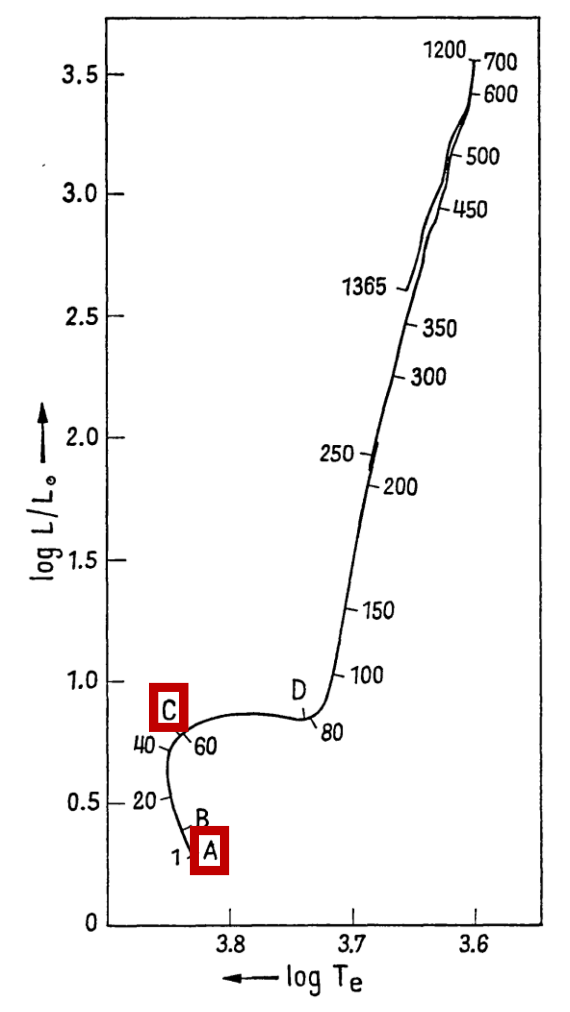
Spectroscopic Survey of Blue Horizontal Branch Stars

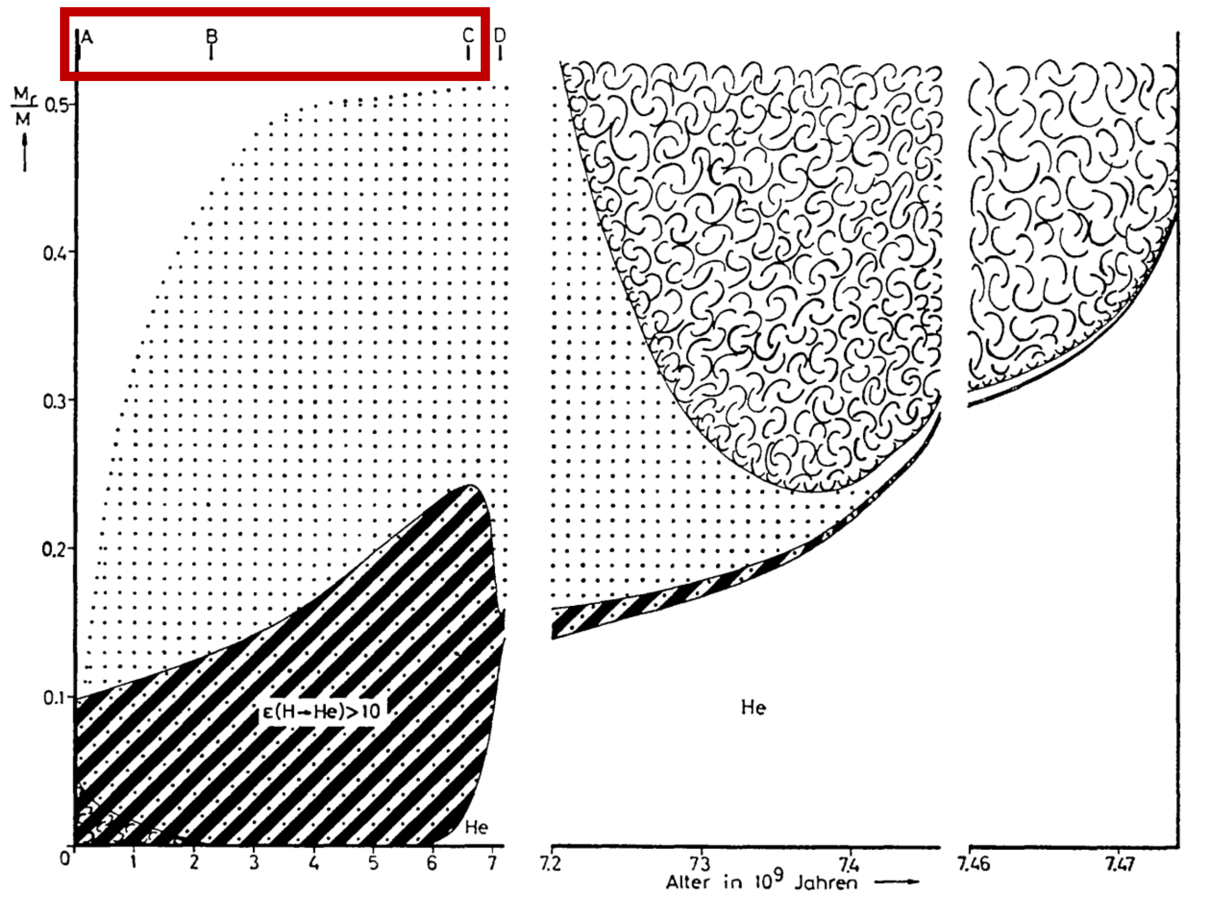
Stephan Geier

Single low-mass stellar evolution



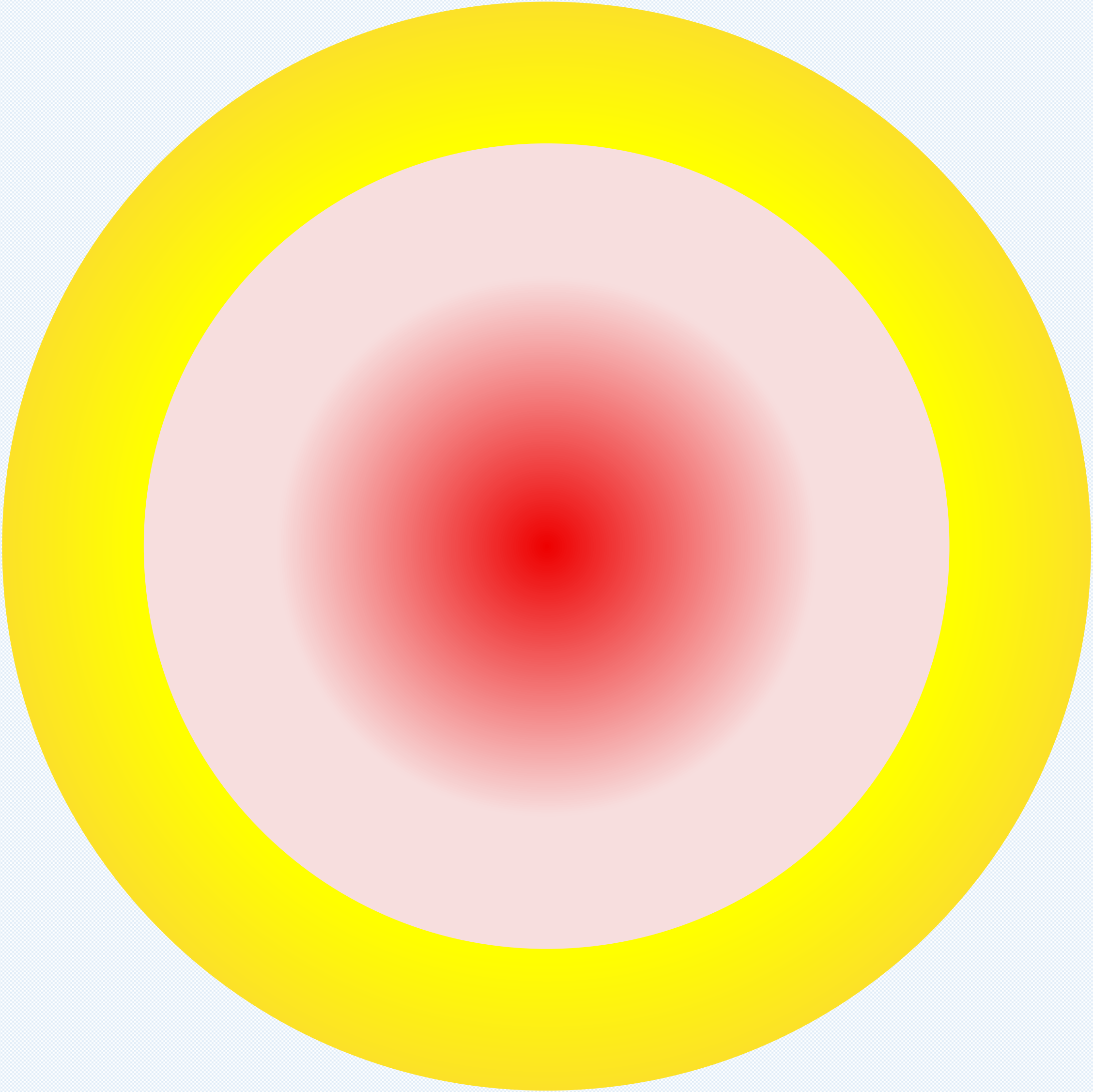
Thomas 1967, ZA, 67, 420

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



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

Single low-mass stellar evolution



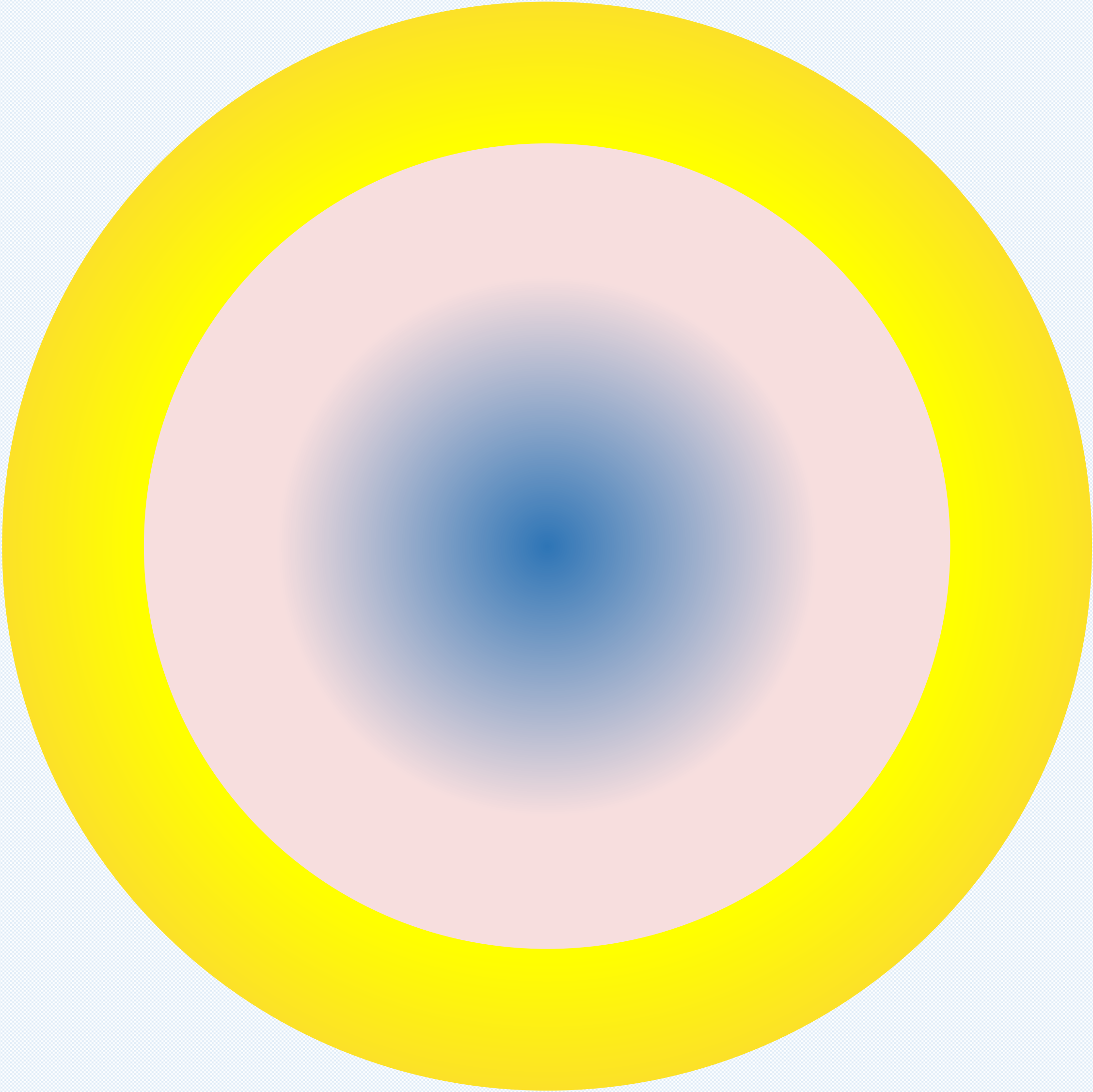
In **low-mass stars** the core is **radiative**

→ No efficient mixing in the core

→ Hydrogen is consumed starting in the center

→ Smooth transition to shell burning

Single low-mass stellar evolution

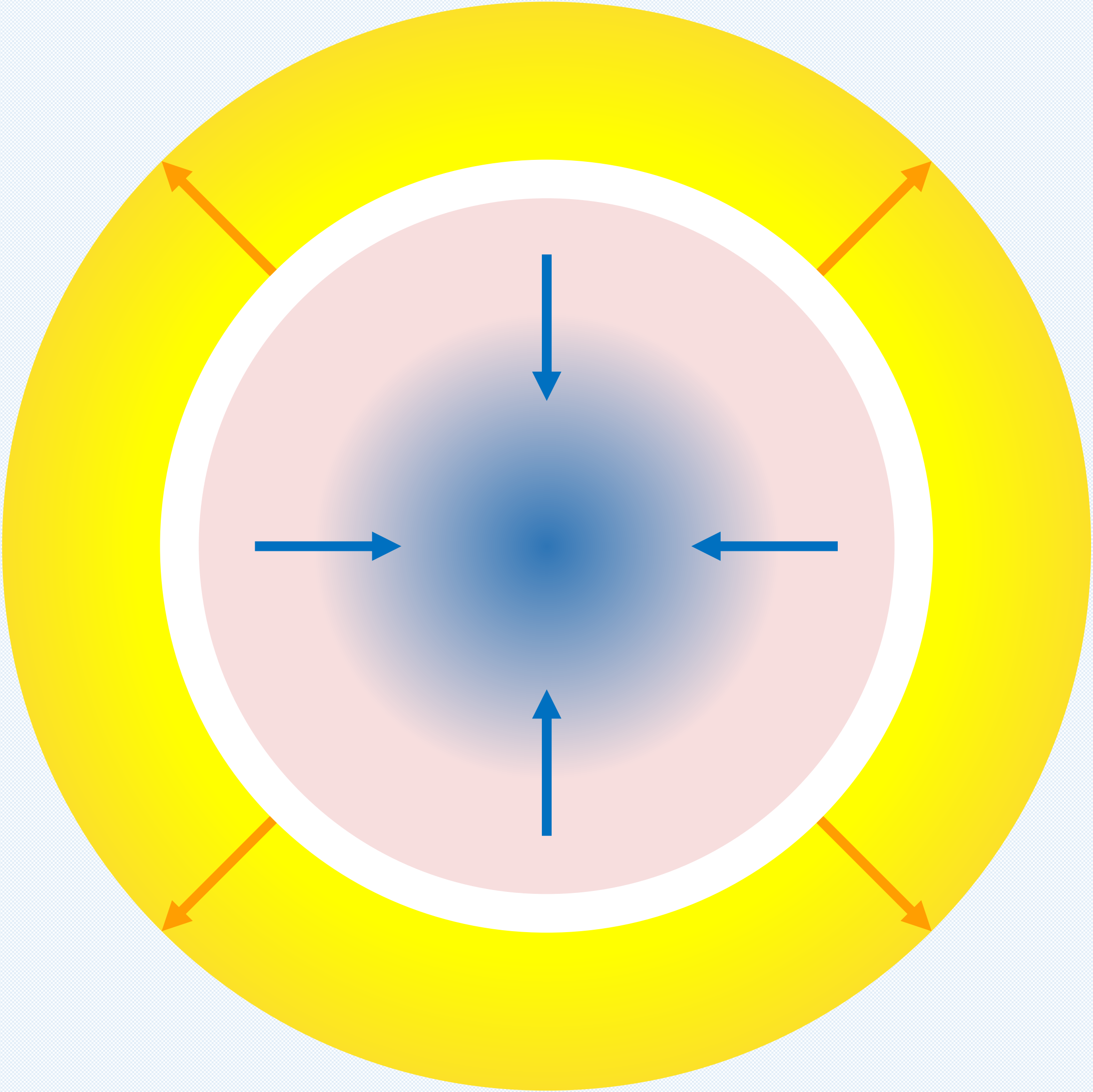


Due to the high density in the core, the electron gas becomes **degenerate**

→ Isothermal, degenerate core is stable

→ Core can grow in mass

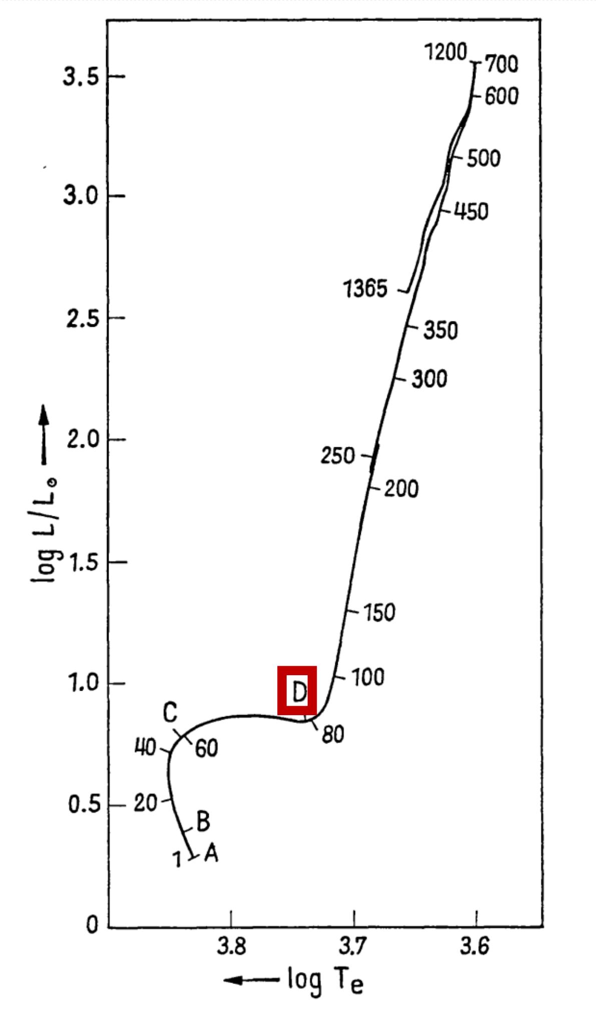
Single low-mass stellar evolution



No heating during core contraction
due to equation of state

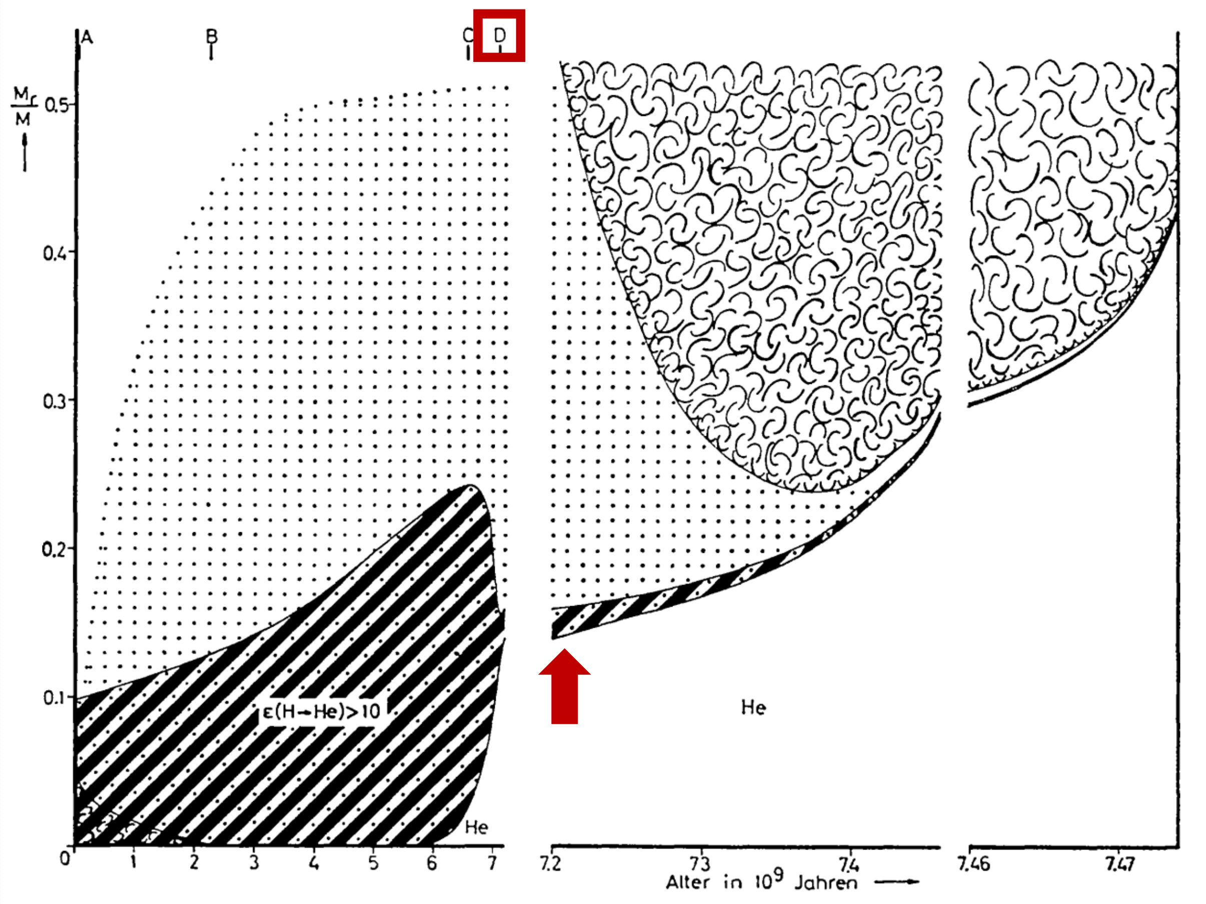
$$P_{\mathrm{e}} = 1.0036 \times 10^{13} \left(\frac{\rho}{\mu_{\mathrm{e}}}\right)^{5/3}$$

Single low-mass stellar evolution



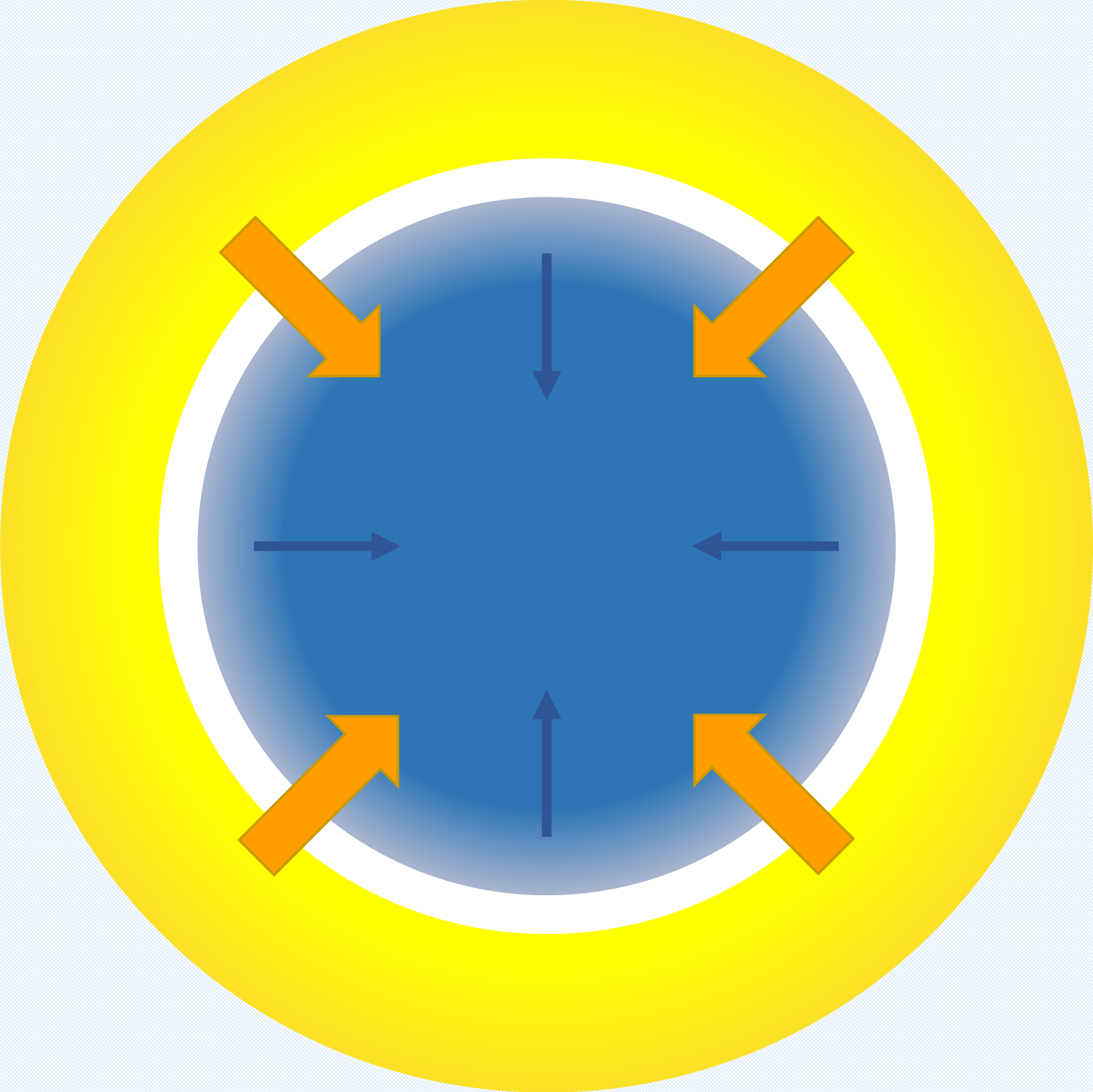
Thomas 1967, ZA, 67, 420

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



H-shell burning starts → Core contracts, envelope expands

Single low-mass stellar evolution

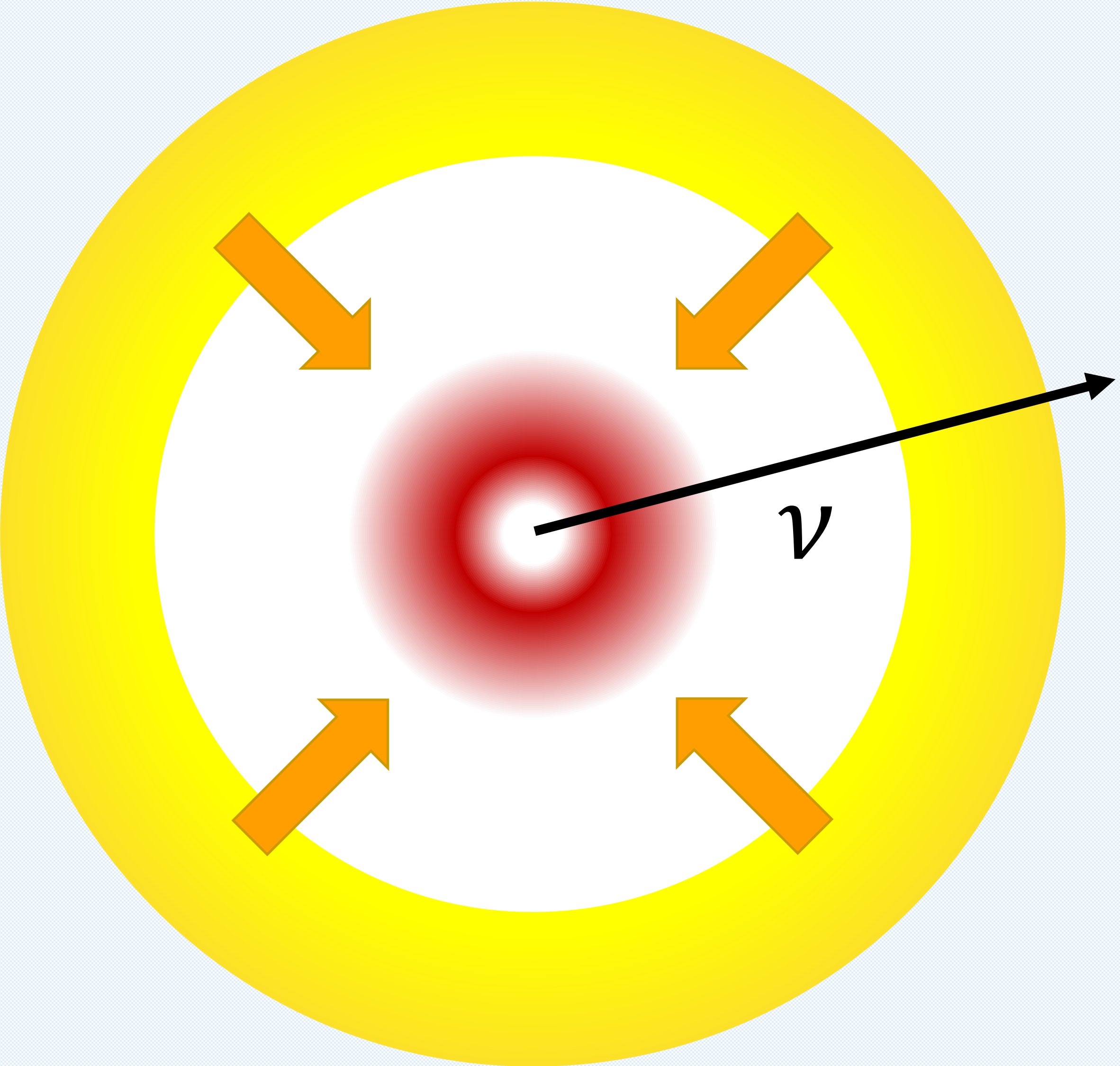


Temperature of the core increases

→ Increase of temperature in the H-burning shell

→ Core contraction heats transition layer between core and shell

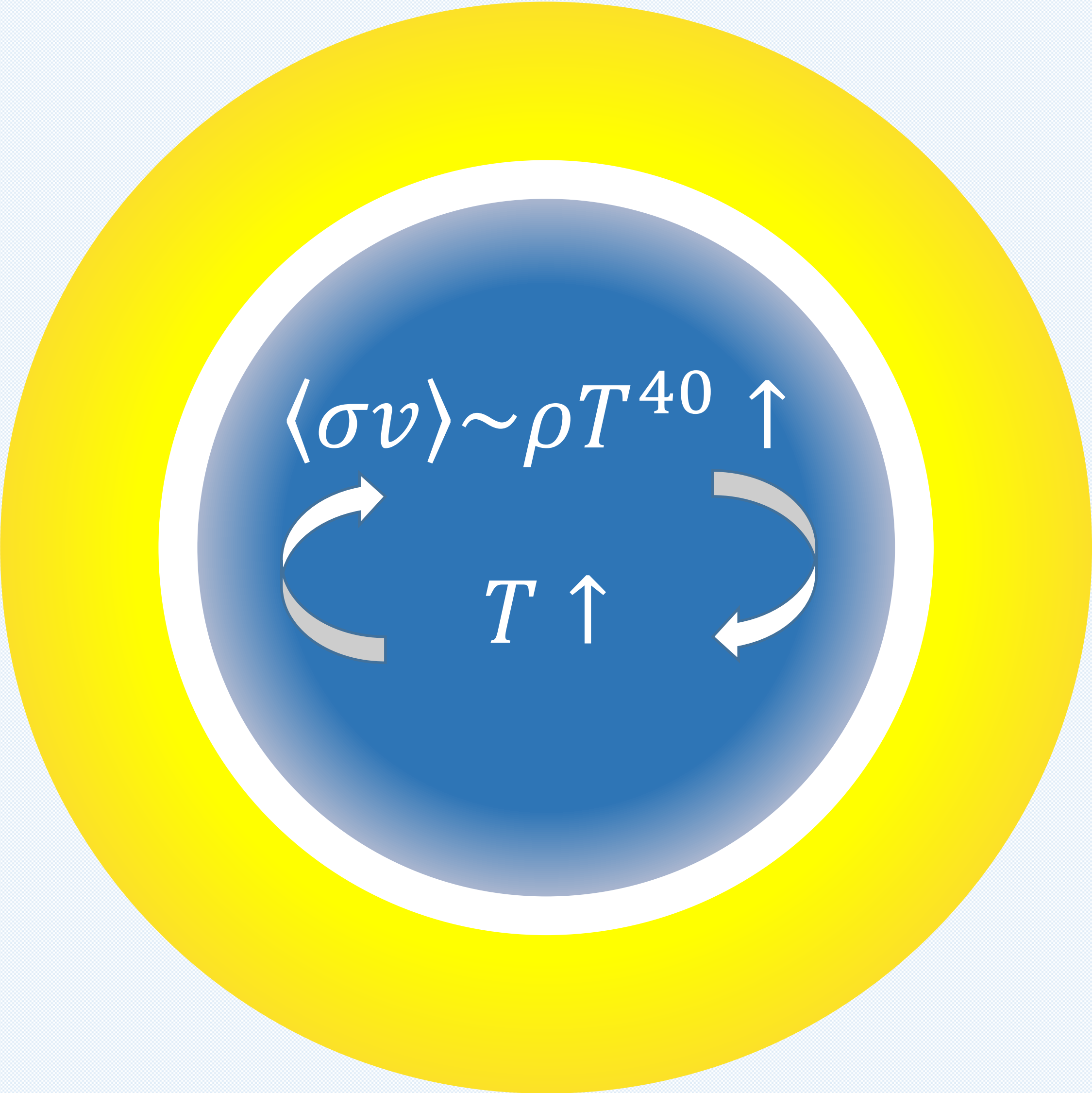
Single low-mass stellar evolution



Critical temperature for helium burning $(\sim 10^8\ \mathrm{K})$ 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

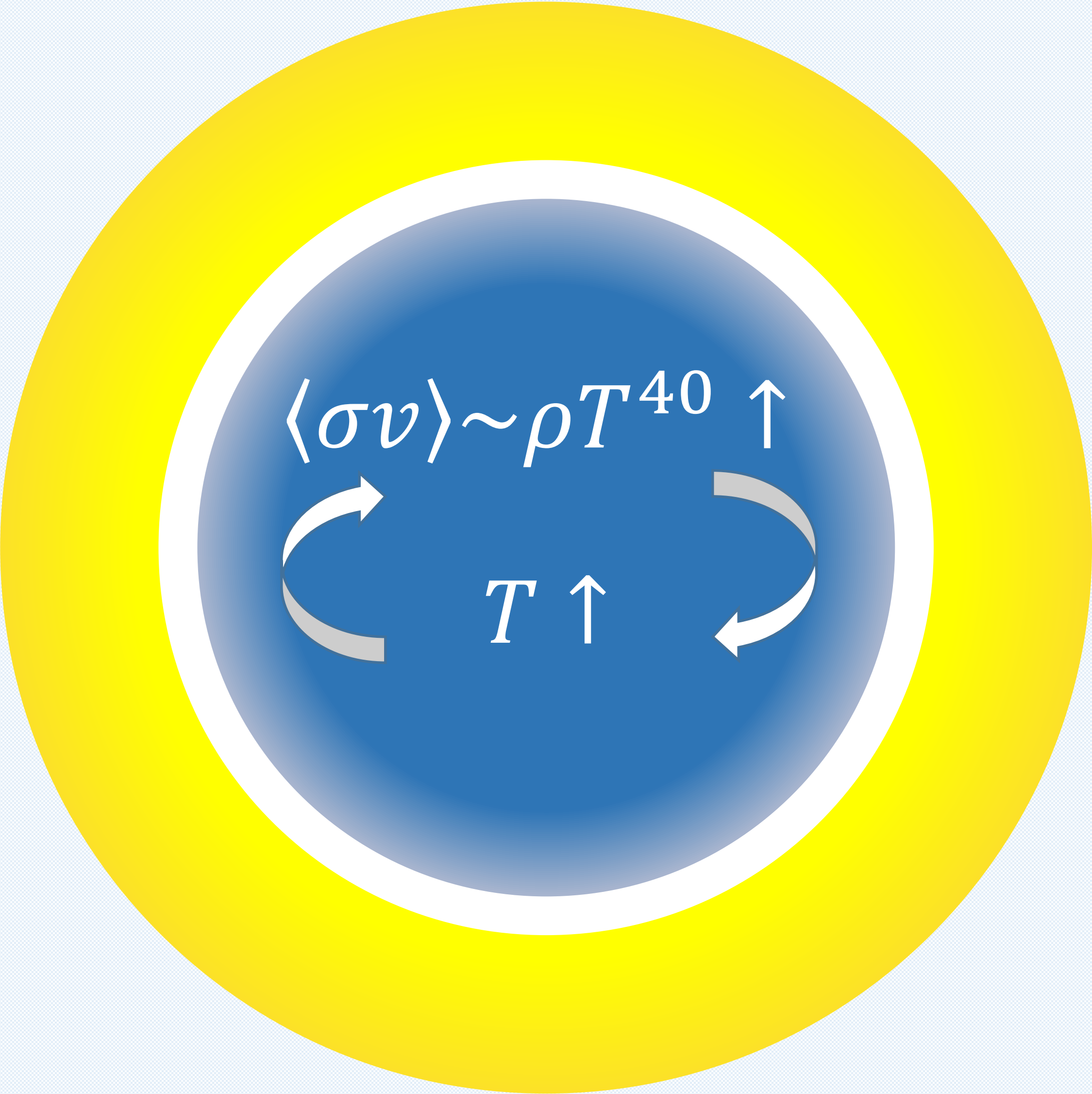
Single low-mass stellar evolution



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

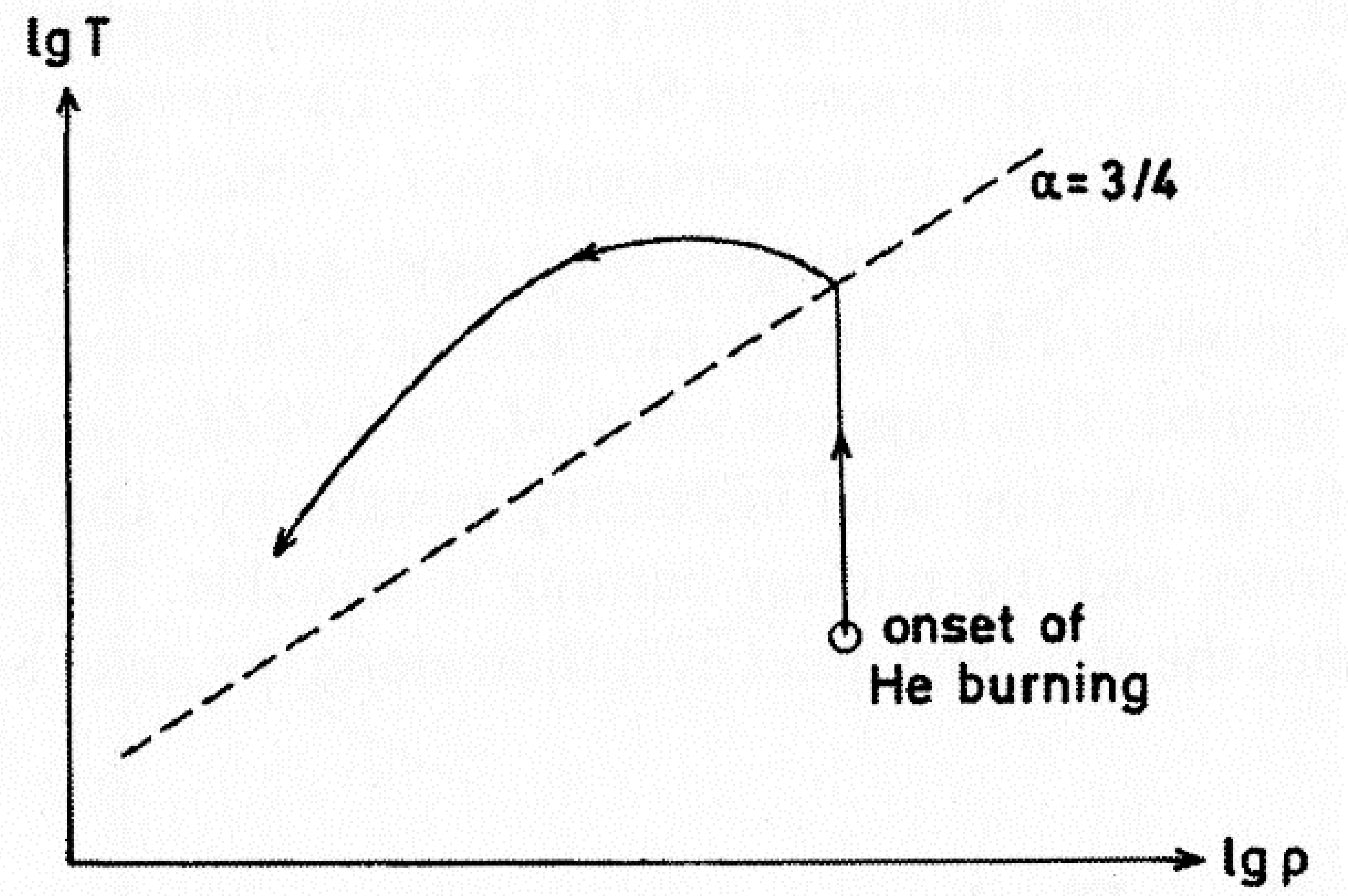
Single low-mass stellar evolution



Runaway burning of helium

Helium flash

Single low-mass stellar evolution



Kippenhahn, Weigert & Weiss 2012

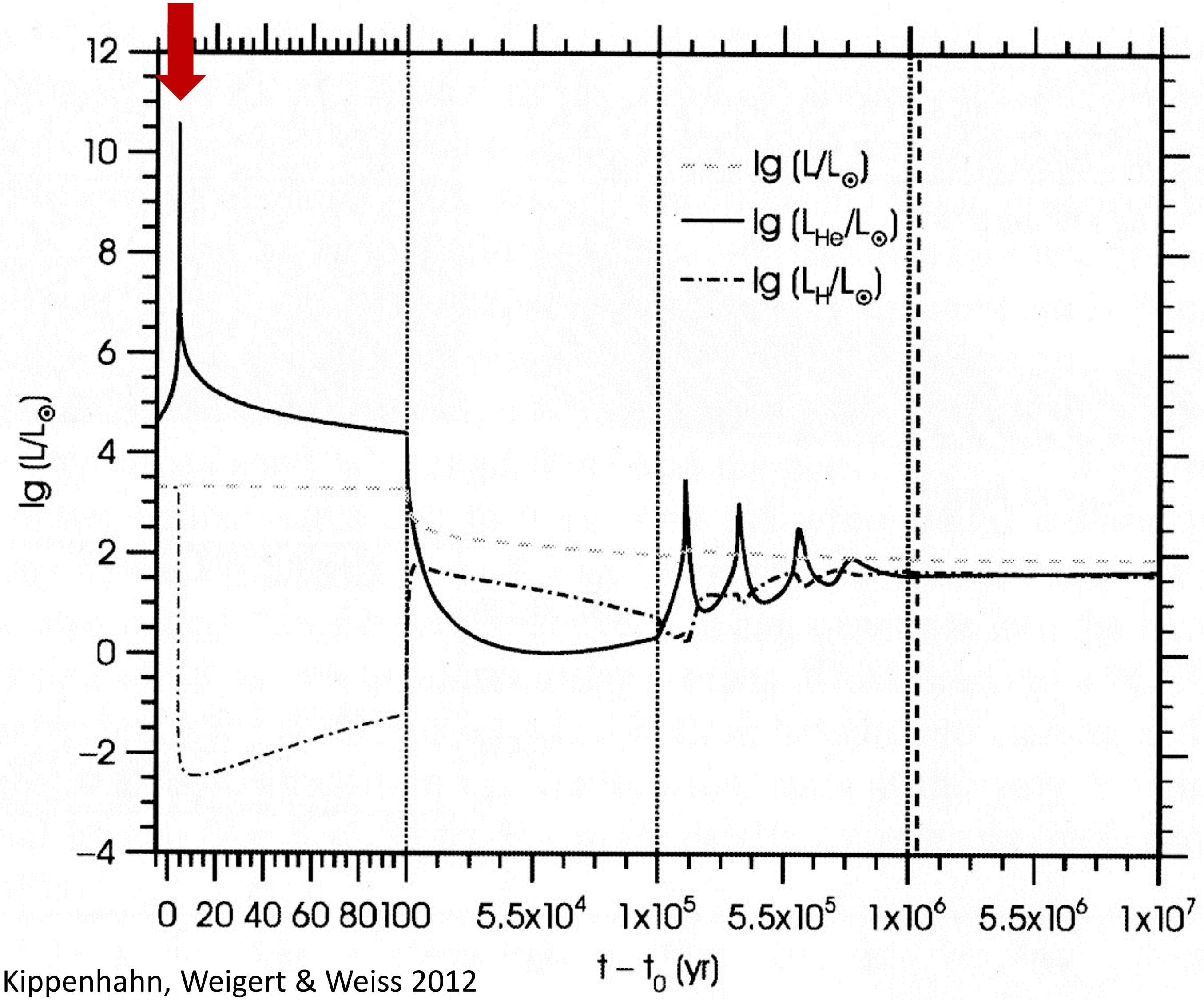
Runaway burning of helium under degenerate conditions

→ Degeneracy is lifted

→ Core expands, density drops

→ **Stable He-core burning**

Single low-mass stellar evolution

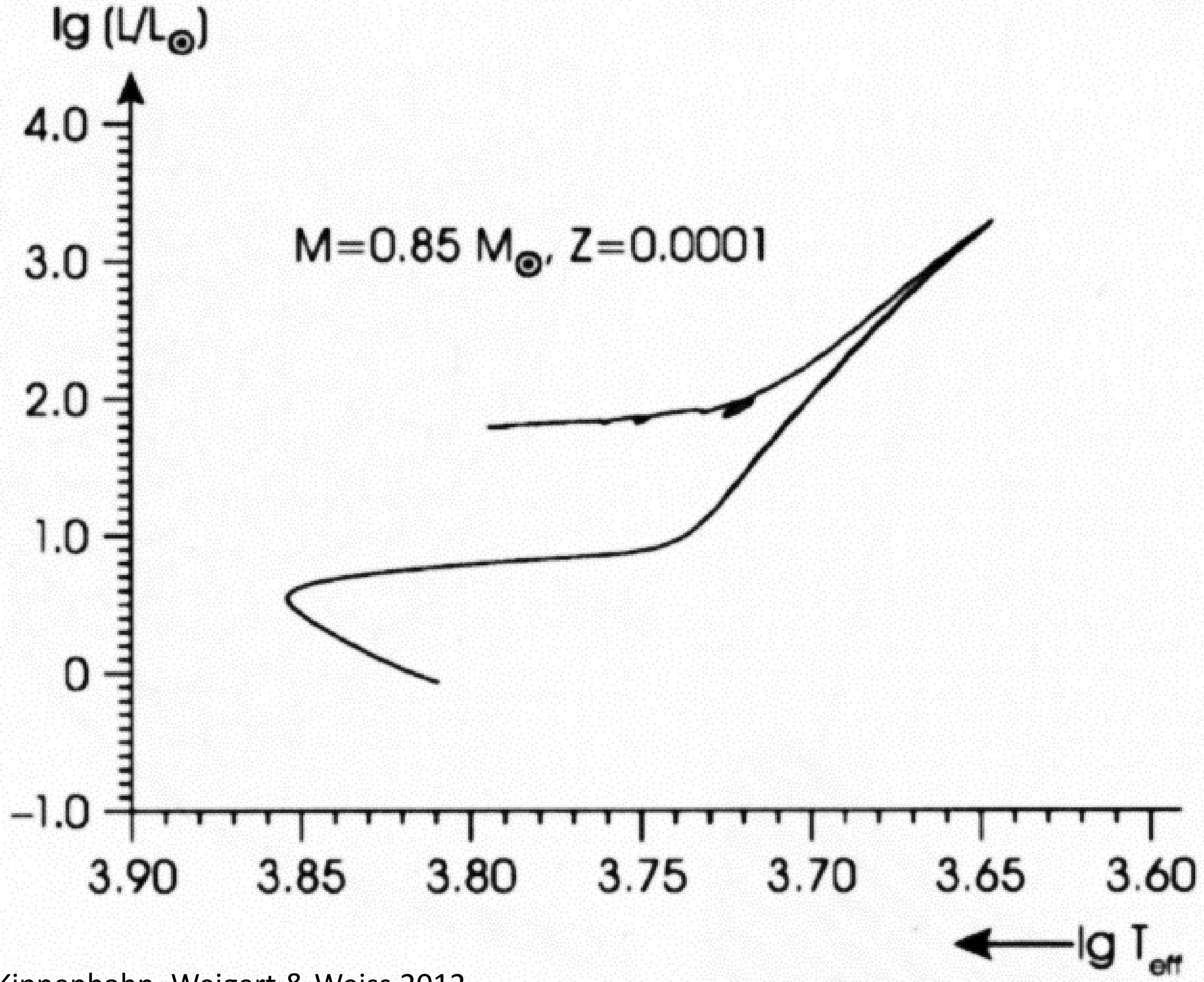


Kippenhahn, Weigert & Weiss 2012

Luminosity of the core during the flash higher than the luminosity of the Galaxy $(10^{11}\ L_\odot)$

→ Trapped in the envelope

Horizontal branch stars



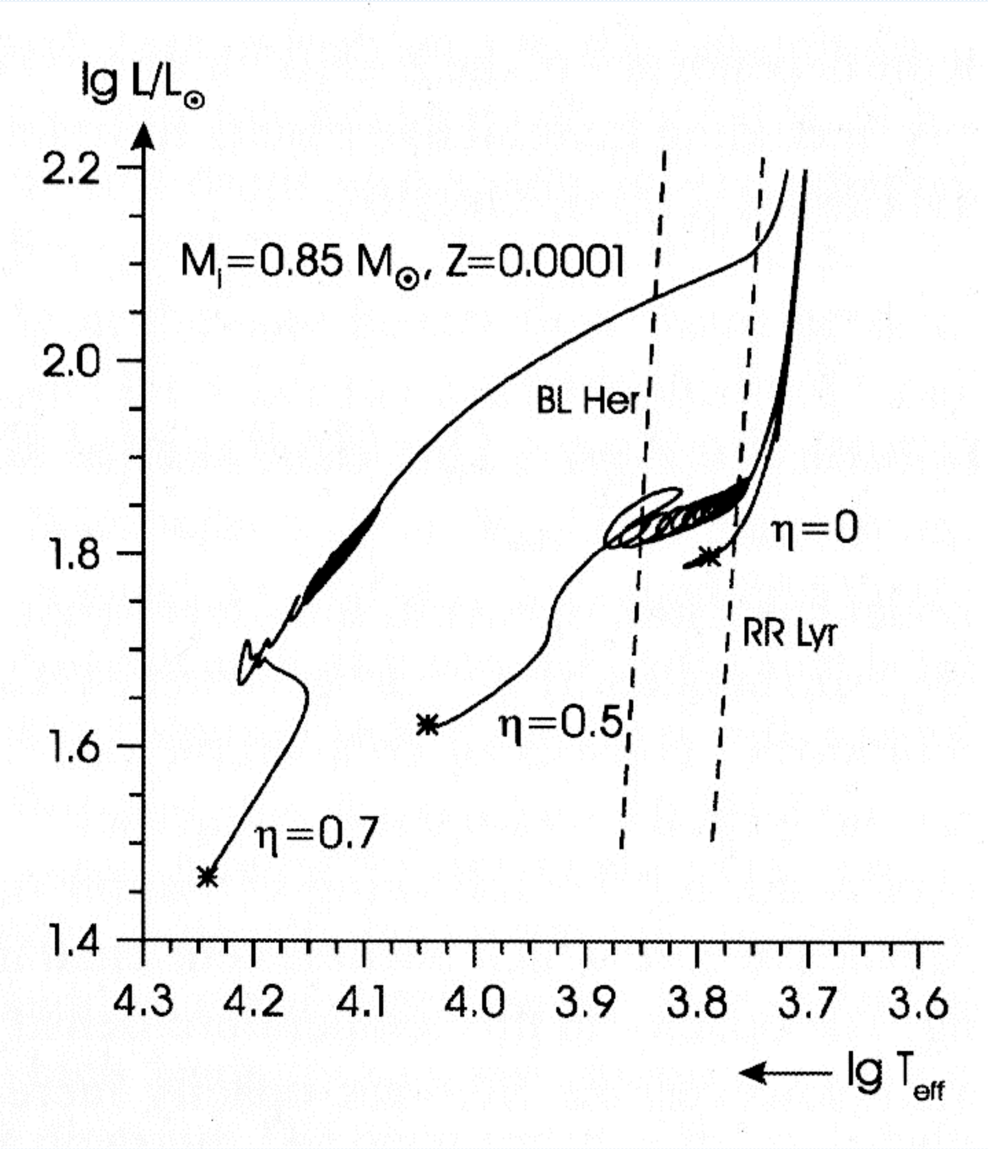
Kippenhahn, Weigert & Weiss 2012

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

→ Stars occupy a region of (about) constant luminosity

Horizontal Branch

Horizontal branch stars



Kippenhahn, Weigert & Weiss 2012

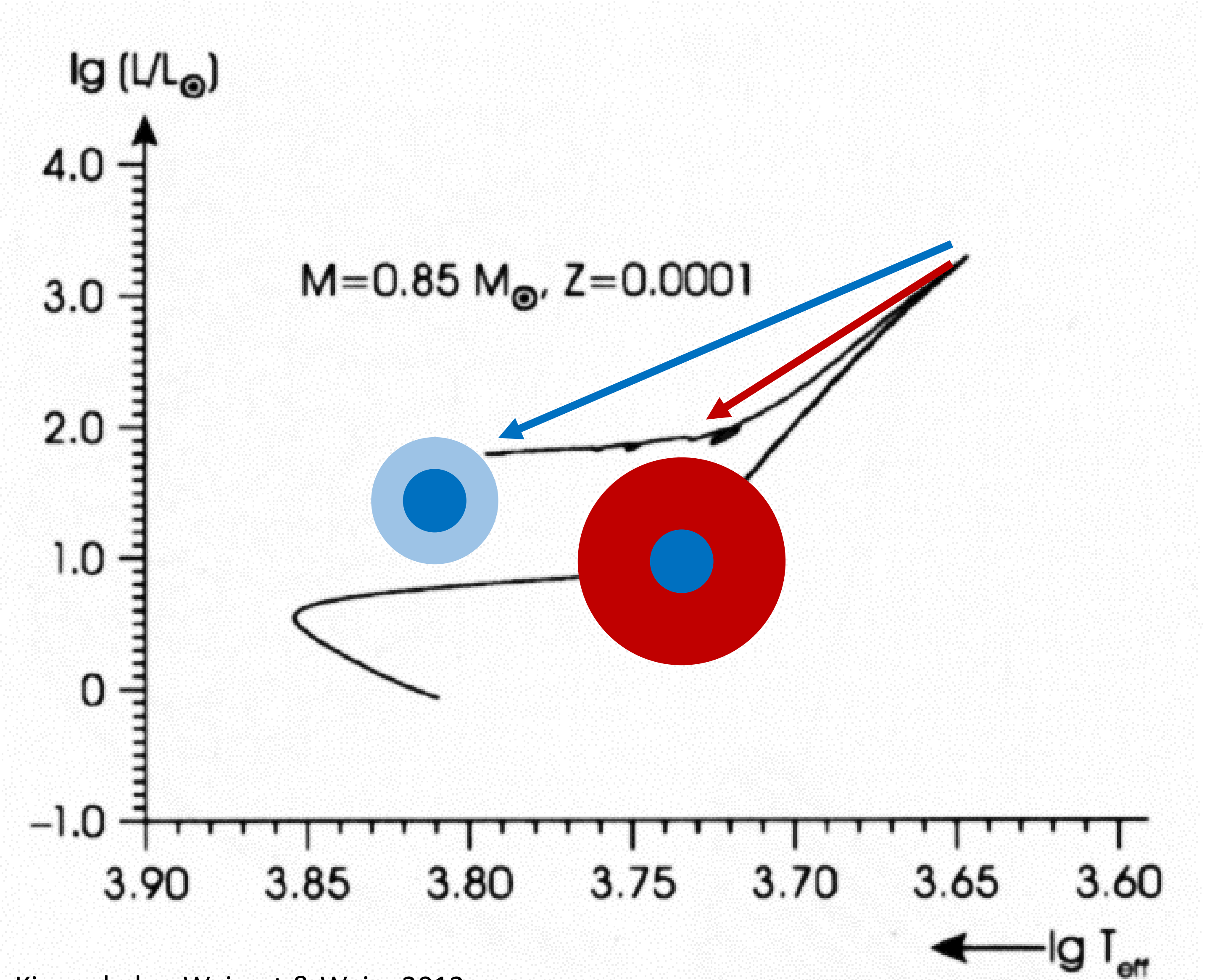
Horizontal Branch stars

→ 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**

Horizontal branch stars



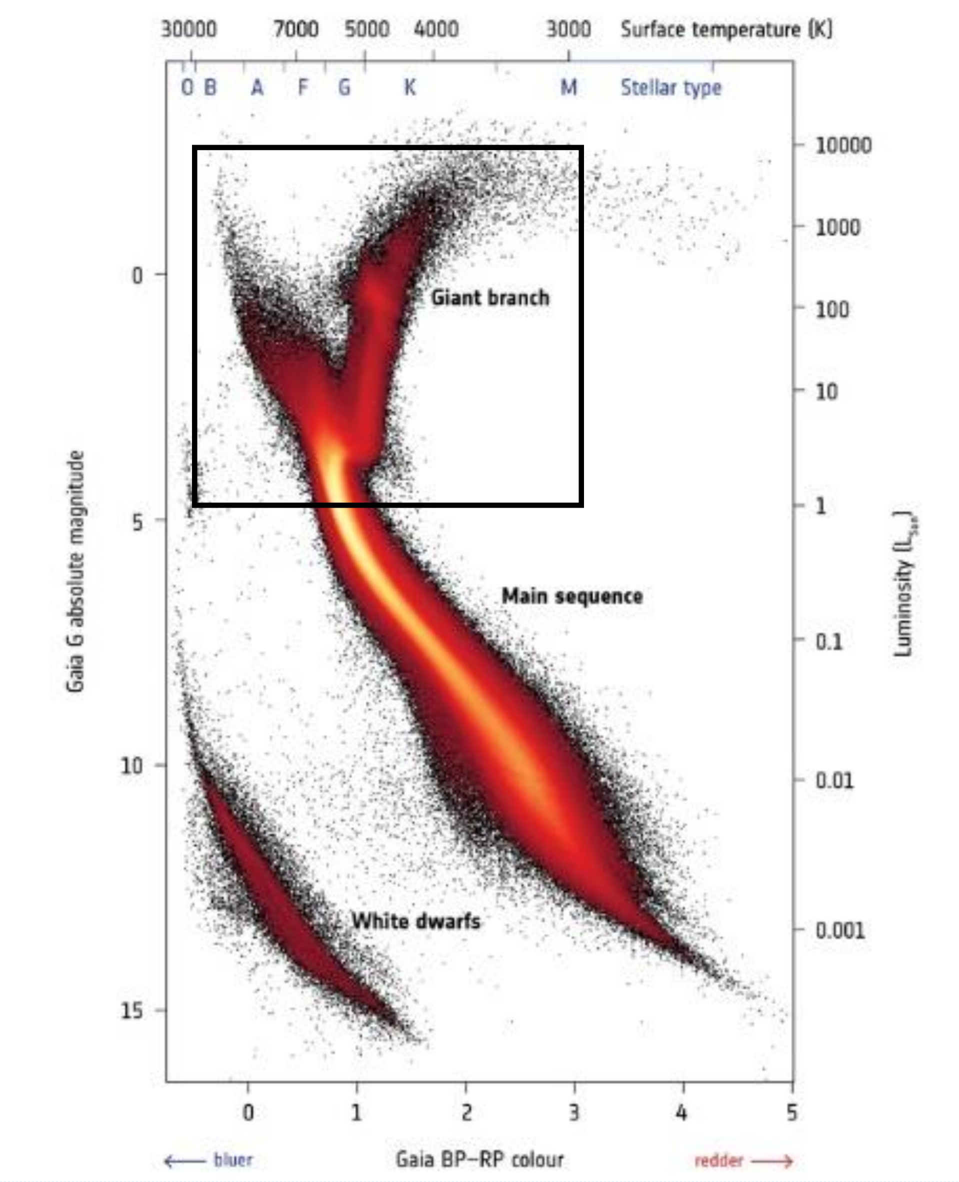
Kippenhahn, Weigert & Weiss 2012

Horizontal Branch stars

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

→ Morphology of HB depends on metallicity and age

Horizontal branch stars



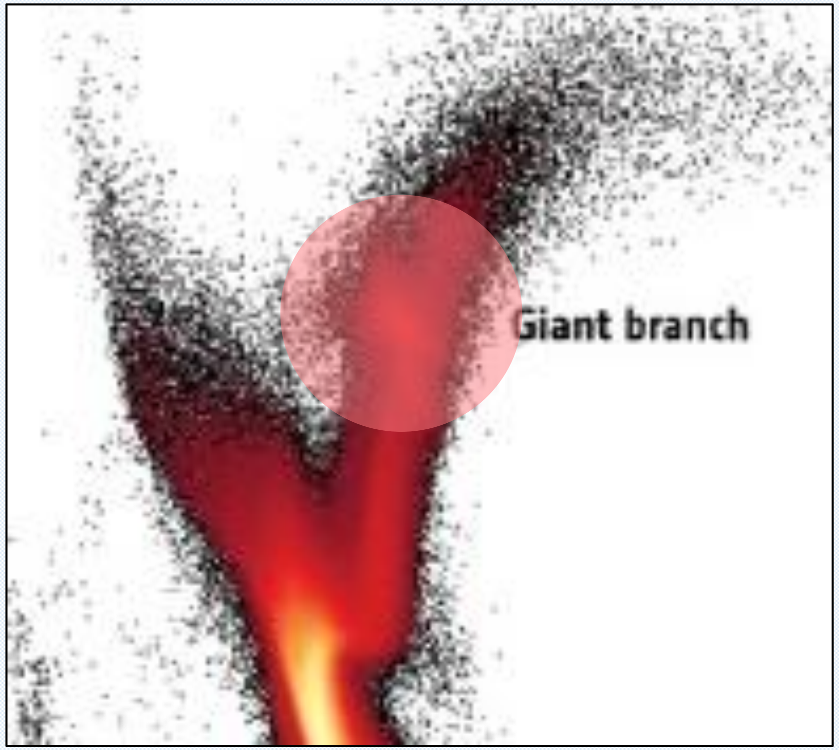
Gaia collaboration 2018, A&A, 616, 10

Red Clump stars

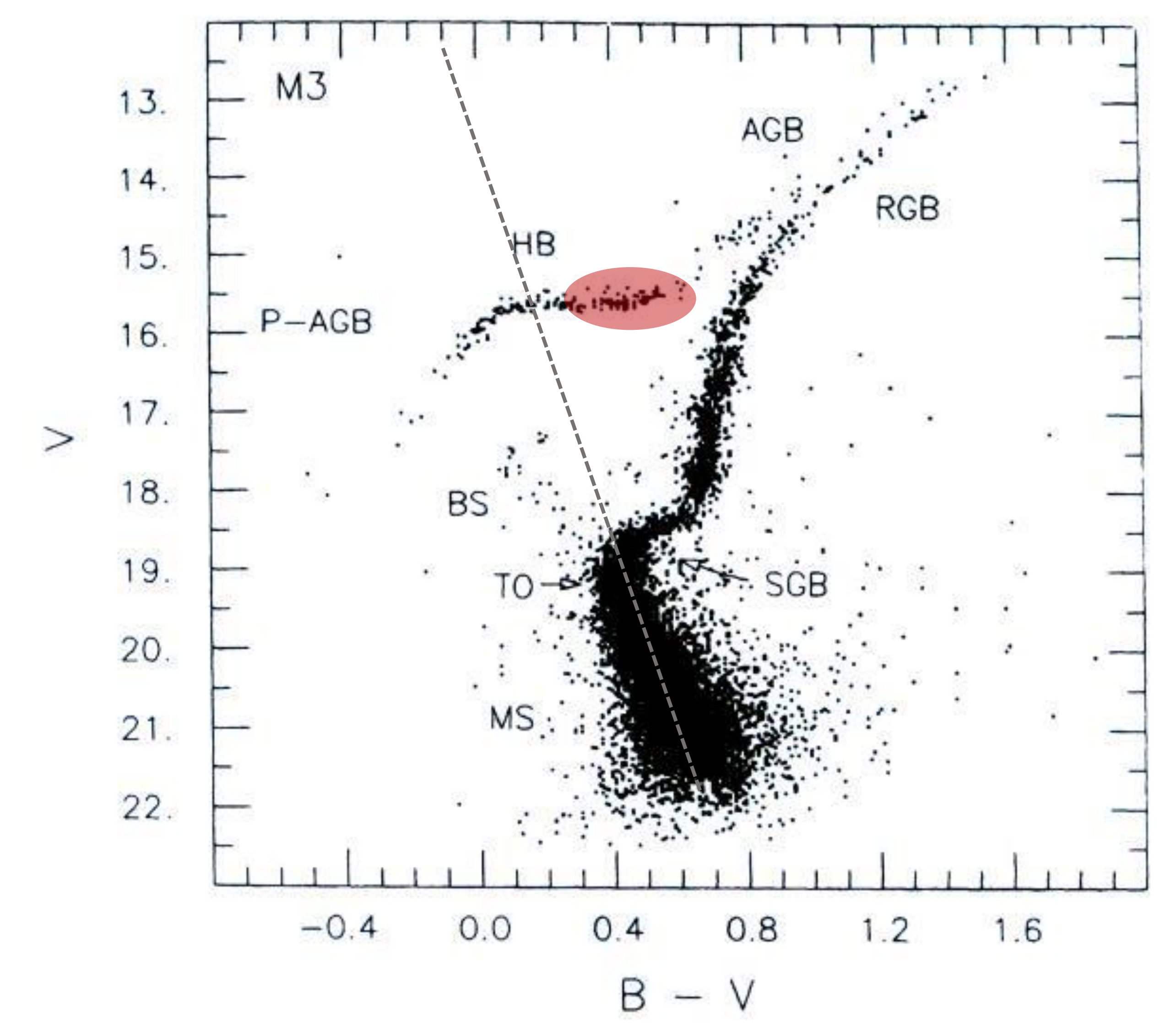
→ Red giants

→ Intermediate mass stars

→ Young population



Horizontal branch stars



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

Red Horizontal Branch (RHB) stars

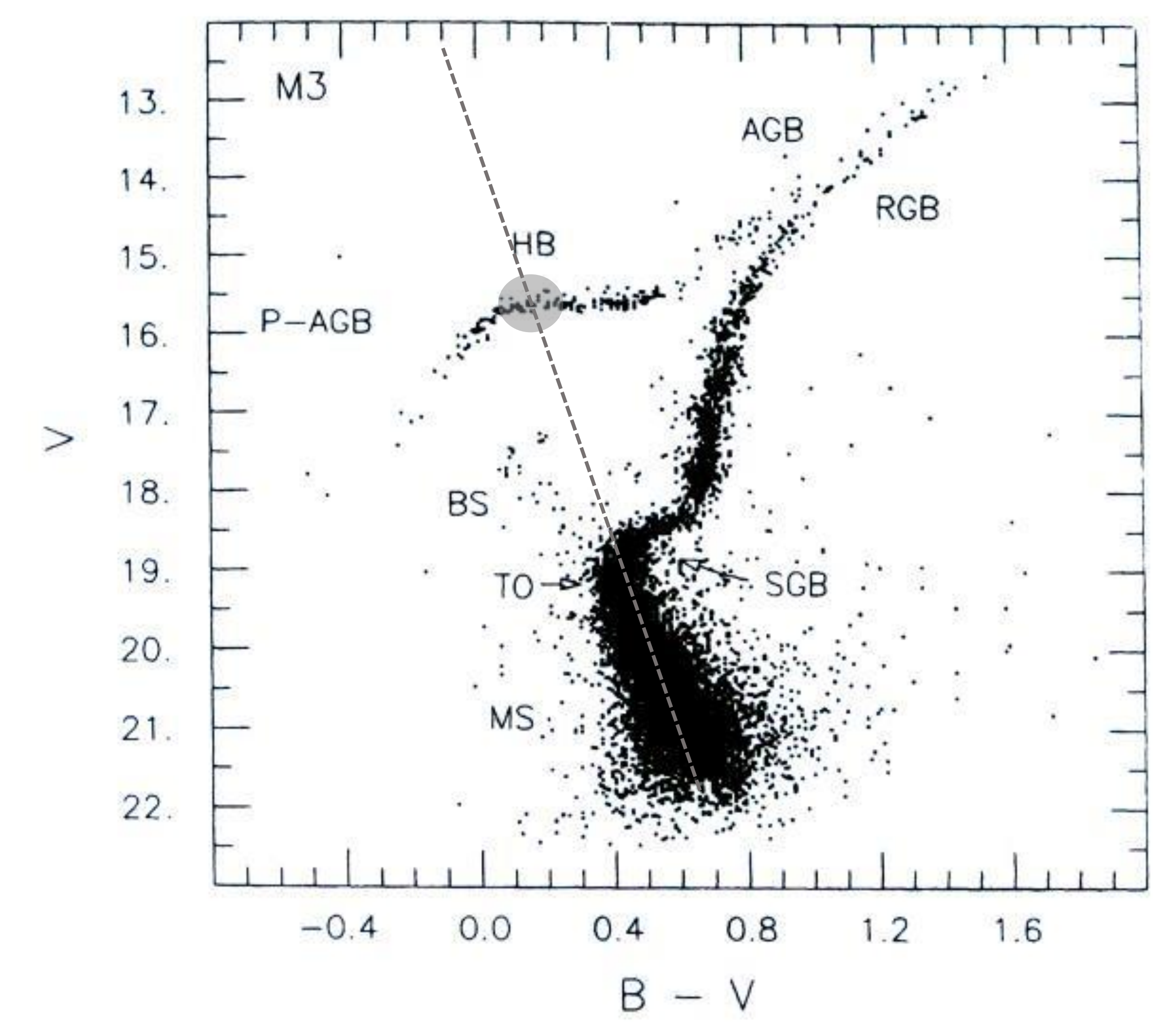
→ Redward of the MS

→ (Sub-)giants

→ Spectral types K, G

→ metal-poor, old population

Horizontal branch stars



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

RR Lyr stars

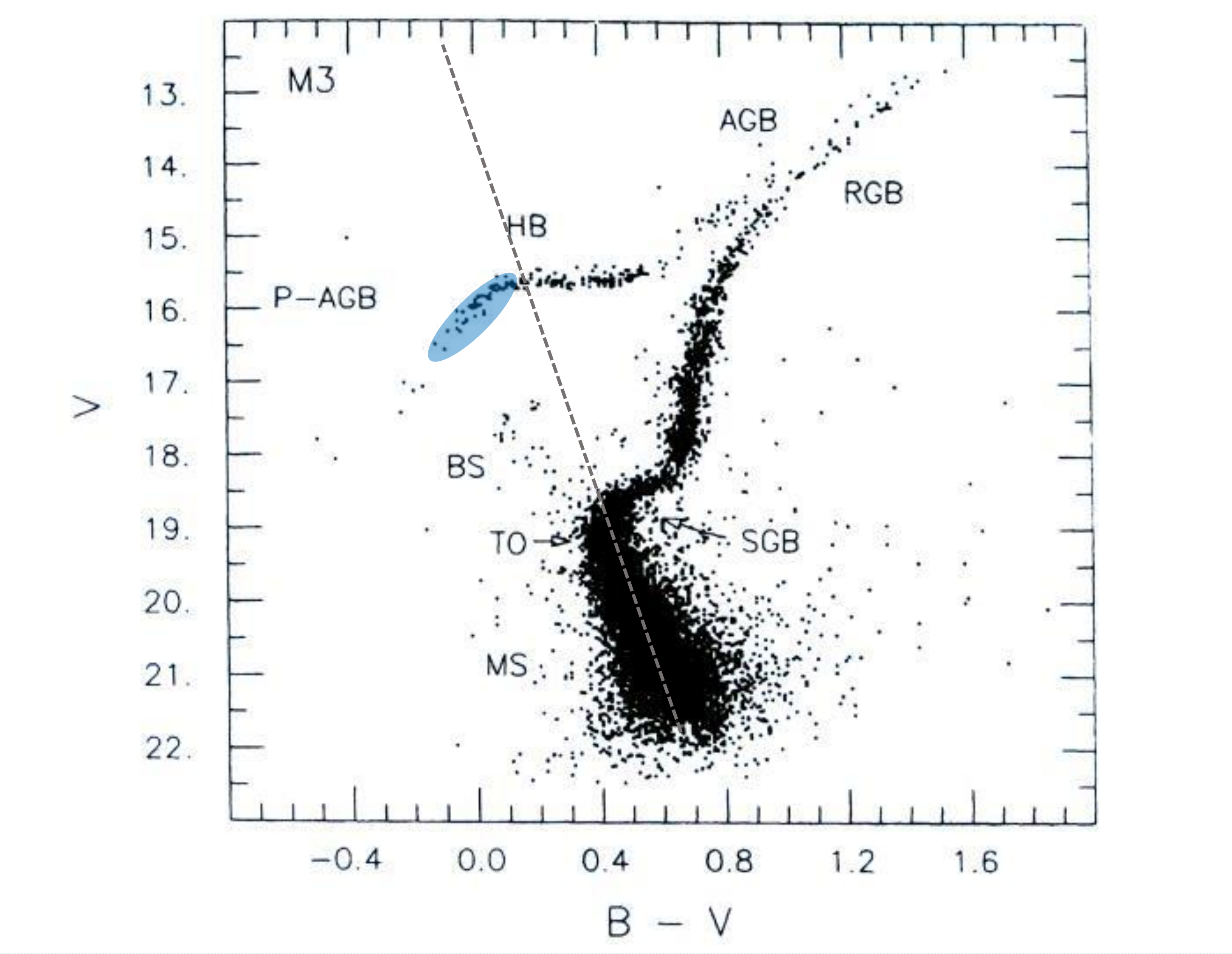
→ (Sub-)giants

→ Spectral types F

→ metal-poor, old population

→ Pulsators

Horizontal branch stars



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

Blue Horizontal Branch (BHB) stars

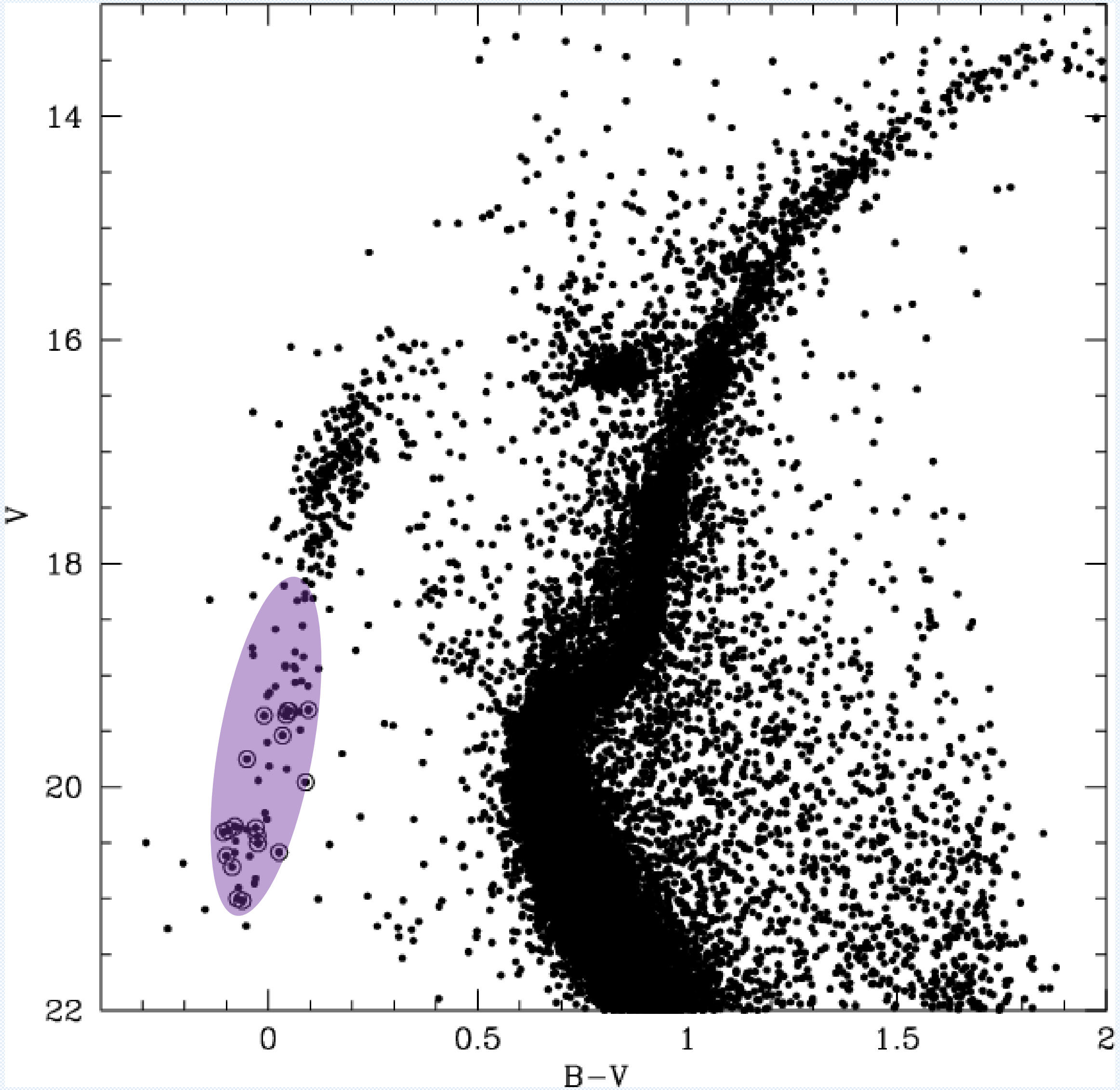
→ Blueward of the MS

→ (Sub-)dwarfs

→ Spectral types A, B (HBA, HBB)

→ chemically peculiar

Horizontal branch stars



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

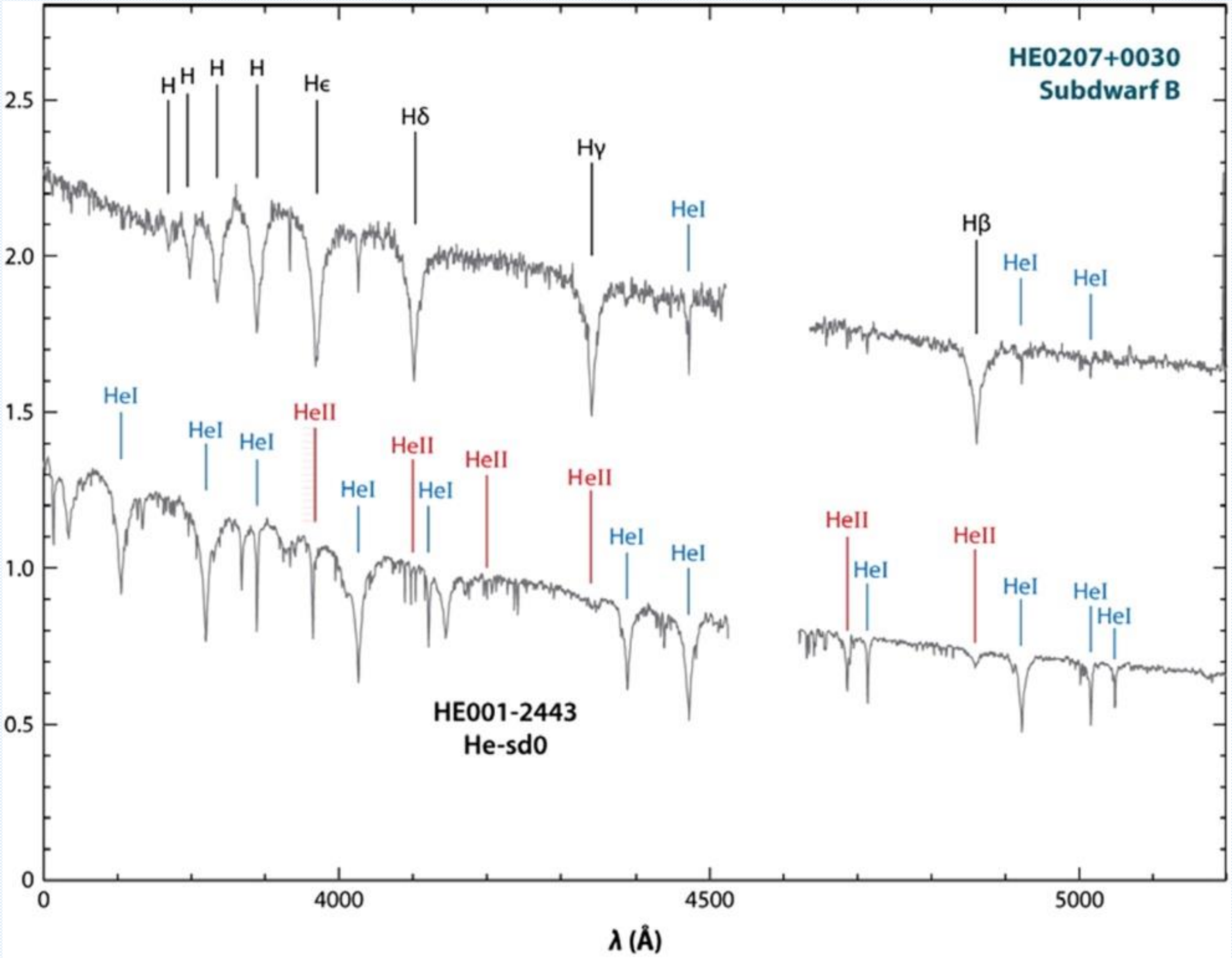
Extreme Horizontal Branch (EHB) stars

→ Subdwarfs

→ Spectral types O, B (sdO, sdB)

→ Extremely thin hydrogen envelopes, **no H-shell burning**

Horizontal branch stars



Heber 2016, PASP, 128, 966

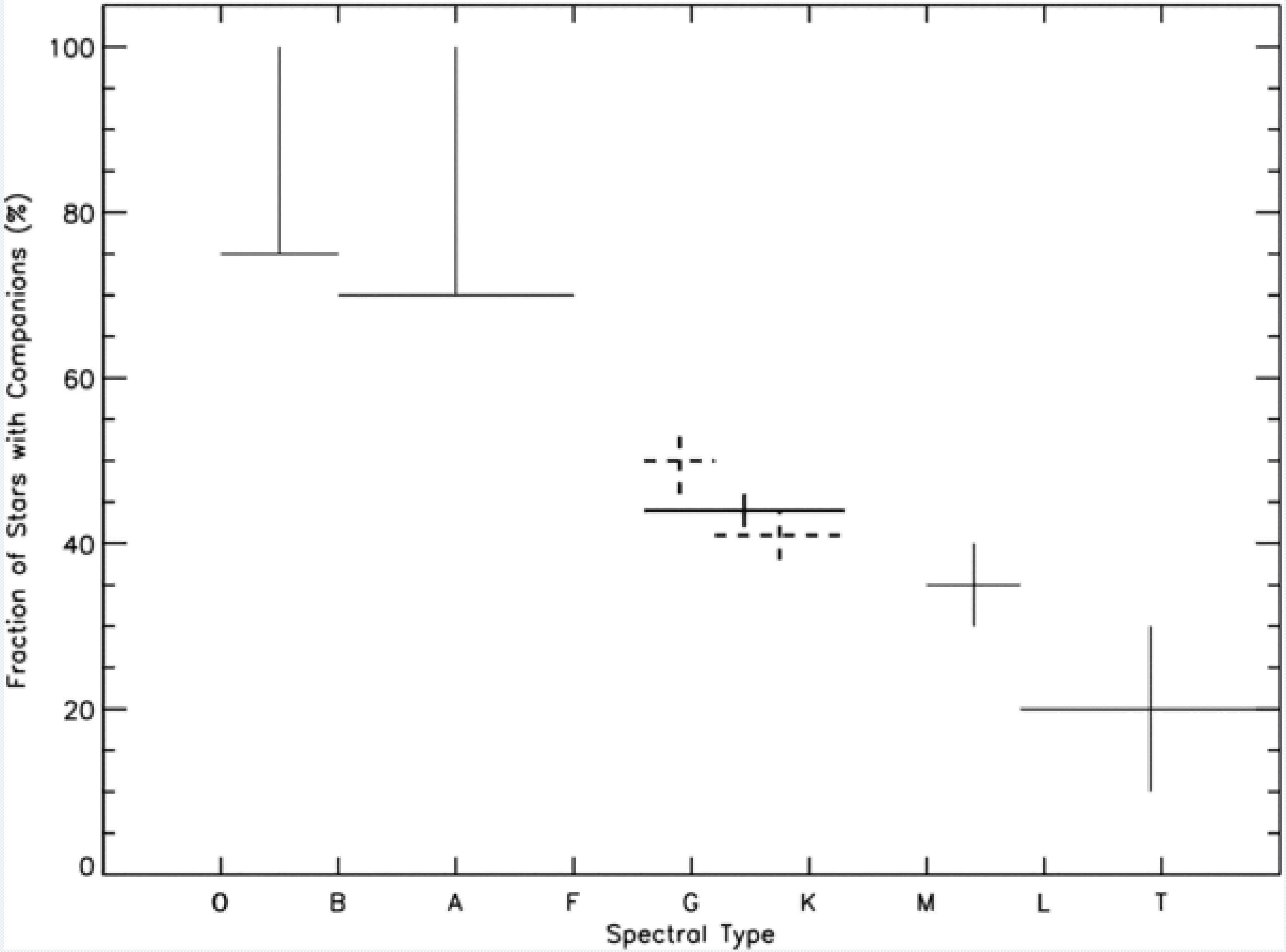
Hydrogen-rich sdBs

→ very low to solar helium content

→ Light elements depleted, heavy elements enriched

→ High binary fraction

Binary evolution



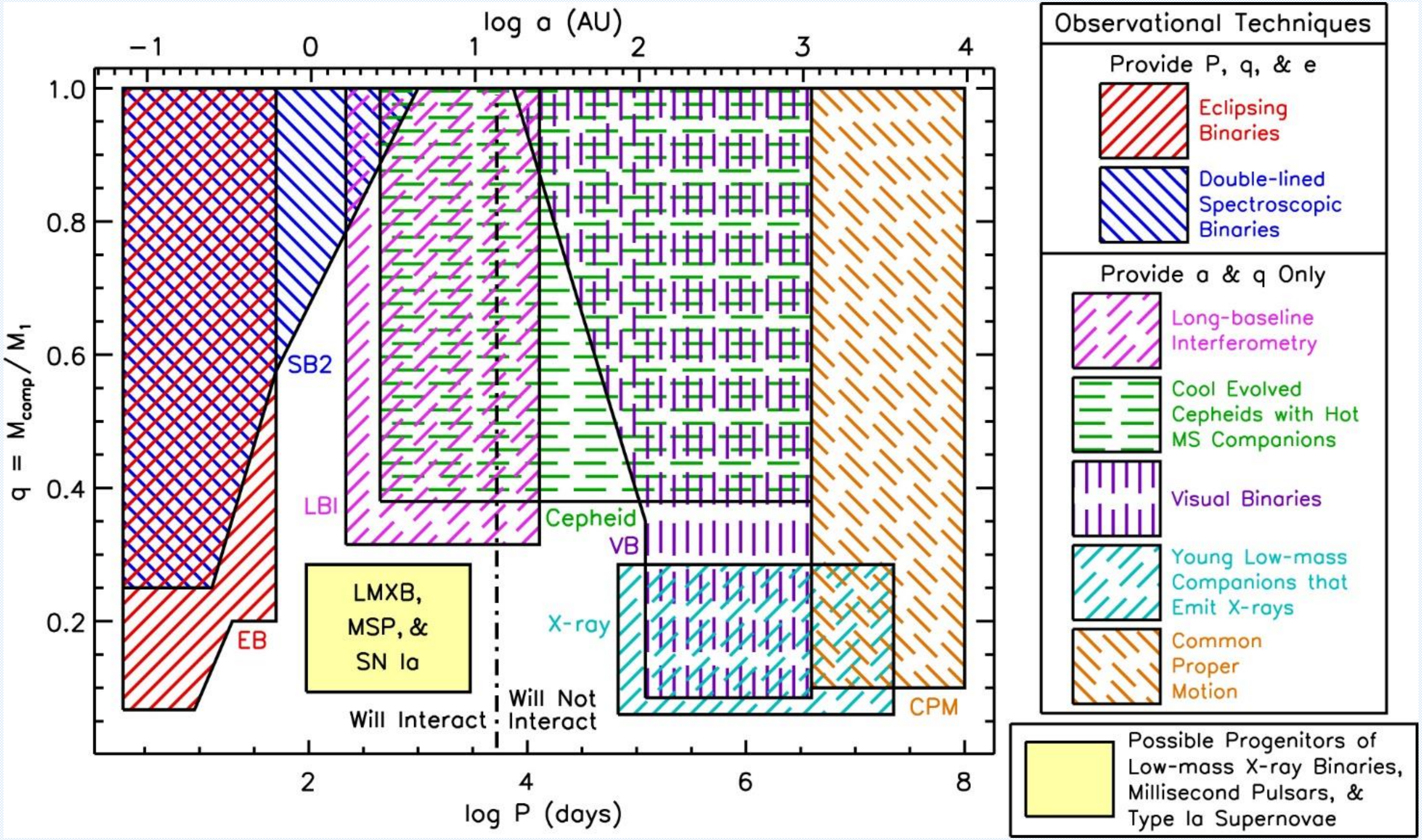
Raghavan et al. 2010, ApJS, 190, 1

Binary fraction on the main sequence depends on stellar mass

$\sim 10\ \%$ **triple**

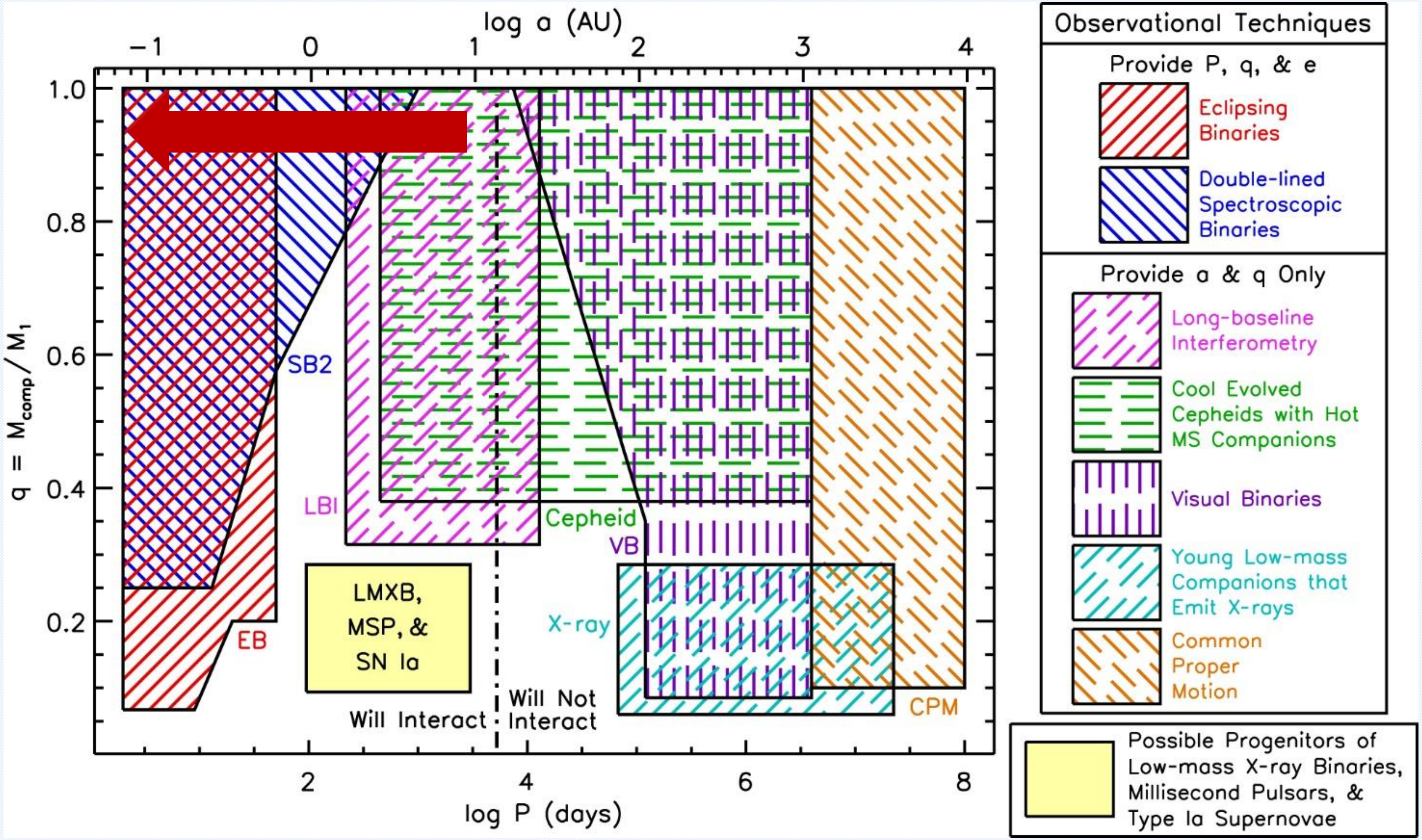
$\sim 1\ \%$ **quadruple or higher multiple systems**

Binary evolution



Moe & di Stefano 2017, ApJS, 230, 2

Binary evolution



Moe & di Stefano 2017, ApJS, 230, 2

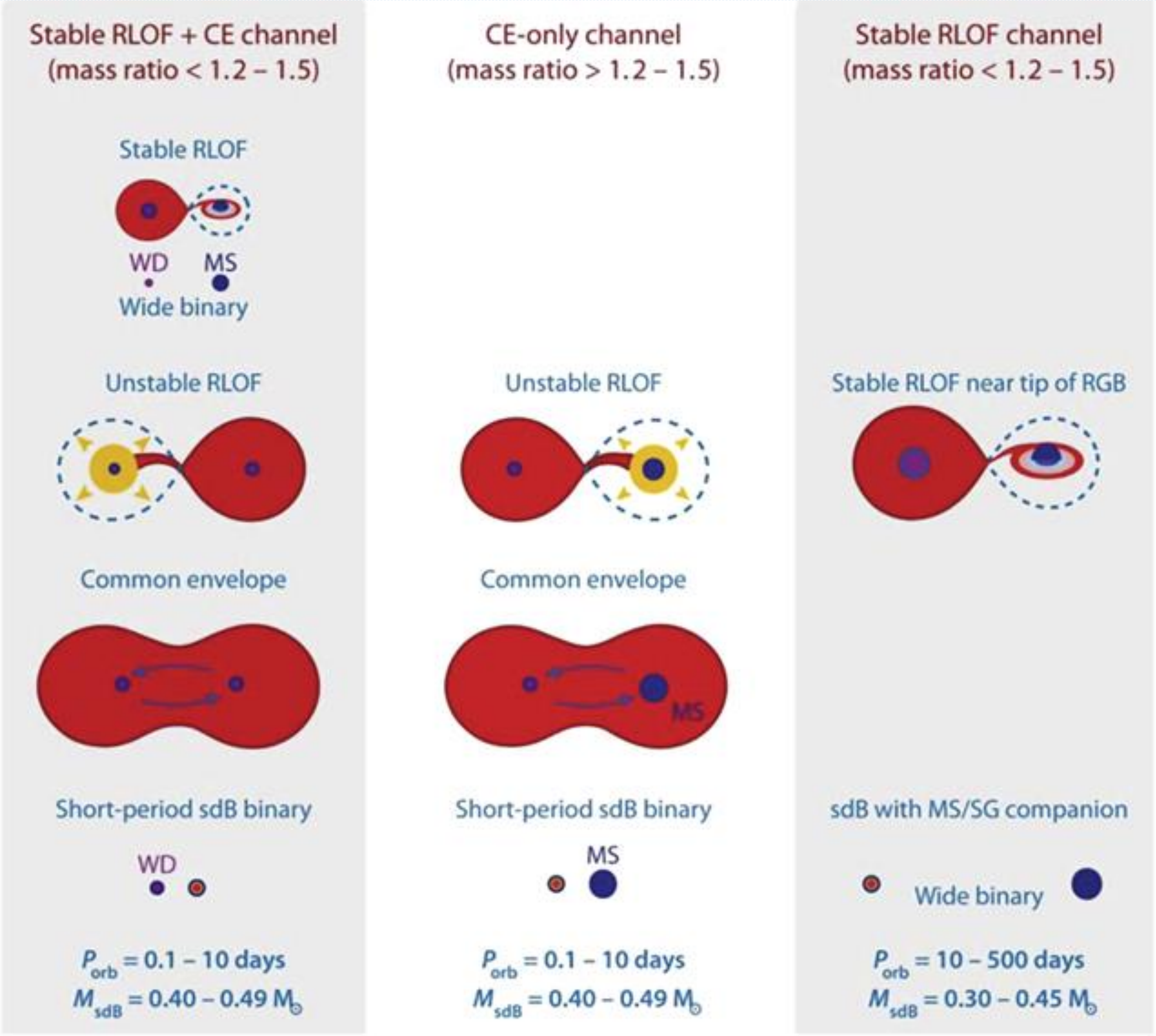
Binary evolution

Reichardt 2016, Youtube

Stable mass transfer

Common envelope phase

Binary evolution



Heber 2016, PASP, 128, 966

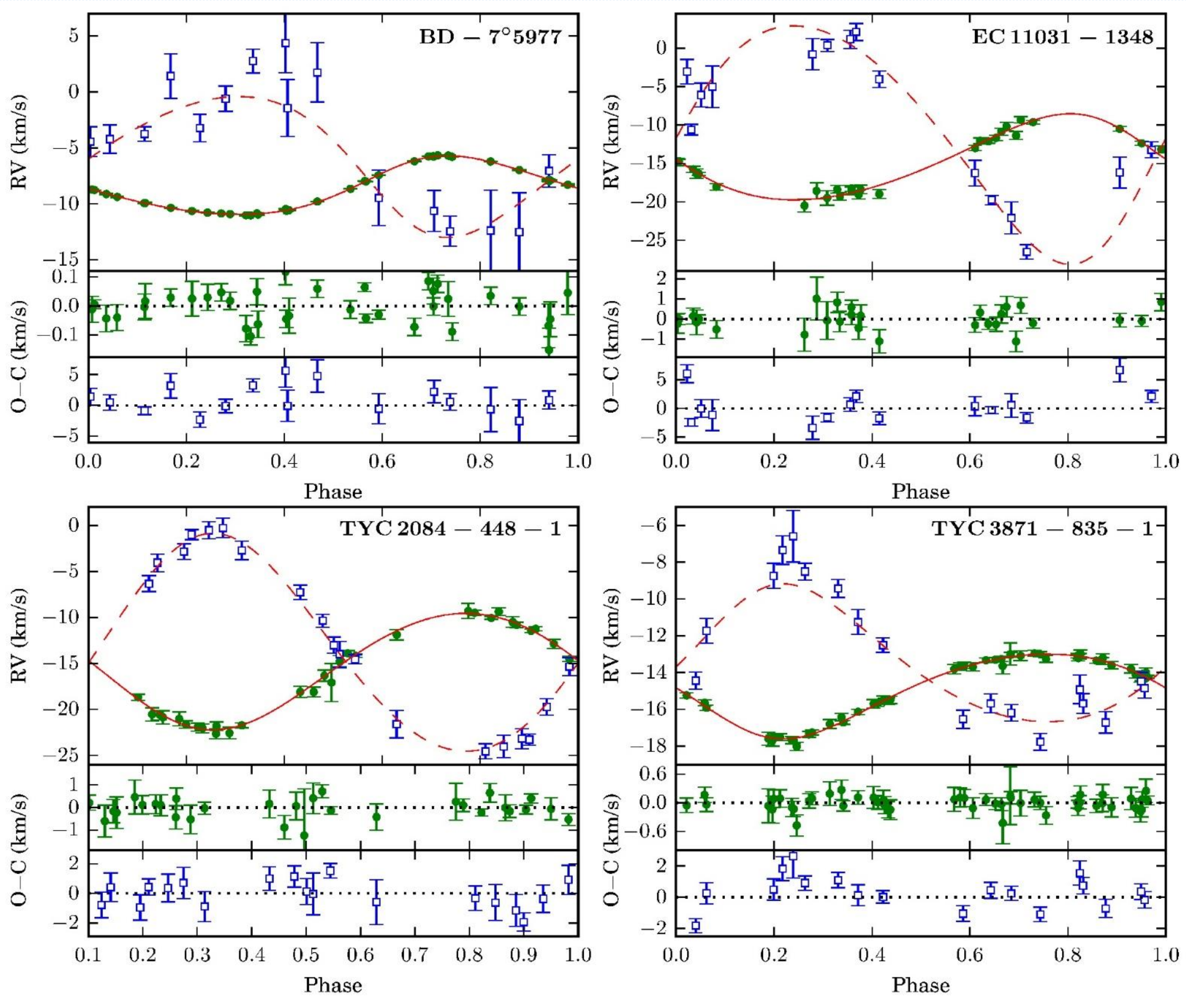
Close binary evolution

→ 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 evolution



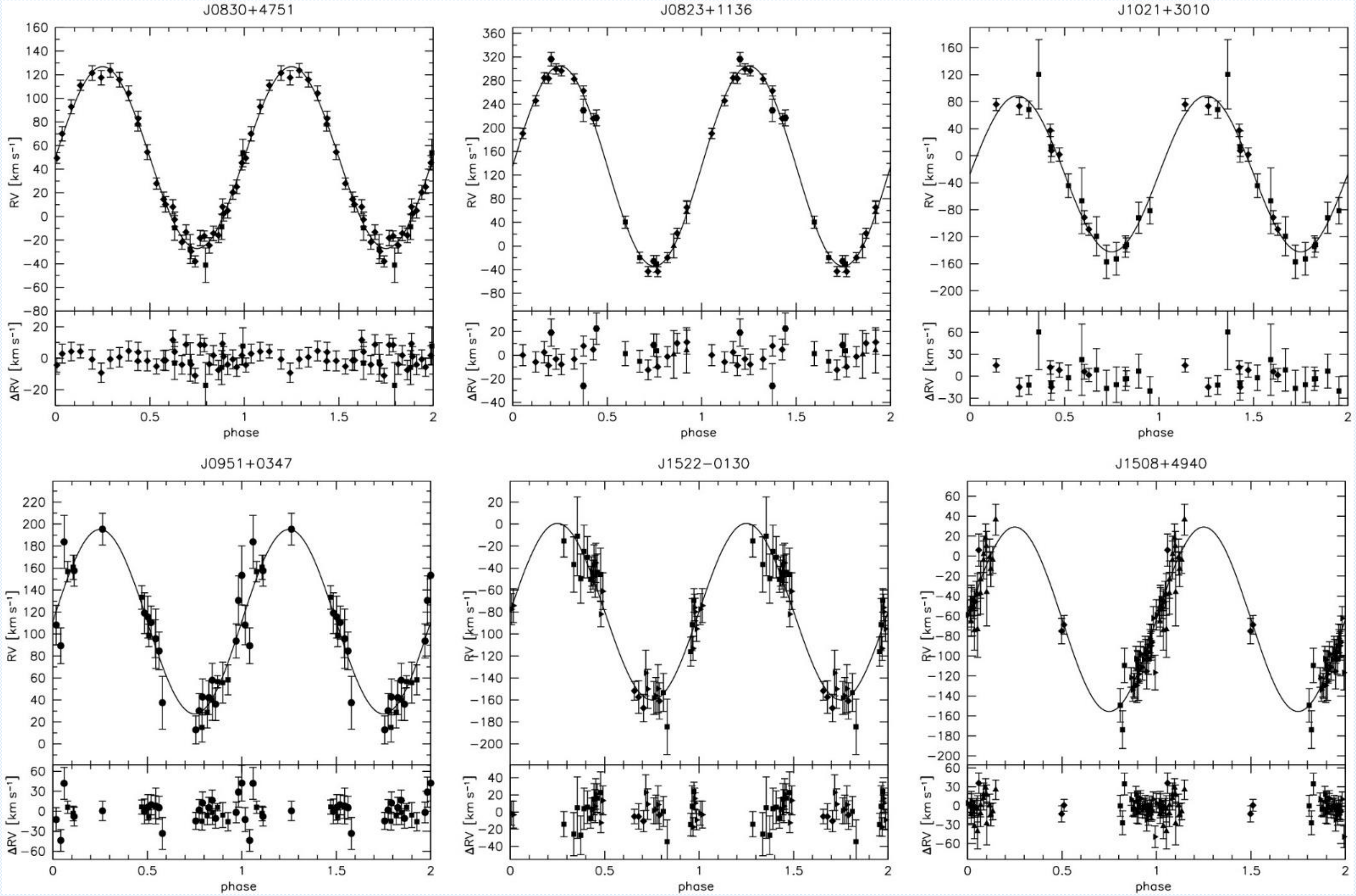
Vos et al. 2017, A&A, 605, 109

$\sim 30\%$ 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

Binary evolution



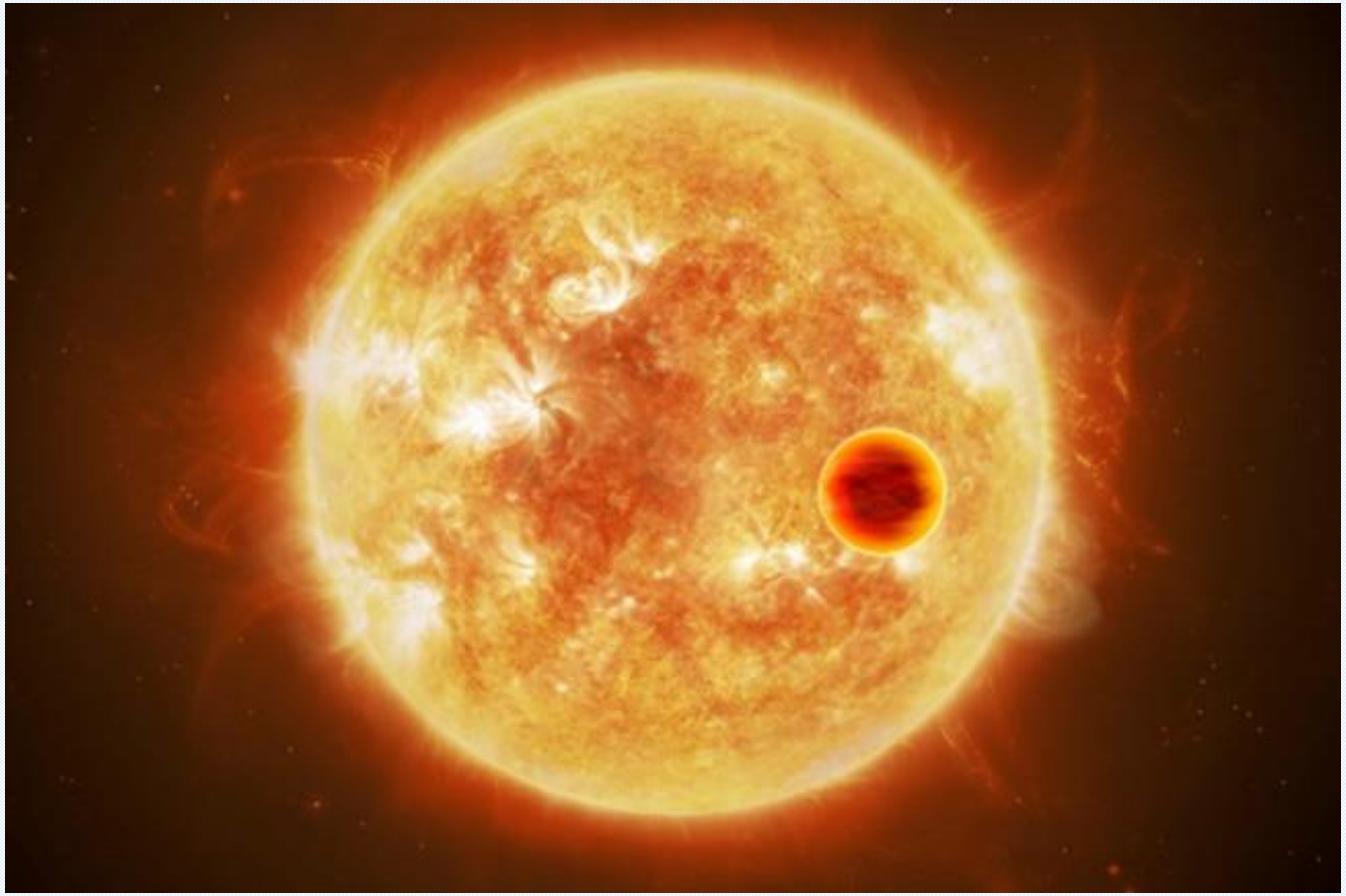
Kupfer et al. 2015, A&A, 576, 44

$\sim 30\%$ 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 evolution

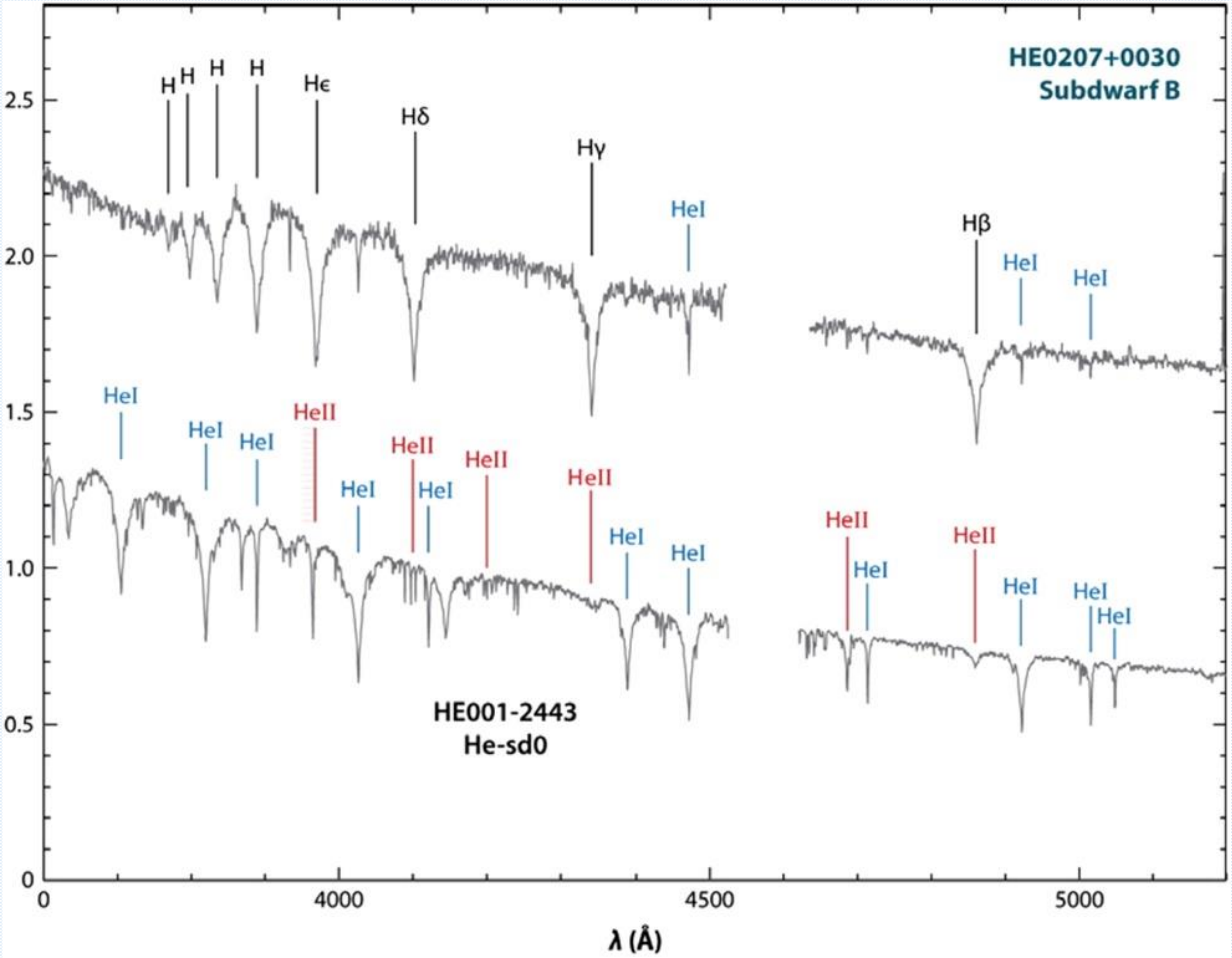

ESA/ATG medialab

$\sim 30\%$ 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?

Binary evolution



Heber 2016, PASP, 128, 966

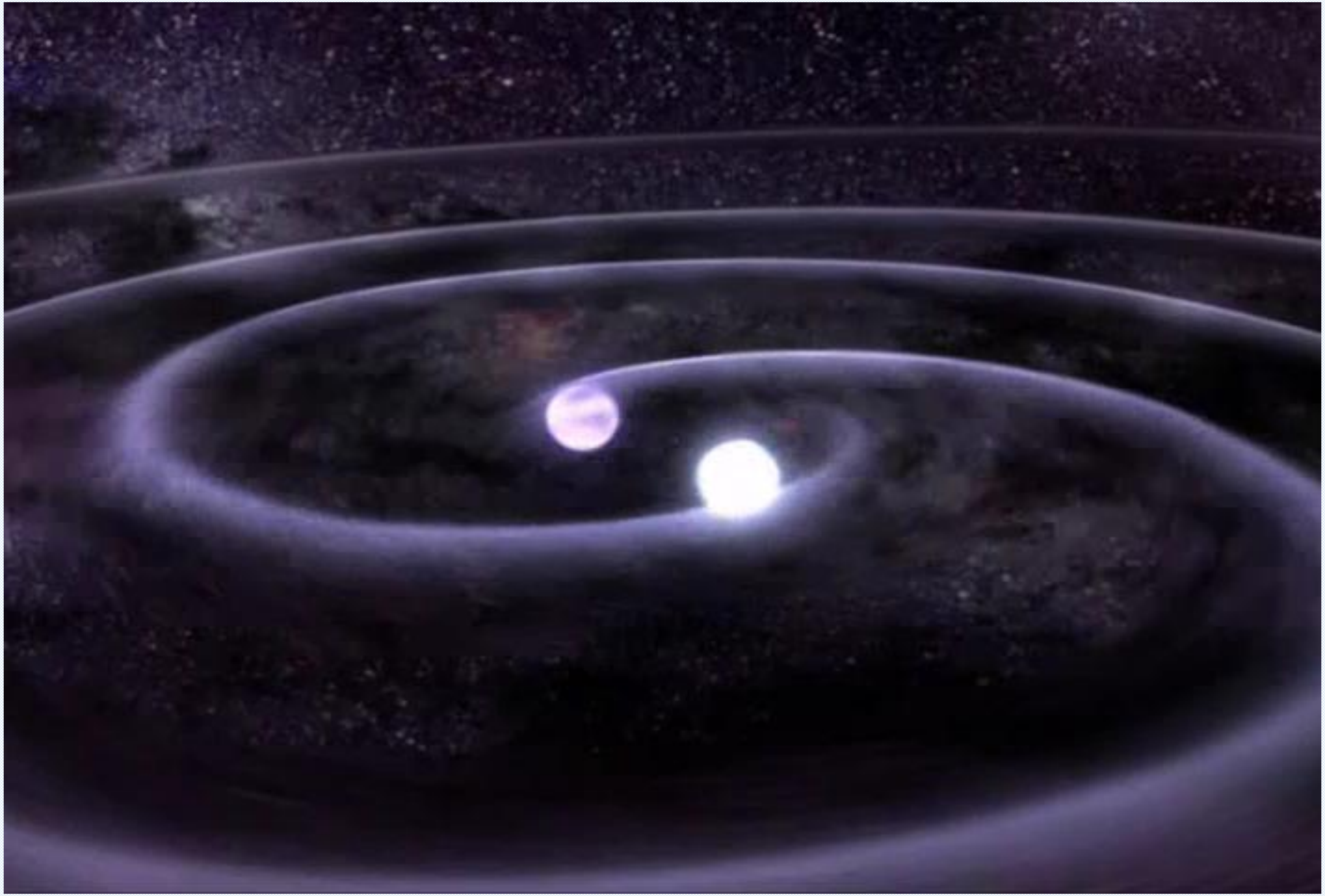
Helium-rich sdO/Bs

→ very high helium abundance

→ Enrichment in carbon and/or nitrogen

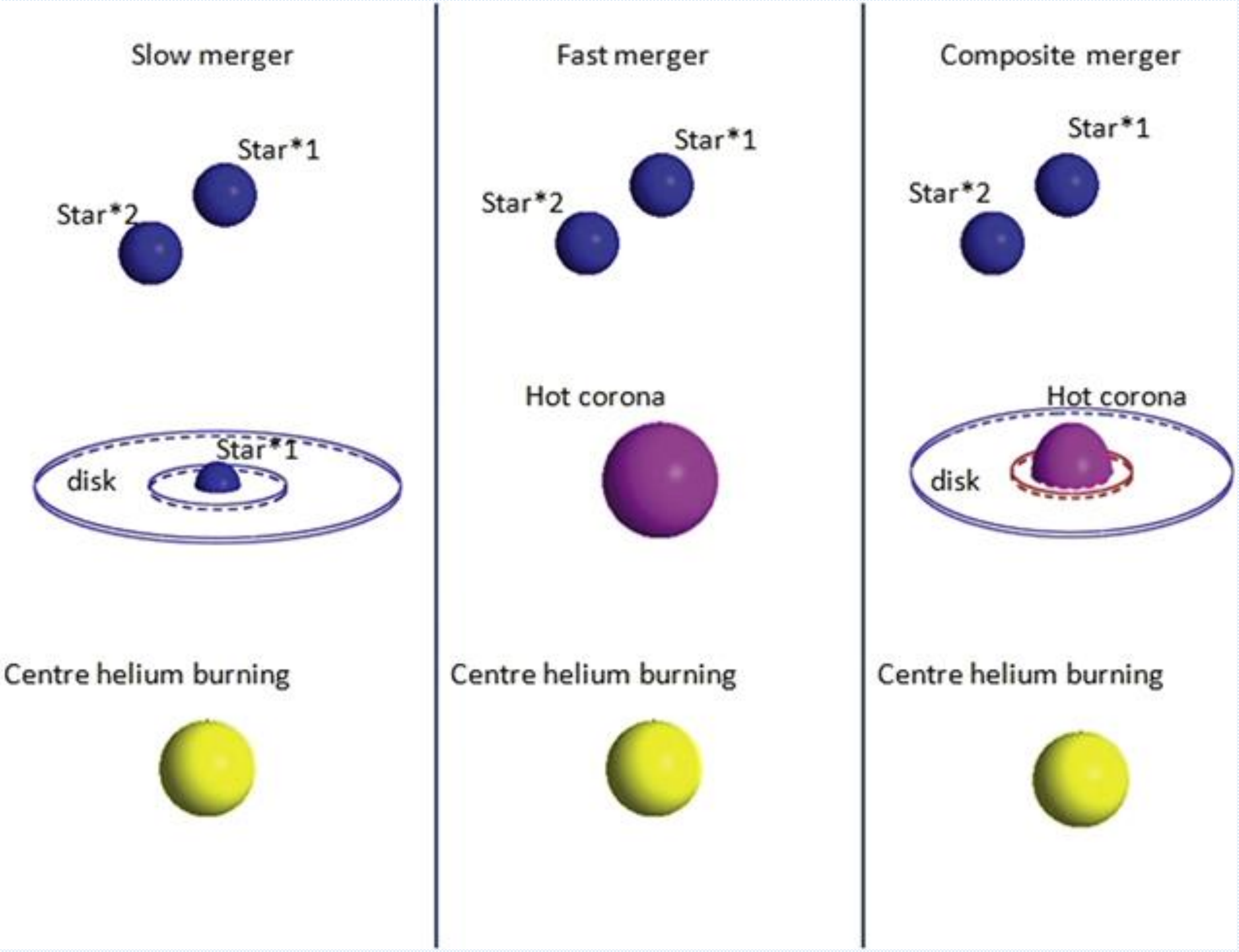
→ Single stars

Binary evolution



NASA

Binary evolution



Heber 2016, PASP, 128, 966

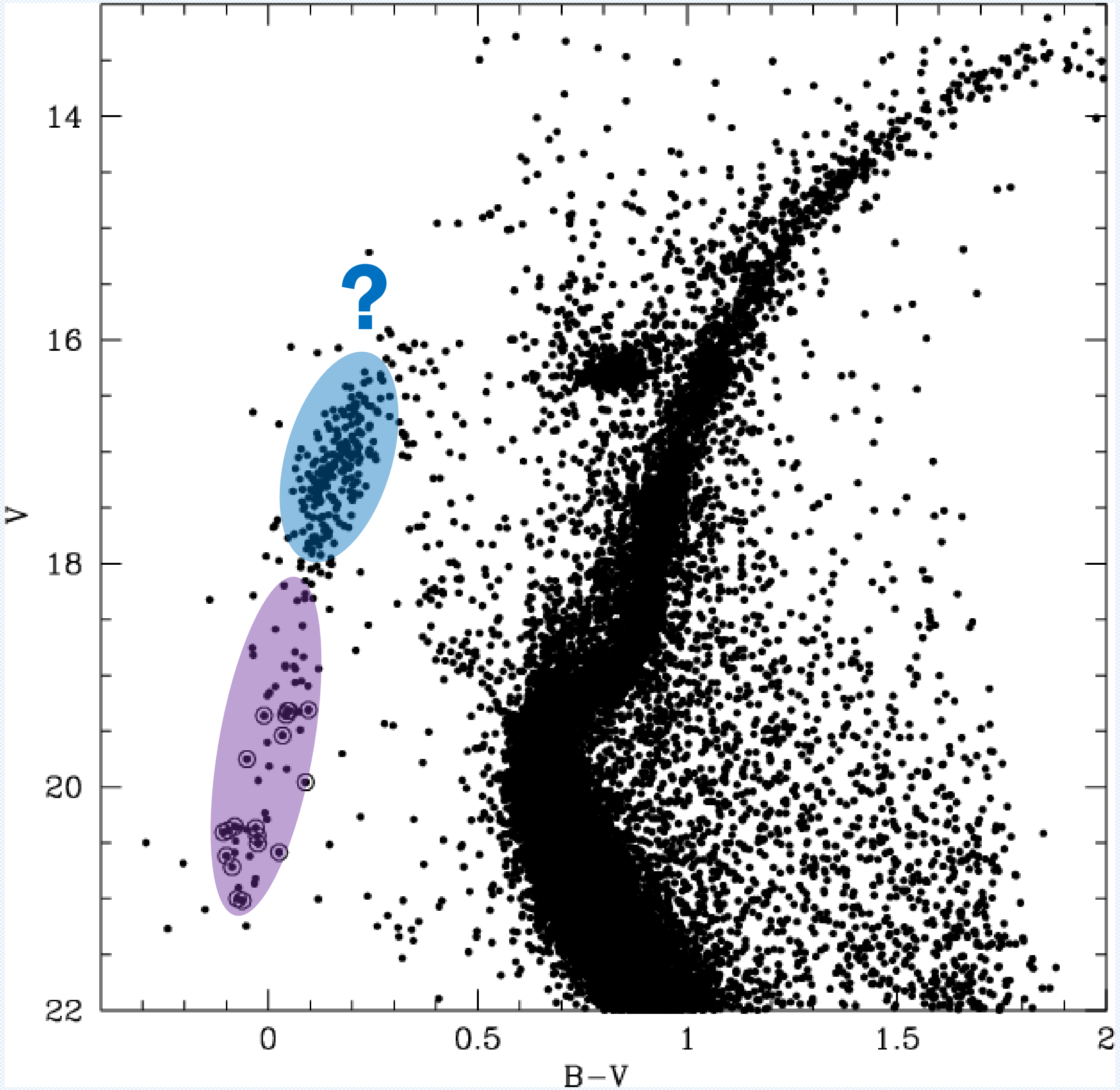
Alternative formation

→ **Close binary evolution**

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

→ Single He-sdO/B stars

How important are binary interactions



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

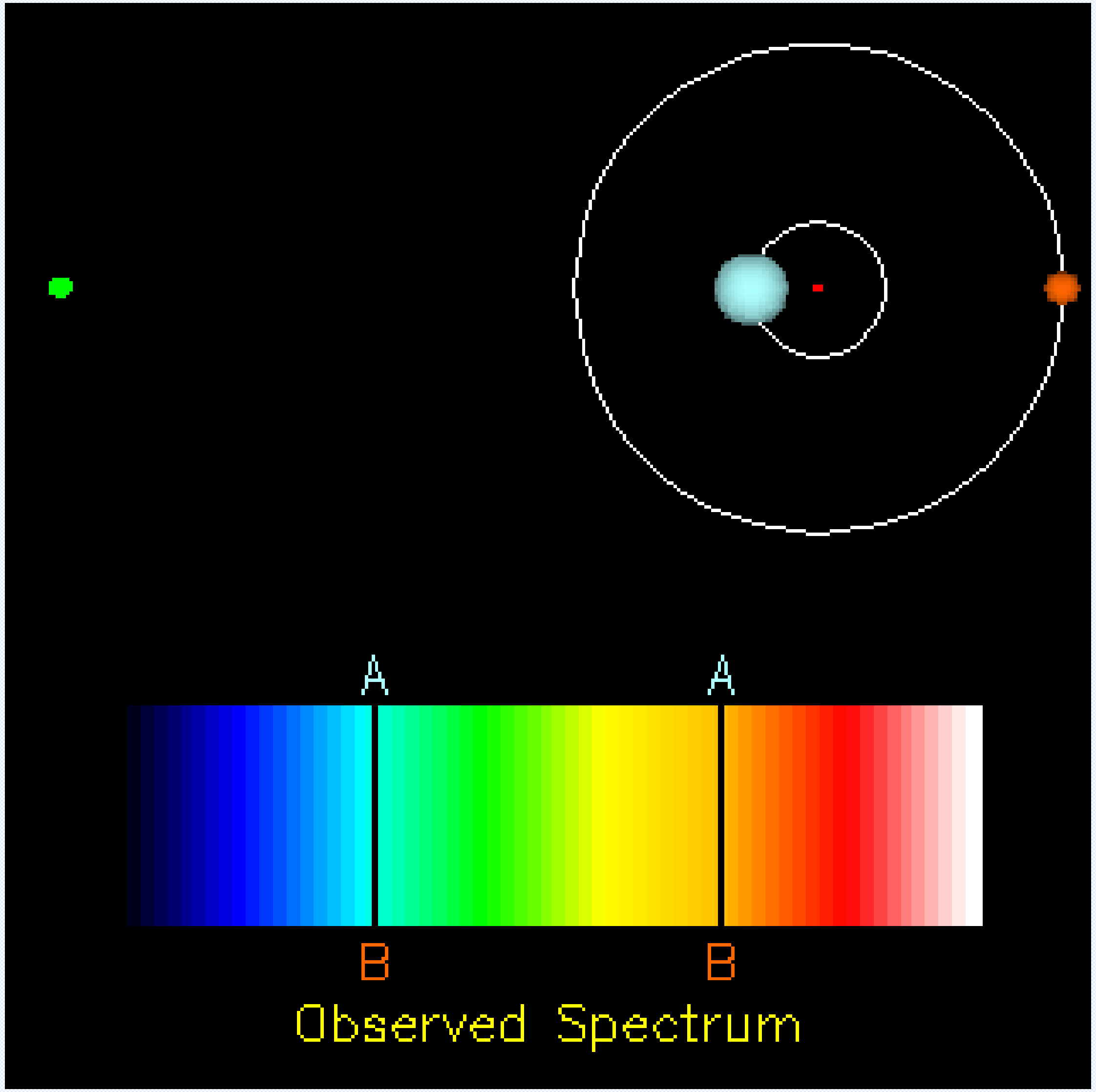
Extreme Horizontal Branch (EHB) stars are the outcome of binary interactions

What about the Blue Horizontal Branch Stars?

Nobody studied them yet
→ Many of the known ones too faint

Survey of bright BHB stars

Spectroscopic binaries



Youtube, Pogge, Ohio State University

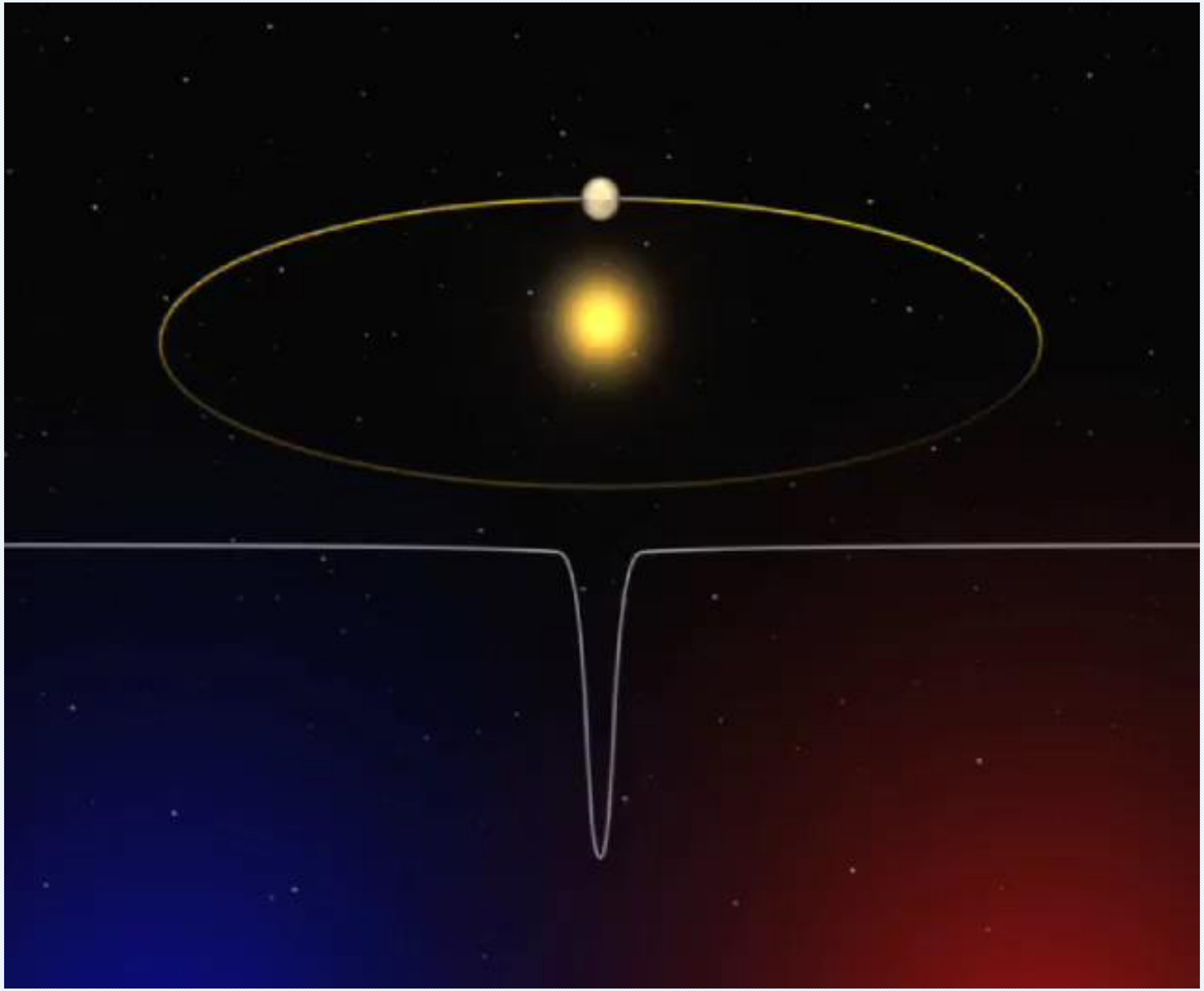
Spectral lines are shifted w.r.t. their rest wavelengths

→ **Doppler effect**

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

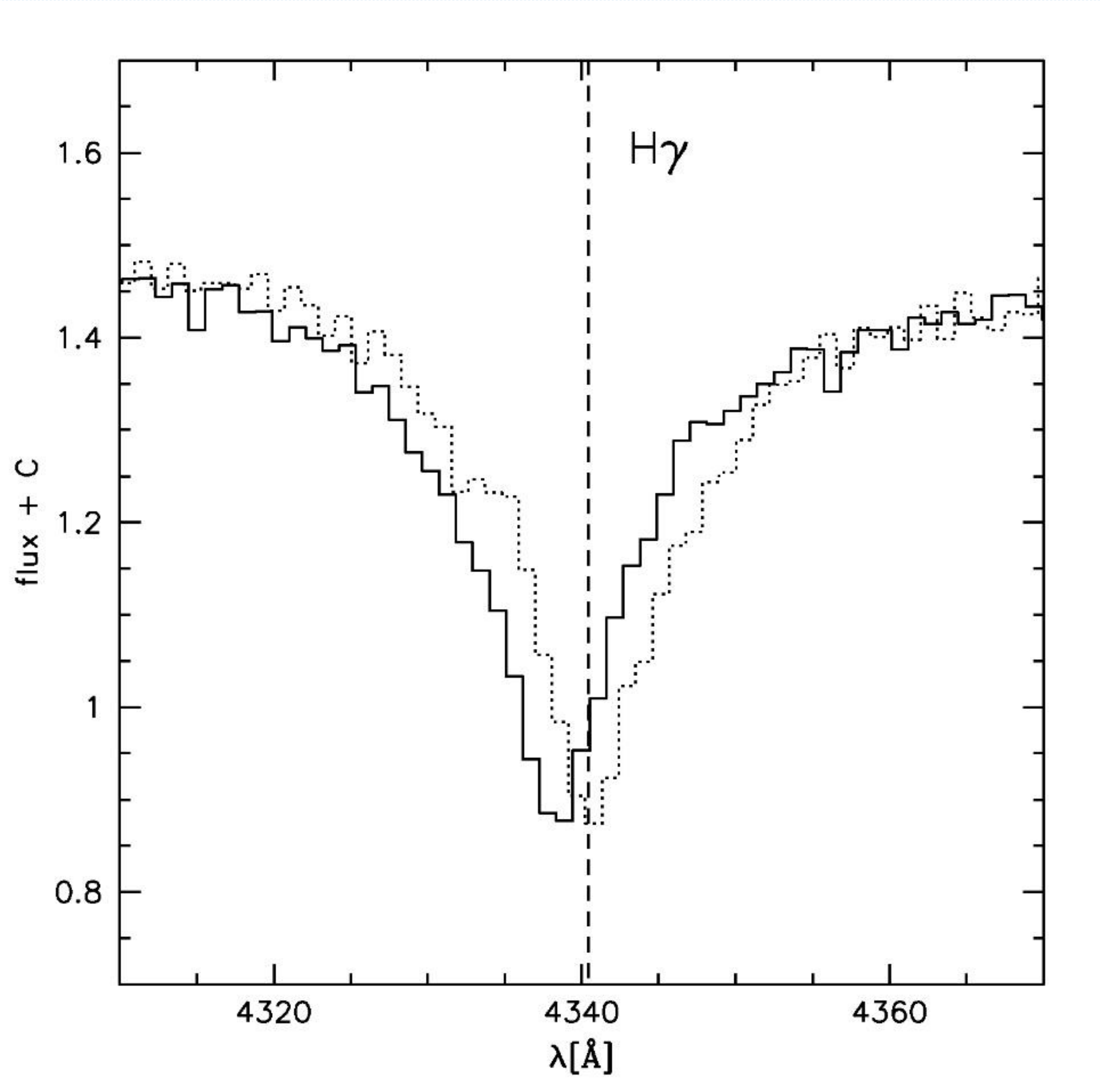
λ	observed wavelength
λ_0	rest wavelength
v	radial velocity

Spectroscopic binaries



ESO

Spectroscopic binaries

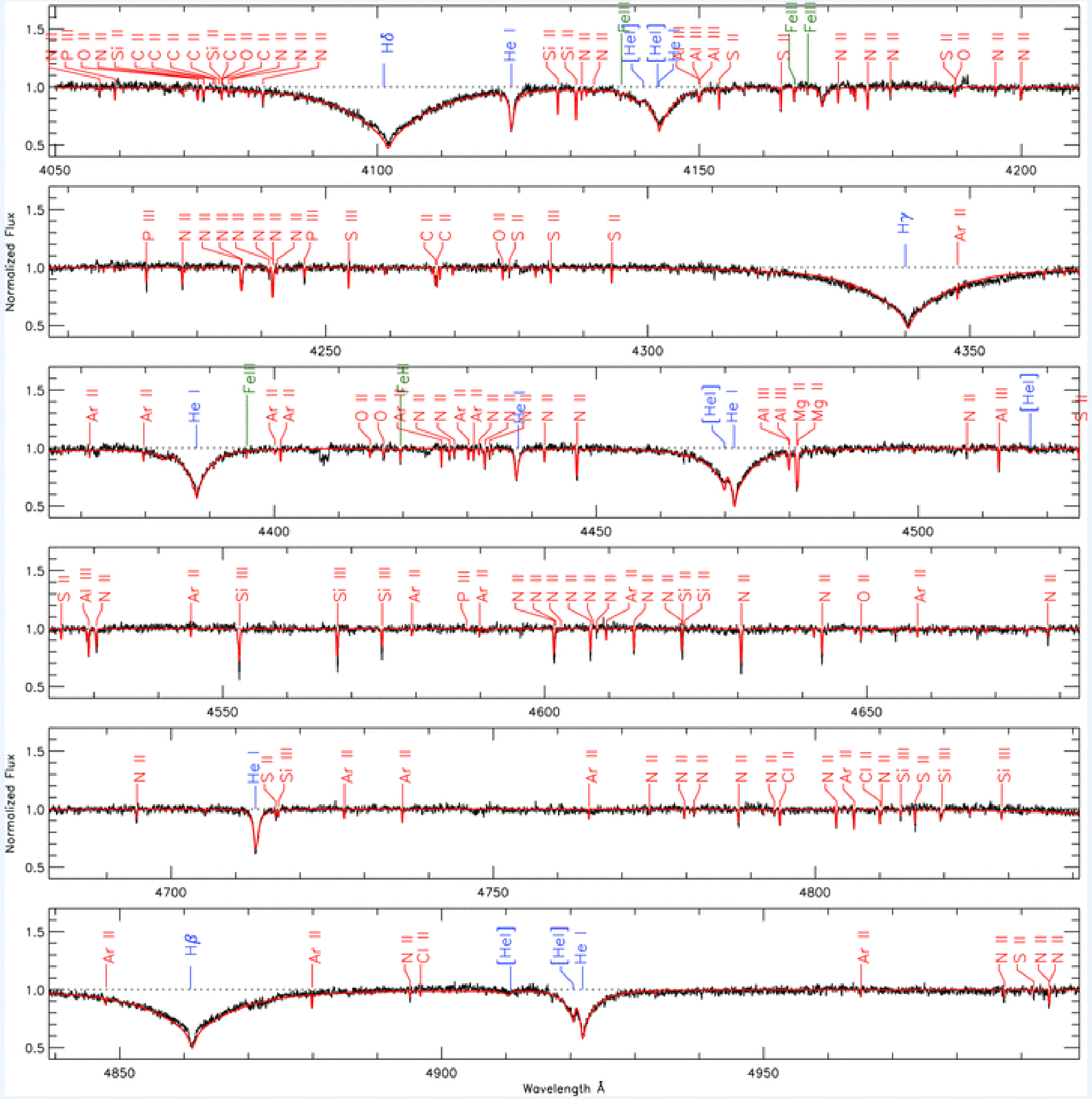


S. Geier

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

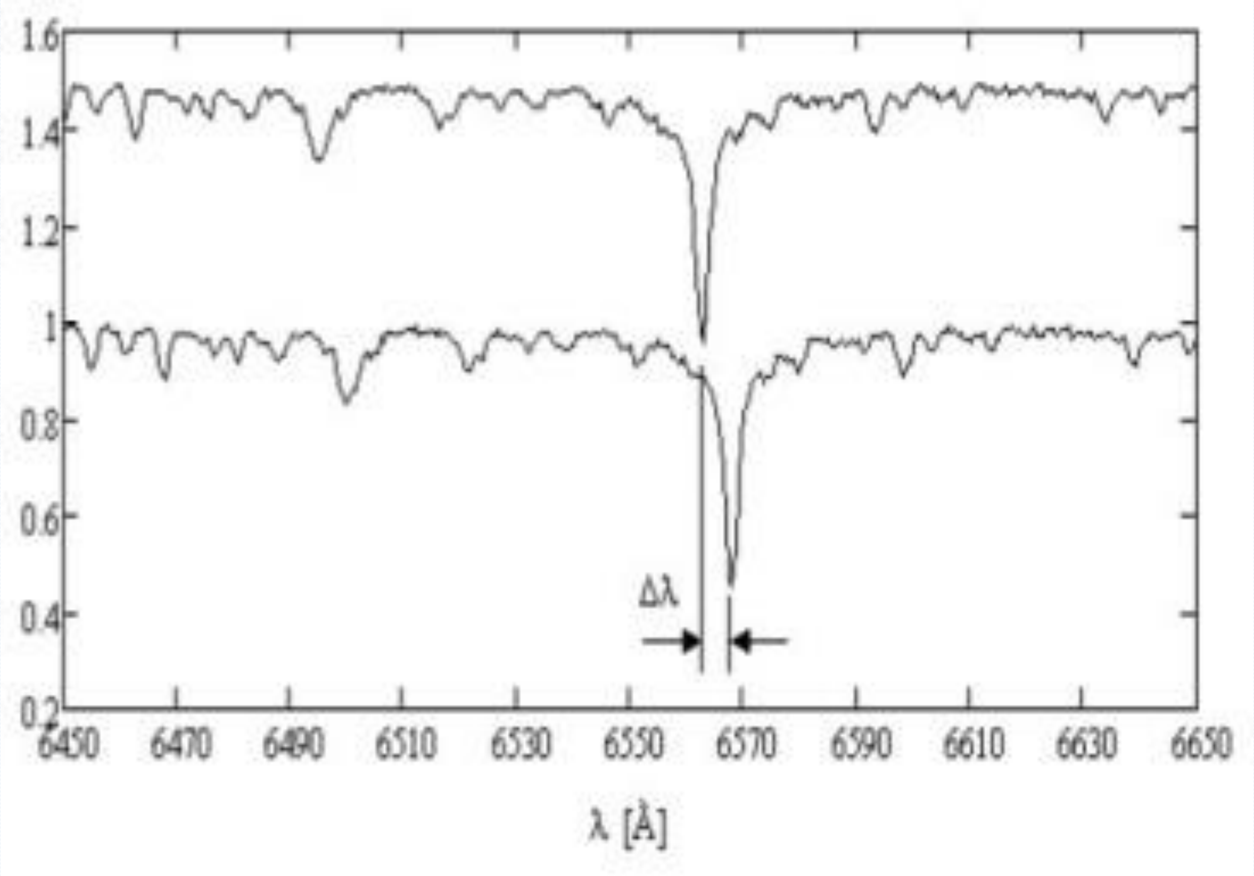
Requirements

→ Good models

→ Small number of lines

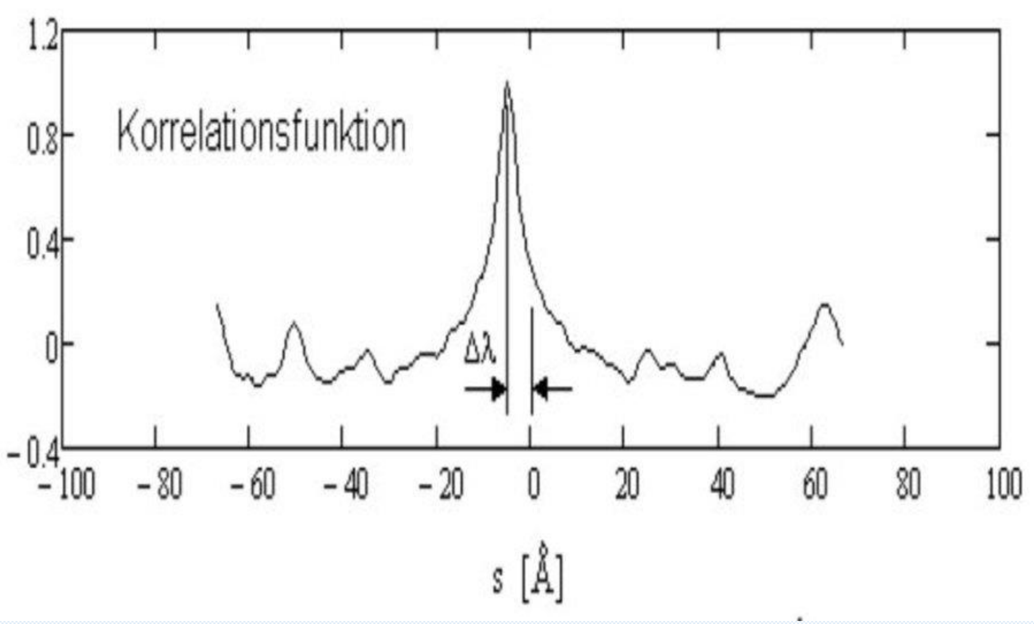
Accuracy limit $\sim 0.1 \text{ km s}^{-1}$

Spectroscopic binaries

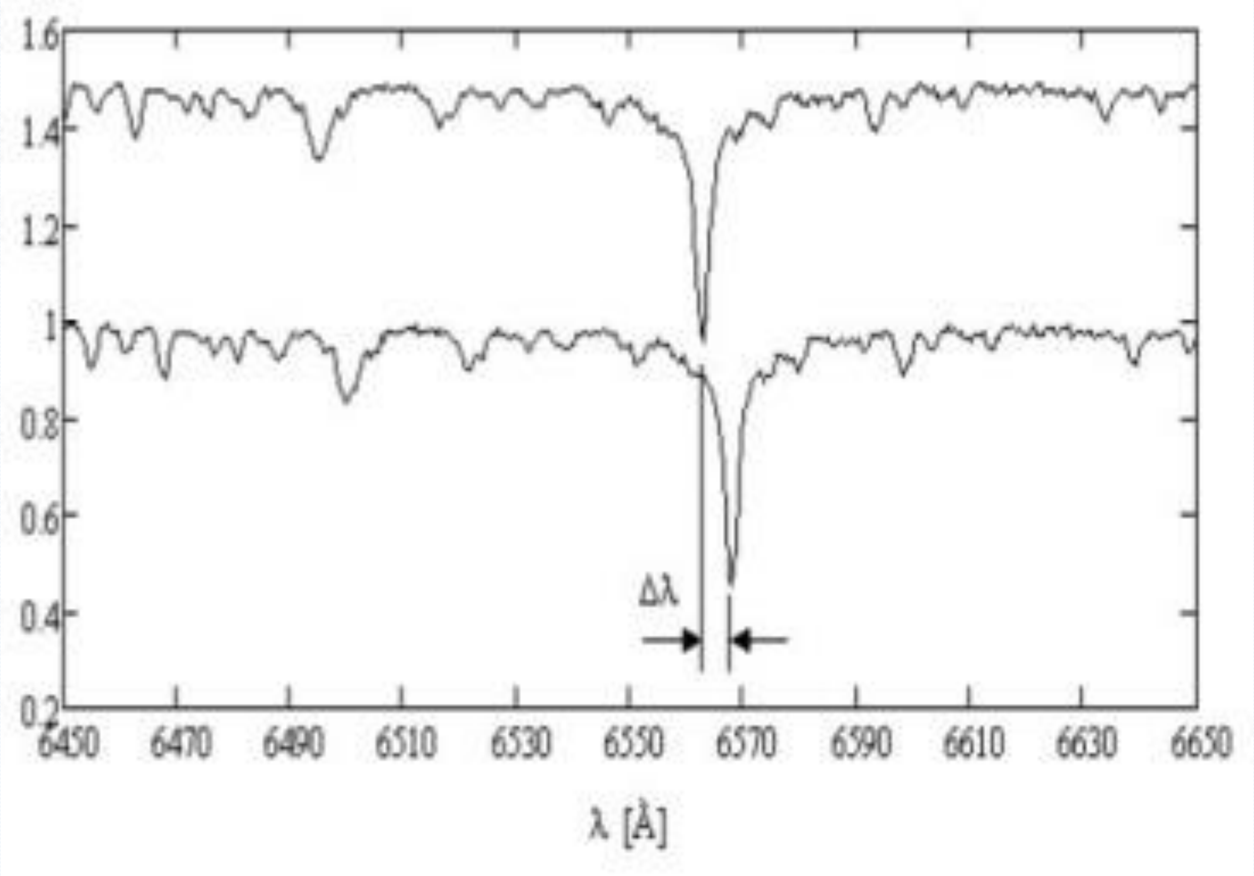


Cross correlation method

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



Spectroscopic binaries



Cross correlation

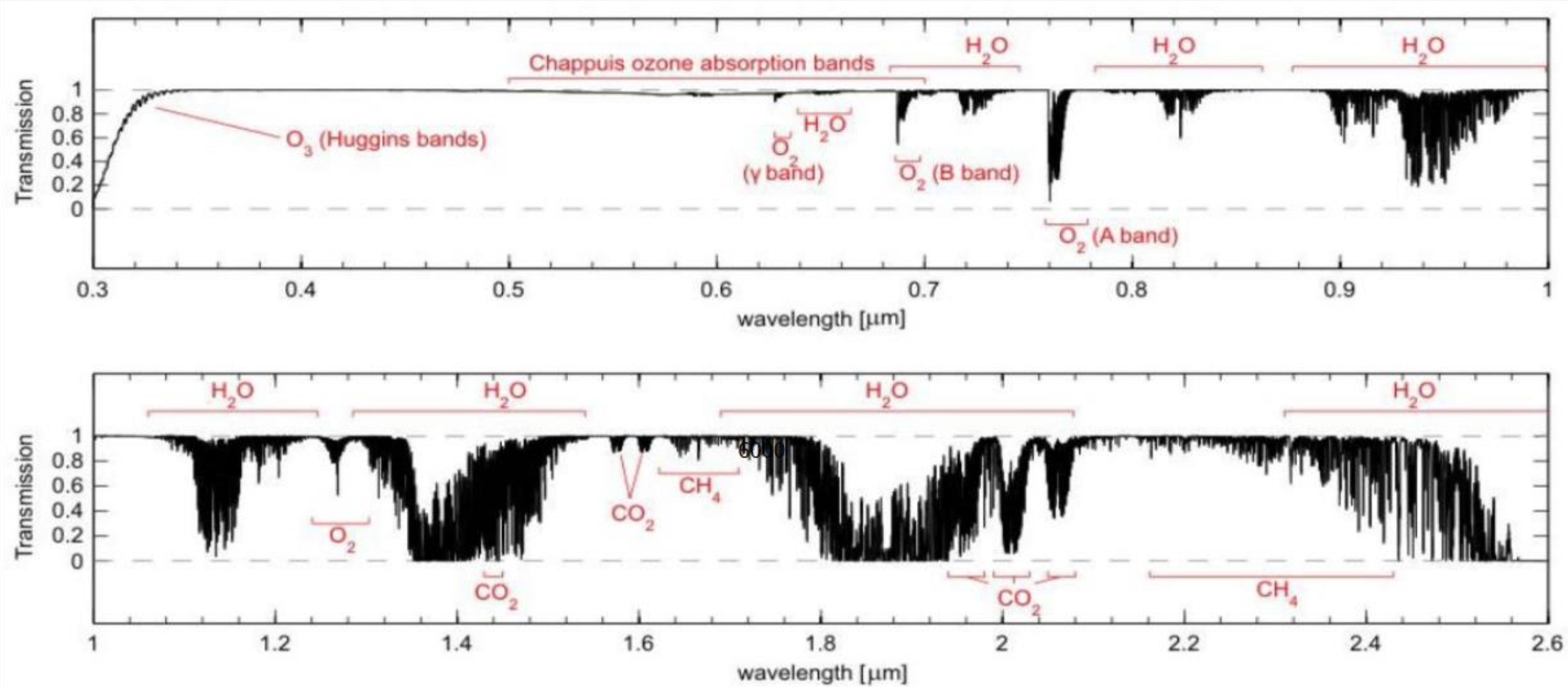
→ Template spectrum or spectrum itself (autocorrelation)

→ All features contribute

→ Applicable to double-lined systems

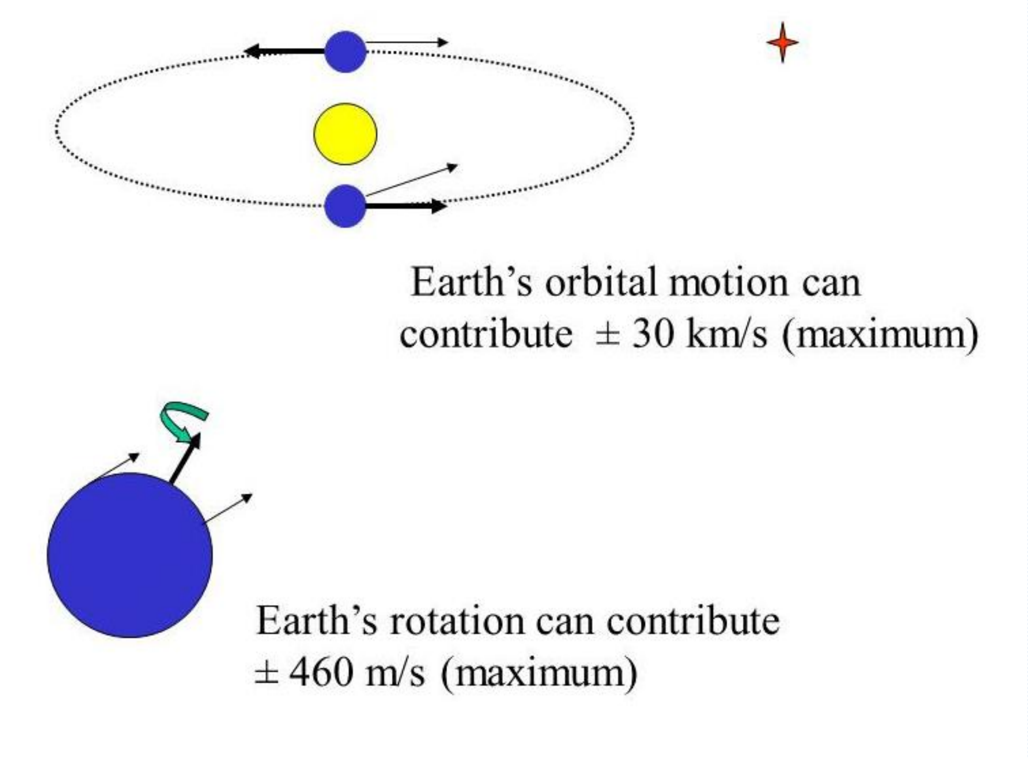
Limitations: Telluric lines, artifacts

Spectroscopic binaries



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

Spectroscopic binaries



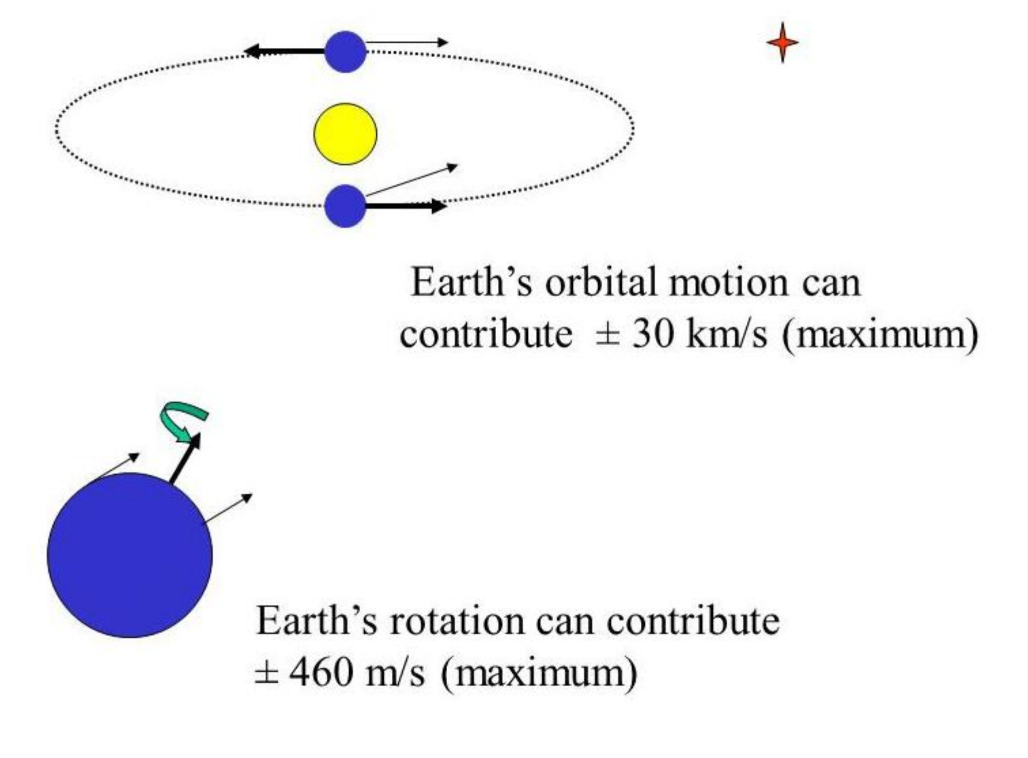
ESO

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



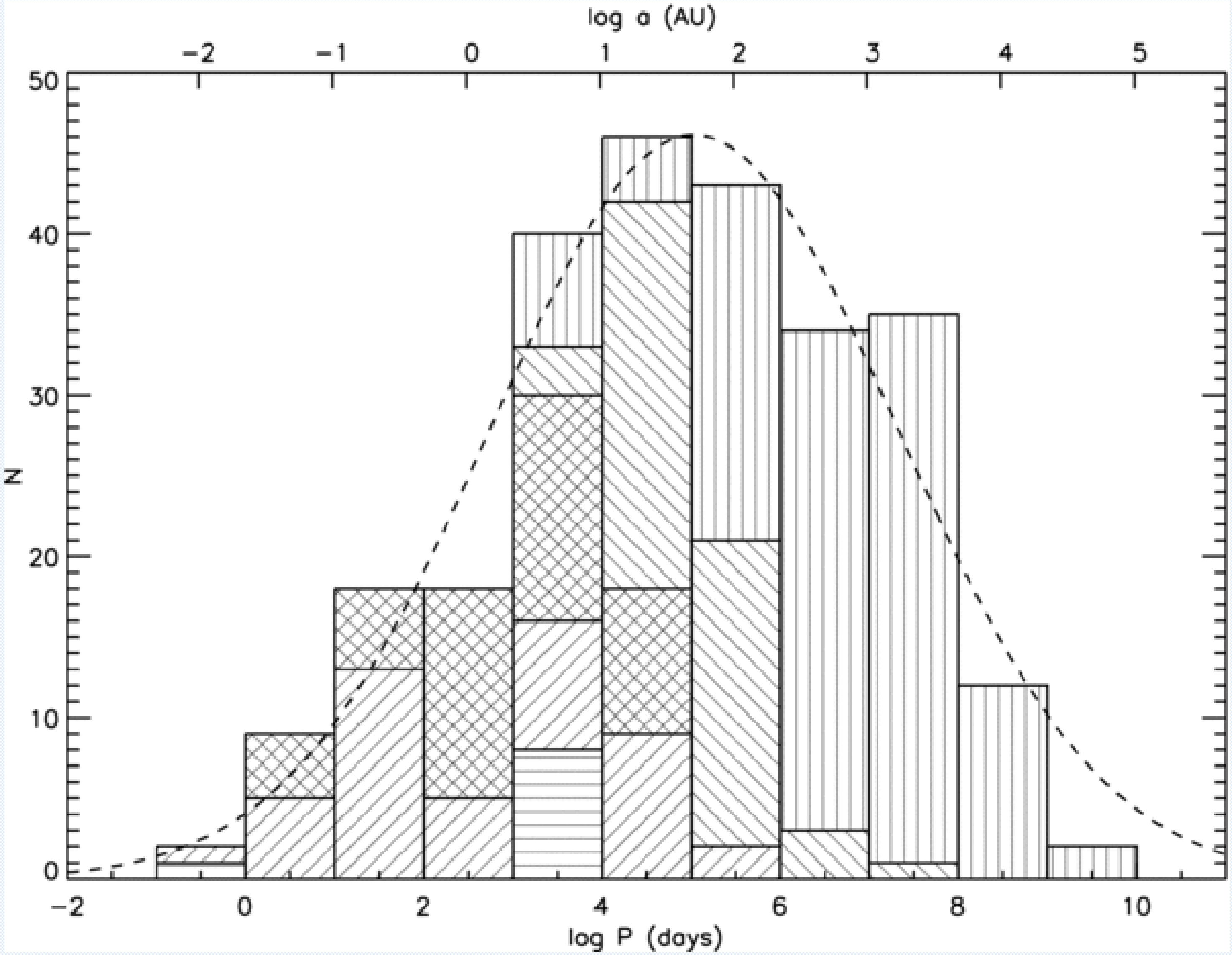
ESO

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

BHB survey

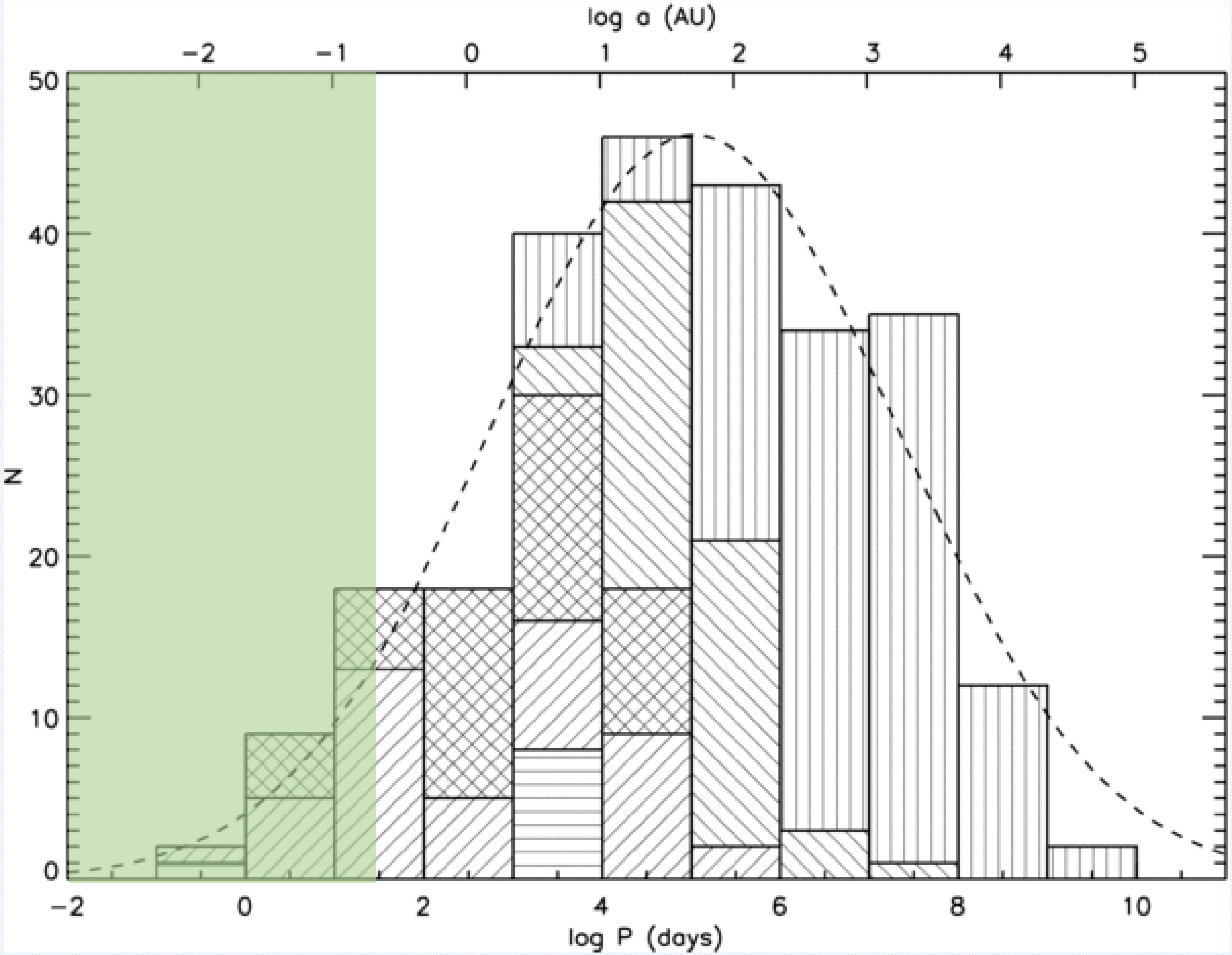


Raghavan et al. 2010, ApJS, 190, 1

Preparatory study at the workshop in 2021

→ RV accuracy of a few km/s

BHB survey



Raghavan et al. 2010, ApJS, 190, 1

Preparatory study at the workshop in 2021

→ RV accuracy of a few km/s

→ Sensitive to orbital periods of several tens of days