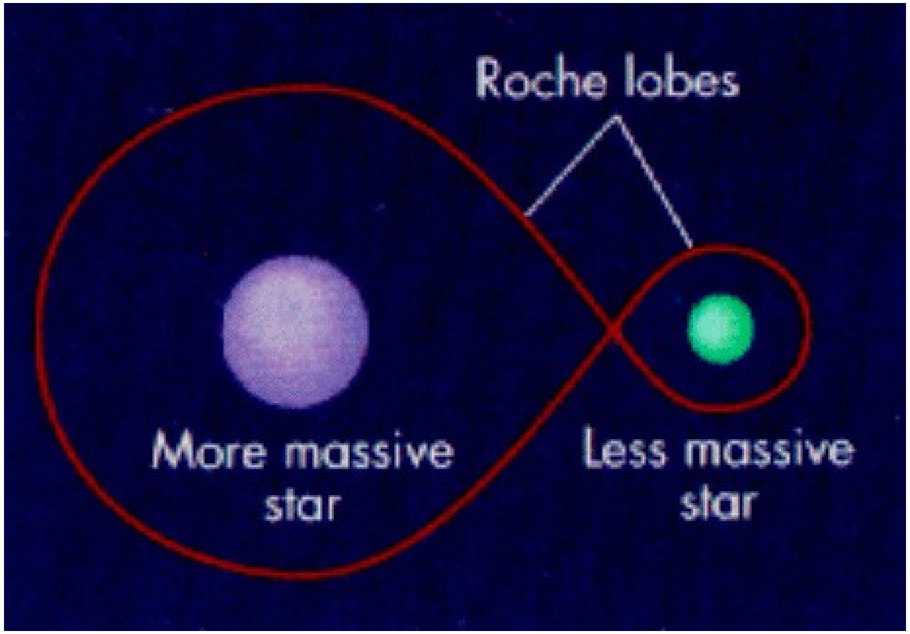
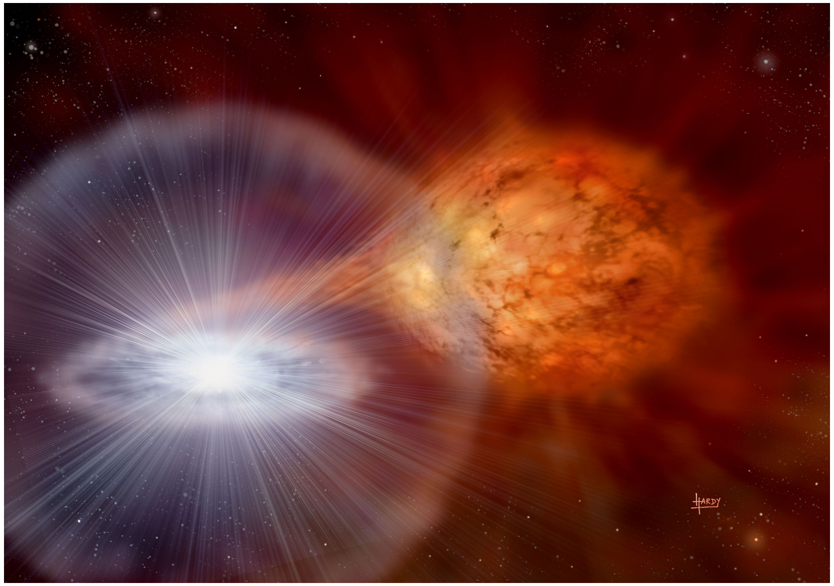
Lecture 11: From M,q,a to vsini, XN, Ω:

Current binary stars research:
From theory to current observations





Herbert Lau

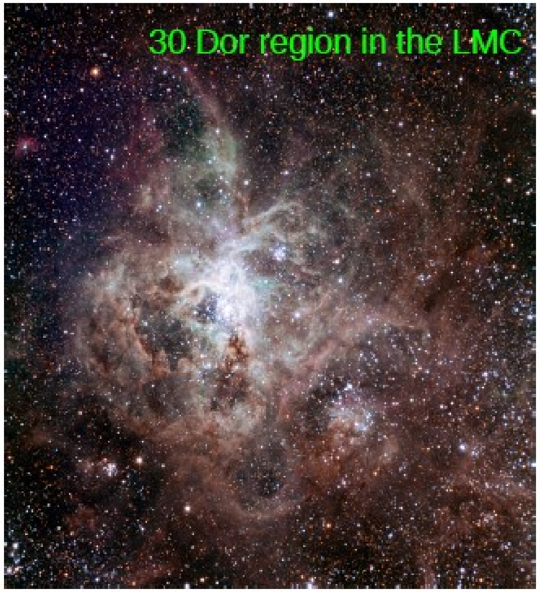
Topics

- Binary fraction and how binary interactions change observations.
- e.g. Observed Mass Function
- Observed abundances
- Thermohaline Mixing
- Binary as “archaeology” tool:
  e.g. Carbon Enhanced Metal Poor stars

VLT/FLAMES Tarantula Survey

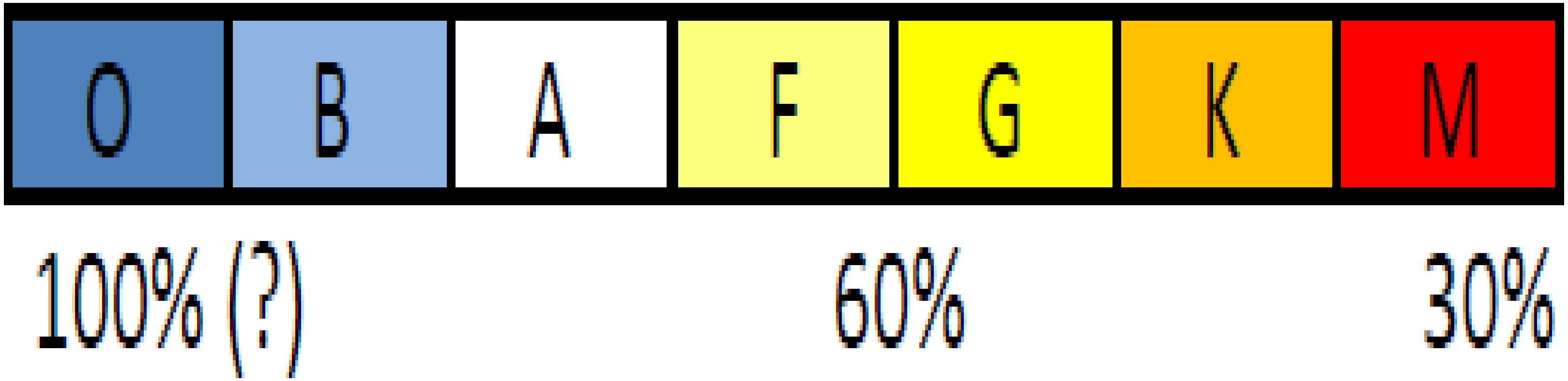
- Multi-epoch spectroscopy of 800 massive stars
- Stellar rotation, mass loss, multiplicity
- 30 Dor: Young starburst region

Radial Velocity measurement
→ detection of binary



Evans et al., Messenger 2011

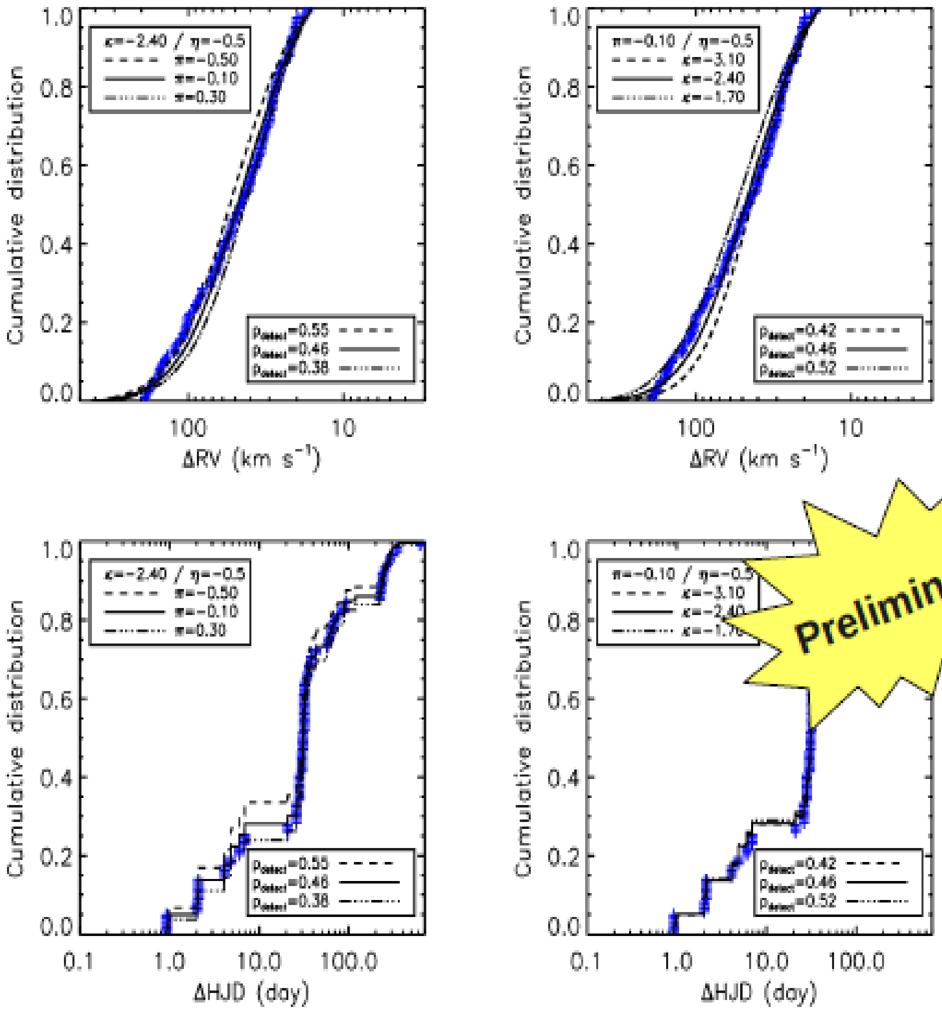
Binary Fraction



Massive

Low Mass

Mason et al 2009, Duquennoy & Mayor (1991)



Preliminary

O-star best parameters

$f_{\log P} \sim (\log P)^{\pi}$ ... $\pi = -0.45 \pm 0.3$

$f_q \sim q^{\kappa}$ .... $\kappa = -1.0 \pm 0.4$

$f_{bin} = 0.51 \pm 0.04$

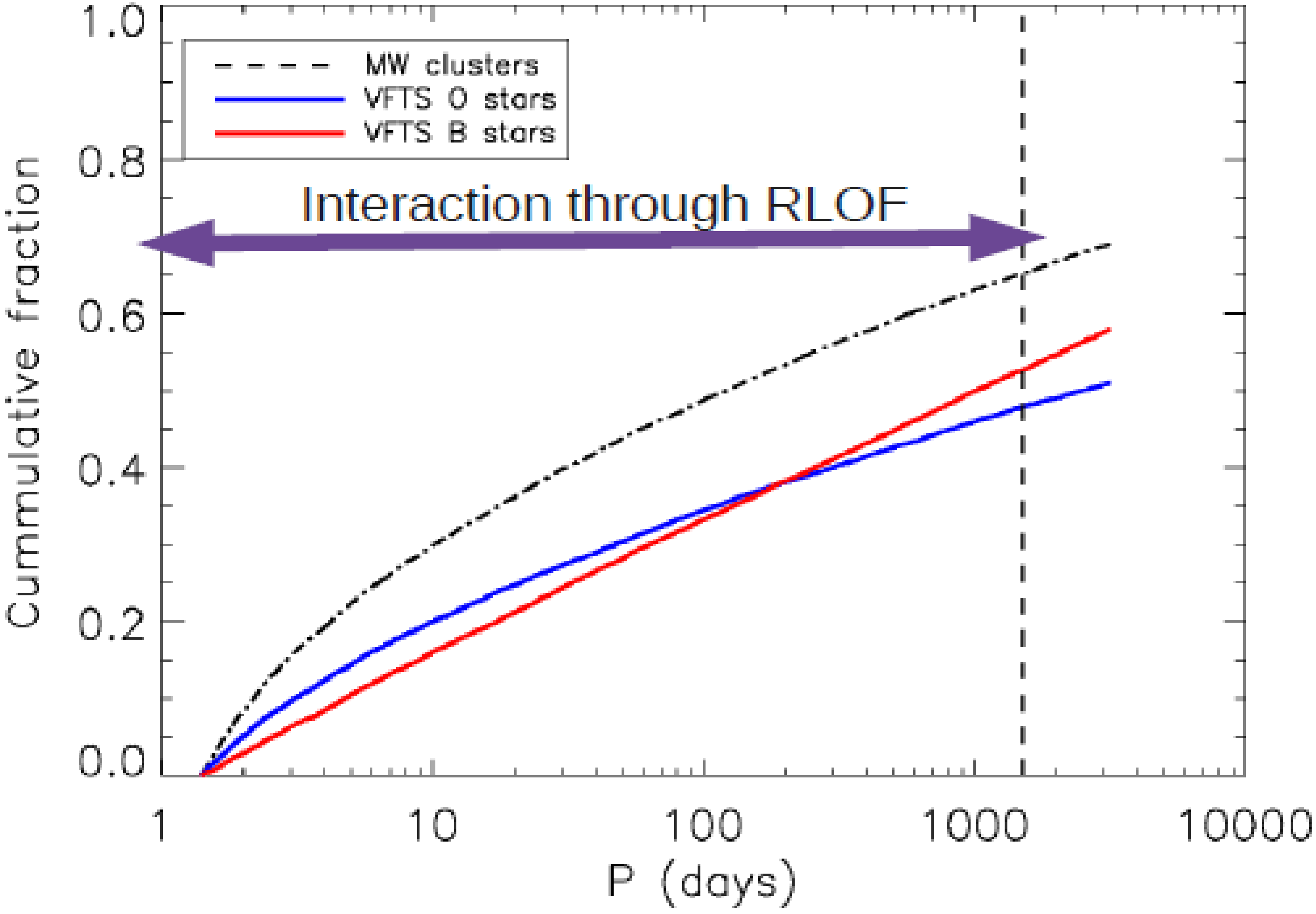
B-star best parameters

$f_{\log P} \sim (\log P)^{\pi}$ ... $\pi = -0.1 \pm 0.5$

$f_q \sim q^{\kappa}$ .... $\kappa = -2.4 \pm 0.8$

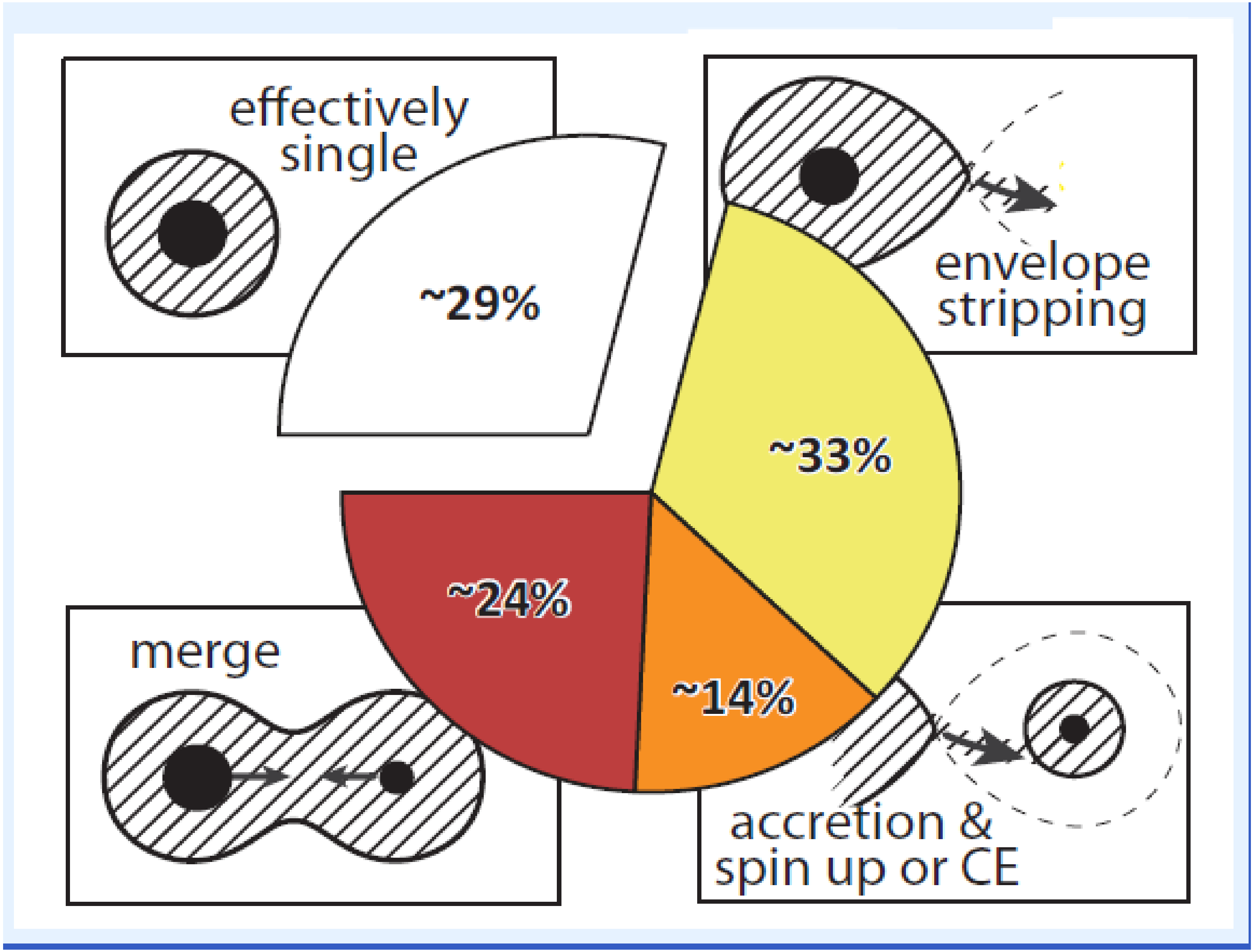
$f_{bin} = 0.56 \pm 0.11$

Sana et al 2013, A&A 550, 108

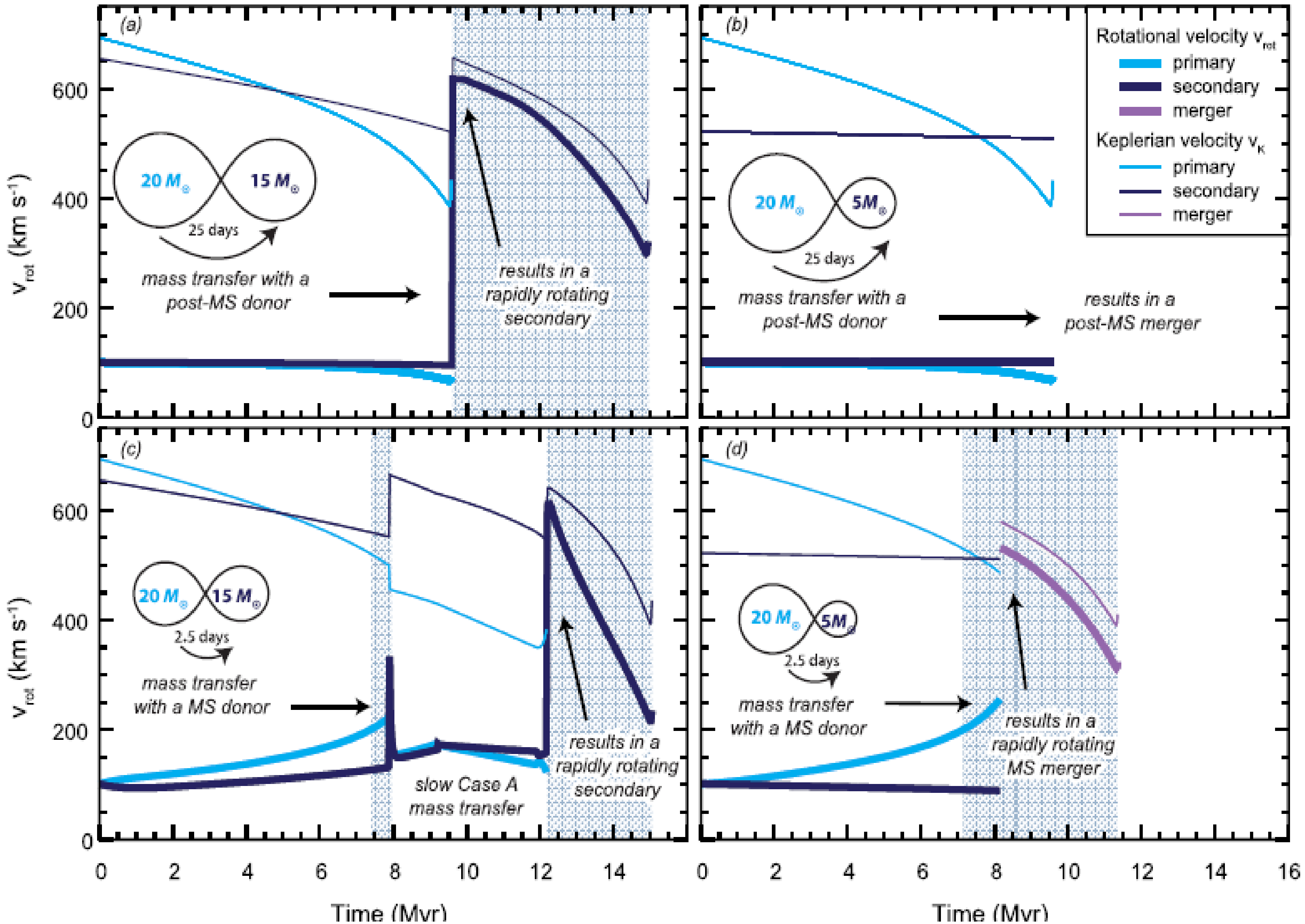


Interaction through RLOF

Figure by Sana 2013



Sana et al 2012, Science



De Mink et al 2013

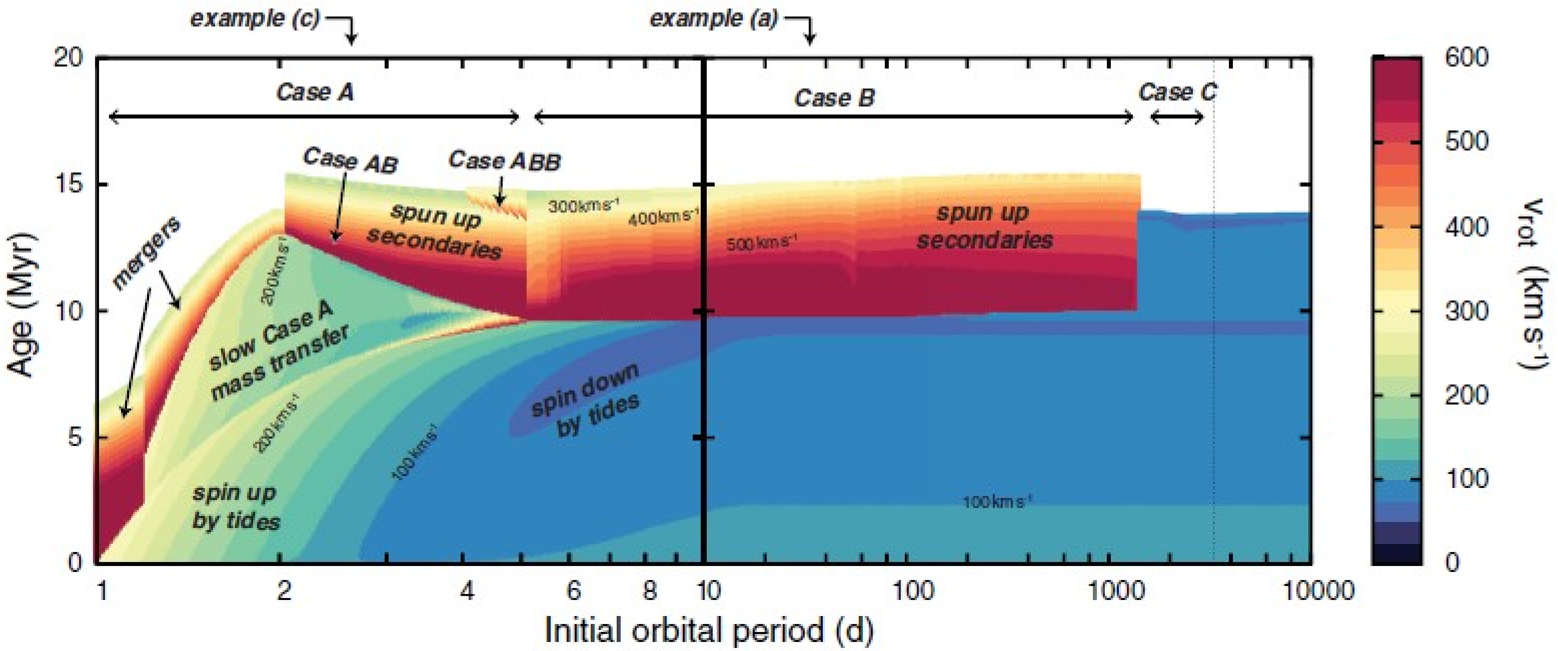
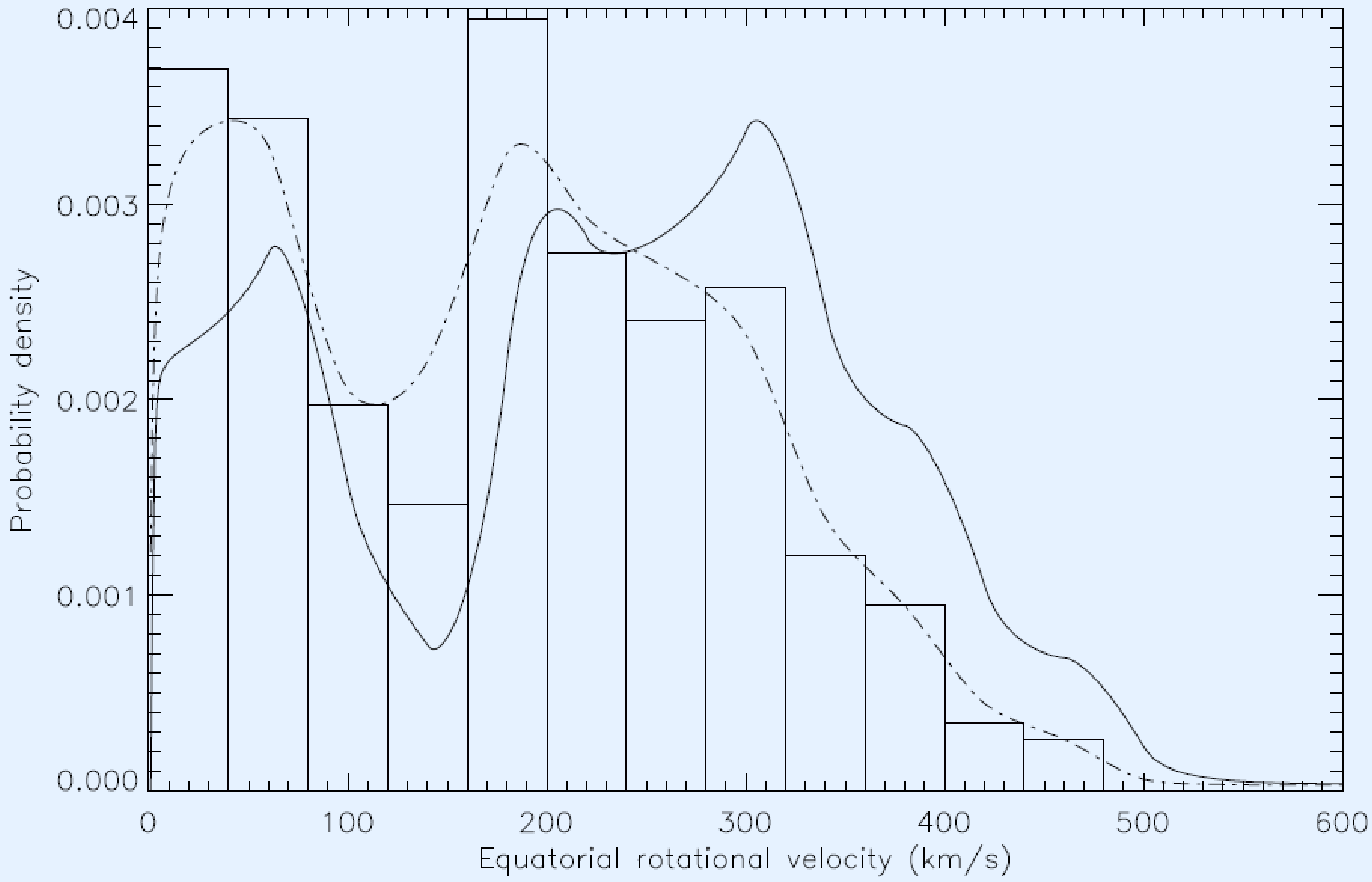


Figure 3. Rotational velocity (color shading) as a function of initial orbital period and time for the brightest main-sequence star in a binary system. We adopt initial masses of 20 and 15 $M_\odot$, initial rotational velocities of $100\,\mathrm{km\,s^{-1}}$, and a metallicity of $Z = 0.008$. As the stars evolve along the main sequence their rotational velocity is altered by stellar winds, internal evolution, tides, and most notably mass accretion. The vertical dotted line indicates the maximum separation for which this system interacts by mass transfer. The examples shown in panels (a) and (c) of Figure 2 are part of this simulation.

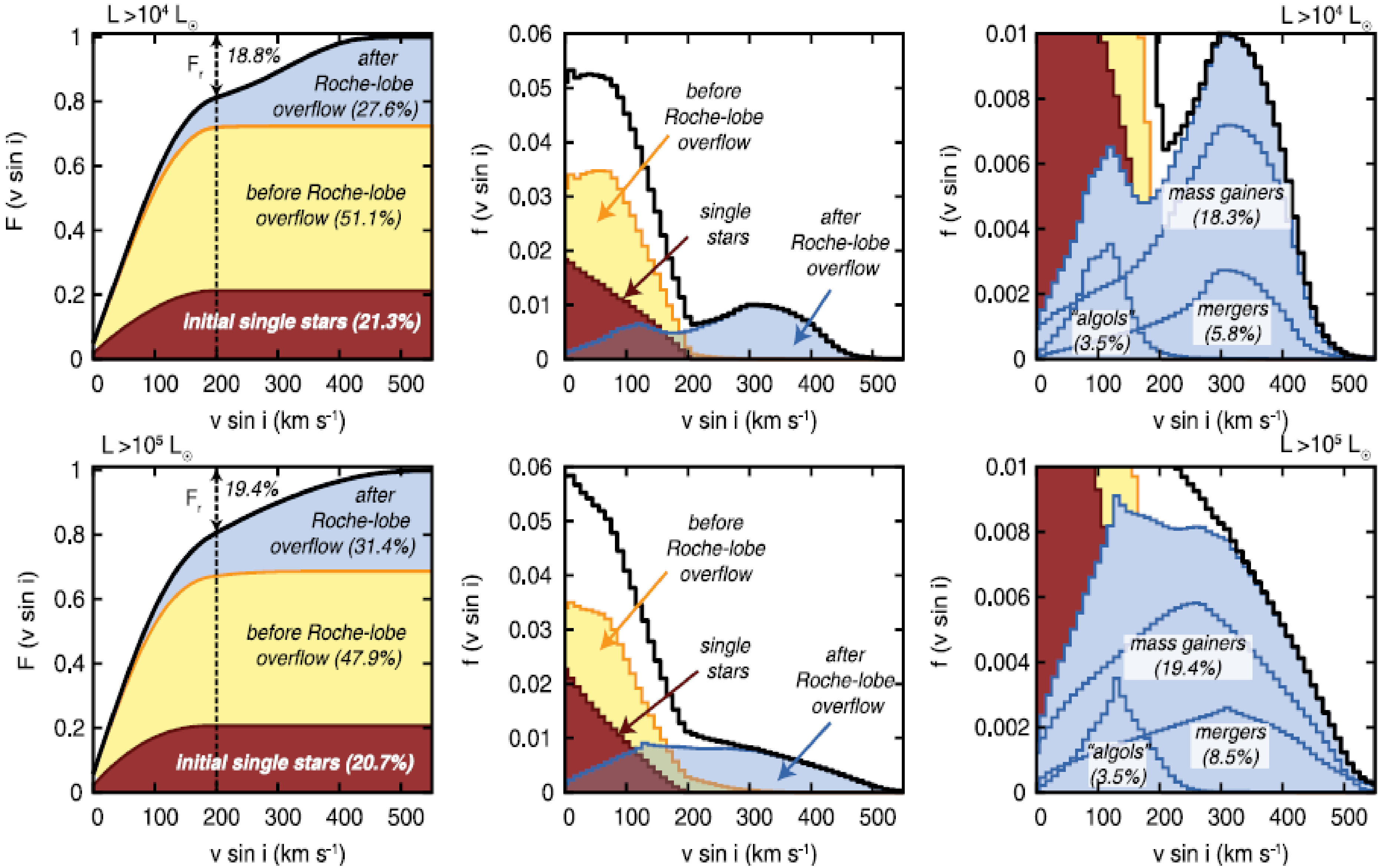
(A color version of this figure is available in the online journal.)

De Mink et al 2013

The rotation rates: early B stars



Dufton et al. 2013

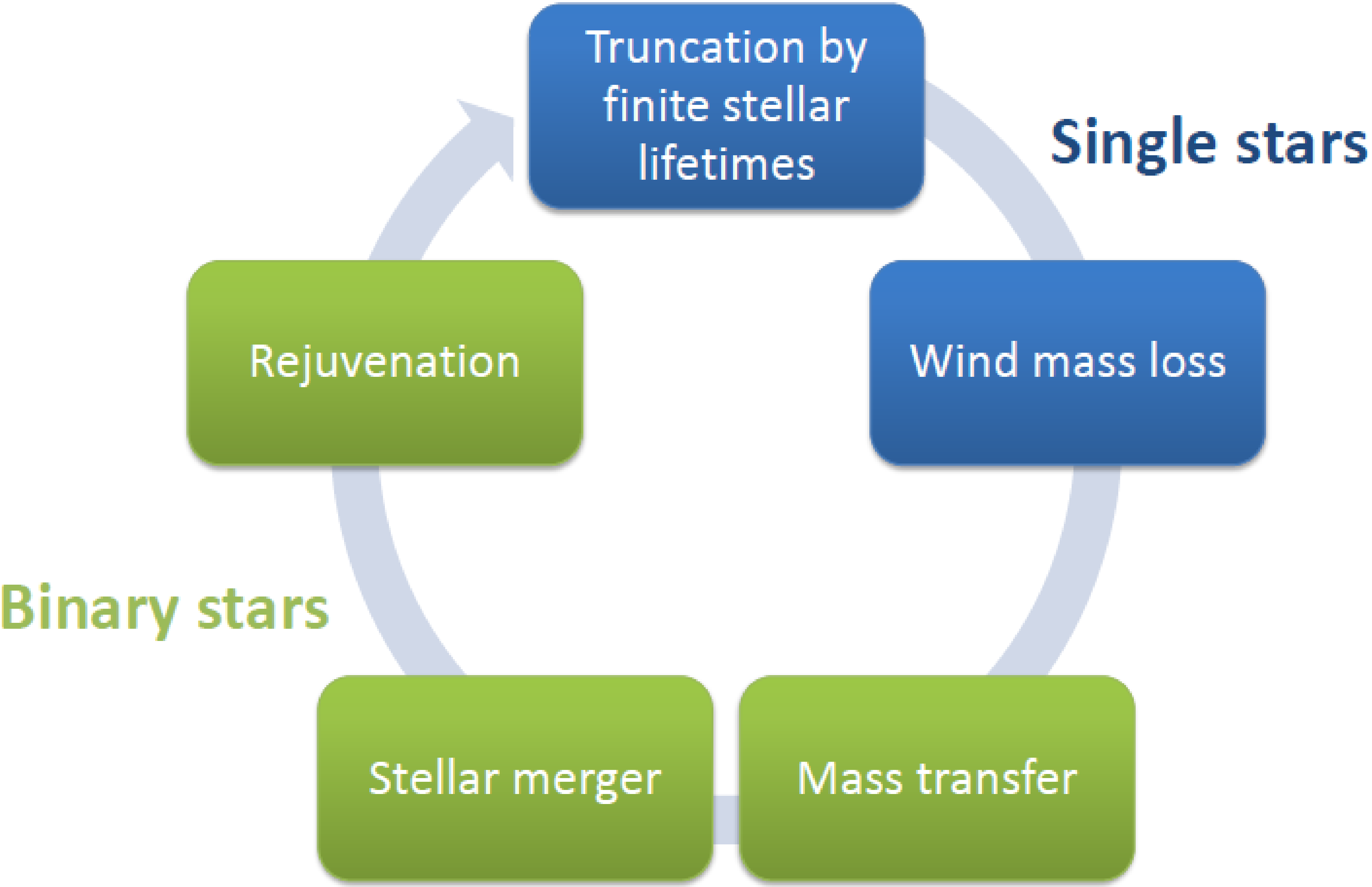


De Mink et al 2013

Key points:

- Most stars (especially massive stars) are not single stars.
- Observed single stars can be product of mergers!
- Wide Binary (with no interaction) are the best single stars

Evolutionary effects on mass functions



Truncation by finite stellar lifetimes

Single stars

Wind mass loss

Mass transfer

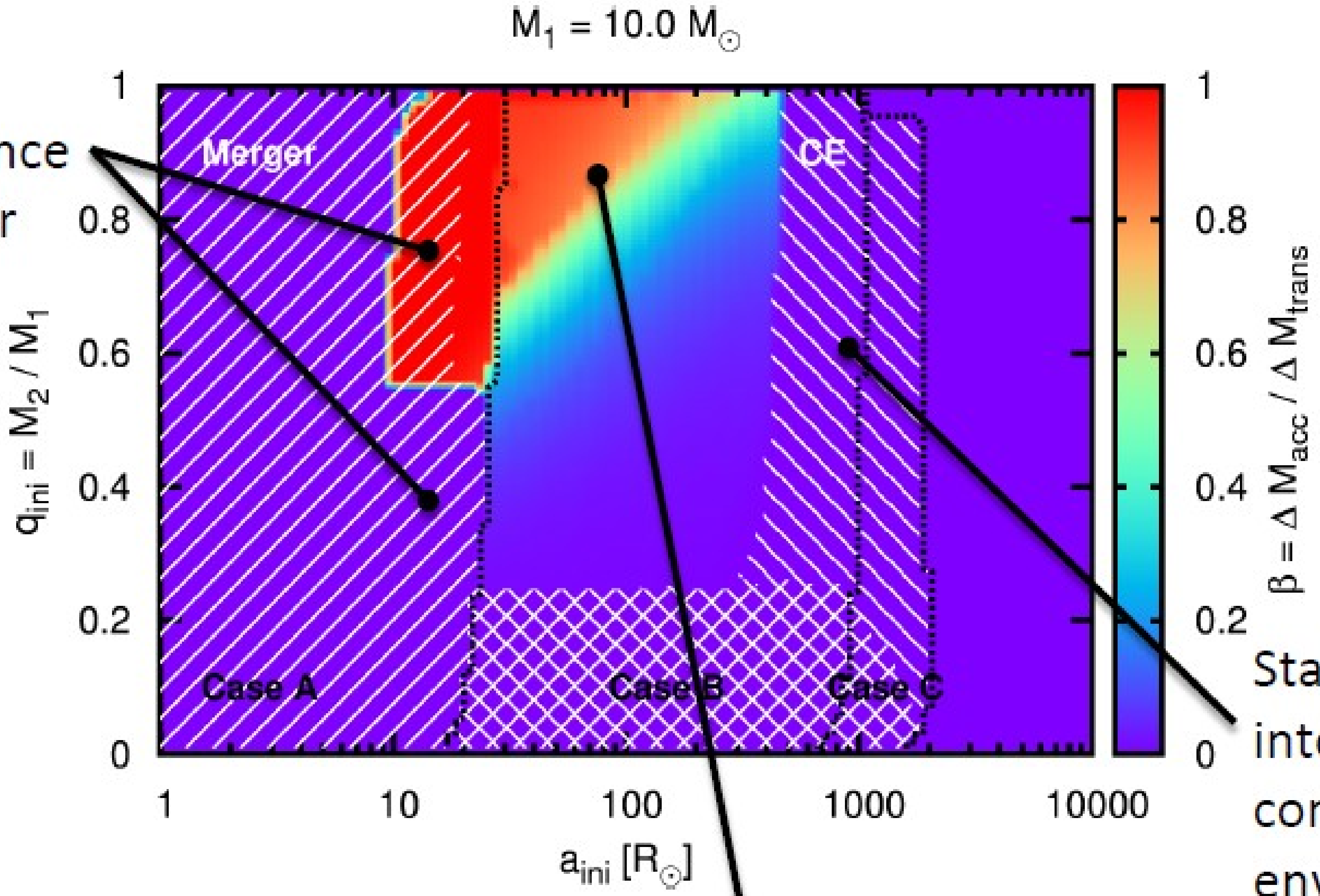
Stellar merger

Binary stars

Rejuvenation

Figure by Fabian Schneider

Binary parameter space



Main-sequence merger

Mass transfer limited by thermal timescale

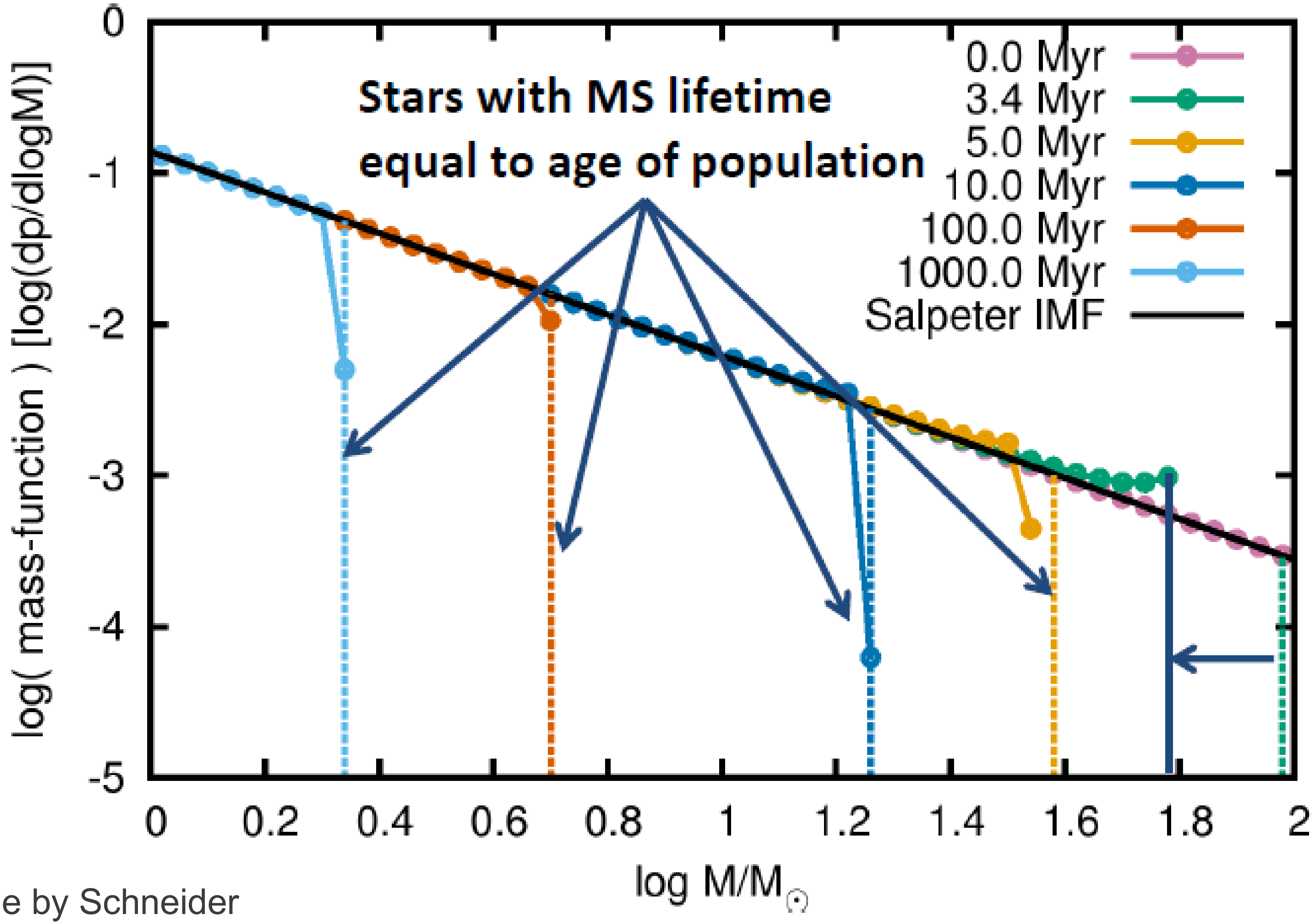
$$\tau_{\rm KH} = \frac{GM^2}{2RL}$$

Stars go into common envelope evolution and do not merge

Slide by Schneider

Main sequence single stars

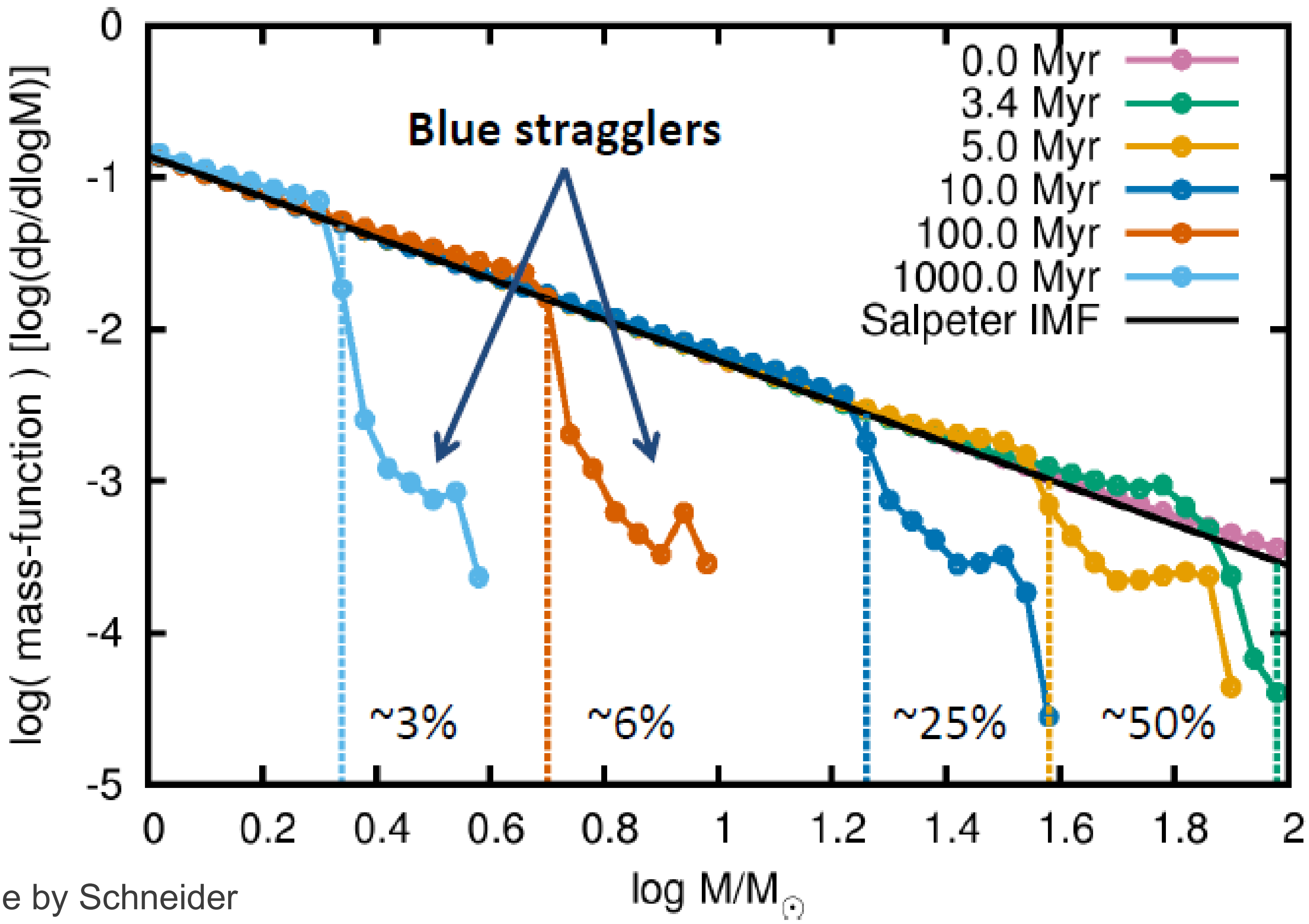
- **Wind mass loss** reduces stellar masses → accumulation of stars



Slide by Schneider

Main sequence binary stars

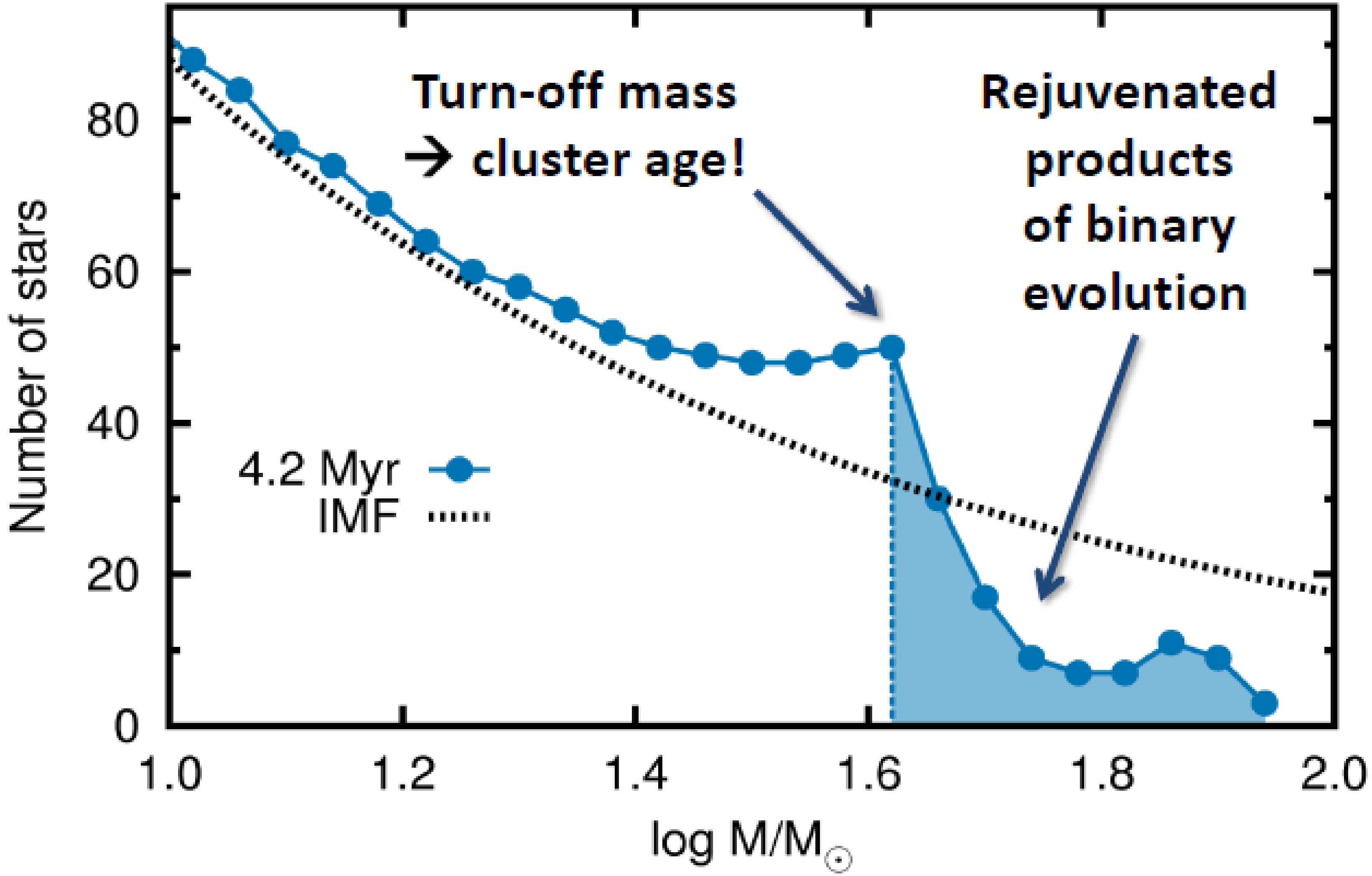
- **Mass transfer, stellar mergers** and **rejuvenation** shape PDMFs



Slide by Schneider

PDMF: binary stars

- **Mass transfer**, **stellar mergers** and **rejuvenation** create a tail



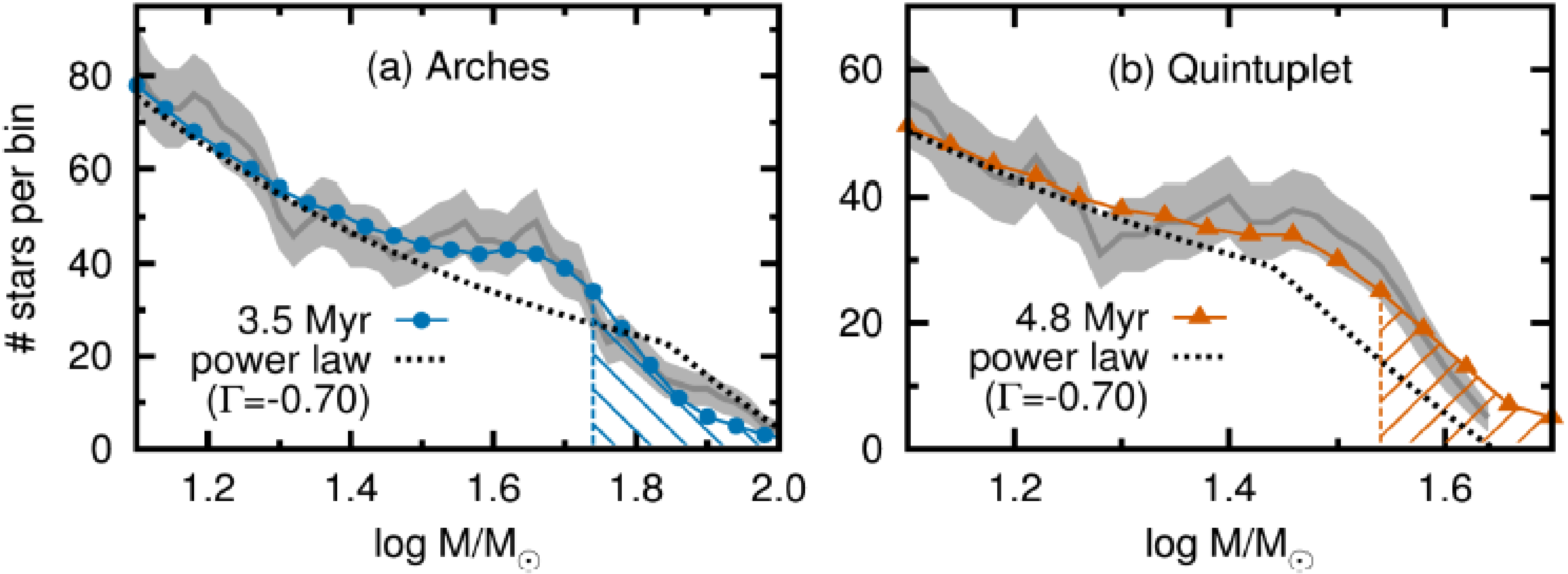
Turn-off mass → cluster age!

Rejuvenated products of binary evolution

Slide by Schneider

Comparison with observations

- PDMFs from Stolte et al. 2005 and Hußmann et al. 2012



- **Bump** and **tail** explained by our models:
  - Arches: $t = 3.5 \pm 0.3\,(\mathrm{model}) \pm 0.6\,(\mathrm{obs.})\,\mathrm{Myr}$
  - Quintuplet: $t = 4.8 \pm 0.3\,(\mathrm{model}) \pm 1.1\,(\mathrm{obs.})\,\mathrm{Myr}$
- **The most massive stars are rejuvenated binary products**

➔ Resolves cluster age problem

Slide by Schneider

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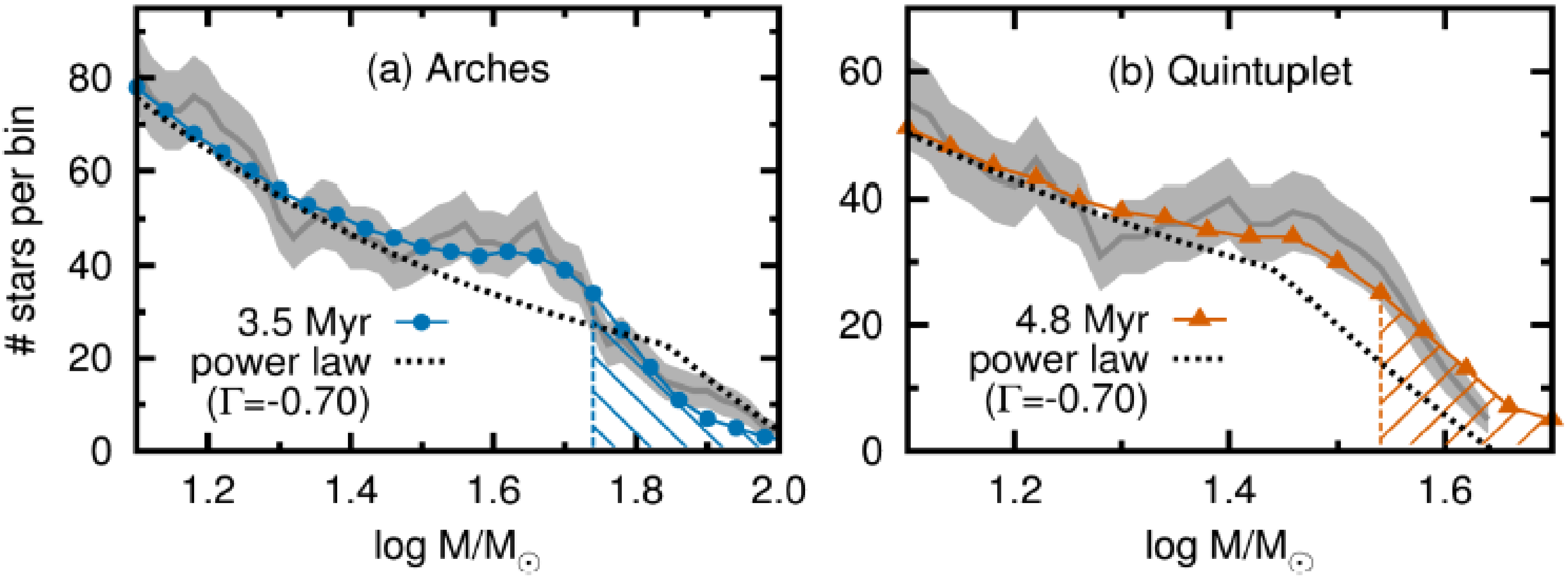

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➔ Resolves cluster age problem

Slide by Fabian
Schneider

Implication on stellar mass limit

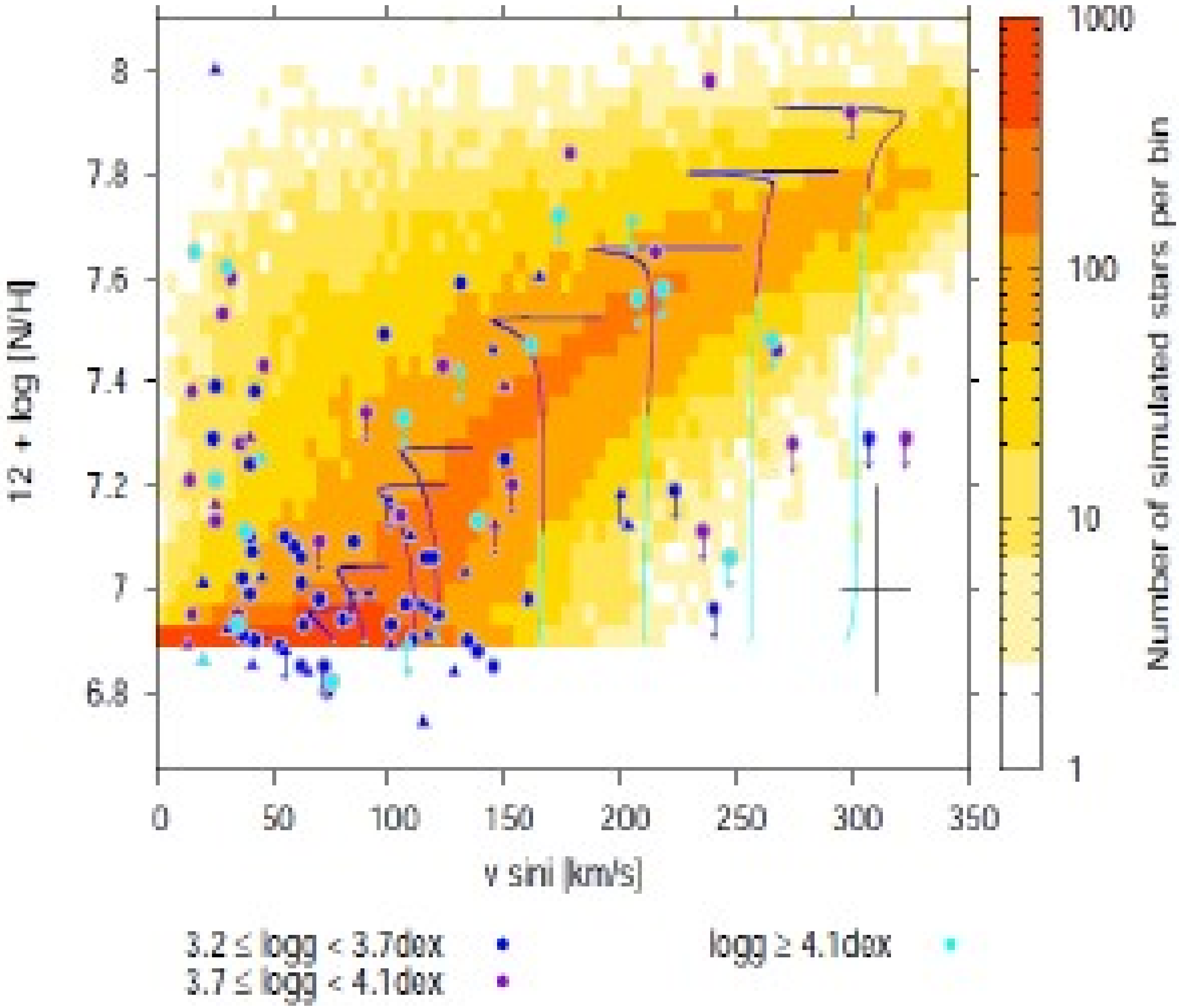
- Are there an upper mass limit for massive stars??
- 160-320 solar mass in R136
  (Crowther et al 2010)
- They are likely to be binary products
- Observed mass does not necessarily give the actual upper mass limit, so observations of supermassive stars does not necessarily contradict theory.

Key Points:

- The current observed Mass Function is significantly altered by binary interaction (and mass loss).
- The most massive stars are typically produce of binary mergers!

How Binary can affect surface abundances?

- Materials transferred from primary to secondary will change the secondary surface abundances.
  But : Do the material just sit on top of the surface?
- What happen to primary that lose significant mass?
- Effect of spin-up due to mass transfer?



Brott et al 2011

“Hunter” diagram

Rotational mixing cannot predict a significant portion of massive MS stars that are either

1) N-rich slow rotators
2) N-poor fast rotators

Binary interaction such as mass accretion can spin up the stars, while mass loss can spin down the stars.

→ Previously rotationally mixed stars may appear slow rotators due to mass loss?

→ Recently spun up secondaries may yet to enhance surface nitrogen?

.

- There are many possible explanations, but we do not know whether those scenarios are frequent enough to explain the observed frequcies
- As covered in last lecture, we need population synthesis to cover the large input parameters space.
- Models are made with population synthesis code BONNfires.

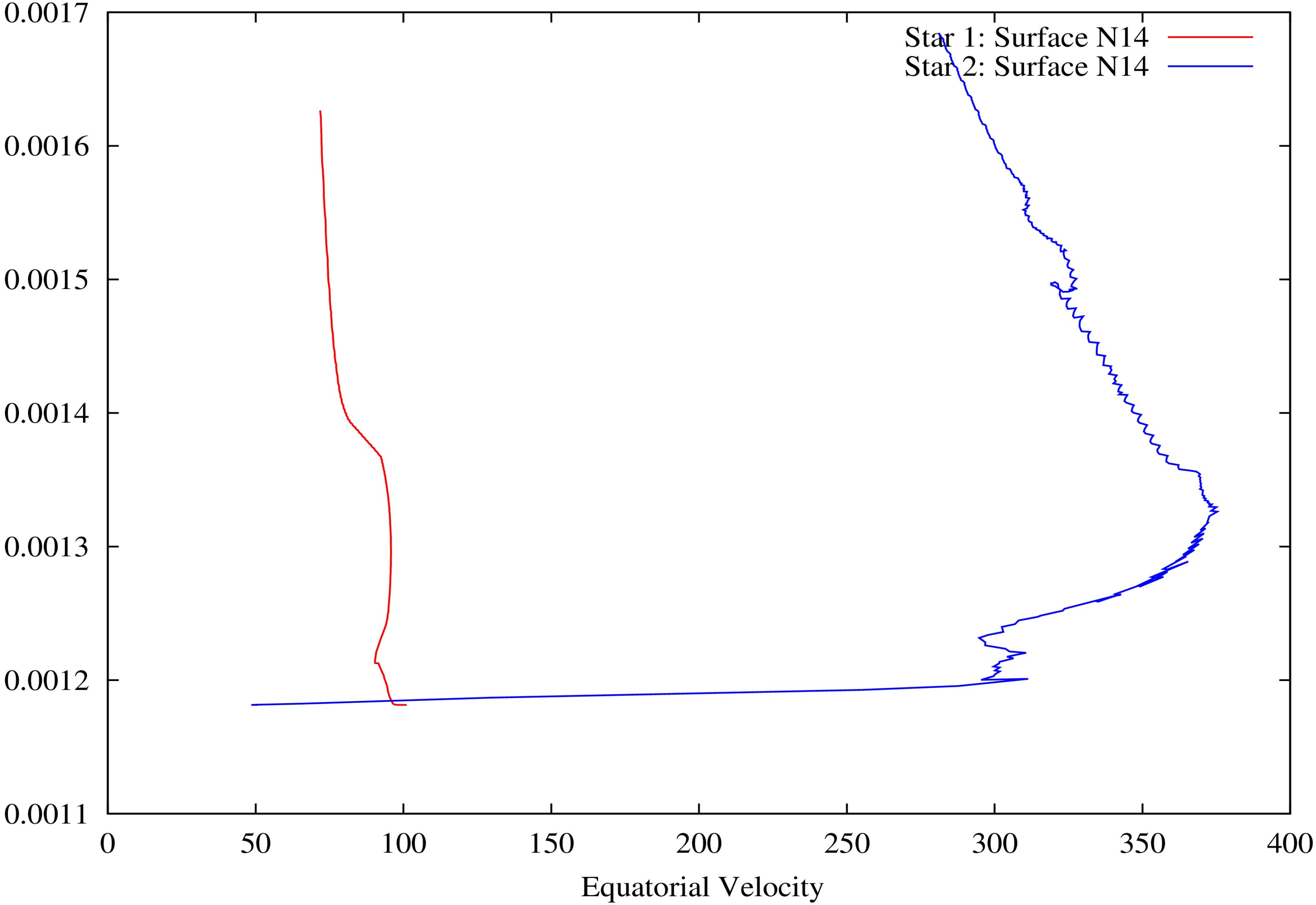
A binary sample

- Primary = 20$M_\odot$
- Secondary = 15$M_\odot$
- Primary initial rotational velocity= 100km/s
- Secondary Vrot= 50km/s
- Initial sep = 28 $R_\odot$

log(N/H)+12

BONNfire's "Hunter Diagram"

7.06

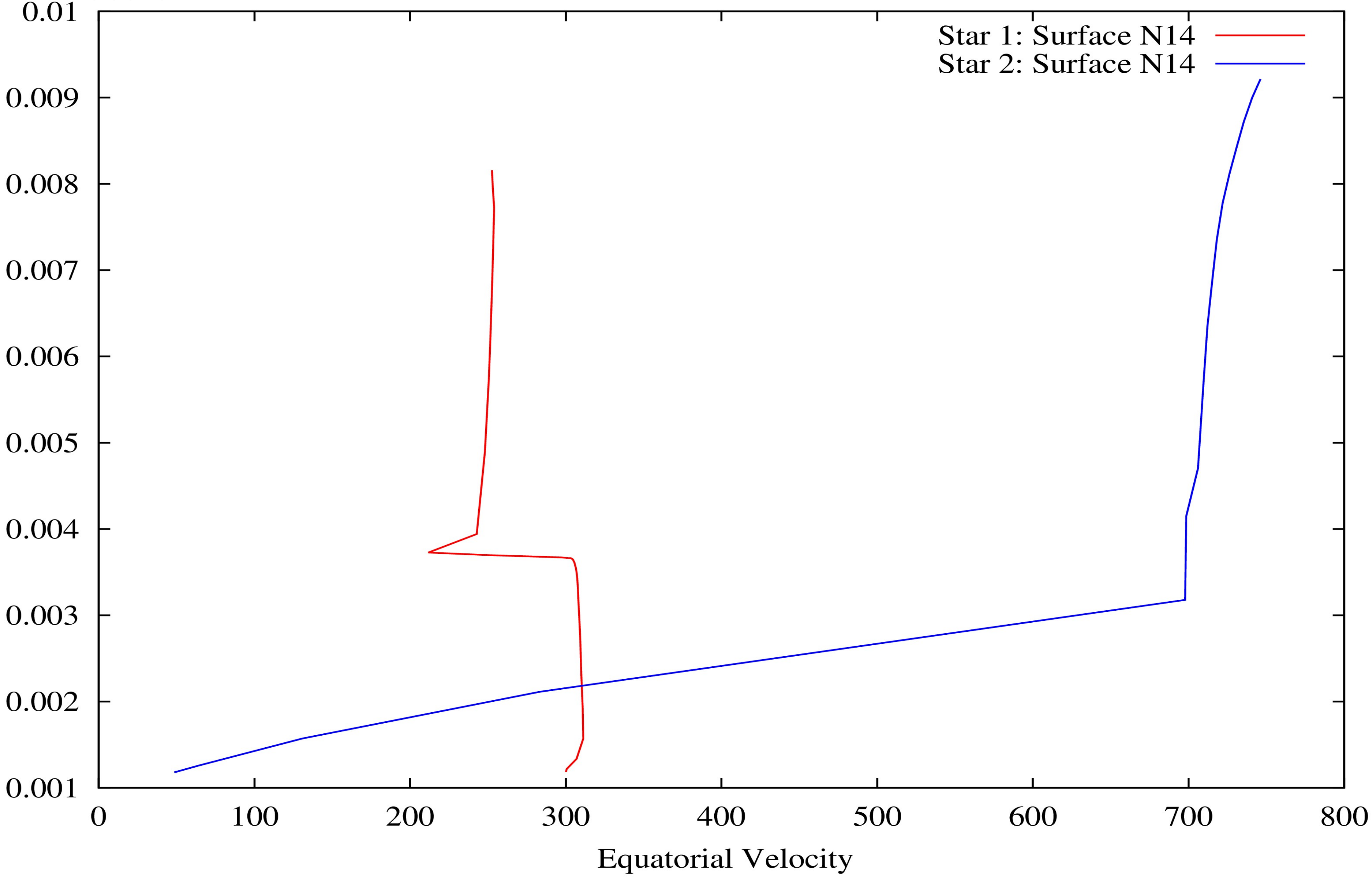


Faster Prinary Initial Velocity 100lm/s → 300km/s

log(N/H)+12

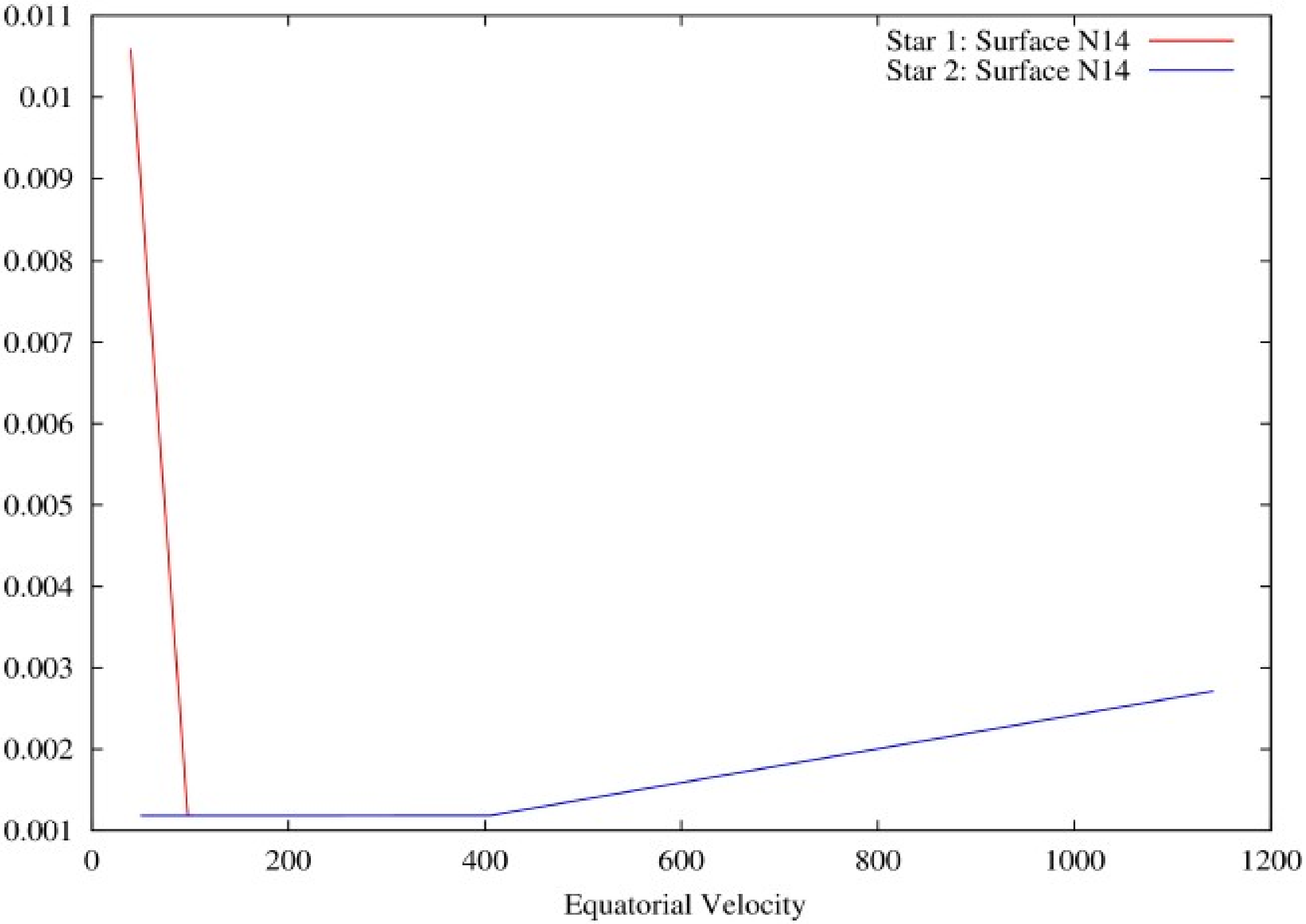
Notice the change of scale!

7.85



Or in a very close binary.

Closer binary initial separation15$R_\odot$



Key Points

- Mass gainer is spun up and accrete materials from primary.
  The surface composition is altered by
  1) materials accreted
  2) rapidly fast rotation can lead to rotational mixing from the core
- For mass loser, the inner core and be exposed due to significant mass loss.
- Caveat: Mergers will complicate things.

From most recent mergers models

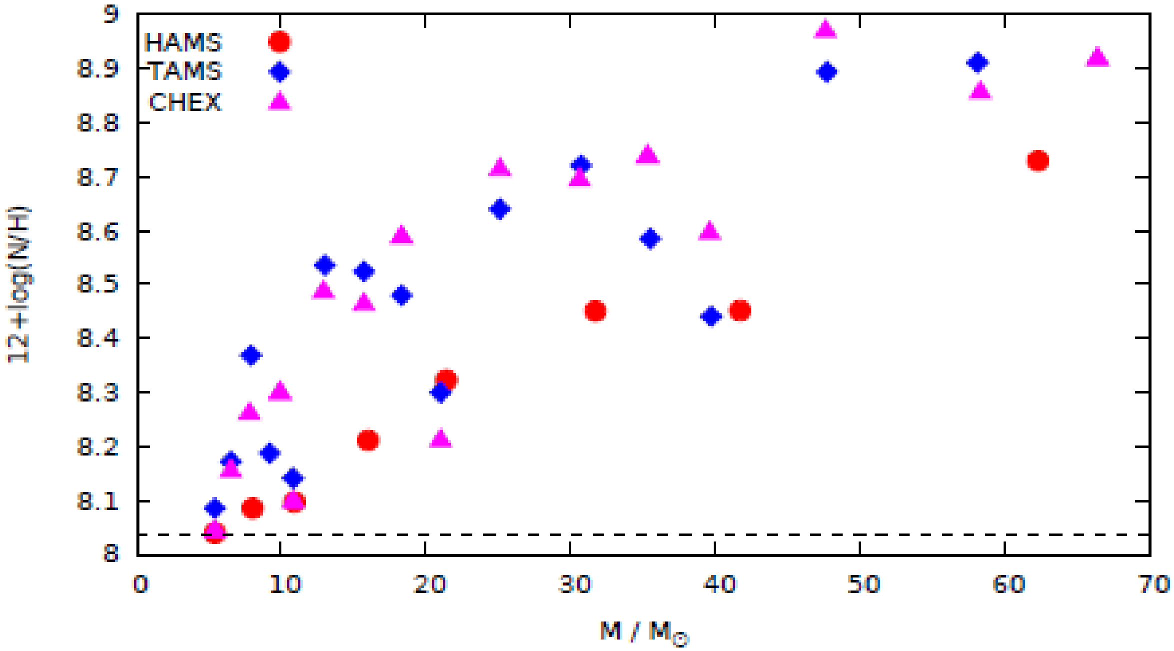


Figure 15. Surface abundance of nitrogen for our merger models, as a function of total mass. The dashed line represents our ZAMS composition.

Figure from Glebbeek et al 2013

And a merged star may not behave exactly like a single star.

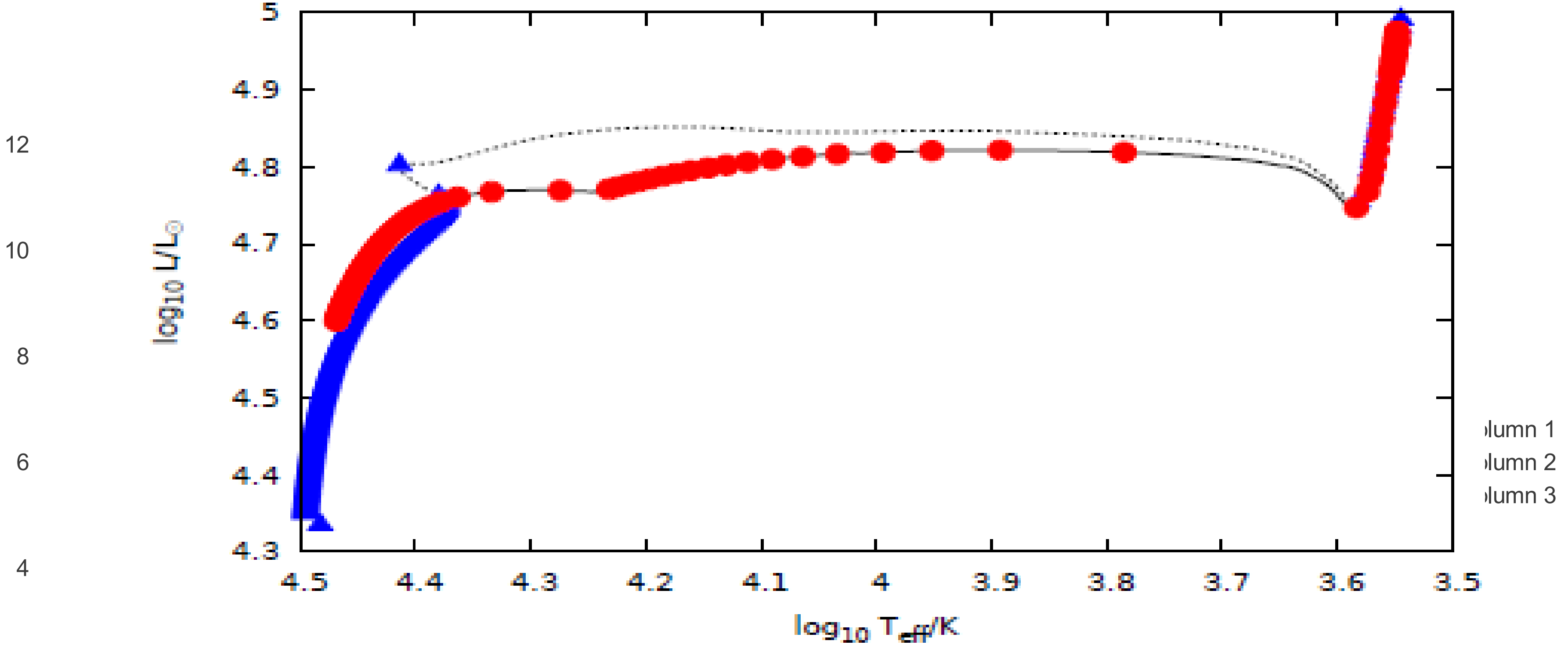


Figure 10. Evolution track of the TAMS 10+7 merger product (solid line) compared to the evolution track of a normal star of the same mass (dotted line). Points are plotted along the curves every 50 000 years. Note that the merger product spends a considerably longer time in the blue part of the region corresponding to the Hertzsprung gap than the normal star of the same mass.

Thermohaline mixing

- What happens to material that *accretes*?
- In general it comes from an *evolved* star i.e. one in which $\mathrm{H} \rightarrow \mathrm{He}$, $\mathrm{C, N, O} \rightarrow \sim 98\%\,\mathrm{N}$ etc.
- i.e. the molecular weight is larger

$$\rho = n \times m_{\mathrm{H}} \times \mu$$

$$\mu = \frac{4}{6X + Y + 2}$$

- Unstable to *thermohaline instability*
- See e.g. https://secure.wikimedia.org/wikipedia/en/wiki/Thermohaline

Thermohaline in ink

Thermohaline in stars

- Relies on thermal transport so instability occurs on thermal timescale τMIS (i.e. fast)
- Kippenhahn et al. 1998: diffusion model

$$D_{\mathrm{th}} = \frac{16acT^3H_{\mathrm{P}}}{(\nabla_{\mathrm{ad}} - \nabla)c_{\mathrm{P}}\,\rho\kappa}\left|\frac{d\mu}{dr}\right|\frac{1}{\mu}$$

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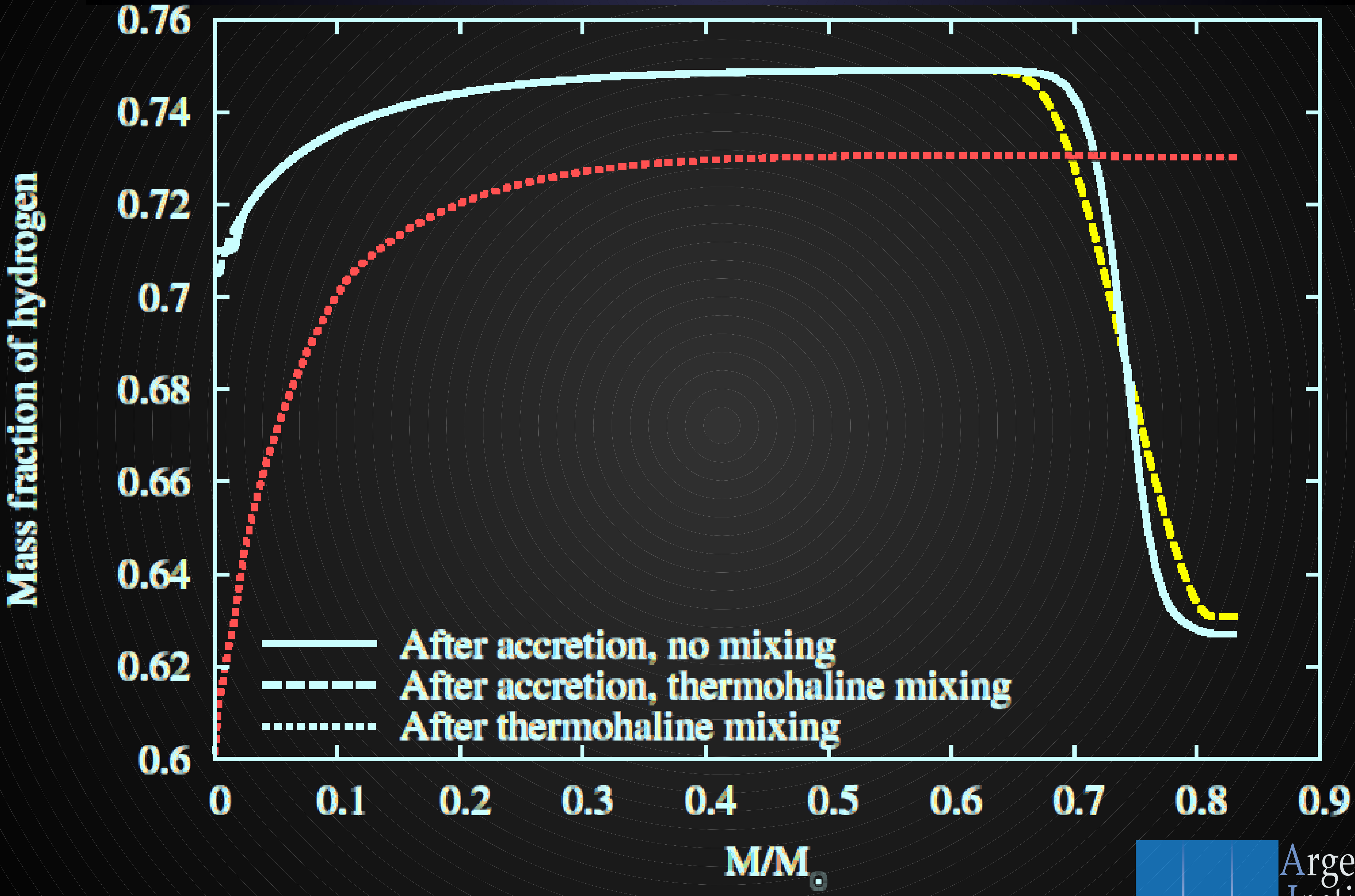
Thermohaline example



Stancliffe et al 2007 A&A 464,L57

Binary as “archeology” tool

- For first few generations of stars (metal-poor) stars, most of them have already ended their lives as Supernovae/Planetary nebula and is now WD/BH.
- However, if they have a low mass binary companion accreting materials from them during their lives, the surface abundances can help us deduce the evolution of the system.
- Example: Carbon-enhanced Metal-Poor (CEMP) stars

CEMP stars

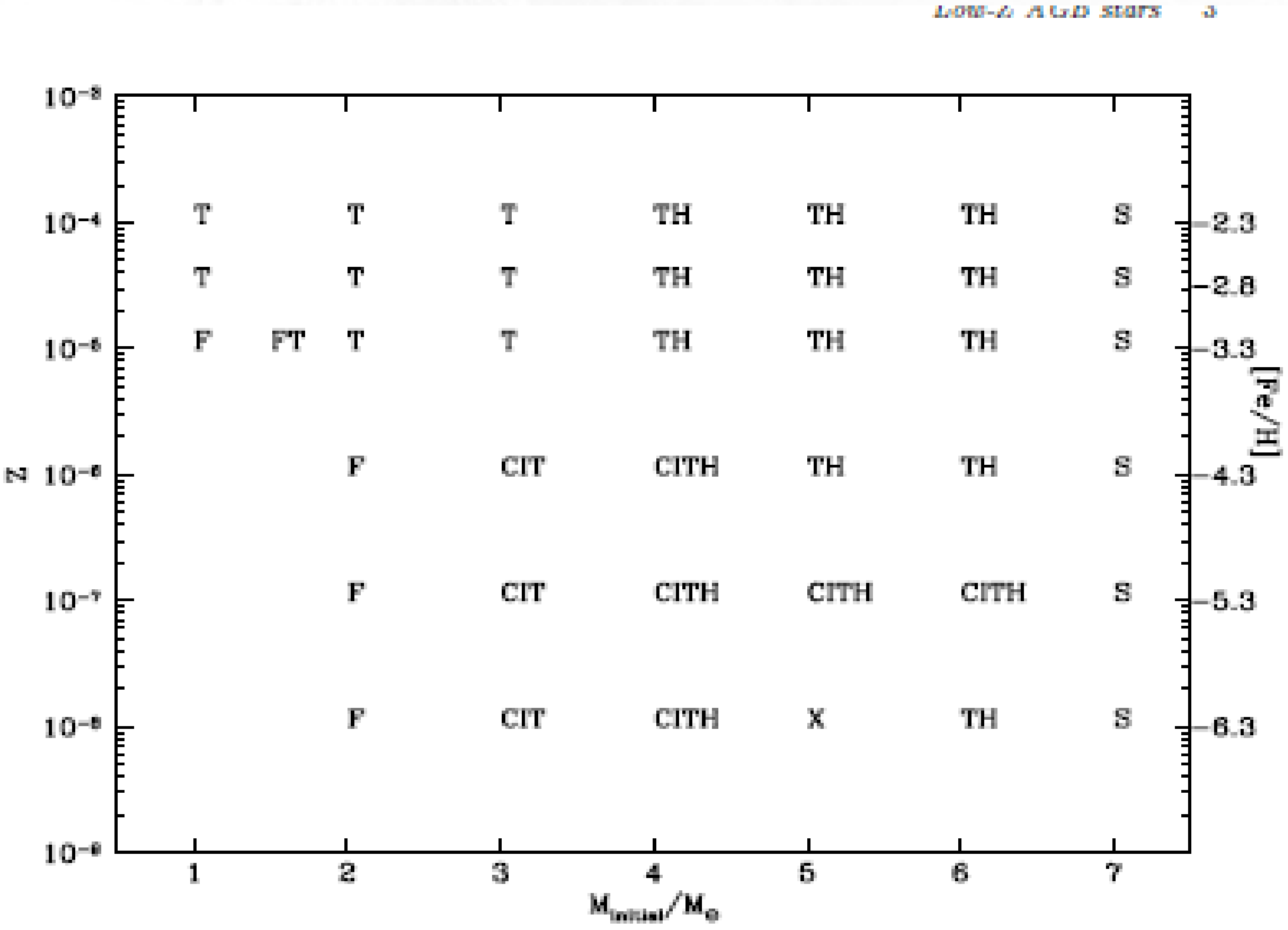
- Low mass (~0.8M) stars
  metal poor ([Fe/H] <-2)
  carbon enhanced ([C/Fe] > 1.0)
  around 20% of metal-poor stars.
  (Review paper by Beers & Christlieb 2005)
- Variation of other abundances, in particular:
  nitrogen enhancement,
  s-process, r-process isotopes.
- Possible formation scenarios:
  binary mass transfer from AGB star
  binary mass transfer from rotating massive stars
  formed from SN remnant ….

- s-process isotopes are made in AGB stars
- r-process isotopes are associated with supernovae.
- Some CEMP-s stars have indication of binary companion through velocity variation
  → consistent with current belief.
- Strong Nitrogen enhancement indicates CNO cycle that convert C to N

Bigger picture

- If we can find out the mass range for the primary/formation channel of observed CEMP stars:
- can find out whether how initial mass function depends on metallicities.
  e.g. How much metal are required for low-mass star to form.
- Independent test from star formation theory
- IMF particularly important for early Universe reionization and chemical evolution

Stars with different mass/metallicity have different nucleosynthesis signature



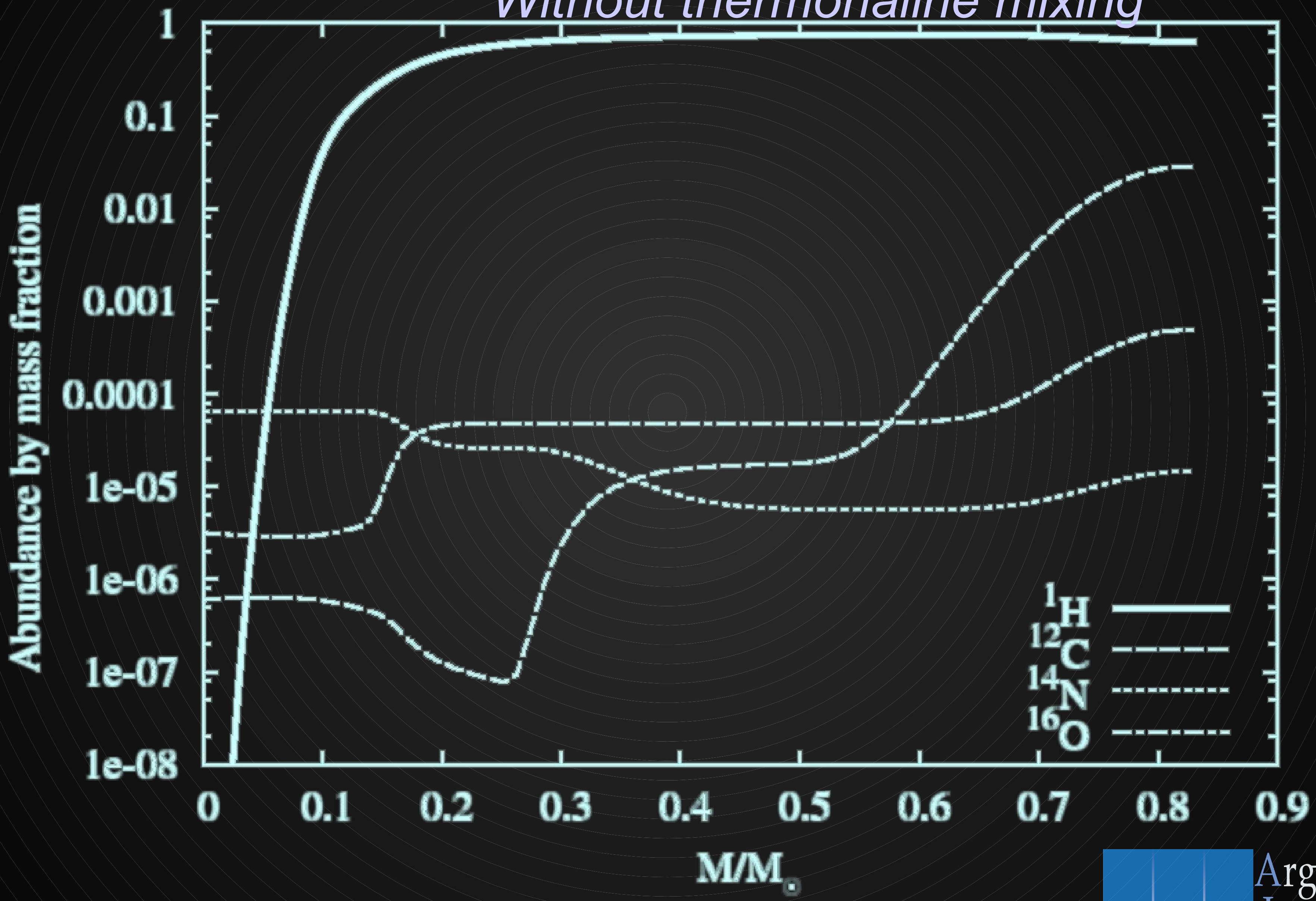
Lau et al (2009)

Complications:

- In order to deduce what is the initial primary mass, we need to model how mixing (e.g. thermohaline mixing) can affect our current observations.
- Detailed models for AGB/massive stars do vary due to treatment of convection, rotational mixing etc.
- Population synthesis is used to estimate frequency of different channels, but so far no perfect match for frequencies of different CEMP stars with different abundance patterns.

CEMP star: [C/Fe]=3.25

Without thermohaline mixing



Stancliffe et al 2007 A&A 464,L57

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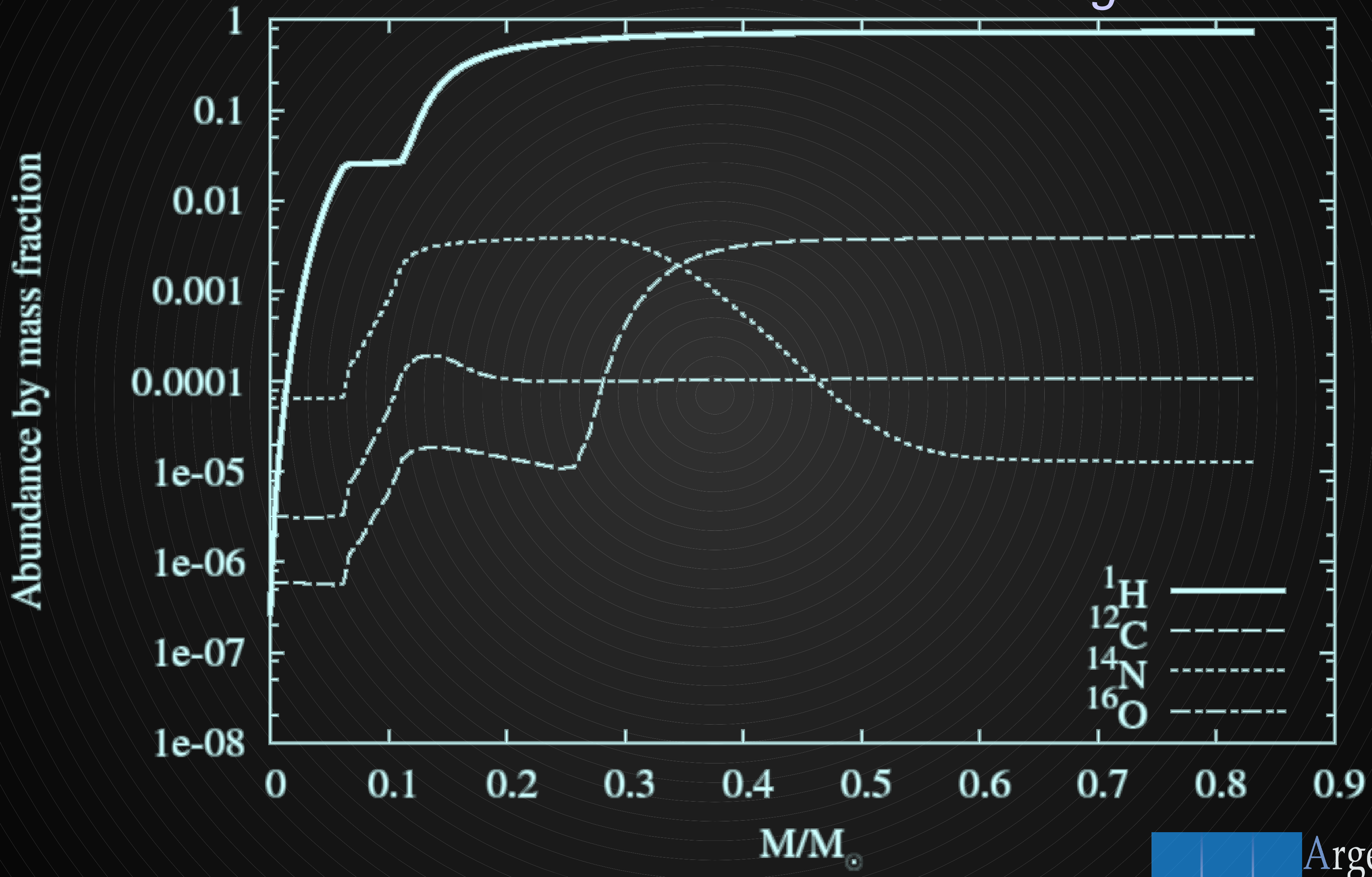
CEMP star: [C/Fe]=2.41

With thermohaline mixing



Stancliffe et al 2007 A&A 464,L57

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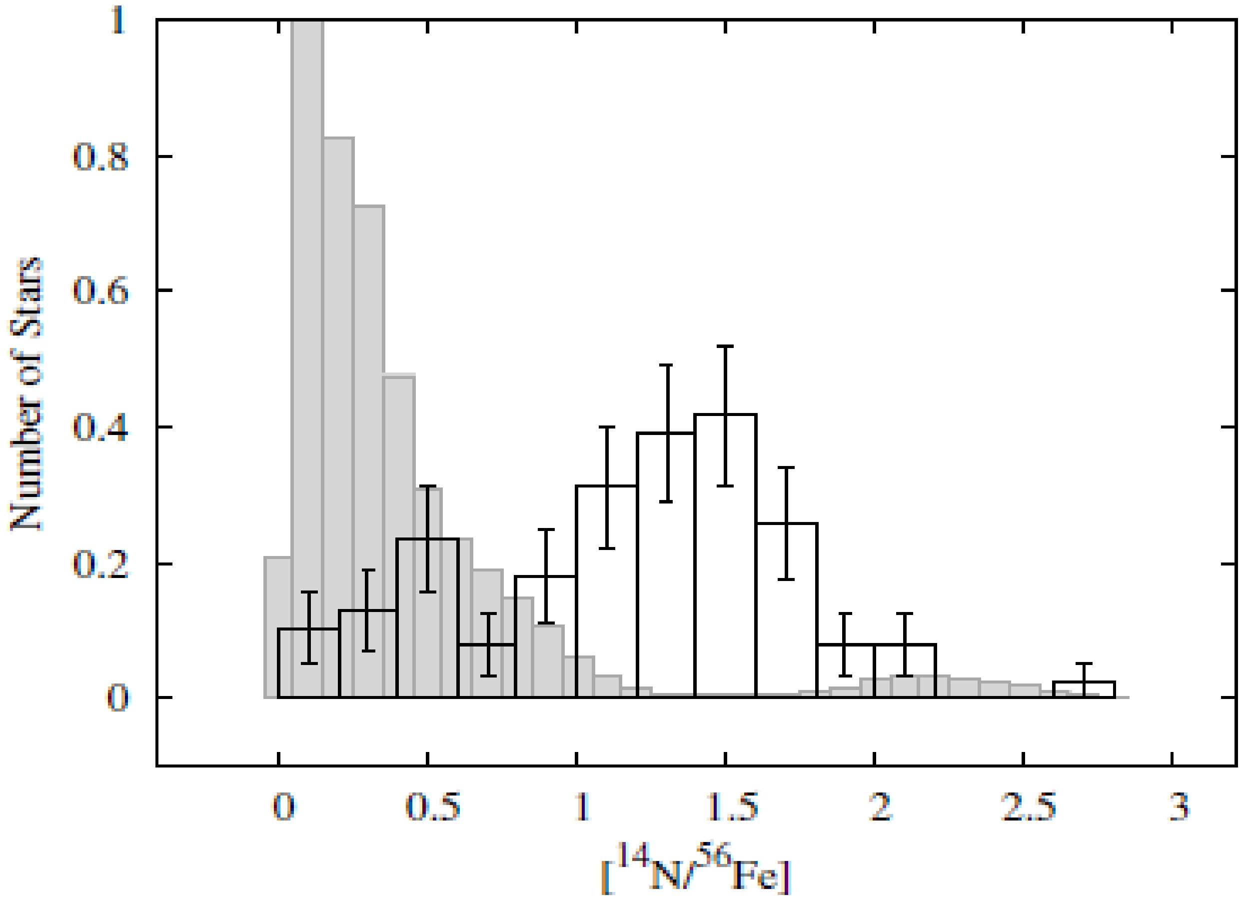


Fig. 7. The distribution of [N/Fe] in our default CEMP population *A* (filled histogram) compared to observations (open histogram with Poisson error bars).

Izzard et al 2009, A&A , 508, 1359

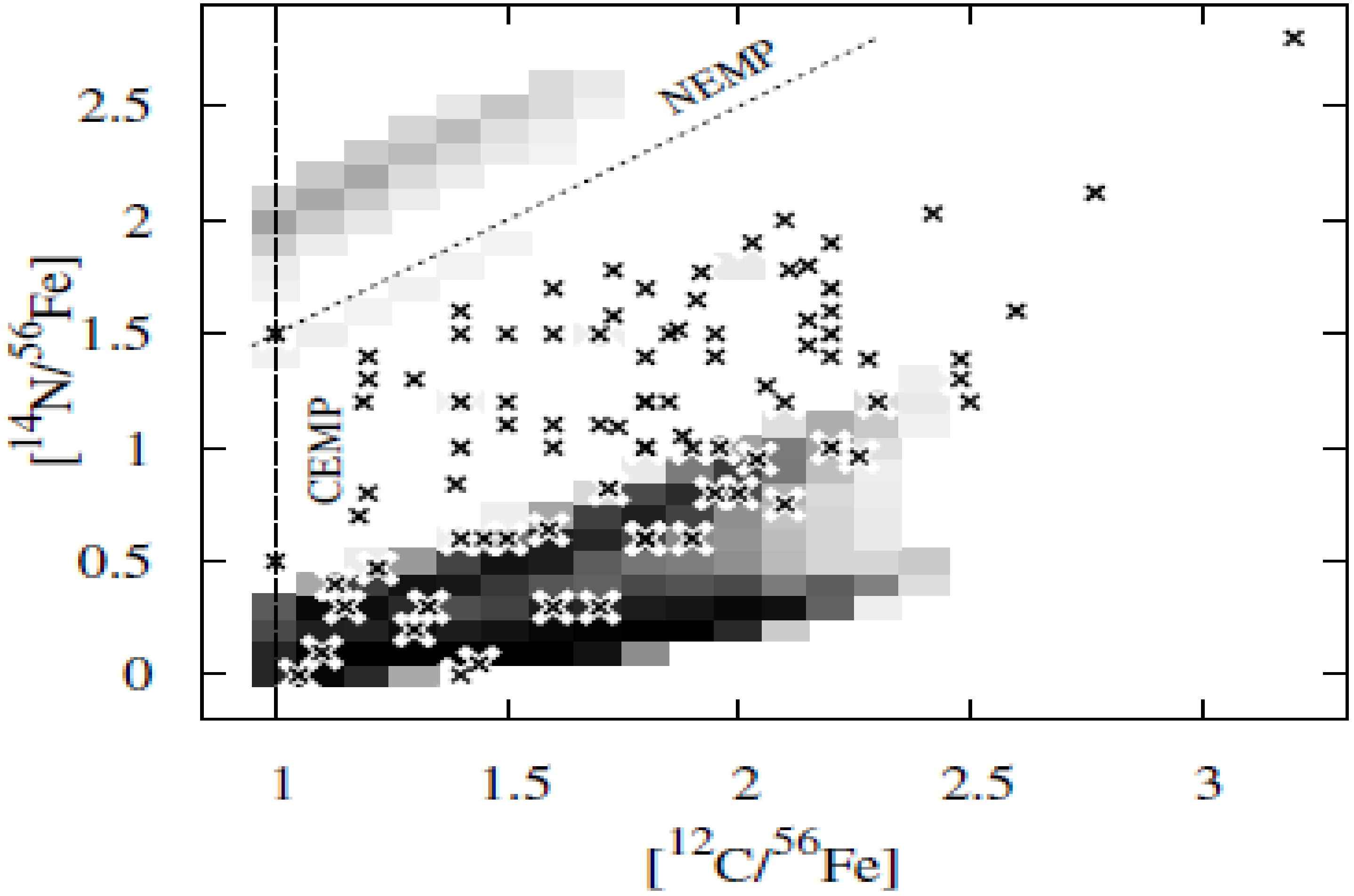
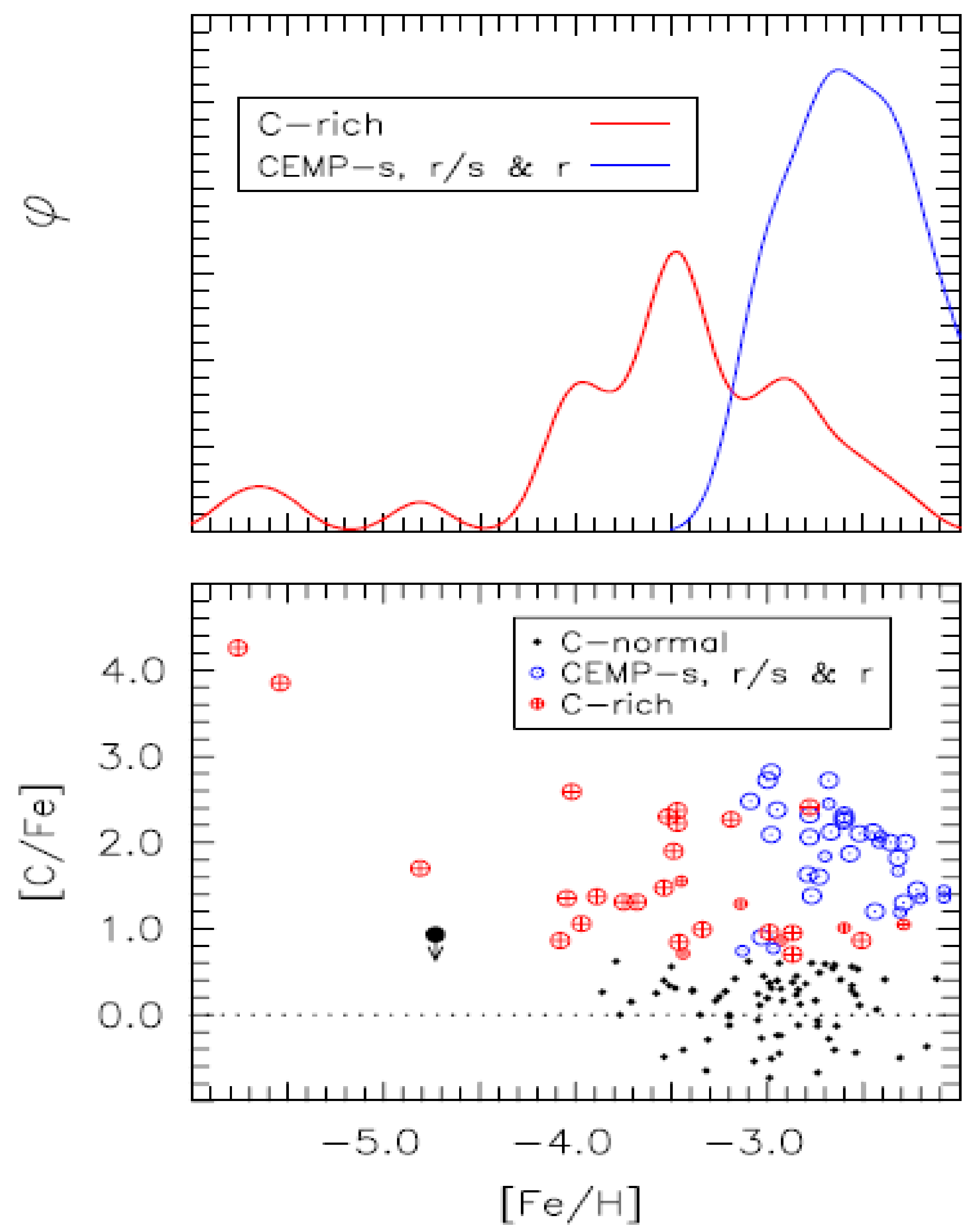


Fig. 8. The distribution of [N/Fe] versus [C/Fe] in our default CEMP population, model set *A* (darker grey indicates a larger density of stars). The vertical dashed line indicates our CEMP selection criterion ([C/Fe] ≥ 1) and the diagonal dashed line shows our NEMP selection criteria ([N/Fe] ≥ 1 and [N/C] > 0.5). Observed CEMP stars are indicated by crosses.

Izzard et al 2009, A&A , 508,1359



Norris et al 2013
ApJ, 762, 28

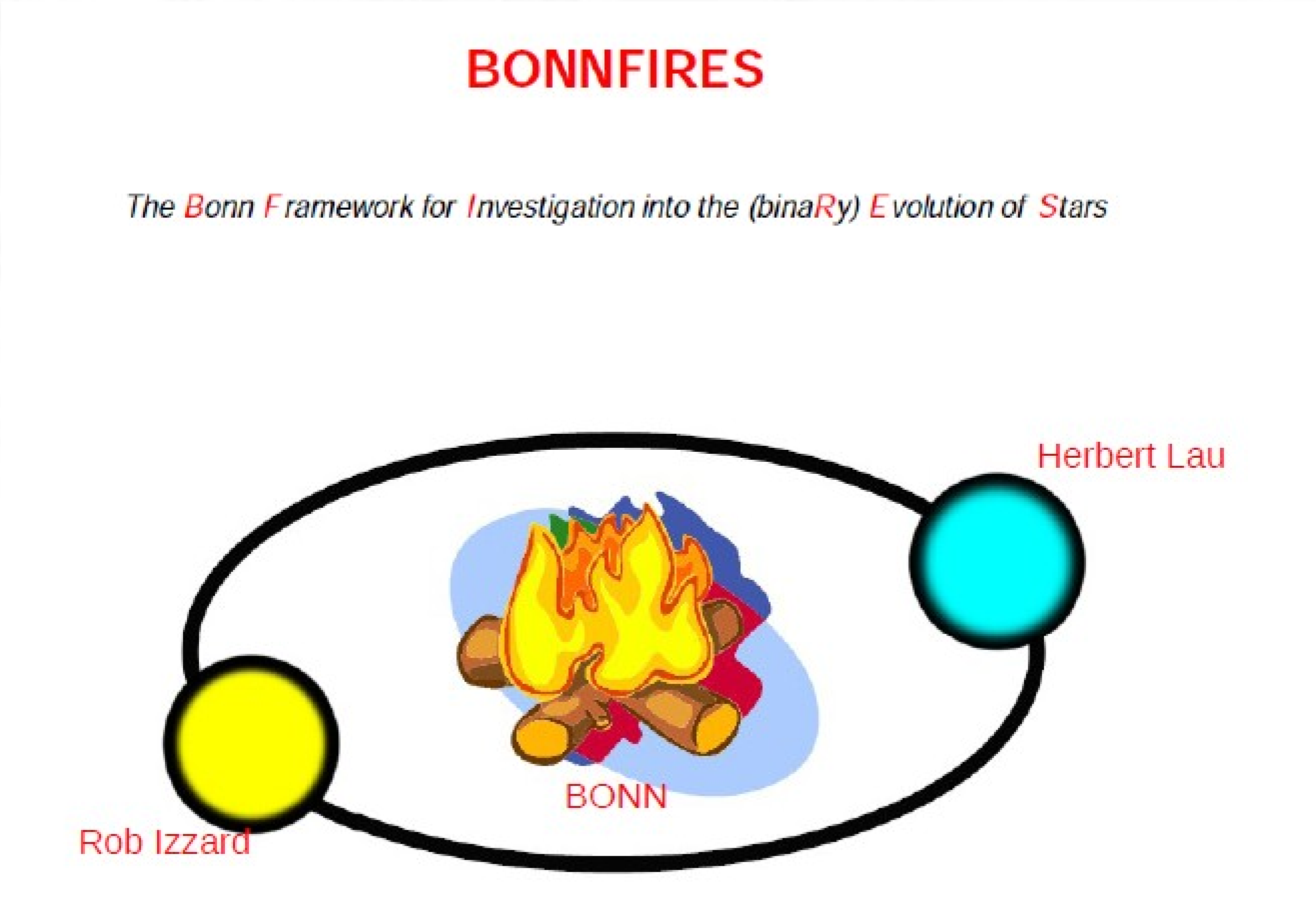
:

- The C/N abundances don't match.
  Lack of nitrogen-enhanced stars.
- Lack of s-process CEMP extremely metal-poor stars observed can tell use either
  1) formation channel changed
  2) AGB behaviour changed below critical metallicity
- Mergers may also form some CEMP stars
  Particular those that has no indication of companion.

Key Points

- Observed abundances of low mass star companion gives us hints of the primary companion
- Caveat: lots of uncertainties in both binary and single stars physics...

THANK YOU



BONNFIRES

The Bonn Framework for Investigation into the (binaRy) Evolution of Stars