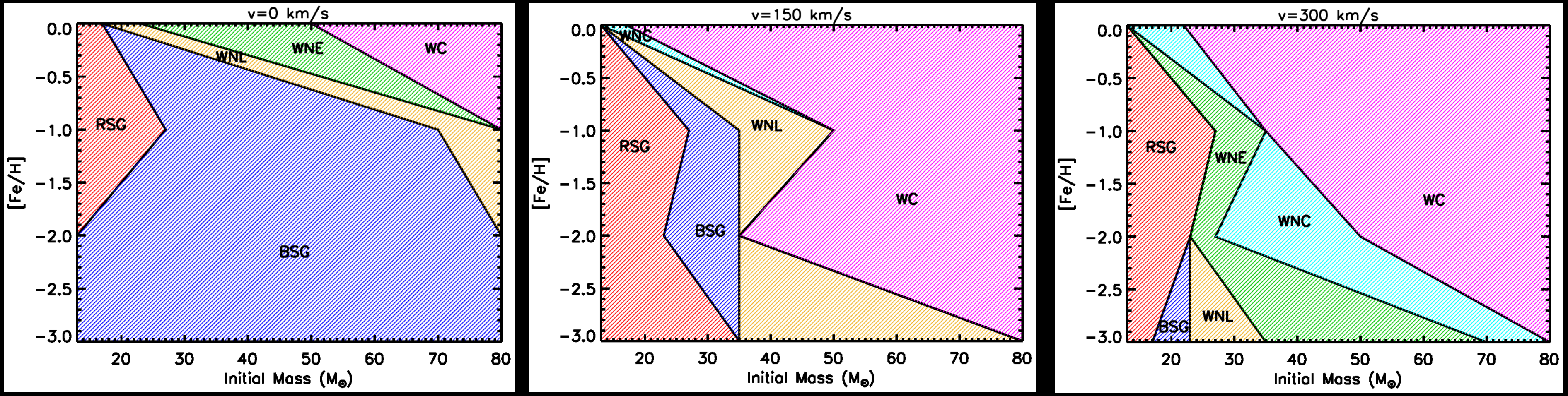
Non Rotating Models: the decrease of Mass Loss with metallicity implies:

- RSG progenitors increase down to [Fe/H]=-1 and then disappears below [Fe/H]=-2
- WR progenitors progressively decrease and disappear below [Fe/H]=-2

Some Predictions Still To Be Verified

Due to the dramatic speed up of the advanced evolutionary stages the location of the star in the HR diagram does not change significantly during these phases

RSG = Red Supergiant (extended) SN Progenitor
BSG = Blue Supergiant (compact) SN Progenitor
WX = Wolf-Rayet (compact) SN Progenitor with no or very little H



Non Rotating Models: the decrease of Mass Loss with metallicity implies:

- RSG progenitors increase down to [Fe/H]=-1 and then disappears below [Fe/H]=-2
- WR progenitors progressively decrease and disappears below [Fe/H]=-2

Rotating Models: the inclusion of rotation reduces the minimum mass entering the WR phase and increases the maximum mass becoming RSG @ all metallicities

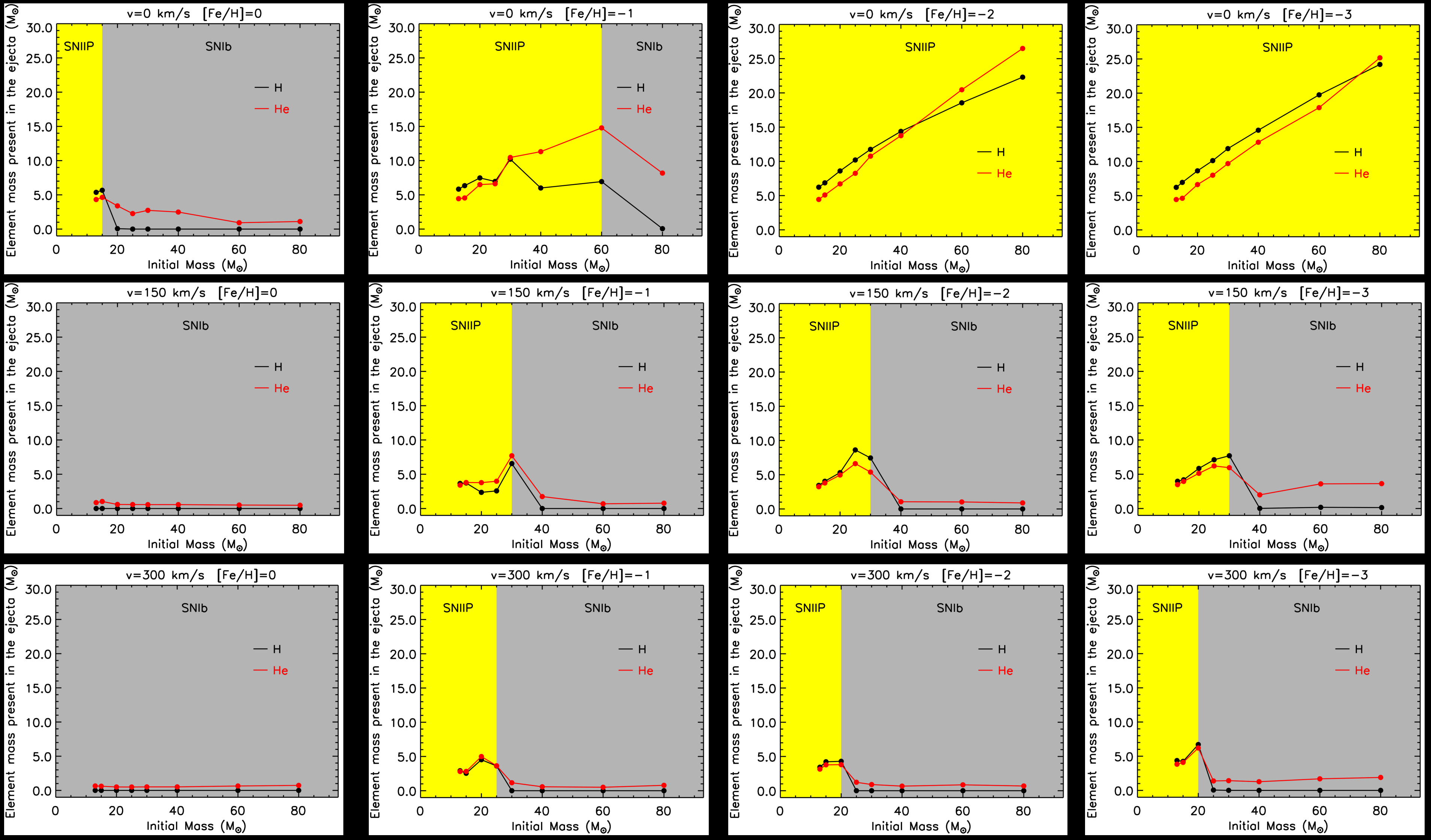
- RSG progenitors increase at lower metallicities (reduction of effective gravity)
- WR progenitors increase at lower metallicities (direct/indirect enhancement of mass loss

INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Some Predictions Still To Be Verified

Limiting H/He masses for the formation of the various SNe from Hachinger+ 2012

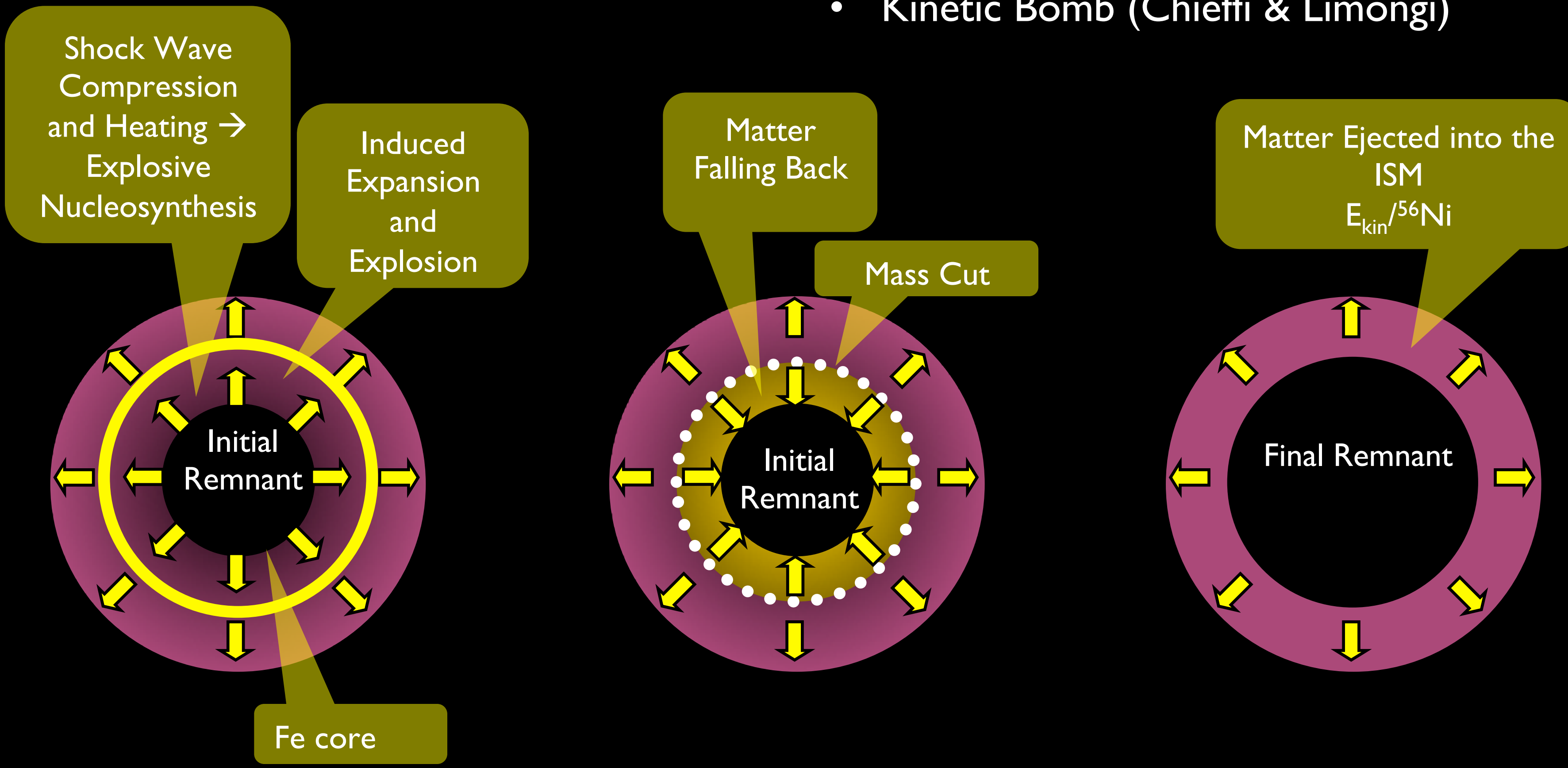


- Increasing fraction of SNIIP with decreasing [Fe/H] and with decreasing v
- No SNIc predicted for any [Fe/H] and v

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)

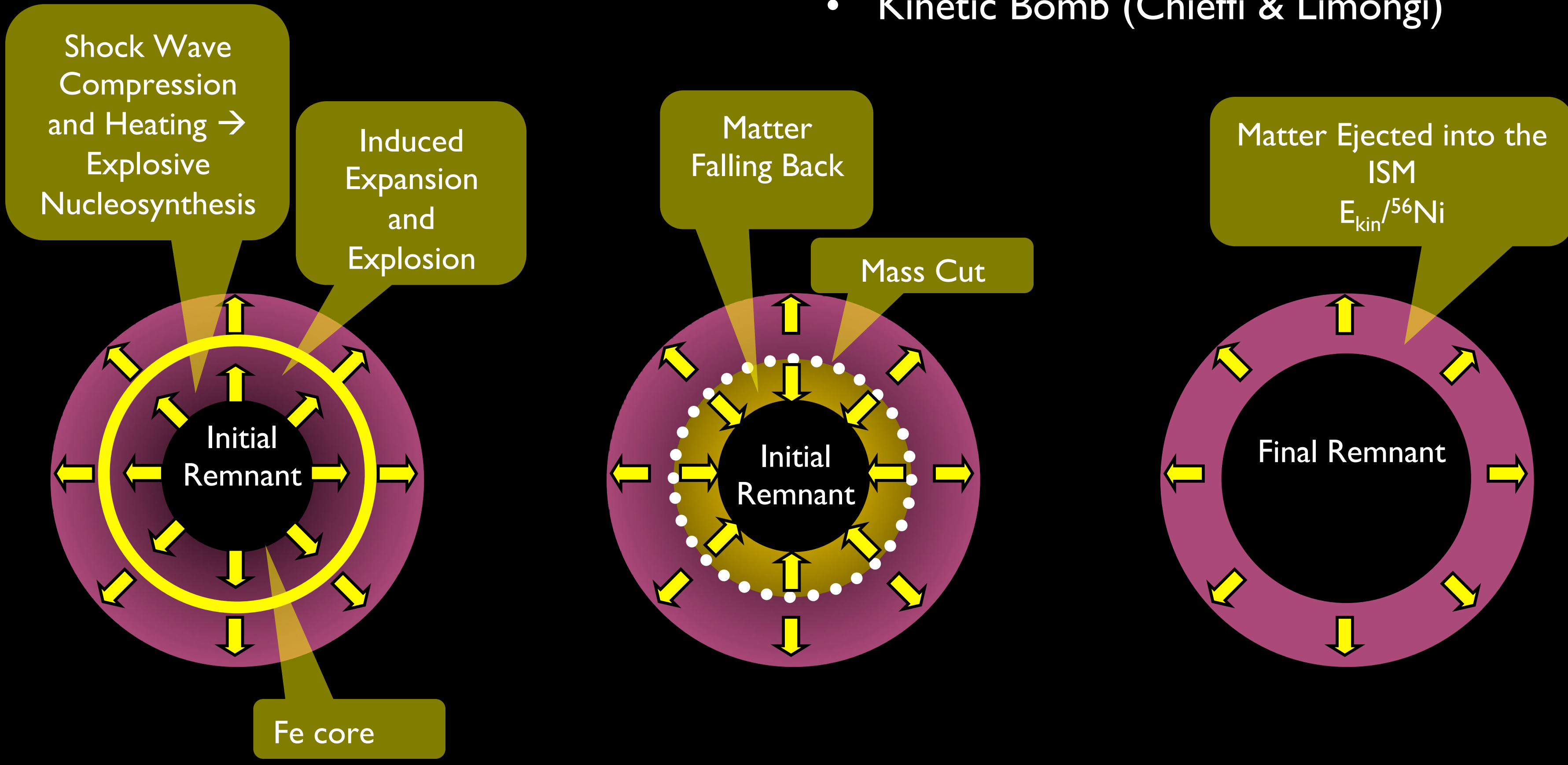


FB depends on the binding energy: the higher is the binding energy the higher is the mass of the remnant

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)

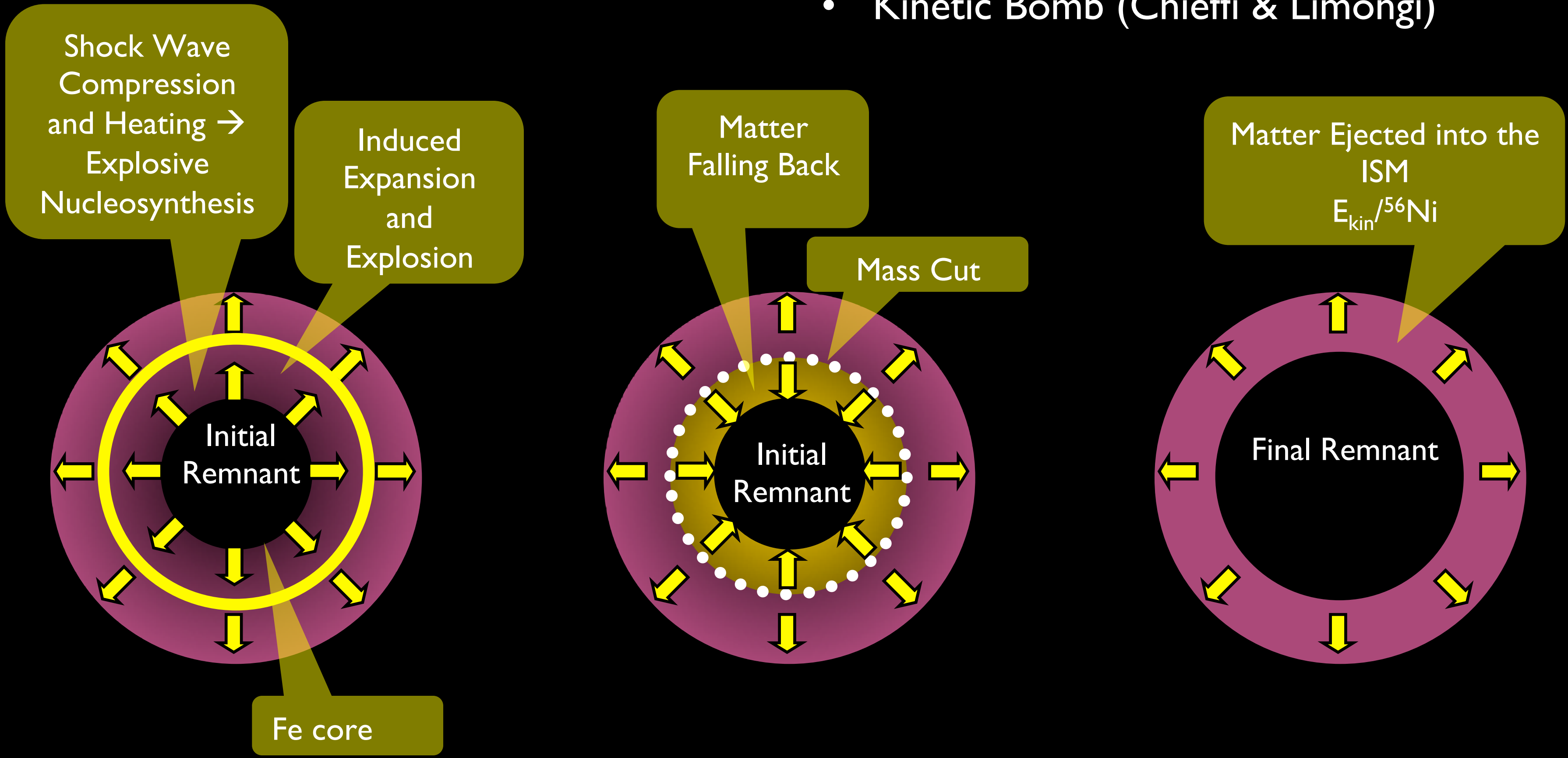


FB (mass cut) depends on the explosion energy: the higher is the explosion energy the higher is the mass of the remnant

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)



The mass cut is highly uncertain in these kind of "induced explosions" → we cannot define with precision this quantity

Chemical Enrichment due to a Single Massive Star

Ejected Masses (often called Yields)

Let's assume for semplicity that

$$M_{cut} \implies 0.1\ M_\odot\ {}^{56}\mathrm{Ni}$$

$$Y_i = \int_{M_{\rm cut}}^{M_{\rm tot}} X_i\ dm$$

Production Factors

$$\mathrm{PF}_i = \frac{Y_i}{Y_i^{\rm ini}}$$

$$\mathrm{PF}_i = \frac{\displaystyle\int_{M_{\rm cut}}^{M_{\rm tot}} X_i\ dm}{\displaystyle\int_{M_{\rm cut}}^{M_{\rm tot}} X_i^{\rm initial}\ dm}$$

The Production Factors (PFs) provide information on the global enrichment of the matter and its distribution

Chemical Enrichment due to a Single Massive Star

For models with Solar initial composition

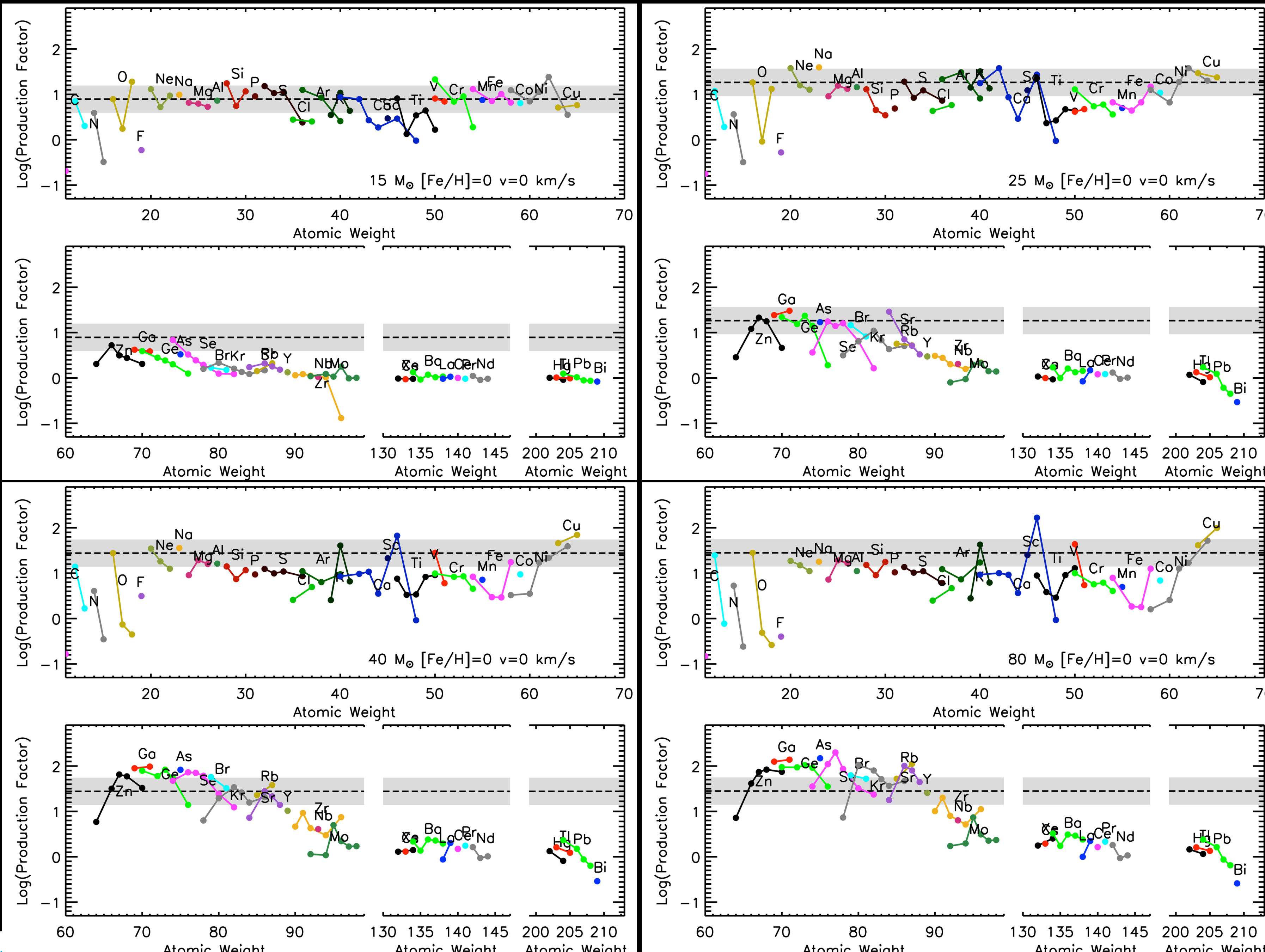
$$\mathrm{PF}_i = \frac{\int_{M_{\rm cut}}^{M_{\rm tot}} X_i \; dm}{\int_{M_{\rm cut}}^{M_{\rm tot}} X_i^{\rm initial} \; dm} \quad \Rightarrow \quad \mathrm{PF}_i = \frac{\int_{M_{\rm cut}}^{M_{\rm tot}} X_i \; dm}{\int_{M_{\rm cut}}^{M_{\rm tot}} X_i^{\odot} \; dm}$$

The average metallicity Z grows slowly and continuously with respect to the evolutionary timescales of the stars that contribute to the environment enrichment

Most of the solar system distribution is the result (as a first approximation) of the ejecta of "quasi "–solar-metallicity stars.

→ We expect PFs ~ constant for all the isotopes (at least those produced by massive stars)

this is a check for the models!


Log(Production Factor)
Atomic Weight
15 M⊙ [Fe/H]=0 v=0 km/s
25 M⊙ [Fe/H]=0 v=0 km/s
40 M⊙ [Fe/H]=0 v=0 km/s
80 M⊙ [Fe/H]=0 v=0 km/s
C N O F Ne Na Mg Al Si P S Cl Ar K Ca Sc Ti V Cr Mn Fe Co Ni Cu
Zn Ga Ge As Se Br Kr Rb Sr Y Zr Nb Mo
Xe Cs Ba La Ce Pr Nd
Hg Tl Pb Bi

Chemical Enrichment due to a Generation of Massive Stars

The integration of the yields provided by each star over an initial mass function $\phi(m)$ provides the chemical composition of the ejecta due to a generation of massive stars

Yield averaged over a IMF

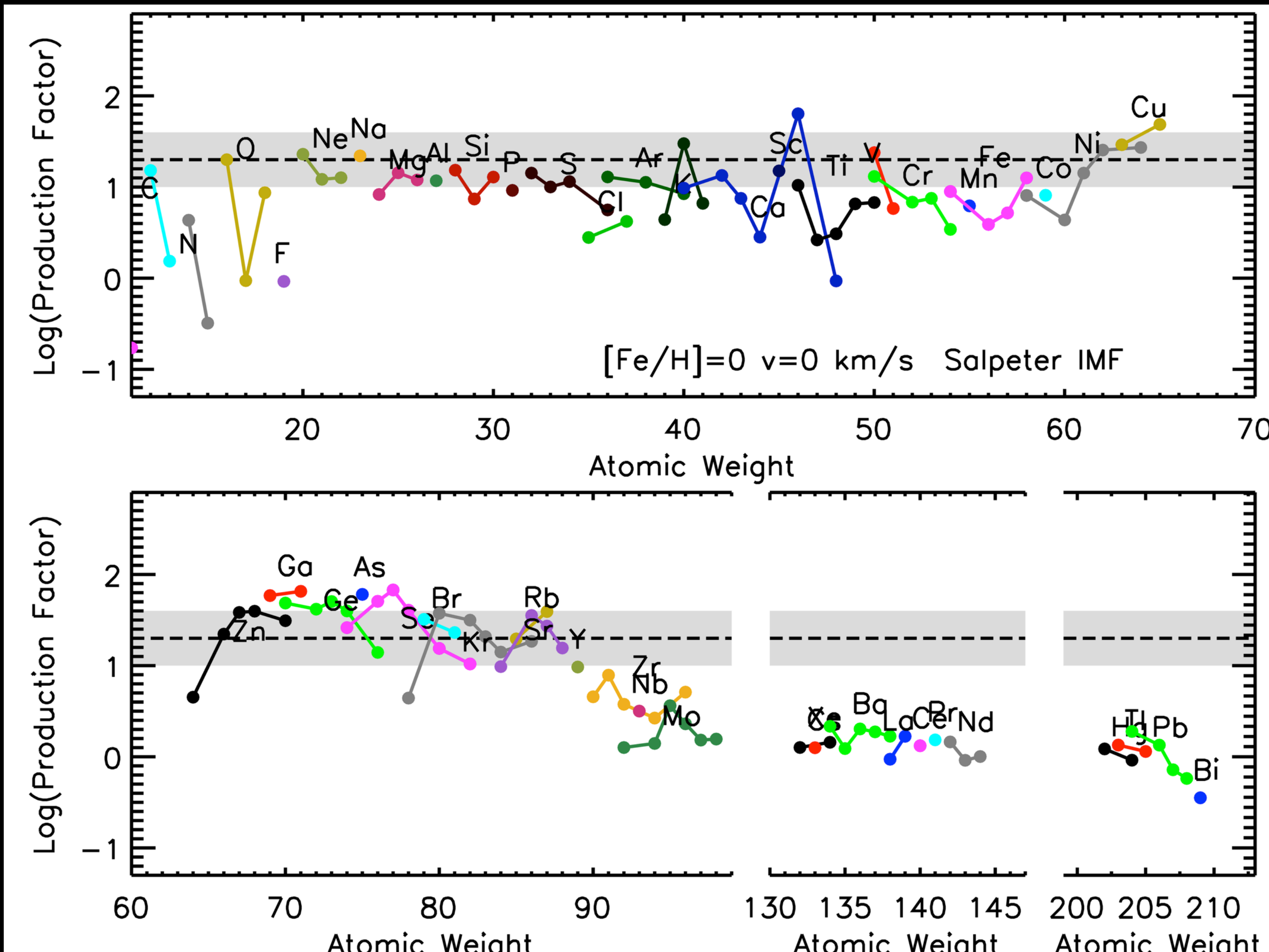
$$Y_i^{\rm IMF} = \int_{M_{\rm bot}}^{M_{\rm top}} X_i \ \phi(m) \ dm$$

Production Factor averaged over a IMF

$$\mathrm{PF}_i = \frac{\displaystyle\int_{M_{\rm bot}}^{M_{\rm top}} X_i \ \phi(m) \ dm}{\displaystyle\int_{M_{\rm bot}}^{M_{\rm top}} X_i^{\rm ini} \ \phi(m) \ dm}$$

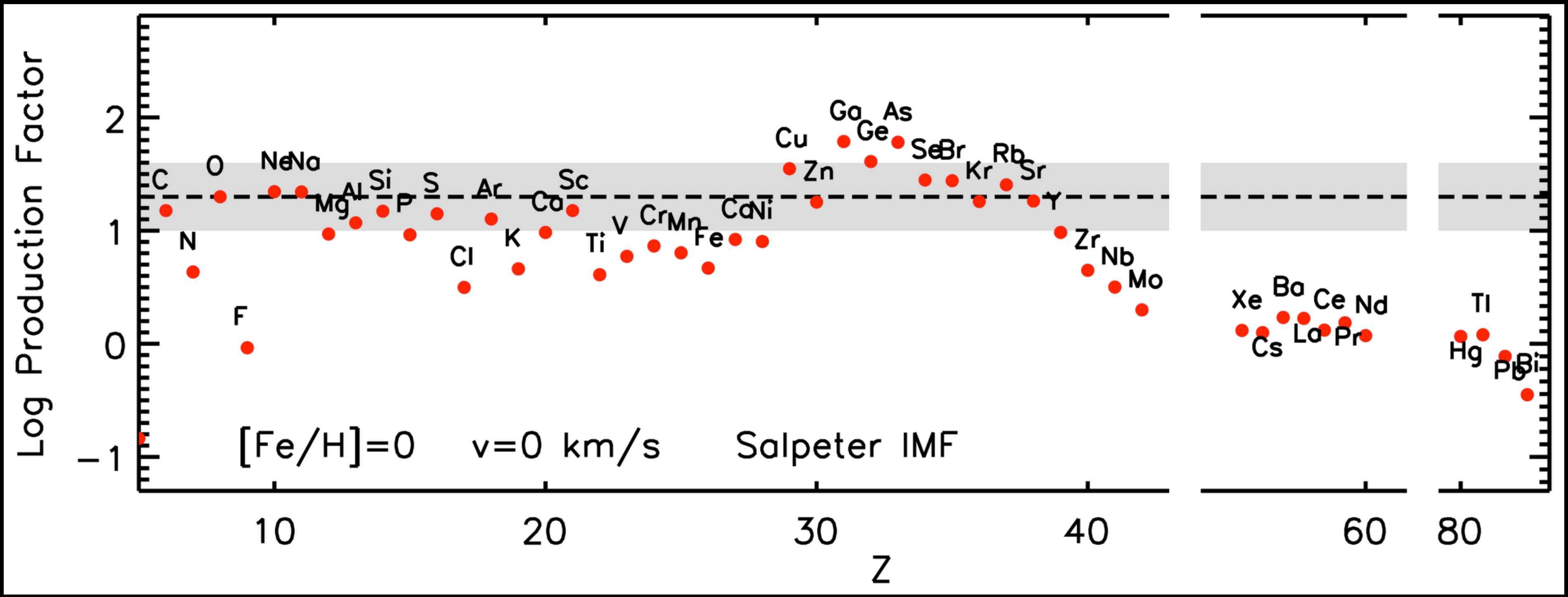
Chemical Enrichment due to a Generation of Massive Stars

Isotopic Yields averaged over a Salpeter IMF



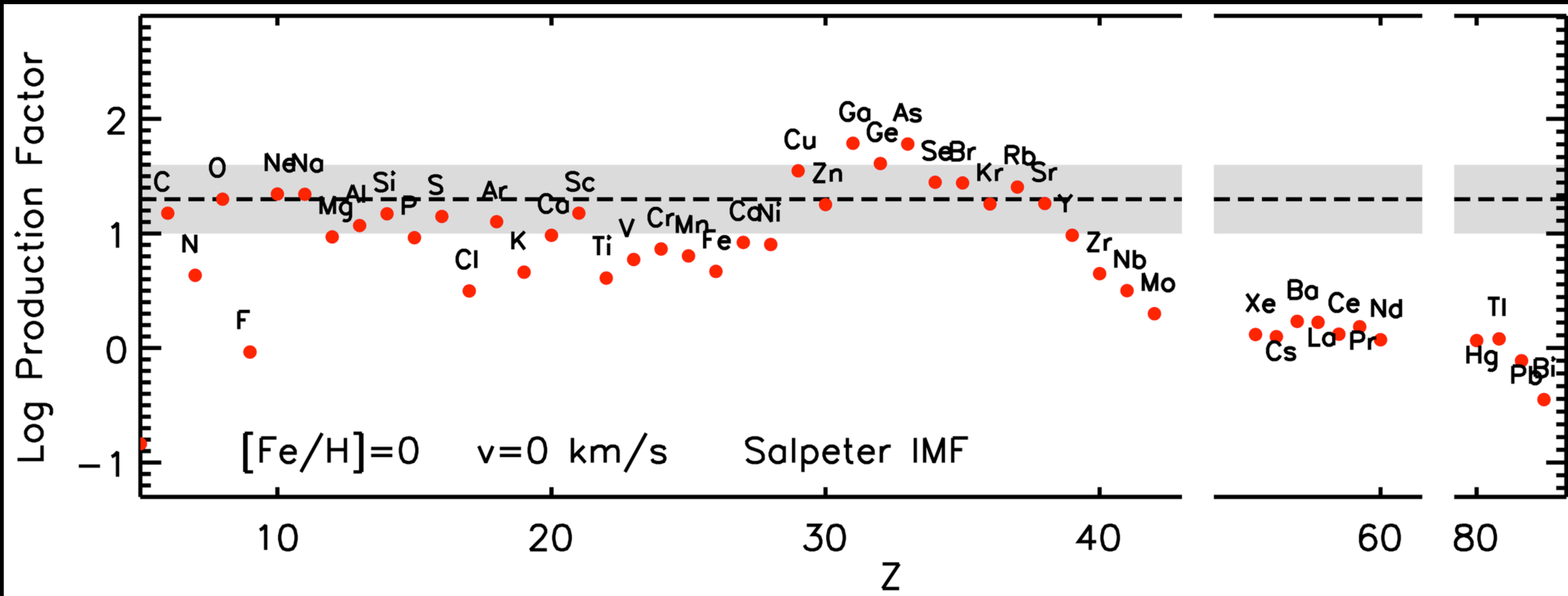
Chemical Enrichment due to a Generation of Massive Stars

Element Yields averaged over a Salpeter IMF



Chemical Enrichment due to a Generation of Massive Stars

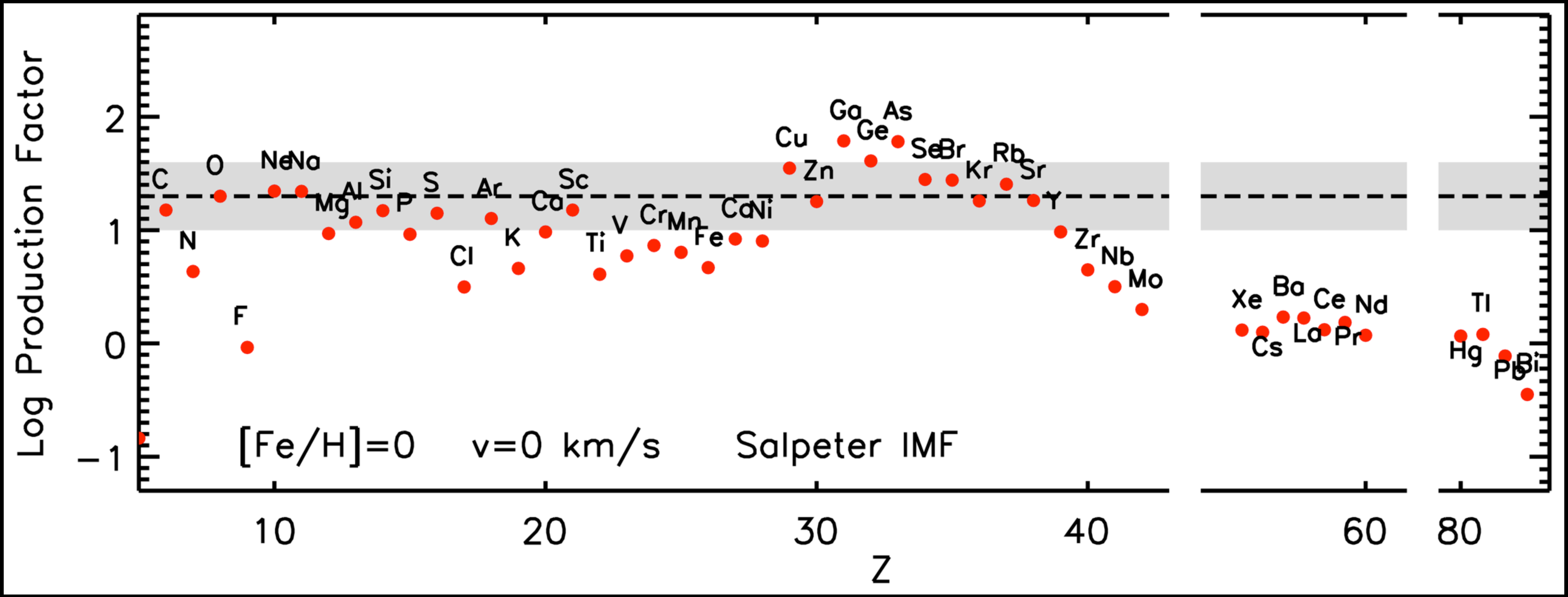
Element Yields averaged over a Salpeter IMF



- The majority of the elements from C to Sc are coproduced with O. Some of them are underproduced by more than a factor of 2 (N F Cl K)

Chemical Enrichment due to a Generation of Massive Stars

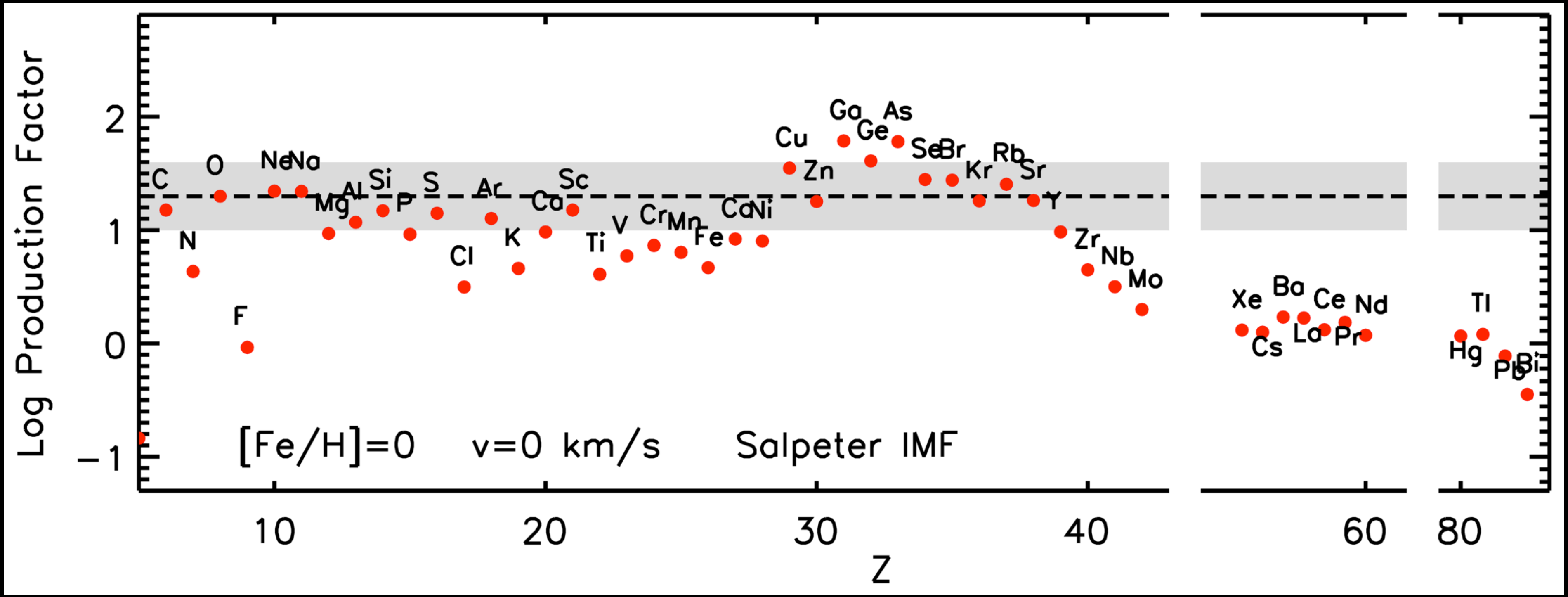
Element Yields averaged over a Salpeter IMF



- The majority of the elements from C to Sc are coproduced with O. Some of them are underproduced by more than a factor of 2 (N F Cl K)
- The iron peak elements (Ti-Ni) are "correctly" underproduced compared to O (but this depends on the specific choice of the mass cut)

Chemical Enrichment due to a Generation of Massive Stars

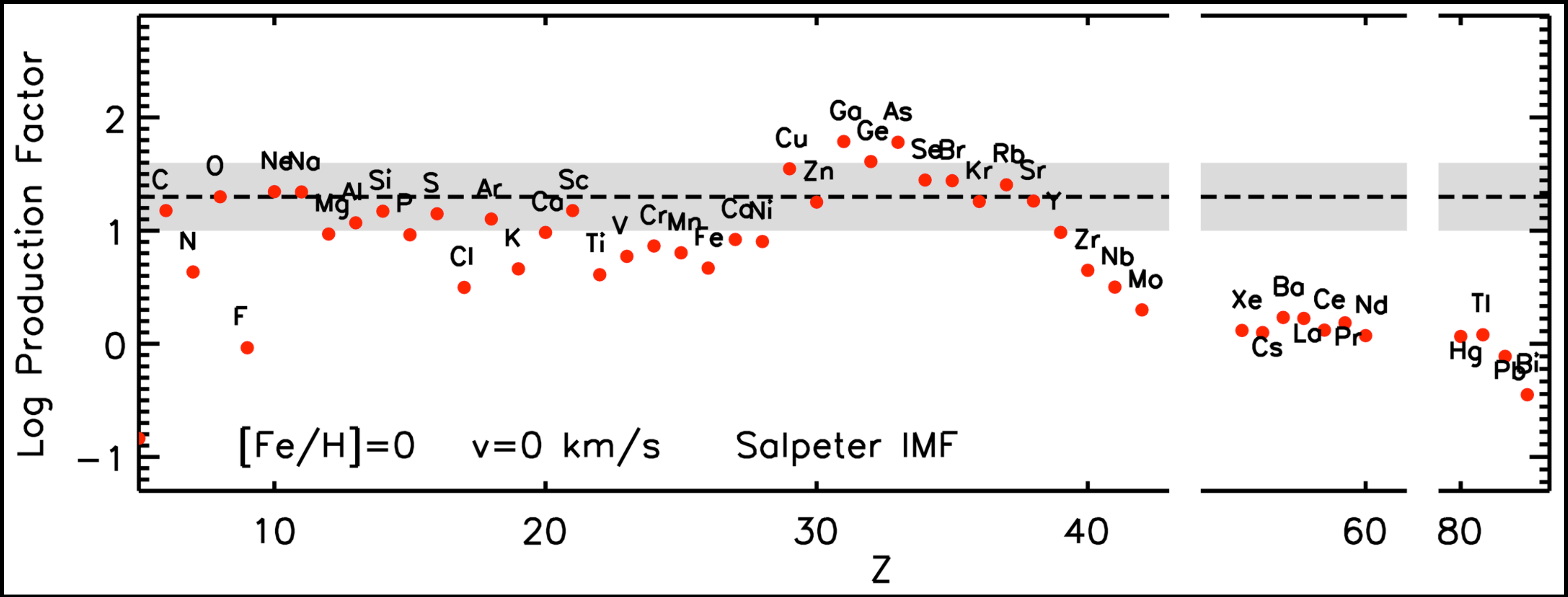
Element Yields averaged over a Salpeter IMF



- The majority of the elements from C to Sc are coproduced with O. Some of them are underproduced by more than a factor of 2 (N F Cl K)
- The iron peak elements (Ti-Ni) are "correctly" underproduced compared to O (but this depends on the specific choice of the mass cut)
- The elements around Ge are substantially overproduced

Chemical Enrichment due to a Generation of Massive Stars

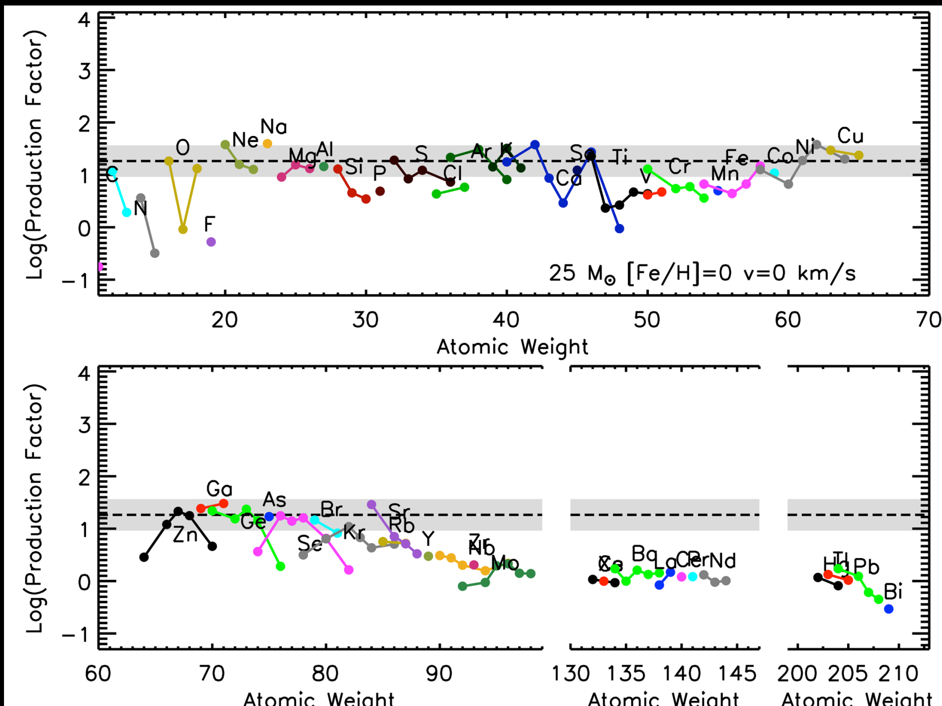
Element Yields averaged over a Salpeter IMF

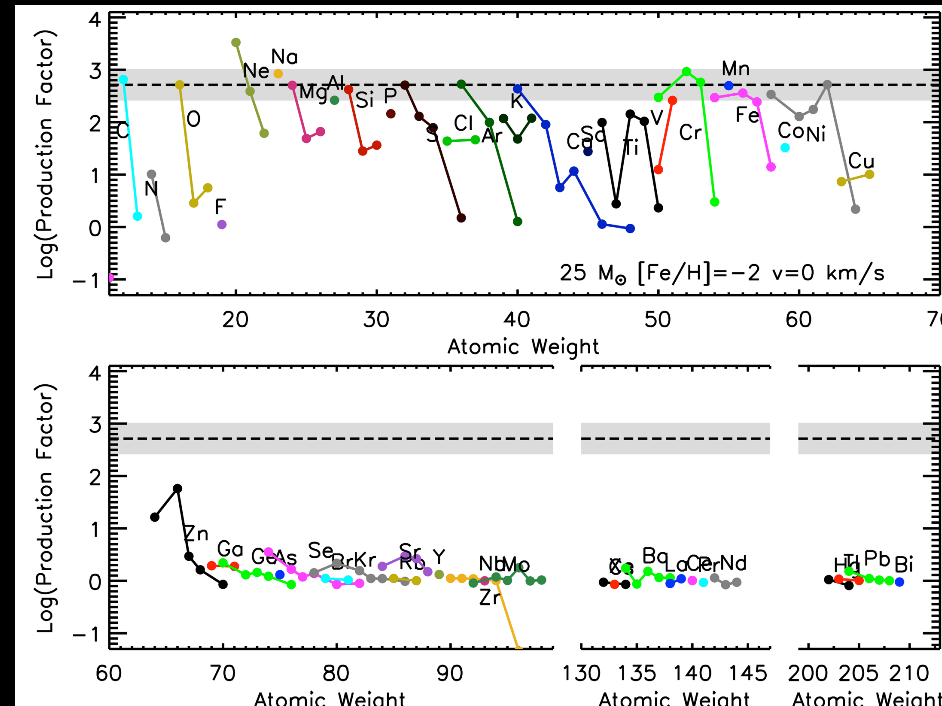


- The majority of the elements from C to Sc are coproduced with O. Some of them are underproduced by more than a factor of 2 (N F Cl K)
- The iron peak elements (Ti-Ni) are "correctly" underproduced compared to O (but this depends on the specific choice of the mass cut)
- The elements around Ge are substantially overproduced
- No production of elements heavier than Zr

Chemical Enrichment due to a Single Massive Star: The effect of the Metallicity

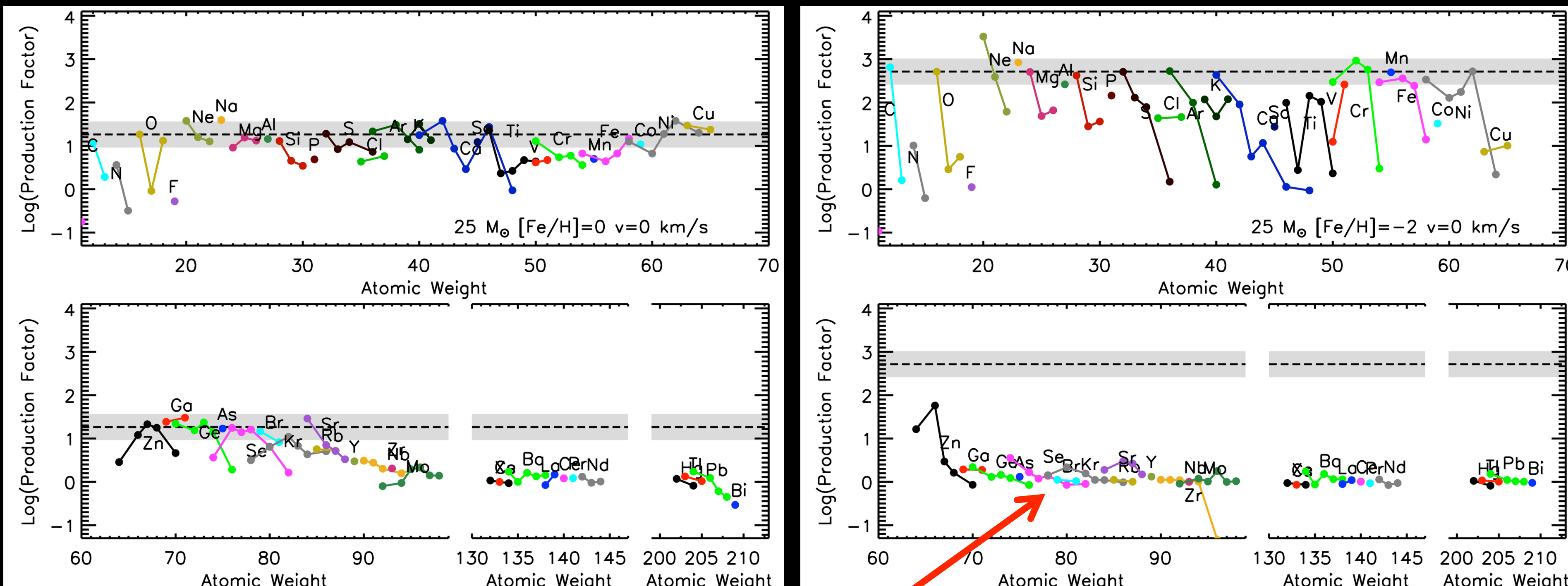
Production Factors increase substantially for lower metallicities





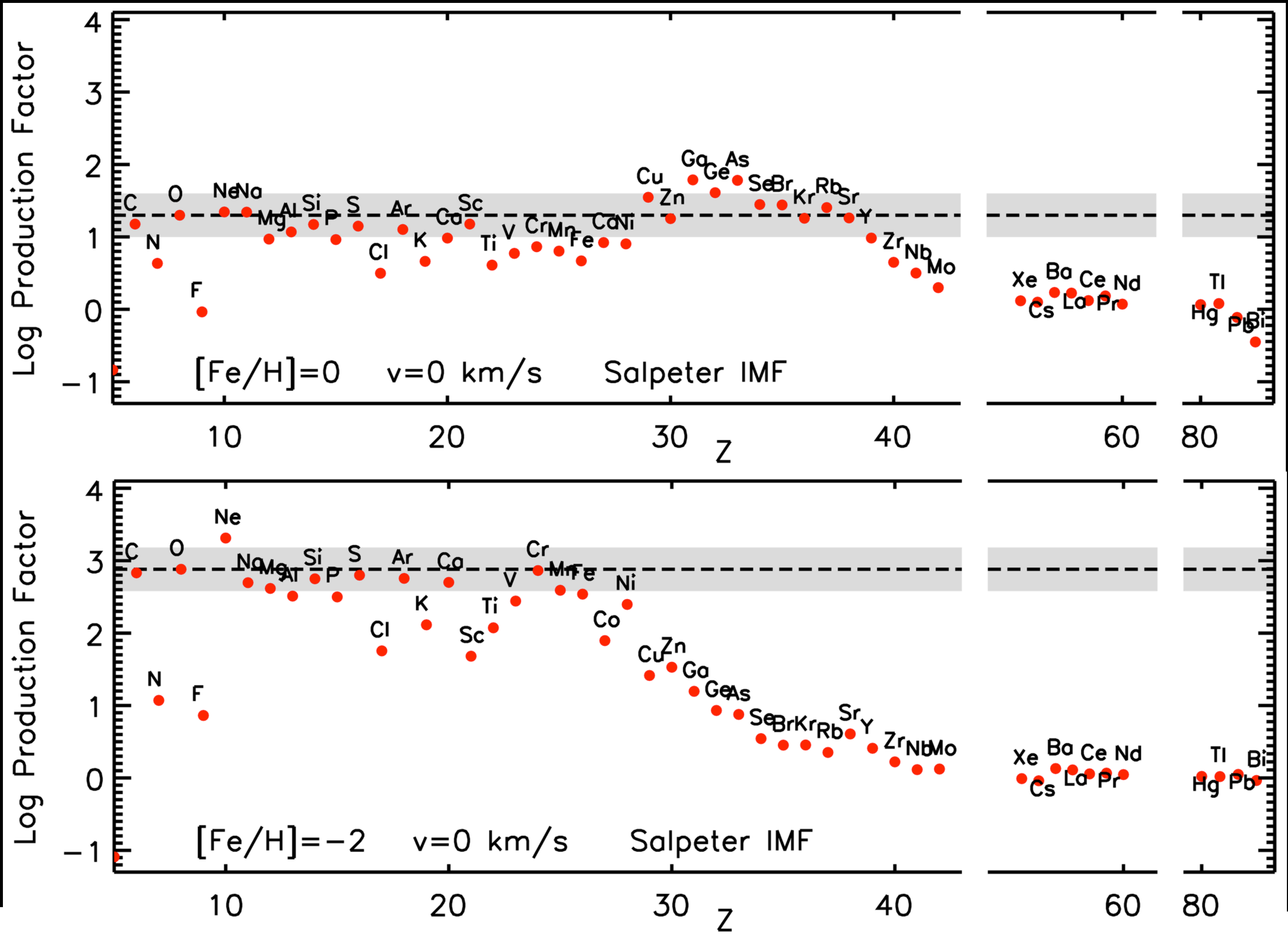
Chemical Enrichment due to a Single Massive Star: The effect of the Metallicity

Decreasing the metallicity the efficiency of the neutron captures (secondary processes) decreases dramatically

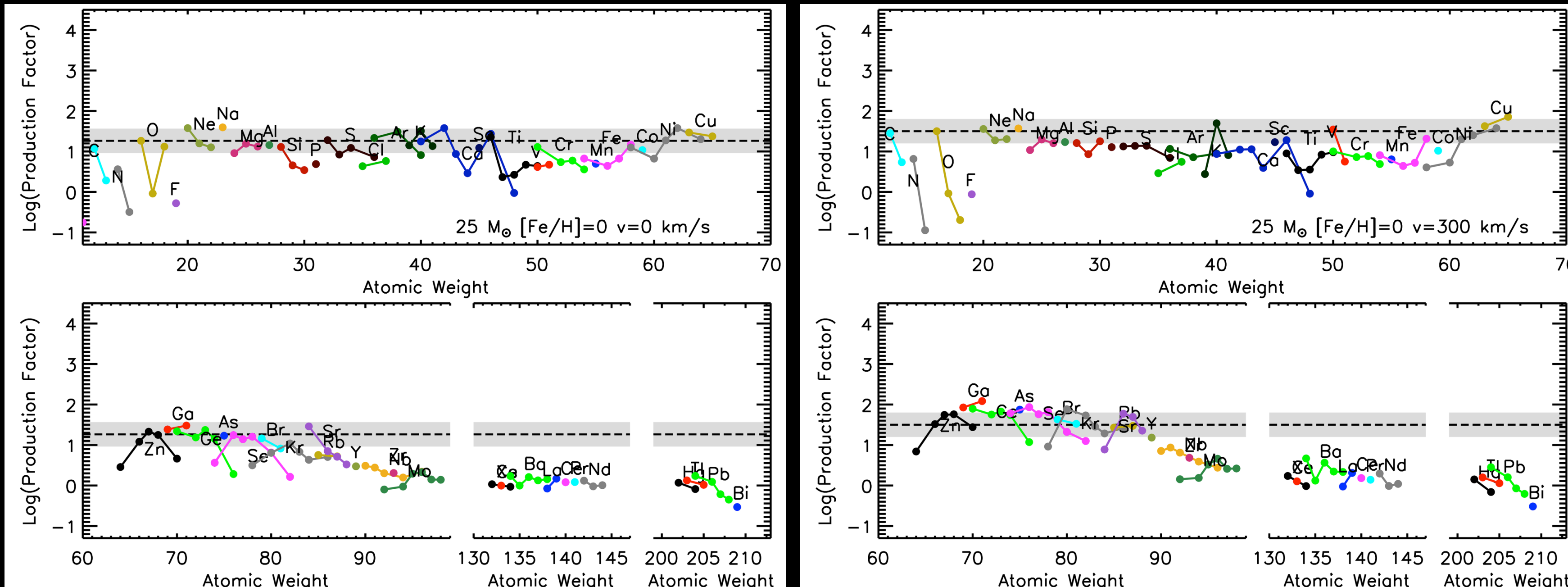


No production of elements heavier than Zn

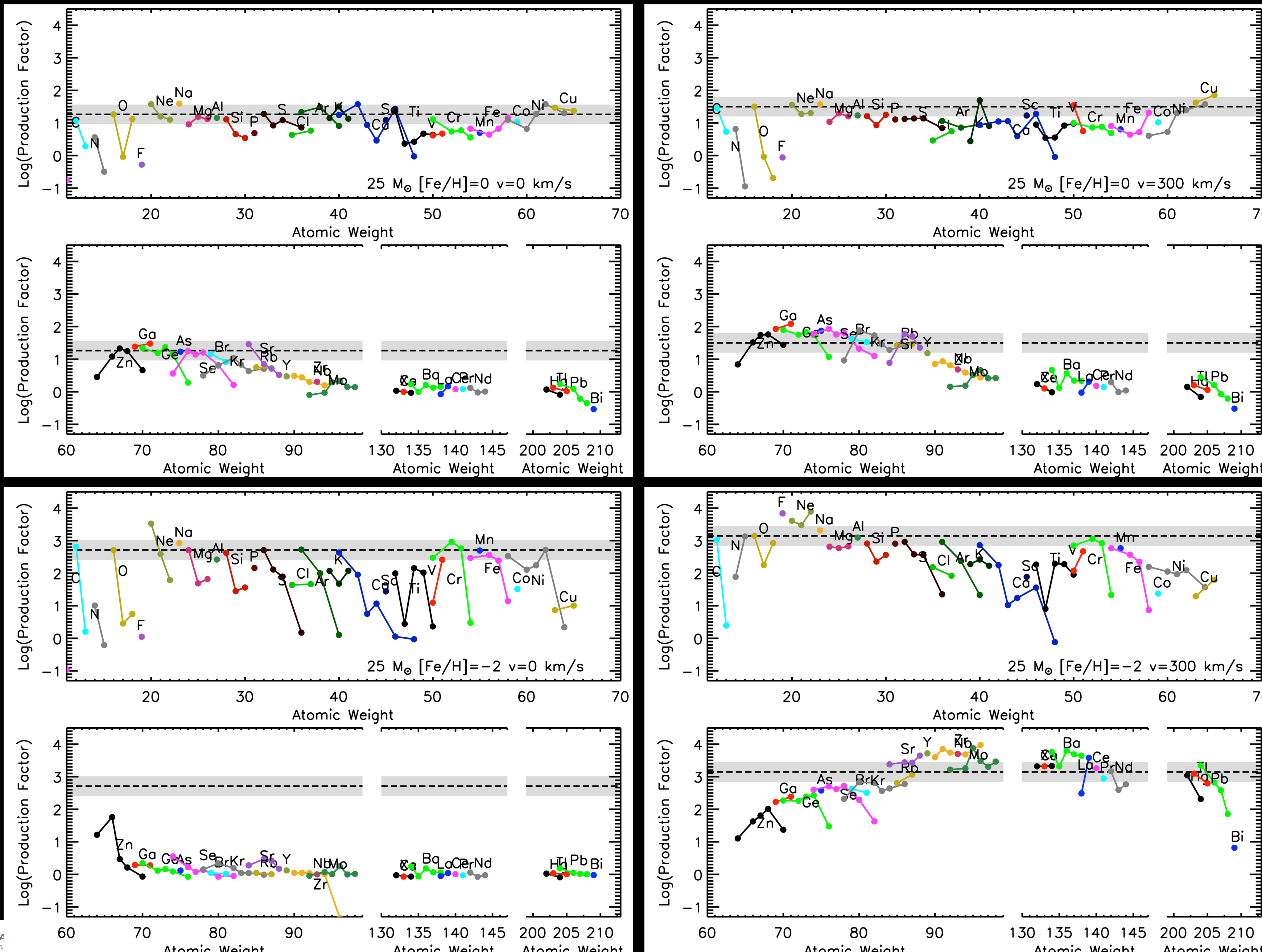
Chemical Enrichment due to a Generation of Massive Star: The effect of the Metallicity



Chemical Enrichment due to a Single Massive Star: The role of Rotation

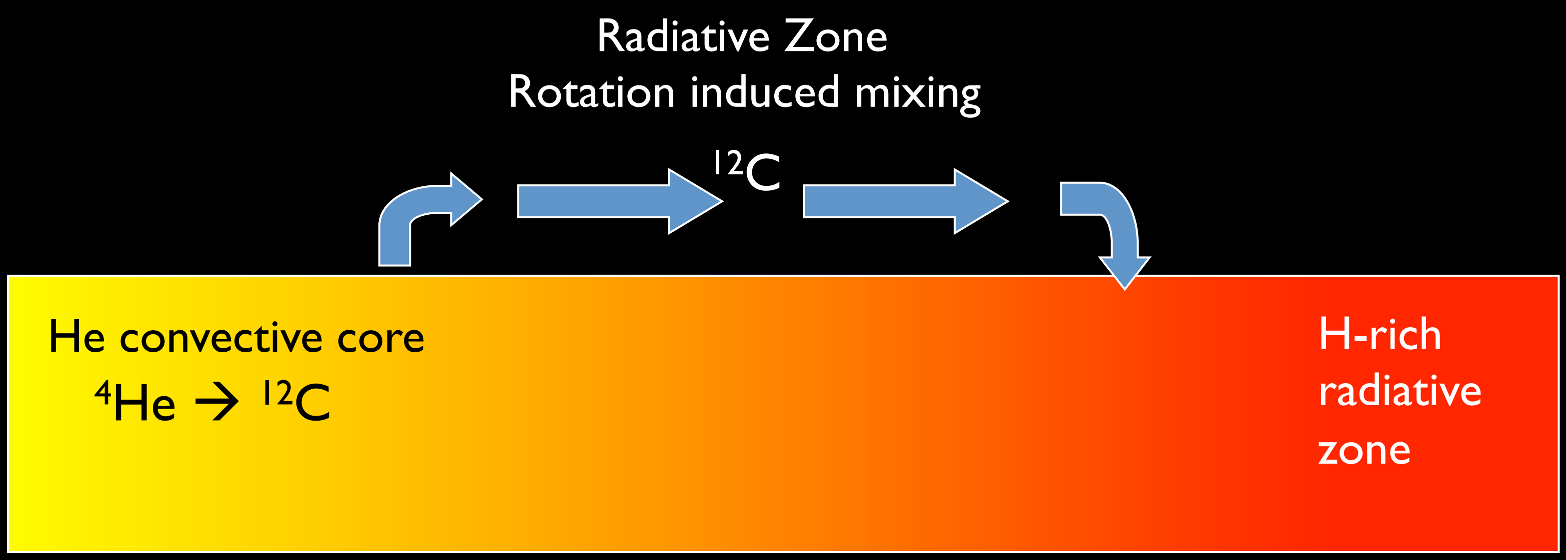


Chemical Enrichment due to a Single Massive Star: The role of Rotation



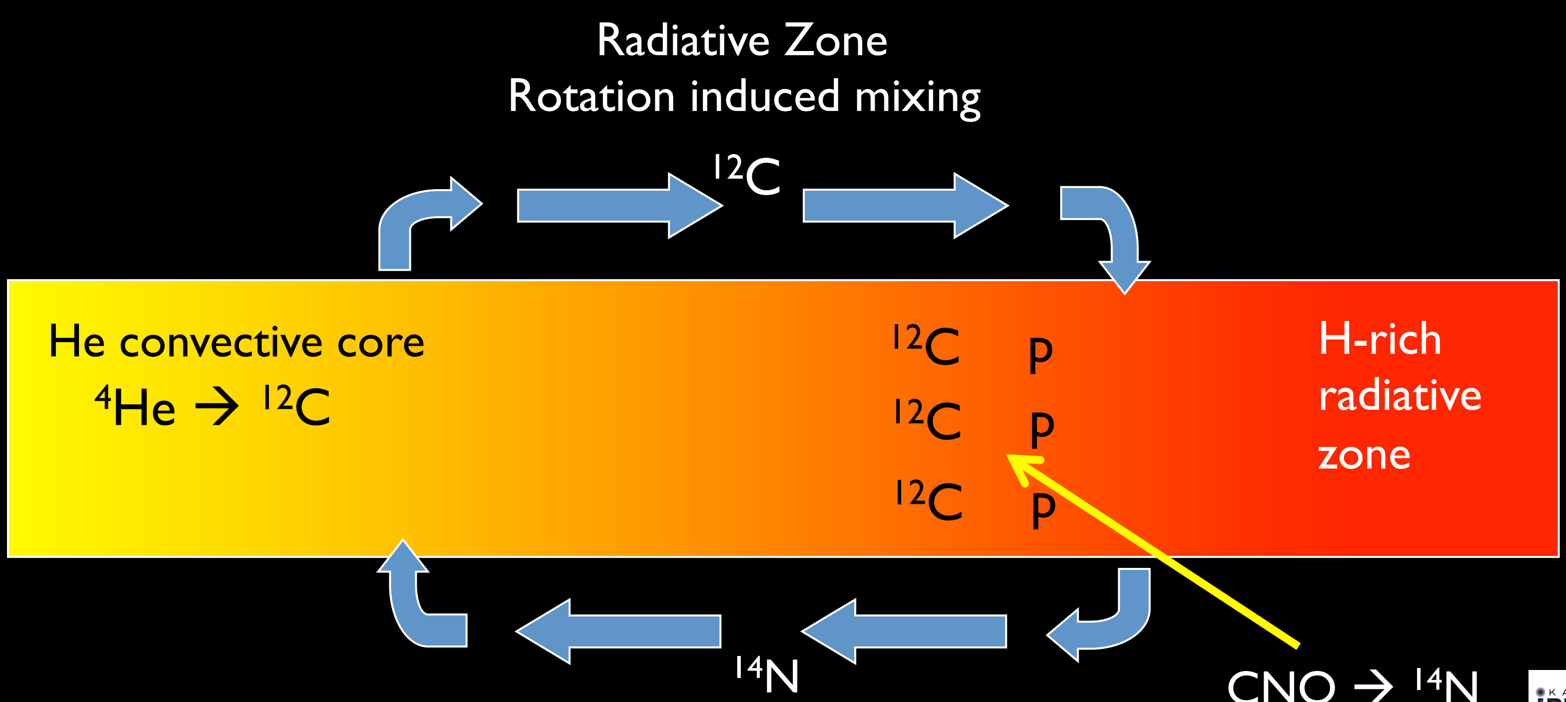
s-process nucleosynthesis in rotating massive stars

- Rotation induced mixing brings newly fresh synthesized ^{12}C from the He convective core up to the tail of the H burning shell



s-process nucleosynthesis in rotating massive stars

- Rotation induced mixing brings newly fresh synthesized ^{12}C from the He convective core up to the tail of the H burning shell
- ^{12}C is converted into primary ^{14}N (CNO) which is mixed down into the He convective core.

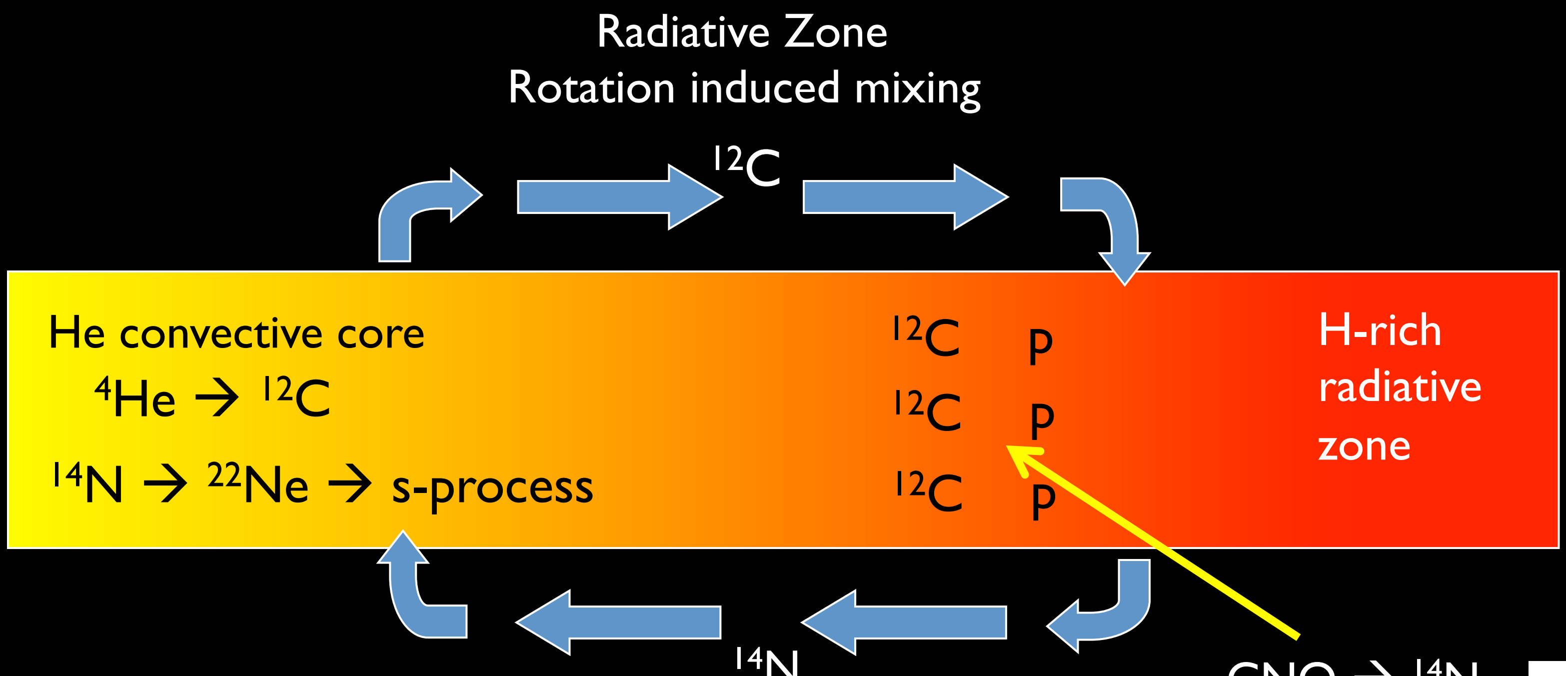


INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

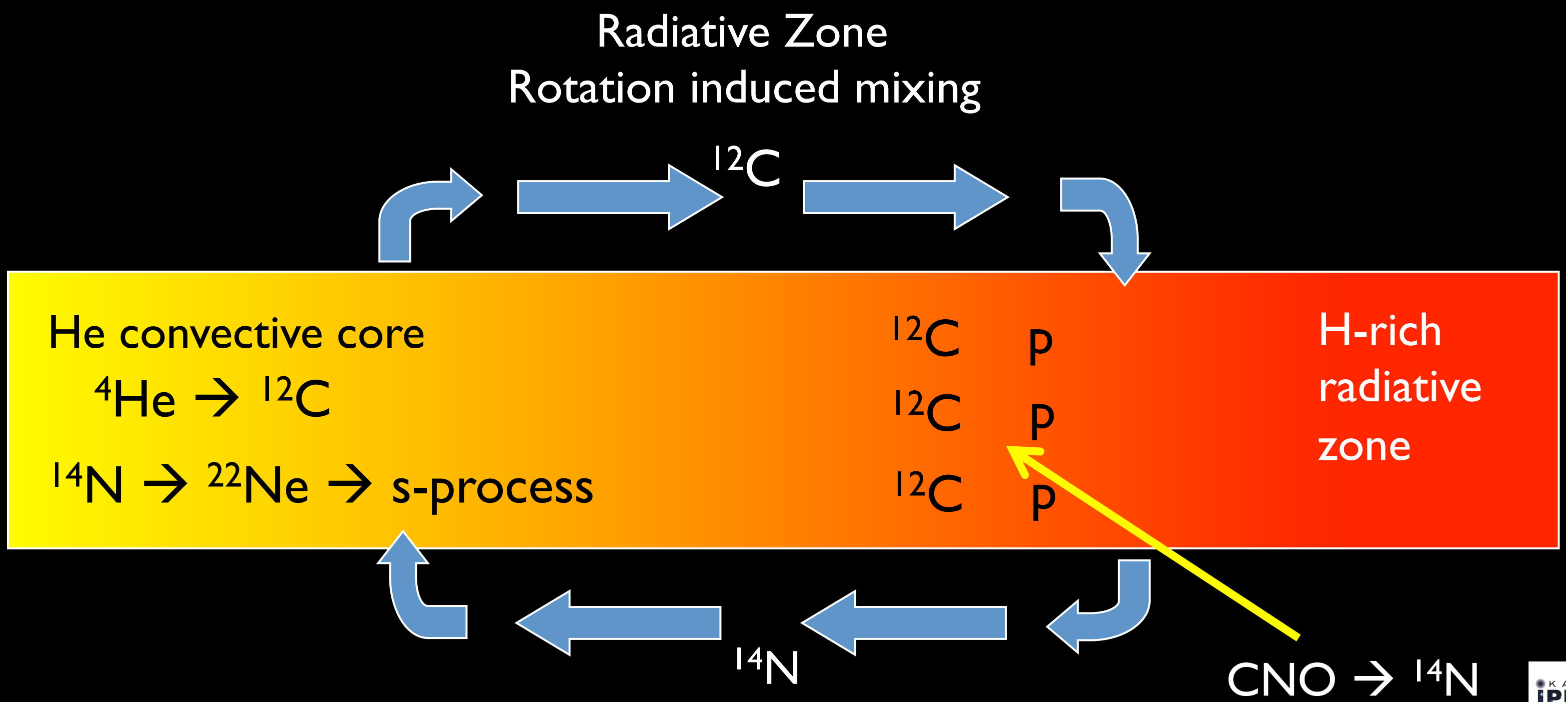
s-process nucleosynthesis in rotating massive stars

- Rotation induced mixing brings newly fresh synthesized ^{12}C from the He convective core up to the tail of the H burning shell
- ^{12}C is converted into primary ^{14}N (CNO) which is mixed down into the He convective core.
- ^{14}N is converted into ^{22}Ne and s-process nucleosynthesis is activated.

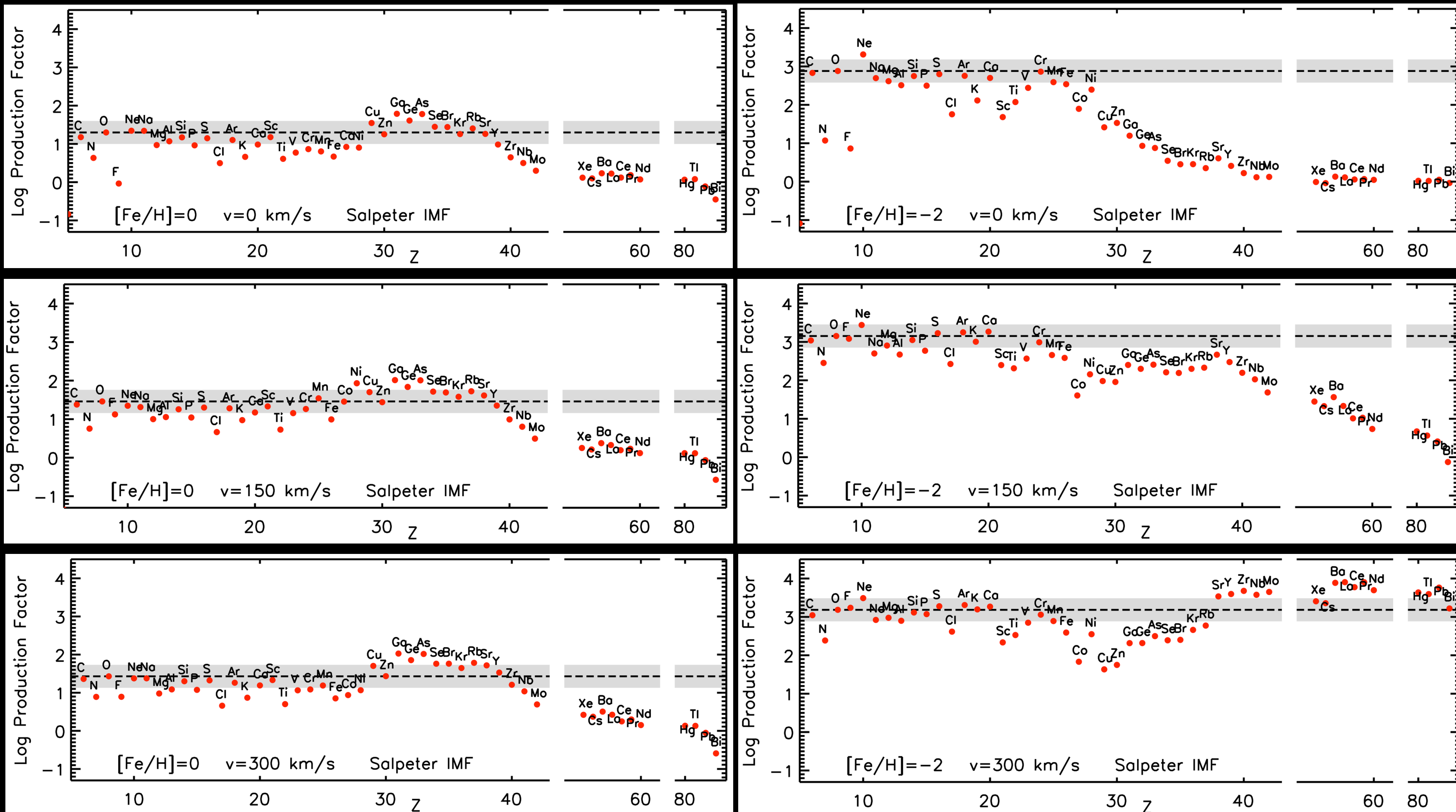


s-process nucleosynthesis in rotating massive stars

- Rotation induced mixing brings newly fresh synthesized ^{12}C from the He convective core up to the tail of the H burning shell
- ^{12}C is converted into primary ^{14}N (CNO) which is mixed down into the He convective core.
- ^{14}N is converted into ^{22}Ne and s-process nucleosynthesis is activated.
- After core He depletion, s-process nucleosynthesis can be also activated in the He shell (it depends on the initial mass)



Chemical Enrichment due to a Generation of Massive Star: The role of Rotation



INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Summary and Conclusions

The inclusion of rotation makes:

- Larger cores (direct effect)
- More efficient mass loss (indirect effect)

The inteprlay between these two effects lead to:

- More compact structure @ preSN stage → more massive remnants
- Increase of the RSG and WR SN progenitors at all metallicities
- Increase of SNIb/SNII fraction at all metallicities

Nucleosynthesis:

- PFs of the majority of the elements increase with the mass for any fixed metallicity and increase for any fixed mass with decreasing the metallicity
- No production of elements heayer than Zn is obtained in non rotating models for metallicities [Fe/H]<-1
- The inclusion of rotation enhances the production of N, F and all the elements heavier than Zn up to Pb (primary ^{14}N production)
- This effect is higher for lower metallicities (more efficient rotational mixing) and for lower mass models (higher angular momentum for a fixed initial velocity)

INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE