Binary and Multiple Stars in the Era of Big Sky Surveys
9-13 September Litomyšl

Spectroscopic binaries in the Gaia-ESO Survey, Gaia and 4MOST

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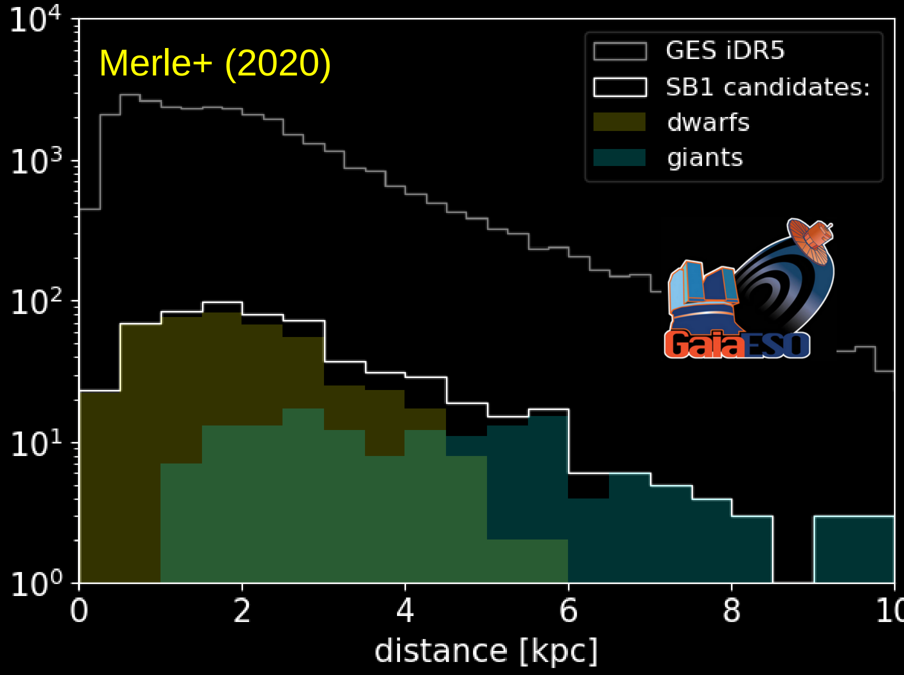
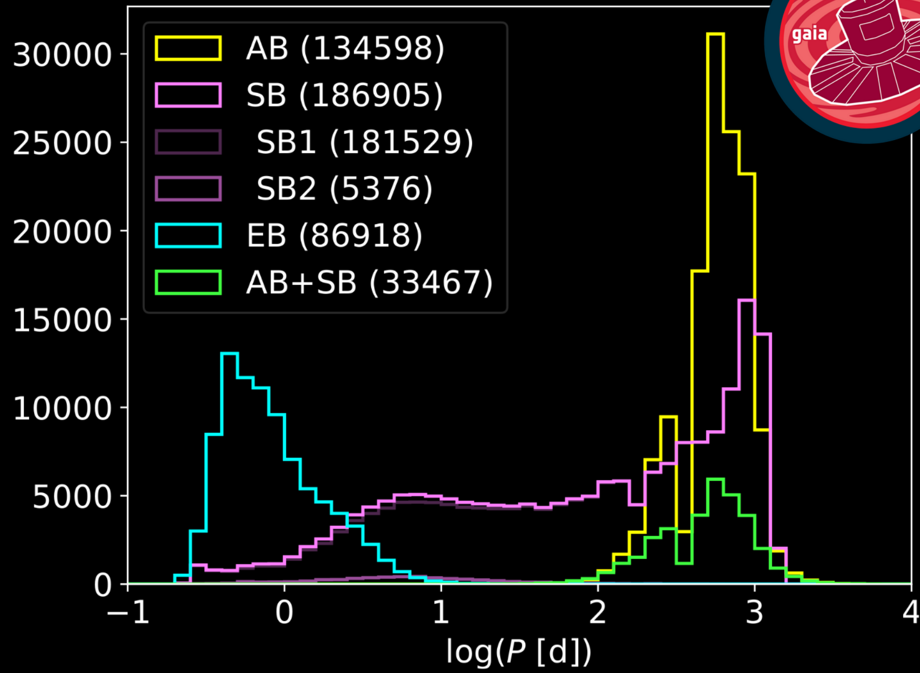
Why spectroscopic binaries (SB)?

- Their detection is insensitive to the distance
- They probe a wide range of orbital periods





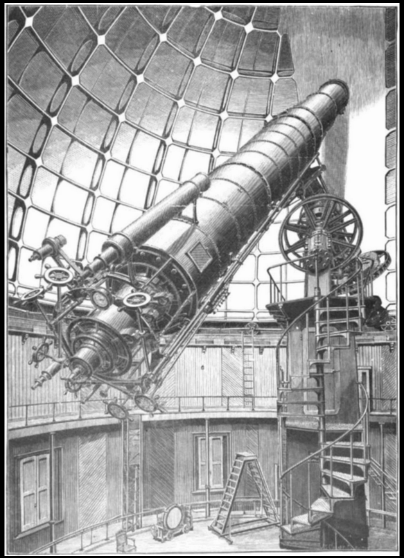
An historical catalogue of spectroscopic orbits: the ***SB9***

v1: Campbell & Curtis (1905)
v2: Campbell (1910)
v3: Moore (1924)
v4: Moore (1936)
v5: Moore & Neubauer (1948)

v6: Batten (1967)
v7: Batten+ (1978)
v8: Batten+ (1989)

2000: IAU initiative from commission G1 “Binary and multiple star systems” (former commission 30)

v9: Pourbaix+ (2004)



Lick Telescope
140 SB (1905)

Dominion Astrophysical Observatory
740 SB (1967)

An historical catalogue of spectroscopic orbits: the ***SB9***

The Ninth Catalogue of Spectroscopic Binary Orbits (***SB9***, Pourbaix+ 2004): last release by D. Pourbaix in March 2021 with ~ 4000 SB

- 5000 orbits
- 4000 systems:
  - 70% SB1
  - 30% SB2

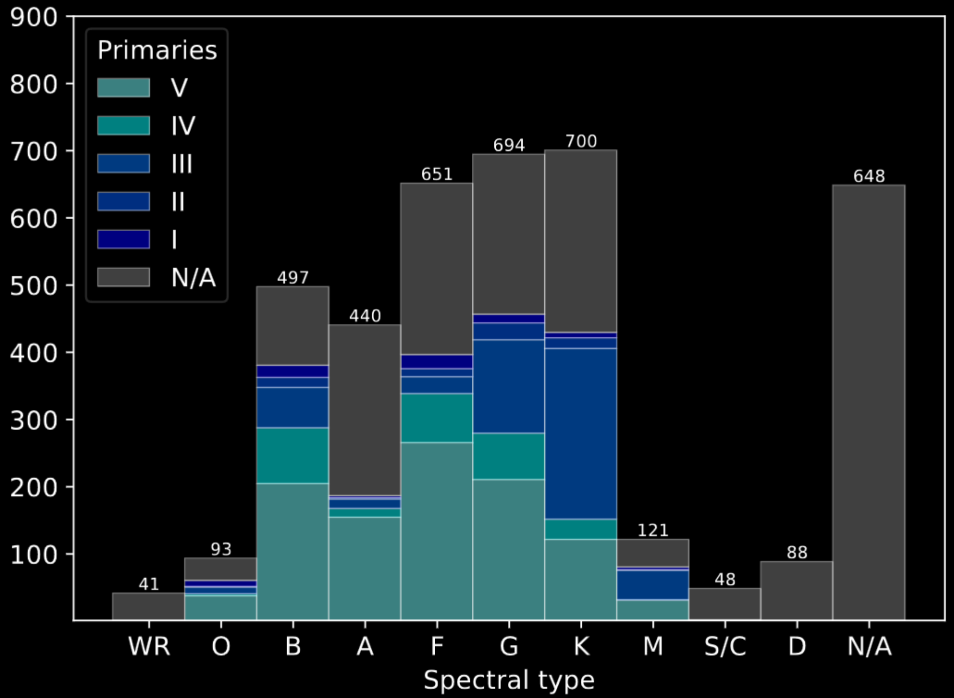
Dimitri Pourbaix

1969 - 2021

- Available at:
  - ULB: https://sb9.astro.ulb.ac.be/
  - Also on CDS Vizier: B/sb9

Main contributors

- Roger Griffin: 45 papers + 100 RV sets in electronic format
- Jean-Michel Carquillat, Maurice Imbert, Alain Jorissen
- Laszlo Szabados (orbits and RV of Cepheids)
- Dave Stickland (IEU orbits and data)
- Elena Glushkova (lots of orbits from Russian authors)
- Roger Leiton (data entry)



Binaries in large spectroscopic surveys

- The past: Gaia-ESO Survey
- The present: Gaia
- The future: 4MOST

The past: Gaia-ESO Survey (GES)

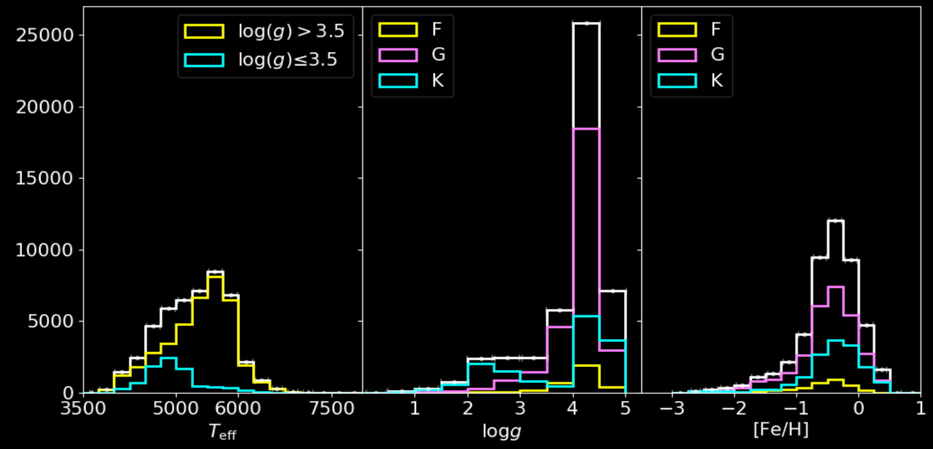
With GIRAFFE (*R* ~20 000) and UVES (R = 47 000) spectrographs

Study of the formation history of stellar populations of the Milky-Way:
> 100 000 stars in bulge, discs, halo and stellar clusters (Gilmore+ 2022, Randich+ 2022)

GES DR5.1 final release in July 2023: https://www.eso.org/qi/catalogQuery/index/393

Observing strategy not adapted to the detection of binaries but:

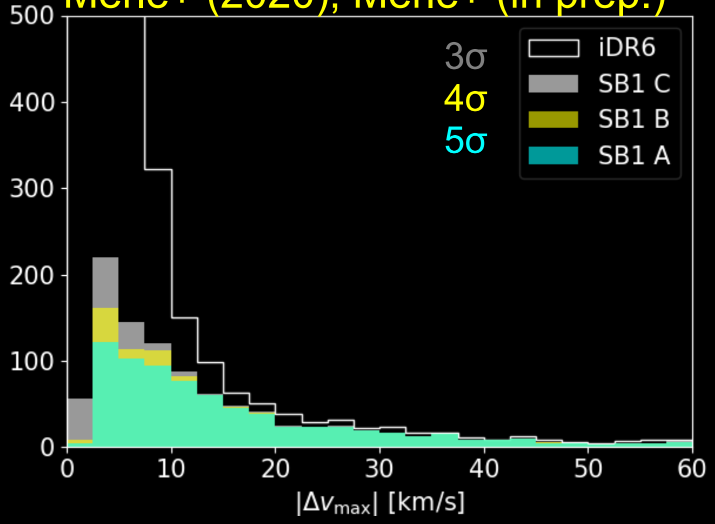
- Merle, Van Eck, Jorissen+ (2017): ~ 340 SB2, ~10 SB3 & 1 SB4
- Merle, Van der Swaelmen, Van Eck+ (2020): ~800 SB1
- Van der Swaelmen, Merle, Van Eck+ (accepted) > 430 SB2

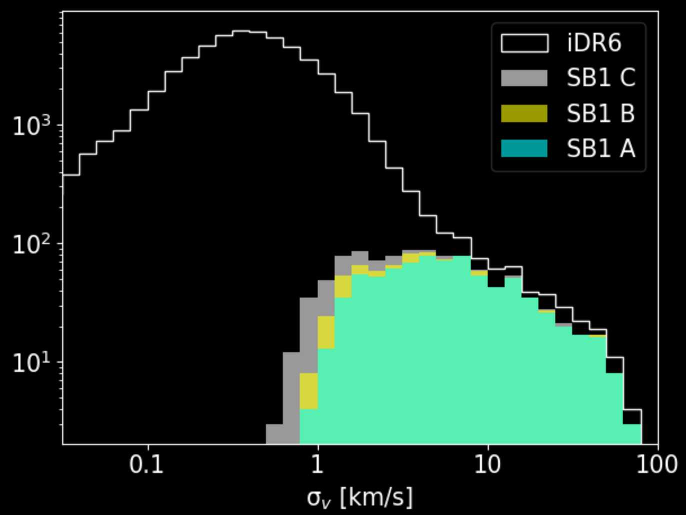


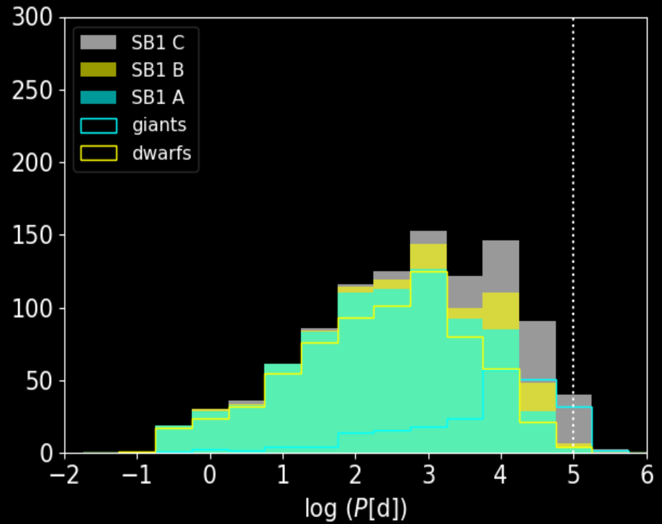
Kopal 2024

The past: Gaia-ESO Survey (GES)

Merle+ (2020), Merle+ (in prep.)







$$P = 9.650 \times 10^4 \frac{1}{K^3} \frac{\sin^3 i}{(1 - e^2)^{3/2}}$$

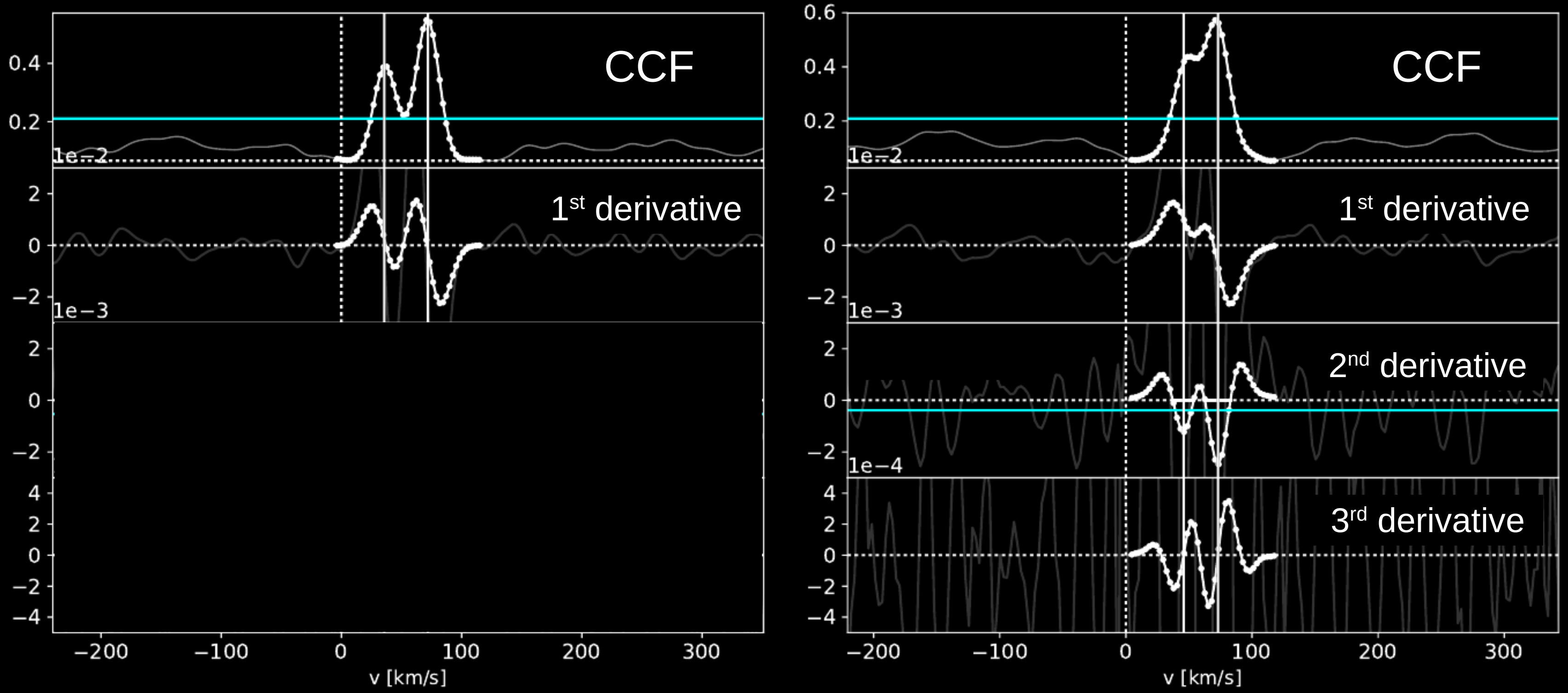
- RV amplitude estimator: $K = \sqrt{2}\,\sigma_v$
- mass of the primary: $M = 1\ M_\odot$
- mass ratio $q = 0.25$
- random inclination on the sky: $i = 68°$
- median eccentricity in the SB9: $e = 0.2$

According to Moe & Di Stefano (2017):

- 70% ± 10% have M dwarfs secondaries
- 30% ± 10% contain compact remnant companions:
  - Sirius-like binaries with hot white dwarfs
  - Barium stars

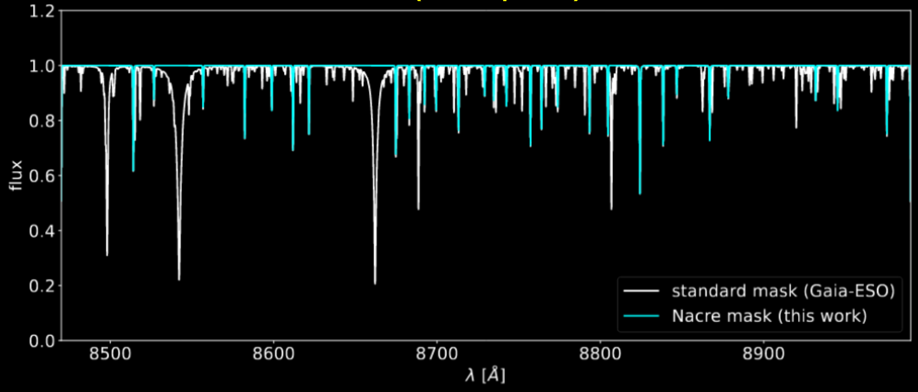
The past: Gaia-ESO Survey (GES)

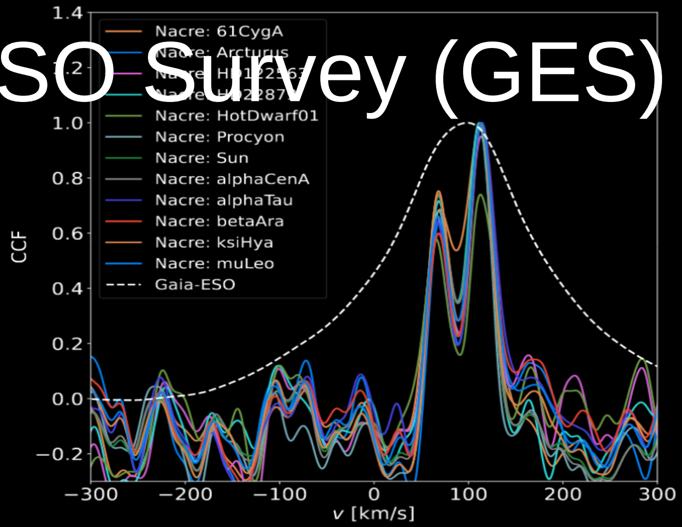
- DOE for multi-peaks Cross-Correlation Function (CCF) Merle et al. (2017)
- Also used in: Kravchenko et al. (2019) – Betelgeuse, Traven et al. (2020) – GALAH, Merle et al. (2022) – SB4
- Under implementation in the 4MOST galactic pipeline

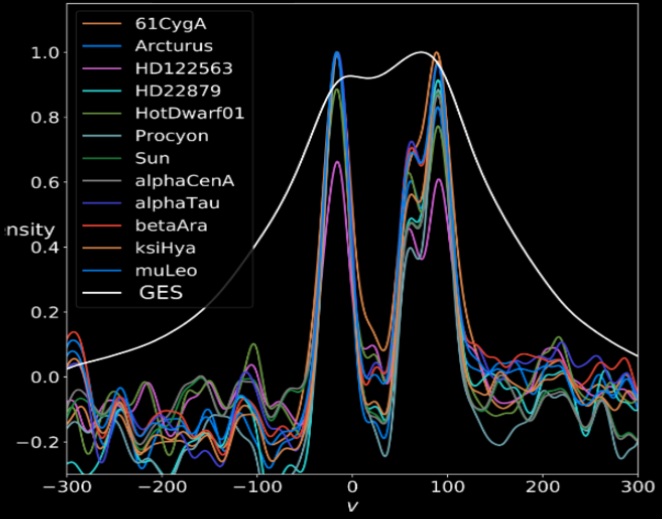


The past: Gaia-ESO Survey (GES)

Van der Swaelmen+ (accepted)







New sets of CCFs with optimized masks for HR10 & HR21

NArrow Cross-Correlation Experiment (NACRE):

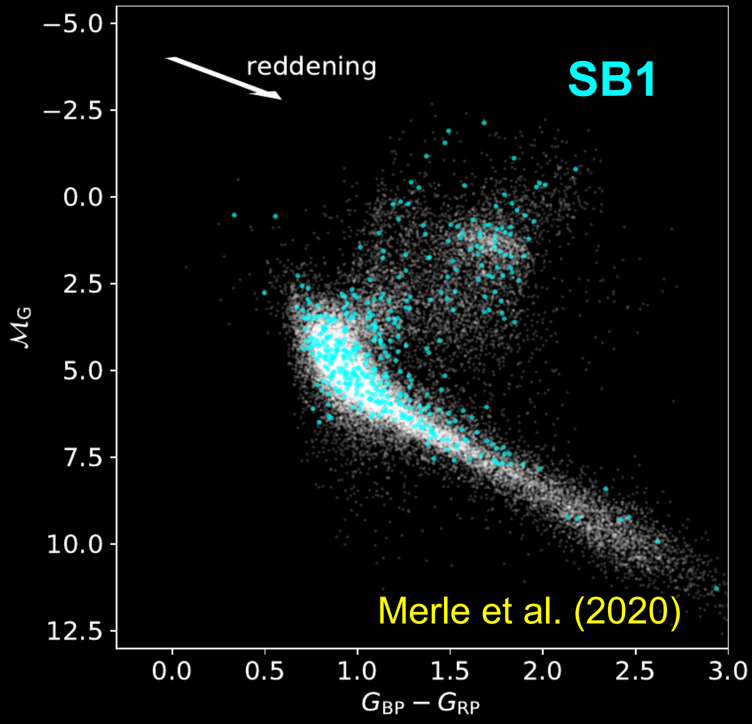
- Template stars among FGK benchmark stars (Jofré+ 2015)
- Selection of at least 10 weak and unblended lines
- Masking the Ca II IR triplet, H lines and tellurics at the red end

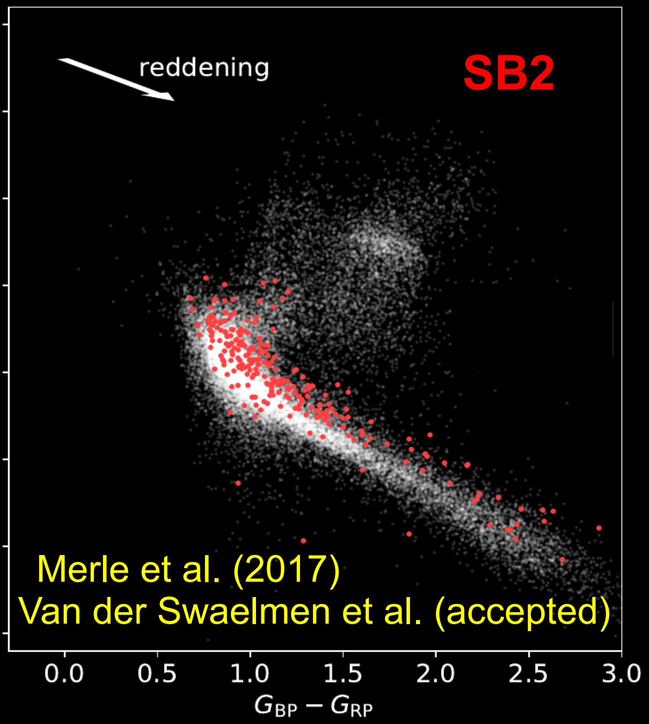
Sensitivity in setup HR21 increases at the level of HR10:

- Decrease of the Δv_{min} from ~60 to 25 km/s
- Increase of the number of SB2 and SB3 by 1/3

The past: Gaia-ESO Survey (GES)

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)

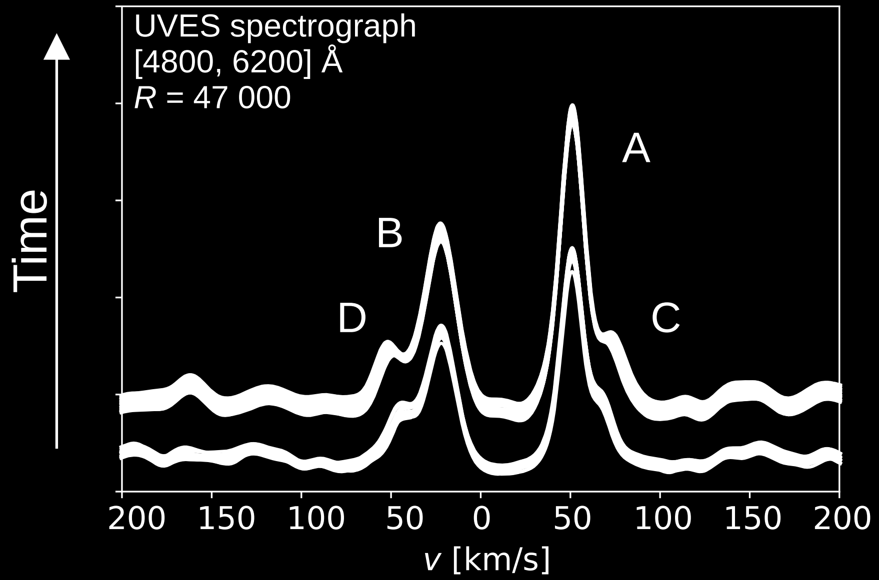
SB1 detection efficiency: 19%
SB2 detection efficiency: 62%

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 past: Gaia-ESO Survey (GES)



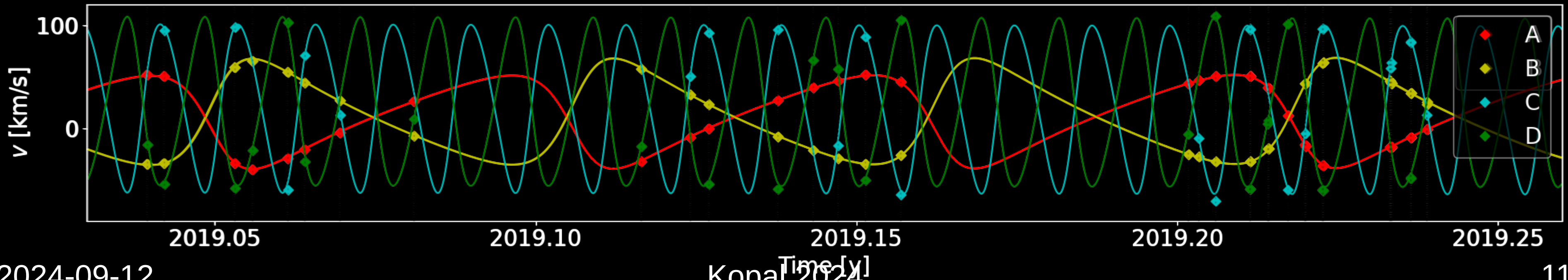
HD 74438: SB4 discovered in UVES/GES
Member of the nearby open cluster IC 2391

Follow-up with HRS/SALT and HERCULES/UCMJO

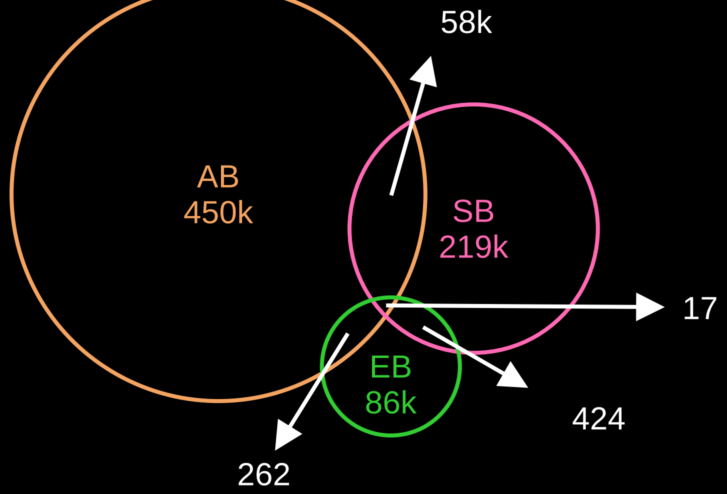
2+2 architecture (2 hierarchical levels)
Inner orbits of 4 and 21 d for an outer orbit of 5.7 y

Evolution scenarios can lead to form SN Ia
(Merle et al. 2022, Nature Astronomy)

GRAVITY/ESO proposal accepted (P112/P114)



The present: Gaia

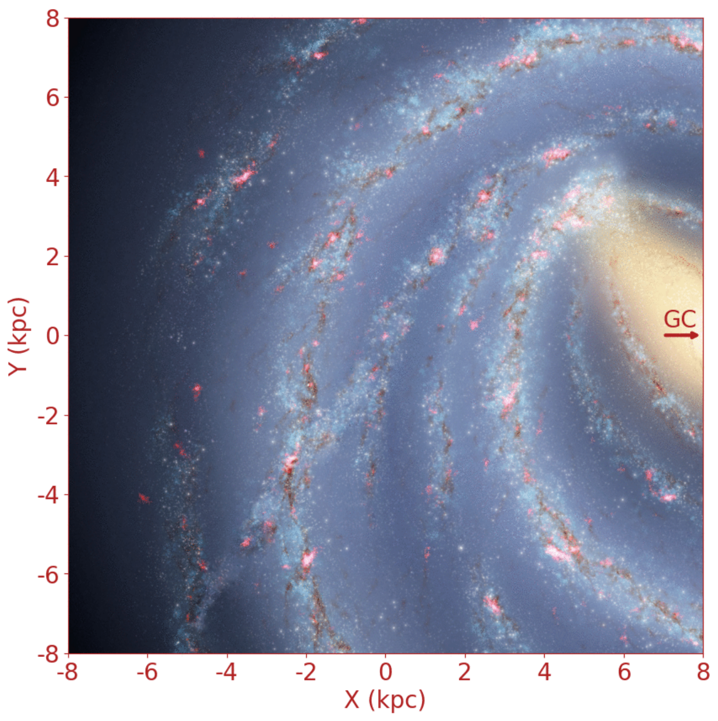


Gaia DR3:

- Non-Single Star (NSS) catalogue
of 800k binaries (Gaia coll., Arenou+ 2023)

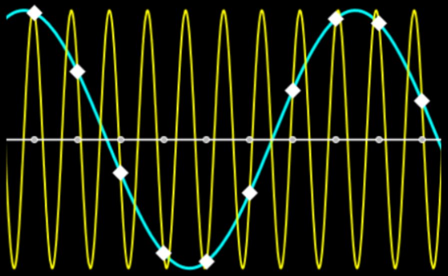
- Catalogue of variables (Eyer+ 2023)
  - 2 millions of EB (Mowlavi+ 2023)
  - 6300 ellipsoidal variables (Gomel+ 2023)

- Multiple Star Classifier (Gaia coll., Creevey+ 2023)
  - BP/RP excess
  - 480 millions of sources with $T_{\mathrm{eff},1}$, $T_{\mathrm{eff},2}$, $\log g_1$, $\log g_2$, [Fe/H], extinction and distance
  - Need validation!



ESA/Gaia/DPAC - CC BY-SA 3.0 IGO. Acknowledgements: created by Nathalie Bauchet, based on the data described in "Gaia DR3: Stellar multiplicity, a teaser for the hidden treasure" by the Gaia Collaboration, Arenou, F., et al. 2022.

The present: Gaia

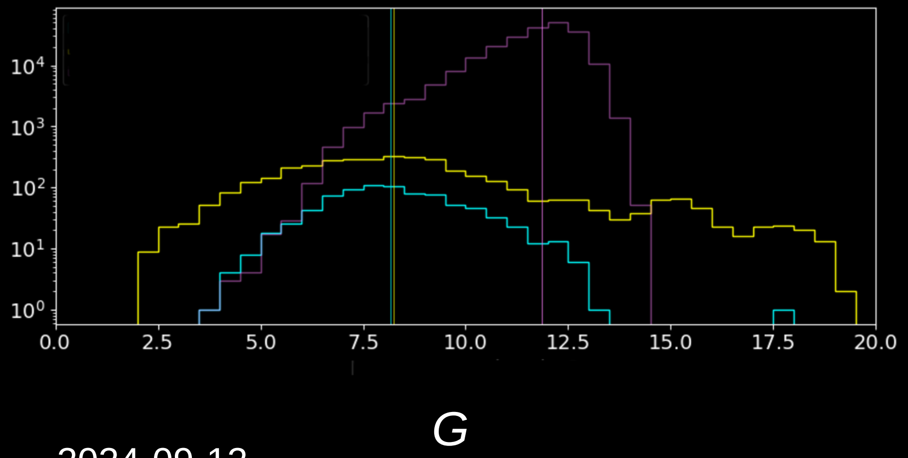


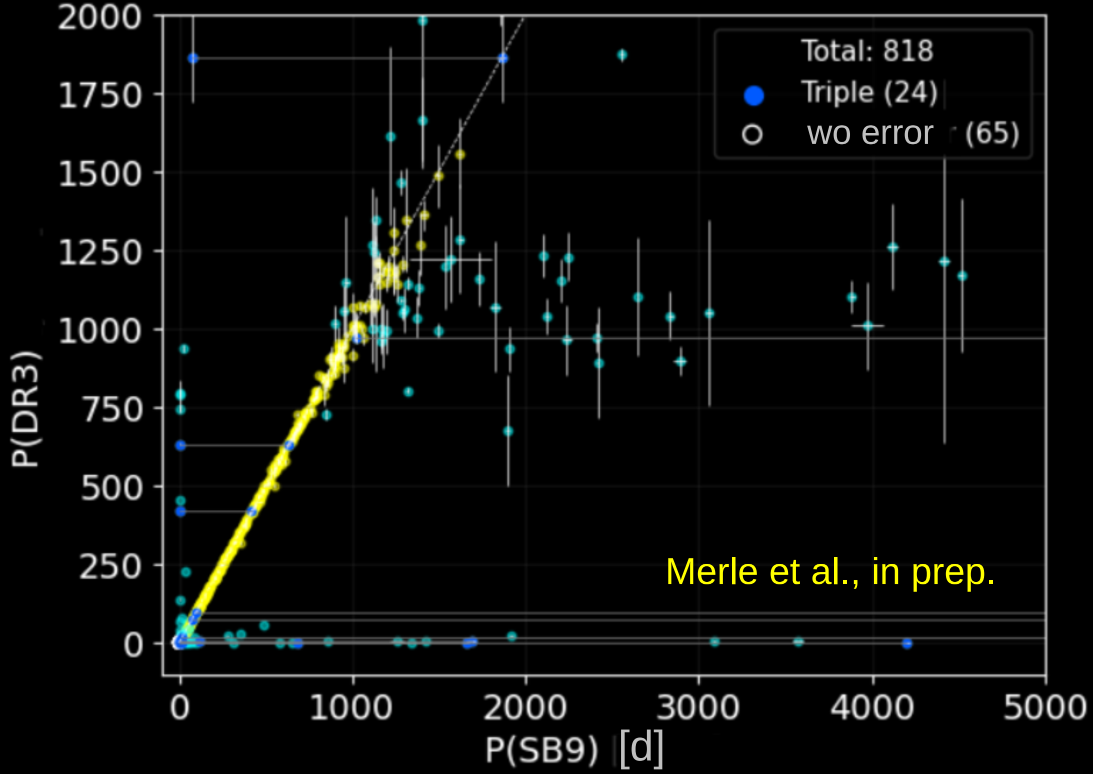
Aliasing

Cross-match:

SB9 (4k SB) x NSS (219k SB)

= 820 common SB only!





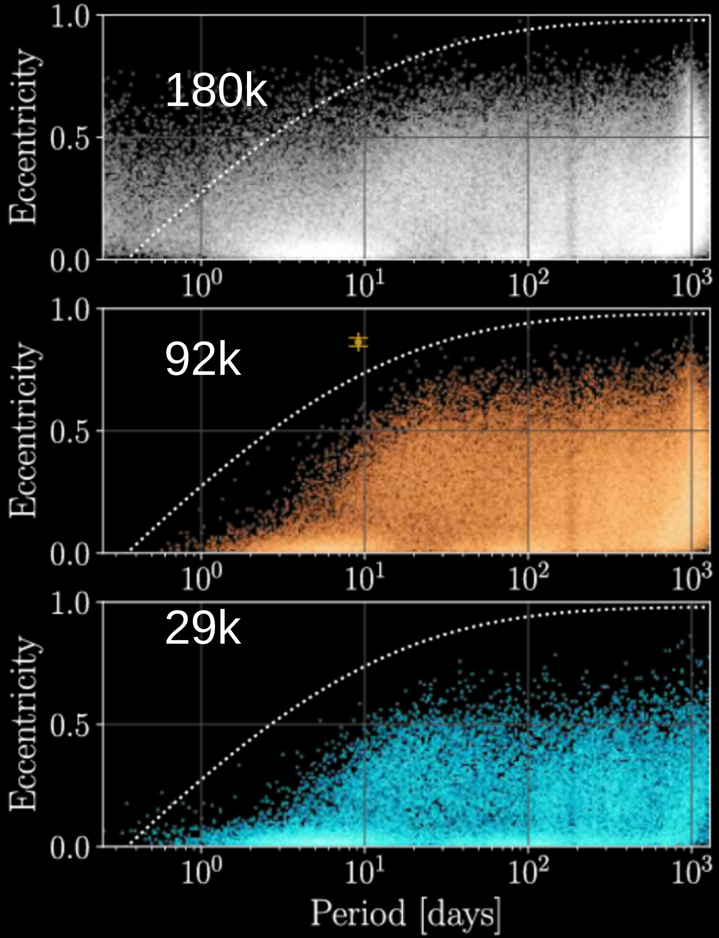
- Threshold: $\Delta P/P > 0.1$
- About 13% outliers!

The present: Gaia

Eccentricity-period diagram for NSS SB1

Bashi+ (2022)
External validation
Clean sample of about 92k SB1

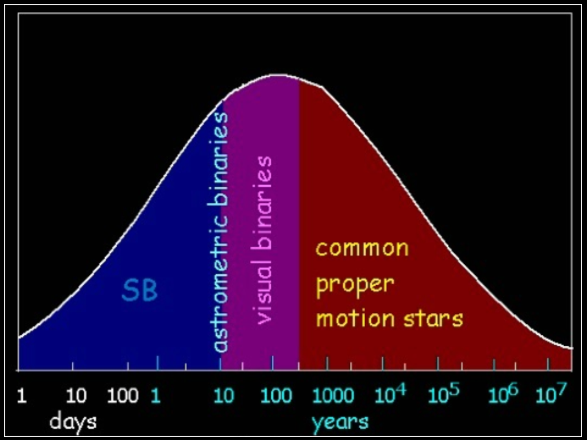
Gaia coll., Arenou+ (2023)
Significance level $K/\sigma_K > 40$



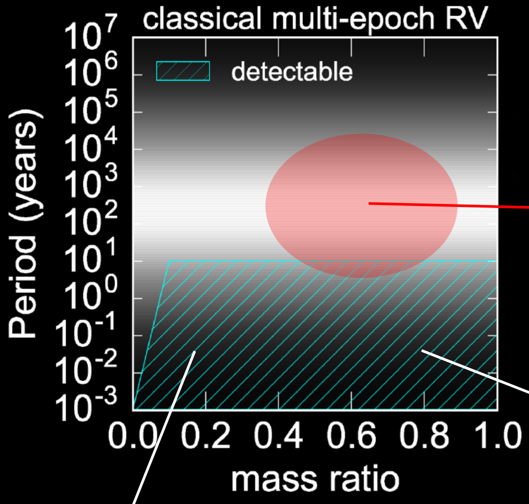
The future: 4MOST

- 4-m Multi-Object Spectroscopic Telescope on VISTA/ESO
- 4 square degrees field of view
- Optical wavelength coverage
- 2400 fibres per single exposure
- Low-resolution: 4 000 – 8 000, 1 600 fibres, Vmax ~20
- High resolution: ~20 000, 800 fibres, Vmax ~16
- 5 y survey starting in 2025

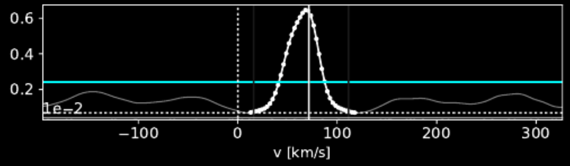
The future: 4MOST



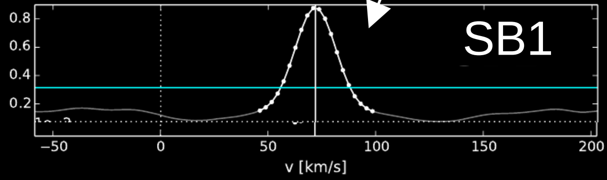
Period distribution

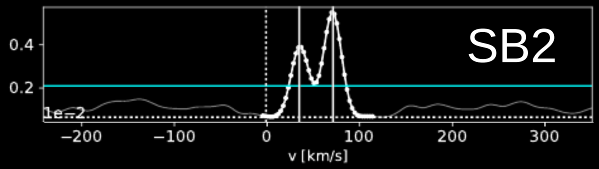


UNRESOLVED SB2



Probe the SB2 properties beyond the 10 y limit

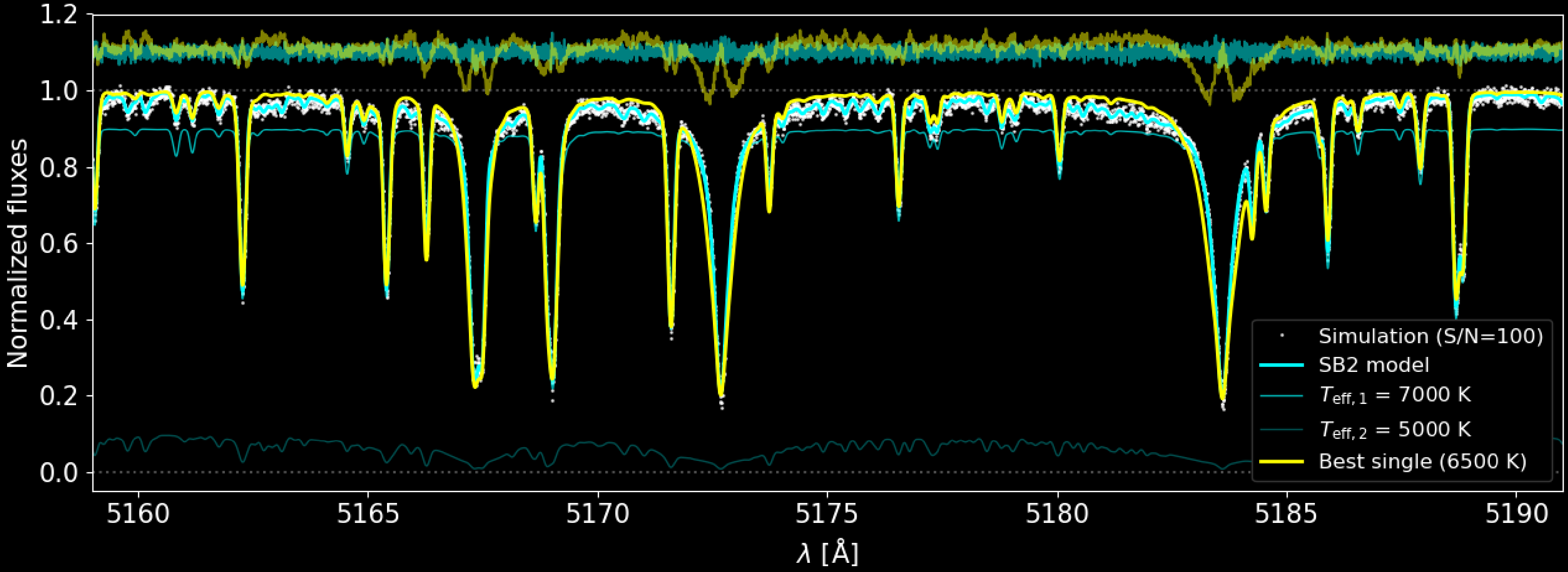




The future: 4MOST

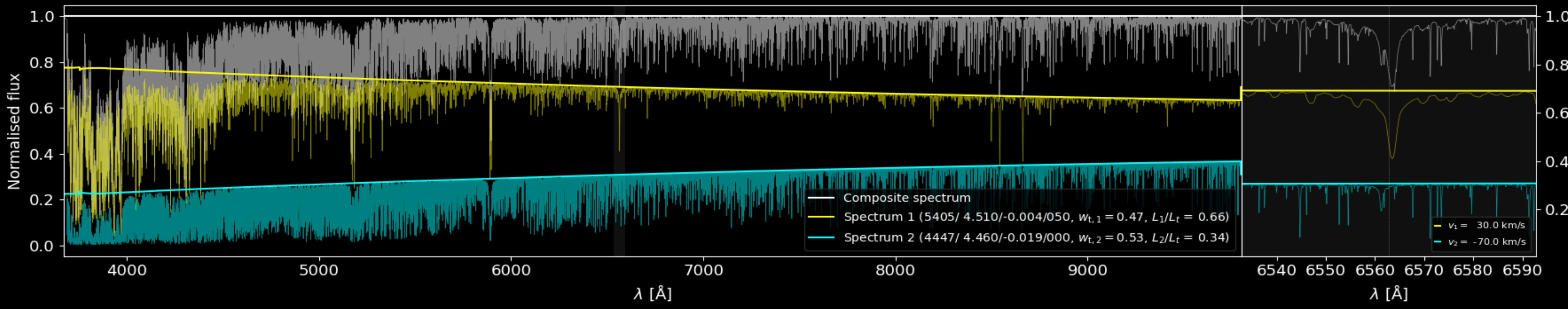
First characterisation: El-Badry+ (2018) on APOGEE spectra in IR (2 500 unresolved SB2)

Also feasible in the visible wavelength range of 4MOST:



The future: 4MOST

$f_t(\lambda) = (R_1/D)^2 [F_1(\lambda) + (R_2/R_1)^2 F_2(\lambda) + \ldots]$
assuming D = 10 pc, f_t being the flux received at this distance and
F_1 and F_2 the specific fluxes of each component



Test sample of 1000 twins SB2 composite spectra

- Computation at solar metallicity
- Following random normal $N(0, 100)$ radial velocities
- $v \sin i$ = 0 km/s
- S/N = 100

Performance on SB2 detection for HRS

- Individual RV components
  - Precision on RV components: 0.13 ± 0.04 km/s
  - Accuracy on RV components: 0.04 ± 0.41 km/s
- RV difference between components
  - Detection threshold: 22.5 km/s
  - Precision: 0.20 ± 0.05 km/s
  - Accuracy: 0.5 ± 0.4 km/s

Summary

The SB9 catalogue (Merle+, in prep.) can serve as a benchmark of SB for validation and for preparing future surveys

The Gaia-ESO Survey has revealed about 1k new SB but follow-up is needed for them

Gaia NSS catalogue provides huge and homogeneous samples of 450k AB, 220k SB and 85k EB!

Massive large spectroscopic surveys has the potential to reveal many new ‘unresolved’ binaries