Outcomes of Massive Star Mergers

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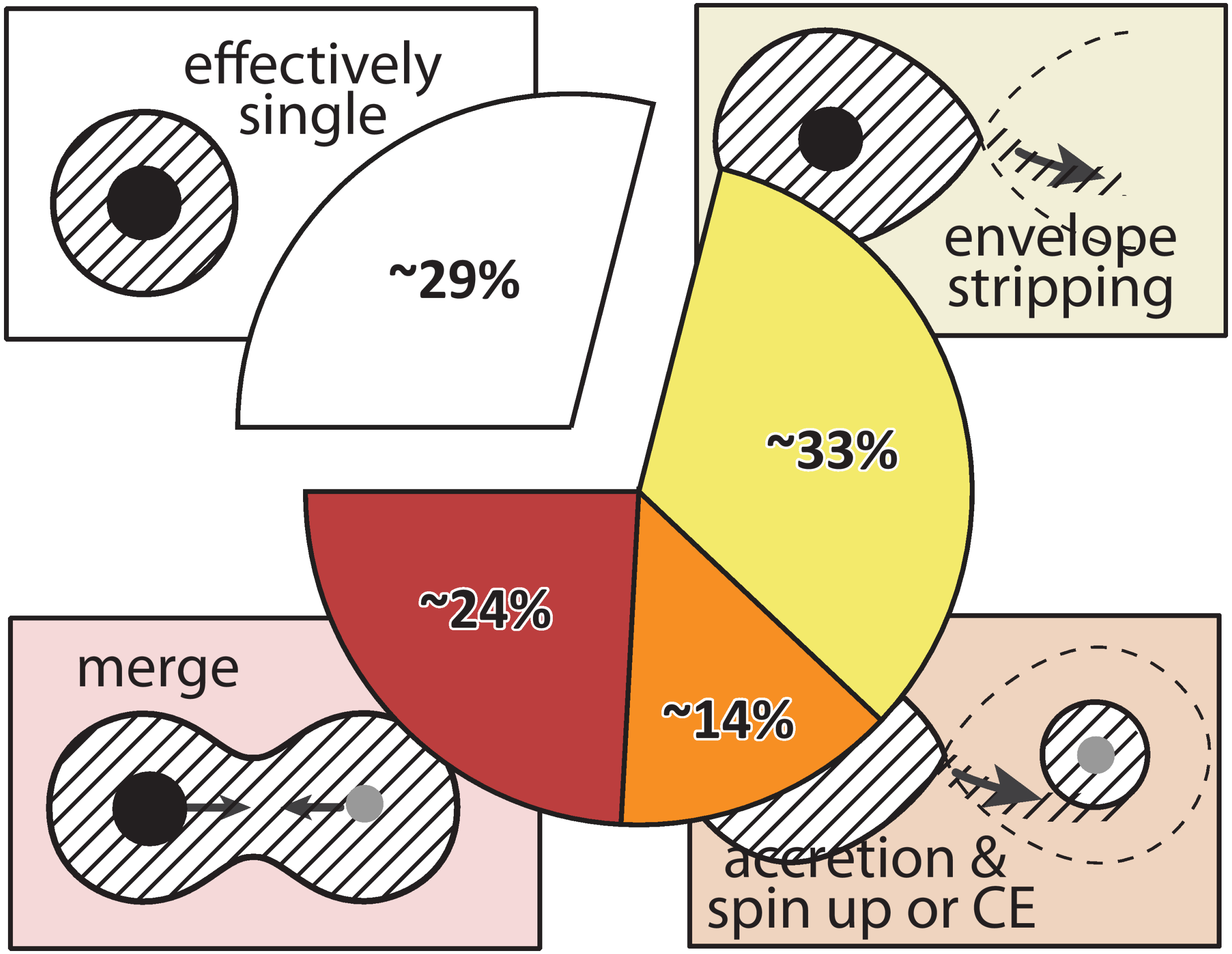
Massive Star Mergers

- Sana et al. (2012, Science): >70% of all O stars interact with a binary companion during their life

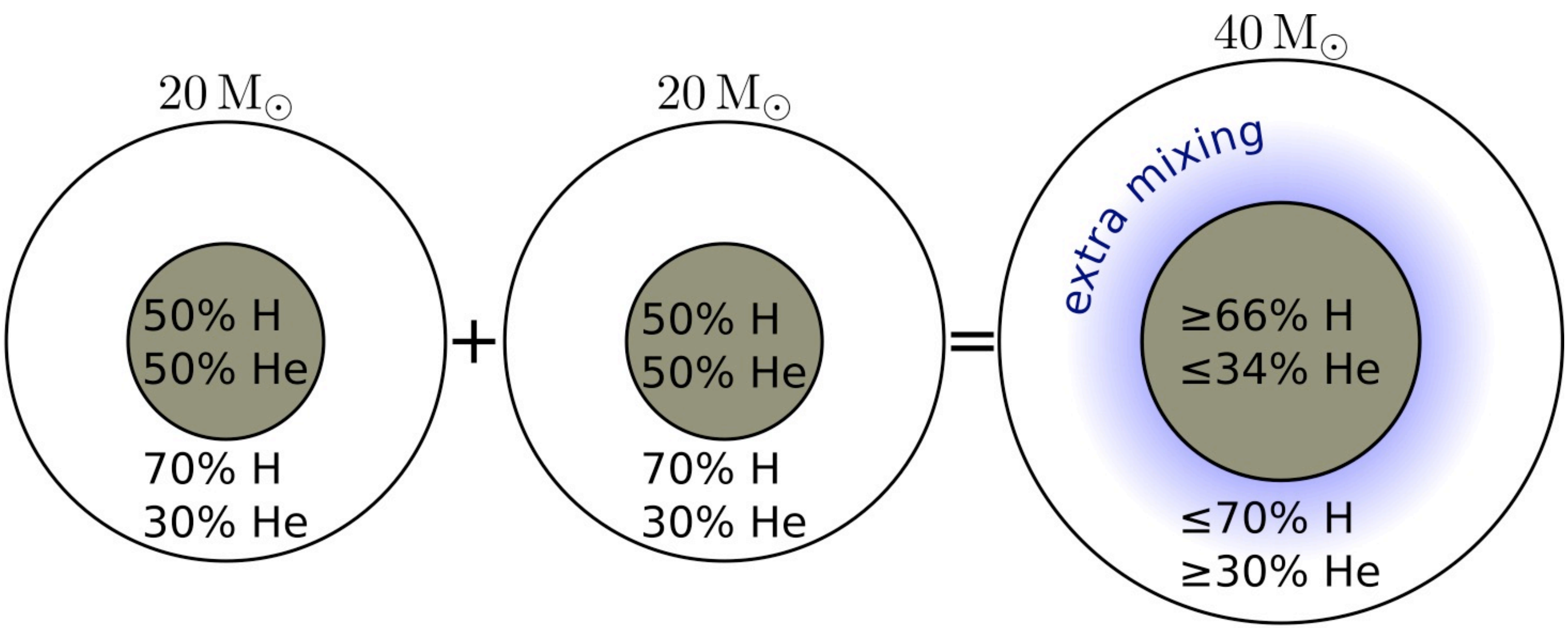


Credit: S.E. de Mink

Merger Fingerprints

- **Pre main-sequence merger** (e.g. tidal interaction with circumbinary disk; Stahler 2010, Korntreff+2012)
  - No observable signatures expected (maybe ejecta?)
- **Main-sequence merger** (e.g. binary stars, cluster dynamics)
  - Ejecta/nebula (short lifetime, low chance to observe)
  - Rapid rotation? Slow rotation?
  - Surface chemical enrichment: Nitrogen, Helium?
  - **Rejuvenation!**
- **Post main-sequence merger** (e.g. Case B merger or from common-envelope evolution)
  - Maybe similar to main-sequence mergers

Rejuvenation of main-sequence mergers



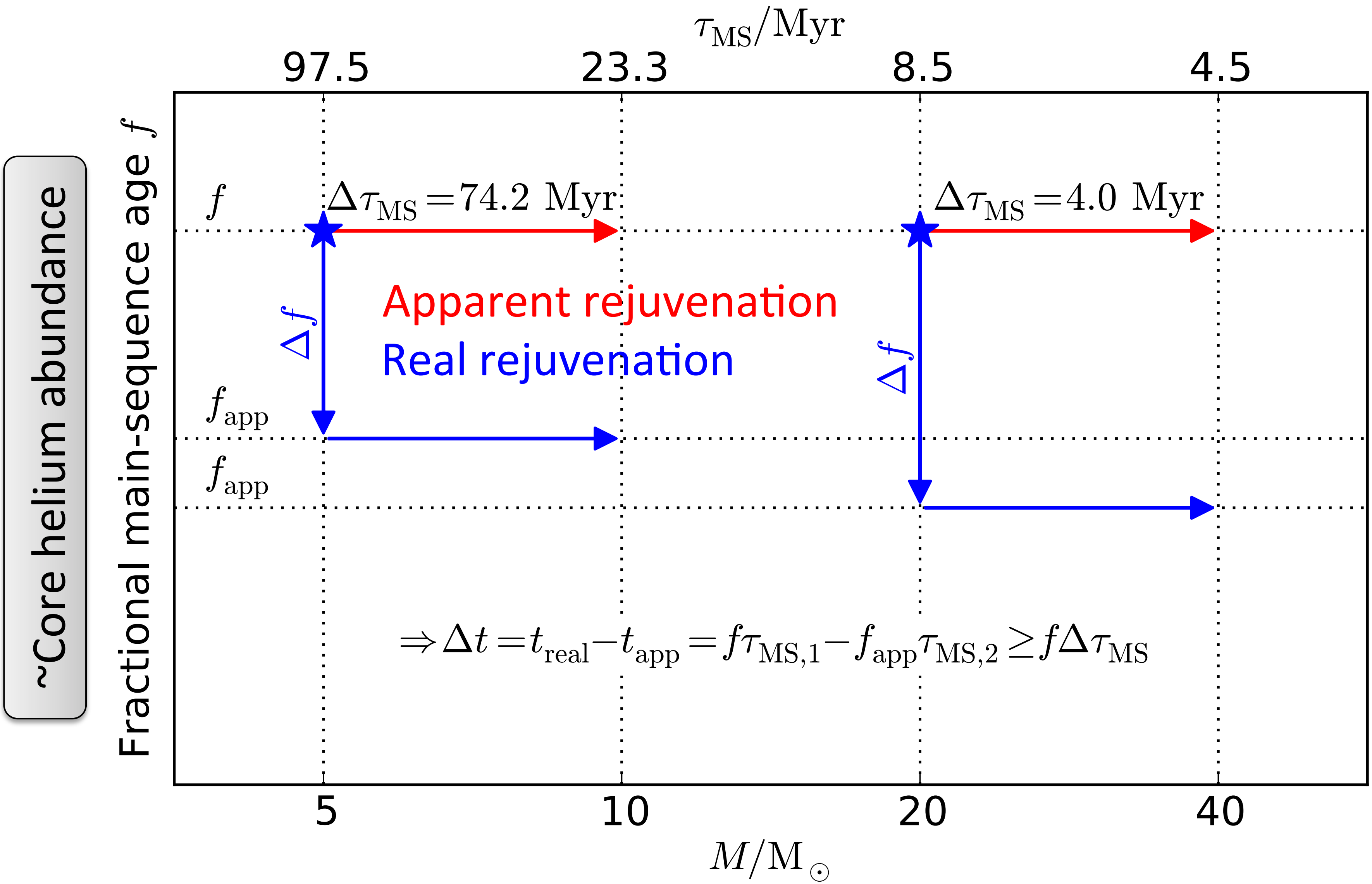
Schneider et al. (2016)

$$Q_{\mathrm{c},0} = 0.45 \qquad Y_{\mathrm{c},0} = 0.5 \qquad Q_{\mathrm{c}} = 0.67$$

$$\Rightarrow Y_{\mathrm{c}} = \frac{Q_{\mathrm{c},0}}{\alpha Q_{\mathrm{c}}} Y_{\mathrm{c},0} \leq Y_{\mathrm{c},0} \qquad \Rightarrow \Delta Y_{\mathrm{c}} = Y_{\mathrm{c},0} - Y_{\mathrm{c}} \propto Y_{\mathrm{c},0}$$

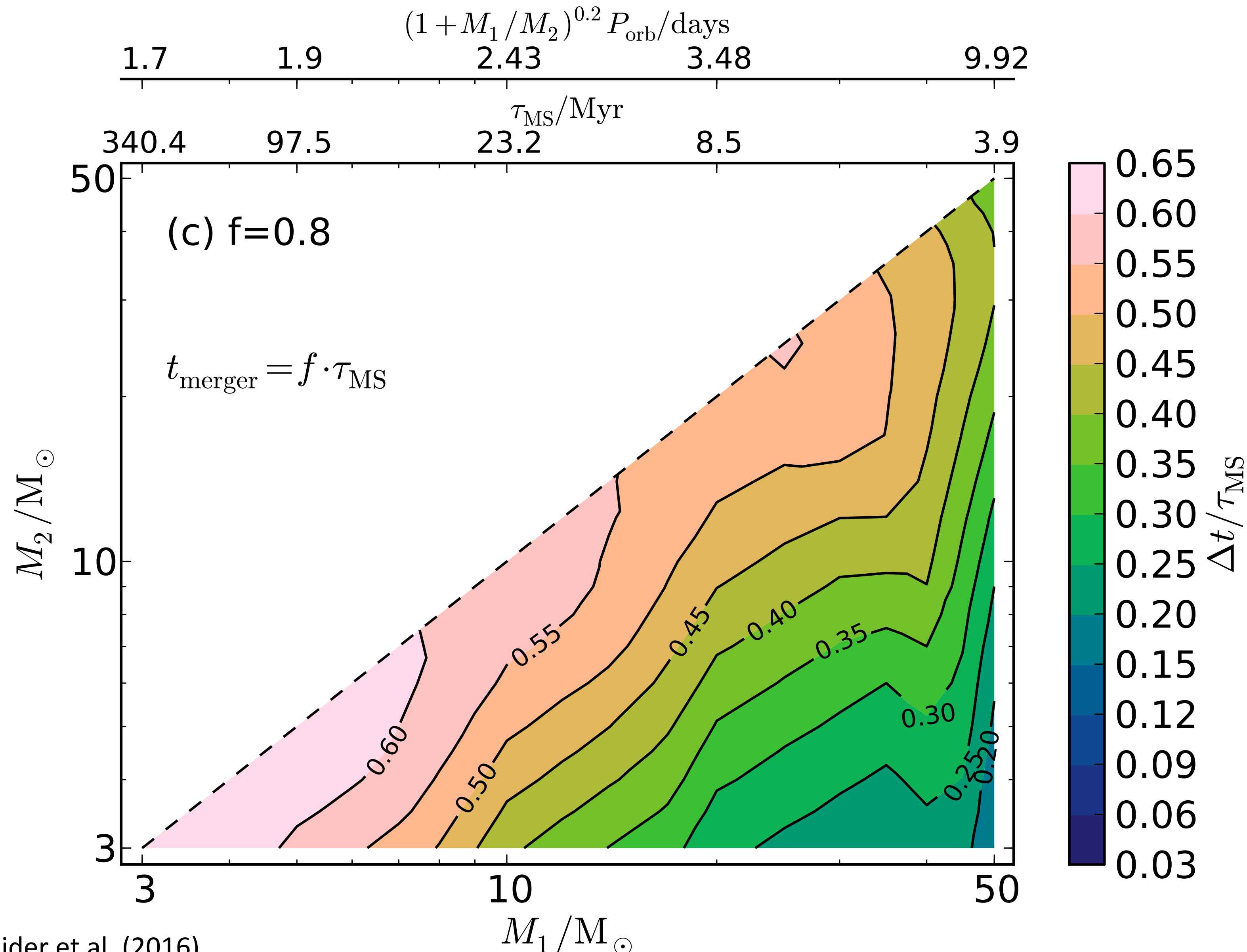
The merger product will look younger than its progenitors.

Rejuvenation of main-sequence mergers



Schneider et al. (2016)

Rejuvenation of main-sequence mergers

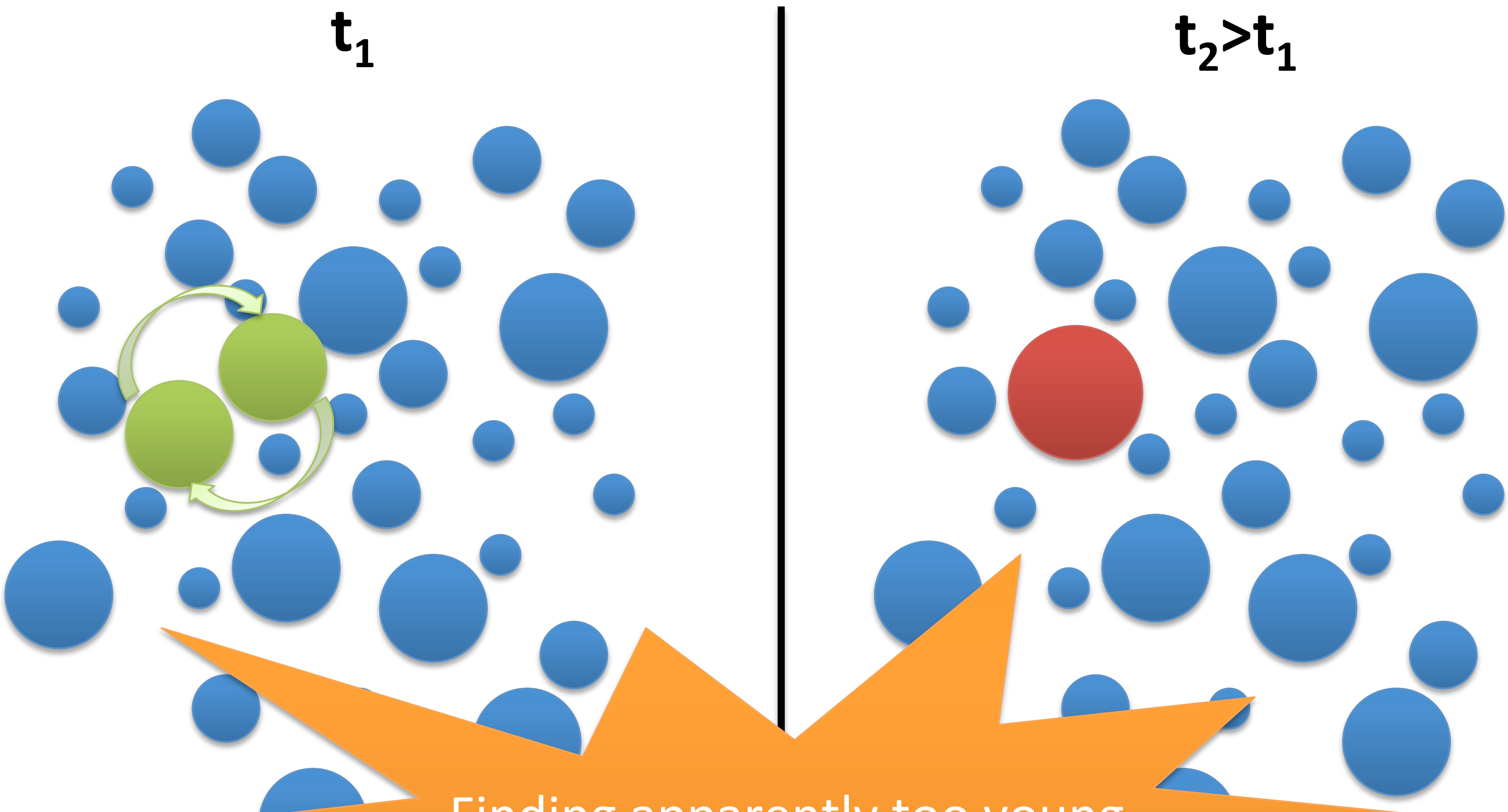


Rejuvenation in units of MS lifetime

Schneider et al. (2016)

Comparison clocks: cluster members

- **Comparison clocks** needed to find rejuvenated stars



Finding apparently too young stars is ***necessary*** but ***not sufficient*** condition!

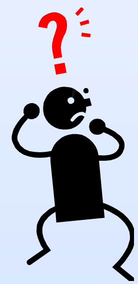
THE MOST MASSIVE STARS

Two problems

Cluster age problem

Arches: (Martins et al. 2008)

- WNh stars: 2-3 Myr
- O stars: 3-4 Myr



Quintuplet:

(Liermann et al. 2012, Figer et al. 1998)

- WNh stars: 2.1-3.6 Myr
- Pistol star: <2.1 Myr
- O/WC stars: ~4 Myr

Brightest stars appear to be younger

Maximum mass problem

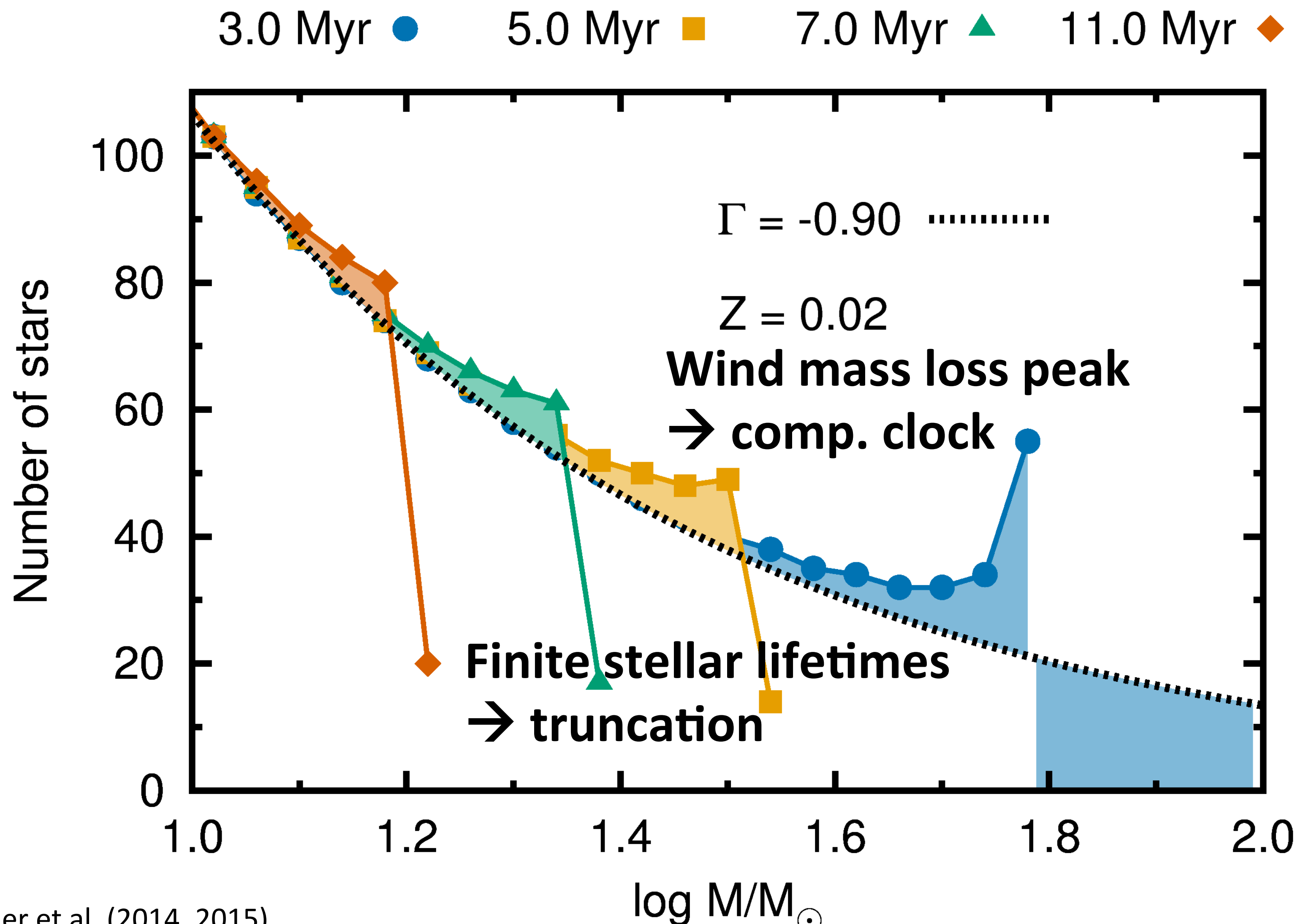
$M_{max} \approx 150\ M_{\odot}$
(Weidner&Kroupa 2004, Figer 2005, Oey&Clarke 2005, Koen 2006)

BUT:

- 160-320 $M_{\odot}$ stars in R136 (Crowther et al. 2010)
- Further >150 $M_{\odot}$ stars in 30 Dor (Bestenlehner+2014)
- SN2007bi: PISN from initial 250 Msun star?! (Gal-Yam et al. 2009)

Present-day mass functions: single stars

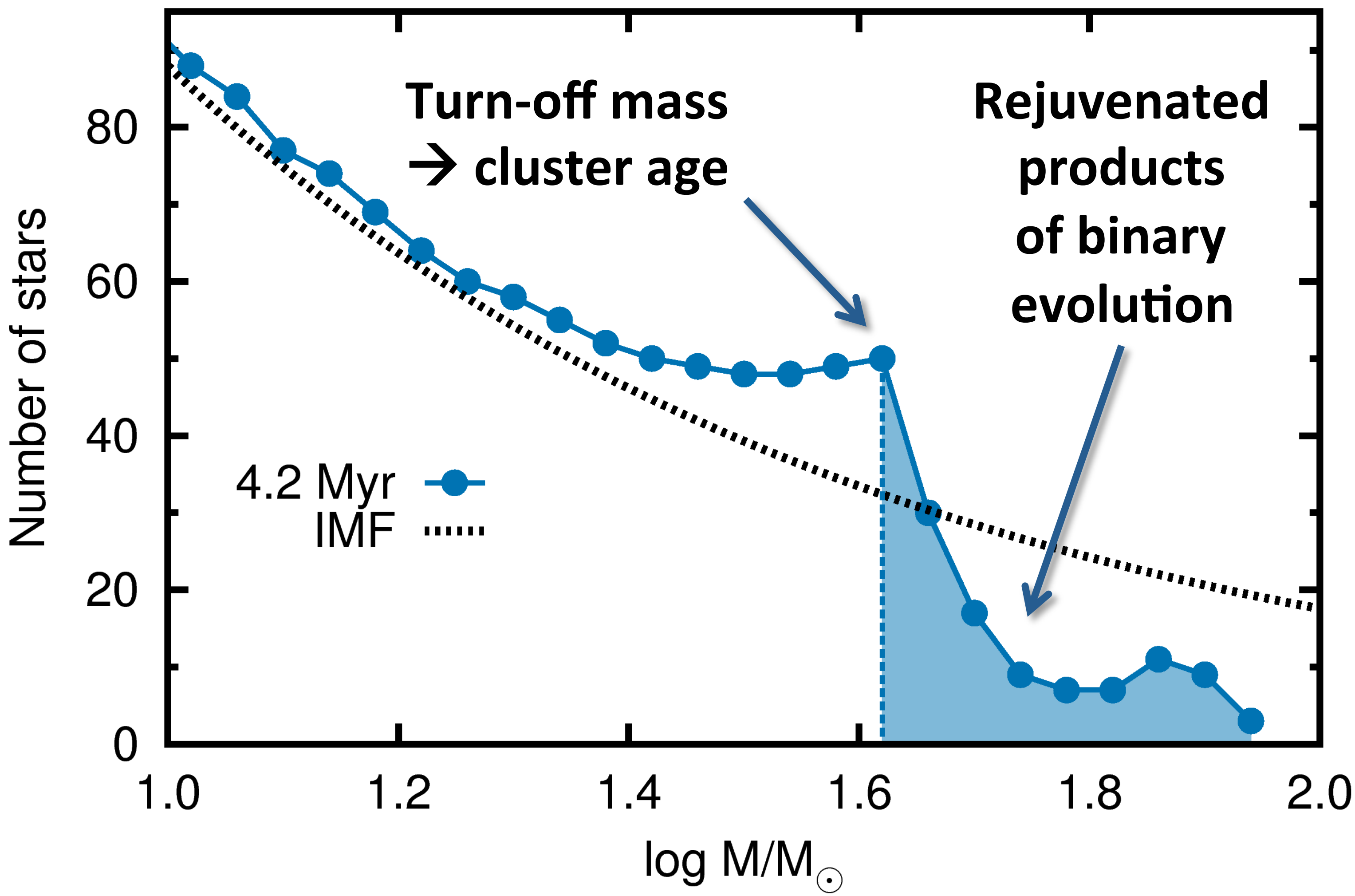
- IMF = distribution of stellar masses at birth; $\xi(M) \sim M^{\Gamma}$



Schneider et al. (2014, 2015)

Present-day mass functions: binary stars

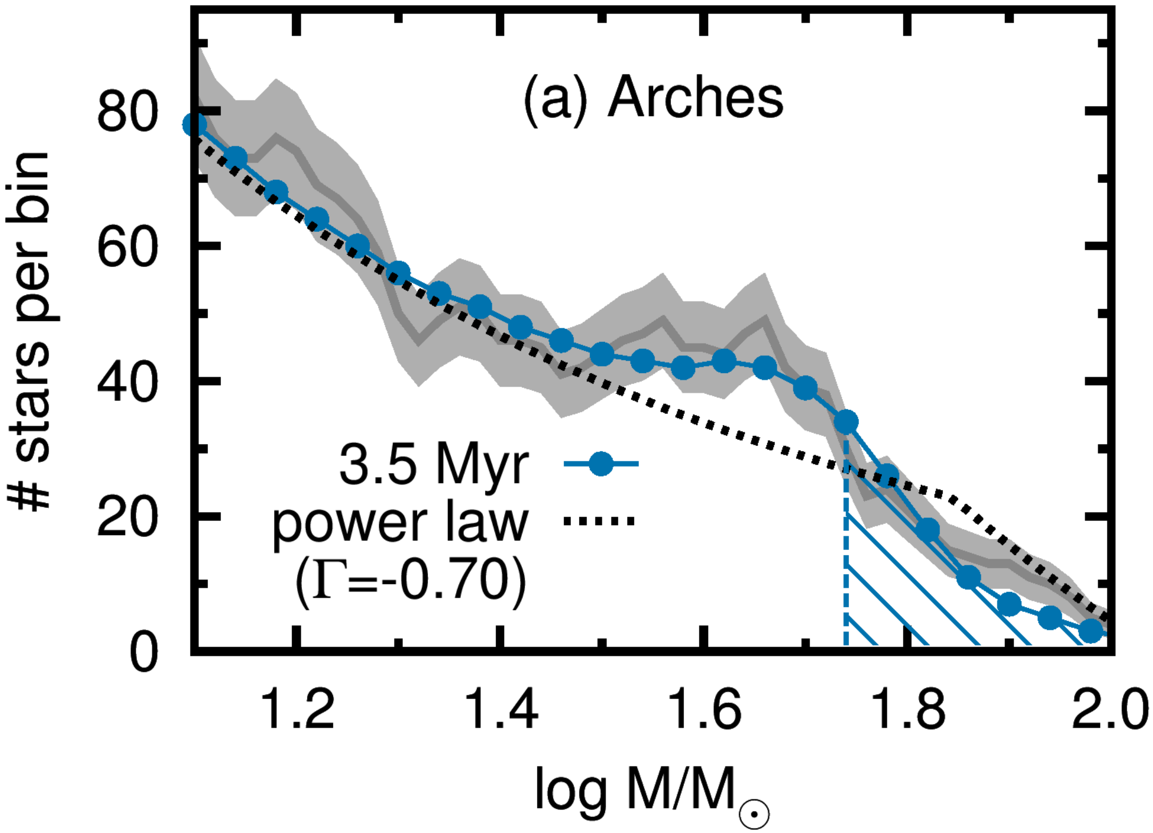
- **Mass transfer, stellar mergers** and **rejuvenation** create a tail



Schneider et al. (2014, 2015)

Comparison with observations

- Arches mass function from Stolte et al. (2005)

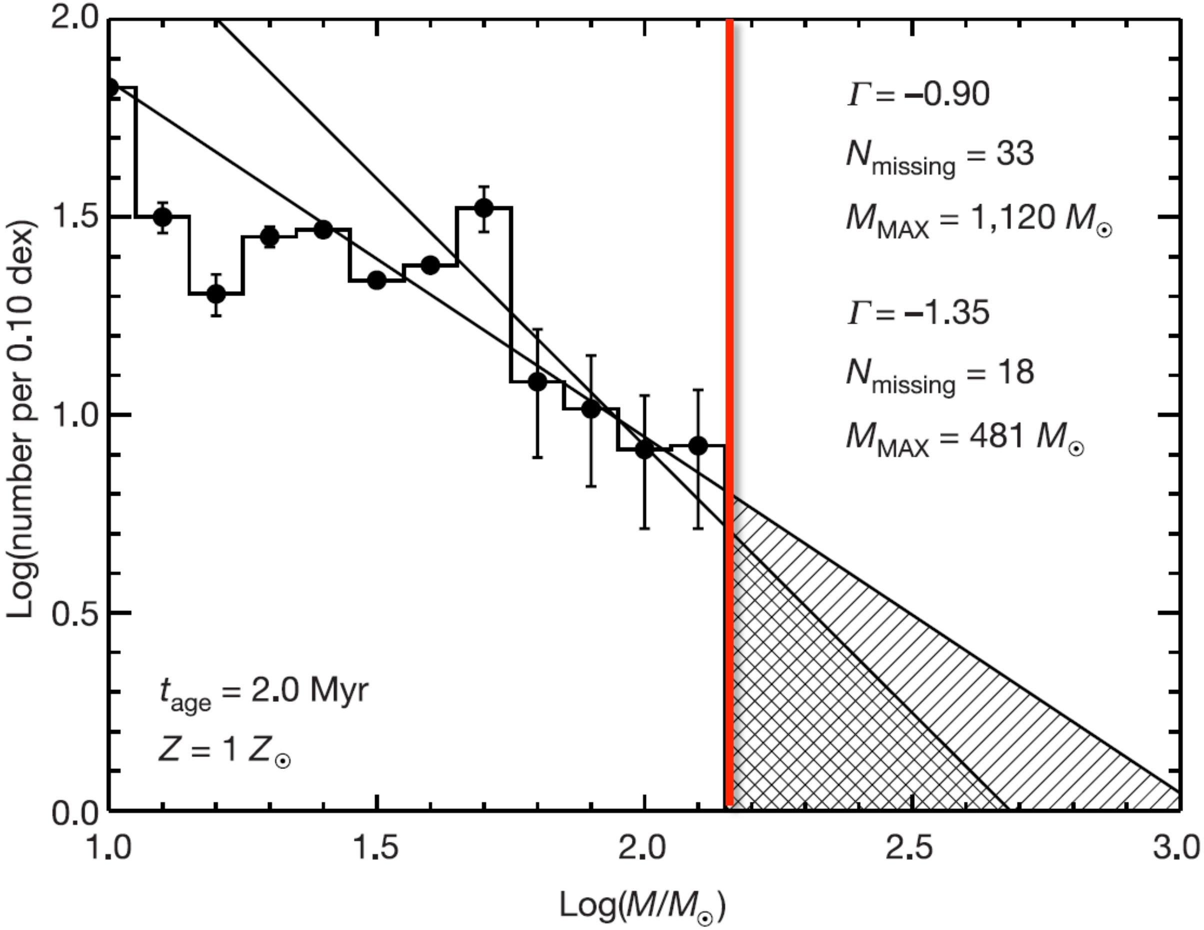


- **Bump** and **tail** explained by our models
- **The most massive stars are rejuvenated binary products**
- Age: 3.5±0.7 Myr

→ **Resolves cluster age problem**

Schneider et al. (2014)

The maximum mass problem



- What truncated the mass function of Arches?
- Figer (2005): upper mass limit of 150 $M_\odot$
- Schneider et al. (2014): finite stellar lifetimes

→ Resolves maximum mass problem

Figer 2005

The stellar upper mass limit

- Arches likely too old to determine M_{max}
- Most massive stars likely binary products

- **Consider R136:**
  - Probably all stars alive (de Koter et al. 1998, Massey & Hunter 1998, Crowther et al. 2010, 2016)
  - Still, the most massive stars may be binary products!

The stellar upper mass limit from R136

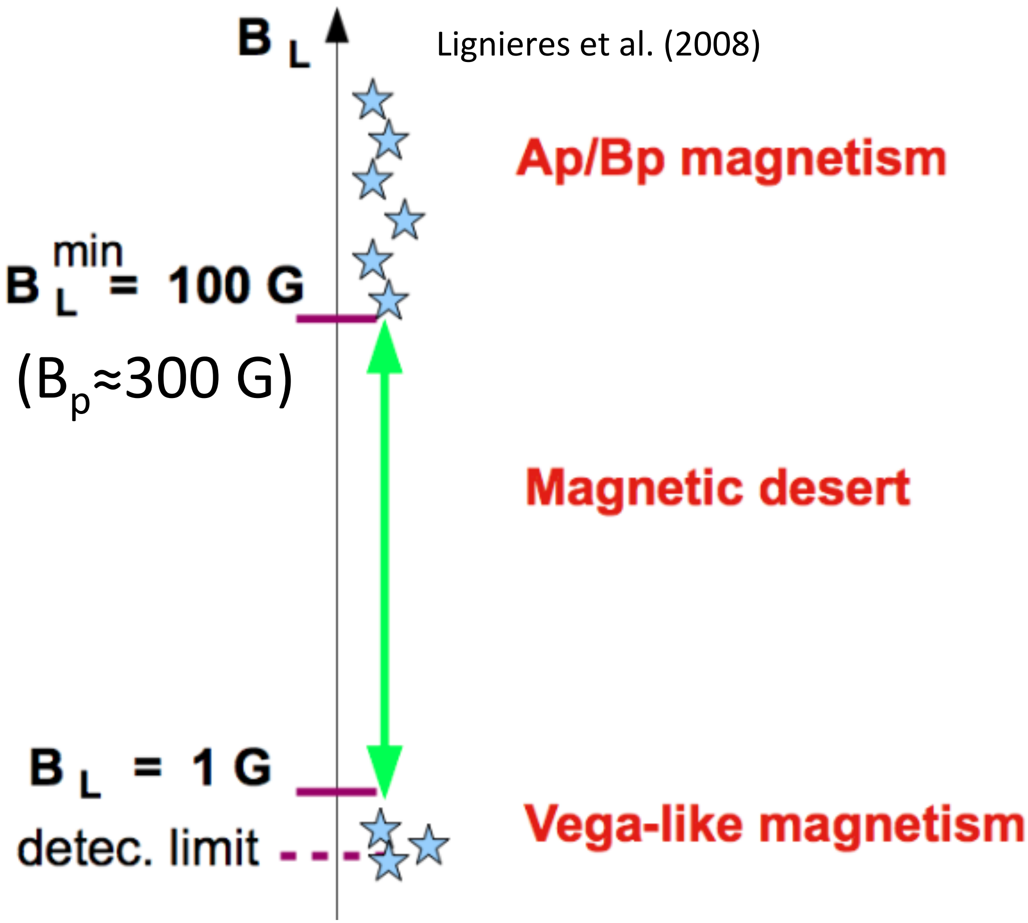
- Which M_{max} needed to form the observed 150-320 $M_\odot$ stars?

$M_{up}/M_\odot$	Single stars	Binary stars
150	✗	✗ $P_{\geq 280} = 0\%$
200	✗	✓ $P_{\geq 280} = 20\%$
300	✓	✓ $P_{\geq 300} = 70\%$
400	✓ $P_{\geq 350} = 63\%$	⚠ $P_{\geq 400} = 41\%$
500	⚠ $P_{\geq 400} = 70\%$	✗ $P_{\geq 500} = 33\%$
>500	✗ $P_{\geq 400} > 70\%$	✗

M_{max} likely in range 200-500 $M_\odot$ → PISNe!

ORIGIN OF MAGNETIC FIELDS IN MASSIVE STARS

Strong magnetic fields in massive stars



≈10% of MS and pre-MS massive stars; no correlation with rotation (Donati & Landstreet 2009, Ferrario et al. 2015, MiMeS, BOB; Kochukhov & Bagnulo 2006)

Record holder: Babcock's star (A0) with $\mathbf{B_p \approx 34}$ **kG**

Dearth in close binaries: established in Ap stars, now confirmed in OB stars, too (BinaMIcS: Neiner&Alecian 2013, Alecian+2015, Neiner+2015; see also Carrier+2002)

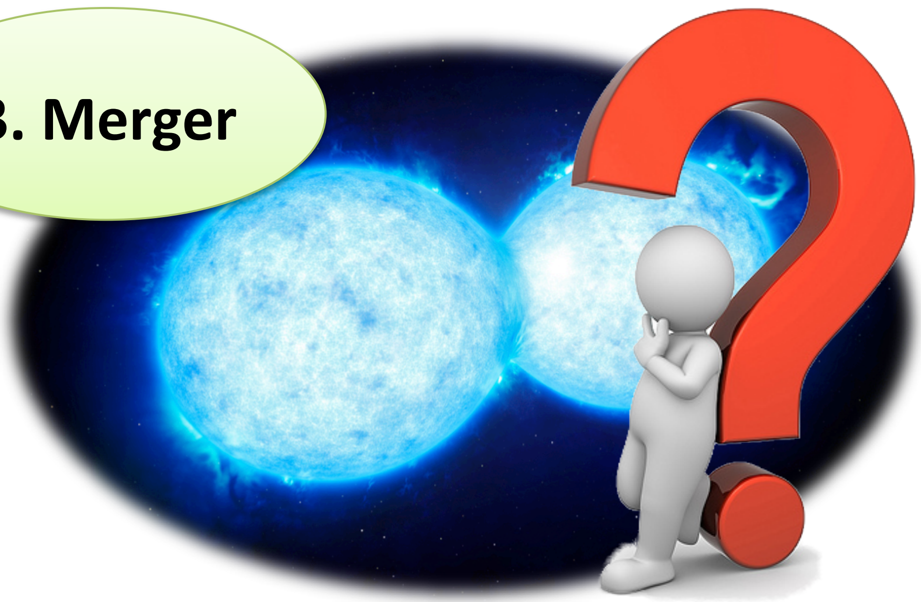
Few close, magnetic binaries known; only 1 with two magnetic stars (Shultz et al. 2015)

Origin of magnetic fields in massive stars

1. Star formation

2. Dynamo

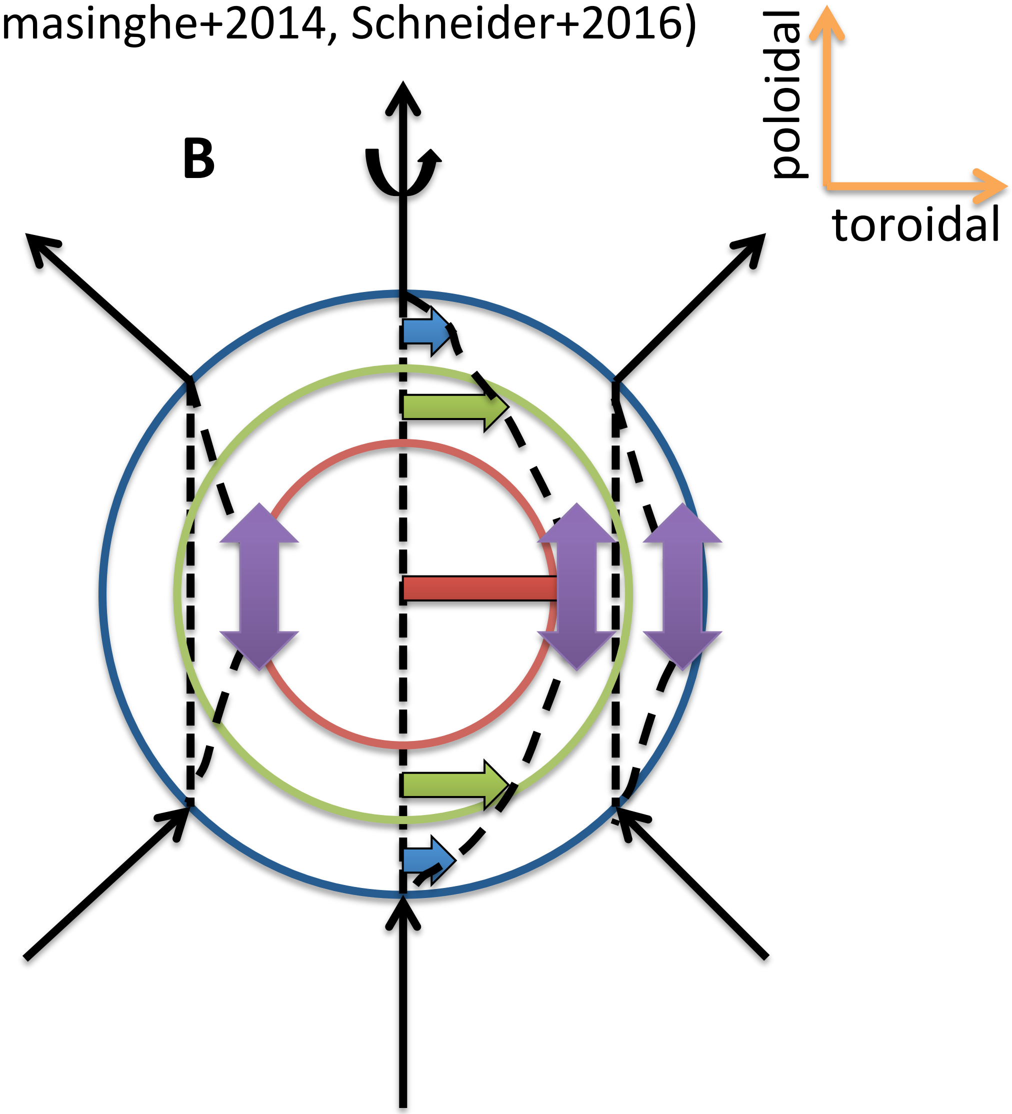
3. Merger

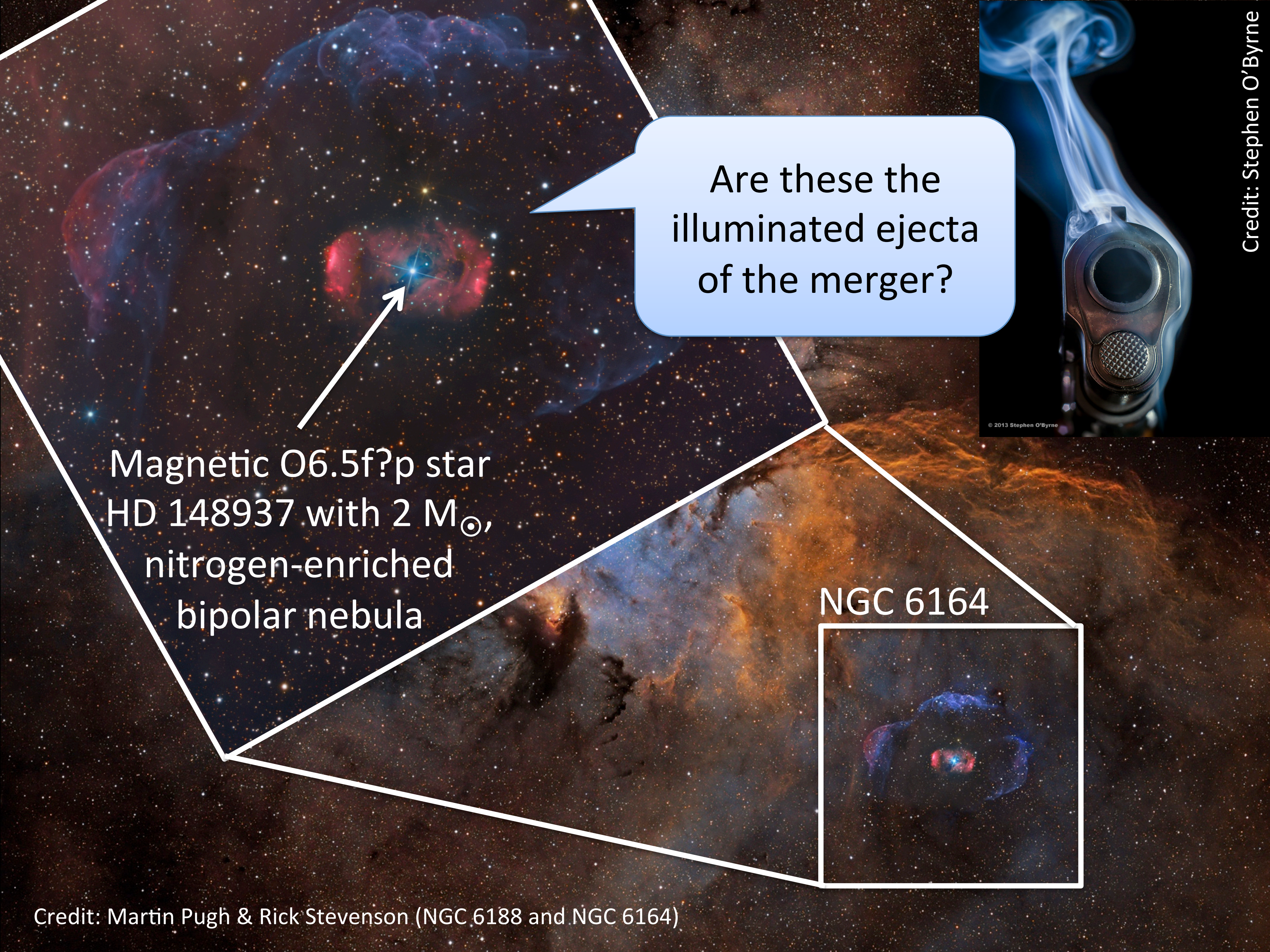


Merger hypothesis – a *handwavy* explanation

- B-field amplification: **differential rotation** and, e.g., **MRI** (Ferrario+2009; Langer 2012; Wickramasinghe+2014, Schneider+2016)

1. Wind-up existing seed field (**differential rotation**)
2. Re-generate poloidal comp. (**turbulence**, e.g. MRI)
3. Continue with step 1. for B-field **amplification**

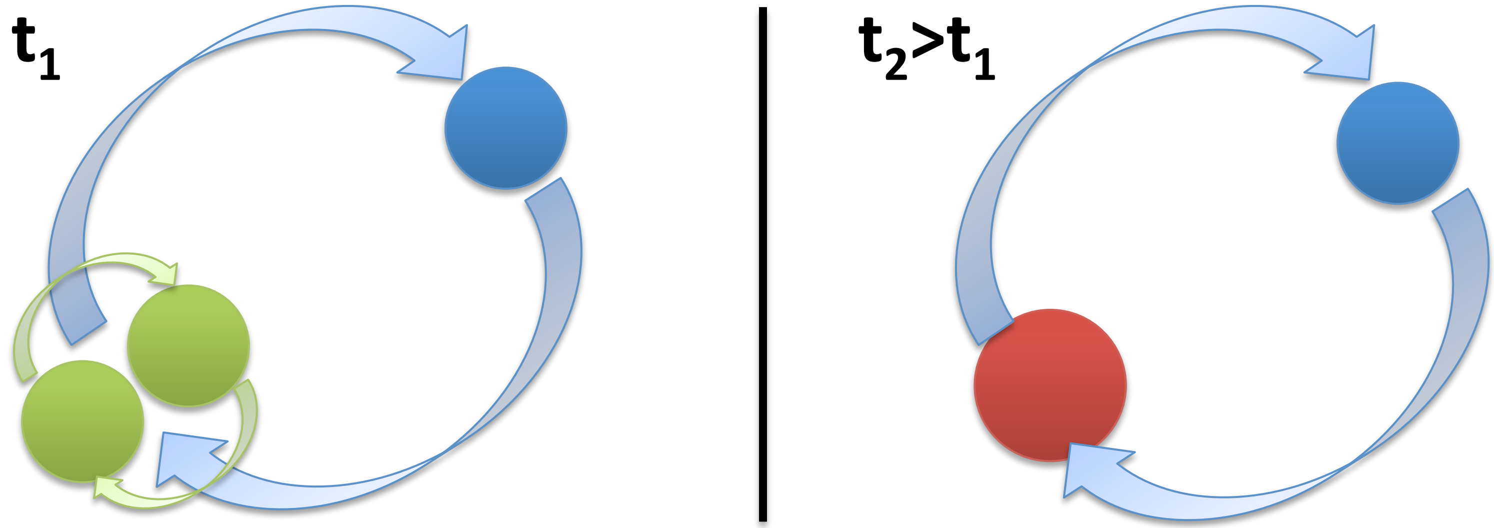




Are these the illuminated ejecta of the merger?
Credit: Stephen O'Byrne
© 2013 Stephen O'Byrne
Magnetic O6.5f?p star HD 148937 with 2 $M_\odot$, nitrogen-enriched bipolar nebula
NGC 6164
Credit: Martin Pugh & Rick Stevenson (NGC 6188 and NGC 6164)

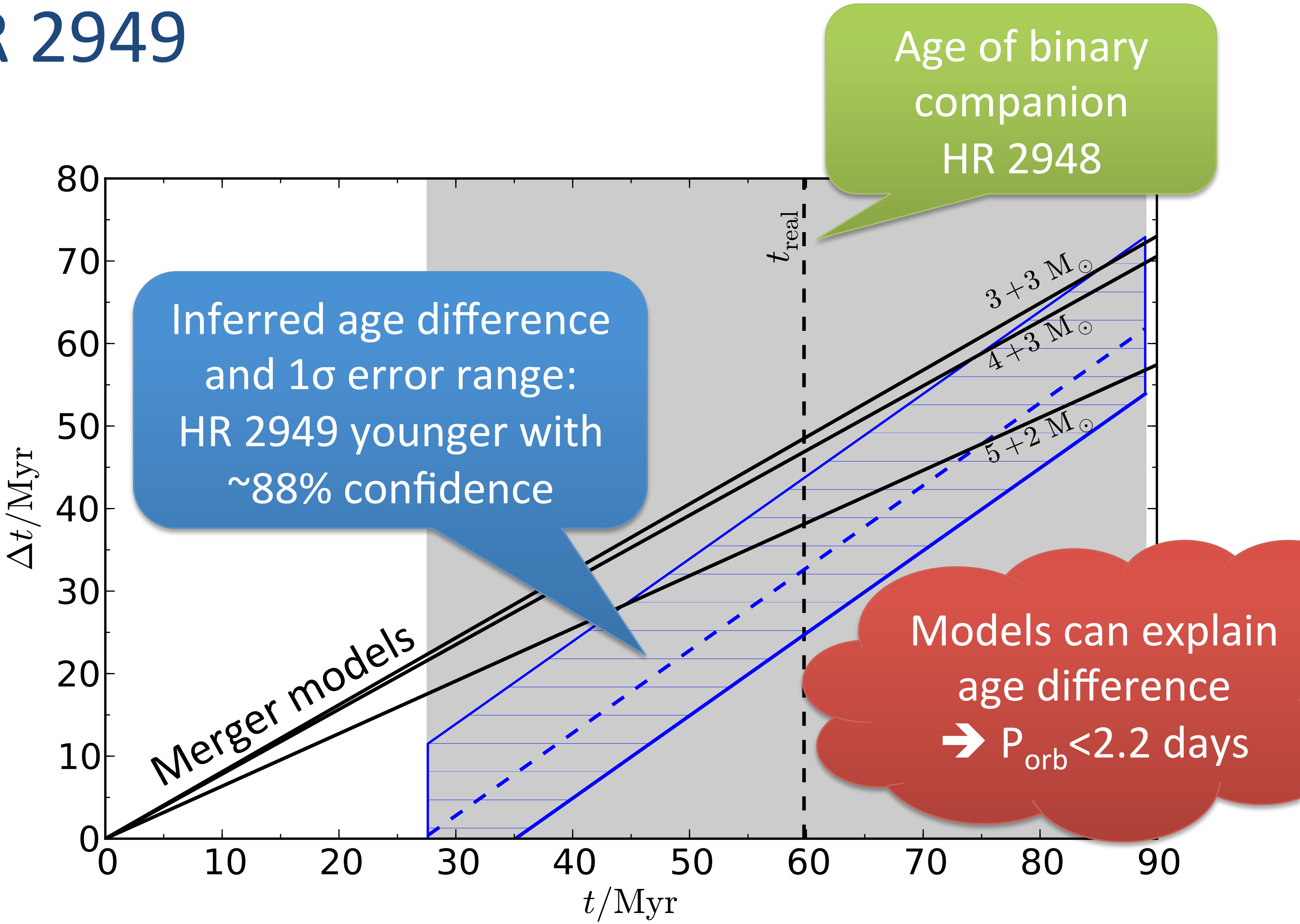
HR 2949

- HR 2948 (4 $M_\odot$) and HR 2949 (6 $M_\odot$) visual pair of B-stars, 7.3 arcsec separated on sky (distance ~139 pc [van Leeuwen+2007]) → orbital separation > 2×10^5 $R_\odot$ (wide binary if grav. bound)
- HR 2949 more massive and magnetic, B_p=2.4kG (Shultz+2015)
- **Scenario**: initial triple star system



- Take stellar parameters of Shultz+2015 and derive apparent ages for both stars using Bayesian code BONNSAI (Schneider+2014)

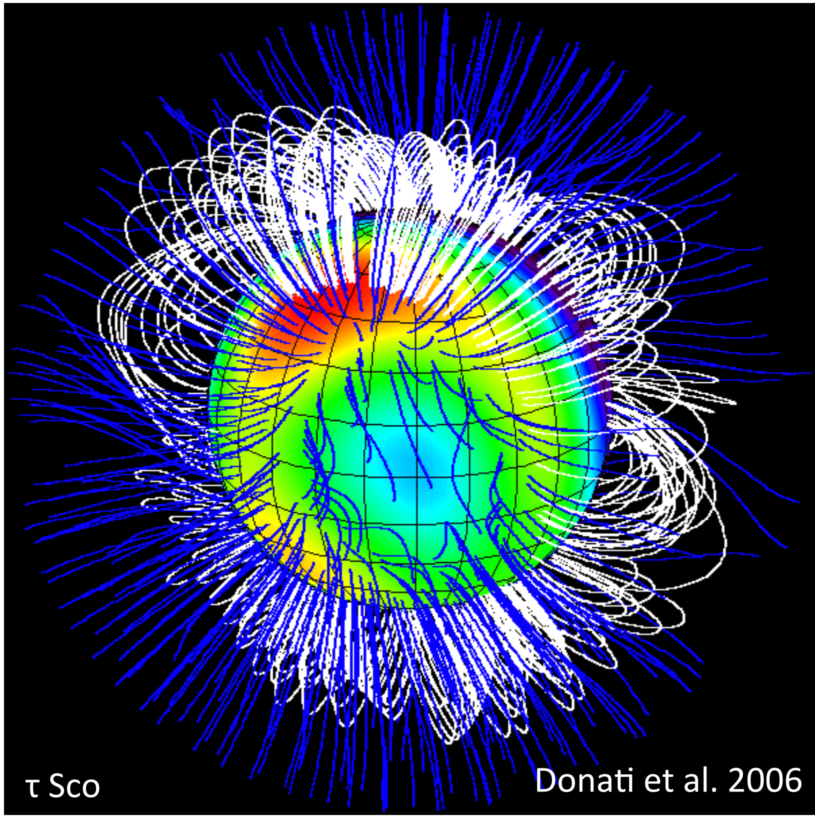
HR 2949


Age of binary companion HR 2948
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
$\Delta t/\mathrm{Myr}$
t/Myr
t_{real}
$3+3\ \mathrm{M}_\odot$
$4+3\ \mathrm{M}_\odot$
$5+2\ \mathrm{M}_\odot$
Merger models
Inferred age difference and 1σ error range: HR 2949 younger with ~88% confidence
Models can explain age difference
➔ P_{orb}<2.2 days

τ Sco

- 16 $M_\odot$; member of Upper Scorpius association; Upper Sco: about 11 Myr old (Pecaut et al. 2012)
- Complex magnetic field, 500 G (Donati et al. 2006)

- τ Sco considered spectral standard → many people derived stellar parameters
- We use parameters of
  - **M05**: Mokiem+2005
  - **SD06**: Simon-Diaz+2006
  - **NP14**: Nieva & Przybilla 2014
- and derive apparent ages for τ Sco using the Bayesian code BONNSAI (Schneider+2014)

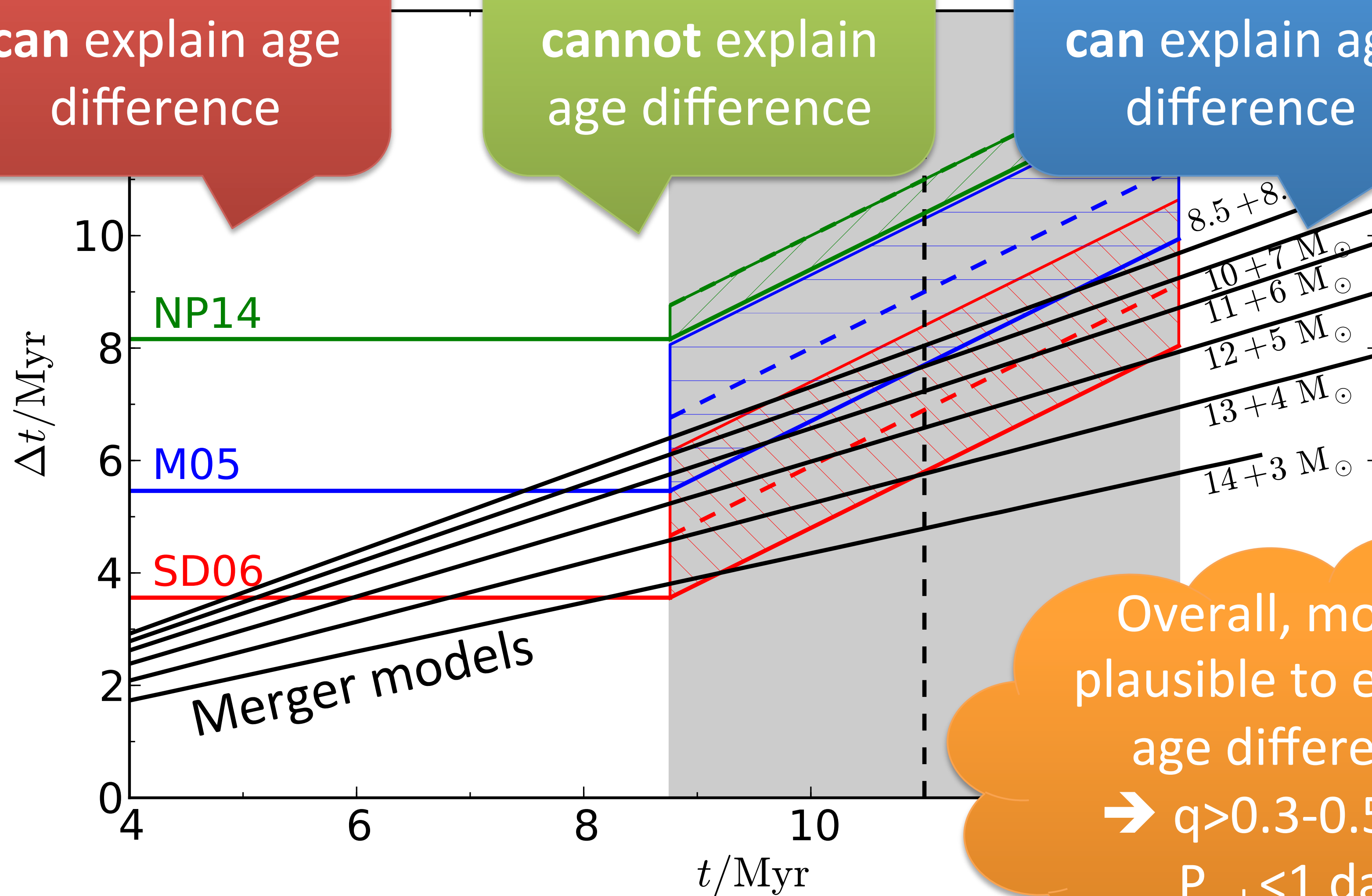


τ Sco

SD06: models **can** explain age difference

NP14: models **cannot** explain age difference

M05: models **can** explain age difference



Overall, models plausible to explain age difference
➔ q>0.3-0.5 and P_{orb}<1 day

SUMMARY

Summary

- ~**25%** of all massive stars merge with companion
- Identify main-sequence merger products by **rejuvenation**
  → requires **comparison clocks**

- **The most massive stars** in clusters likely **merger** or other binary mass-transfer products
  → massive counterpart of classical **blue stragglers**
  - Binary products form **mass-function tail**
  - Affects inference of **stellar upper mass limit**
    → Re-determination: $M_{max} \approx 200\text{-}500\ M_\odot$

- **Origin of strong magnetic fields in massive stars**
  - **HR 2949** and **τ Sco** apparently too young and age discrepancies compatible with **merger** scenario
  - Powerful **new method** to pin-down origin of B-fields

Credit: ESO/L. Calçada

Thank you for your attention!