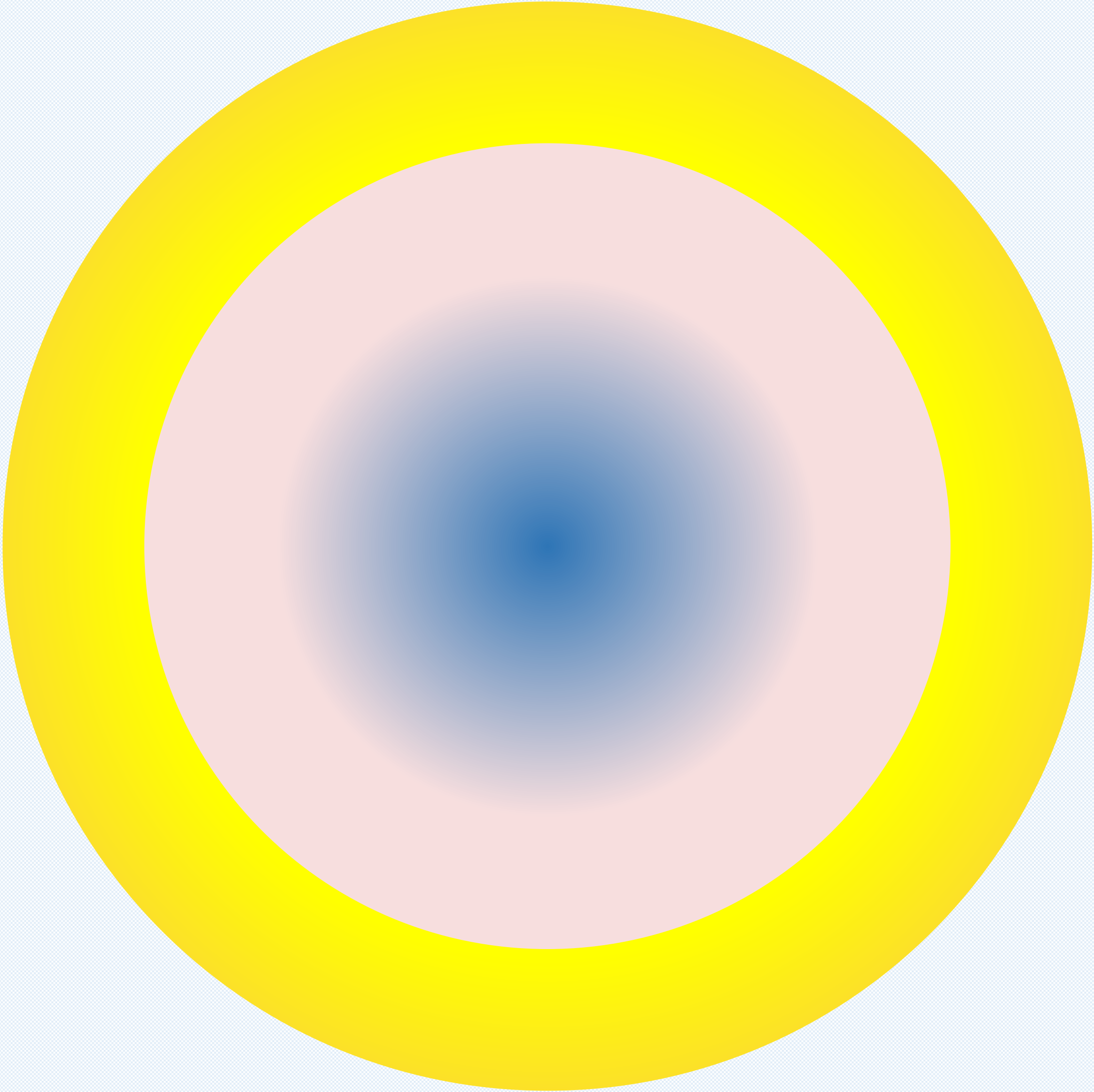
Spectroscopy of evolved stars

Research workshop on evolved stars, Ondrejov 2021

Stephan Geier

Evolution through helium burning



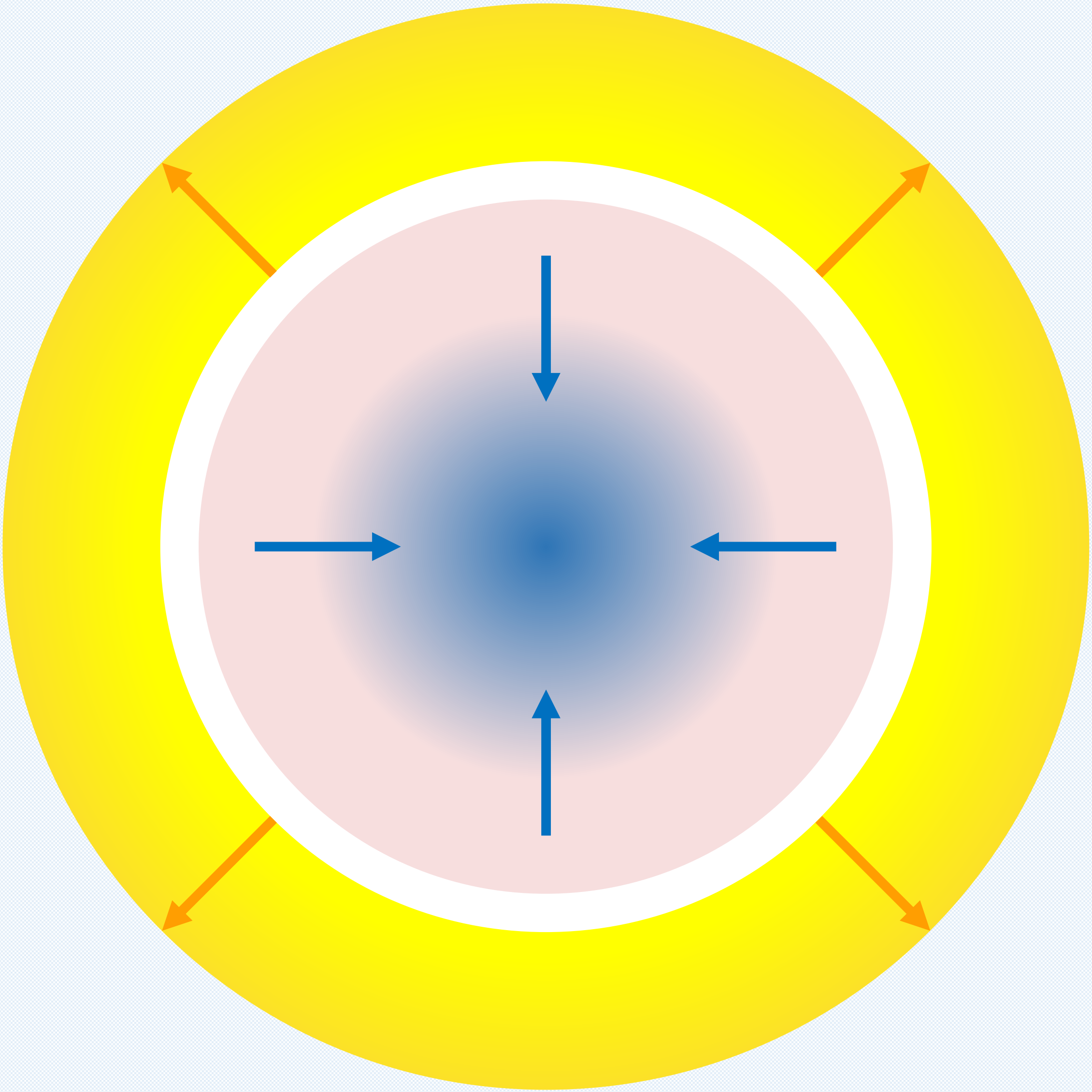
Due to the high density in the core, the electron gas becomes **degenerate**

→ Isothermal, degenerate core is stable

→ **Schönberg-Chandrasekhar** limit is not important

→ Core can grow in mass

Evolution through helium burning



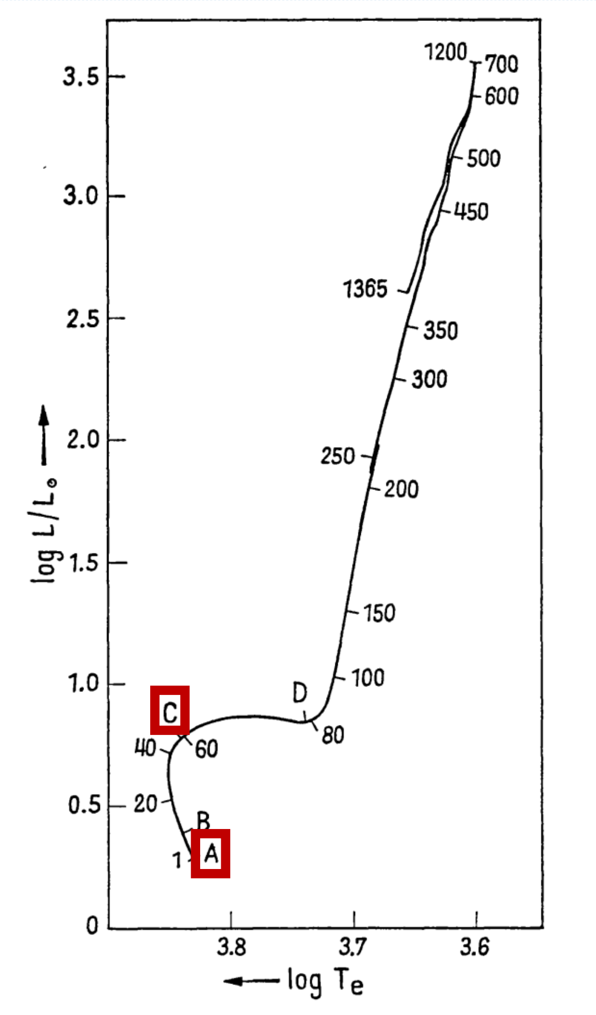
No rapid contraction of the core

→ **No Hertzsprung gap**

No heating during core contraction due to equation of state

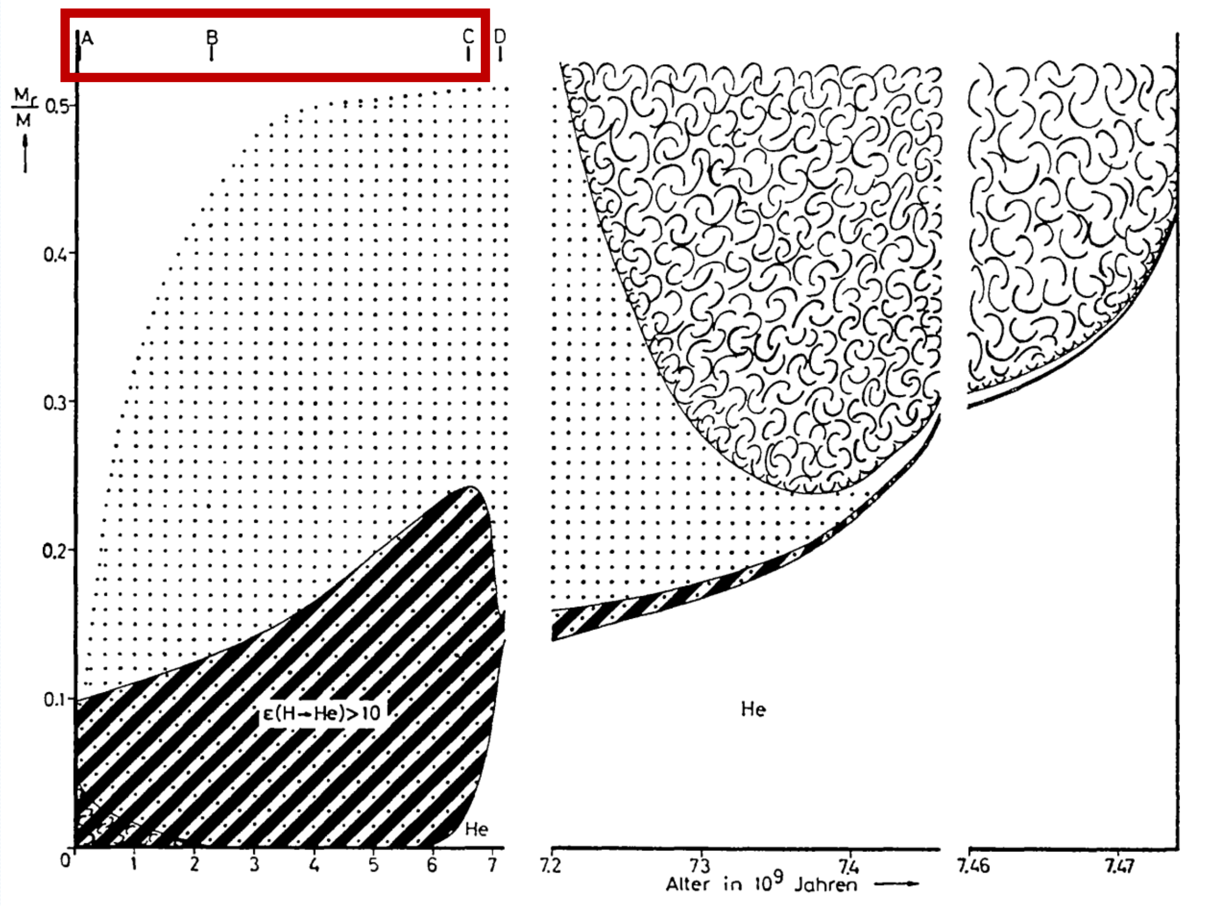
$$P_{\mathrm{e}} = 1.0036 \times 10^{13} \left(\frac{\rho}{\mu_{\mathrm{e}}}\right)^{5/3}$$

Evolution through helium burning



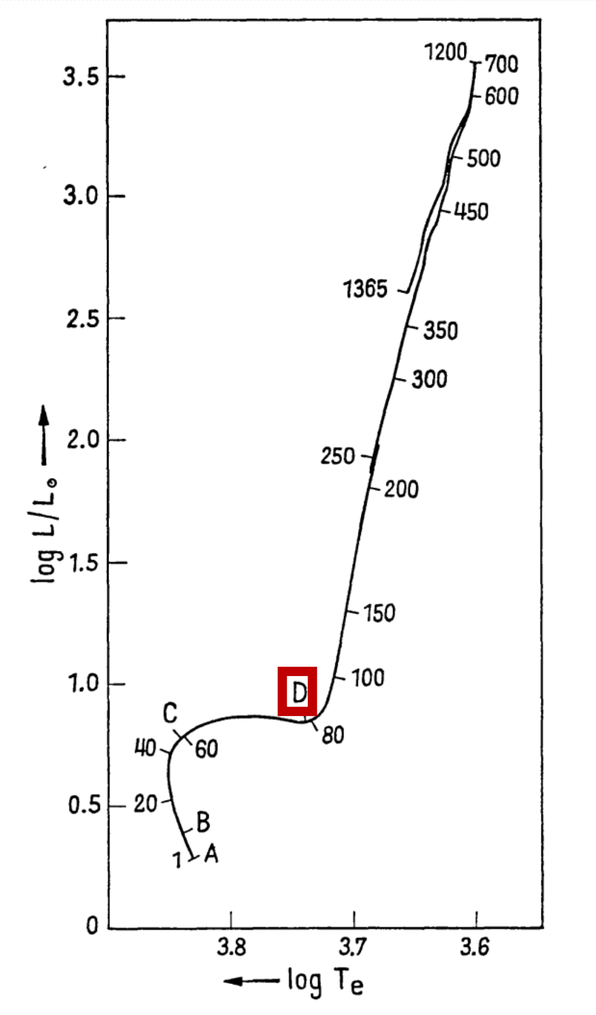
Thomas 1967, ZA, 67, 420

$1.3\ M_{\odot}$ Radiative core **(Low mass)**



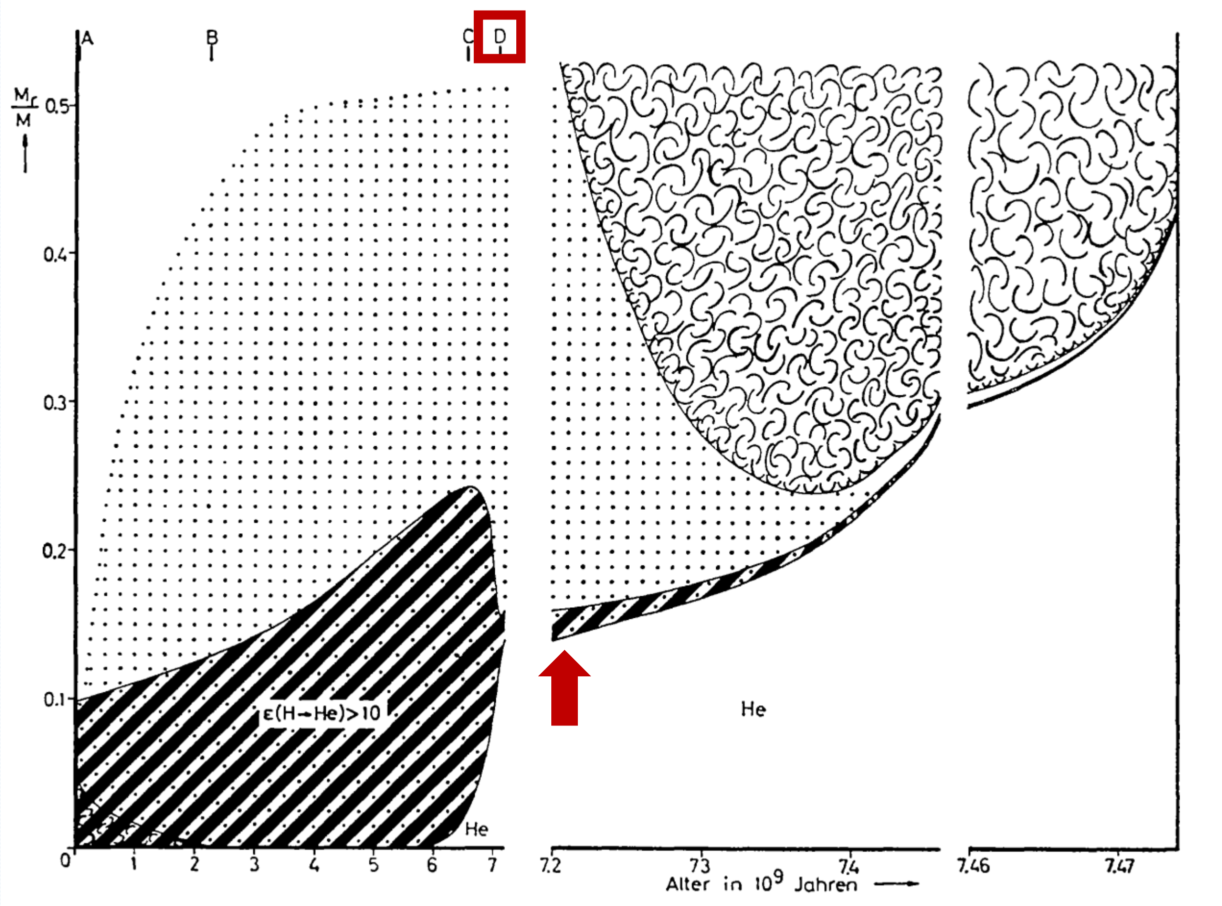
Degenerate helium core grows in mass due to central H-burning

Evolution through helium burning



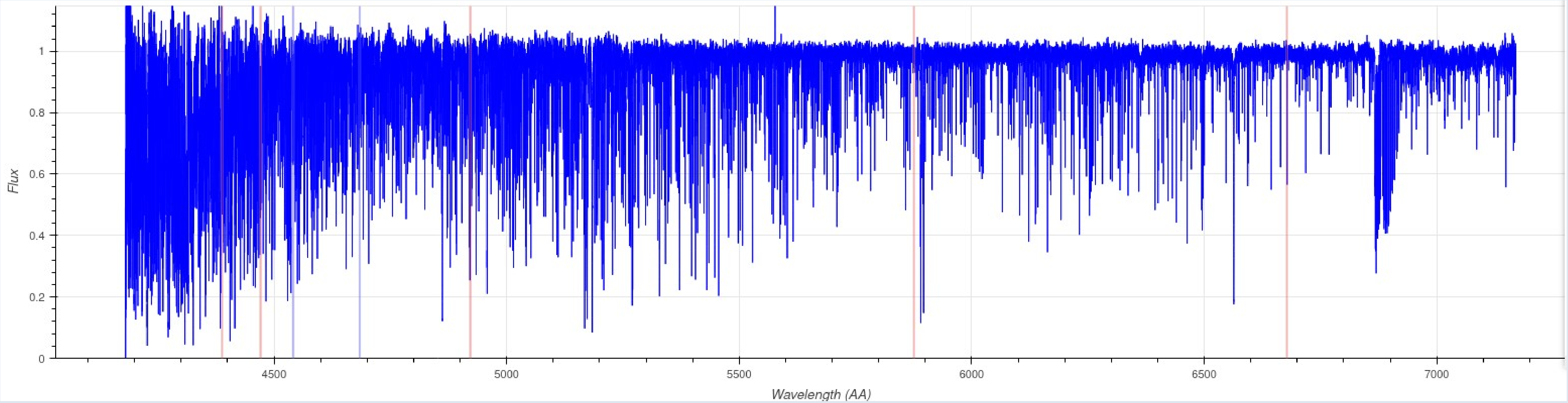
Thomas 1967, ZA, 67, 420

$1.3\ M_\odot$ Radiative core **(Low mass)**



H-shell burning starts → Core contracts, envelope expands

Red giant

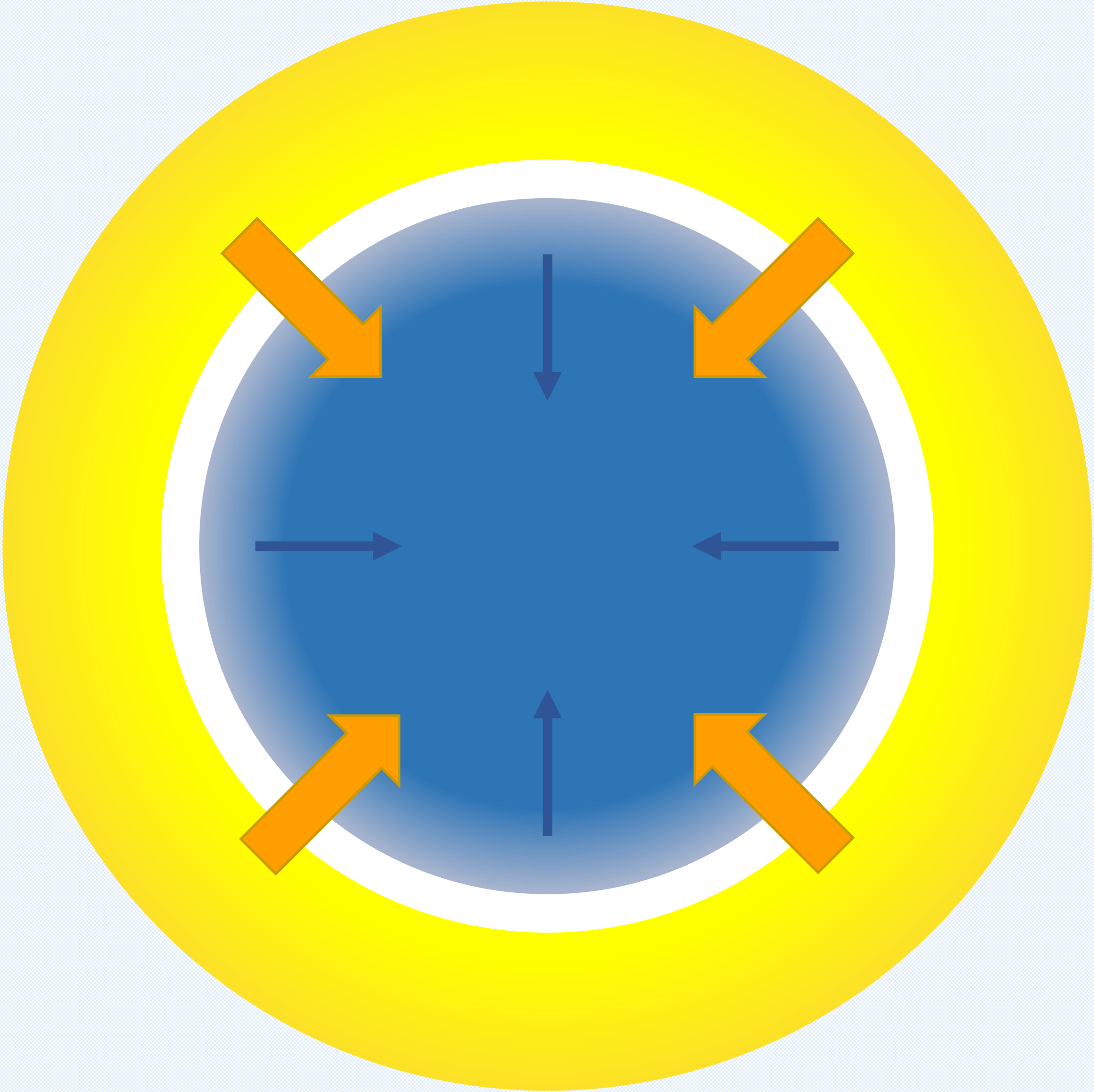


AOTS database

Spectral type M/K III

Very cool stars with many absorption lines (TiO bands)

Evolution through helium burning

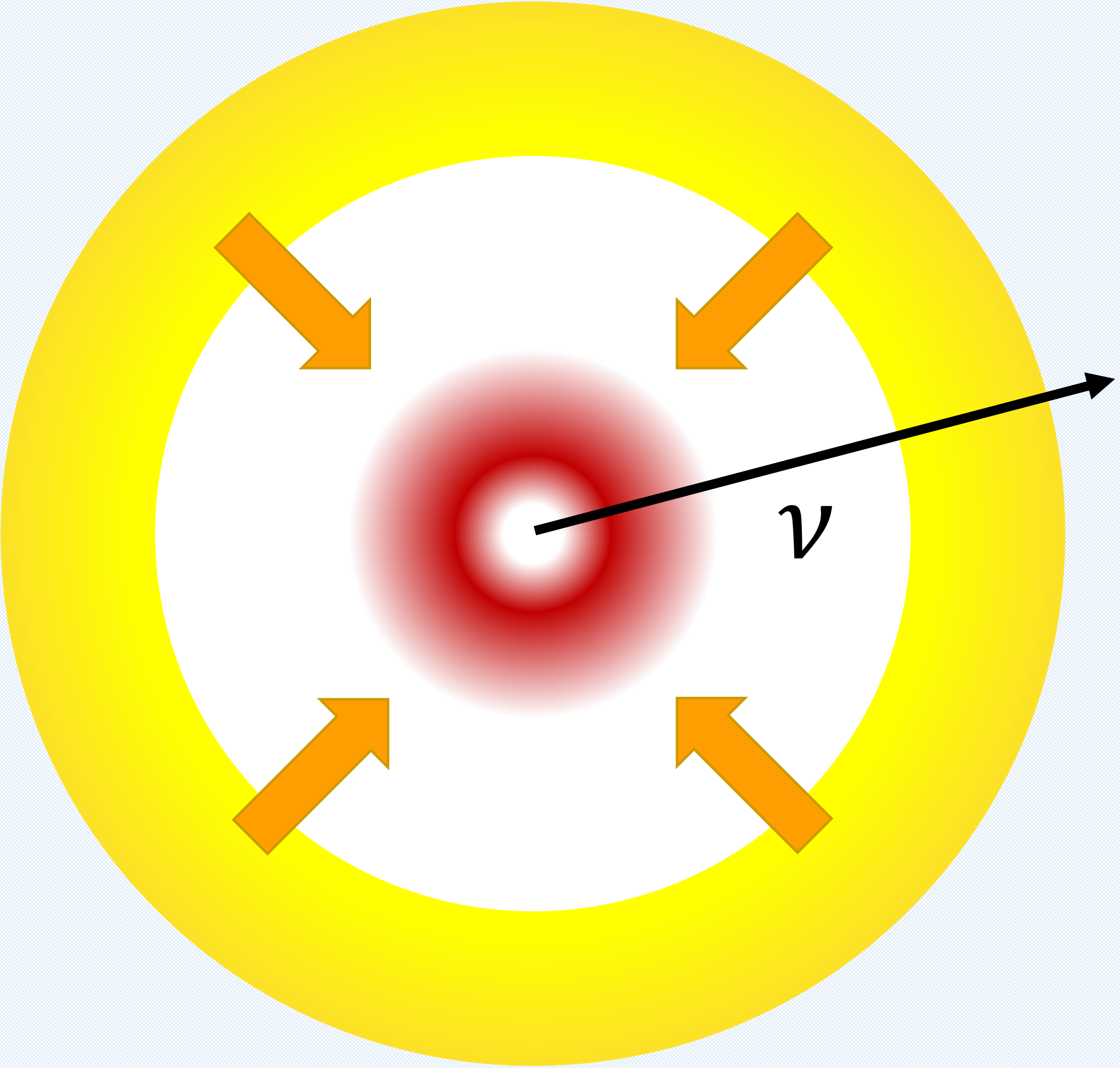


Temperature of the core increases

→ Increase of temperature in the H-burning shell

→ Core contraction heats transition layer between core and shell

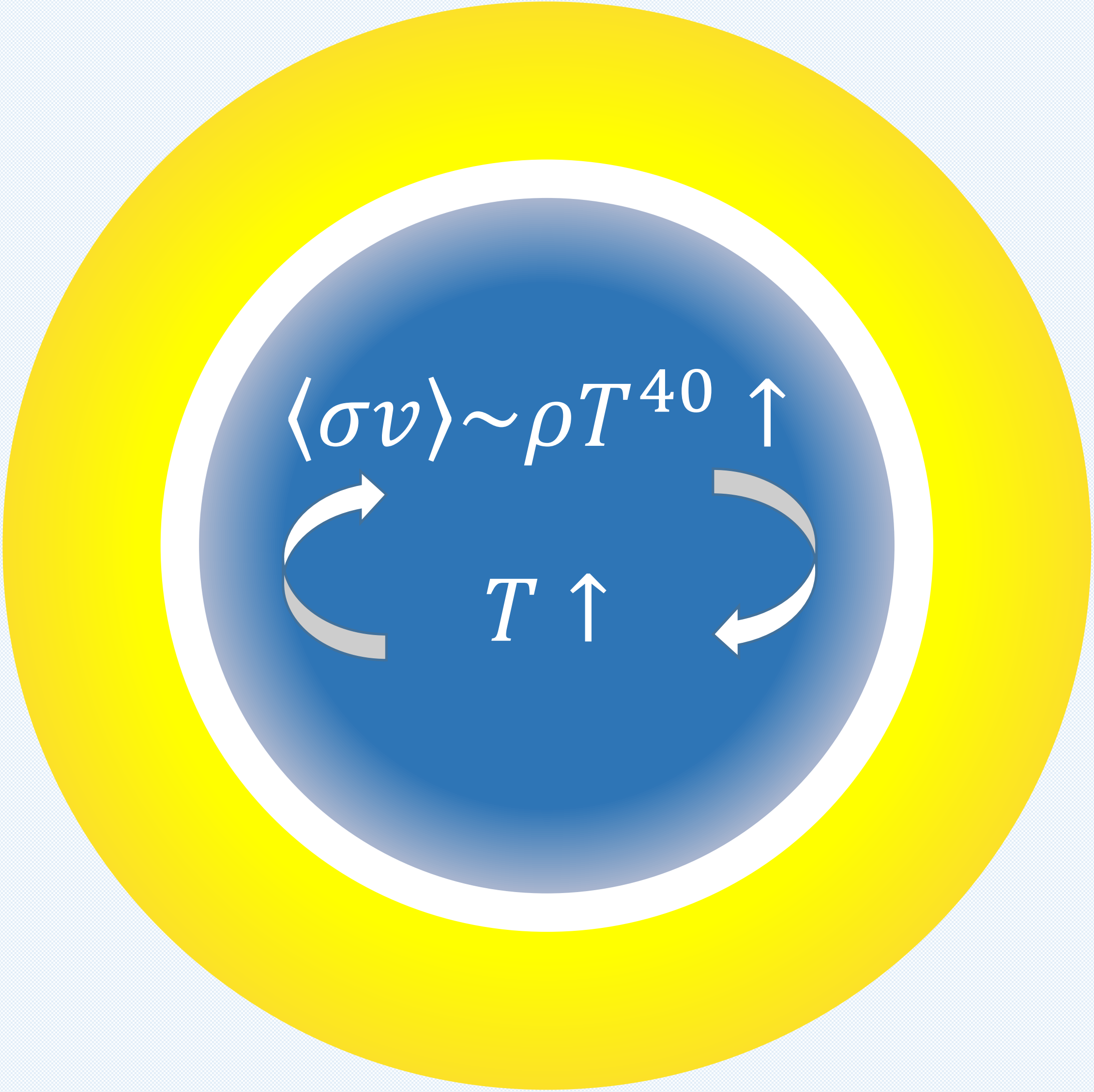
Evolution through helium burning



Critical temperature for helium burning ($\sim 10^8$ K) is reached for a **core mass of about** $0.48\ M_\odot$

Due to **energy losses via neutrinos** in the center, helium is ignited in a shell

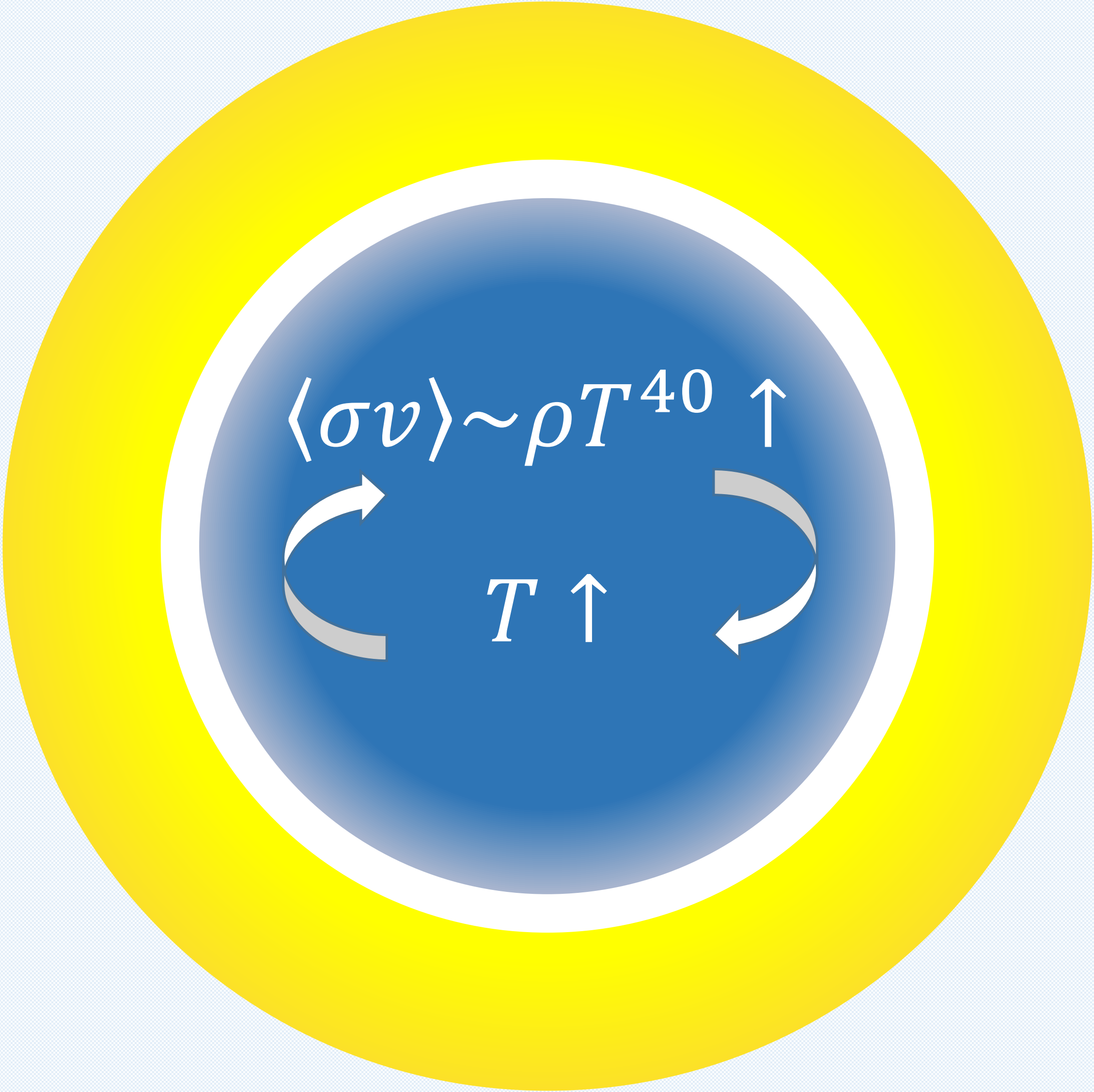
Evolution through helium burning



Due to the **high temperature dependency** of the 3α reaction rate $\langle\sigma v\rangle \sim \rho T^{40}$, nuclear energy is released fast and increases the core temperature

Degenerate gas cannot expand with increasing temperature

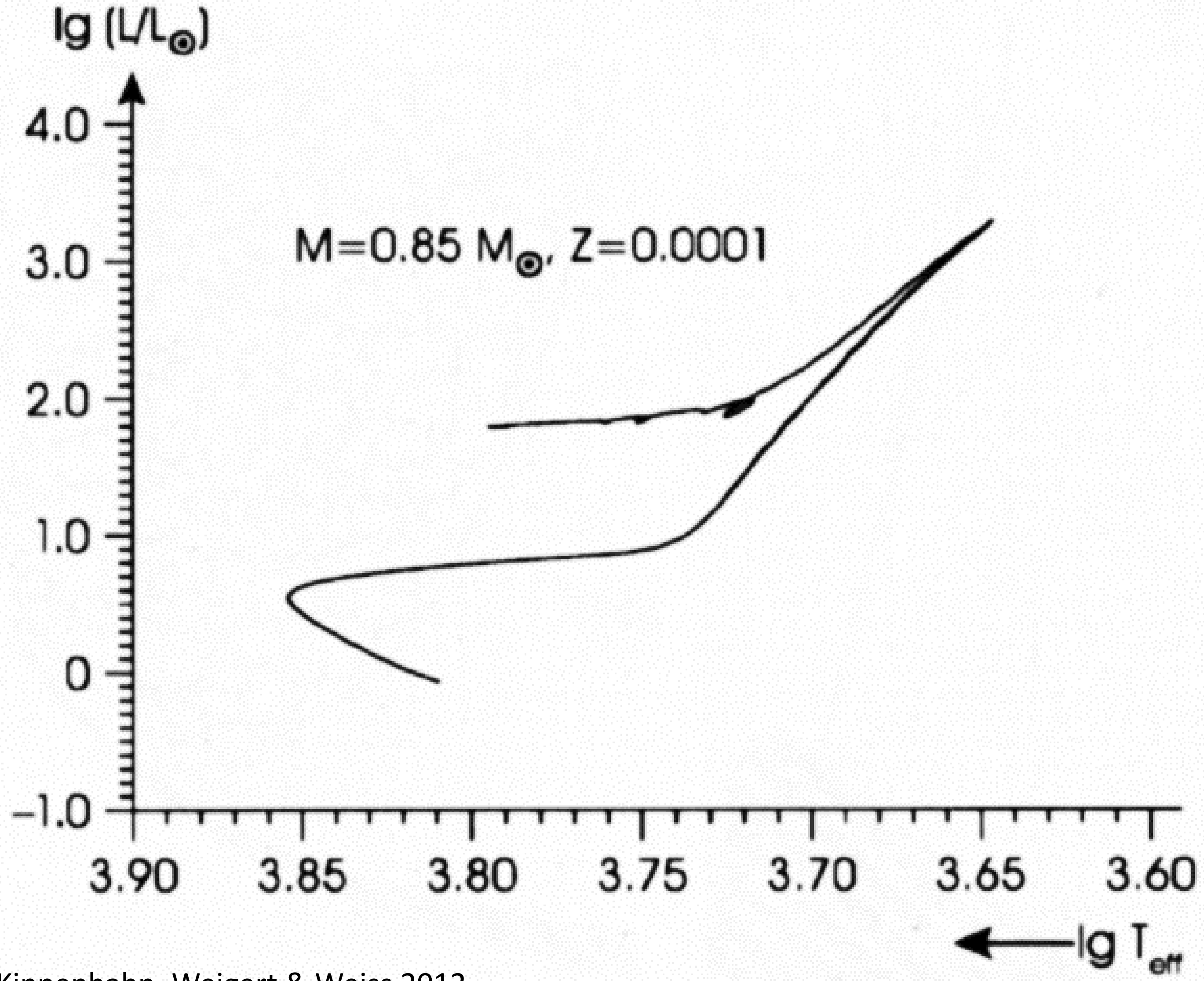
Evolution through helium burning



Runaway burning of helium

Helium flash

Evolution through helium burning



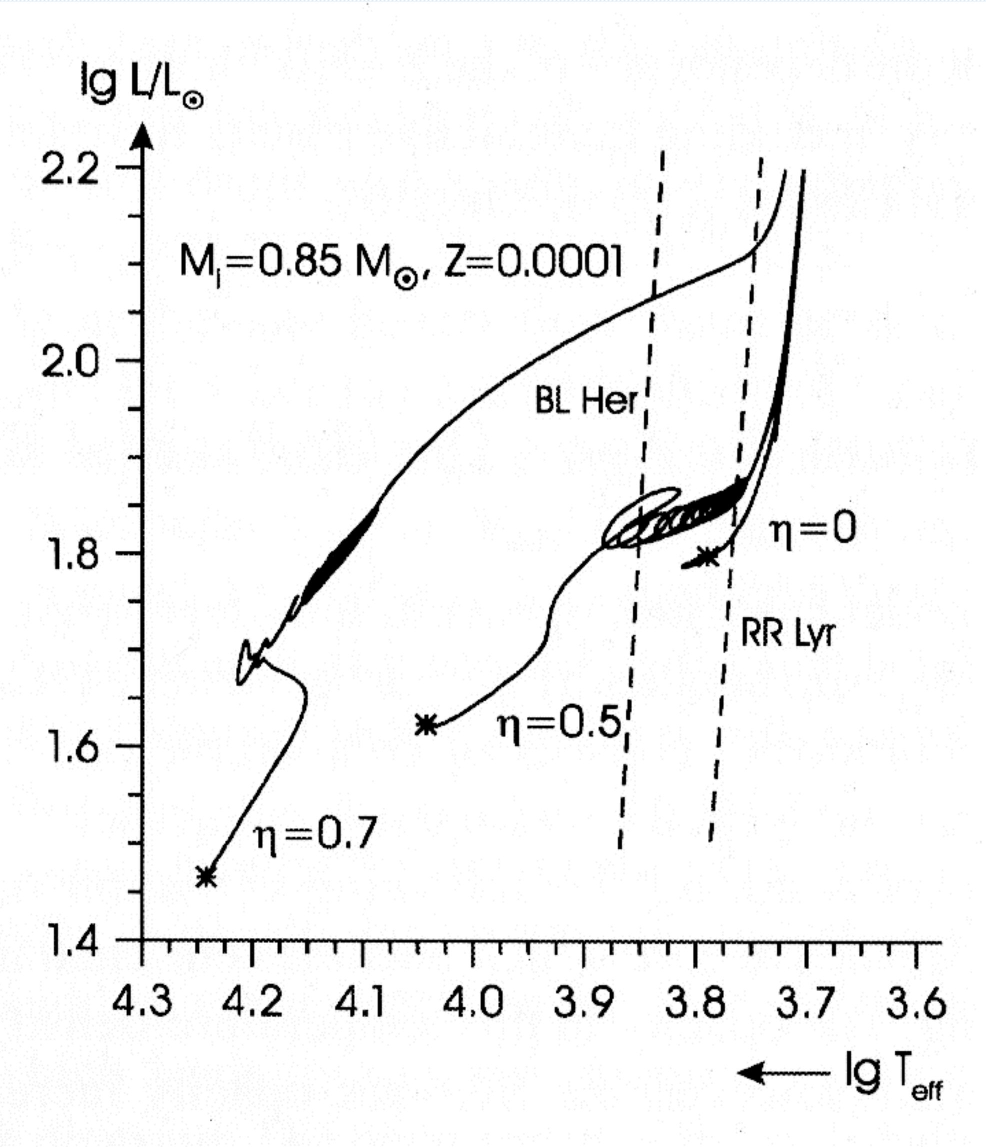
Kippenhahn, Weigert & Weiss 2012

Phase of **stable He-core** and H-shell burning

→ Stars occupy a region of (about) constant luminosity

Horizontal Branch

Evolution through helium burning



Kippenhahn, Weigert & Weiss 2012

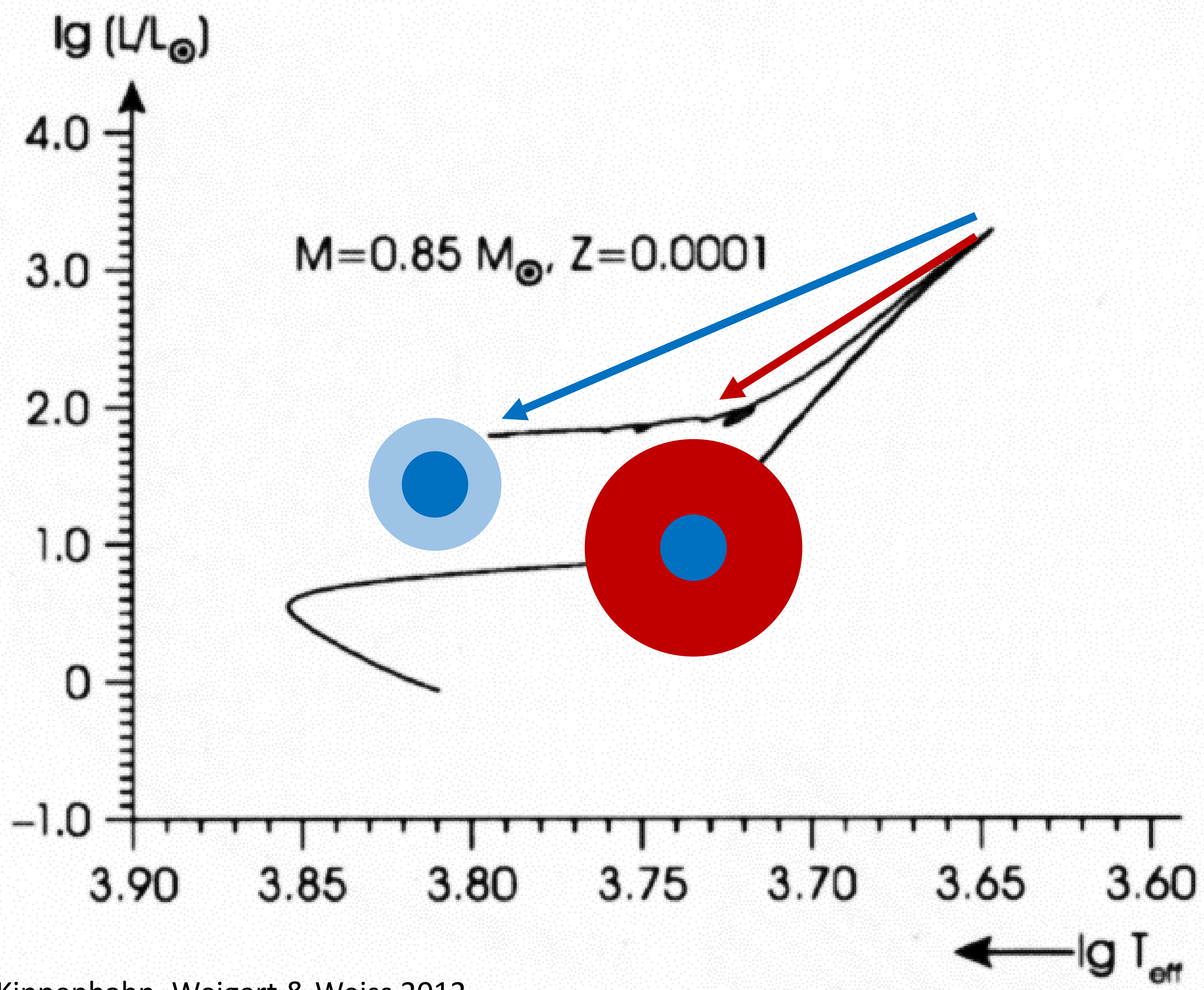
Horizontal Branch stars

→ Different mass loss η on the RGB leads to **different thickness of the hydrogen envelopes**

→ Mass of the He-core is constant $(\sim 0.48\ M_\odot)$

→ **Diverse types of HB stars**

Evolution through helium burning



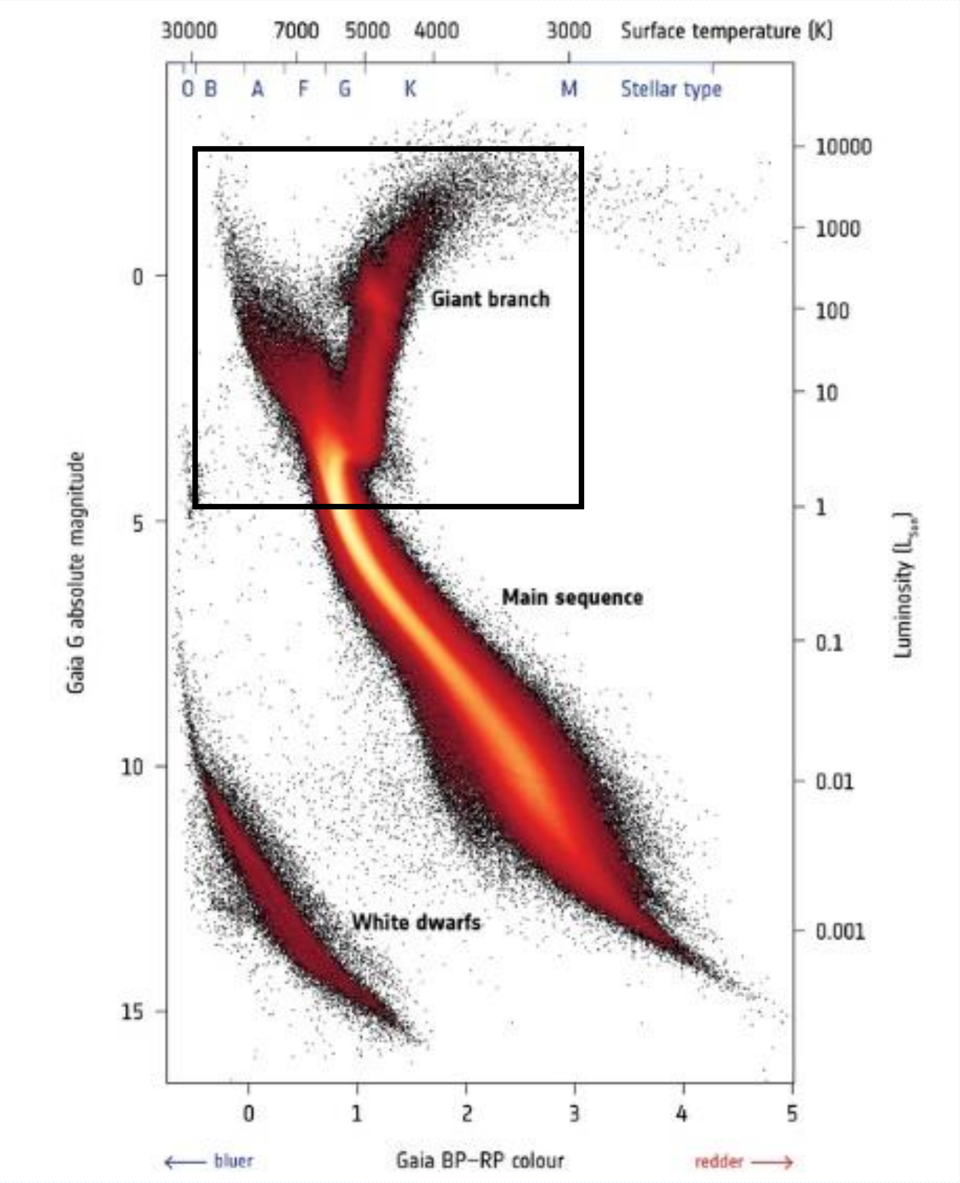
Kippenhahn, Weigert & Weiss 2012

Horizontal Branch stars

→ The thinner the hydrogen envelope, the bluer the HB star

→ Morphology of HB depends on metallicity and age

Evolution through helium burning



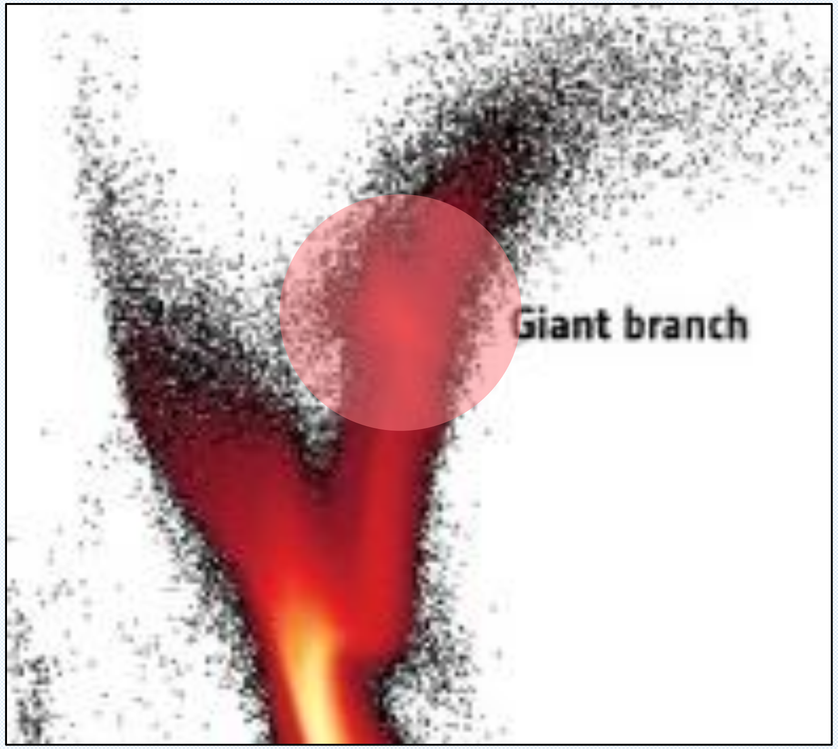
Gaia collaboration 2018, A&A, 616, 10

Red Clump stars

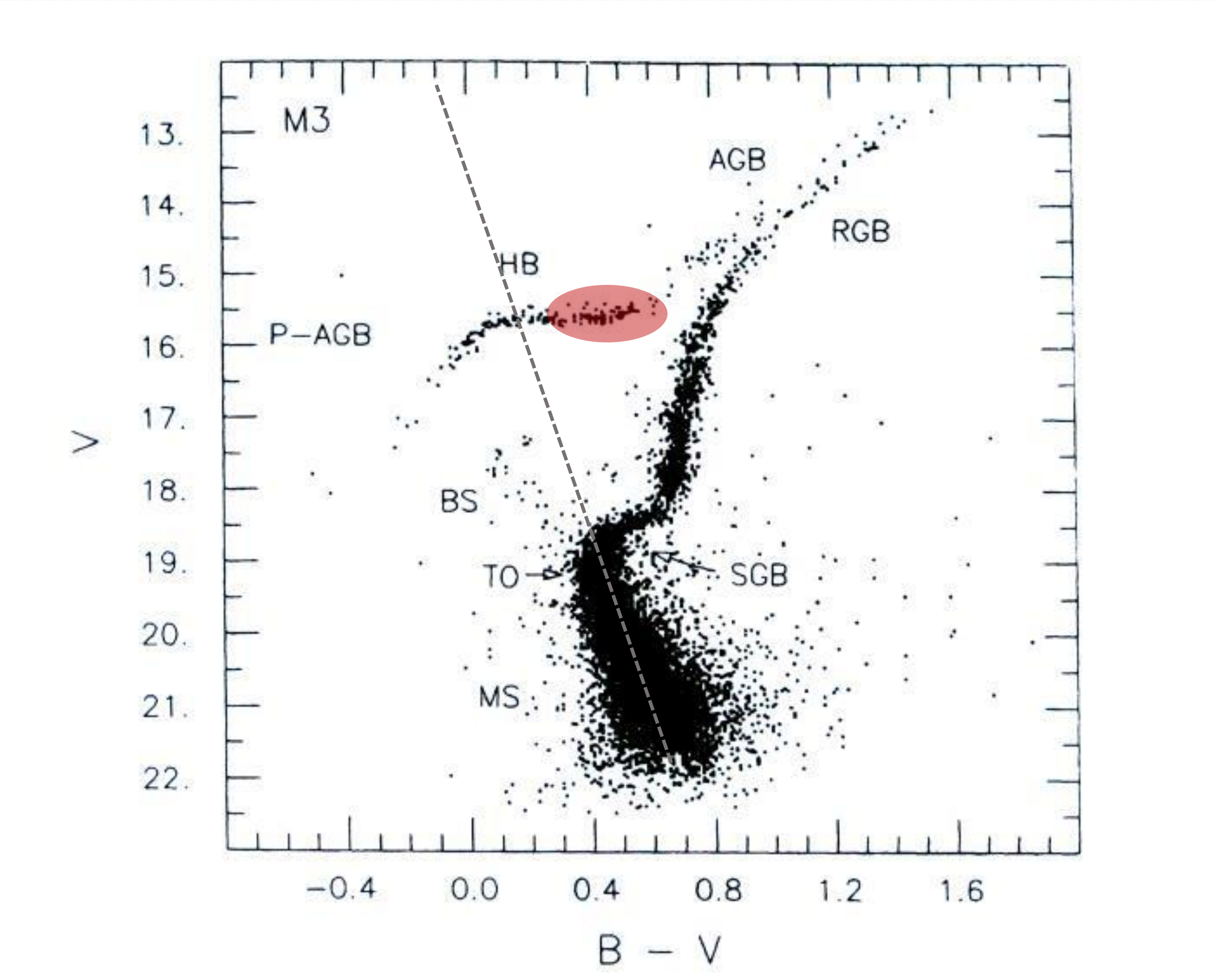
→ Red giants

→ Intermediate mass stars

→ Young population



Evolution through helium burning



Renzini & Fusi Pecci 1988, ARA&A, 26, 199

Red Horizontal Branch (RHB) stars

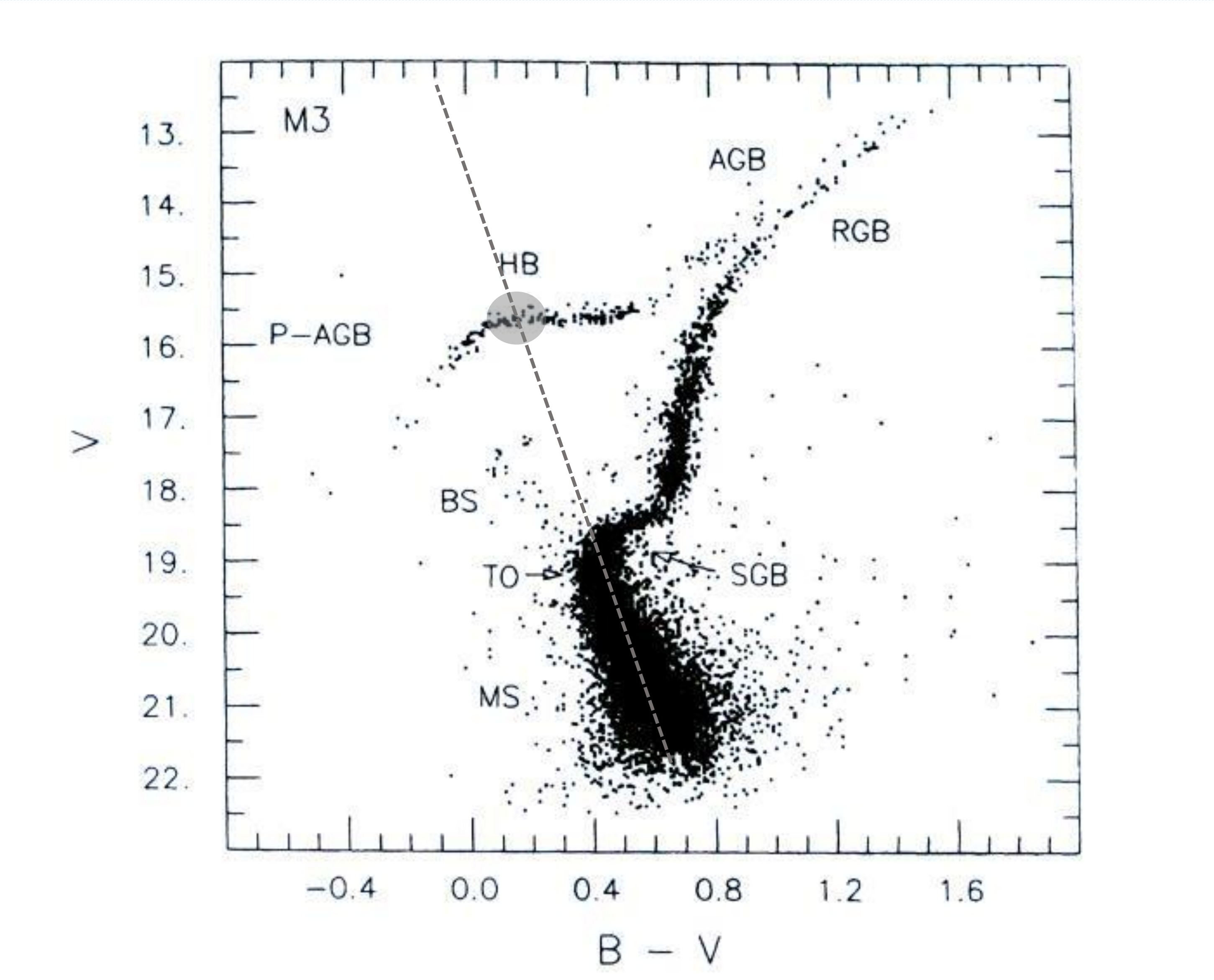
→ Redward of the MS

→ (Sub-)giants

→ Spectral types K, G

→ metal-poor, old population

Evolution through helium burning



Renzini & Fusi Pecci 1988, ARA&A, 26, 199

RR Lyr stars

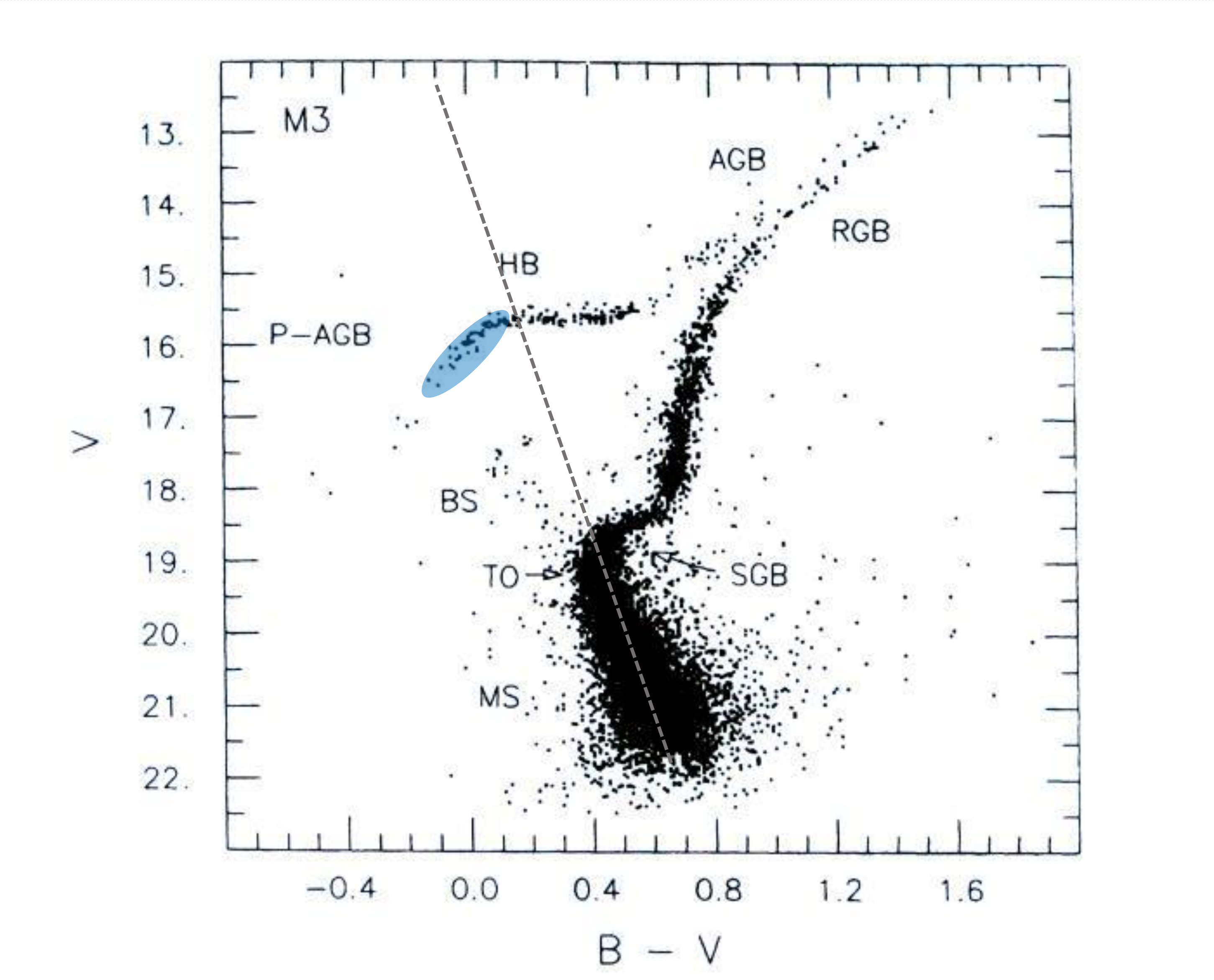
→ (Sub-)giants

→ Spectral types F

→ metal-poor, old population

→ Pulsators

Evolution through helium burning



Renzini & Fusi Pecci 1988, ARA&A, 26, 199

Blue Horizontal Branch (BHB) stars

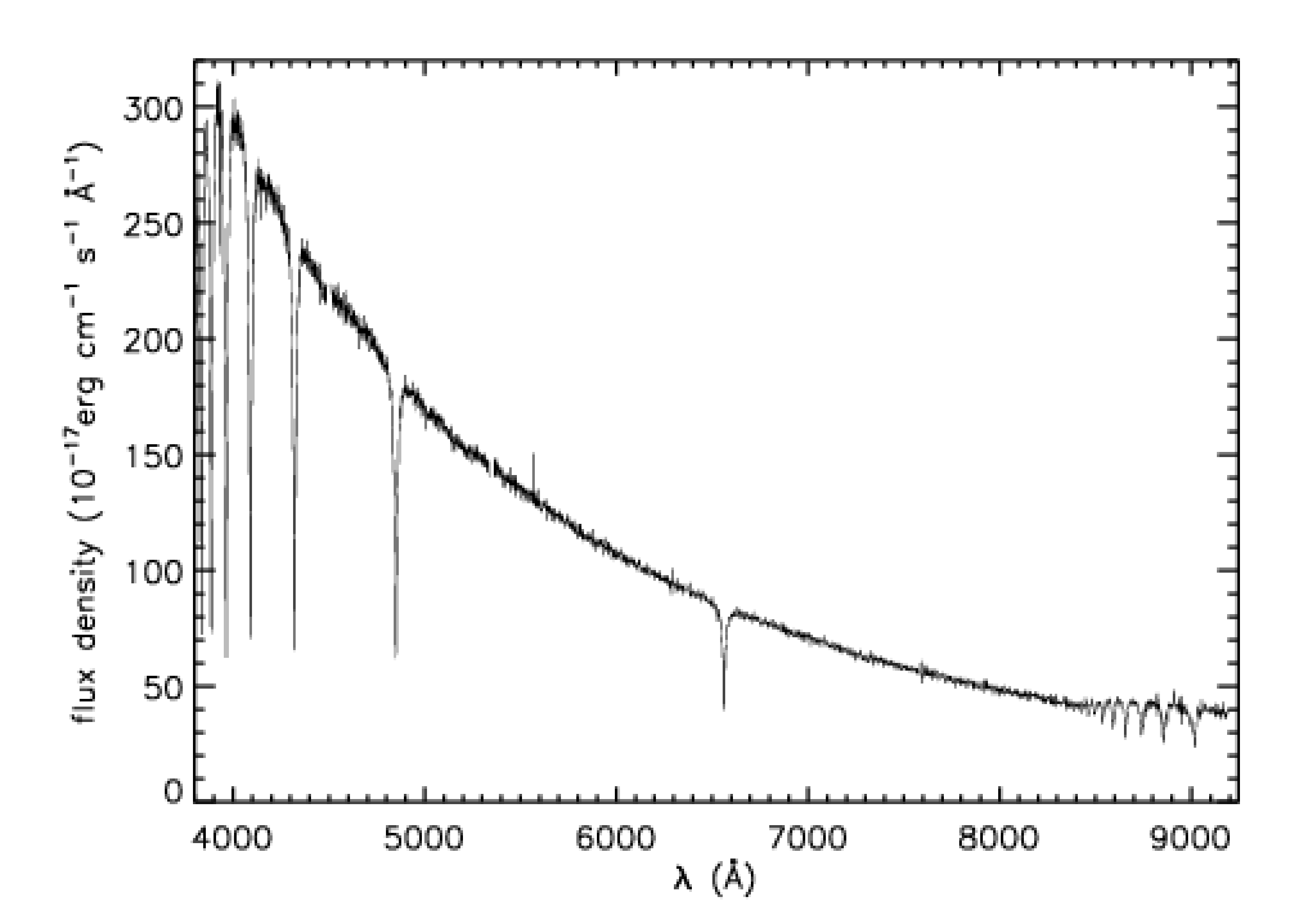
→ Blueward of the MS

→ (Sub-)dwarfs

→ Spectral types A, B (HBA, HBB)

→ chemically peculiar

Evolution through helium burning



Xue et al. 2008, ApJ, 684, 1143

Blue Horizontal Branch (BHB) stars

→ low helium content

HBB > 11500 K

→ Light elements depleted, heavy elements enriched

→ Slow rotation

Binary populations

Statistical models can be used to determine the true binary fractions

Selection effects have to be taken into account

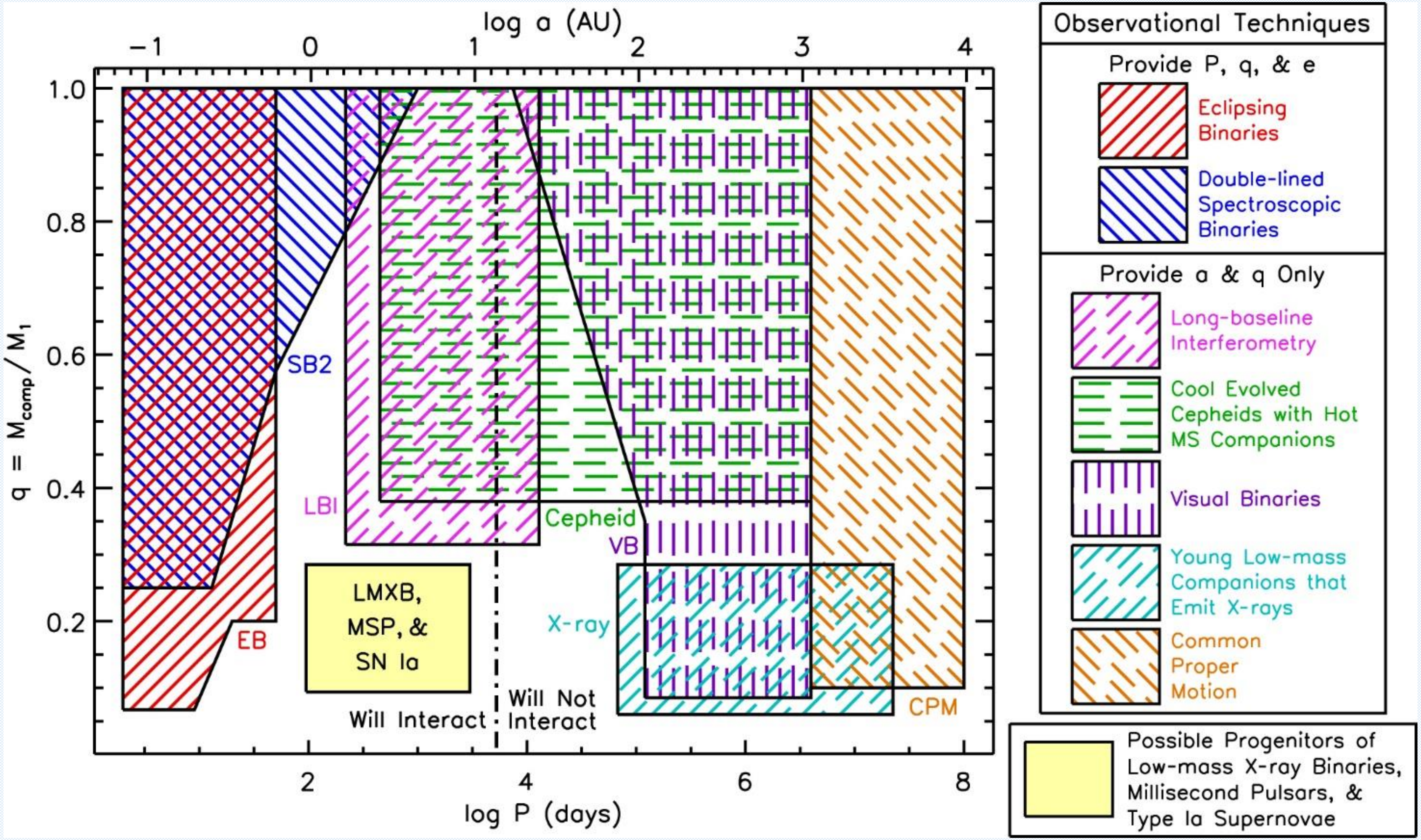
→ Sample selection (e.g. area-, magnitude-, volume-limited)

→ Sensitivity biases (e.g. long periods for visual binaries, short period for photometric/spectroscopic binaries)

→ Projection effects on the celestial sphere

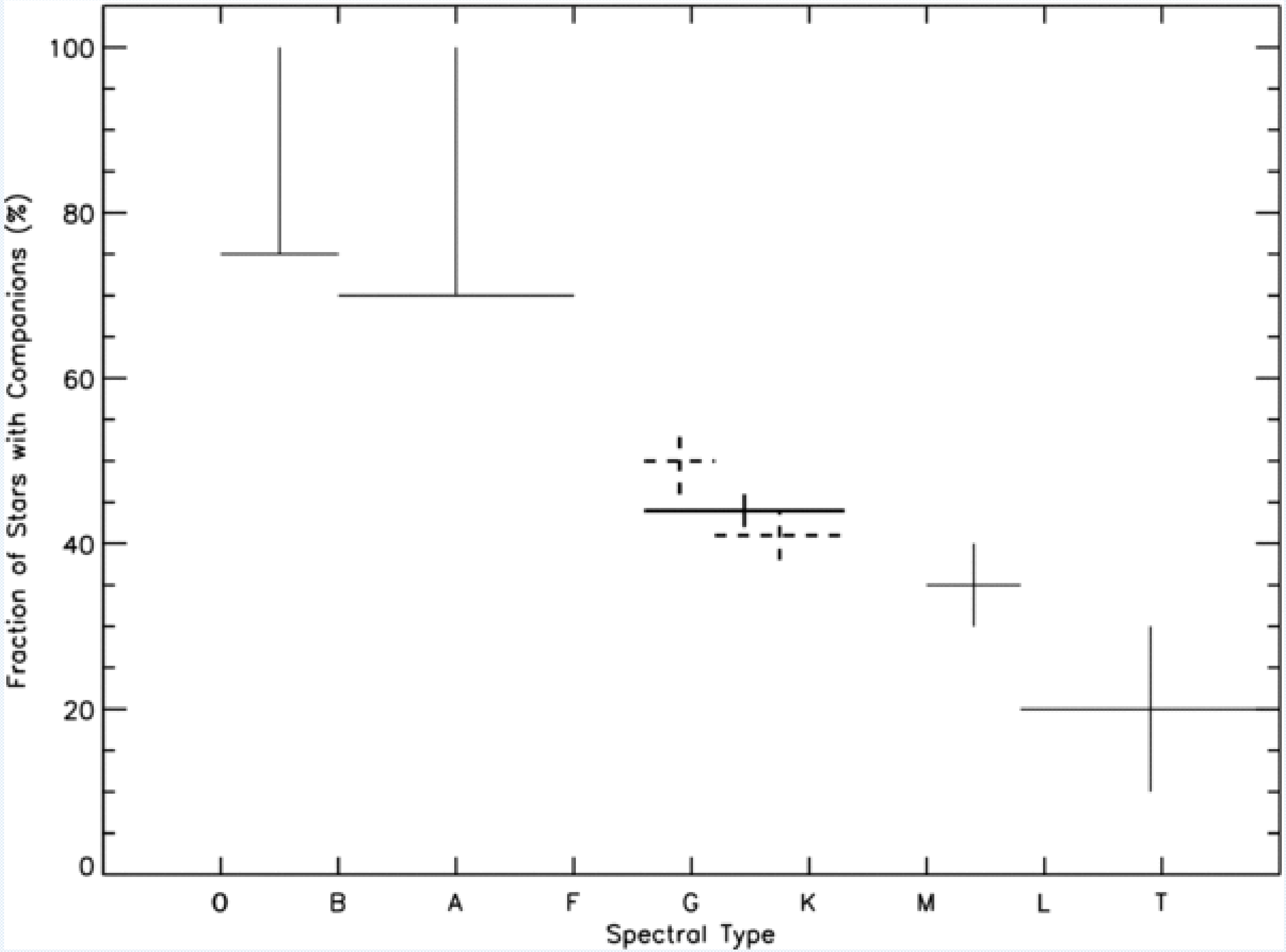
→ Contamination by different kinds of objects (e.g. pulsators, flare stars)

Binary populations



Moe & di Stefano 2017, ApJS, 230, 2

Binary populations



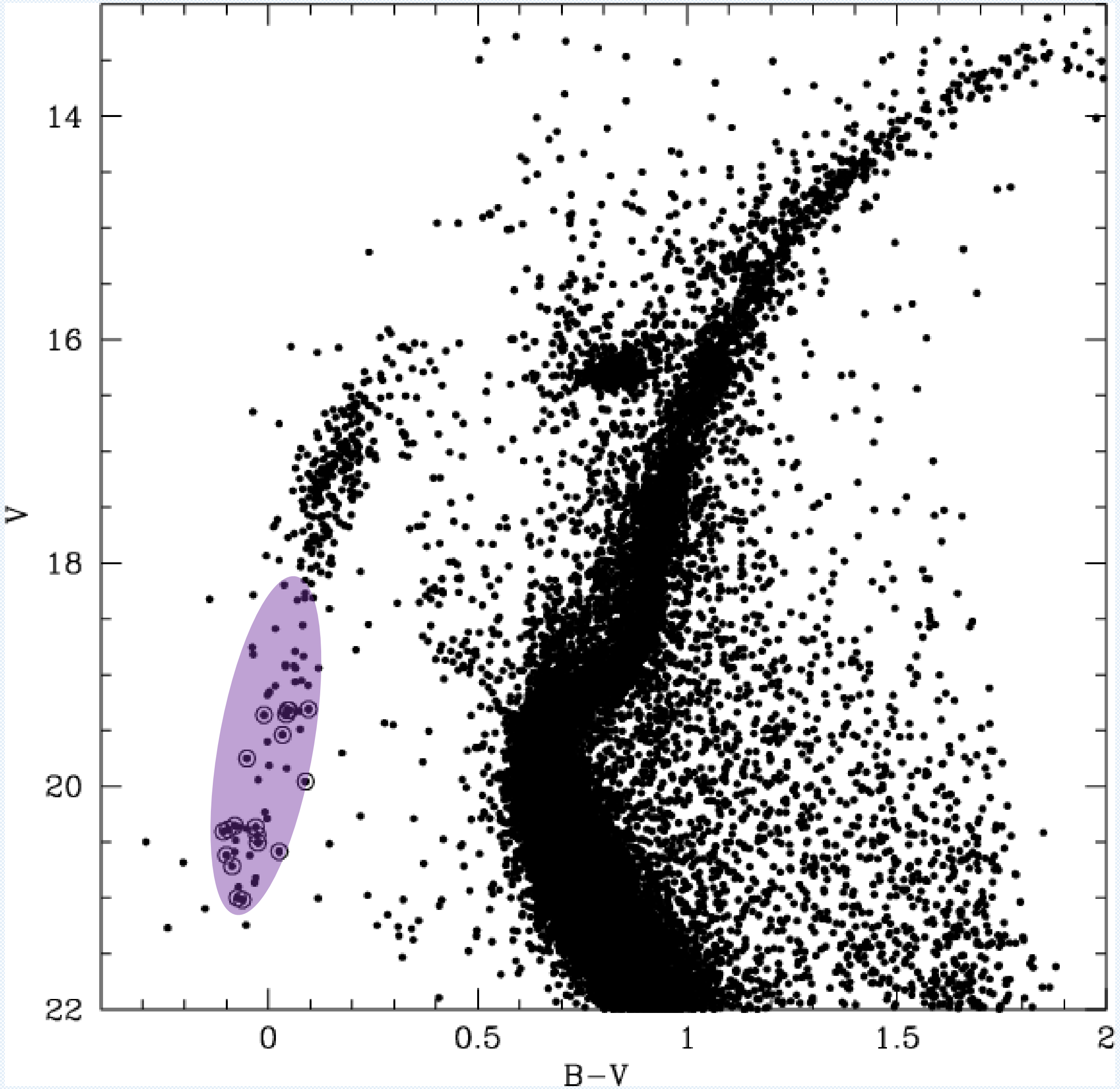
Raghavan et al. 2010, ApJS, 190, 1

Binary fraction on the main sequence depends on stellar mass

$\sim$10 % triple

$\sim$1 % quadruple or higher multiple systems

Binary populations



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

Extreme Horizontal Branch (EHB) stars

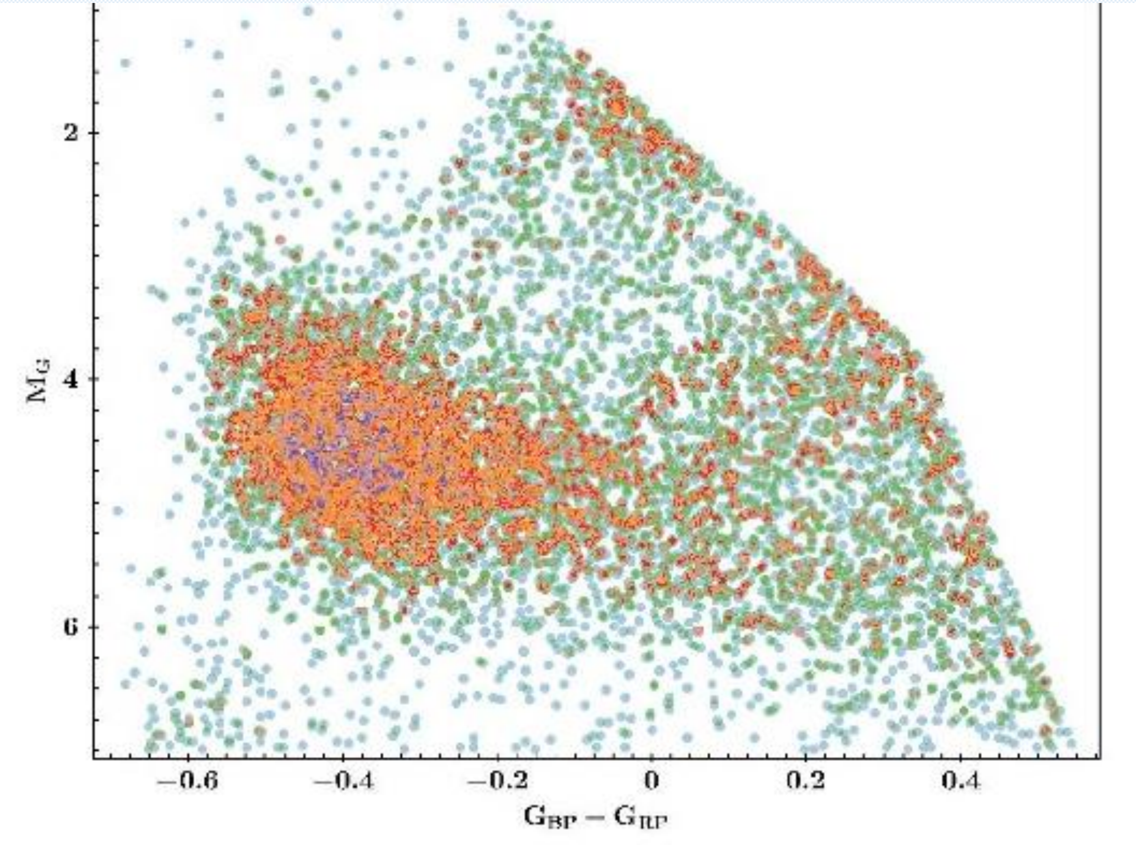
→ Hot subdwarfs

→ Spectral types O, B (sdO, sdB)

→ Extremely thin hydrogen envelopes, no H-shell burning

→ **Not formed in standard stellar evolution**

Binary populations



Geier et al. 2019, A&A, 621, 38

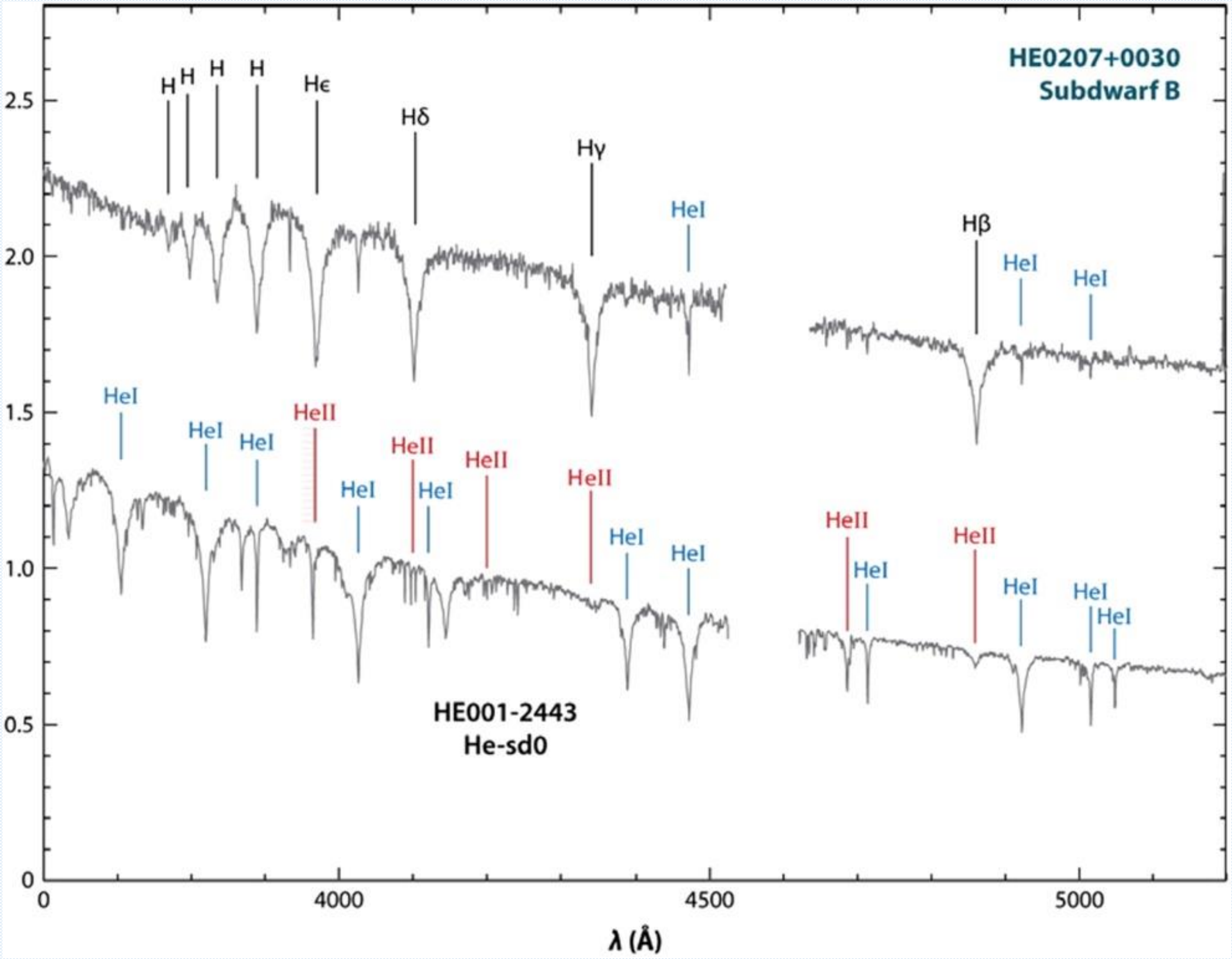
Extreme Horizontal Branch (EHB) stars

→ About 6000 are known

→ 40000 candidates have been found

→ Present in all Galactic populations

Binary populations



Heber 2016, PASP, 128, 966

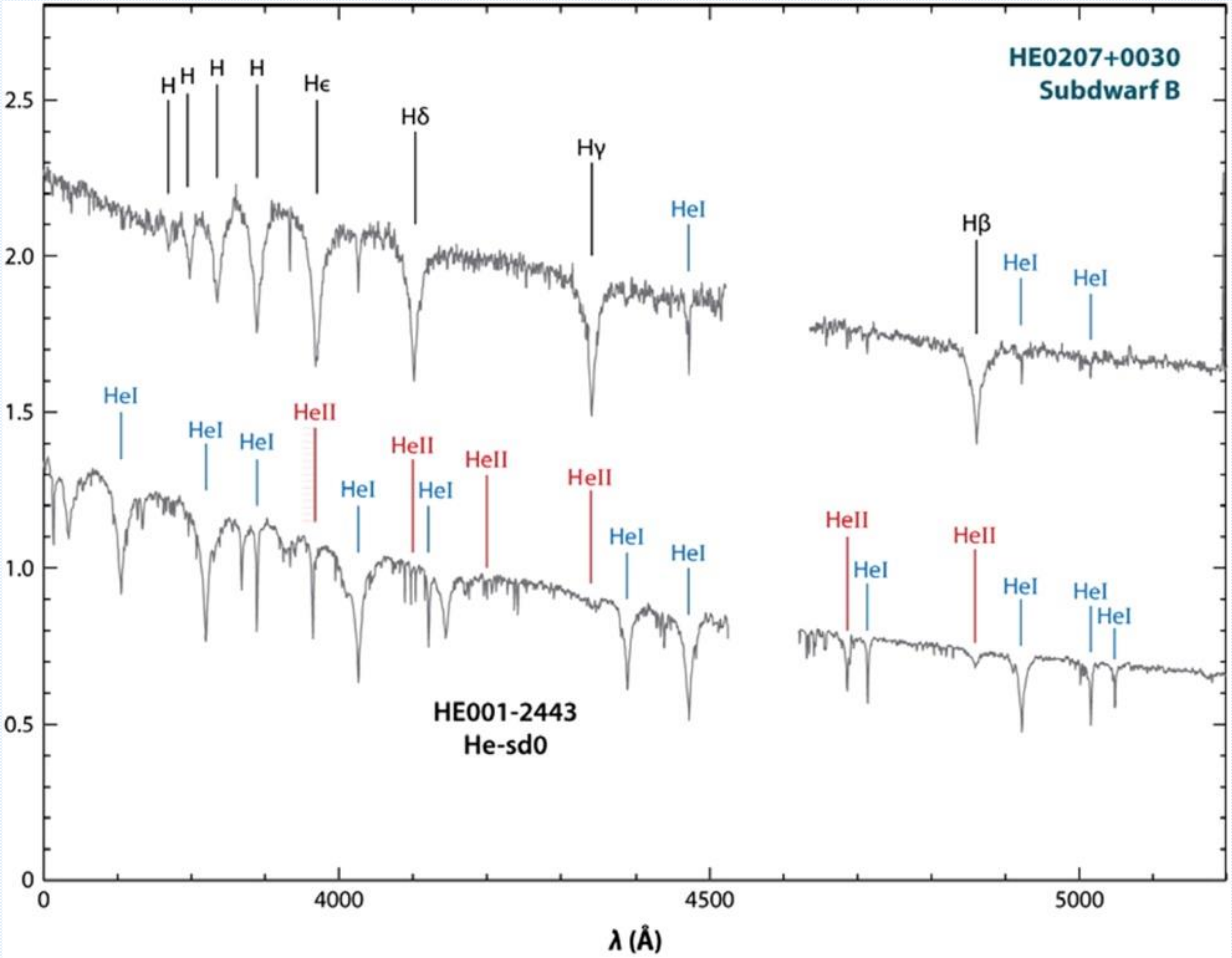
Hydrogen-rich sdBs

→ very low to solar helium content

→ Light elements depleted, heavy elements enriched

→ **High binary fraction**

Binary populations



Heber 2016, PASP, 128, 966

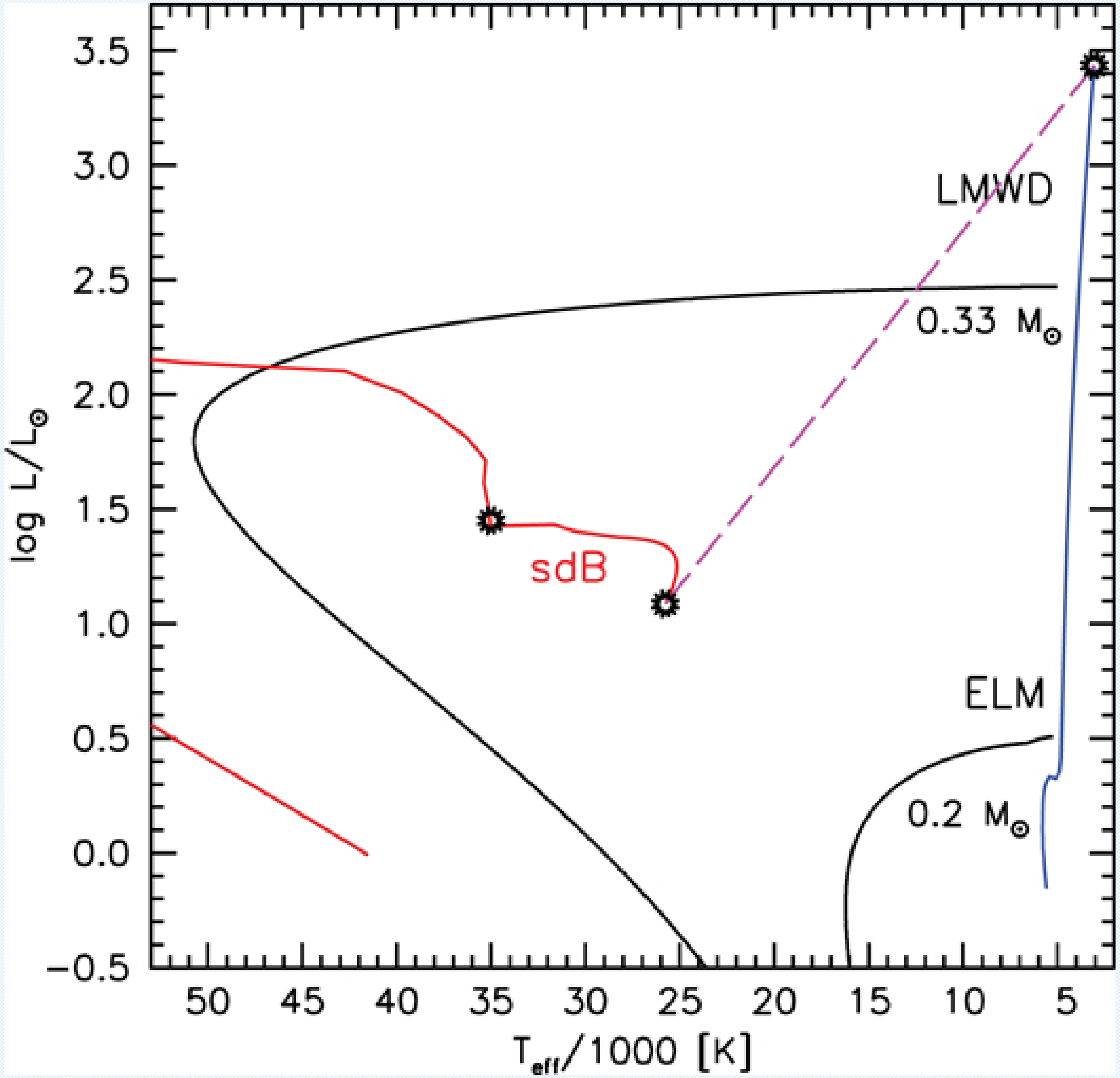
Helium-rich sdO/Bs

→ very high helium abundance

→ Enrichment in carbon and/or nitrogen

→ **Single stars**

Binary populations



Heber 2016, PASP, 128, 966

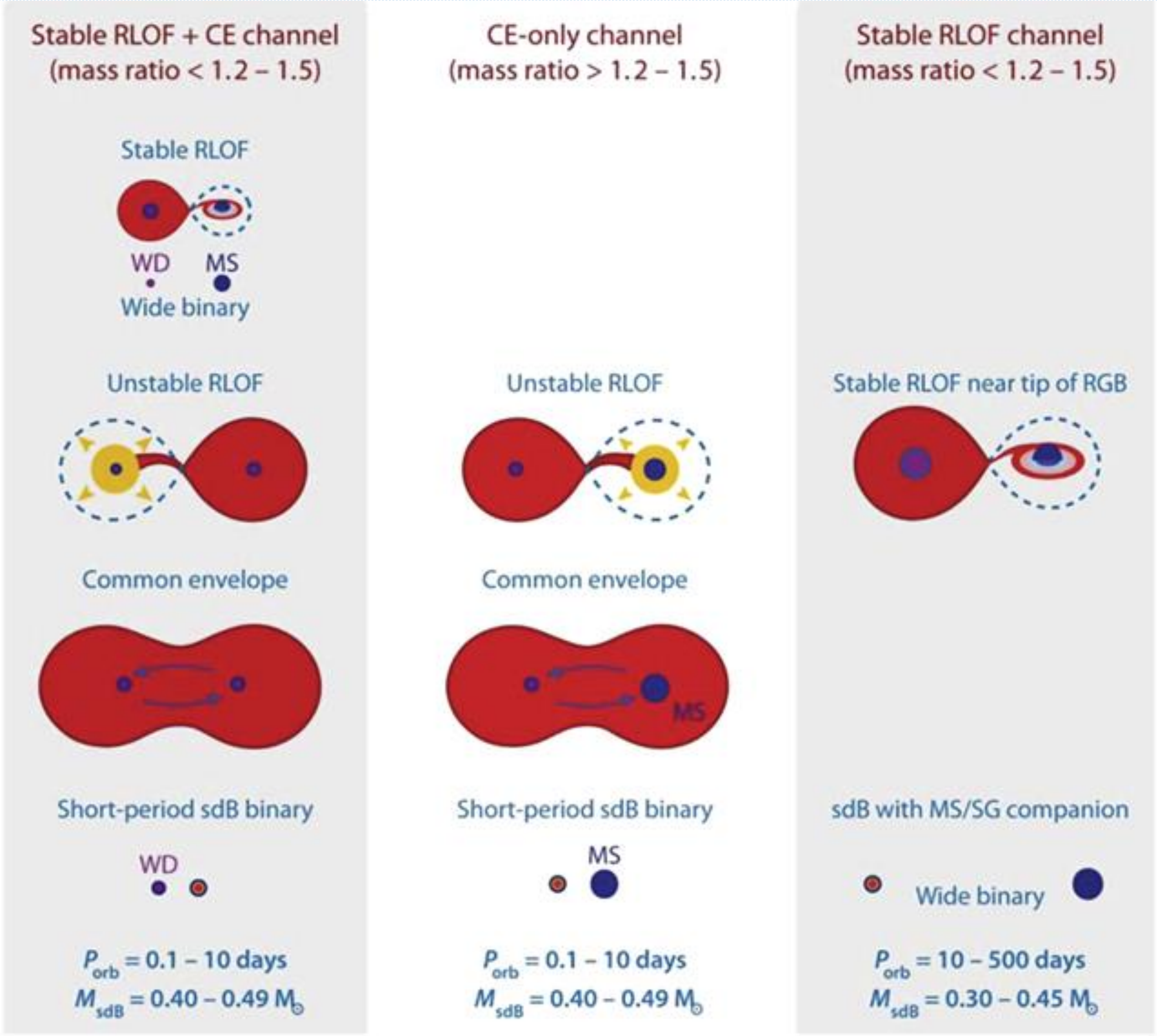
→ Envelope stripping of a low-mass star at the tip of the RGB

→ **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

Binary populations



Heber 2016, PASP, 128, 966

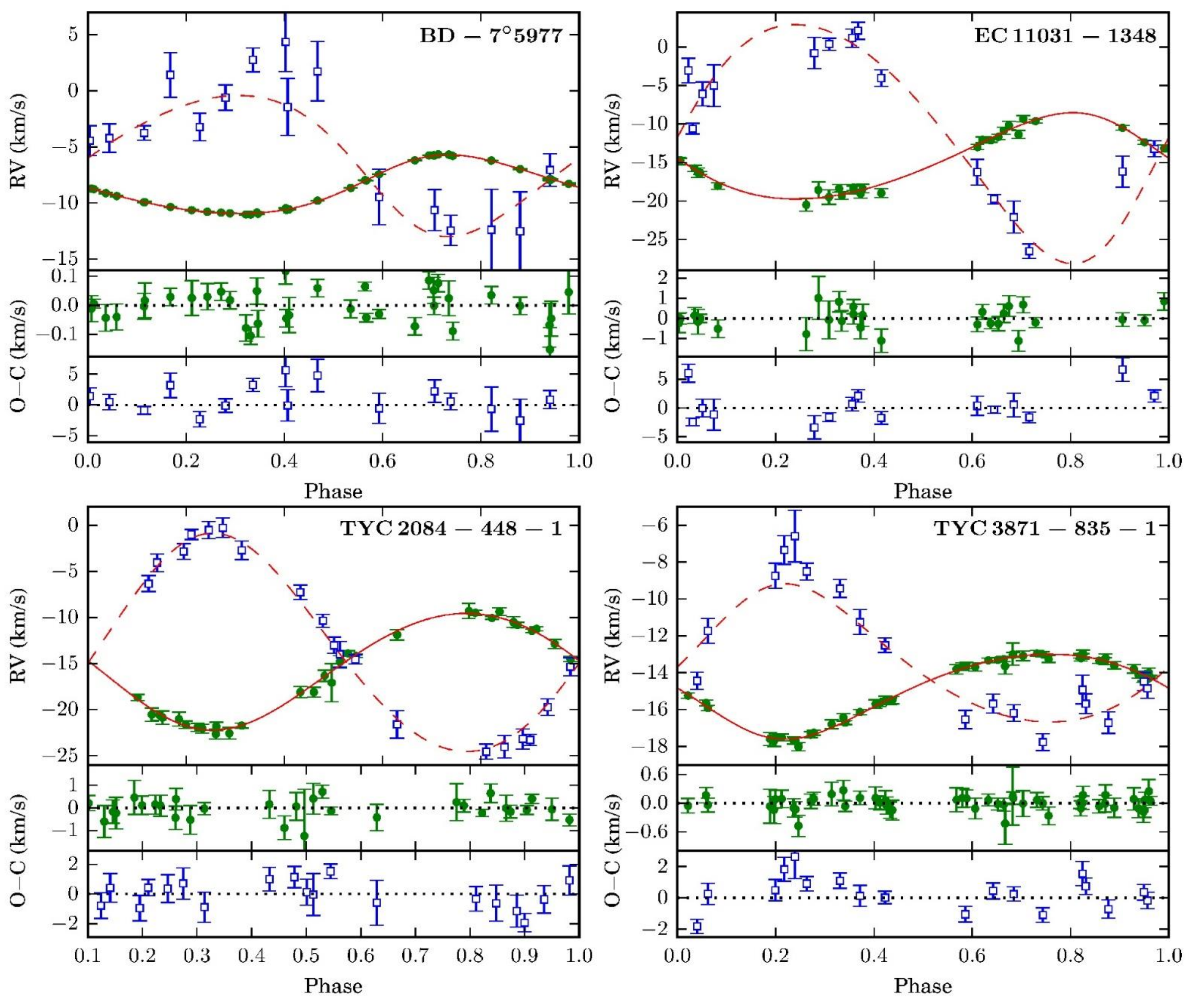
Close binary evolution

→ 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

Binary populations



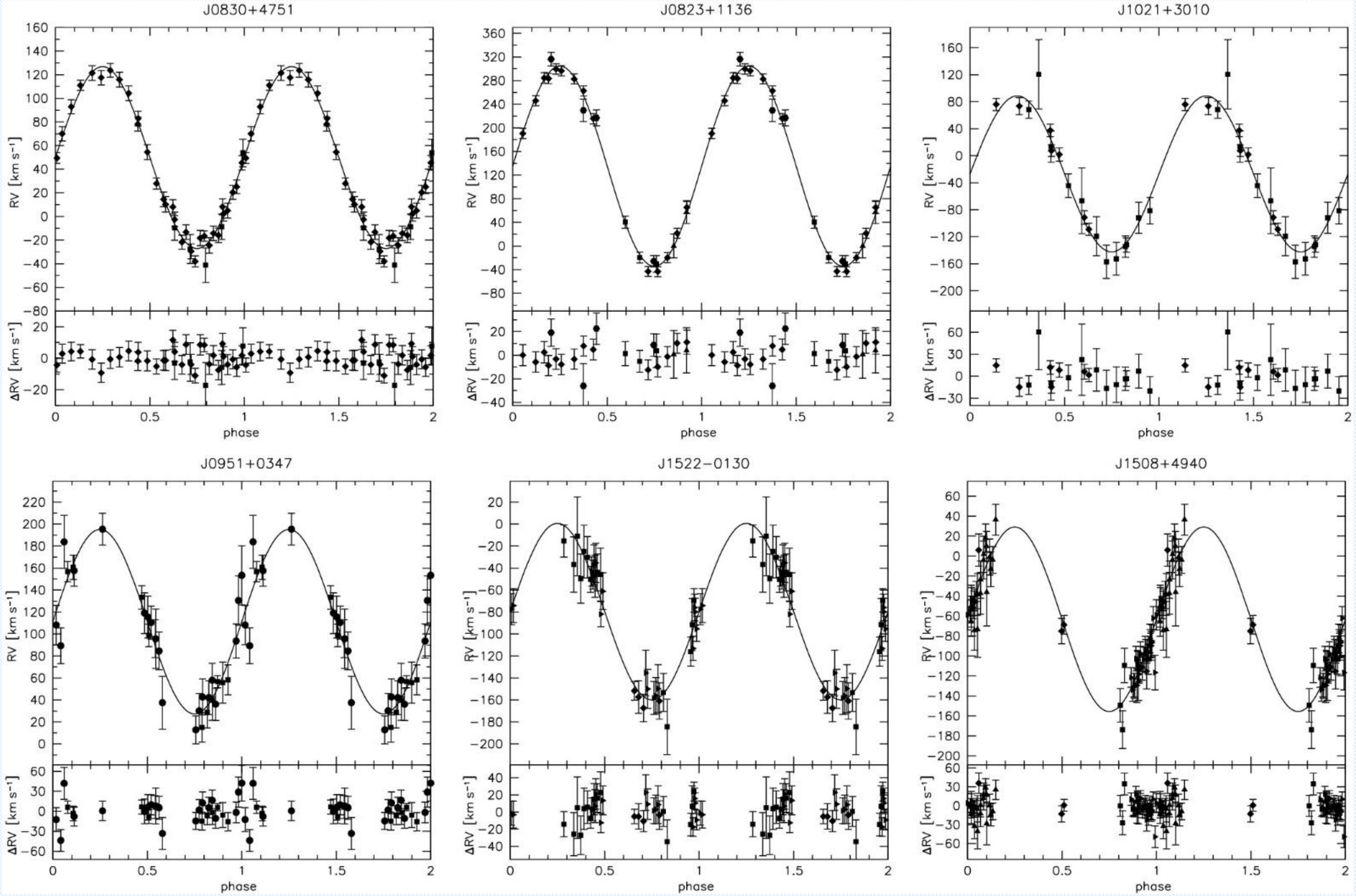
Vos et al. 2017, A&A, 605, 109

$\sim 30\%$ 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 ($P = 300 - 1200$ d) are in the appropriate range for prior RLOF mass-transfer

Binary populations



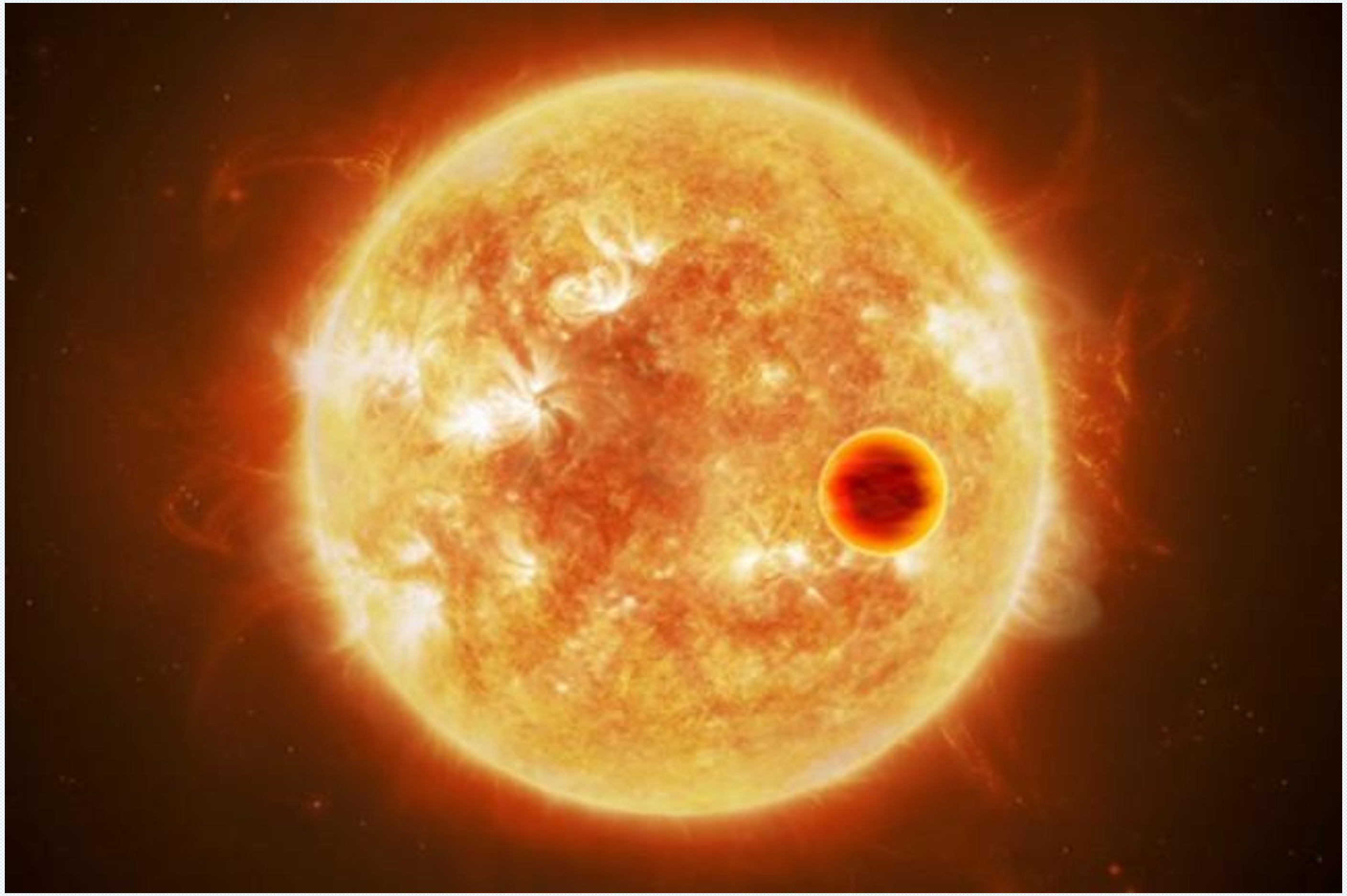
Kupfer et al. 2015, A&A, 576, 44

$\sim 30\%$ 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

Binary populations



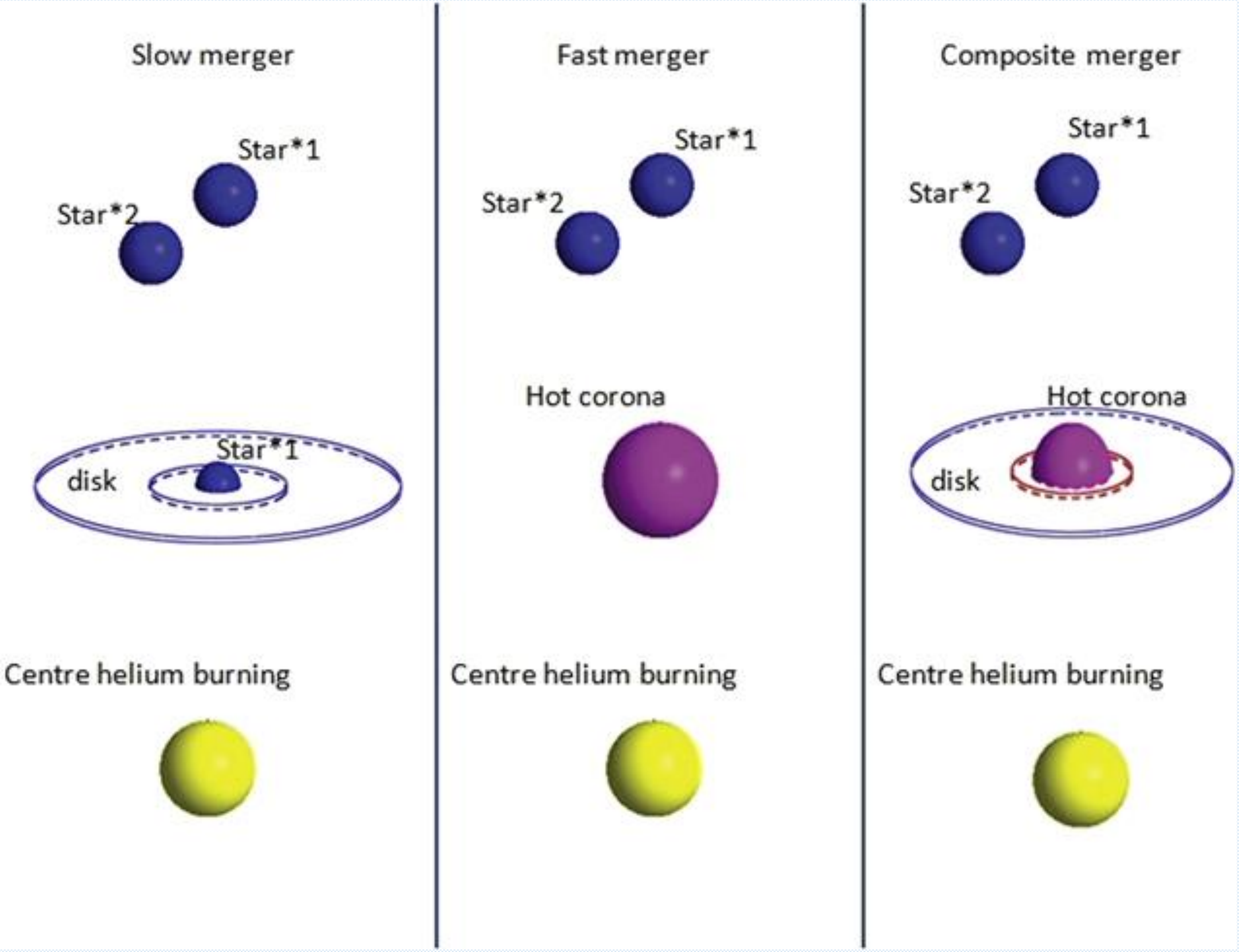
ESA/ATG medialab

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

$\rightarrow$ Close substellar companions such as brown dwarfs or planets

$\rightarrow$ Evaporation or merger during CE evolution?

Binary populations

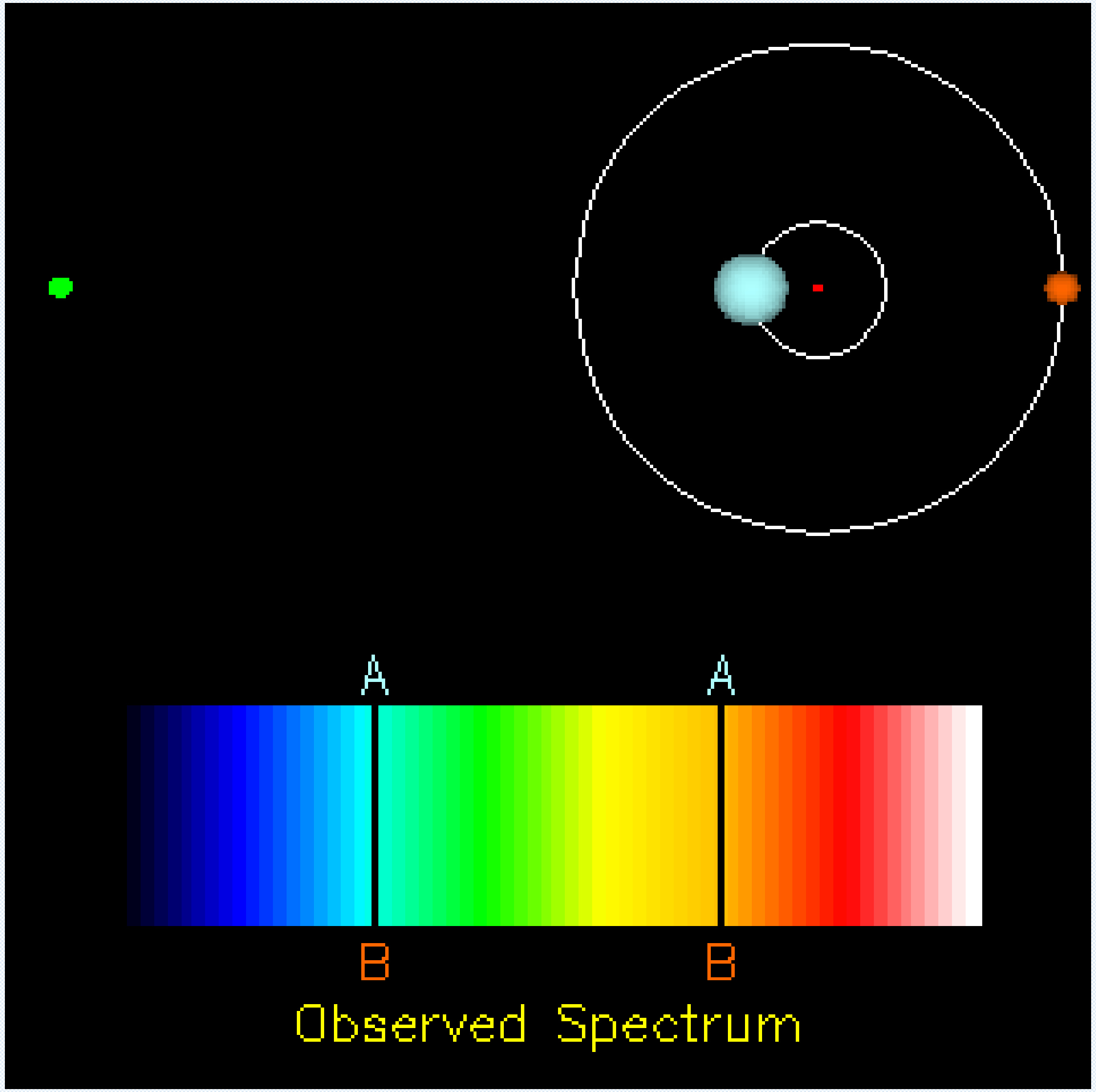


Zhang & Jeffery 2012, MNRAS, 419, 452

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

→ Single He-sdO/B stars

Spectroscopic binaries



Youtube, Pogge, Ohio State University

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

→ Doppler effect

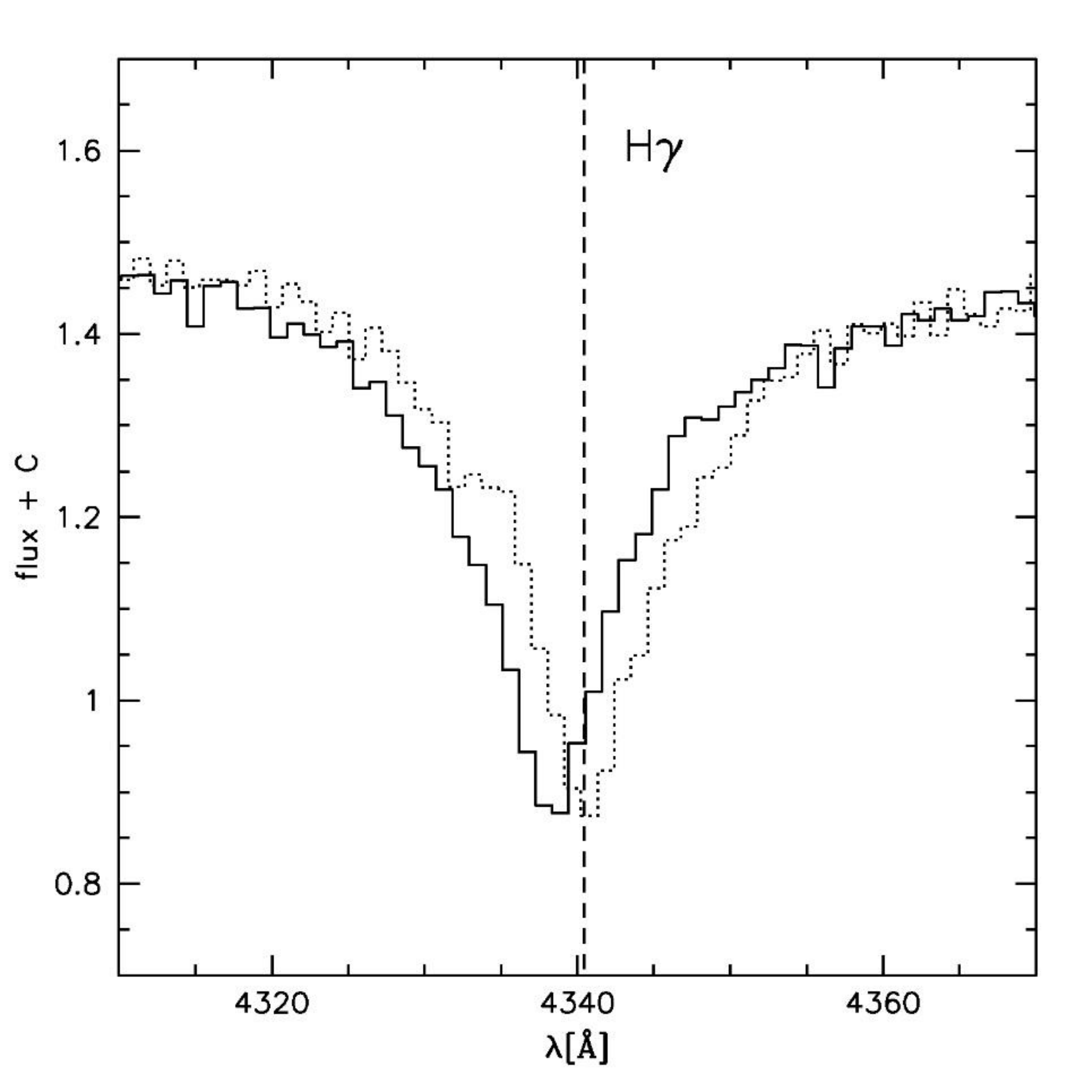
$$\frac{\lambda-\lambda_0}{\lambda_0} = \frac{\Delta\lambda}{\lambda_0} = \frac{v}{c} \quad \text{for } v \ll c$$

λ **observed wavelength**

λ_0 **rest wavelength**

v **radial velocity**

Spectroscopic binaries

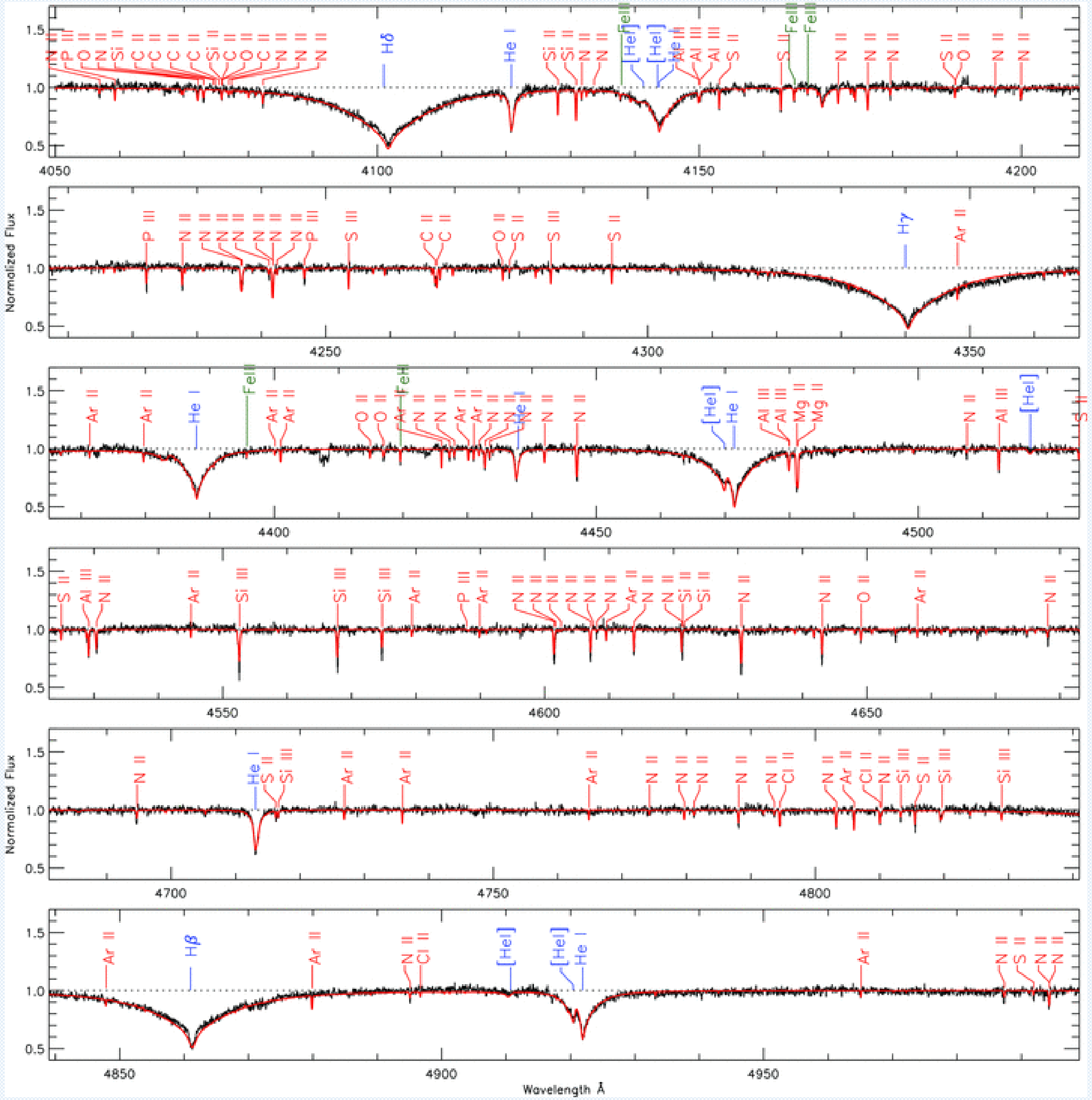


S. Geier

Measuring line-shift

→ **Radial velocity**

Spectroscopic binaries



Naslim et al. 2012, MNRAS, 423, 3031

Model fitting

→ Simple models matching the line shapes (Gaussian, Voigt profiles)

→ Model spectra

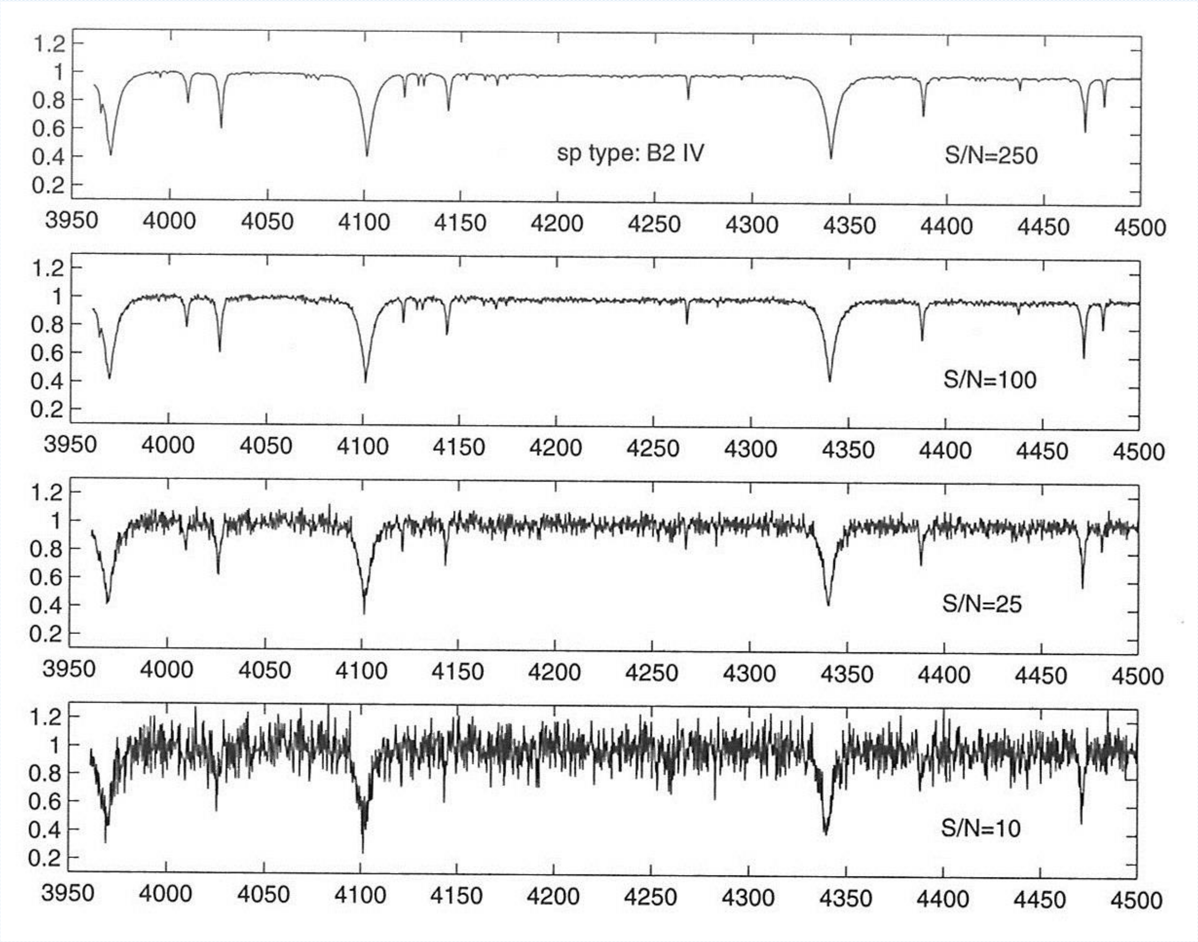
Requirements

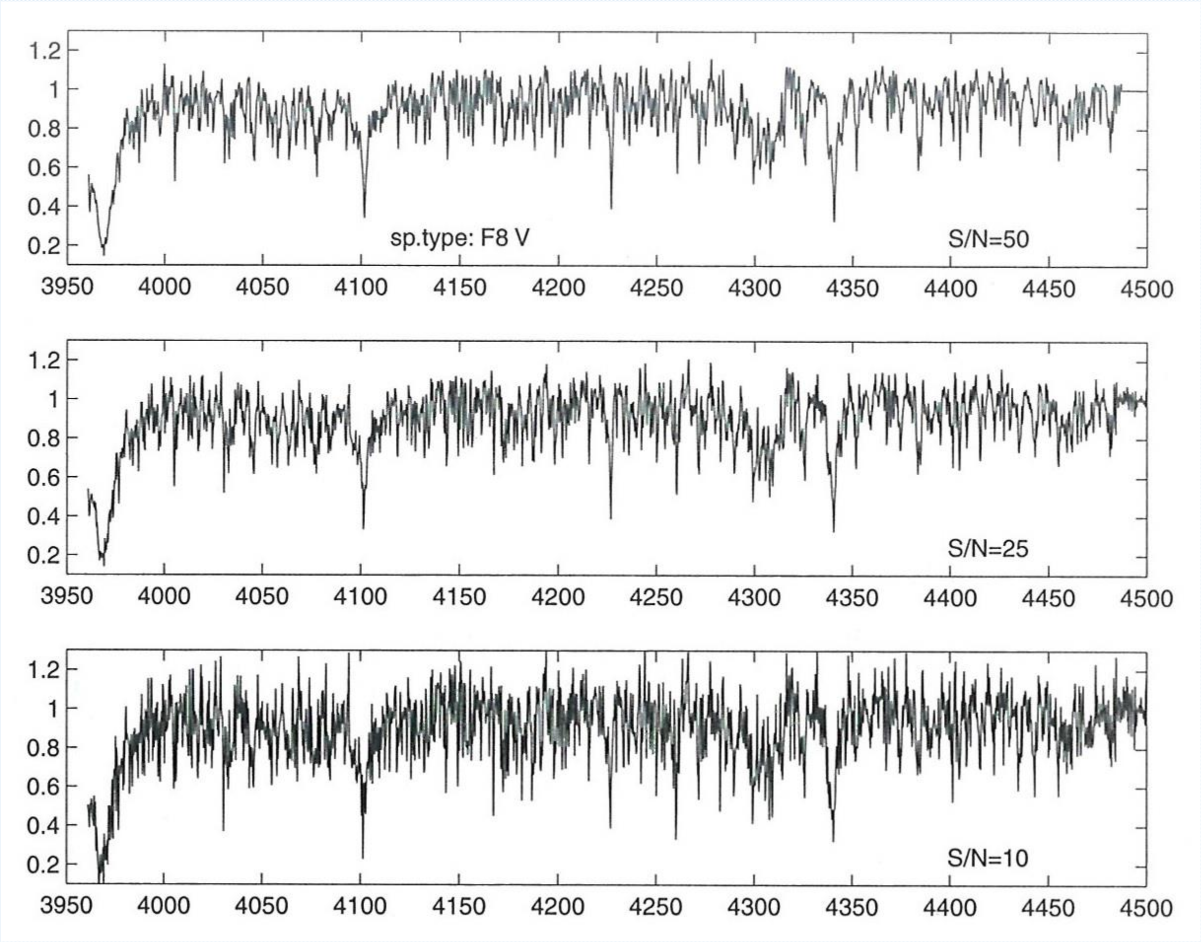
→ Good models

→ Small number of lines

Accuracy limit $\sim 0.1\ \mathrm{km\ s^{-1}}$

Spectroscopic binaries

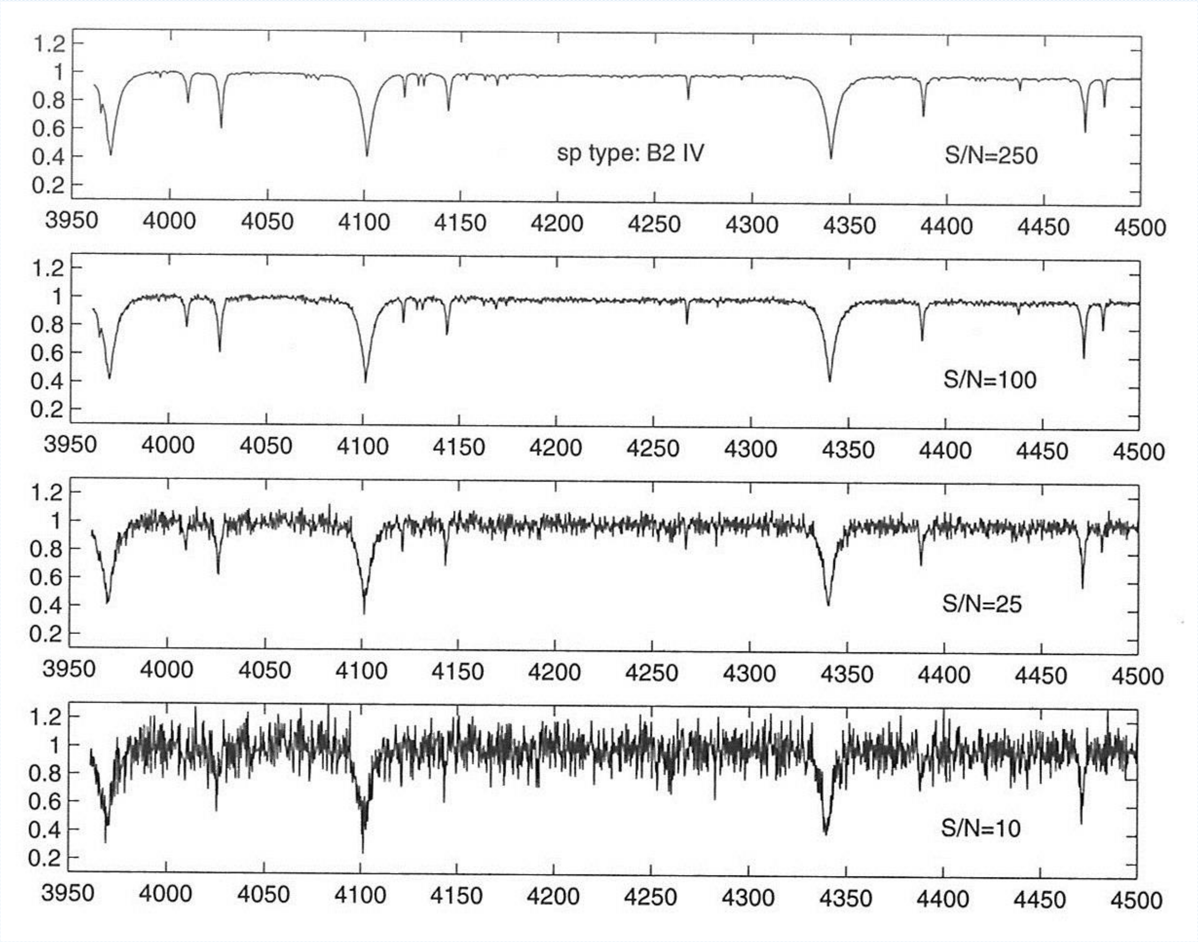


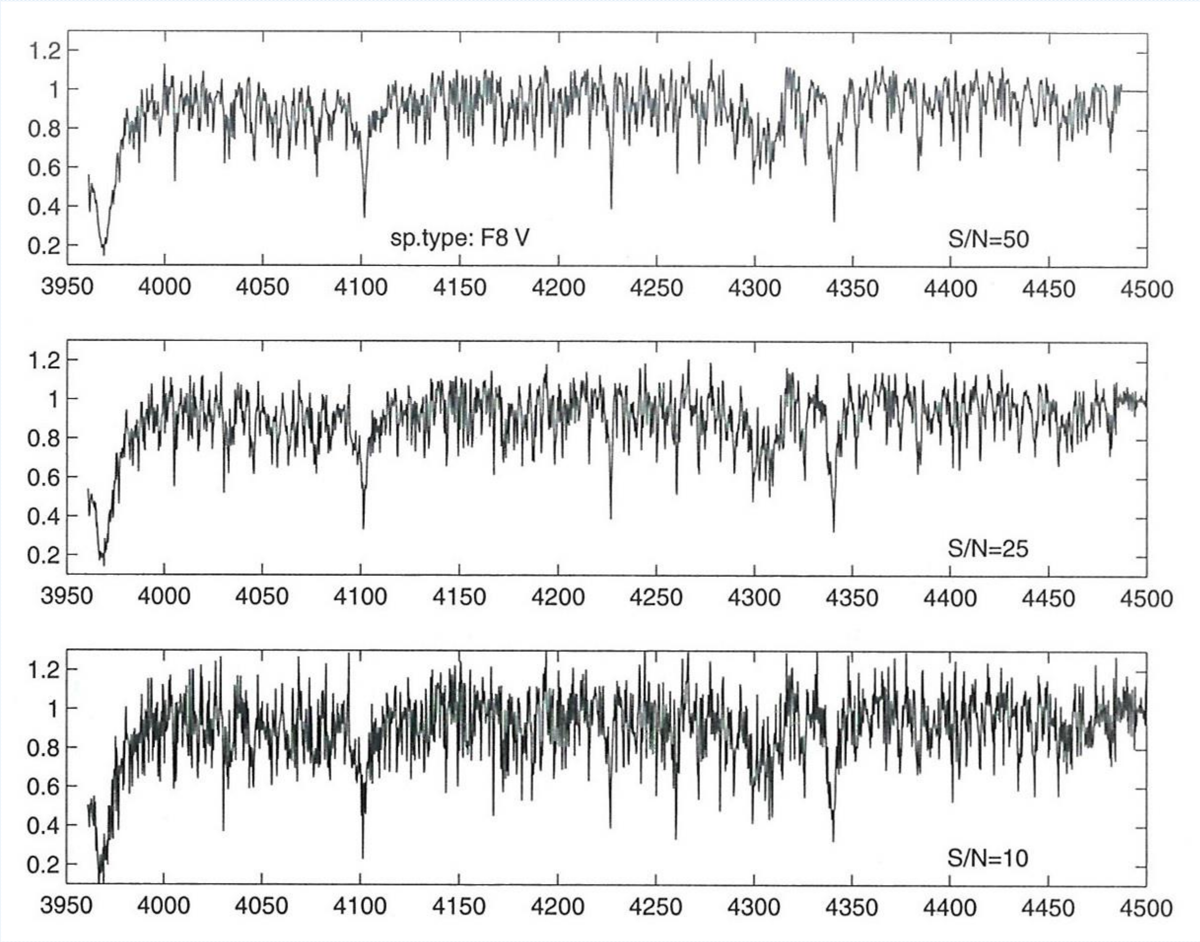


Hilditch 2001

Hot stars better suited due to smaller number of lines

Spectroscopic binaries

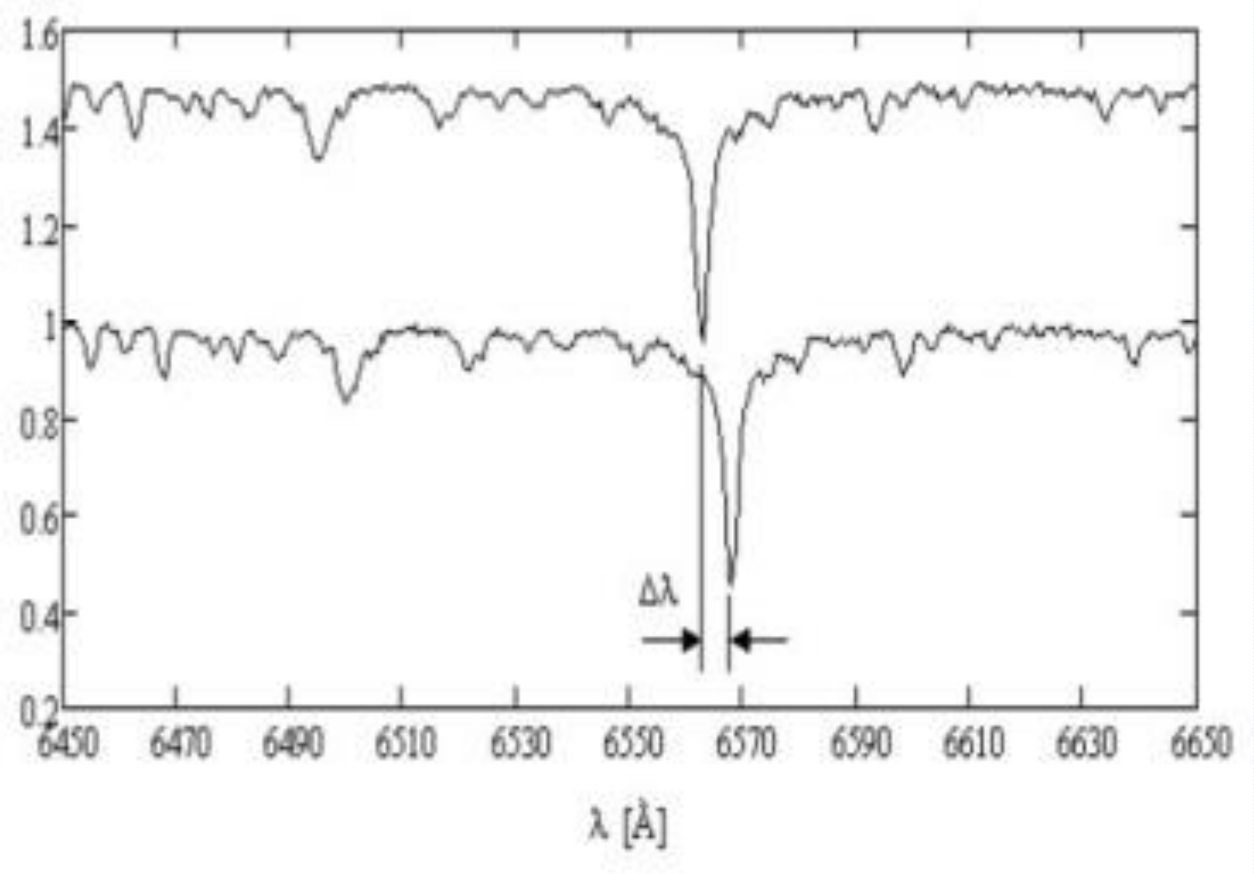




Hilditch 2001

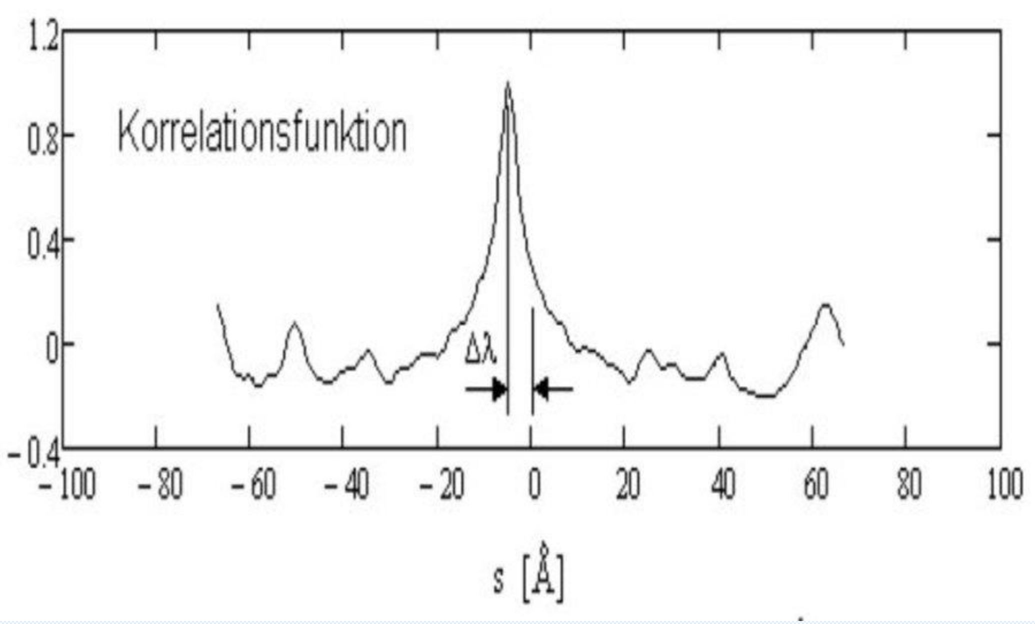
No sufficiently detailed full models for cool stars

Spectroscopic binaries

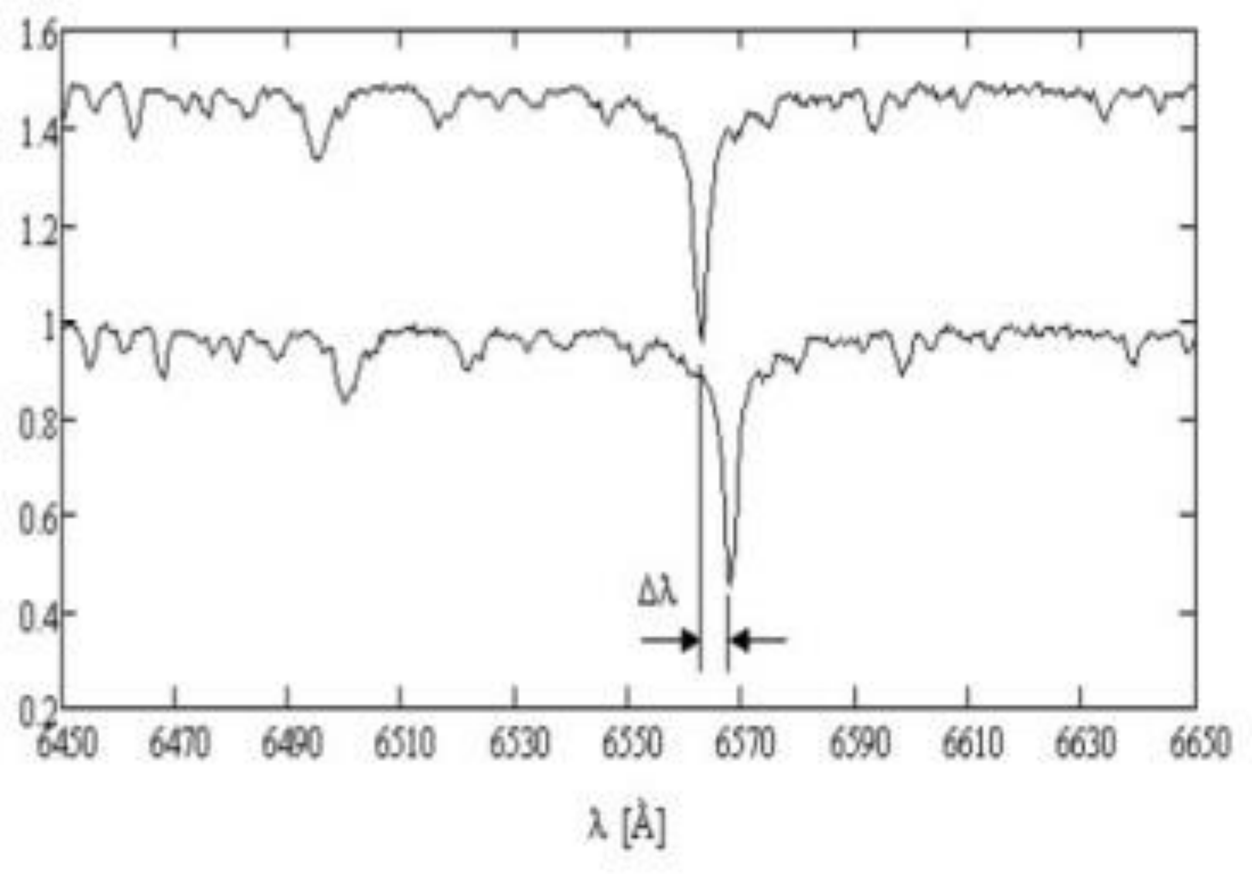


Cross correlation method

$$c(s) = \sum_{i=1}^{n} A_i \, B_{i-s}$$



Spectroscopic binaries



Cross Correlation

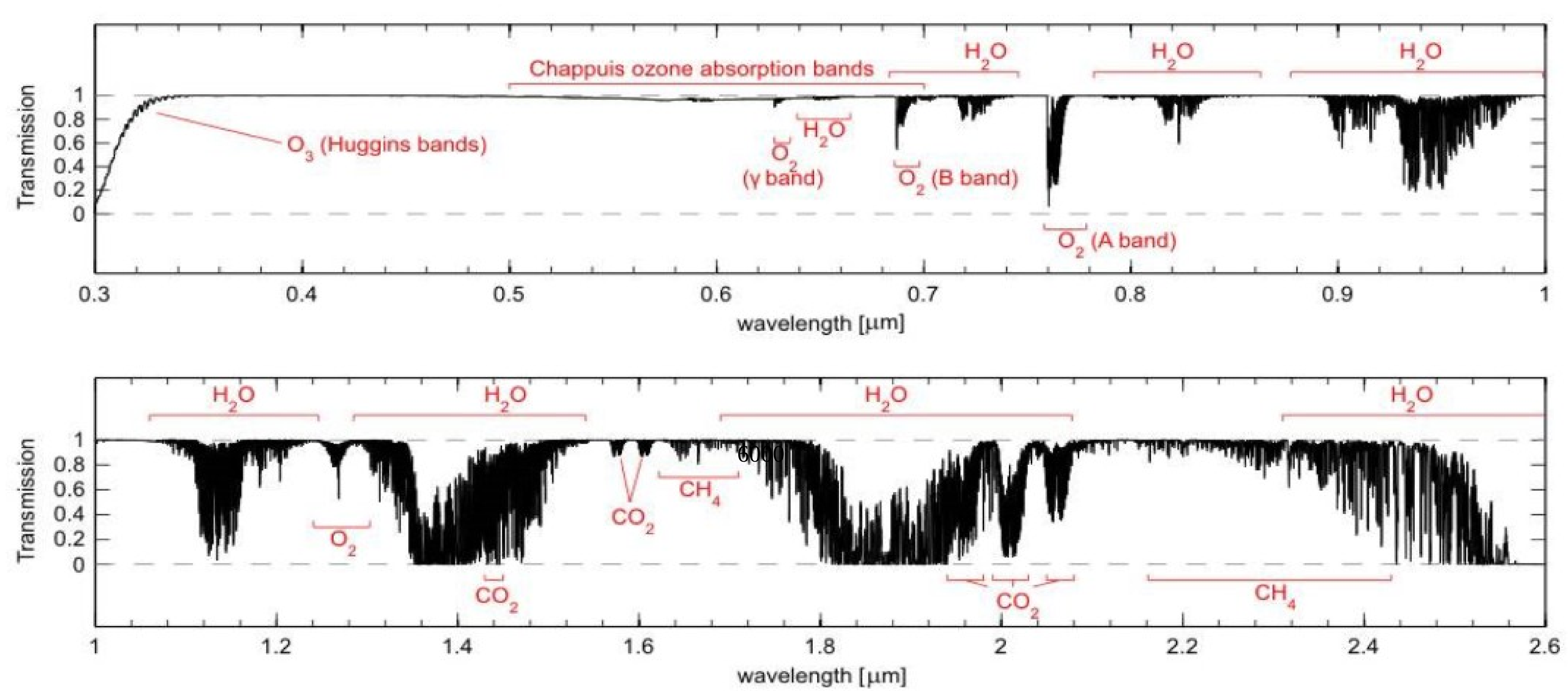
→ Template spectrum or spectrum itself (autocorrelation)

→ All features contribute

→ Applicable to double-lined systems

Limitations: Telluric lines, artifacts

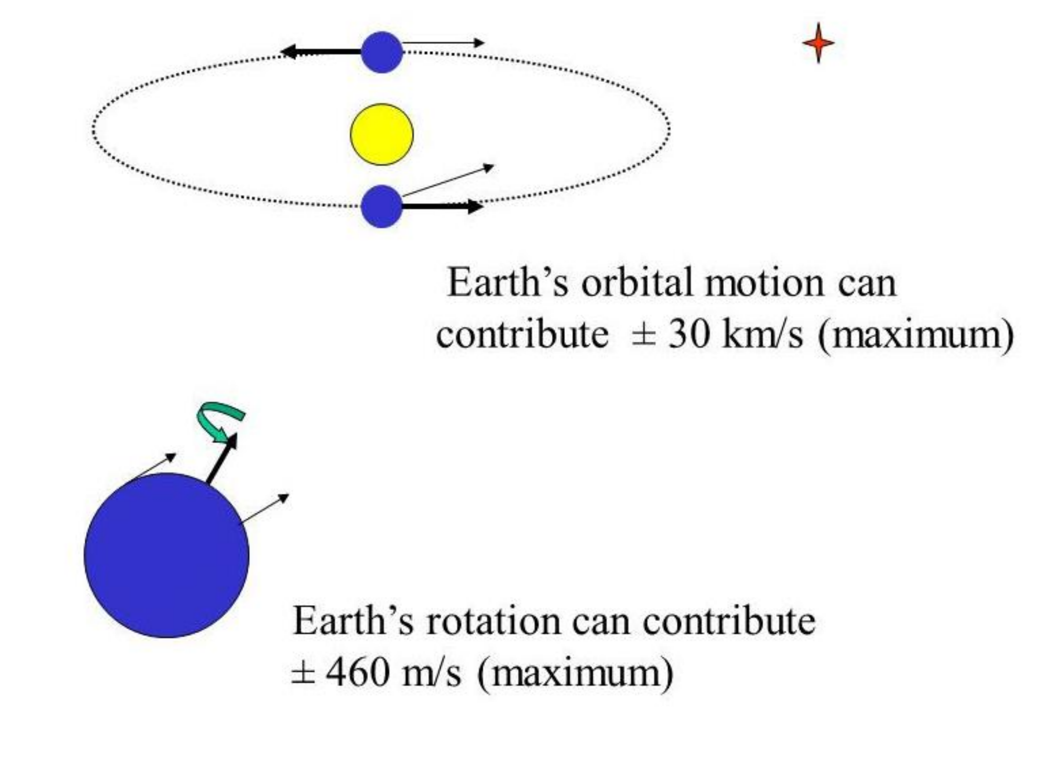
Telluric lines



Smette et al. 2015, A&A, 576, 77

Telluric lines in the optical start at wavelength redder than 660 nm

Spectroscopic binaries



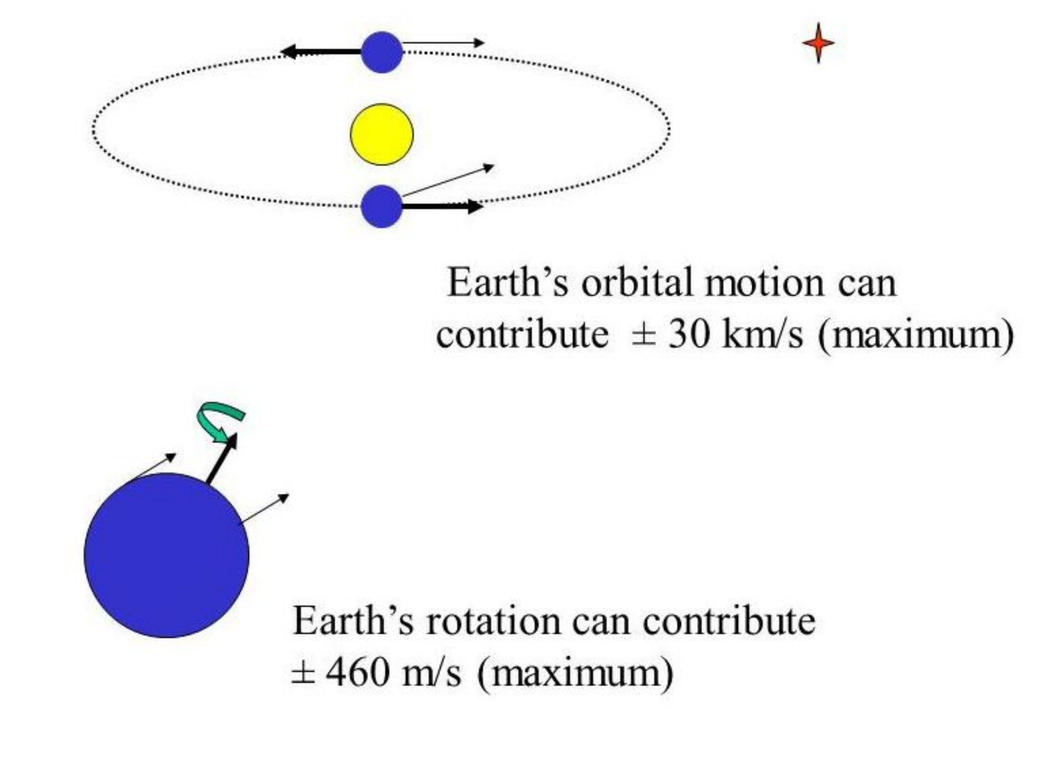
ESO

RVs and times must be **corrected for Earths motion** around the barycenter of the solar system (up to $\pm 30\ \mathrm{kms}^{-1}$ in RV and $\pm 8\ \mathrm{min}$ in time)

→ Location of the telescope must be known (GPS)

→ Most accurate determination of observation time: High-speed photometers measure photon weighted midpoint of exposures

Spectroscopic binaries



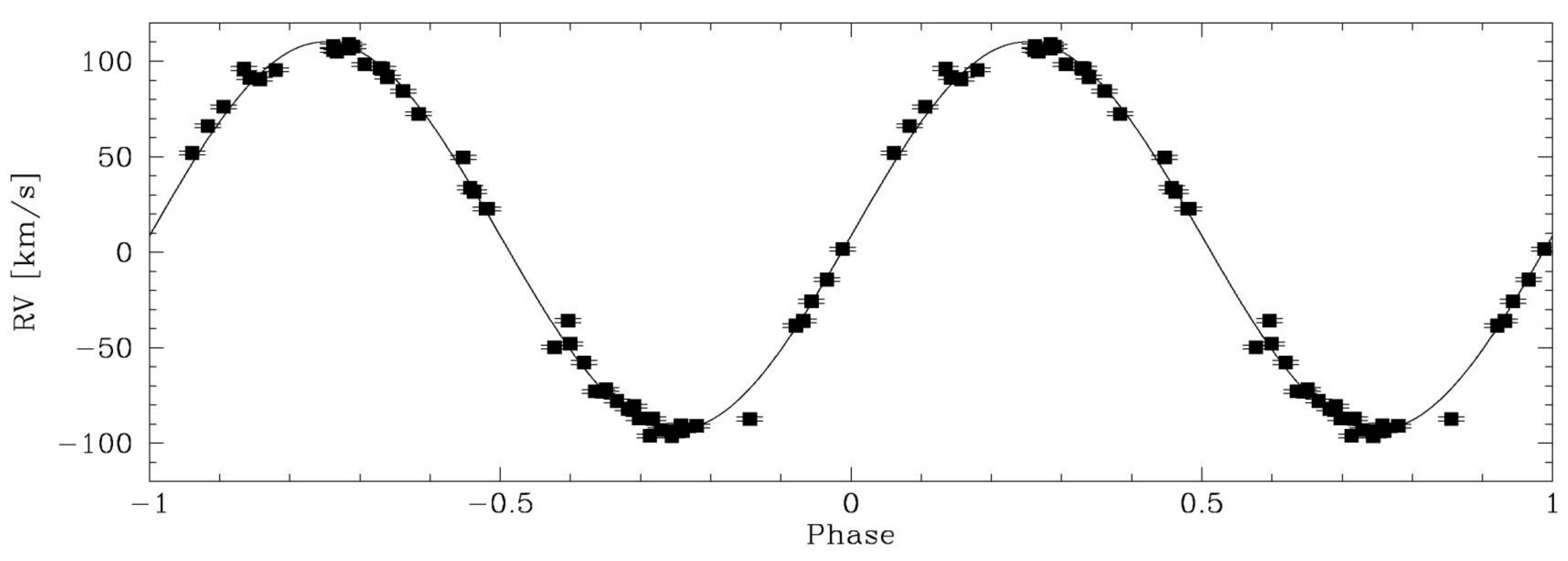
ESO

RVs and times must be **corrected for Earths motion** around the barycenter of the solar system (up to $\pm 30\ \mathrm{kms}^{-1}$ in RV and $\pm 8\ \mathrm{min}$ in time)

→ For close binaries with high RV shifts often slightly less accurate **heliocentric corrections** are used

→ Times are approximated by adding **half of the exposure time** to the starting time

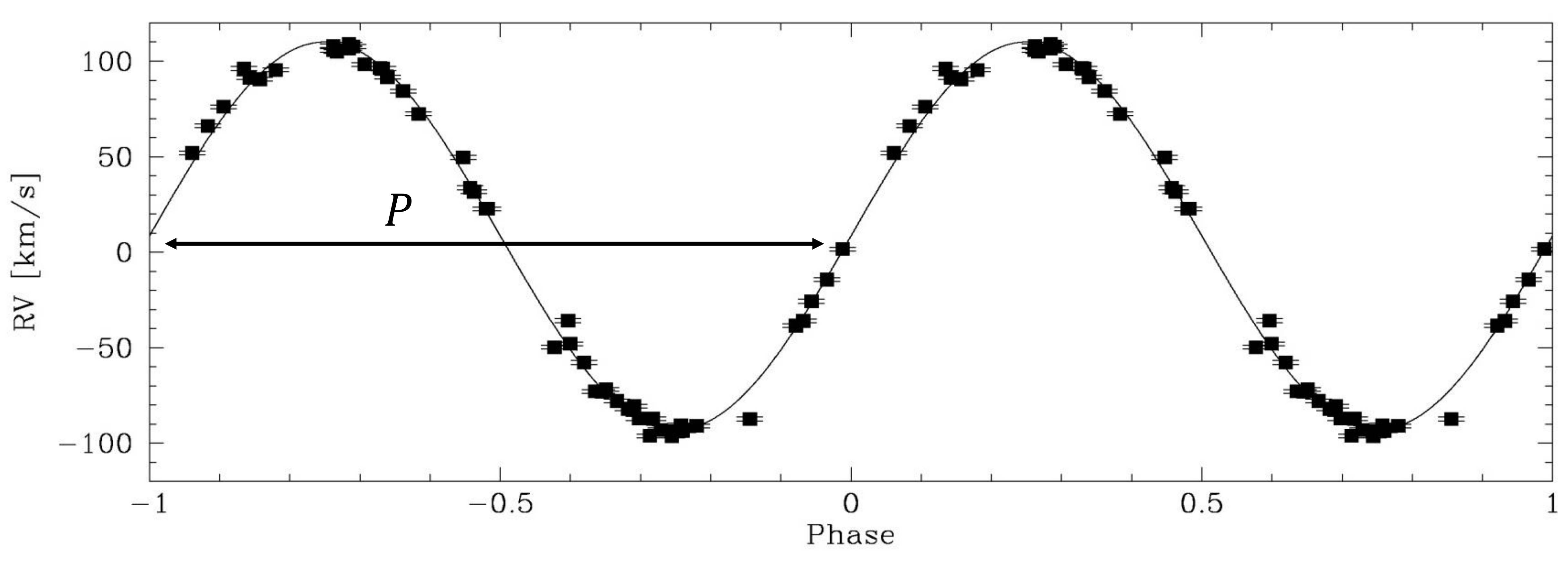
Single-lined binaries



S. Geier

Orbital parameters of the visible component

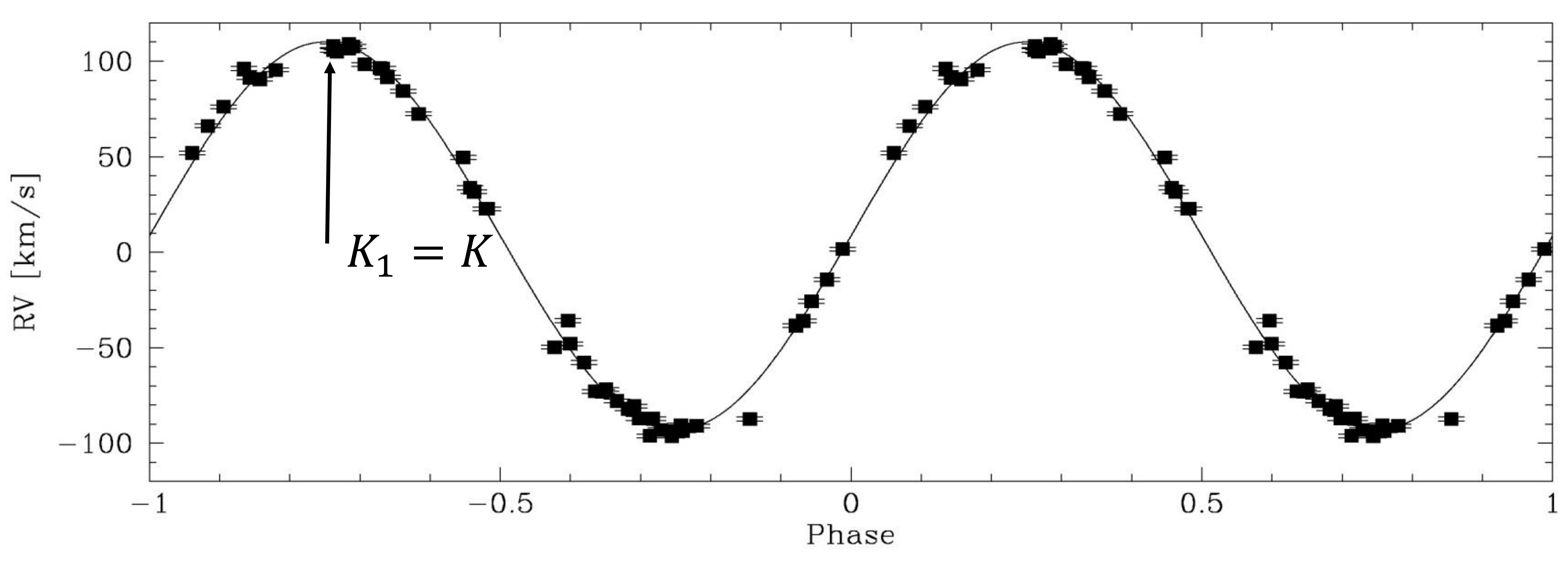
Single-lined binaries



S. Geier

Orbital parameters of the visible component

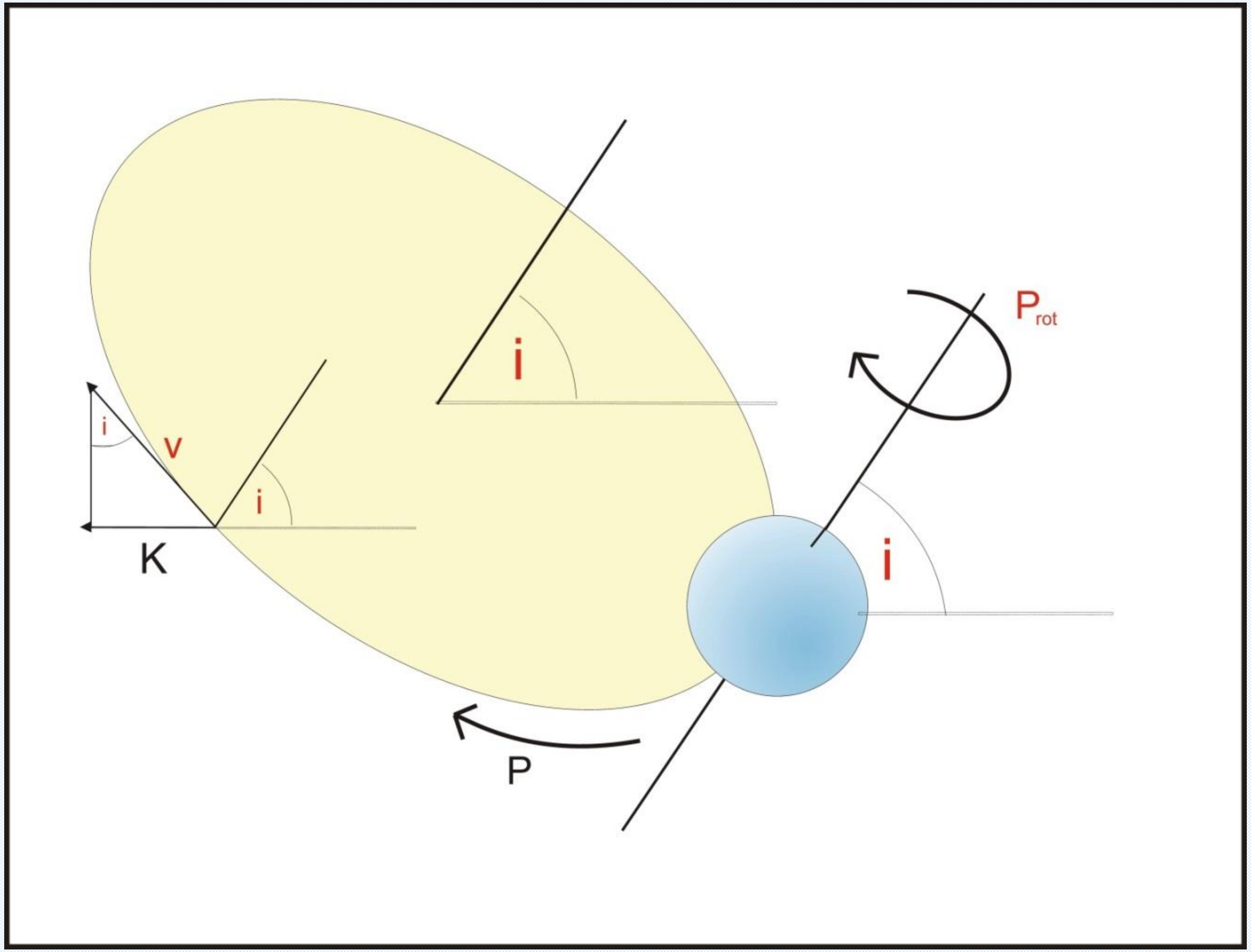
Single-lined binaries



S. Geier

Orbital parameters of the visible component

Single-lined binaries

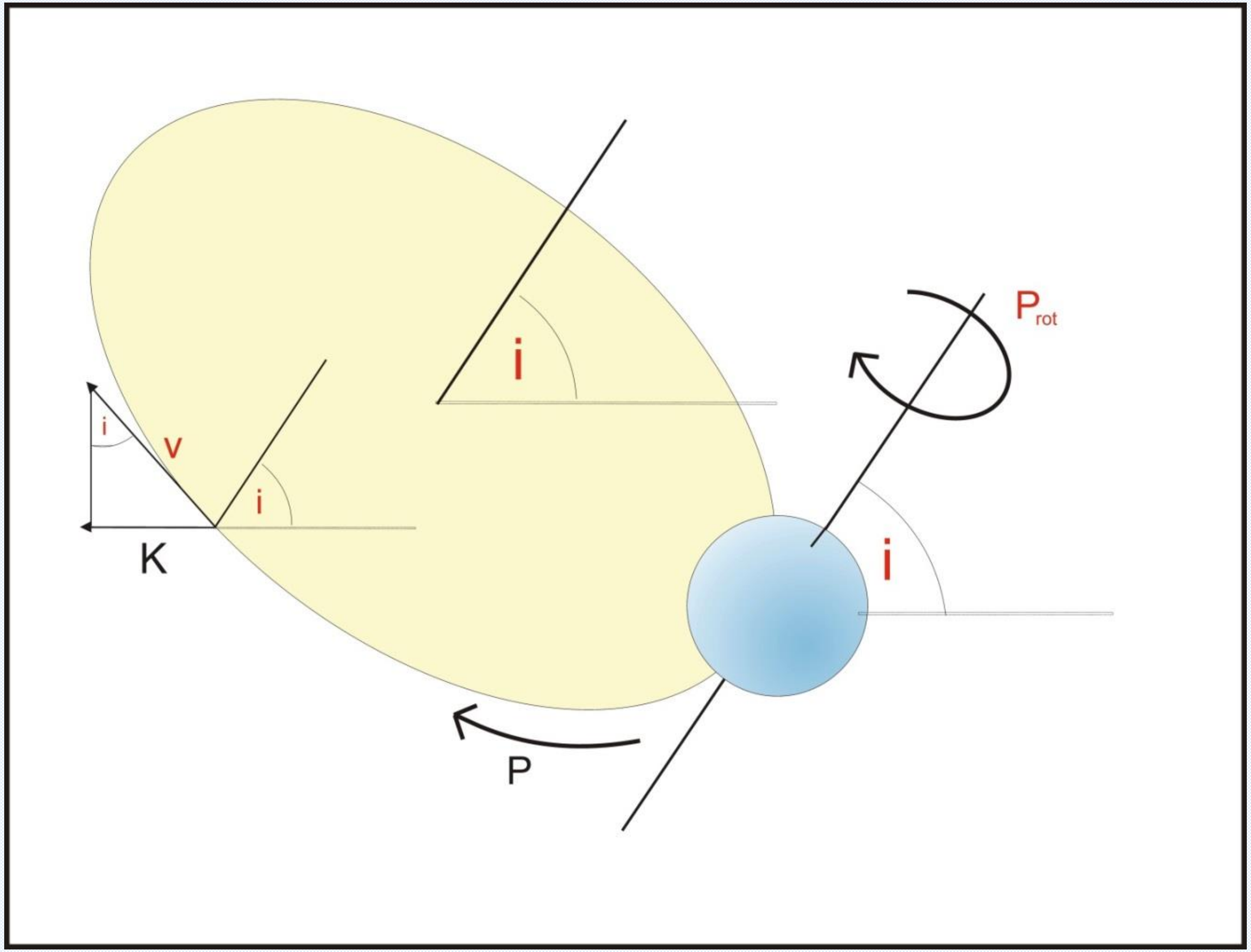


S. Geier

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



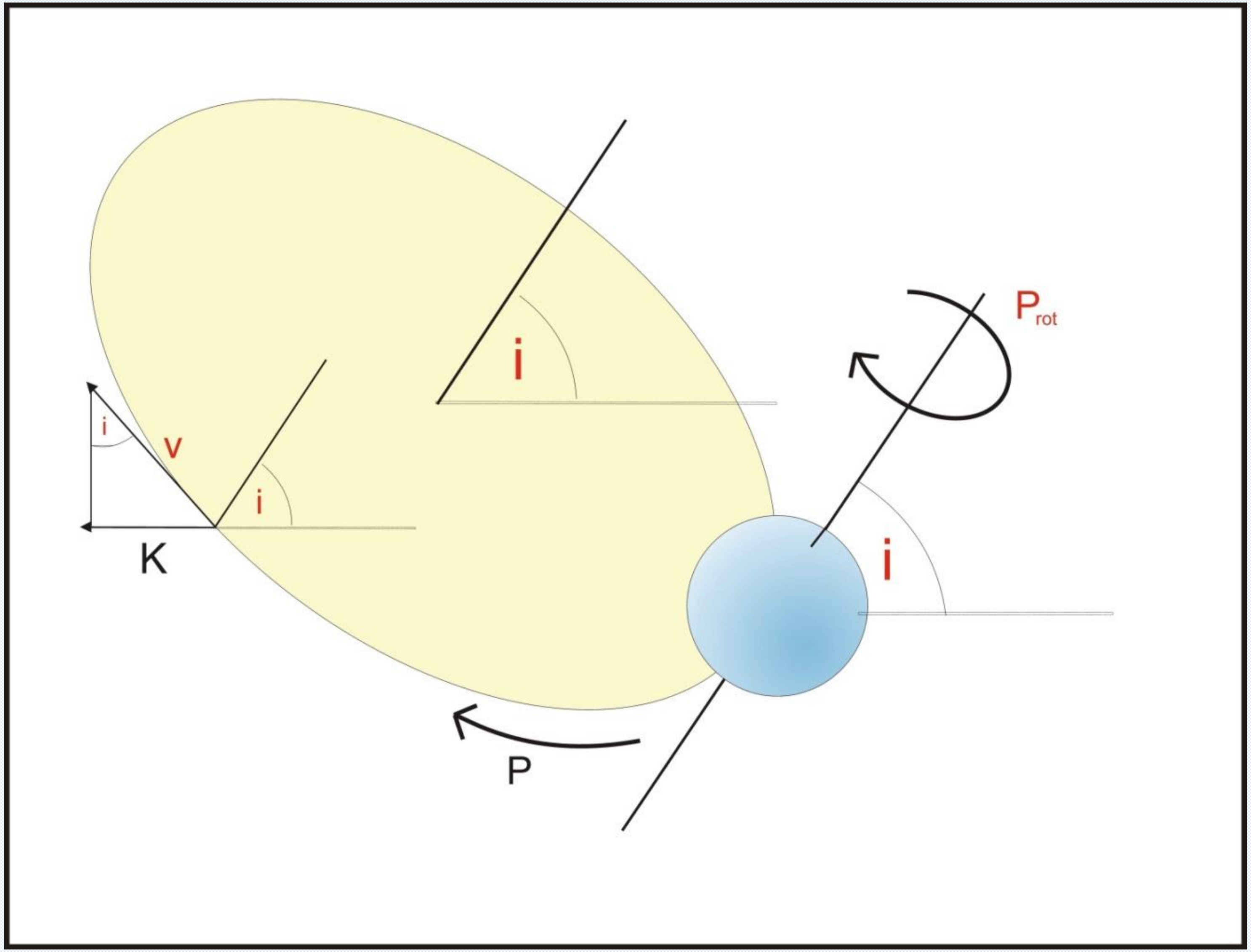
S. Geier

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

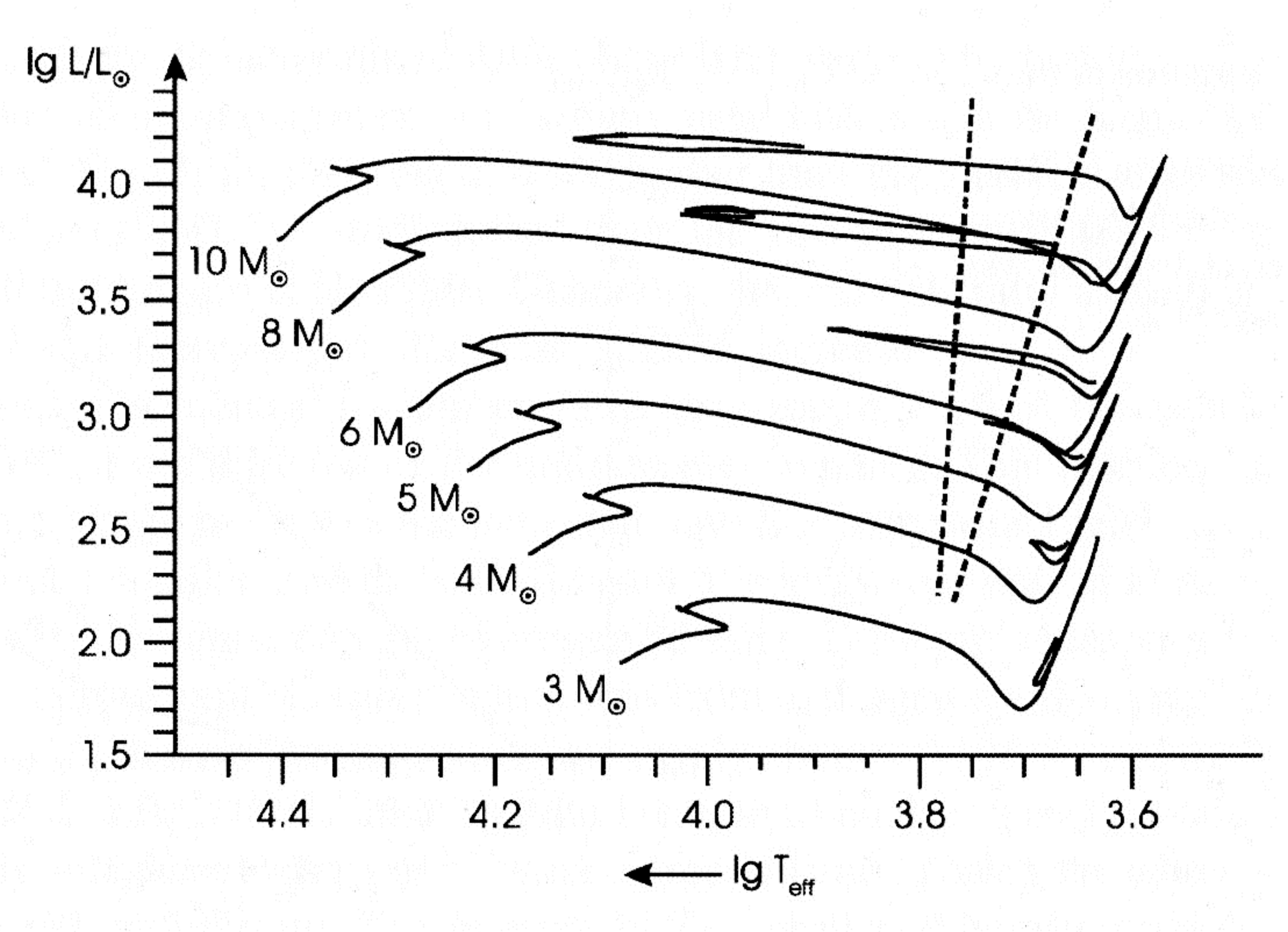
Inclination angle

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

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

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

Single-lined binaries



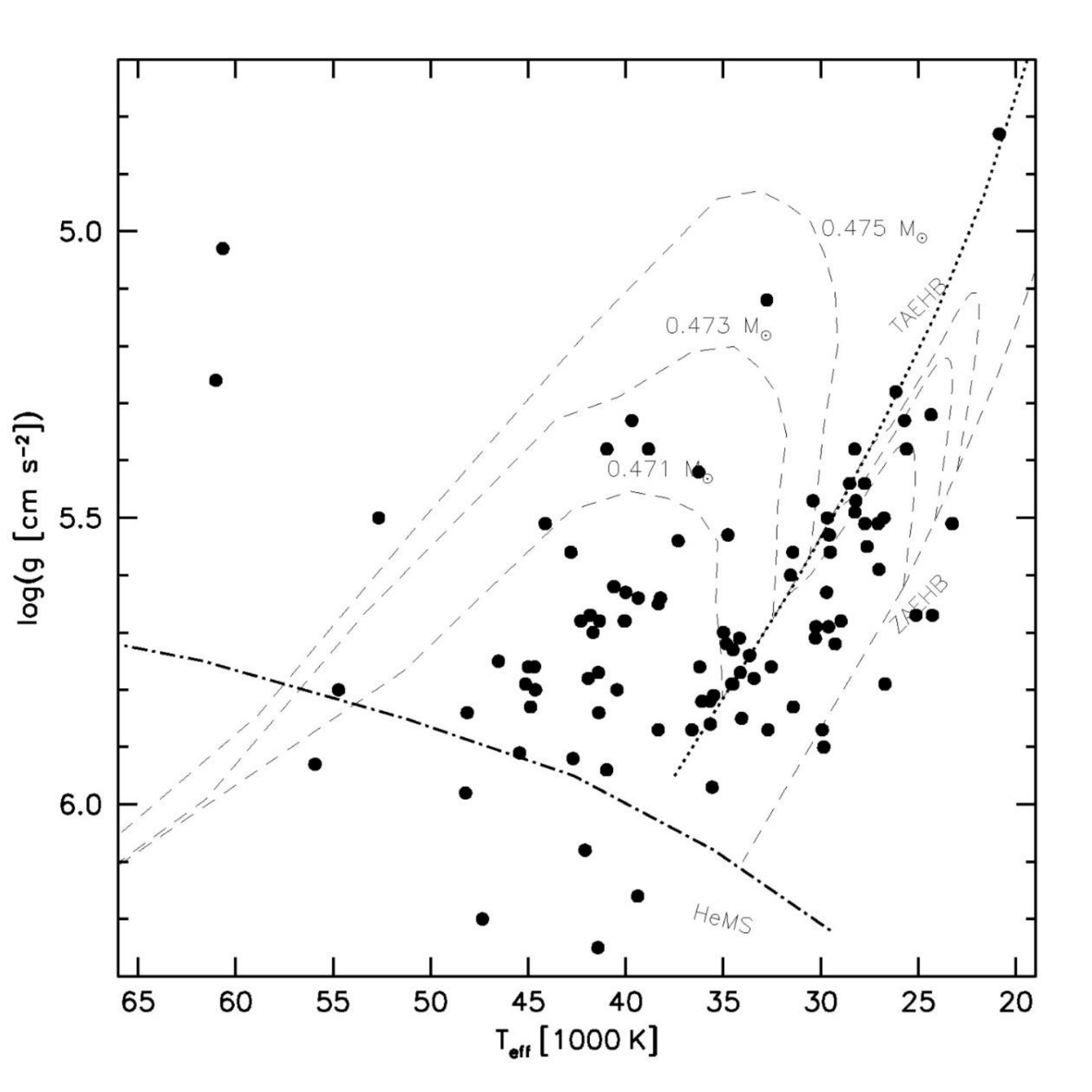
Kippenhahn, Weigert & Weiss 2012

Mass and radius of the visible component can be determined by comparing the measured quantities to stellar evolution tracks

Photometry/astrometry

→ **Colour (temperature), absolute magnitude (luminosity)**

Single-lined binaries



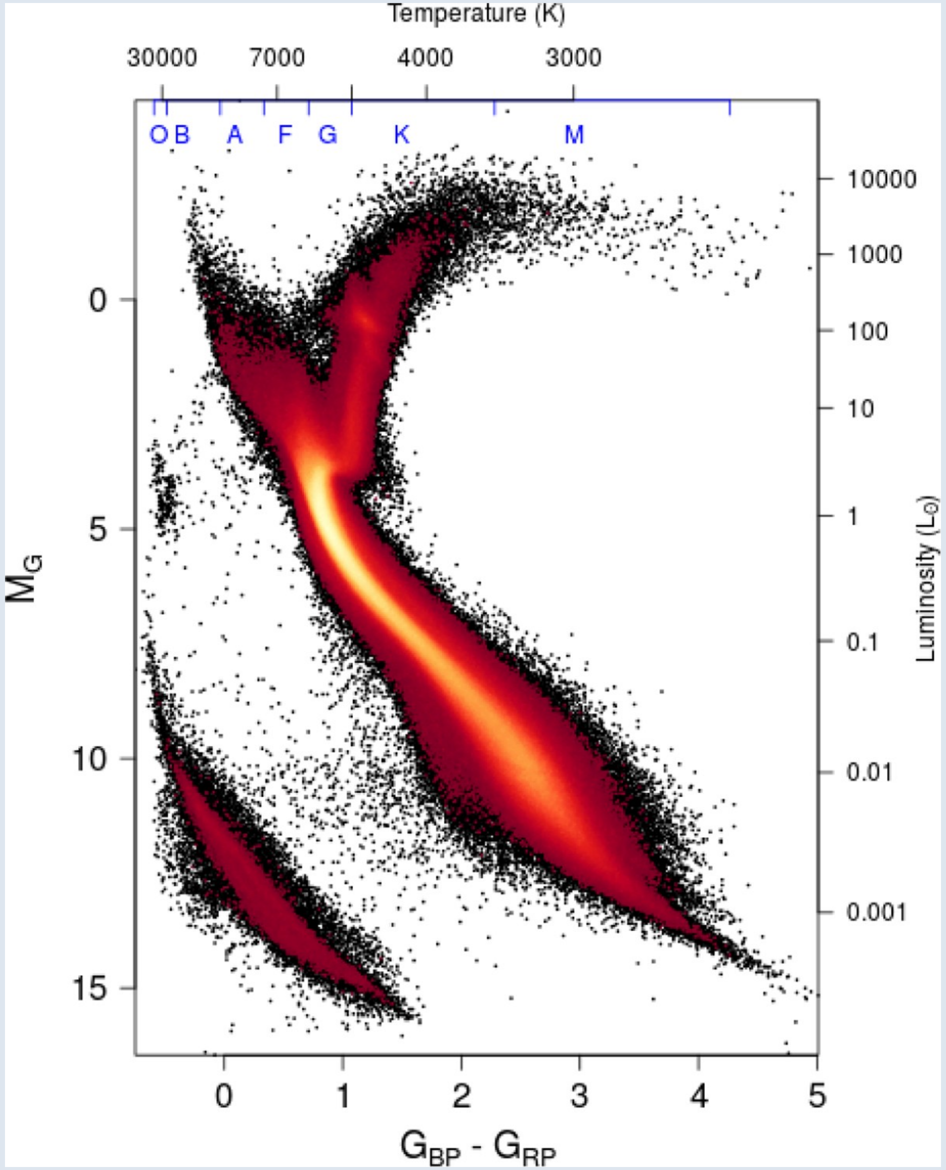
S. Geier

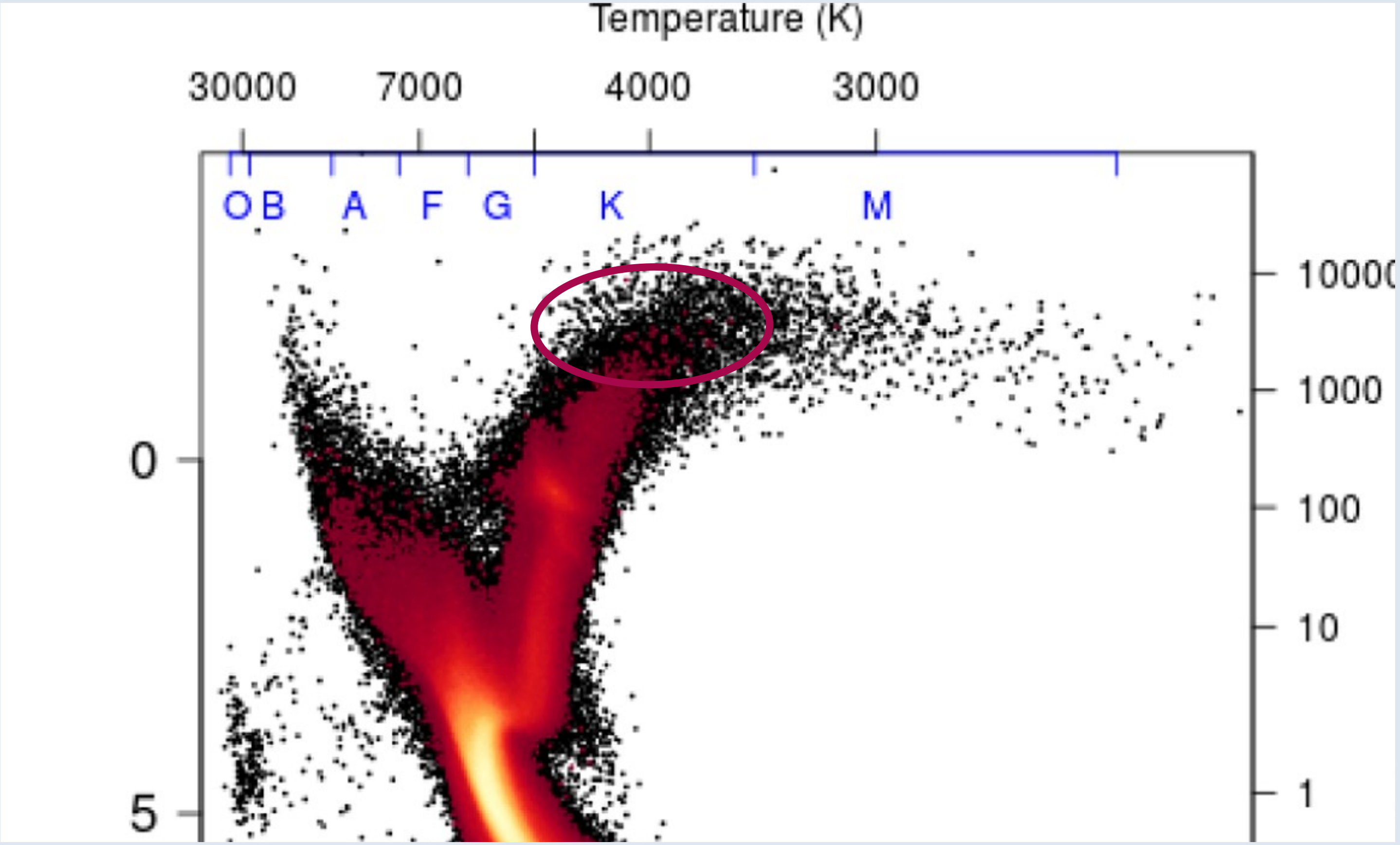
Mass and radius of the visible component can be determined by comparing the measured quantities to stellar evolution tracks

Spectroscopic analysis

→ Effective temperature, surface gravity

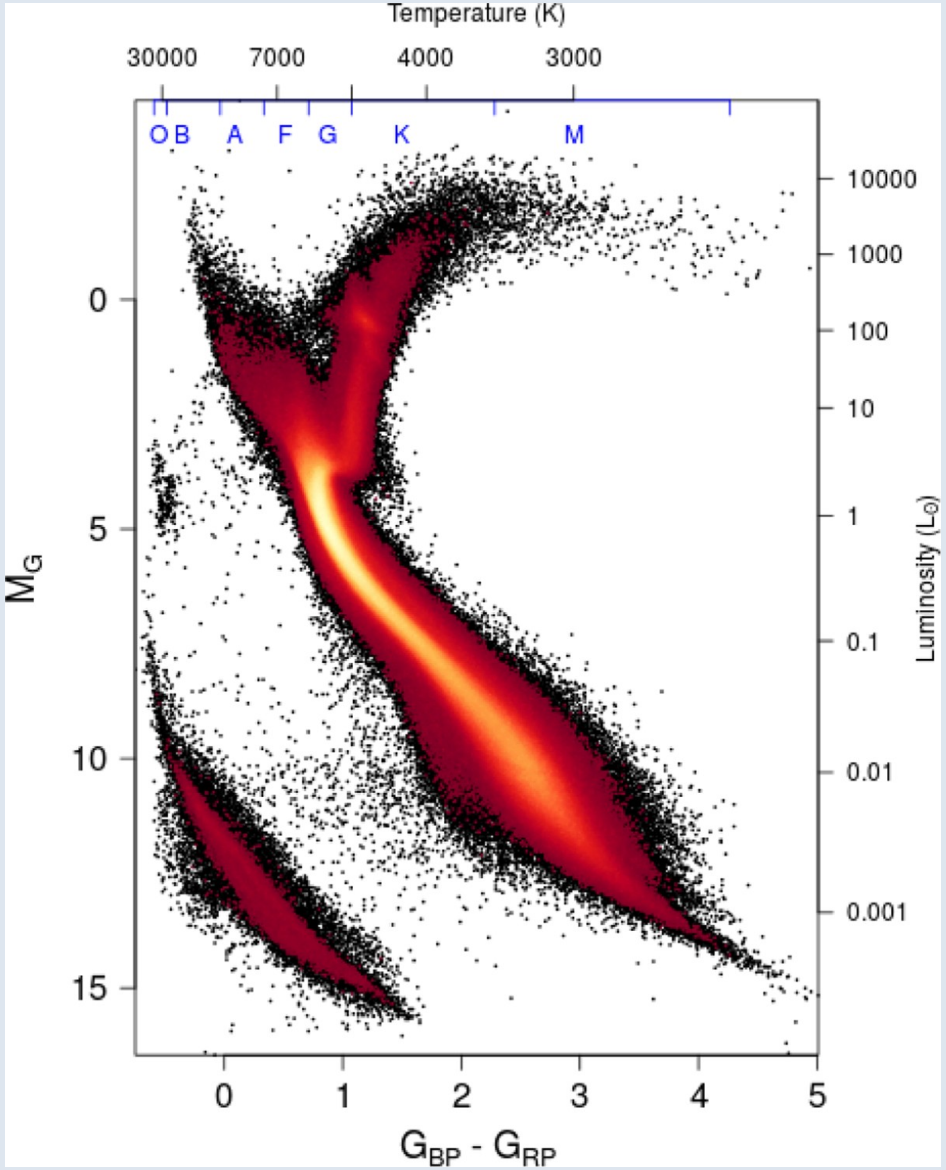
Samples to be observed

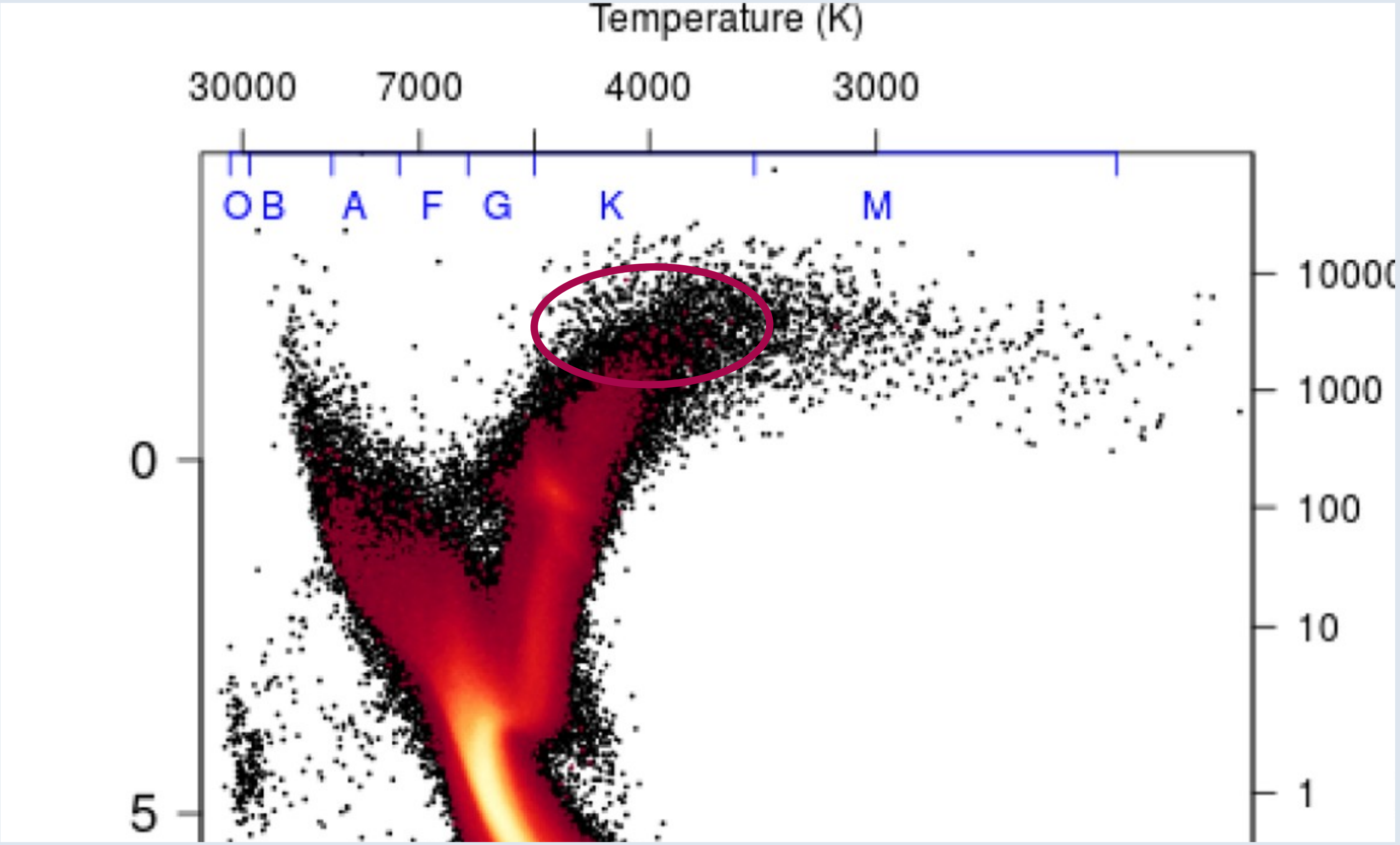




100 stars located at the tip of the RGB randomly selected from a volume-limited 500 pc sample

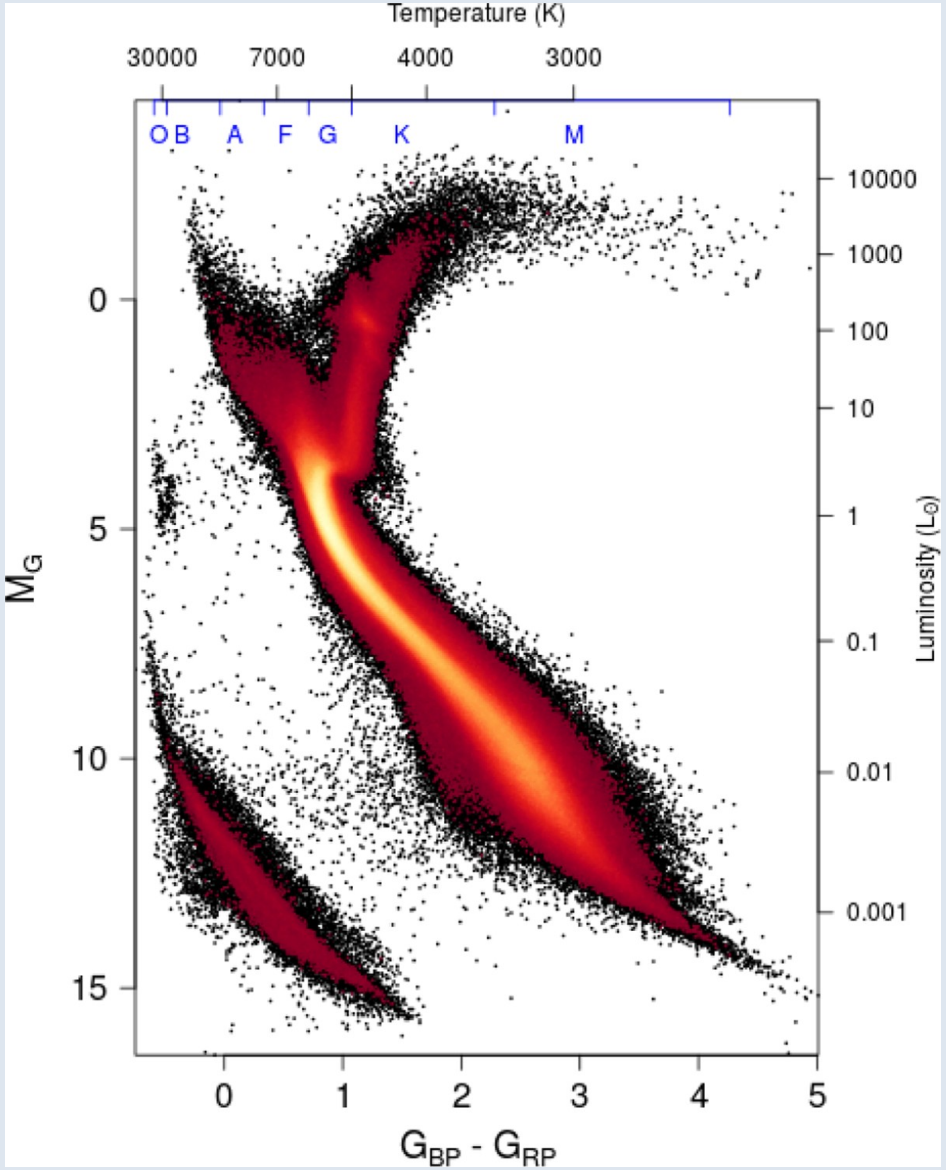
Samples to be observed

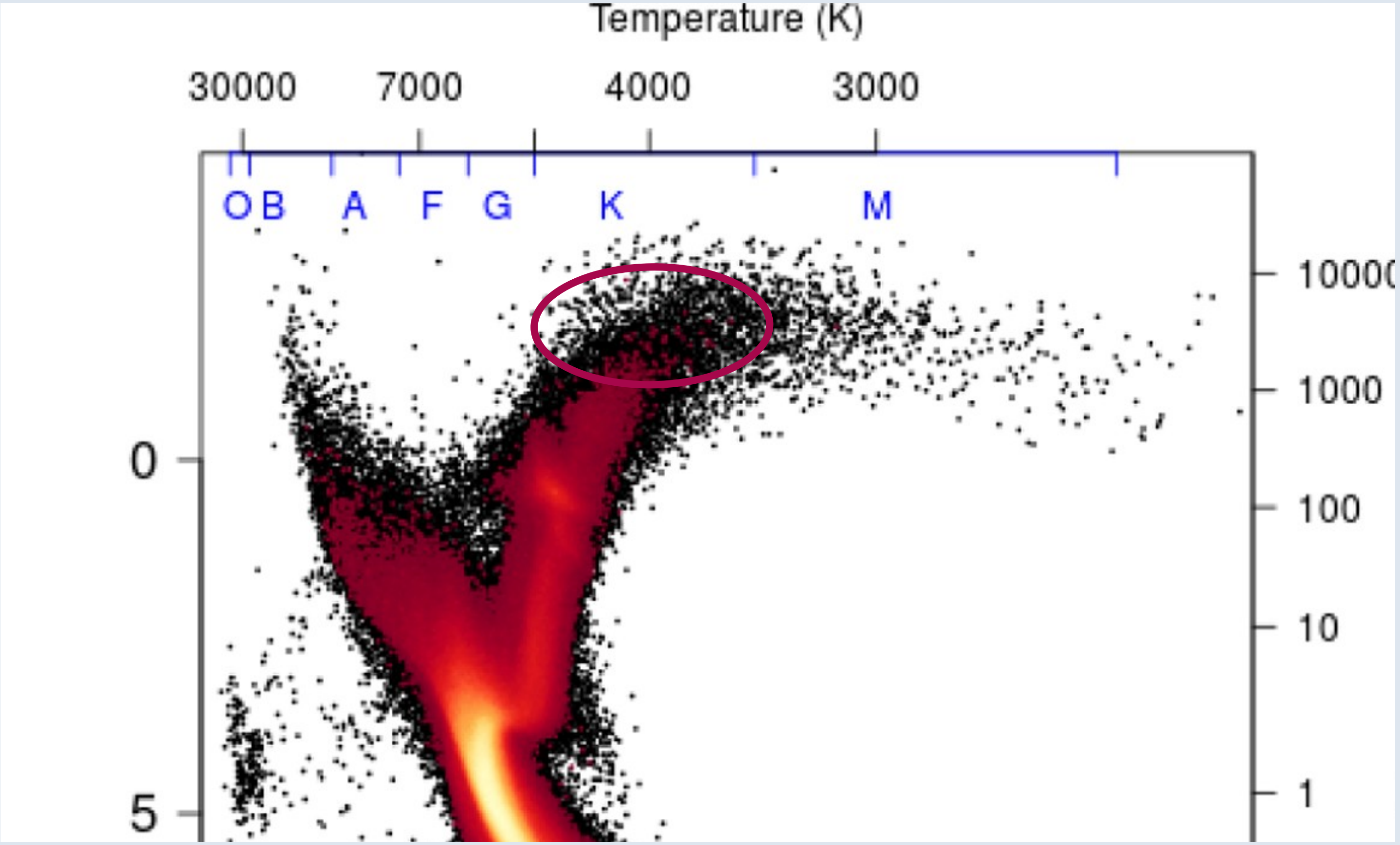




Goal: Search for RV variations of the order of a few km/s indicative of an unseen companion in a wide binary (period of yrs)

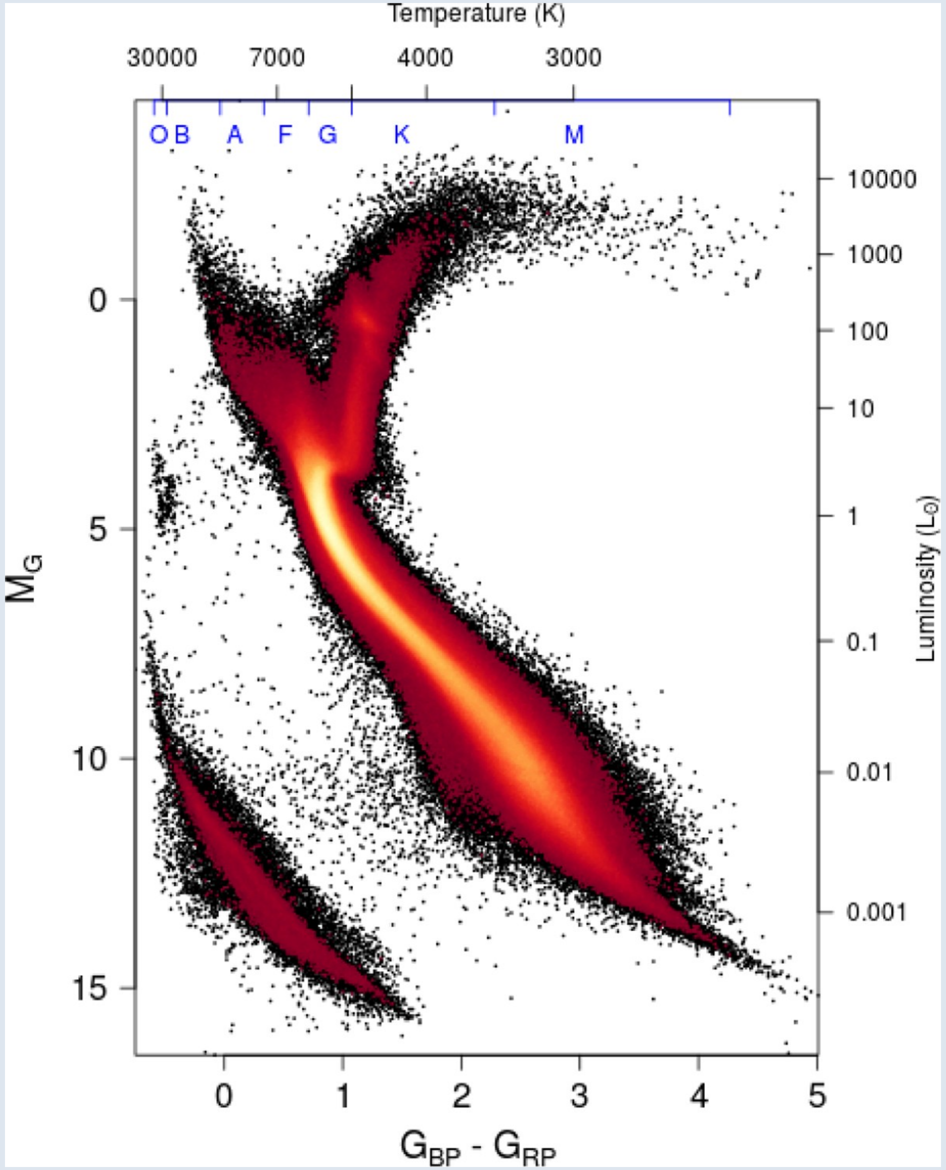
Samples to be observed

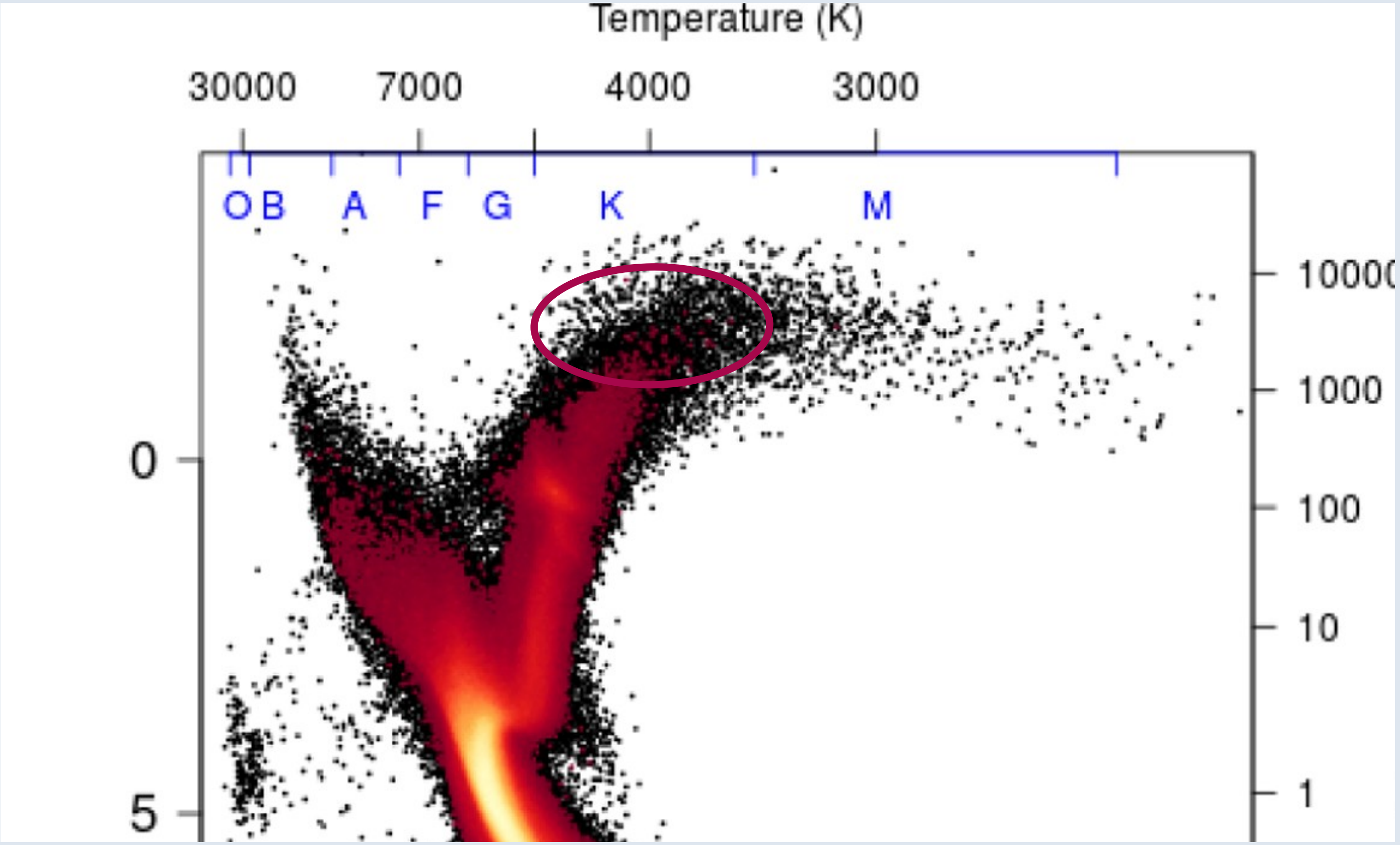




First epoch spectra have been observed in Ondrejov in 2019/20

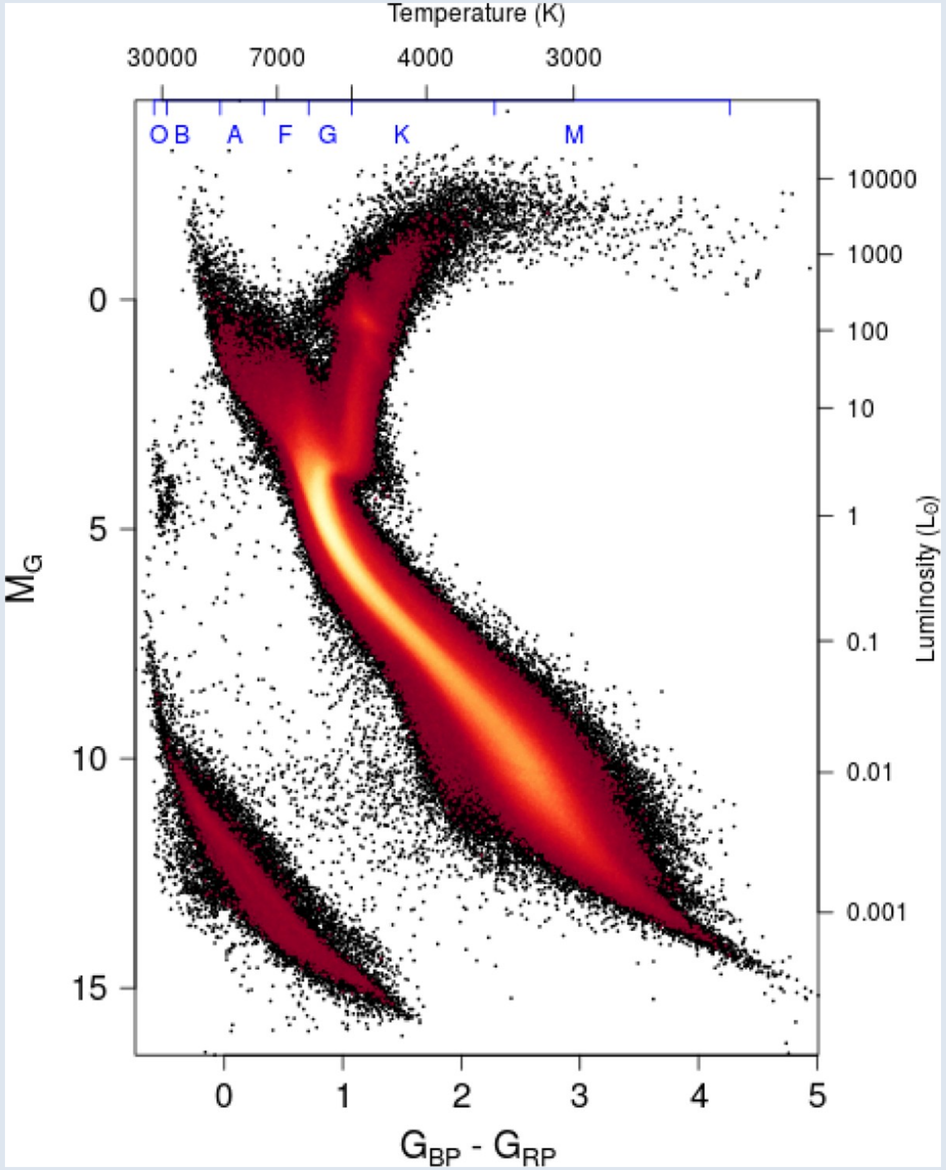
Samples to be observed

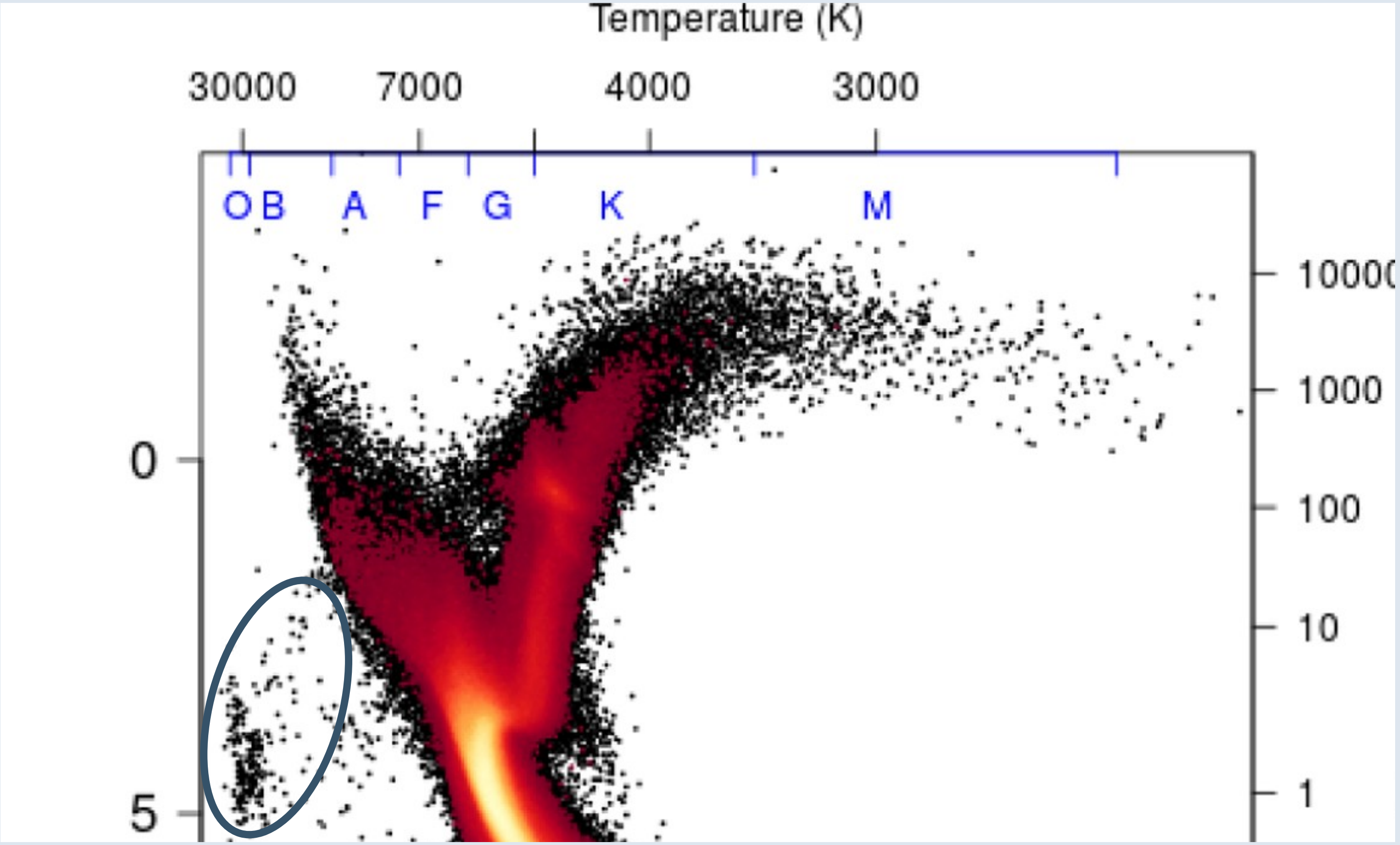




Strategy: Obtain second epoch spectra and measure the relative RV shift by cross-correlation

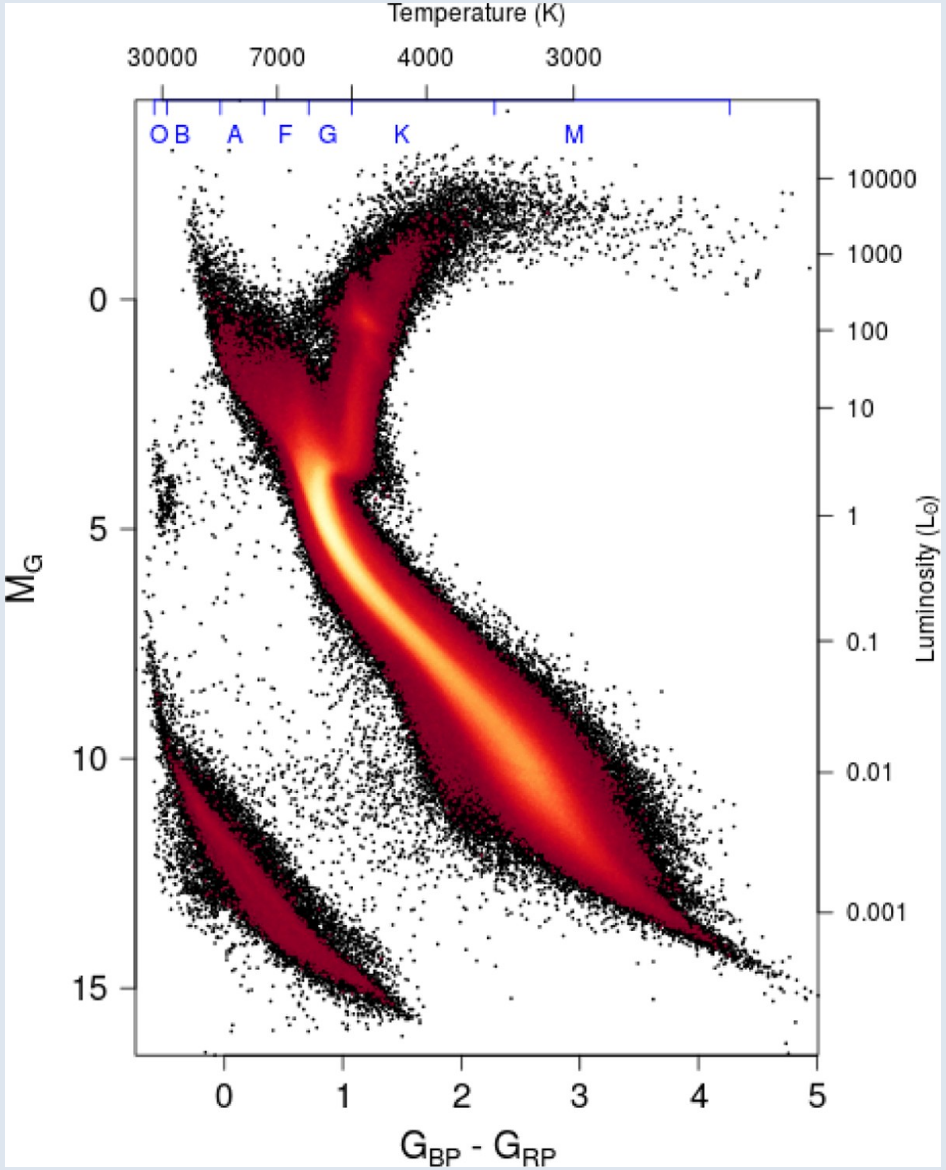
Samples to be observed

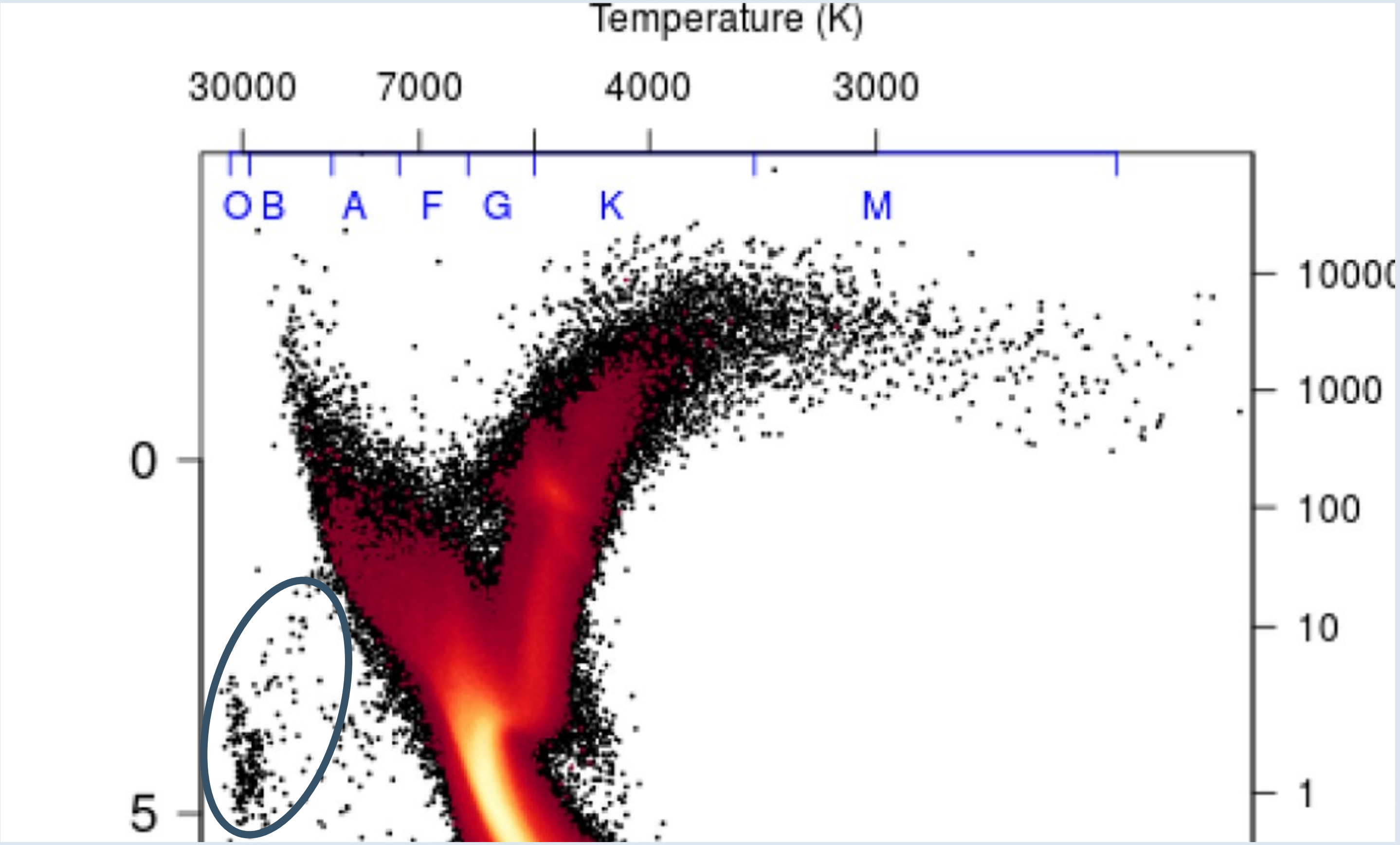




Volume-complete 500 pc sample of BHB and EHB stars

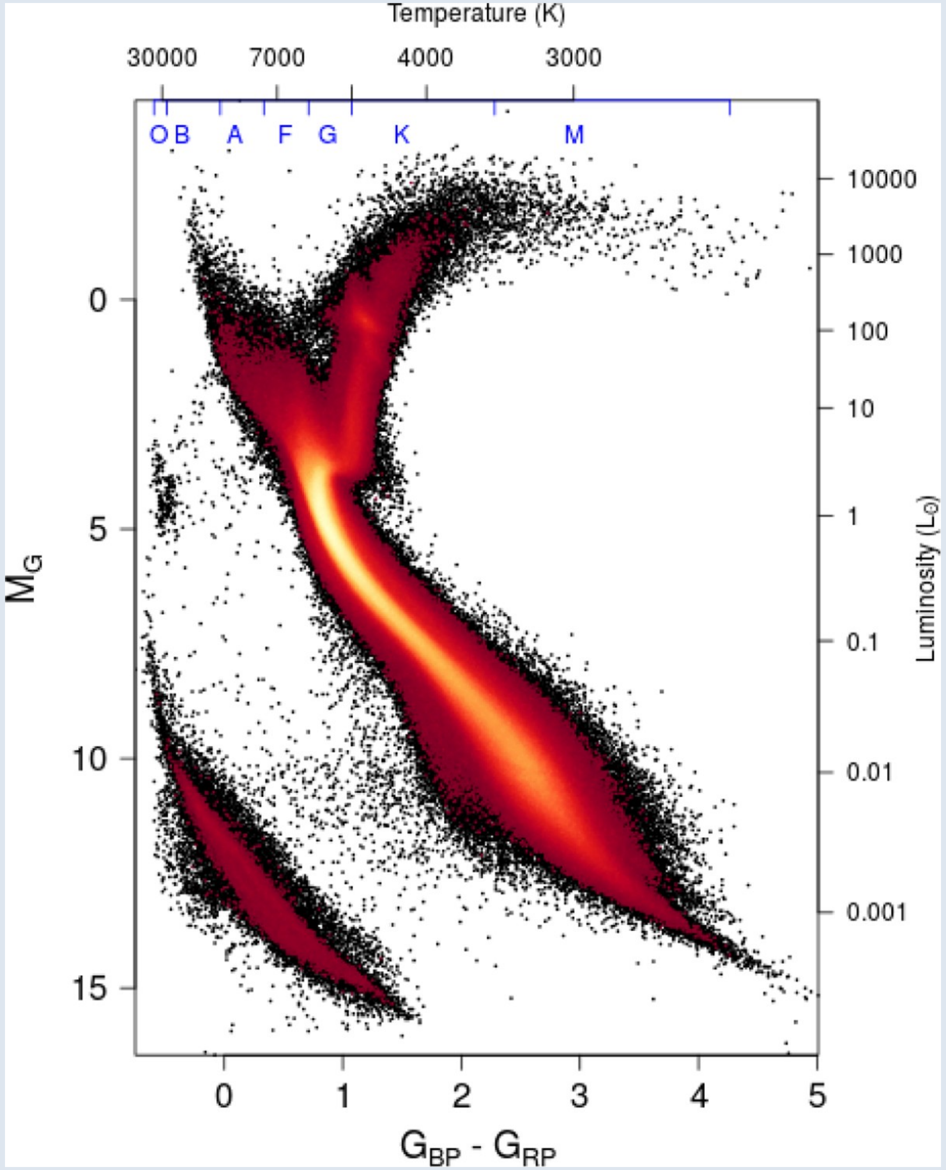
Samples to be observed

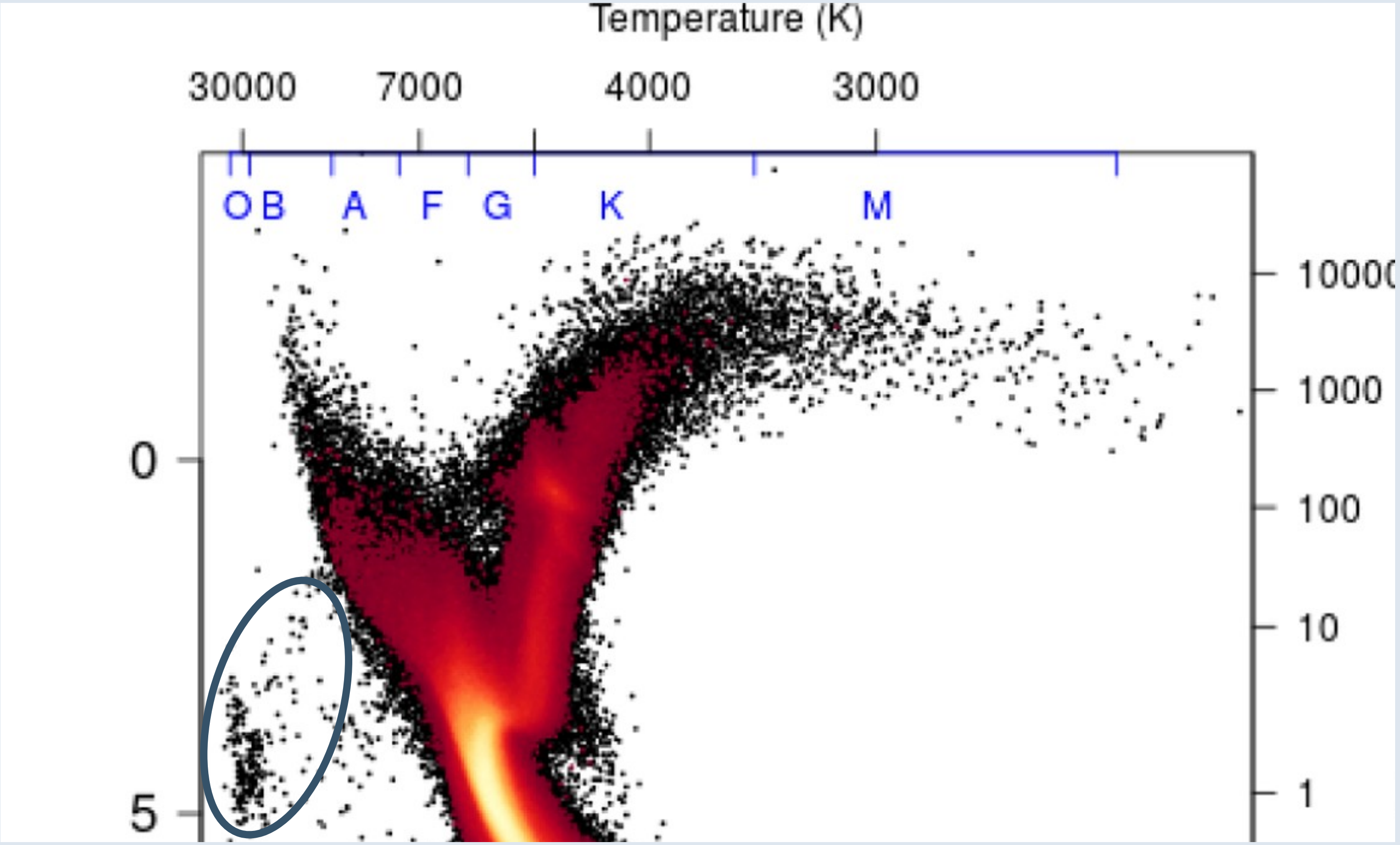




Goal: Determine the fraction of close binaries with periods of hours to days (RV shifts up to a few 100 km/s)

Samples to be observed





Strategy: Take two epochs within a few nights, measure the RVs and perform a spectroscopic analysis by fitting models