Stripped helium stars

finding their progenitors

Spectroscopic project

Who am I?

Stephan Geier

Born and raised in a small village in Franconia (Northern Bavaria)

Studied physics at University Erlangen (+history & archaeology)

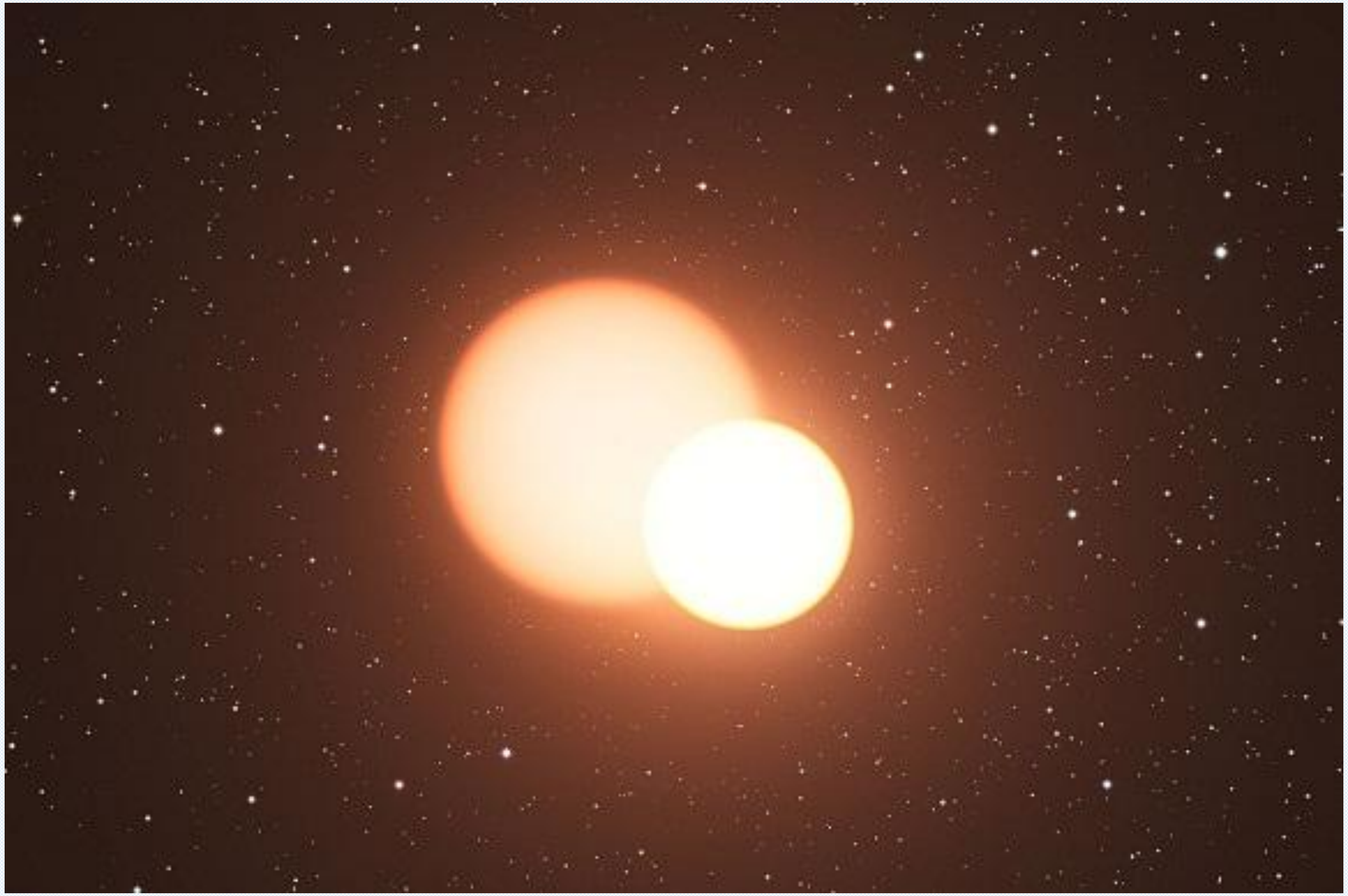
2009+2011 PhDs (physics & history): Bamberg observatory + Erlangen

2009-2016 PostDocs: Bamberg, ESO Garching, and University of Warwick

2016-2018 Staff scientist, University of Tübingen

Since 2018 Professor, University of Potsdam

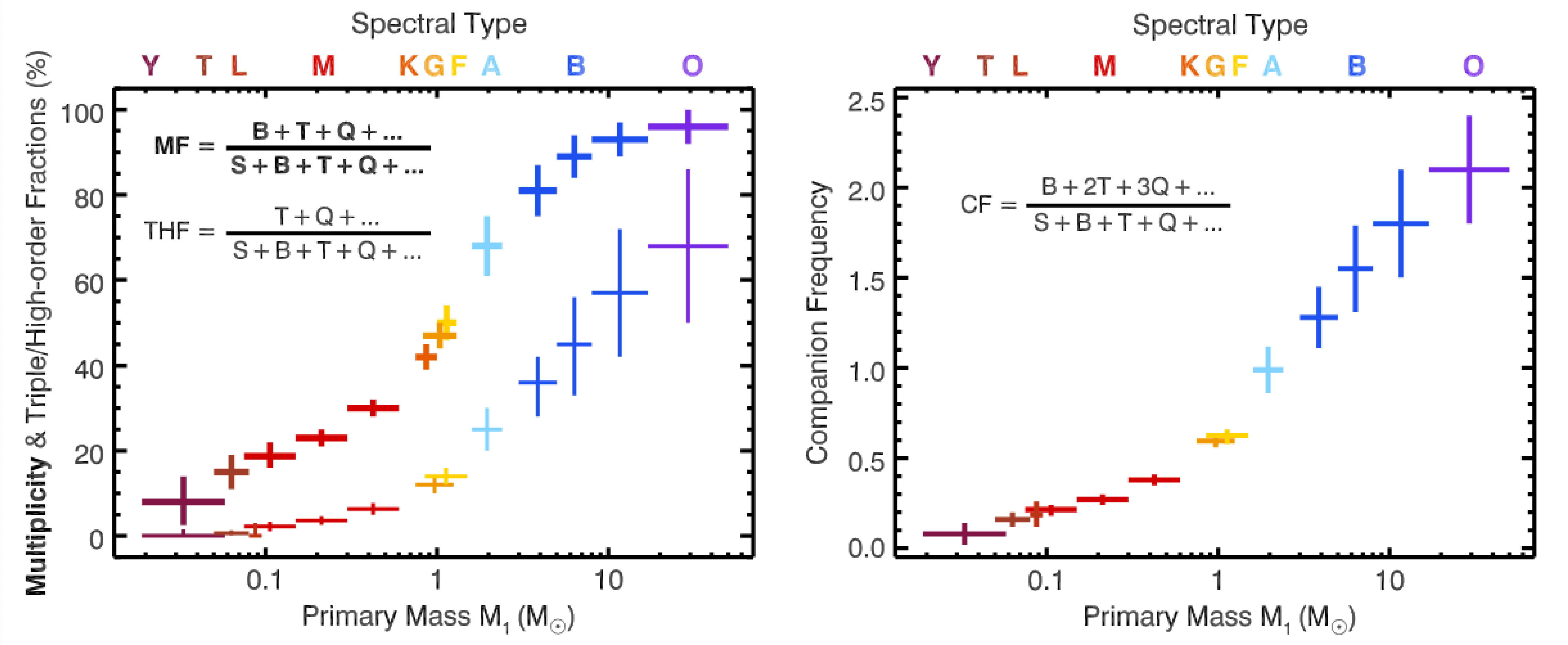
Binary populations



ESO

Binary and multiple star systems are common

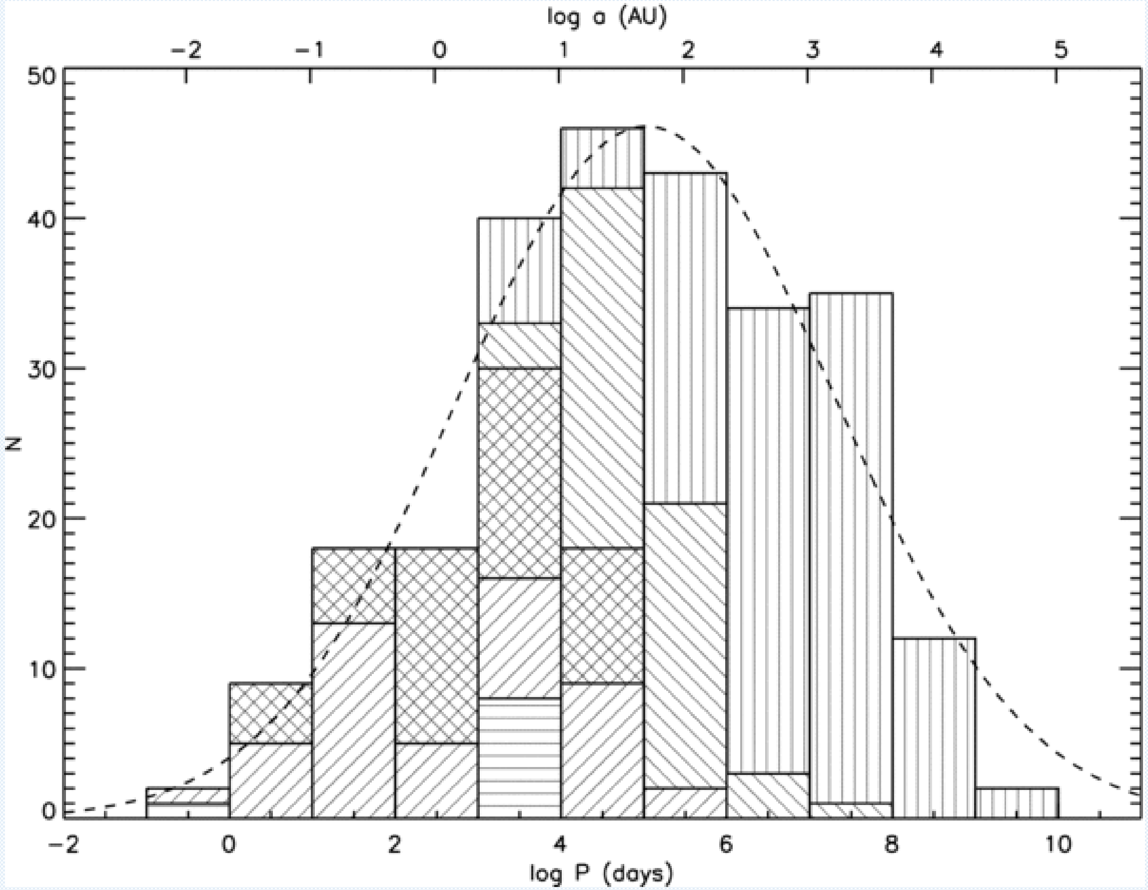
Binary populations



Offner et al. 2023, ASP, Conf. Ser., 534, 275

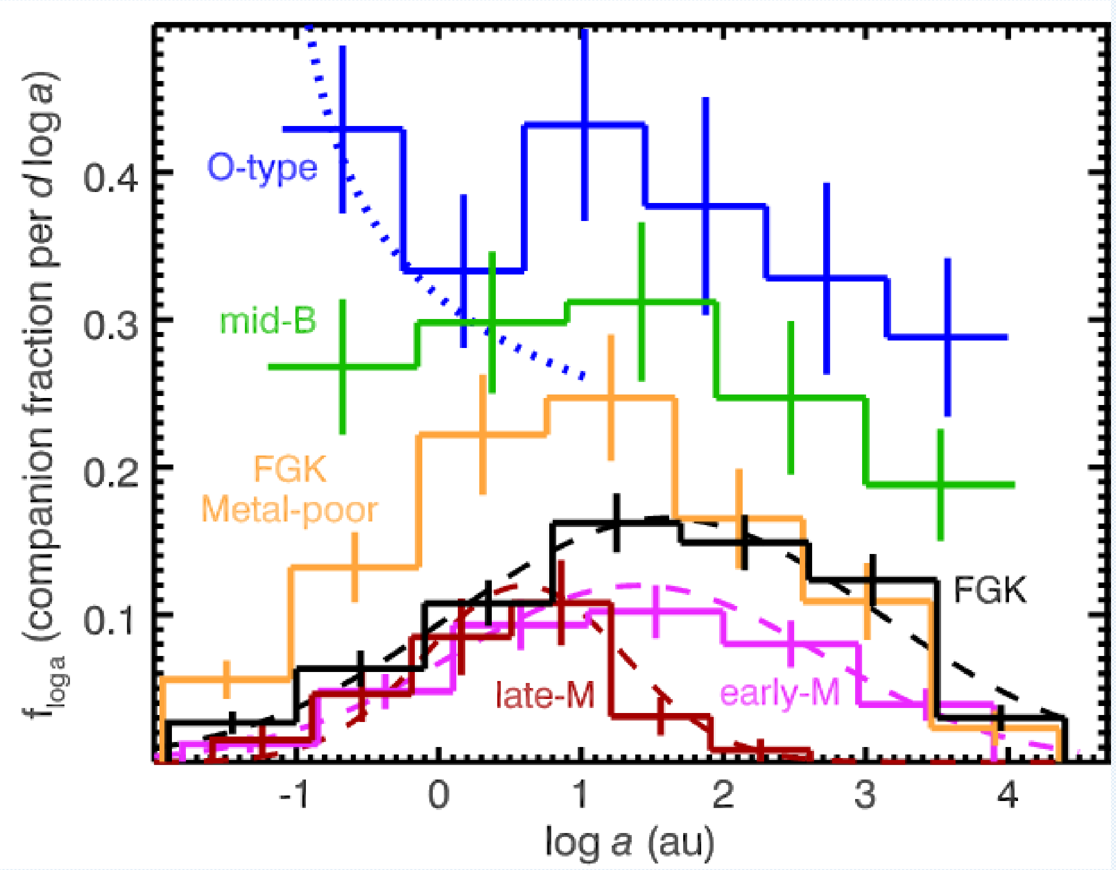
Multiplicity fraction on the main sequence depends on stellar mass

Binary populations



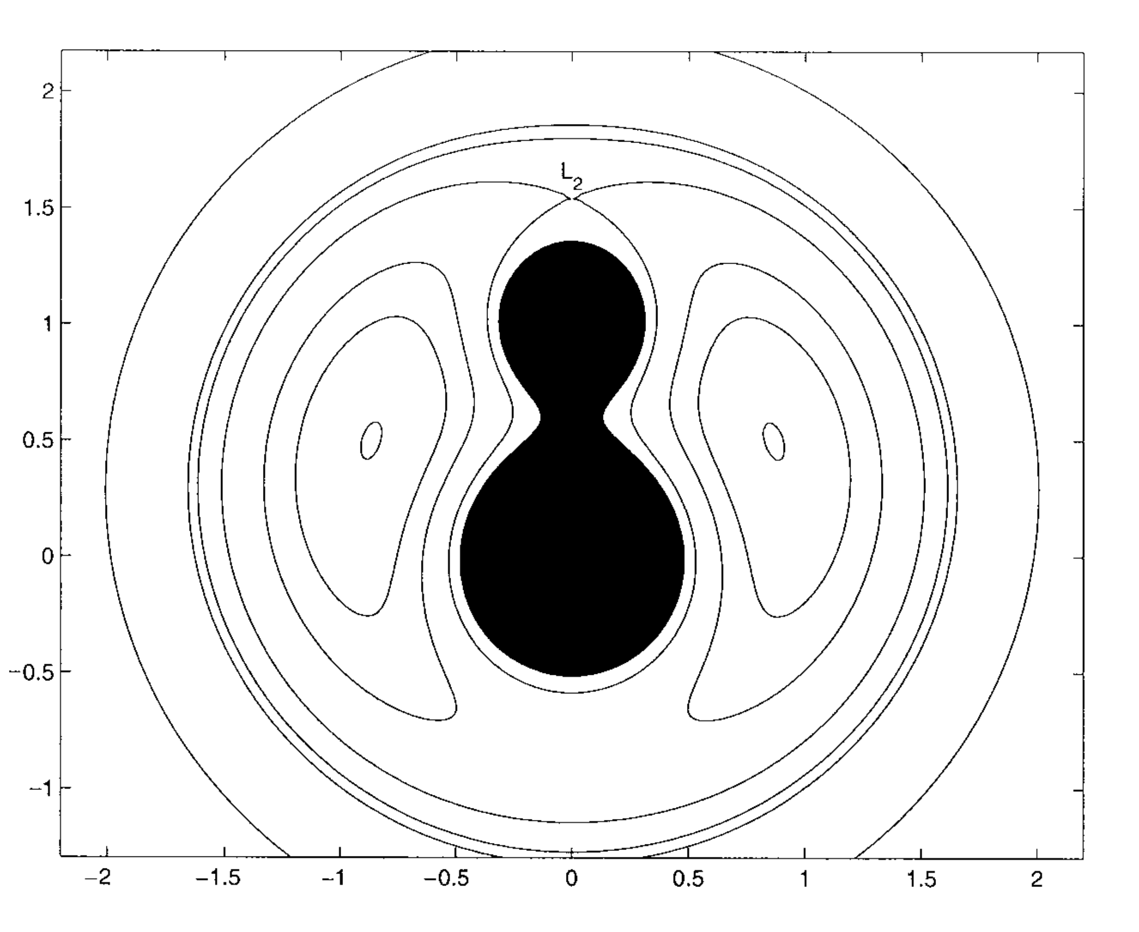
Raghavan et al. 2010, ApJS, 190, 1

Broad period/separation distribution



Offner et al. 2023, ASP, Conf. Ser., 534, 275

Binary evolution



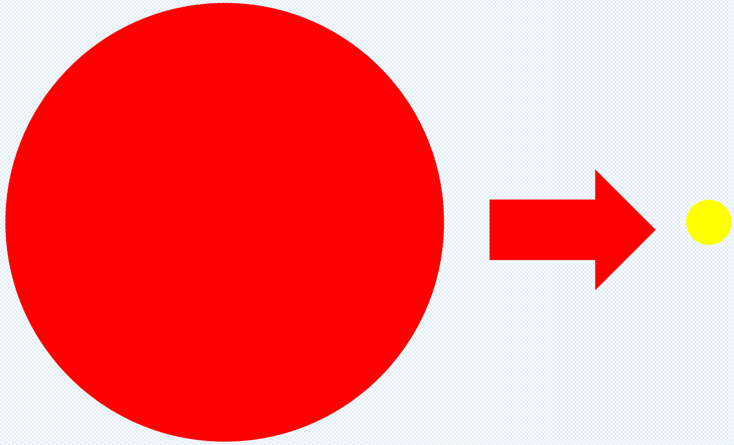
Hilditch 2001

In wide binaries, where the **separation is much larger than the Roche radii** of both components, the stars **evolve like single stars**

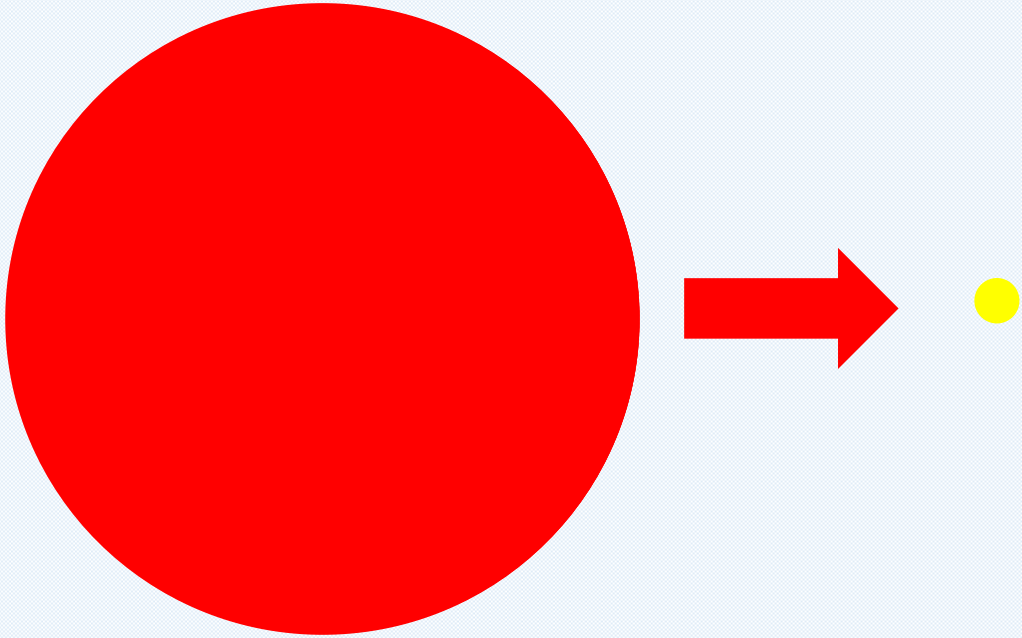
Due to significant changes in the stellar radii, interactions might happen in later stages of stellar evolution

As soon as one of the components overfills its Roche lobe, the star interacts with its companion

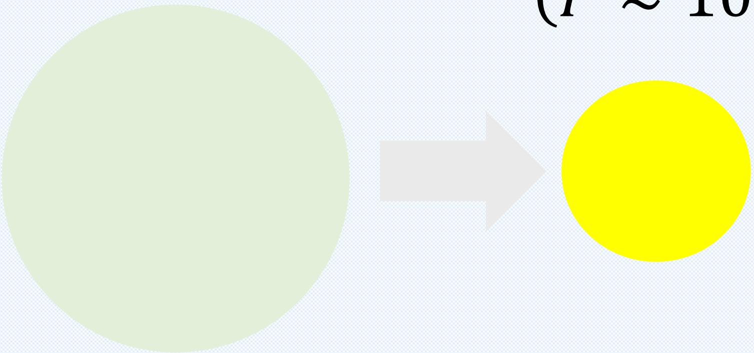
Binary evolution



First red giant branch star fills Roche lobe
$(P \approx 10 - 100\ \mathrm{d}) \rightarrow$ **Case B**

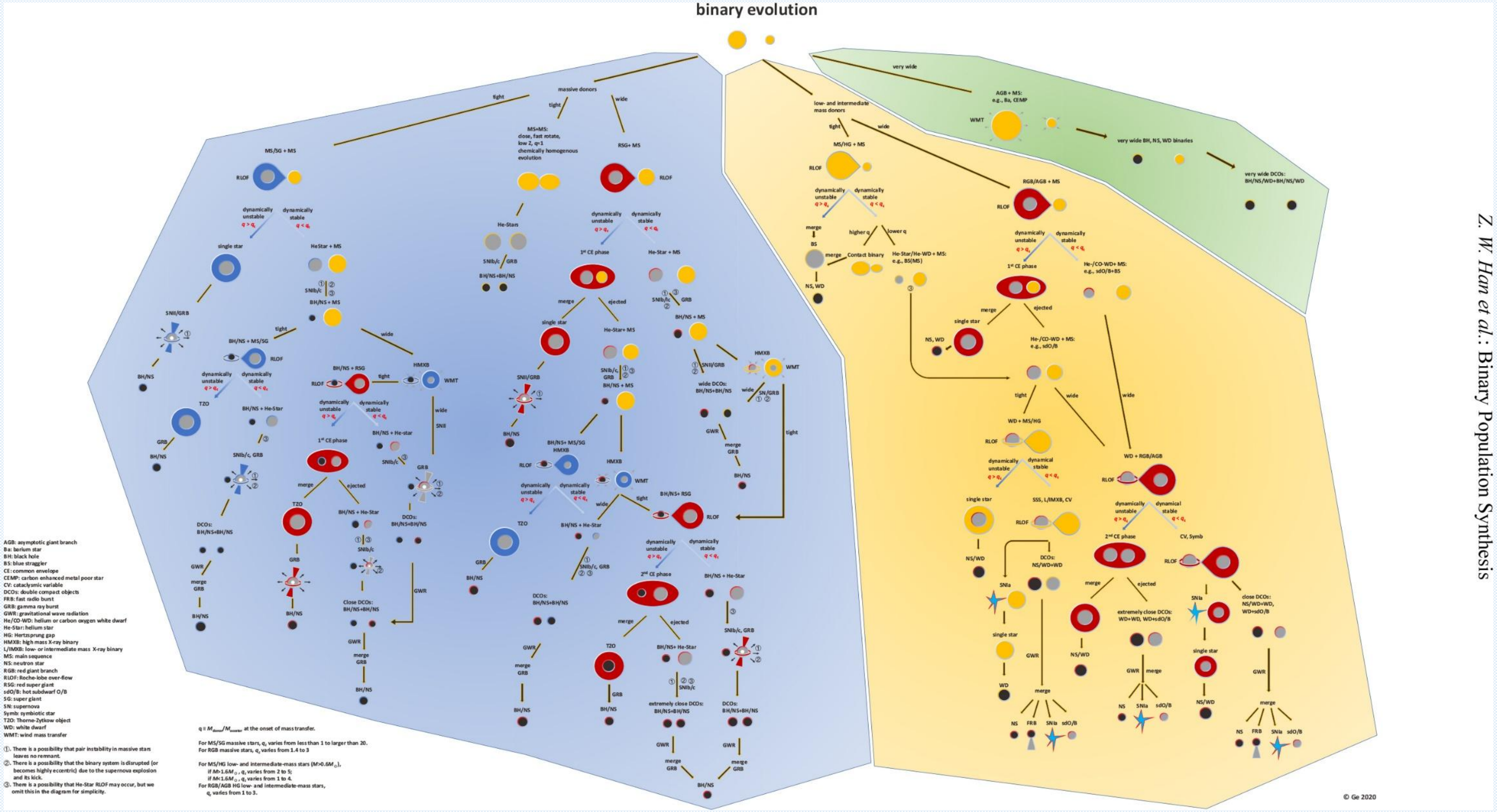


Asymptotic giant branch star fills Roche lobe
$(P \approx 100\ \mathrm{d}) \rightarrow$ **Case C**



Main sequence stars fills Roche lobe
$(P \approx 1 - 10\ \mathrm{d}) \rightarrow$ **Case A**

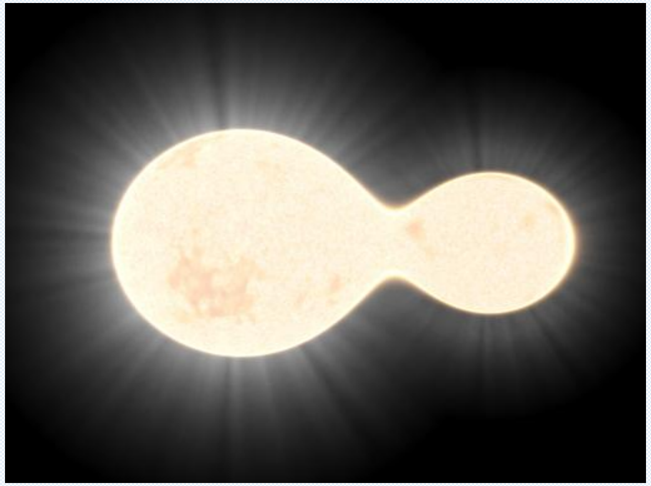
Binary evolution

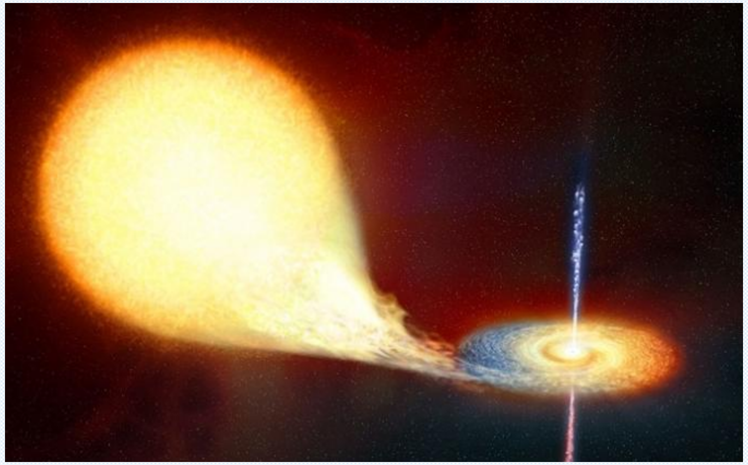


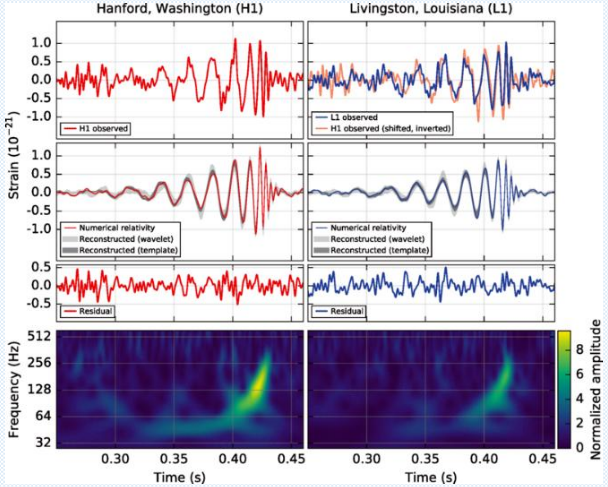
Han et al. 2020, RAA, 20, 161

Understanding binary evolution needed to understand stellar evolution

Binary evolution



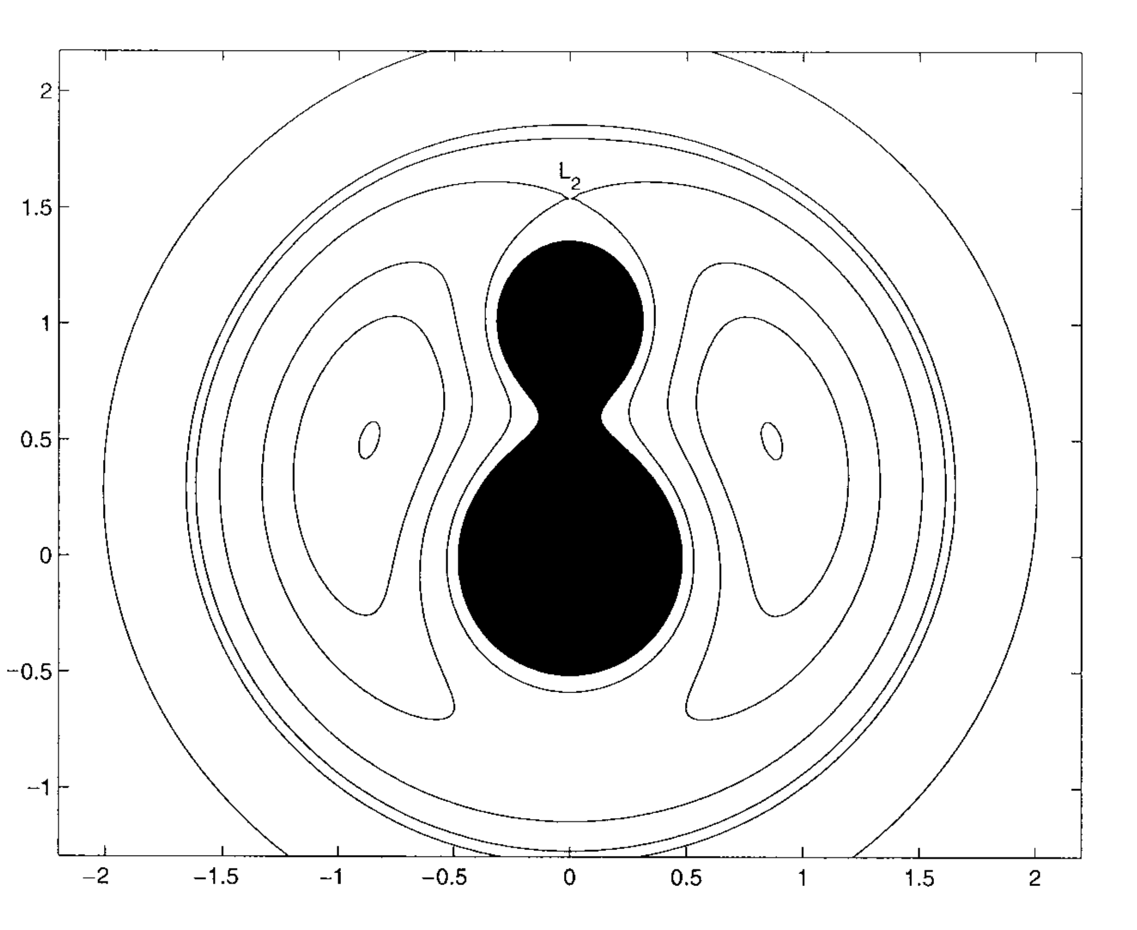




ESA, ESO, NASA, Caltech/JPL

Understanding binary interactions important for other fields of astrophysics

Binary evolution



Hilditch 2001

Mass transfer from the Roche lobe filling star (**donor**) to the companion (**accretor**)

Details of mass transfer depend on the mass ratio **(stability criterion)**

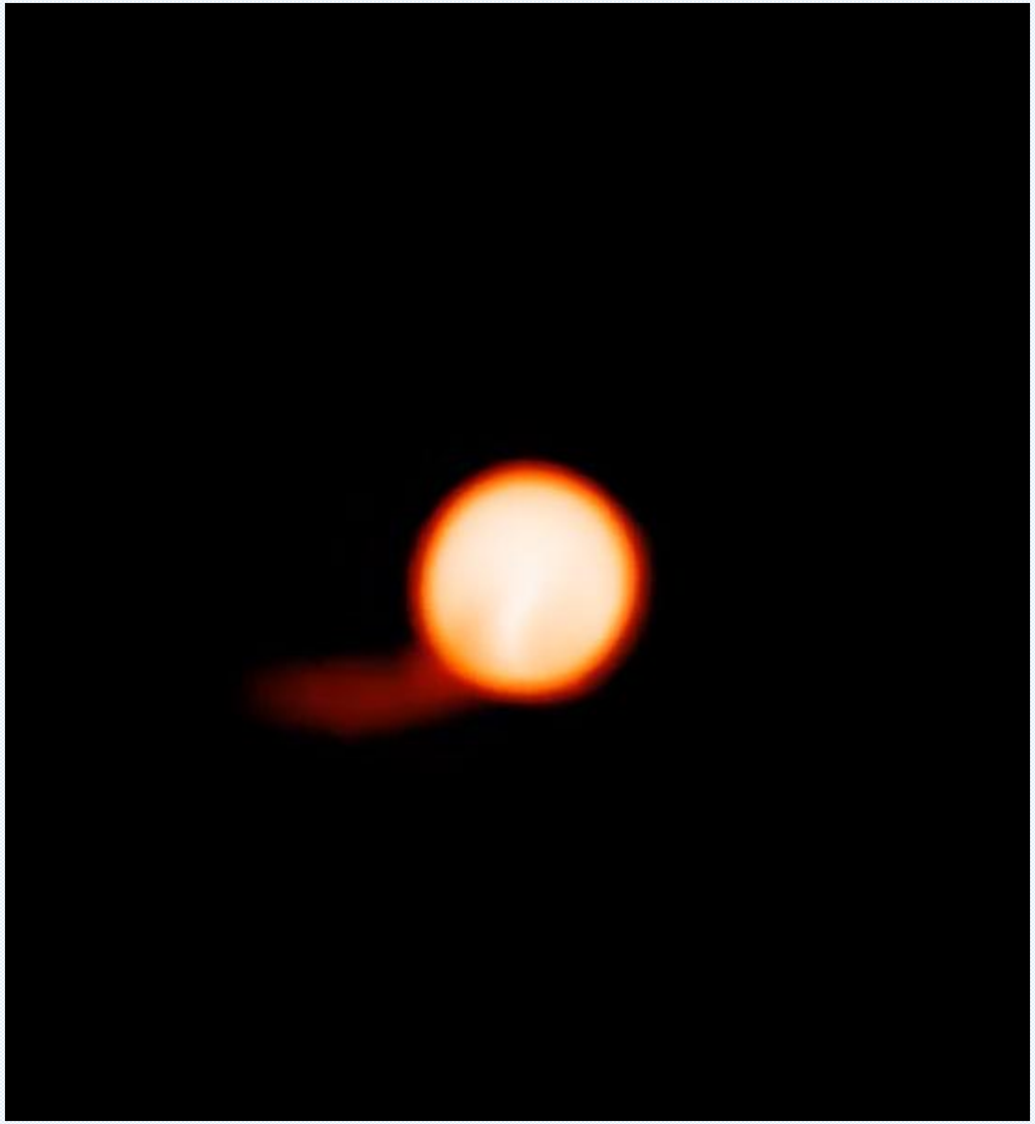
$$\frac{M_{\mathrm{donor}}}{M_{\mathrm{accretor}}} = \frac{M_{\mathrm{d}}}{M_{\mathrm{a}}}$$

Binary evolution

ESO/M. Kornmesser

$\frac{M_\mathrm{d}}{M_\mathrm{a}} < q_\mathrm{crit} \rightarrow$ **Stable Roche-lobe overflow**

Binary evolution

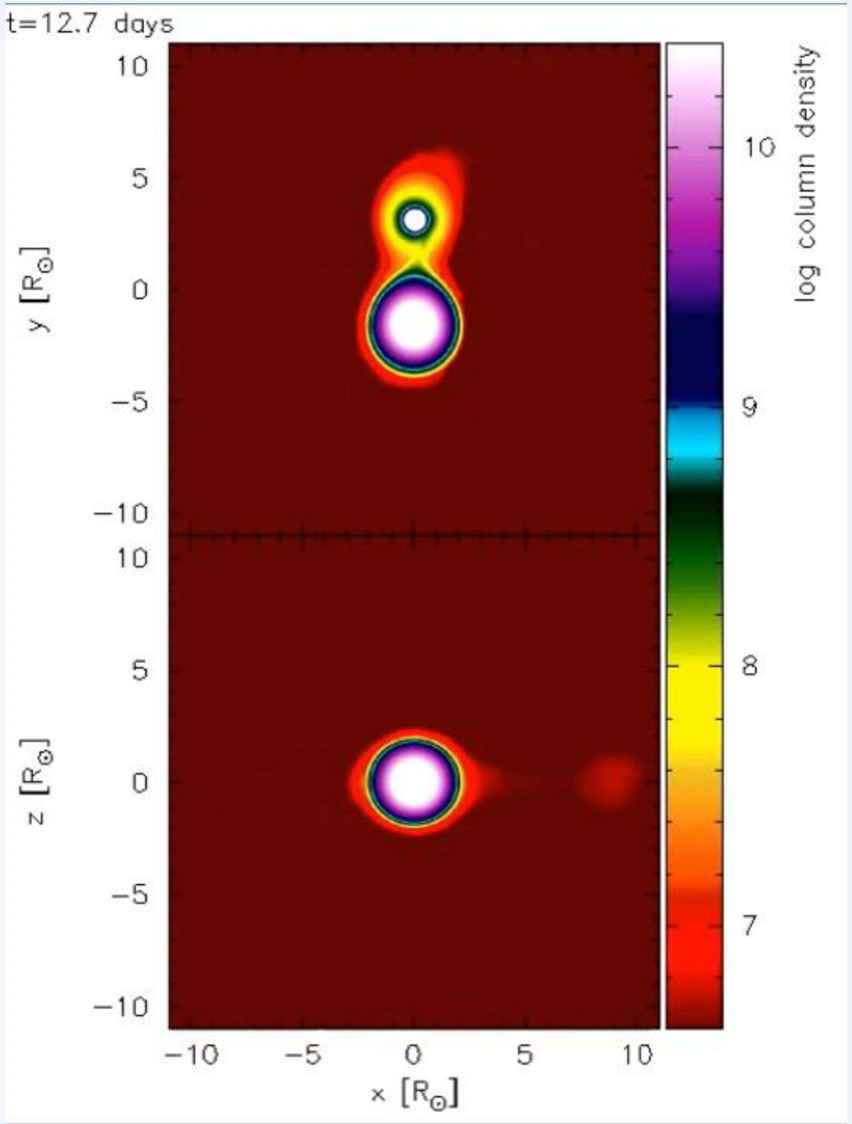


Youtube/Thomas Reichardt

If the accretor fills it‘s Roche lobe too rapidly $\left(\frac{M_{\mathrm{d}}}{M_{\mathrm{a}}} > q_{\mathrm{crit}}\right)$**, mass transfer becomes unstable**

→ Common envelope phase

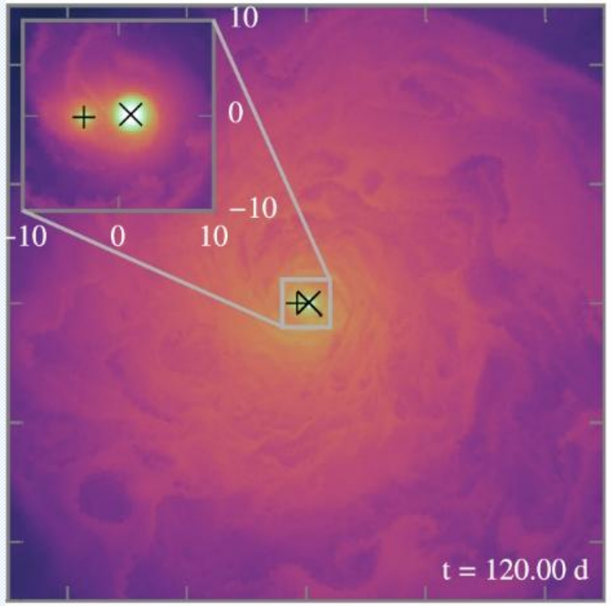
Binary evolution



Ivanova et al. 2013, A&AR, 21, 59

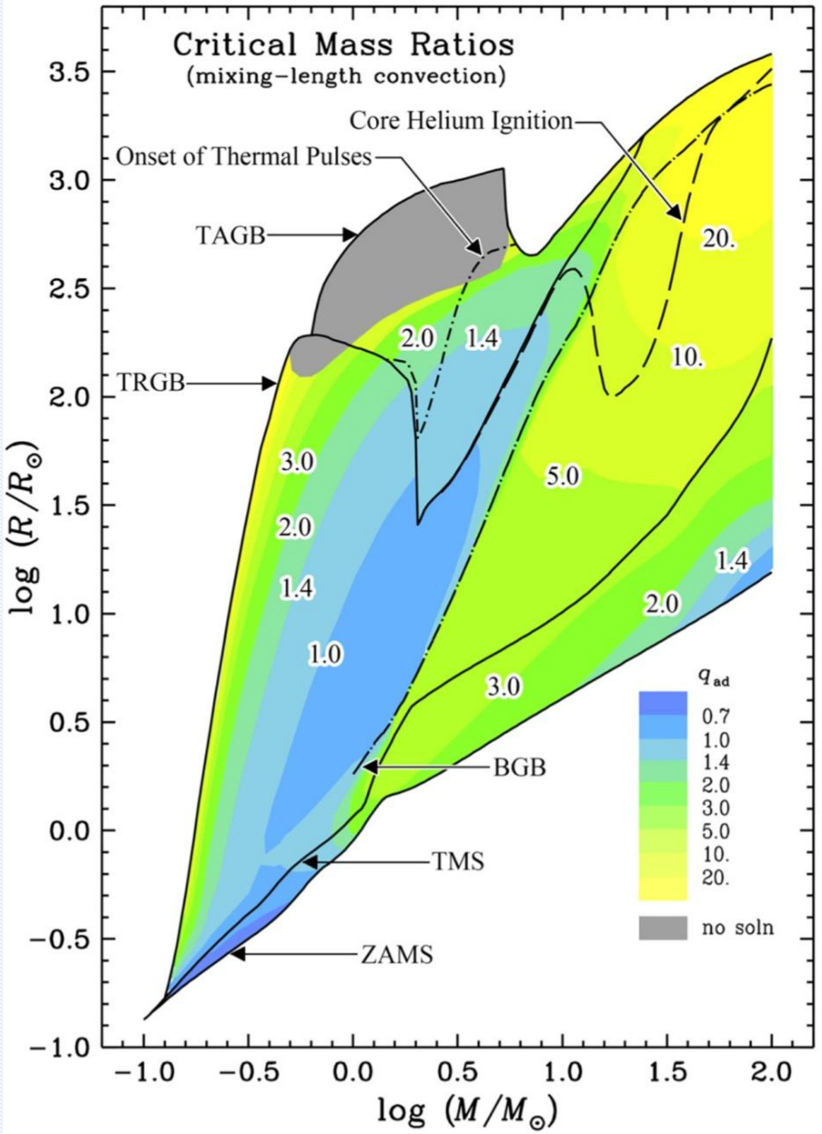
Spiral-in without envelope ejection
→ **Binary merger** forming a single star

Envelope completely ejected
→ **Close binary**



Ohlmann et al. 2016, ApJ, 816, L9

The problem



Ge et al. 2020, ApJ, 899, 132

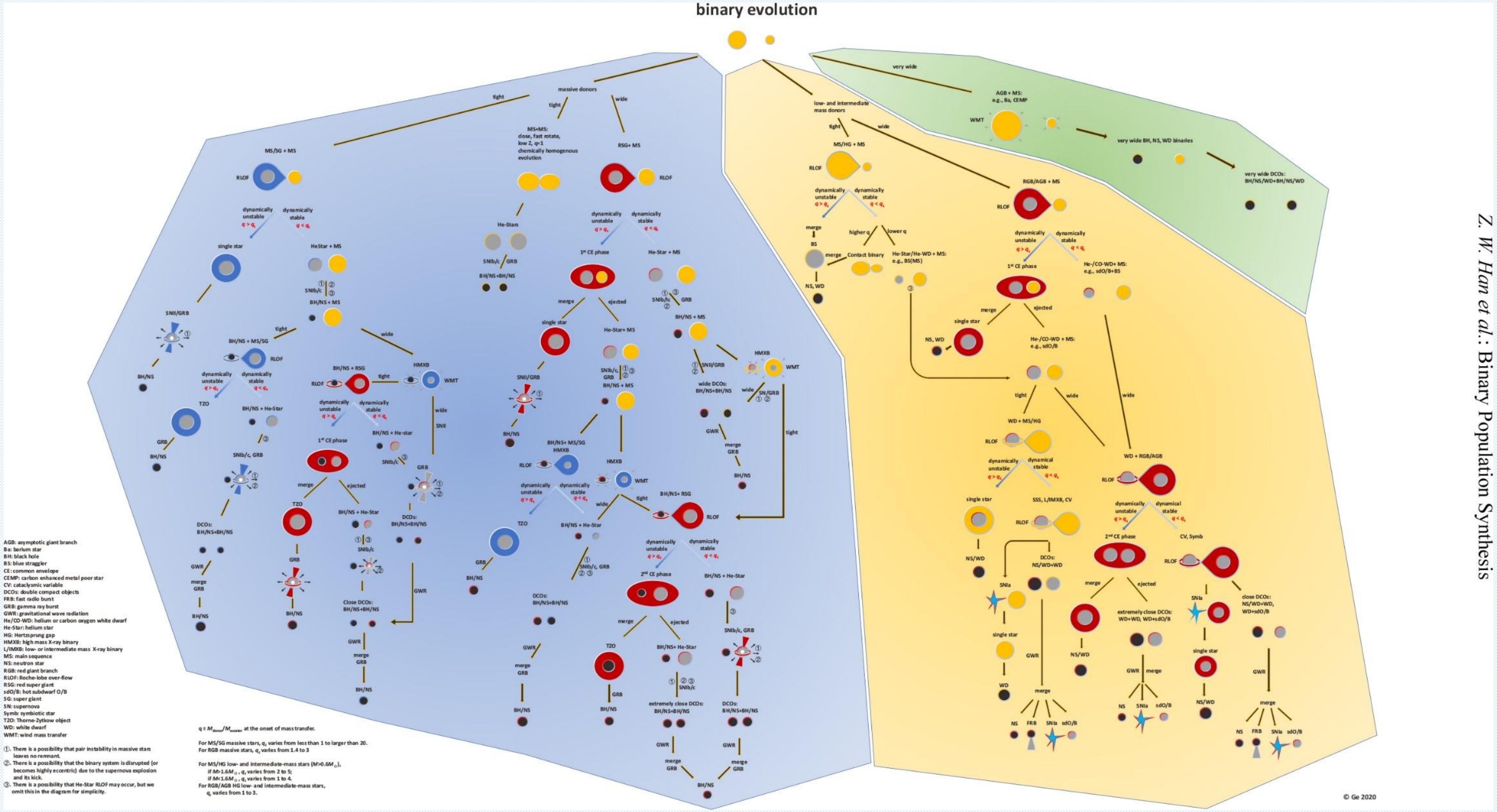
That is all theory!

Observational constraints needed to verify and improve the theoretical models

Which binaries do which type of mass transfer?
→ What is q_{crit}?

How do interactions change the binary systems?
→ How conservative is stable RLOF?
→ How efficient is the CE phase?

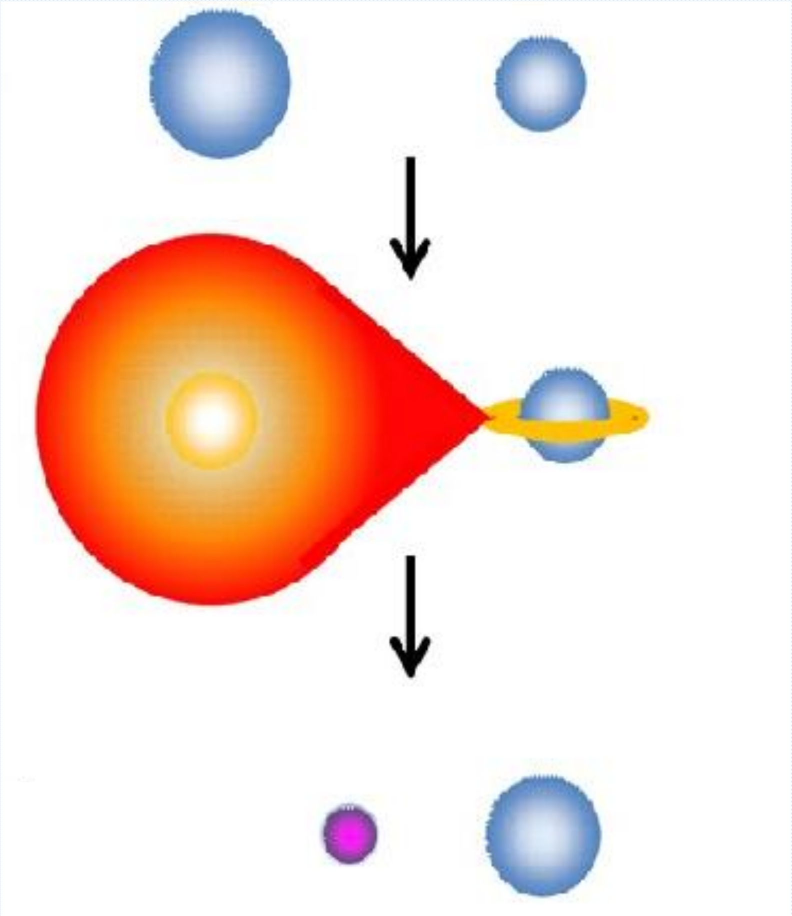
The problem



Han et al. 2020, RAA, 20, 161

Understanding the details of interactions needed to understand evolution

The method



Lazarus et al. 2014, MNRAS, 437, 1485 modified by Geier

Interactions are happening on short timescales
→ hard to observe directly

Indirect approach:

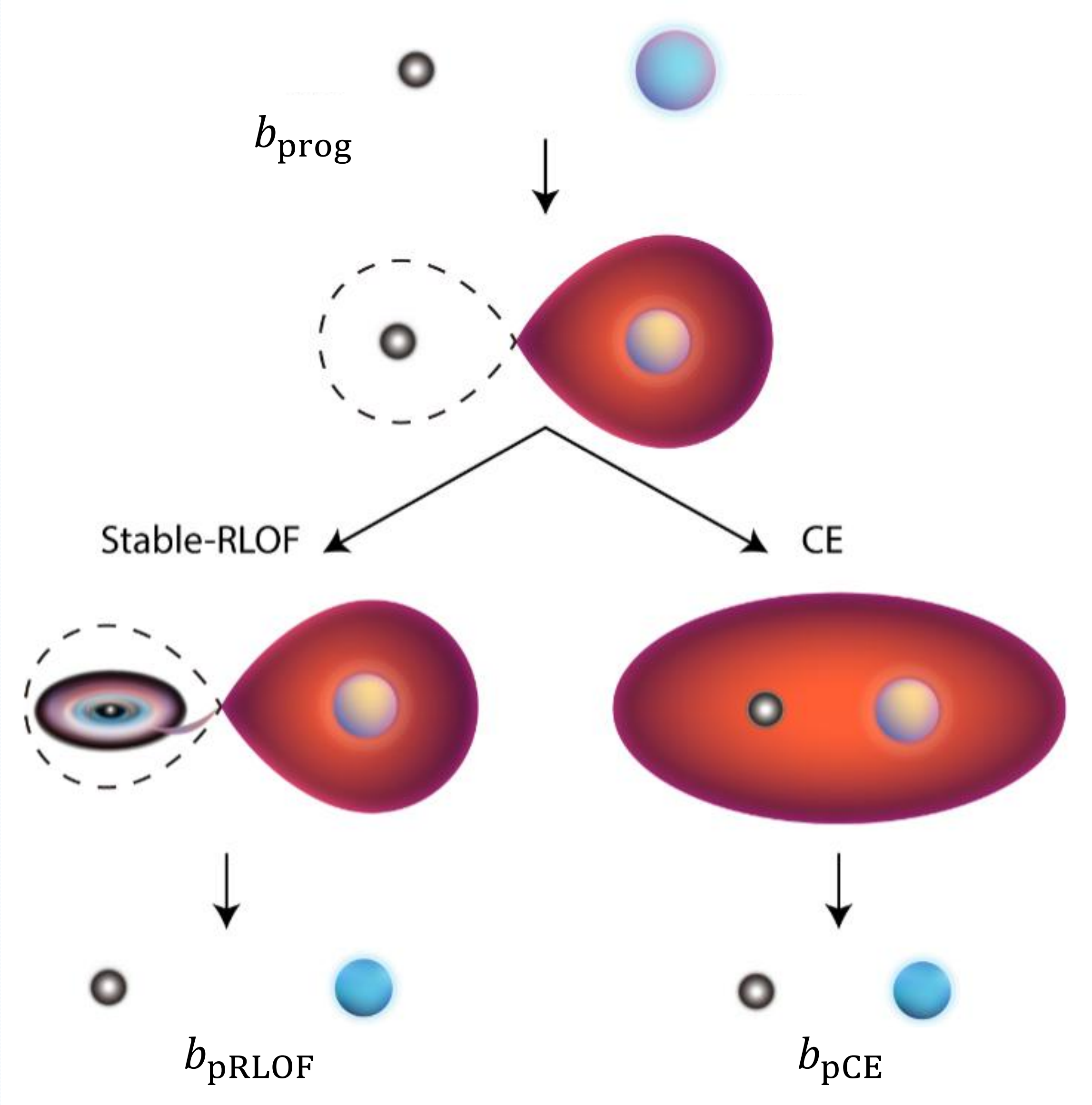
Find and study the progenitors of an interaction

Find and study systems after the interaction

Compare the system's parameters

→ **Exchanged mass and angular momentum, CE efficiency, mass loss**

The method



Wu et al. 2020, A&A, 634, A126 modified by Geier

Studying populations of binaries allows to probe evolution channels

Counting the number (birthrates) of progenitors

Counting the number (birthrates) of post-CE and post-RLOF systems

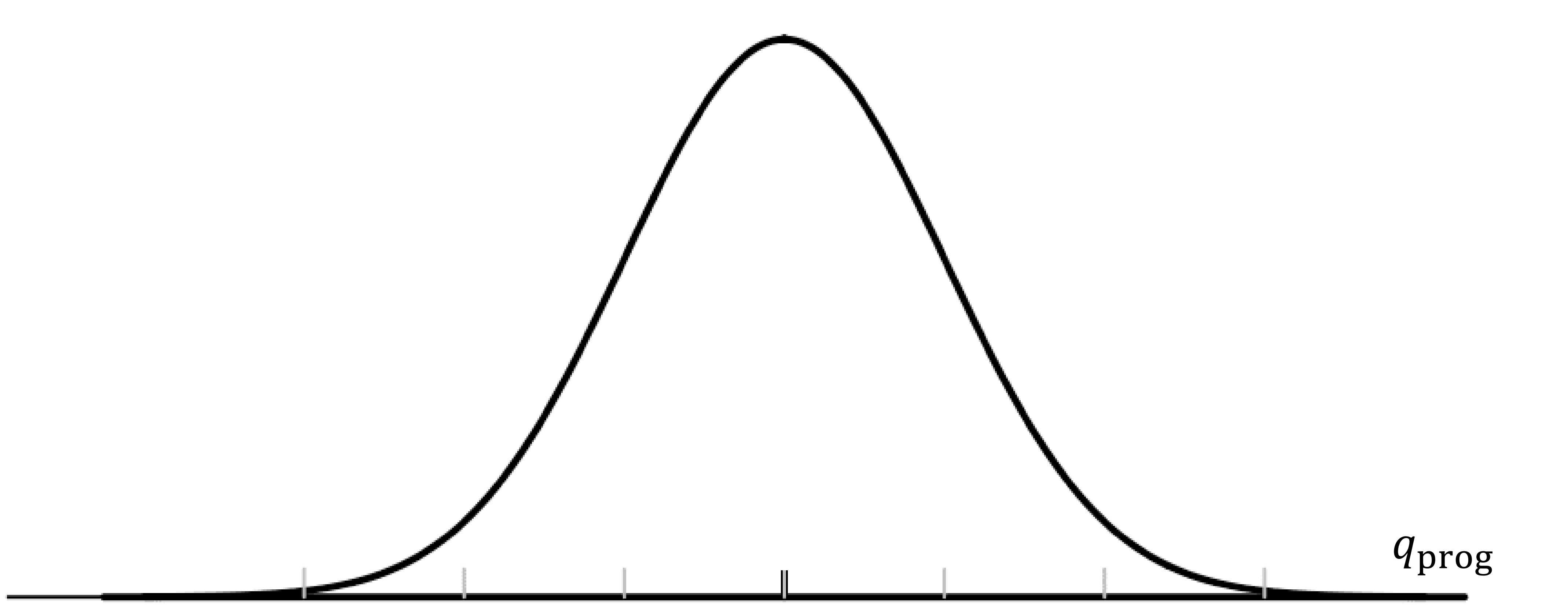
If those are the only channels:

$$b_{\text{prog}} = b_{\text{pRLOF}} + b_{\text{pCE}}$$

If not:

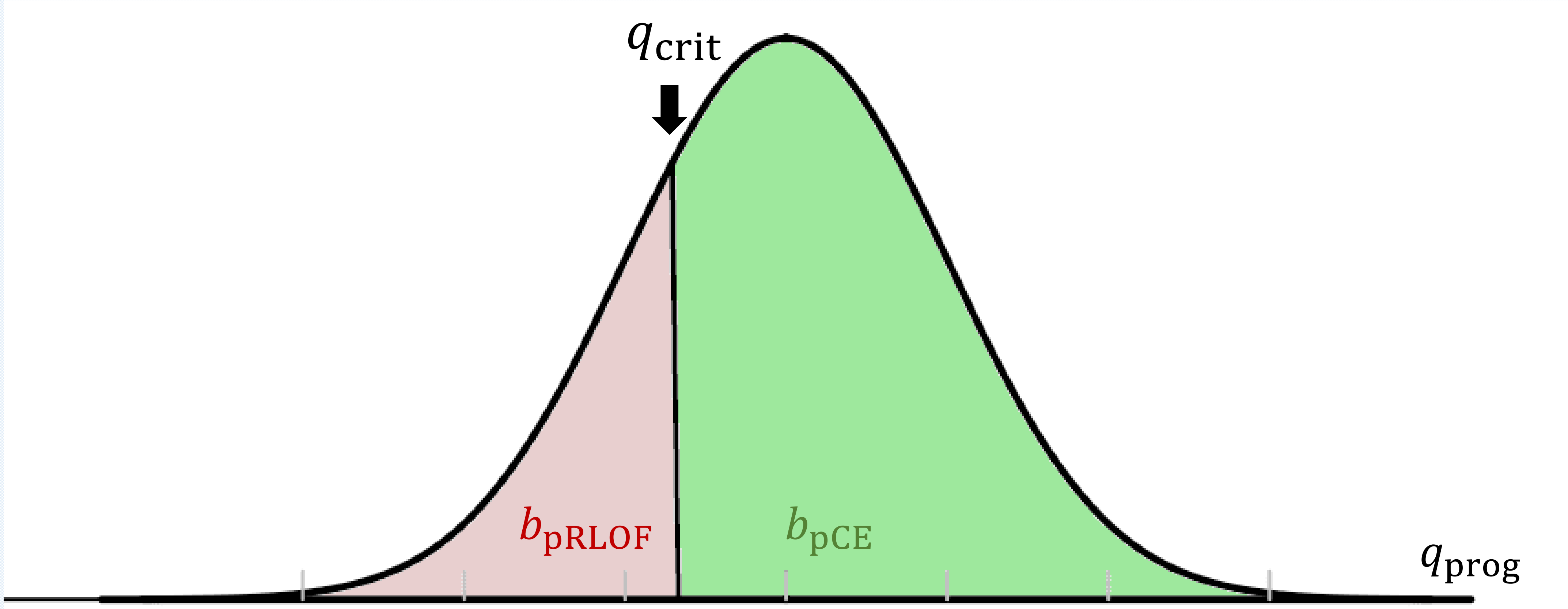
$$b_{\text{prog}} = b_{\text{pRLOF}} + b_{\text{pCE}} + b_{\text{merger}}?$$

The method



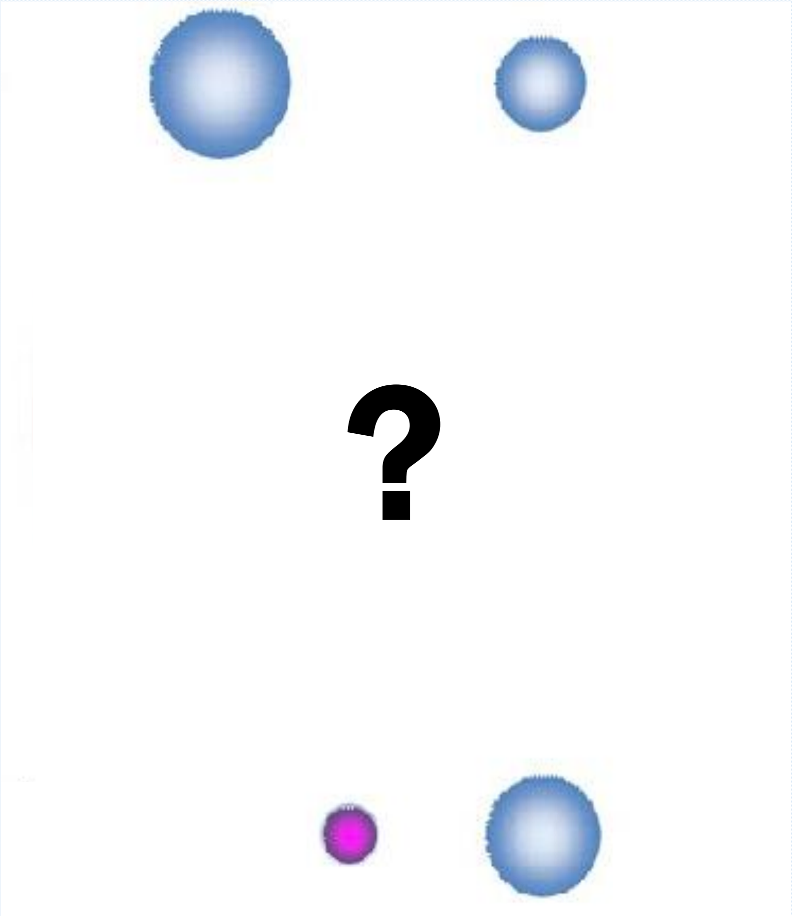
Distribution of progenitor mass ratios: Area corresponds to b_{prog}

The method



Assuming that post-RLOF systems have the lowest q and $b_{\rm prog} = b_{\rm pRLOF} + b_{\rm pCE}$ we can determine $q_{\rm crit}$

The method



Lazarus et al. 2014, MNRAS, 437, 1485 modified by Geier

How can we be sure that binaries are progenitors and outcome of a specific interaction?

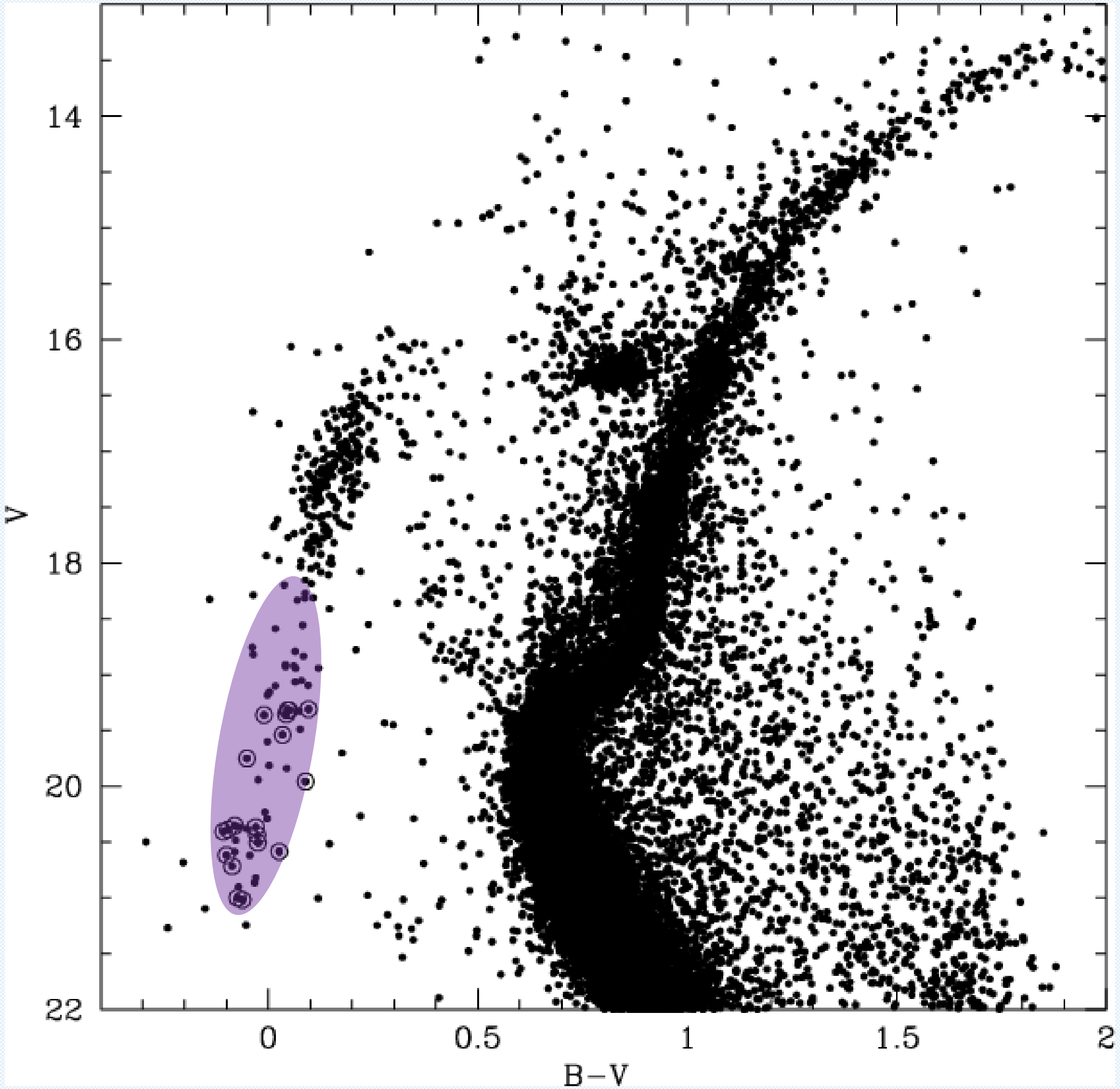
In general, we can‘t

→ Mass loss history, mass transfer details and history are uncertain

→ Degeneracies possible: Same outcome with different progenitors

To put constraints on interactions we need to find cases where we can be sure!

Stripped helium stars



Moehler et al. 2004, A&A, 415, 313

Extreme Horizontal Branch (EHB) stars

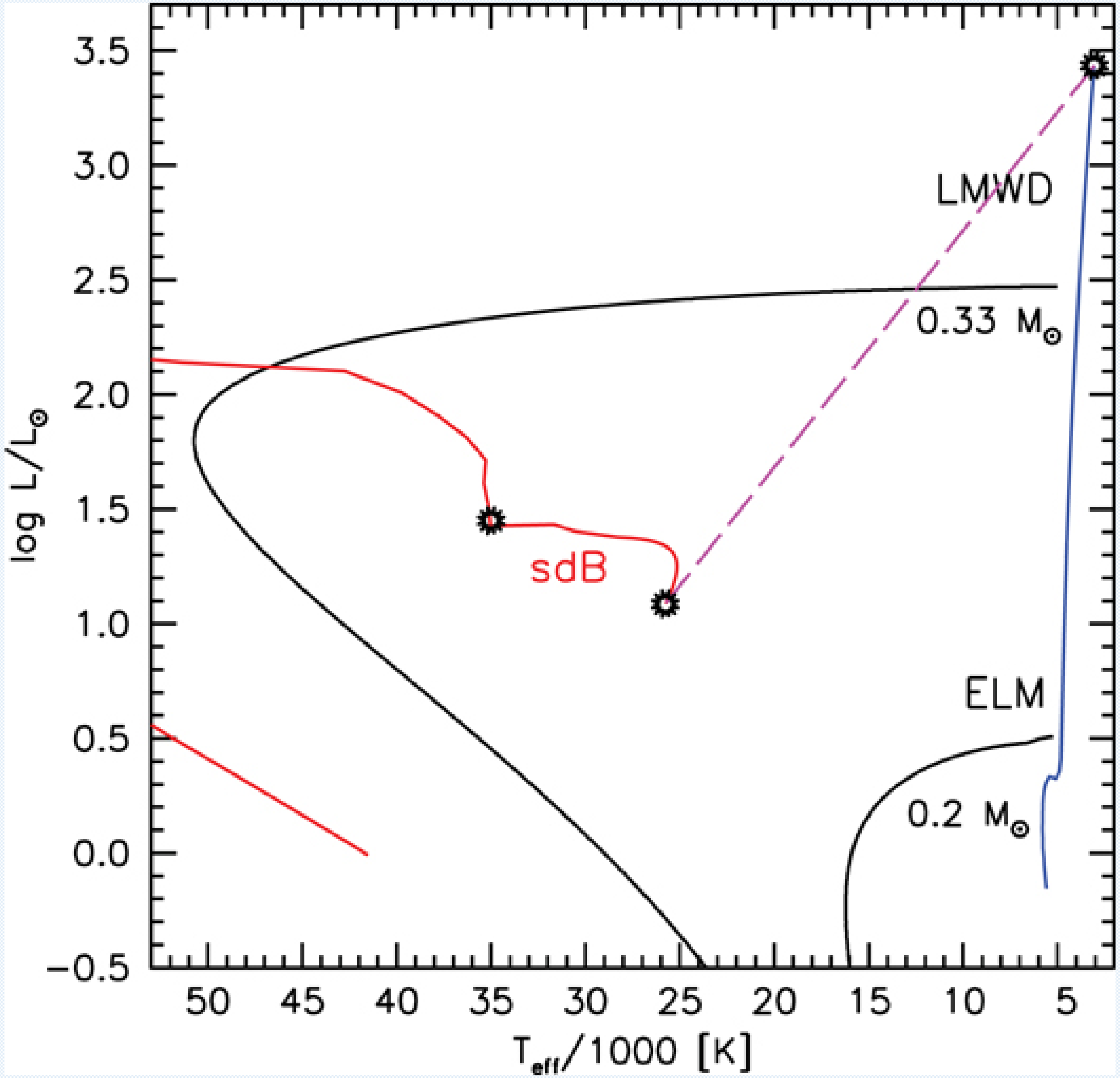
→ Hot subdwarfs

→ Spectral types O, B (sdO, sdB)

→ Extremely thin hydrogen envelopes, no H-shell burning

→ **Not formed in standard stellar evolution**

Stripped helium stars



Heber 2016, PASP, 128, 966

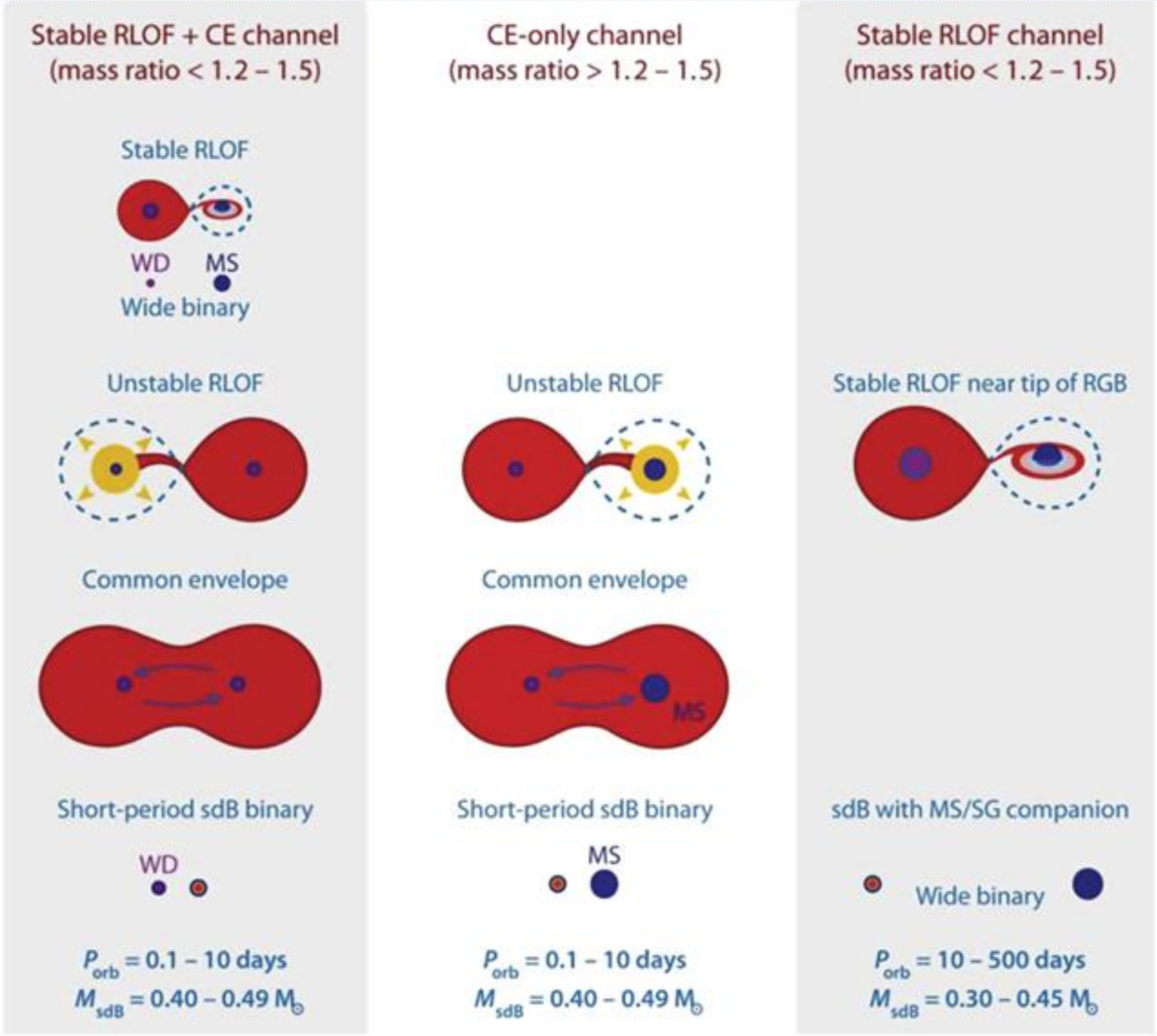
→ Envelope stripping of a low-mass star at the tip of the RGB

→ **Star ignites core helium-burning** under degenerate conditions

→ Due to the very thin remaining H-envelope, the star settles at the EHB

→ Evolutionary timescale 10^8 yr

Stripped helium stars



Heber 2016, PASP, 128, 966

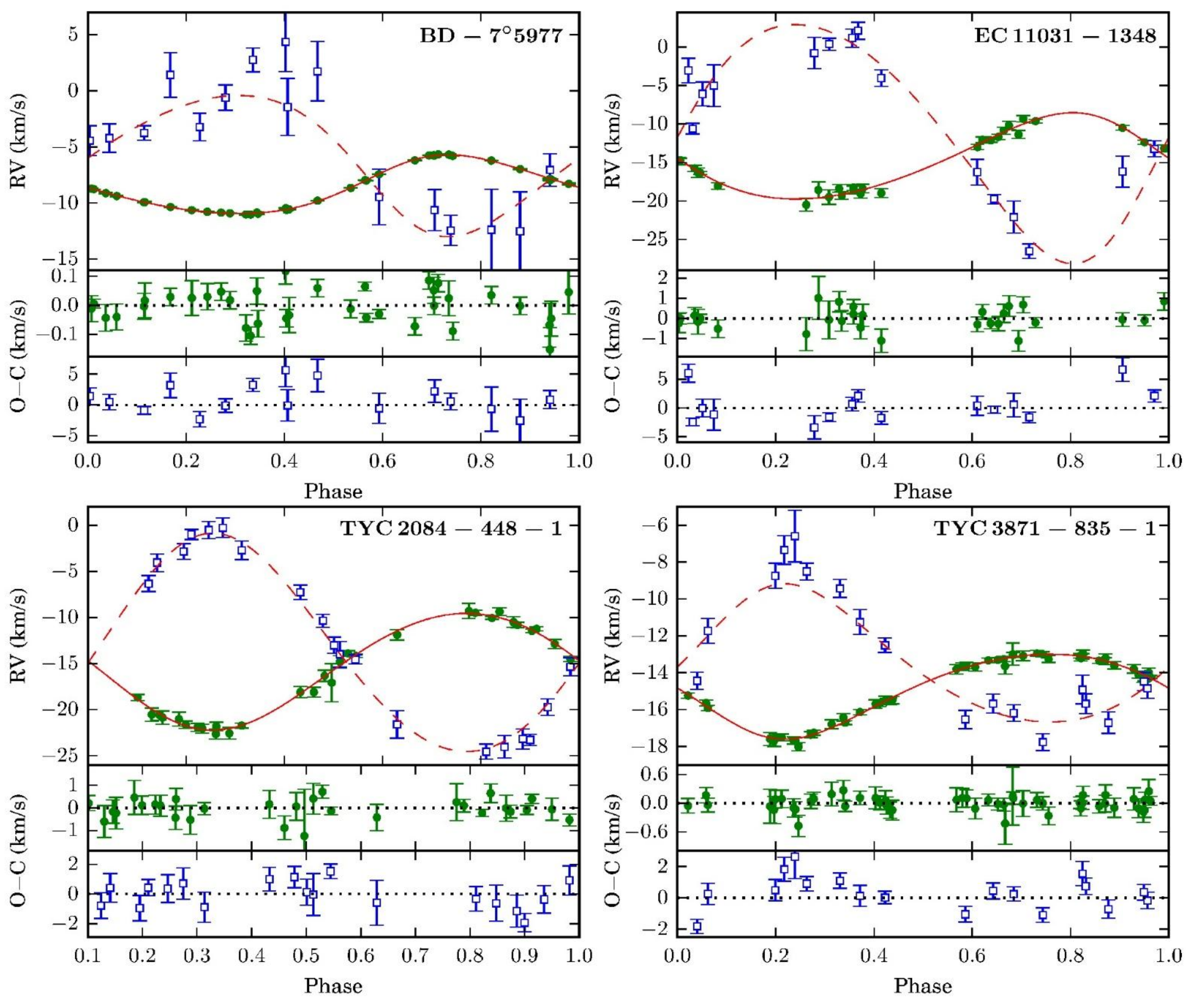
Close binary evolution

→ Helium-burning **core** of a red giant **stripped by binary interaction**

→ Stable and unstable mass-transfer possible

→ sdO/Bs predicted to be in close and wide binaries

Stripped helium stars



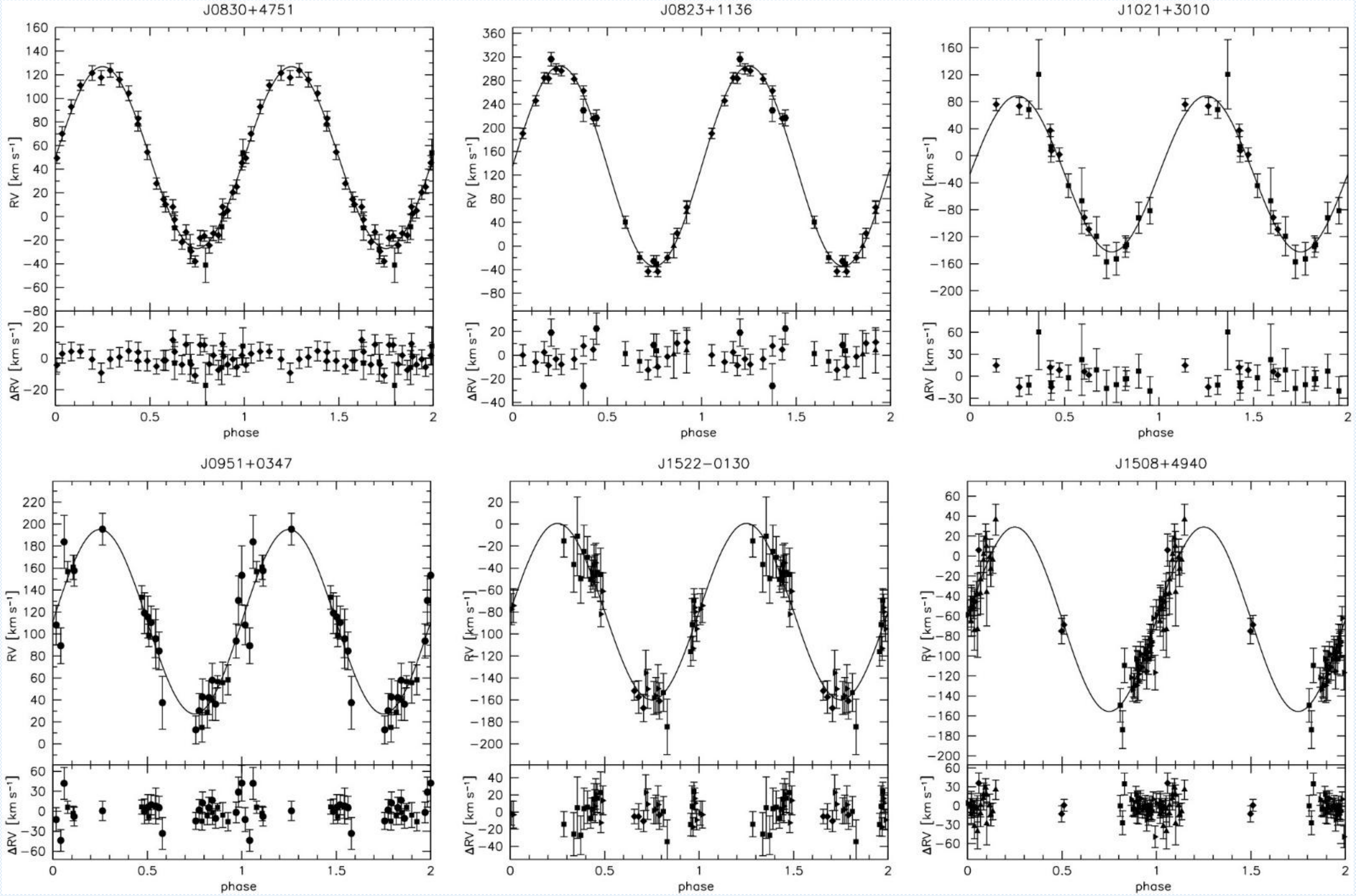
Vos et al. 2017, A&A, 605, 109

$\sim 30\%$ of the sdO/Bs are in **composite double-lined binaries**

Companions are K/G/F-type main sequence stars

The orbital periods of the ~ 30 solved systems $(P = 300 - 1200\ \mathrm{d})$ are in the appropriate range for prior RLOF mass-transfer

Stripped helium stars



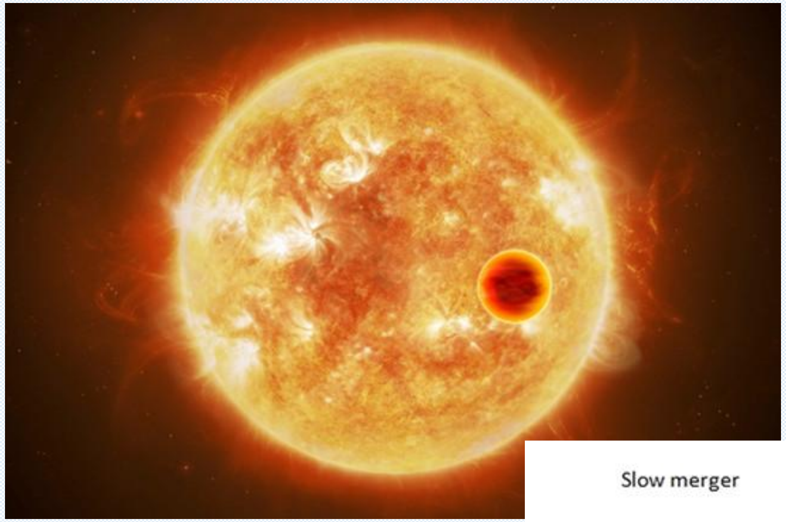
Kupfer et al. 2015, A&A, 576, 44

$\sim 30\%$ of the sdO/Bs are in **single-lined close binaries**

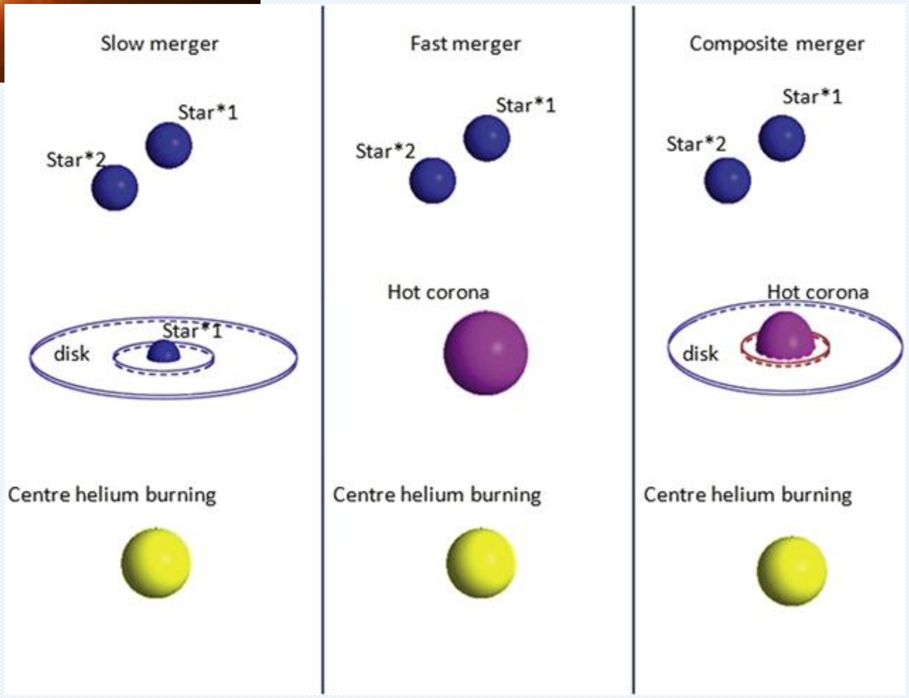
Companions are M-type main sequence stars, brown dwarfs and white dwarfs

The orbital periods of the ~ 300 solved systems $(P = 0.03 - 30\ \mathrm{d})$ are typical for post-CE systems

Stripped helium stars



ESA/ATG medialab



Zhang & Jeffery 2012, MNRAS, 419, 452

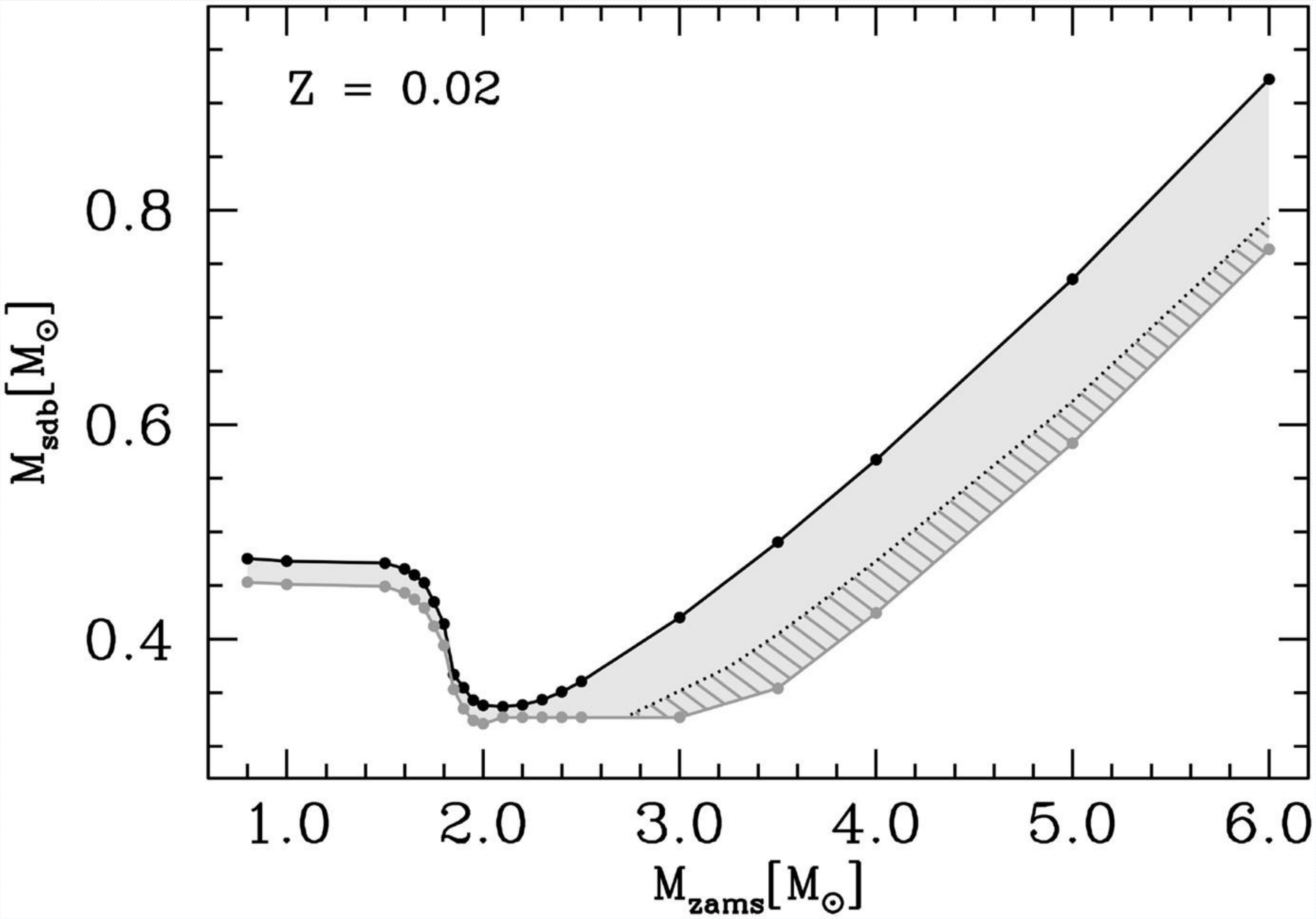
$\sim 30\%$ of the sdO/Bs **don't show any signs of binarity**

→ Close substellar companions such as brown dwarfs or planets

→ Evaporation or merger during CE evolution?

→ **Merger** of white dwarfs of pure helium composition

Stripped helium stars

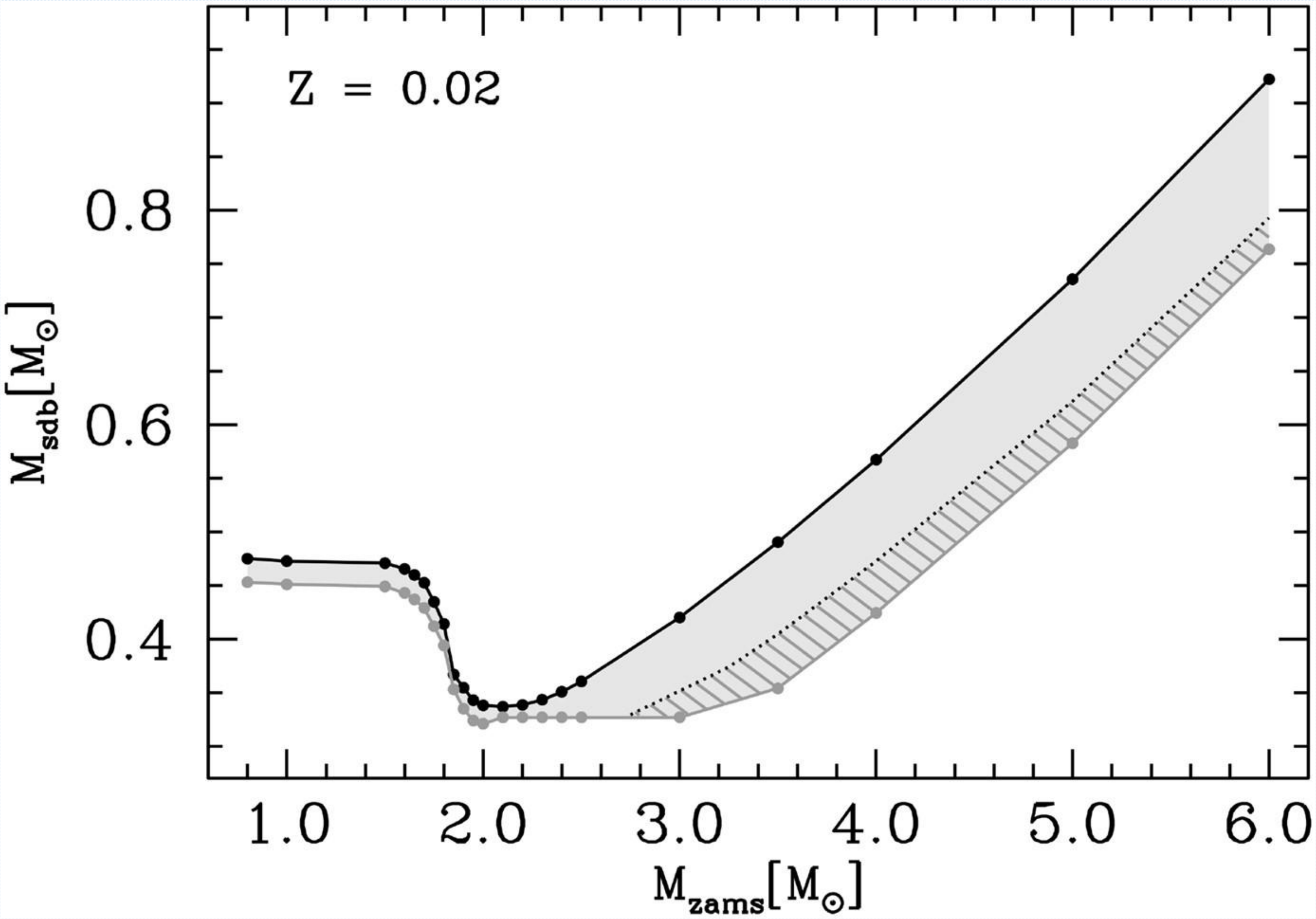


Arancibia-Rojas et al. 2024, MNRAS, 527, 11184

For low-mass stars ($< 2\ M_\odot$), the helium star mass is independent of the progenitor mass

→ Different progenitor binaries for the same outcome possible

Stripped helium stars

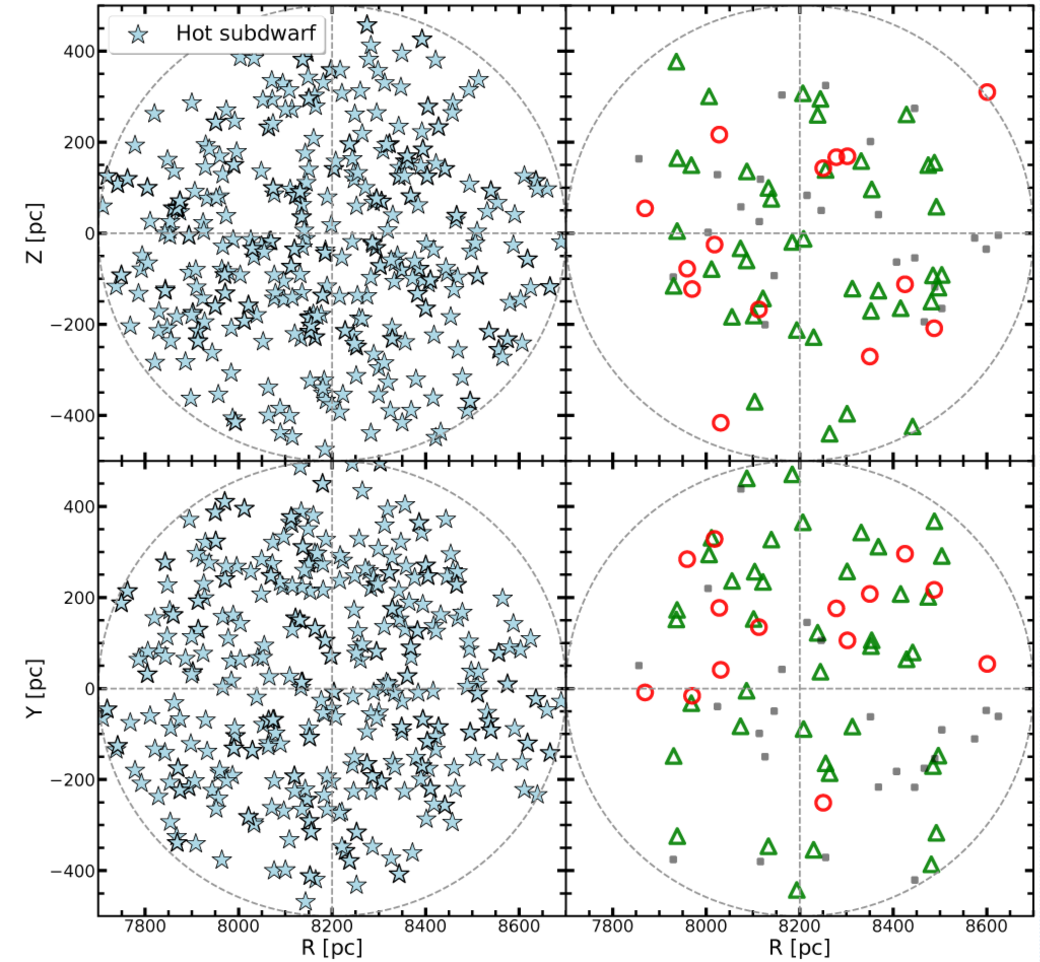


Arancibia-Rojas et al. 2024, MNRAS, 527, 11184

But for intermediate masses $(2 - 6\ M_\odot)$ the He star mass is related to the progenitor mass

→ If we know the He star mass, we know the mass of the progenitor!

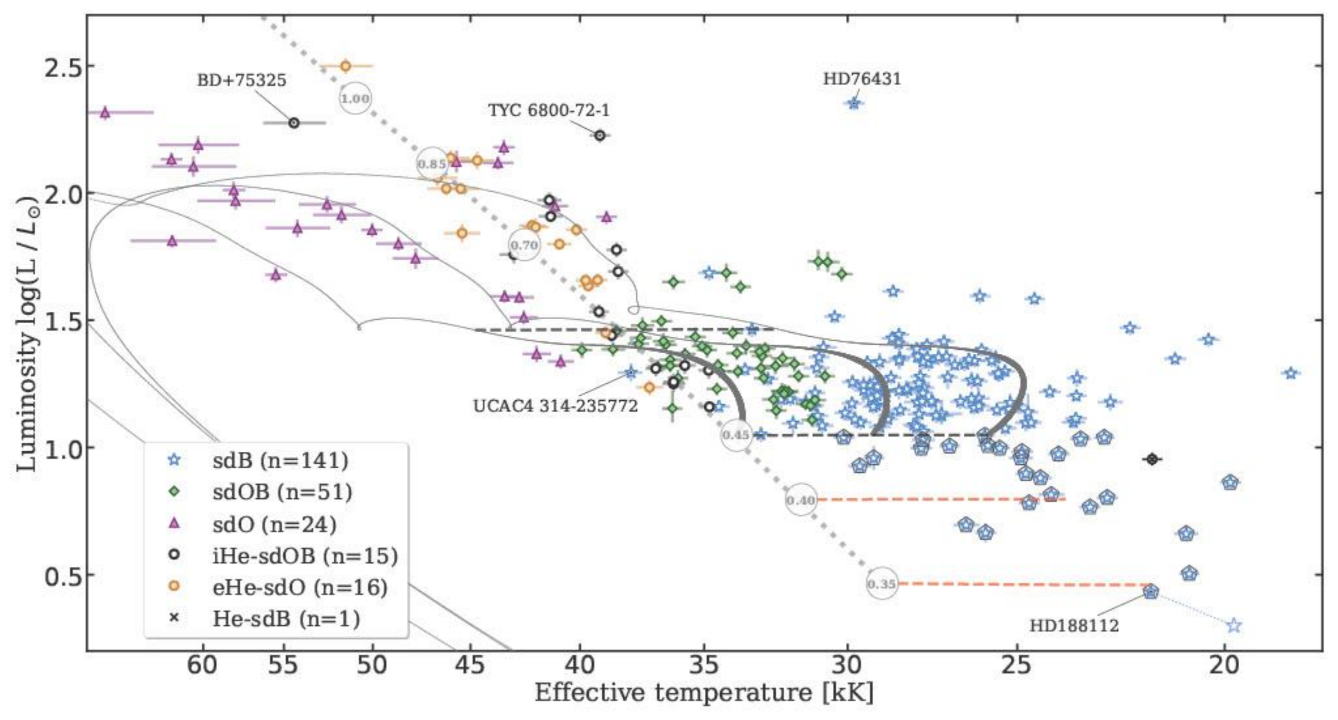
Stripped helium stars



Dawson et al. 2024, A&A, 686, A25

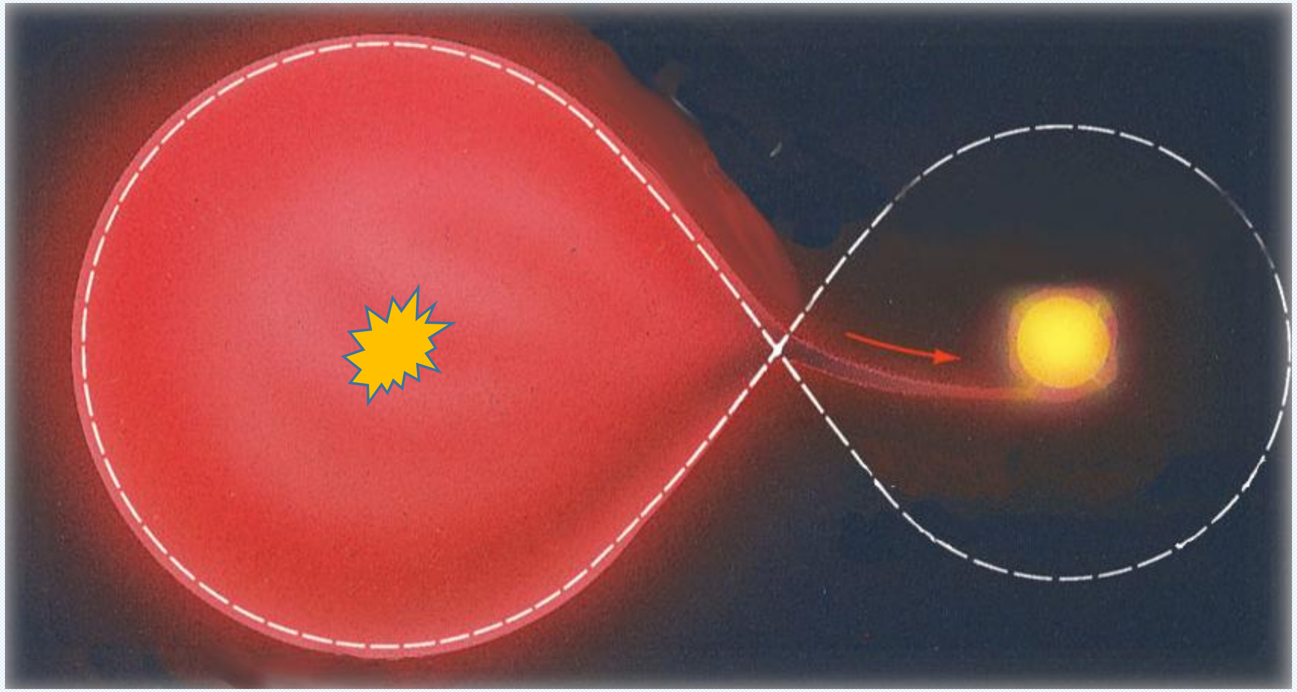
Volume-complete sample of sdO/Bs within 500 pc

Almost completely characterised



Dawson et al. in prep.

Progenitors of stripped helium stars



Pearson Inc. 2011 modified by Geier

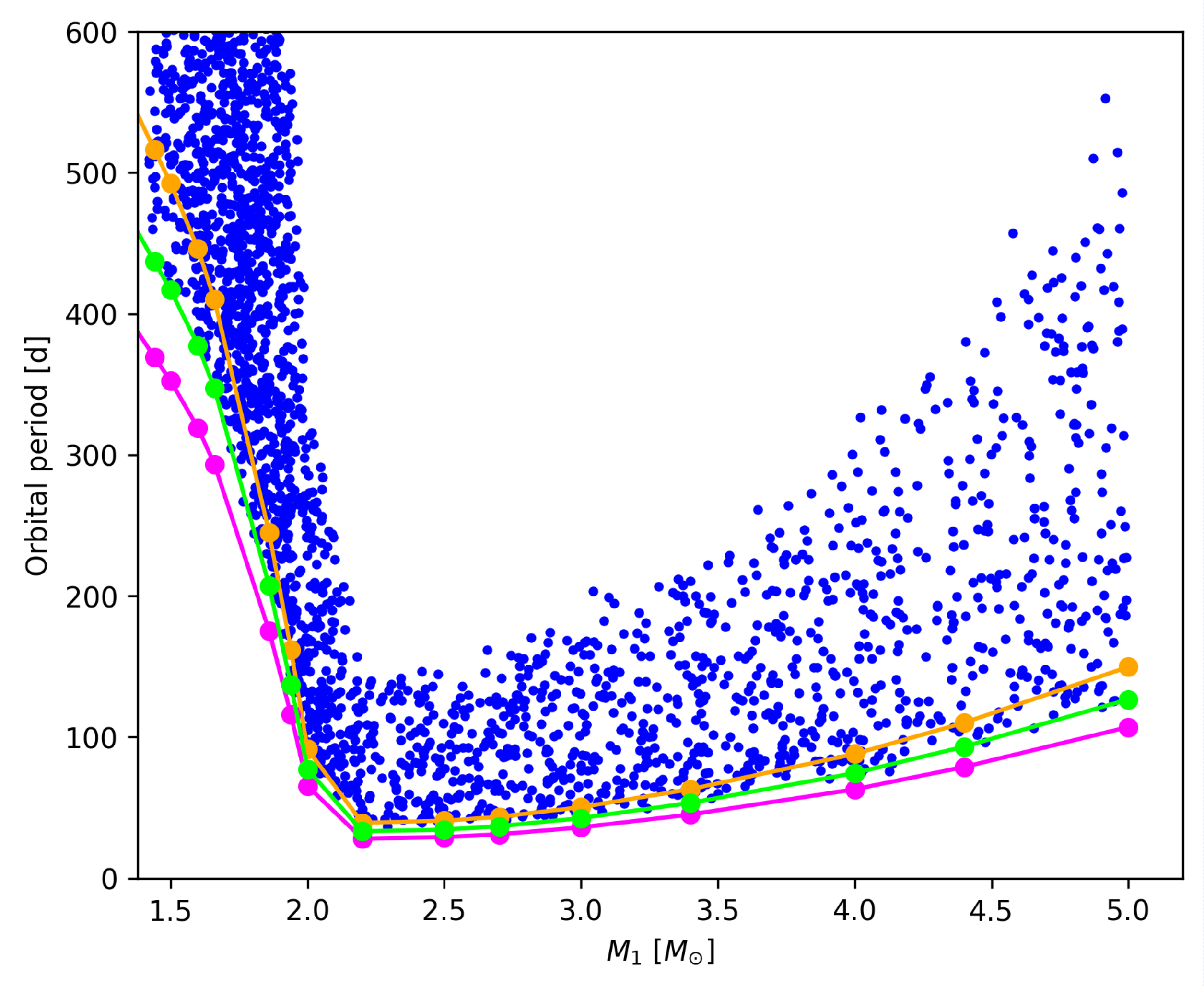
To form a He core-burning star, it must fill its Roche lobe when He-fusion starts

$$R_{\mathrm{prog,He}}(M_{\mathrm{prog}}) = R_{\mathrm{Roche}}(q, P)$$

$R_{\mathrm{prog,He}}$ **taken from stellar evolution models for stars with** M_{prog}

→ **The orbital period of the progenitor binary is a function of** M_{prog} **and** q

Progenitors of stripped helium stars



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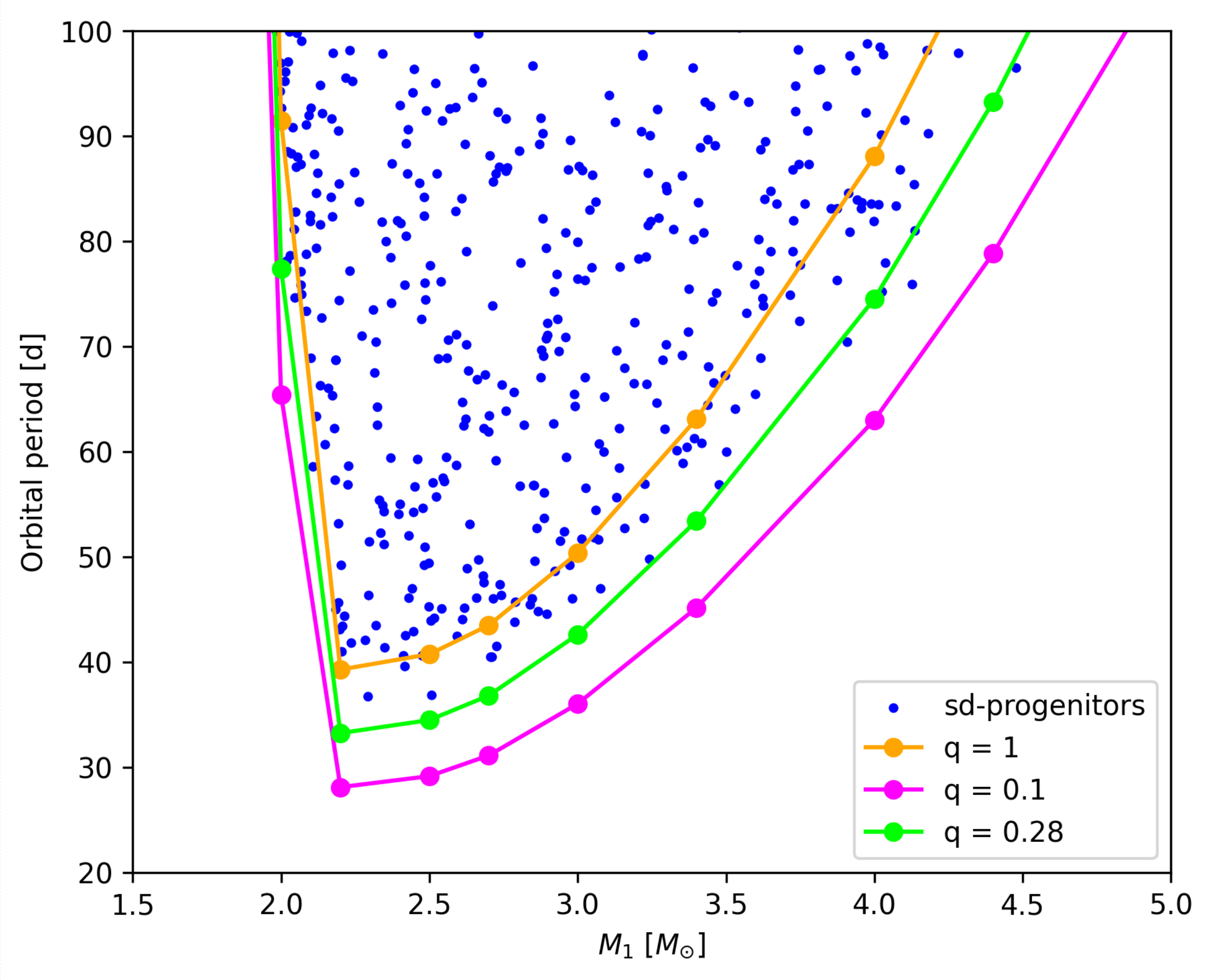
Progenitors of stripped helium stars



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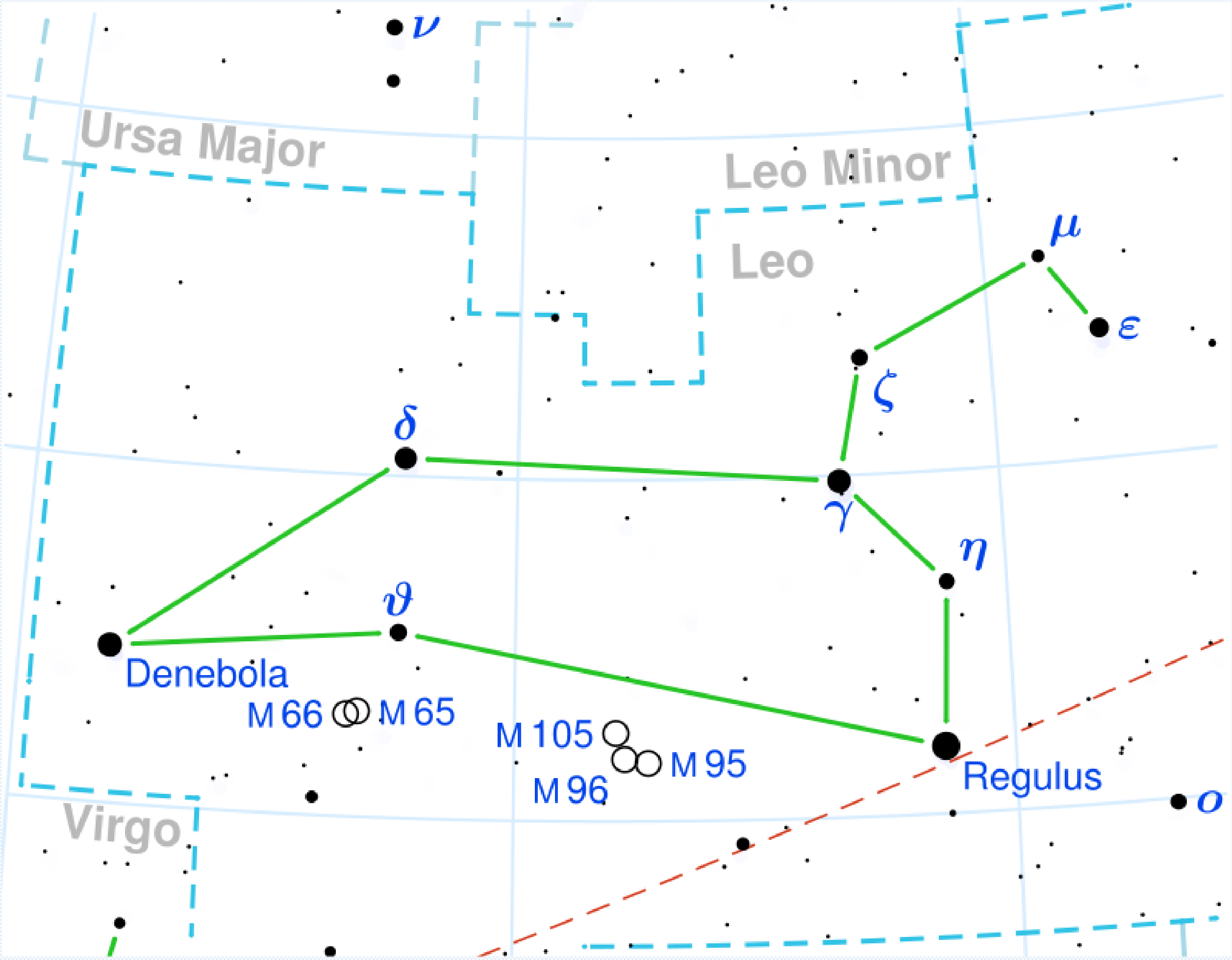
Progenitors of stripped helium stars



We can now search for binaries fulfilling those criteria

Kl833x9/Torsten Bronger/Wikipedia

The project

We aim at determining the birthrate of close binaries with primary stars of intermediate mass qualifying as candidates for stripped He-star progenitors

- **Find all candidates within 100 pc from the Sun observable from Ondrejov**

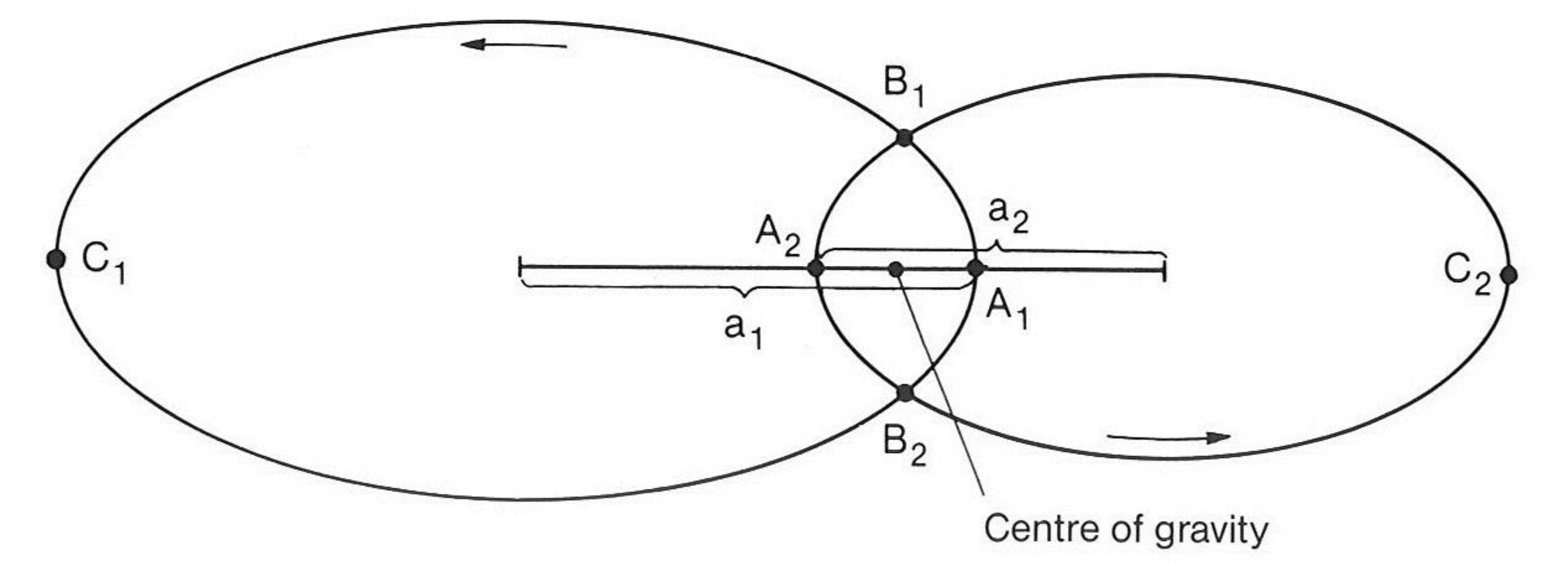
- Previous work

  $\rightarrow$ All intermediate mass stars within 100 pc have been selected (~ 600) from Gaia DR3 based on colour and absolute magnitude

  $\rightarrow$ All stars have been checked in the literature and objects not qualifying as candidates have been excluded

  $\rightarrow$ ~ 5 progenitor candidates found, ~ 300 **stars still need to be checked**

Binaries



Measured quantities

$a_{1,2}$ major semi-axes (+ distance)

P orbital period

i, ω, Ω orientation angles

Visual binaries

Major semi axis of relative orbit

$$a = a_1 + a_2$$

Total mass of the binary system

$$M_1 + M_2 = \frac{4\pi^2 a^3}{GP^2}$$ (Keplers third law)

Mass fraction of the binary system

$$\frac{M_1}{M_2} = \frac{a_2}{a_1}$$

Binaries

Major semi axis of relative orbit

$$a = a_1 + a_2$$

Total mass of the binary system

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Binaries

Major semi axis of relative orbit

$$a = a_1 + a_2$$

Total mass of the binary system

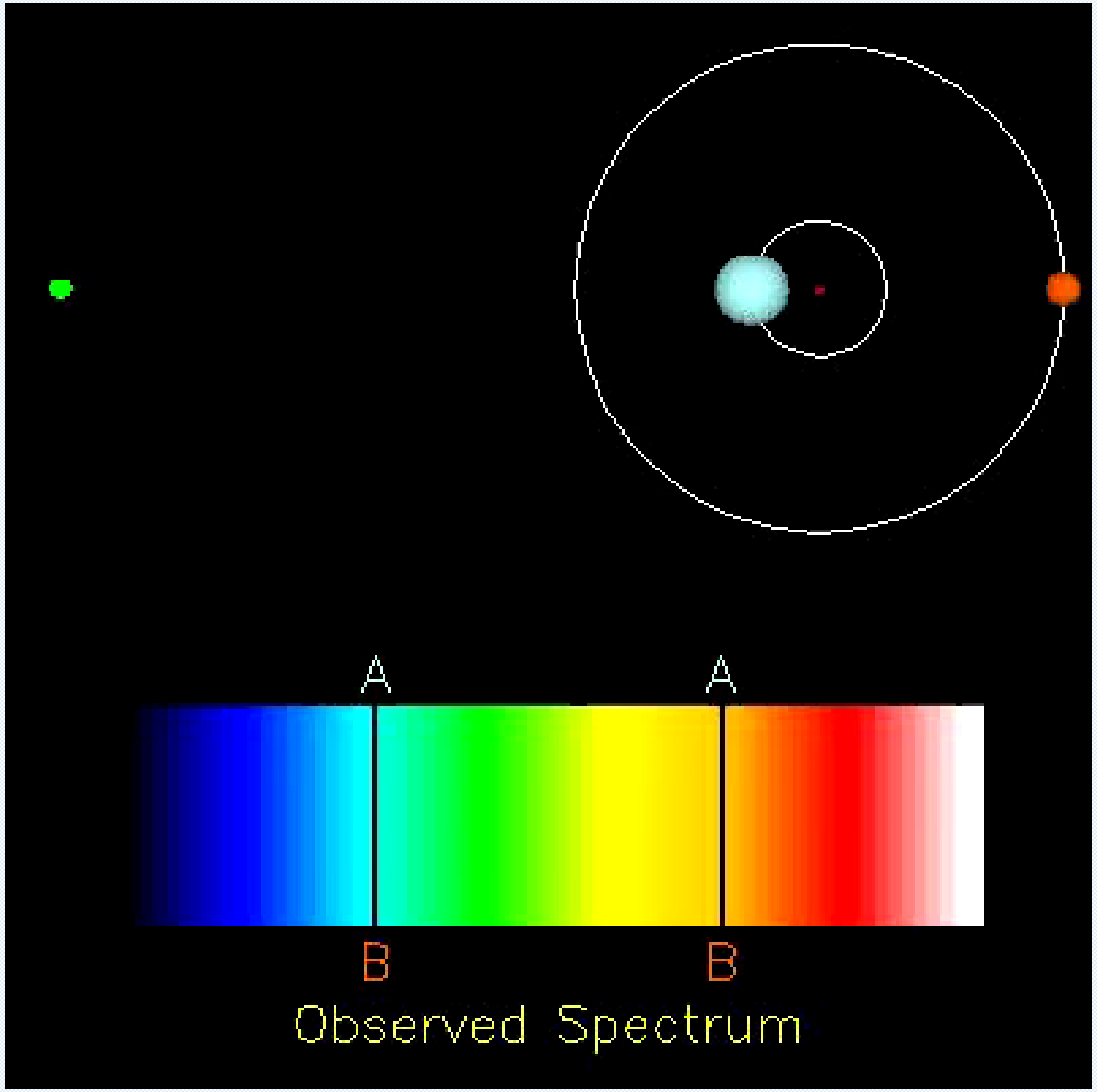
$$M_1 + M_2 = \frac{4\pi^2 a^3}{GP^2} \quad \text{(Keplers third law)}$$

Mass fraction of the binary system

$$\frac{M_1}{M_2} = \frac{a_2}{a_1}$$

$\rightarrow$ **Component masses** M_1, M_2

Spectroscopic binaries



Youtube, Pogge, Ohio State University

Spectral lines are shifted w.r.t. their rest wavelengths

→ **Doppler effect**

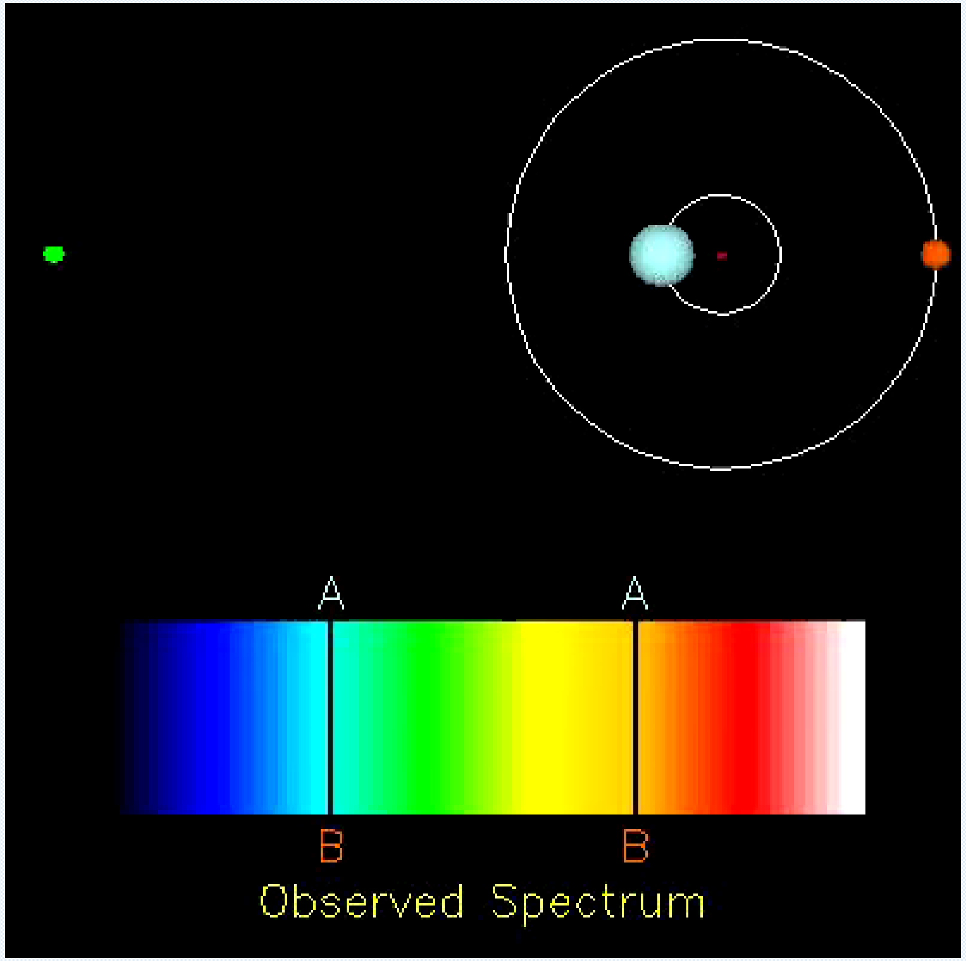
$$\frac{\lambda - \lambda_0}{\lambda_0} = \frac{\Delta\lambda}{\lambda_0} = \frac{v}{c} \quad \text{for } v \ll c$$

λ observed wavelength

λ_0 rest wavelength

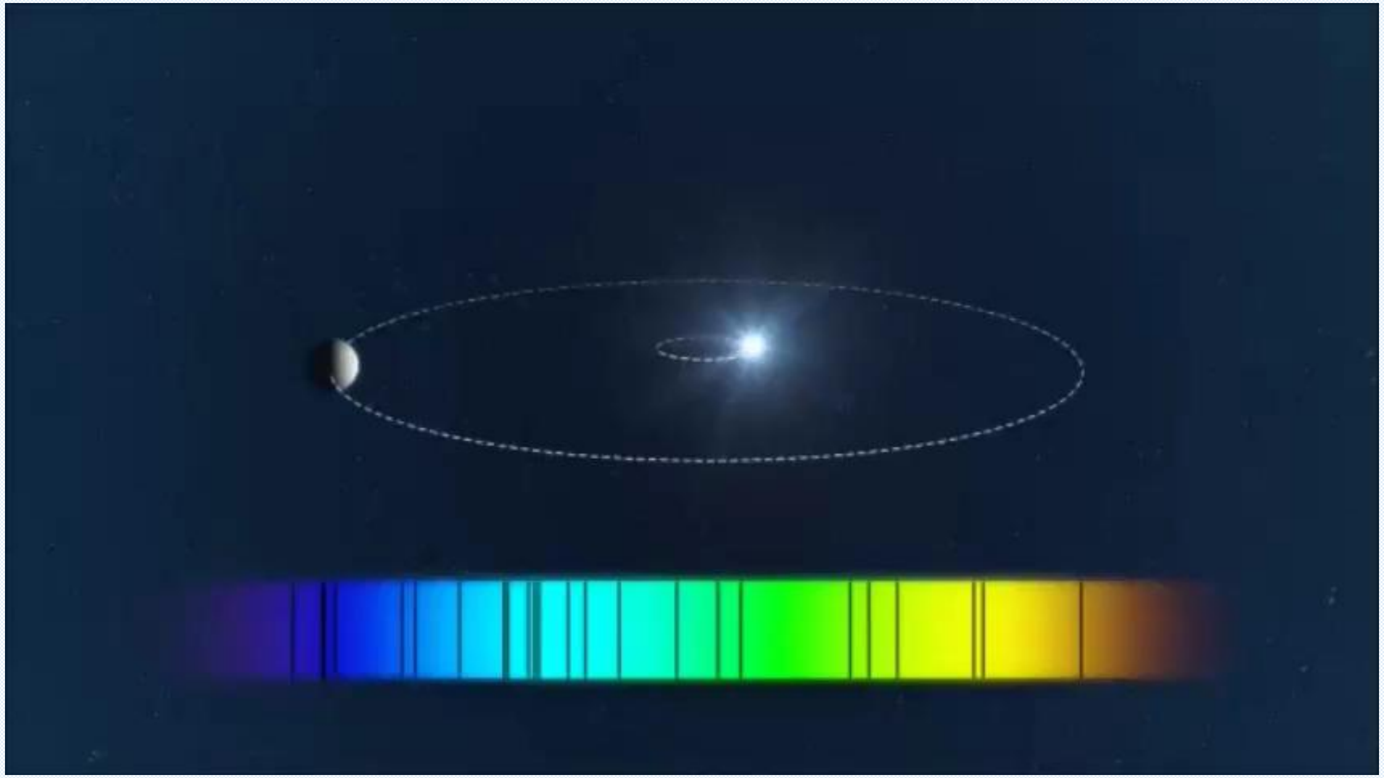
v radial velocity

Spectroscopic binaries



Youtube, Pogge, Ohio State University

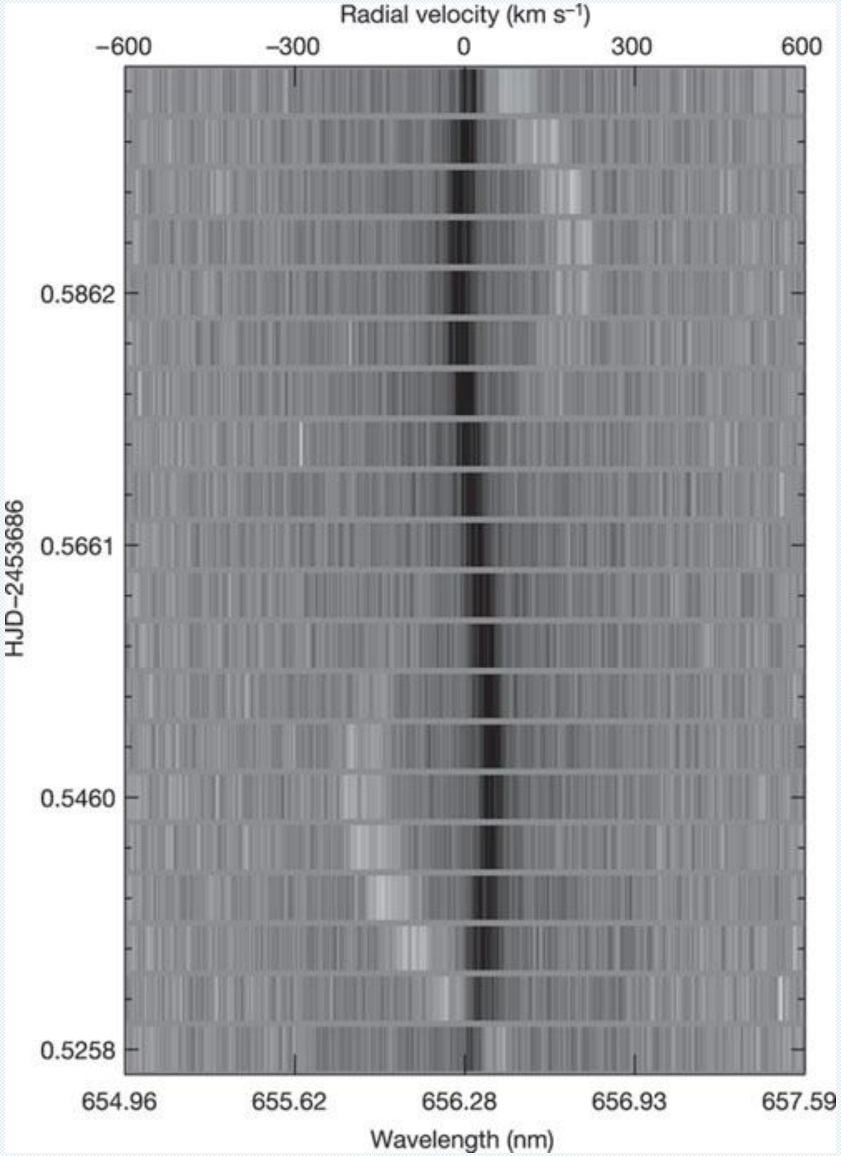
Double-lined binary



ESO

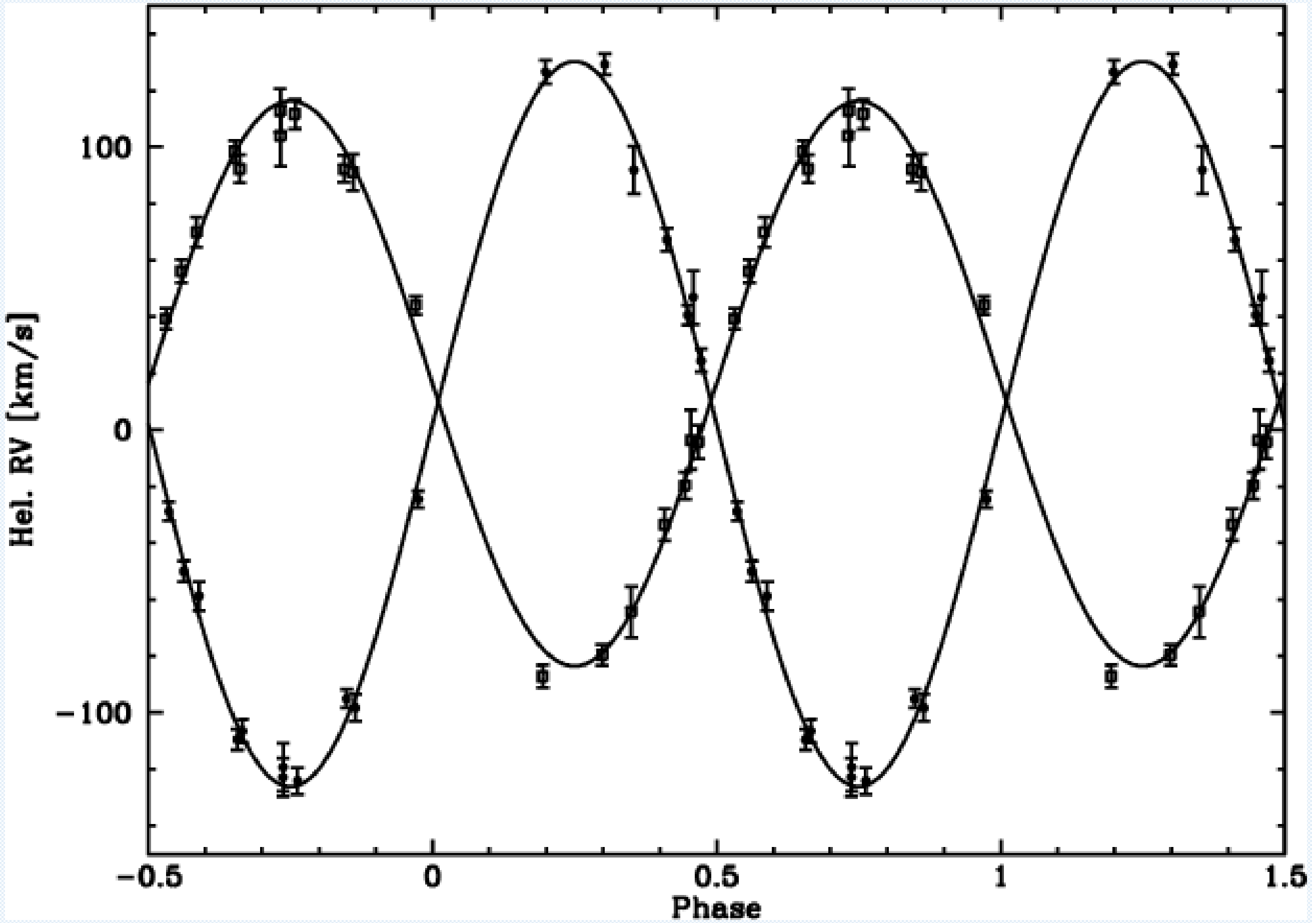
Single-lined binary (e.g. exoplanet system)

Double-lined binaries



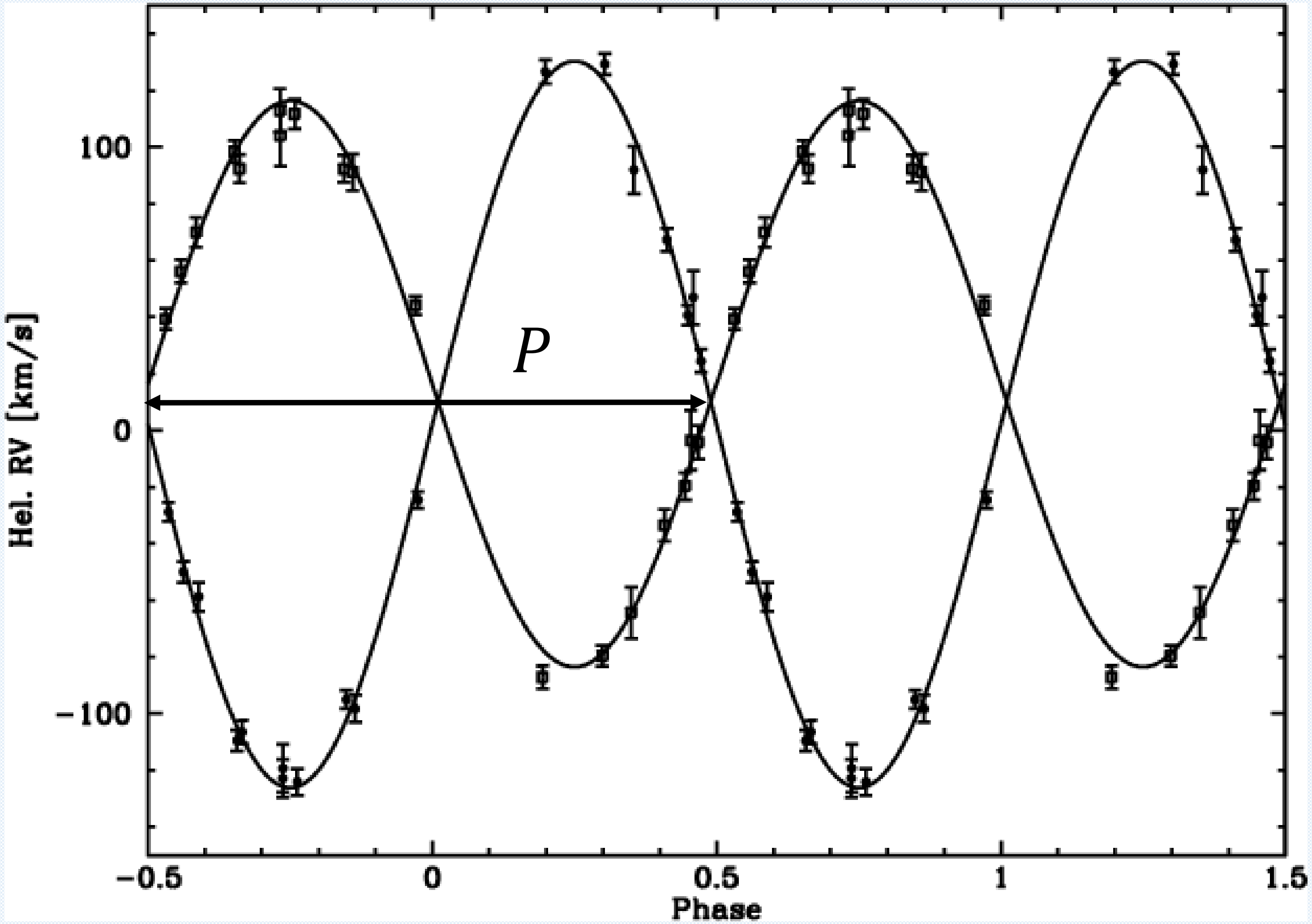
Maxted et al. 2006, Nature, 442, 543

Radial velocity curve → fit Keplerian orbit



Napiwotzki et al. 2002, A&A, 386, 957

Double-lined binaries



Napiwotzki et al. 2002, A&A, 386, 957

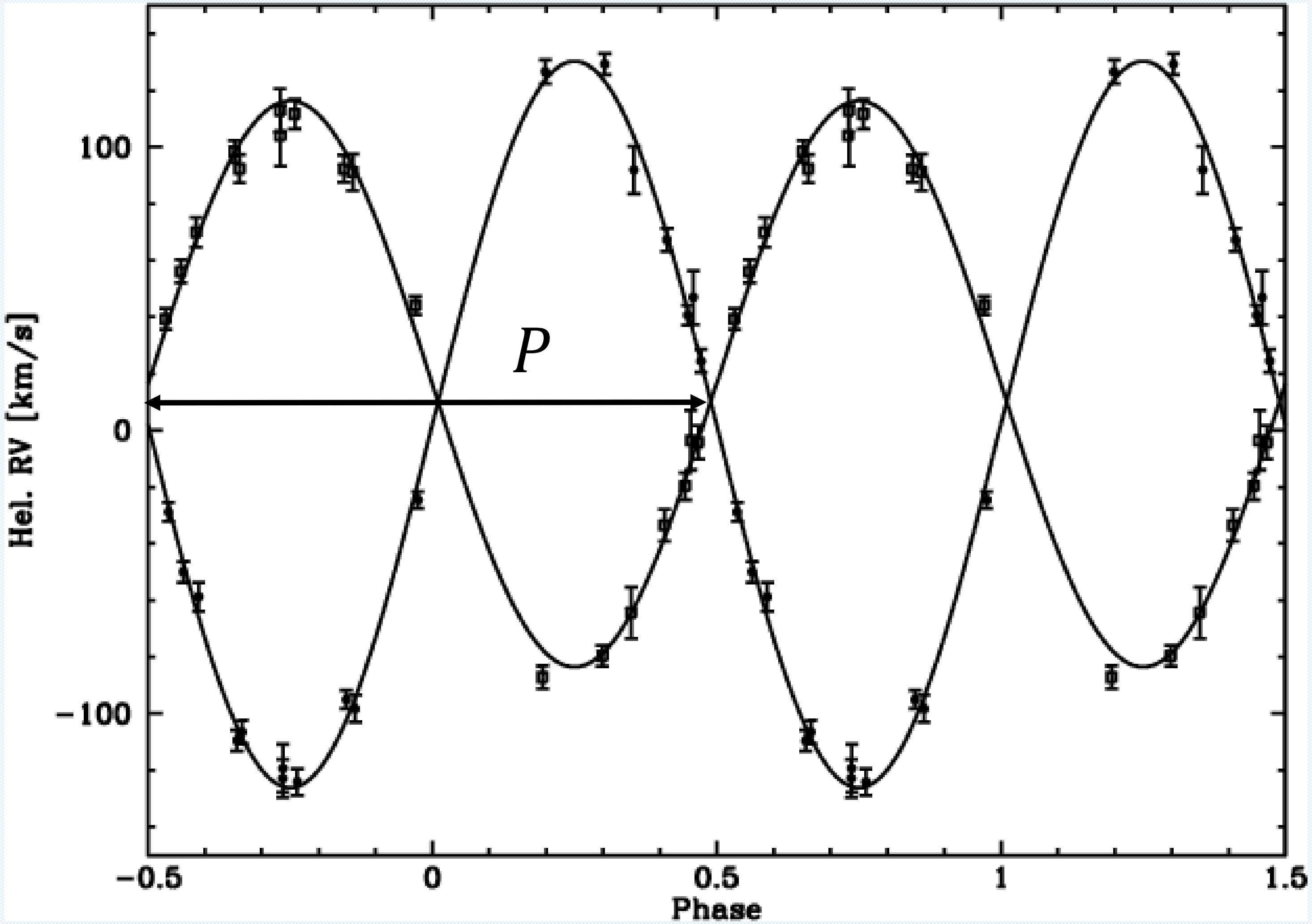
Radial velocity curve → Orbital period P

Phased radial velocity curve

→ Relative to a certain time T_0 the epochs t_n of the measured RVs in HJD can be converted to phases $0 \leq \Phi_n \leq 1$

$$\Phi_n = \mathrm{frac}\left(\frac{T_0 - t_n}{P}\right)$$

Double-lined binaries



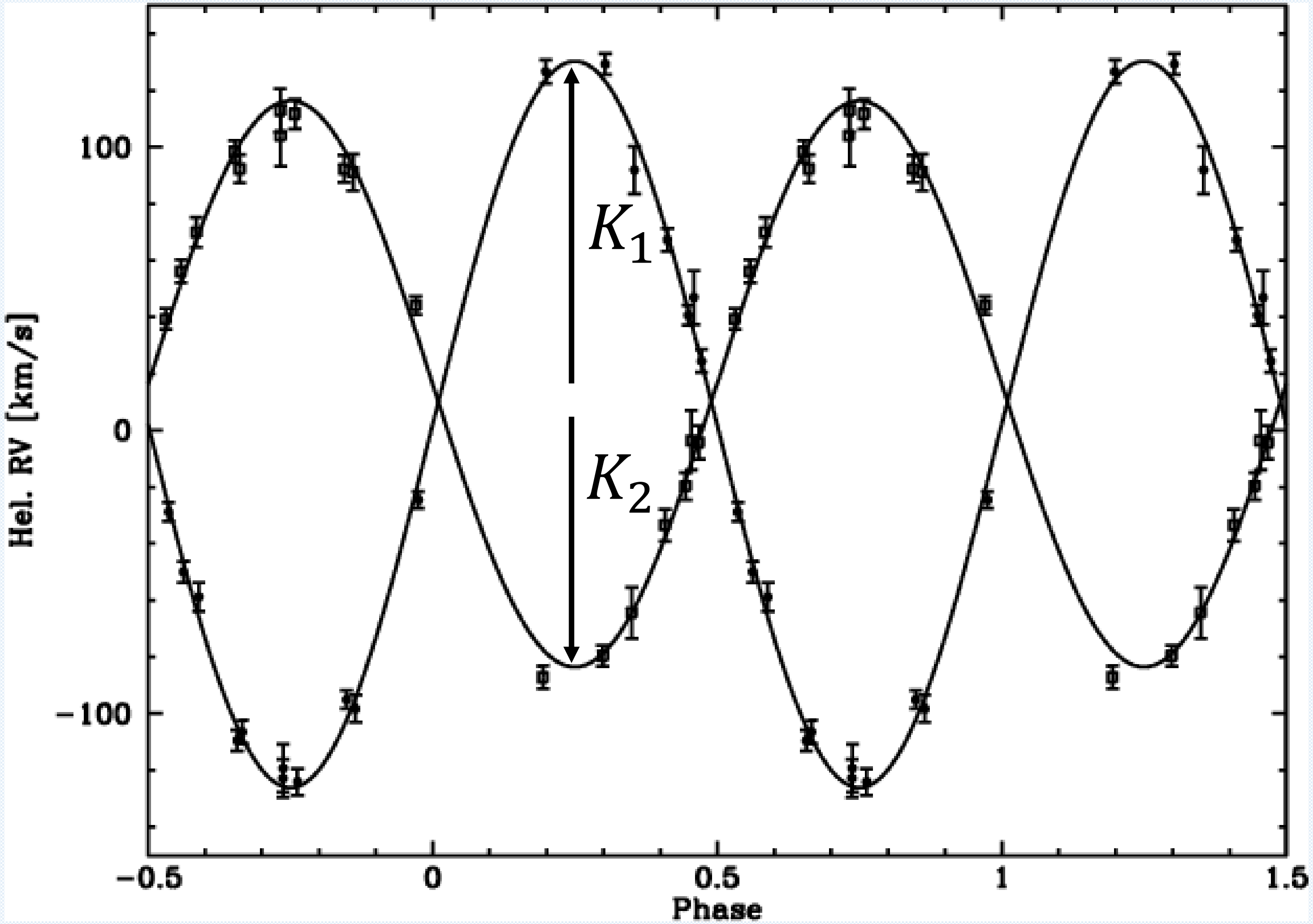
Napiwotzki et al. 2002, A&A, 386, 957

Phased time-series of periodically variable values allow us to combine measurements taken at very different epochs

→ **A homogeneous and dense phase coverage is needed to measure the orbital parameters precisely**

Radial velocity curve → Orbital period P

Double-lined binaries



Napiwotzki et al. 2002, A&A, 386, 957

Radial velocity curve → Radial velocity semi-amplitudes $K_{1,2}$

Double-lined binaries

$$a = a_1 + a_2$$

$$\frac{M_1}{M_2} = \frac{a_2}{a_1} \Rightarrow a_1 = \frac{aM_2}{M_1 + M_2}$$

Circular Orbit

(K observed RV, u absolute RV, i inclination angle)

$$K_{1,2} = u_{1,2} \sin i$$

$$\Longrightarrow K_1 = \frac{2\pi a_1}{P} \sin i = \frac{2\pi a}{P} \frac{M_2 \sin i}{M_1 + M_2}$$

Double-lined binaries

$$K_1 = \frac{2\pi a}{P} \frac{M_2 \sin i}{M_1 + M_2} \Rightarrow a = \frac{PK_1}{2\pi} \frac{M_1 + M_2}{M_2 \sin i}$$

$$M_1 + M_2 = \frac{4\pi^2 a^3}{GP^2}$$ **(Keplers third law)**

Binary mass function

$$\Rightarrow f(M_1, M_2) = \frac{K_{1,2}^3 P}{2\pi G} = \frac{M_{2,1}^3 \sin^3 i}{(M_1 + M_2)^2}$$

Double-lined binaries

$$f(M_1, M_2) = \frac{K_{1,2}^3 P}{2\pi G} = \frac{M_{2,1}^3 \sin^3 i}{(M_1 + M_2)^2}$$

$$K_{1,2} = \frac{2\pi a_{1,2}}{P} \sin i$$

$$\Rightarrow \frac{K_1}{K_2} = \frac{a_1}{a_2} = \frac{M_2}{M_1}$$

Double-lined binaries

$$f(M_1, M_2) = \frac{K_{1,2}^3 P}{2\pi G} = \frac{M_{2,1}^3 \sin^3 i}{(M_1 + M_2)^2}$$

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Double-lined binaries

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$$K_{1,2} = \frac{2\pi a_{1,2}}{P} \sin i$$

$$\Rightarrow \frac{K_1}{K_2} = \frac{a_1}{a_2} = \frac{M_2}{M_1}$$

Inclination angle needed to solve the system

Double-lined binaries

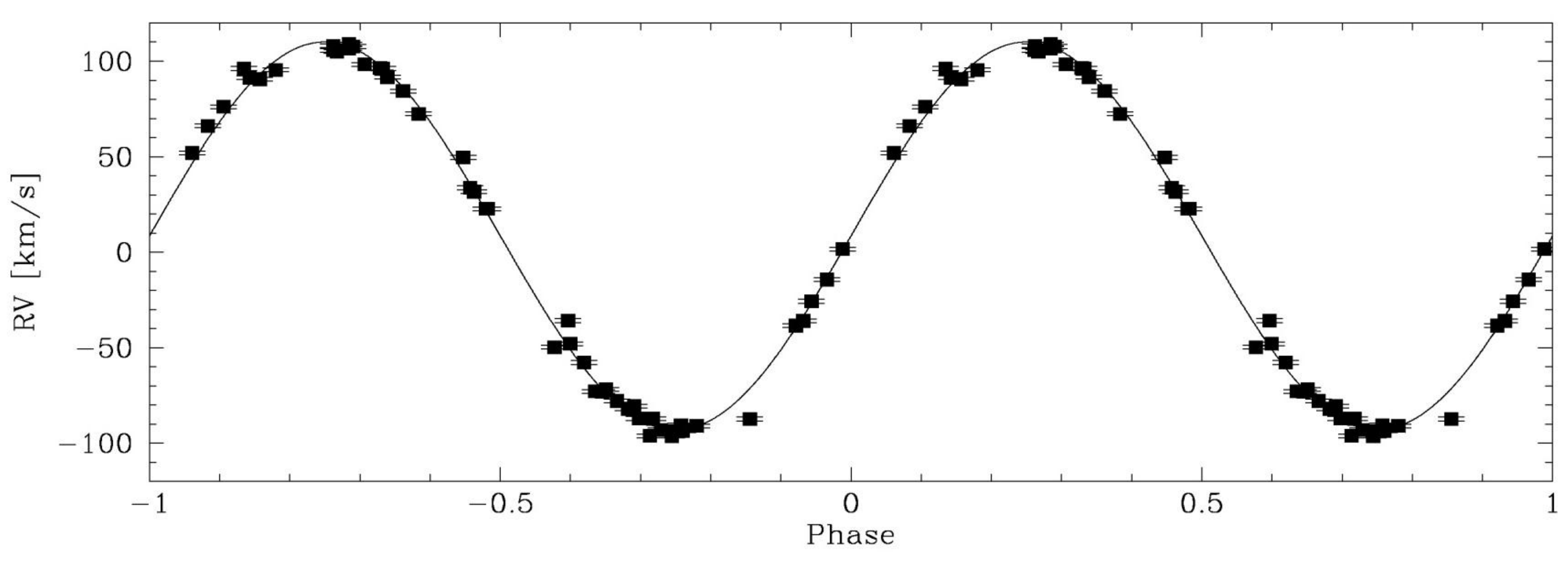
General case: Eccentric orbits

$$f(M_1, M_2) = \frac{K_{1,2}^3 P (1 - e^2)^{3/2}}{2\pi G} = \frac{M_{2,1}^3 \sin^3 i}{(M_1 + M_2)^2}$$

$$K_{1,2} = \frac{2\pi a_{1,2}}{P(1 - e^2)^{1/2}} \sin i$$

$$\Rightarrow \frac{K_1}{K_2} = \frac{a_1}{a_2} = \frac{M_2}{M_1}$$

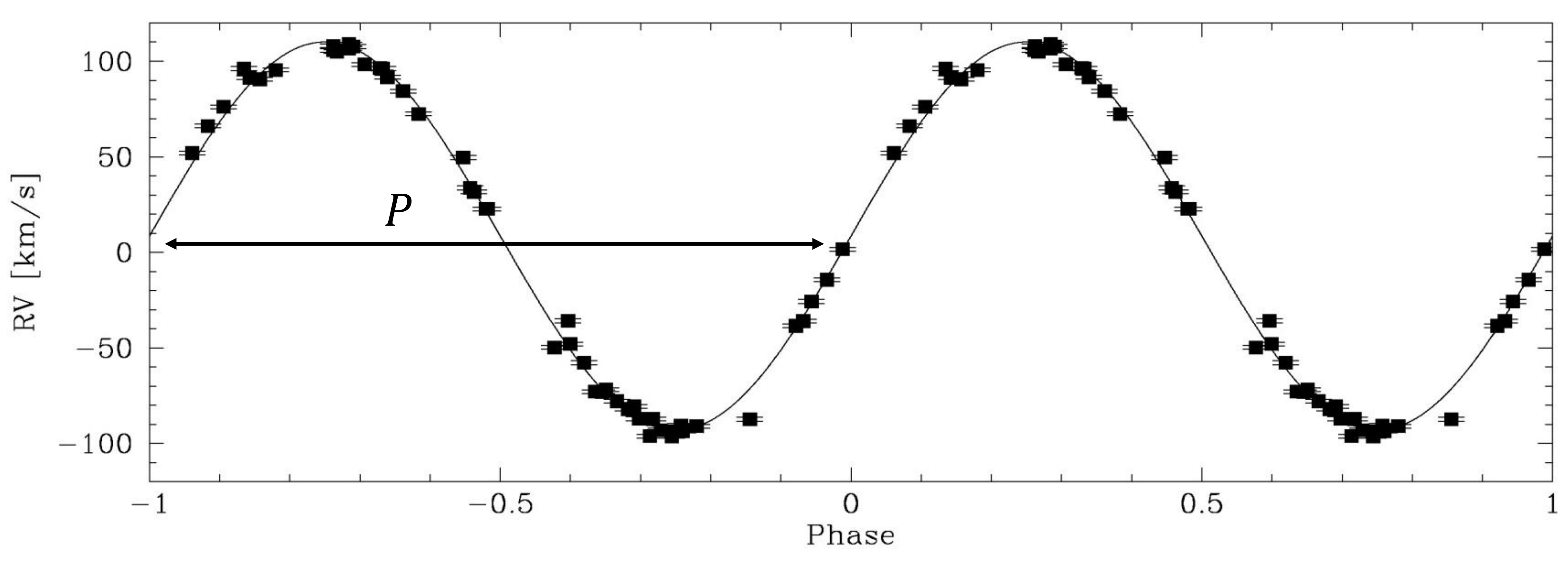
Single-lined binaries



S. Geier

Orbital parameters of the visible component

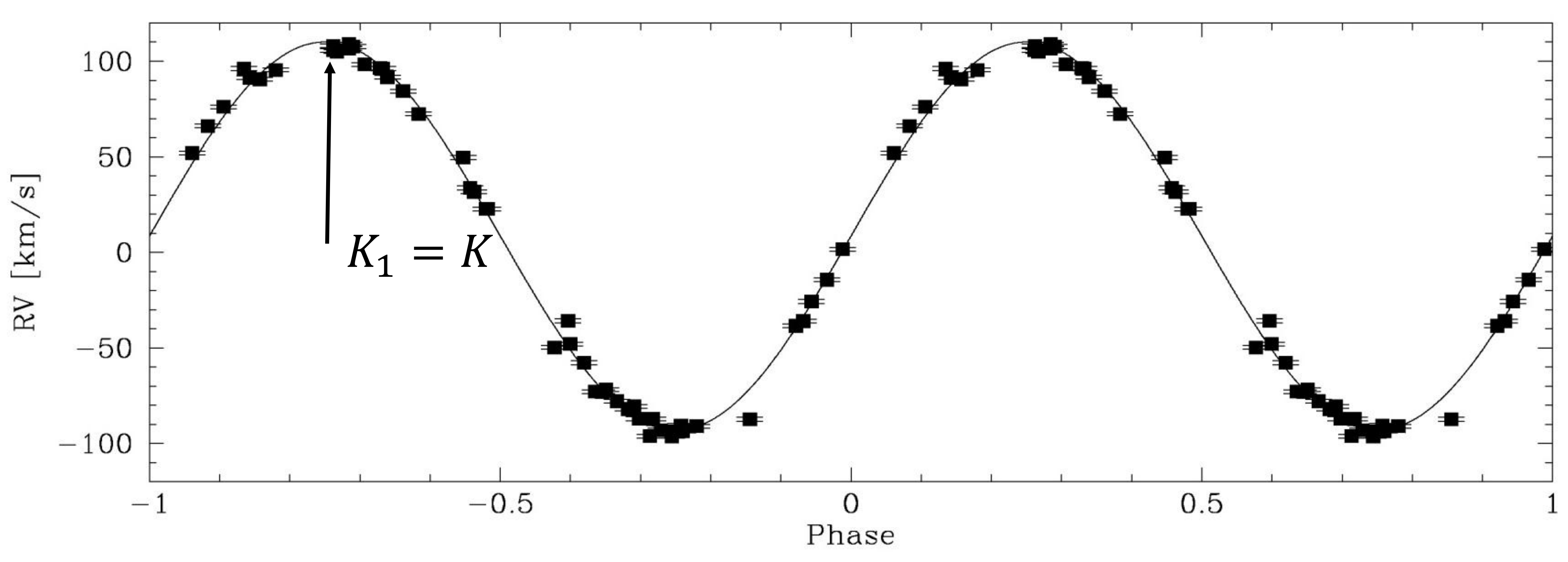
Single-lined binaries



S. Geier

Orbital parameters of the visible component

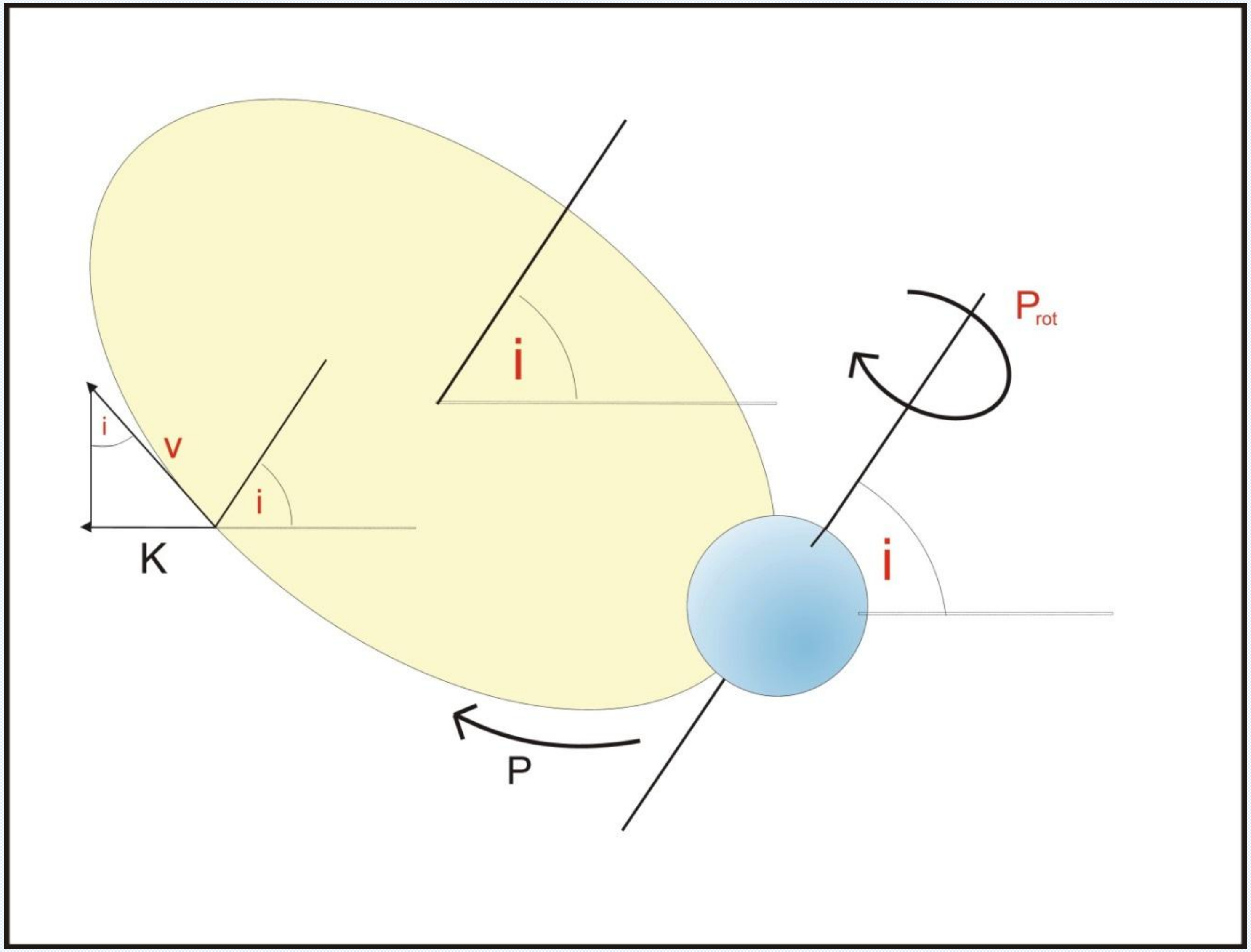
Single-lined binaries



S. Geier

Orbital parameters of the visible component

Single-lined binaries

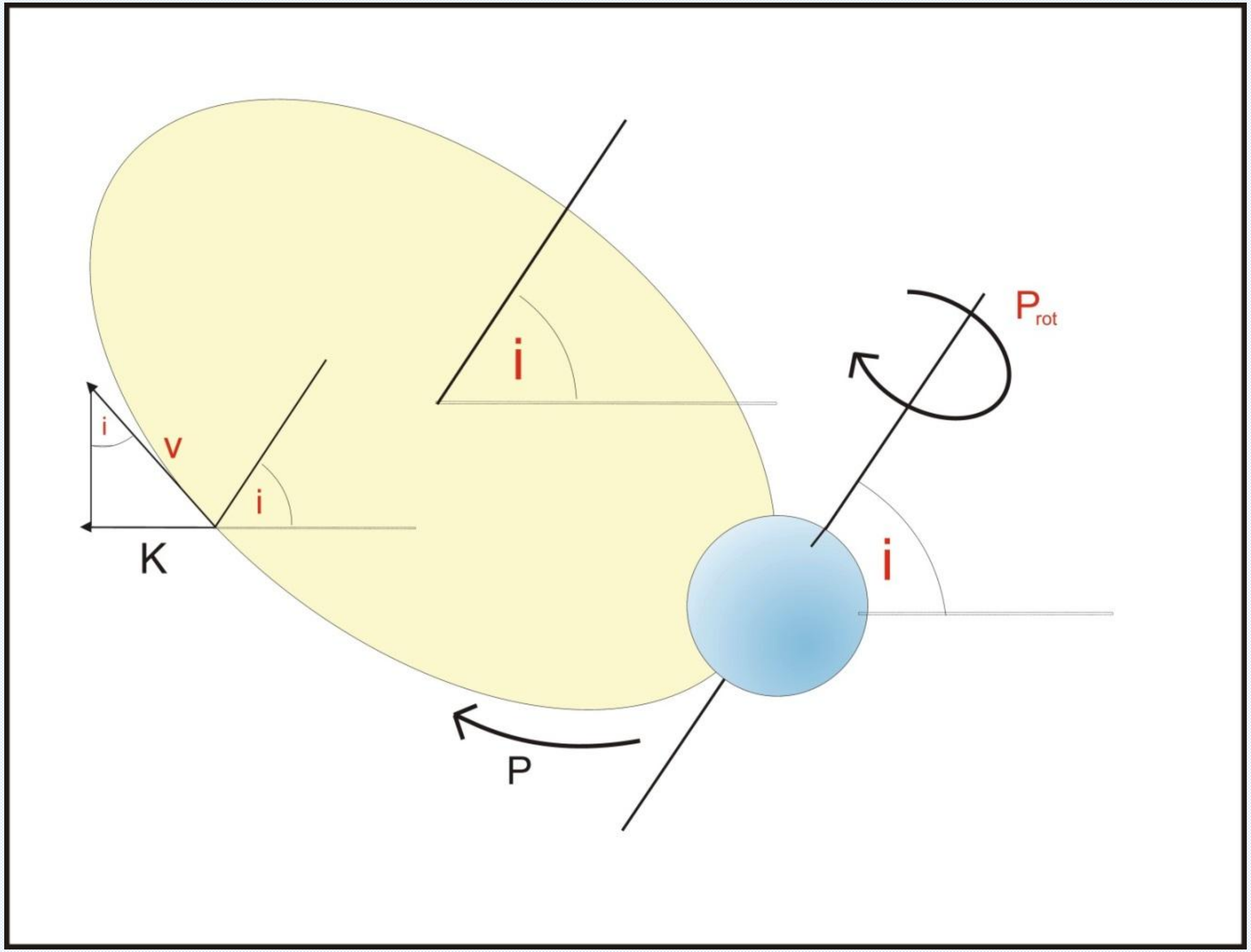


S. Geier

Binary mass function

$$\frac{K^3 P}{2\pi G} = \frac{M_2^3 \sin^3 i}{(M_1 + M_2)^2}$$

Single-lined binaries



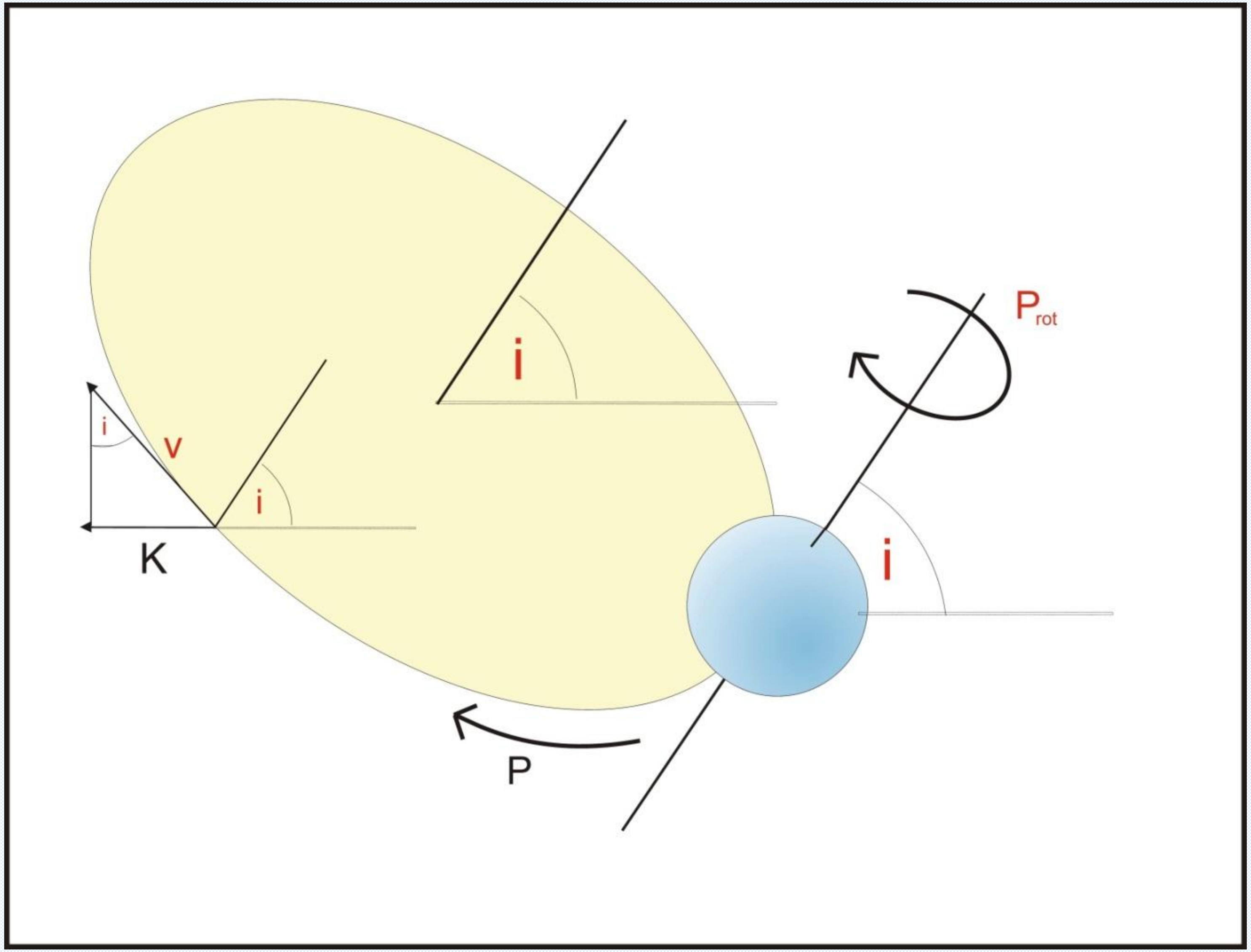
S. Geier

Binary mass function

$$\frac{K^3 P}{2\pi G} = \frac{M_2^3 \sin^3 i}{(M_1 + M_2)^2}$$

Problem underdetermined

Single-lined binaries



S. Geier

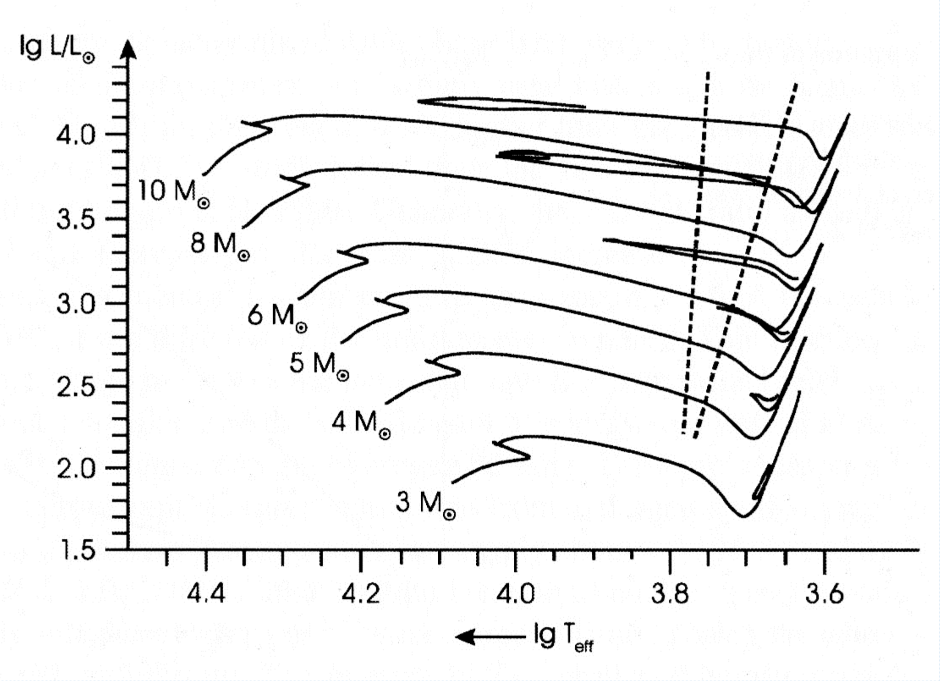
Inclination angle

$i \leq 90° \Rightarrow \sin i \leq 1$

$$\Rightarrow \frac{K^3 P}{2\pi G} \leq \frac{M_2^3}{(M_1 + M_2)^2}$$

If M_1 is known, a lower limit for M_2 can be derived

The project



Kippenhahn, Weigert & Weiss 2012

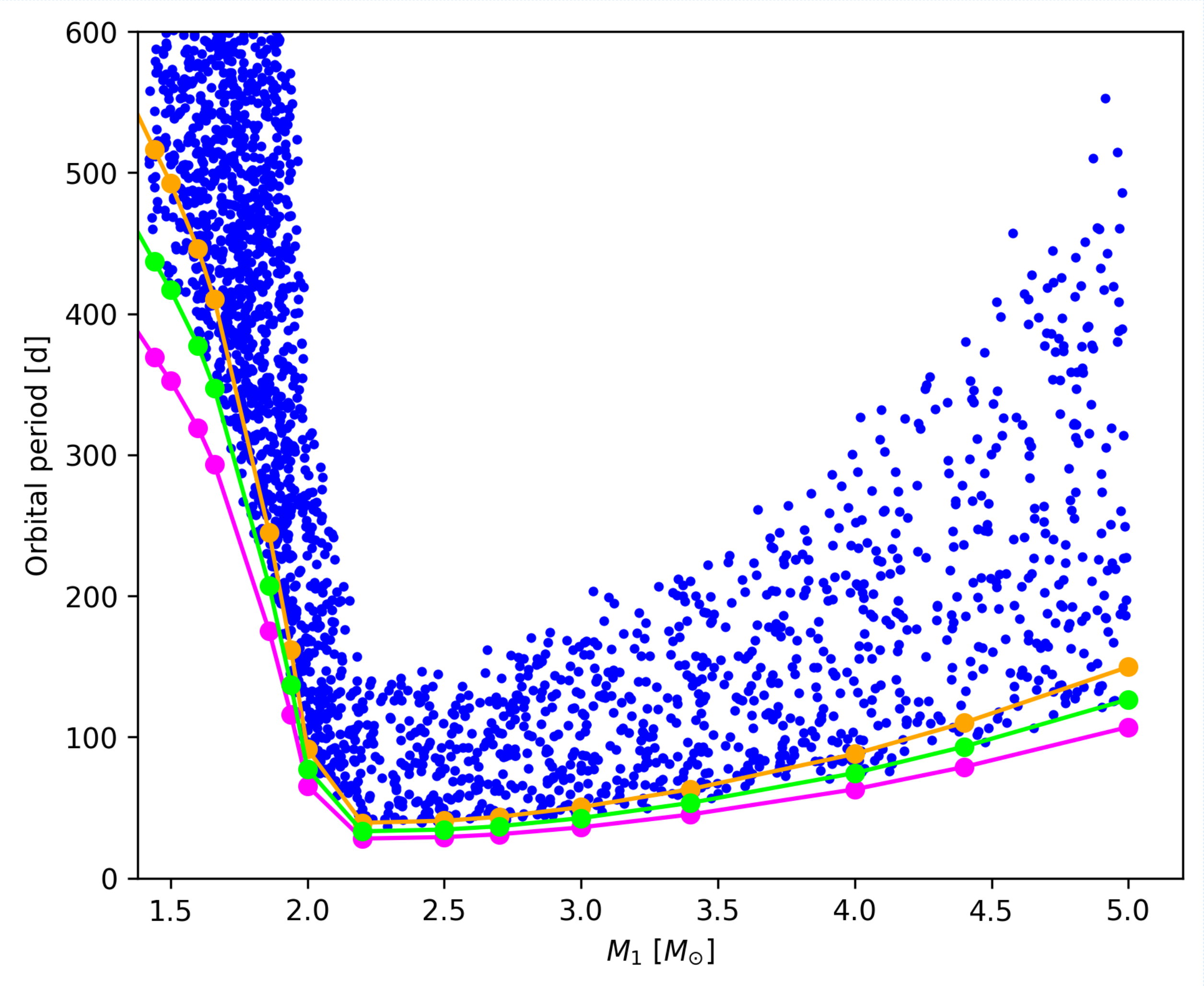
Masses of the primaries can be determined by comparing the measured quantities to stellar evolution tracks

→ Colour (temperature), absolute magnitude (luminosity)

→ Our sample consists of main sequence stars and the Gaia BP-RP colours can be used to determine their masses (see the catalogue provided)

→ **Determine the masses of all stars**

The project



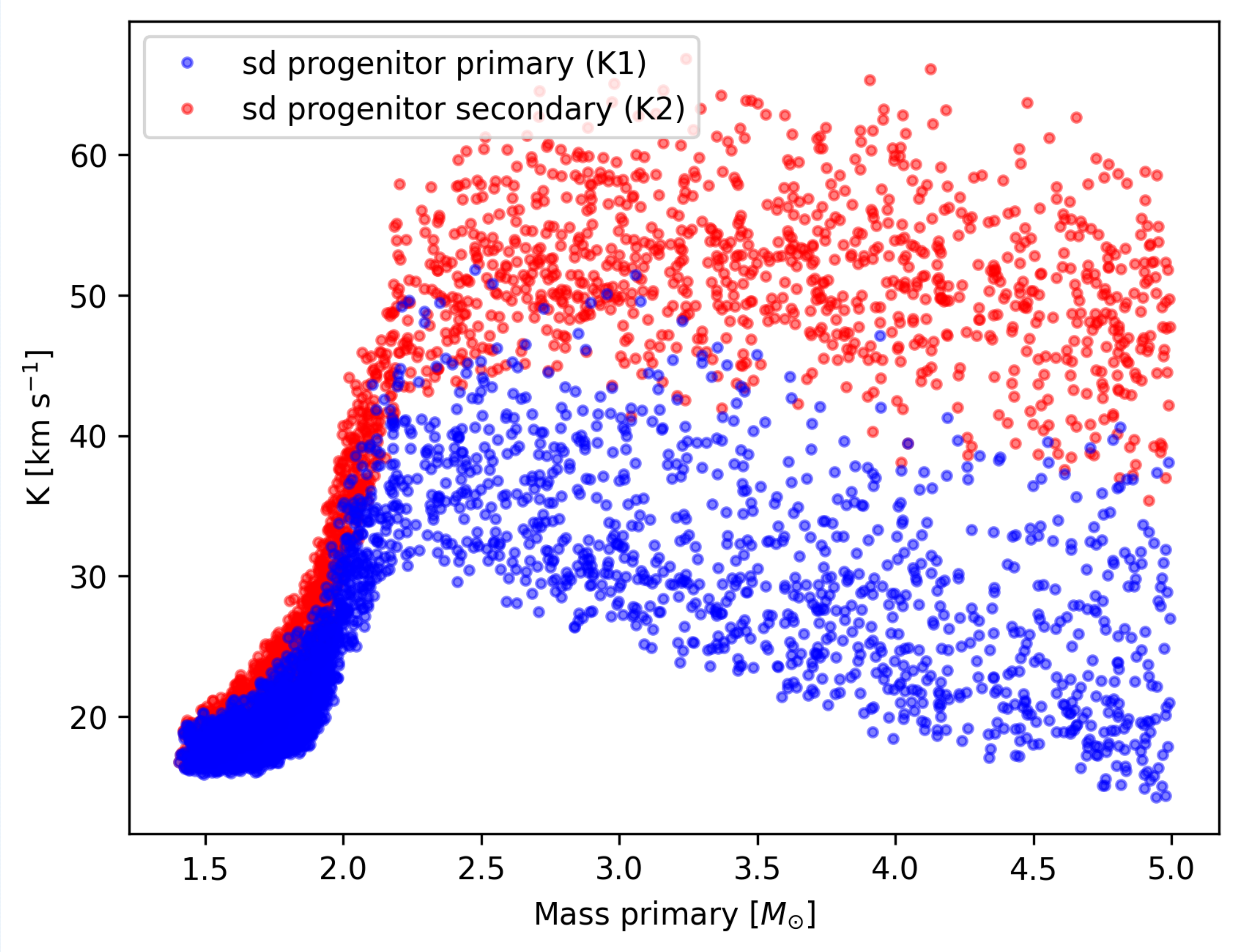
→ **Select the stars observable from Ondrejov**

→ **Prioritize targets, with maximum phase coverage in 7 days ($M - P$ relation!)**

→ **Prepare and optimize the observing schedule**

→ **Observe at least two epochs with the OES at the 2m-Perek telescope**

The project



→ **Determine the maximum RV shifts ΔRV**

→ **Progenitor candidates must follow the $M - K$ relation**

→ **Remove stars with $\Delta RV = 0\ \mathrm{km/s}$ (no binaries) or $\Delta RV > 2K$ (too close binaries) from the candidate list**

→ **Prepare and optimize the schedule for follow-up observations**

The project

→ Obtain follow-up observations of the remaining candidates

→ Fit Keplerian orbits to the RV curves and determine orbital parameters and (minimum) masses of the companions

→ Prepare a list of rejected and still valid candidates as preparation for further observations

GOOD LUCK!