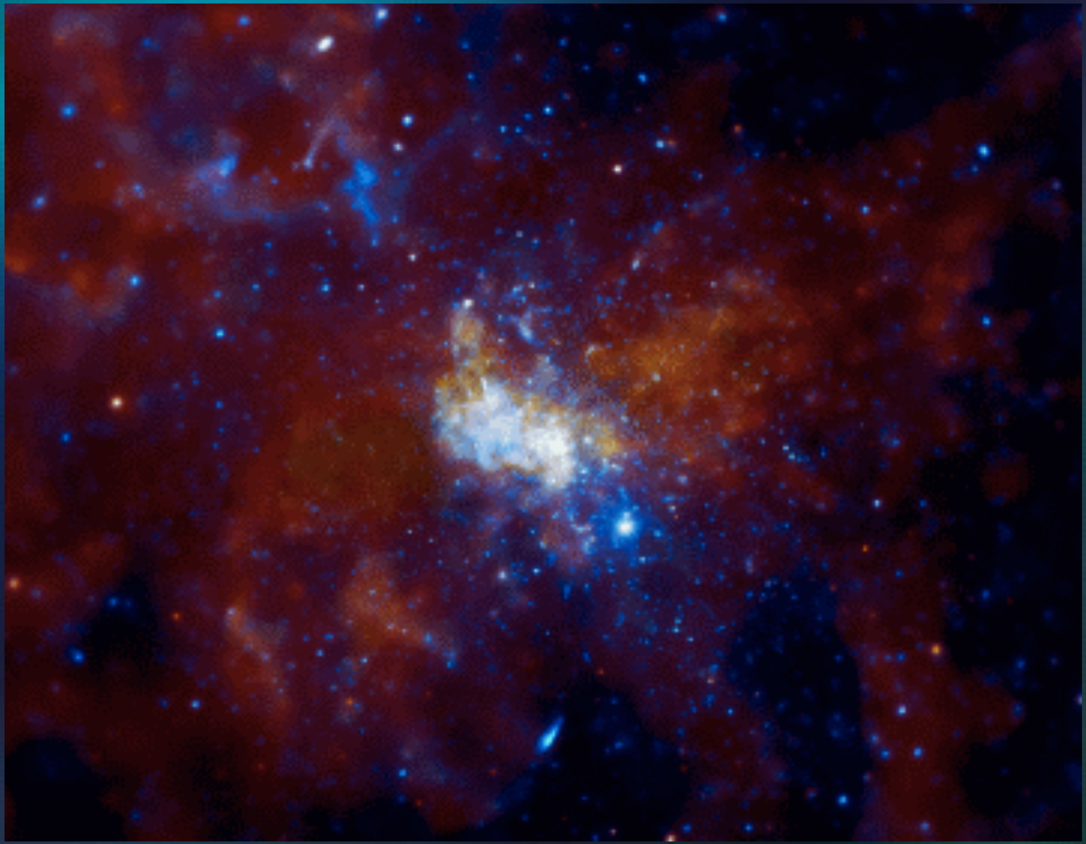
STELLAR ASTROPHYSICS
Why theory badly needs the help of observations



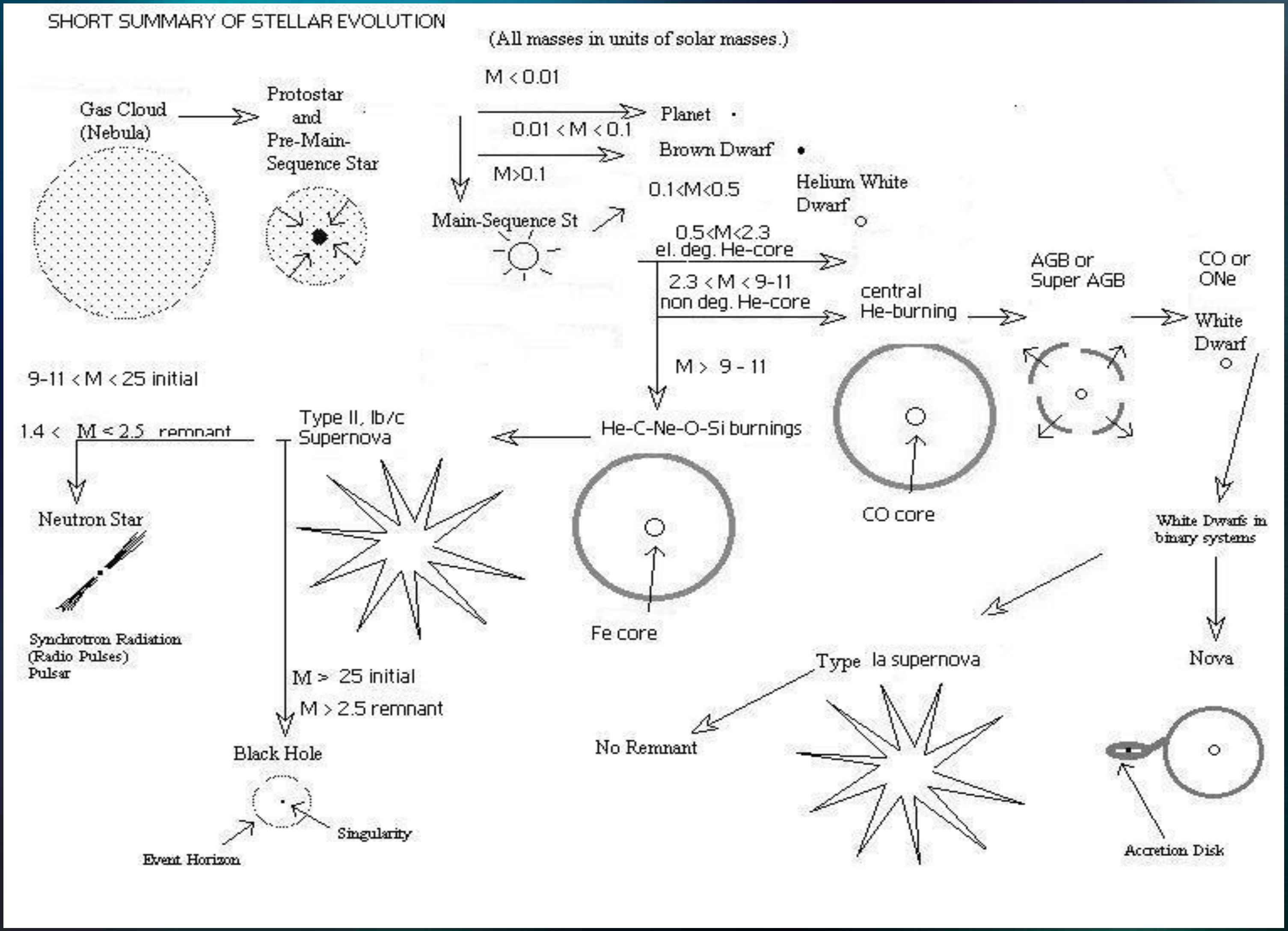
Maurizio Salaris

ASTROPHYSICS
RESEARCH INSTITUTE

LIVERPOOL
JOHN MOORES
UNIVERSITY

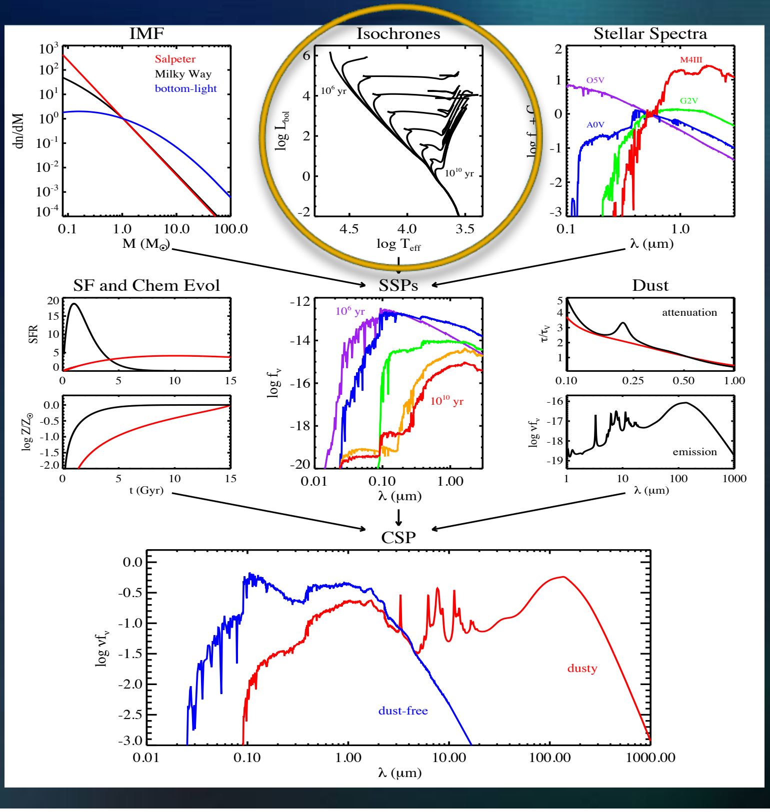
STELLAR ASTROPHYSICS

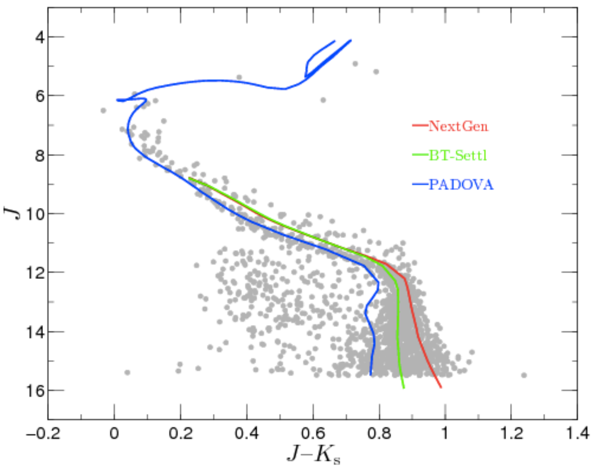
Study of appearance, structure, composition and evolution of stars

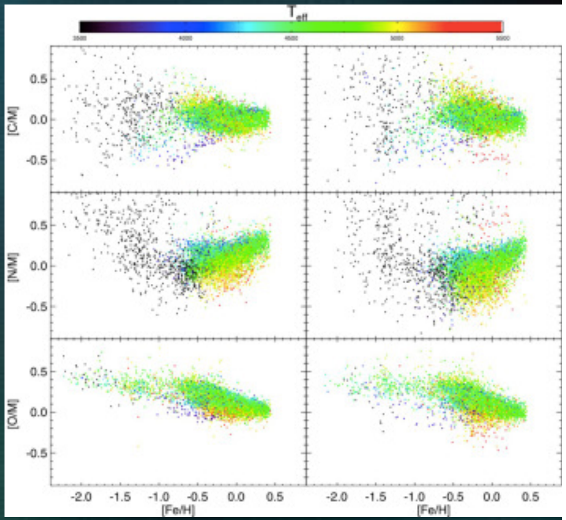


Theoretical stellar models are one of the main tools to investigate the formation and evolution of Galactic and extragalactic stellar systems

The theoretical interpretation of the current flow of high-precision and large-volume data requires an increased accuracy of the predictions of stellar model theory







OUTLINE

- Pre-MS accretion
- Non-convective chemical element transport during MS and RGB
- AGB evolution
- Rotational mixing and massive star evolution
- SN progenitors

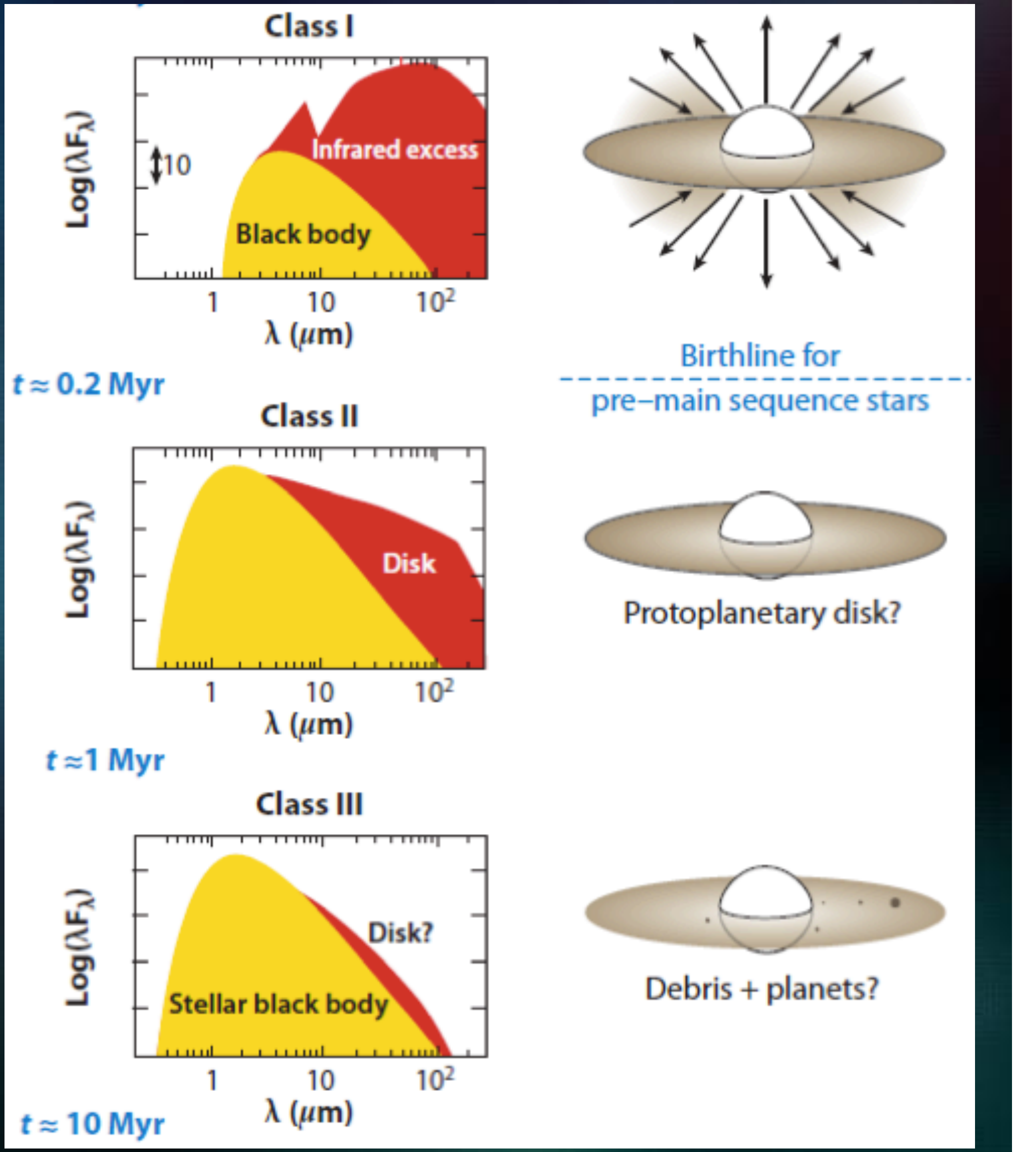
PRE-MS accretion

In the model of magnetospheric accretion, matter from a circumstellar disk falls onto a pre-MS star along its magnetic field lines.
The impact of the material onto the stellar surface produces an accretion shock, which radiates at UV wavelengths. The material accreting onto a young star also produces hydrogen emission lines that offer an additional tracer of accretion.

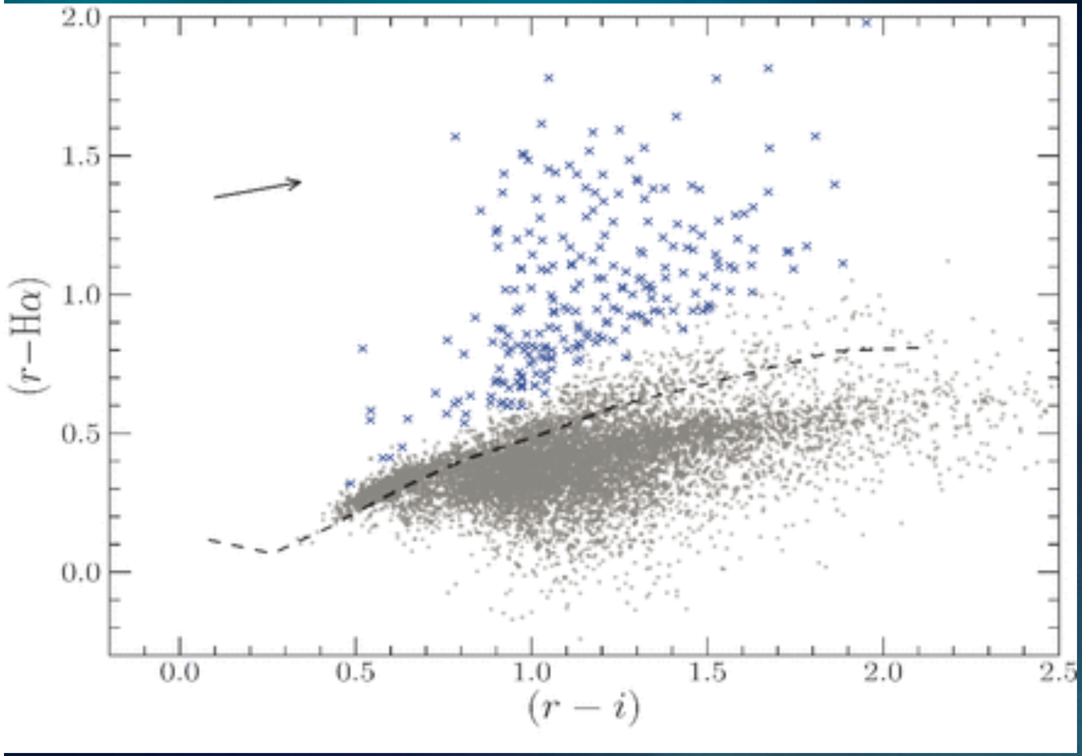
Uncertainties about disk modeling, timescales and mechanisms for the removal of the disk

Implications for planet-formation models

Potential for explaining discrepancy between cosmological Li predictions and observations in PopII stars (Fu et al. 2015)



Kalari et al. (2015)



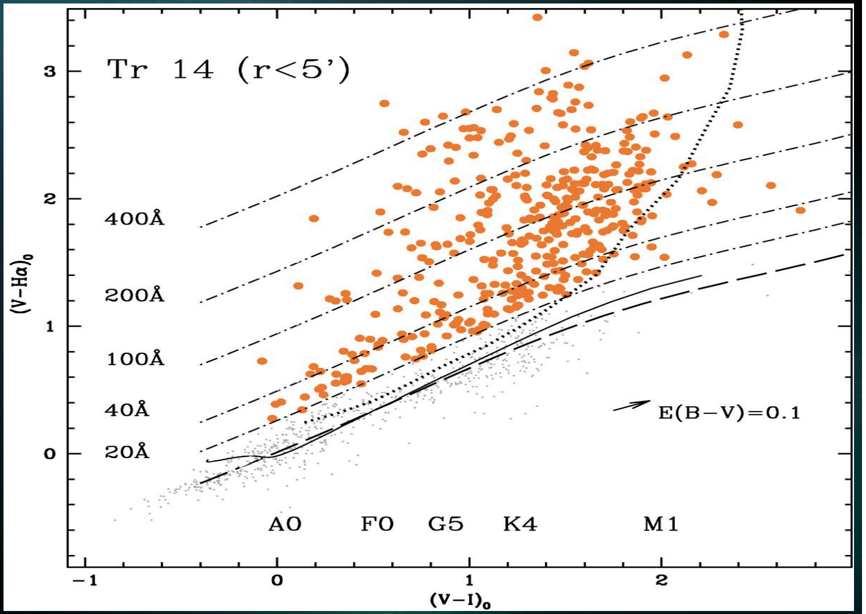
PMS stars in the Lagoon nebula (VPHAS+)

$$\log\ L_{\rm acc} = (1.13 \pm 0.07)\log\ L_{\rm H\alpha} + (1.93 \pm 0.23)$$

$$\dot{M}_{\rm acc} = \frac{L_{\rm acc} R_*}{G M_*}\left(\frac{R_{\rm in}}{R_{\rm in} - R_*}\right).$$

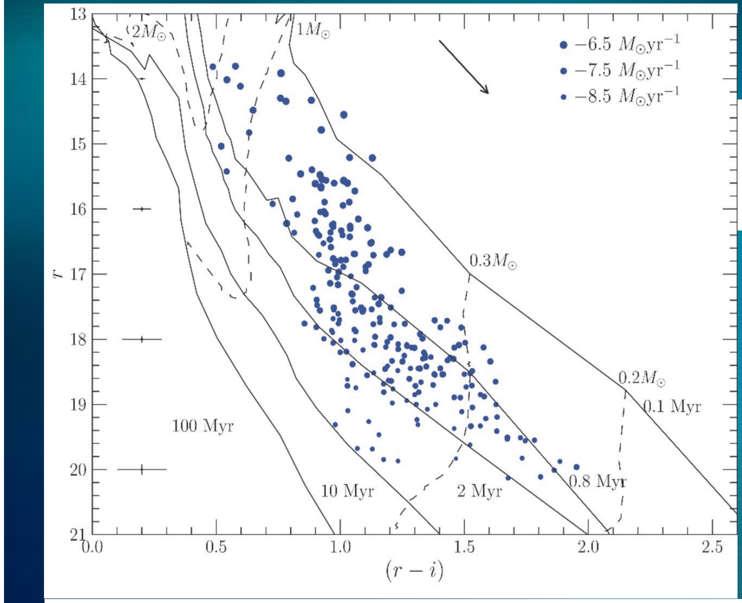
Beccari et al. (2015)

Trumpler 14 in the Carina nebula

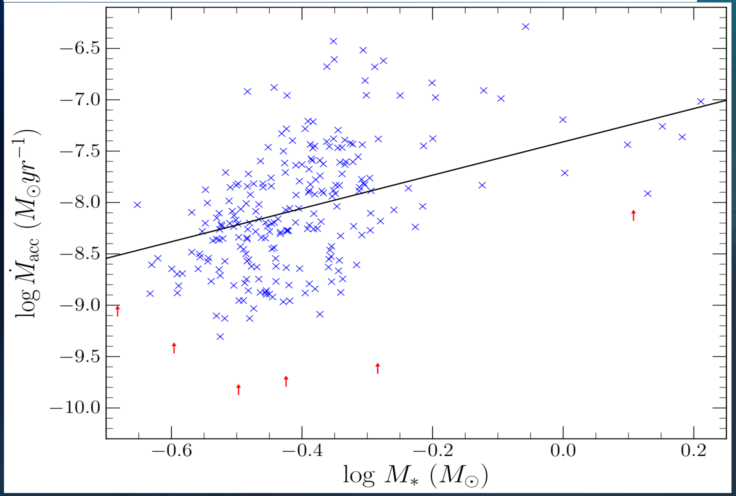


Kalari et al. (2015)

$$\dot{M}_{\rm acc} \propto M_*^{2.14\pm0.3}$$



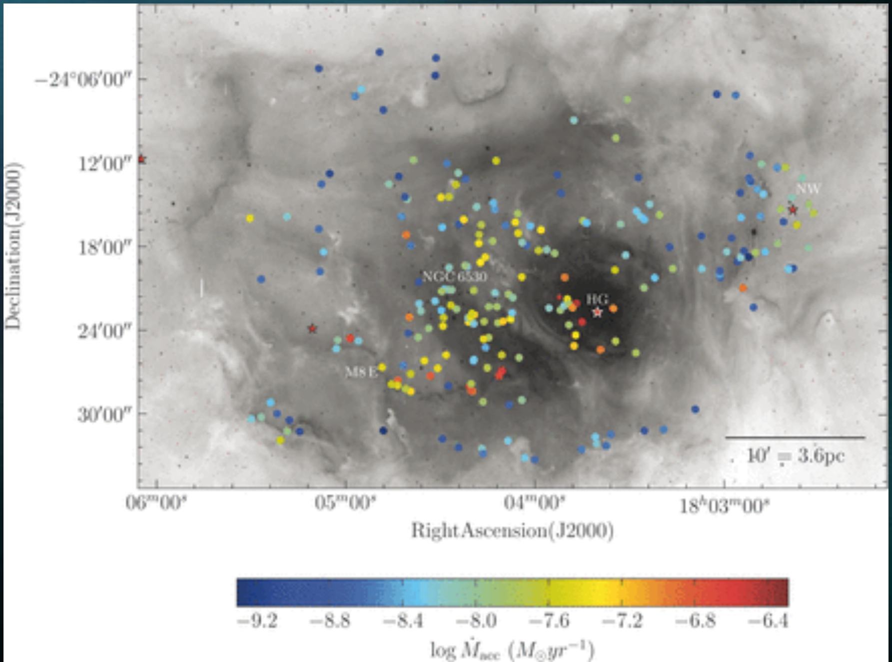
WARNING: episodic early accretion (if true) and/or starspots can affect the pre-MS tracks (Baraffe & Chabrier 2010, Somers & Pinsonneault 2015)



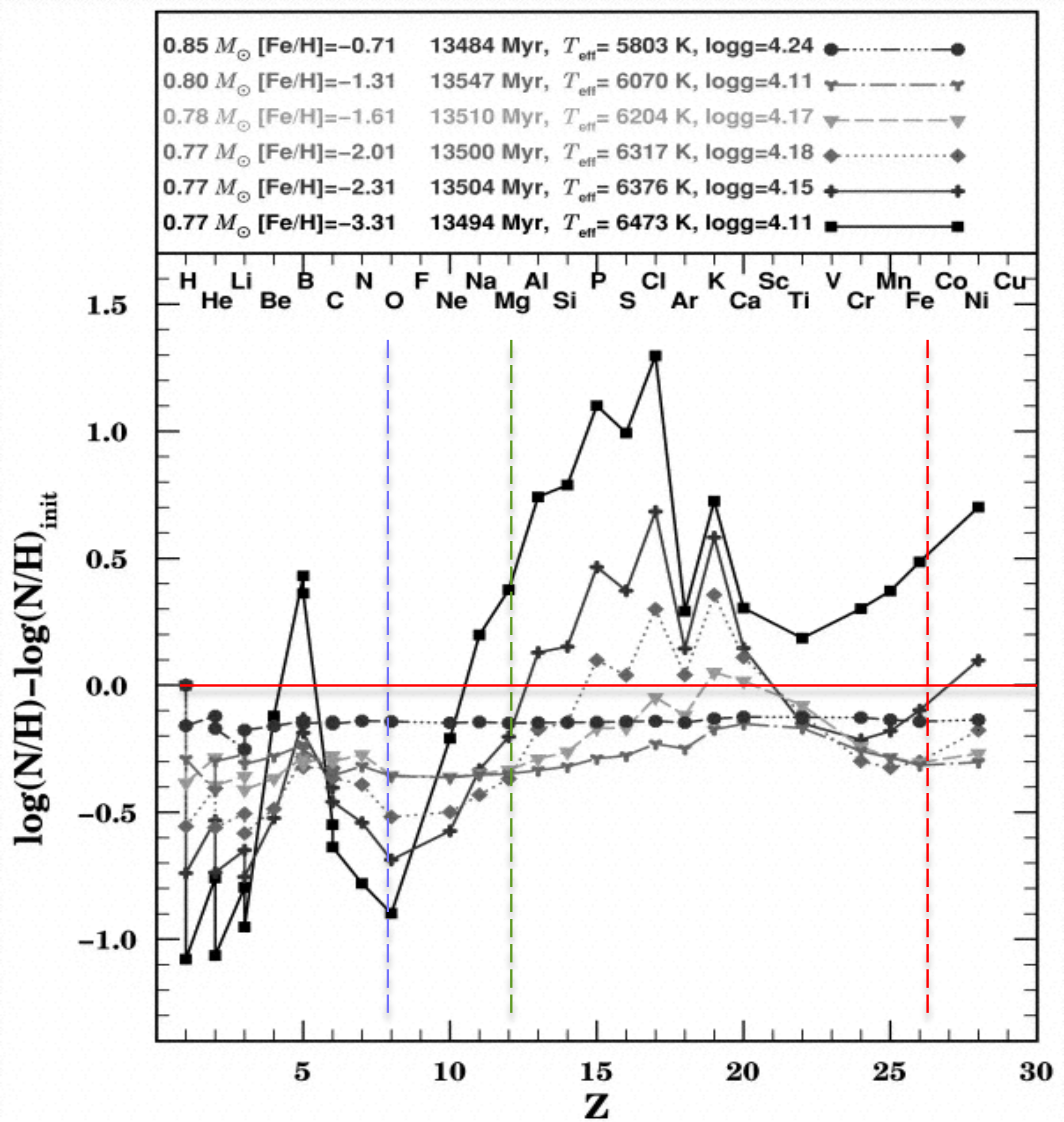
$$\log \dot{M}_{\rm acc} \simeq -\frac{1}{2}\times\log t+\frac{3}{2}\times\log m-\frac{1}{3}\times\log Z-7.9$$

(De Marchi & Panagia 2015)

Spatial distribution of accretion rates



Gravitational settling-levitation on the MS



Richard et al.
(2002)

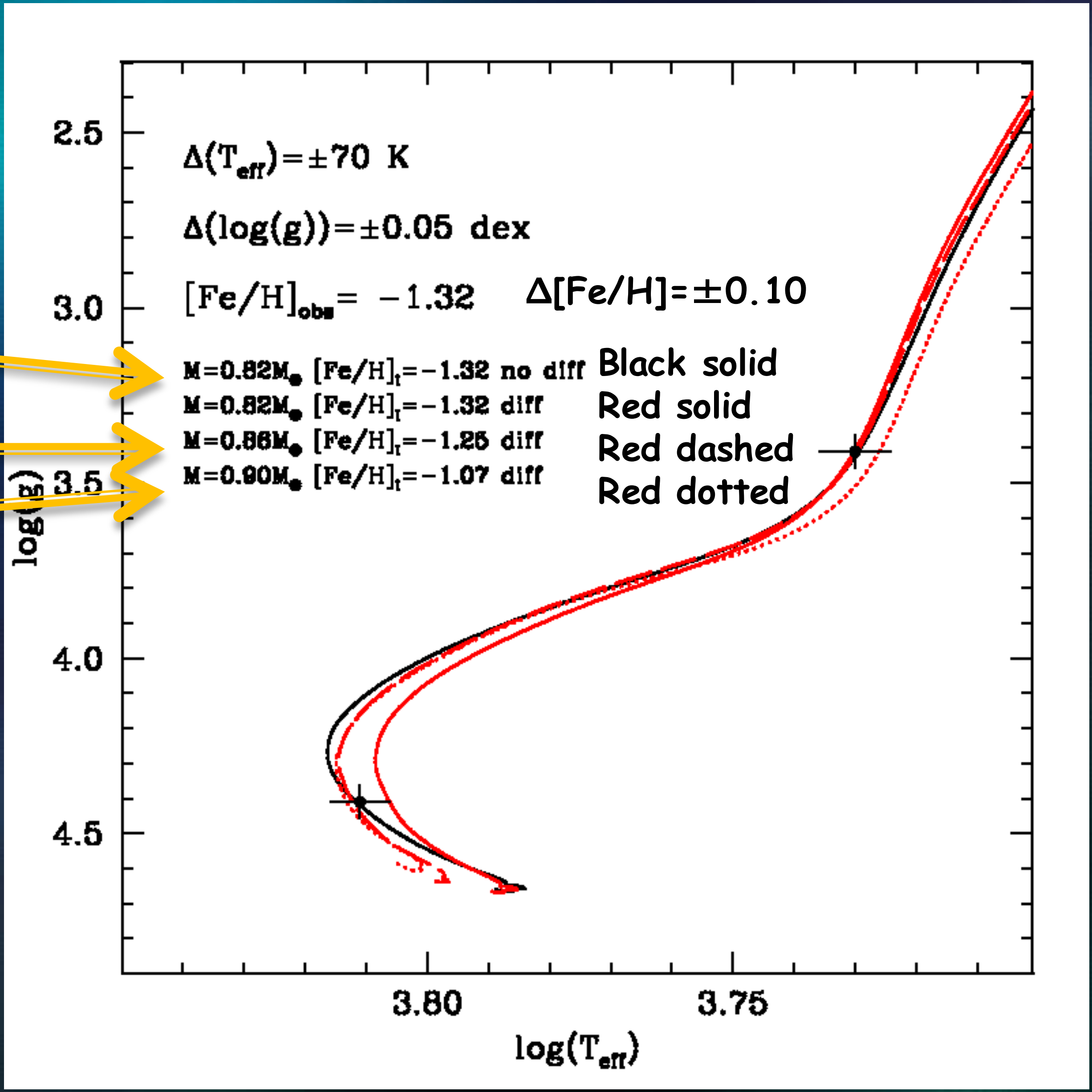
EFFICIENCY OF ATOMIC DIFFUSION AND AGE OF FIELD STARS

MS

≅8.5 Gyr

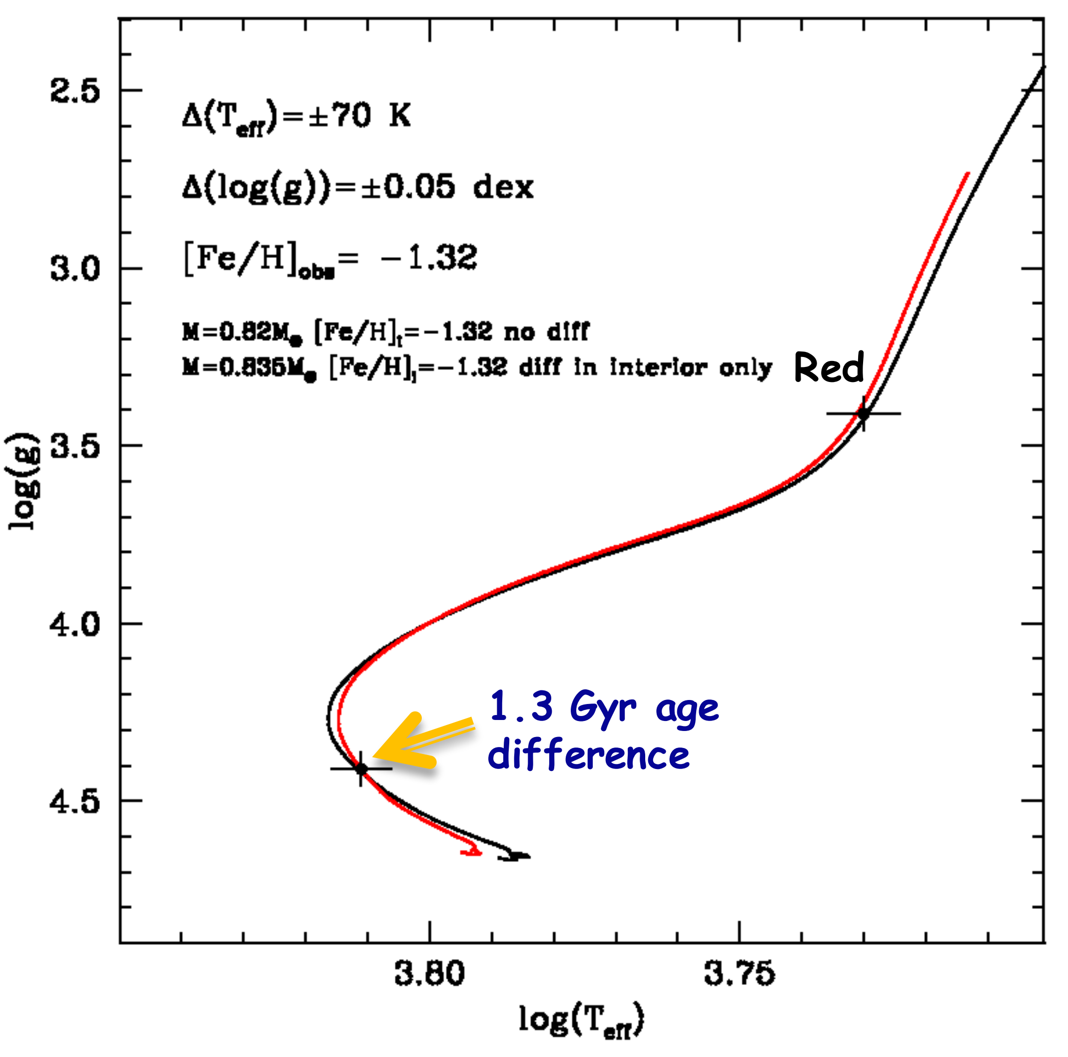
≅6 Gyr

≅5 Gyr



Zero-order test with atomic diffusion inhibited from envelopes

Spectroscopy of GCs tells us that gravitational settling-levitation are strongly inhibited (at least) for the convective envelope



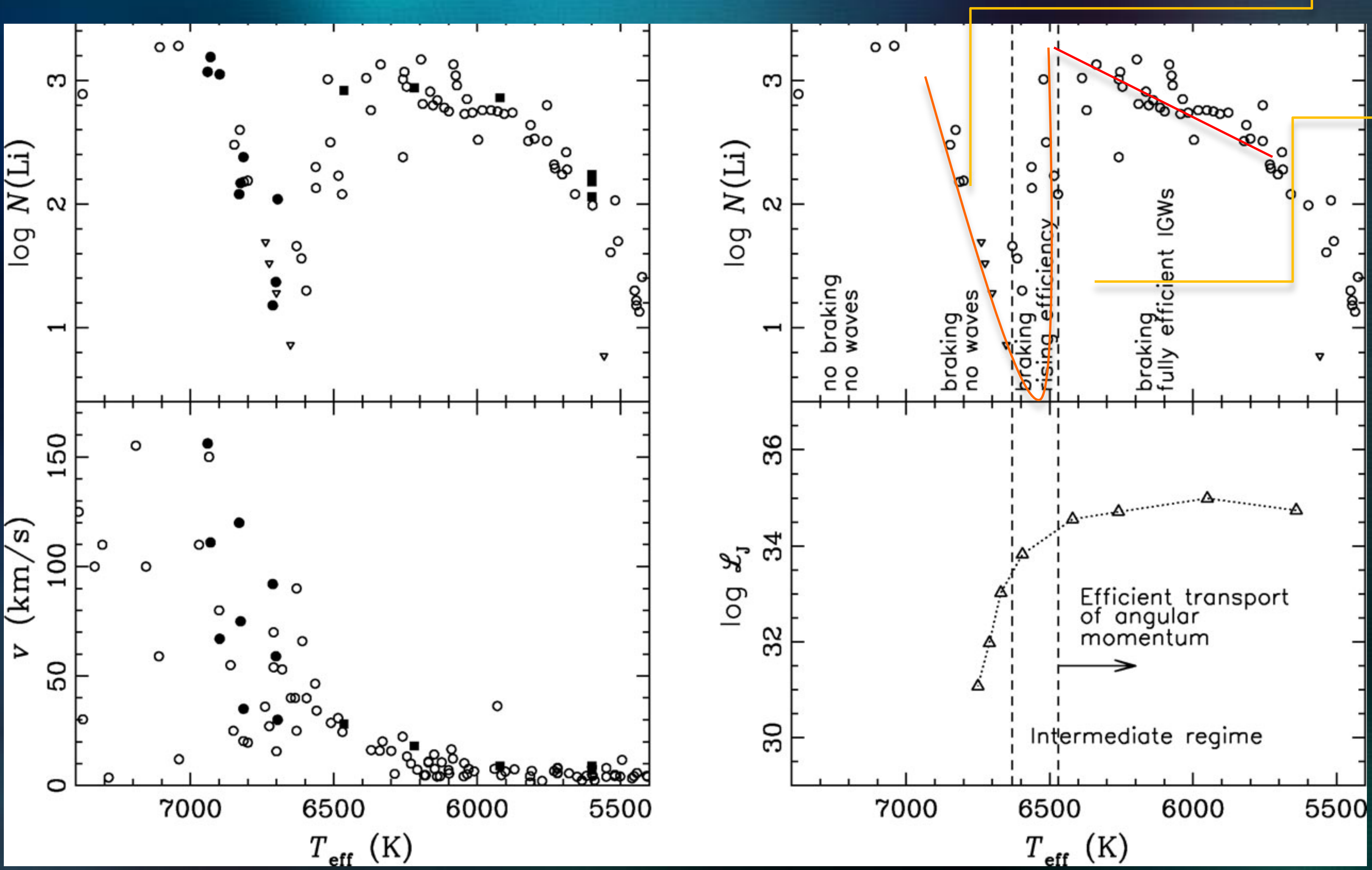
1.3 Gyr age difference

Diffusion and more in open clusters. An example

Hyades

Charbonnel & Talon (2009)

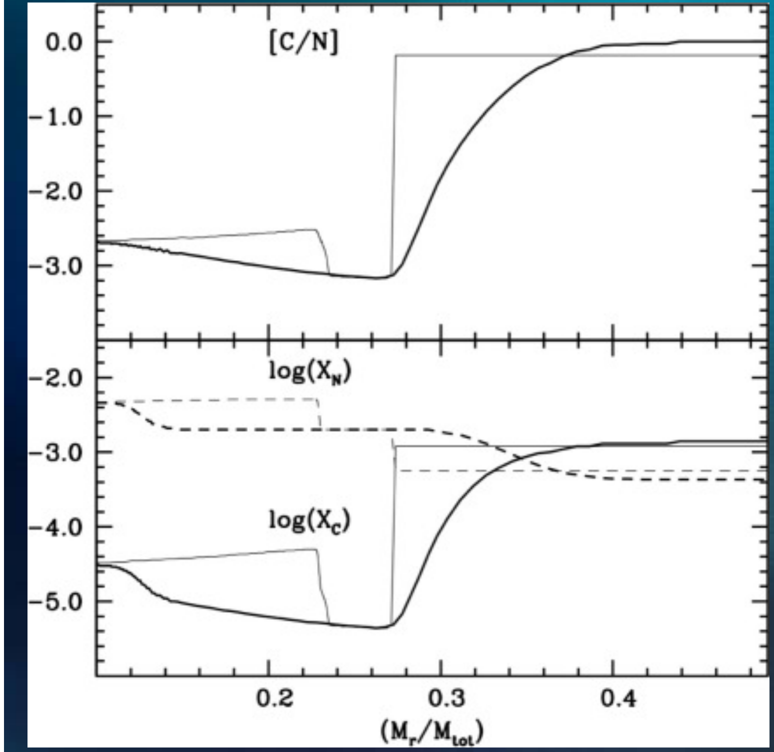
Surface brakes
Increase diff rot.
More rotational mixing and
Li destructions



Gravity
waves
decrease
diff.
rotation.

Li
destruction
decreases

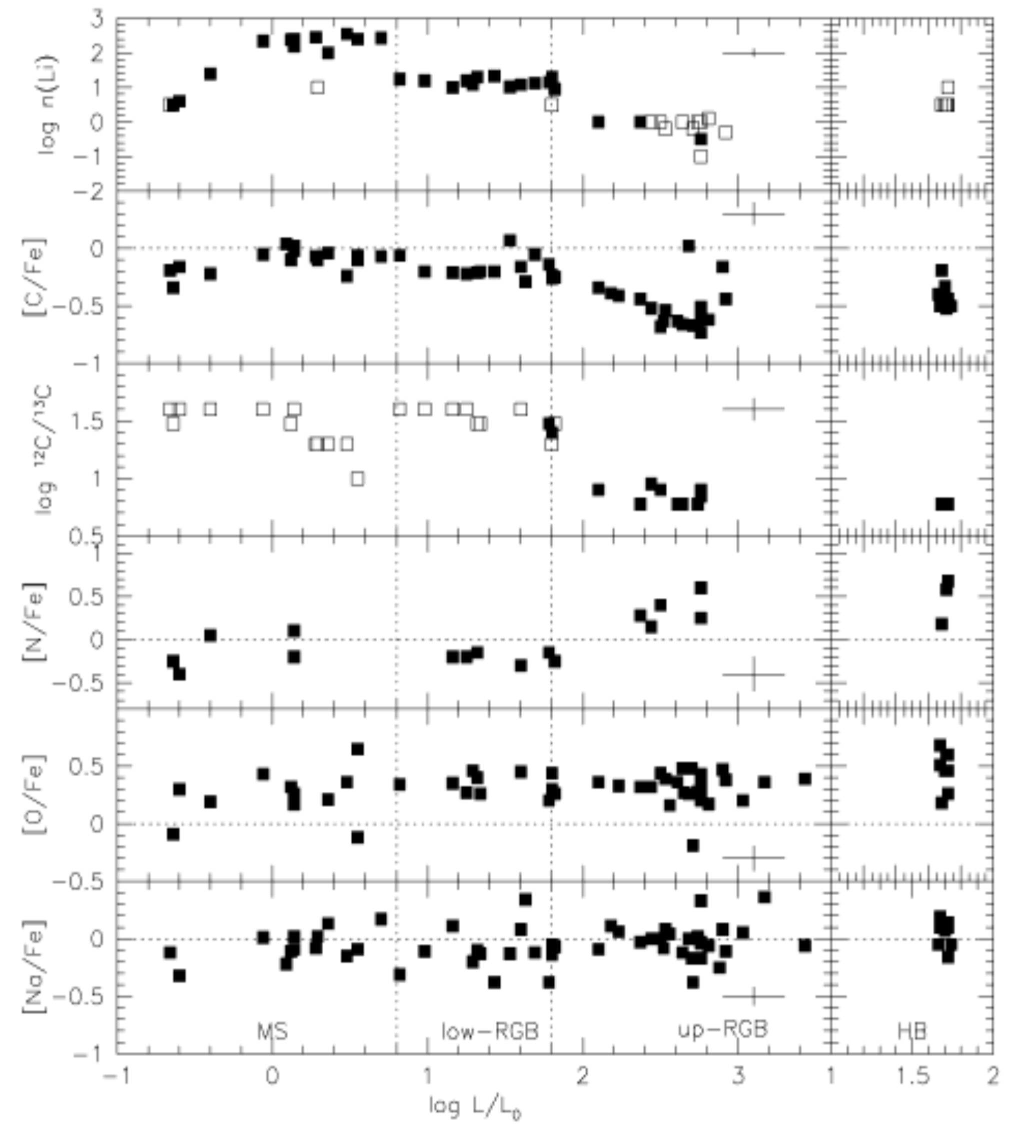
RGB extra-mixing after first dredge up



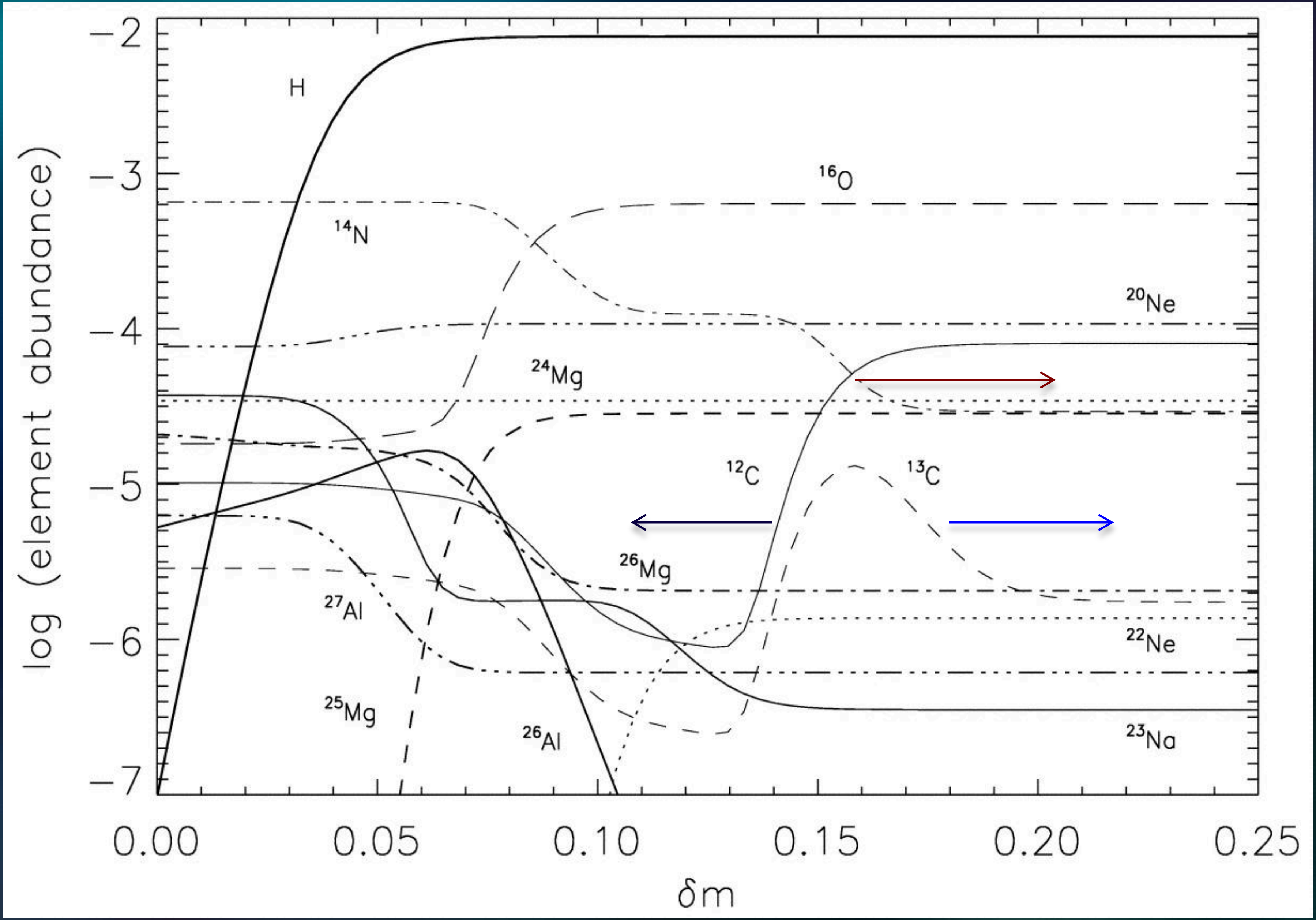
Salaris et al. (2015)

1st dredge up

Field halo stars

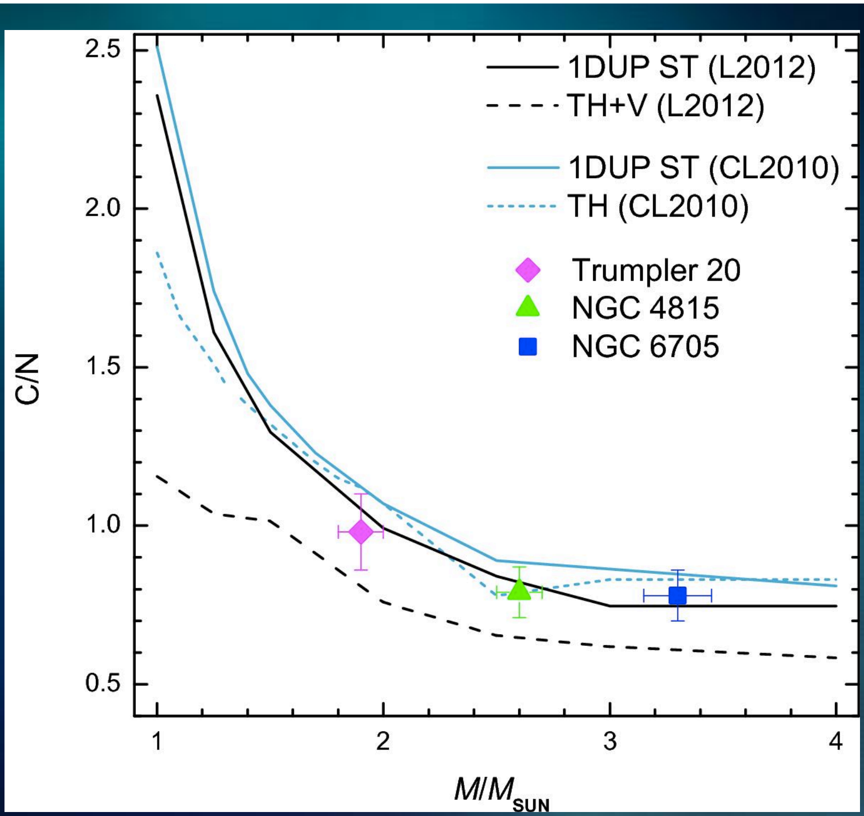


Gratton et al. (2000)



Salaris et al. (2002)

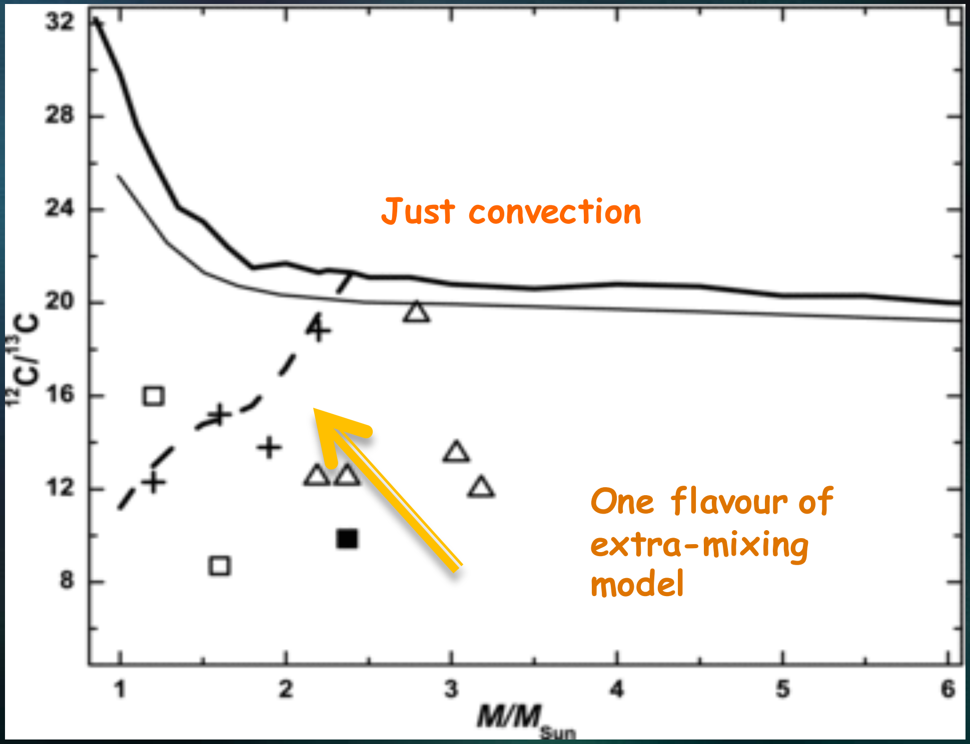
Bottom conv. envelope at δm=1
Bottom H-burning shell at δm=0



Tautvaisiene et al. (2015)

(GAIA-ESO)

!! Free parameters !!



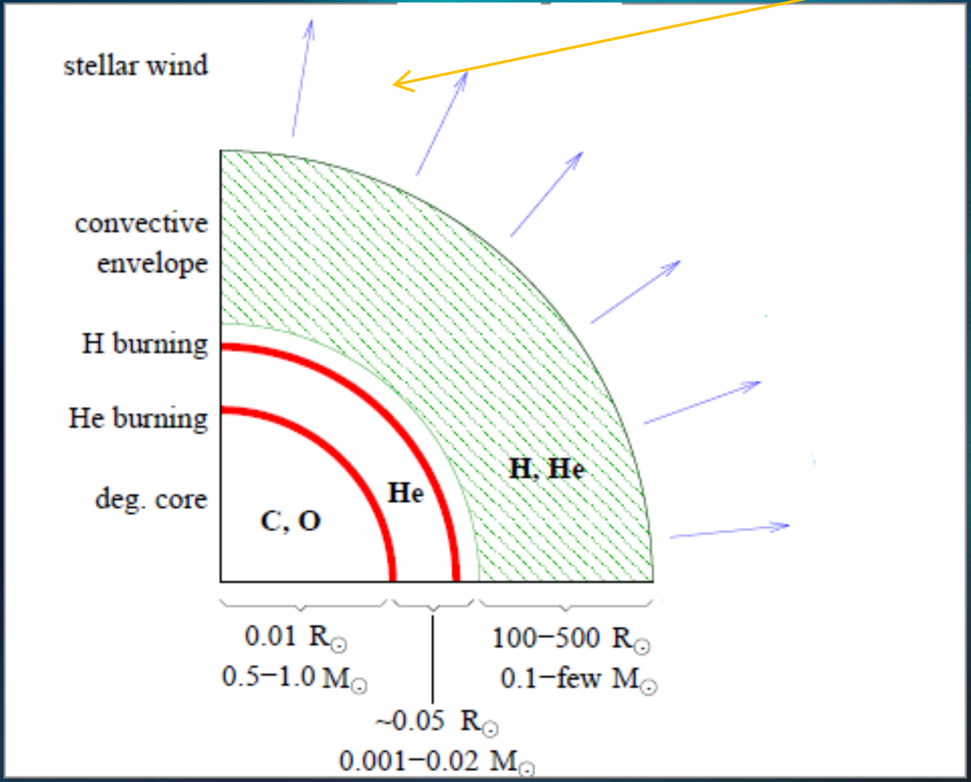
Mikolaitis et al. (2010)

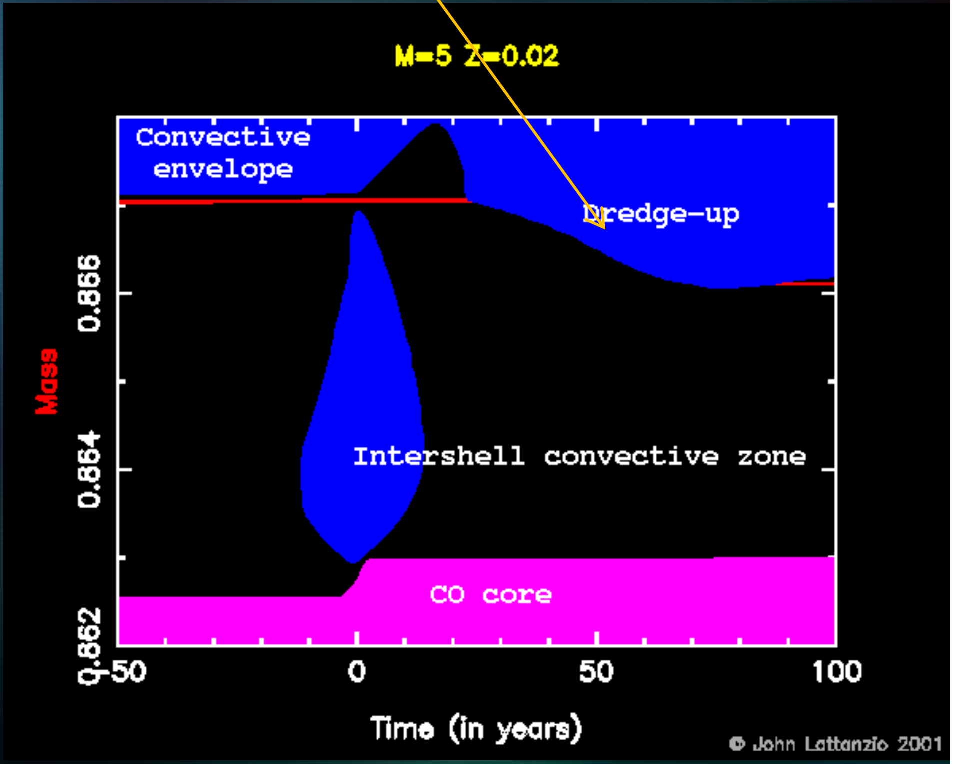
RC star abundances in open clusters

AGB stars

Mass loss, boundaries of convection

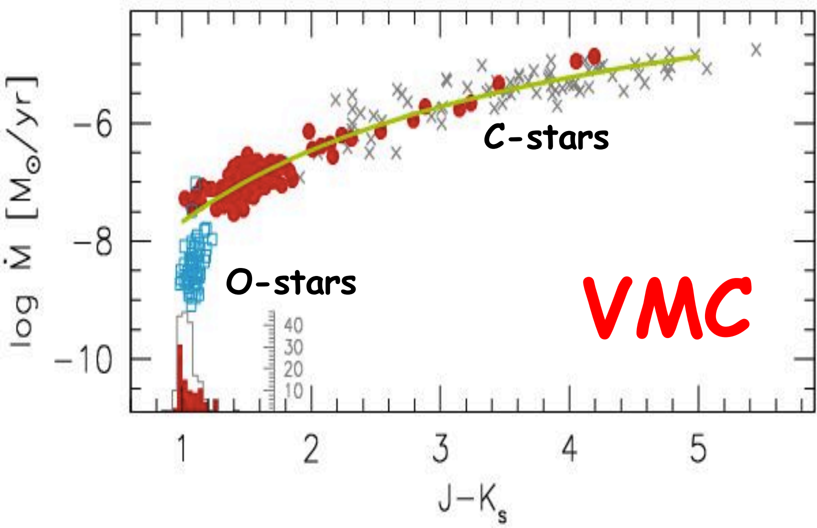
UNCERTAIN !!!!!



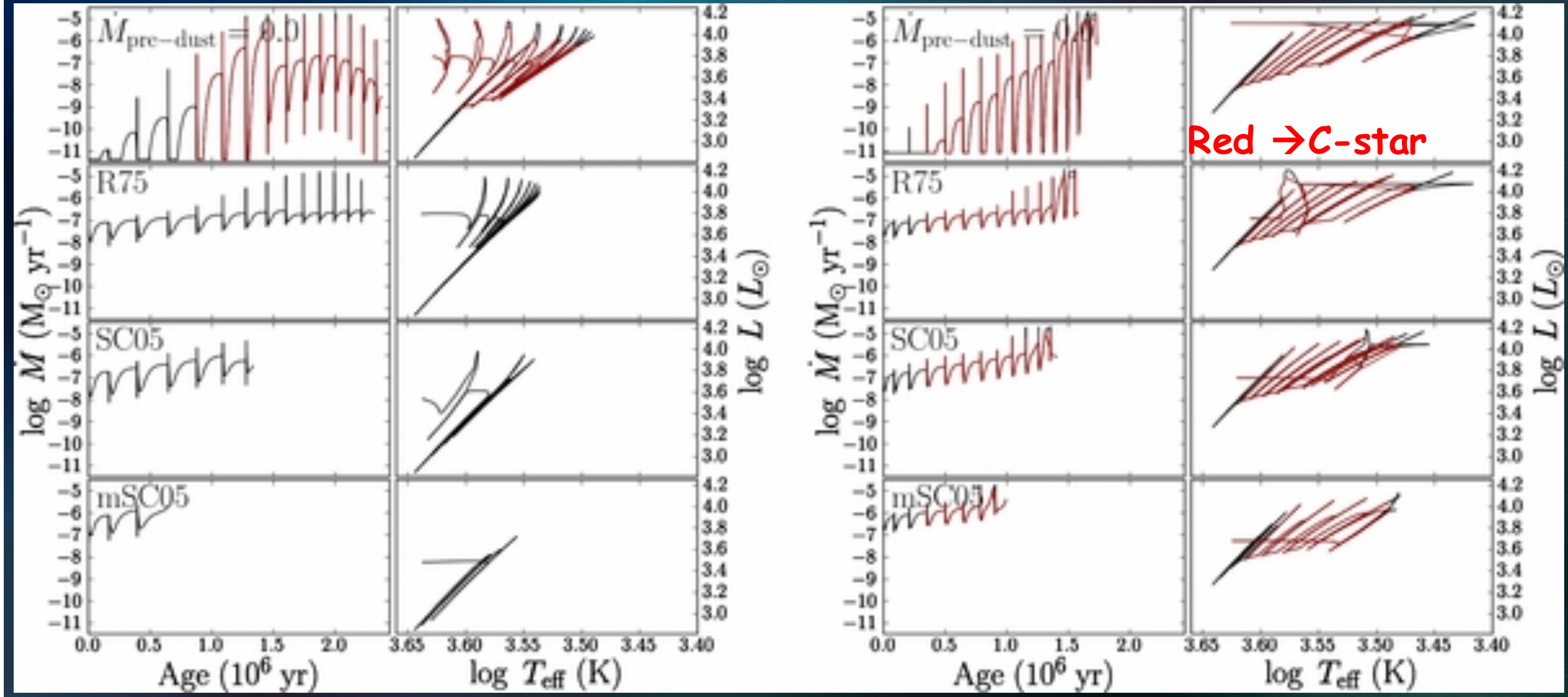


© John Lattanzio 2001

Mass loss



Gullieuszik et al. (2012)

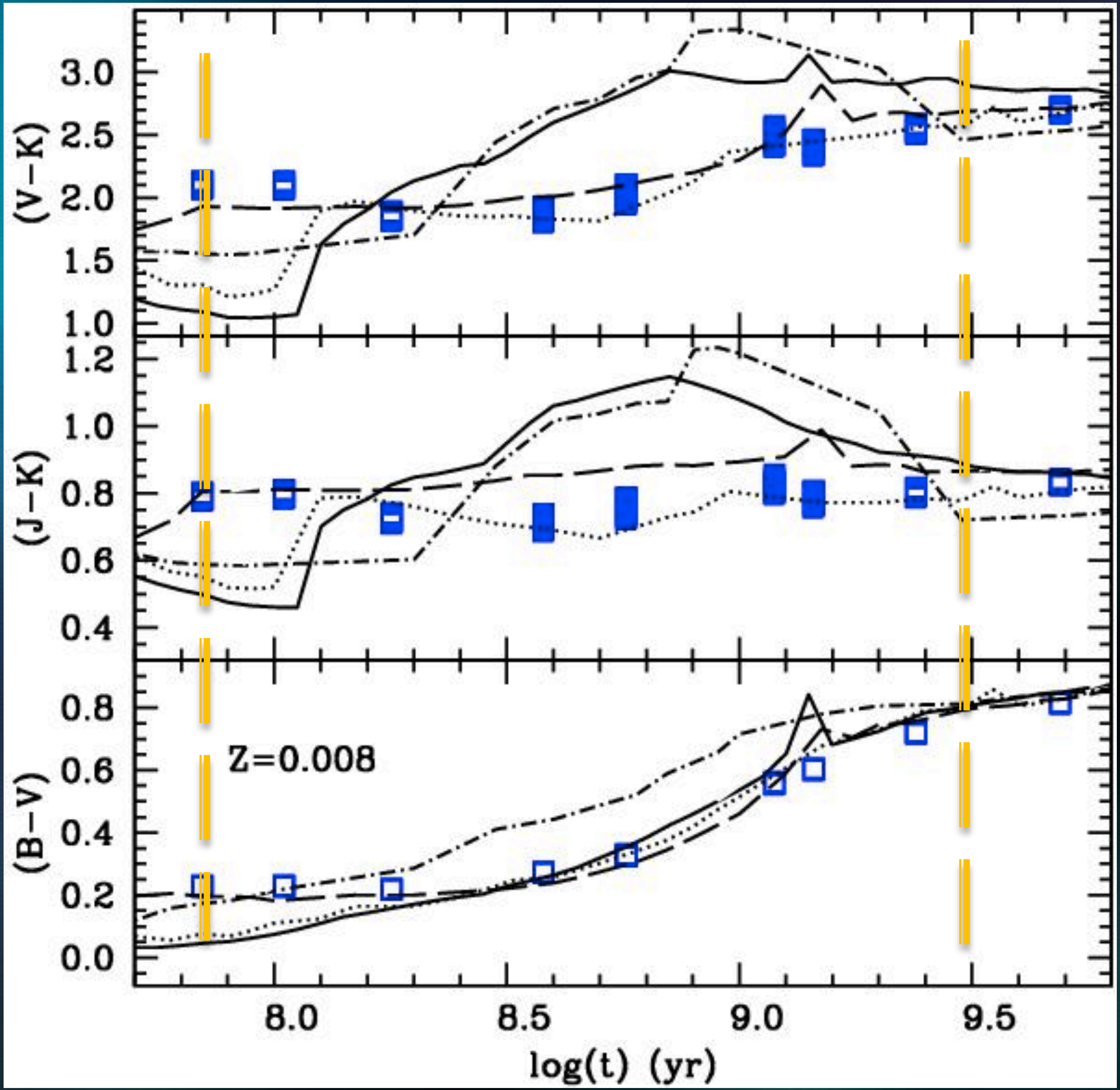


Rosenfield et al (2014)

Four different prescriptions for mass loss before the TPs (1 and 2 $M_\odot$ models) (Z=0.001)

Salaris et al.
(2014)

Integrated near-IR colours of stellar populations dominated by AGB stars



Uncertain yields

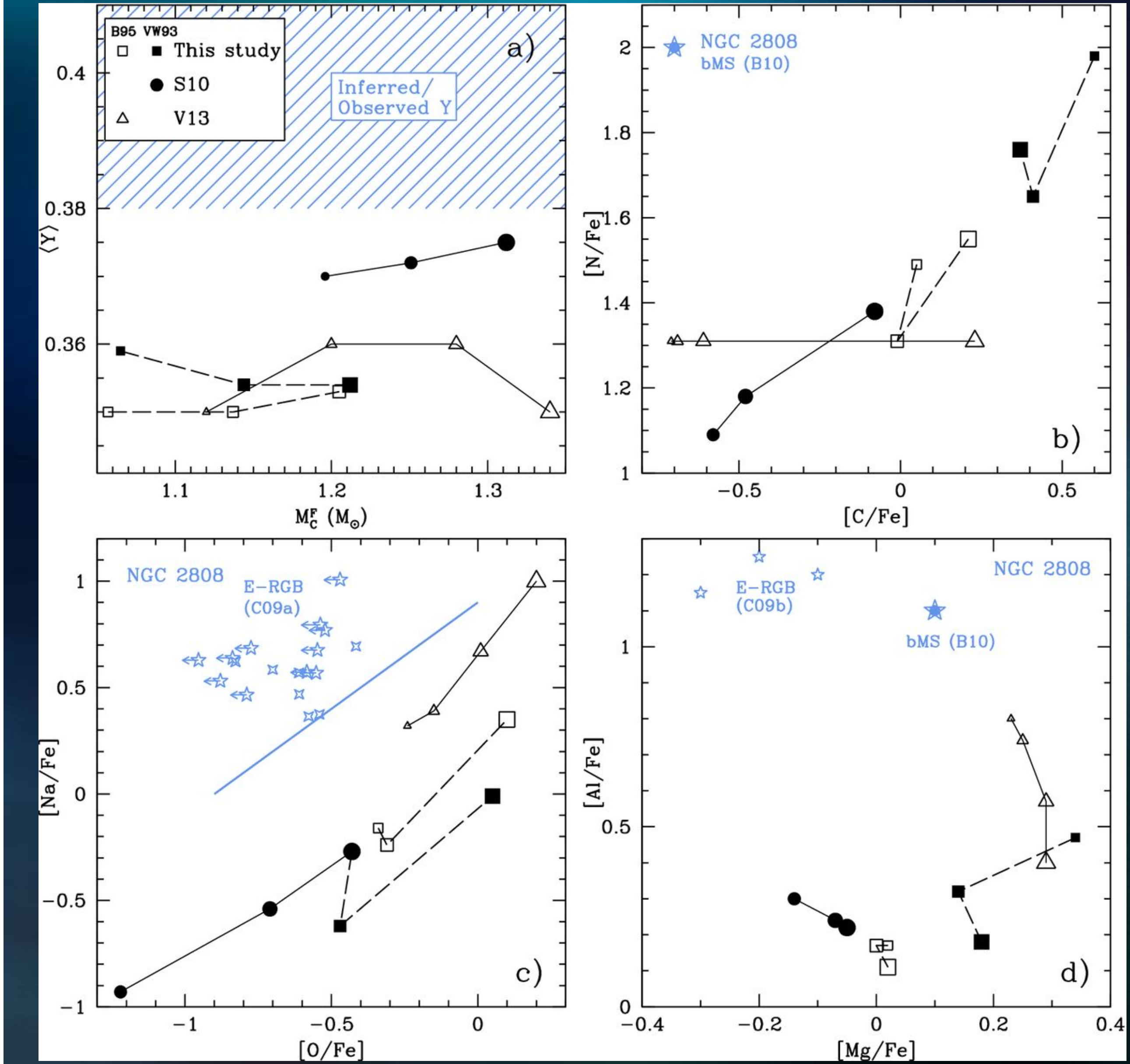
Doherty et al. (2014)

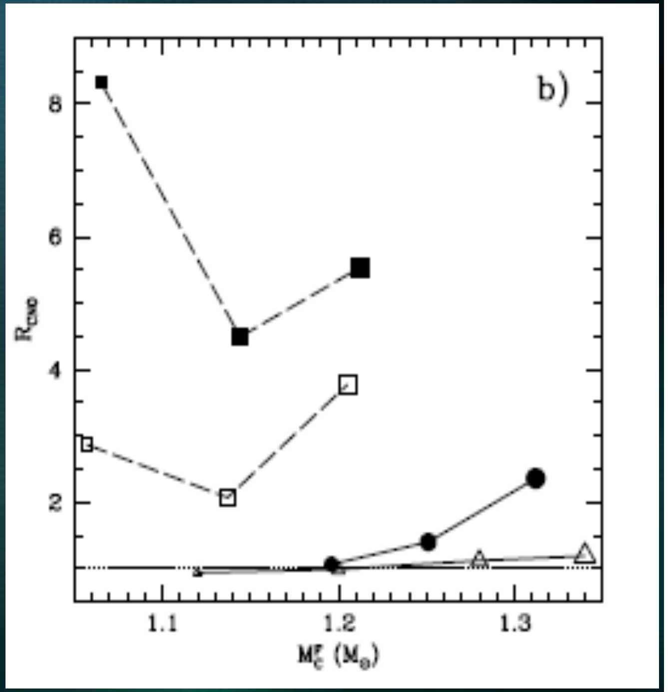
Super-AGB models only

Z=0.001
M=6.5, 7.0, 7.5 M$_\odot$

V13 M=6.0, 6.5 ,7.0, 7.5 M$_\odot$

S10 M= 8.0, 8.5, 9.0 M$_\odot$





Rotation of massive stars

Shellular rotation → ω and c.c. constant on an isobar

Roche approximation → mass centrally concentrated

Equivalent volumes → Adoption of the radii of the equivalent spheres

Strong horizontal turbulence
(Zahn 1992)

Standard 1D stellar evolution equations with the addition of ‘form factors’.
Radius of the sphere the encloses the same volume as the corresponding isobar
Thermodynamic quantities are mean values over an isobar

$$\rho \frac{\partial X_i}{\partial t}\bigg|_{M_r} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho\, r^2 D_{\rm chem}\frac{\partial X_i}{\partial r}\right)$$

Chemical element transport

$$\rho \frac{\partial}{\partial t}(r^2\bar{\Omega})_{M_r} = \frac{1}{5r^2}\frac{\partial}{\partial r}(\rho\, r^4\bar{\Omega}\, U_2(r)) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho\, D_{\rm ang}\, r^4\frac{\partial\bar{\Omega}}{\partial r}\right)$$

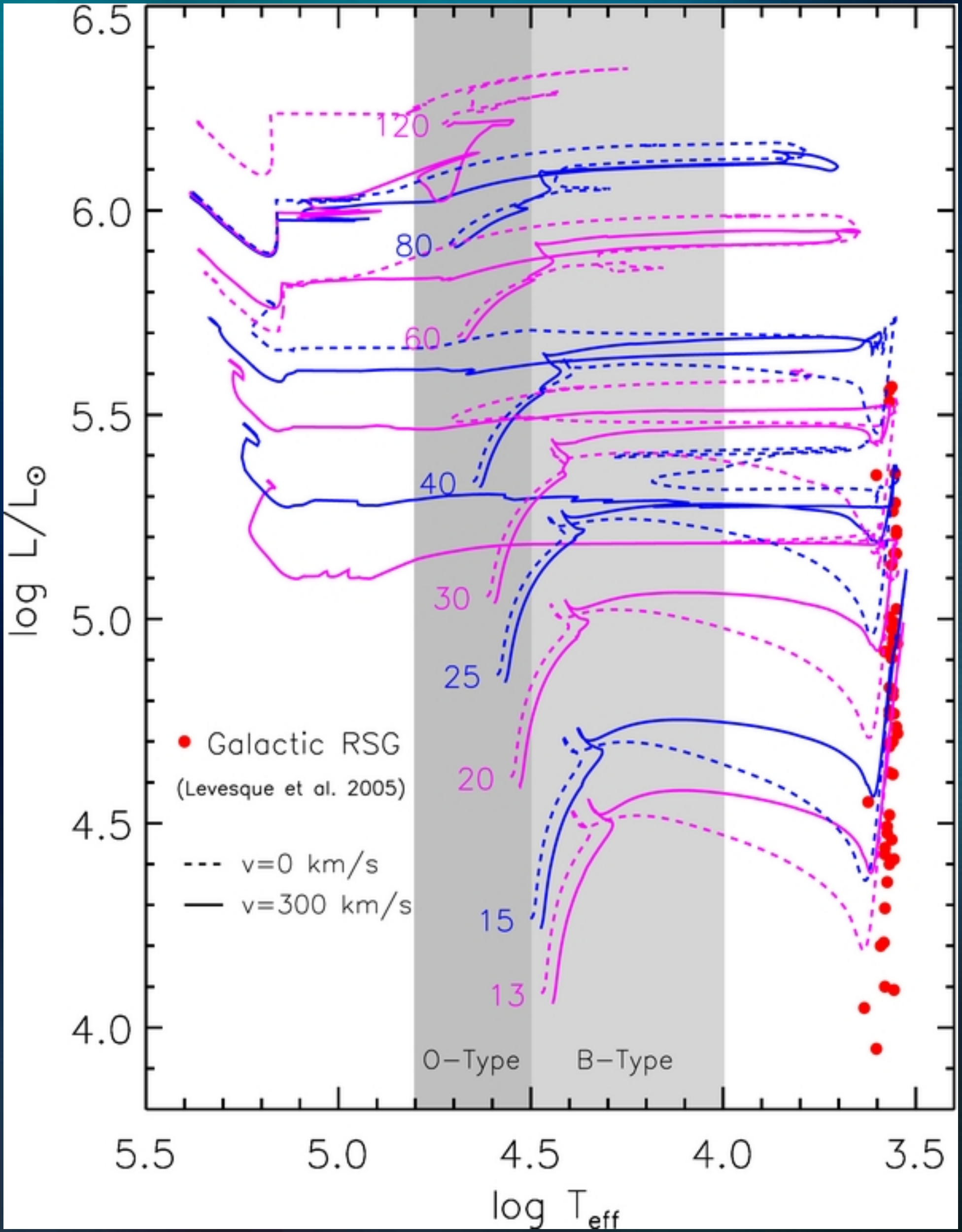
Angular
momentum transport

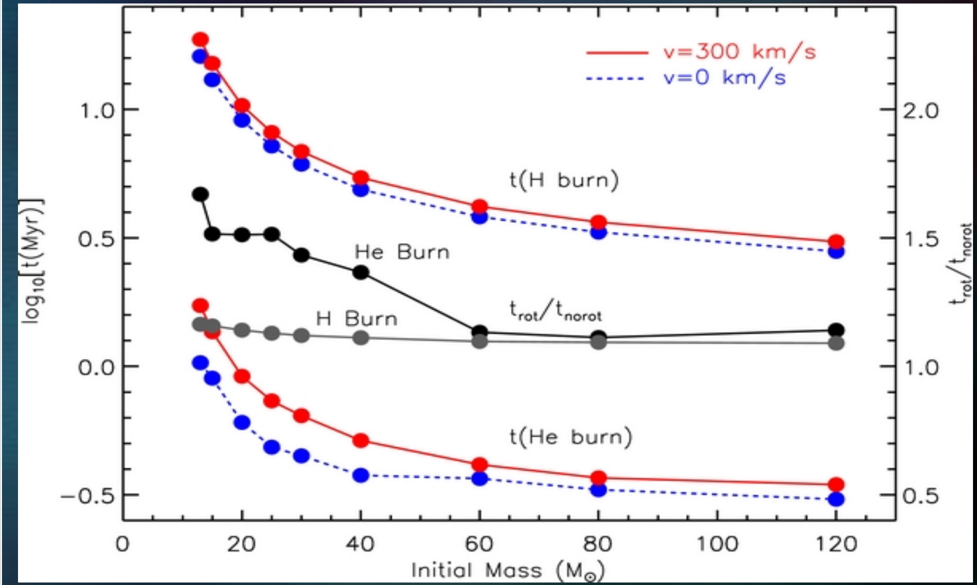
Ω=angular velocity on an isobar

U_2=radial component of the meridional circulation velocity

2D simulations by Rieutord et al. do not confirm the shellular rotation approximation

Asteroseismic data show that the inner rotational profile of low-mass red giant branch stars is much flatter than predicted by rotating models





Chieffi & Limongi (2013)

Effect of different angular momentum and chemical diffusion efficiencies

$$D_{chem} = D_{shear} + D_{eff}$$

$$\rho \frac{\partial X_i}{\partial t}\Big|_{M_r} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho\, r^2 D_{\rm chem}\frac{\partial X_i}{\partial r}\right)$$

Meridional circulation

$$D_{\rm eff} = \frac{1}{30}\frac{|r\,U(r)|^2}{D_{\rm h}}.$$

Horizontal diffusion

$$\rho \frac{\partial}{\partial t}(r^2\bar{\Omega})_{M_r} = \frac{1}{5r^2}\frac{\partial}{\partial r}(\rho\, r^4\bar{\Omega}\, U_2(r)) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho\, D_{\rm ang}\, r^4\frac{\partial\bar{\Omega}}{\partial r}\right)$$

Meridional circulation
(radial component)

$$D_{ang} = D_{shear}$$

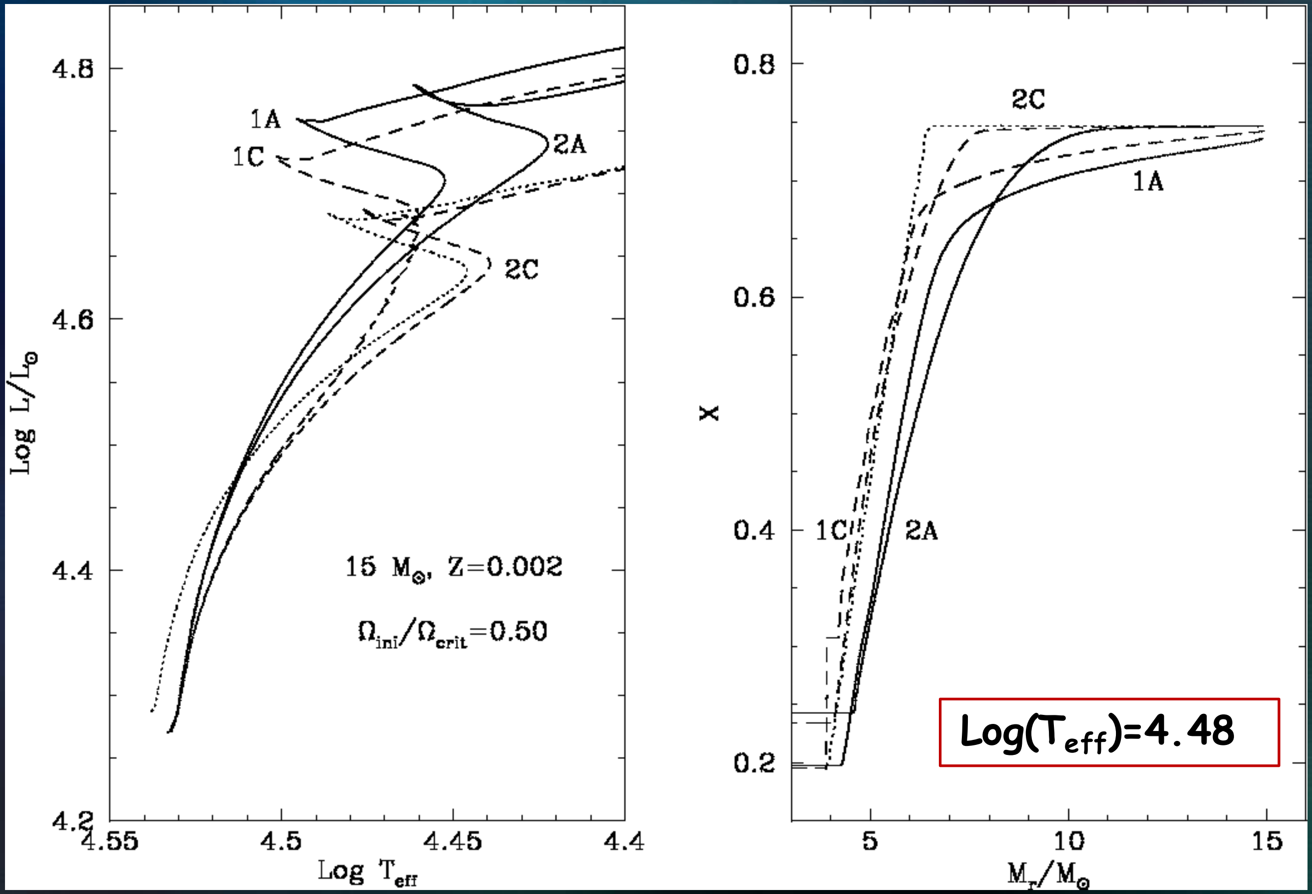
Meynet et al. (2013)

Different combinations of:

i) Two prescriptions for vertical shear diffusion coefficient D_{shear} (1 and 2)
ii) Three prescriptions for horizontal shear diffusion, D_h (A, B, C)

D_h controls the efficiency of mixing in regions with strong μ gradients (e.g. The edge of convective H-core during MS)

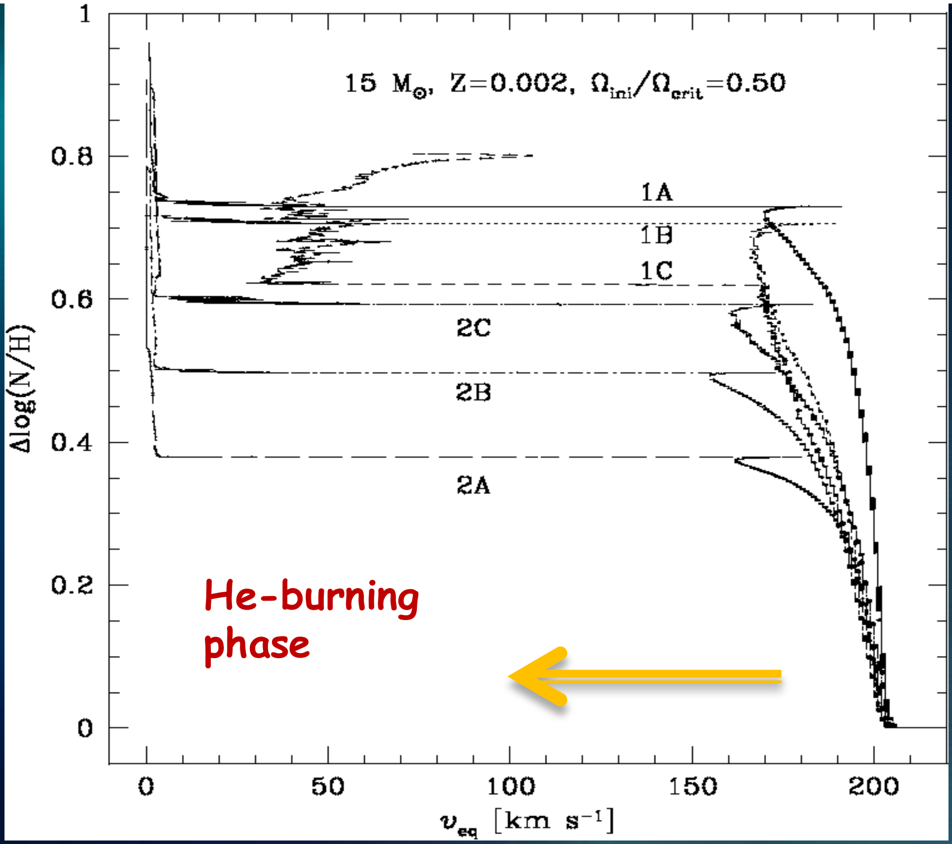
D_{shear} controls the efficiency of mixing in regions with weak or vanishing μ gradients



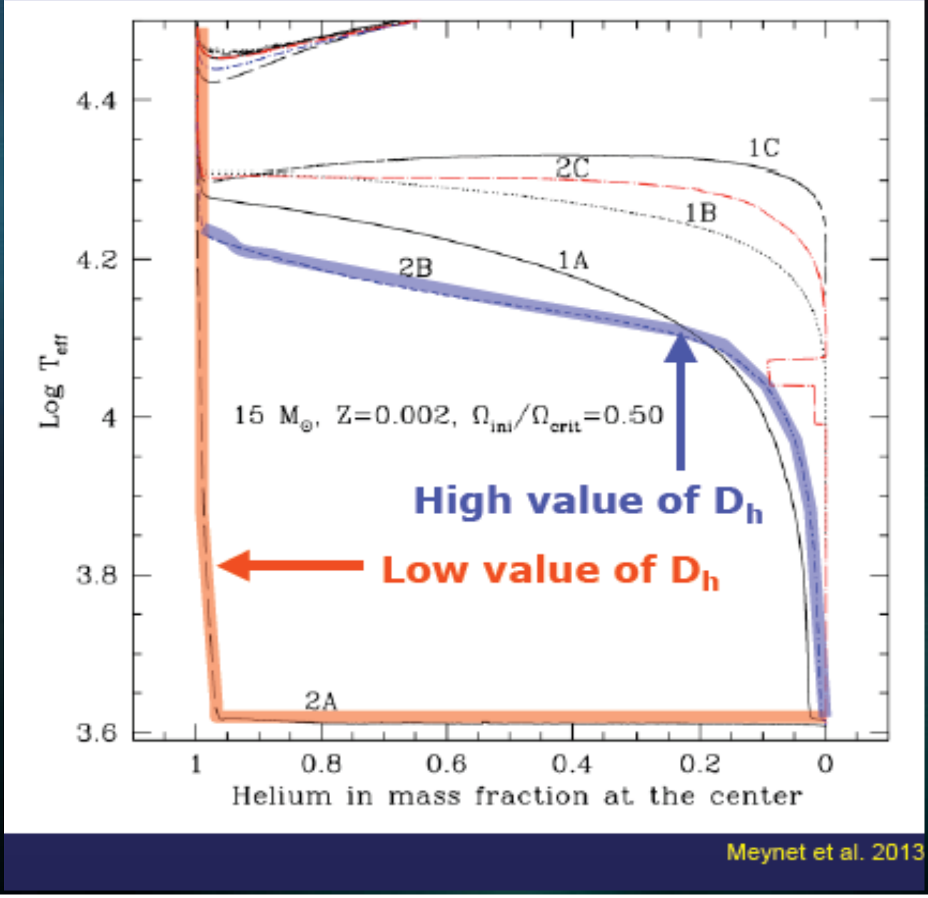
MS lifetimes vary within ~ 15%, comparable to the effect of neglecting rotation

Meynet et al. (2013)

Evolution of surface N/H ratio



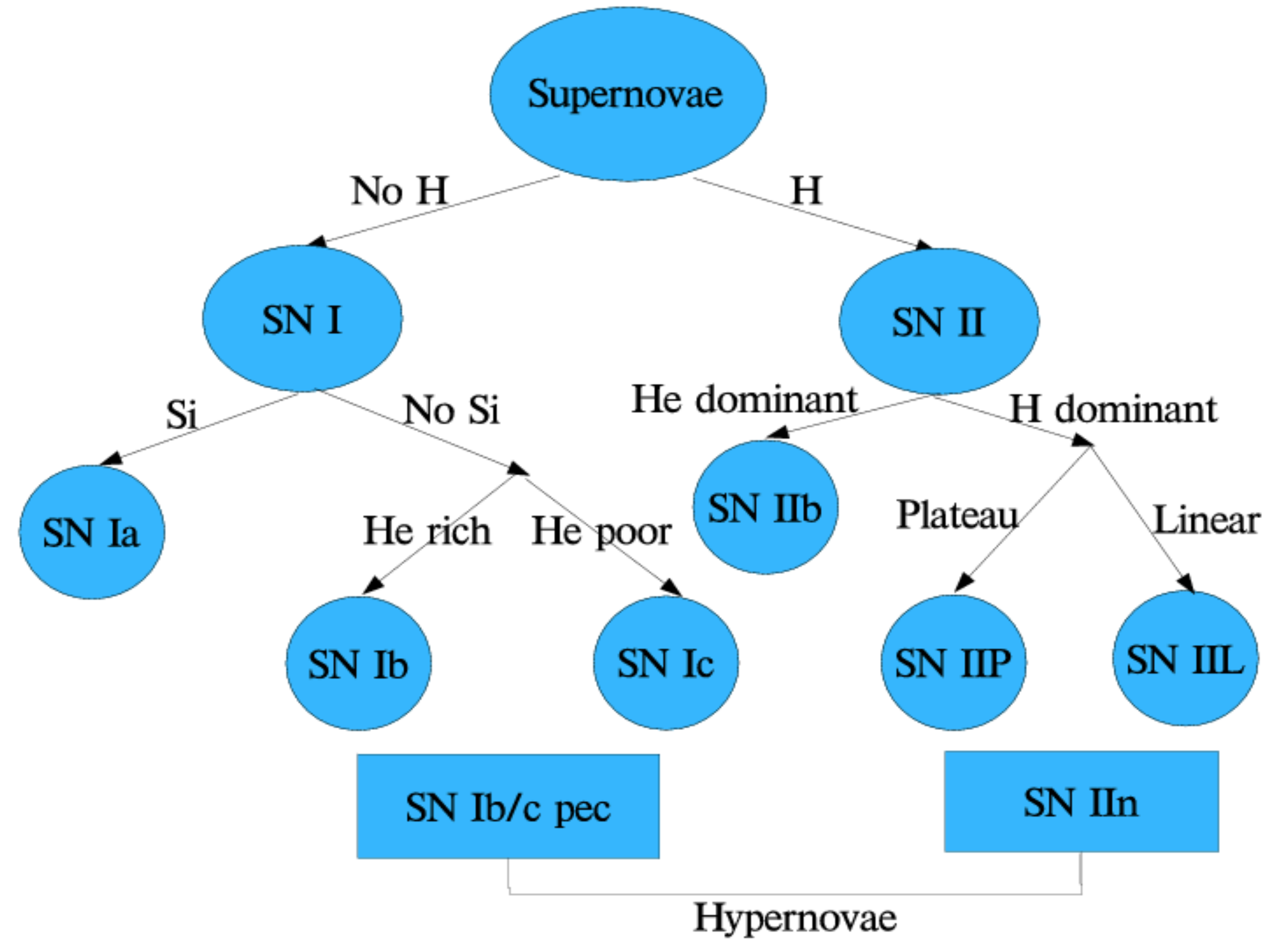
The outputs most affected by these different prescriptions are the shape of evolutionary tracks, blue-to-red evolution, surface enrichments.



Meynet et al. 2013

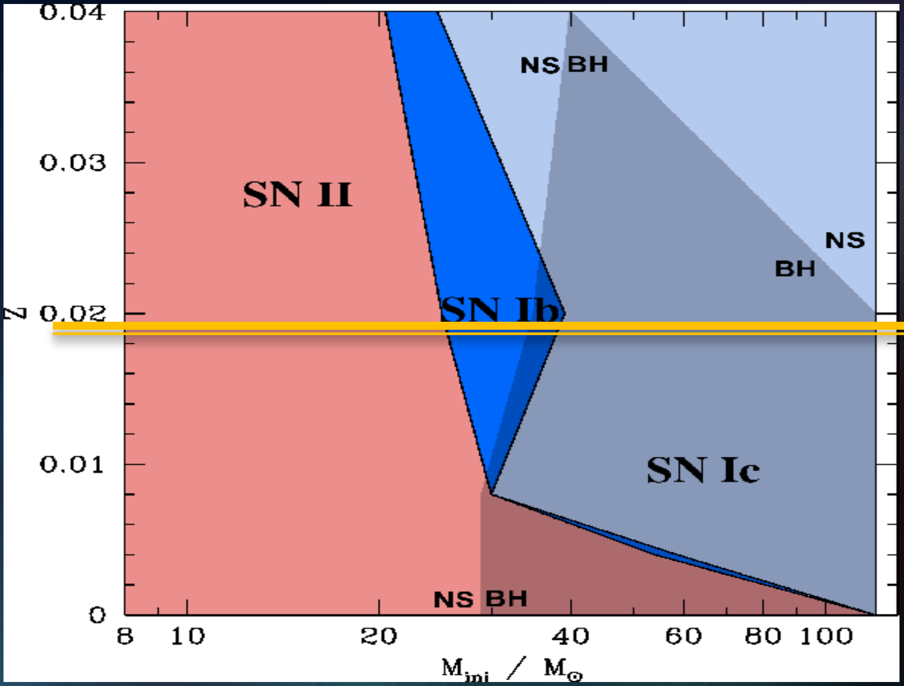
SN progenitors

Observers' SN classification

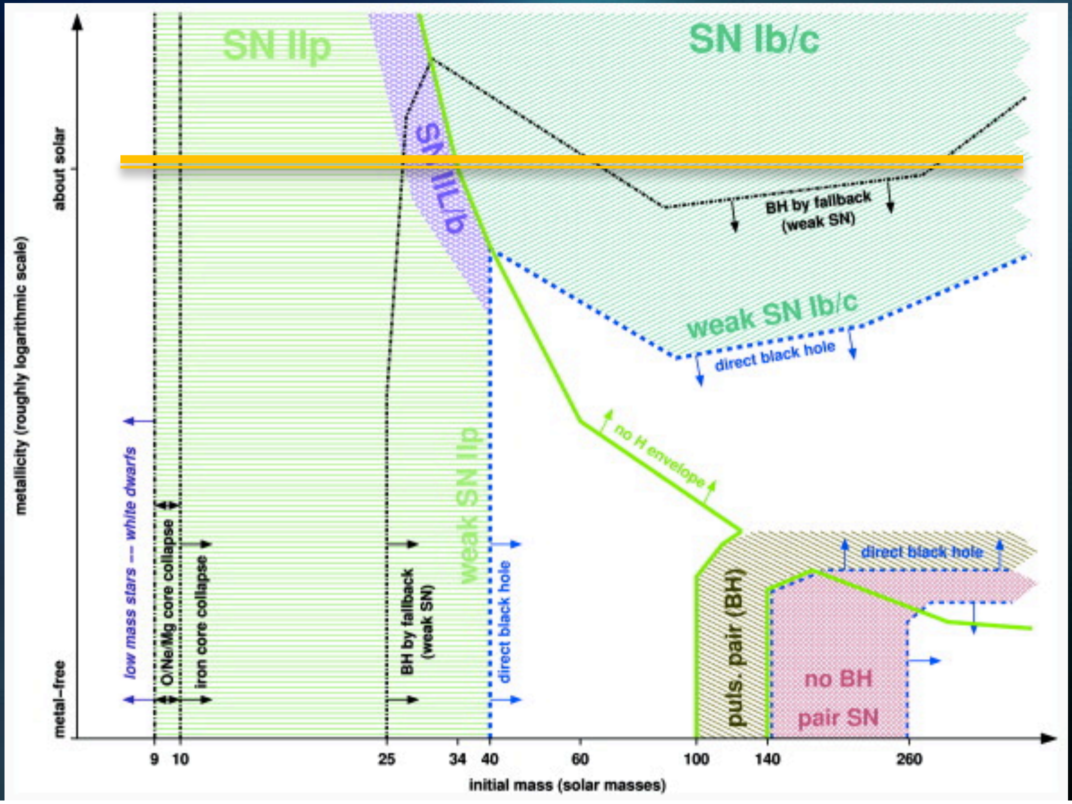


Theoretical predictions for the progenitors

They are essentially based on assumptions about how the surface chemical composition of the models maps onto the observational classification



Georgy et al. (2009)



Heger et al. (2003)

Core collapse events

Determining factors from the progenitor evolution

Initial mass
Mass of CO core at collapse
Rotation and magnetic fields
Stellar density profile

↓

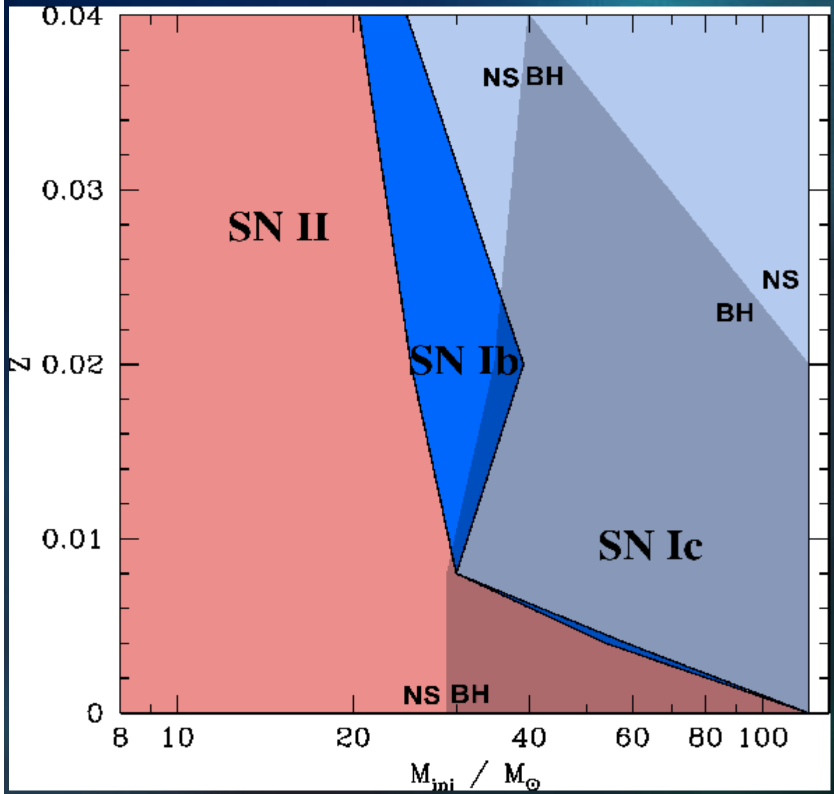
Light curve and spectral evolution
Explosion energy and nucleosynthesis
Type of remnant

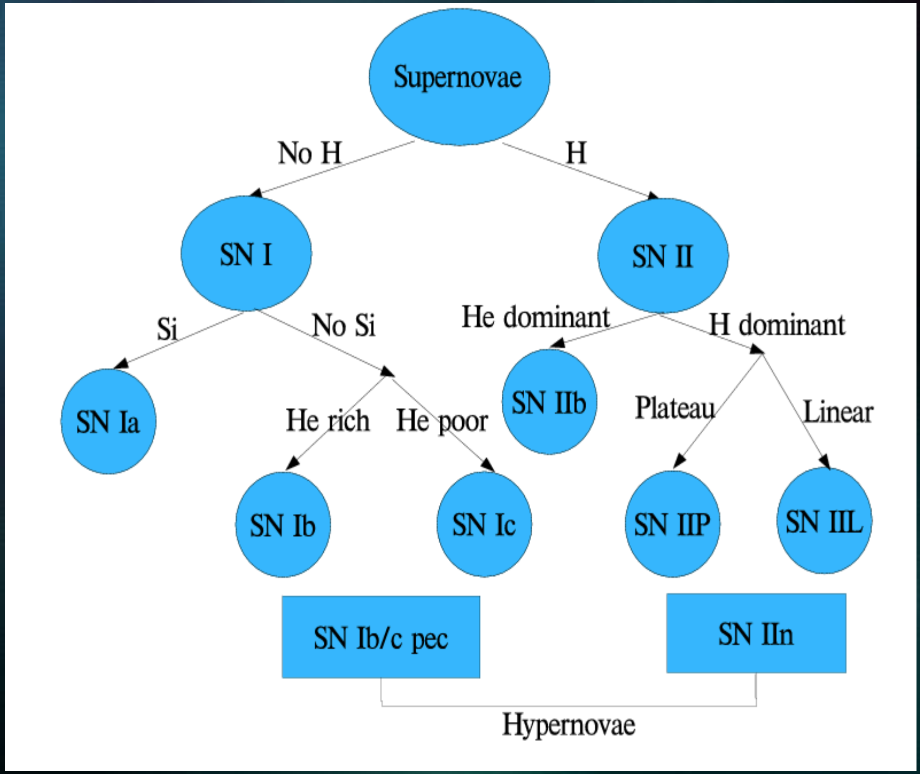
Is this matching correct?

Critical parameters in the models are mass loss, convective mixing, treatment of rotational mixing (and magnetic fields?)

Binaries?

(PESSTO)





CONCLUSIONS

“During the last couple of decades, it became obvious that the art of modeling stars in the 21st century relies on the art of modeling transport processes” (angular momentum, chemical elements - Talon & Charbonnel 2009)

The current generation of 1D (non-hydro) stellar models is limited by some long-standing, well-known shortcomings that need to be addressed systematically.

Observational constraints (like those coming from the ESO public surveys discussed at this conference) are crucial to constrain the existing models, to highlight the need to include additional physical processes and more in general to help identifying the necessary methods towards the creation of the next generation of stellar models that can meet the new observational challenges