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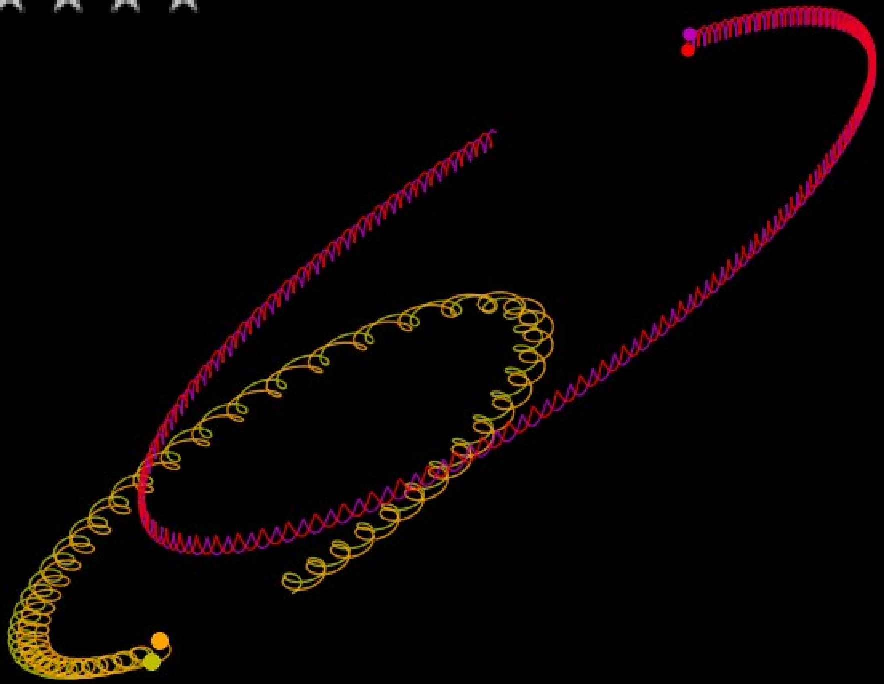


Dancing with the stars: a review on stellar multipicity

Thibault Merle – ROB / ULB

3rd BINA Workshop

Thursday, March 23, 2023

ULB

Outline

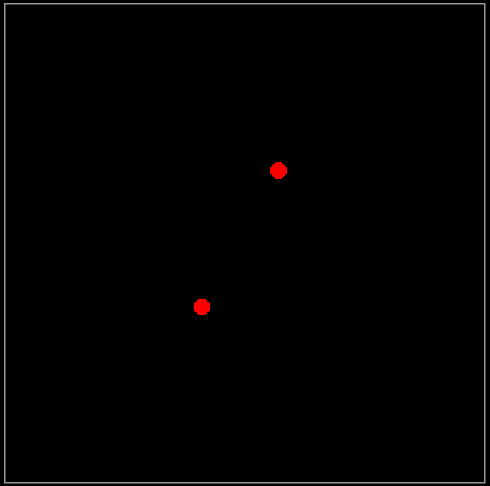
Introduction: stellar evolution and famous multiple stars

I. Why do we care about stellar multiples?

II. Multiple stars in the era of massive surveys

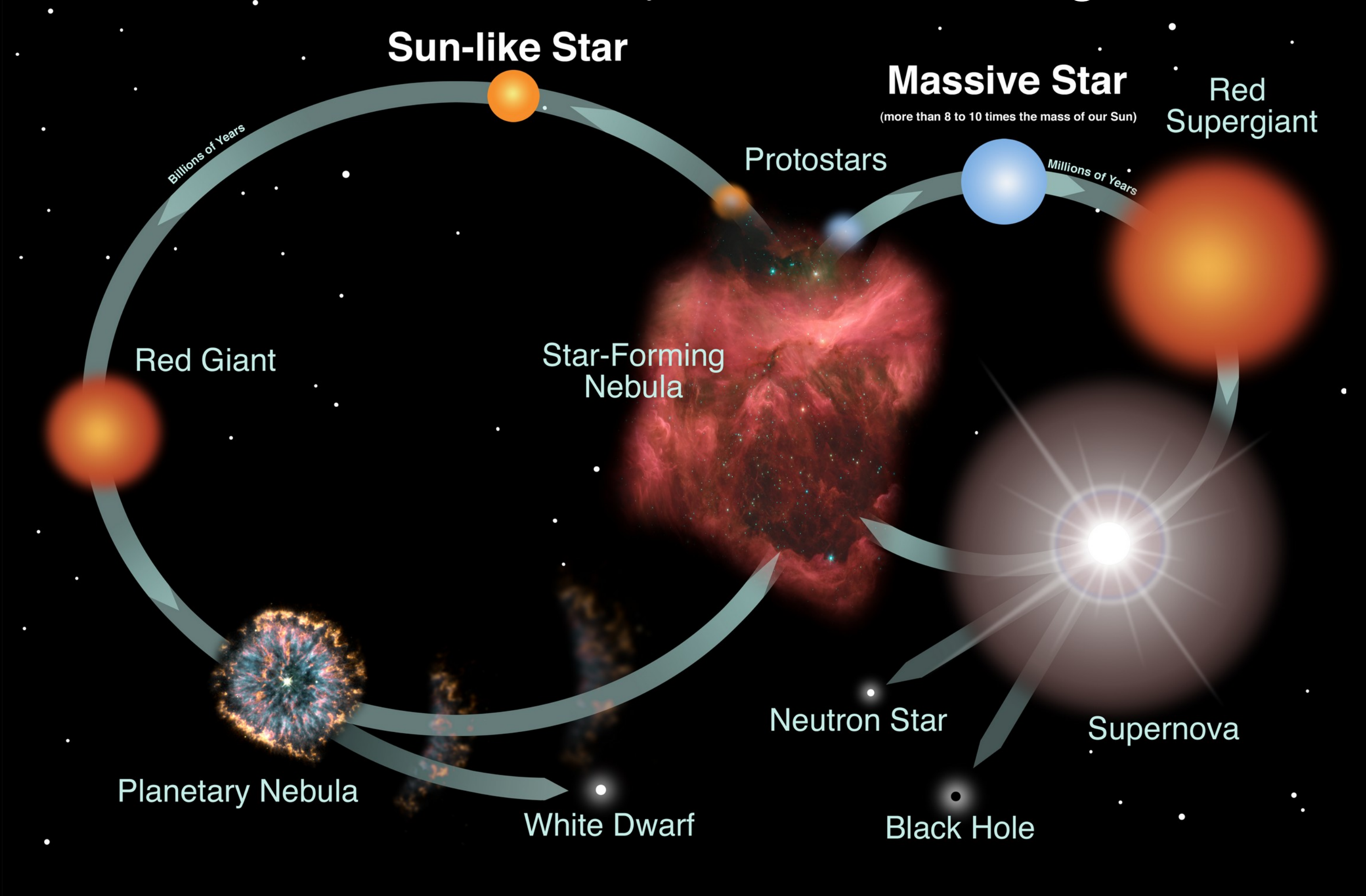
III. The Gaia revolution

Conclusion



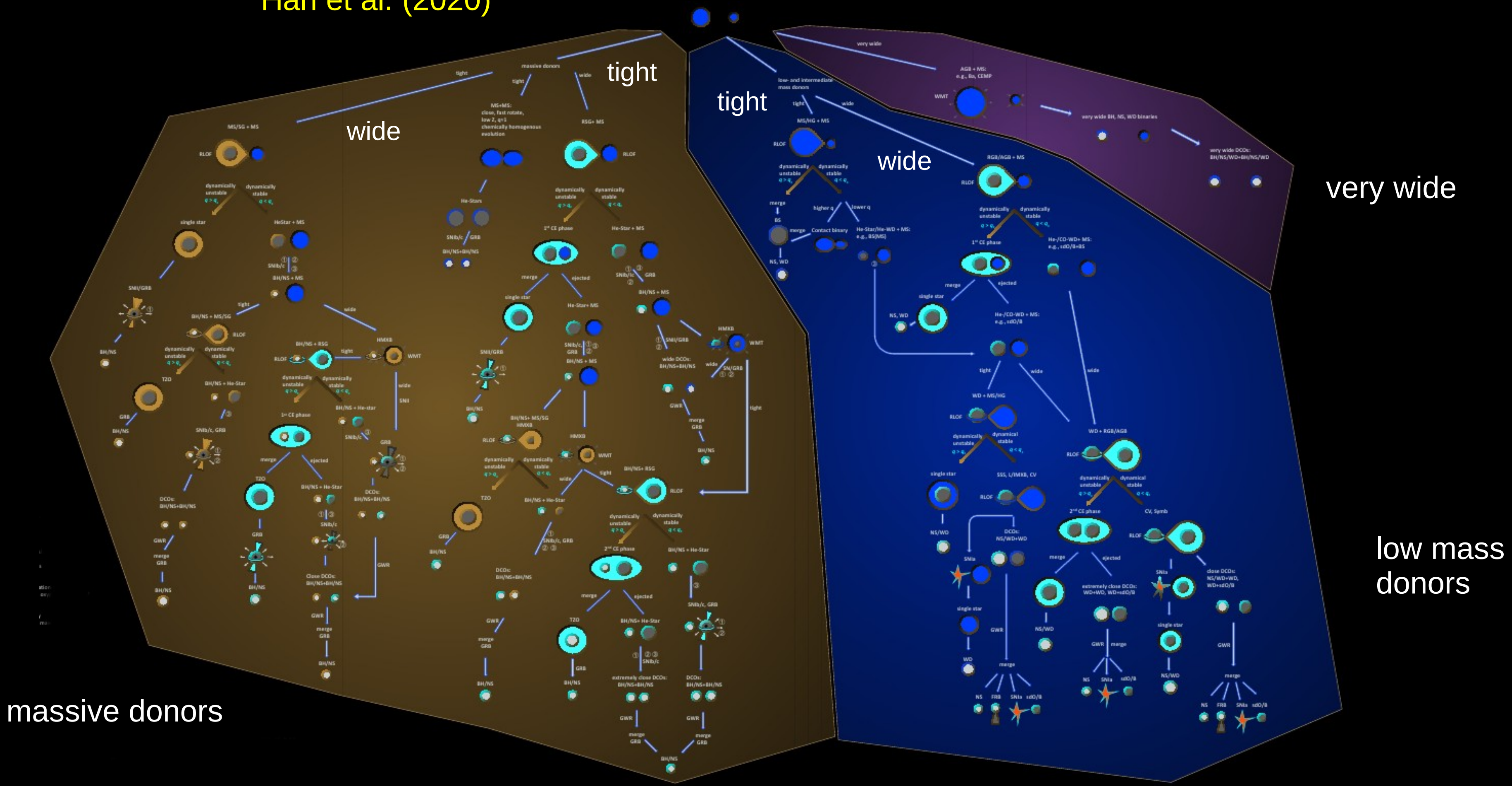
/!\ Strongly biased /!

Introduction: single star evolution

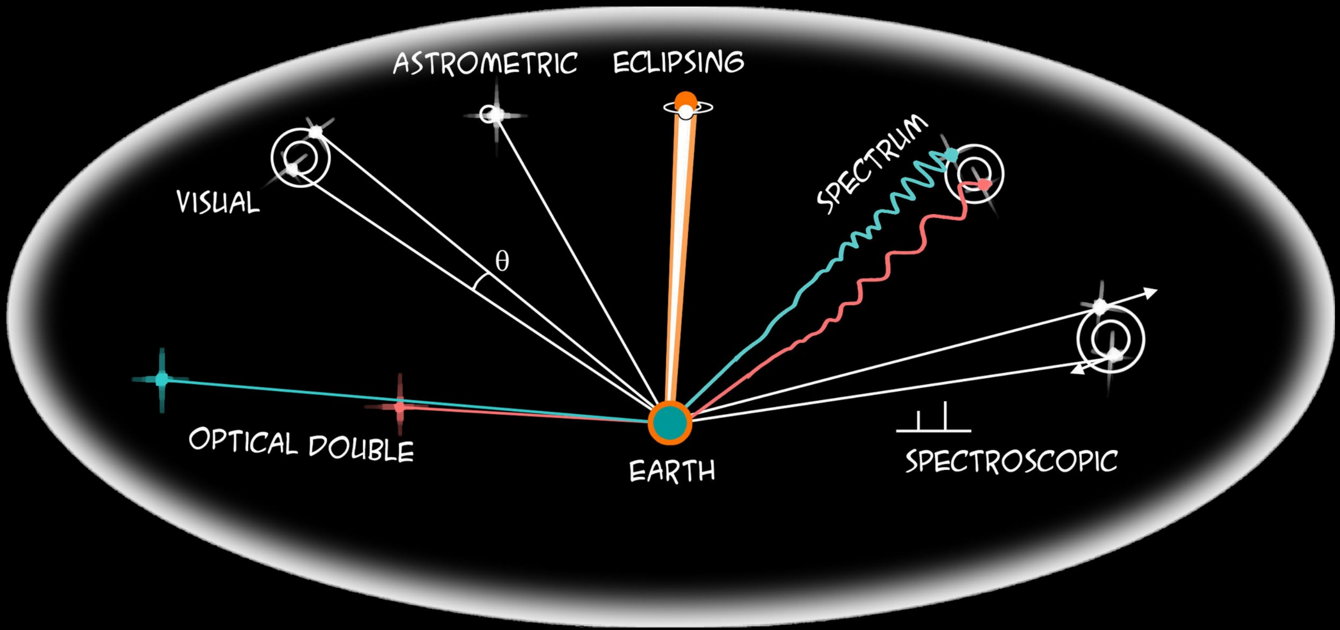


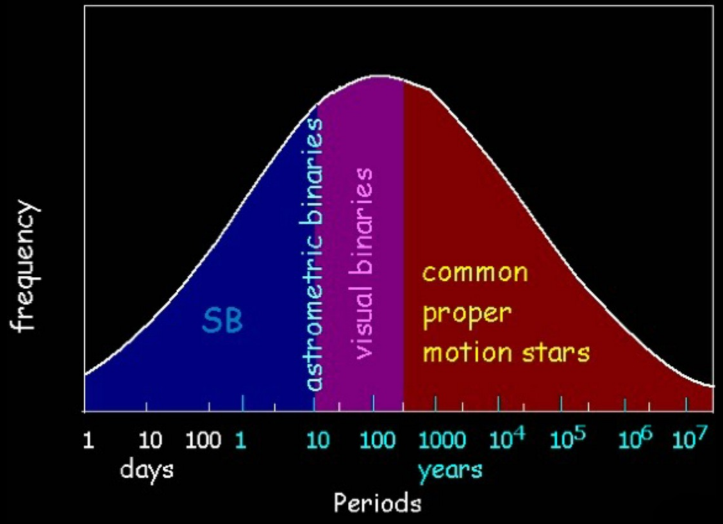
Introduction: binary star evolution

Han et al. (2020)



Introduction: how do we detect stellar multiples?



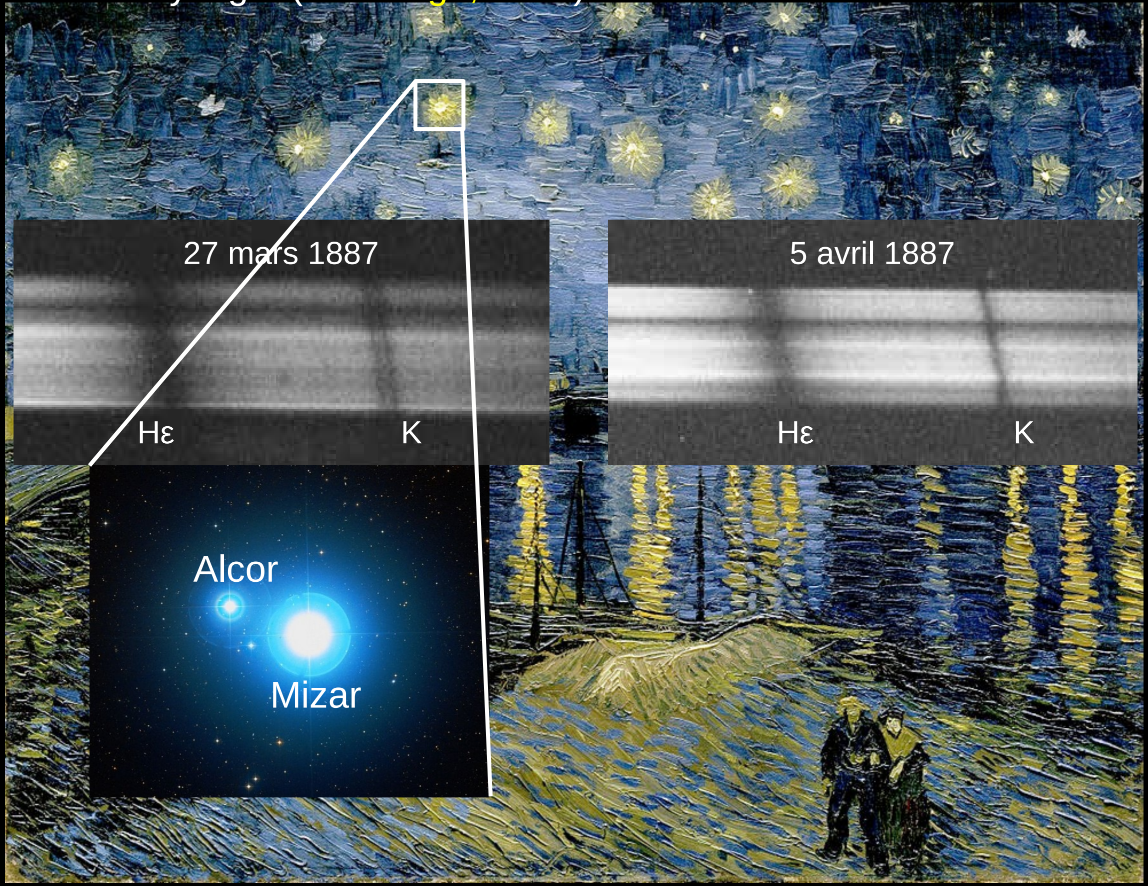


$\log(P[\mathrm{d}]) \sim 5 \Leftrightarrow$ 270 y, $\sigma \sim 2.5$

Visual/astrometric/interferometric binaries = AB
Eclipsing/photometric binaries = EB
Spectroscopic binaries = SB

Introduction: Mizar & Alcor (Vashistha & Arundhati)

The starry night (Van Gogh, 1888)



Alcor discovered by Al-Sufi (964)

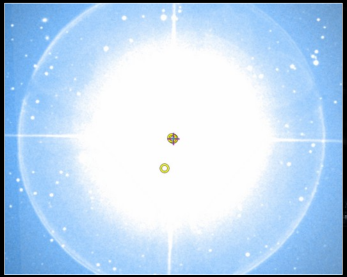
Several historical premieres with Mizar:

- First telescopic binary (Castelli, Galileo 1617)
  → Mizar AB
- First photography of a double star
  (Whipple & Bond 1857)
- First spectroscopic binary (SB2, Maury 1889)
  → Mizar Aab
- One of the first SB resolved by interferometry (~1925)

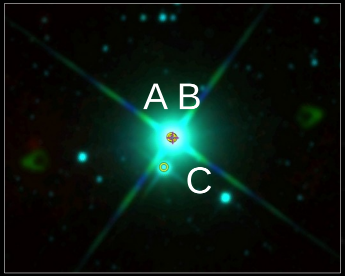
Actually a high-order system:

(Mizar Aab + Mizar Bab) + Alcor AB

Introduction: the Castor sextuplet (α Gem (2+2) + YY Gem)



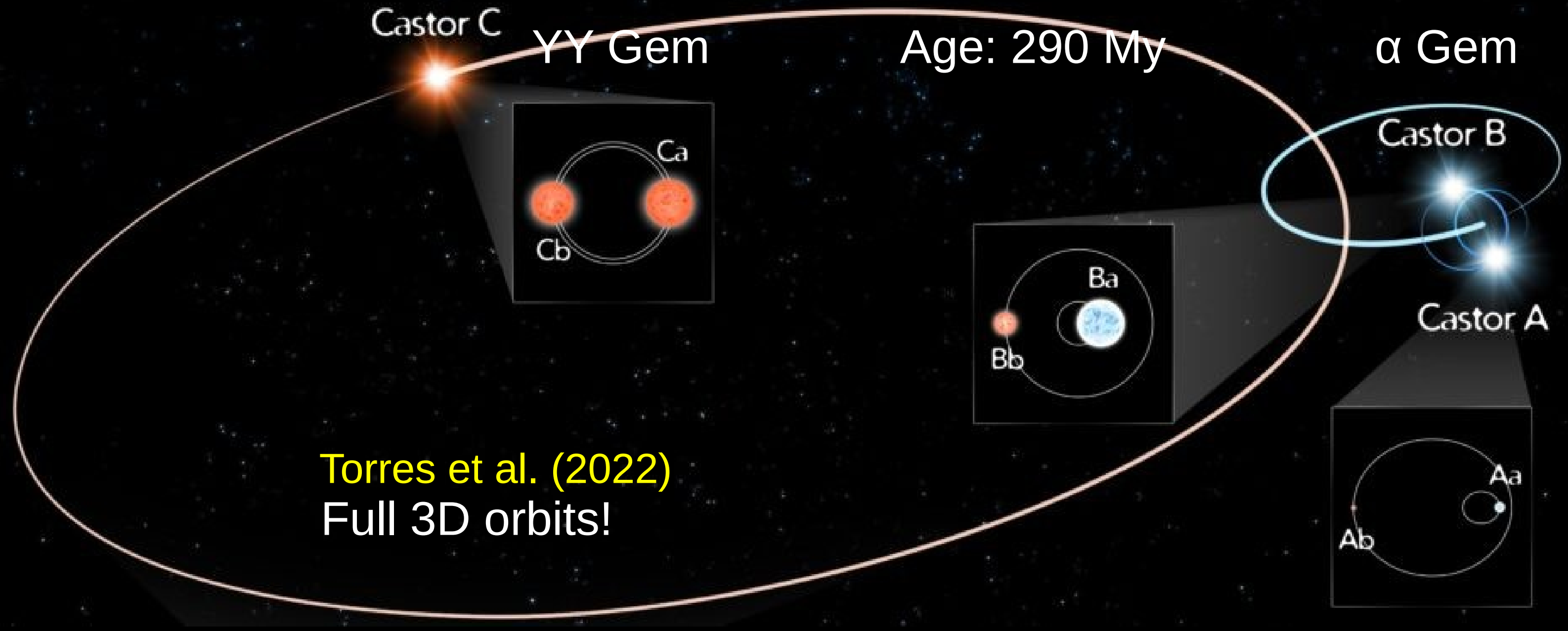
~13'



YY Gem

Age: 290 My

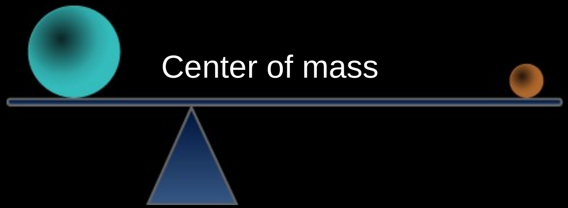
α Gem



Torres et al. (2022)
Full 3D orbits!

Castor Aa, Ab (AIV+MV): 9.2 d, e = 0.48, a = 0.12 au (SB1)
Castor Ba, Bb (AIV+MV): 2.9 d, e = 0, a = 0.05 au (SB1)
Castor A,B: 459.1 y, e = 0.34, a = 102 au (VB)
Castor Ca, Cb (MV+MV): 0.8 d, e = 0, a = 0.02 au (EB+SB2)
Castor AB,C: ~14.5 ky, a > 1060 au

I. Why do we care about stellar multiples?
1. Benchmarking

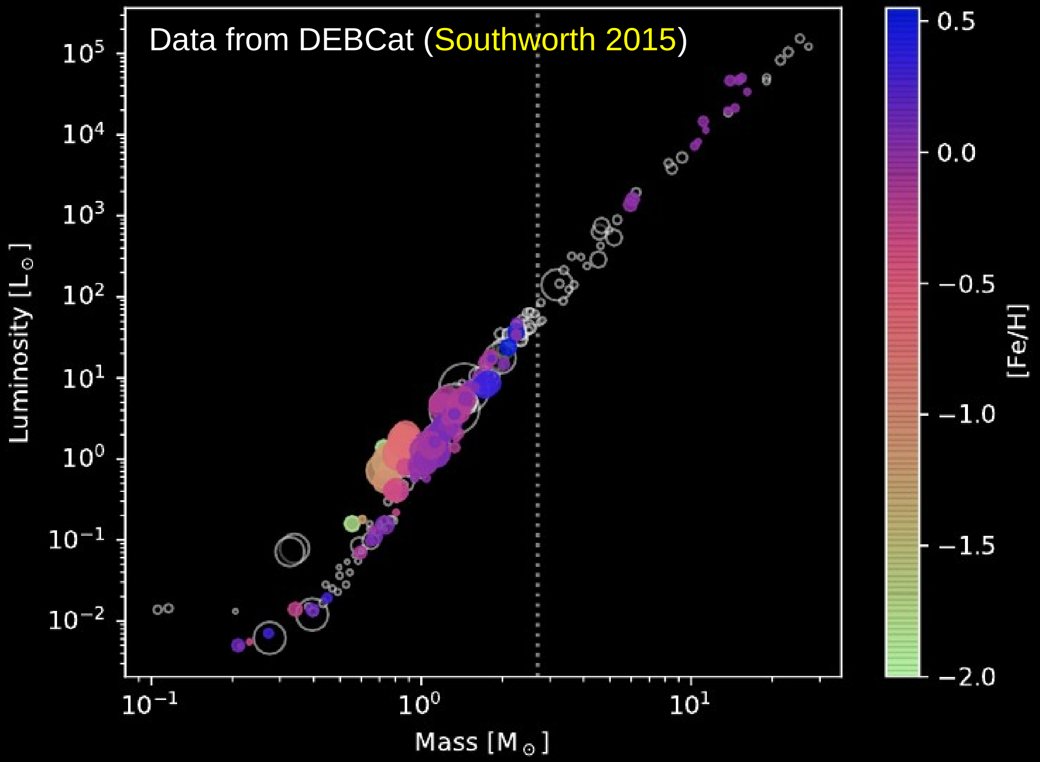


Fundamental stellar parameters:
- Mass
- Radius
- Luminosity
- Parallax

Detached binary stars evolve as single stars:
- Cornerstones on which single-star evolutionary models are anchored (e.g. Paczyński 1970, Iben 1984, Kippenhahn 2013, etc.)
- Provide precise mass-radius and mass-luminosity calibration scales (e.g. Eker+ 2018, Moya+ 2018, …)

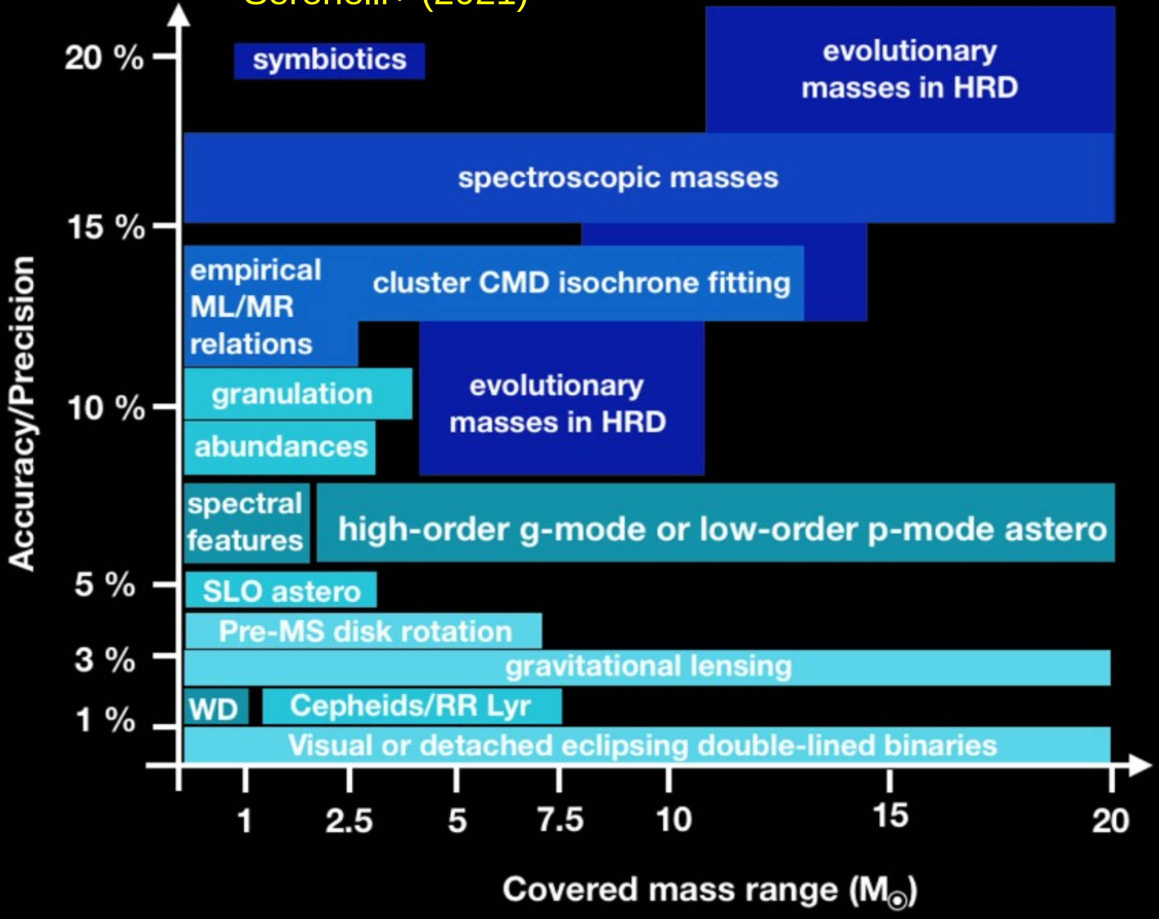
Found at all evolutionary stages and spectral-types

Major role in the synthesis of elements: chemically peculiar stars (CEMP, Ba stars), SN Ia, NS mergers, etc.



I. Why do we care about stellar multiples?
1. Benchmarking

Serenelli+ (2021)



The **mass** of a star is
the most fundamental parameter for its:

- structure
- evolution
- final fate

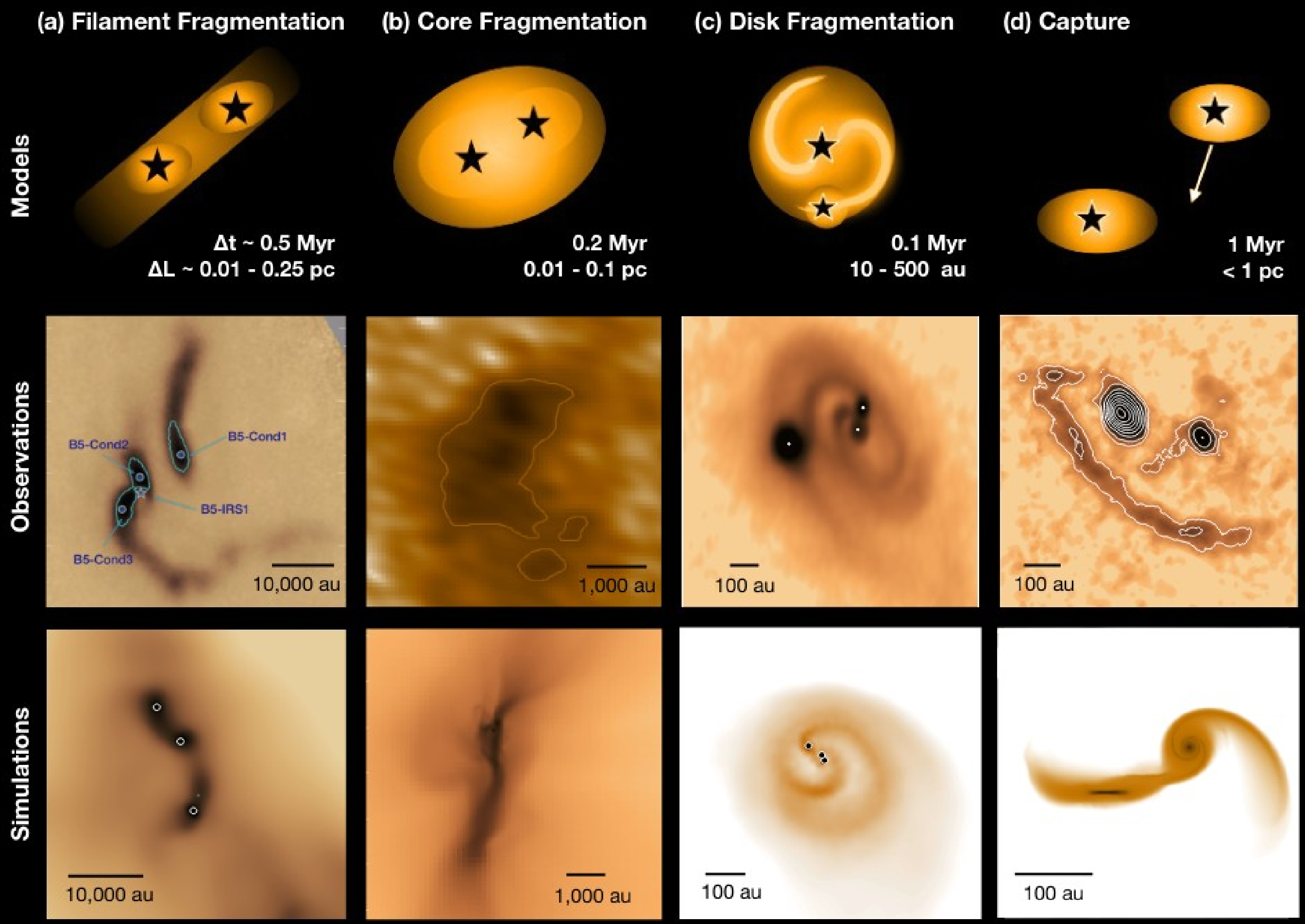
The mass ladder

Light cyan: model independent
Dark blue: strongly model dependent

WD: White Dwarf
MS: Main Sequence
SLO: Solar-Like Oscillations
HRD: Hertzsprung-Russel Diagram
ML/MR: Mass-Luminosity/Mass-Radius
CMD: Color-Magnitude Diagram

I. Why do we care about stellar multiples?

2. Stellar formation



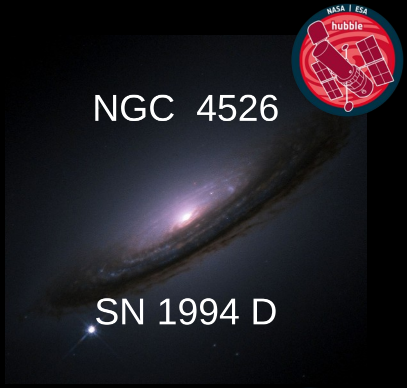
- Elementary mechanisms
  - Filament/core/disk fragmentation
  - Dynamical interaction
- Observations
  - B5 in Perseus (Pineda et al. 2015)
  - SM1N in Ophiuchus (Kirk et al. 2017)
  - L1448 IRS3B in Perseus (Reynolds et al. 2021)
  - RW Aur (Rodriguez et al. 2018)
- Simulations
  - Guszejnov et al. (2021)
  - Offner et al. (2016)
  - Bate (2018)
  - Muñoz et al. (2015)

Offner+ (2022)

I. Why do we care about stellar multiples?
3. Stellar evolution

Sirius

Southern Ring PN



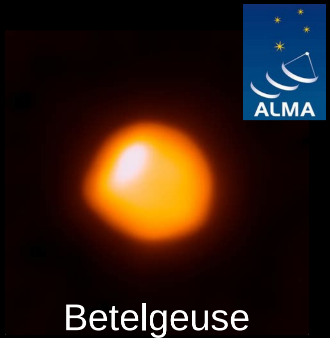
NGC 4526

SN 1994 D

Chandra/Hubble/Spitzer

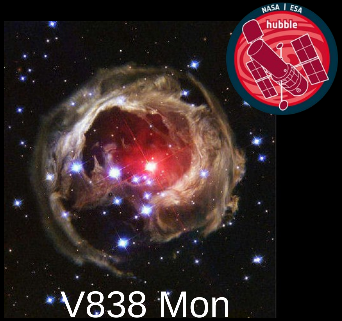
SN 1604

GW 150914

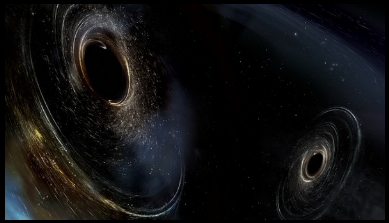


Betelgeuse

η Car

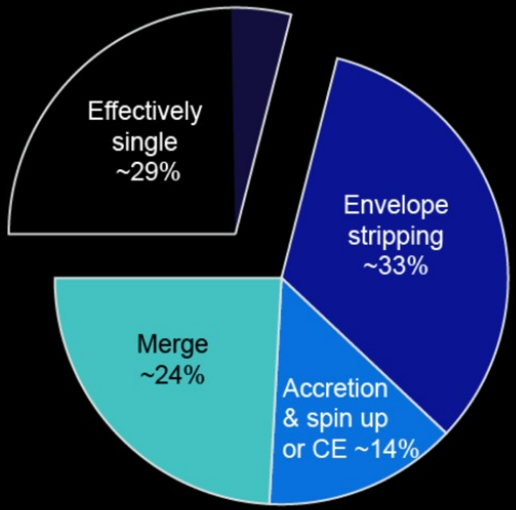


V838 Mon



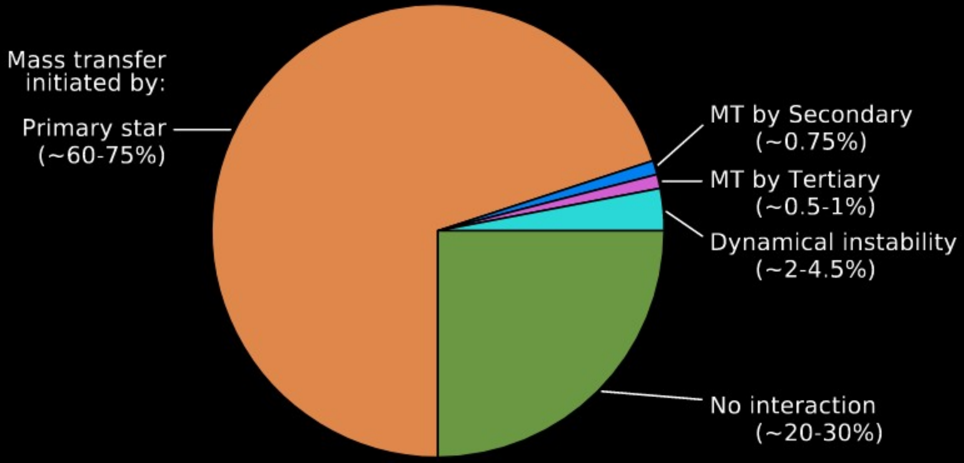
Chemically peculiar stars: Ba stars (e.g. Escorza+ 2023), CEMP stars (e.g. Goswami+ (2016), Karinkuzhi+ 2021), sdOB stars (e.g. Preece+ 2022)

I. Why do we care about stellar multiples?
3. Stellar evolution



O-type binaries

Sana+ (2012)



1-7.5 $M_{\odot}$ primaries in triples

Toonen+ (2020)

II. Multiples in the era of massive surveys

Photometric surveys:

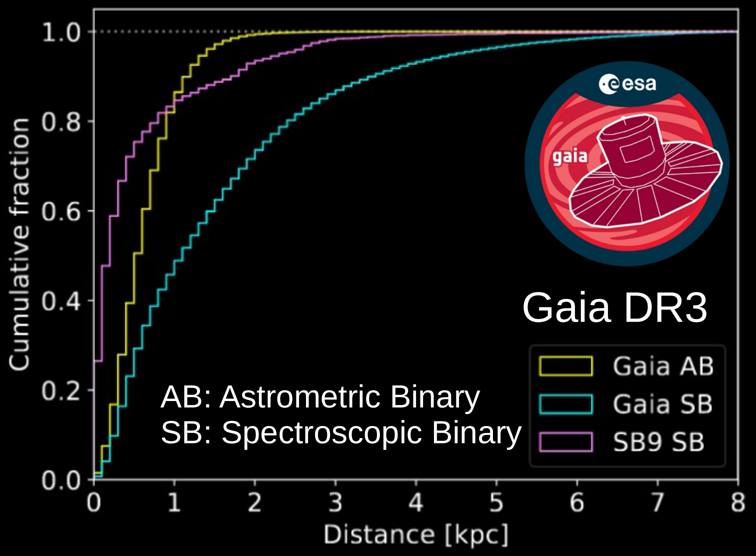
- **OGLE:** 400 000 EB and ellipsoidals (Soszynski+ 2016)
- **Kepler:** 3 000 EB (Kirk+ 2016), 780 contact EB (Kobulnicky+ 2022), 100 doubly EB (Kostov 2022)
- **TESS:** 5 000 EB (Prša+ 2022), 370 EB (Howard+ 2022), 15 000 ellipsoidal candidates (Green+, sub.)
- **ASAS-SN:** 2 900 EB (Christy+ 2022), 35 000 EB (Rowan+ 2022)
- **VVV:** 187 000 EB, 18 000 contact EB (Molnar+ 2022)

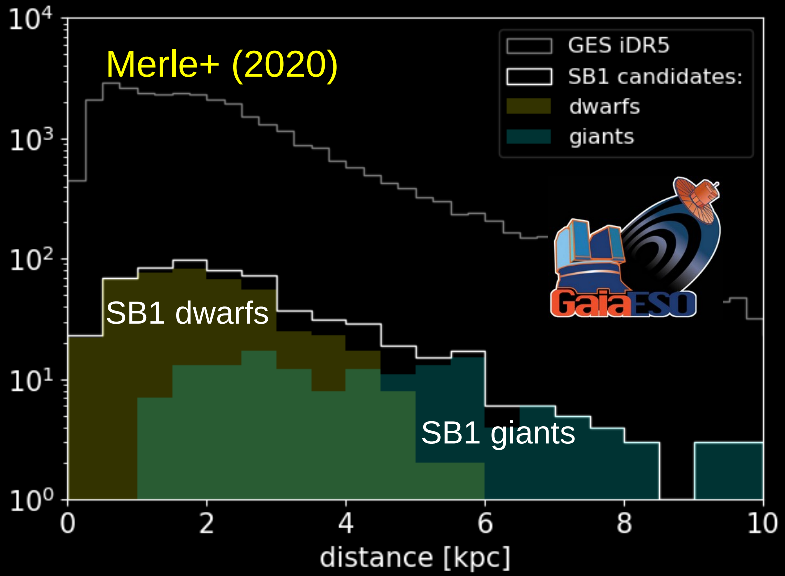
Spectroscopic Surveys:

- **RAVE:** 120 SB2 (Matijeveci+ 2010), 4 000 SB2 (Birko+ 2019)
- **Gaia-ESO:** 1 000 SB1, SB2, SB3, SB4 (Merle+ 2017, 2020, Van der Swaelmen+, in prep.)
- **APOGEE:** 100 SB2 (Fernandez+ 2017) 2 500 unresolved SB2 (El-Badry+ 2018), 20 000 SB1 (Price-Whelan+ 2020), 7 300 candidate SB2s, 800 SB3s, and 20 SB4 (Kounkel+ 2021)
- **GALAH:** 13 000 SB2 (Traven+ 2020)
- **LAMOST:** 256 000 SB1 or variable candidates (Qian+ 2019), 2200 SB2 (Zhang+ 2021), 3100 SB2, 130 SB3 (Li+ 2021), 2500 (Kovalev+ 2022)

II. The Spectroscopic Binaries (SB)

Van der swaelmen+, in prep.





Dimitri Pourbaix

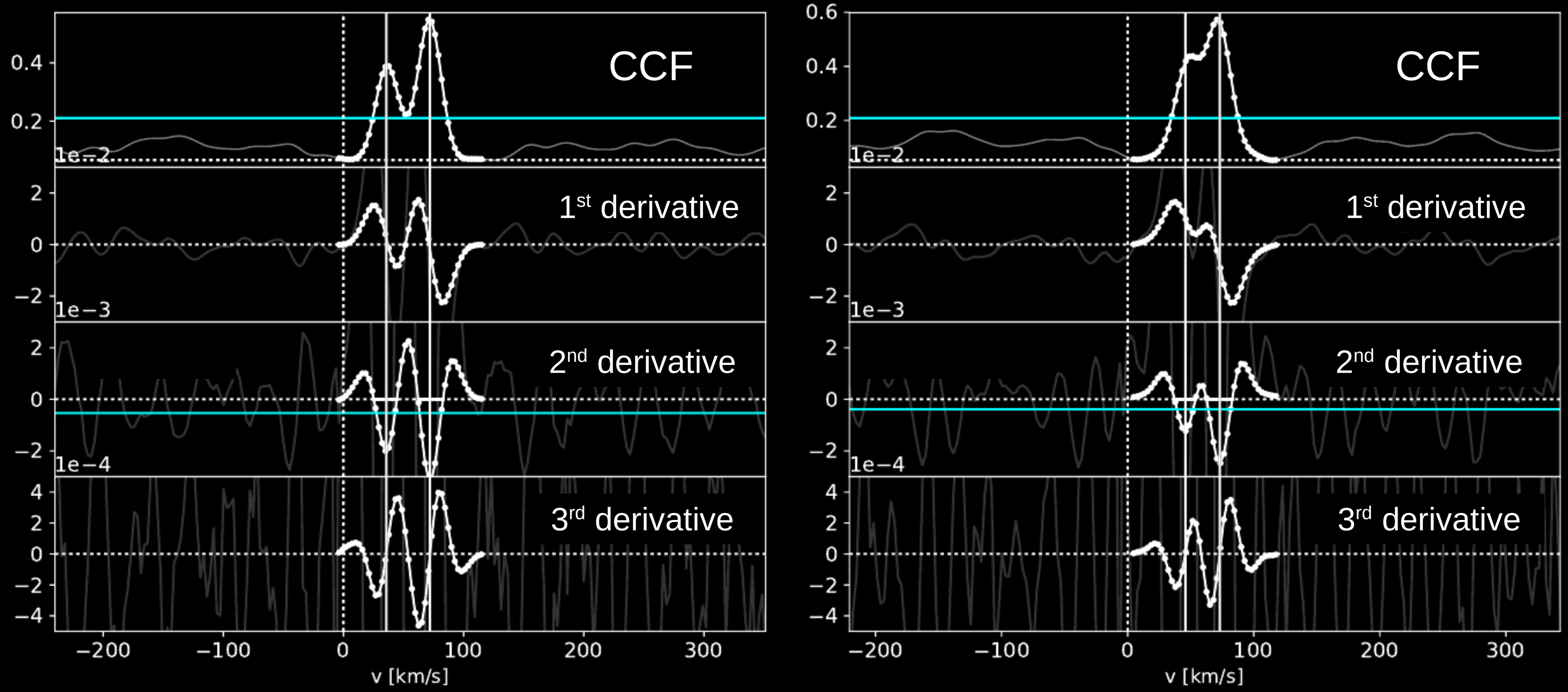
1969 - 2021

The SB9 catalogue

- Their detection is insensitive to the distance
- They probe the shorter part of the period distribution
- The Ninth Catalogue of Spectroscopic Binary Orbits (**SB9**, Pourbaix+ 2004): last release in March 2021 with ~ 4 000 orbits

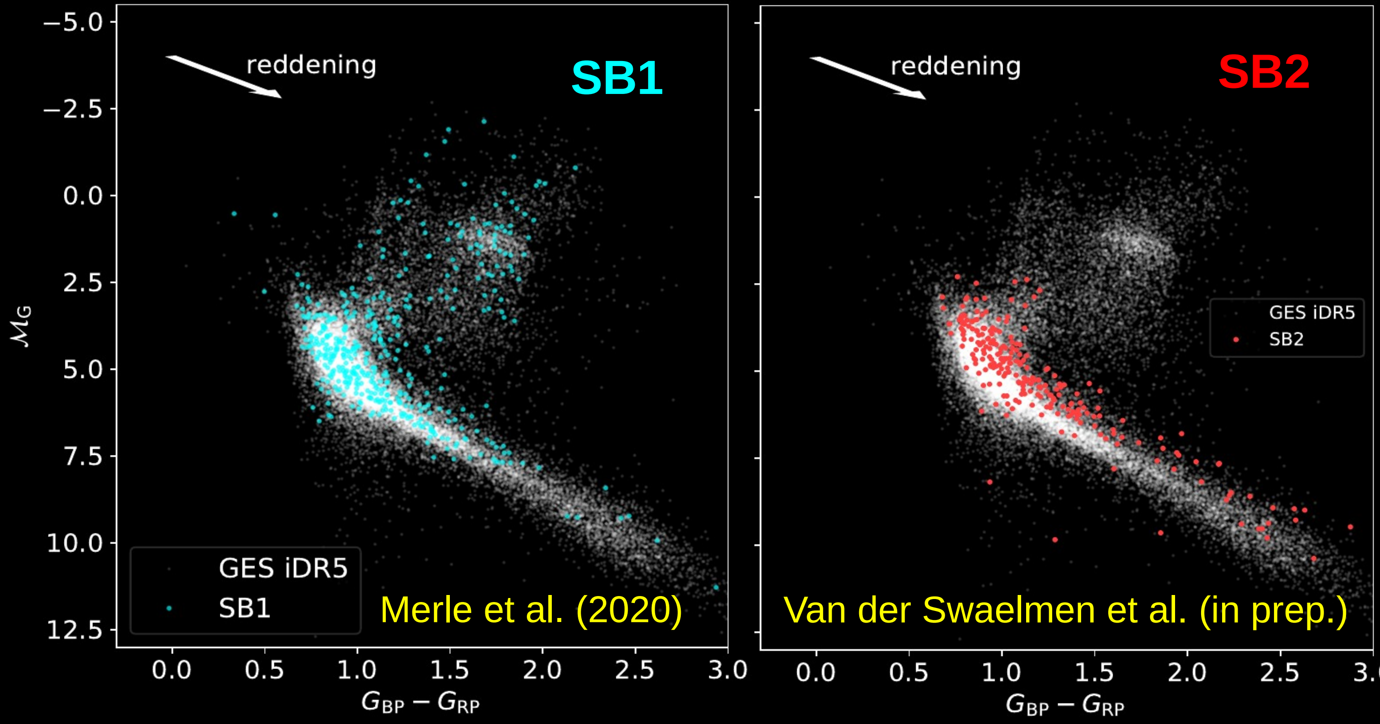
Detection Of Extrema (DOE) to detect SBn ($n \geqslant 2$)

- Basic idea from the ARES code (Sousa et al. 2007)
- Developed in Merle et al. (2017) and also used in Kravchenko et al. (2019), Traven et al. (2020)
- Under implementation in the 4MOST galactic pipeline



The Spectroscopic Binaries (SB)
Statistical properties of SB1 & SB2 in the Gaia-ESO Survey

Parallaxes and G, BP, RP photometry from Gaia DR2:
Locii in the color-absolute magnitude diagram of **SB1** and **SB2**



Monte Carlo simulations to estimate the detection efficiency of our methods using the SB9 (Pourbaix+ 2004-2014)

SB1 detection efficiency: 19%
SB2 detection efficiency: 62%

Total GES SB frequency: 12%

SB1 frequency: 9.8 ± 1.8%
SB2 frequency: ~ 2%

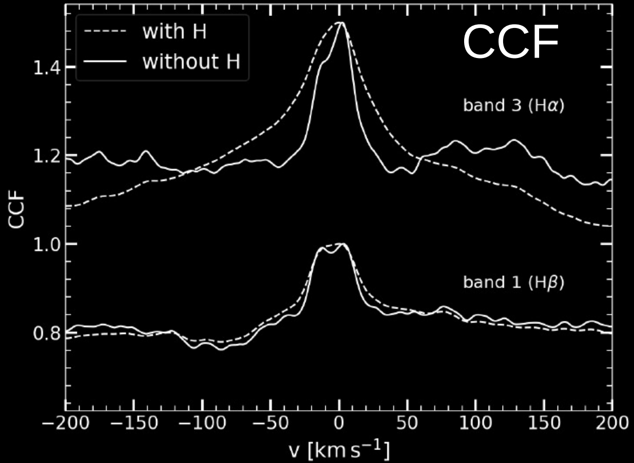
Close binary fraction from Moe & Di Stefano (2017): 15 ± 3%

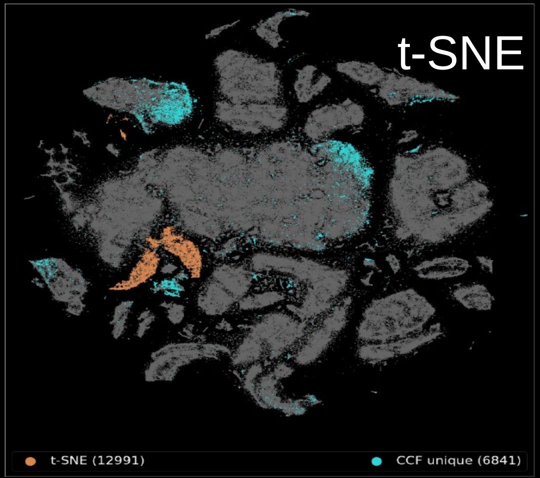
The Spectroscopic Binaries (SB)
SB2 in GALactic Archeology with Hermes (GALAH) survey

~500 000 stars

V magnitude: [12-14]

Resolution: 28 000



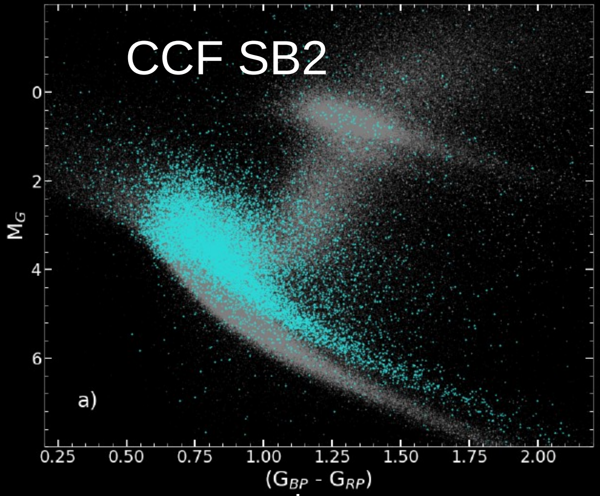


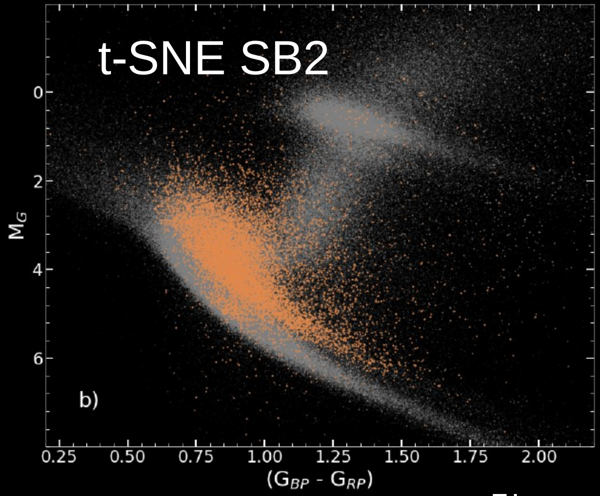
Classical approach (CCF): 14 000
Machine learning approach t-SNE*: 13 000
*t-distributed Stochastic Neighbour Embedding

Combined techniques: 12 000 SB2

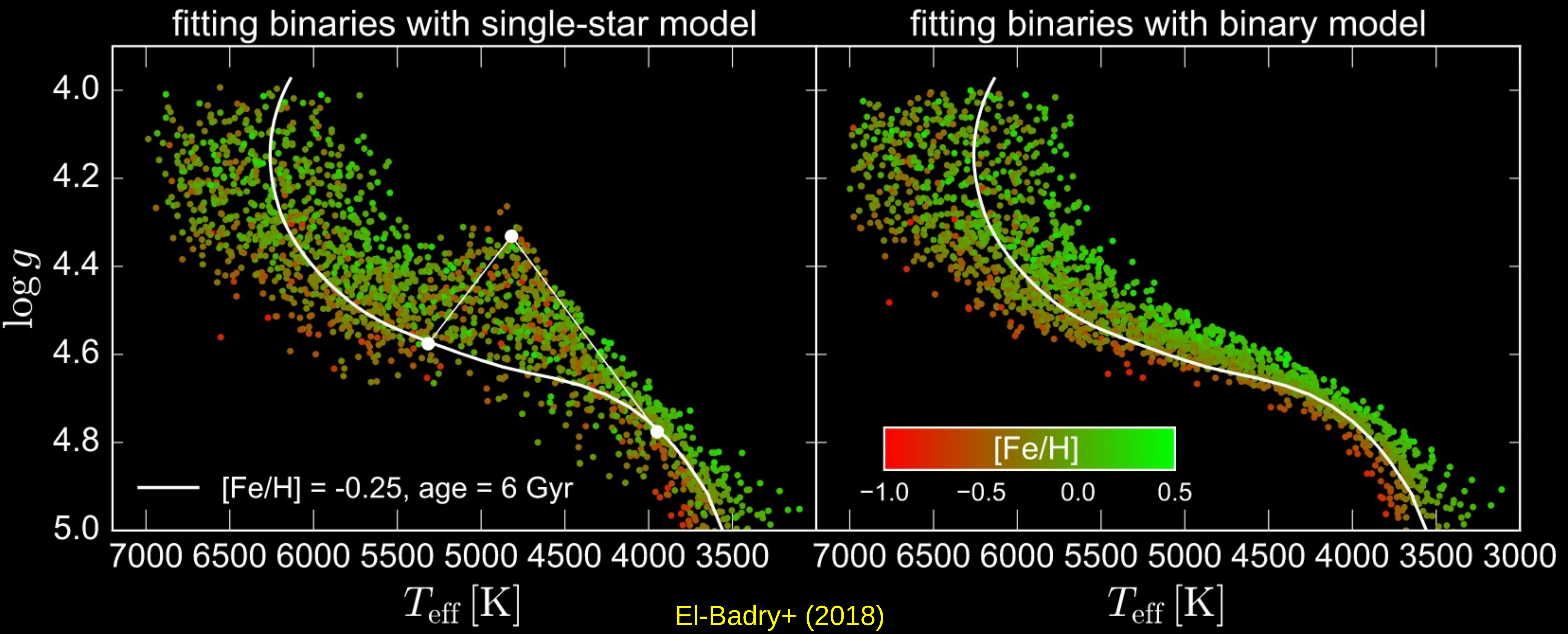
Astrophysical characterizationwith Bayesian inference ➔ $T_{\rm eff}$, log g, [Fe/H] and R

Traven+ (2019, 2020)





The Spectroscopic Binaries (SB)
The unresolved cases

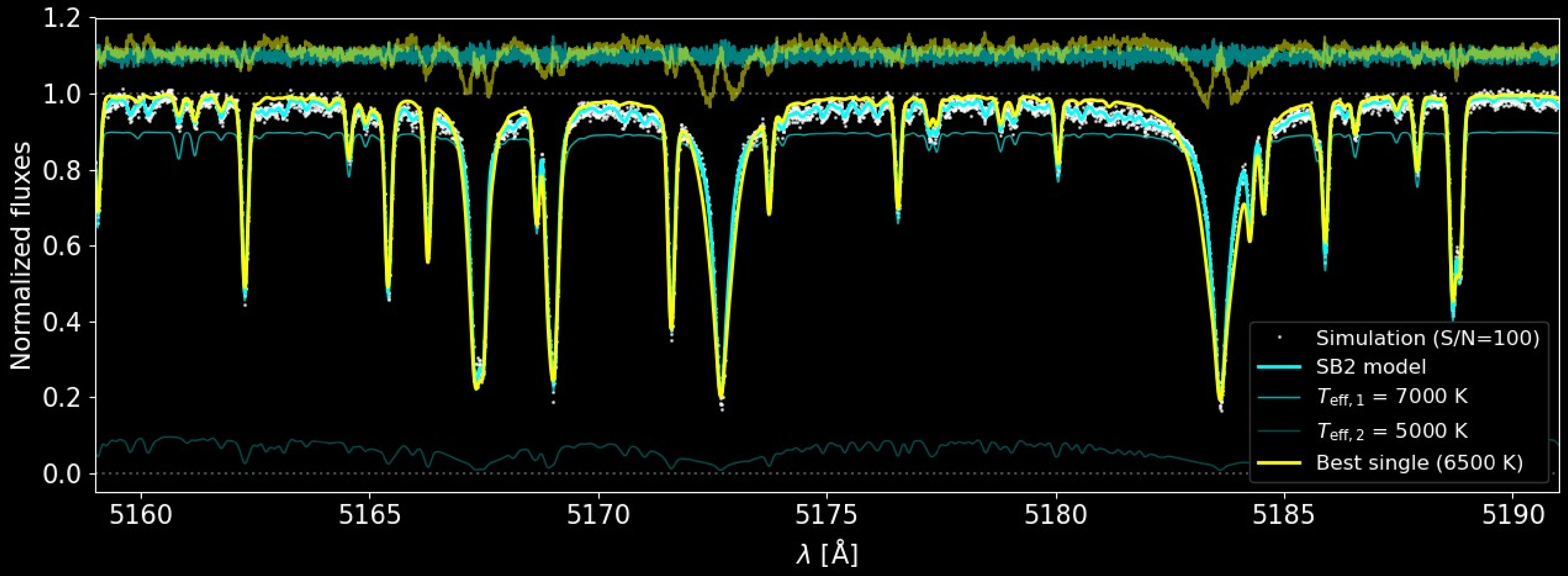


El-Badry+ (2018)

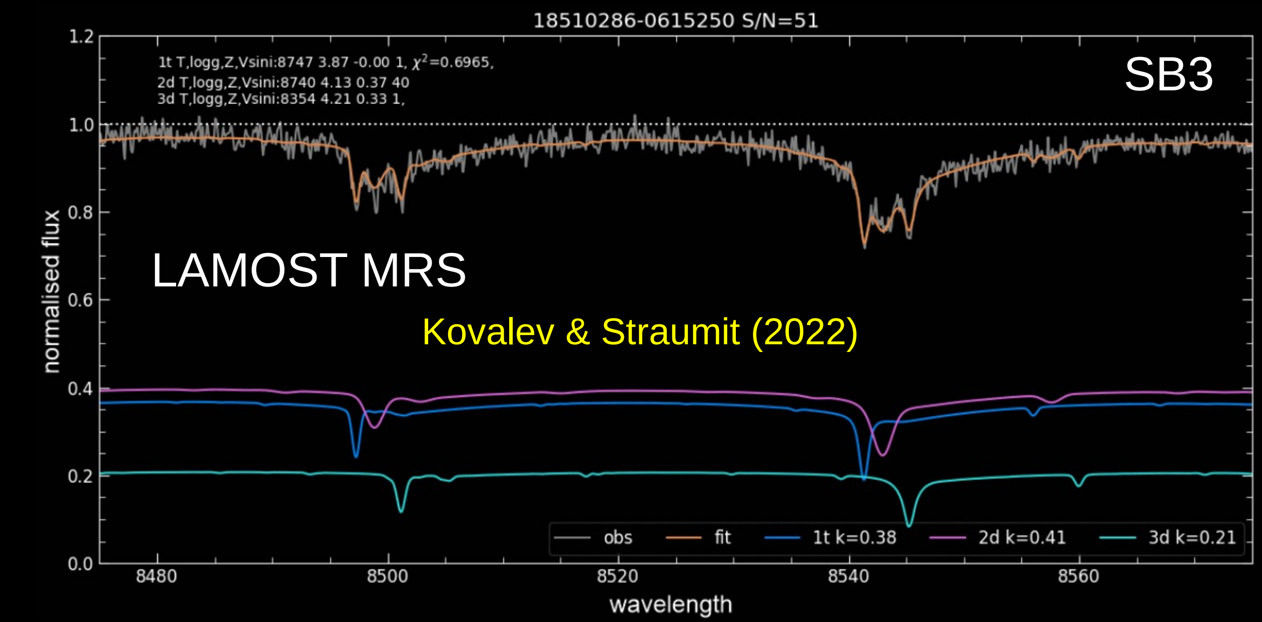
The Spectroscopic Binaries (SB)
The unresolved cases

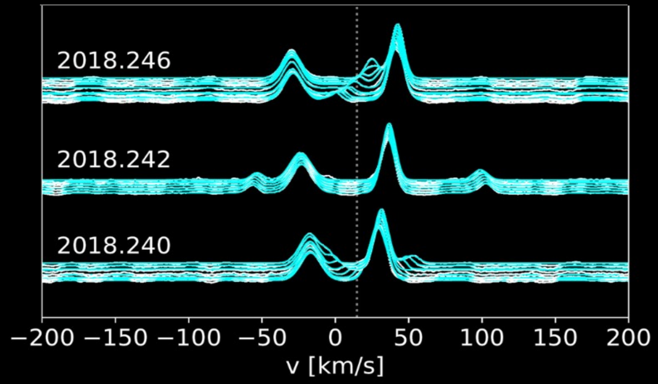
First characterisation: El-Badry+ (2018) on APOGEE spectra in IR (2 500 unresolved SB2)

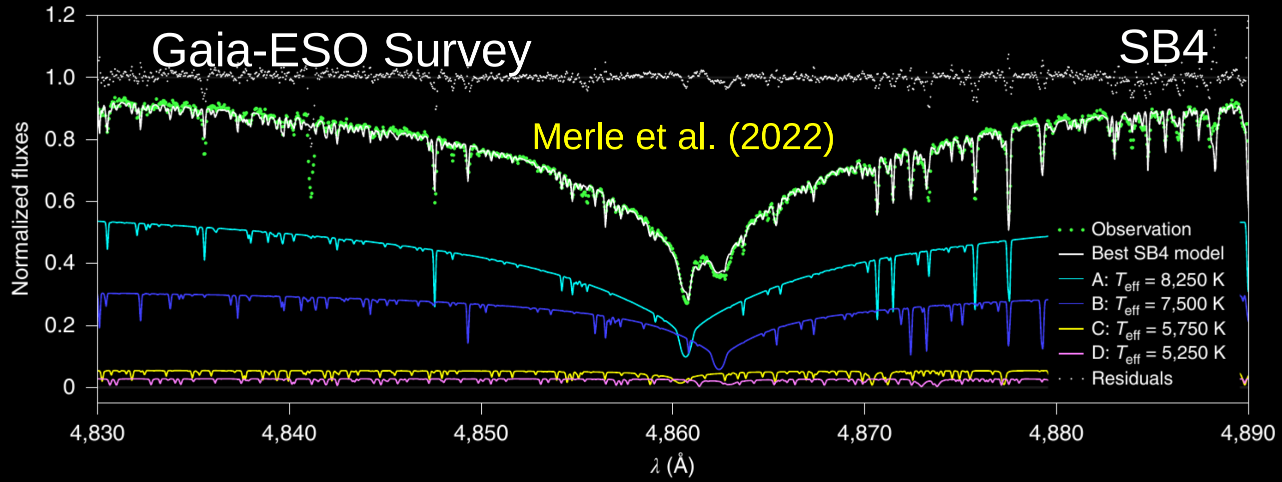
Also feasible in the visible wavelength range of Gaia-ESO survey and HERMES spectra:

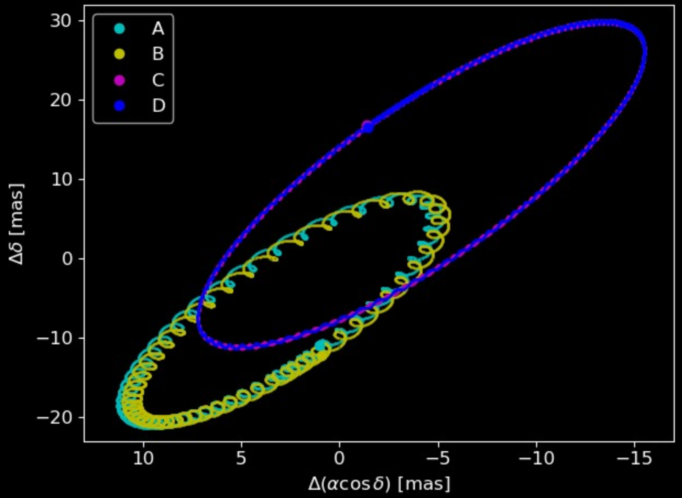


Examples of high-order SB



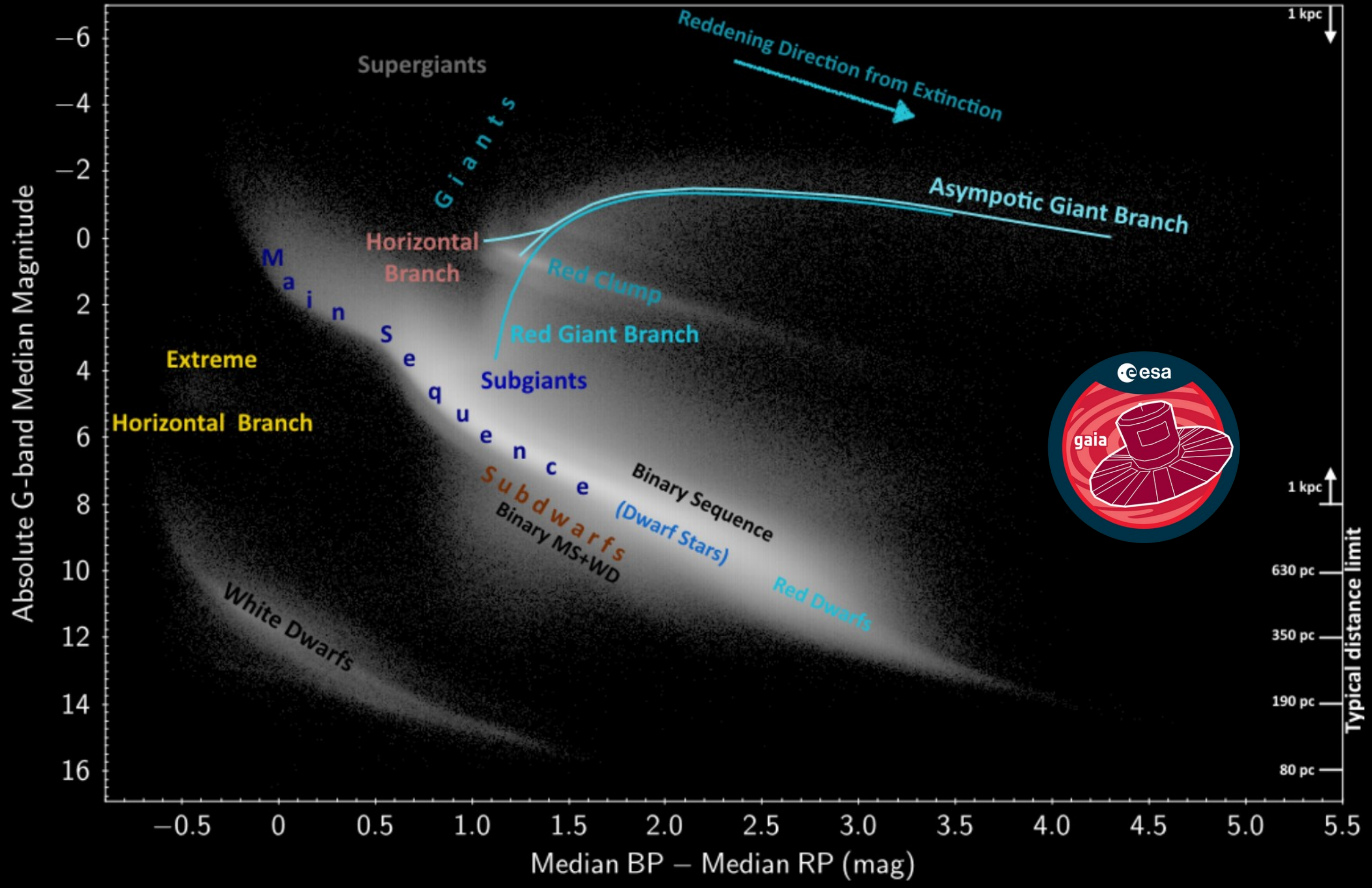






III. The Gaia revolution
1. HR diagram

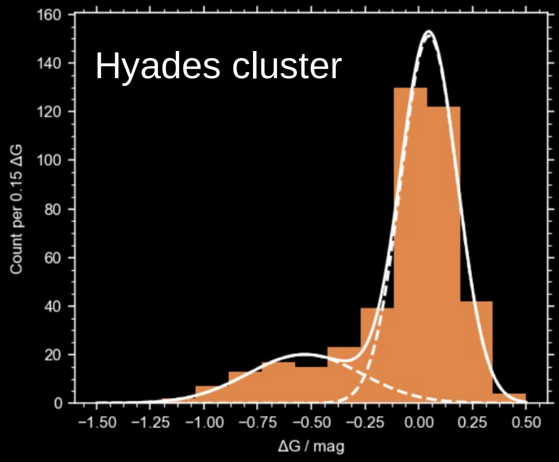
Gaia col., Eyer+ (2018)



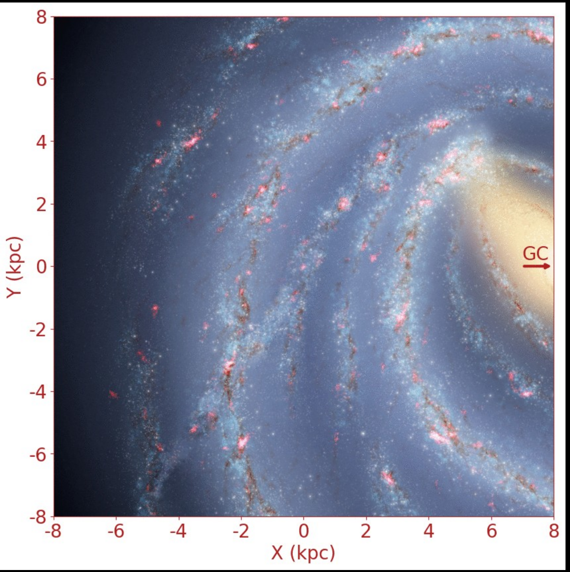
See also:
For Binary MS+WD
Rebassa-Mansergas+ (2021)
Ren+ (2023)

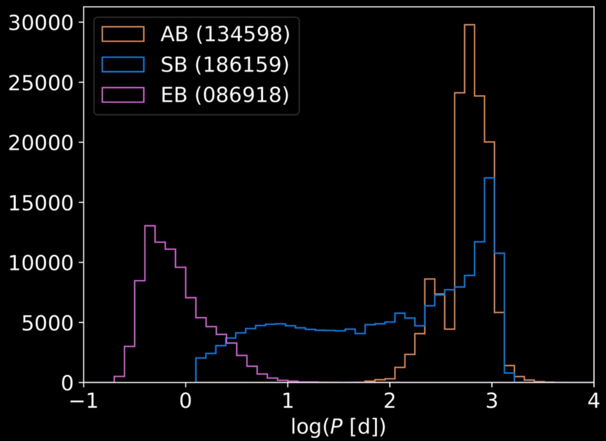
For the Binary MS
Gaia col., Babusiaux+ (2018)

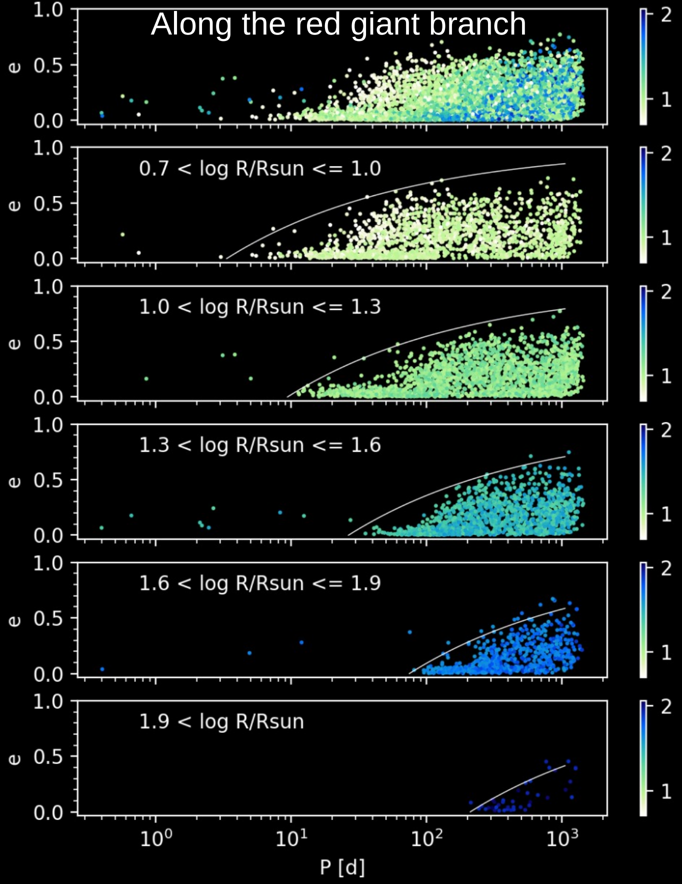
Gaia Catalogue of Nearby stars
Gaia col., Smart+ (2021)



III. The Gaia revolution
2. Astrometric/spectroscopic/eclipsing binaries







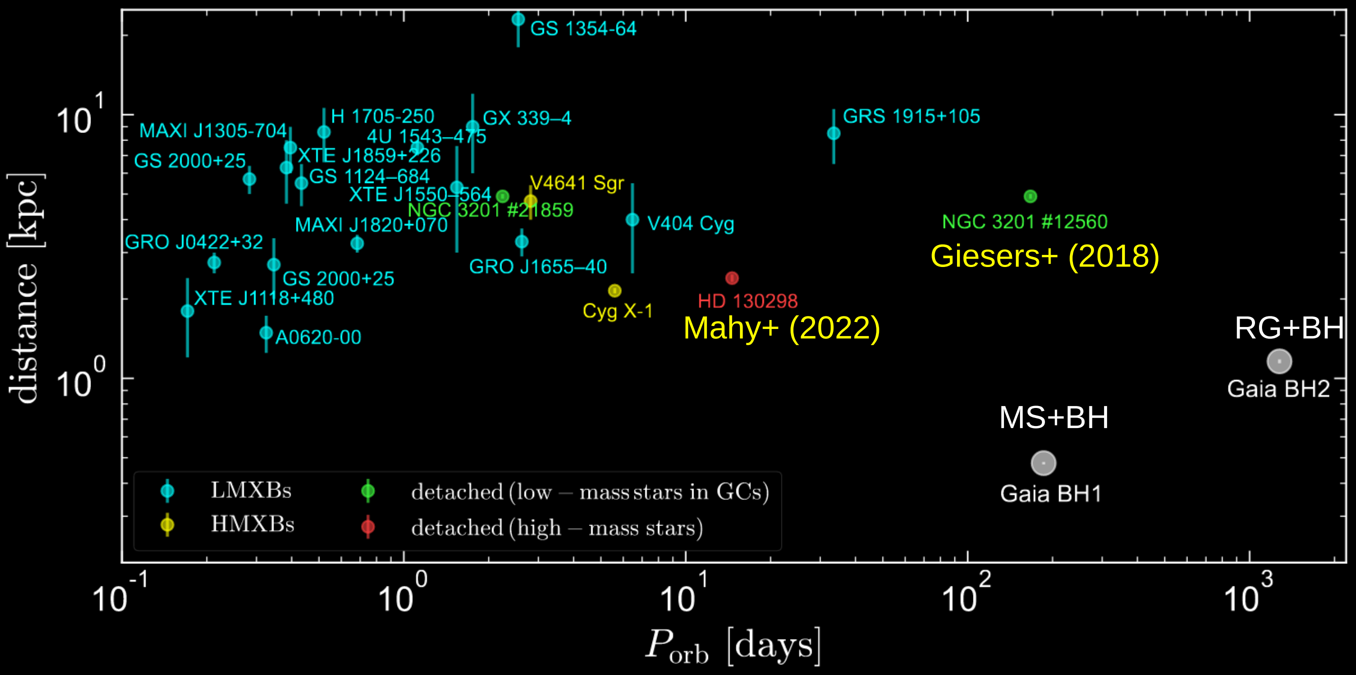
Gaia collaboration, Arenou, Babusiaux+ (2022)

- Non-Single Star (NSS) catalogue with 440 000 binaries
- Measured masses for 195 000 binaries

But also:

- Binaries along the RGB/AGB
- EL CVn systems
- Ultra-Cool Dwarf binaries (UCD)
- Compact object companions

III. The Gaia revolution
3. Binaries including a dormant BH



Low and High-mass X-ray binaries (LMXB & HMXB)
from Remillard & McClintock (2006) and Corral-Santana et al. (2016)

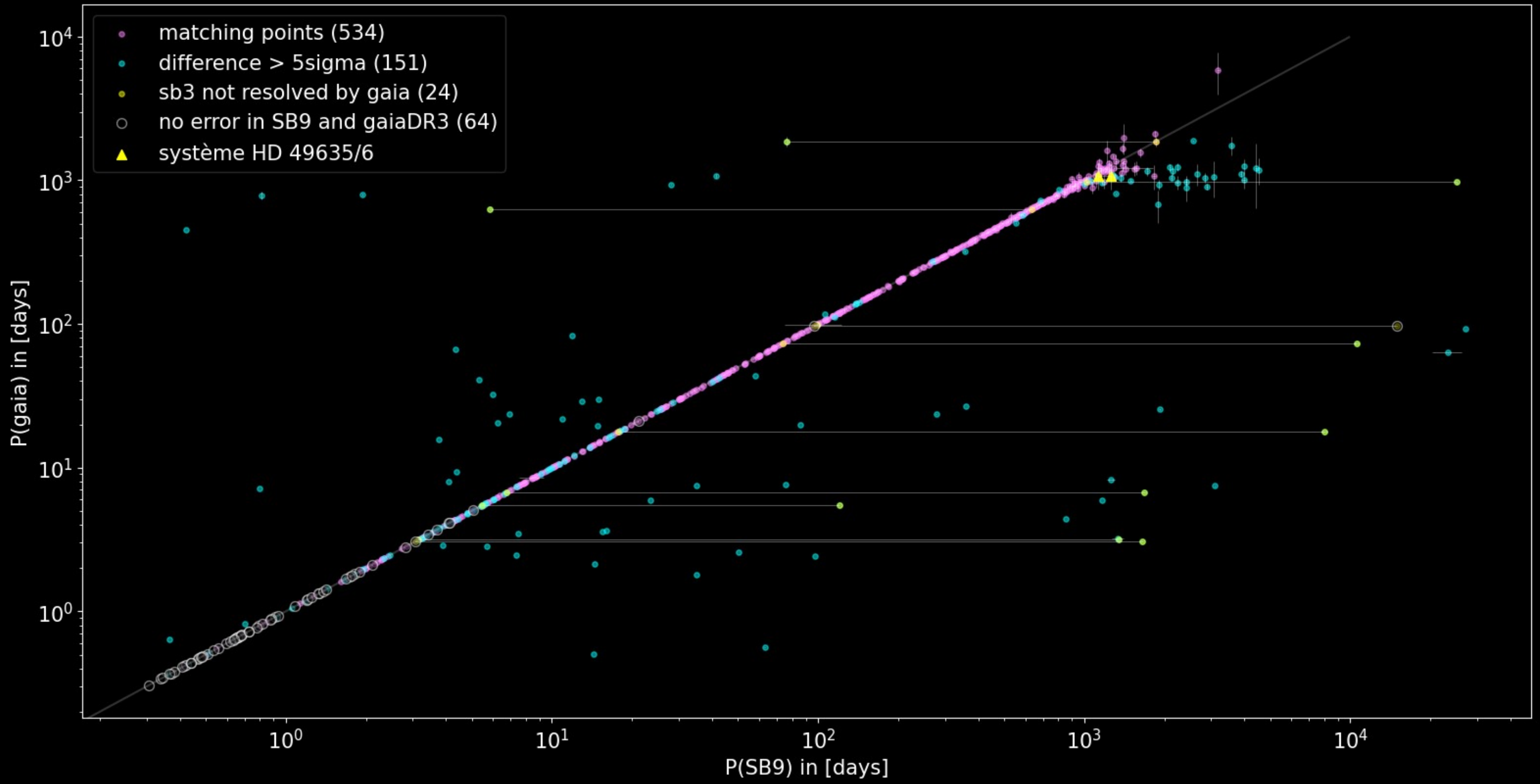
- A Sun-like star orbiting BH (El-Badry+ 2023)
- A red giant orbiting a BH (El-Badry+ 2023, submitted)
- Discovered with Gaia astrometry and spectroscopy
- 2BH with 8 $M_\odot$ (initial mass ~25 $M_\odot$)

Uncertain formation scenarios
- Common envelope evolution
- Exchange interaction in a dense cluster
- Stellar triple scenario

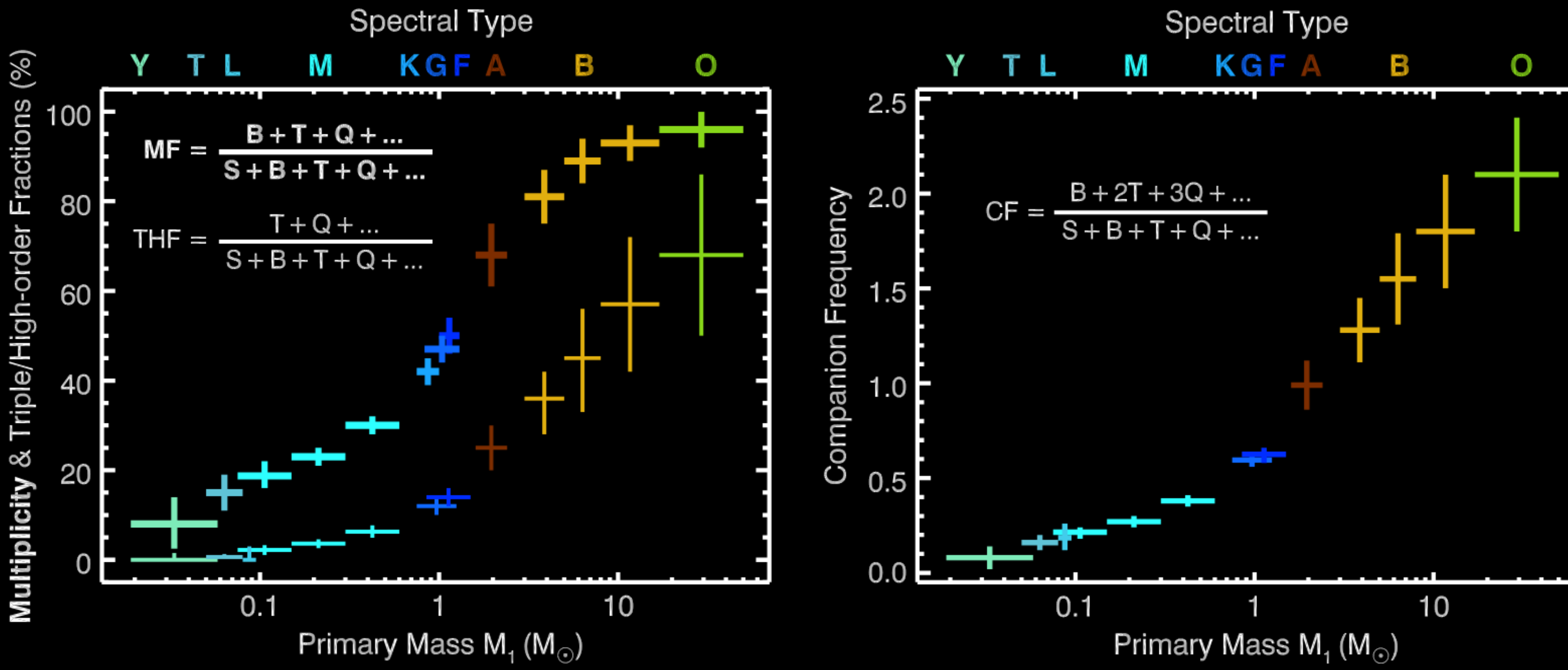
- Future evolution
  - RG+BH → symbiotic X-ray binary? → wide binary with RC or sdB?
  -
- BH-NS mass gap?

III. The Gaia revolution
4. A word of cautious

Credit: J. Desuter



Multiplicity fraction vs. Mean number of companions



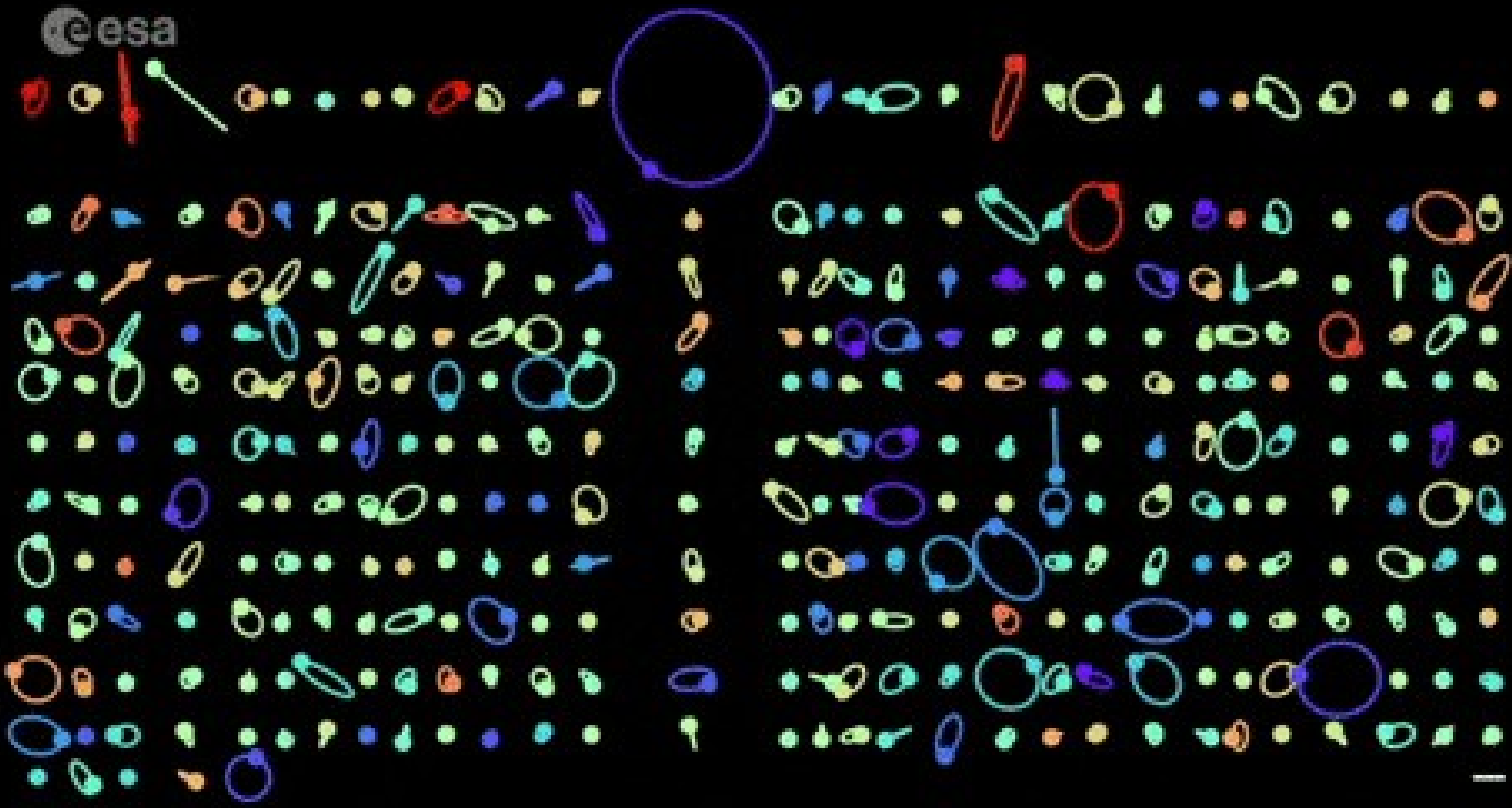
Offner et al. (2022)

See also: Duquennoy & Mayor (1991), Raghavan+ (2010), Tokovinin (2014), Duchêne & Kraus (2013), Moe & Di Stefano (2017), Furhmann+ (2017), etc.

Dancing with the stars: a review on stellar multiplicity
Conclusion

- Stellar binaries and multiples are ubiquitous for all spectral-type and for all evolutionary status.
- ~1000 to 100 000 binary stars are now routinely detected by large photometric and spectroscopic surveys, but their full orbital characterizations often require additional follow-up observations in spectroscopy.
- Astrometric – Photometric – Spectroscopic Binaries probe different part of the period distribution.
- Gaia offers a unique, homogeneous and the largest sample of binaries.
- Higher-order systems seems to interact more often than binaries.

Dancing with the stars: a review on stellar multiplicity



Binary and multiple stars heterogeneous databases

- Whashington Double Stars catalogue (WDS, Mason+ 2001-2020) http://www.astro.gsu.edu/wds

155 159 stellar systems

- The Binary Star dataBase (BSB, Kovaleva 2015) http://bdb.inasan.ru

120 000 stellar systems of multiplicity 2 to more than 20

- Multiple Star Catalogue (MSC, Tokovinin 2018) https://www.ctio.noirlab.edu/~atokovin/stars/stars.php

> 3 000 curated systems with 3 to 7 components each.

- The Ninth Catalogue of Spectroscopic Binary Orbits (SB9, Pourbaix+ 2014-2021) https://sb9.astro.ulb.ac.be/

> 4 000 spectroscopic orbits

- The Detached Eclipsing Binary catalogue (DEBcat, Southworth) https://www.astro.keele.ac.uk/jkt/debcat/

> 320 systems