Padova,
October 1980

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Effects of stellar physics on the chemical yields

André Maeder
Geneva Observatory

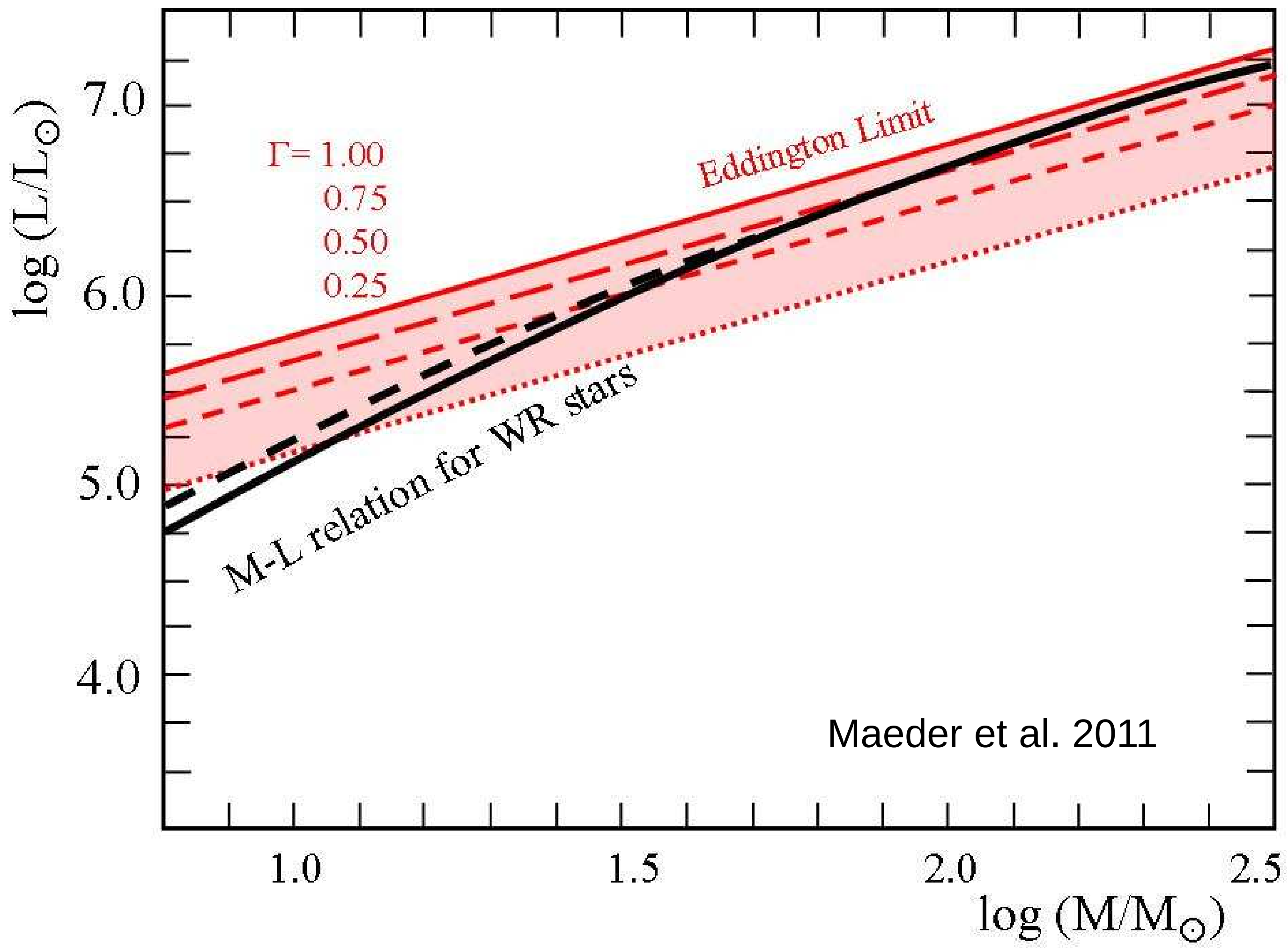
In collaboration
with Georges Meynet

- MASS LOSS
- ROTATION-MIXING
- BINARY EVOLUTION
- MAGNETIC EFFECTS

What mass loss in pre- supernova stages of massive stars ?

Case of WR stars

The proximity to the Eddington limit is the physical reason for the onset of WR type mass loss
Gräfener et al. 2011



Eddington Limit $\Gamma = 1$

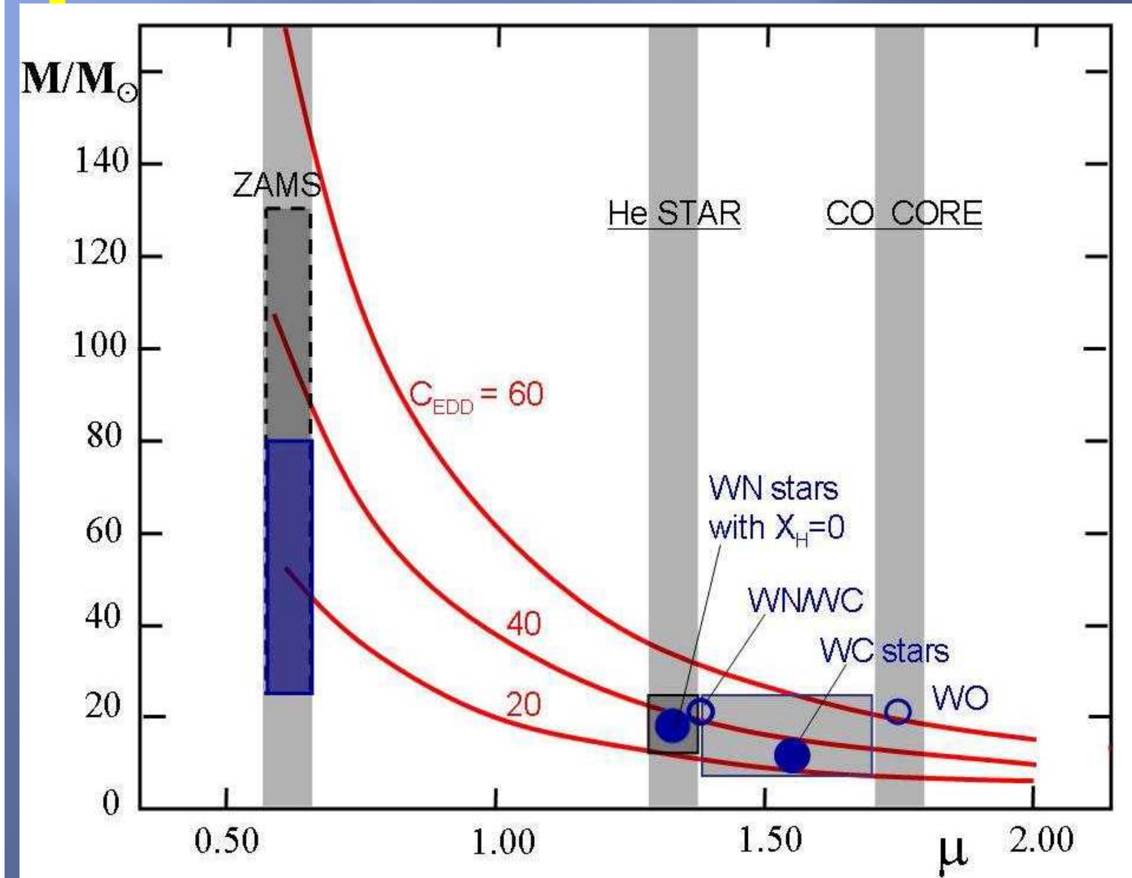
→ $\mu^2 M =$ const.

Maeder et al., A&A 539, A110 (2012)

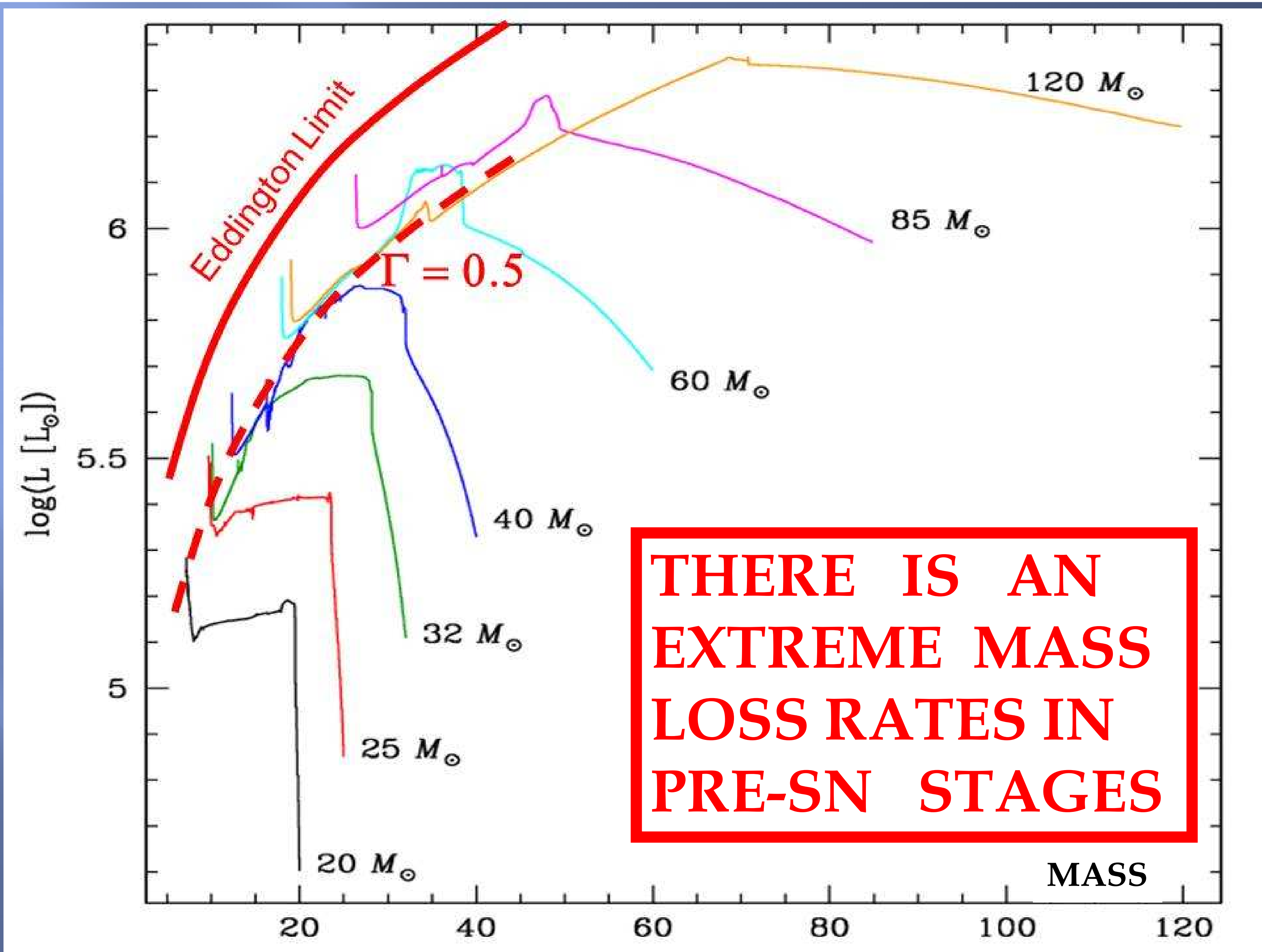
For homologous sequences

const ~ 30

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -2\,\frac{M}{\mu}\,\frac{\mathrm{d}\mu}{\mathrm{d}t}$$



WR mass loss rates are determined by composition changes



Eddington Limit
Γ = 0.5
120 M☉
85 M☉
60 M☉
40 M☉
32 M☉
25 M☉
20 M☉
log(L [L☉])
6
5.5
5
20
40
60
80
100
120
MASS
THERE IS AN EXTREME MASS LOSS RATES IN PRE-SN STAGES

Mixing vs. mass loss :

$$T \sim \frac{\mu M}{R} \quad \Rightarrow \quad T \sim M^{0.3}$$

$$R \sim \mu^{0.5} M^{0.7} \quad \Rightarrow \quad \rho \sim \frac{M}{R^3} \sim \frac{1}{M^{1.1}}$$

Higher M

→ Higher T

Lower ρ

MASS LOSS :

$$\frac{P_{rad}}{P_{gas}} \sim \frac{T^3}{\rho}$$

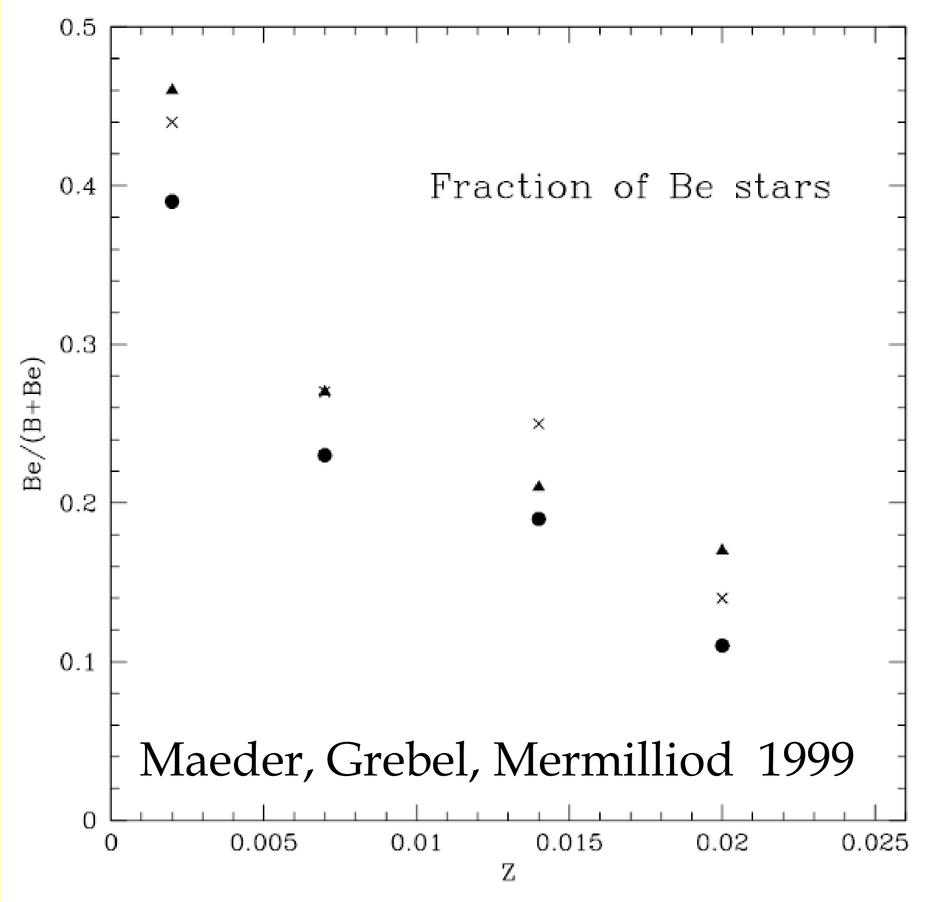
MIXING: shear ~ thermal diffusivity

$$K = \frac{4ac\,T^3}{3C_P\,\kappa\,\rho^2}$$

Mass loss and mixing strongly favoured !

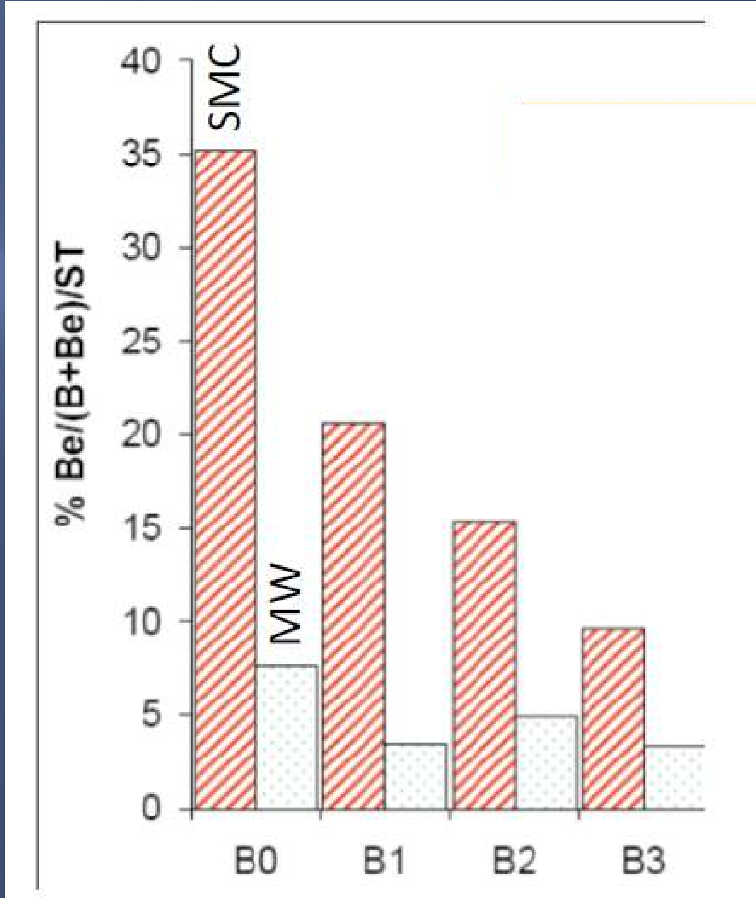
THREE PROPERTIES OF ROTATION AT LOW Z

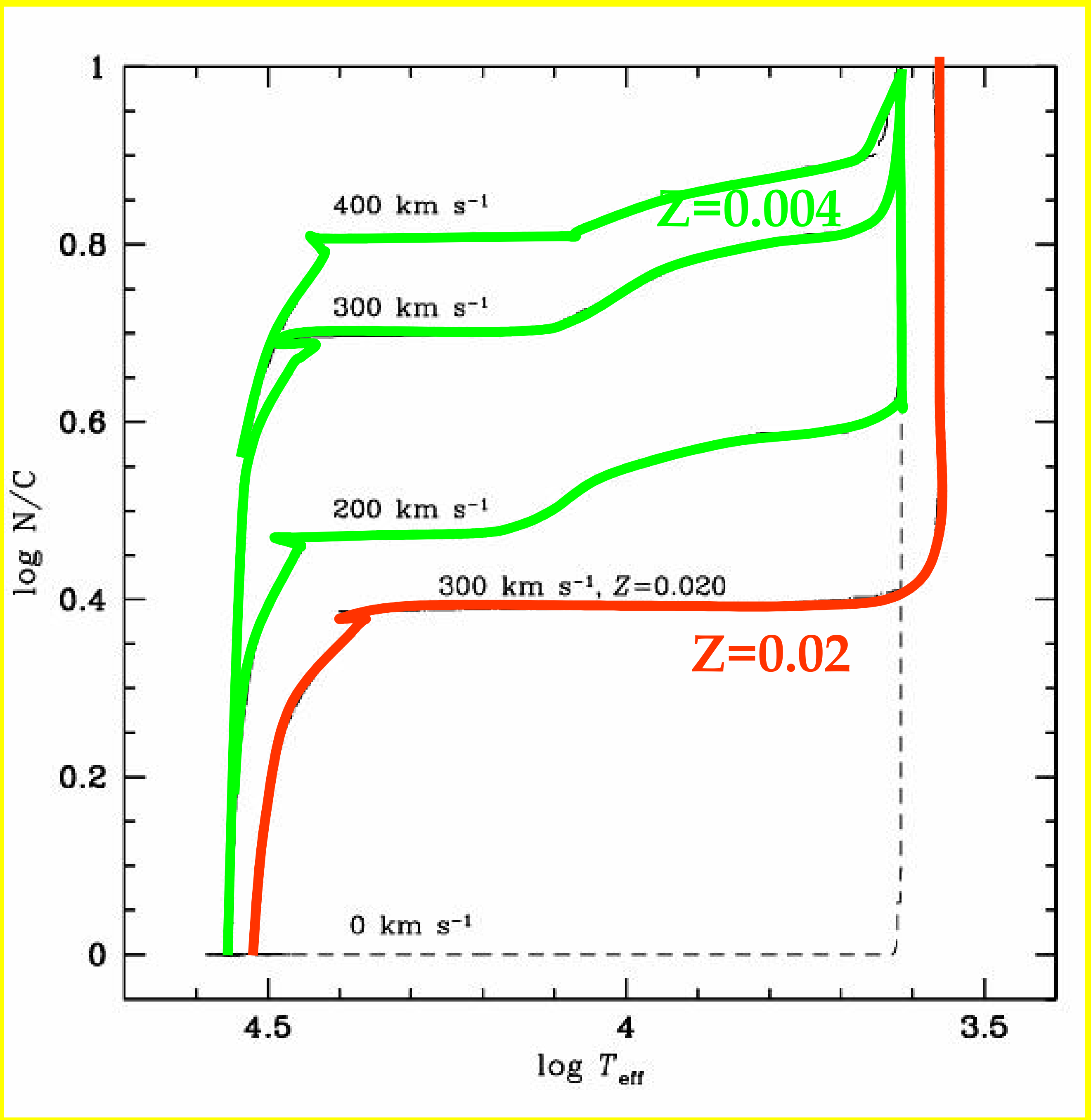
-1. More fast rotators



Confirmed by:

Wisniewski & Björkman, 2006
Mokiem et al . 2006
Martayan et al. 2007
Martayan et al. 2010



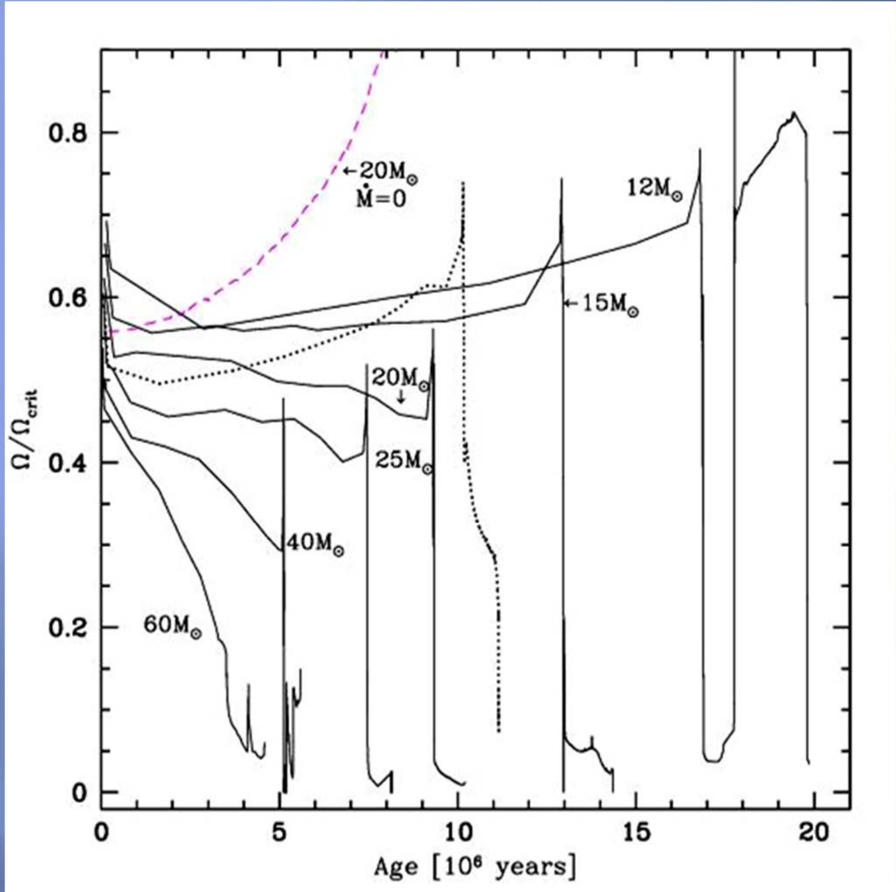


- 2.

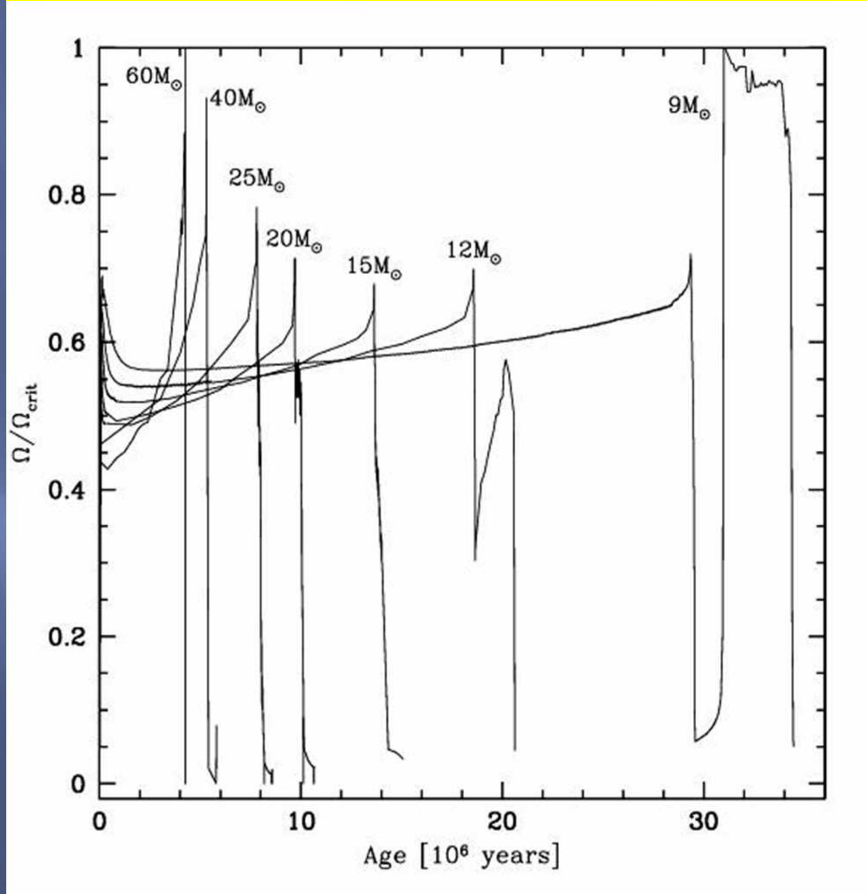
Higher N/C at lower Z

MORE MIXING

Z=0.02: drastic deacrease for highmasses



Z=0.004: more stars reach break-up velocities.



Maeder & Meynet, 2001

-3. Low Z stars reach critical rotation → **ROTATIONAL MASS LOSS**

NEW STABILITY CRITERION

Maeder et al. A&A, 553, A1 (2013)

- the effects of thermal gradients, SCHWARZSCHILD
- the thermohaline mixing, ULRICH, KIPPENHAHN
- the semiconvective diffusion, LEDOUX CRITERION
- the shear mixing to the local excess of energy in differential rotating layers, RICHARDSON CRITERION
- the stabilizing or destabilizing effect of the distribution of angular momentum, RAYLEIGH-TAYLOR
- the radiative losses, DUDIS
- the transport of heat by the horizontal turbulence, ZAHN
- the element diffusion in the medium due to the horizontal turbulence. ZAHN

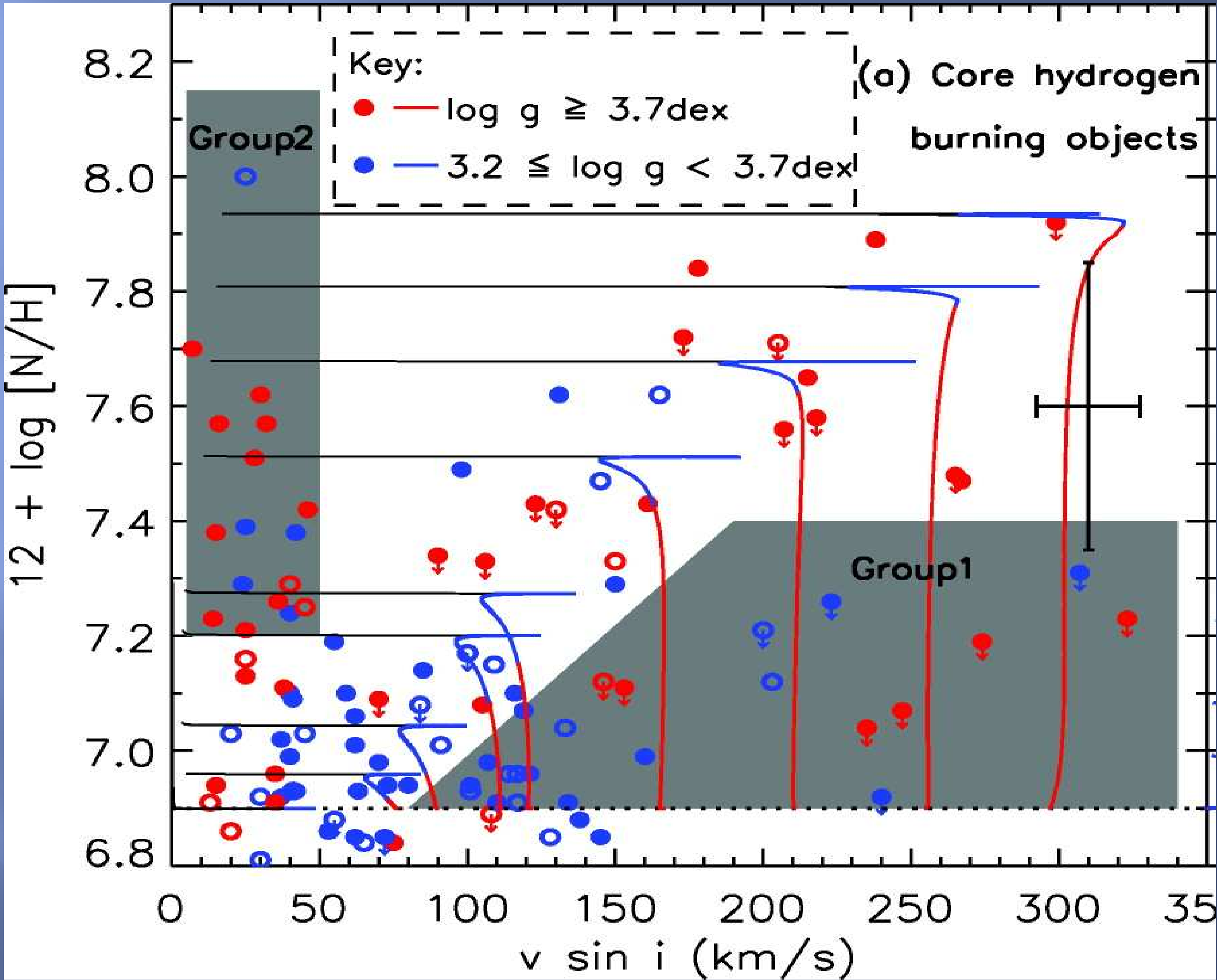
STABLE , IF

$$\left[N_{\rm ad}^2 + N_\mu^2 + N_{\Omega-\delta v}^2\right] x^2 + \left[N_{\rm ad}^2 D_{\rm h} + N_\mu^2 (K + D_{\rm h}) + N_{\Omega-\delta v}^2 (K + 2D_{\rm h})\right] x + N_{\Omega-\delta v}^2 (D_{\rm h} K + D_{\rm h}^2) > 0\,,$$

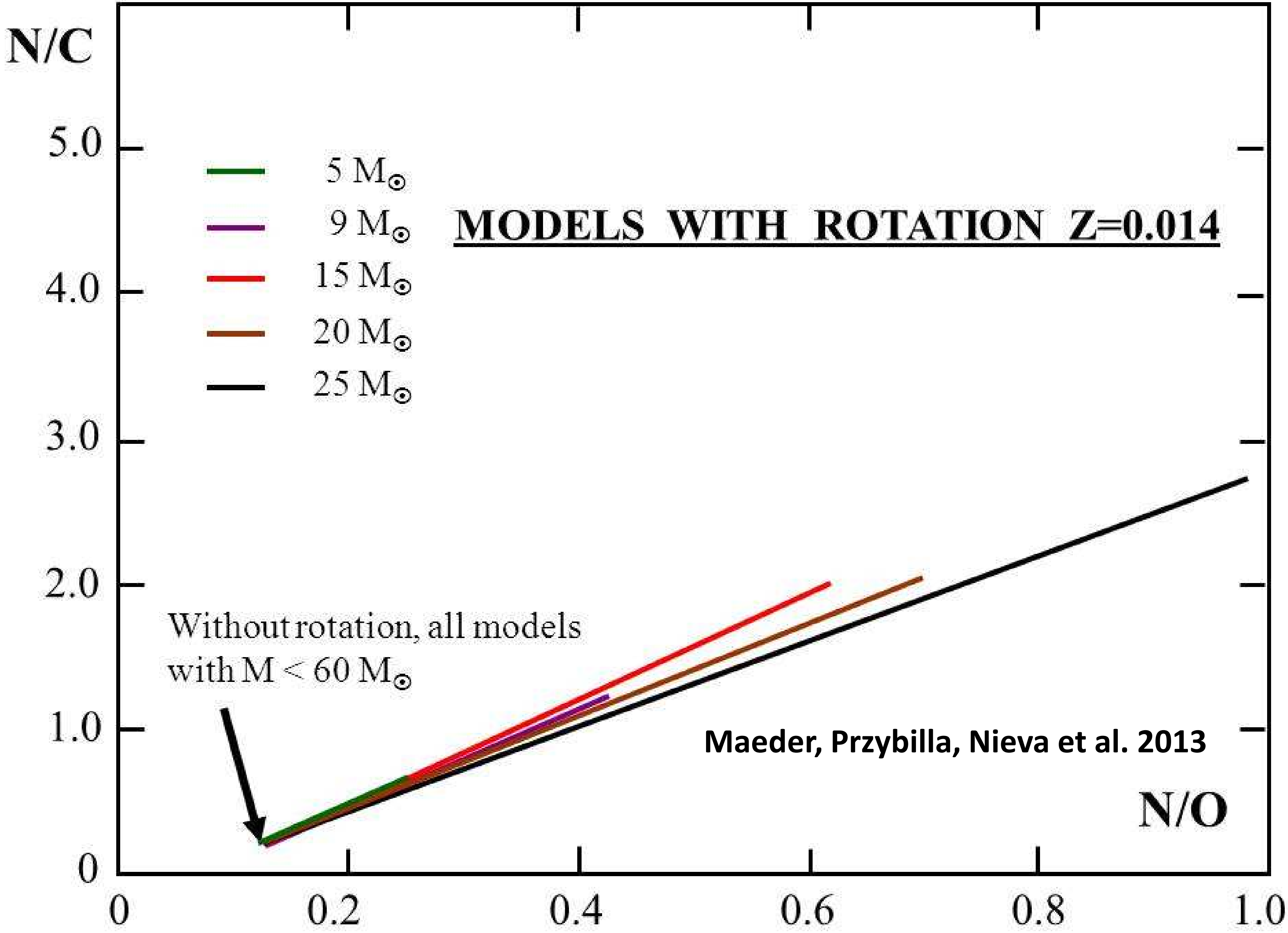
with

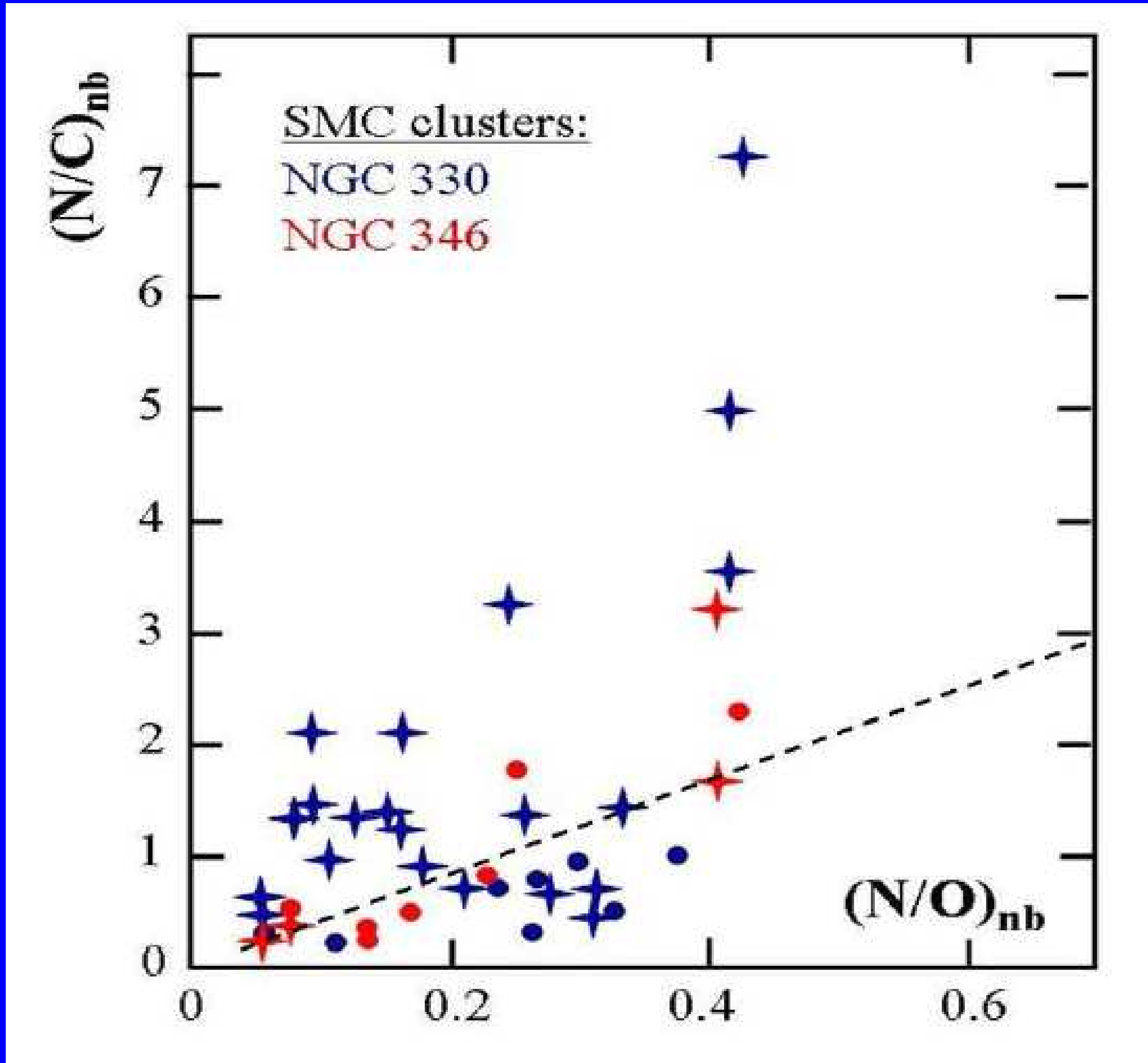
$$N_{\Omega-\delta v}^2 = \frac{1}{\varpi^3} \frac{d\left(\Omega^2 \varpi^4\right)}{d\varpi} \sin\vartheta - \mathcal{R}i_{\rm c} \left(\frac{dv}{dr}\right)^2 .$$

Possible damping or amplification of mixing effects !



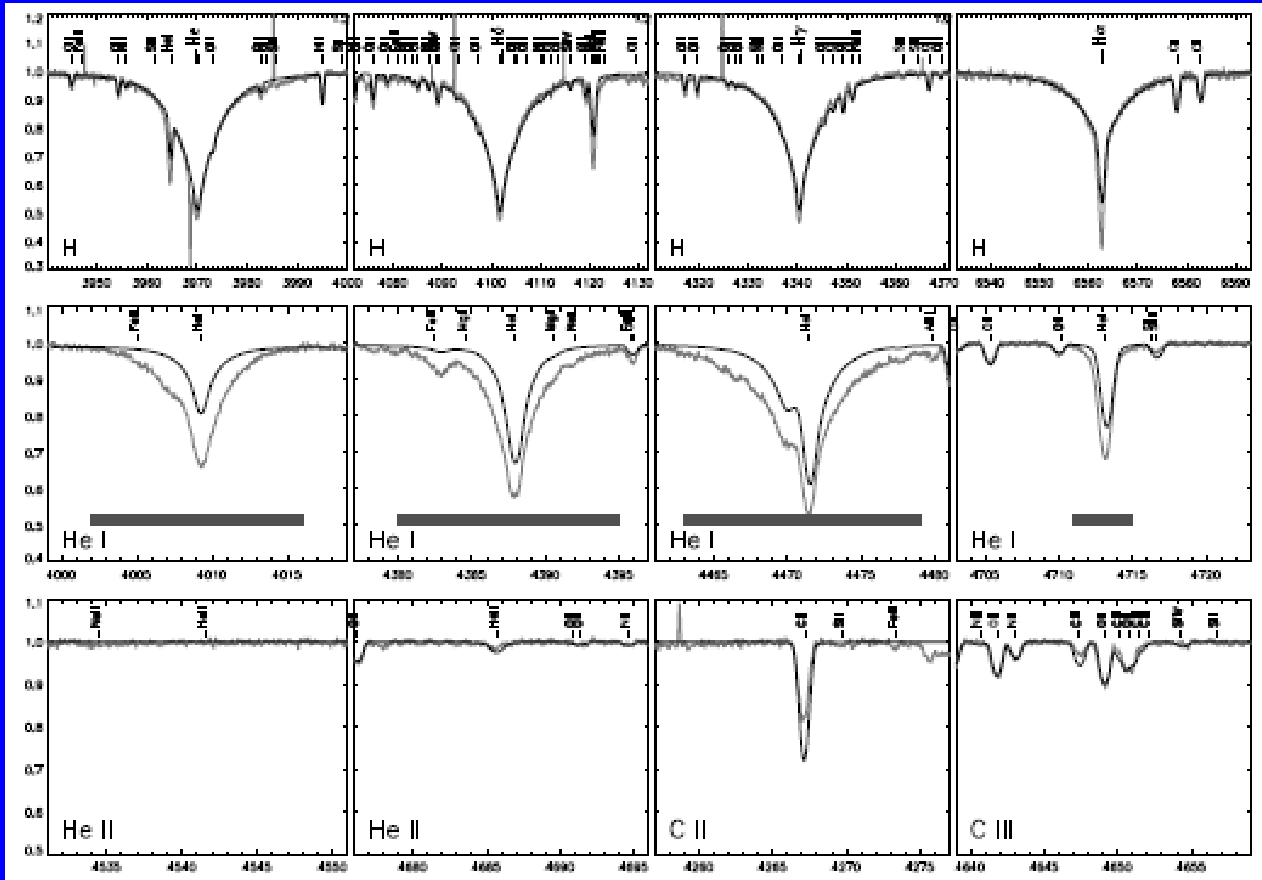
Hunter et al. 2008


N/C
5.0
4.0
3.0
2.0
1.0
0
5 M⊙
9 M⊙
15 M⊙
20 M⊙
25 M⊙
MODELS WITH ROTATION Z=0.014
Without rotation, all models
with M < 60 M⊙
Maeder, Przybilla, Nieva et al. 2013
N/O
0
0.2
0.4
0.6
0.8
1.0



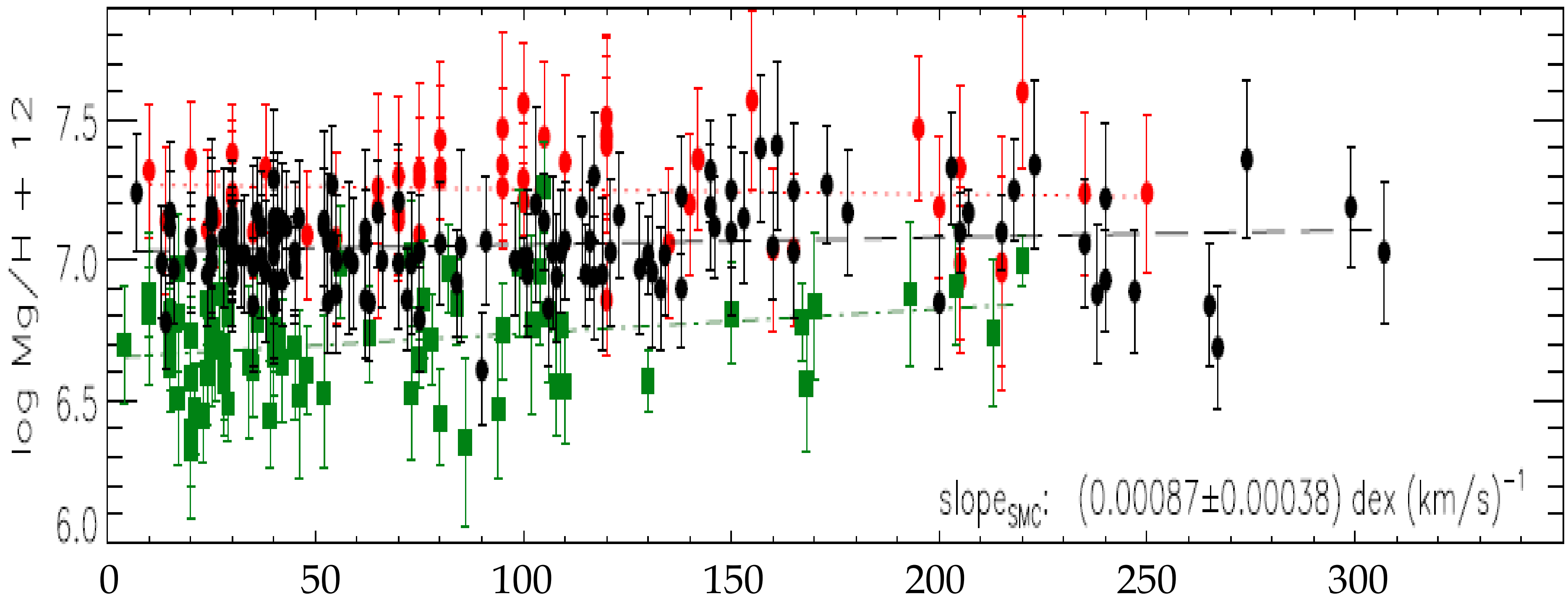
From VLT- FLAMES survey (Hunter et al. 2009)

NGC 3293-034



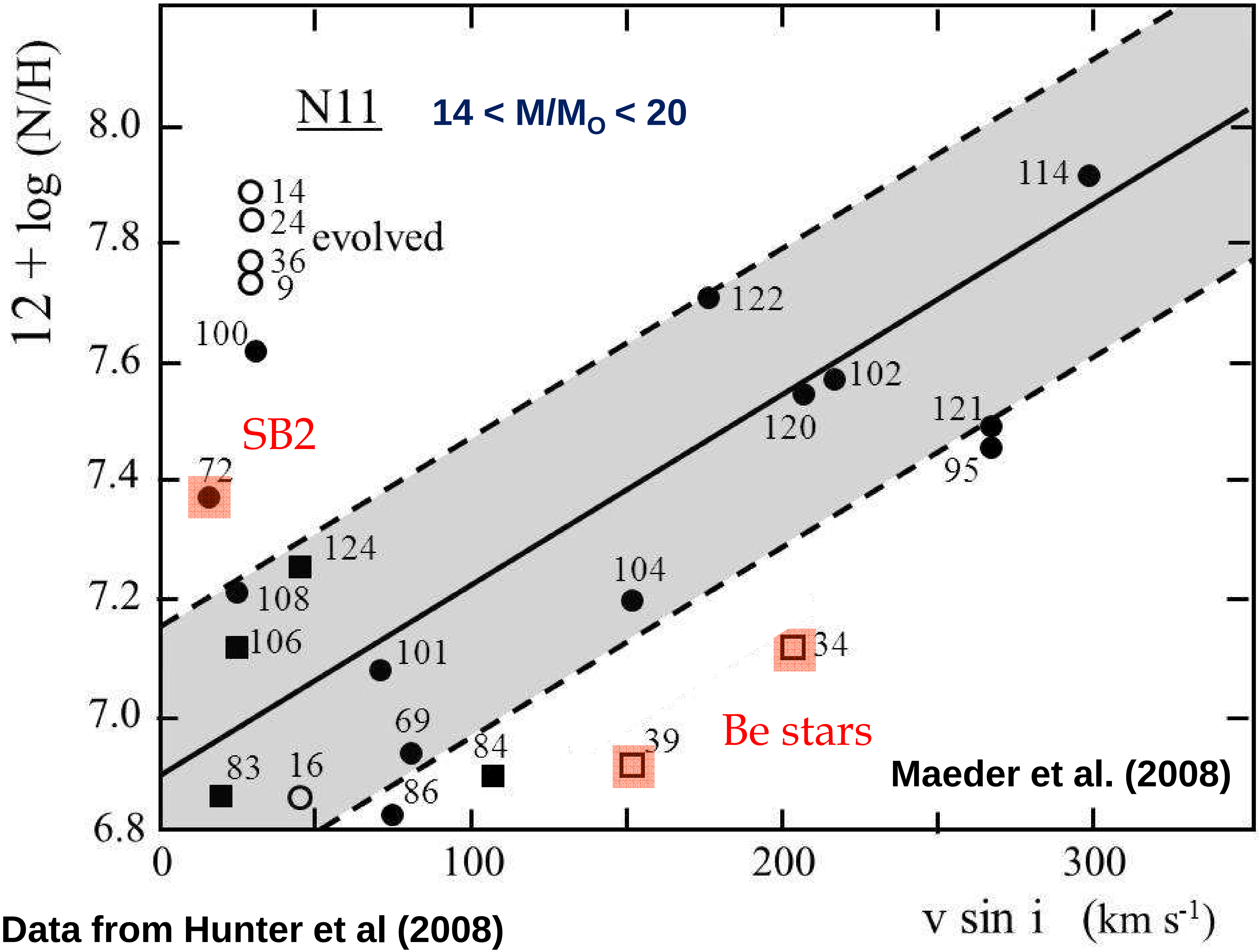
Ex. of fit of spectra and ADS models calculated by Przybilla with Hunter et al. parameters

Maeder, Przybilla, Nieva et al. 2013



Mg/H is not constant with v sin i !

Maeder, Przybilla, Nieva et al. 2013



Data from Hunter et al (2008)

BINARIES: Tidally shear induced mixing (TISM)

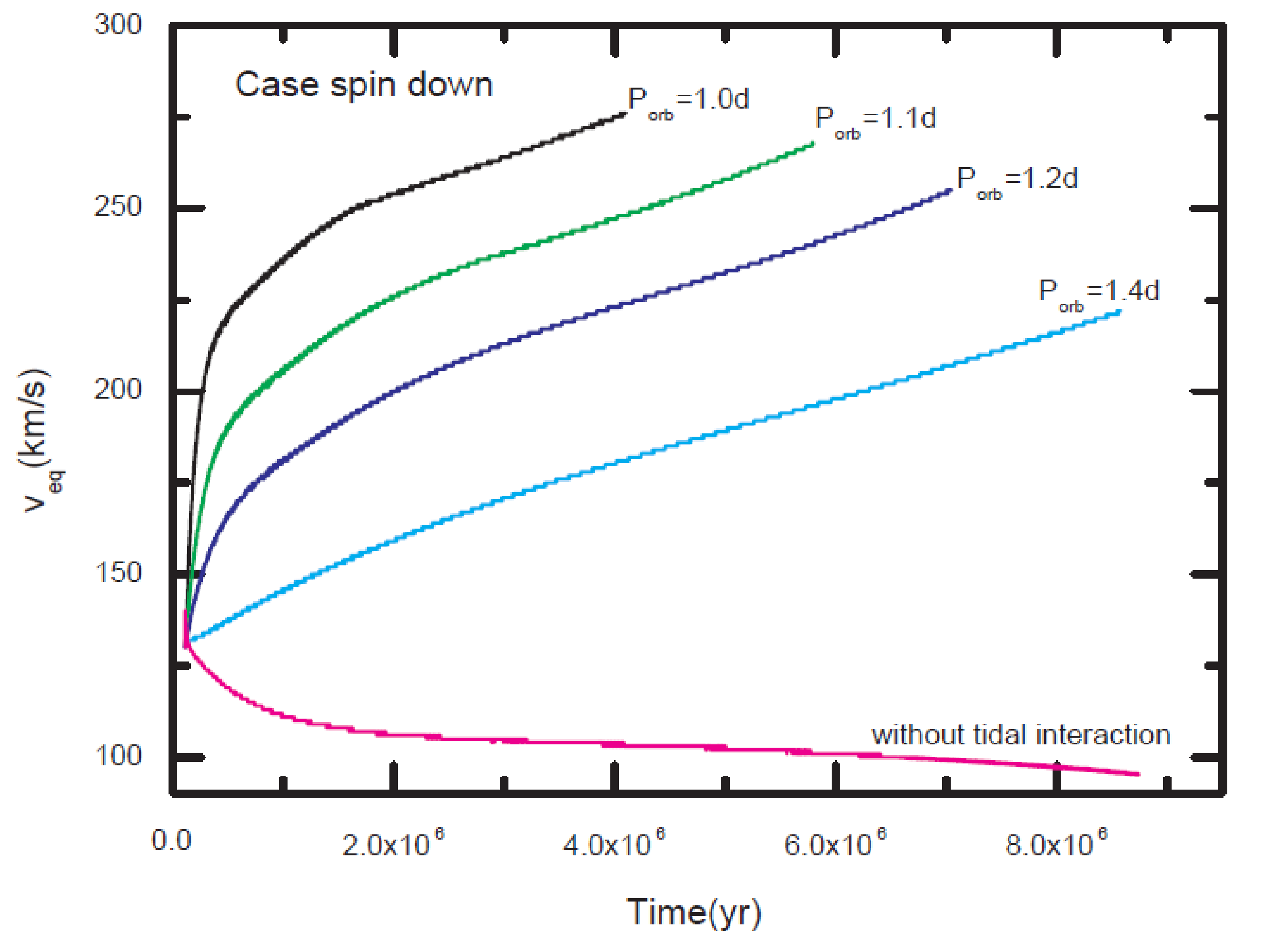
Song, Maeder, Meynet, Huang, Ekström, Granada (2013)

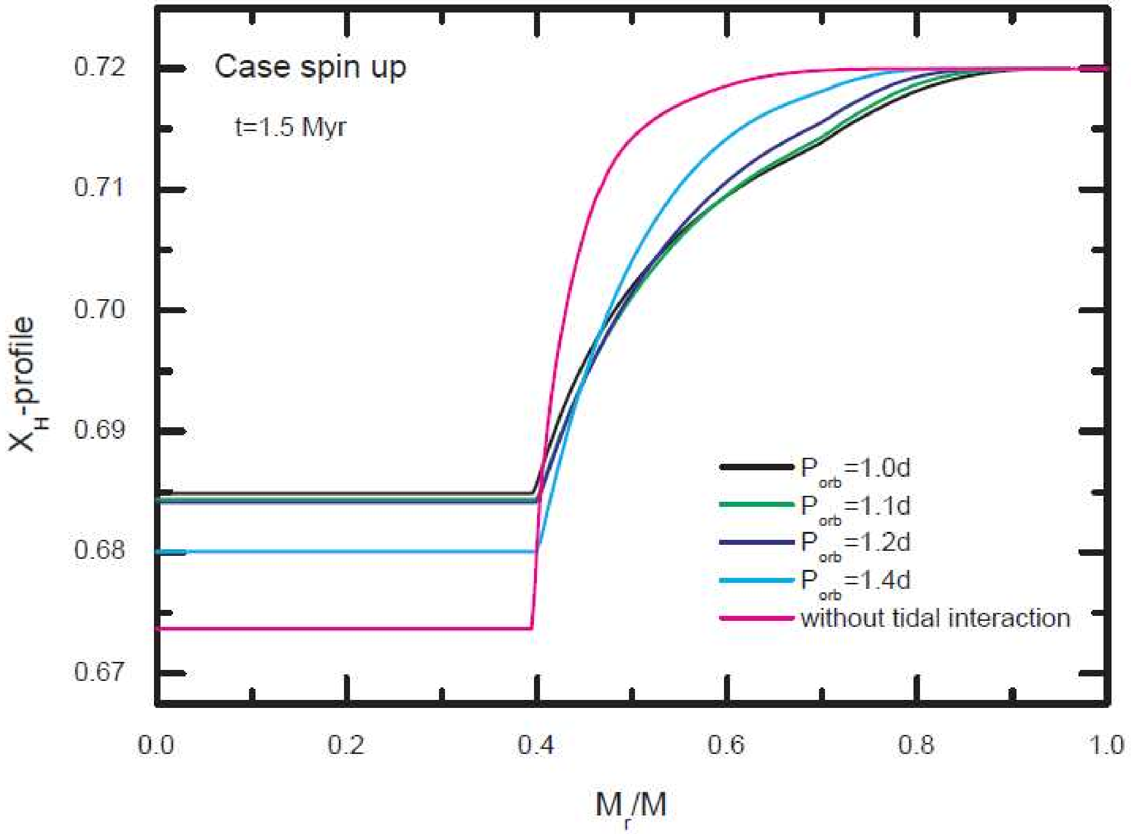
Tidal interaction + meridional circulation + shears + horizontal turbulence in binary models (15 $M_\odot$ + 10 $M_\odot$)

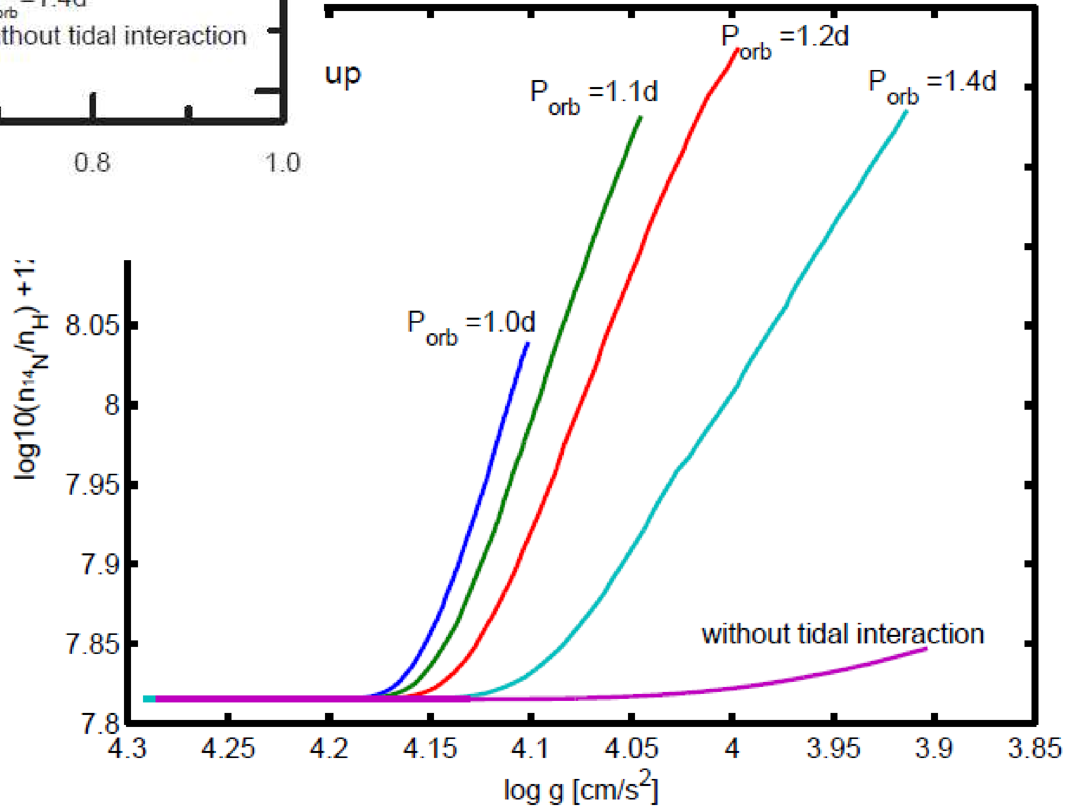
CASE SPIN UP:

v_{ini}/v_{crit}=0.2 ,

P_{orb}= 0.9-1.4 d







STRONG MIXING before RLOF !

TISM in BINARIES

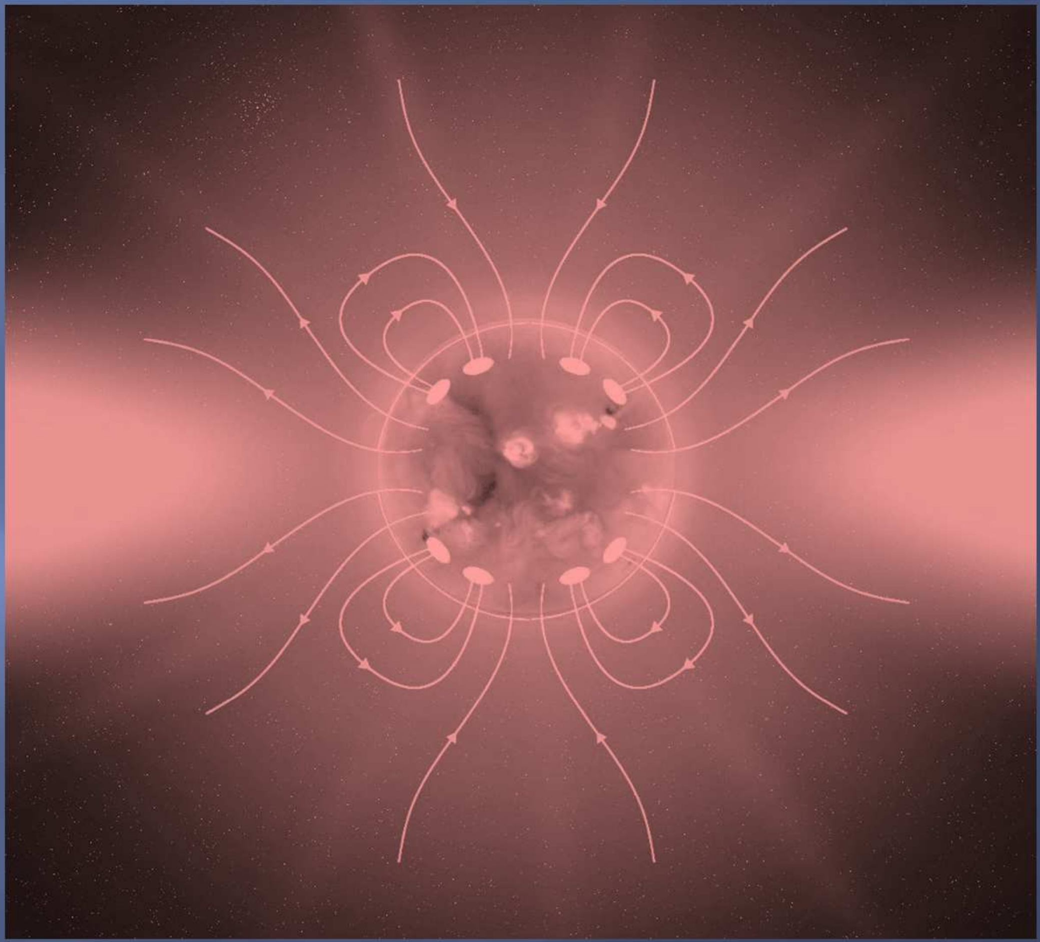
- Internal mixing and larger cores → YIELDS
- Homogeneous before RLOF , for high masses

  → thus, no RLOF !
- Differential rotation at synchronisation
- If spin up, lot of angular momentum conveyed to the core → GRBs ?

External magnetic field

$$\eta(r) \equiv \frac{B^2/8\pi}{\rho v^2/2}$$

ud-Doula & Owocki (2002)



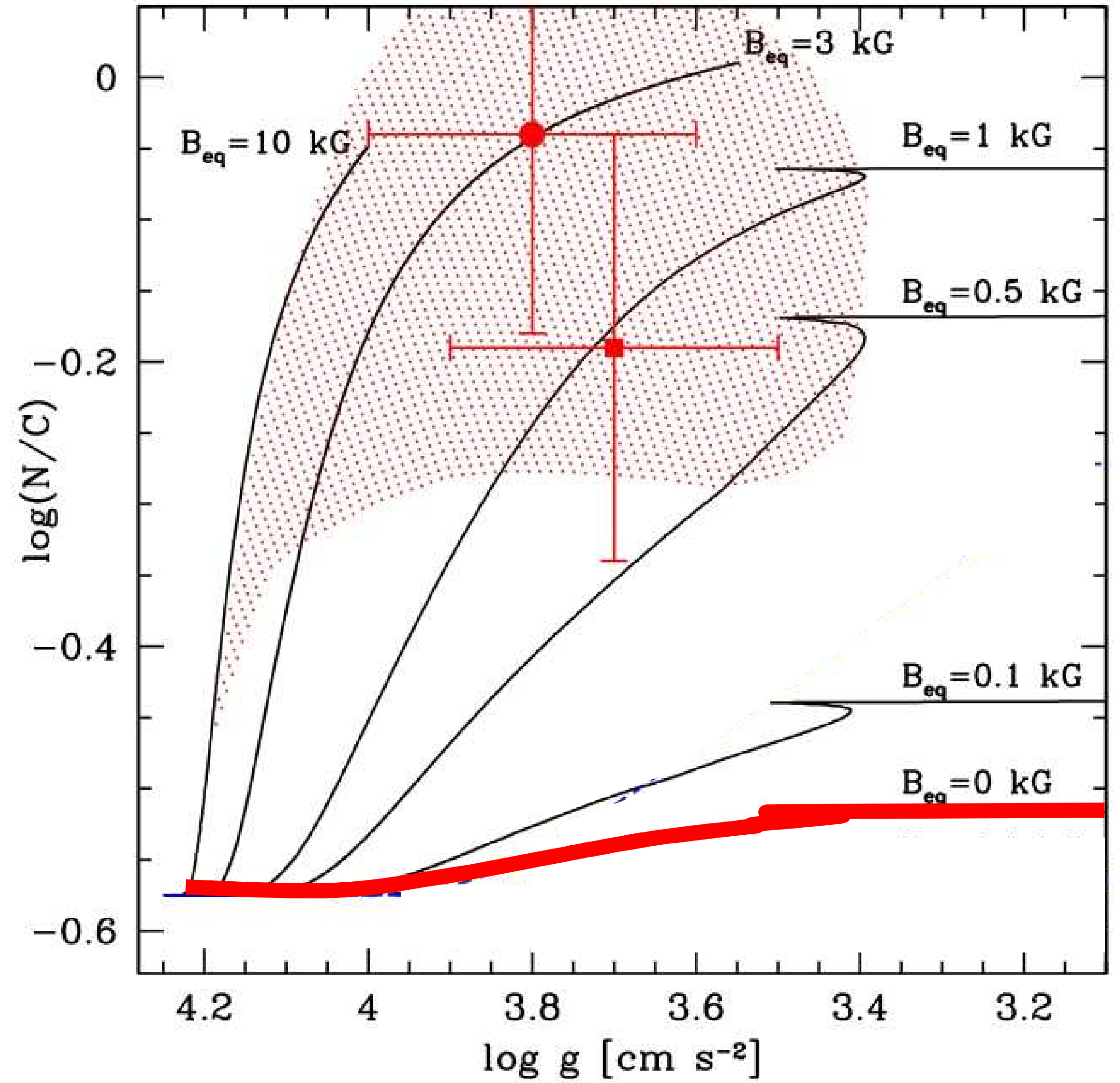
$$\frac{\mathrm{d}J}{\mathrm{d}t} = \frac{2}{3}\dot{M}\Omega R_*^2[0.29 + (\eta_* + 0.25)^{1/4}]^2$$

Meynet, Eggenberger, Maeder 2011

10 M

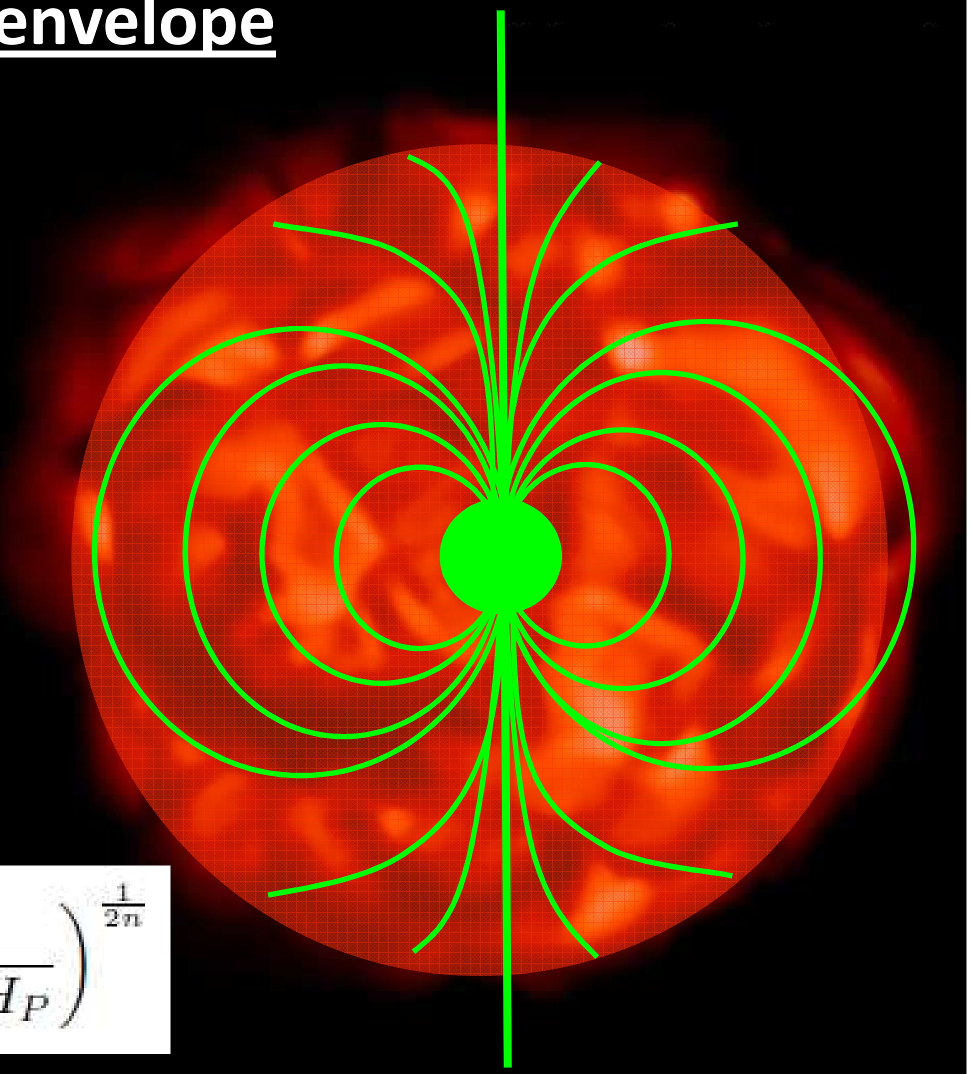
V_{ini}=200 km s^{-1}

Z=0.014



Magnetic coupling coupling-envelope

- Asteroseismology (KEPLER), red giant KIC 8366339: core rotates only 10 x faster than surface
  Beck et al. (2012),
- Additional braking mechanism
  (Eggenberger et al. 2012)
- Pulsar models rotate too fast
  (Heger et al. 2004)



Truncation radius:

$$\left(\frac{r_t}{R_c}\right) = \left(\frac{2\,B_c^2}{\pi\alpha^2\,g\varrho\delta(\nabla - \nabla_{\mathrm{ad}})H_P}\right)^{\frac{1}{2n}}$$

Loss of angular momentum by the core:

$$\frac{dJ_c}{dt} = -\left(\frac{2}{3}\right)\int_{M_c}^{M(r_t)} r^2\,[\Omega_c - \Omega(M_r)]\,\sigma_B(M_r)\;dM_r$$

Maeder & Meynet
In prep.

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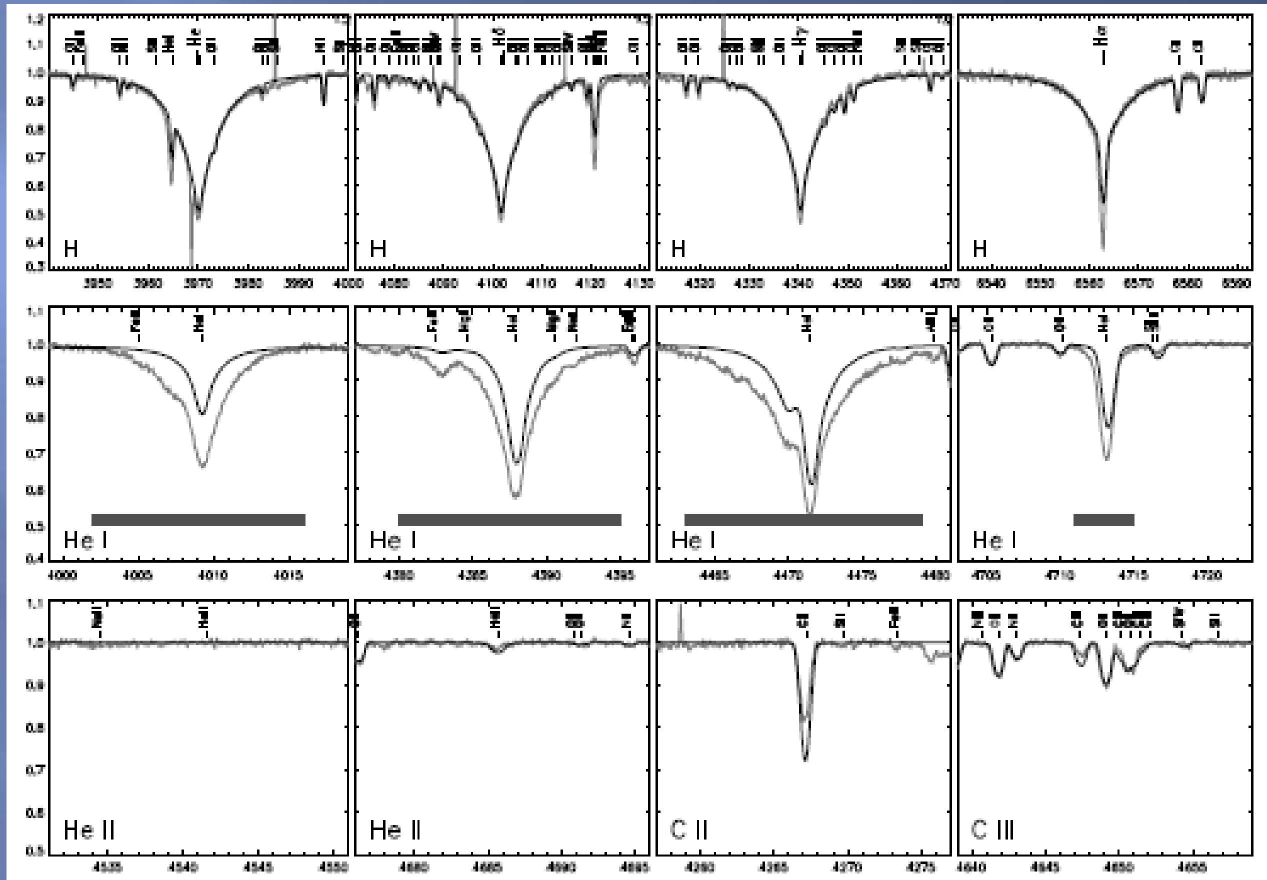
NGC 3293-034



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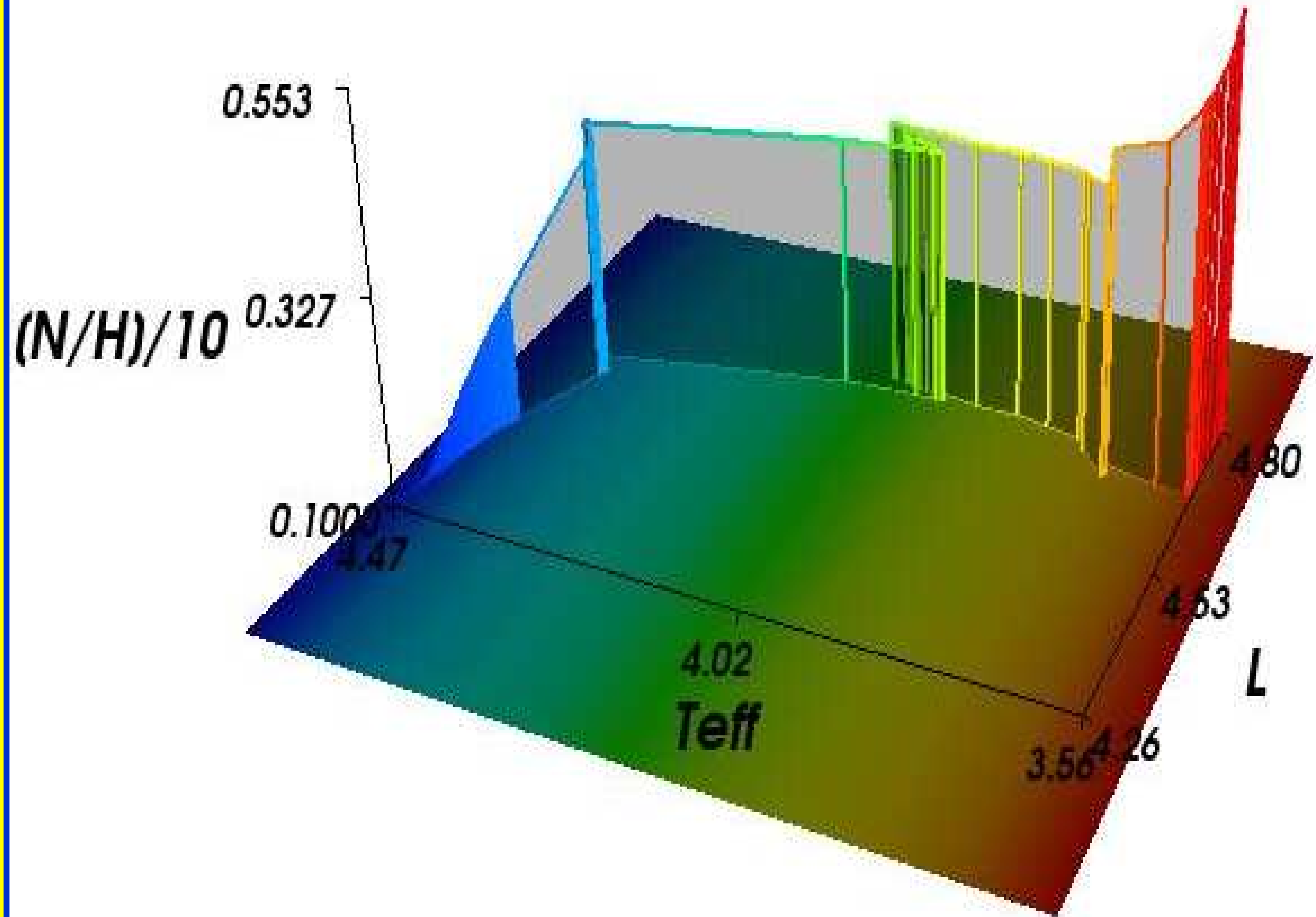
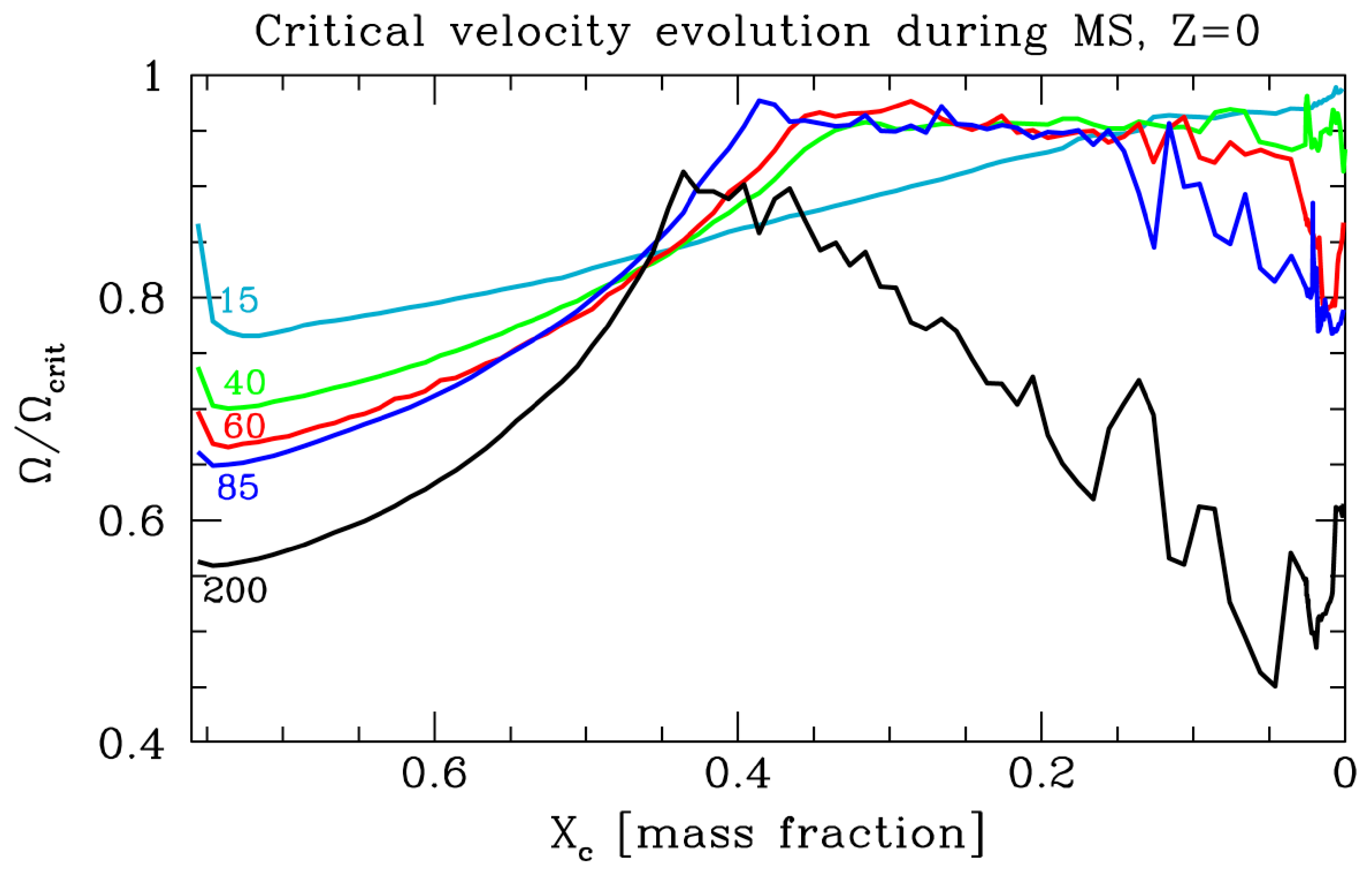
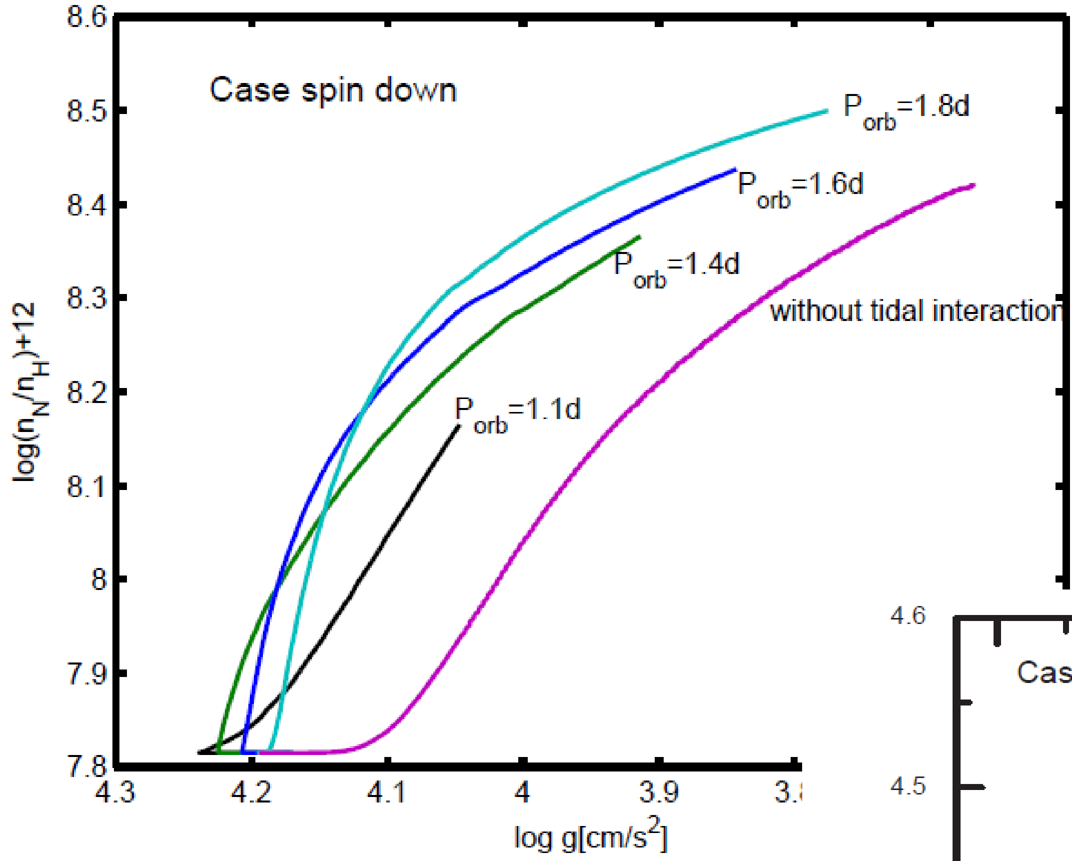


0.553
0.327
(N/H)/10
0.1000
4.47
4.02
Teff
3.56
4.26
4.53
4.80
L

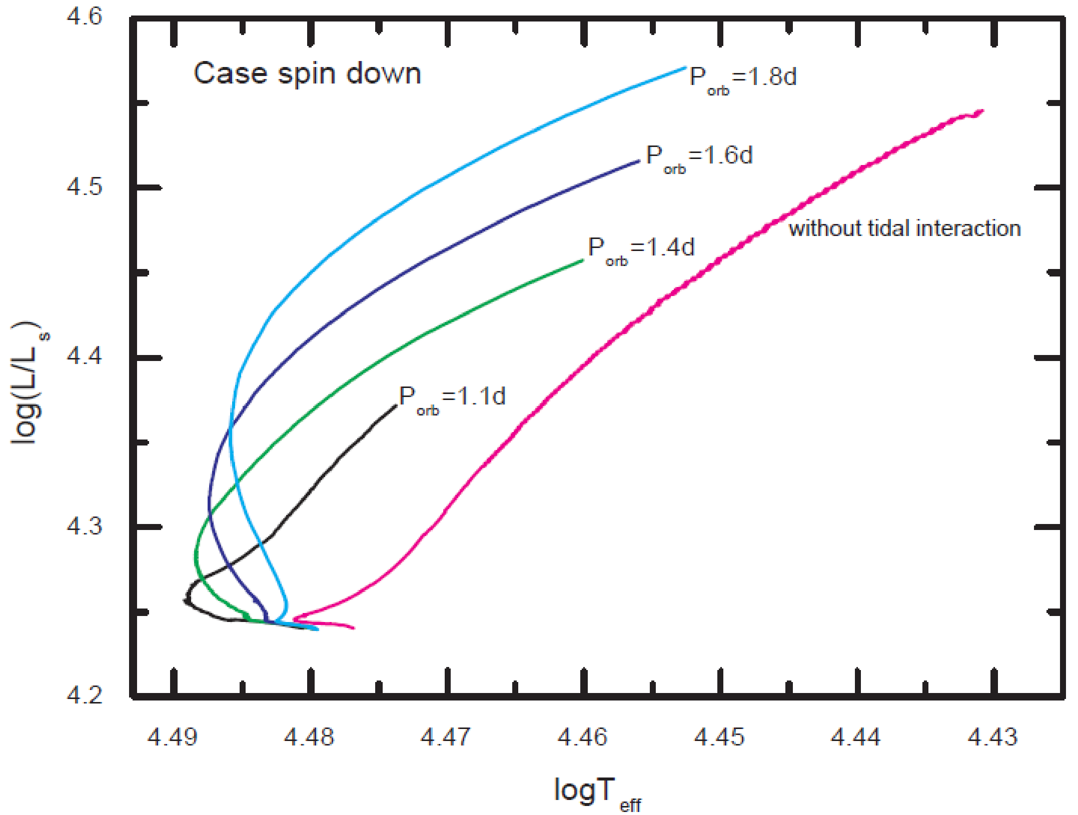
At low Z: Large fraction of MS spent at break--up



Ekström, Meynet, Maeder 2005



Moderate N-enrichment



Initial track ~ homogeneous

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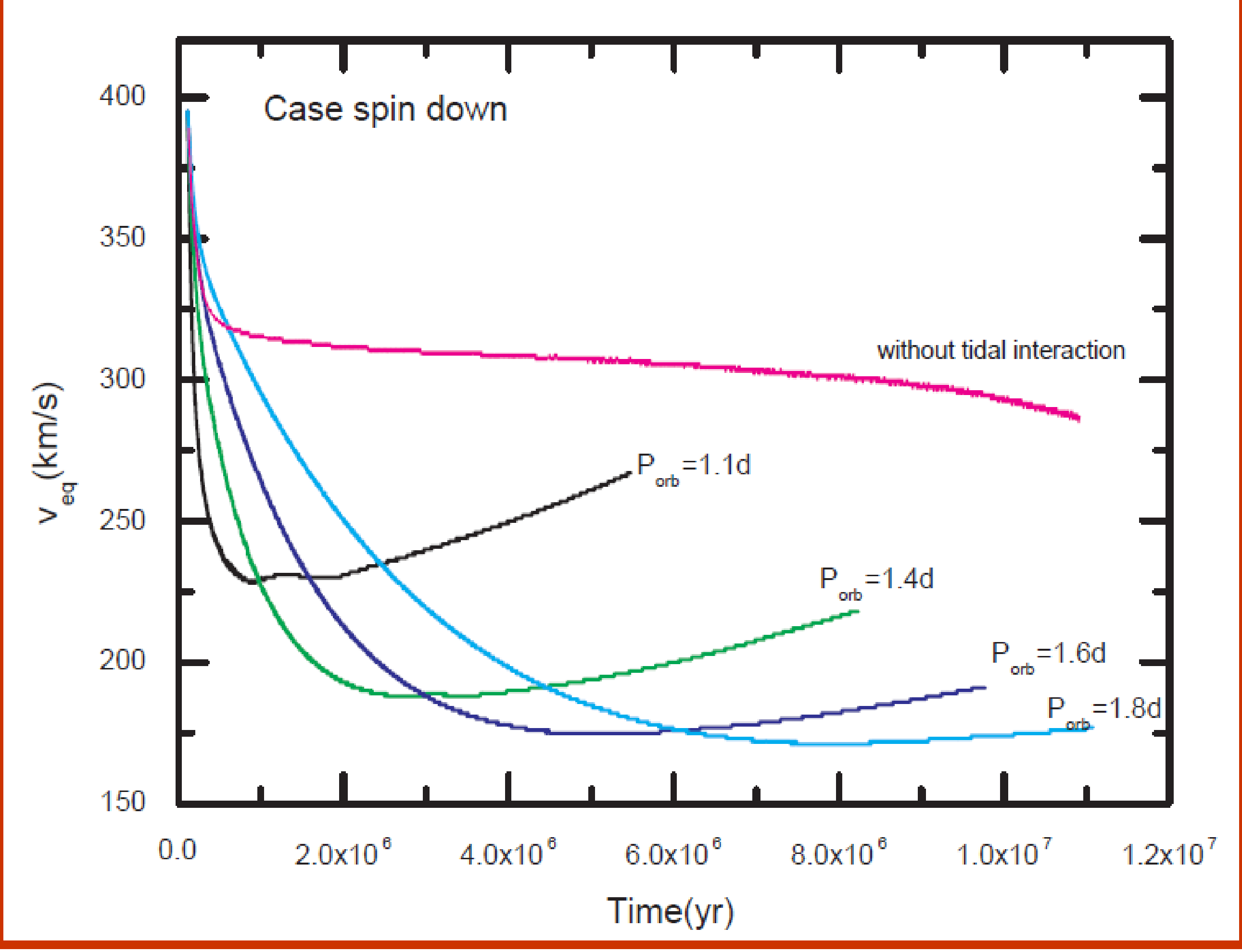
CASE SPIN DOWN:

v_{ini}/v_{crit}=0.6 ,

P_{orb}= 1.1-1.8 d



N/C vs. N/O plot: depends only on nuclear properties, Independent on mass and rotation, ~linear up to 0.6

(Maeder, Przybilla, Nieva ,Meynet et al. 2013)

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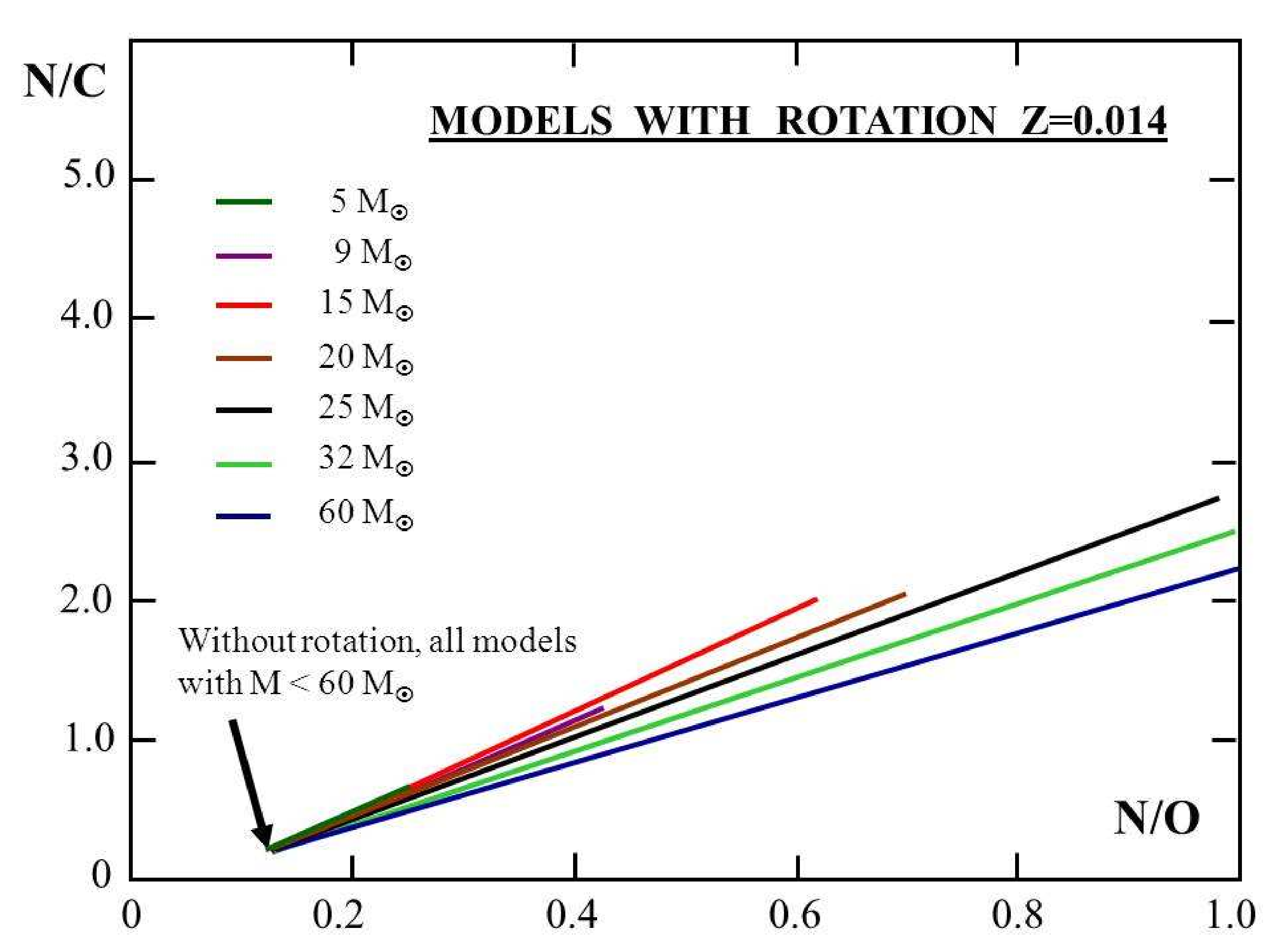
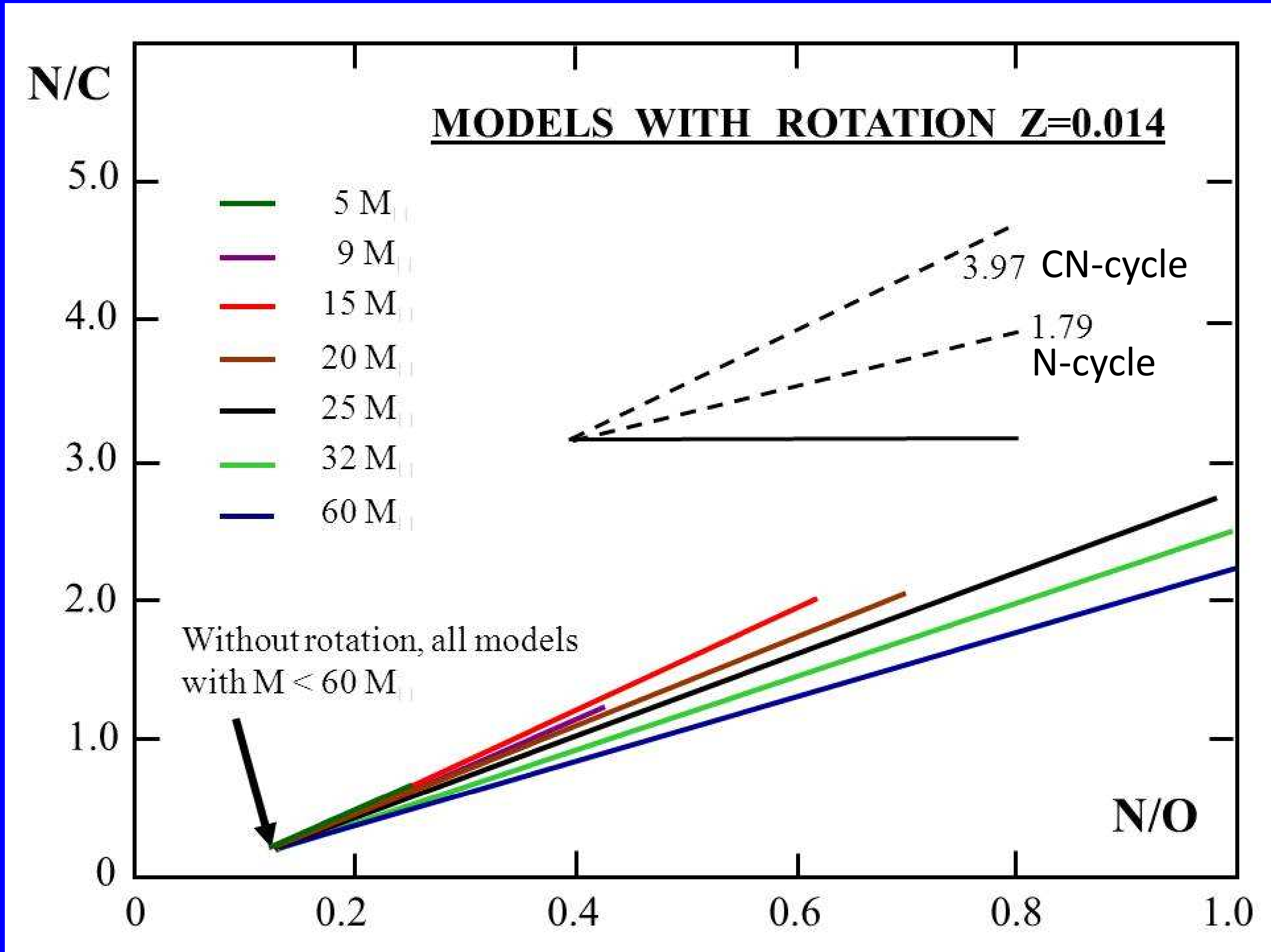
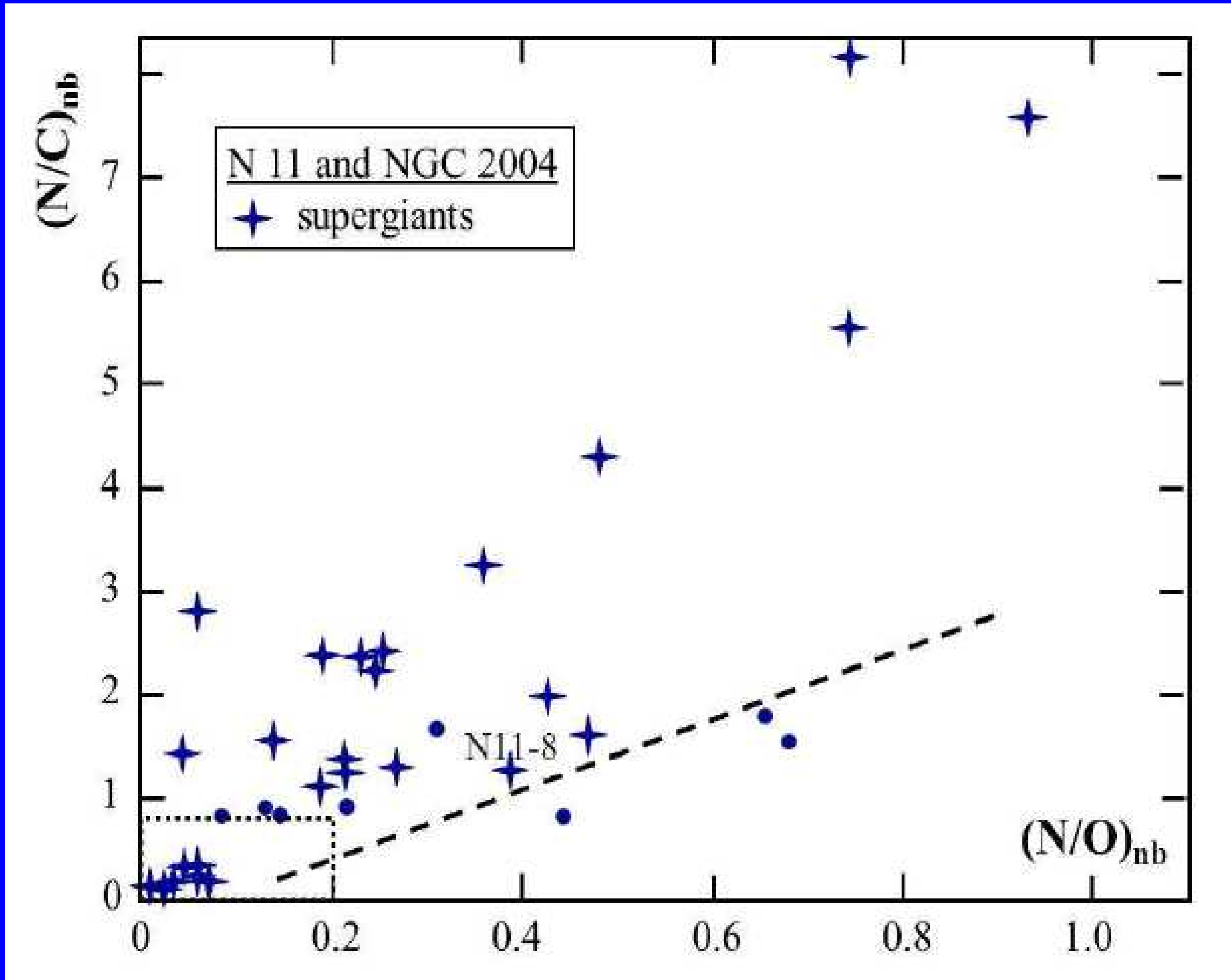


N/C vs. N/O plot: depends only on nuclear properties, Independent on mass and rotation, ~linear up to 0.6

(Maeder, Przybilla, Nieva ,Meynet et al. 2013)





From VLT- FLAMES survey (Hunter et al. 2009)

CASE SPIN UP:

$v_{ini}/v_{crit}=0.2$,

$P_{orb}= 0.9\text{-}1.4$ d