Formation and Evolution of Massive Stars: Current Surveys

Alex de Koter
University of Amsterdam & KU Leuven

ASTRONOMICAL INSTITUTE
ANTON PANNEKOEK

Importance of MOS studies

Large sample size

➔ statistical tests

Homogeneous data set & simple selection criteria

➔ homogeneous analysis

➔ control of biases

Potential for serendipitous discoveries

Brings together different fields of astrophysics

Take away

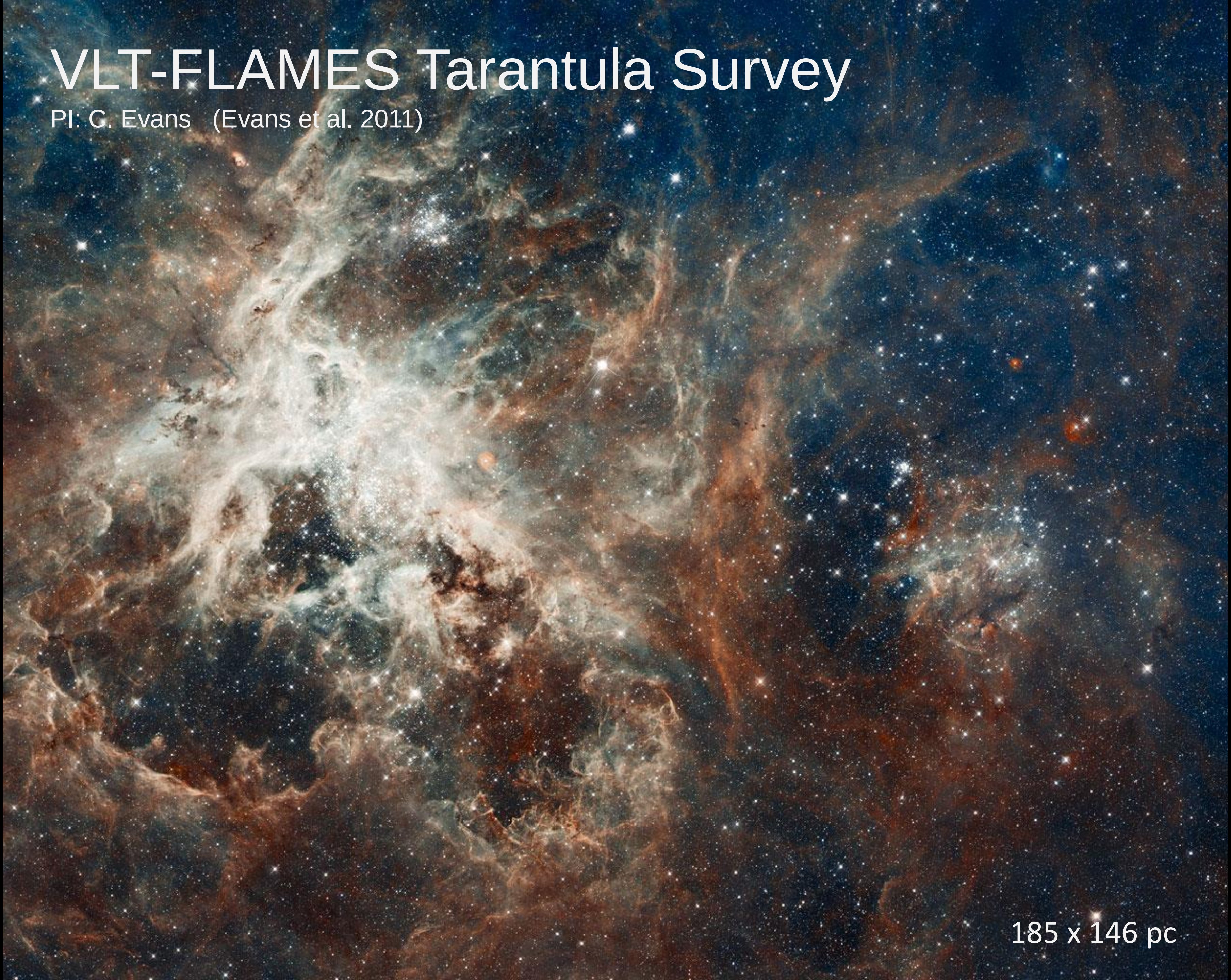
Probably all massive stars are formed as multiples…

… most of them have orbits so close that interaction will occur at some point during evolution…

… leading to a merger of the two stars for a sizable fraction of the systems

VLT-FLAMES Tarantula Survey

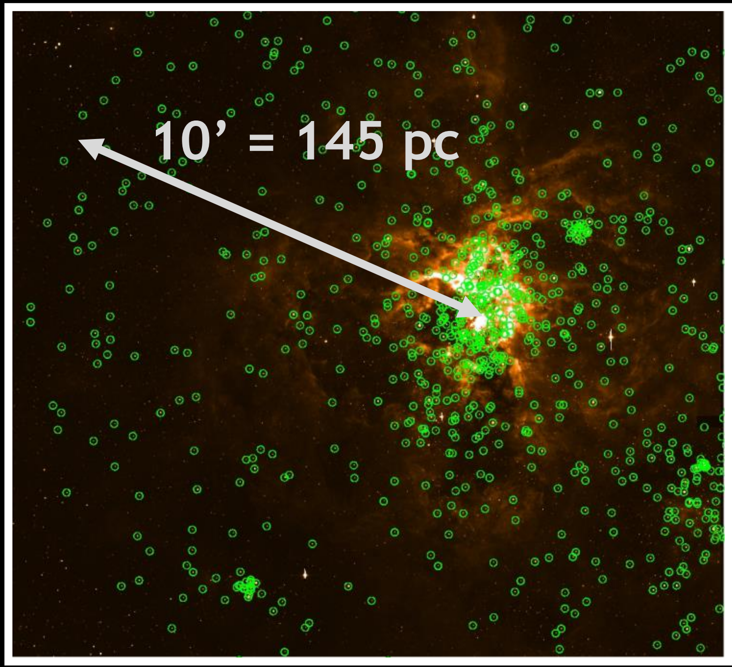
PI: C. Evans (Evans et al. 2011)



VLT-FLAMES Tarantula Survey

PI: C. Evans (Evans et al. 2011)

- Multi-epoch spectroscopy of over 800 massive stars in 30 Doradus
- FLAMES: 132 MEDUSA fibers feed the Giraffe spectrometer
- No colour cut
- V < 17 mag
- 15" (4 pc) exclusion radius in core for fibers
- 6 to 8 epochs
- 22,000 spectra



VLT-FLAMES Tarantula Survey

PI: C. Evans (Evans et al. 2011)

One of largest concentrations of massive stars in Local Group

Bright H II regions with rich set of populations

Closest unobscured view of young starsburst

Template to understand distant star-forming galaxies

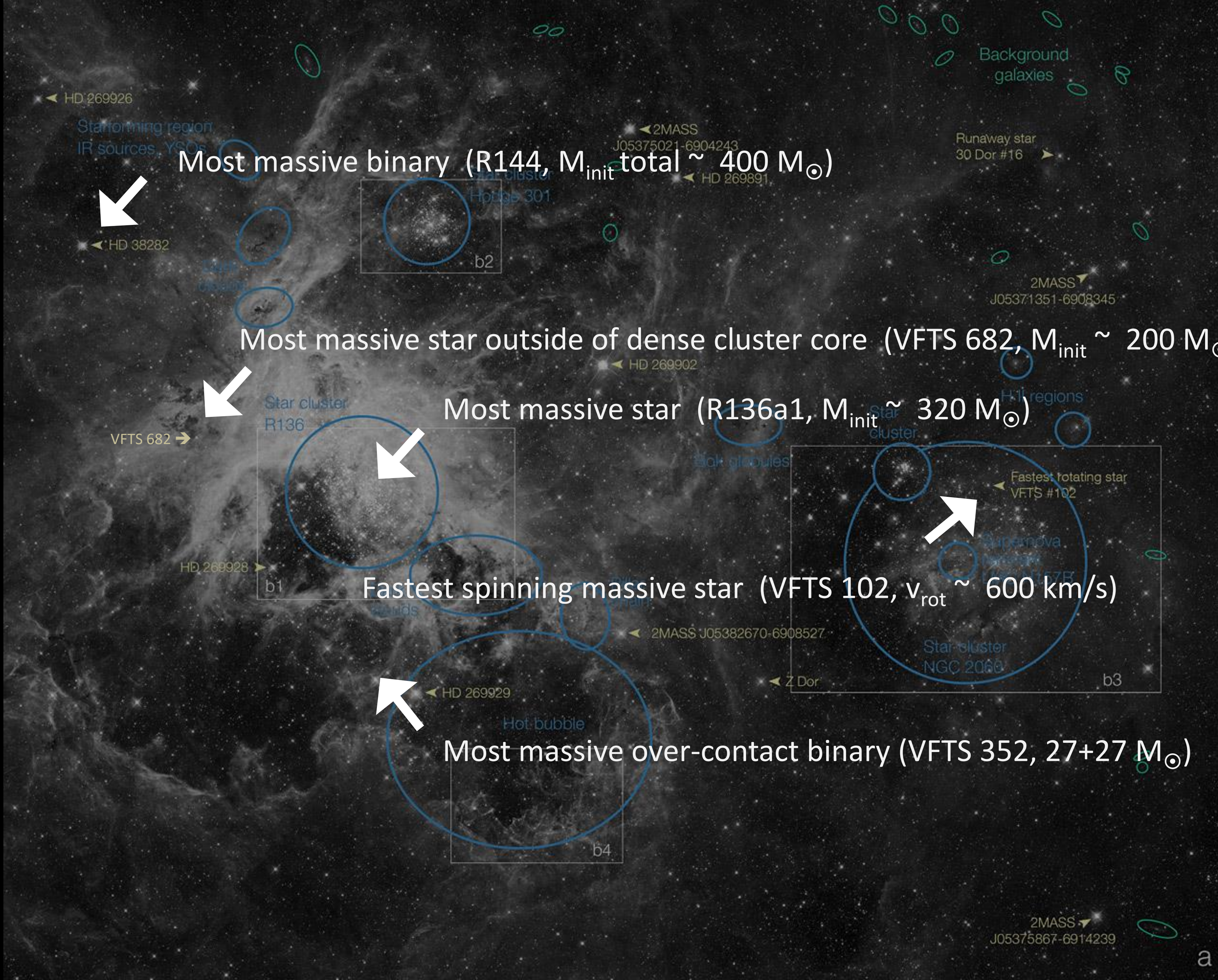
Scientific goals:

Role of stellar spin, mass loss, overshooting & multiplicity in evolution

Census of the nearest young starburst

Starformation history of the region

Dynamics of the region


Most massive binary (R144, M_{init} total ~ 400 $M_{\odot}$)
Most massive star outside of dense cluster core (VFTS 682, M_{init} ~ 200 $M_{\odot}$)
Most massive star (R136a1, M_{init} ~ 320 $M_{\odot}$)
Fastest spinning massive star (VFTS 102, v_{rot} ~ 600 km/s)
Most massive over-contact binary (VFTS 352, 27+27 $M_{\odot}$)
HD 269926
HD 38282
VFTS 682
HD 269928
2MASS J05375021-6904243
HD 269891
HD 269902
Background galaxies
Runaway star 30 Dor #16
2MASS J05371351-6908345
Star cluster R136
Fastest rotating star VFTS #102
2MASS J05382670-6908527
Z Dor
HD 269929
Hot bubble
Star cluster NGC 2060
2MASS J05375867-6914239
b1
b2
b3
b4
a

VLT-FLAMES Tarantula Survey

PI: C. Evans

Main catalogues

1. Observing campaign and YSOs (Evans+2011)
2. Spectral typing & special categories (Walborn+2014)

Individual objects

3. VFTS 016: most massive runaway star (Evans+2010)
4. R139: most massive evolved O-star pair (Taylor+2011)
4. VFTS 102: fastest spinning O star (Dufton+2011)
4. VFTS 698: peculiar B[e] supergiant (Dunstall+2012)
5. VFTS 682: a 150 $M_{\odot}$ star in appartent isolation (Bestenlehner+2011)
6. VFTS 822: candidate Herbig B[e] star (Kalari+2014)
7. VFTS 352: most massive overcontact binary (Almeida+ in prep)

Dynamics of the central region

10. Evidence for cluster rotation (Hénault-Brunet+ 2012a)
11. R136 is virialized (Hénault-Brunet+ 2012b)

Population properties

12-13. Spin of the single O & B stars (Dufton+ 2013, Ramírez-Agudelo+2013)

14. Spin of O star primaries (Ramírez-Agudelo+ in prep)

15-16. Multiplicity of the O & B stars (Sana+2013, Dunstall+ in prep)

17. Feedback (Doran+2013)

VLT-FLAMES Tarantula Survey

PI: C. Evans

Interstellar Medium

18. DIBs and S I (van Loon+2013)

19. Optical & NIR extinction law (Maíz Apellániz+2014)

Sub-populations

20. Isolated high-mass stars (Bressert+2011)

21. Wind properties at top of main sequence (Bestenlehner+2014)

22. Nature of O Vz stars (Sabín-Sanjulián+2014)

23-24. Properties of O stars (Sabín-Sanjulián+ in prep; Ramírez-Agudelo+ in prep)

25-26. Nitrogen abundances of O stars (Grin+ in prep., Sabín-Sanjulián+ in prep)

27. Classifications & RV of B stars (Evans+ 2-15)

28. Properties of B supergiants (McEvoy+ 2015)

Single & binary evolution

29. Bayesian tool for testing evolution (Schneider+ 2014)

30. Rotation of very massive stars (Köhler+ 2015)

31. Effects of binary interaction on rotation (de Mink+ 2013)

Westerlund 1

PI: J.S. Clark (Clark et al. 2005)

Westerlund 1

PI: J.S. Clark (Clark et al. 2005)

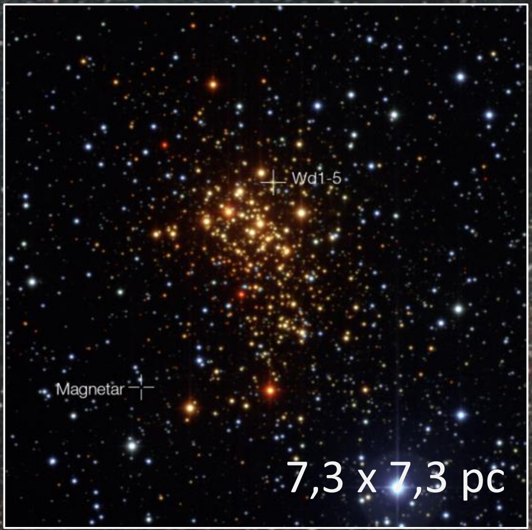
Formed in splendid isolation (unlike 30 Dor)

Near instantaneous starburst (unlike 30 Dor)

Cluster core easily probed (unlike 30 Dor)

Unprecedented cohort of Yellow Hypergiants & Red Supergiants (unlike 30 Dor)

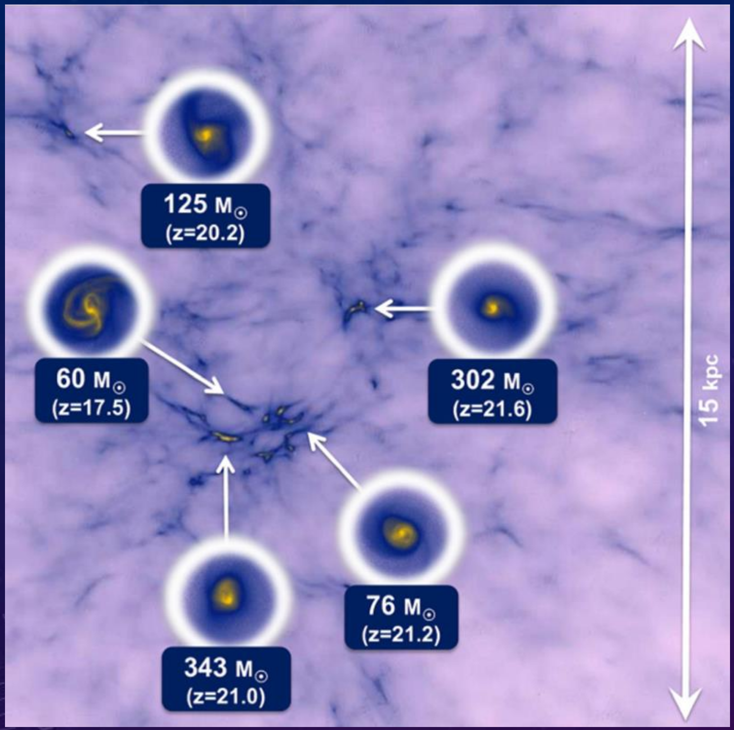
Formation of a proto-globular cluster in the Local Universe (unlike 30 Dor)



175 x 135 pc

Bigger context of Massive Stars

First Stars



Hirano et al. 2014,
primoridal star formation in cosmological context

Thought to have been massive (10-1000 $M_\odot$)

Radiation feedback of Lyman (H ionizing) and Lyman-Werner (H_2 dissociation) fotons

Chemical feedback

Production of up to ~10^2 $M_\odot$ black holes

Role in (delaying) galaxy formation

Bigger context of Massive Stars

End products

SNe progenitors

Distribution of final products

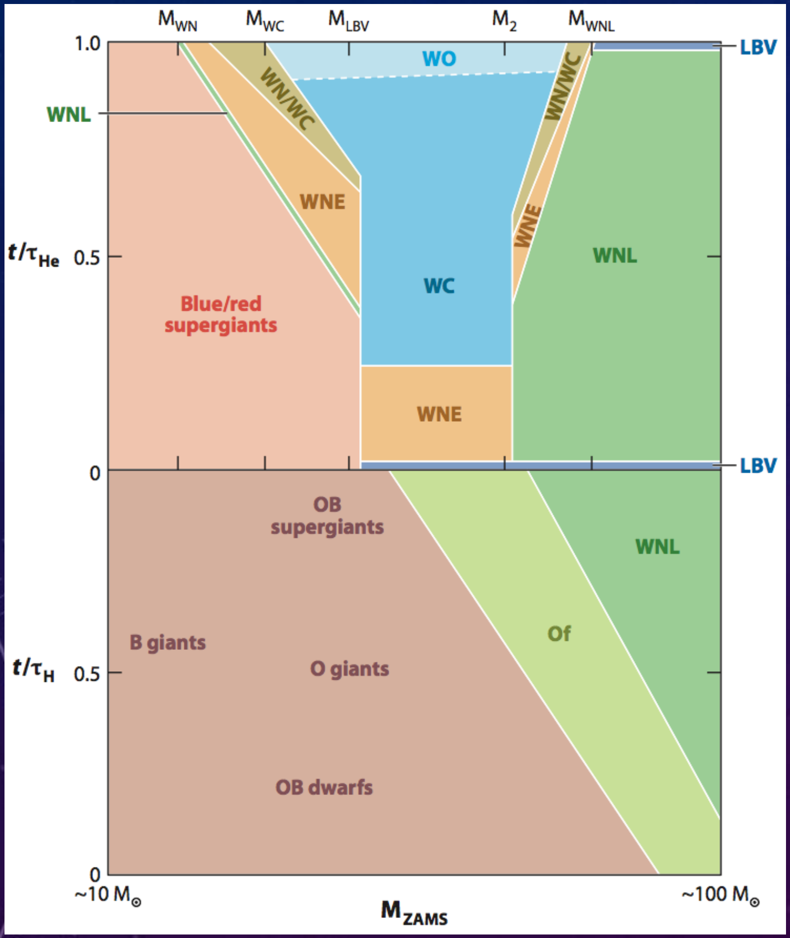
ccSNe types / GRBs and NSs & BHs

Feedback & dust formation

ccSNe delay-time distribution

Bigger context of Massive Stars

End products



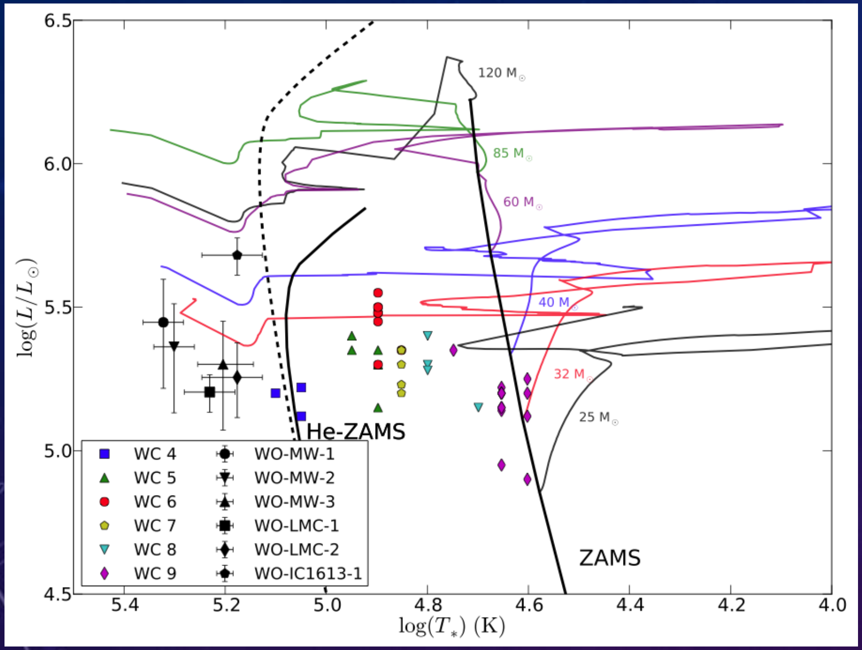
Langer 2012

SNe progenitors

Bigger context of Massive Stars

End products

SNe progenitors

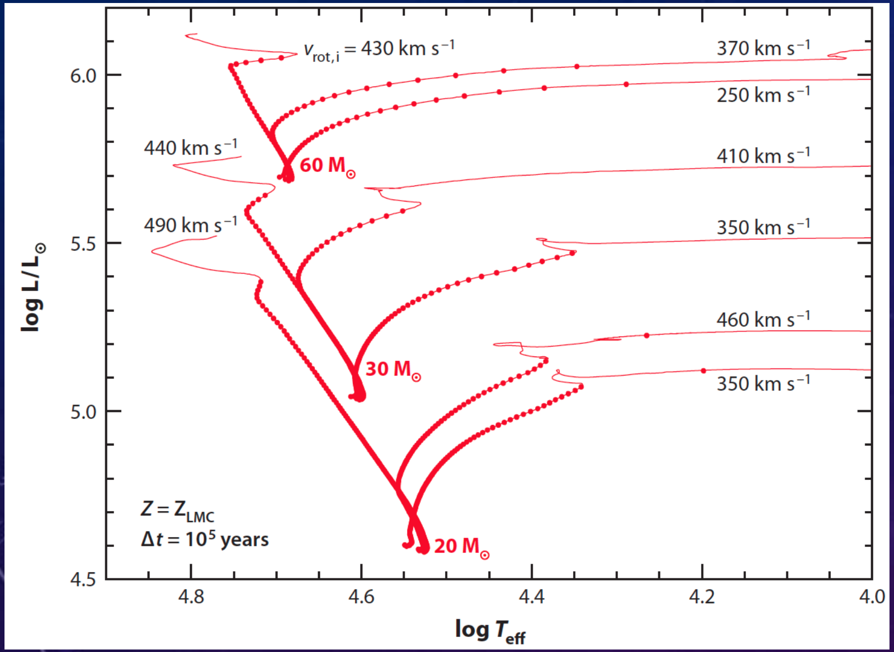


Tramper et al. 2015 (submitted)

"WO stars (M_{init} ~ 40-60 $M_\odot$) … are post core-helium burning and predicted to explode as type Ic supernovae within <u>a few thousand years</u>."

Bigger context of Massive Stars

End products

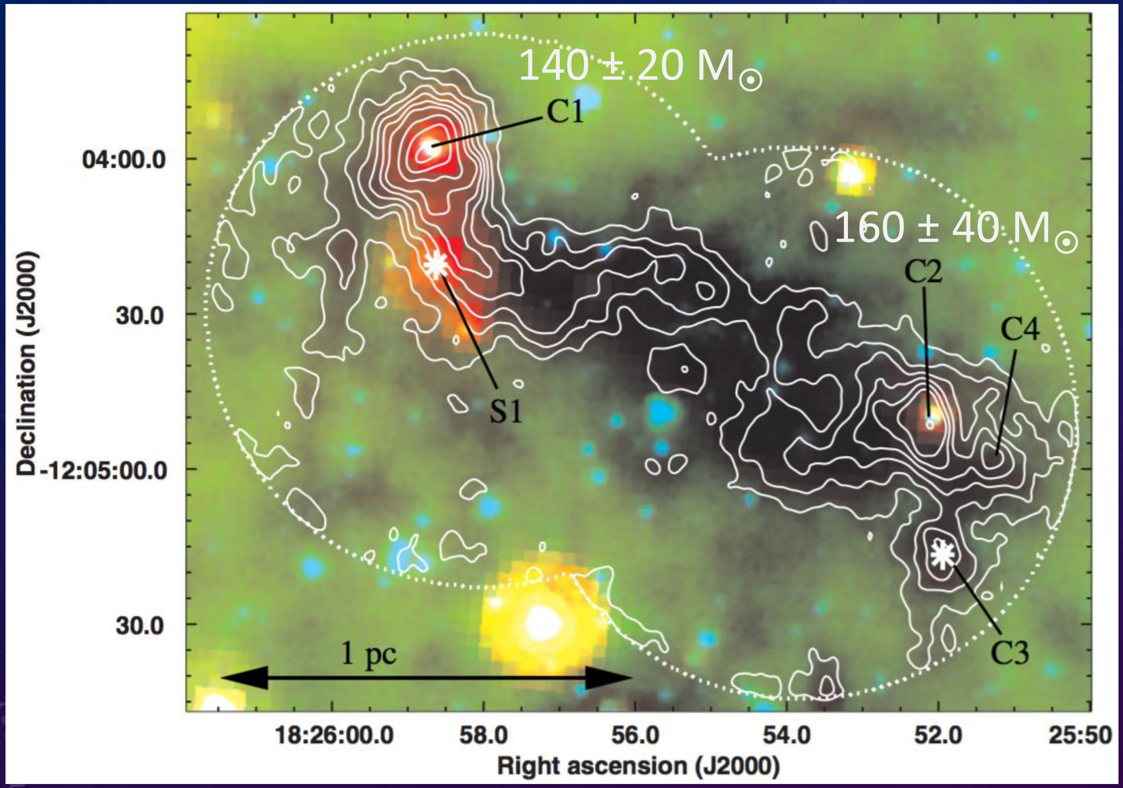


Brott et al. 2011

Distribution of final products
ccSNe types / GRBs

Bigger context of Massive Stars

Formation

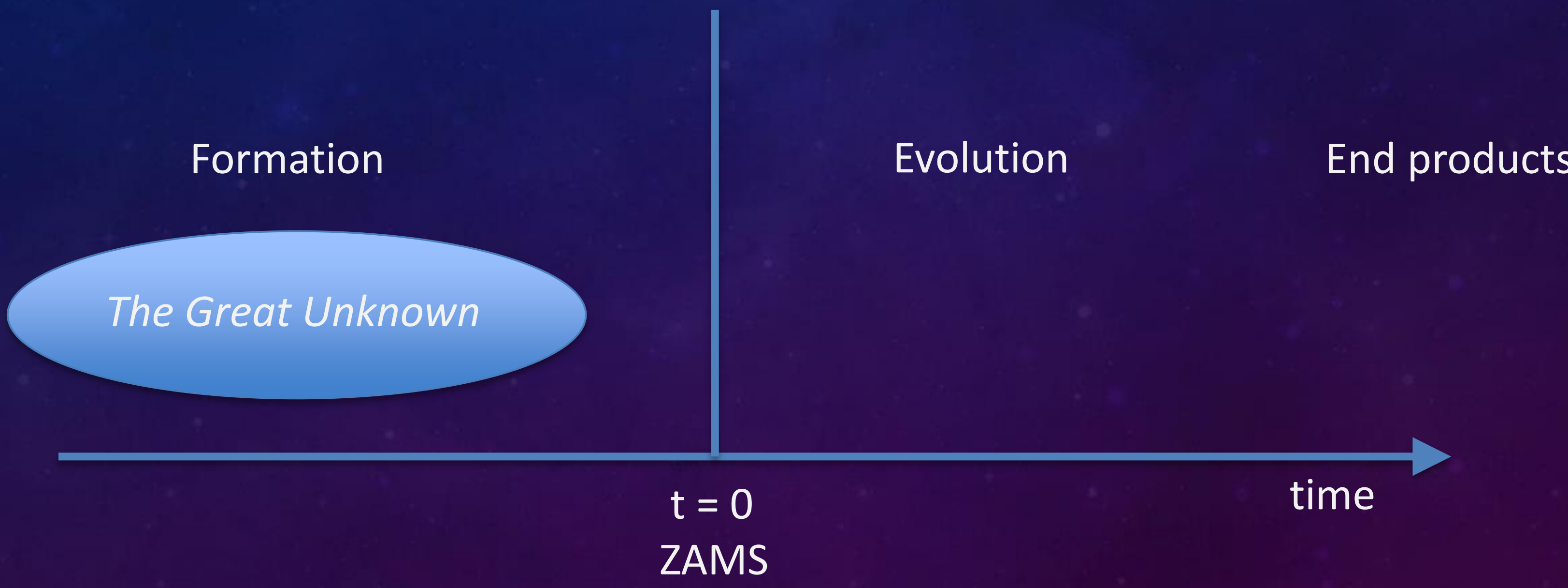


Dark Cloud G19.30+0.07 (VLA)
Devine et al. 2011.

Formation of Massive Stars

Outcome of Formation

- IMF
- Multiplicity properties
- Spin distribution
- Magnetic field distribution

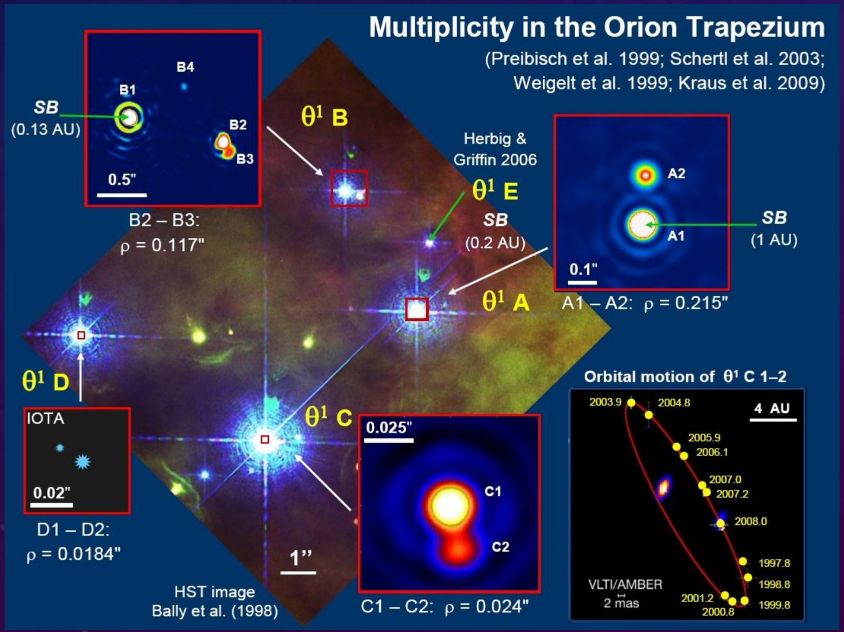


Outcome of Formation:

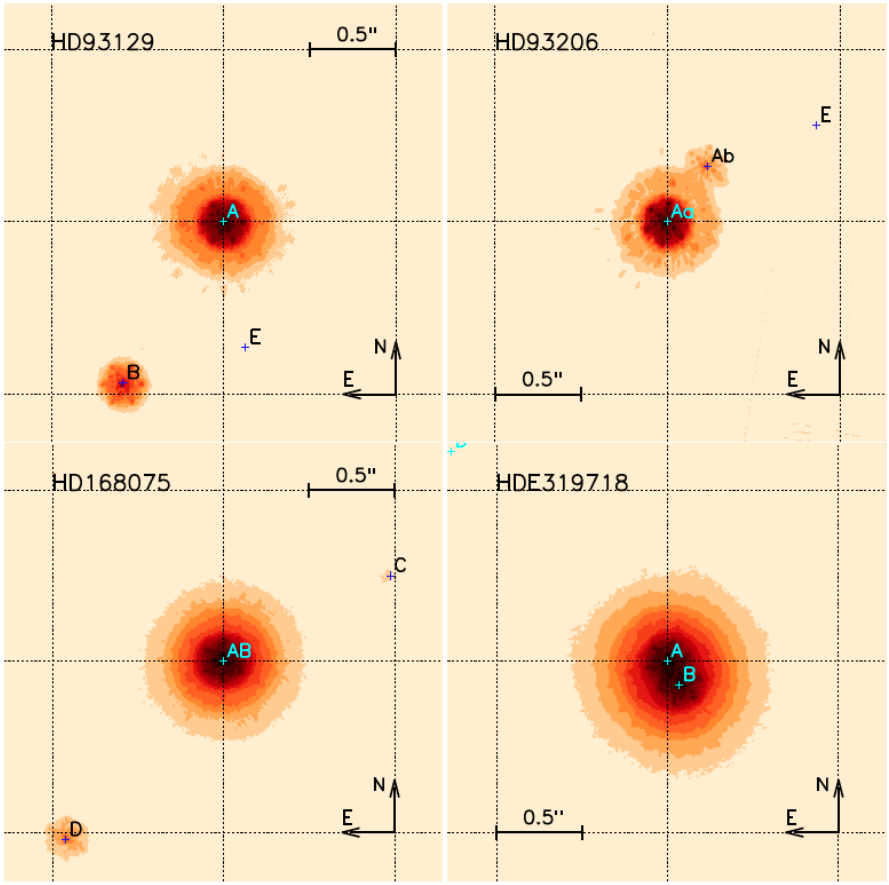
Multiplicity properties of O-type stars ($M_{init} \geq 15\ M_{\odot}$)

75% of O-type stars in clusters and associations have at least one companion
Mason et al. 2009

All 5 bright Orion Trapezium Cluster stars (A through E) are multiples
Preibisch et al. 1999, Schertl et al. 2003, Weigelt et al. 1999, Kraus et al. 2009



Southern Massive Stars at High Angular Resolution (SMASH+)



Sana et al. 2014

Interferometric survey of Galactic O-stars to systematically explore the separation range between 1-200 mas

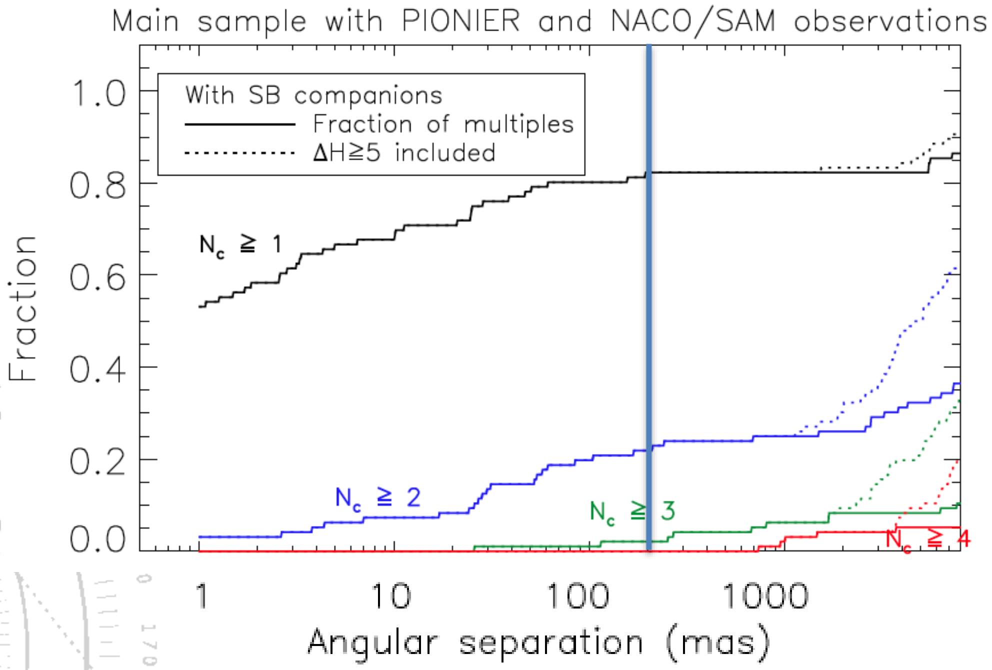
Adaptive optics
    250-8000 mas (NACO FOV)
Aperture masking
    30-250 mas (NACO/SAM)
Long-baseline interferometry
    1-45 mas (PIONIER)

Magnitude limited sample (H < 7.5) of 174 southern targets;
117 with PIONIER; 162 with NACO

196 newly resolved companions

Multiplicity properties of the sample

All luminosity classes



Sana et al. 2014

Take away

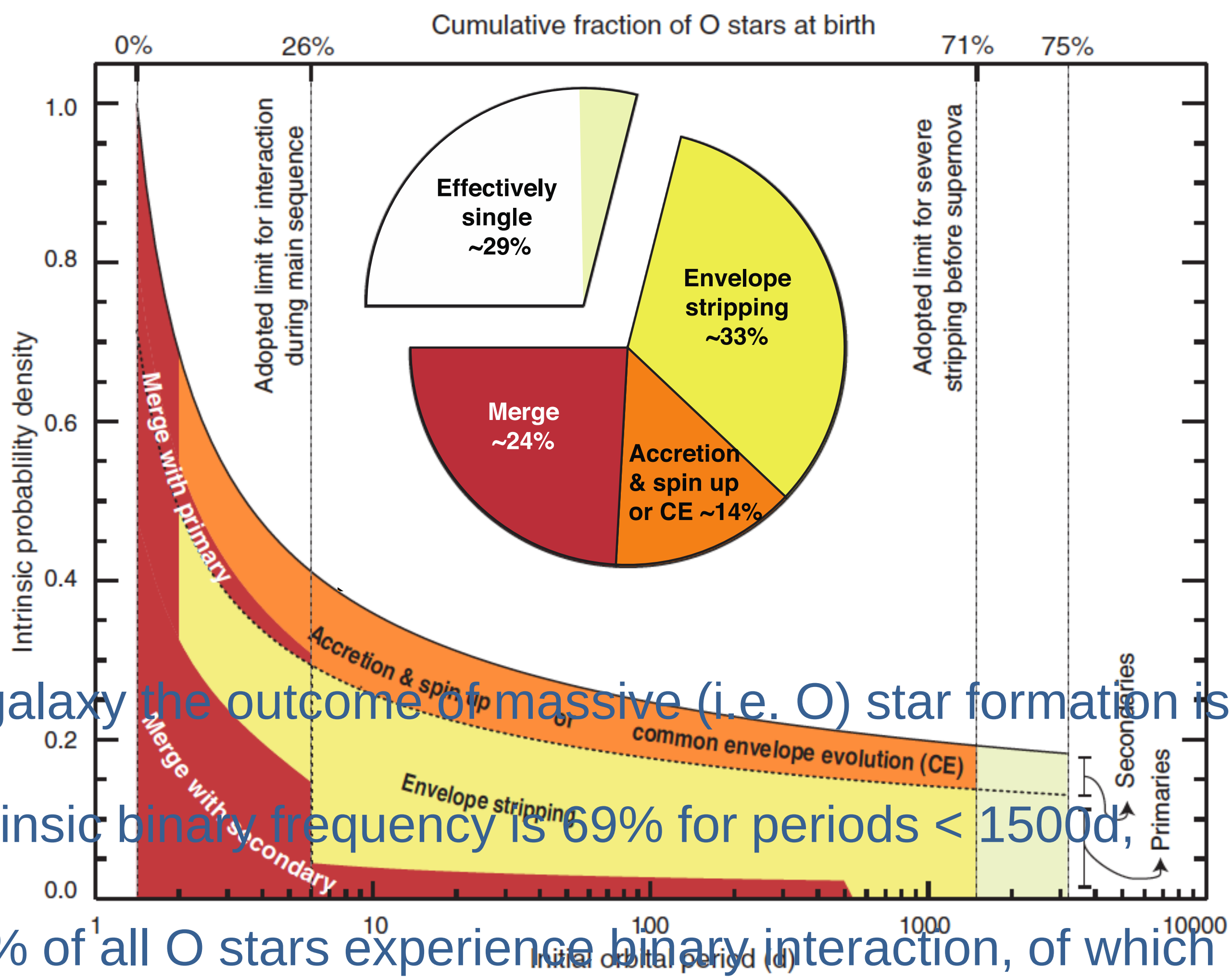
Multiplicity properties place constraints on formation scenario

Krumholtz (2014):

"Accretion-based models predict … massive stars are … very likely to have low-mass companions at seperations of ~ 100-1000 AU."

"The authors of collisional models have not thus far published detailed predictions for massive binary properties, but … its seems likely that the dense dynamical environment required for collisions would strip any low-mass distant companions from massive stars."

Binaries show a strong preference for close pairs



In our galaxy the outcome of massive (i.e. O) star formation is such that

- Intrinsic binary frequency is 69% for periods < 1500d,
- 71% of all O stars experience binary interaction, of which 24% merge, being mostly in systems with periods initially < 6d

Sana et al. 2012

Take away

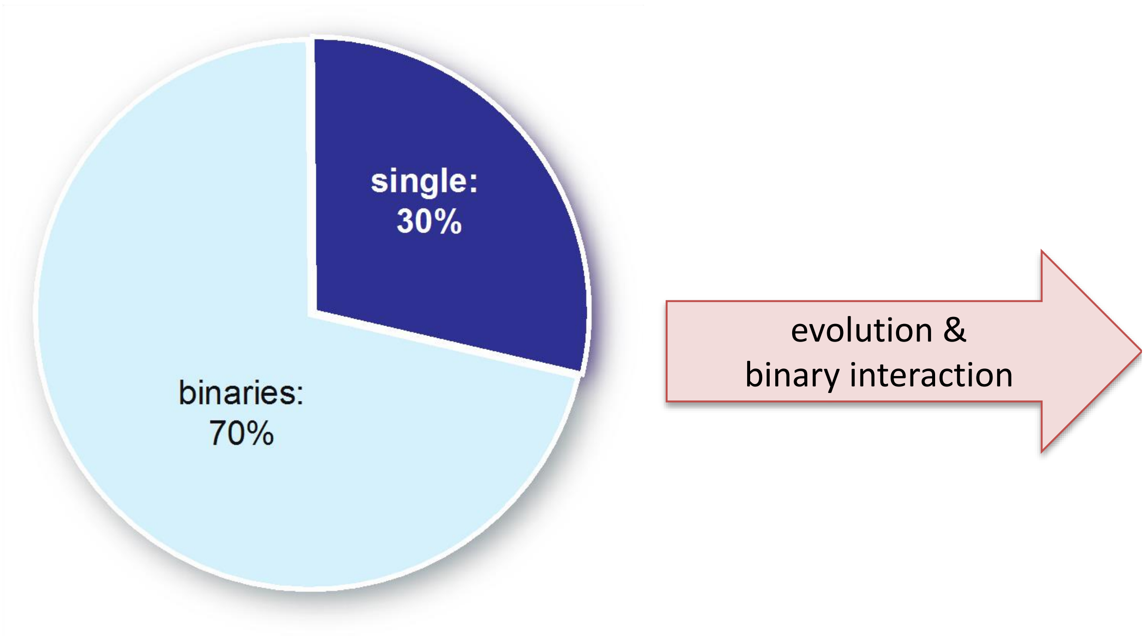
If one thinks one observes a single O star …

… it actually means that either …

… one has not looked hard enough for companions …

… or it used to be a binary …

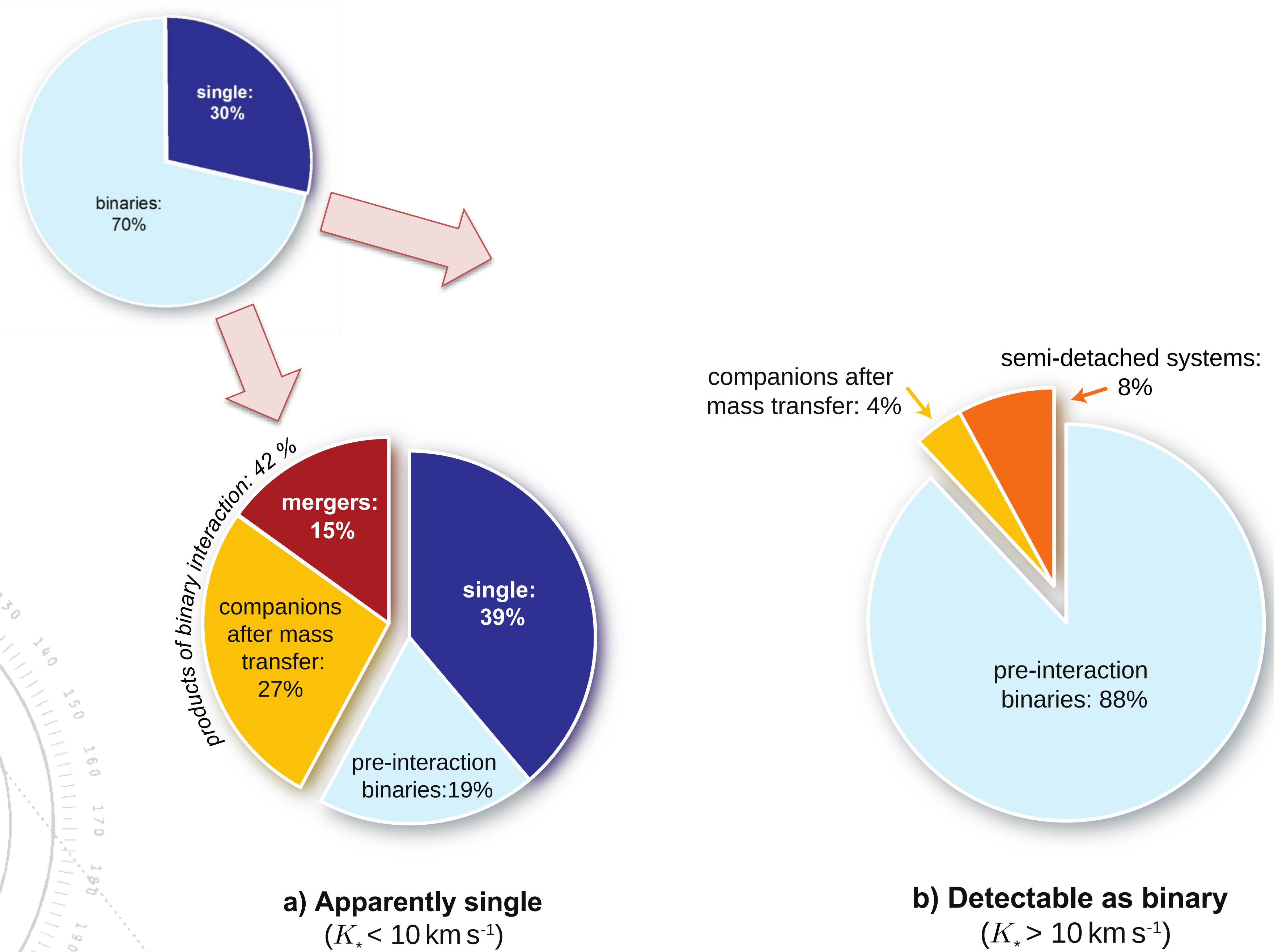
Incidence of binary products



Conditions at birth

Assuming continuous star formation

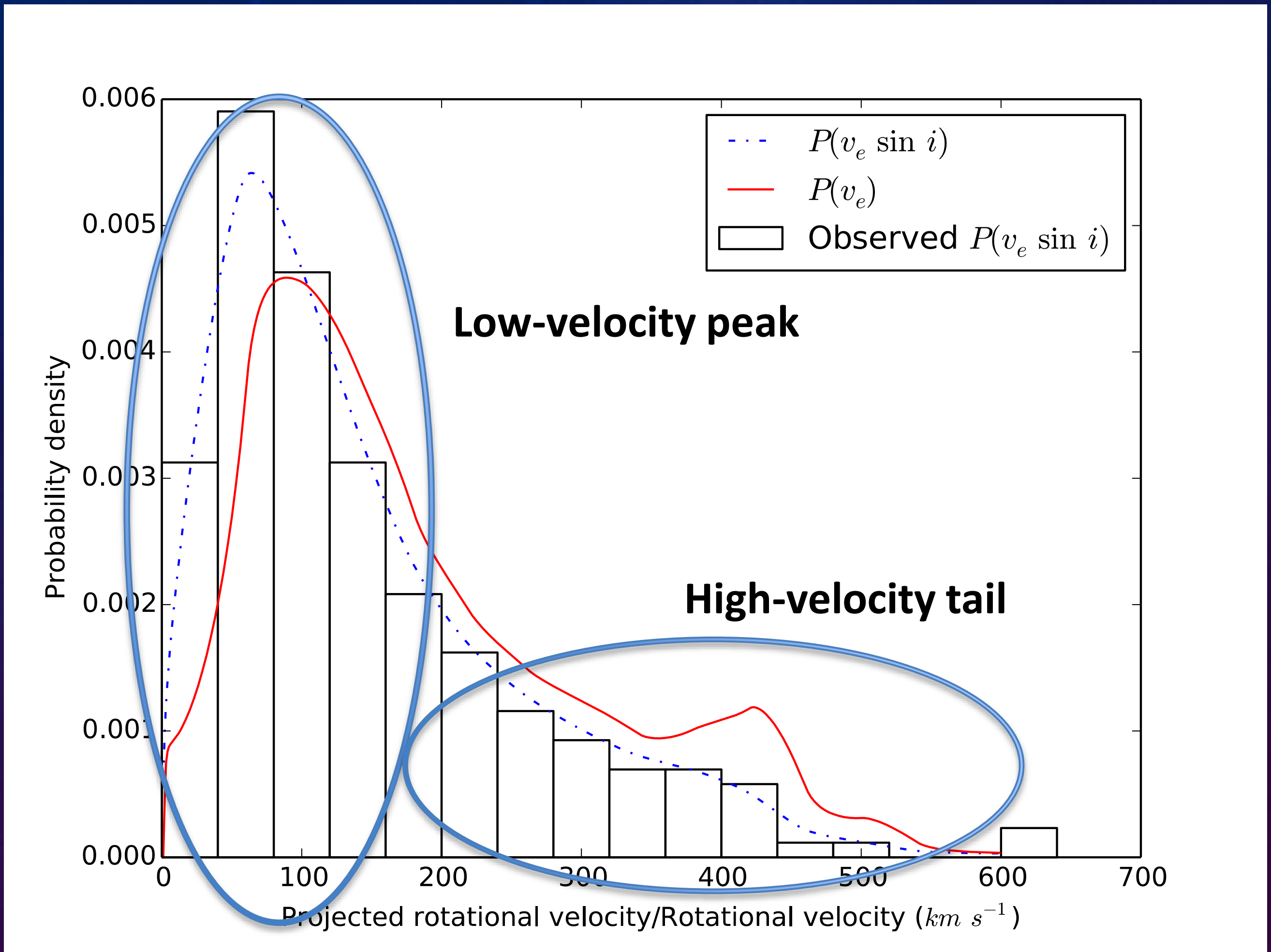
De Mink et al. (2014)



De Mink et al. (2014)

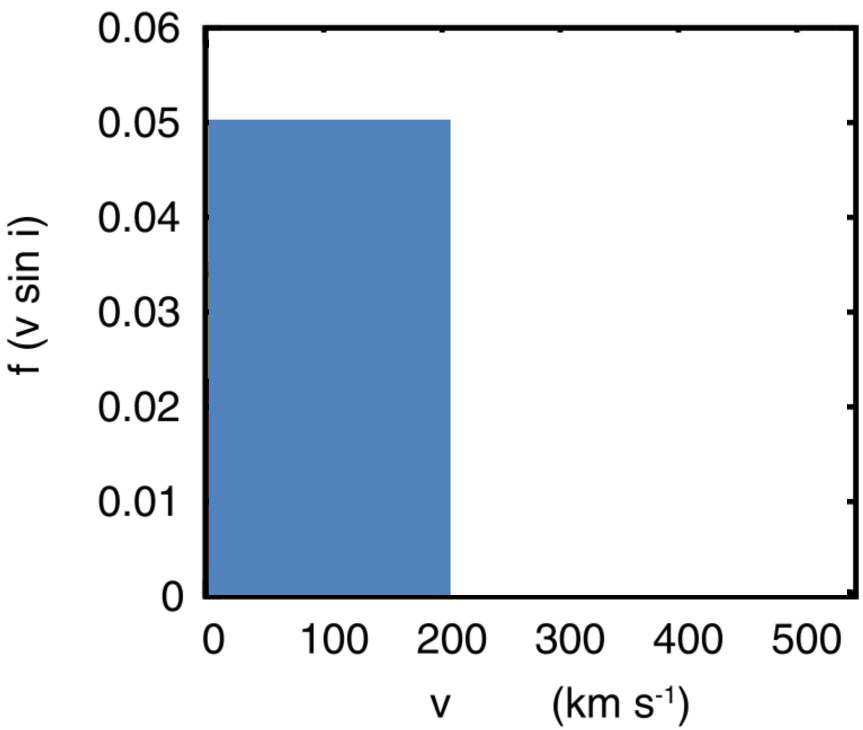
Outcome of Formation:

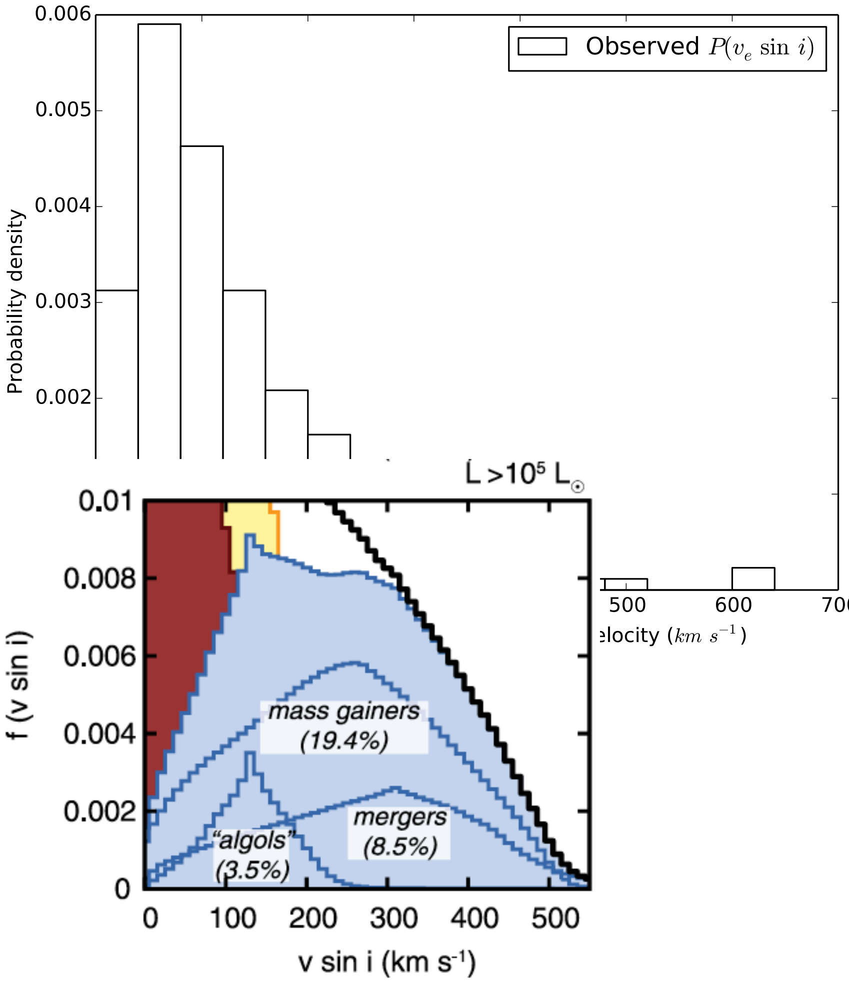
Spin properties of presumed single O-type stars



Ramírez-Agudelo et al. 2013

Impact of binarity on the spin distribution





de Mink et al. 2013

Take away

Most O stars have v_{rot} < 200 km/sec

➔ impact of rotation on evolution is limited

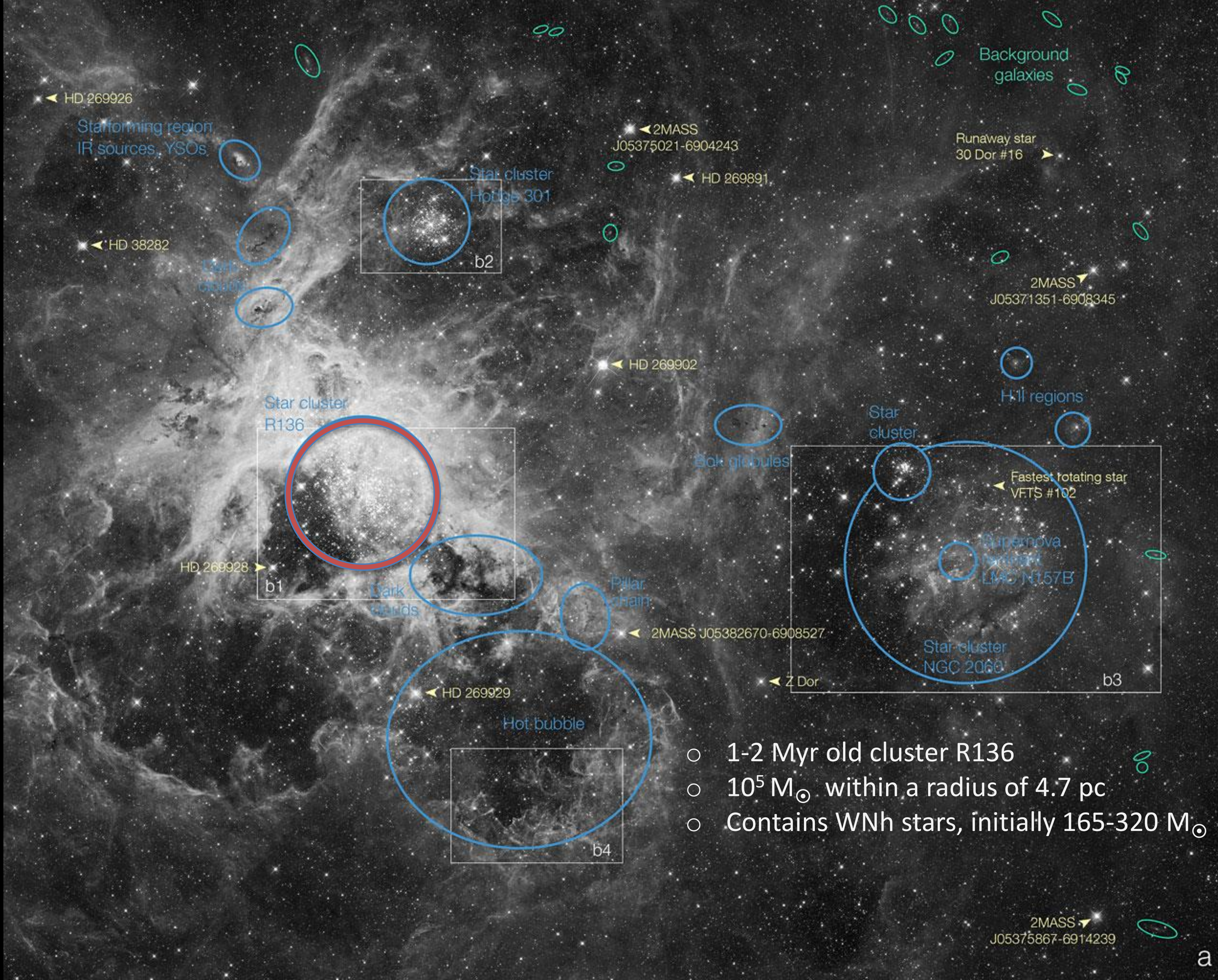
About 20% of O star population has v_{rot} > 200 km/sec

➔ Rotation needs to be taken into account

➔ Compatible with binary evolution simulation

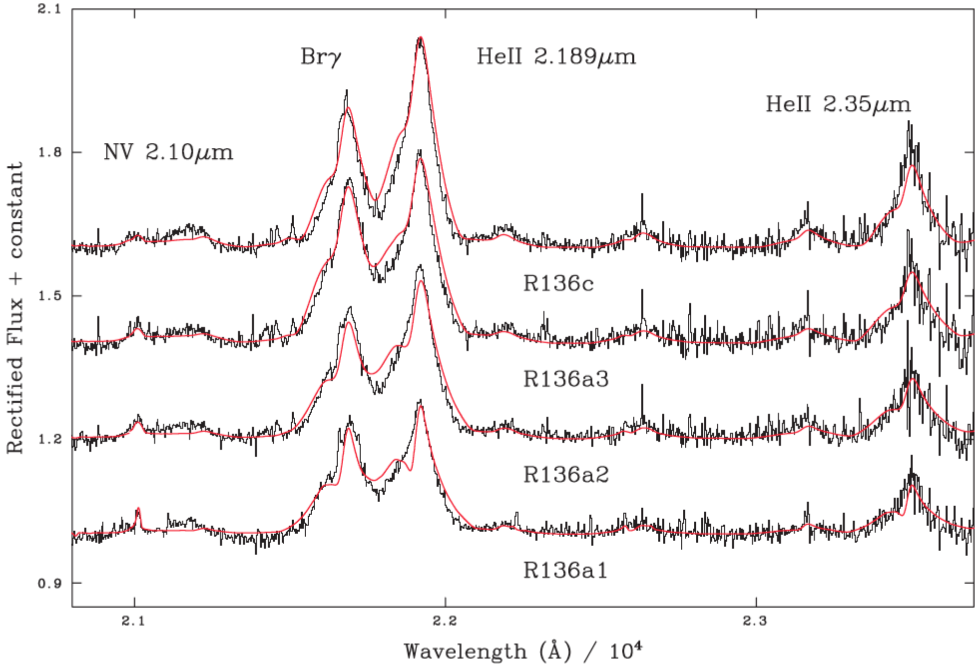
Do genuine single fast rotators exist?

➔ Do most/all GRB progenitor candidates have a binary past?

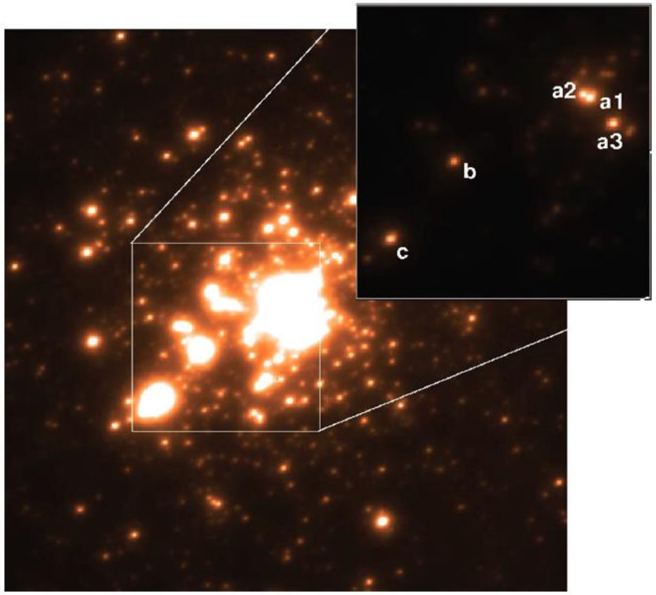


- 1-2 Myr old cluster R136
- $10^5\ M_\odot$ within a radius of 4.7 pc
- Contains WNh stars, initially 165-320 $M_\odot$

The most massive stars: WNh stars



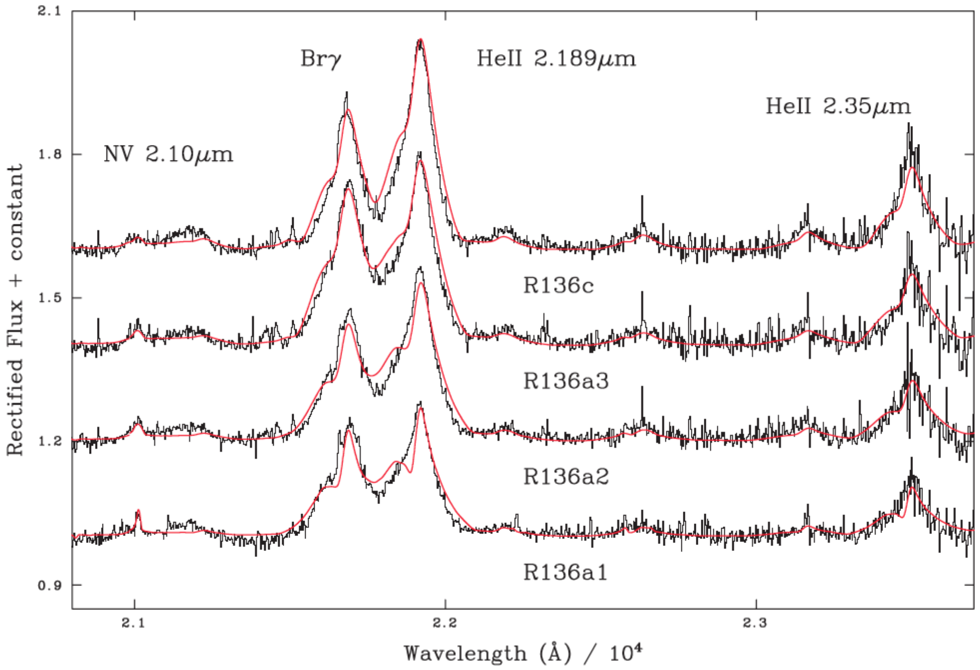
Crowther et al. 2010



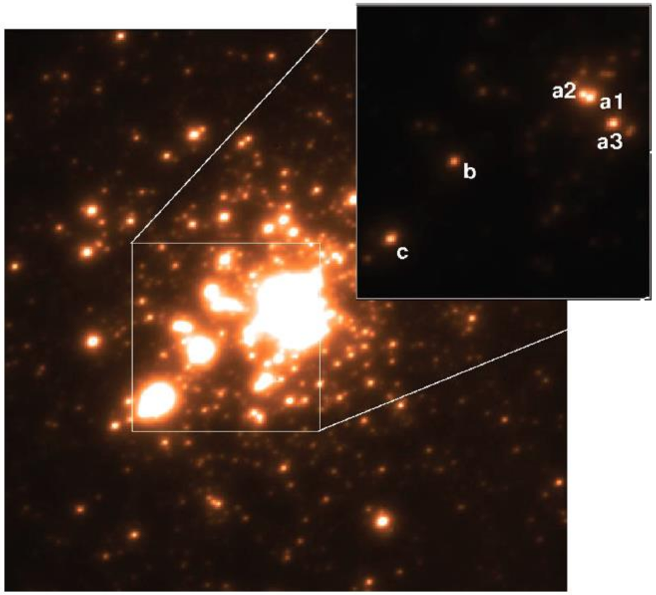
VLT MAD K image Campbell et al. 2010

- Exceptionally massive (a1, a2, a3) = (M_{init} ~ 320, 240, 165 $M_{\odot}$)

The most massive stars: WNh stars



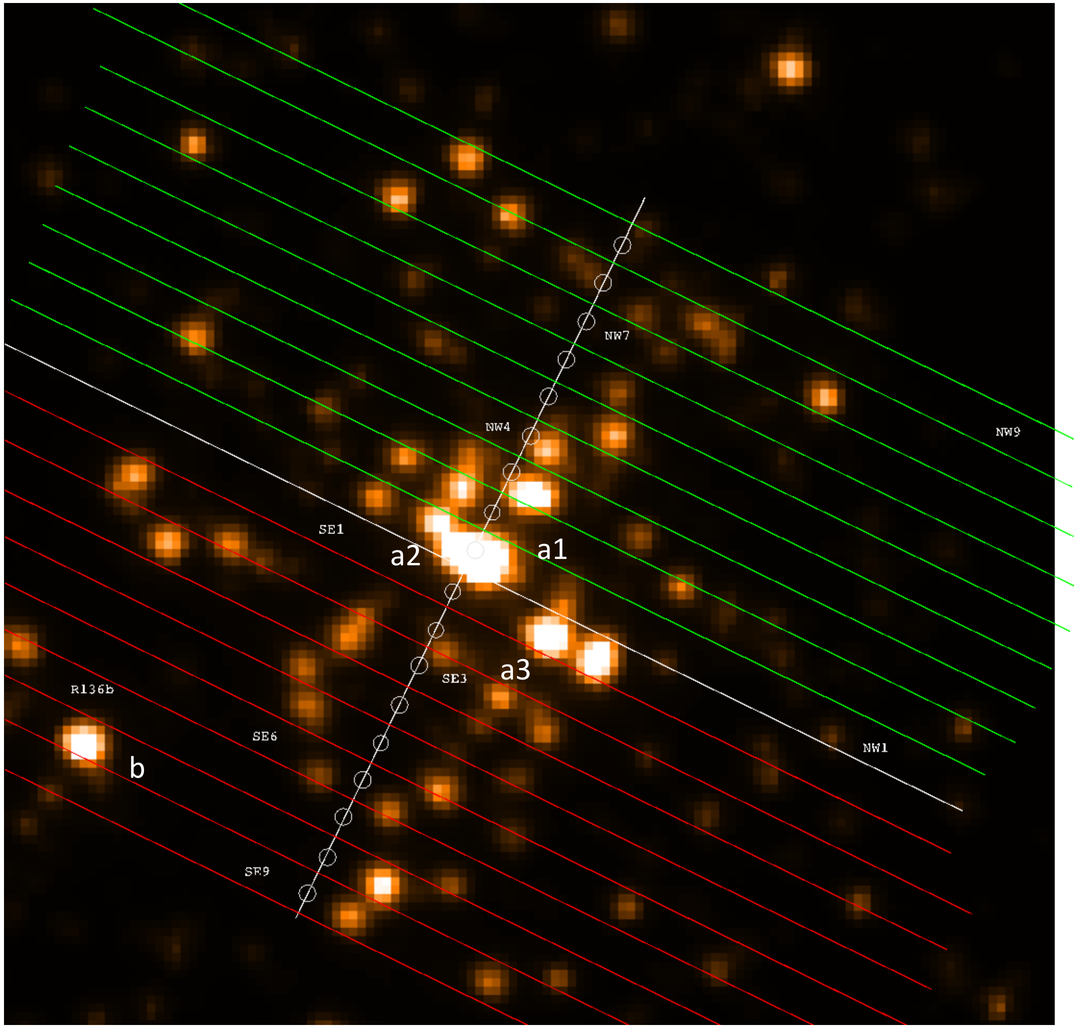
Crowther et al. 2010



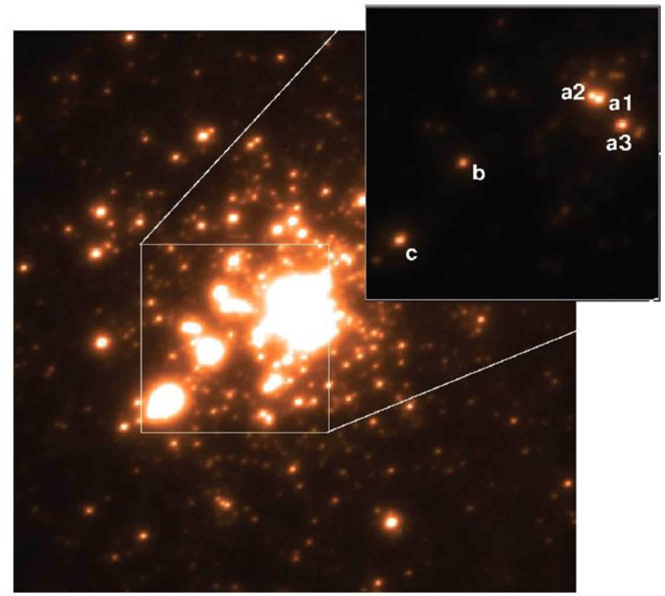
VLT MAD K image Campbell et al. 2010

- Exceptionally massive (a1, a2, a3) = (*log* $L/L_\odot$ ~ 6.94, 6.78, 6.58)

The most massive stars: WNh stars

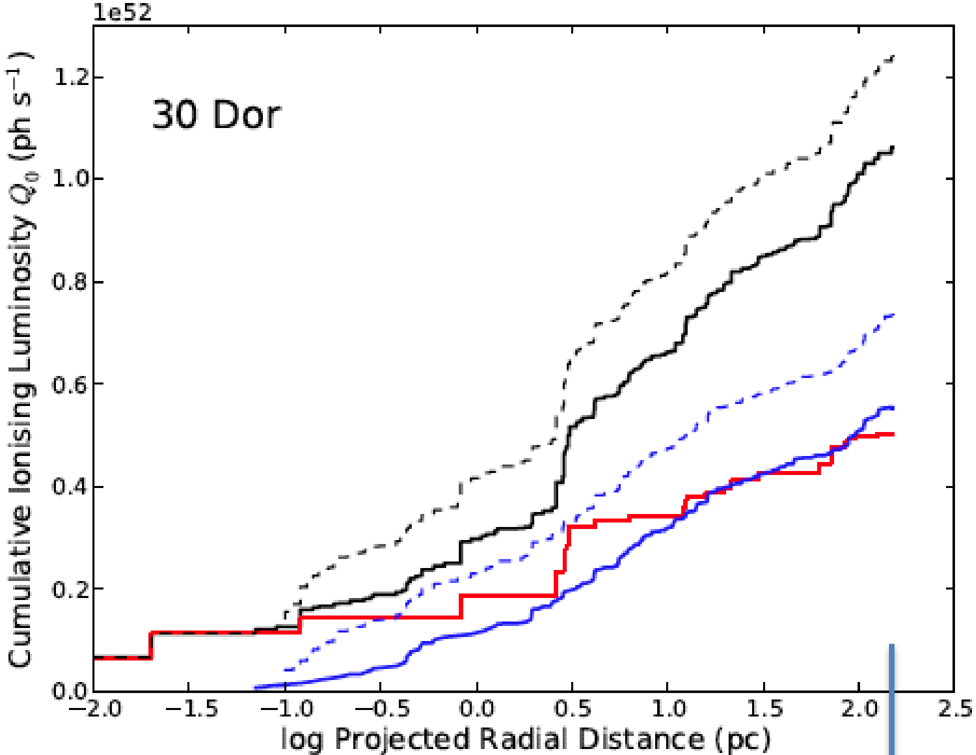


Cycle 19 STIS/HST programme (PI: P. Crowther)



VLT MAD K image Campbell et al. 2010

Ionizing energy output



Total

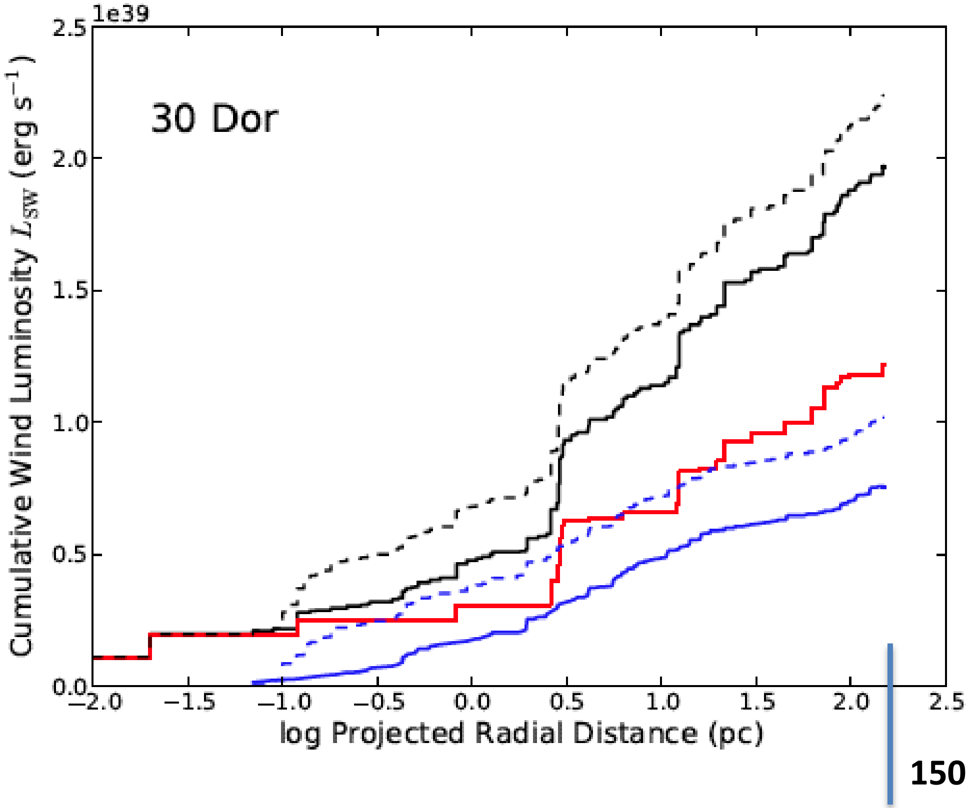
469 OB stars (~60%)

31 Wolf-Rayet + Of/WN stars (~40%)

150 pc

Doran et al. 2013

Kinetic energy output



Total

31 Wolf-Rayet + Of/WN stars (~50%)

469 OB stars (~50%)

Doran et al. 2013

Take away

Small set of Wolf-Rayet & Of/WN stars account for ~half the ionizing flux and wind kinetic energy

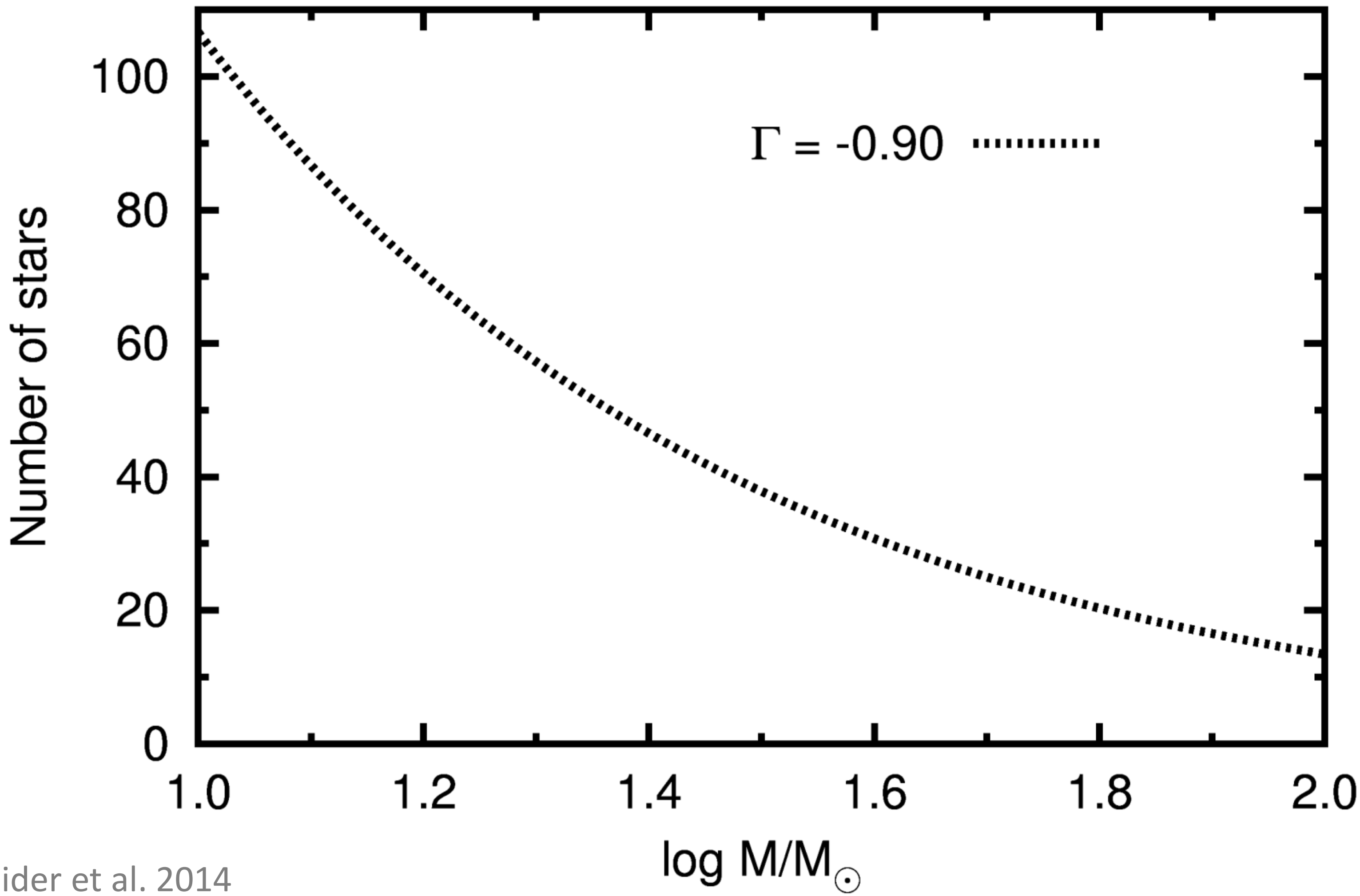
Stars >100 $M_{\odot}$ account for ~25% of each, but not taken into account in population synthesis models (Starburst99)

Effects of binary interaction may become visible in other ways…

… they may affect the mass function

The initial mass function (IMF)

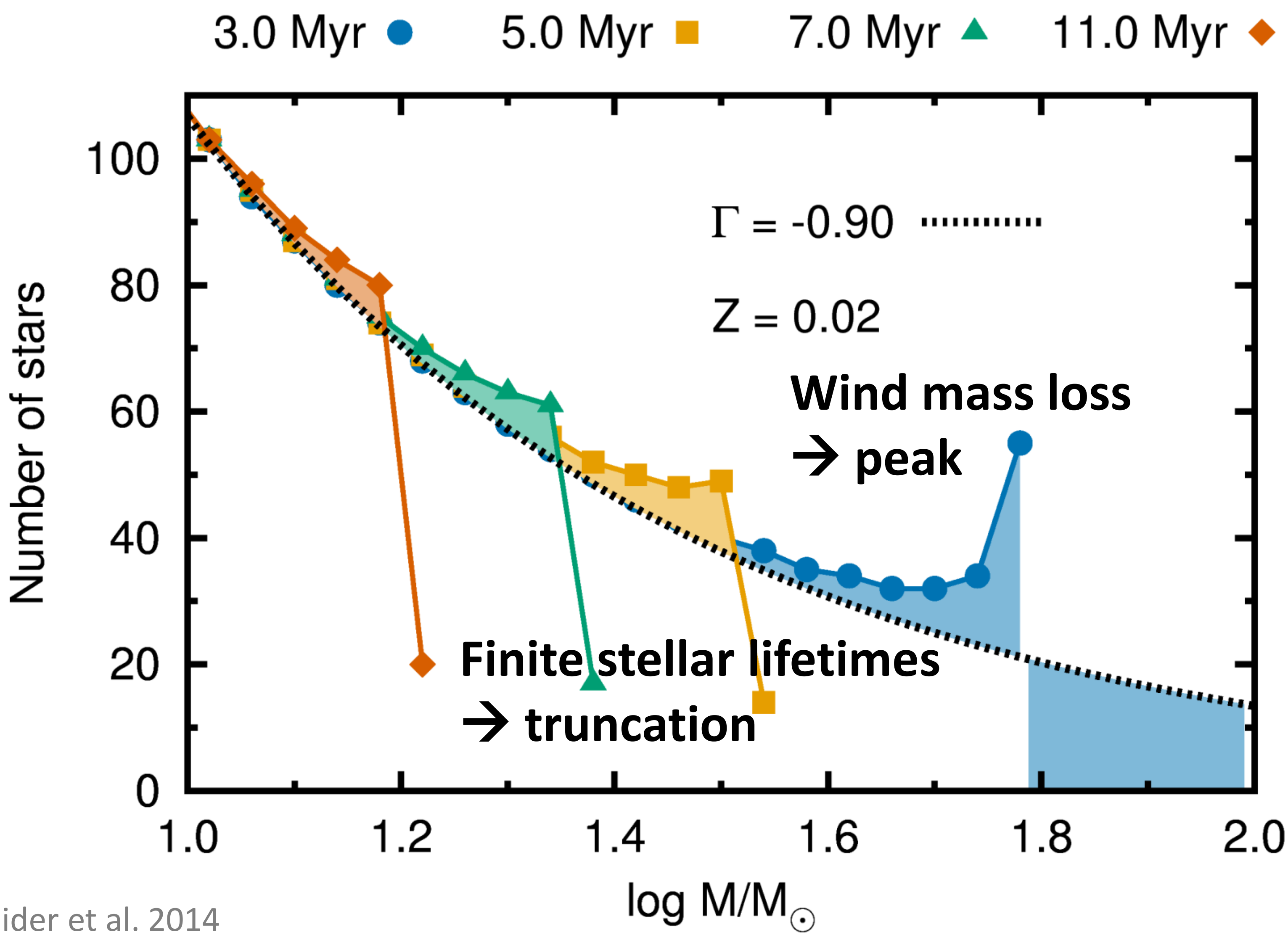
- IMF = distribution of stellar masses at birth



Schneider et al. 2014

The present day mass function (PDMF)

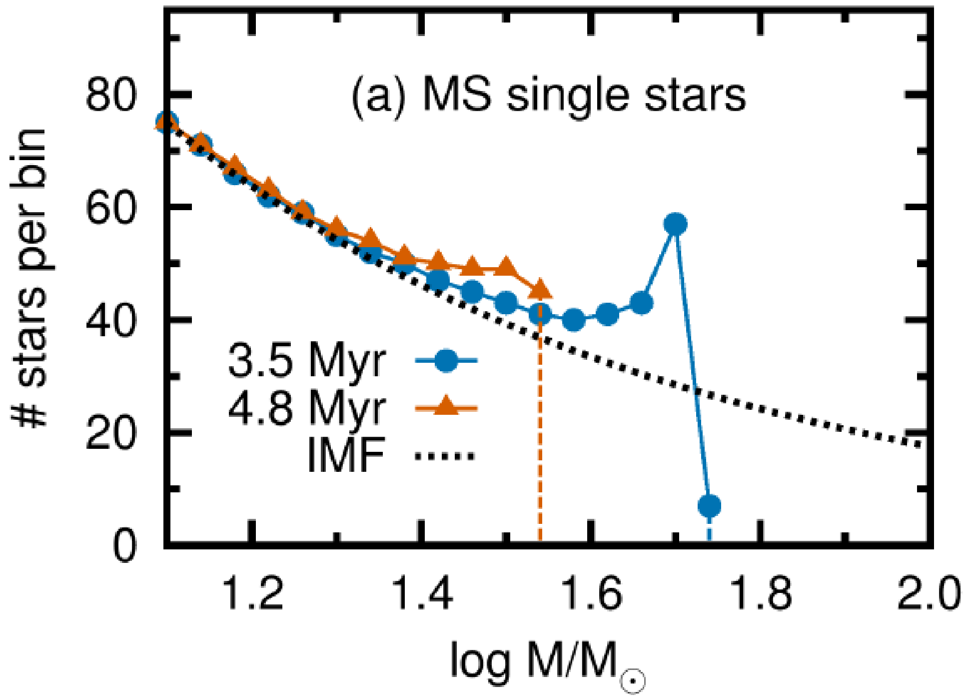
- How does single star evolution shape the mass function?



Schneider et al. 2014

The present day mass function (PDMF)

- How does binary star evolution shape the mass function?

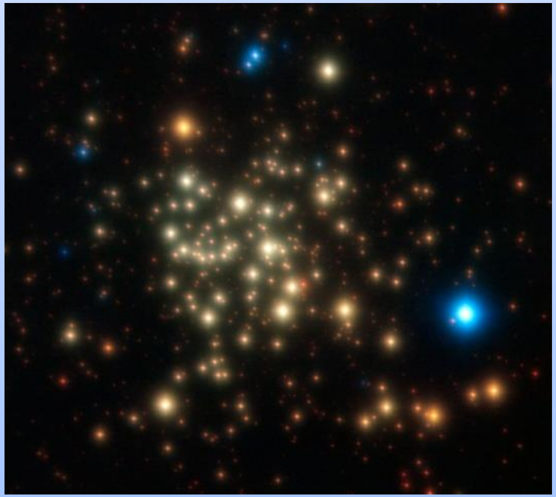


Schneider et al. 2014

Comparison with observations

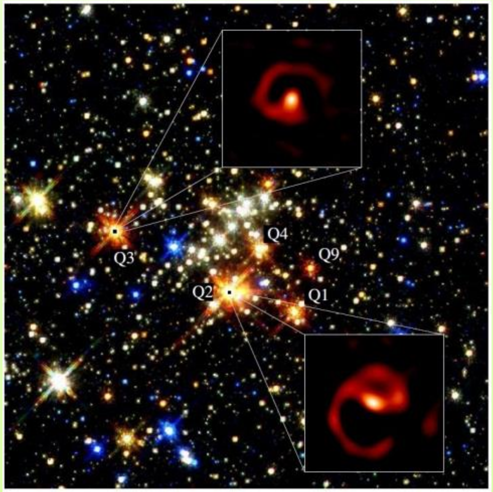
Arches

- Mass: $< 7 \times 10^4\,\mathrm{M}_\odot$
- Age: $2 - 4\,\mathrm{Myr}$
- Most luminous stars are WNh
- No WC stars



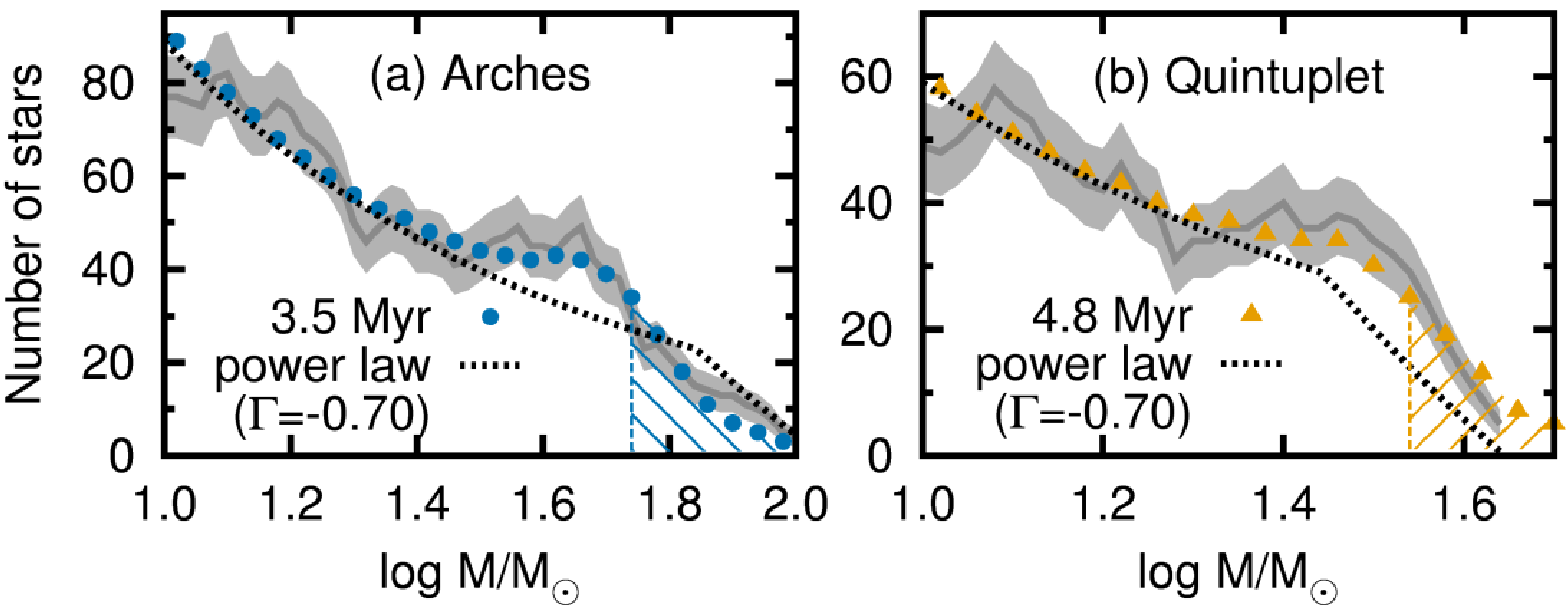
Quintuplet

- Mass: $\sim 10^4\,\mathrm{M}_\odot$
- Age: $\sim 4\,\mathrm{Myr}$
- WNh (7), WC (14), LBV (2) among them the Pistol star, OB (93)



Comparison with observations

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

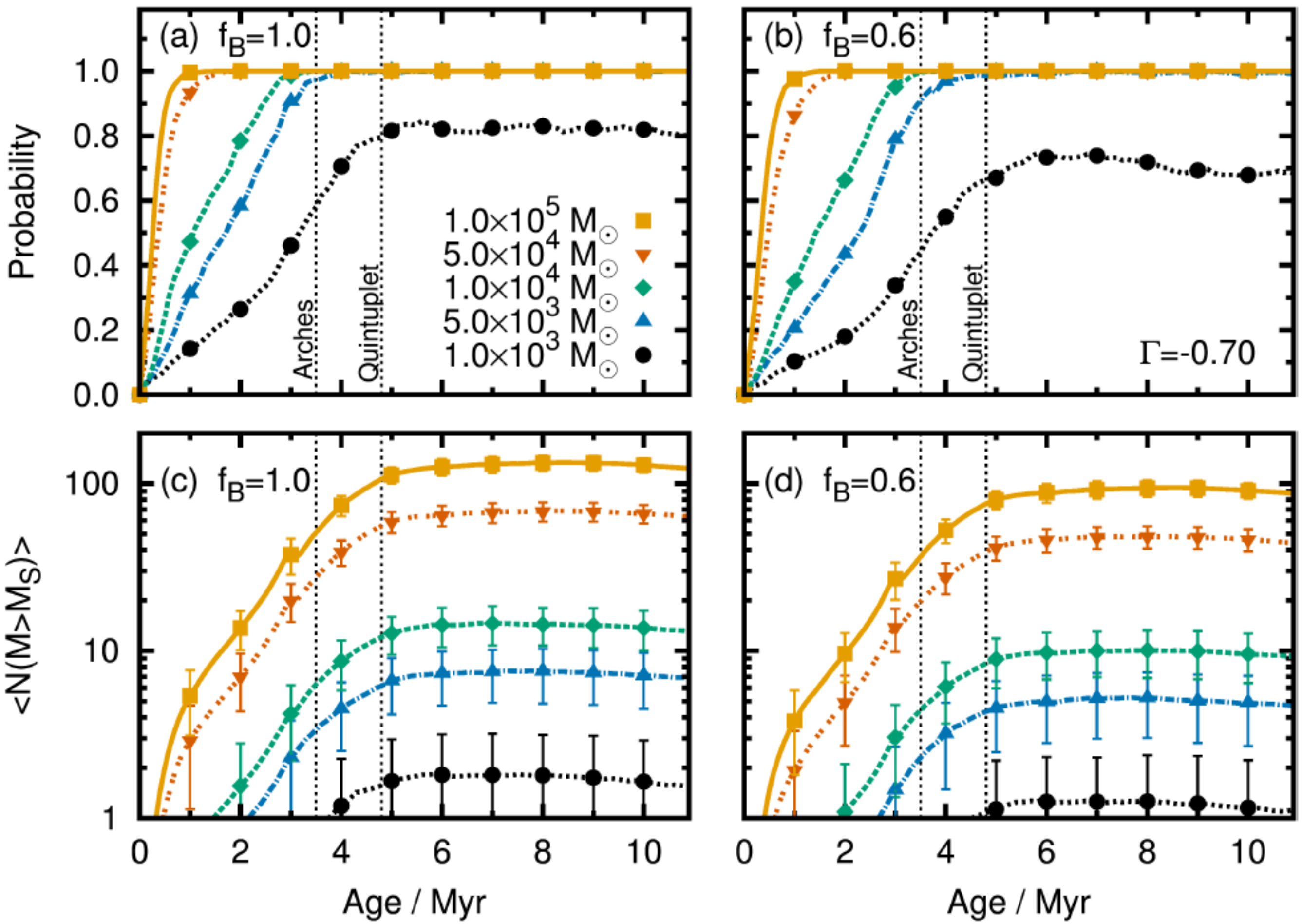


- **Prediction:** Tail stars are rejuvenated and hence should appear younger than less massive stars
- **Indeed observed**: Martins et al. (2008), Liermann et al. (2012)

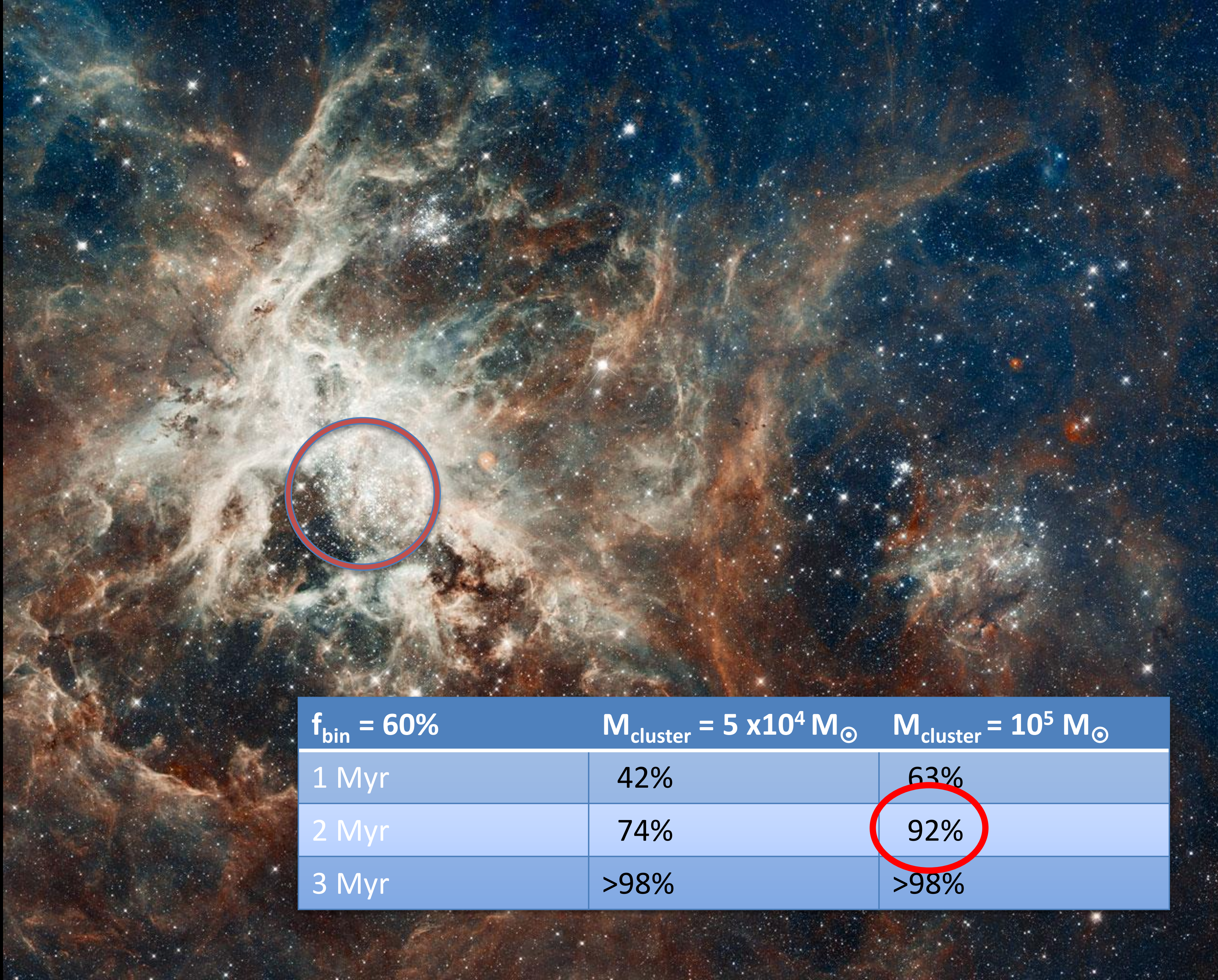
> 99.9% certain that most massive star in both clusters is a binary product

Probability most massive star is a binary merger

Average number of stars more massive than the most massive genuine single star



9.2±3.0 (Arches) and 7.5±2.9 (Quintuplet) most massive stars products of binary evolution



f_{bin} = 60%	$M_{cluster}$ = 5 x10^4 $M_{\odot}$	$M_{cluster}$ = 10^5 $M_{\odot}$
1 Myr	42%	63%
2 Myr	74%	92%
3 Myr	>98%	>98%

Take away

Most massive stars (of type WNh) may have a binary interaction history

Concluding remarks

MOS studies allow for robust tests of massive star evolution theory

- rotation & rotational mixing
- multiplicity
- mass loss
- core overshooting

Outcome of massive star formation may yield vital clues to the elusive formation mechanism of massive stars

Perhaps *all* massive stars are part of multiple systems, many of which are close, implying a pivotal role for binary interaction

Most massive stars (of type WNh) may be dominated by binary interaction products

MOS future: do similar studies as VFTS in lower metallicity environments (needs bigger telescope – see talk Chris Evans)

Characteristics of Mergers / Mass gainers

Surface abundances

Peculiar rotation rates

Circum-stellar medium

Magnetic field

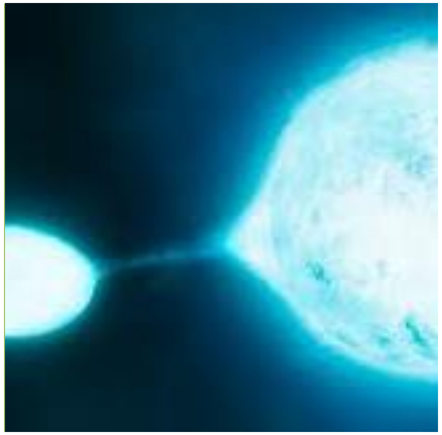
Runaway

(Lack of) Binarity

Excess UV flux / hard X-ray

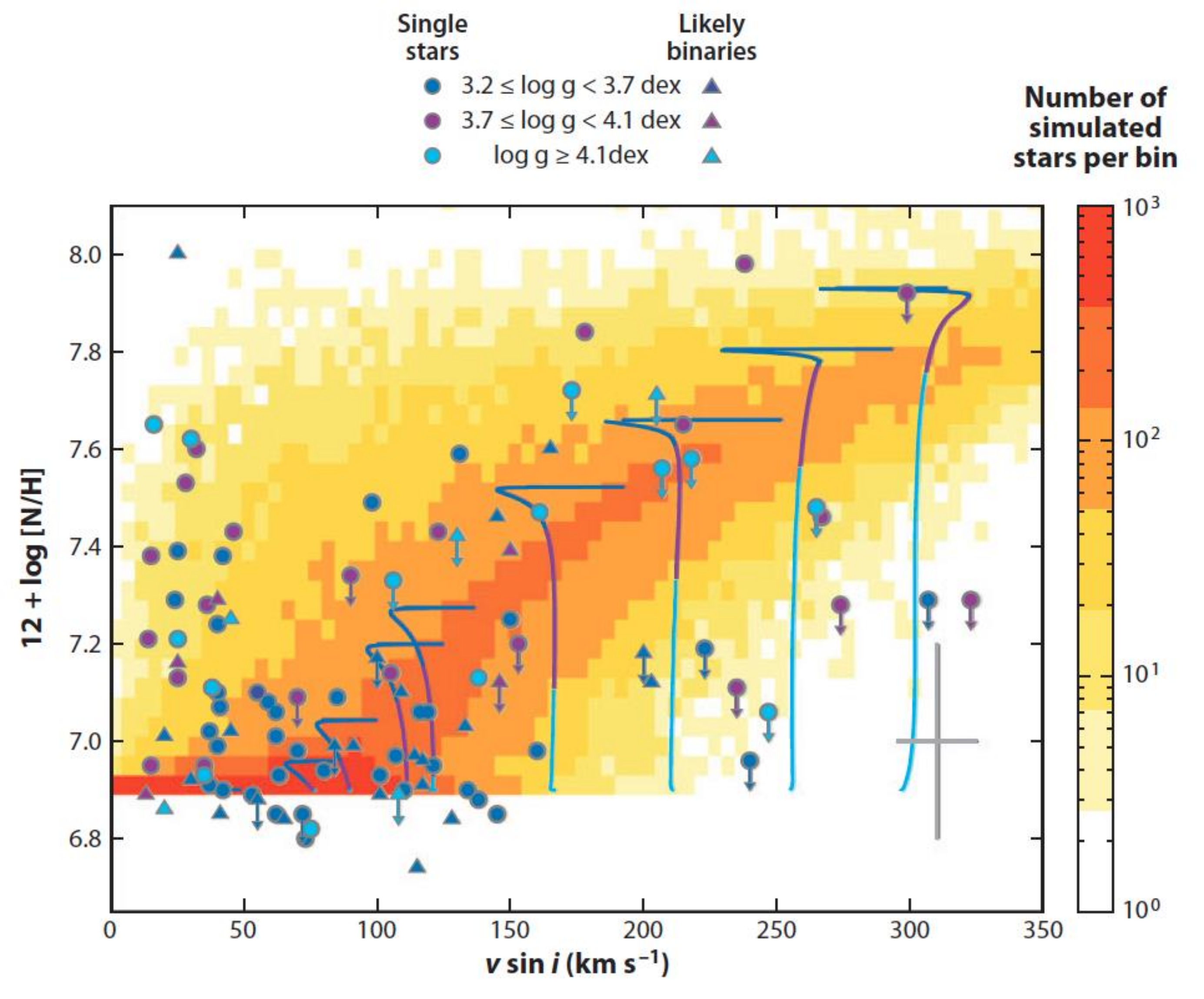
Apparent young age

None are unique/necessary



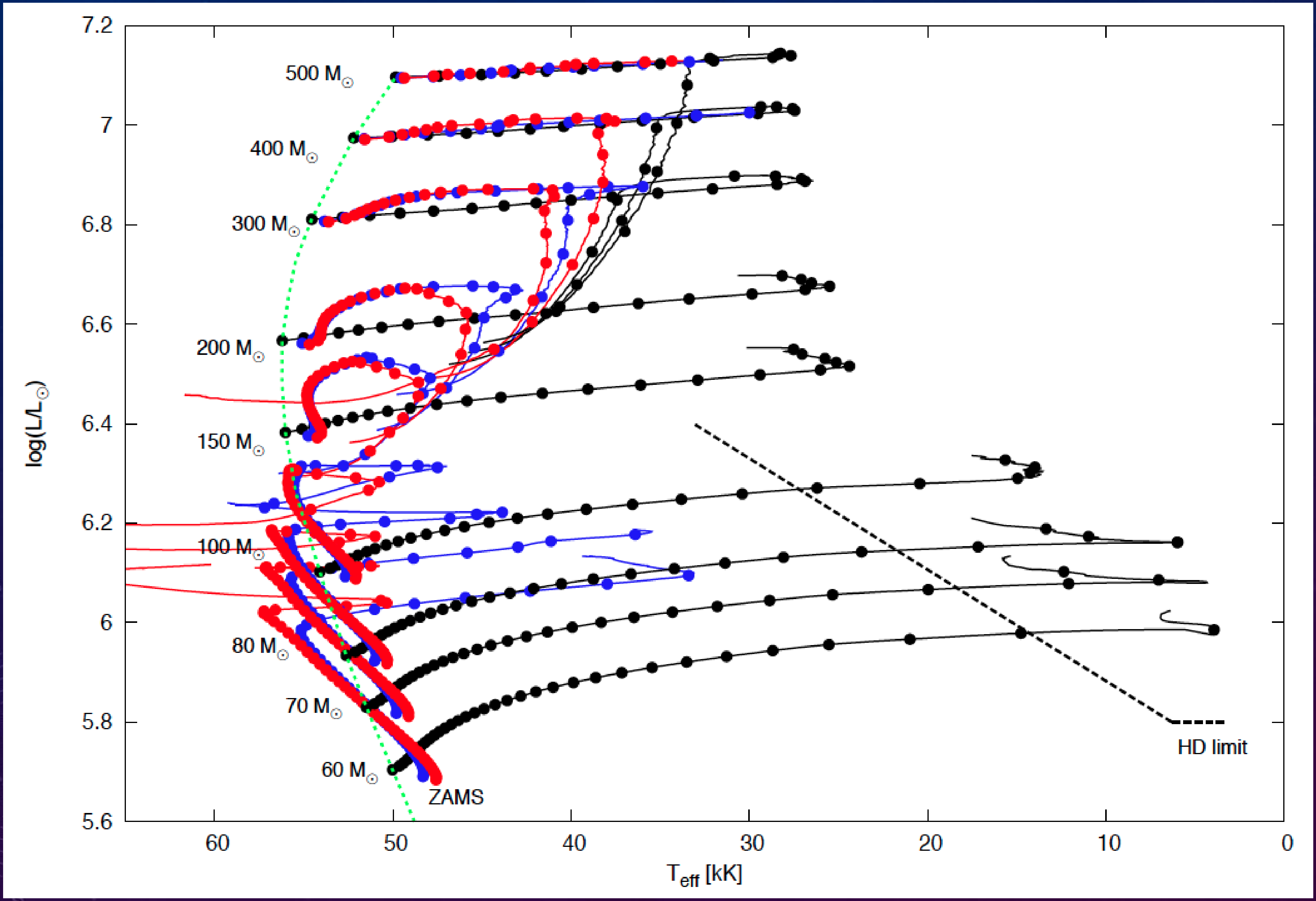
De Mink+ 2013

Hunter diagram - rotatinal mixing calibration



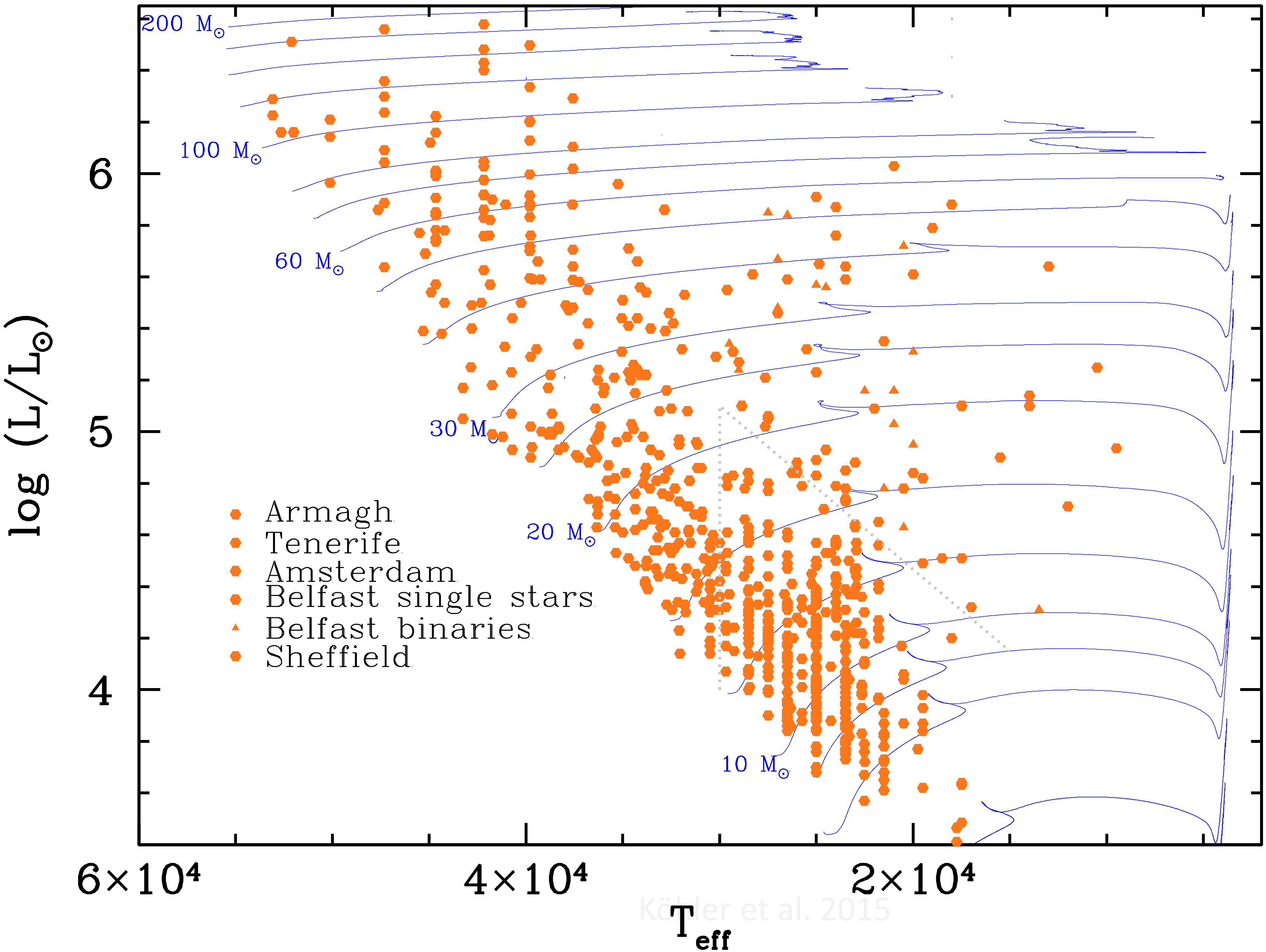
Hunter et al. 2008; Brott et al. 2011

Stellar evolution 60-500 $M_\odot$

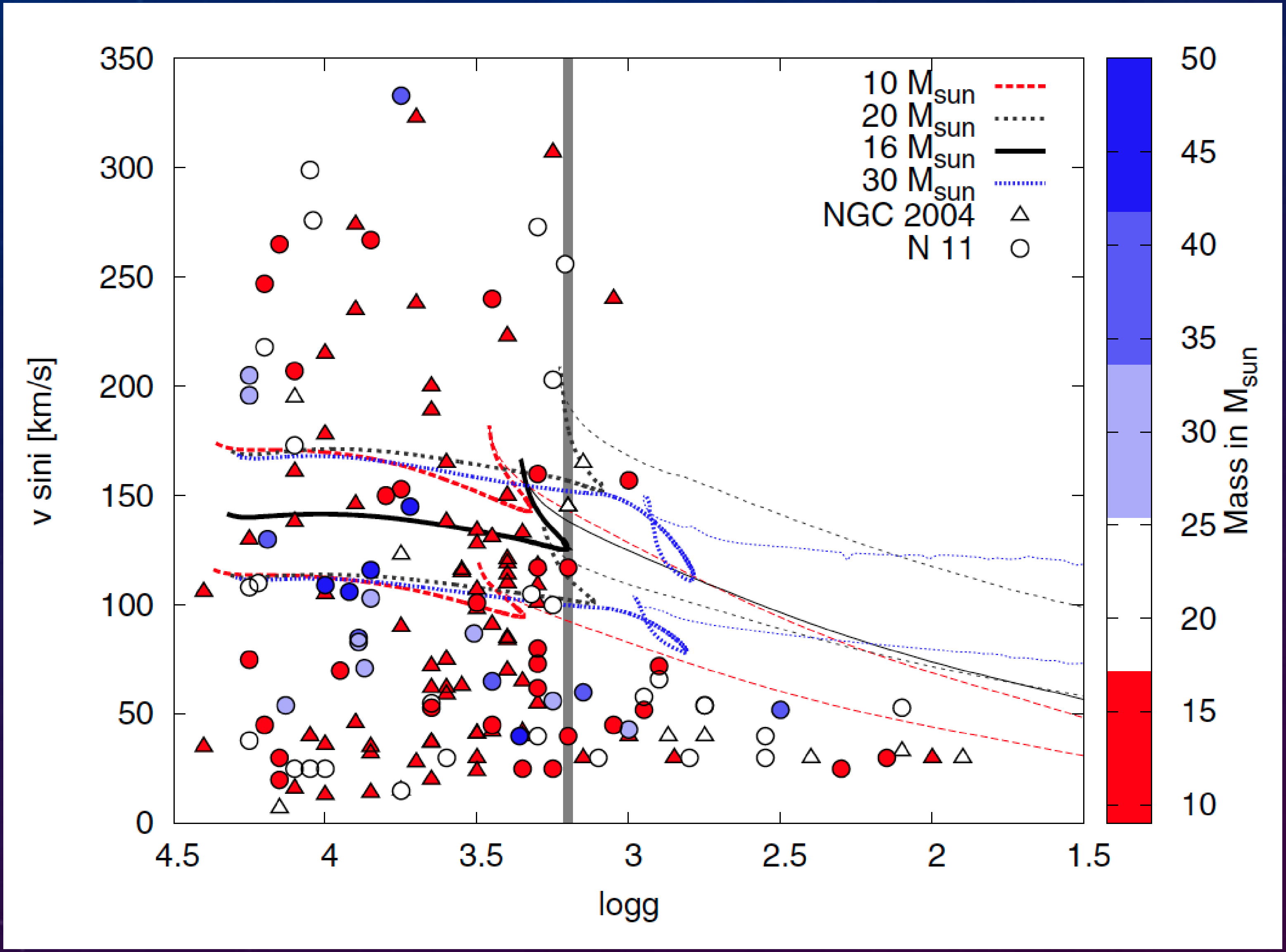


Köhler et al. 2015

Preliminary HRD of VFTS field



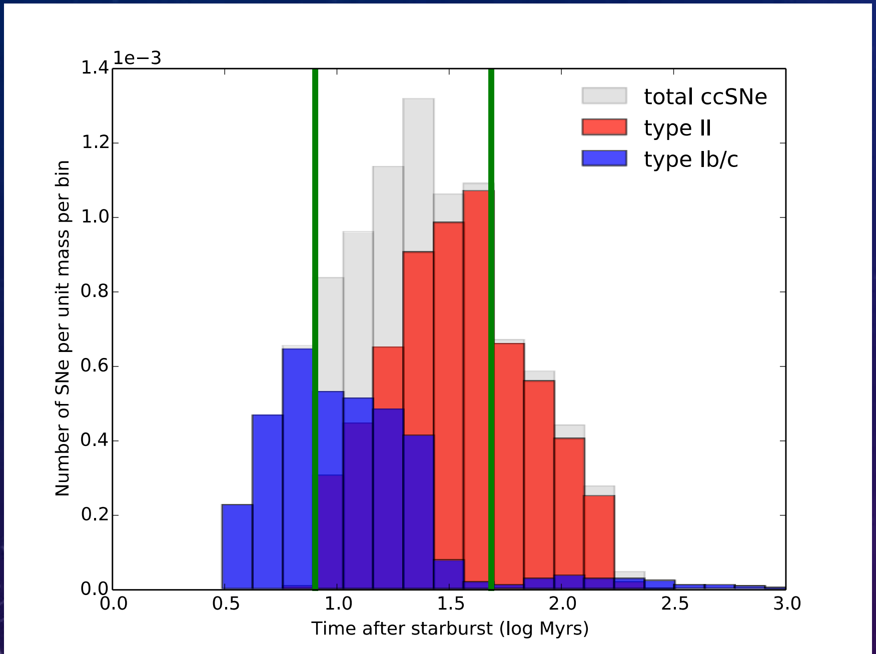
Core overshooting calibration



Brott et al. 2011

Bigger context of Massive Stars

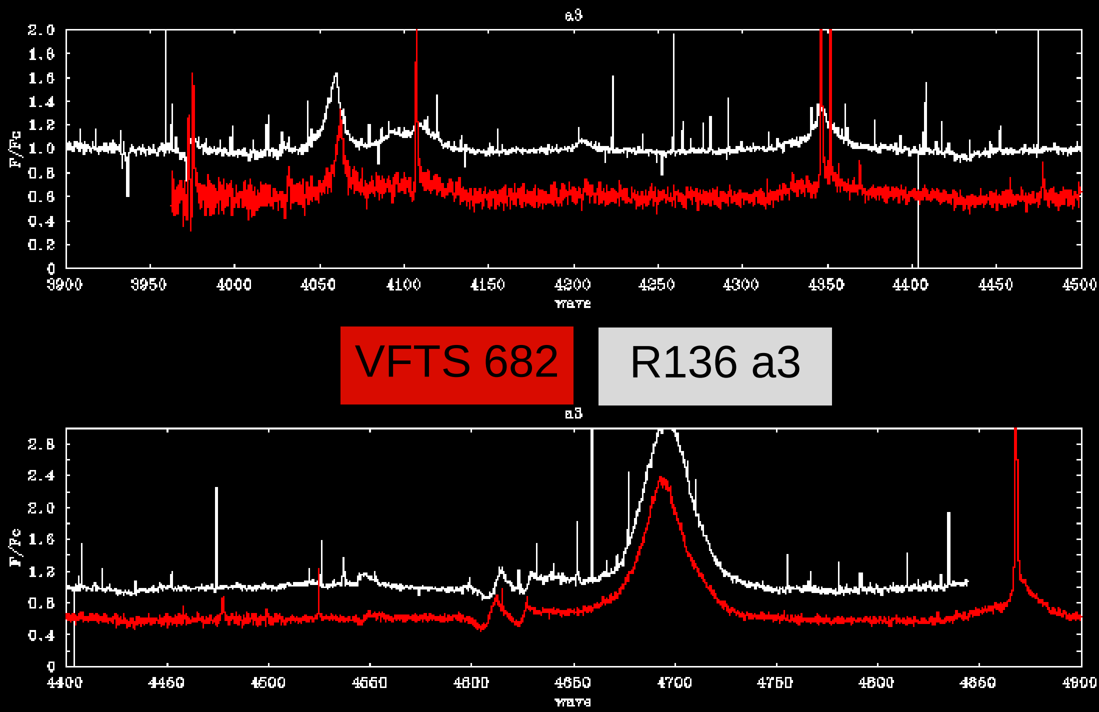
End products



Zapartas et al. 2015 (in prep)

ccSNe delay-time distribution

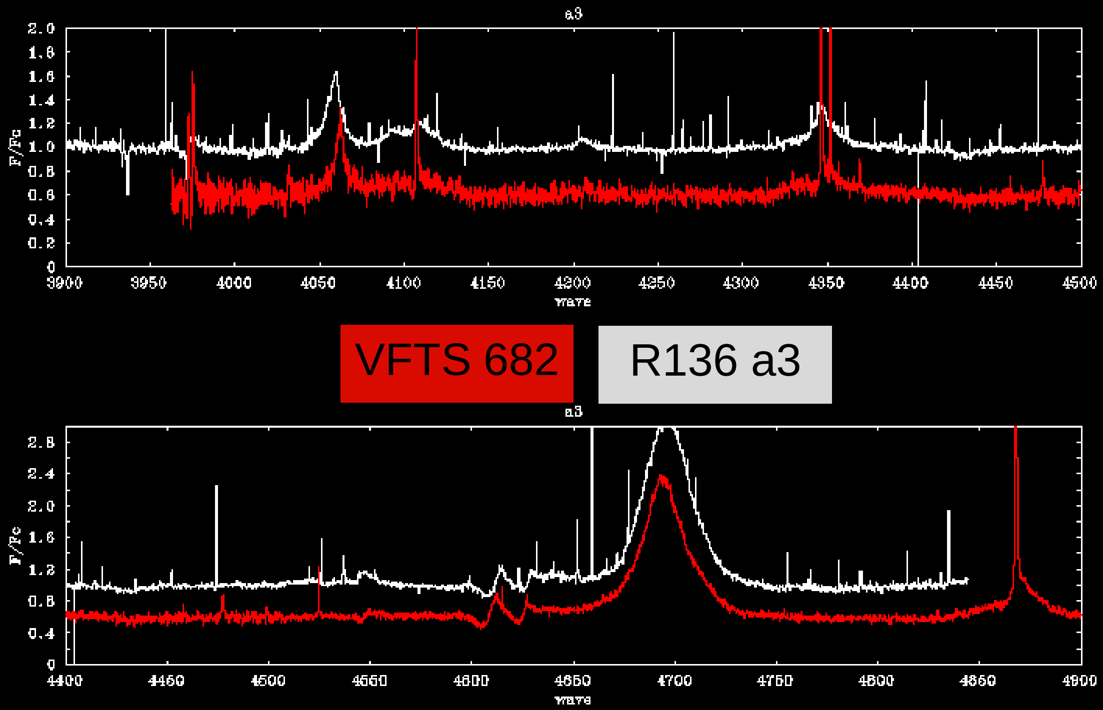
WN5h star VFTS 682



Bestenlehner et al. 2011

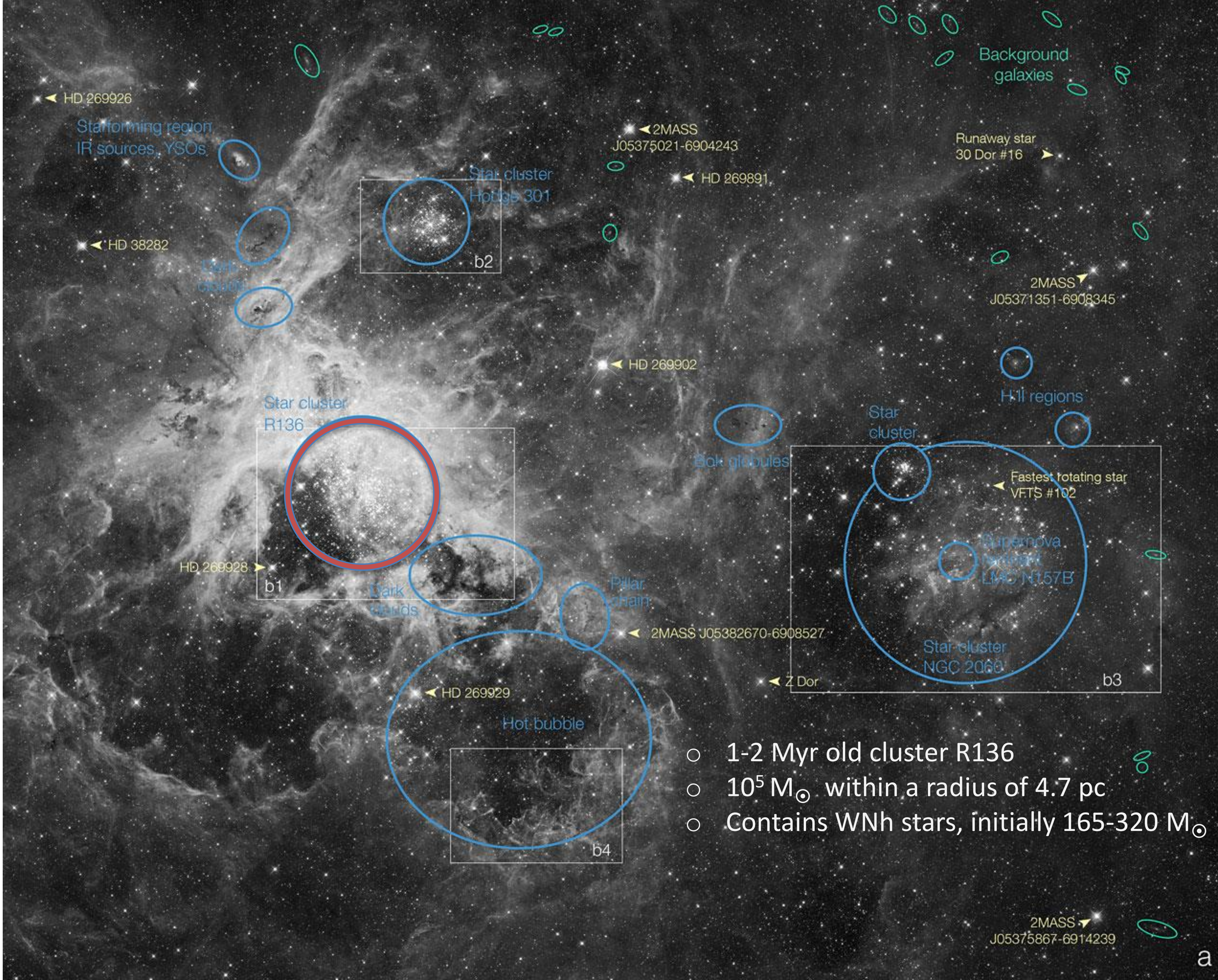
- Exceptionally massive WN5h star (M_{init} ~ 200 $M_{\odot}$); the first one of this type to be found *outside* of a massive young cluster
- Spectroscopic "twin" of R136a3 (M_{init} ~ 240 $M_{\odot}$)

WN5h star VFTS 682



Bestenlehner et al. 2011

- The star is in (the line-of-sight toward) an active star forming region
- Did it form in situ or is it a slow runaway object (~40 km/sec) from R136?
- This poses an interesting challenge for either massive star formation theory or dynamical ejection scenarios (or both)



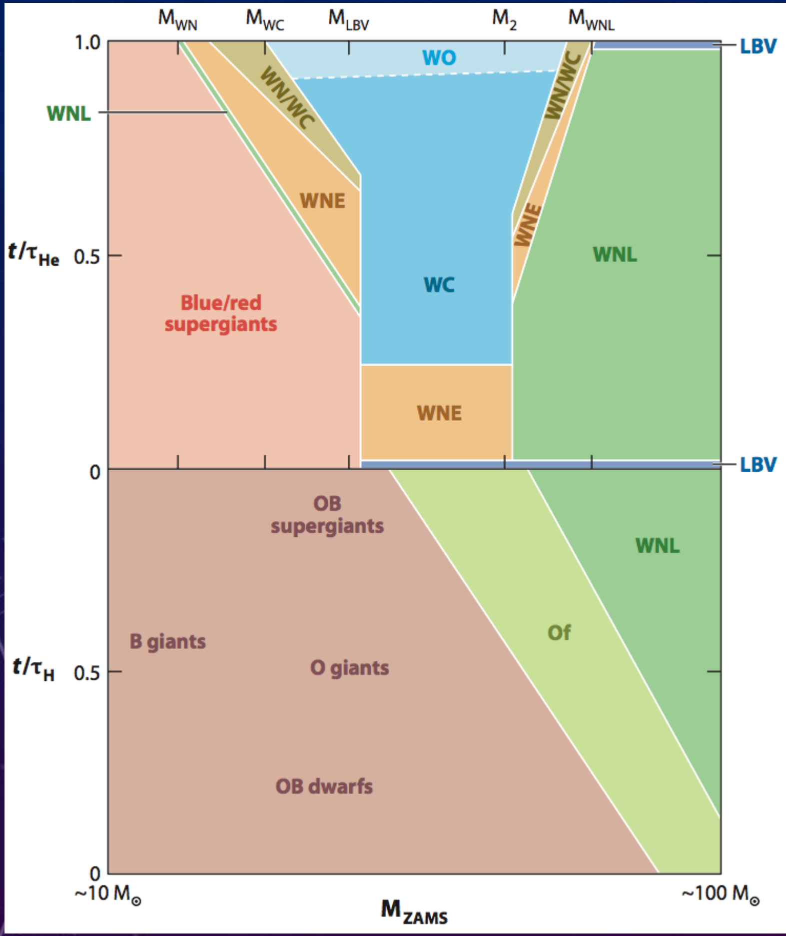
- 1-2 Myr old cluster R136
- 10^5 $M_\odot$ within a radius of 4.7 pc
- Contains WNh stars, initially 165-320 $M_\odot$

Characteristics of mergers / mass gainers

- Surface abundances
  - Enhancement of N, He, depletion of C, O and absence of fragile elements Li, Be, B, F
- Peculiar rotation rates
  - Rapid rotation as a result of spin-up or very slow rotation through magnetic breaking
- Circum-stellar medium
  - (bipolar)ejection nebula or a circum-binary disk
- Magnetic field
- Peculiar proper motion / radial velocity / remote location /bow shock
  - runaway stars, walk-away stars
- Excess UV flux / hard X-ray
  - indicating stripped or compact companion
- Apparant young age
  - Younger and more luminous than host population (massive analogue of blue stragglers)

Bigger context of Massive Stars

End products



Langer 2012

SNe progenitors

Distribution of final products

SNe (GRBs) types and NSs &BHs

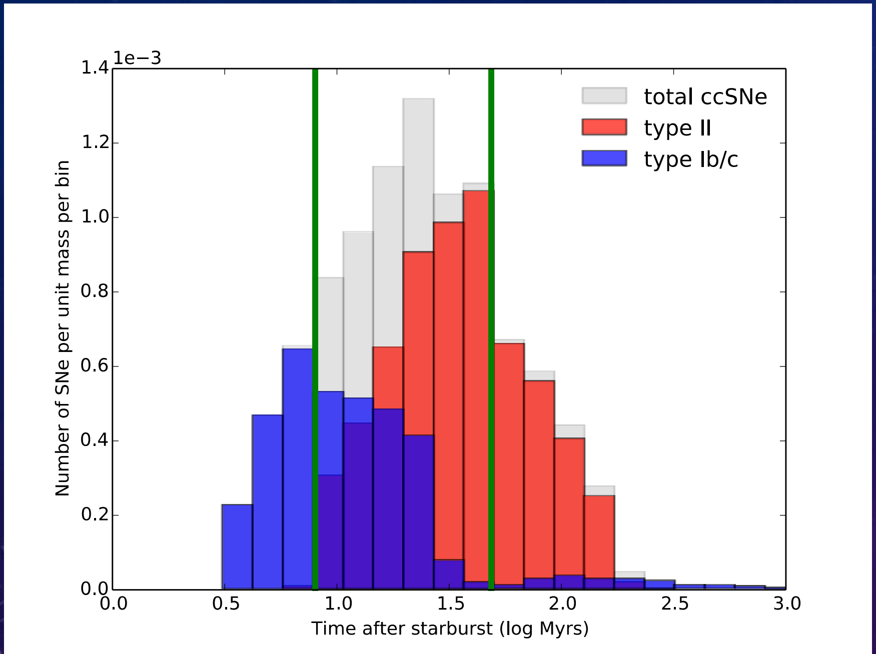
Feedback

Delay-time distribution

Effect of binary evolution

Bigger context of Massive Stars

End products



Zapartas et al. 2015 (in prep)

SNe progenitors

Distribution of final products

SNe (GRBs) types and NSs &BHs

Feedback

Delay-time distribution

Effect of binary evolution