ESO Colloquium – Santiago

Thursday 4th December 2025

Bridging Past and Future:

Exploring Spectroscopic Binaries from SB9 through Gaia to the 4MOST large survey

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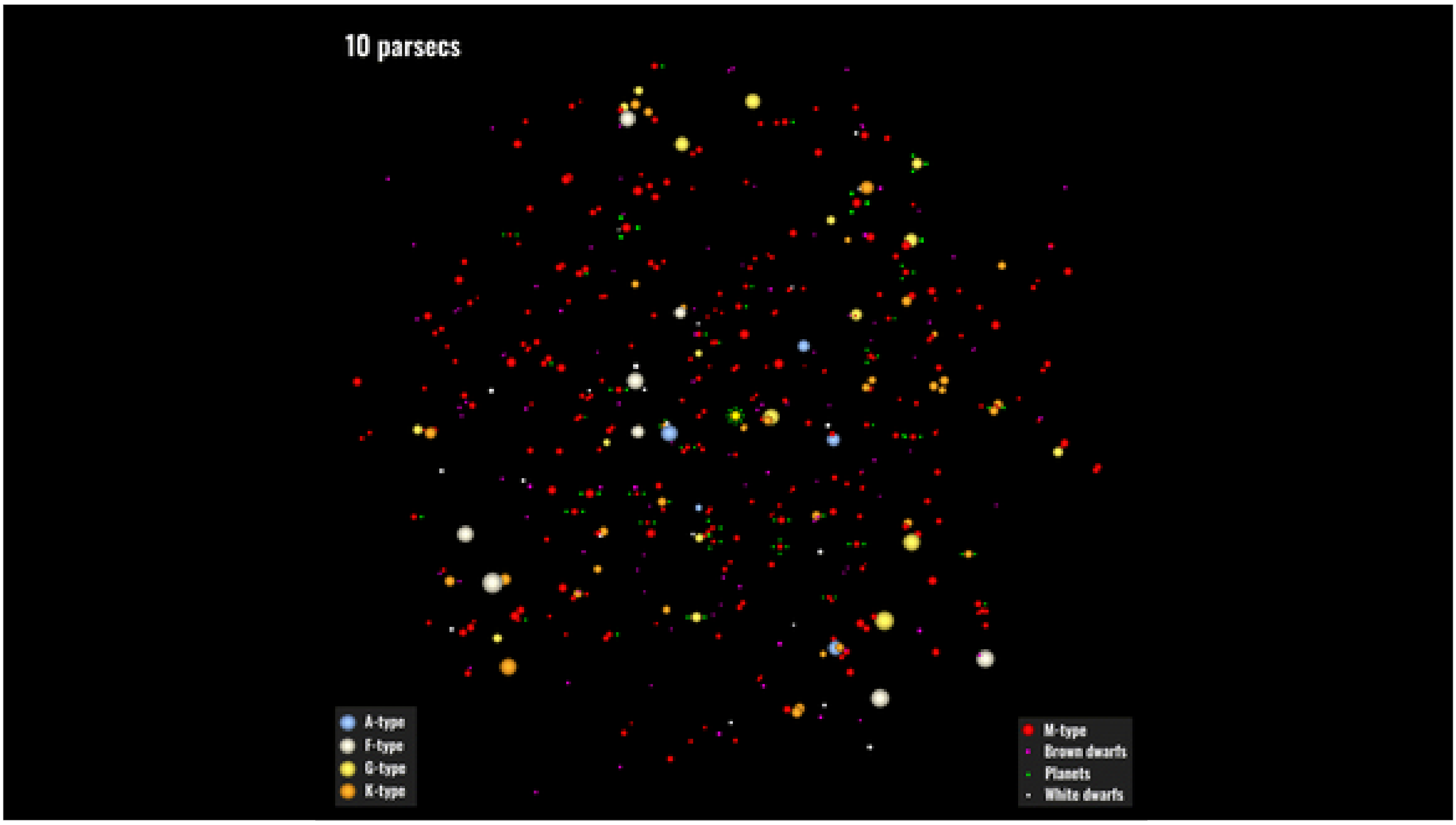
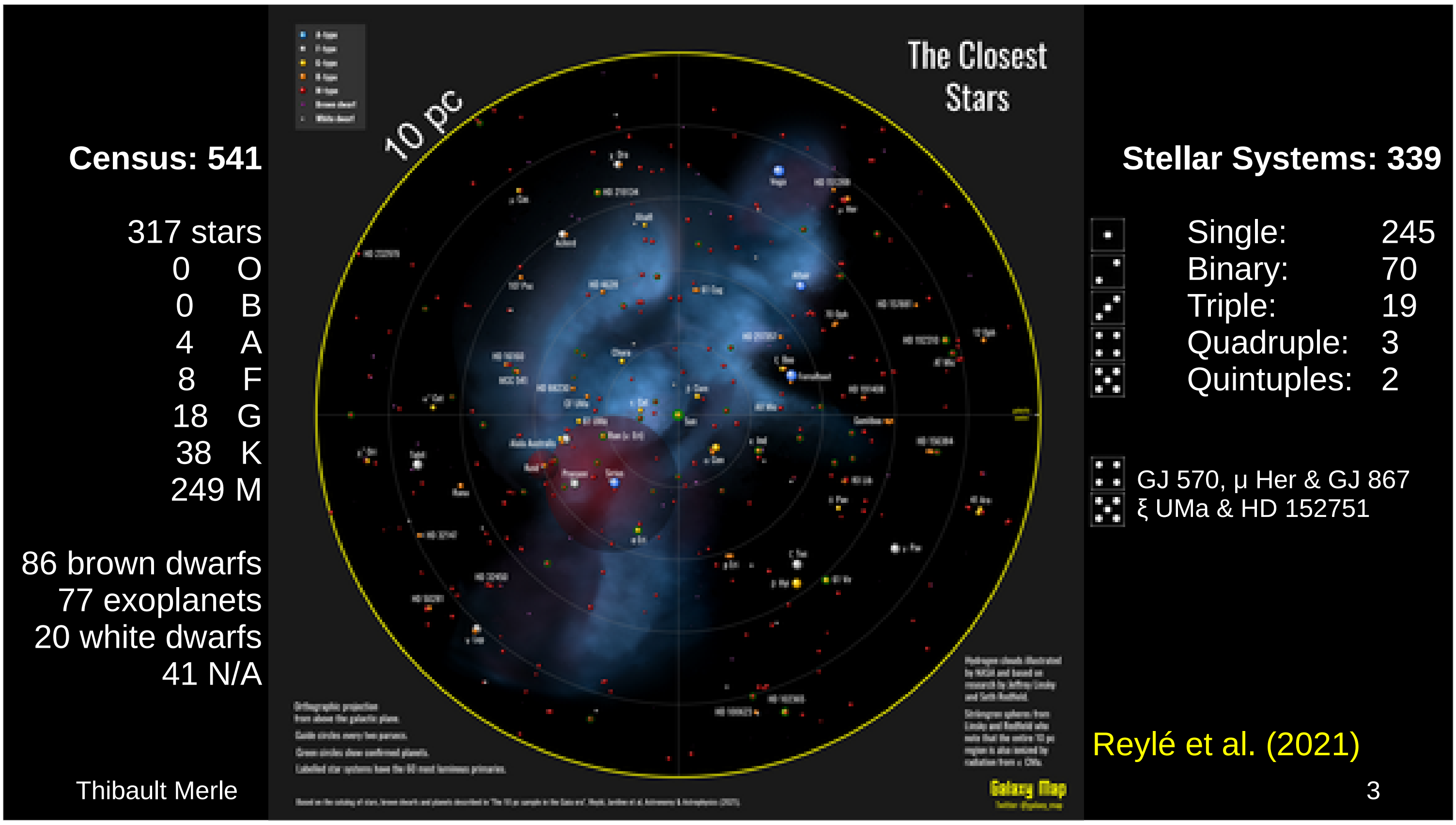


I we look at our Solar neighborhood, in the 10 pc sample around the Sun, we notice two striking features:

- Low mass stars largely predominate
- Binaries and multiples are quite frequent



When we look at the Solar Neighborhood,
in the 10 pc sample
Orthographic projection from above the Galactic plane

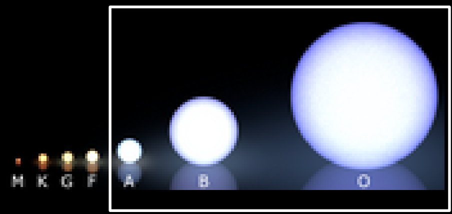
The first striking feature is that there is no massive stars
4 A-type (Sirius, Altair, Vega, Fomalhaut (α PsA (Piscis Austrini))
8 F-type (Procyon A, Pi^3 Ori A, Chi Dra, β Com, ...)
99% are late-type stars and the vast majority are M dwarfs.

~(94/339) = 28% are in binaries or higher multiples

Quadruples:
GJ 570 (3+1): 5.9 pc (K, M, and BD) wide outer (inner: 2kyr, 300 d)
Mu Her (2+2): 8.3 pc (G, M) wide outer (inner: 100 and 43 yr)
GJ 867 (2+2): 8.9 pc (M, M) wide outer (inner: 4 and 2 d)

Quintuples:
HD 152751 (2+1+1+1): 6.4 pc (5 M-type)
Xi UMa (Alula Australis, 2+2+1): 8.3 pc (F/G, G, BD)

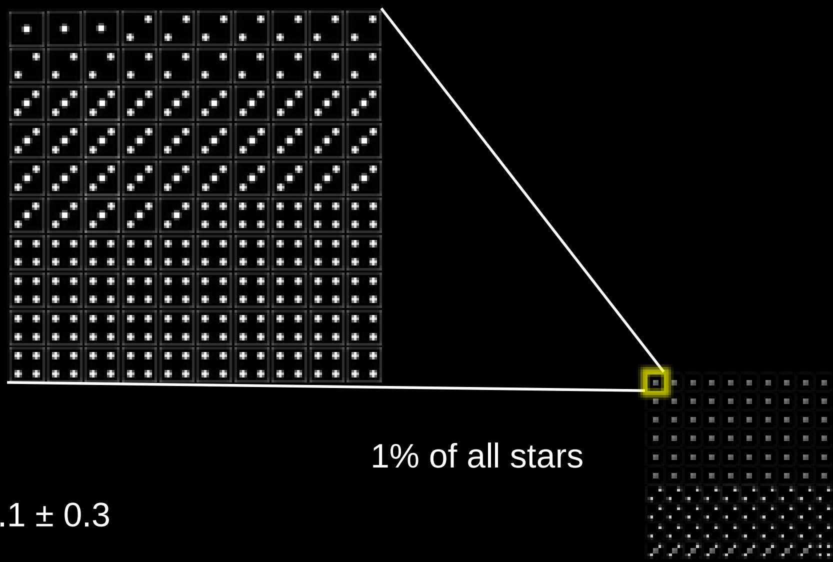
Multiplicity statistics in early-type stars



Single: 3 ± 3%
Binary: 17 ± 5%
Triple: 35 ± 3%
Quadruple+: 45 ± 11%

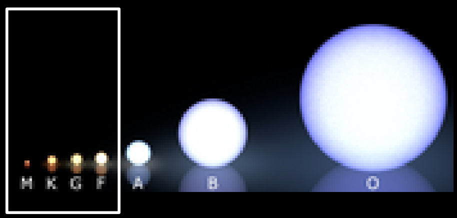
Multiplicity fraction: 97 ± 13%

Moe & Di Stefano (2017)



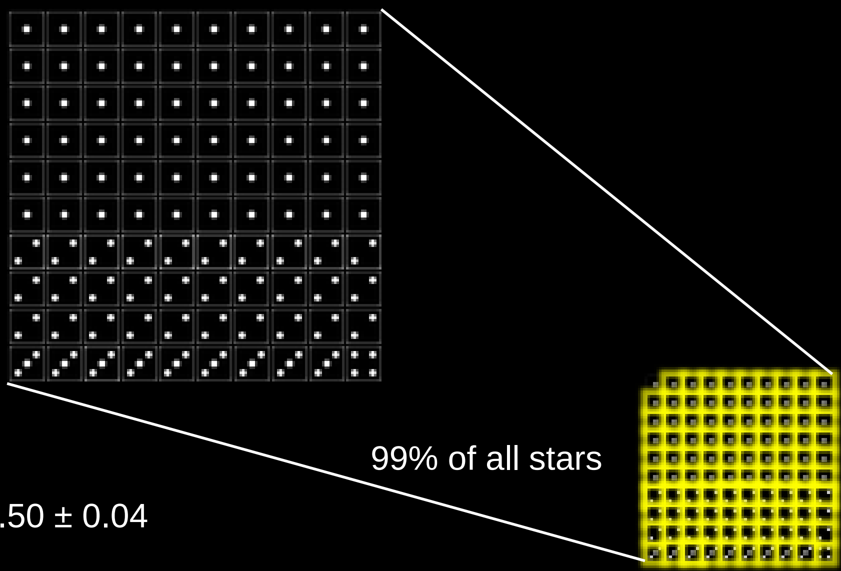
Mean number of companions: 2.1 ± 0.3

Multiplicity statistics in late-type stars



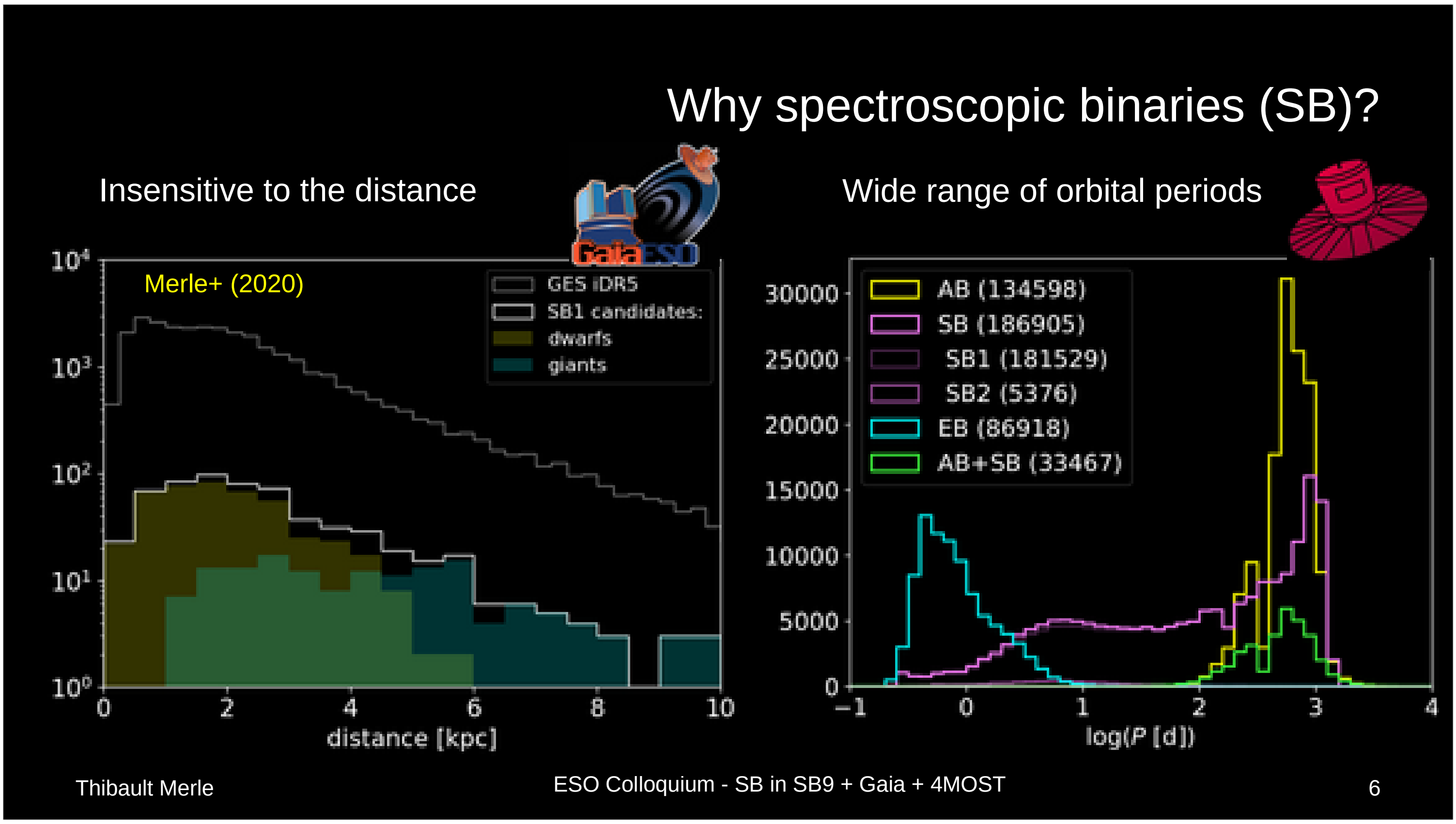
Single: 60 ± 4%
Binary: 30 ± 4%
Triple: 9 ± 2%
Quadruple+: 1 ± 3%

Multiplicity fraction: 40 ± 5%



Moe & Di Stefano (2017)

Mean number of companions: 0.50 ± 0.04



Among binaries the ones detectable spectroscopically have the advantage to be insensitive to the distance.

If we look at the distribution of stars with the distance of the ground-based spectroscopic survey Gaia-ESO

We noticed that the SB1 candidates decrease at the same rate with the distance, meaning that the fraction of detected binaries by spectroscopy is constant.

Looking in more details we see however that there is a bias between close and distant SB: indeed distant ones are dominated by SB whose primary is a giant. This is a selection bias called the Malmquist bias which leads to the preferential detection of brighter objects.

SB are also the kind of observed binaries that bridge the gap between short-period binaries like EB, and longer-period binaries like AB.

The local maximum around 8 days is the reflect of the presence of SB2.

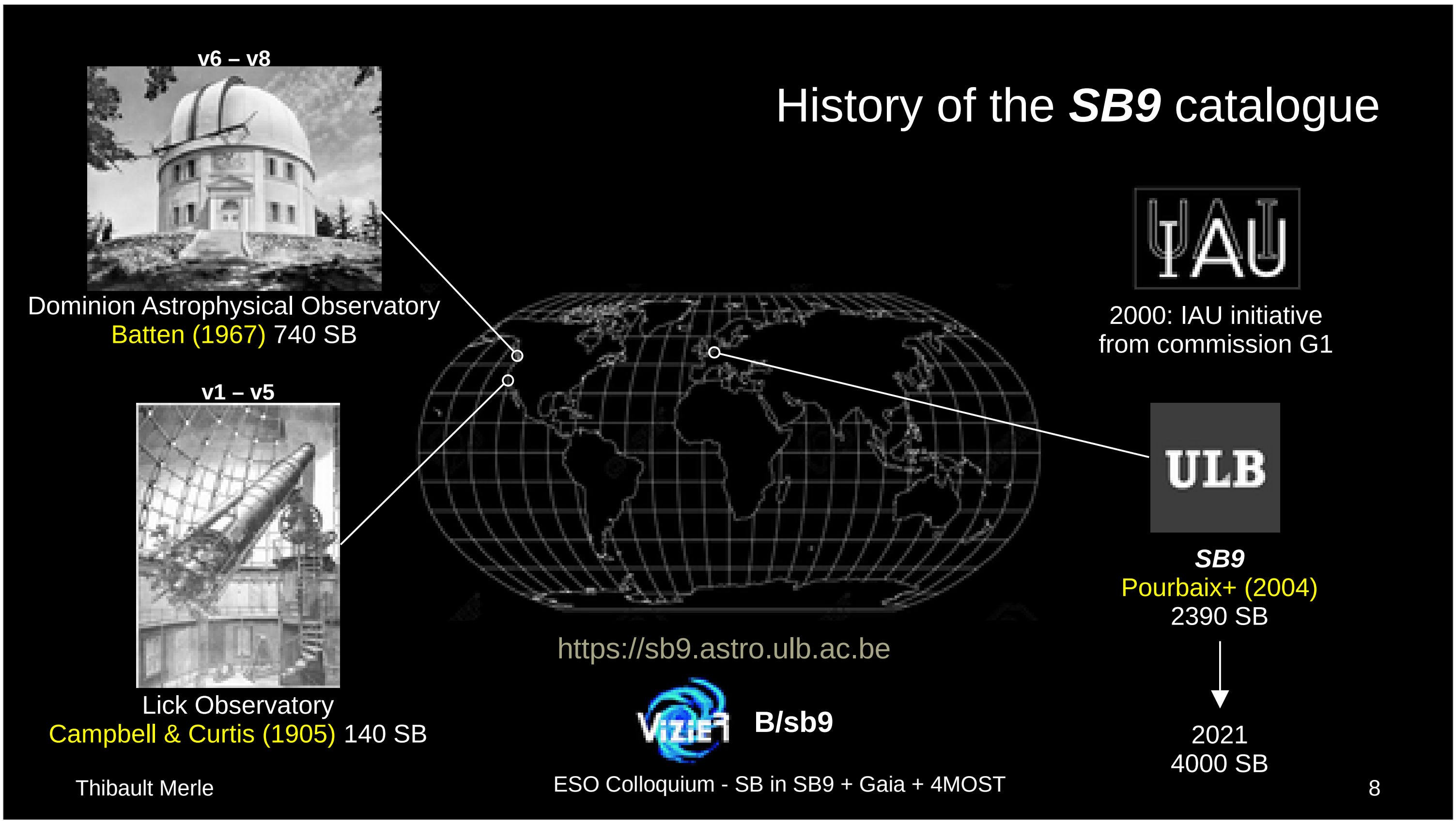
Outline

- The SB9 catalogue and its evolution
  - History
  - Content including triples and quadruples
  - Evolution of the catalogue
- Comparison of SB9 with Gaia DR3
  - Gaia color-absolute magnitude diagram
  - SB9 x NSS common sample
  - Its characteristics
- Spectroscopic binaries in 4MOST
  - A massive MOS survey
  - First light
  - Multiple stars detection and characterisation

In this talk, I will present the history of the Ninth catalogue of spectroscopic binary orbits, its present content and its evolution.

Then I will present its cross-match with Gaia DR3, its HR diagram and comparison with the binaries of the Non-Single Star catalogue.

Finally I will present the 4MOST ground-based spectroscopic survey and what it is plan in term of detection and characterisation of SB.



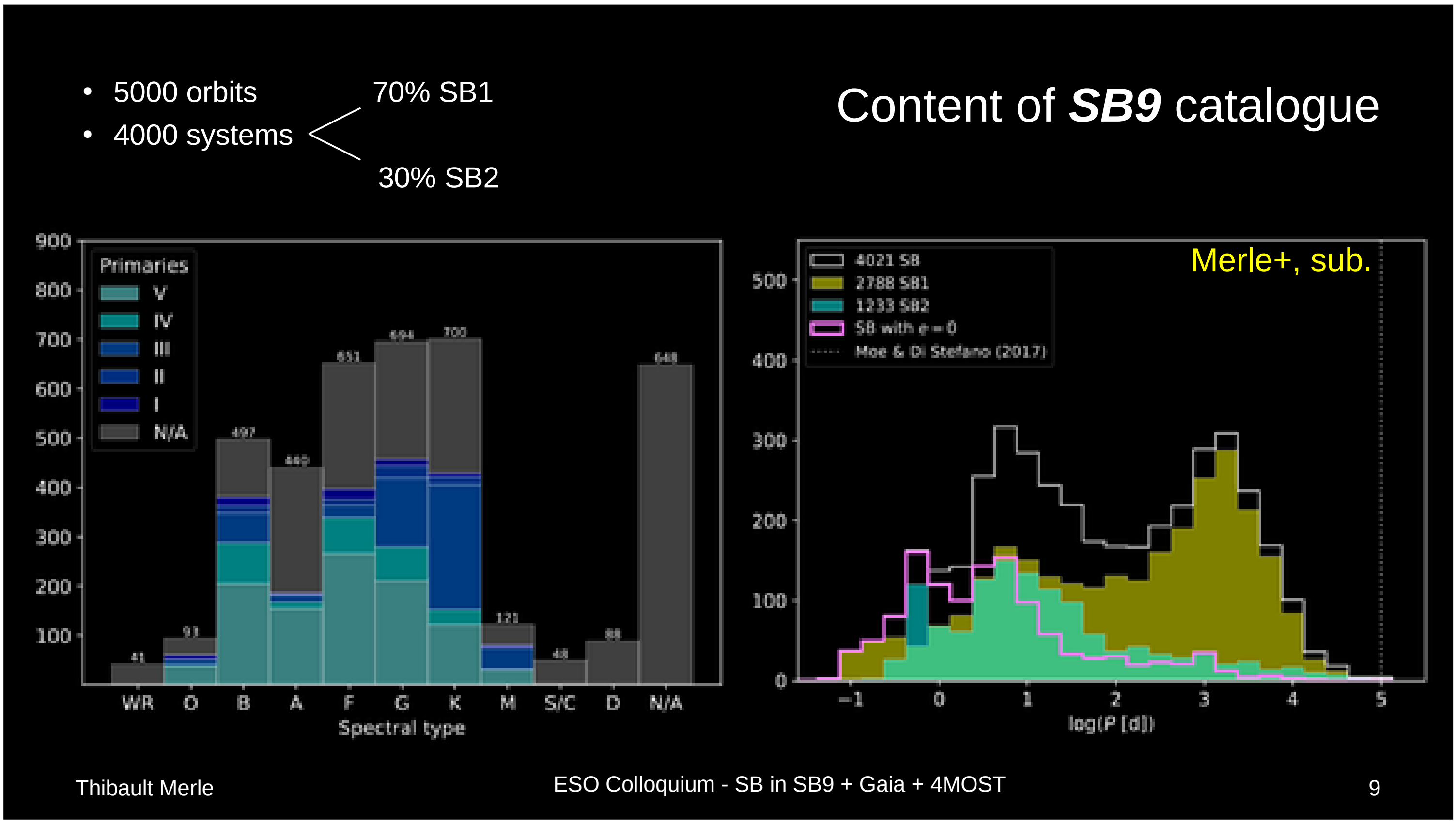
The SB9 catalogue is the online continuation of a series of paper catalogues on spectroscopic orbits.

Campbell was Director of the Lick Observatory and a pioneer in radial velocity measurements.

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)

IAU initiative from Commission G1 “Binary and multiple stars systems” the former commission 30 on RV.



The SB9 currently contains 5000 orbits because it is first of all an heterogeneous collection of spectroscopic orbits belonging to 4000 spectroscopic systems.

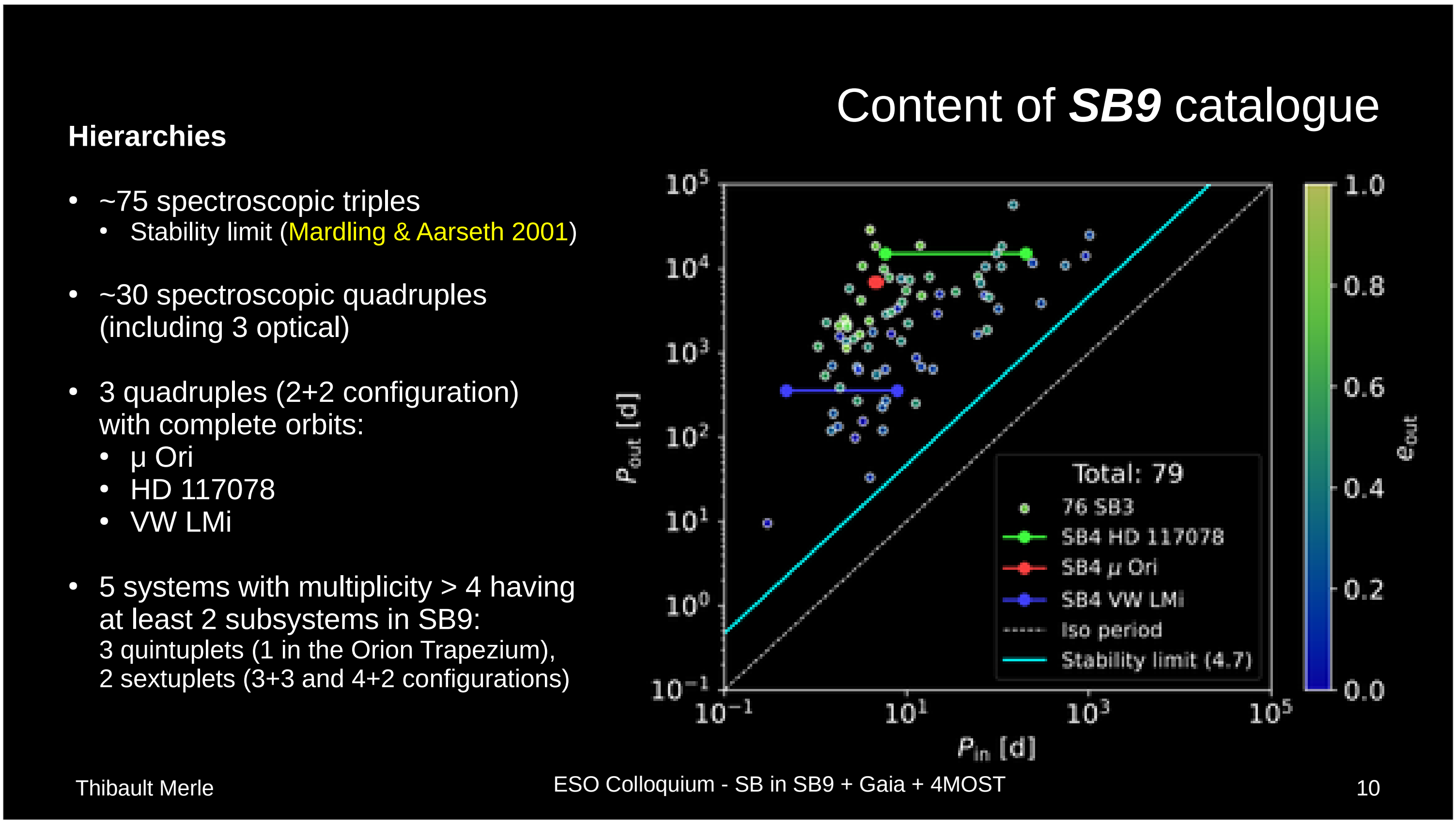
Its include 2/3 of SB1 and 1/3 of SB2

SB9 is biased toward massive stars and quite underpopulated toward late type stars.
Many systems did not have a spectral type classification included.
This reflect the history of the catalogue and the fact that apparent brightest stars that we can measure are biased toward early types.

On the right the distribution of SB as a function of the logarithm of the period.
3 local maxima:
Just below 0.6 day: physical effect 0.4 d => contact binaries (FGM main sequence)
Just below 7 days: physical effect => triple evolution
Max of O and B-type stars, secular evolution through KL cycles with tidal friction (Bataille, 2018)
Around 1800 days (5 years): dominated by SB1. selection effect
RV variations drops below the detection limit of current spectrographs.

Below 1 d all orbits are circularized, below 10 d, 50% of orbits circularised.

Longest period VB SB2 HIP 10952 with P=320 yr wide K0V binary
Shortest period dwarf nova GW Lib with P=1.3 h



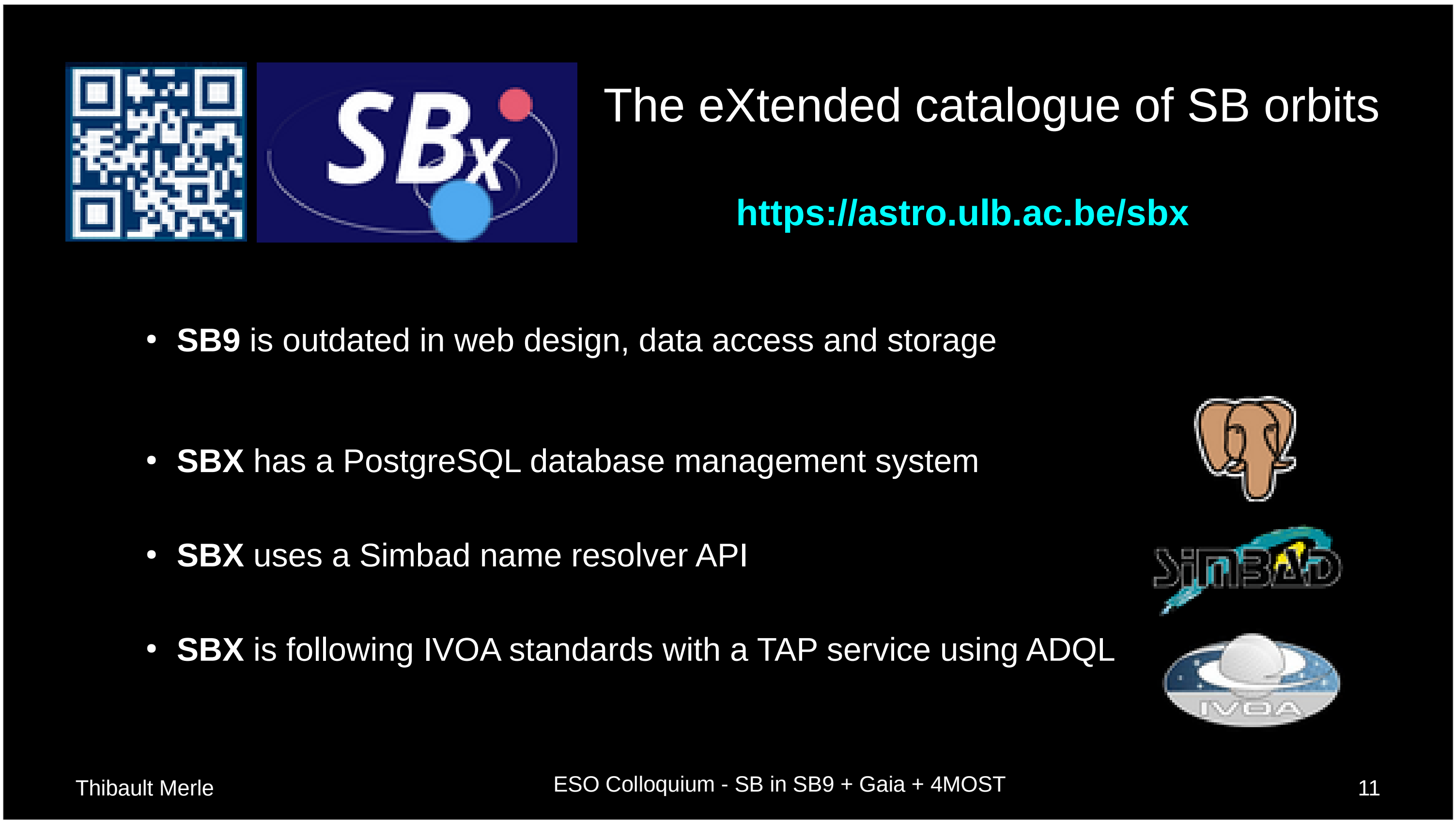
In the SB9 catalogue, there are also about 100 higher-order systems:

- 75 triples,
- 30 quadruples,
- and ~5 systems with higher order multiplicity

with at least 2 subsystems in SB9.

Pout-Pin diagram for triples and the 3 completes 2+2 quadruples
The stability limit has a period ratio (outer/inner) of about 5 for hierarchical triple with coplanar orbits (Mardling and Aarseth 2001)

The one with the shortest outer period is TZ Boo which is also an EB.
The second one is HD165590



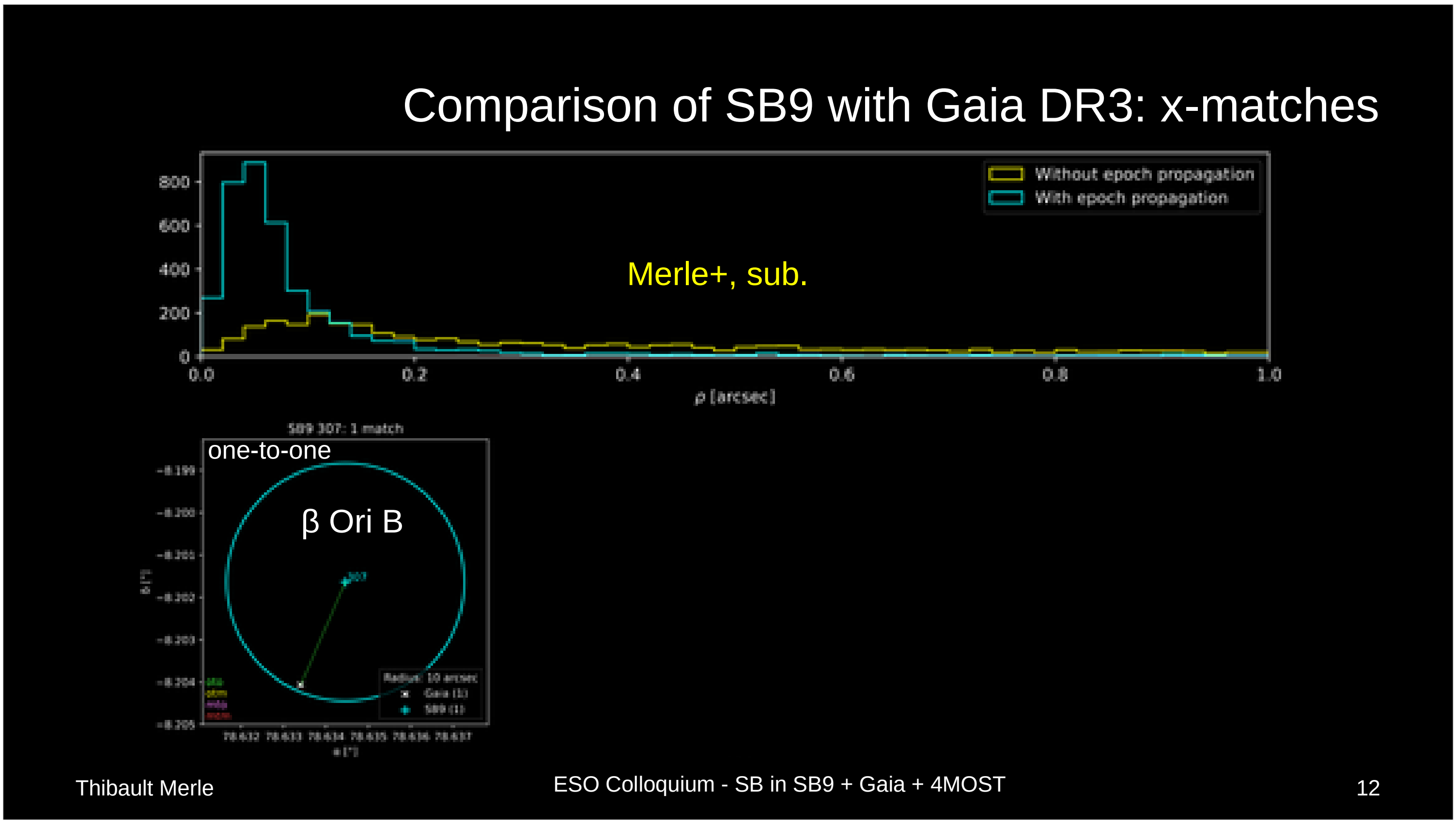
We are migrating the SB9 catalogue toward a standard database facilitating accessibility and interoperability.

SB9 was fairly enlarge in terms of content compared to SB8 almost doubling the amount of SB, but using text files.

This was a nice master thesis in Big Data done recently by Simon Alexandre to port SB9 toward SBX.

You can flash the QR code and try a few bright stars like Capella, Polaris, alf Cen etc. to have the orbital parameters and see the RV curve.

T: to obtain this new catalogue with needed to perform a careful cross-match with Gaia DR3 to obtain, not only position but also proper motion and parallaxes.



Angular separation of the cross-matches without (yellow) and with (cyan) back propagation of the epoch from 2016 to 2000.

The median separation is divided by a factor of 4 when back propagation is considered (0.06 arcsec).

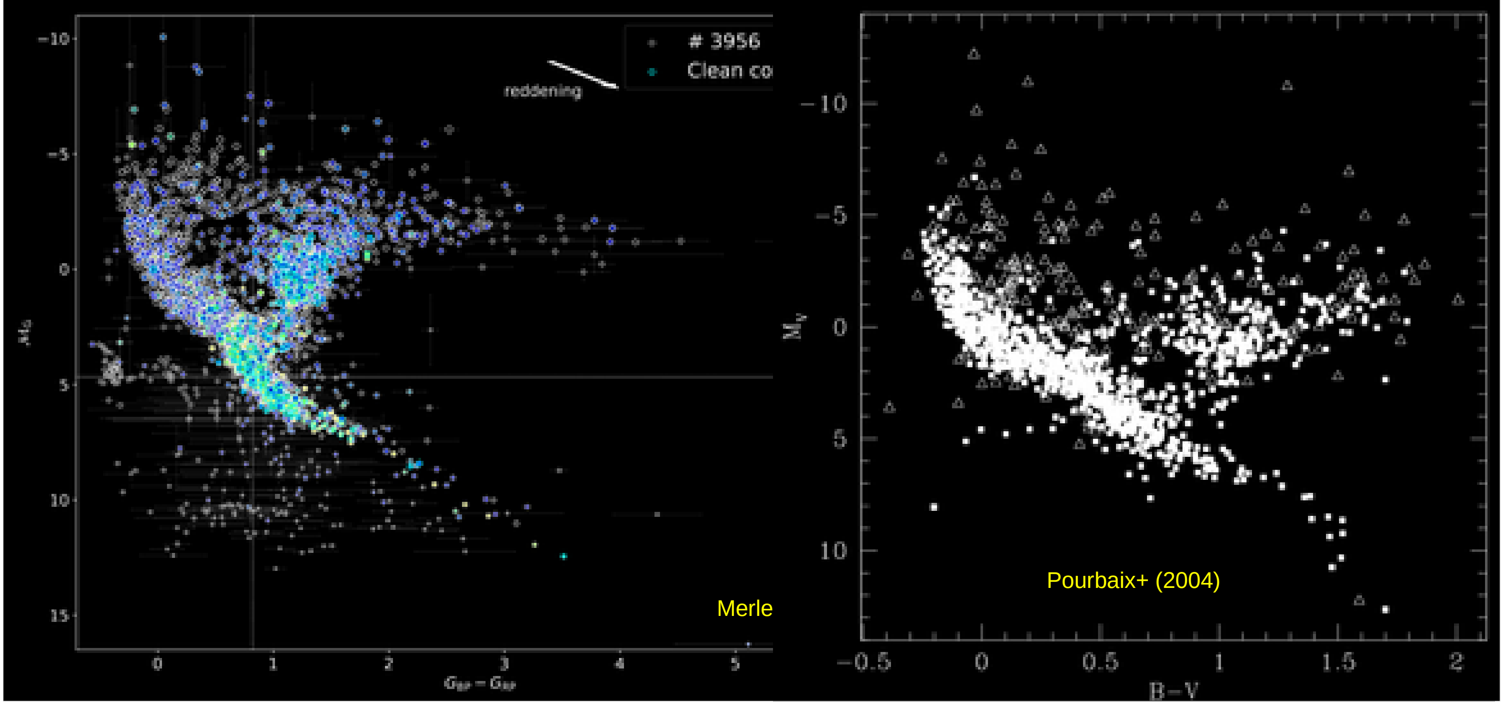
SB2 to Gaia

oto xmatch: β Ori B (G~6.6) was wrongly assigned to component A in SB9 explaining such separation in the match

Zoom on mto: 2 SB9 systems forming a triple unresolved by Gaia (separated by 0.15 arcsec)

Otm and mtm: in an open cluster

Gaia color-magnitude diagram of SB9 systems



Brightest systems:
α Cen, Sirius, Capella, Procyon, Polaris, Castor A and B, Algol, etc.

Faintest systems: Hulse-Taylor pulsar, LMXB, NS+WD

+ a few stars without parallax

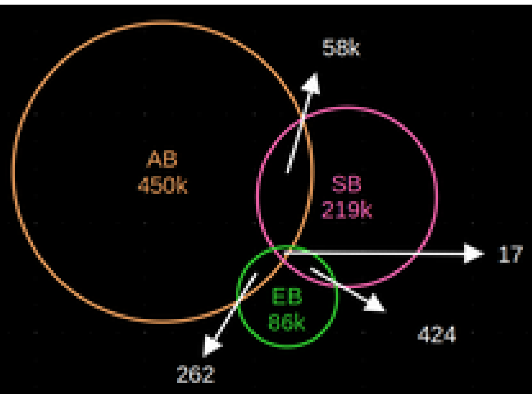
Extreme-horizontal branch (strong mass loss on the horizontal branch)
D'Cruz+ 1996

Position of the G2V star at the intersection of the dotted lines

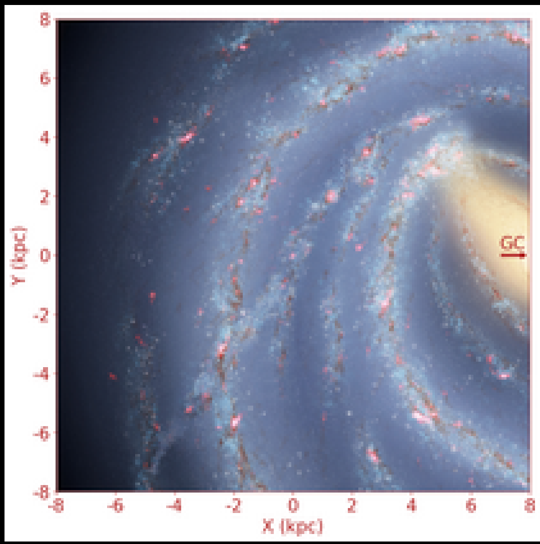
In cyan the common sample of 660 SB

We can compare with the CMD based on Hipparcos parallaxes.

T: How do we obtain this common sample?



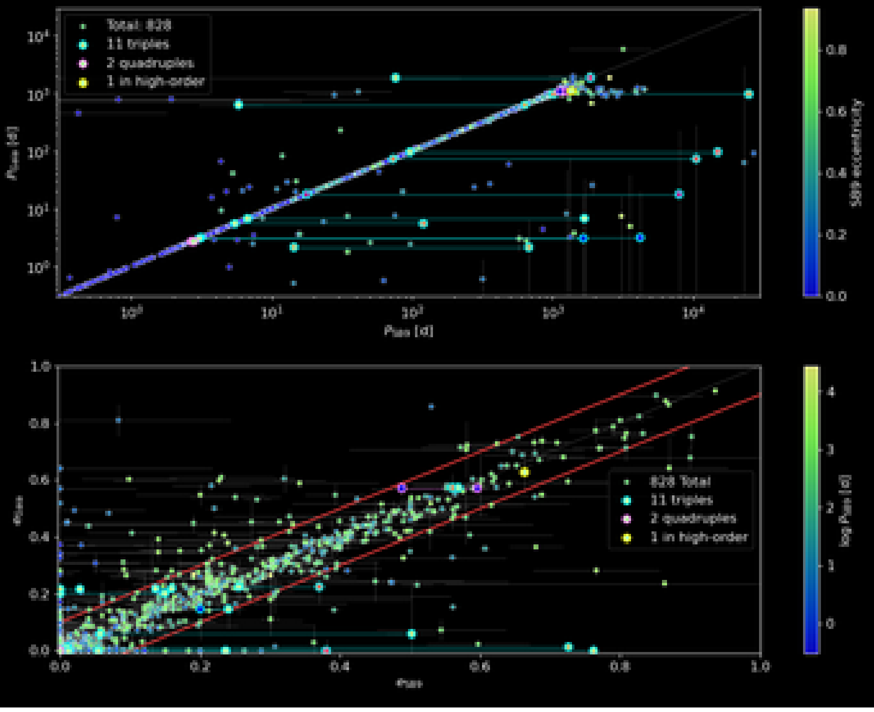
Gaia DR3 binaries content



ESA/Gaia/DPAC

- 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 $T_{\rm eff,1}$, $T_{\rm eff,2}$, logg_1, logg_2, [Fe/H], extinction and distance
  - Need validation!

SB9 x Gaia DR3 NSS common sample



<u>P_{Gaia} vs. P_{SB9}</u>

Selection 1: $|\Delta P|/P < 0.1$
=> ~70 outliers

<u>e_{Gaia} vs. e_{SB9}</u>

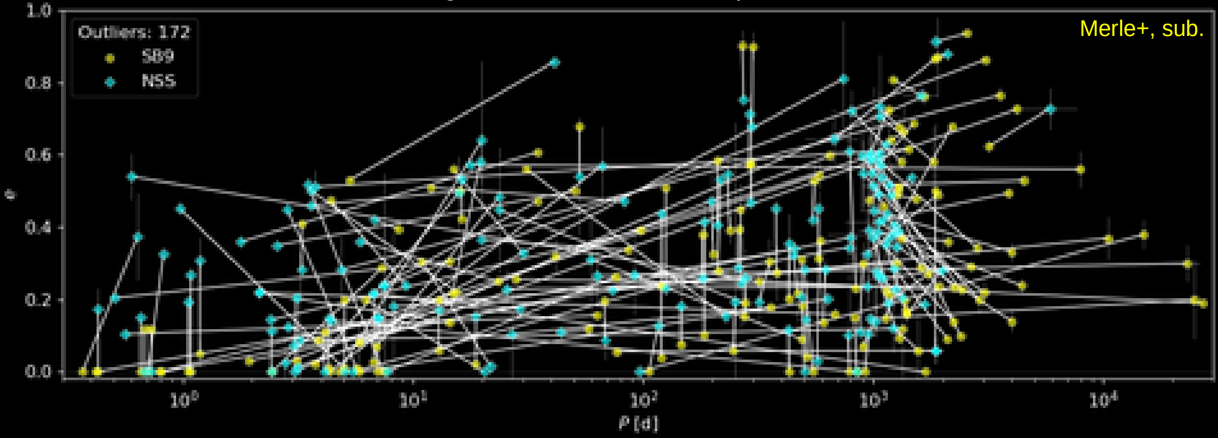
Selection 2: $|e| < 0.1$
=> ~170 outliers

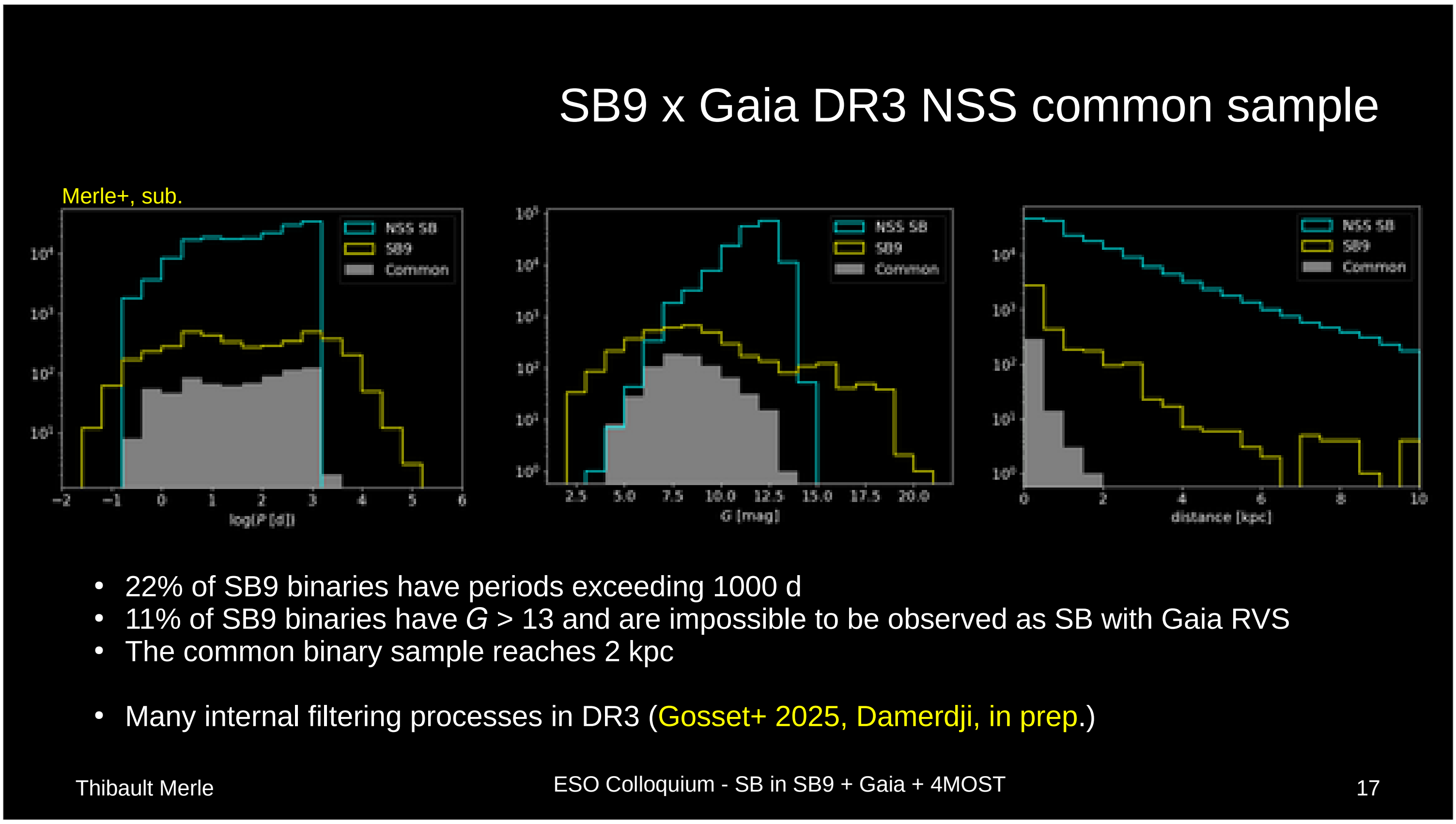
Clean sample
= selection 1 & selection 2

Common sample: 830
Clean sample: 655

SB9 x Gaia DR3 NSS common sample

- **Common** sample of ~830 binaries: 1/5 of SB9 catalogue
- **Clean** common sample of 655 SB9 binaries:
  351 SB, 151 SB+AB, 81 AB, 57 EB, and 15 SB+EB in NSS
- **Outliers**:
  Many SB9 binaries with periods larger than 1000 d
  Some Gaia binaries with high eccentricities at short periods





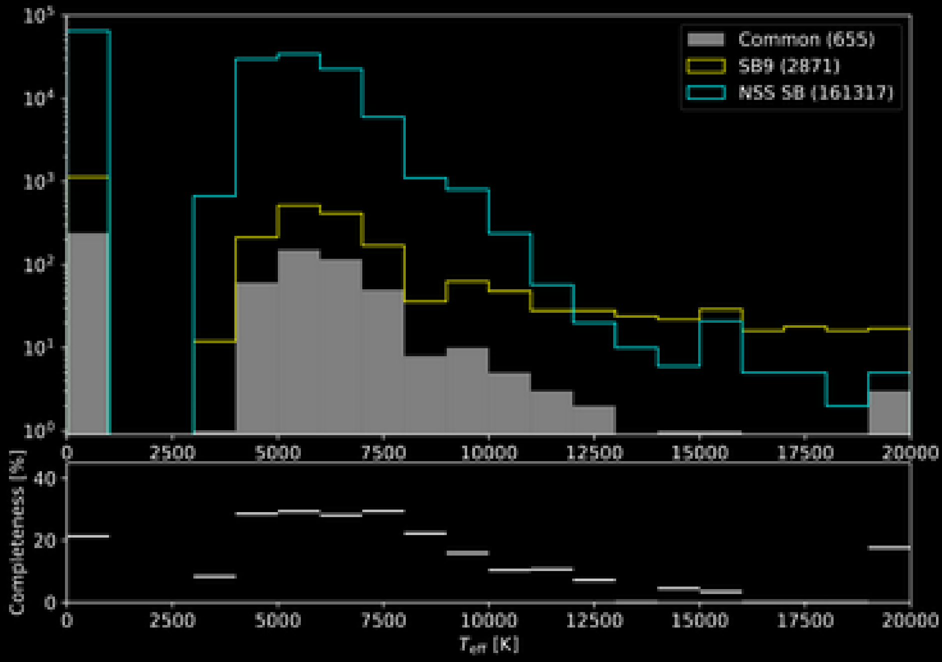
This limited overlap is primarily due to:

- selection cuts in NSS SB1 analysis
- Brighteness limit,
- Temporal baselines,
- And partial orbital solution in NSS.

22% of SB9 binaries have periods exceeding 1000 d
10% of SB9 binaries have G > 13

In Gosset 2025:
SB1 sample restricted to FGK primaries.
the various fits were further filtered internally on the basis of several quality measures to discard spurious solutions.

SB9 x Gaia DR3 NSS common sample



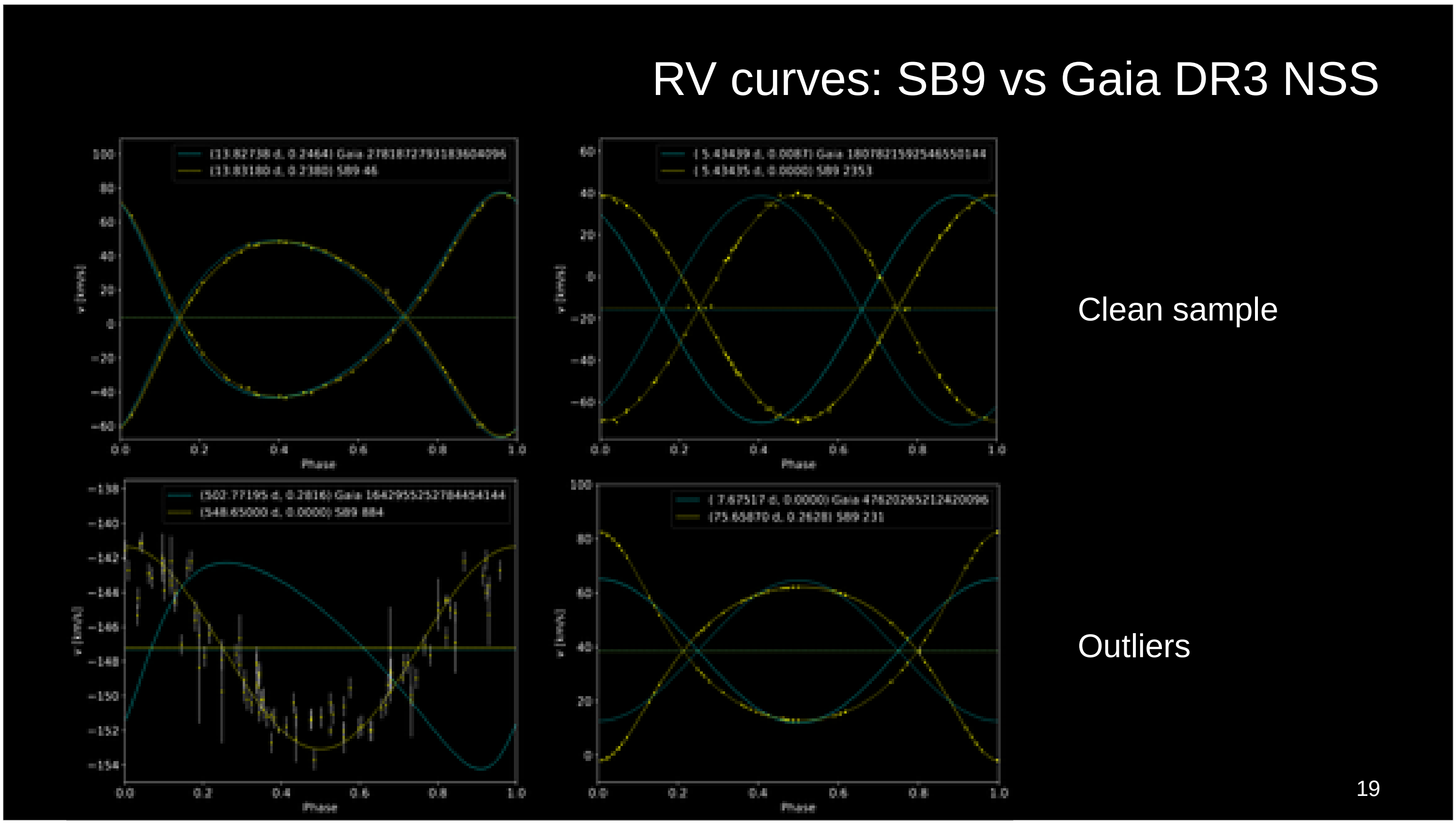
Common:
- *G* magnitude in [4.2, 13]
- Periods in [0.3, 1558] d

T_{eff} from Gaia DR3 GSPphot
At 0 K, without T_{eff}

Completeness = Common/SB9 per bin of T_{eff}
~30% at max for FGK

~20% of SB9 systems in NSS
↗ 25% same *P* and *G* ranges
↗ 30% + FGK spectral type only

Early-type binaries (Teff>12000 K) are over-represented in SB9 while under-represented in Gaia NSS.



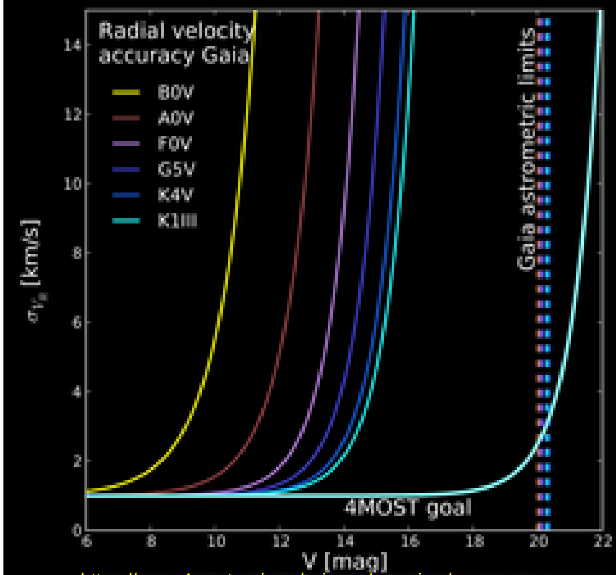
The SB9 solutions with RV are shown in yellow
Gaia solutions in cyan, RV will only provided with Gaia DR4, end of 2026

Top left and top right are in the clean sample

Top left: Good example of SB2
Bottom left: SB1 turns to be an SB2 in Gaia but with different e excluded from the good sample

Top right: Circular binary where the periastron time is necesserily badly defined
Bottom right: factor of 10 difference on period

A massive spectroscopic survey



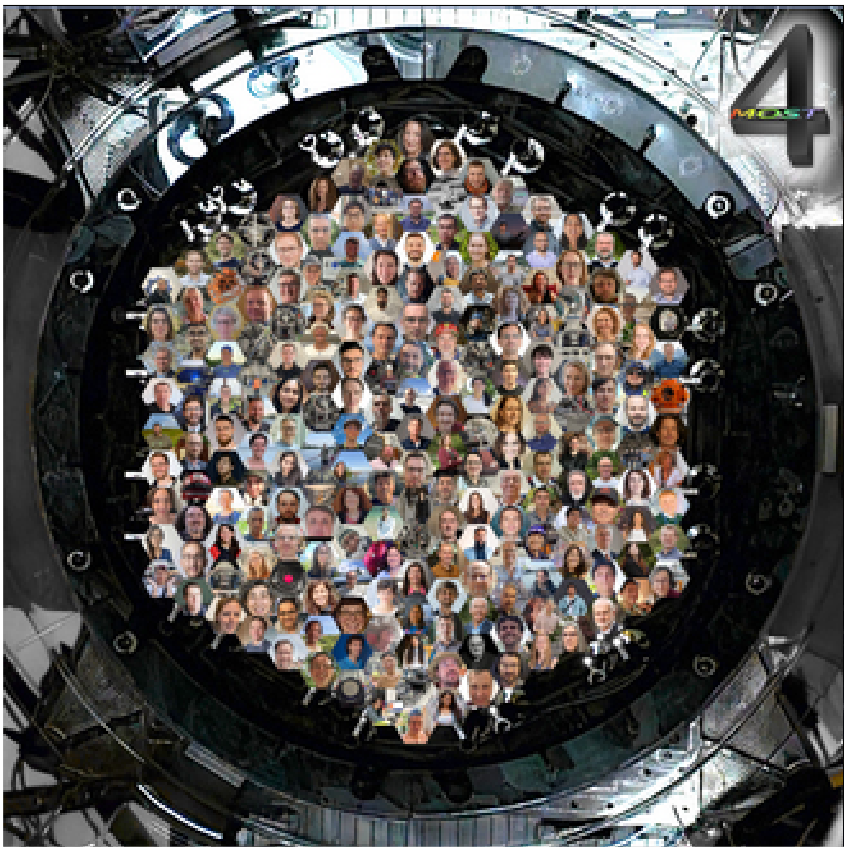
https://www.4most.eu/cms/science/overview/

- 4-m Multi-Object Spectroscopic Telescope on VISTA/ESO
- 2400 fibres per single exposure
- 4 square degrees field of view
- Optical wavelength coverage
- Low-resolution: 4 000 – 8 000, 1 600 fibres, Vmax ~20
- High resolution: ~20 000, 800 fibres, Vmax ~16
- 5 y survey starting in 2026:
  - 20 millions spectra in LR
  - 6 millions spectra in HR
- RV with a precision < 2 km/s for any Gaia source (G < 20)

This is the biggest multi-object spectrograph built to date.

10 consortium surveys: 70%
14 ESO community surveys: 30%
=> 700 scientists involved

9 infrastructure working groups (IWG)
including a Stellar Multiplicity Working Group
as part of IWG2 (survey strategy and simulations)



First light!

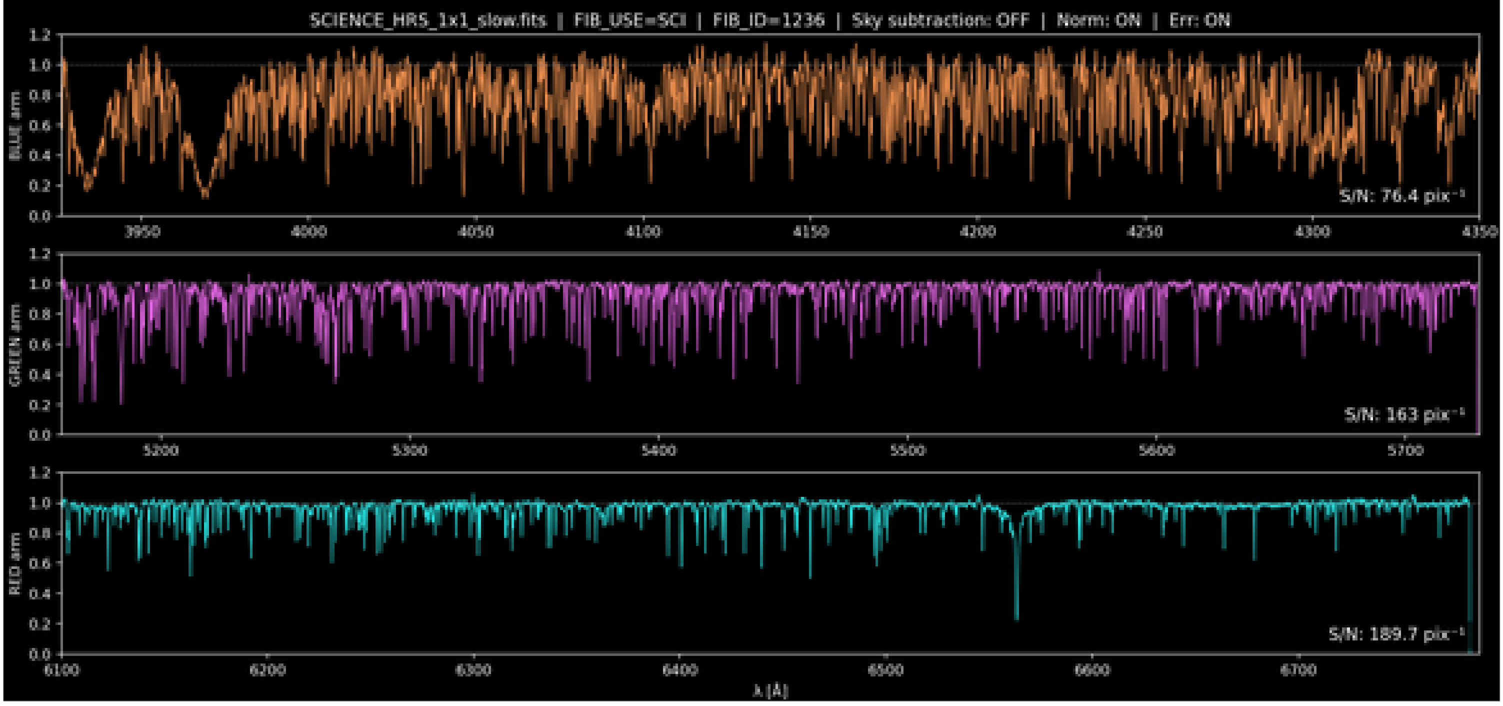
October, 18, 2025

2400 fibres

Sculptor Galaxy

Globular cluster NGC 288

First light



SCIENCE_HRS_1x1_slow.fits | FIB_USE=SCI | FIB_ID=1236 | Sky subtraction: OFF | Norm: ON | Err: ON
BLUE arm
S/N: 76.4 pix⁻¹
GREEN arm
S/N: 163 pix⁻¹
RED arm
S/N: 189.7 pix⁻¹
λ [Å]

Binary nature of many candidates

<u>For unresolved SB2 (~15%)</u>:
- Derivation of atmospheric parameters

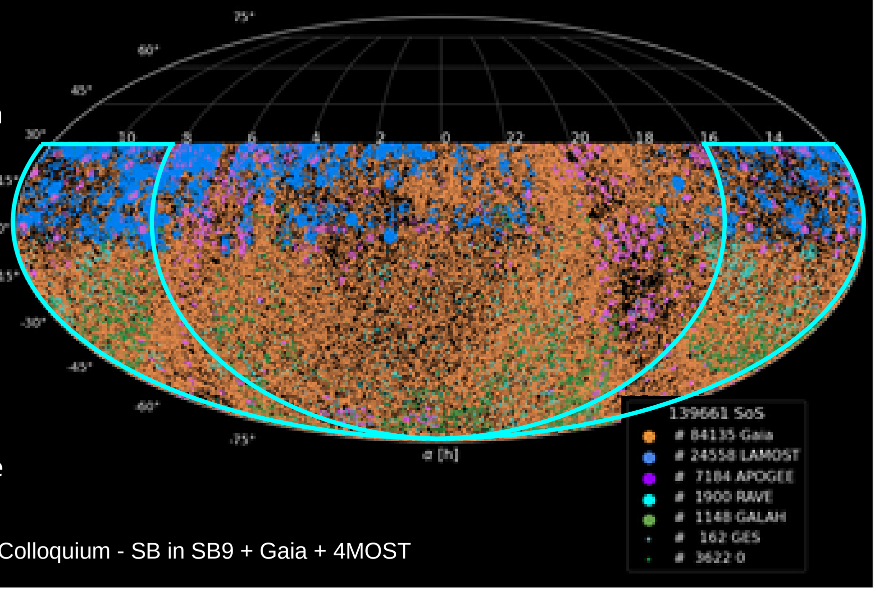
<u>For SB1 (~1.5%)</u>:
- Minimum RV dispersion for SB1 detection
- Set upper limits on orbital periods
- Estimation of the period distribution

<u>For SB2 (few thousands)</u>:
- Partial orbital characterization
- Derivation of atmospheric parameters

<u>For <1% of SB*n*, *n*≥1</u>:
- Full orbital characterization
- Full atmospheric characterization

In addition few tens to hundreds of SB2 will be turn into triples or quadruples.

Survey of Surveys Tsantaki+ (2022)



Thibault Merle

ESO Colloquium - SB in SB9 + Gaia + 4MOST

SoS: 11 millions of stars with RV, 200000 candidates binaries (2%)

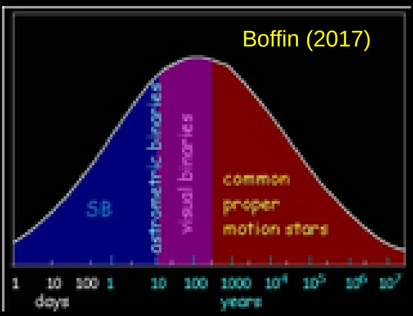
Survey Program Validation SPV in February and March 2026

Between 40000 and 50000 targets.

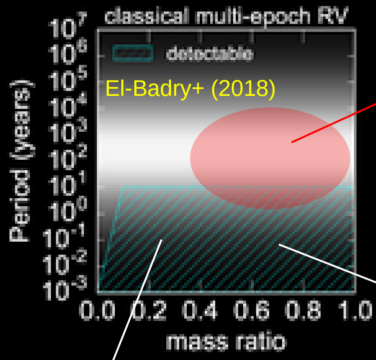
Only 6% have been identified in NSS

6 parameters to fit for SB1, 7 for SB2

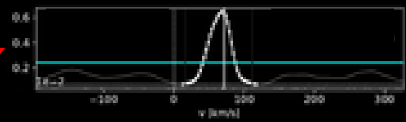
Multiple stars detection & characterization



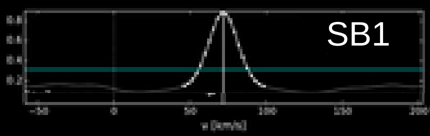
Period distribution

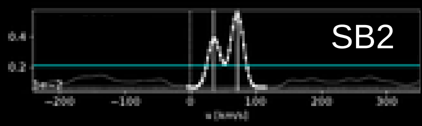


UNRESOLVED SB2



Probe the SB2 properties
beyond the 10 y limit

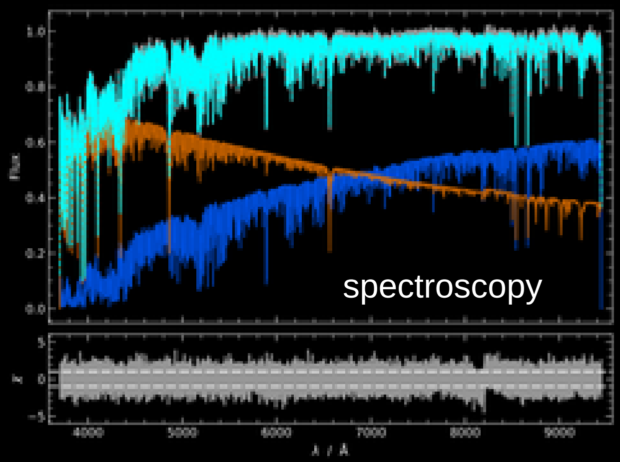


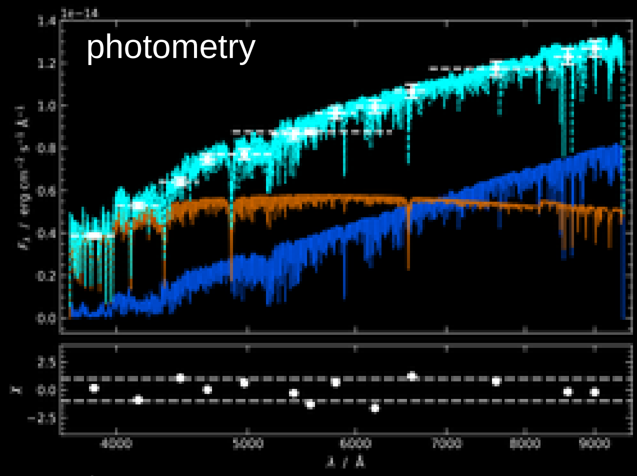


Multiple stars detection & characterization

Composite spectrum =
Main sequence F + subgiant K

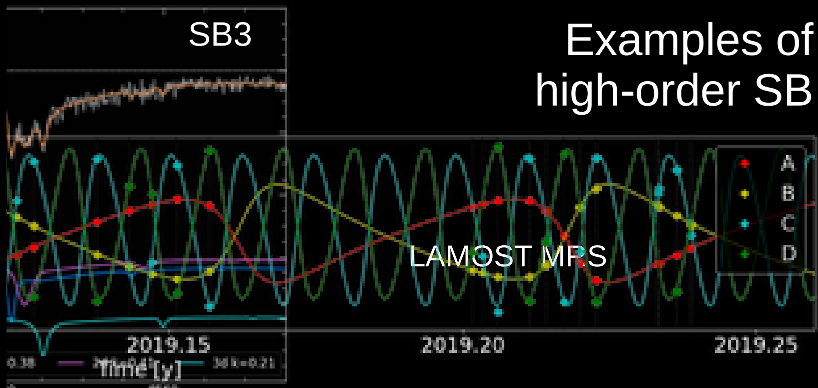
MULTIFIT from M. Dorsch
Approach similar to El-Badry+ (2018) in APOGEE
Using neural networks (*The Payne*, Ting+ 2017)

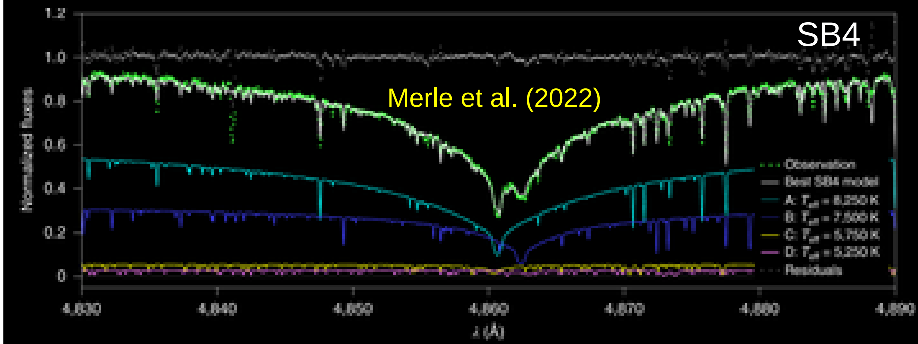


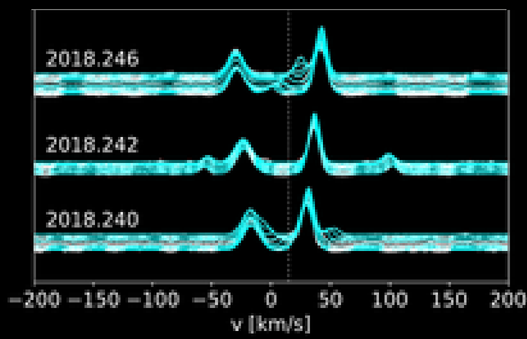


$$\chi^2_{SB} = \chi^2_{spec} + \chi^2_{phot}$$

Examples of high-order SB







Summary

- **SB9 Catalogue and Its Evolution**

The SB9 catalogue compiles thousands of spectroscopic binary orbits, including higher-order multiples, and has evolved into the modern SBX database with improved data access and standards.

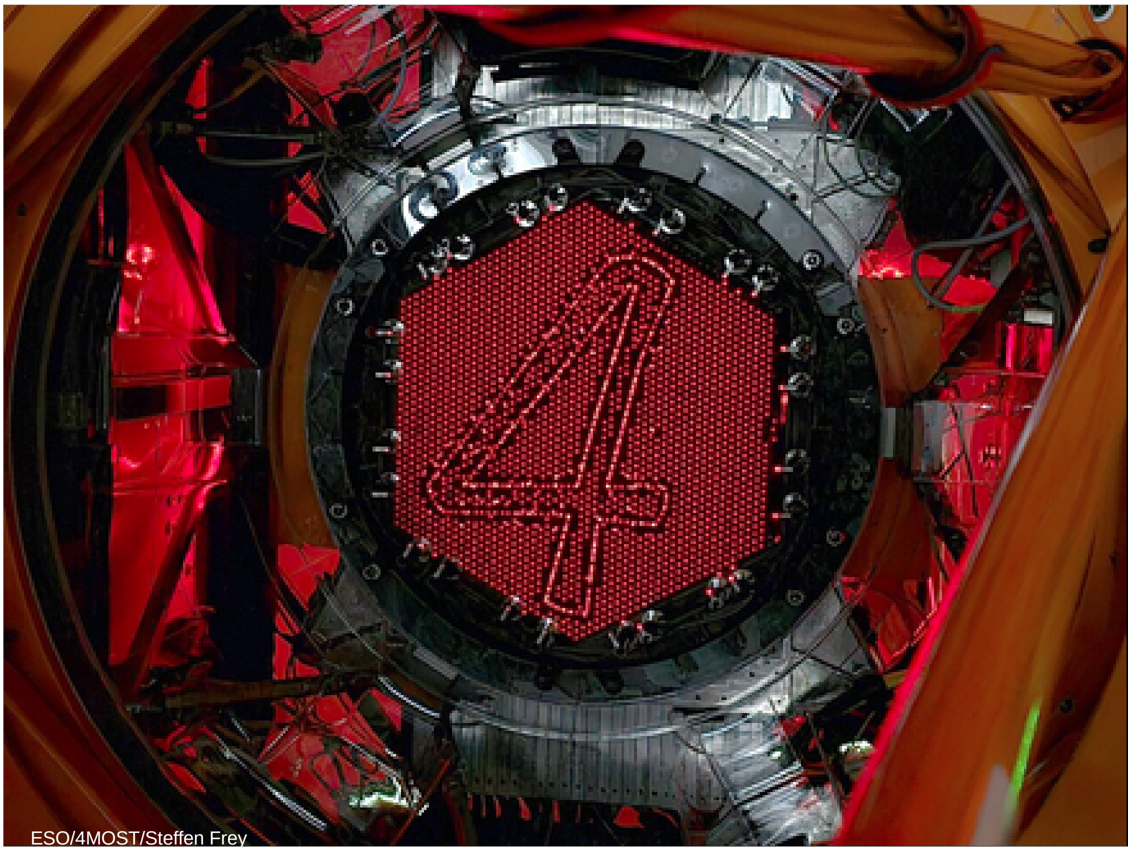
https://astro.ulb.ac.be/sbx

- **Comparison with Gaia DR3**

Cross-matching SB9 with Gaia DR3 NSS reveals only a partial overlap (about 20–25%), highlighting differences in detection limits, period coverage, and the need for further investigation into the completeness of binary catalogues.

- **Spectroscopic Binaries in the 4MOST Survey**

The upcoming 4MOST survey will massively expand spectroscopic binary detection, enabling detailed studies of binary fractions, period distributions, and higher-order multiples across the Galaxy, with new tools and strategies for characterizing both resolved and unresolved systems.


ESO/4MOST/Steffen Frey

Backup

SB9 x Gaia DR3 NSS common sample

1. SB9 systems brighter than *G* ~ 3 represents ~ 130 systems, i.e. 3% of SB9 systems

2. 11% of SB9 binaries have *G* > 13 and are impossible to be observed as SB with Gaia RVS

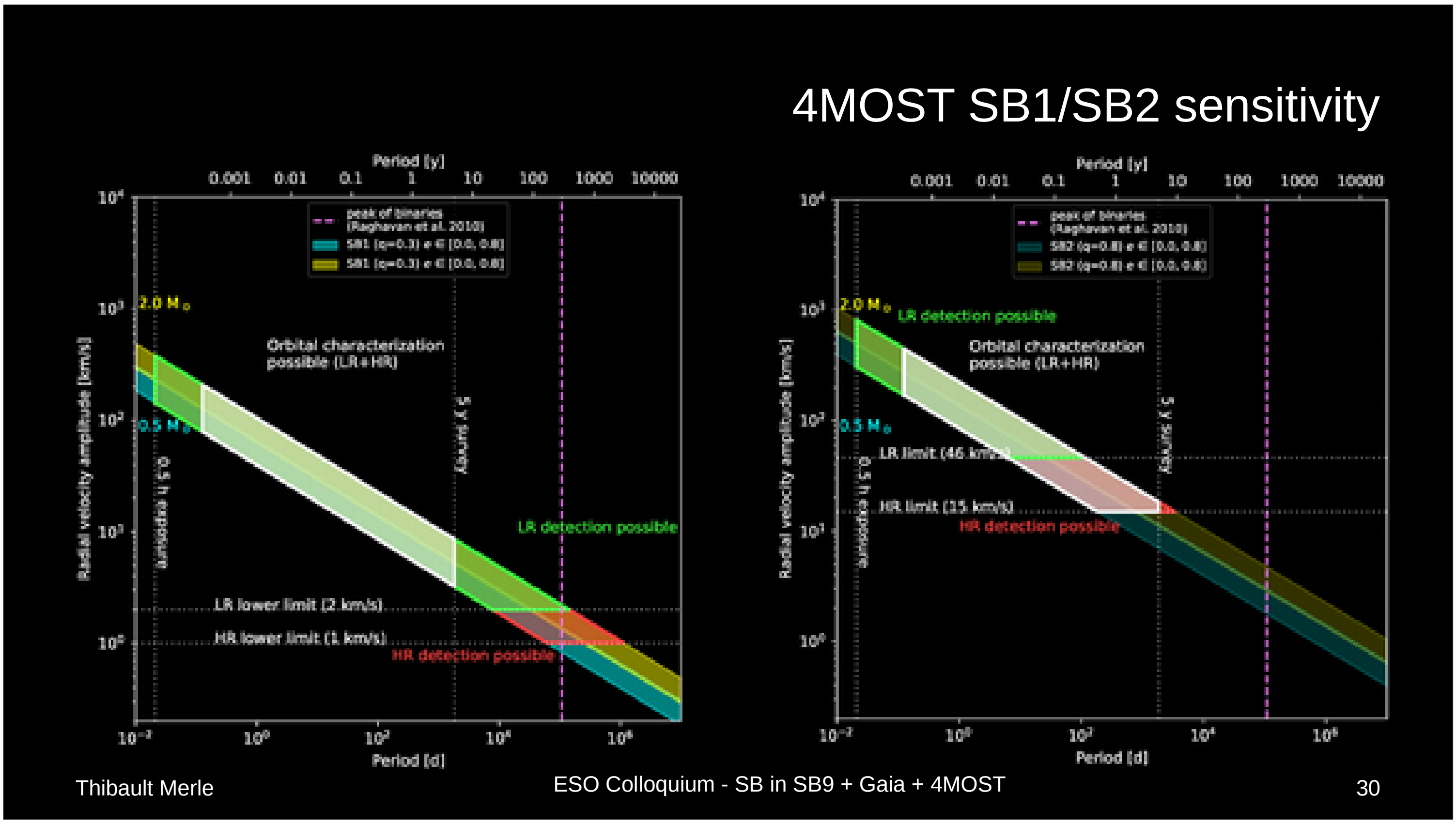
3. 22% of SB9 binaries have periods exceeding 1000 d

4. Early-type binaries (with T_{eff} ≥ 10 000 K) are over-represented in SB9 and under-represented in NSS

5. Binaries for which an astrometric motion is present: incorrect wavelength calibration (Gosset+ 2025)

   Rejection of a binary solution if:
   - F_2 > 3
   - phase coverage have gap >0.3
   - *K* > 250 km/s
   - Etc.

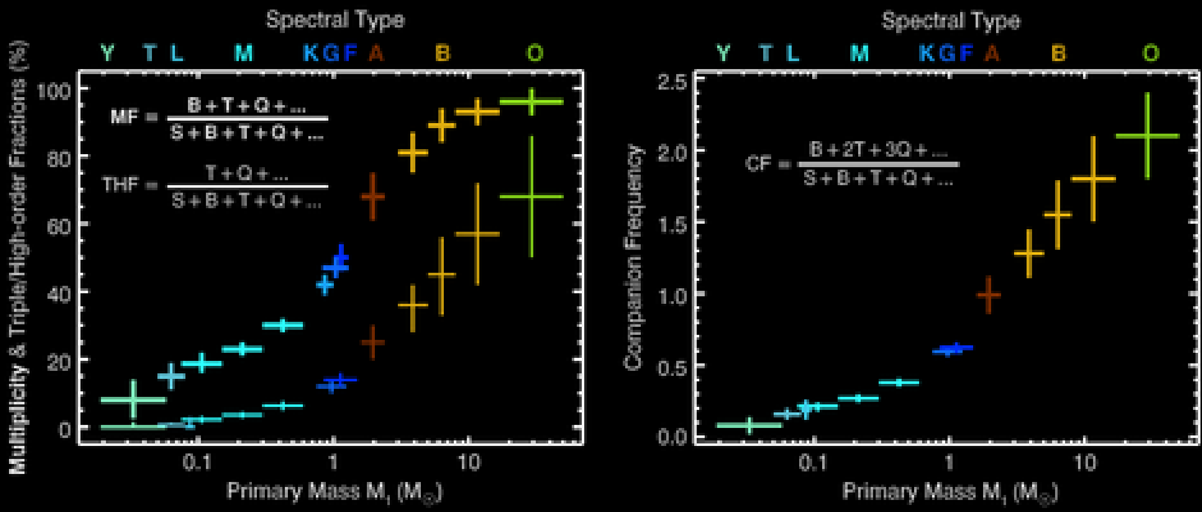
6. Partial orbital solutions (spectroscopic orbital trend, astrometric acceleration) accounts for 7% of SB9



On the left for SB1 detection the RV threshold is about 1 km/s in HR

On the right for SB2 to separate 2 peaks we need 45 km in LR and 15 in HR

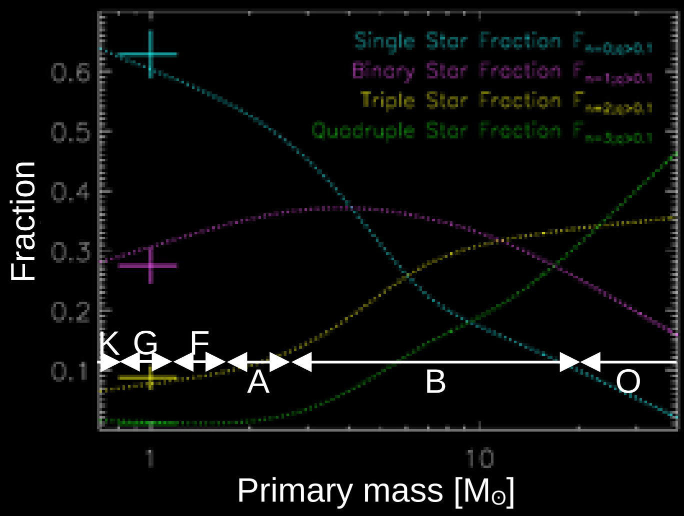
Multiplicity fraction vs. Mean number of companions



Offner et al. (2022)

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

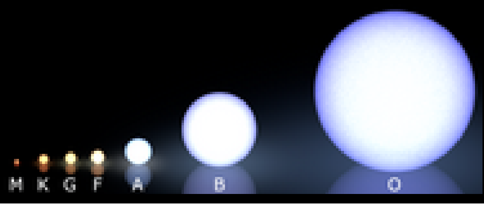
Multiplicity fraction



Moe & Di Stefano (2017)

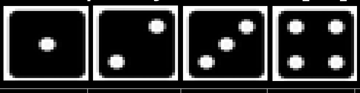
Solar-type stars
~ 40% multiples

Early-type stars
⩾ 90% multiples



Multiplicity statistics in late-type stars

Multiplicity fraction [%]



72.3	20.6	5.6	1.5	0.36	Reylé+ (2021)	10 pc sample (339 systems)
60	30	9	1	0.51	Moe & Di Stefano (2017)	25 pc solar-type sample (404 systems)
47	37	13	5	0.78	Furhmann+ (2017)	25 pc solar-type sample
54	33	8	5	0.64	Tokovinin (2014)	67 pc FG dwarf sample
54	34	9	3	0.61	Raghavan+ (2010)	25 pc solar-type sample (454 systems)
57	38	4	1	0.49	Duquennoy & Mayor (1991)	164 systems FG 22 pc
42	46	9	2	0.70	Abt & Levy (1976)	135 bright FG stars with V<5.5

Mean number of companions

Binary and multiple stars databases
Heterogeneous databases

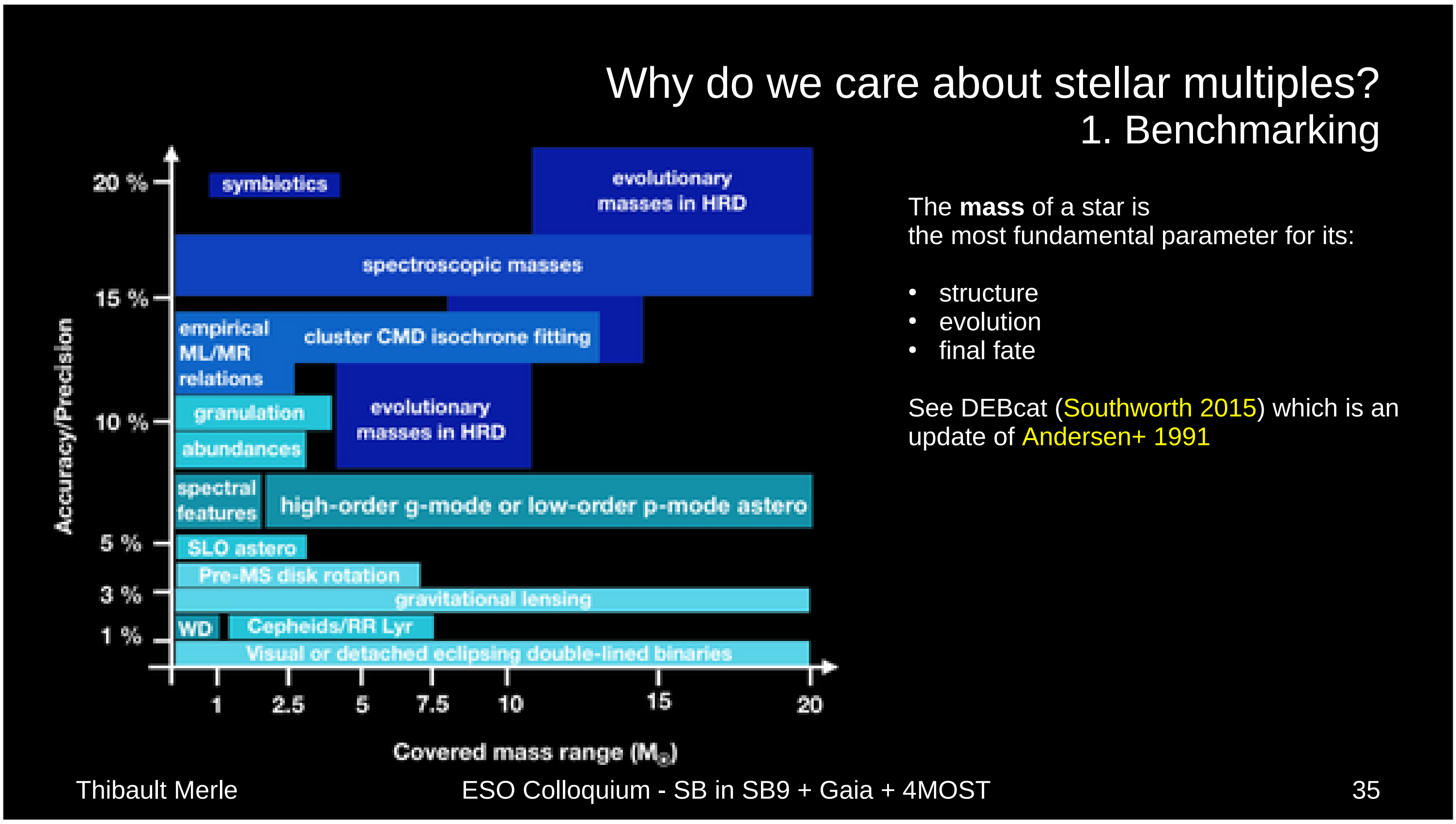
- Whashington Double Stars catalogue (WDS, Mason+ 2001-2020) http://www.astro.gsu.edu/wds
155 159 stellar systems

- 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/
> 370 systems



For fundamental stellar properties like mass, radius and luminosity.

Indeed, detached binaries evolve as single stars
DEBCat contains about 370 systems with accuracy better than 2% on masses and radii. It is the update of the compilation by Andersen (1991).

A simplified sketch of the mass ladder, summarizing the capacity of the various methods
The typical precisions in such a way that the sketch remains well visible.

SLO asteroseismology: masses derived from scaling relations using large frequency separation Δν and frequency at maximum power ν_max, calibrated with grid modeling for RGB/subgiant stars

Symbiotics: Masses from binary dynamics combining radial velocities with light curves/orbit modeling in symbiotic binary systems.

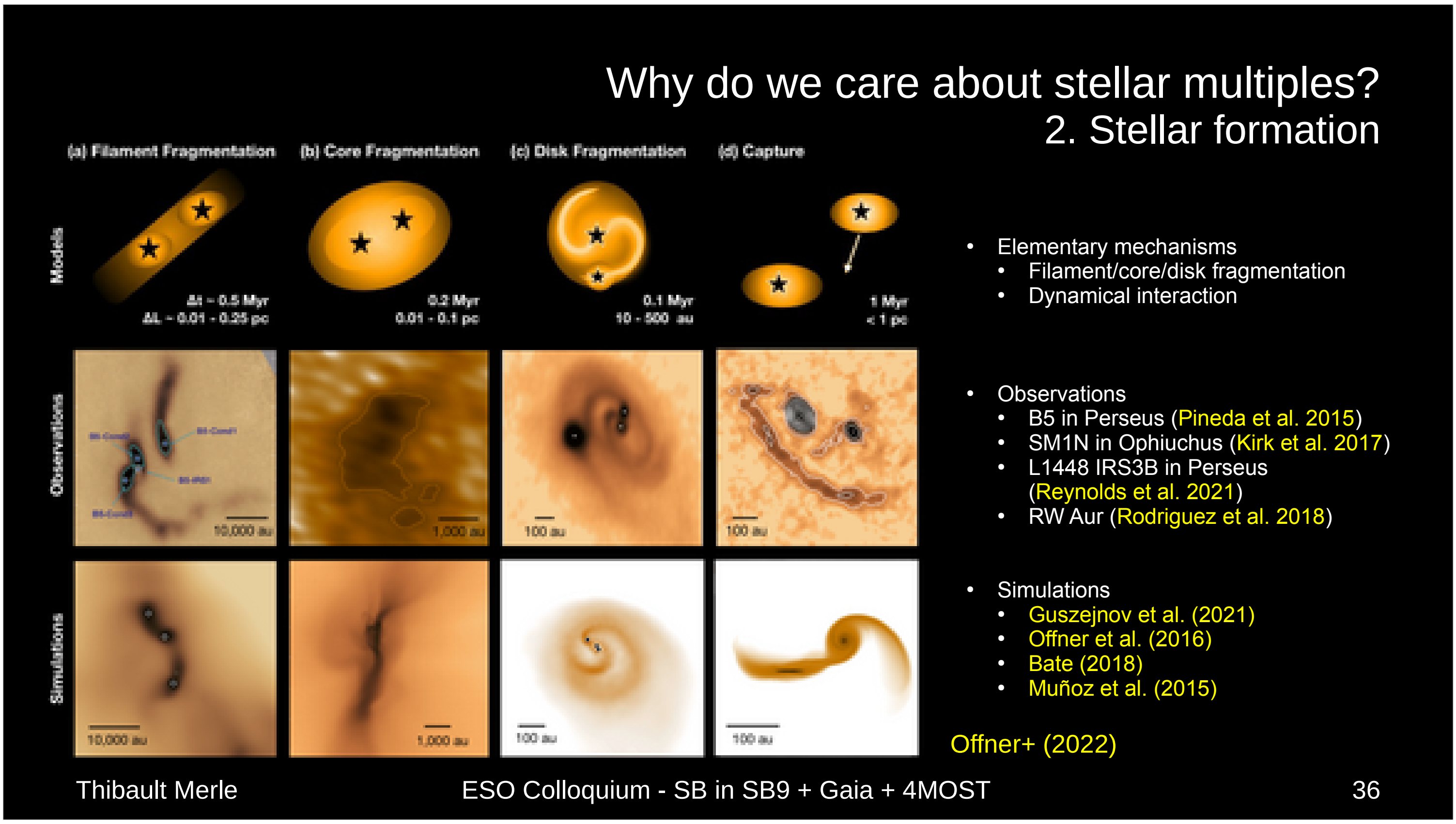
Pre-MS disk rotation: Stellar masses inferred from Keplerian rotation profiles of CO line emission in protoplanetary disks around young stars.

Cepheids/RR-Lyrae: Pulsational masses from period-density relation combined with evolutionary tracks, calibrated via period-luminosity relation and Baade-Wesselink method.

WD: Masses from spectroscopic log g and effective temperature fitting to atmosphere models, or asteroseismology of pulsating WDs via period spacings.

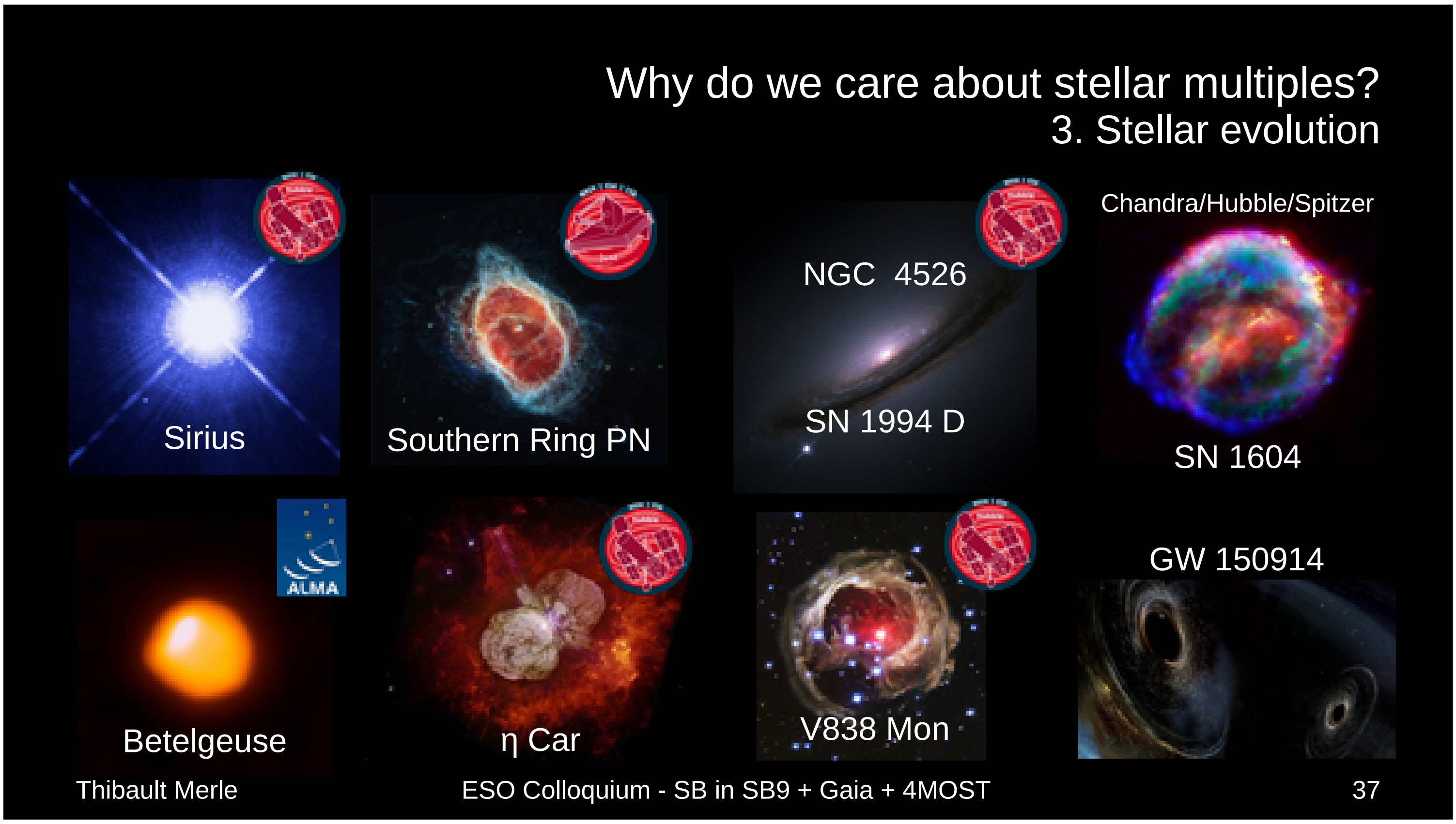
Granulation: Masses estimated via scaling relations linking granulation timescales/amplitudes from light curves to stellar parameters like T_eff and log g

Abundances: Surface abundances (C/N, Li, Hα) used with evolutionary models to estimate mass via mixing/age correlations in low/intermediate-mass stars.



Main elementary formation mechanisms of multiple stars occurring on different spatial and time scales.
They can act alone or in combination: sequentially or simultaneously.
Stars form in dense cores embedded in filaments nearby star-forming regions.
- Fragmentation can occur at the large scale of the filaments (~0.1 pc): rotation & turbulence => velocity and density asymetries
- at the intermediate scale of ovedensities (~0.05 pc): gravitational instability in a shearing disk + cooling criterion
- or at the scale of the protostar (~100 au).
- In addition, dynamical interactions can produce capture and disruption at all scales lower than ~1pc (capture, dynamical evolution, migration)

Stars form by hierarchical collapse of giant molecular clouds caused by the Galactic spiral-arms structure and colliding flows in the interstellar medium. The increase of the density of the gas produces a decrease of the Jeans mass that leads to fragmentation in cascade (hierarchical fragmentation) which stops when the gas becomes optically thick and heats adiabatically increasing the Jeans mass. The protostars form at the smallest scales of the cascade. Gravitational dynamics implies that small scales collapse faster than large ones. At each scale, gas infalls from the upper scale, shrinking the orbits of the newly formed systems.
Tokovinin & Moe 2020 showed with simple prescriptions that most close binaries and compact hierarchical triples are indeed formed by disc fragmentation followed by accretion-driven inward migration. In overall, the inside-out formation in which inner pairs form first seems to be the main scenario to explain the formation of triples and 3+1 quadruples although dynamical interactions (capture, disruption and collision) can make the outside-in formation possible, for instance to set up, at least partially, the 2+2 quadruples.



-Sirius: A spectral type with a WD on a period of 50 y. Difference of 10 magnitudes.
- The Ring Nebula: Planetary Nebula around a binary with a WD companion see face on. The IR camera reveal the presence of the companion. The bright star is still on the MS and will form its own planetary nebula in the future. The trajectories of the stars modify the environment creating asymetries. Each shell represent a event where the progenitor of the WD loose mass.
- SN 1994 D: type Ia supernova in the outskirt of this lenticular galaxy and due to the explosion of a WD whose mass reach 1.4 Mo
- SN 1604 The Kepler SN type Ia, the last SN in our Galaxy

stellar mergers:

Betelgeuse: suspected to be a merger product because the rotational velocity (5.5 km/s) is too high for its spectral-type (M). Red super-giant with 1000 Ro.

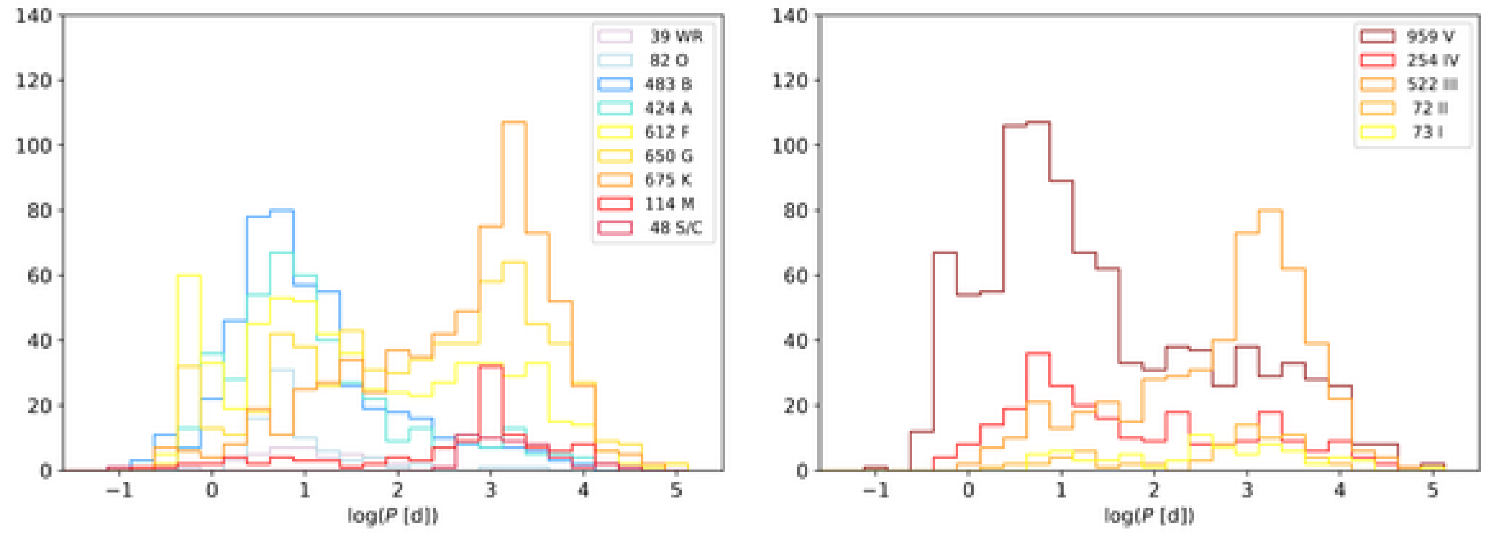
V838 Mon: luminous red nova transient (eruptive variable) in 2002, we can see the expansion of the shells.

eta Car: great eruption in 1890. Possible explanations for the eruptions include: a binary merger in what was then a triple system; mass transfer from Eta Carinae B during periastron passages or a pulsational pair-instability explosion (is a violent, repetitive explosive process in very massive stars)

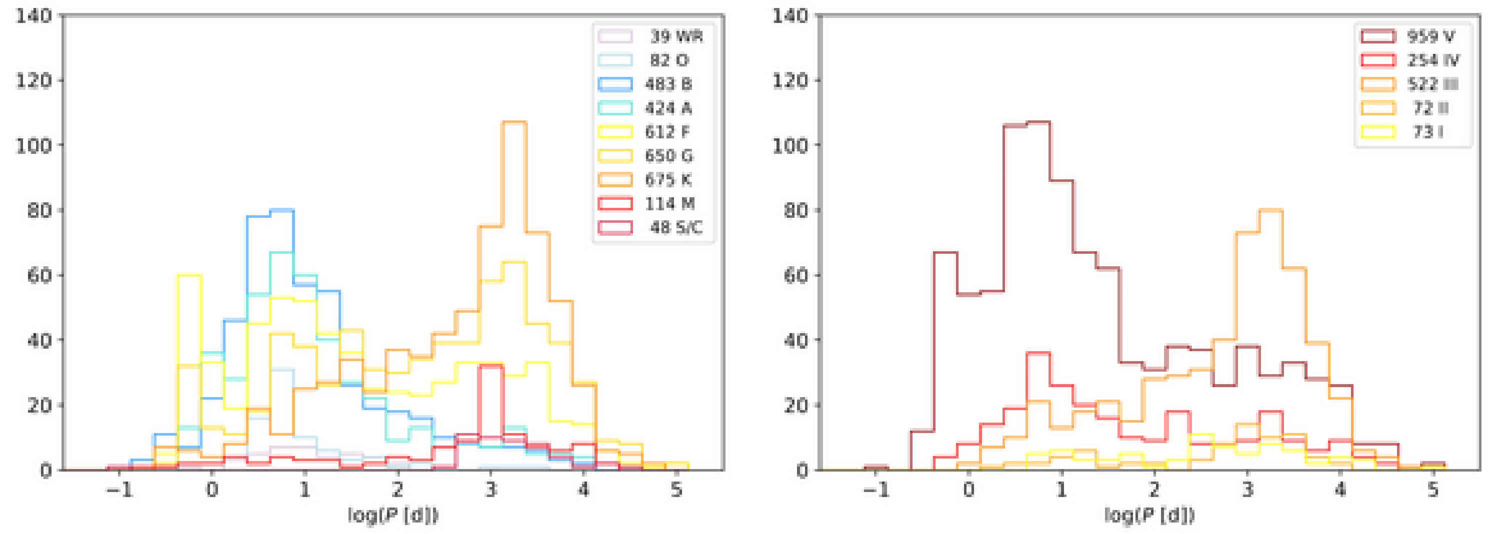
GW150914: the first detection Observation of Gravitational Waves from a Binary Black Hole Merger with 36 and 39 Mo

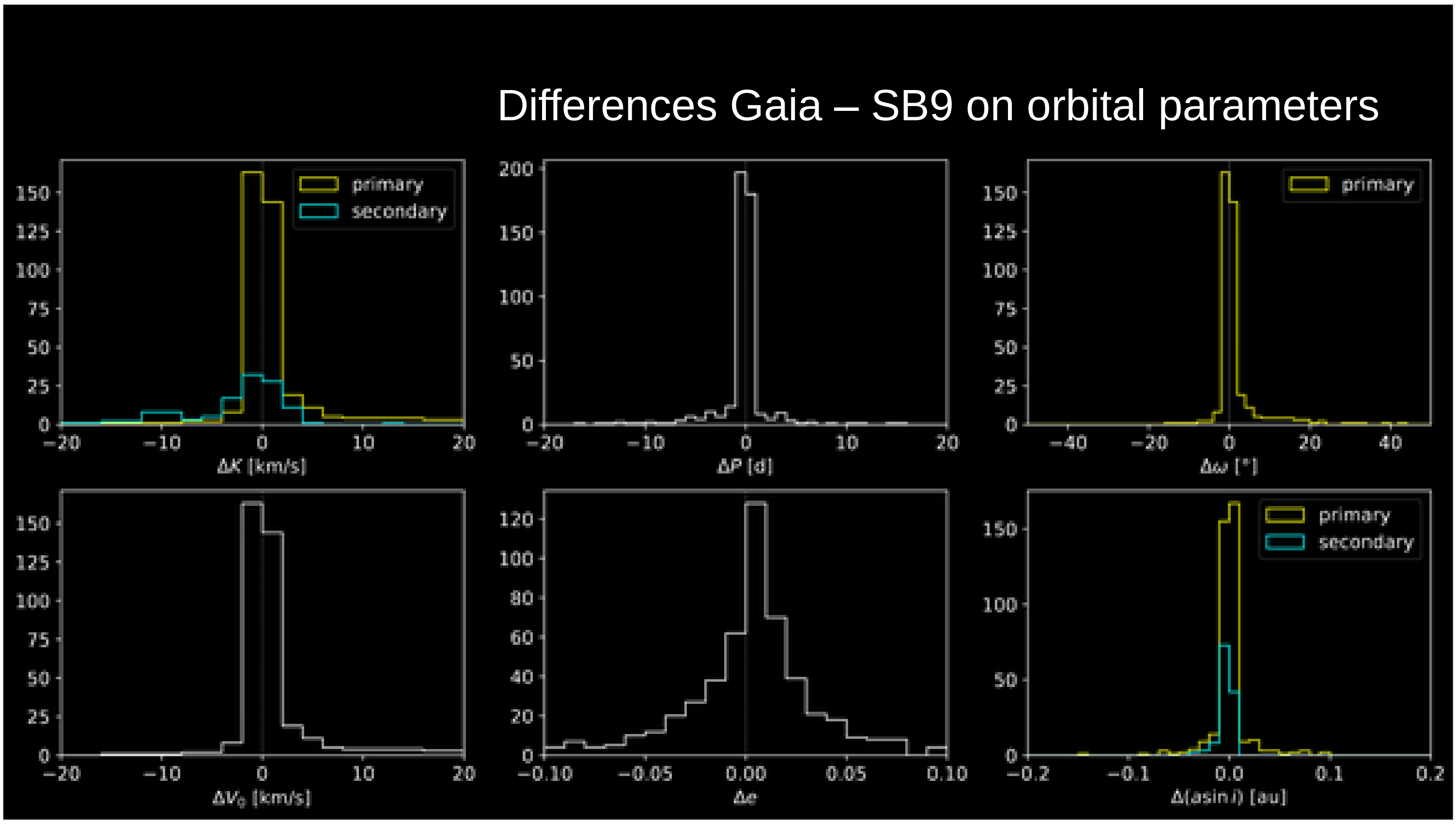
Stellar evolution:
Chemically peculiar stars: Ba stars, CEMP stars, etc.
Stripped stars: sdOB stars

SB9 period distributions as function of spectral type and luminosity class



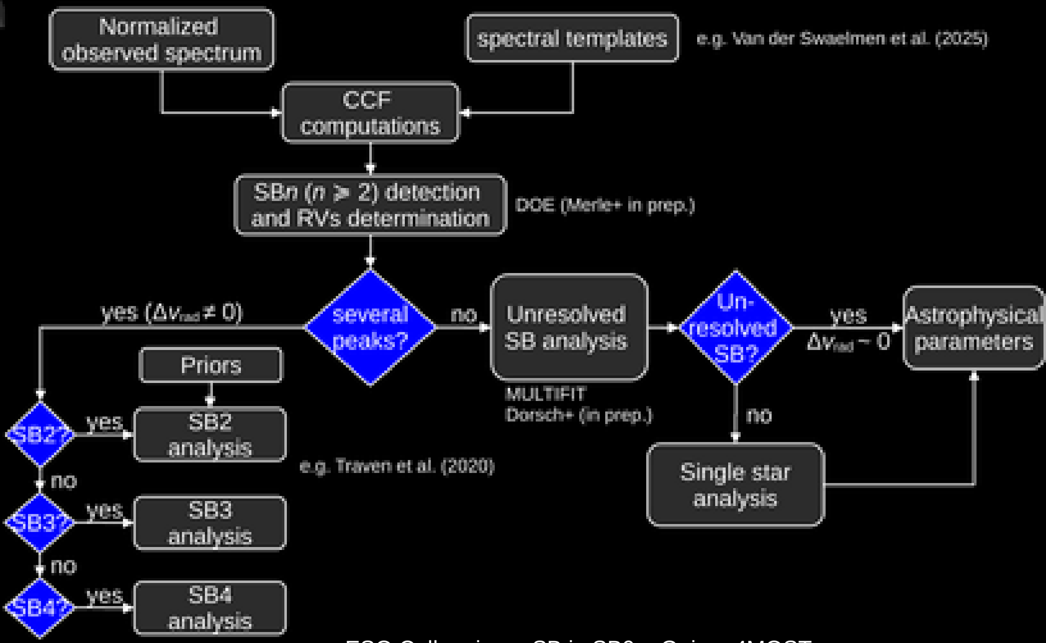
SB9 period distributions
as function of spectral type and luminosity class





Differences Gaia – SB9 on orbital parameters
primary
secondary
ΔK [km/s]
ΔP [d]
Δω [°]
ΔV0 [km/s]
Δe
Δ(asin i) [au]

Galactic Pipeline(4GP) for SB*n* ($n \geq 2$)



SB in 4MOST: preparation of the observations

Low Resolution Galactic survey (S3) input catalogue: ~ 16 $\times$ 10^6 targets
High Resolution Galactic survey (S4) input catalogue: ~ 8 $\times$ 10^6 targets

Crossmatches of the S3 and S4 input catalogues to setup the cadence of observations:

- OGLE (Soszynski+ 2016)

S3: 1 800 binaries (1 400 EB + 400 ellipsoidal)
S4: 290 binaries (130 EB + 170 ellipsoidal)
Both: median separation 0.1 arcsec, $\Delta V = 0.04 \pm 0.3$

- Survey of Surveys (SoS, Tsantaki+ 2022) (using APOGEE, GALAH, Gaia-ESO, RAVE, & LAMOST, with Gaia as a reference)

S3, S4: 6 900, 26 700 binaries
median separation = 0.02 arcsec

- Gaia DR3 (Gaia collaboration 2022)

S3: 26 500 binaries (median separation = 0.004 arcsec)
S4: 99 000 binaries (median separation = 0.02 arcsec)

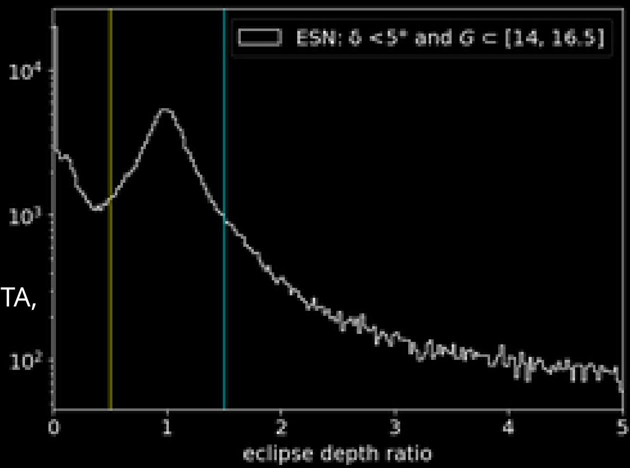
+ preparation of a catalogue of validation on well known SB using DEBCat (Southworth 2015), SB9 (Pourbaix+ 2004), VB+SB catalogue (Piccoti+ 2020), APOGEE DR13+DR16 (Price-Whelan+ 2020, El-Badry et al. 2018), etc.

Follow-up of Gaia EB

Gaia *vari_eclisping_binary* catalogue: ~2 millions

Selection for S3 ESN subsurvey:
- LRS and HRS
- Declination < 5°
- Gaia magnitude range: [14, 16.5]
- Median Gaia *global_ranking*: 0.6, range=[0.4, 0.8]

Eclipse depth ratio [0.5, 1.5] ➡ **110000 Gaia EB selected**



Selection for S4:
- Cross match with S4 subsurveys (DISK, ZDISK, EROSITA, PLATO)
- Maximum exposure time < 15 min in grey time
- Cadence flag updated for 1100 Gaia EB identified

This will increase the number of systems with accurate characterisation by one order of magnitude and serve as benchmark references for galactic archeology surveys.