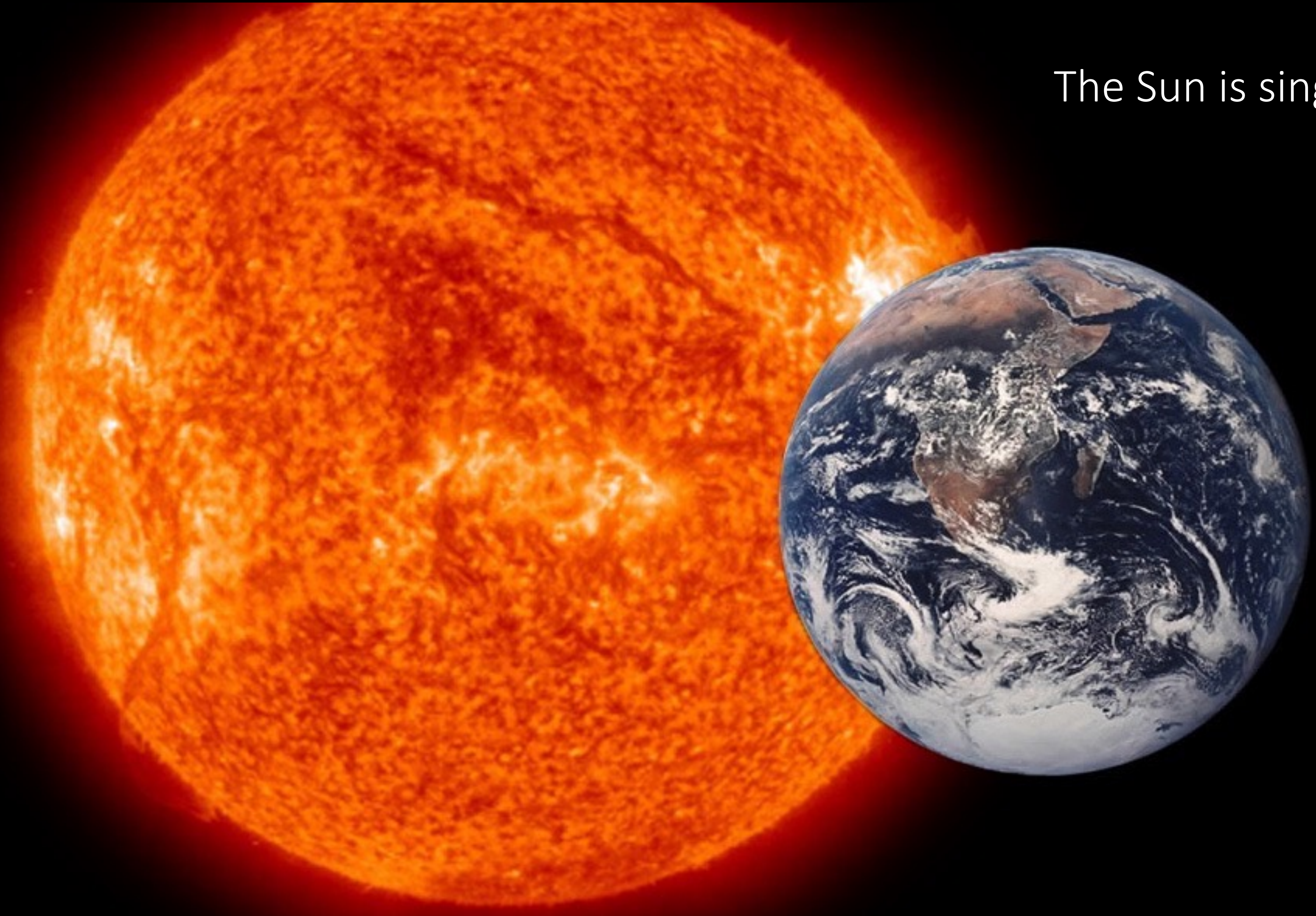
The zoo of binary stars

Henri Boffin

The Sun is single…



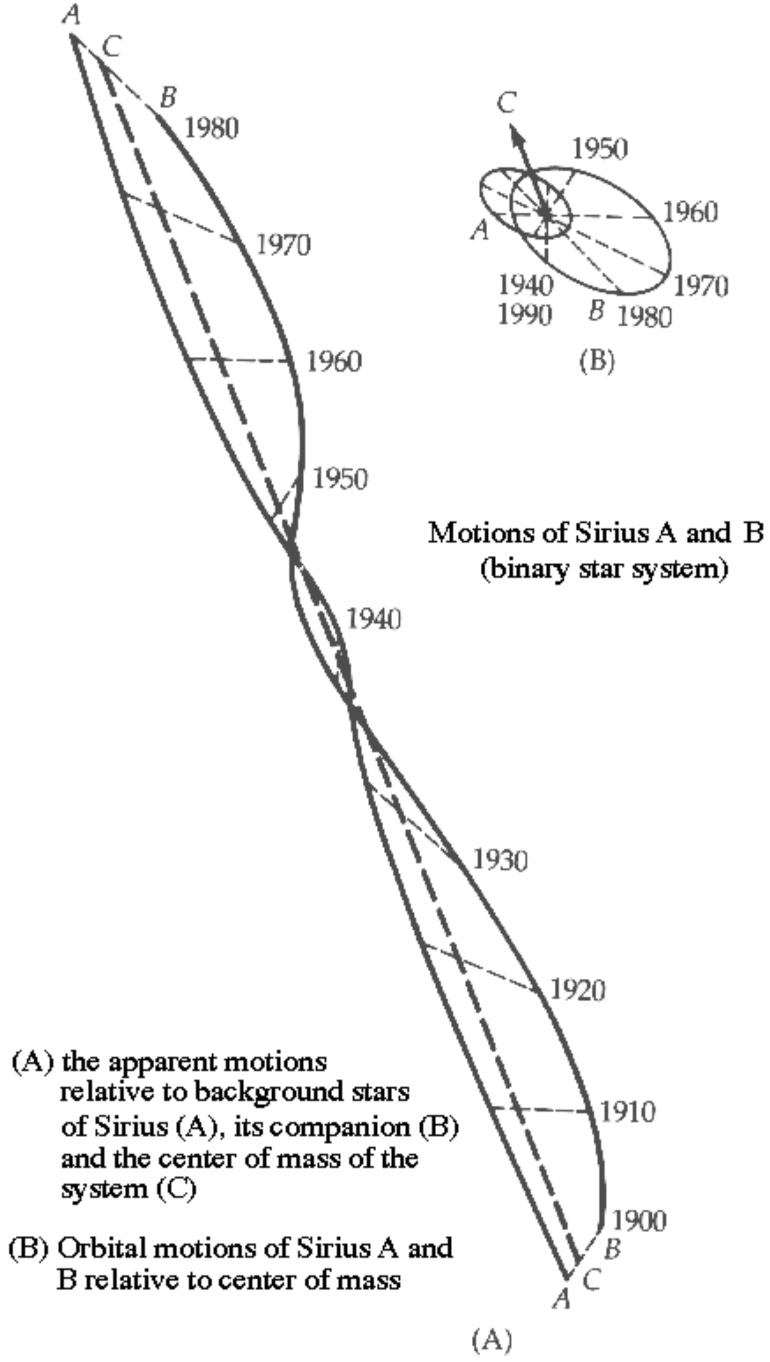
…but most stars aren’t

Star Wars Episode IV: A New Hope.

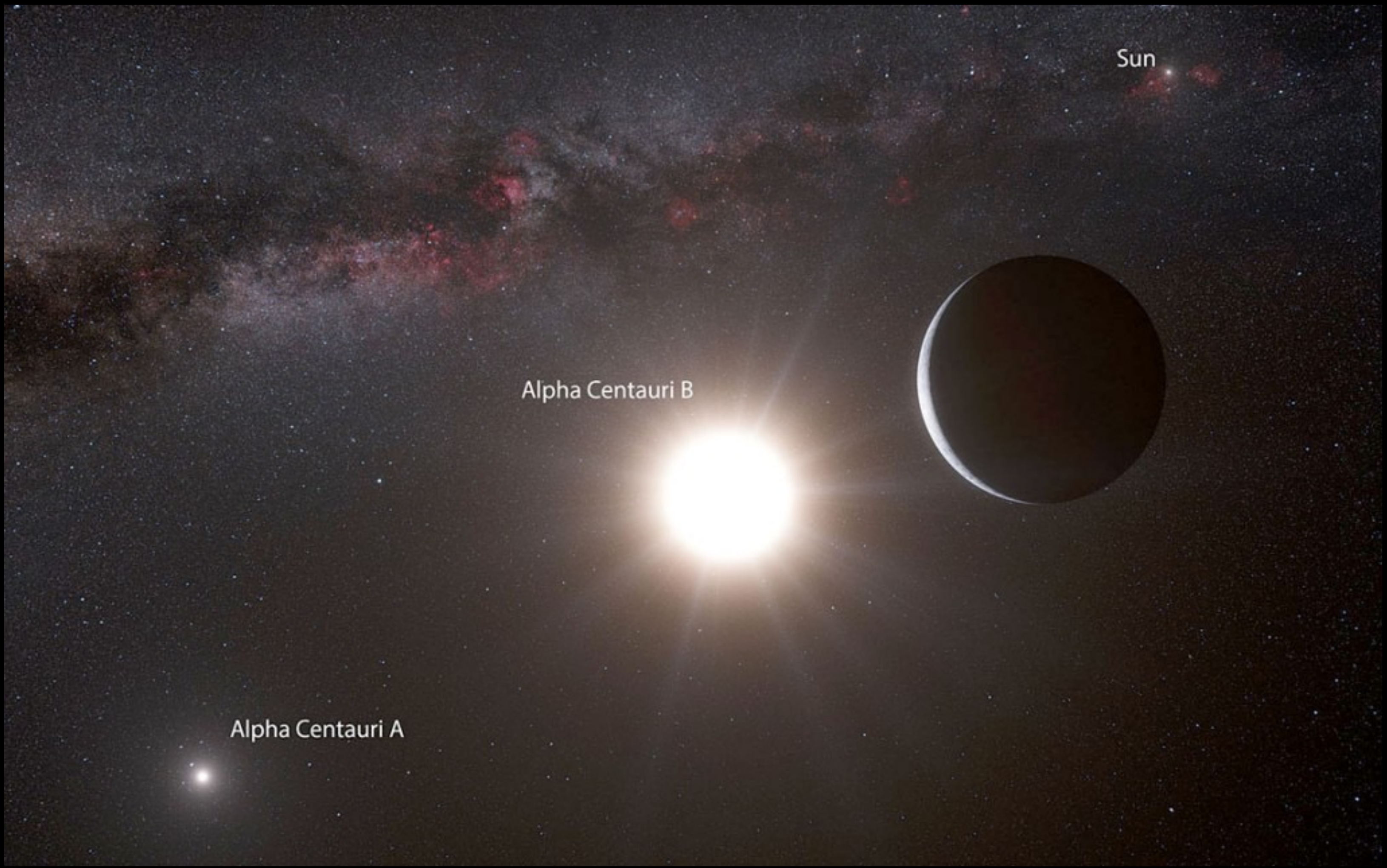
The brightest star in the night sky is a binary

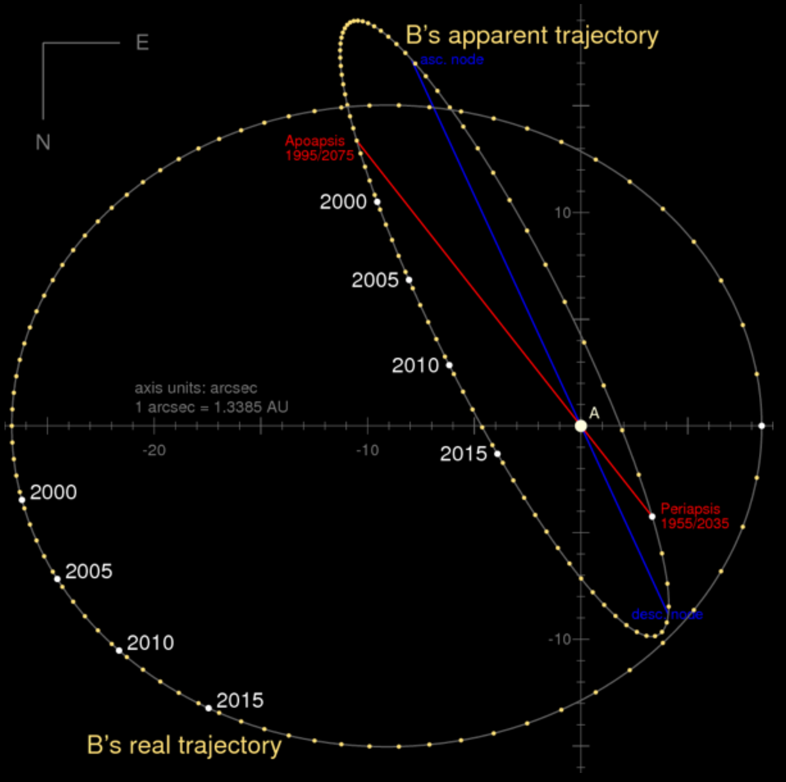
A1V + DA2
P=50 yr

The presence of Sirius B was first detected by observing the wobble in the motion of Sirius A
…an Astrometric Binary



Among the closest ones …





4.37 ly (1.34 pc) away

1.1 M☉ + 0.9 M☉

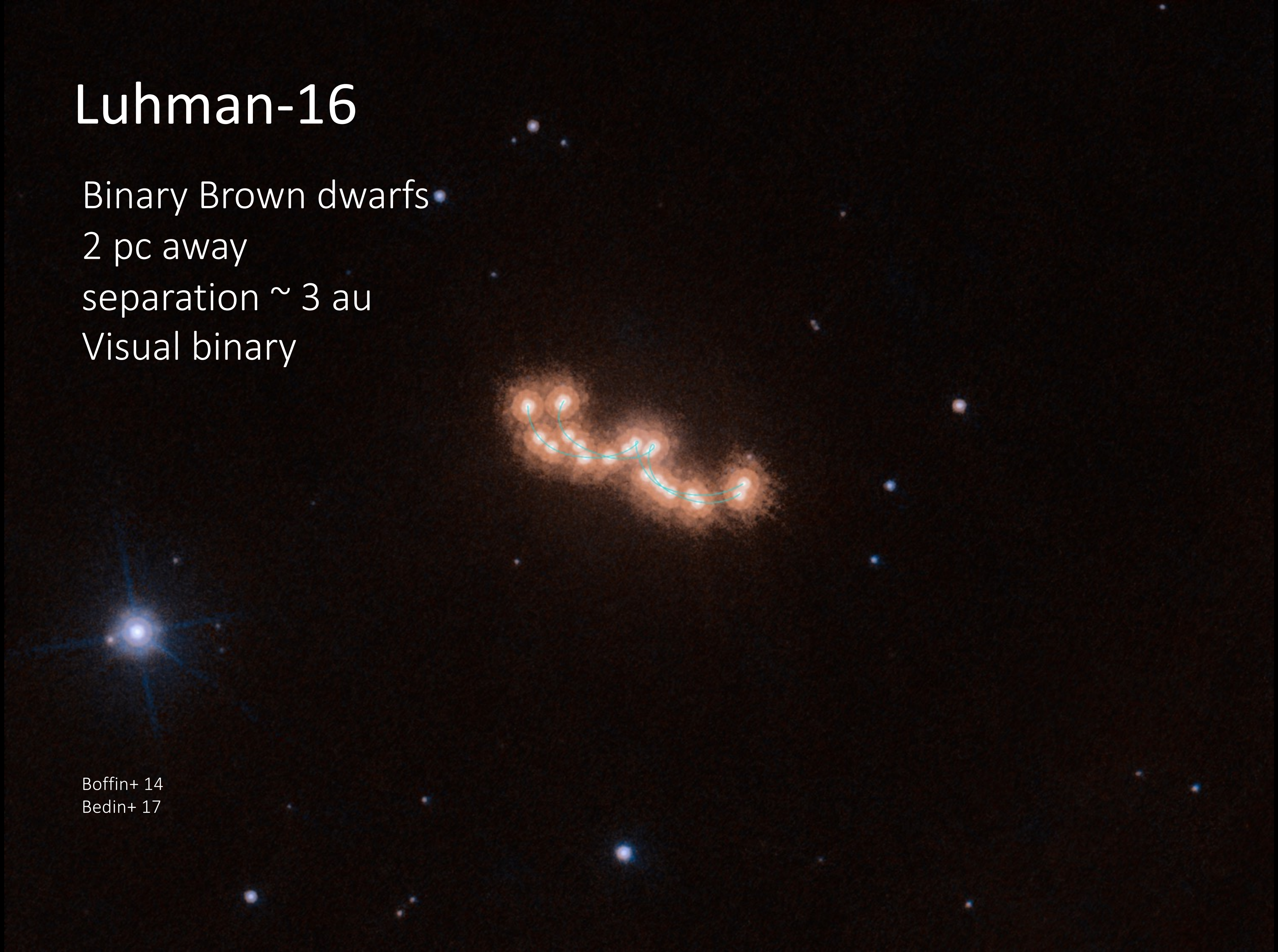
P = 79 years

Visual binary

Triple system with Proxima Centauri

Luhman-16

Binary Brown dwarfs
2 pc away
separation ~ 3 au
Visual binary



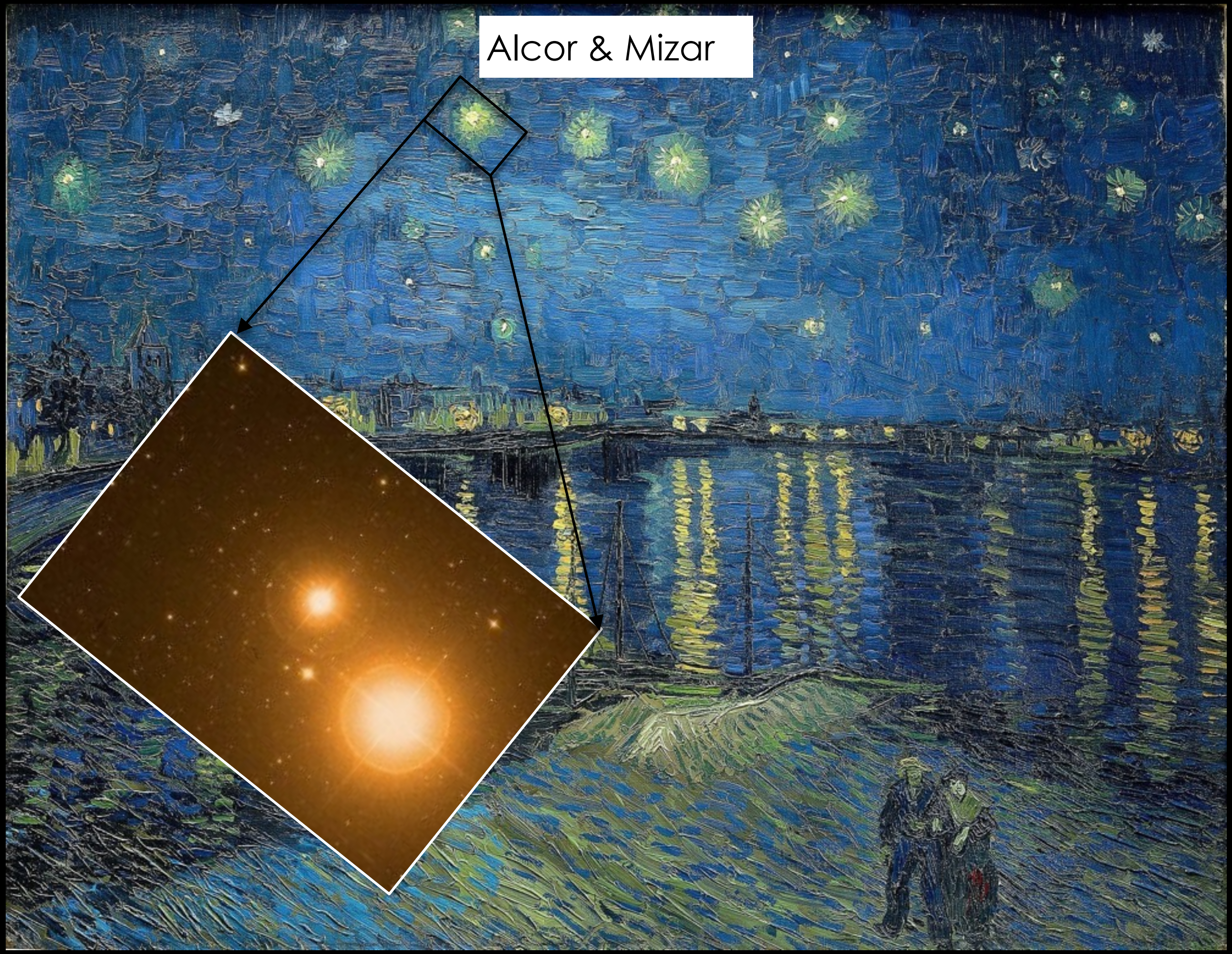
Boffin+ 14
Bedin+ 17

Another famous multiple

Starry night - Van Gogh

Adapted from de Mink 12

Another famous multiple



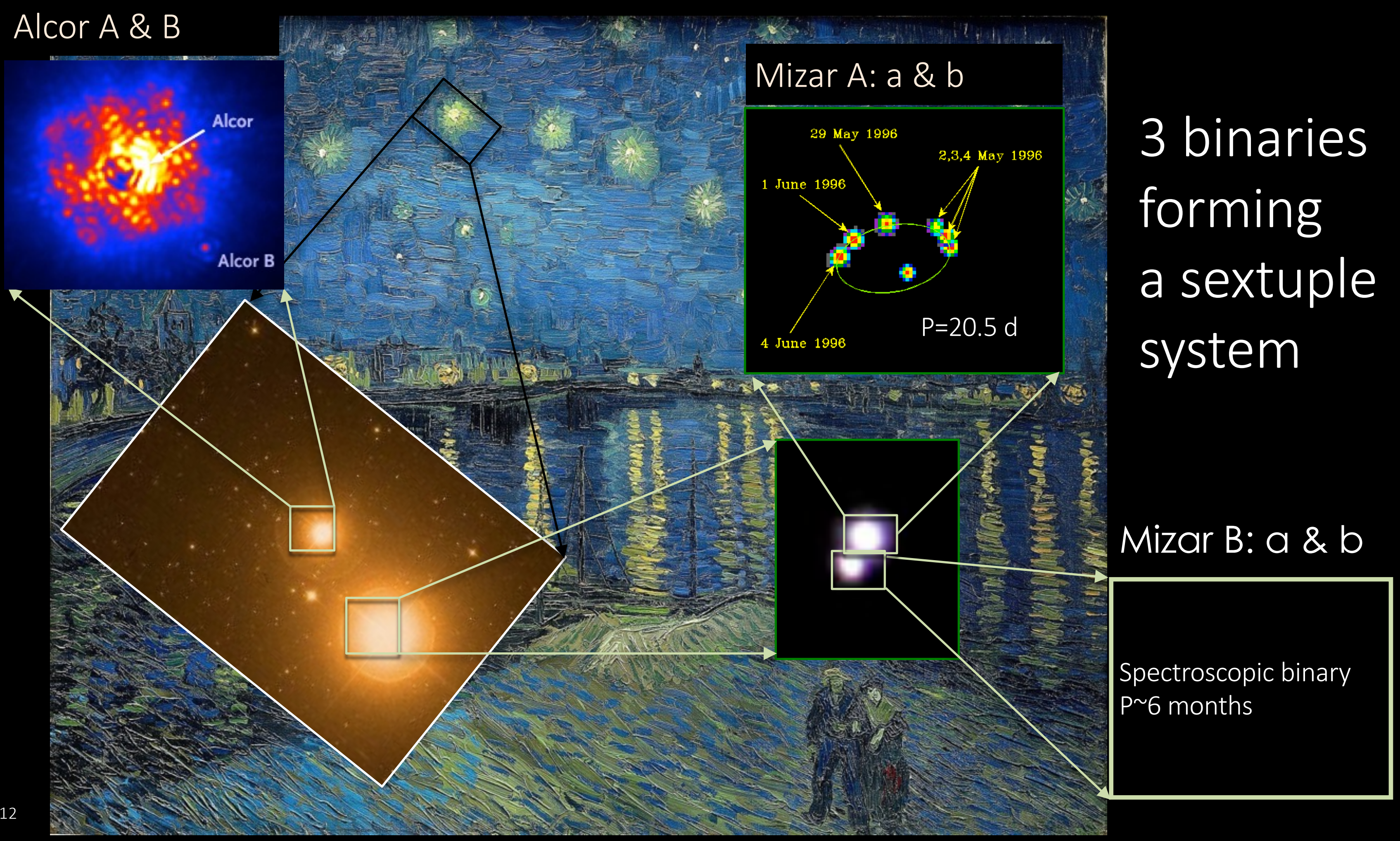
Starry night - Van Gogh

Lifespan star
or "jumyouboshi" (寿命星)

Married couple in
Indian astronomy

Adapted from de Mink 12

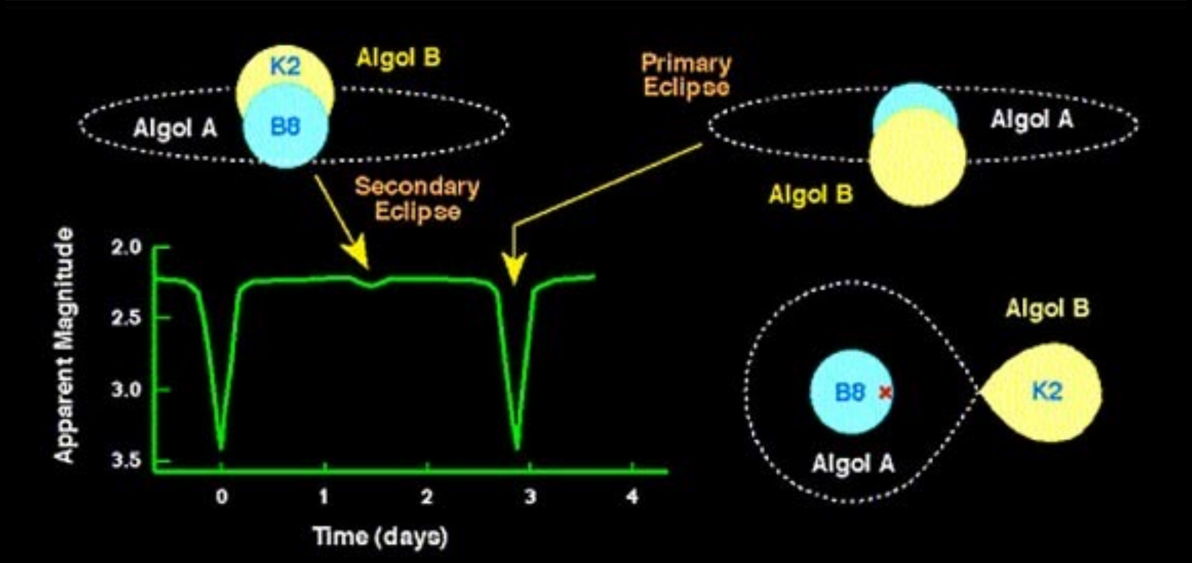
Another famous multiple



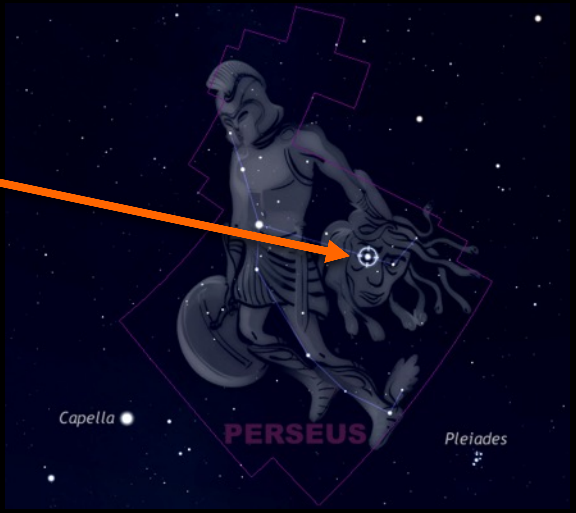
3 binaries forming a sextuple system

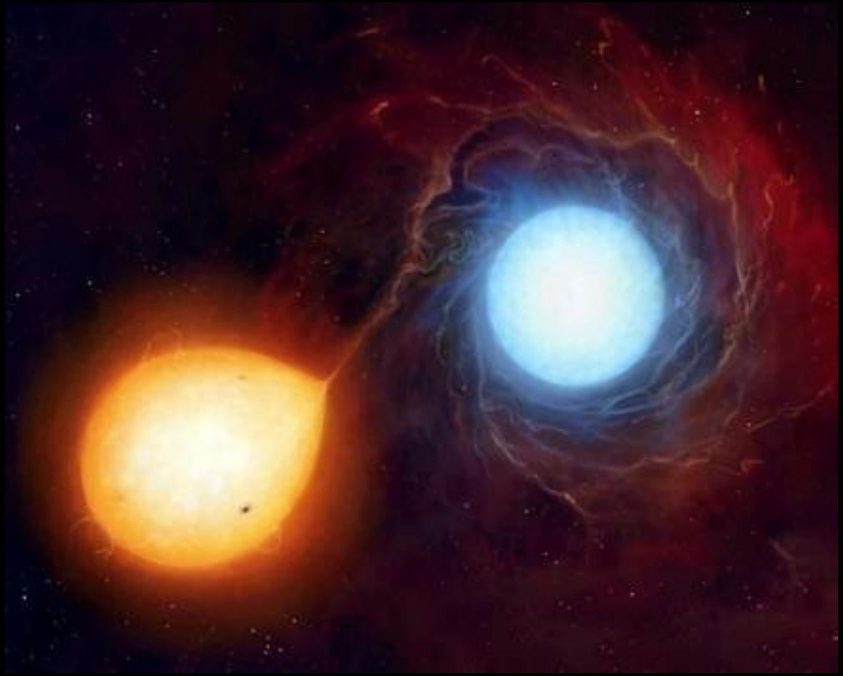
Adapted from de Mink 12

Algol (The Daemon)



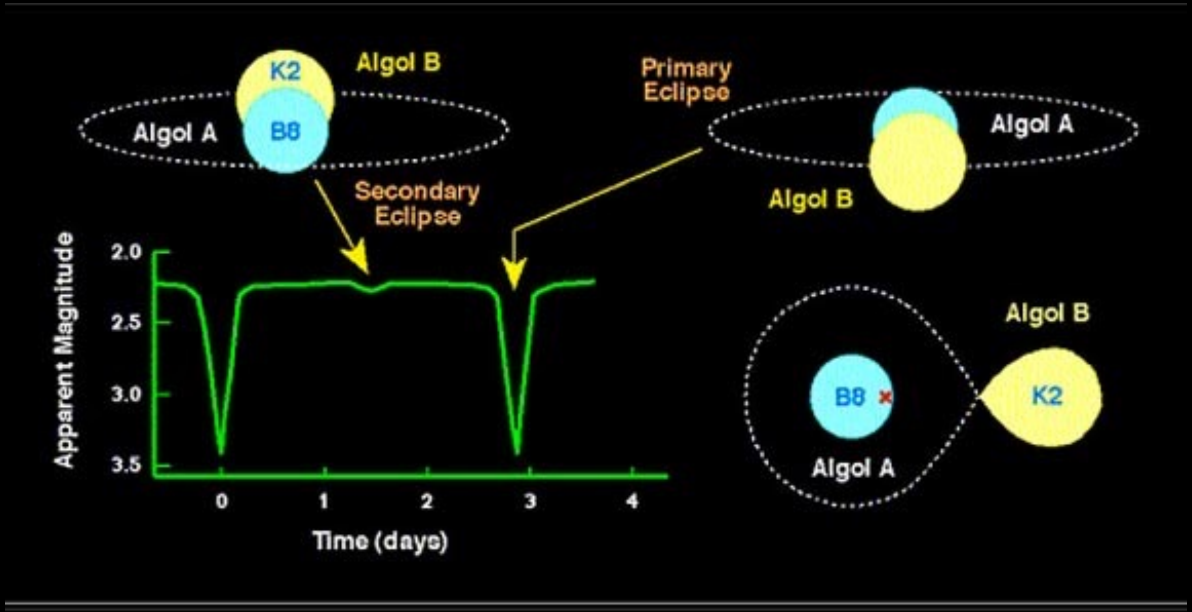
The Algol System



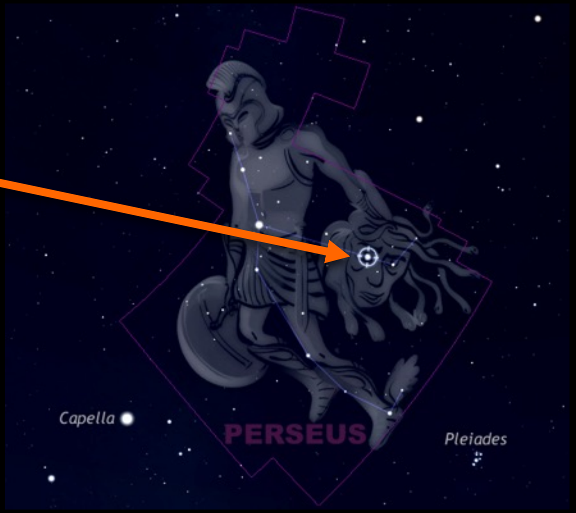


Primary: B8 V, 3.7 M☉
Secondary: K2 IV, 0.8 M☉

Algol (The Daemon)



The Algol System



Primary: B8 V, 3.7 M☉
Secondary: K2 IV, 0.8 M☉

The more evolved star is the less massive!

Algol paradox!

Mass Transfer!

Another extreme: Eta Carinae

LBV 120 $M_\odot$ + 30 $M_\odot$ companion

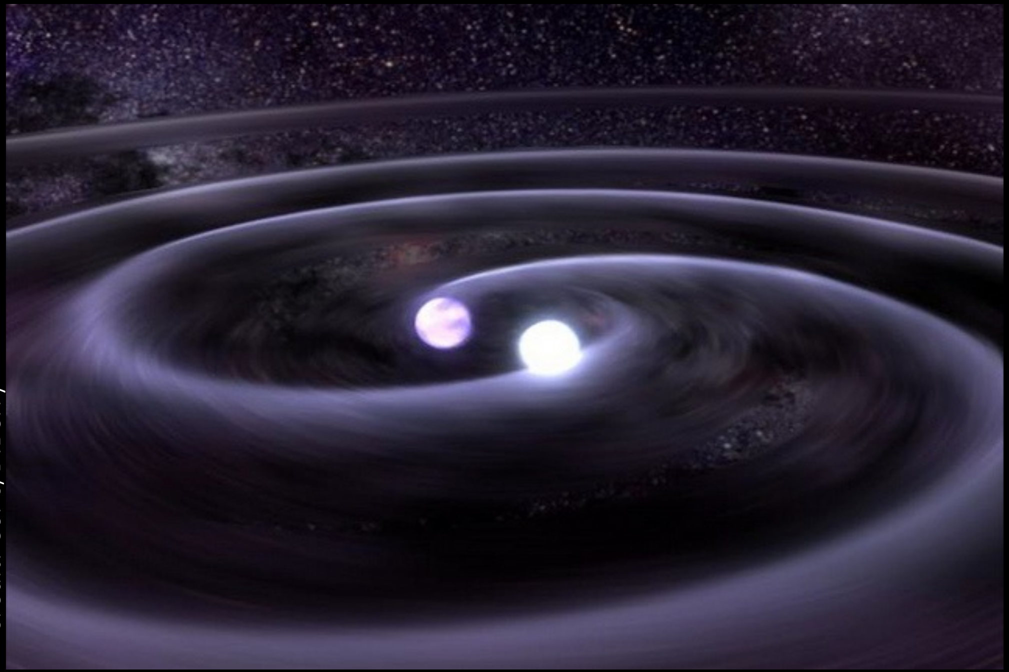
Eccentric system

P = 5.5 years

Undergo outburst

The next Supernova in our Galaxy?

SDSSJ010657.39-100003.3



Credit: GSFC/D.Berry

Kilic+ 11

Detached binary

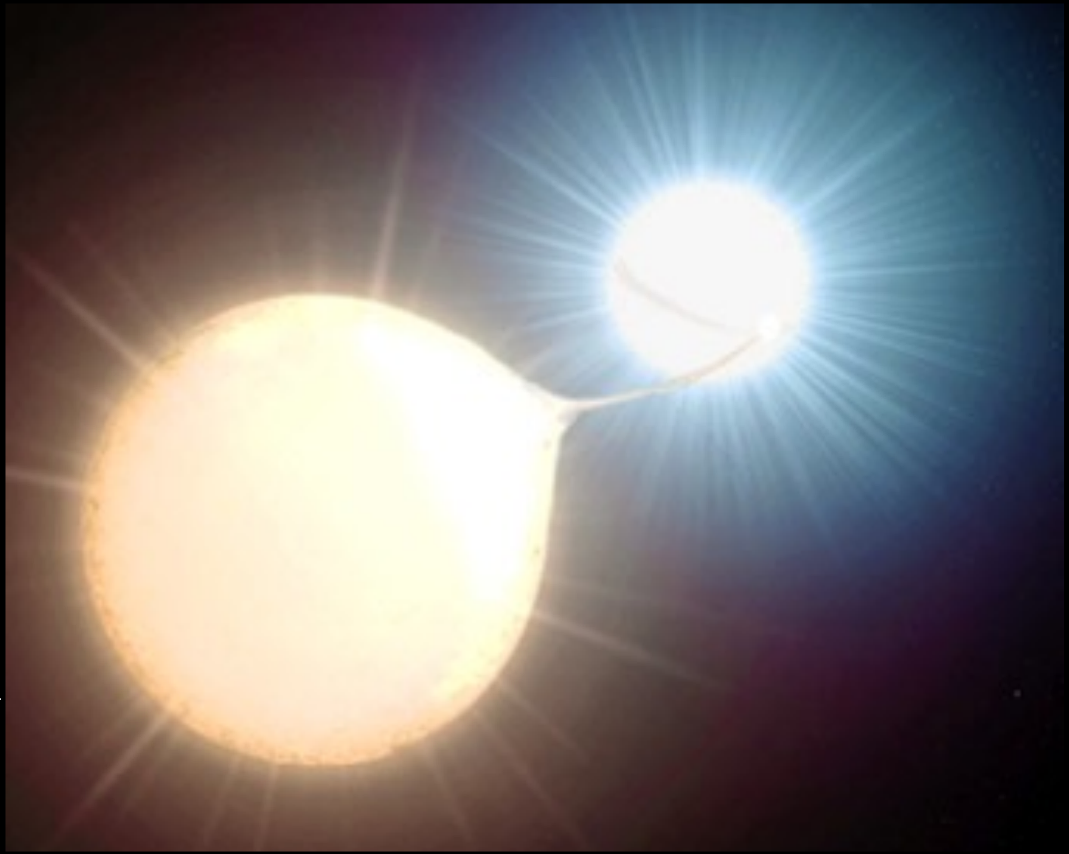
P = 39.1 min

2 WDs

A = 0.32 $R_\odot$

Will merge in 37 Myr to become a sdB star

HM Cancri



S&T: Casey Reed

Roelofs+ 10

Two white dwarfs

One is transferring mass to the other!

Orbital period 321 seconds!

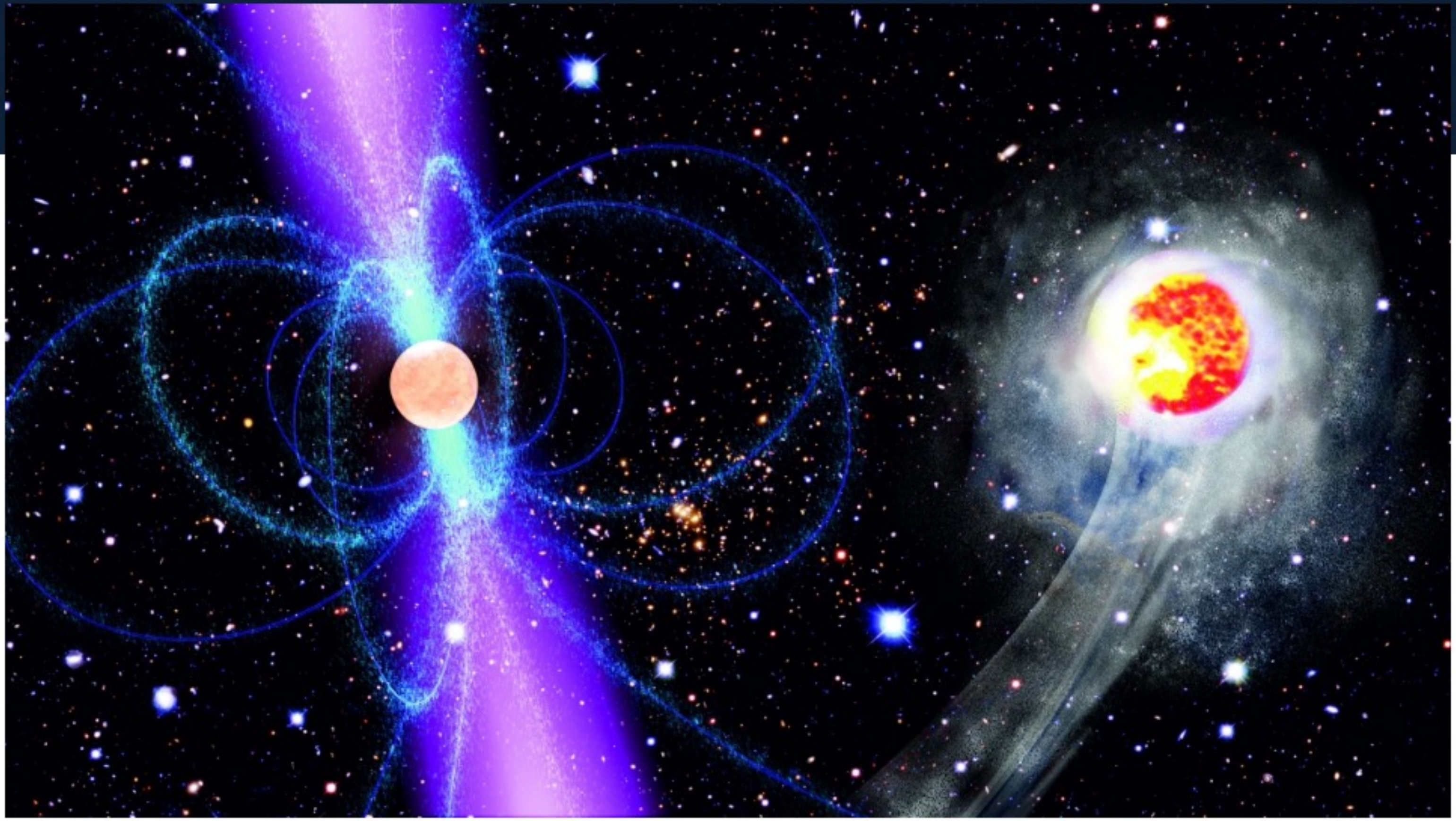
Distance between stars:
<100 000 km

Orbital velocity > 10^6 km/h

Masses: 0.27 and 0.55 $M_\odot$

Super-dense neutron star is fastest ever seen

Astronomers have discovered an ultra-dense star that orbits with a dying stellar companion once every 93 minutes, making it the fastest-orbiting star of its kind.



This artist's impression shows the speedy companion (right) as it races around the pulsar PSR J1311-3430 (left). The energetic gamma-radiation emitted by the pulsar heats and consequently evaporates the companion. The pulsar, which completes one orbit every 93 minutes, is surrounded by its strong magnetic field (blue). NASA/DOE/Fermi LAT Collaboration/AEI

Oct. 25, 2012, 9:36 PM CEST / Source: Space.com

By Mike Wall

Black widow

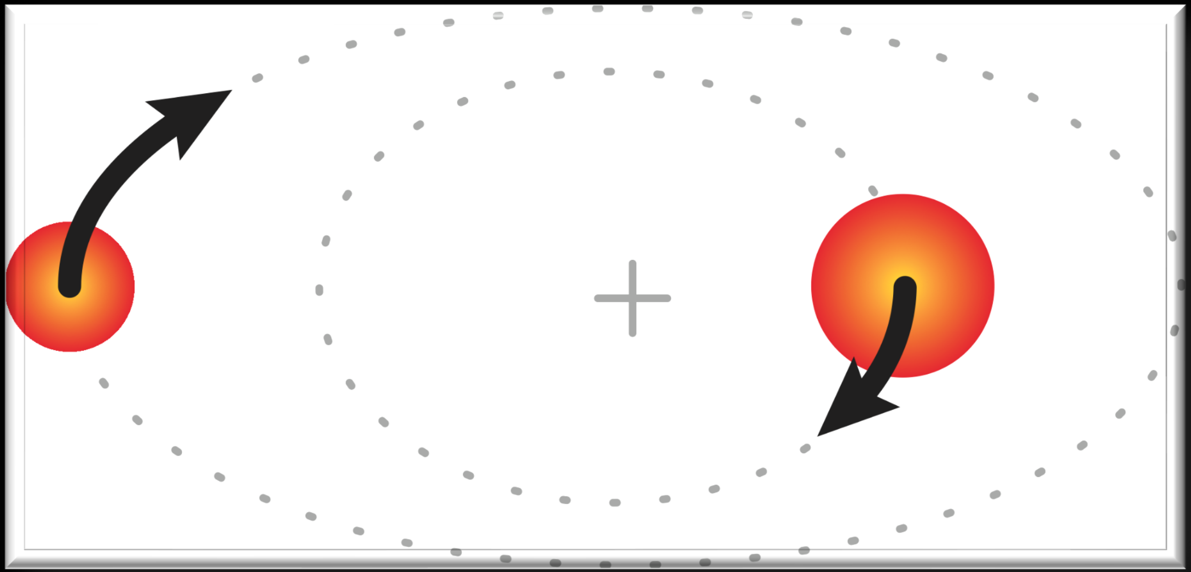
Milli-second pulsar with a low-mass companion

The companion transferred mass to the pulsar and is now being evaporated by the pulsar

A dozen known in MW

Binary star

a system of two stars, which are so close that their gravitational interaction causes them to orbit around their common centre of mass.



Why Binaries?

“*To understand galaxies, we need to understand stars, but since most are members of binary and multiple star systems, we need to study and understand binary stars…*

…And sometimes binary stars are the only way to understand single stars …”

–R. Izzard (2009)

Why Binaries?

Accurate stellar masses, radii, luminosities

Help understand many events, e.g., PNe, novae, short gamma-ray bursts, Type Ia SNe, chemically peculiar stars, blue stragglers

Galactic evolution: Type Ia Sne, novae

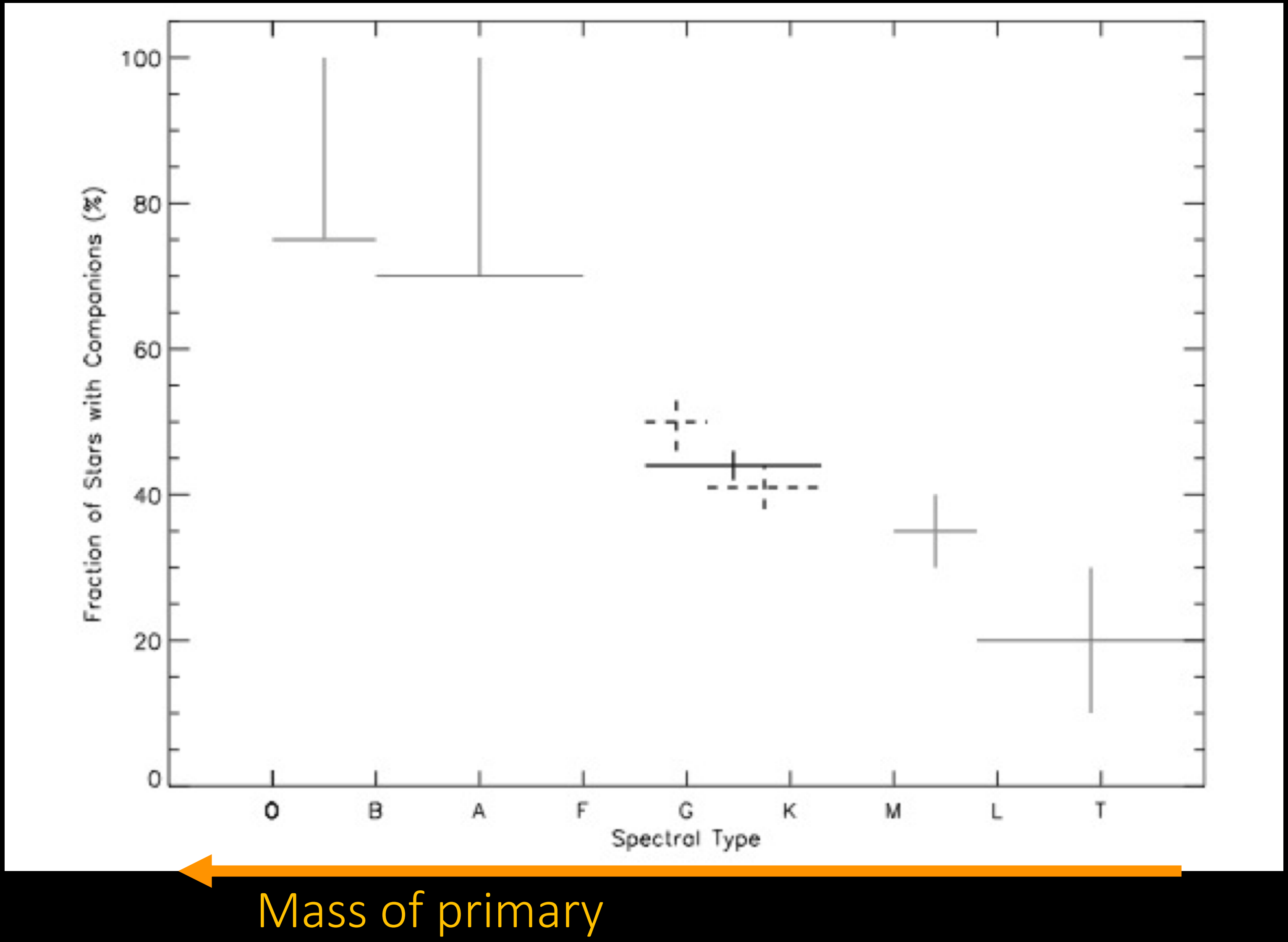
Why Binaries?

"*Even though a star may be single now, it may well have been a member of a binary system in the past.*

Indeed, whenever one is confronted with a new stellar phenomenon, it is probably advisable to first thoroughly explore the possibility of a binary interaction as a cause of the phenomenon before starting to adjust the input physics in the stellar calculation."

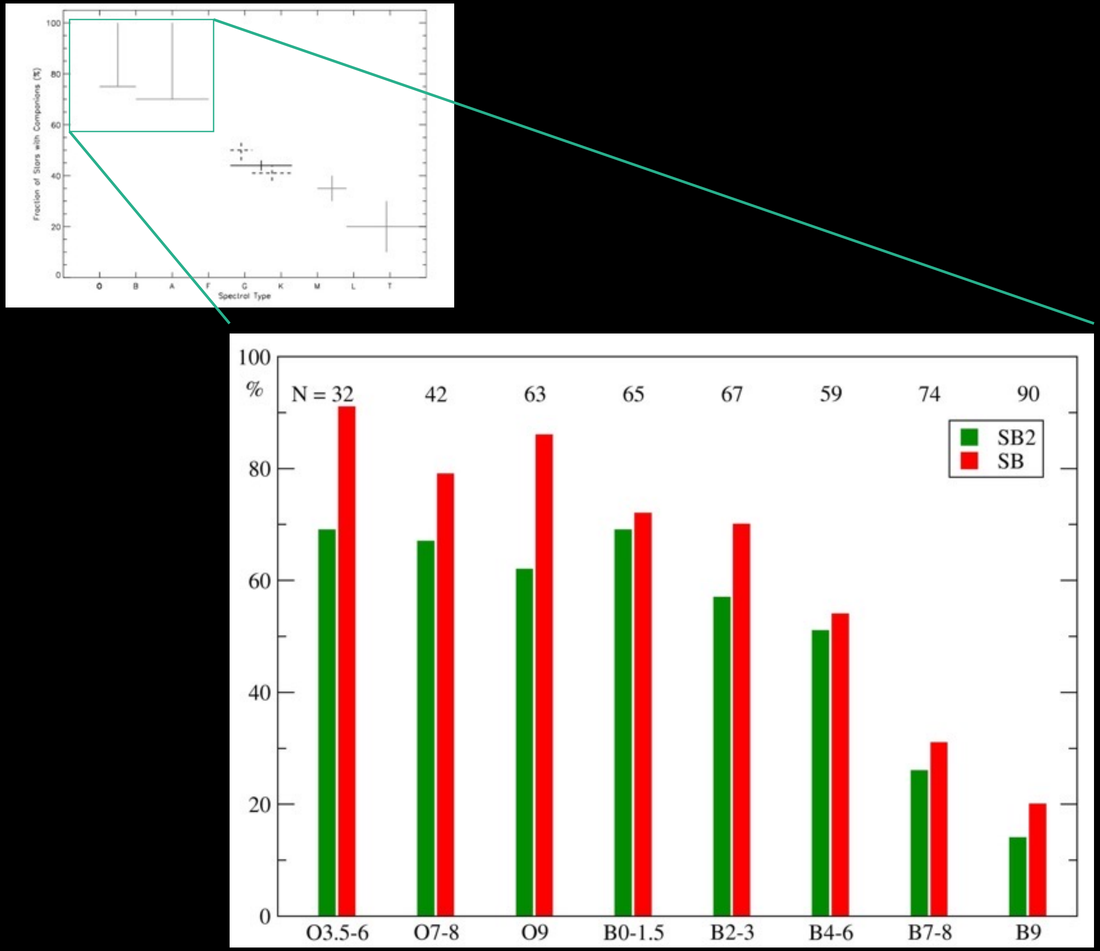
–P. Podsiadlowski

Multiplicity is function of primary mass



Raghavan+ 10
(see also Clark+ 11)

Close binary star fraction of massive stars



Chini+ 12; see also Sana+12

the **close** binary fraction decreases from 90% (80 $M_\odot$) to 20% (3 $M_\odot$)

SB2: O stars like to be born as twins of similar mass

Is a massive star appears to be single…

… you probably did not look hard enough

… or it used to be a binary in the past
(merger, mass gainers, ejected)

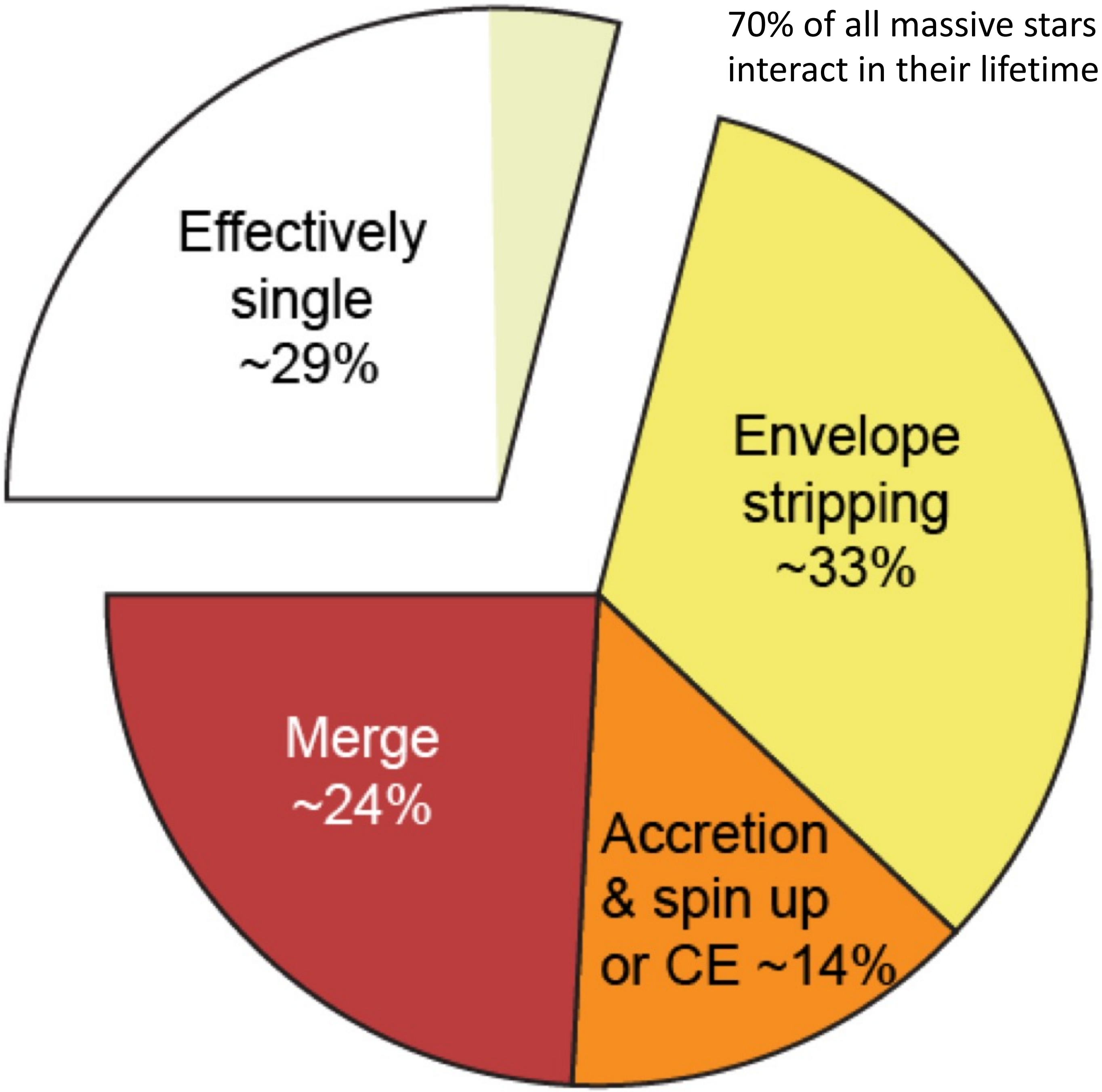
De Mink, 13

Massive stars in 6 young clusters in the Milky Way

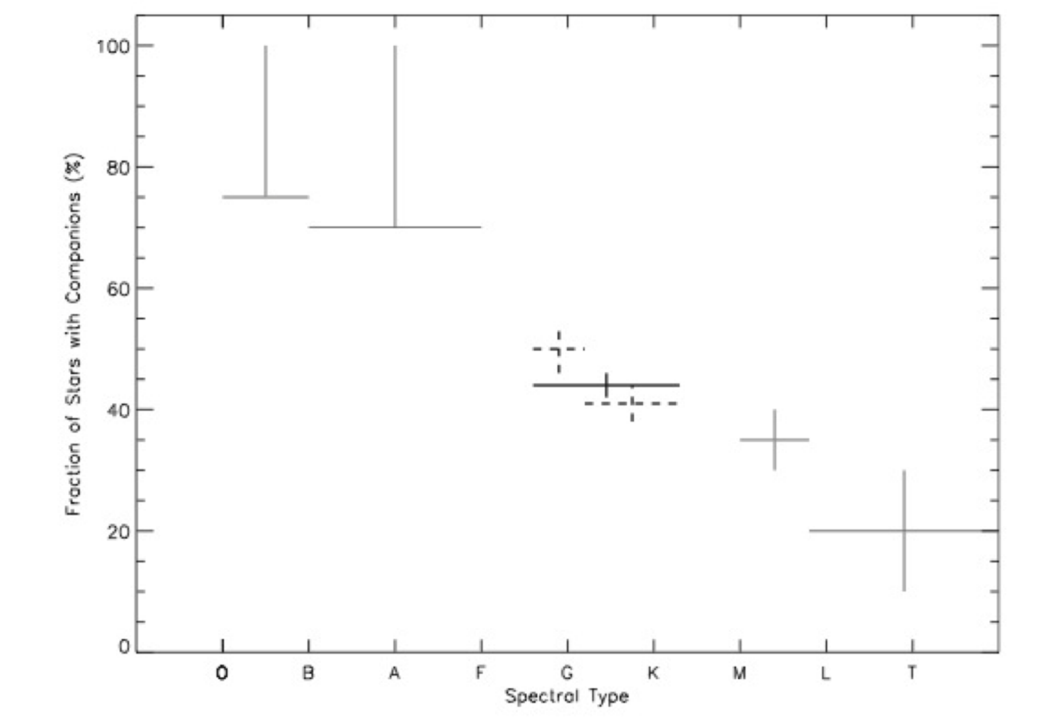
71 single and multiple O-type objects

40 detected binaries

Sana+ 12

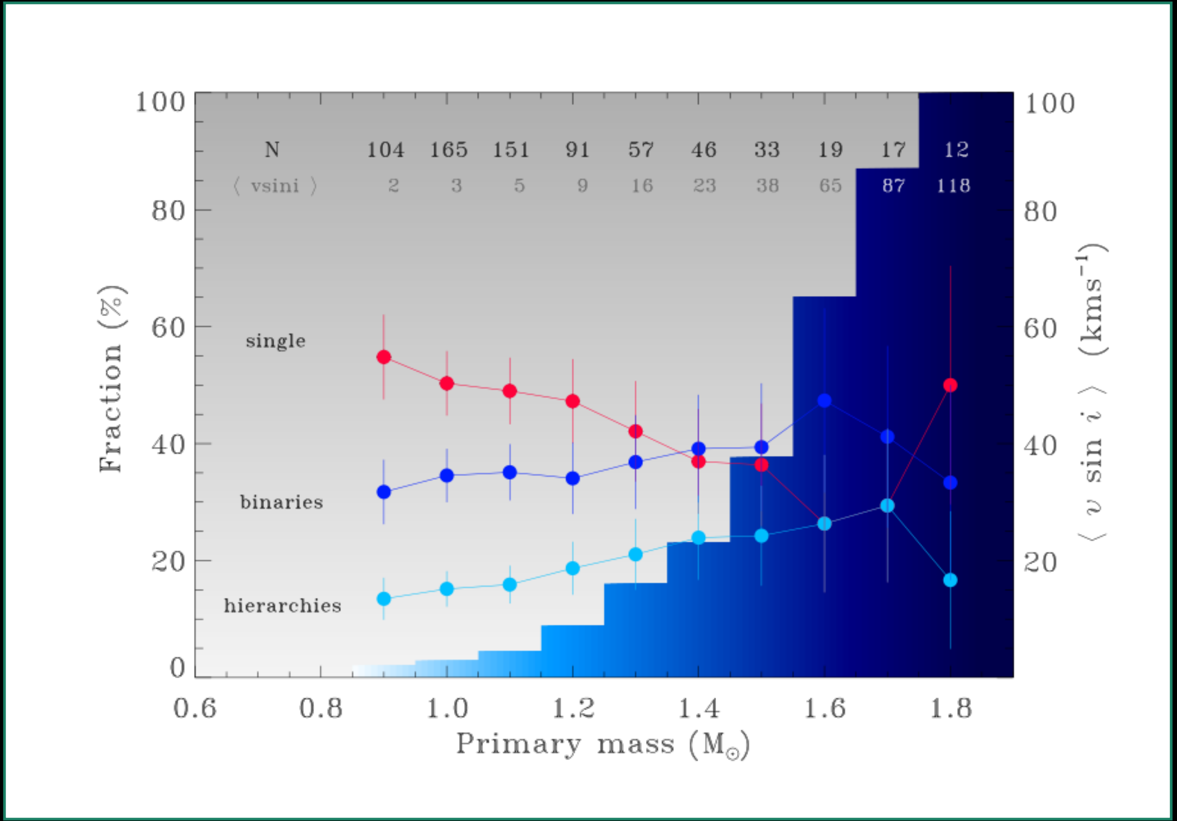


Multiplicity is function of primary mass – low mass stars



Raghavan + 10

Mass of primary



Fuhrmann + 17

But is this the full story?

What about stars that are secondaries?

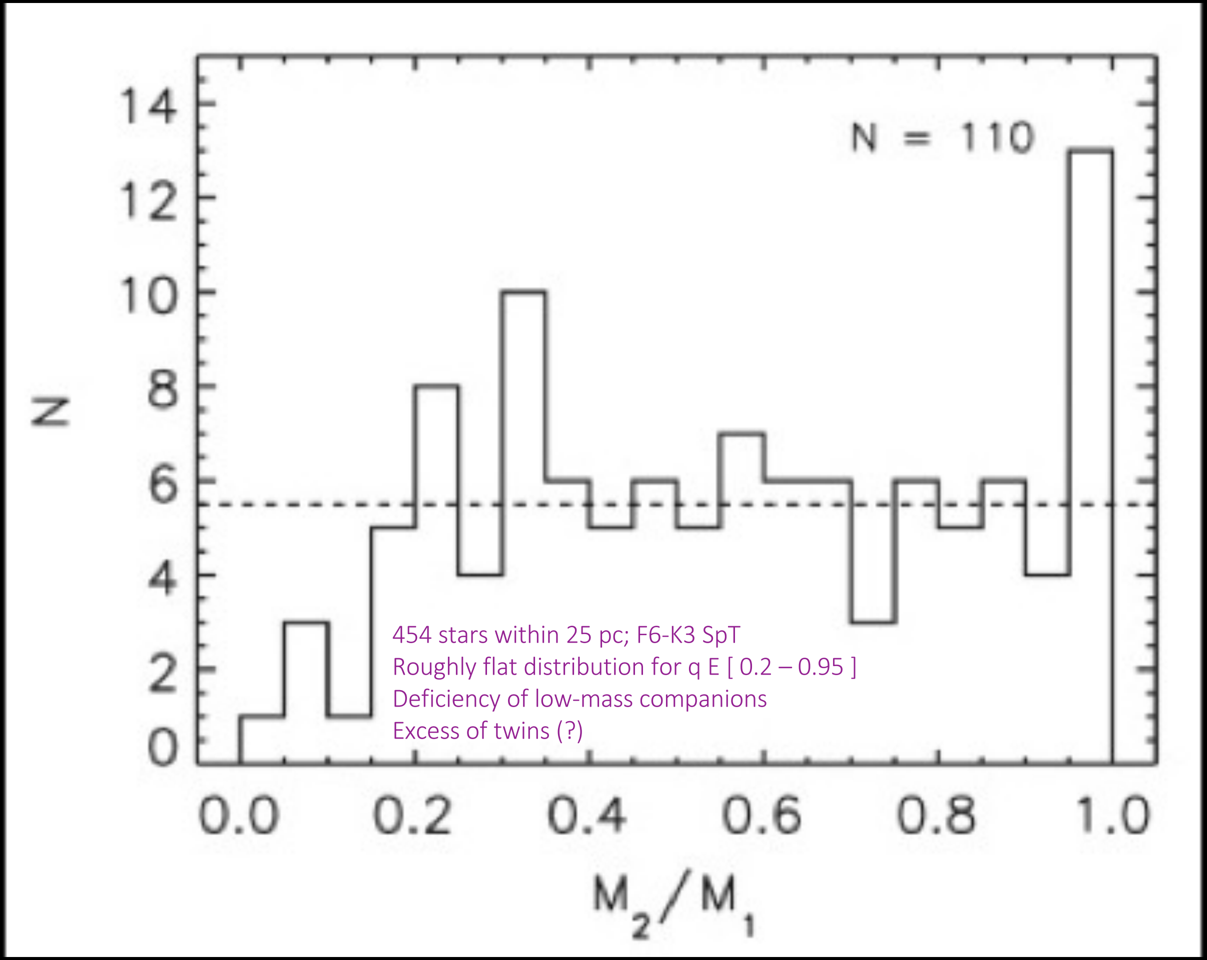
What about the mass ratio distribution?

Binary formation mechanisms?
e.g. random pairing, f(q) constant

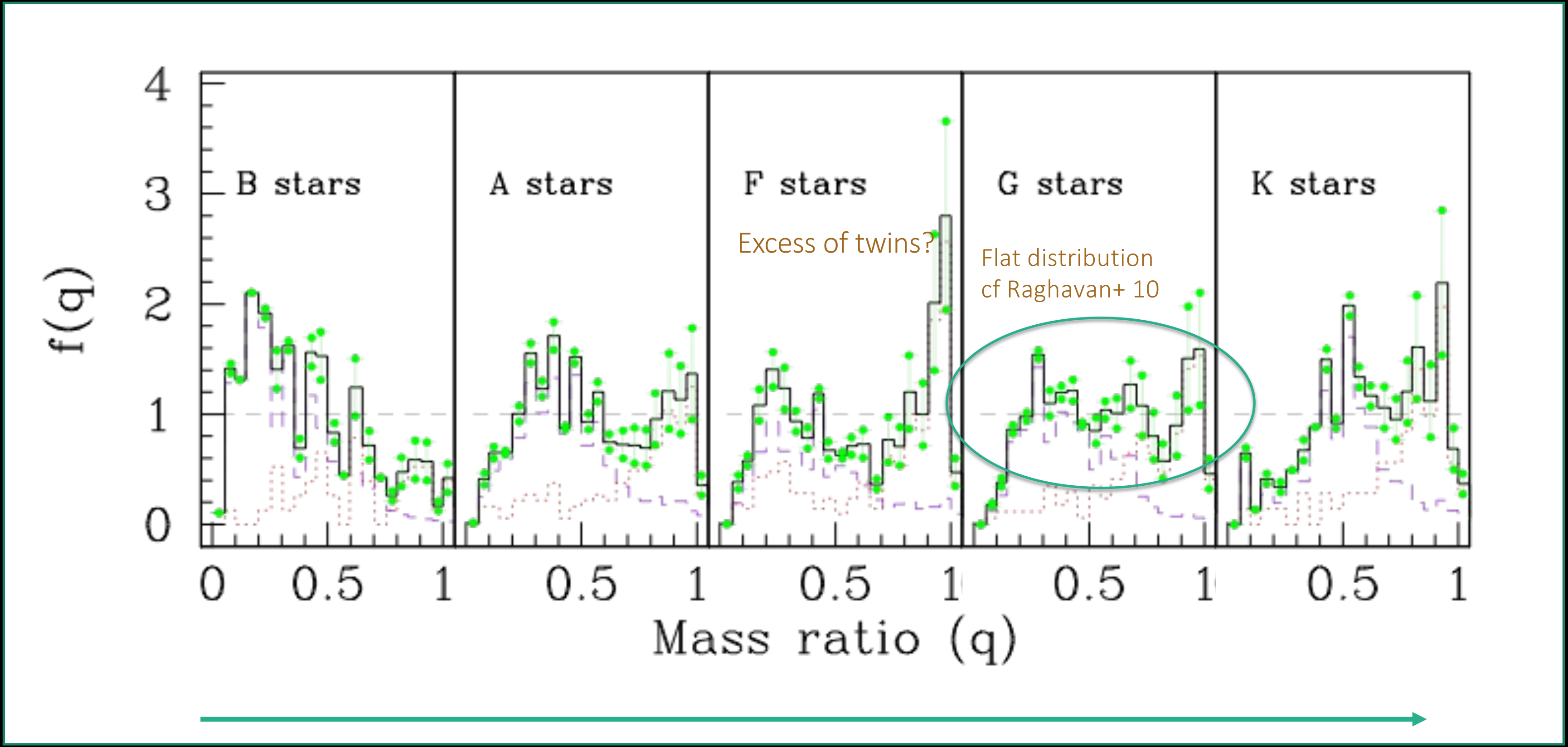
Evolution of binary systems? e.g.
twins population?

Does f(q) depend on M_A?

Raghavan+ 10



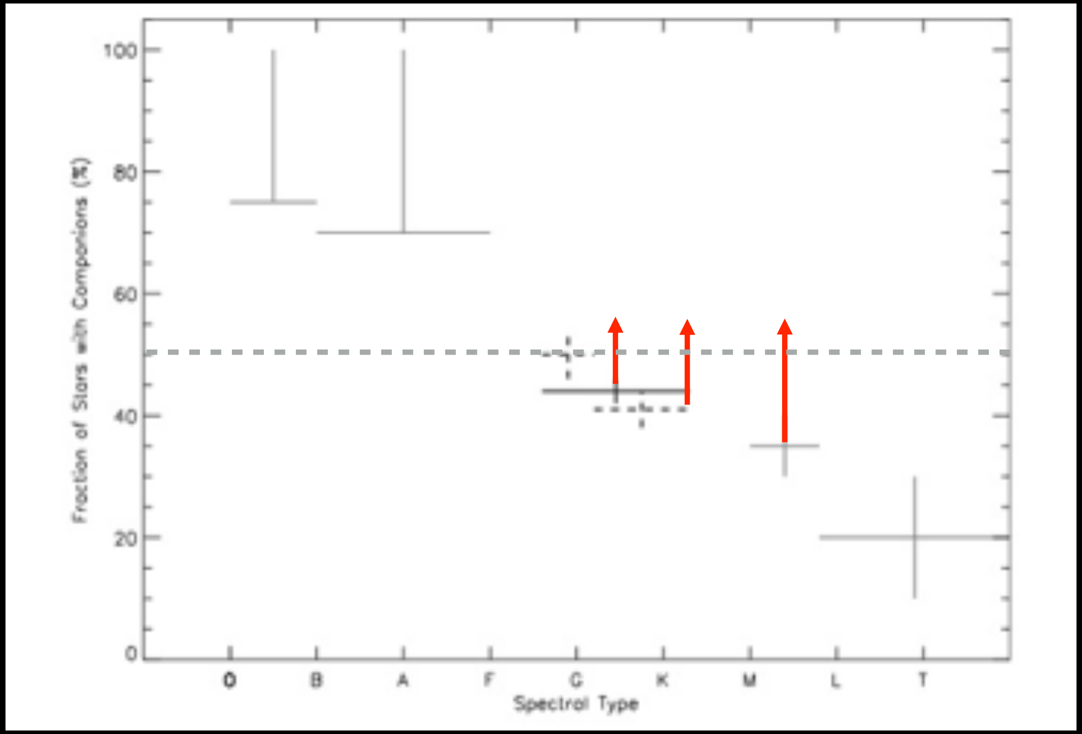
S_B^9 sample: Mass ratio distribution



Continuous distribution?

Boffin & Pourbaix 17

Multiplicity is function of primary mass



Mass of primary

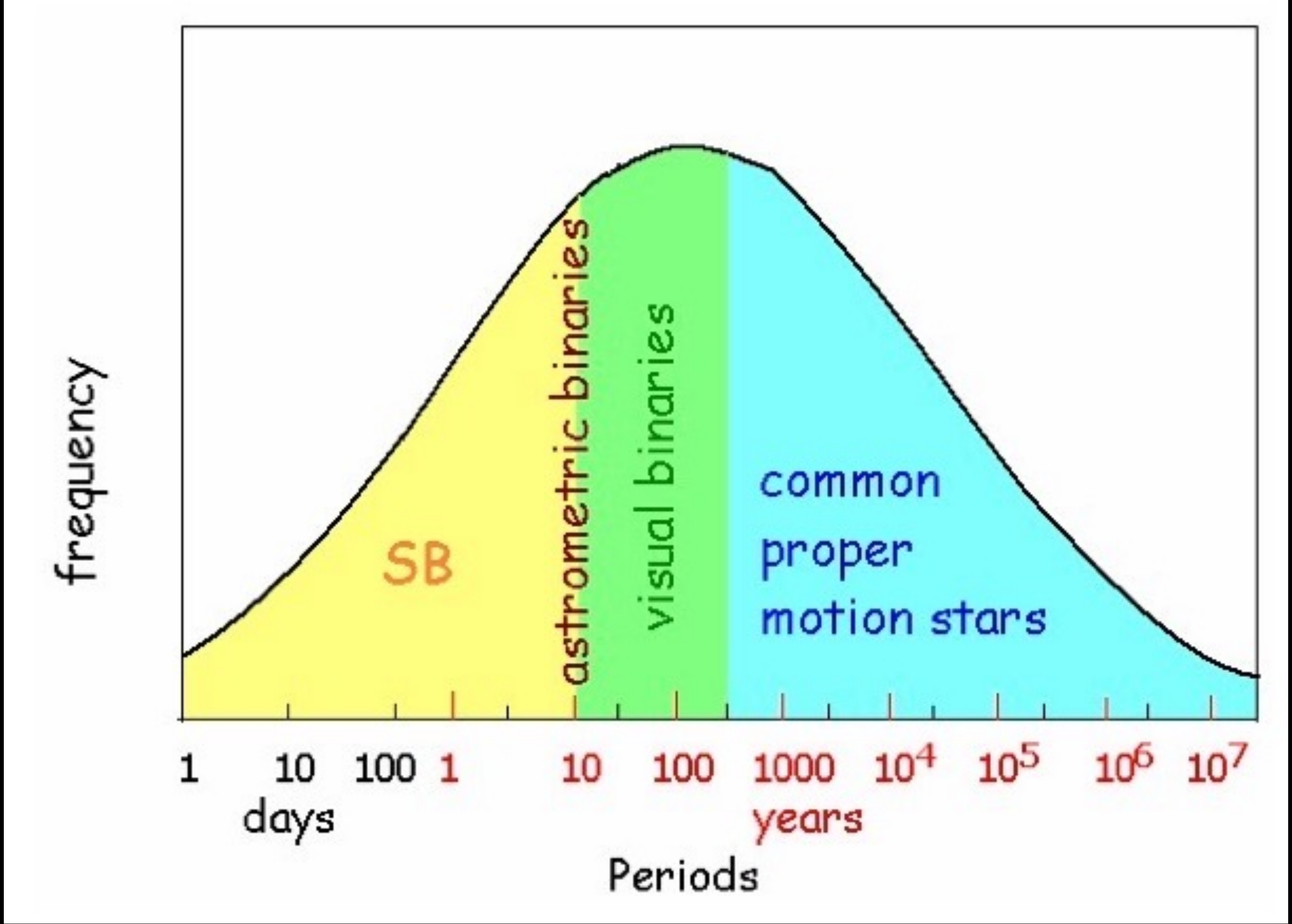
Majority of solar-like stars are in binaries!

Binarity of G, K, M stars may be similar and above 50%

Boffin & Pourbaix 17
See also Whitworth & Lomax 15

Period distribution

F7-K dwarfs



Log-Normal distribution from 1 day to 10 million years

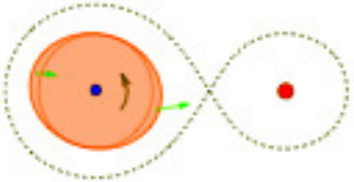
$\langle \log P_{days} \rangle = 4.8$

$\sigma_{\log P} = 2.3$

Duquennoy & Mayor 91
Halbwachs+ 10

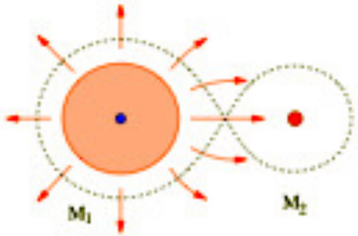
Close binaries

stars in binaries can interact in various ways:



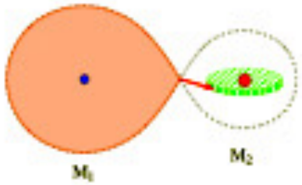
tidal interaction

e, log *P* diag.



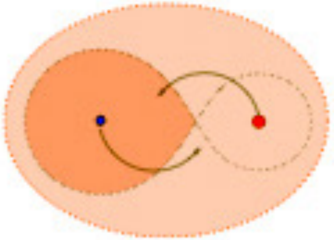
wind accretion

PRGs,
symbiotic stars,
novae, SN Ia



Roche-lobe overflow

CVs, Algols

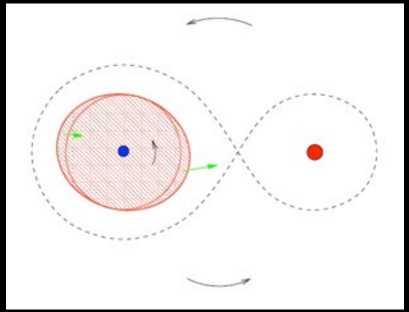


common envelope evolution

sdB, Bin. CSPNe

O. Pols 12

Tidal effects on the orbit



1. Circularisation

$$t_{\rm circ} \sim (q(1+q)/2)^{-1}(a/R)^8$$
$$\sim 10^6 q^{-1}((1+q)/2)^{5/3} P^{16/3} \quad \text{years}$$

Can occur on a timescale shorter than stellar evolution!

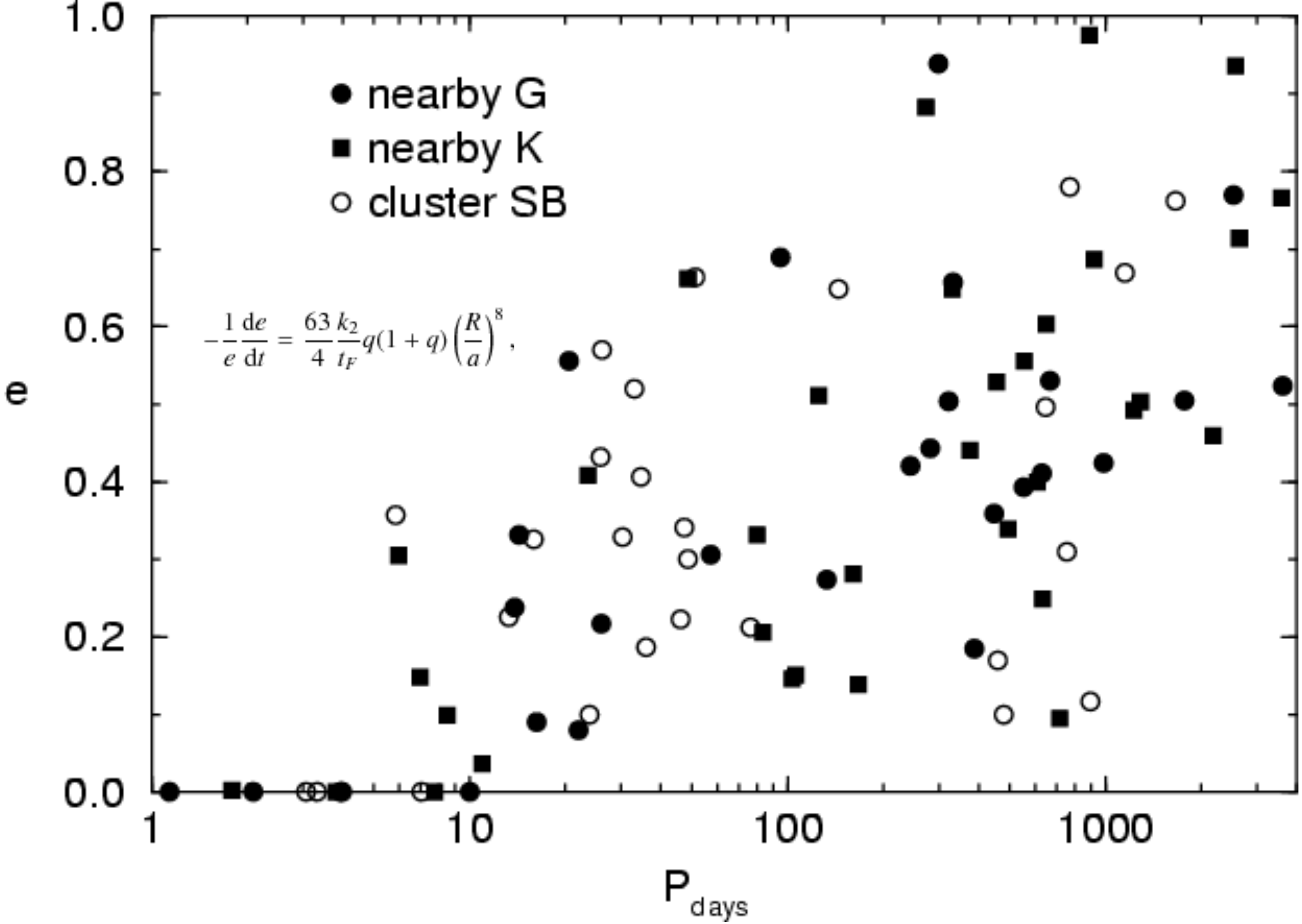
2. Synchronisation of component's rotation

$$t_{\rm sync} \sim q^{-2}(a/R)^6 \sim 10^4((1+q)/2q)^2 P^4 \quad \text{years}$$

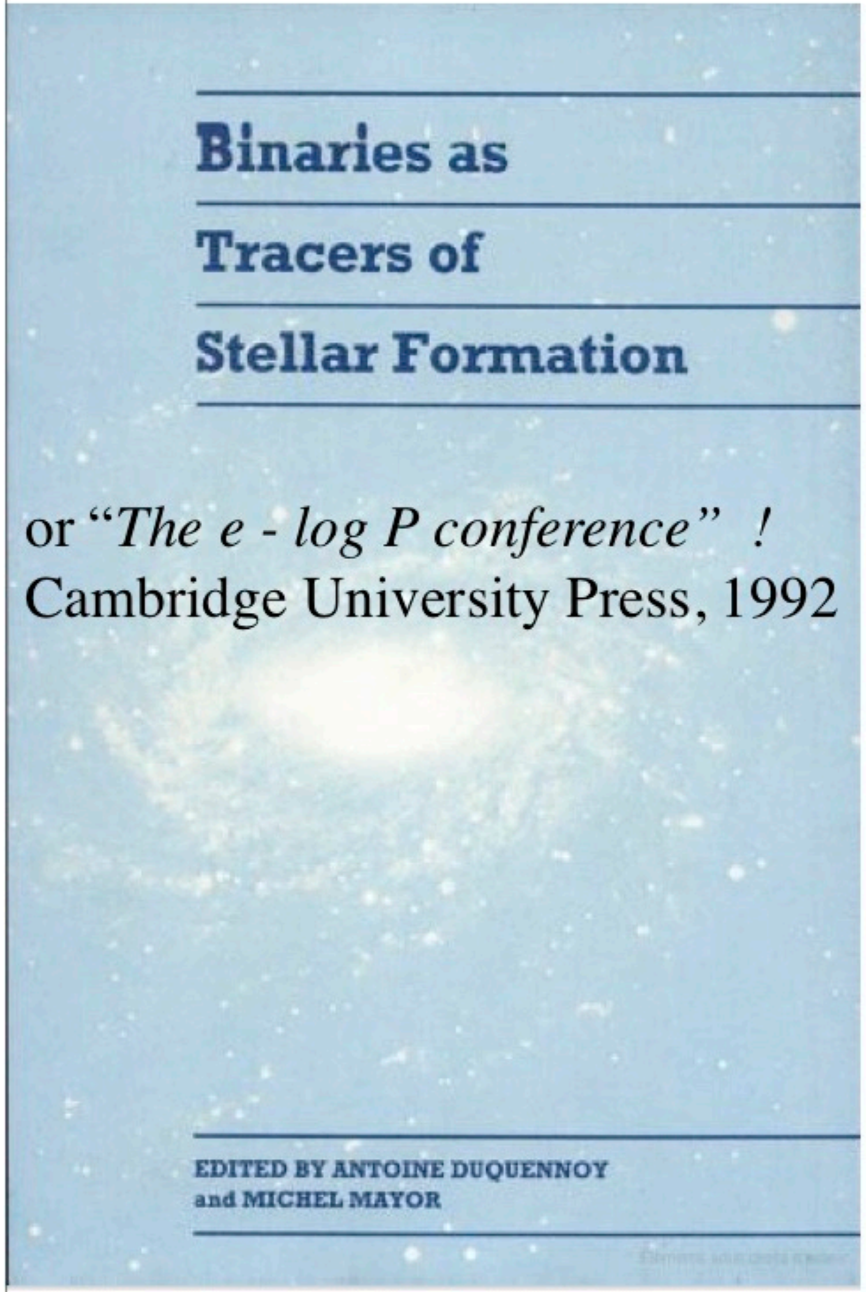
P	t_{sync}	t_{circ}
day	yr	yr
1	10^4	10^6
10	10^8	10^{11}

$t_{sync} << t_{circ}$

Zahn 77



$$-\frac{1}{e}\frac{\mathrm{d}e}{\mathrm{d}t} = \frac{63}{4}\frac{k_2}{t_F}q(1+q)\left(\frac{R}{a}\right)^8,$$



or "*The e - log P conference*" !
Cambridge University Press, 1992

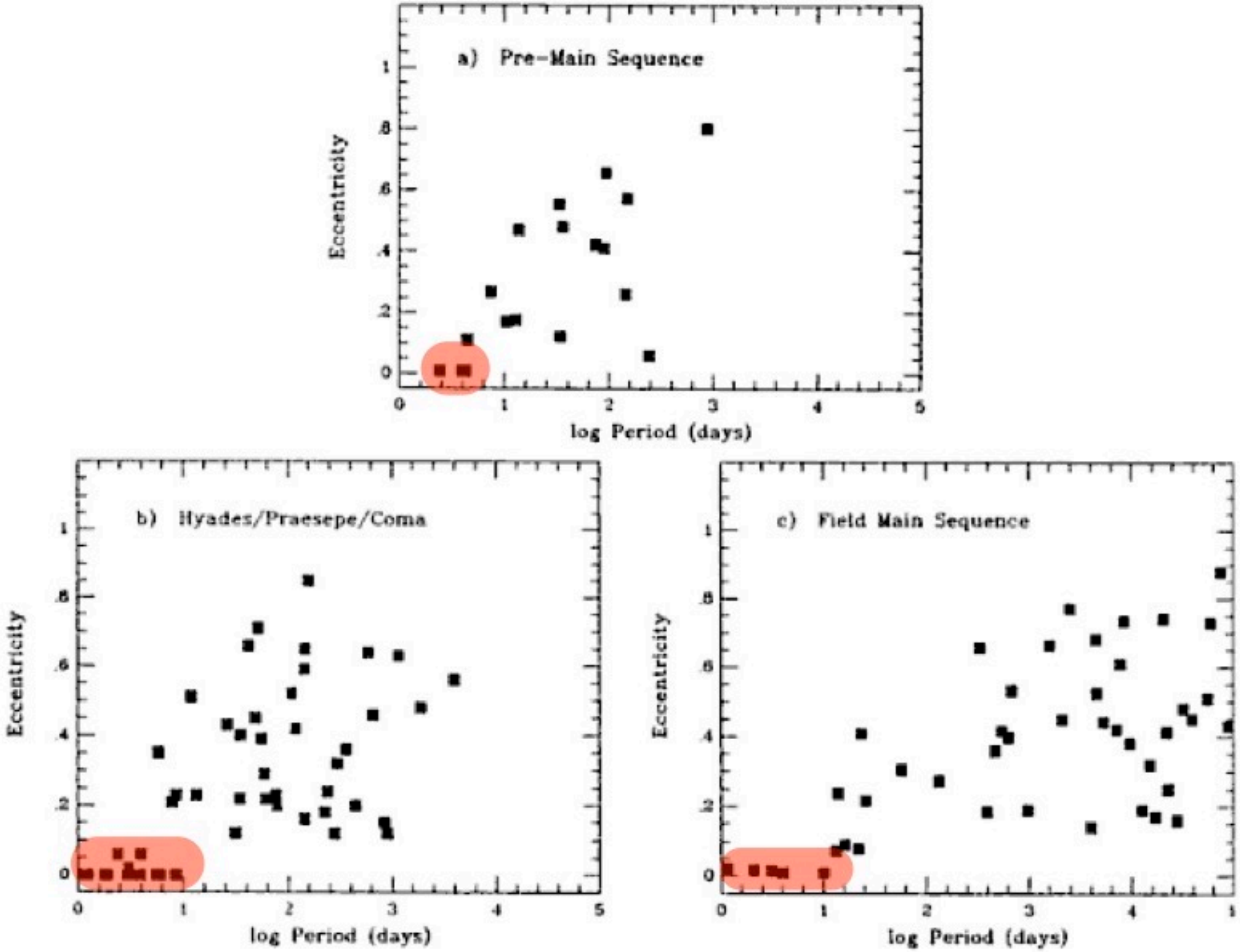
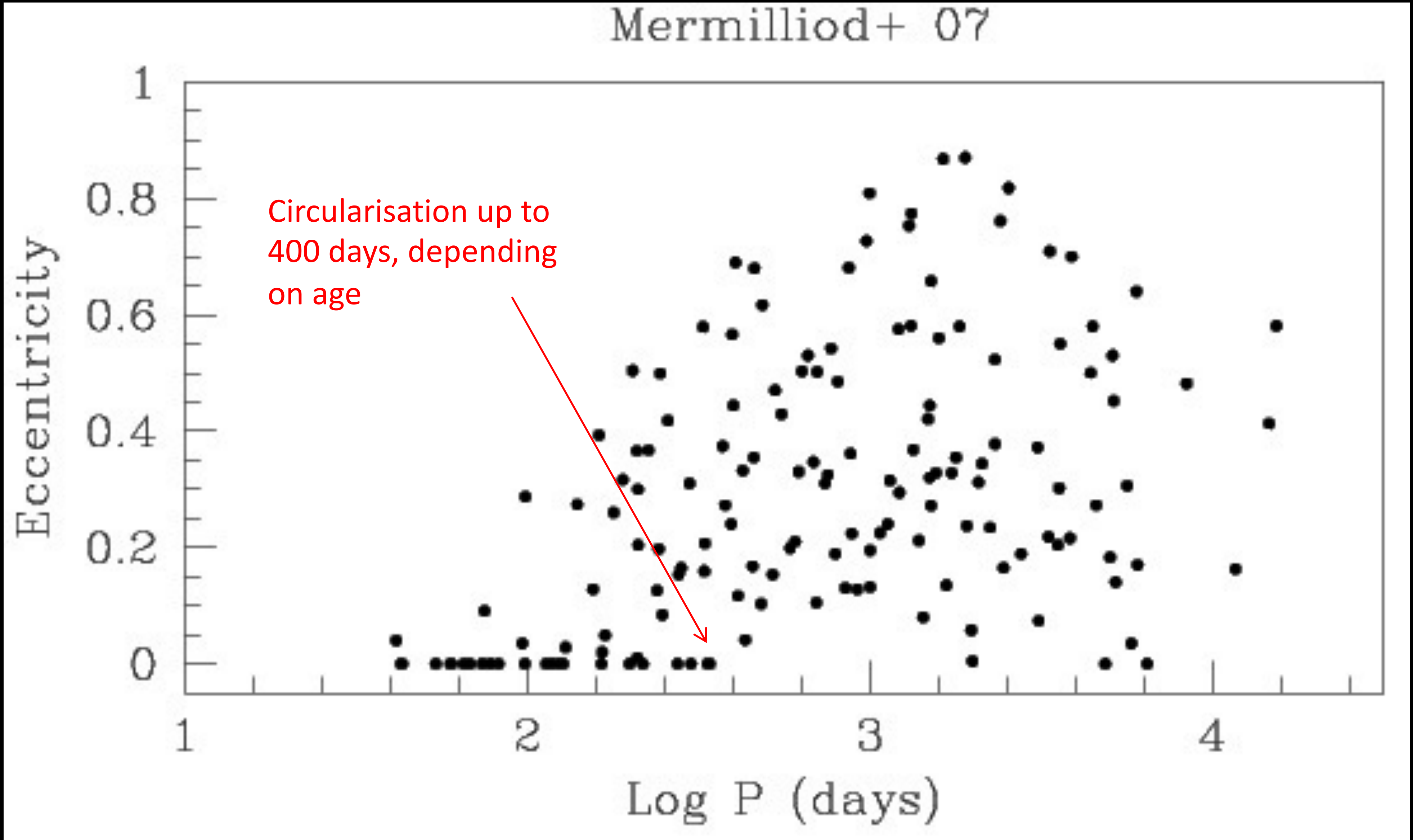
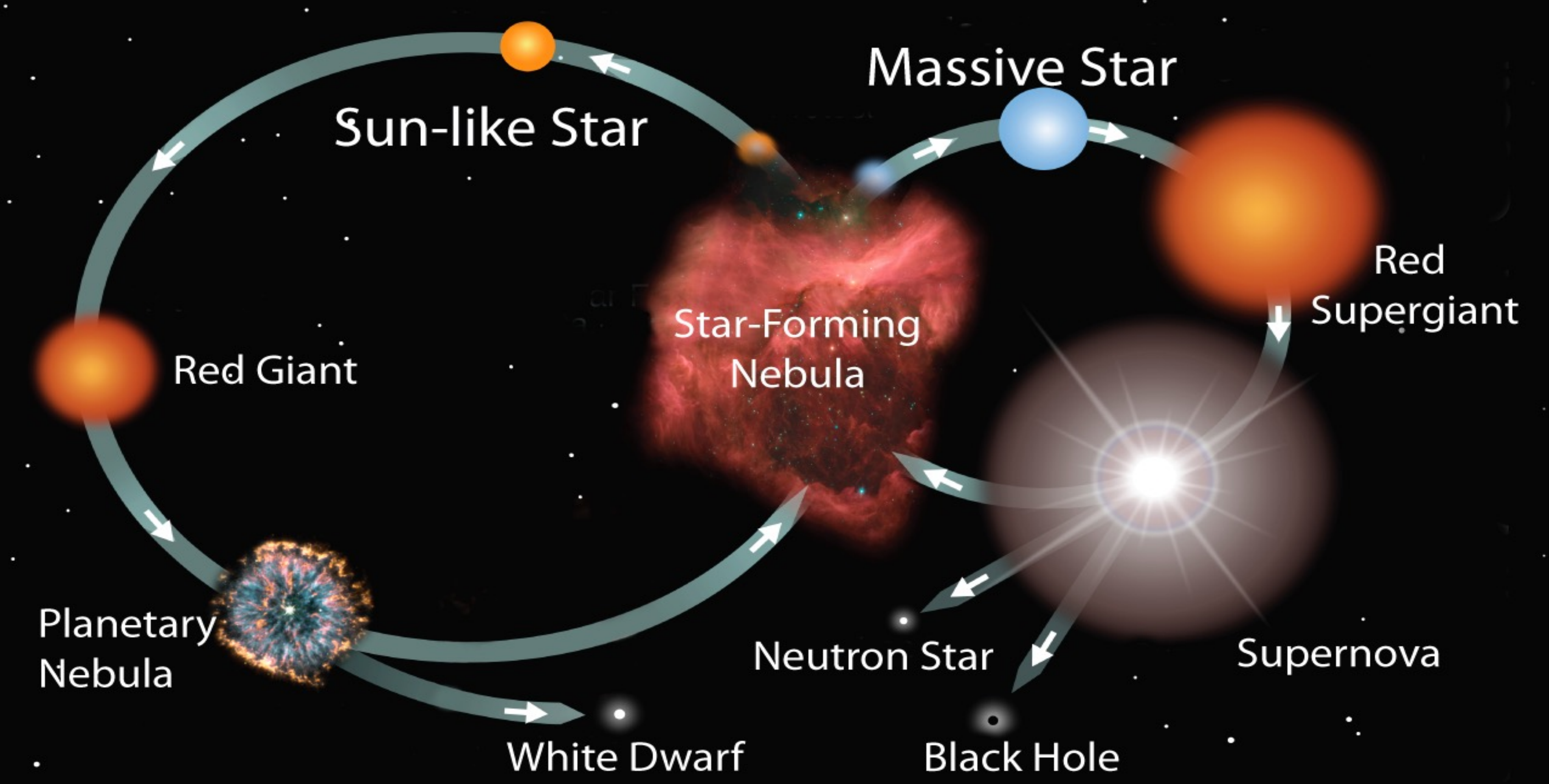


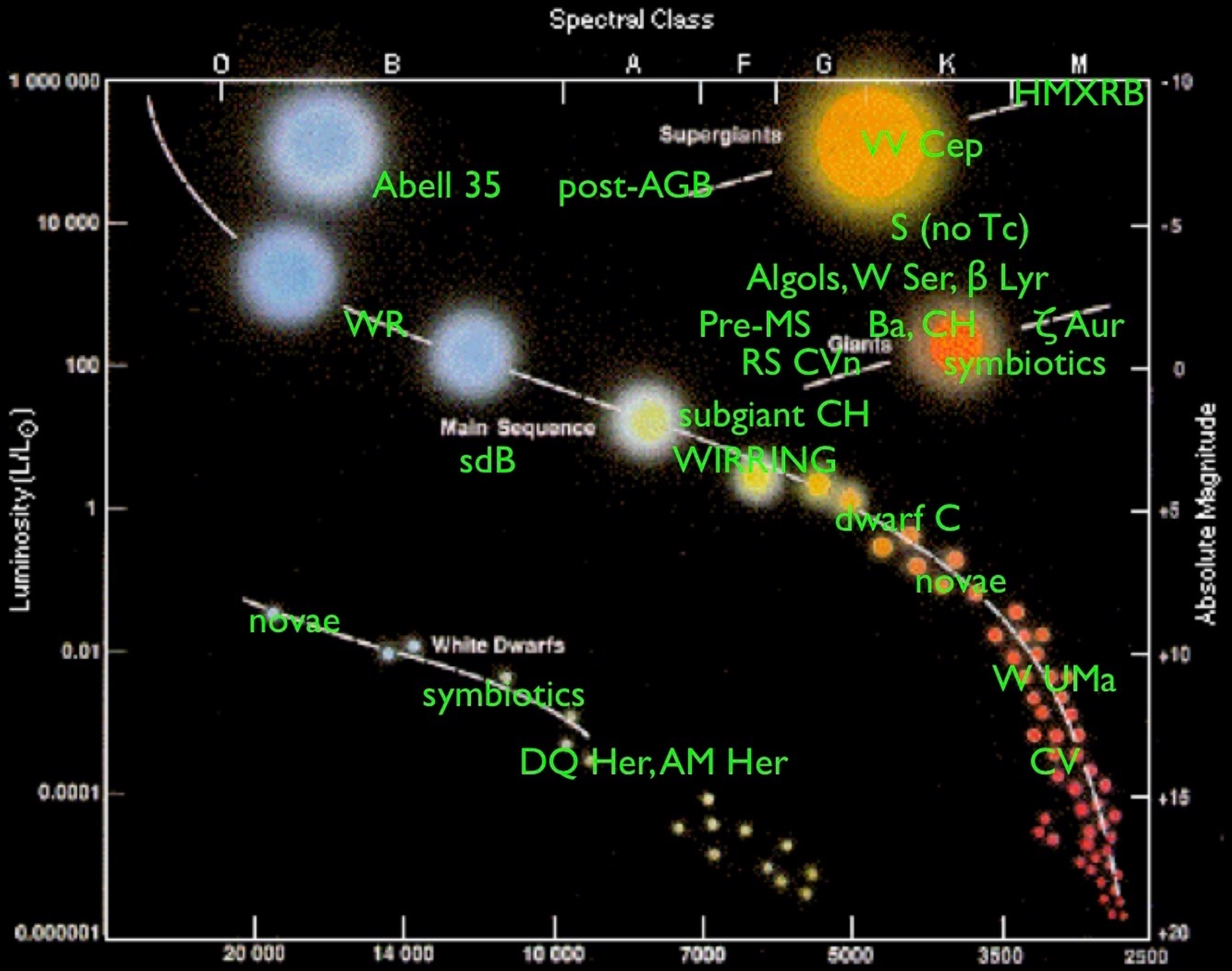
Figure 1. The period-eccentricity distribution for a) pre-main sequence binaries, b) main-sequence solar-mass binaries in the Hyades, Praesepe and Coma clusters [DMM92] and c) main-sequence solar-mass binaries in the field [DuM91].

Red giants in open cluster



THE LIFE CYCLE OF STARS



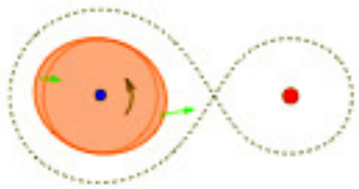


Different kind of systems → a Zoo!

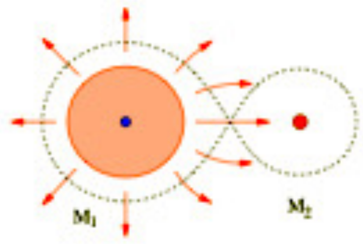
A. Jorissen

Close binaries

stars in binaries can interact in various ways:



tidal interaction



wind accretion

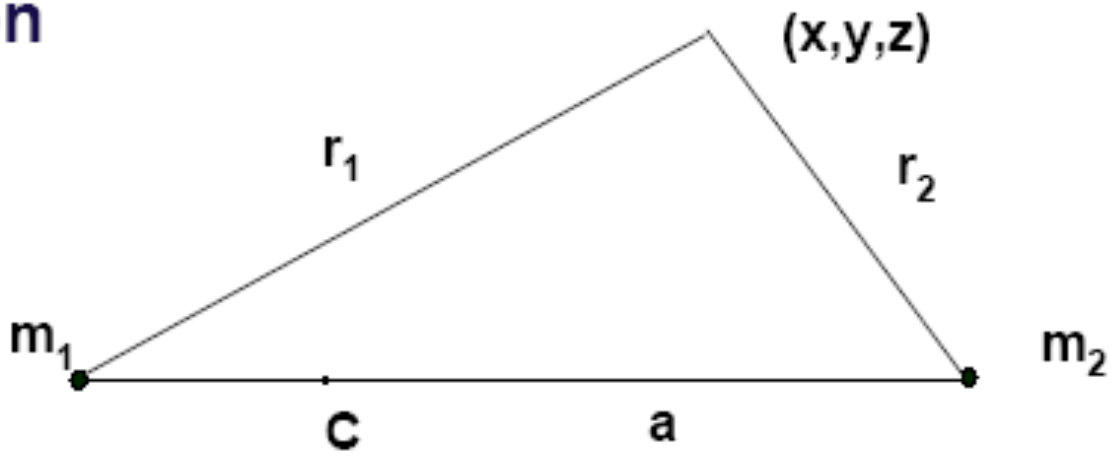
Detached systems

PRGs, symbiotic stars, novae, SN Ia

Roche Potential

Assumes:

- synchronous rotation
- circular orbit
- 2 point masses
- rotating frame



$$\omega^2 = \left(\frac{2\pi}{P}\right)^2 = \frac{G\,M}{a^3}$$

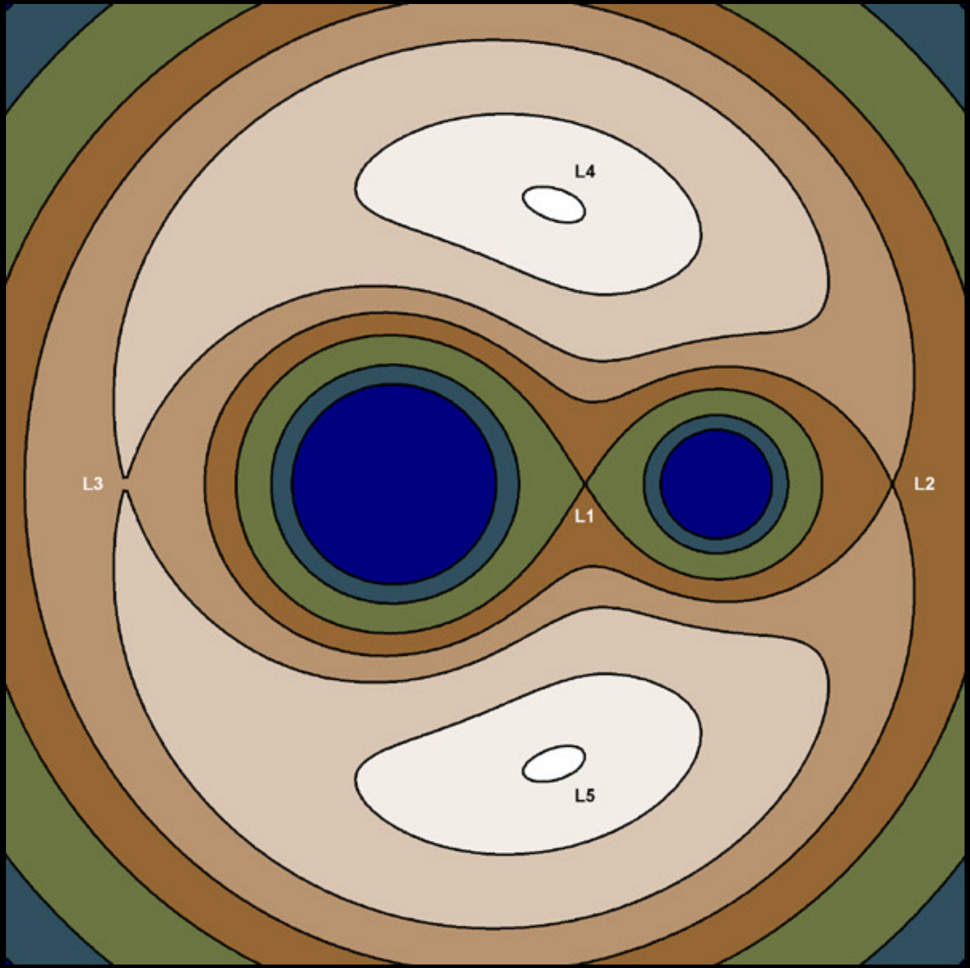
$$r_1^{\ 2} = x^2 + y^2 + z^2 \qquad r_2^{\ 2} = (\ x - a\ )^2 + y^2 + z^2$$

$$\frac{x_c}{a} = \frac{m_2}{M} = \frac{q}{1+q} \qquad q \equiv \frac{m_2}{m_1} \le 1$$

$$\Phi = -\frac{G\,m_1}{r_1} - \frac{G\,m_2}{r_2} - \frac{\omega^2}{2}\left[(\ x - x_c\ )^2 + y^2\right]$$

K. Horne

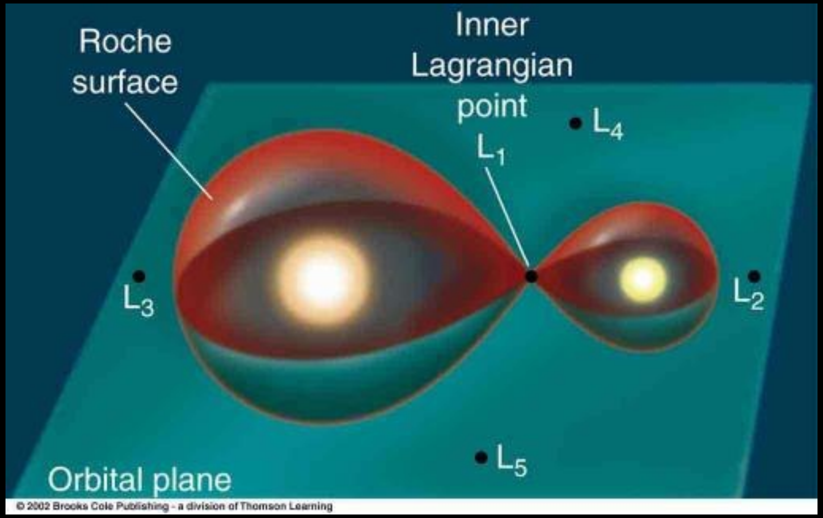
Roche lobe



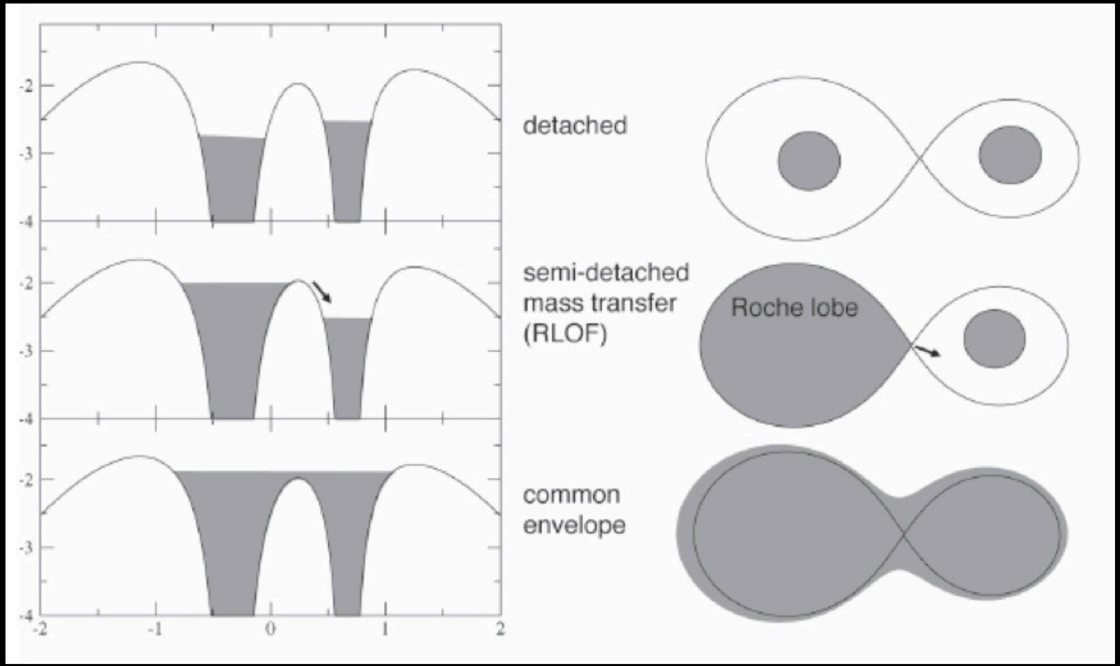
Potential defines limit of stability: Roche lobe

If star is larger than its Roche lobe, mass is transferred to the companion →

Roche lobe overflow (RLOF)



Roche lobe



Eggleton 83

$$\frac{R_L}{a} \approx \frac{0.49\, q^{2/3}}{0.69\, q^{2/3} + \ln\left(1 + q^{1/3}\right)}$$

Comparison between radius of star and R_L defines status of system:

detached

semi-detached

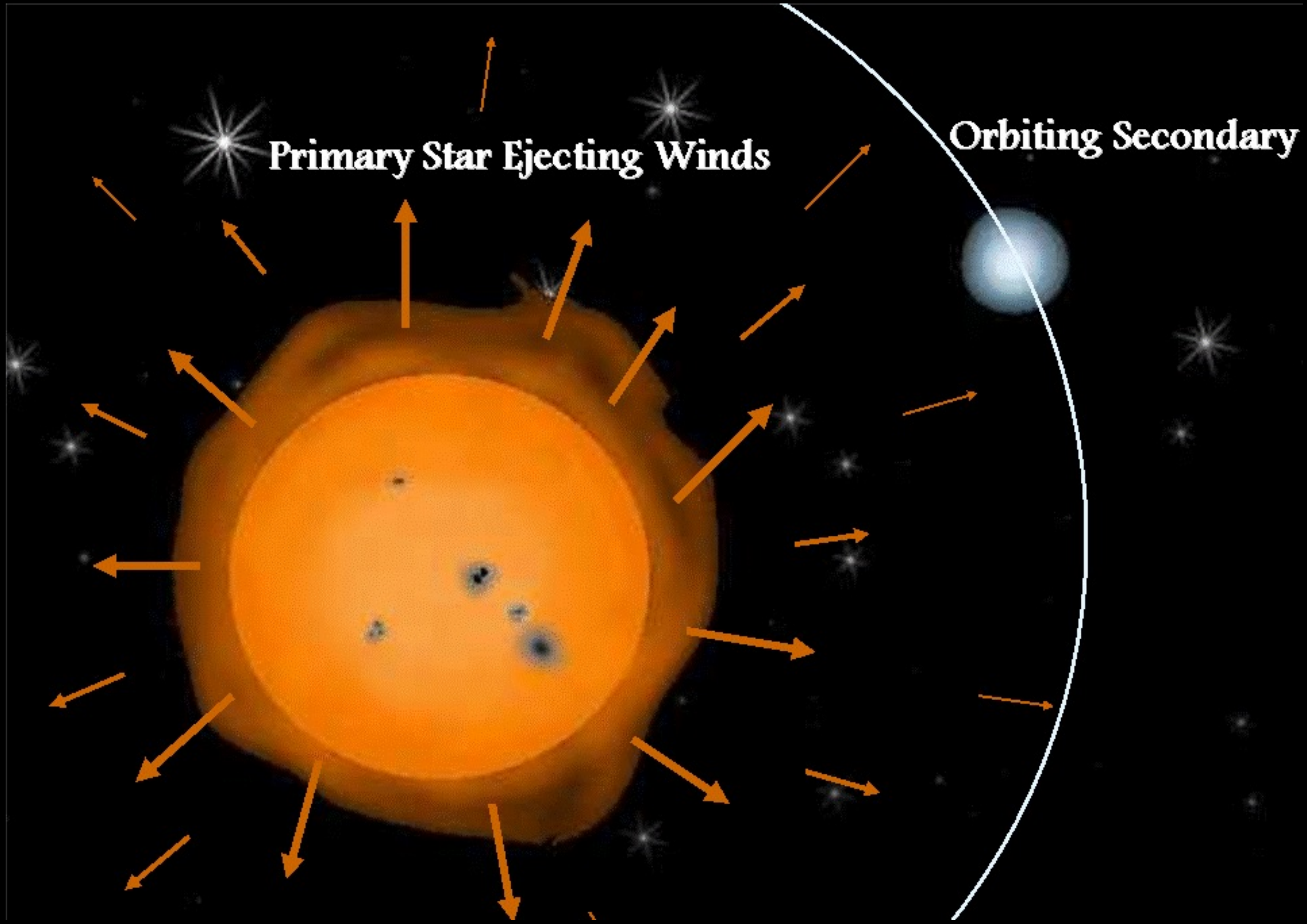
contact

Detached binaries

→ Mass transfer takes place through stellar wind

→ Red giants, AGB stars (for low- and intermediate-mass)
→ Massive stars (O stars, WR stars)

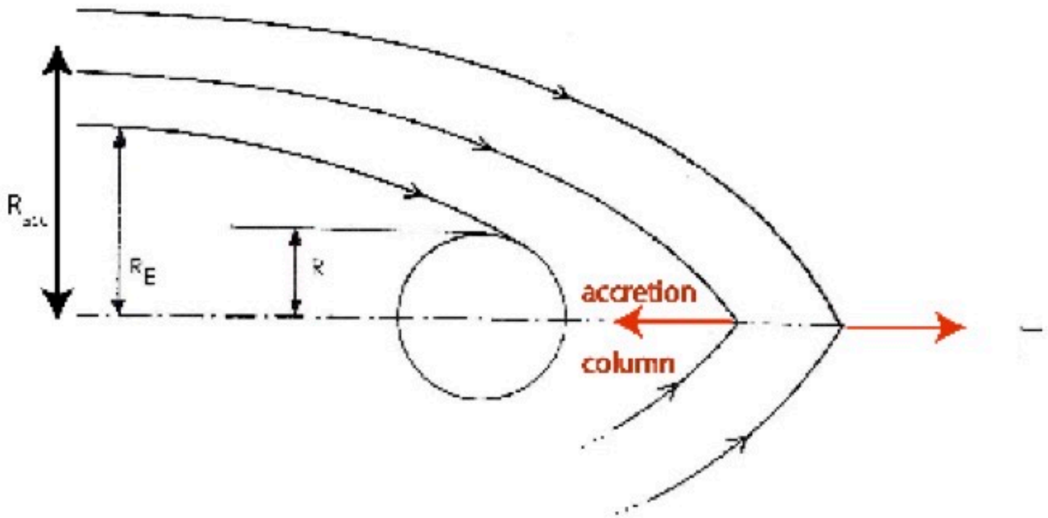
Red giant
Massive star



Main sequence star
WD
NS
BH

1. Hoyle-Lyttleton formalism for a single star accreting matter flowing at a velocity v_∞, with gas pressure unimportant (hence cool gas):

Accretion radius: $v_\infty^2/2 = GM/R_{\rm H-L}$
Accretion rate:
$\dot{M}_{\rm H-L} = \pi R_{\rm H-L}^2 v_\infty \rho_\infty = 2\pi \frac{(G\,M)^2}{v_\infty^3}\rho_\infty$



Hoyle & Lyttleton 1939, Proc. Cam. Phil. Soc. 35, 405
Bondi 1952, MNRAS 114, 195
Bondi & Hoyle 1944, MNRAS 104, 273

2. Bondi formalism for accretion dominated by gas pressure, with zero relative gas-star velocity:

Accretion radius: $c^2/2 = GM/R_{\rm B}$
Accretion rate: $\dot{M}_{\rm B} = \beta\, \pi R_{\rm B}^2 c \rho_\infty$

where c = sound speed, β is a parameter of order unity depending on the polytropic index of the gas.

3. Bondi-Hoyle formalism is an interpolation between these two extreme cases:
Accretion rate:

$$\dot{M}_{\rm B-H} =$$
$$\beta\, \pi R_{\rm H-L}^2 v_\infty \rho_\infty \left(\frac{(v_\infty/c)^2}{1+(v_\infty/c)^2}\right)^{3/2}$$

K. Horne; A. Jorissen

WIND ACCRETION

Numerical simulations (SPH): confirm the validity of the concept for simple wind accretion flows

What about in binary systems?

Boffin & Anzer 1994

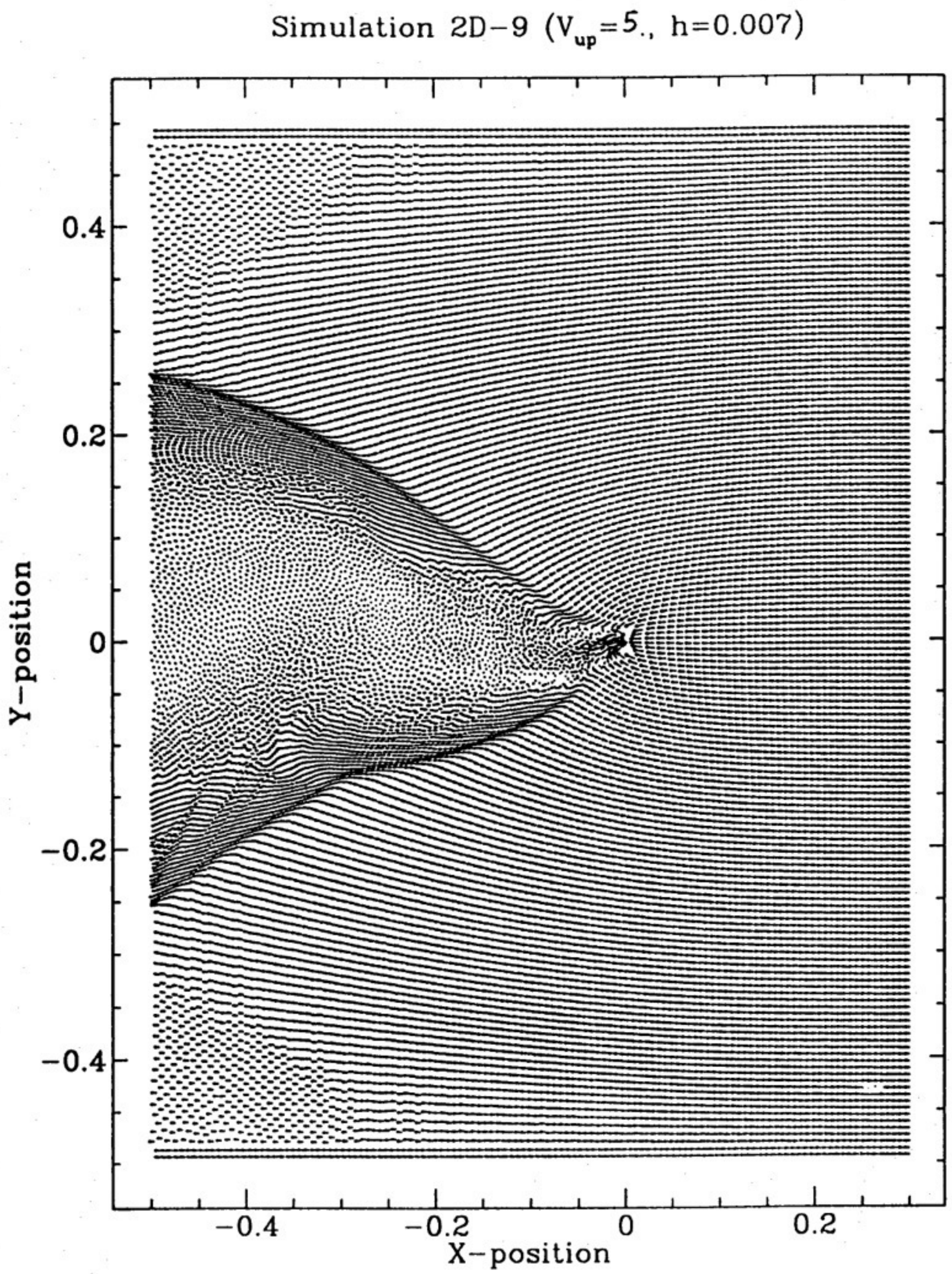


Fig. 9. Density of particles for 2D-9 at t=3

WIND ACCRETION

In binary systems:

v^2_∞ replaced by $(v^2_w + v^2_{orb})$

ρ_∞ computed from mass loss

$$\dot{M}_{acc,2} = -\beta\mu^2 \frac{v_{orb}^4}{(v_w^2 + v_{orb}^2 + c^2)^{3/2}} \dot{M}_{w,1}$$

$$\mu = \frac{M_2}{M_1 + M_2}$$

Results depends on ratio between wind and orbital velocity :

If $v_{orb} << v_w$ → only deflection (Zeta Aurigae and O-type binaries)

If $v_{orb} \approx v_w$ or $v_{orb} > v_w$ → Coriolis effect important → numerical simulations

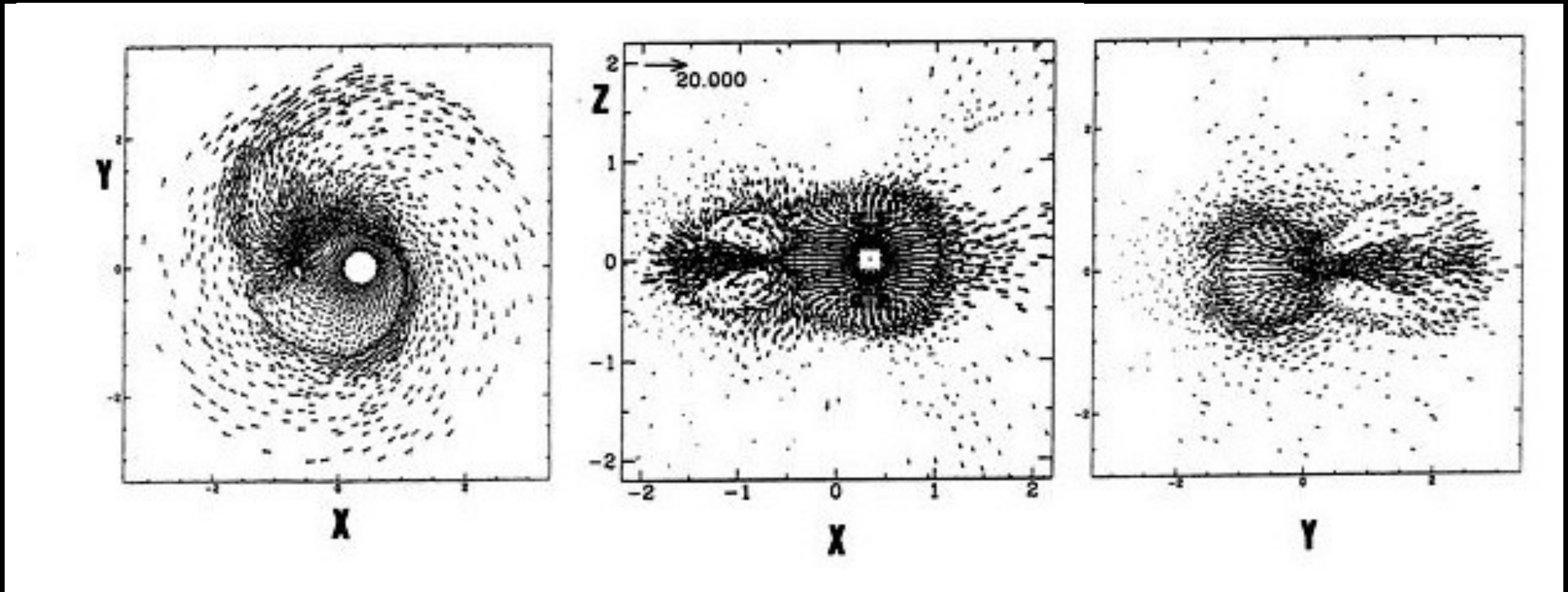
Wind accretion with an AGB

In AGB stars binaries of interest, the wind speed is smaller or comparable to the orbital velocity

v_w = 5–15 km/s < v_{orb} = 20–30 km/s

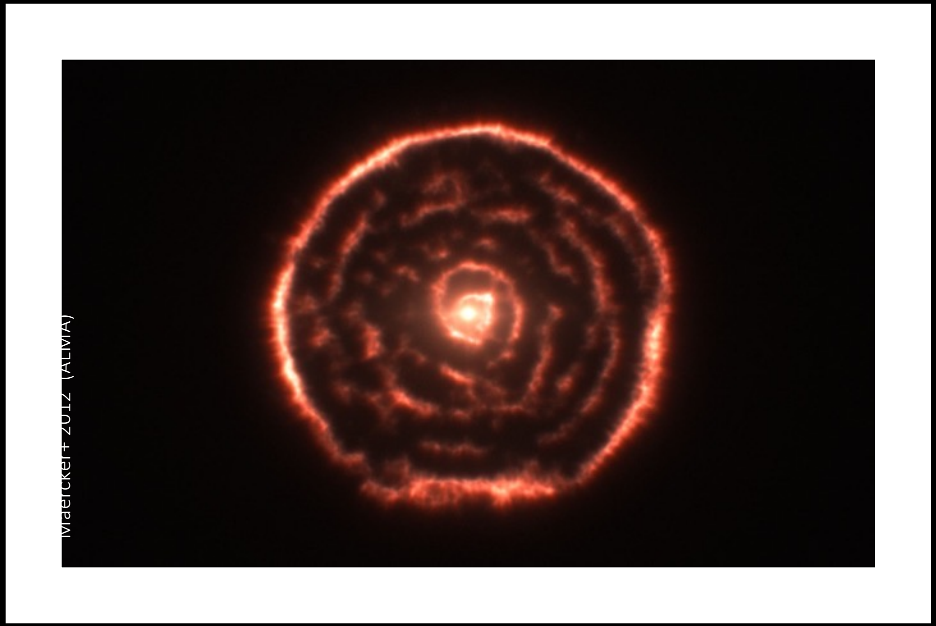
Not a Bondi-Hoyle (even modified) type flow

Coriolis and centrifugal forces play a vital role



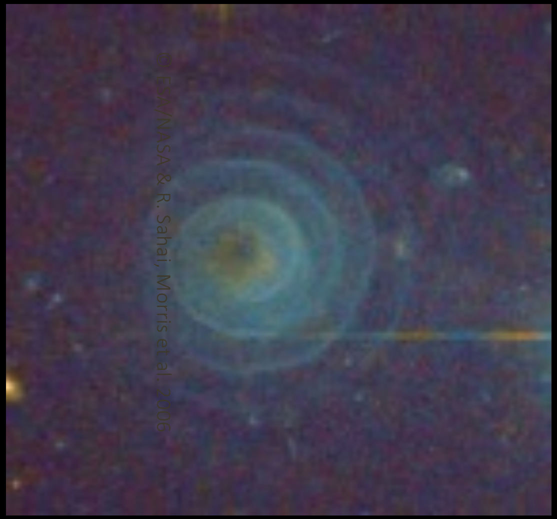
Boffin+ 94, Theuns+ 96

AGB star: R Scl



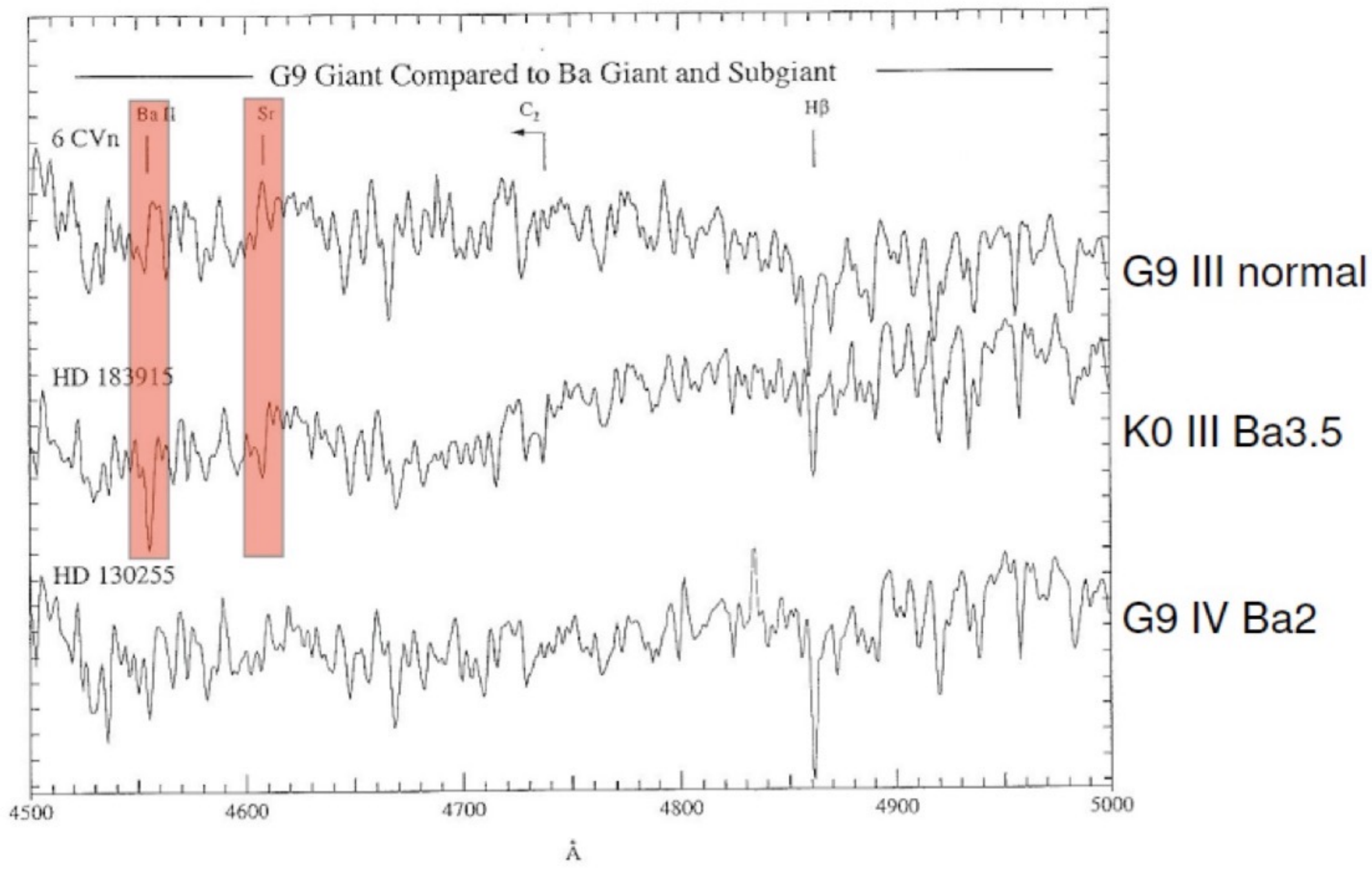
a = 60 AU
P = 350 years (!)
$M_1+M_2 = 2\ M_\odot$
M_1 suffered a thermal pulse event about 1800 years ago that lasted for about 200 years

Carbon star: AFL 3068



A case in point: Barium stars

Ba stars: A class of chemically-peculiar giants known since the 50's



Barnbaum (1996), ApJS 105, 419

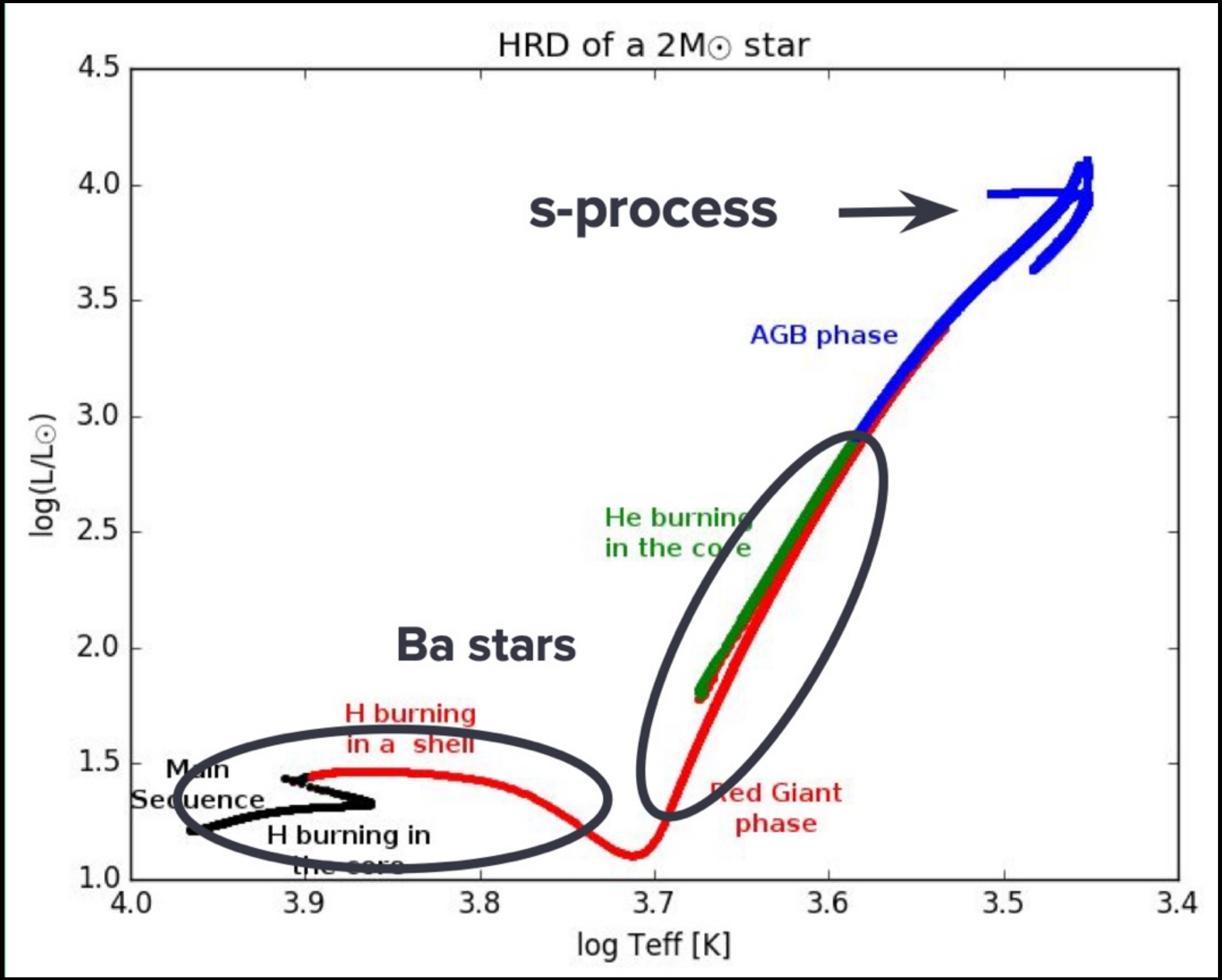
Red giant enriched in s-process elements and carbon

Not evolved enough to have produced these elements

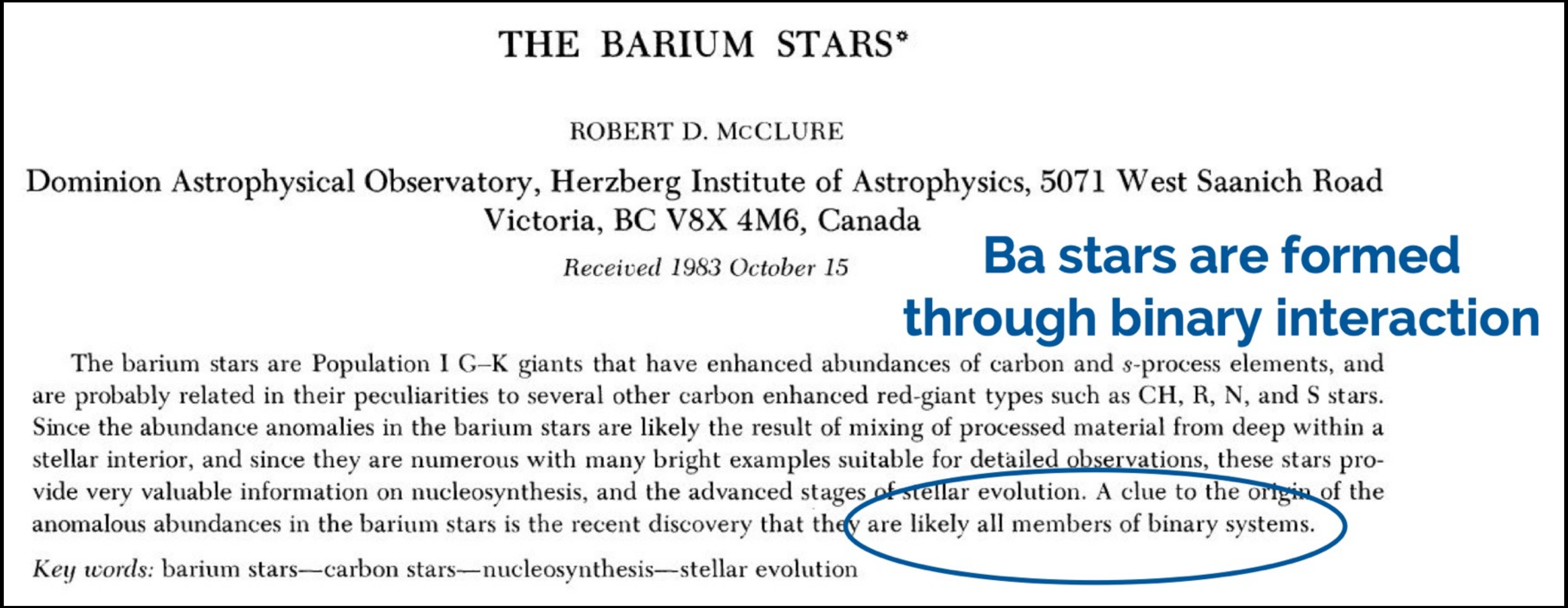
A case in point: Barium stars

The slow-neutron-capture (s-) process of nucleosynthesis takes place at the end of the AGB phase.

Ba stars are not in these phases —> cannot be explained by single star evolution!



A case in point: Barium stars



THE BARIUM STARS*

ROBERT D. McCLURE

Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics, 5071 West Saanich Road
Victoria, BC V8X 4M6, Canada

Received 1983 October 15

The barium stars are Population I G–K giants that have enhanced abundances of carbon and *s*-process elements, and are probably related in their peculiarities to several other carbon enhanced red-giant types such as CH, R, N, and S stars. Since the abundance anomalies in the barium stars are likely the result of mixing of processed material from deep within a stellar interior, and since they are numerous with many bright examples suitable for detailed observations, these stars provide very valuable information on nucleosynthesis, and the advanced stages of stellar evolution. A clue to the origin of the anomalous abundances in the barium stars is the recent discovery that they are likely all members of binary systems.

Key words: barium stars—carbon stars—nucleosynthesis—stellar evolution

Ba stars are formed through binary interaction

Astron. Astrophys. 205, 155–163 (1988)

ASTRONOMY AND ASTROPHYSICS

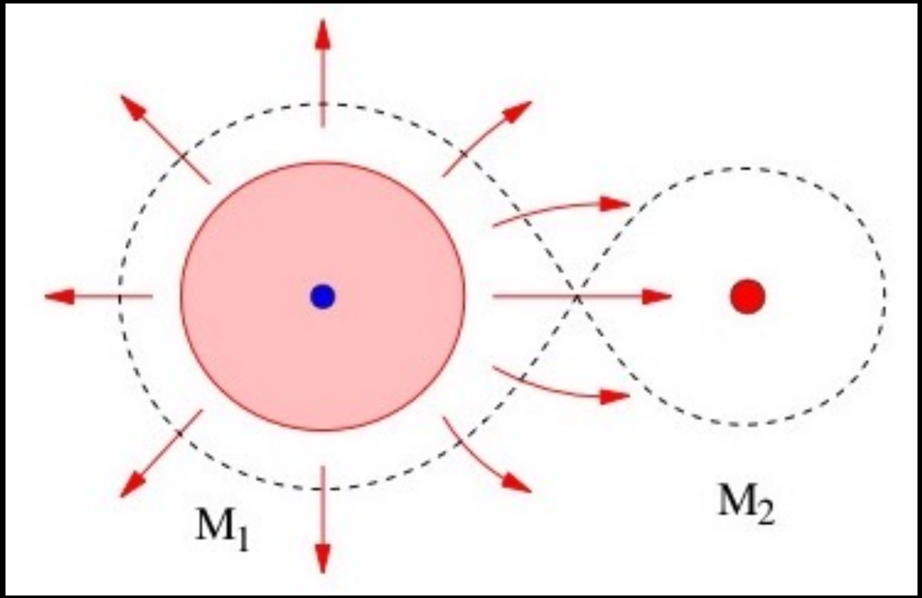
Can a barium star be produced by wind accretion in a detached binary?

H.M.J. Boffin* and A. Jorissen*

Institut d'Astronomie, d'Astrophysique et de Géophysique, Université Libre de Bruxelles, C.P. 165,
Av. F. Roosevelt 50, B-1050 Bruxelles, Belgium

Received January 29, accepted May 18, 1988

Master thesis done in 1987
35th anniversary!



O. Pols

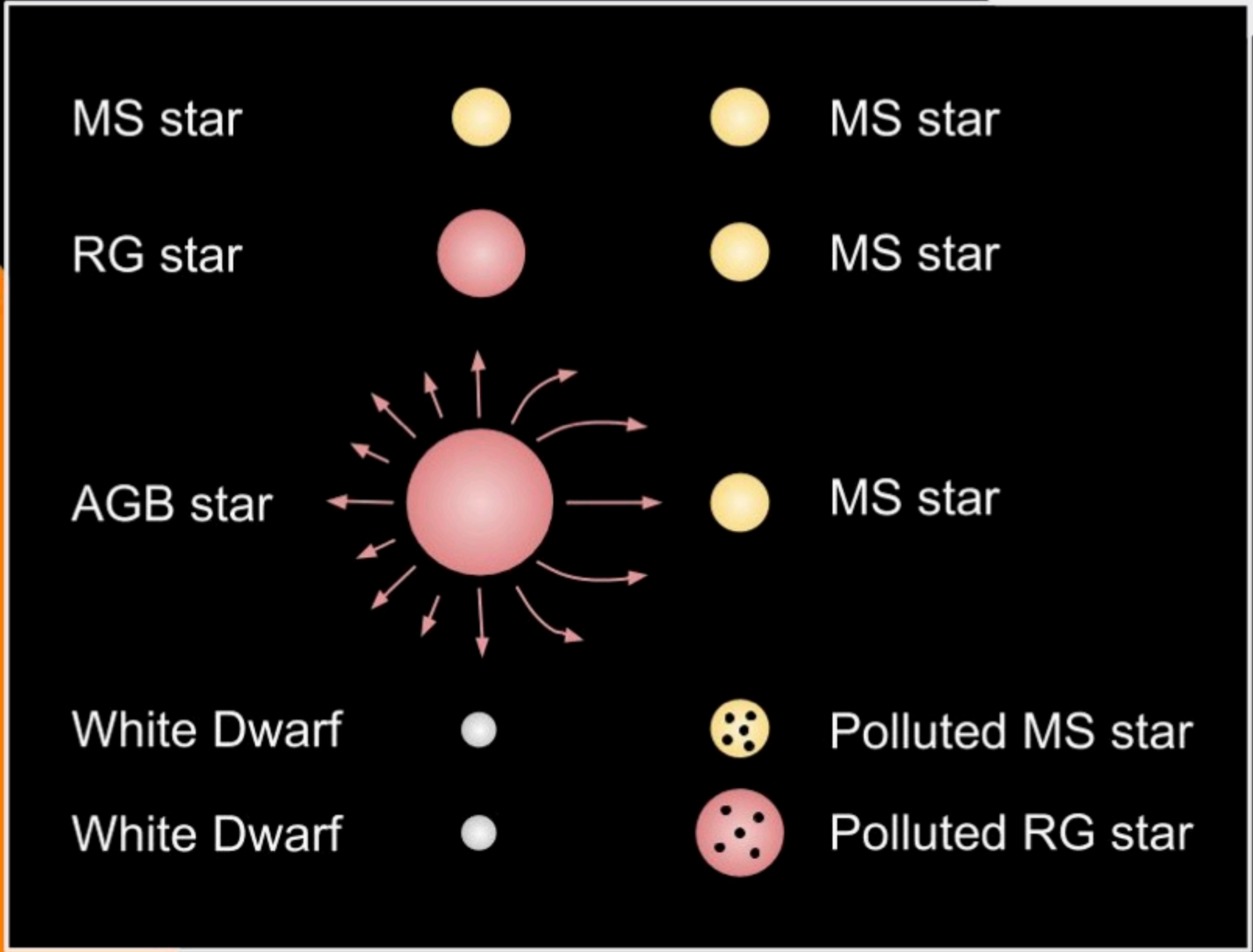
Formation of barium stars

White dwarf companion

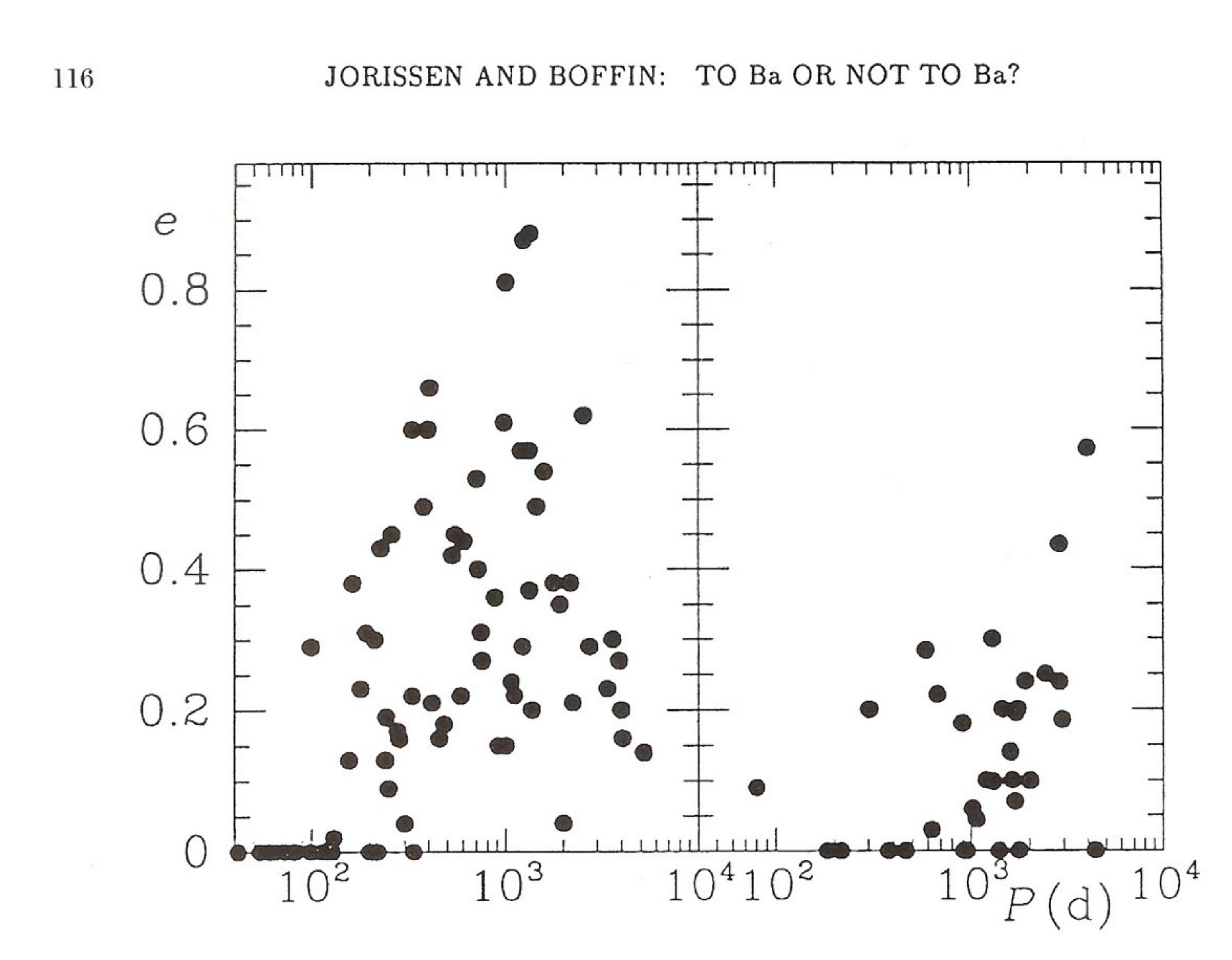
Chemically peculiar star polluted by a former AGB companion.

Prototypical post binary interaction binary system.

Escorza+ 19



Barium stars



Confirmation of model: Period of Ba stars are longer than those of normal giants

But eccentricity? Smaller, but non-zero

And can we really avoid RLOF?

Jorissen & Boffin 92

Fresh out of the oven: PN A 70

Because we still see the planetary nebula, the WD is still fresh out of the oven. Accretion just happened!

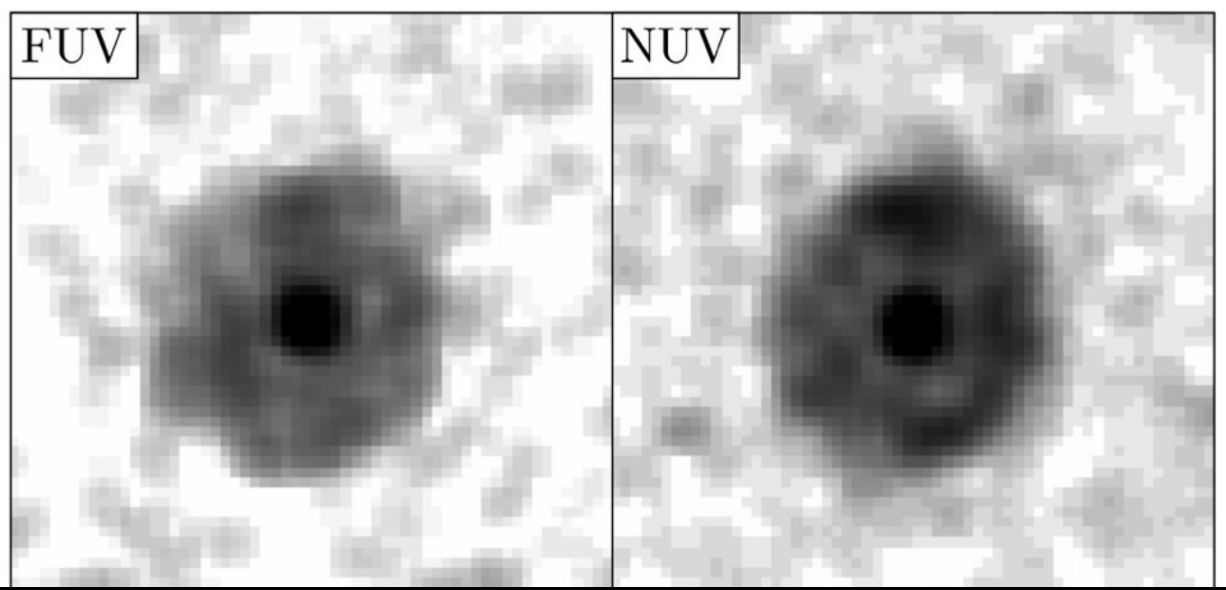
CSPN is G5-G8 subgiant

It is enriched in Ba

UV observations reveal presence of a hot companion

→ Barium star!

Miszalski, Boffin+ 12; Jones, Boffin+ 22

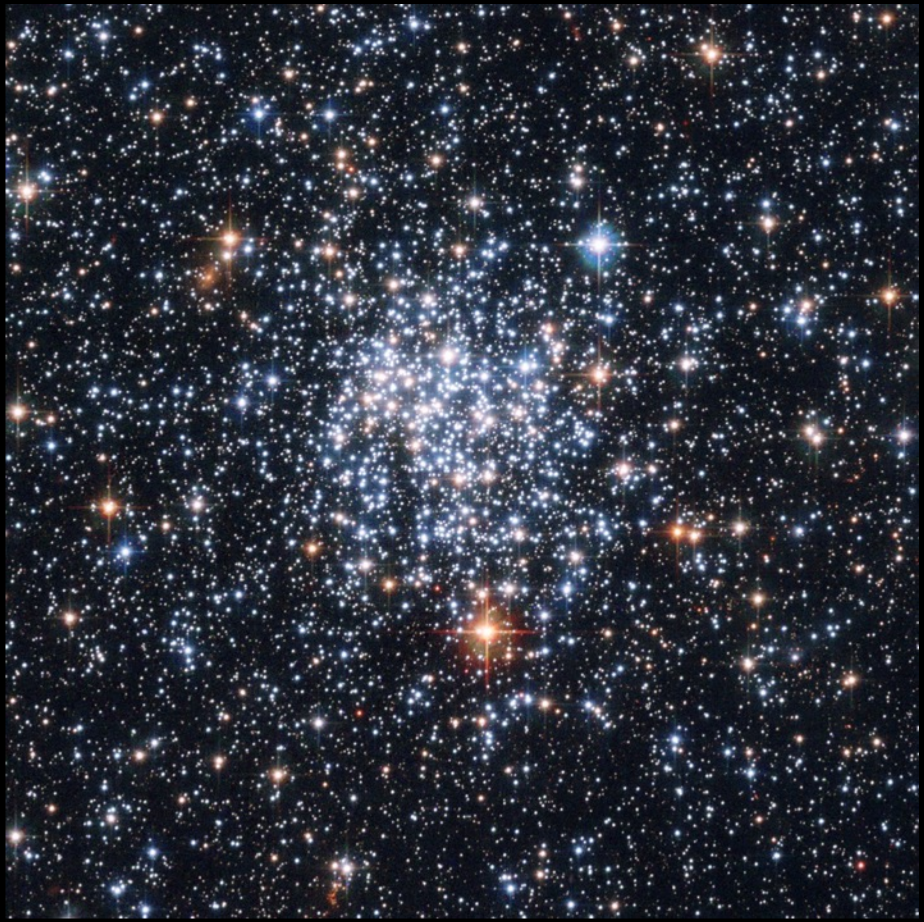


Open clusters

The closest laboratories for studying stellar evolution

A single stellar population

They allow us to find stars that don't lie along the traditional expected path of stellar evolution!



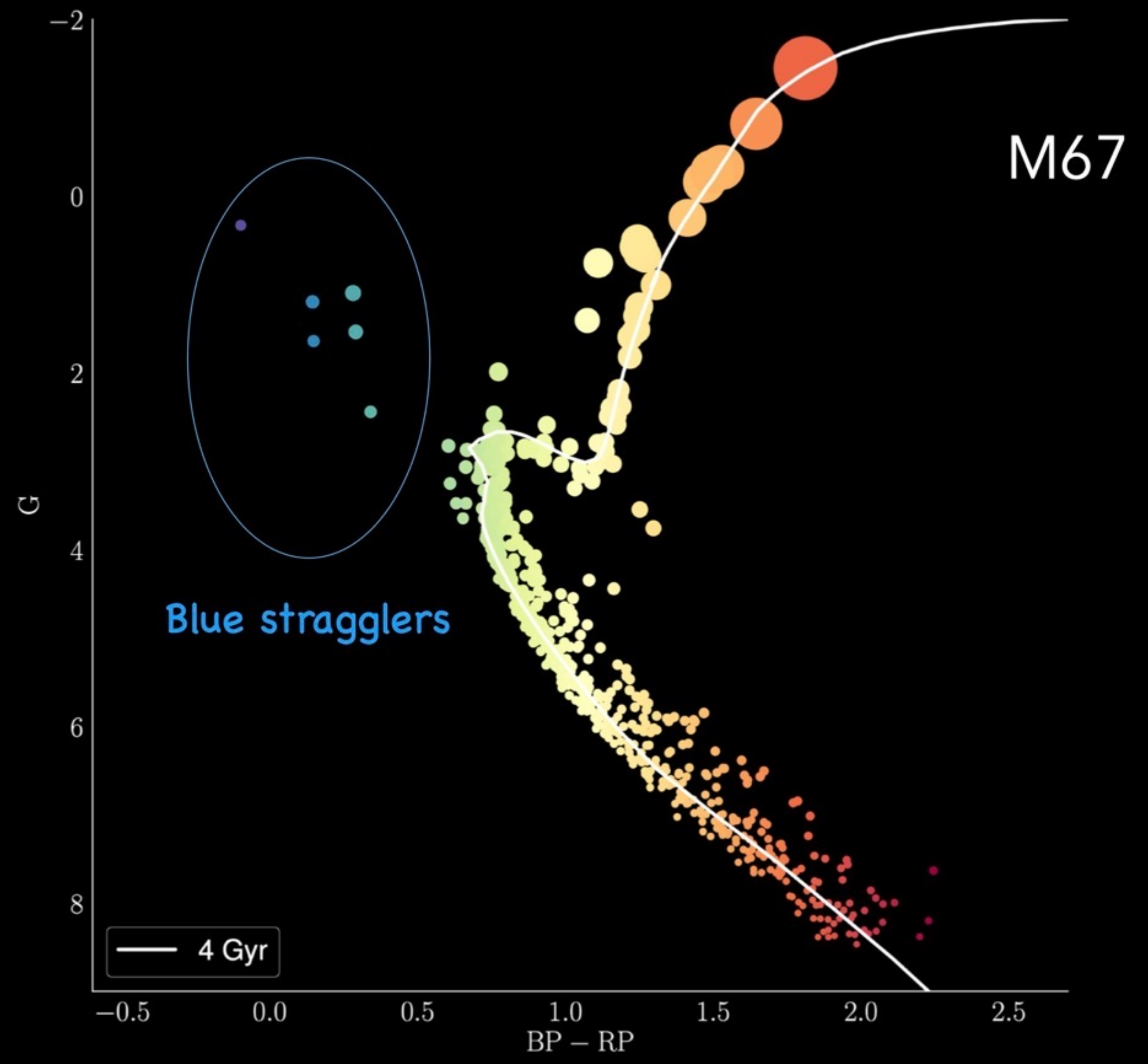
NGC 265
Image Credit: ESA and NASA
Acknowledgment: E. Olszewski (University of Arizona)

Blue straggler stars

Brighter and bluer than main sequence Turnoff (MSTO)

$M_{BSS} > M_{MS}$

Formations mechanisms; binary evolution, stellar collisions and hierarchical triple systems

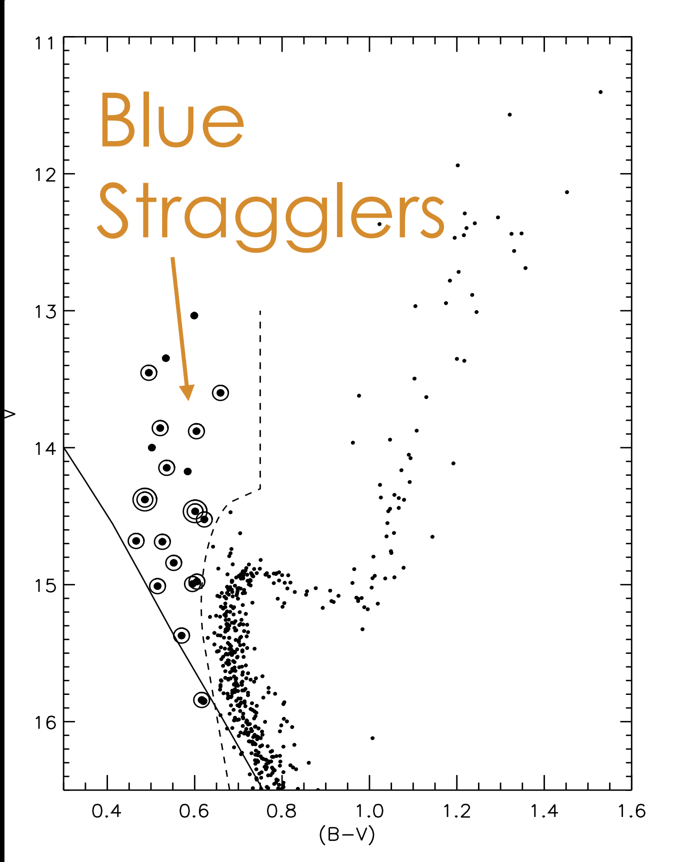


NGC 188 blue stragglers

Binary Frequency
76% ± 21%

Main Sequence
29% ± 3

Mathieu & Geller 2009

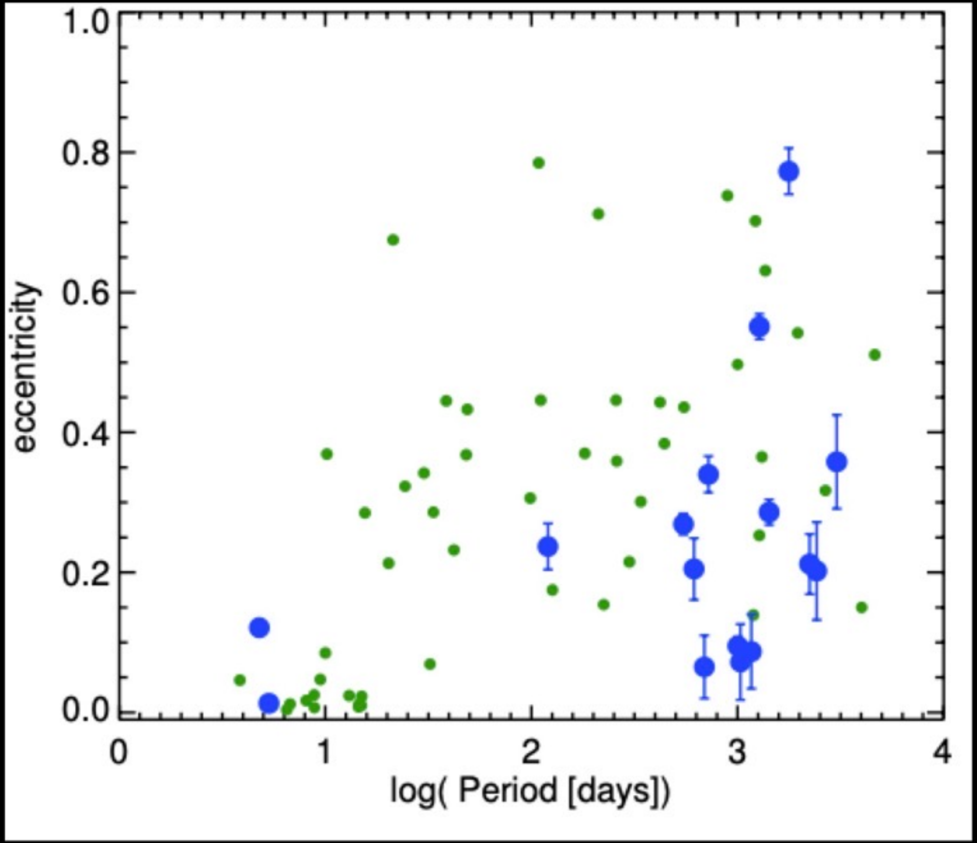


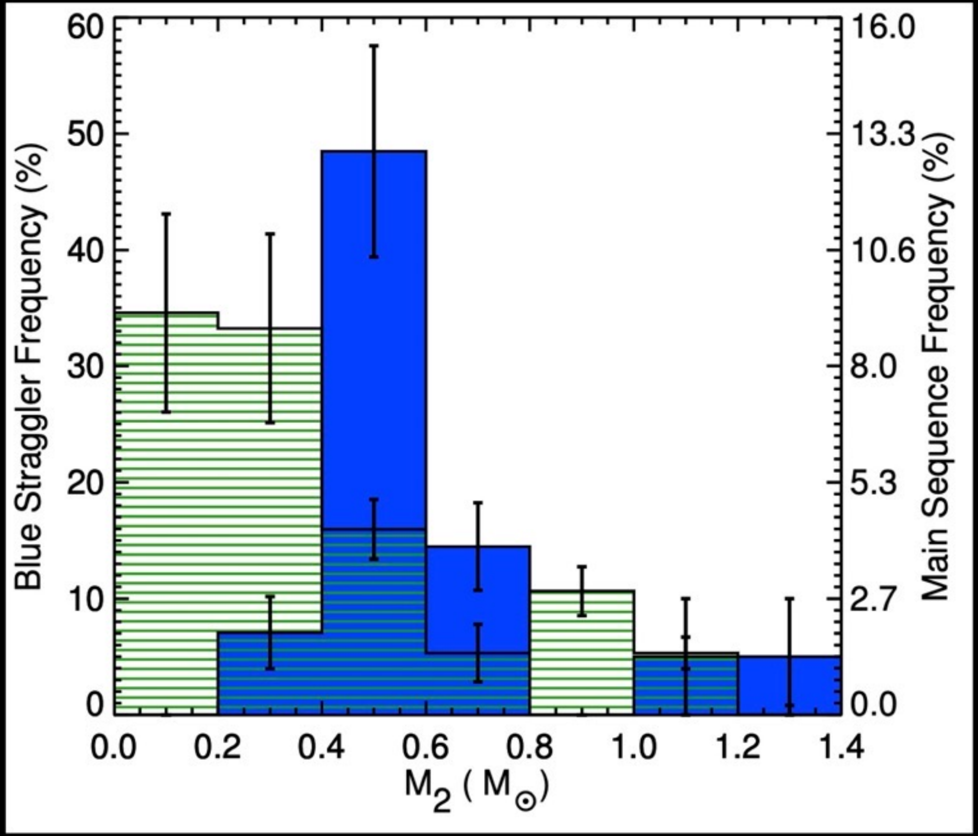
NGC 188 blue stragglers

Mathieu & Geller 2009

Geller+2008

Binary properties reveal formation channel(s)





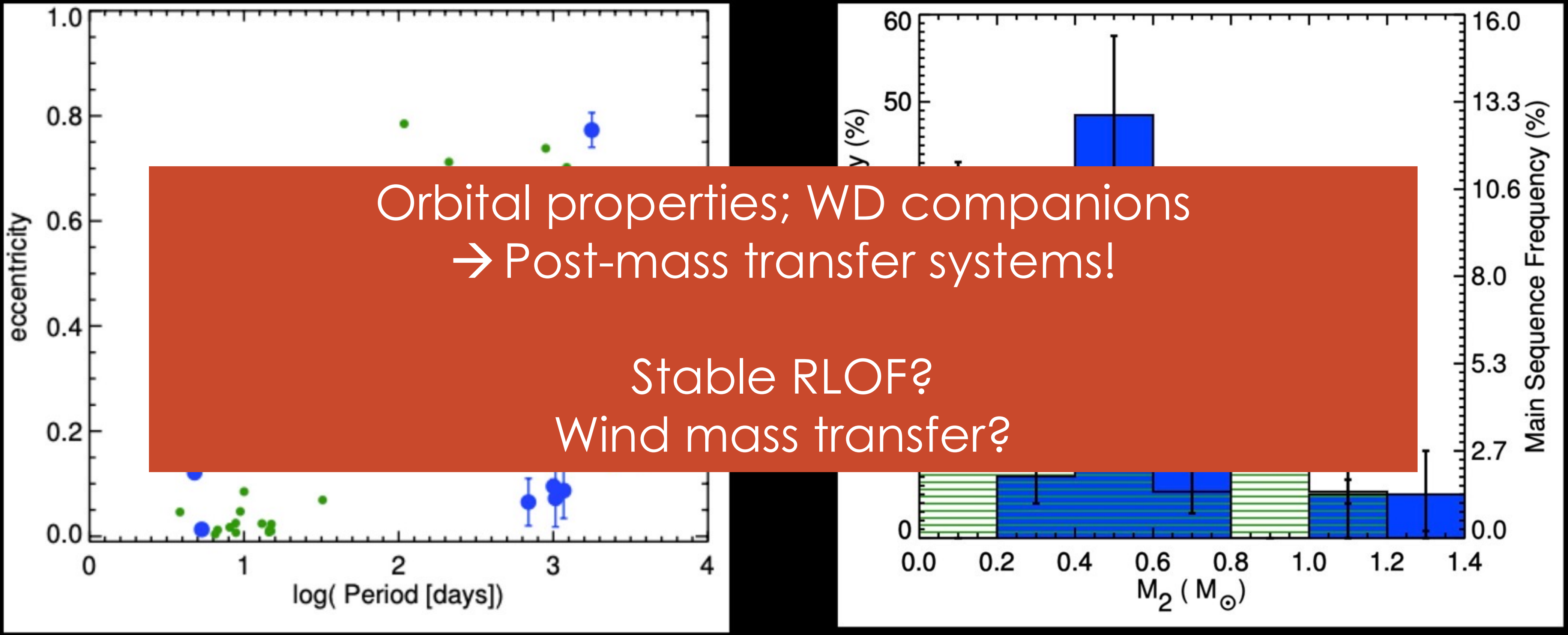
Observed **MS** and **BSS**, log(P) vs. e distribution and mass distribution

NGC 188 blue stragglers

Mathieu & Geller 2009

Geller+2008

Binary properties reveal formation channel(s)



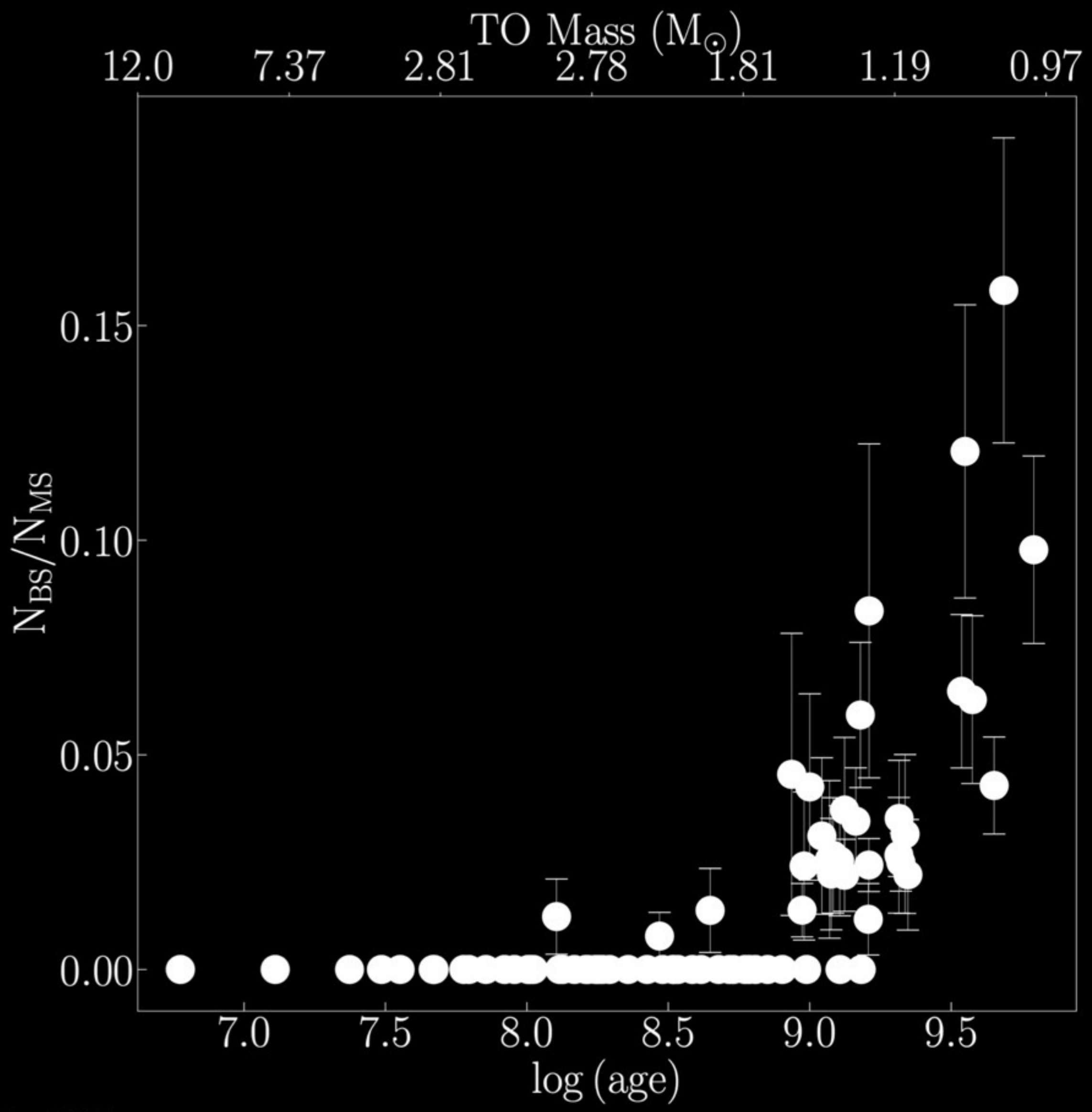
Orbital properties; WD companions

→ Post-mass transfer systems!

Stable RLOF?

Wind mass transfer?

Observed **MS** and **BSS**, log(P) vs. e distribution and mass distribution



Rain+2020

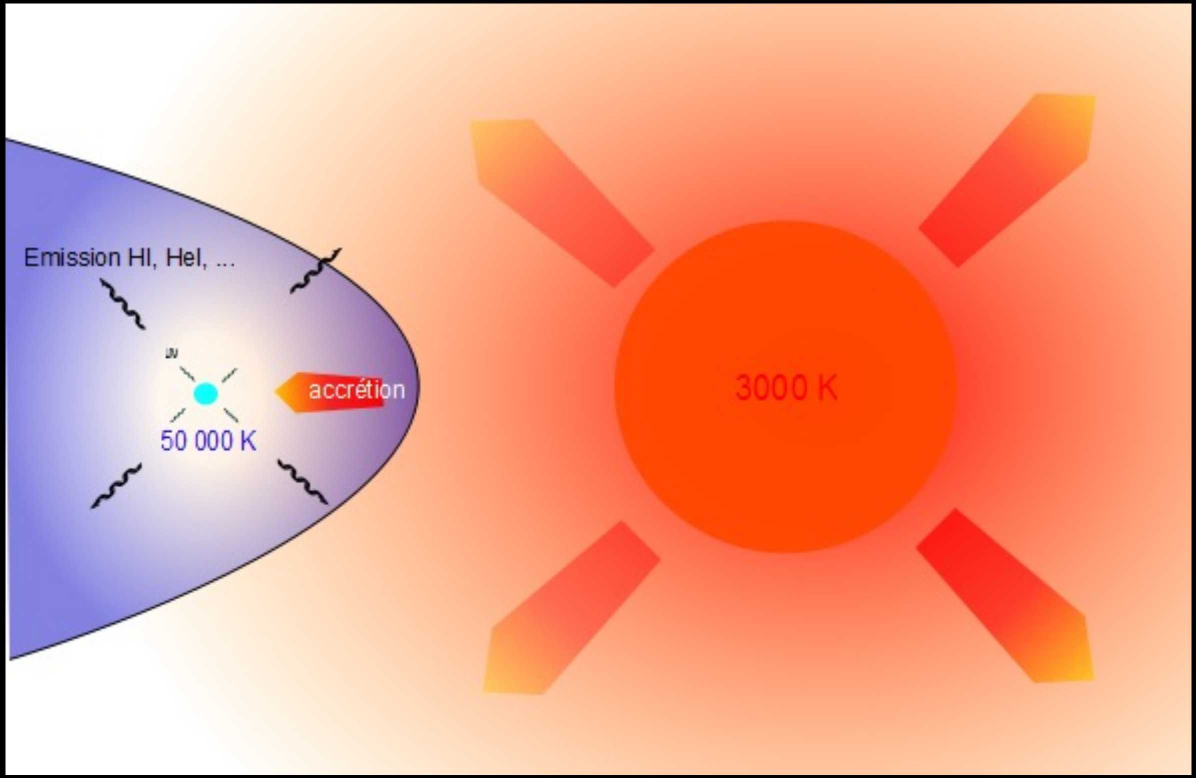
N_{BSS} vs log(age) with Gaia data

(a) BSS frequency is constant until log(age)~ 9

(b) Steep increase until log(age)=10

Symbiotic Stars

a cool red giant and a small hot companion seem to live in general harmony

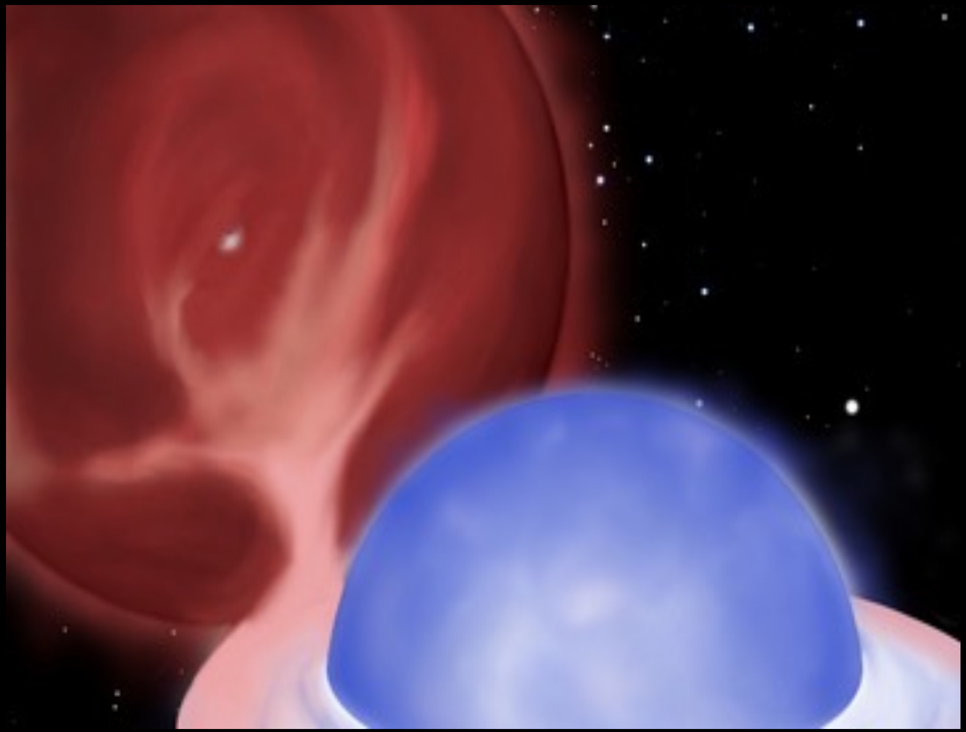


Oxpeckers eat the parasites off of large animals like this African buffalo. But they're also parasites themselves, keeping wounds open and picking at scabs.
Natphotos/Digital Vision/Getty Images
howstuffworks.com

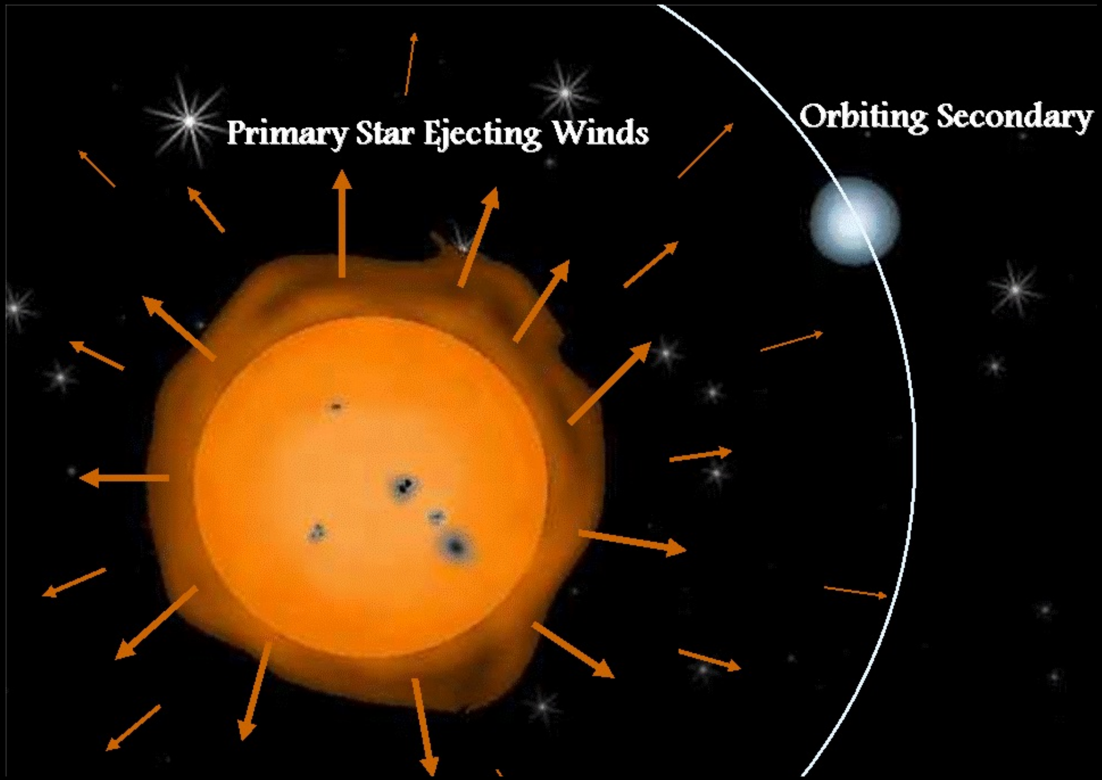
Nature of Mass Transfer?

Symbiotic stars can be divided into two categories based on the nature of the components:

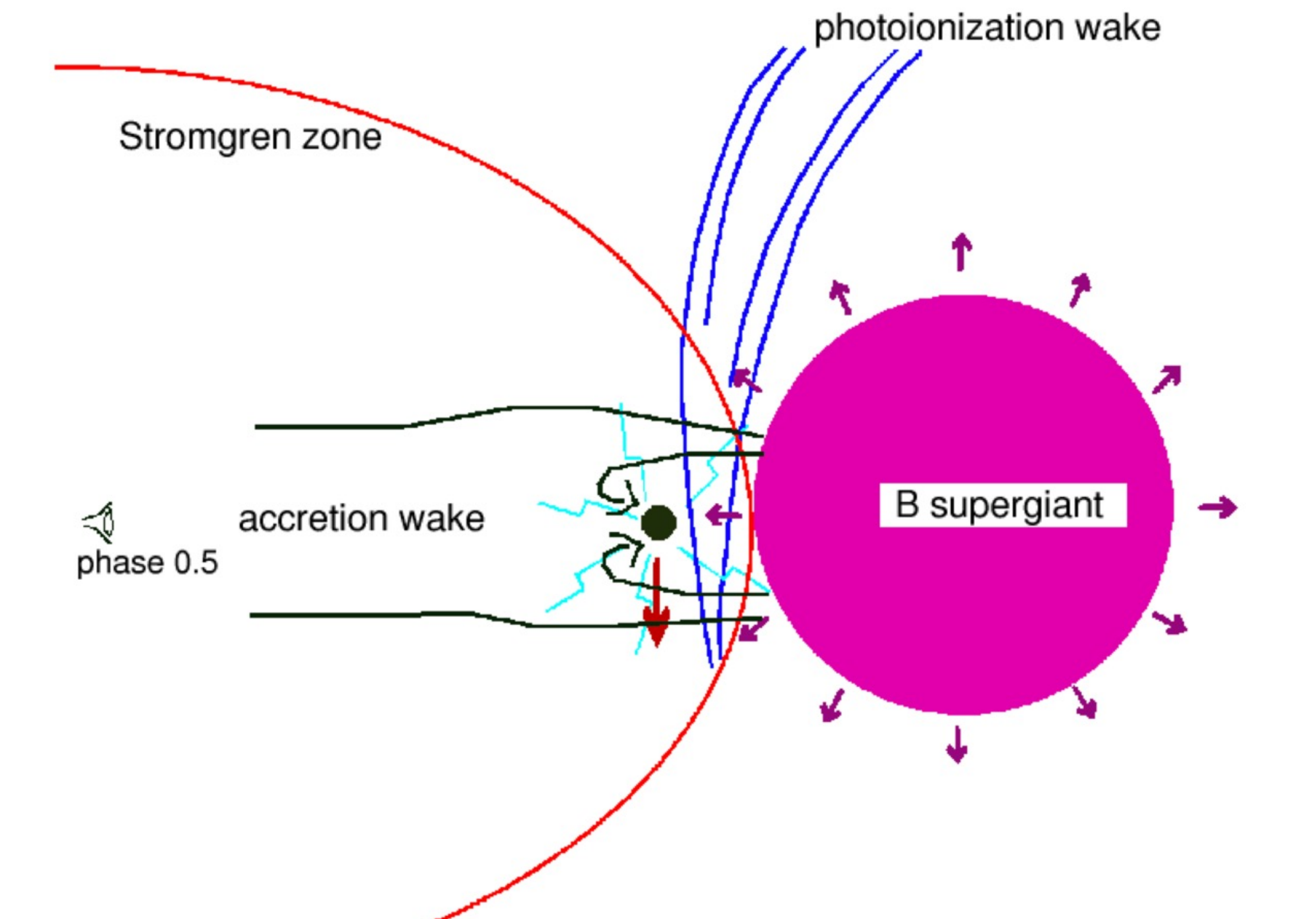
Boffin+ 14



(a) a lobe-filling giant and a A-F main sequence star



(b) a white dwarf or subdwarf and a red giant losing mass in a stellar wind



Goldstein+ 14

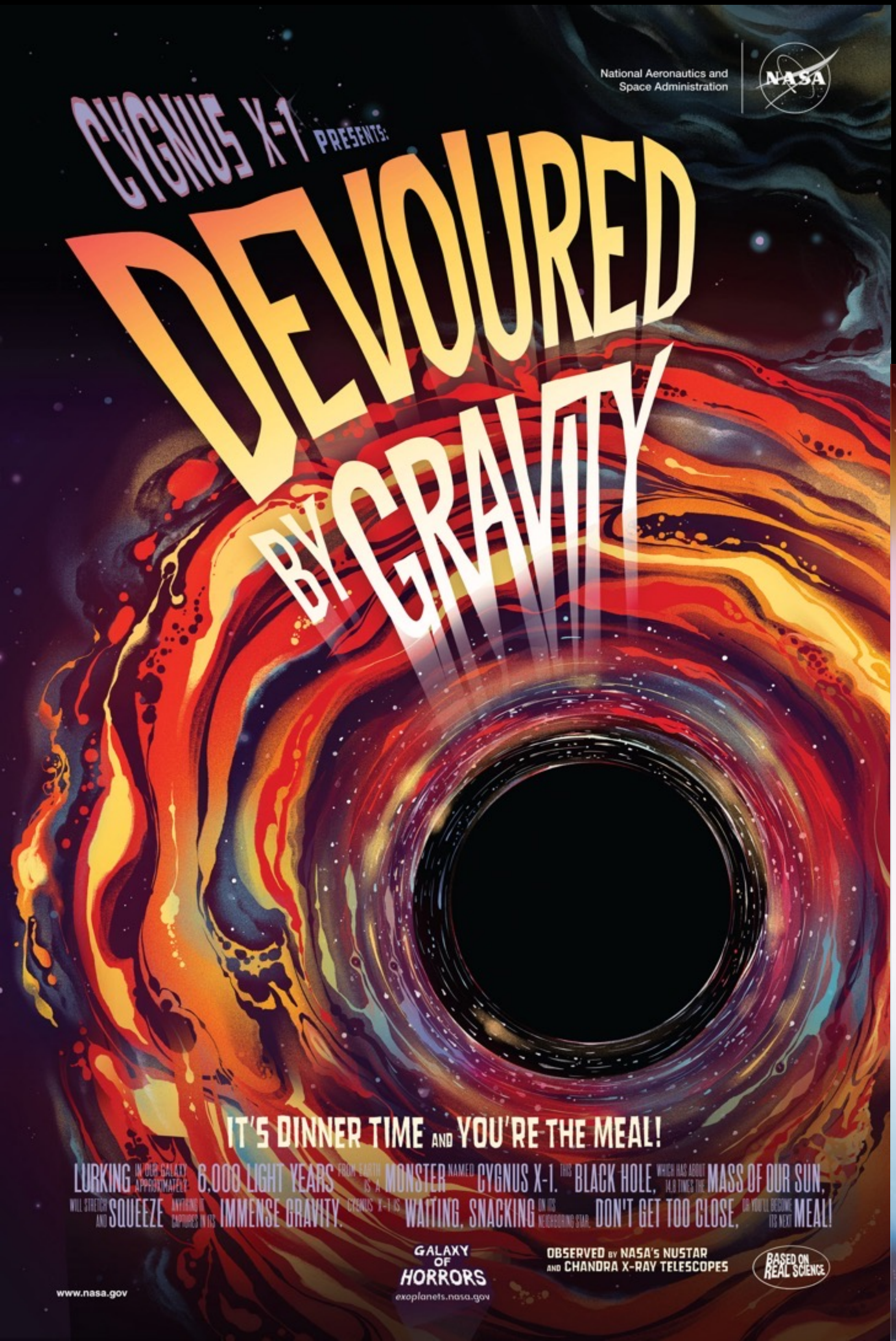
High-mass X-ray binaries

Vela X-1

X-ray binary, consisting of a neutron star and the 23.5 $M_\odot$ B0.5 Ib supergiant star HD 77581

P = 8.964 days

$M_{NS} = (1.86 \pm 0.32)\ M_\odot$



High-mass X-ray binaries

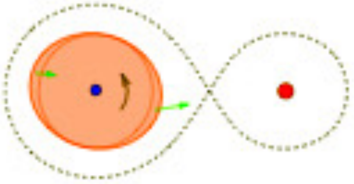
Cygnus X-1

P = 5.599829 days
BH ~ 21 $M_\odot$
Companion: Blue supergiant O9.7 Iab; 20-40 $M_\odot$

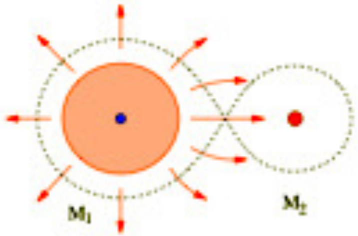
Stellar wind is focused to binary plane and creates an accretion disc

Close binaries

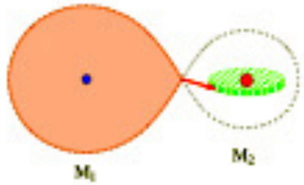
stars in binaries can interact in various ways:



tidal interaction



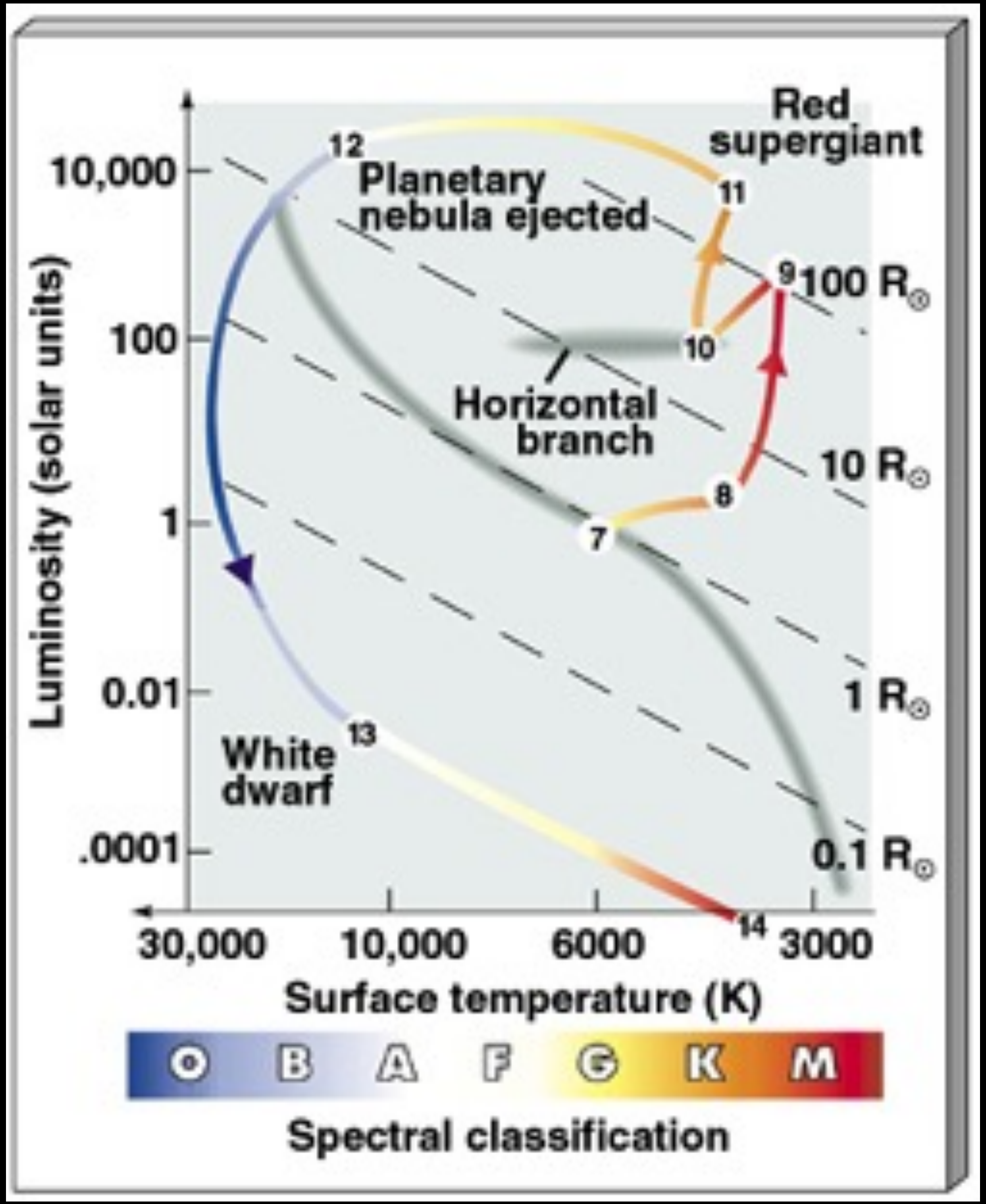
wind accretion



$\boxed{\text{Roche-lobe overflow}}$

Semi-detached systems

CVs, Algols



Roche lobe overflow if

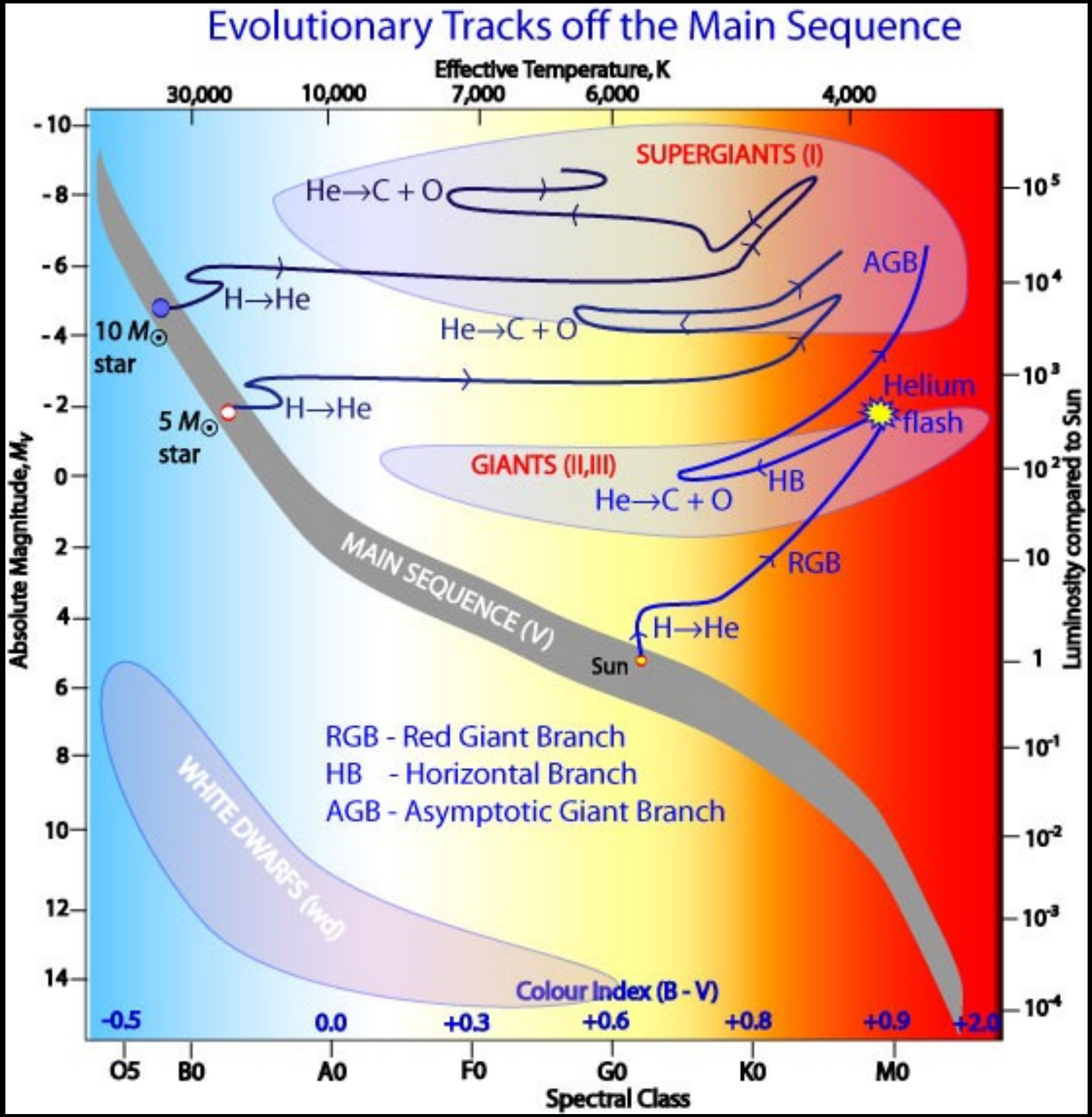
a ~ 1.3 au; P ~ 1 yr

a ~ 0.13 au; P ~ 12 d

a ~ 2-3 R☉; P ~ 5-6 h

a ~ 0.25 R☉; P ~ 30 min

Roche lobe overflow



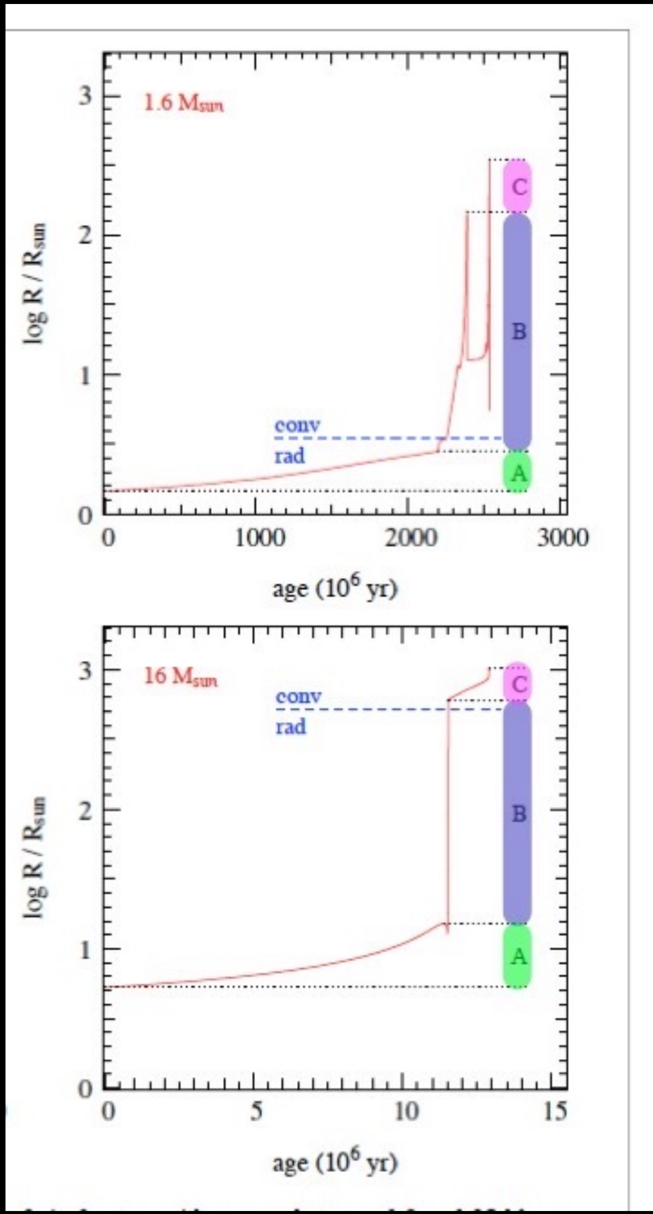
Distinguish case according to stellar evolution stage

Mass-transfer modes : cases A, B and C

case A = RLOF during main sequence

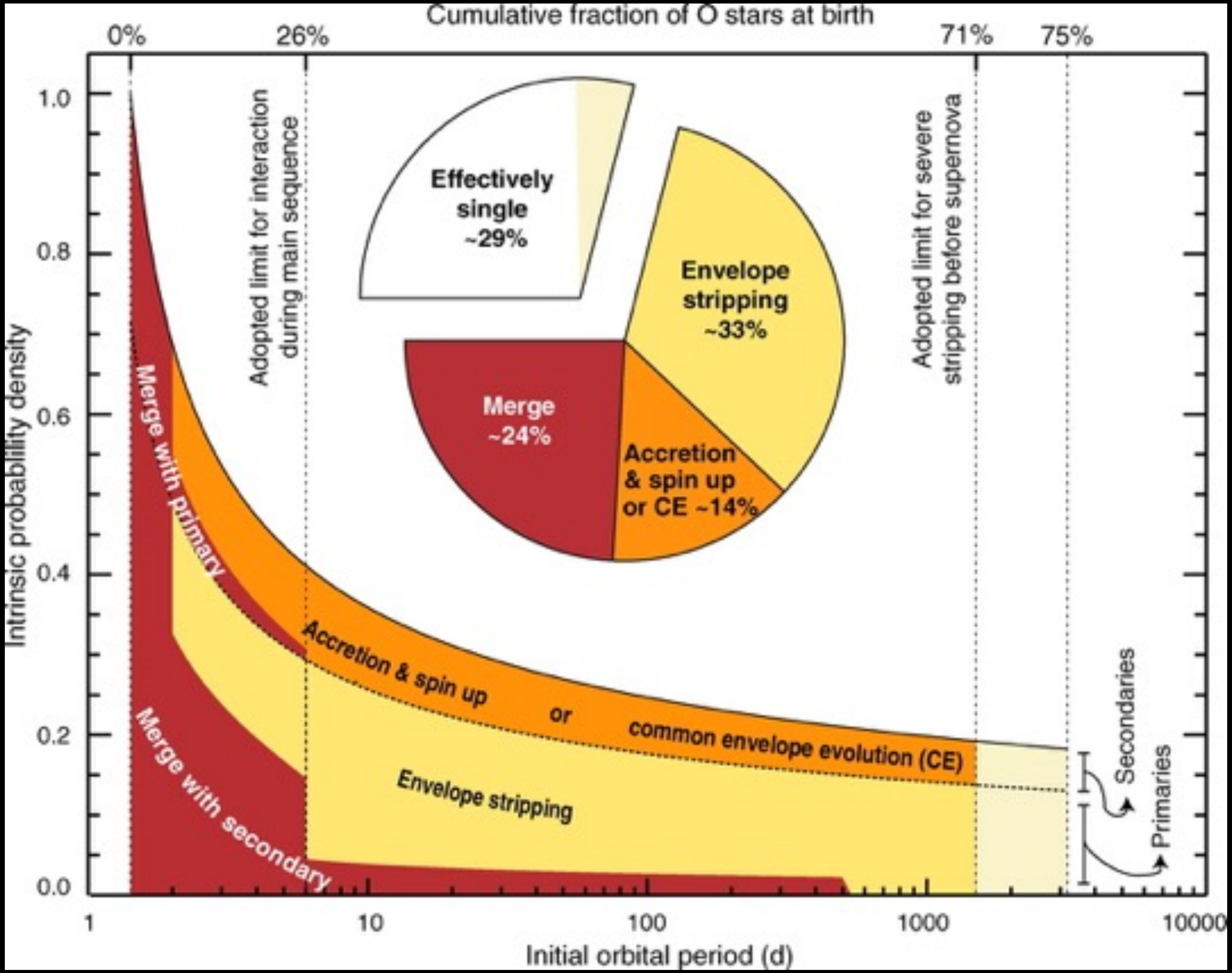
case B = RLOF during first giant branch

case C = RLOF during asymptotic giant branch

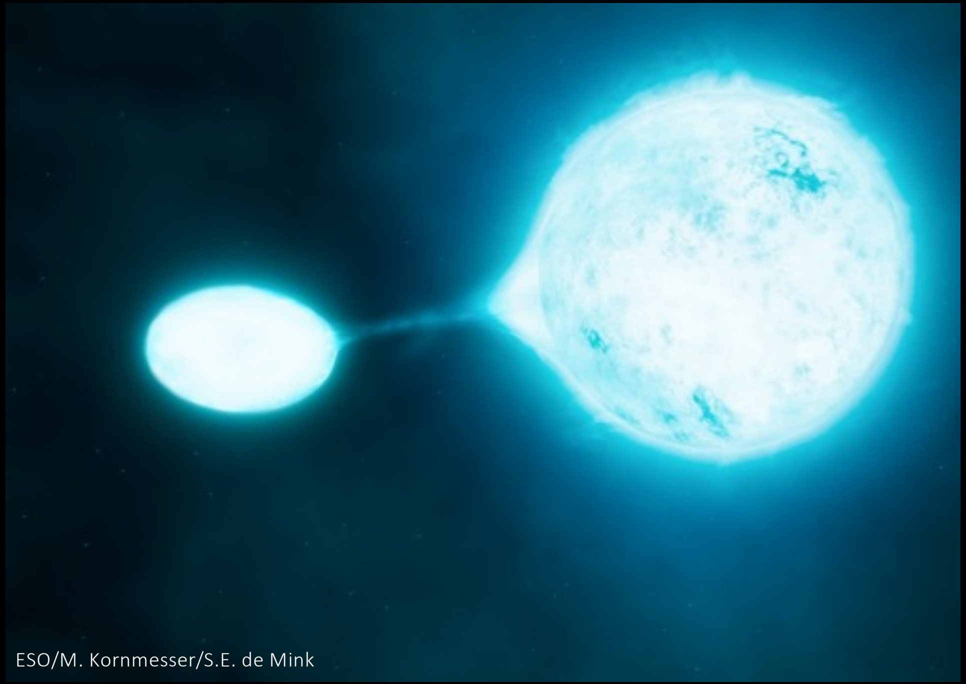


O. Pols

Massive stars interact: Roche lobe overflow

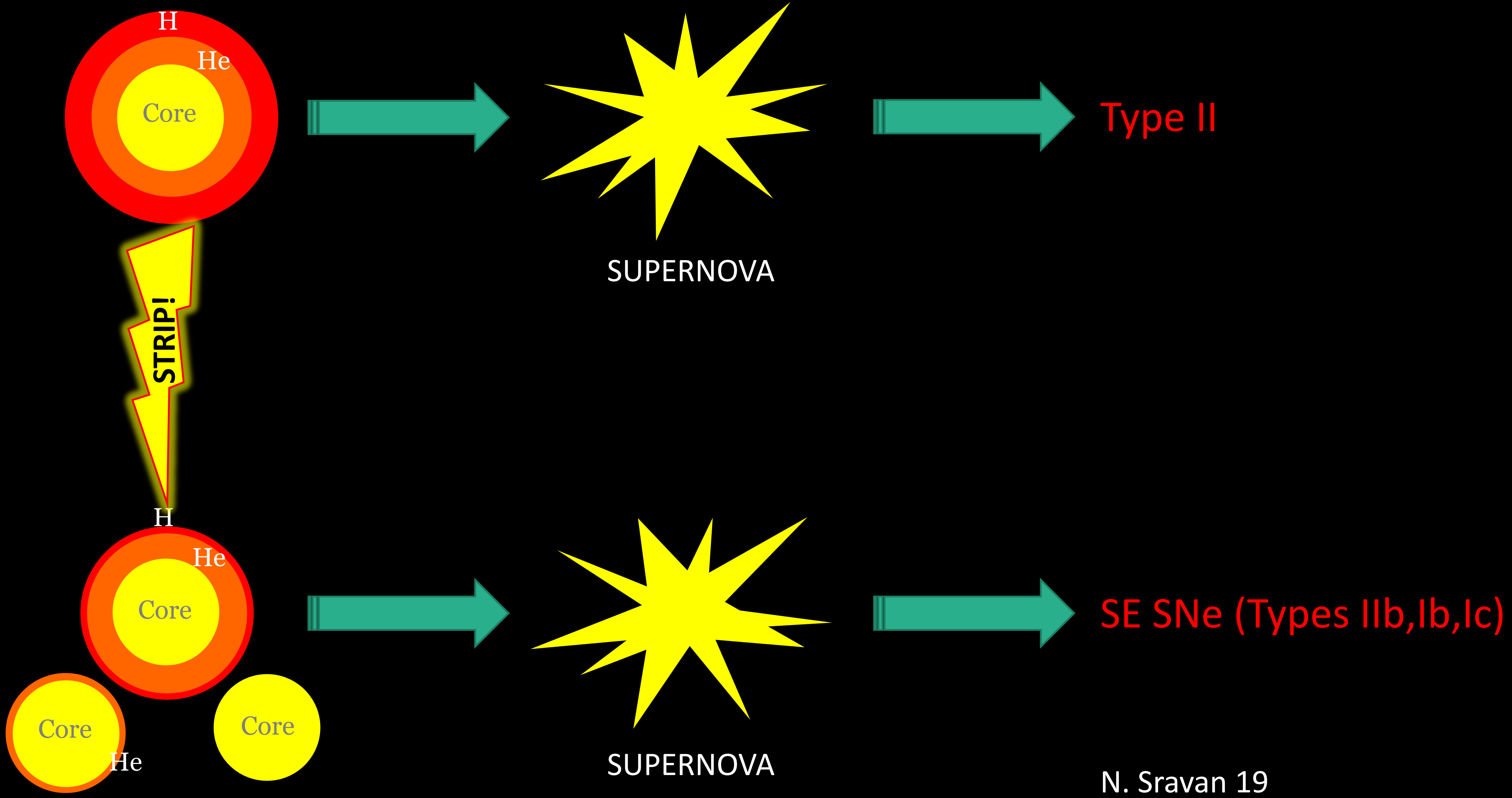


H. Sana et al. Science 2012;337:444-446



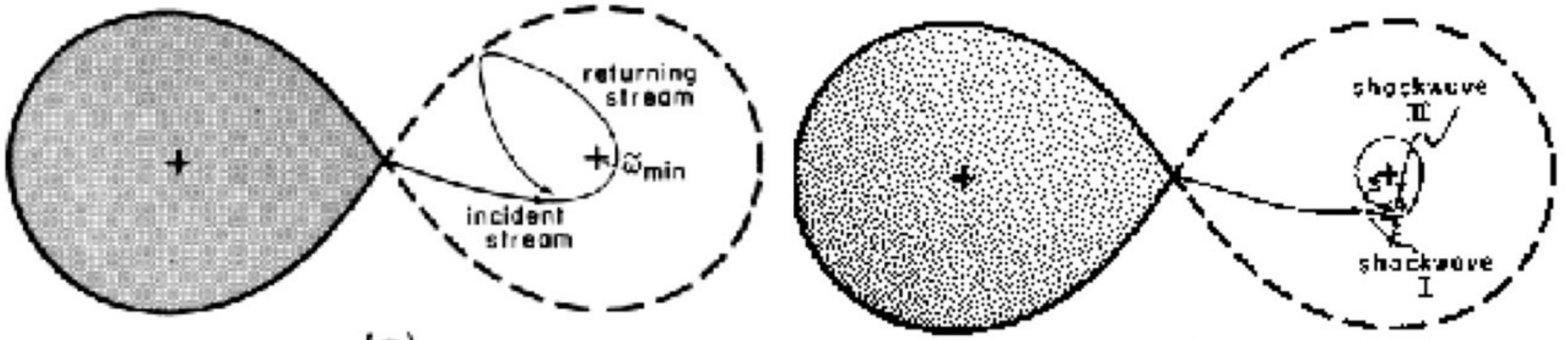
ESO/M. Kornmesser/S.E. de Mink

Stripped Envelope (SE) Sne



N. Sravan 19

Formation of a Ring



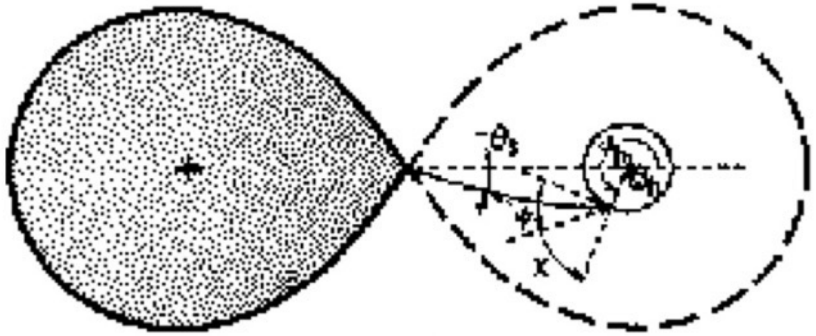
(a) (b)

Circularisation Radius

same angular momentum as L1

$$\left(G\,M\,R_{circ} \right)^{1/2} = \frac{2\pi}{P} R_{L1}^{\ 2}$$

$$\frac{R_{circ}}{a} = \left(1+q\right)\left(\frac{R_{L1}}{a}\right)^4 \approx \left(1+q\right)\left(0.5 - 0.23\log q\right)^4$$



(c)

Coriolis force → angular momentum!

Horne 12

Roche lobe overflow

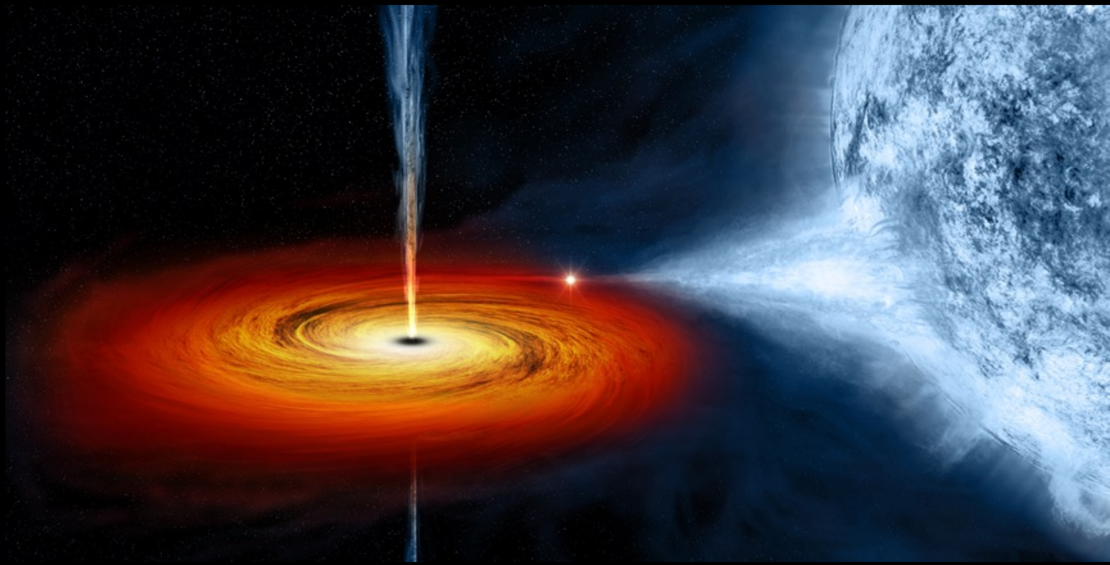
If $R_{circ} > R_*$, a disc forms

If accreting star is compact, jets form

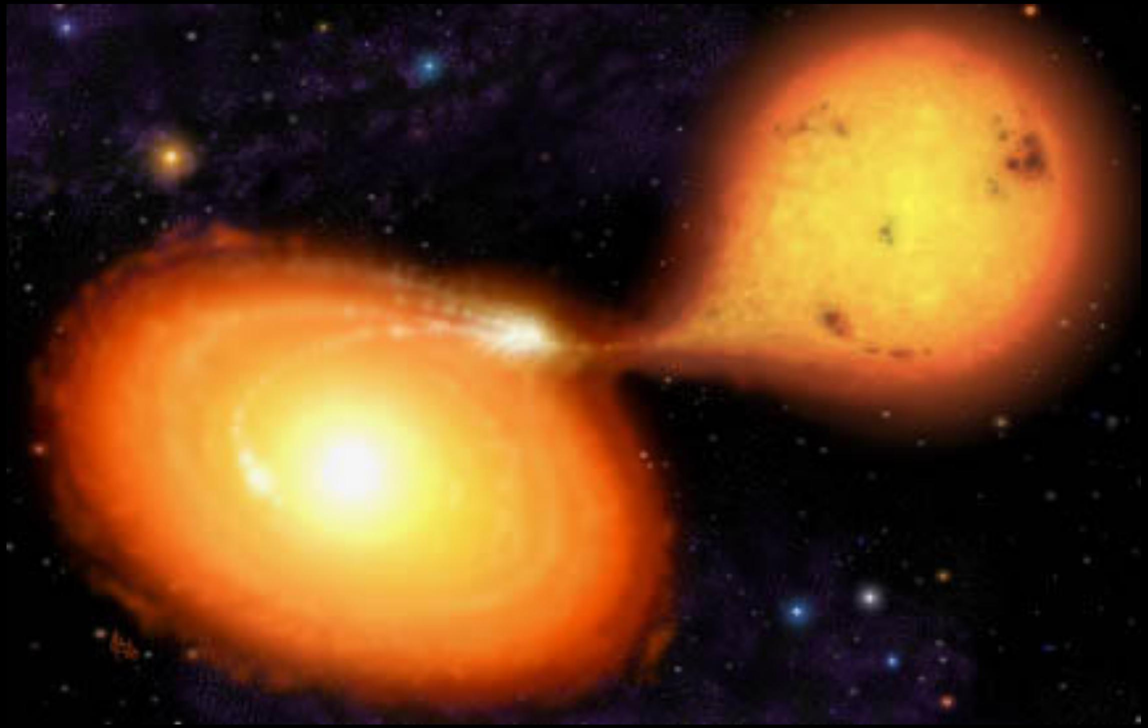
This is the case when accretor is WD (CV), NS (LMXB), BH (HMXB)

Or even a MS if system is wide (symbiotic star)

If MS and short period, then direct impact (Algol)



Cataclysmic variables



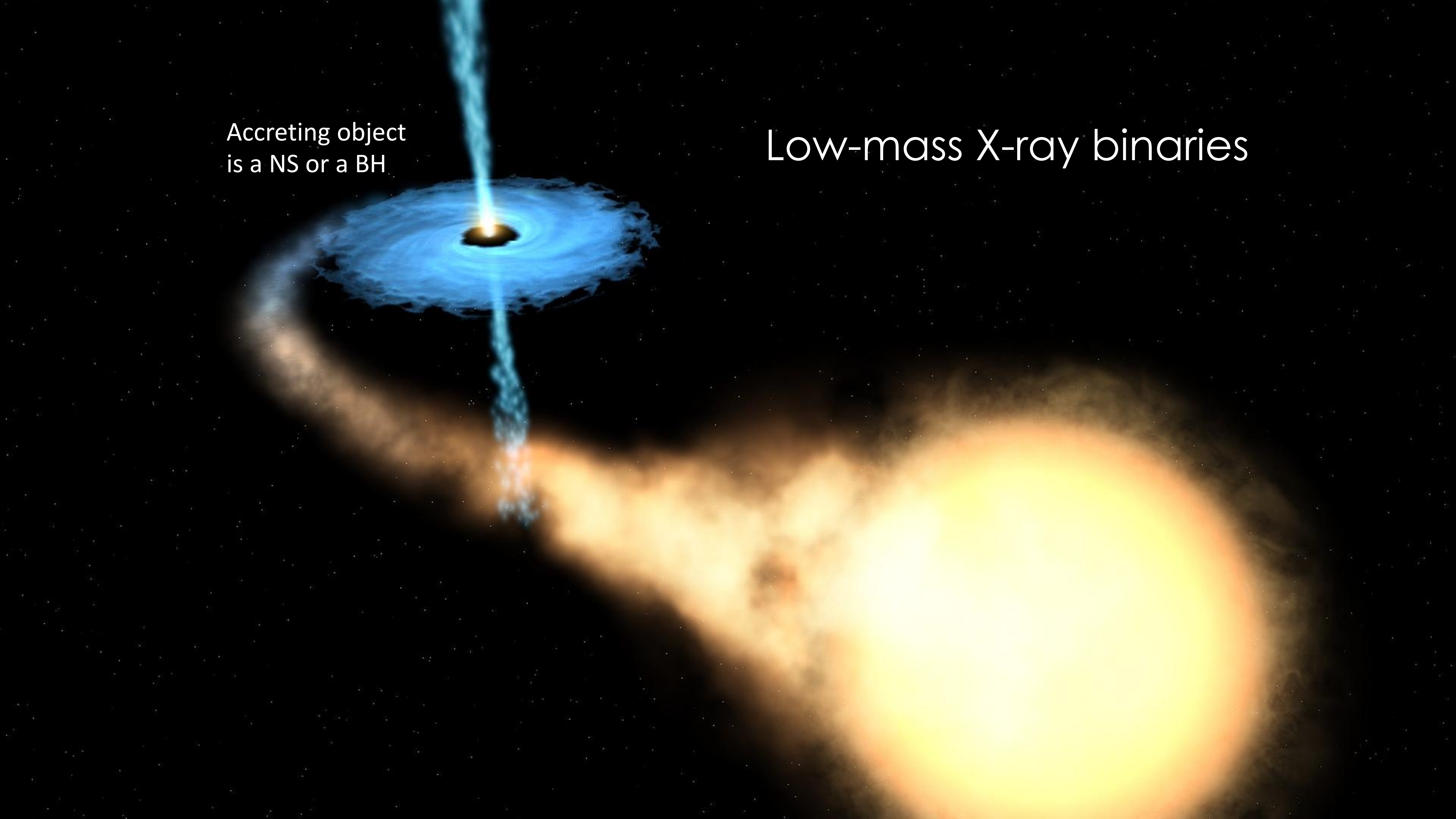
Contains a main sequence star filling its Roche lobe and a white dwarf

Orbital period ~ few hours
Separation ~ 1 solar radius

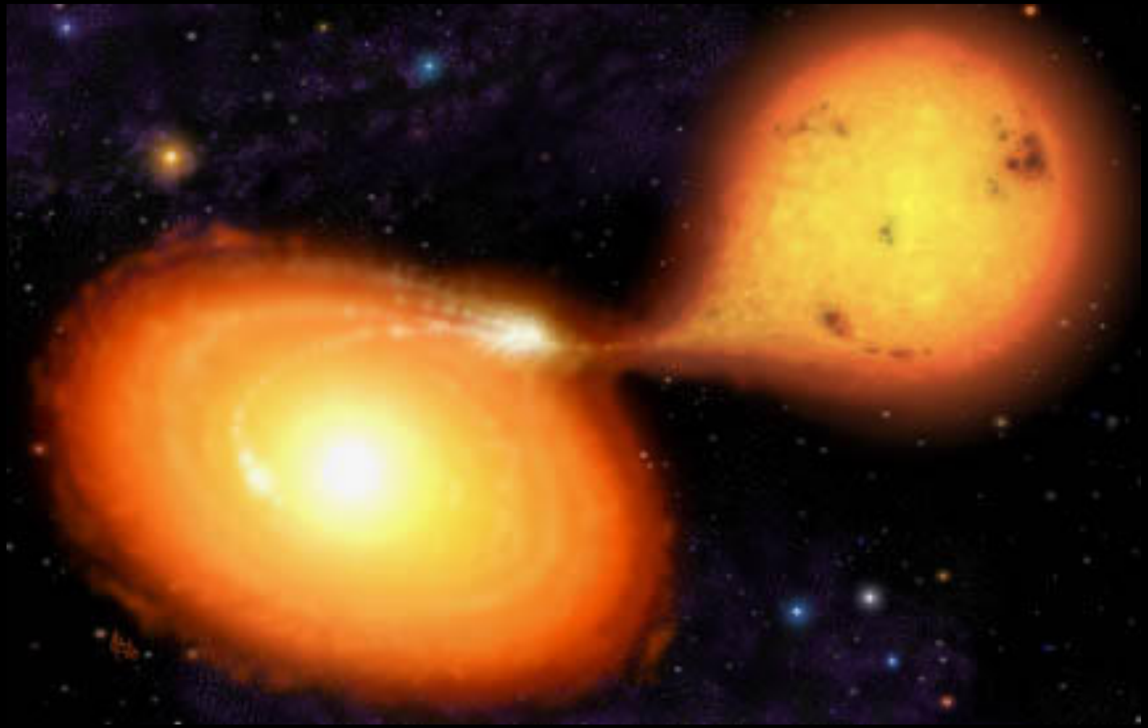
Angular momentum evolution:

- magnetic fields
- gravitational waves

Low-mass X-ray binaries



Cataclysmic variables



Contains a main sequence star filling its Roche lobe and a white dwarf

Orbital period ~ few hours
Separation ~ 1 solar radius

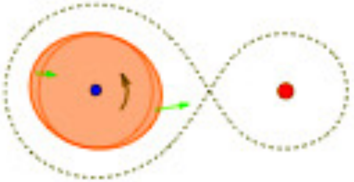
But WD comes from an AGB which reached radius of several hundred solar radii!

→System has considerably shrunk!

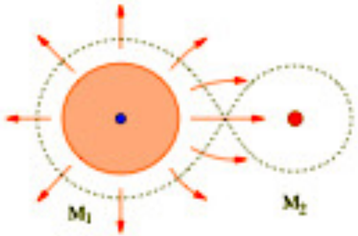
How?
Common envelope evolution

Close binaries

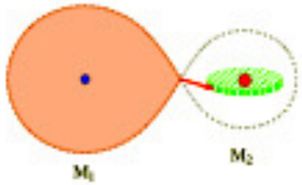
stars in binaries can interact in various ways:



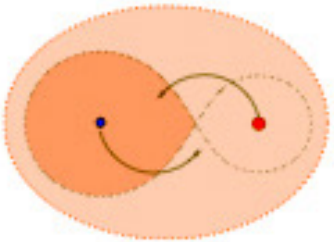
tidal interaction



wind accretion



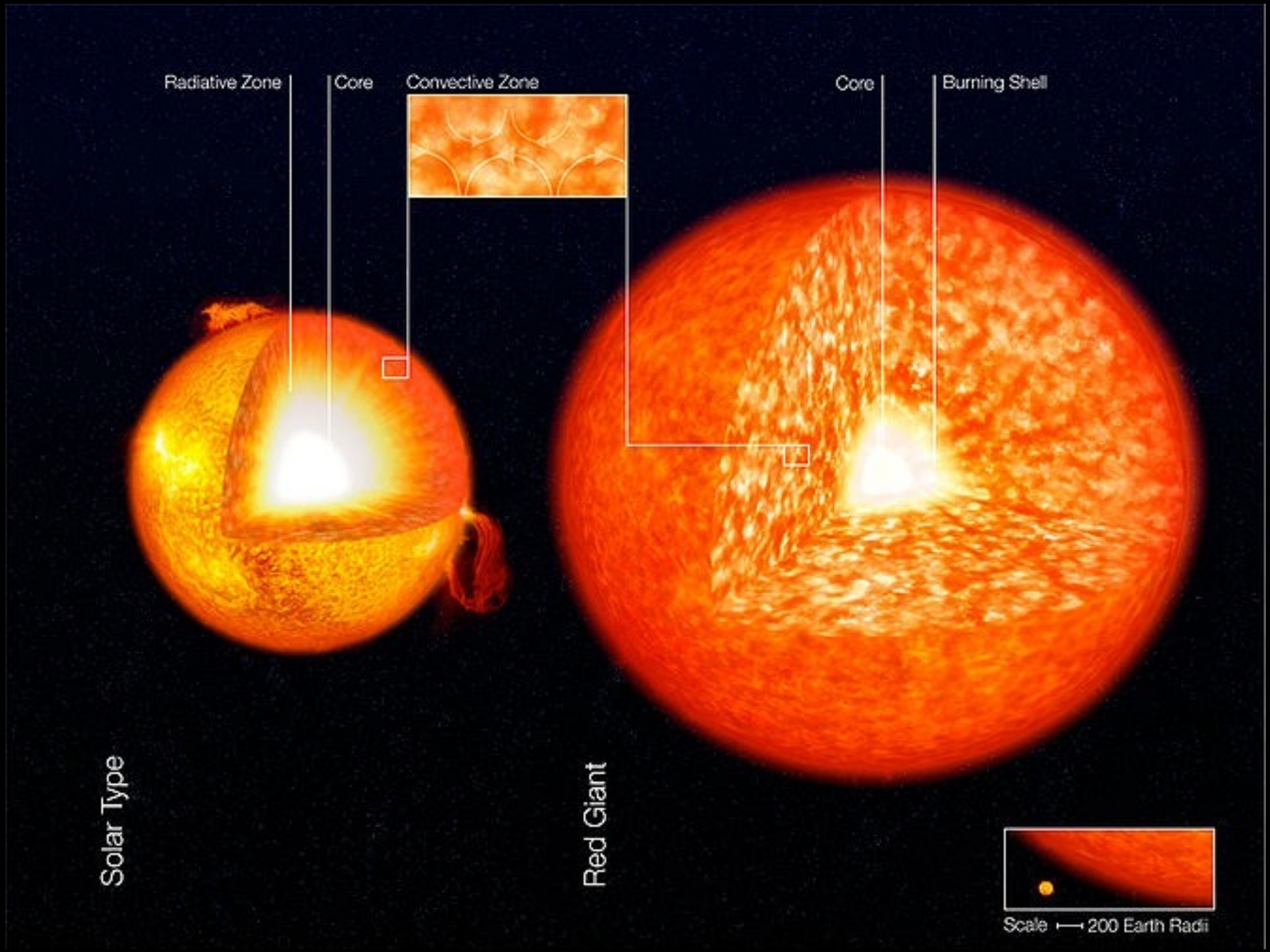
Roche-lobe overflow



common envelope evolution

sdB, Bin. CSPNe

Mass Transfer Instability



Red giants have large convective envelopes → they react to mass loss by expanding

If radius increase is larger than Roche lobe's increase, the transfer becomes dynamically unstable

Common envelope evolution

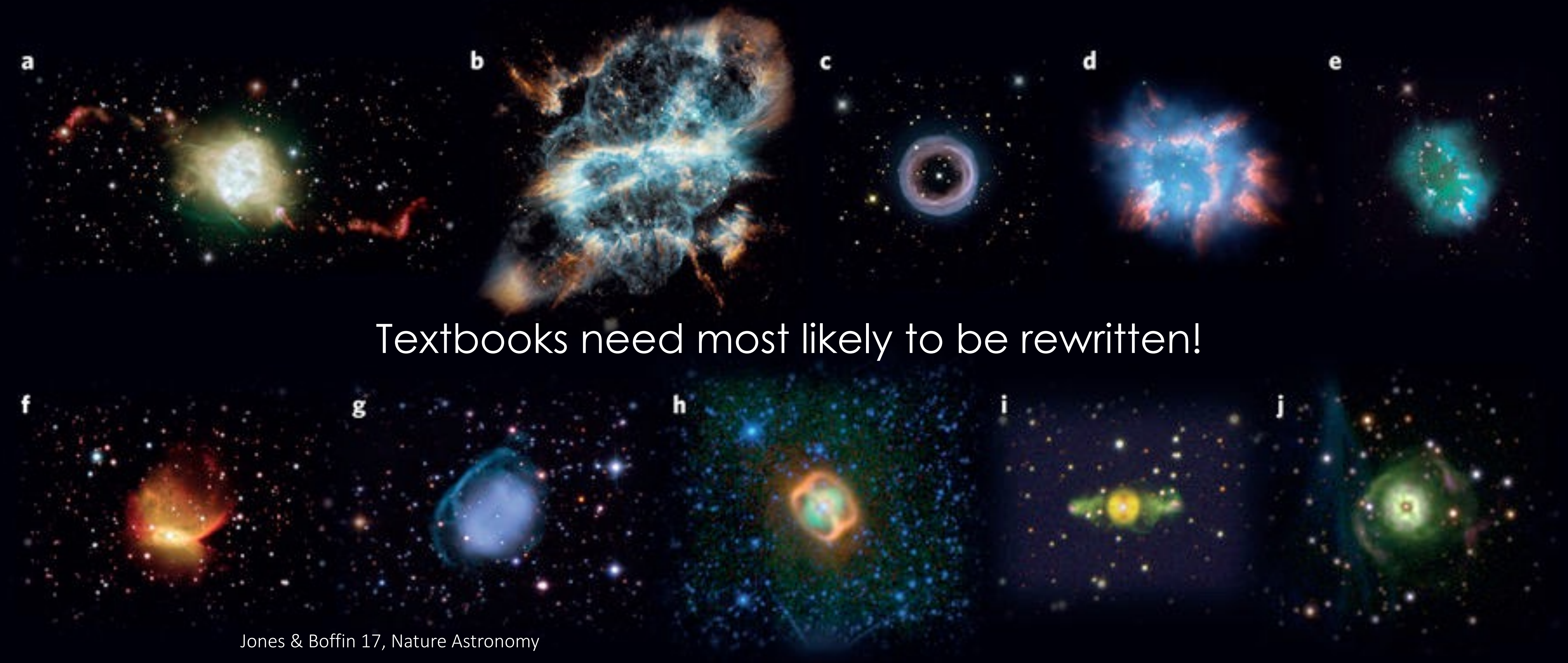
From period of
a few years to
a day or less!

Credit: STScI

The Butterfly Nebula

A planetary nebula

Planetary Nebulae



Textbooks need most likely to be rewritten!

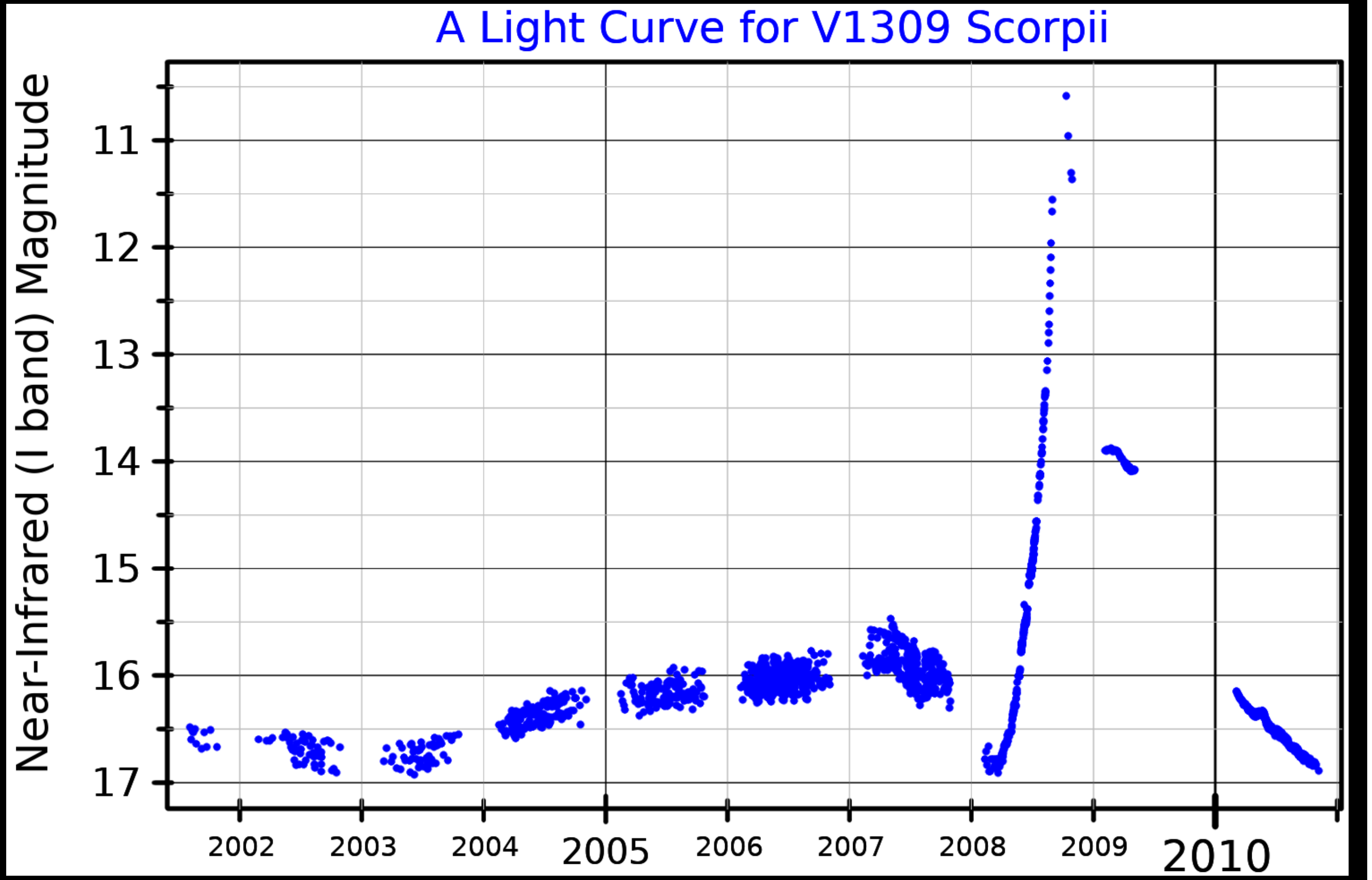
Jones & Boffin 17, Nature Astronomy

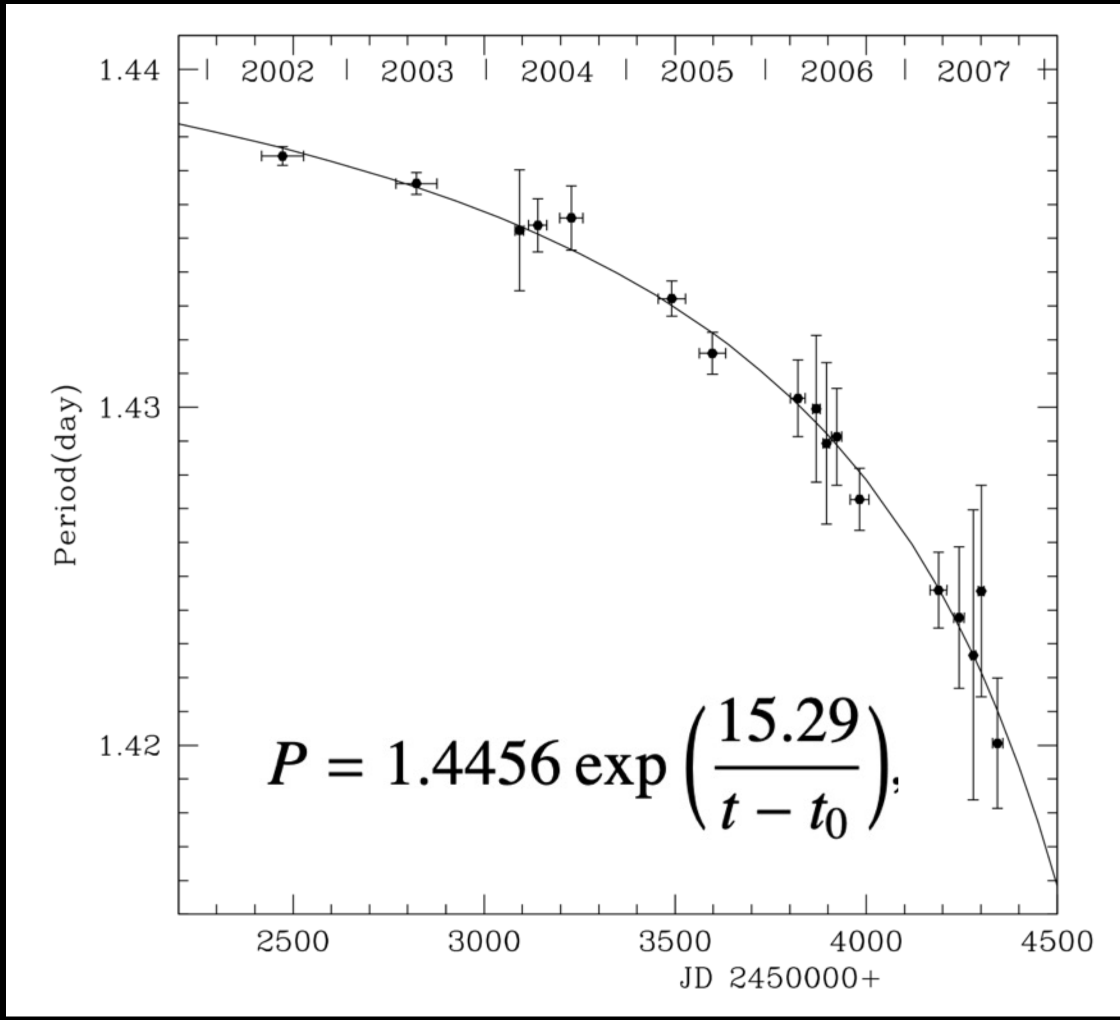
What happens if the common envelope is not ejected?

→ The 2 stars merge!

Luminous red novae

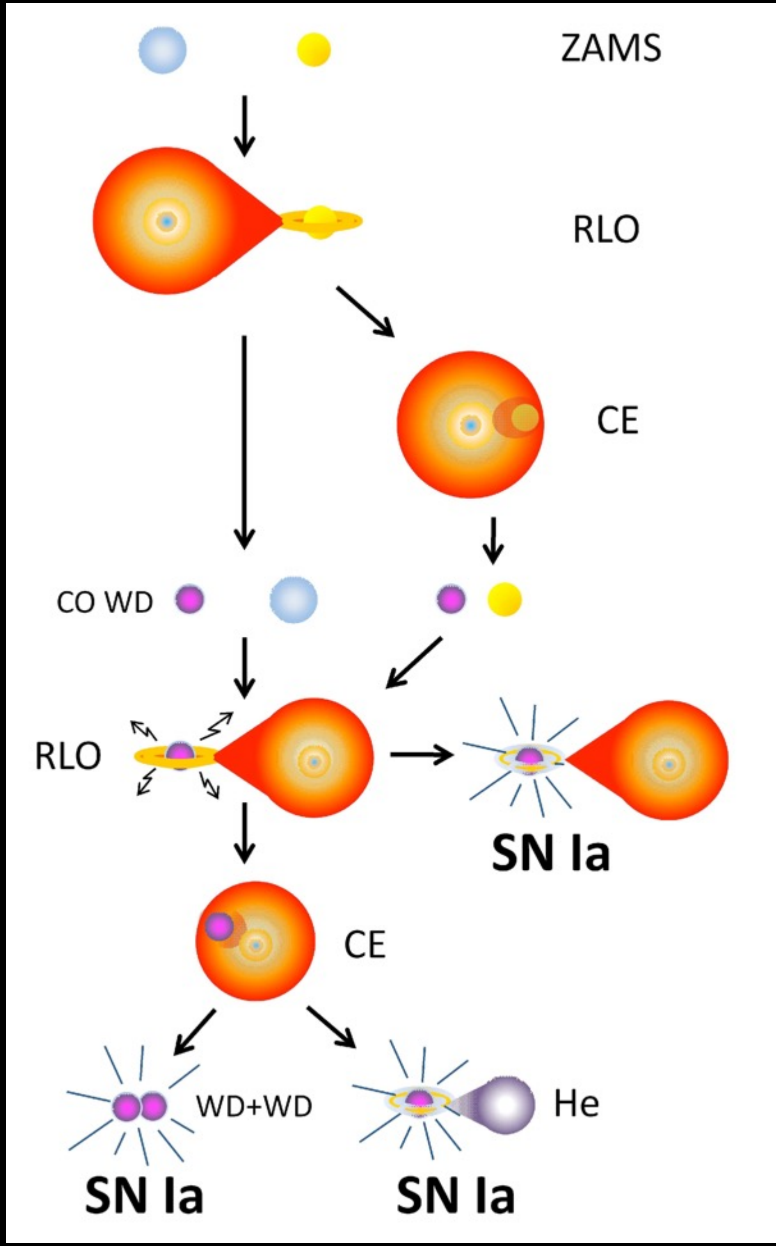
R. Tylenda+



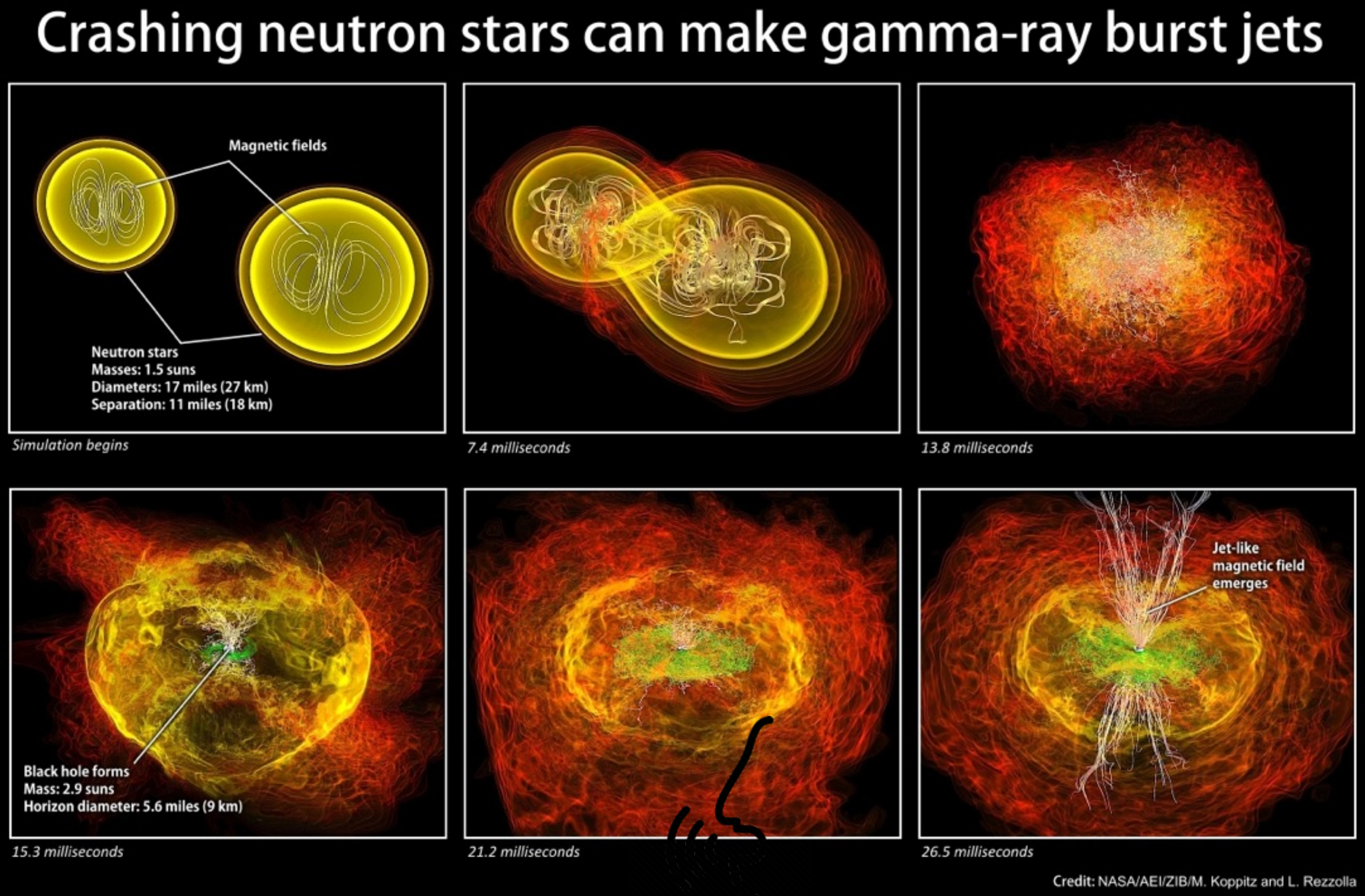


Spread due to photometric signal

Exploding events

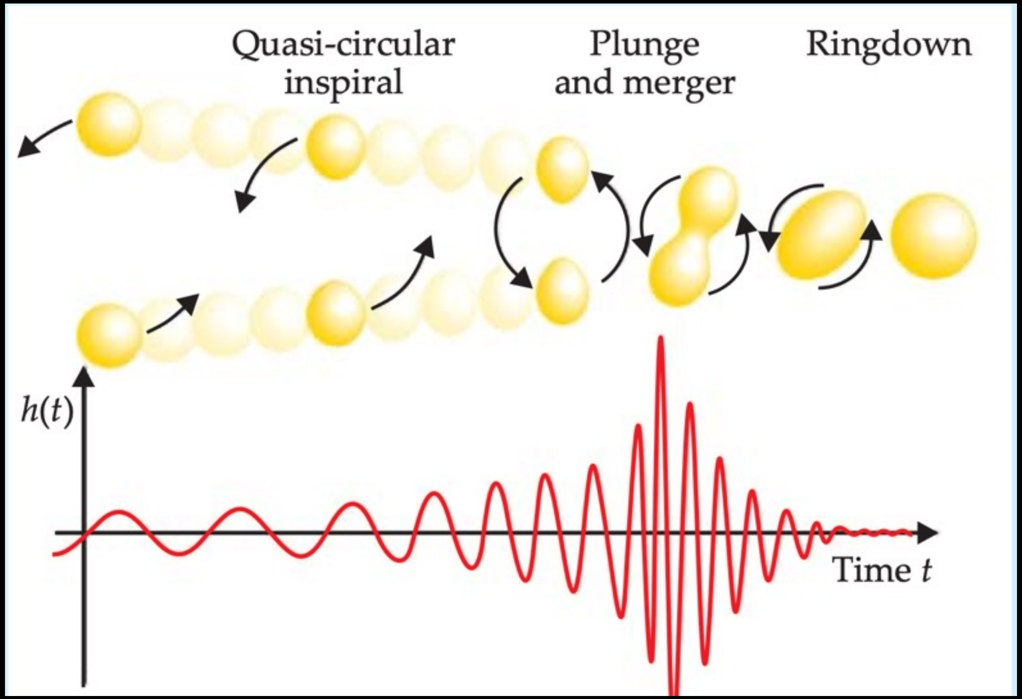


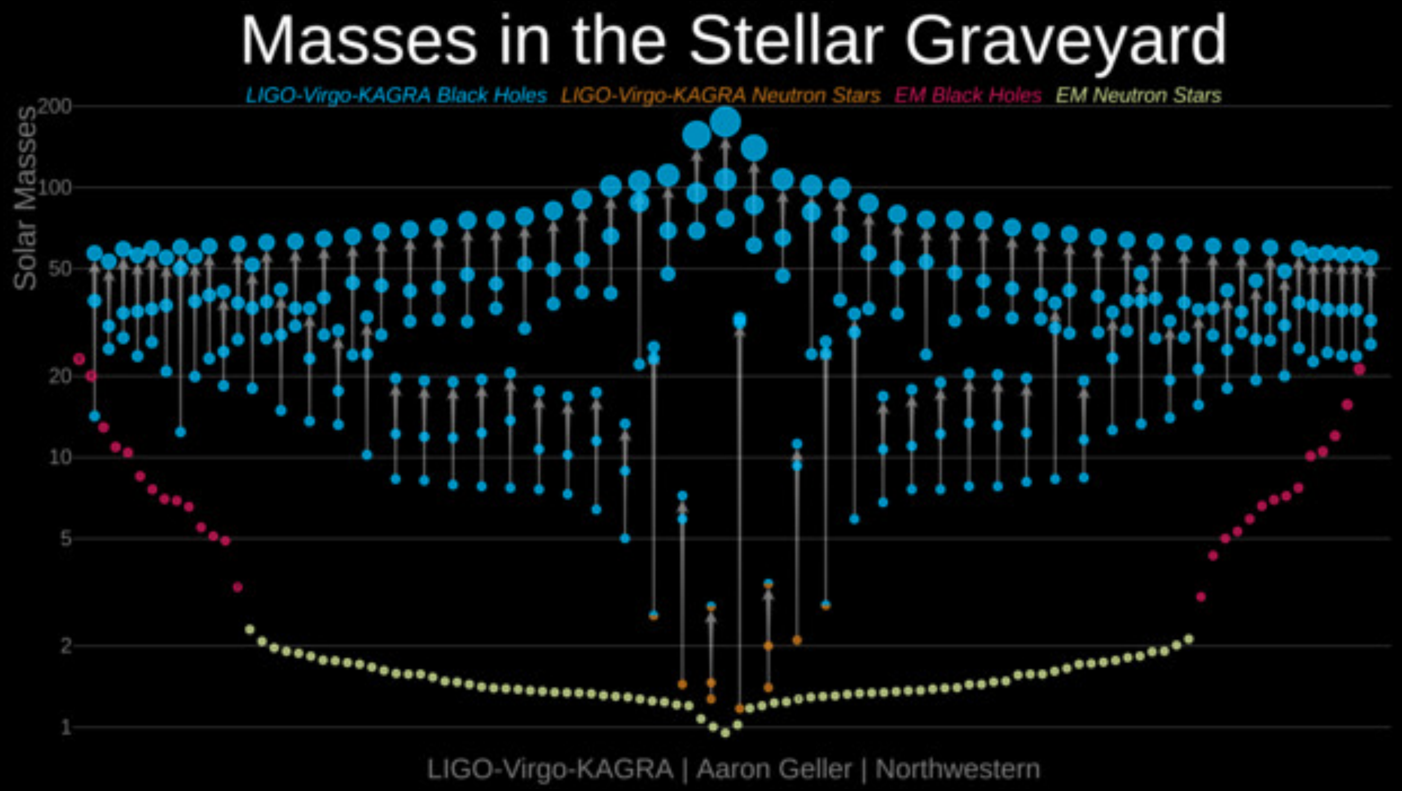
Ivanova+ 13



Mergers of WDs will lead to Type Ia Sne

Mergers of NS or BH will lead to GW emission





What should you have learned?

- Binary stars are everywhere – most massive stars are in binaries and binaries make the most interesting systems
- Interaction can be tidal or mass transfer, and the latter can be via wind or via Roche lobe overflow
- Mass transfer can explain many different classes of binary stars
- Mass transfer can be stable or not
- Common envelope will shrink the orbit and could be responsible for planetary nebulae shapes

hboffin@eso.org


Questions?