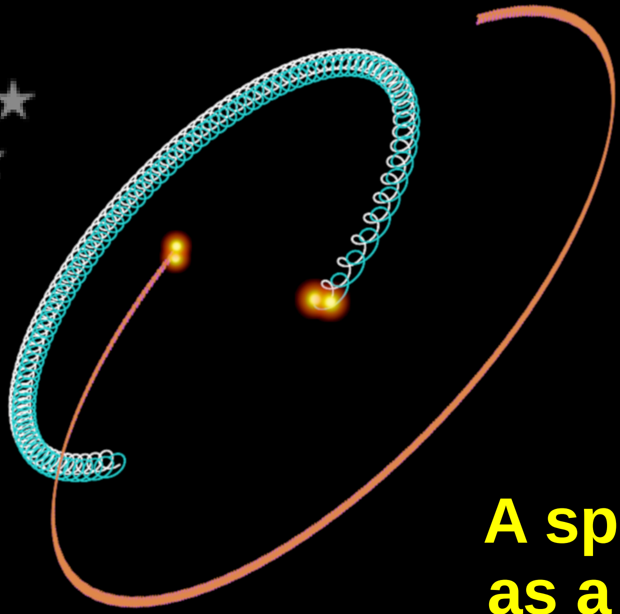

ImBaSE 2022

A spectroscopic quadruple as a possible progenitor of sub-Chandrasekhar type Ia supernova

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- R. Smiljanic (Nicolaus Copernicus Astronomical Center)
- G. Traven & T. Zwitter (University of Ljubljana)
- and Gaia-ESO Survey builders

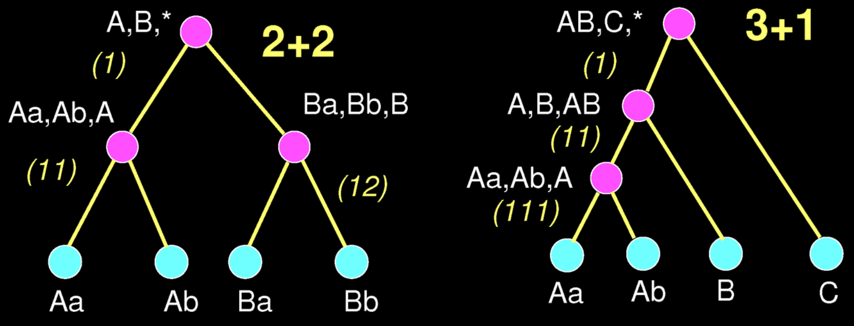
2022-11-18

Why do we care about quadruples?

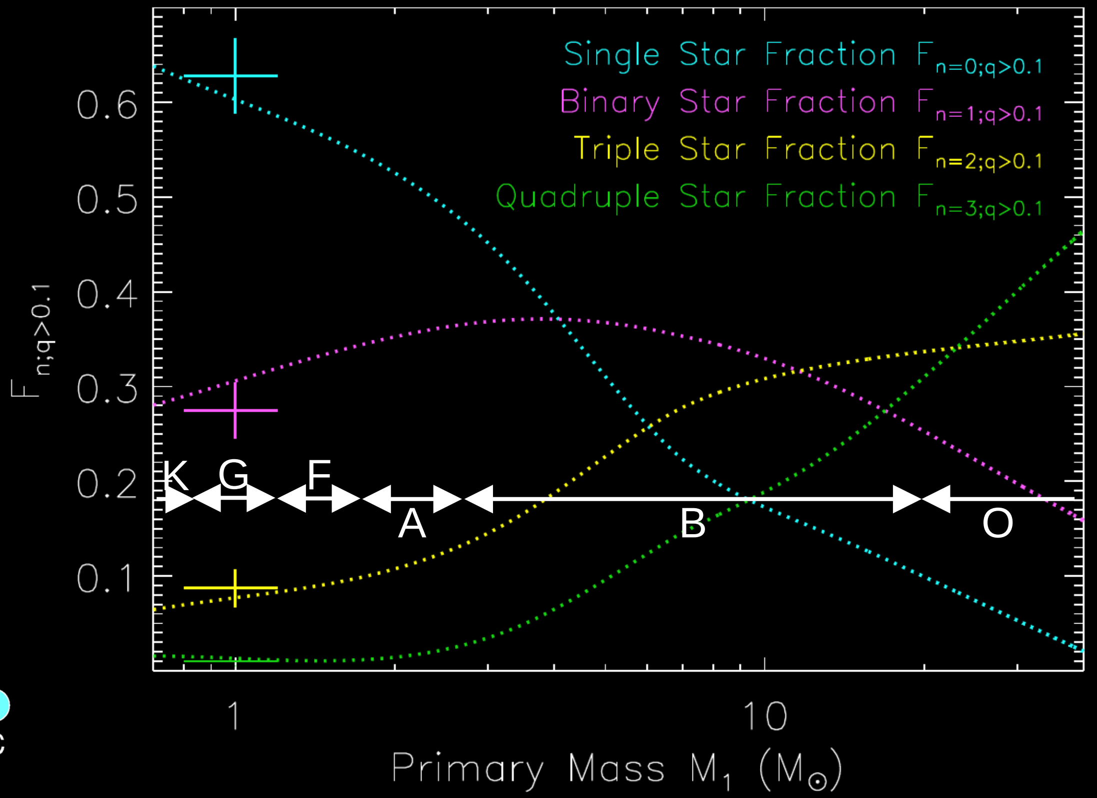
Abundance:
- In late-type stars:
  - from 1% (Moe & Di Stefano 2017)
  - to 4% (Furhmann+2017)

- In early-type stars:
  can reach more than 40%

Architecture:



Moe & Di Stefano (2017)



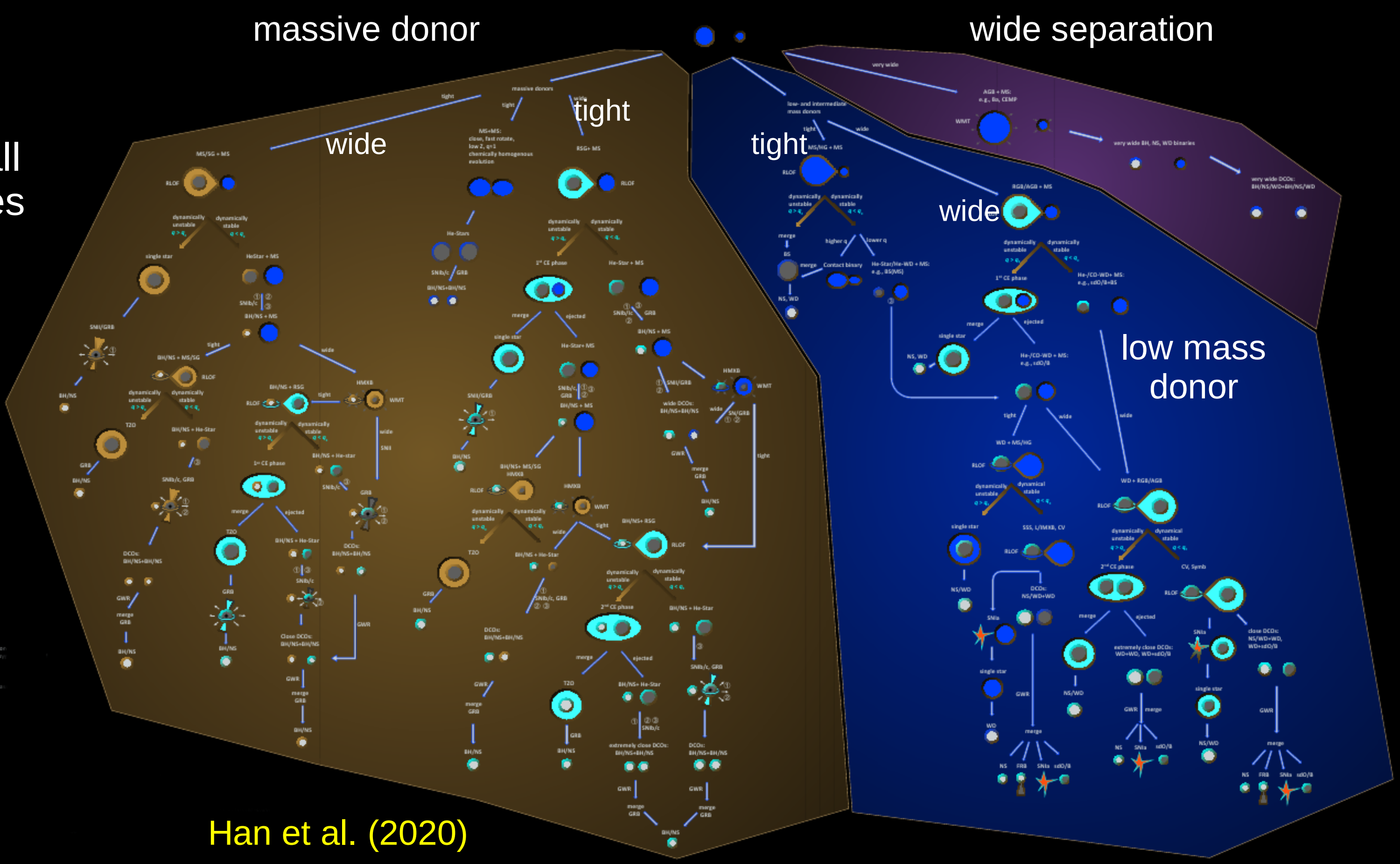
What are the end products of stellar quadruples?

Actually, we can imagine all the end products of binaries and triples with additional channels depending on the architecture.

Multiple disruptions

Multiple merger events

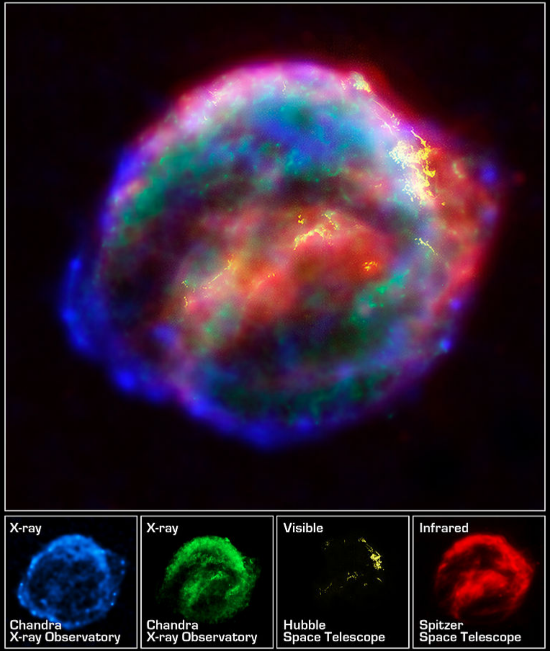
Mutliple combination of stellar evolution with dynamics (e.g. triple CE)



Han et al. (2020)

How type Ia supernovae form?

HST(NASA/ESA)-Image
of Supernova 1994D
in galaxy NGC 4526



Kepler's Supernova Remnant • SN 1604 ssc2004-15a
NASA, ESA / JPL-Caltech / R. Sankrit & W. Blair (Johns Hopkins University)

Review on progenitors SNIa:
Wang & Han (2012)

Chandrasekhar-mass channel:

- Single-degenerate model
- Double-degenerate model

Sub-Chandrasekhar-mass channel:

- Mergers (e.g. Pakmor et al. 2013, Shen et al. 2018)
- Head-on collisions (Toonen et al. 2018)

Non-LTE analysis support the last channel for 70-85% of all normal SNIa (Eitner et al. 2020, Flörs et al. 2020)

Multiples stars in the Gaia-ESO Survey

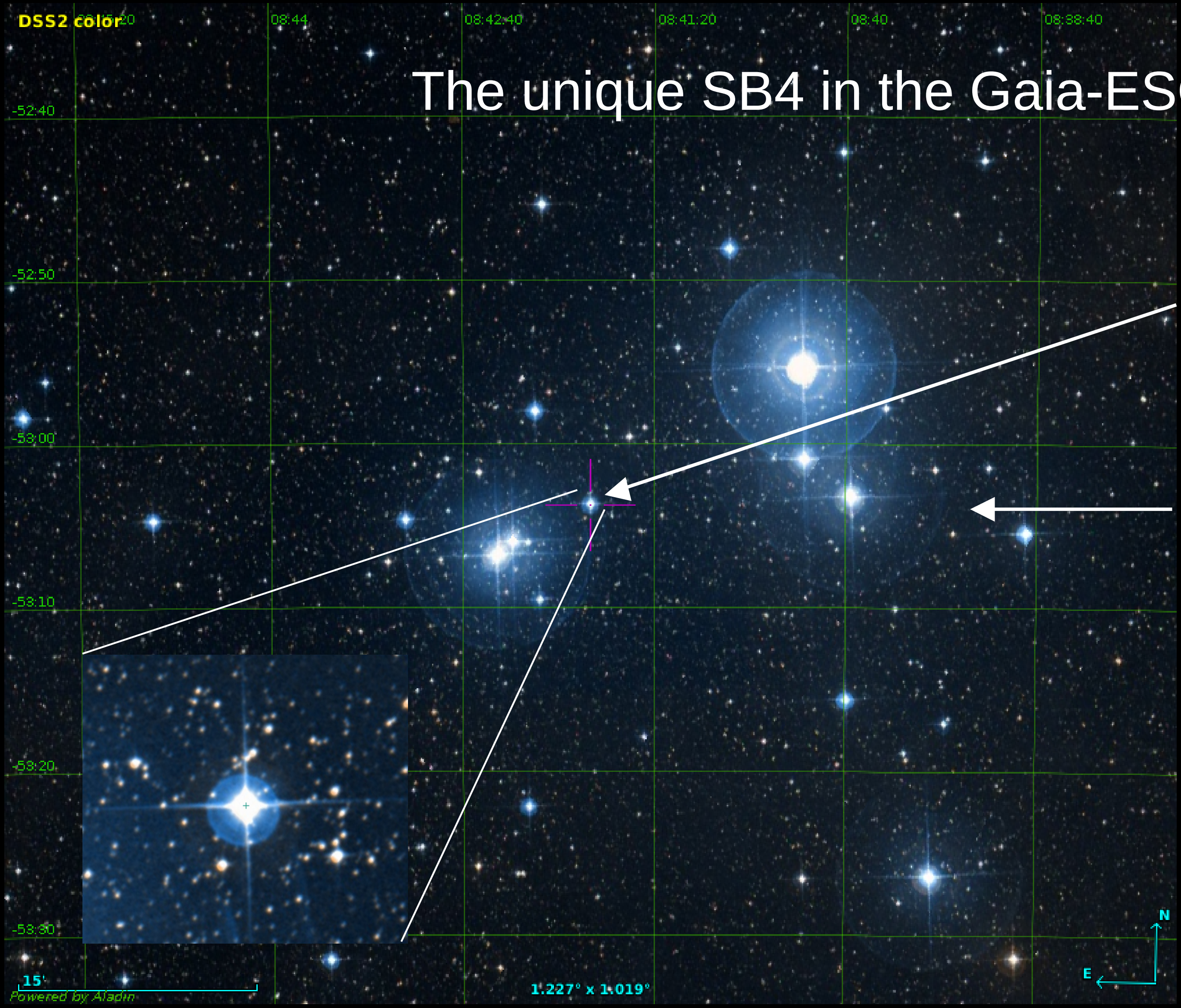
Study of the formation history of stellar populations of the Milky-Way:
100 000 stars in bulge, discs, halo and stellar clusters (Gilmore et al. 2022, Randich et al. 2022)

GES DR5 final release in June 2022: https://www.eso.org/qi/catalogQuery/index/393

Observing strategy not adapted to the detection of binaries but:

- Merle et al. 2017: ~ 340 SB2, ~10 SB3 & 1 SB4
- Merle et al. 2020: ~800 SB1
- Van der Swaelmen, Merle et al. (in. prep) > 430 SB2

The unique SB4 in the Gaia-ESO Survey



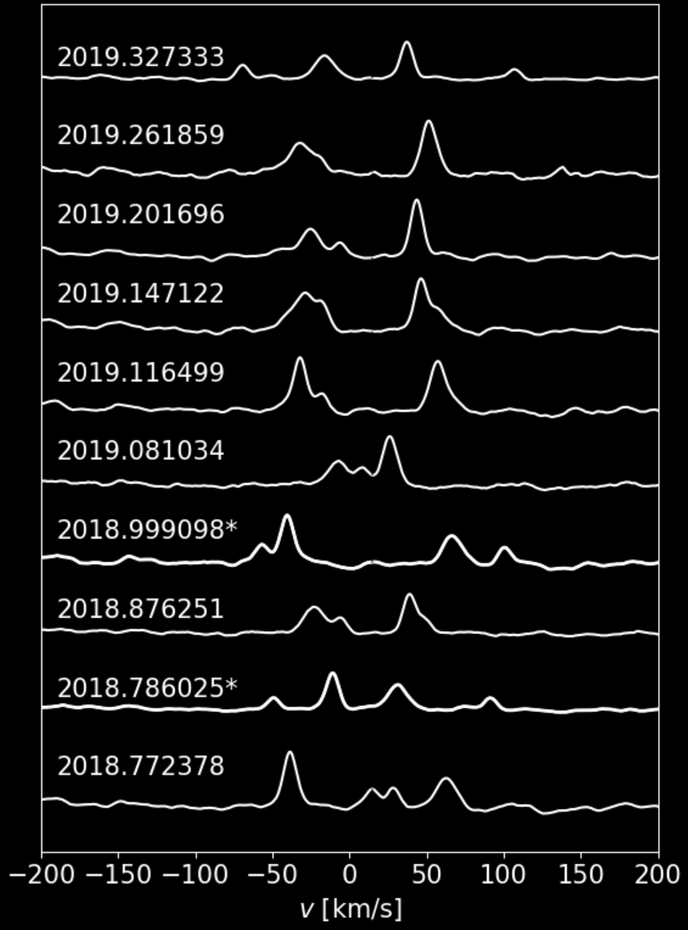
SB4 = spectroscopic quadruple

HD 74438 (V = 7.5)
Spectral type: A2V
$M \sim 3\ M_\odot$

Open Cluster IC 2391
N = 325 (Gaia collab. 2018)
$v = 14.98 \pm 0.17$ km/s (Bravi et al. 2018)
$d = 146 \pm 8$ pc (Gaia collab. 2018)
Age = 43^{+15}_{-7} Ma (Randich et al. 2018)

Already suspected to be a triple:
0.9 mag above the main sequence
(Platais et al. 2007)

Spectroscopic follow-up with HRS/SALT & HERCULES/UCMJO

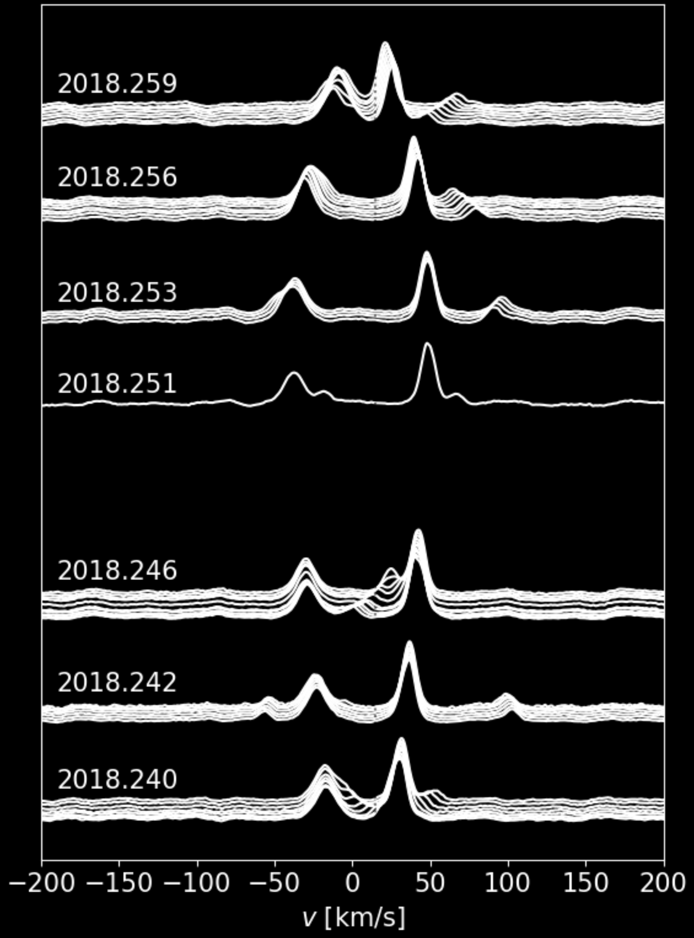


HRS spectrograph
Hearnshaw et al. (2002)

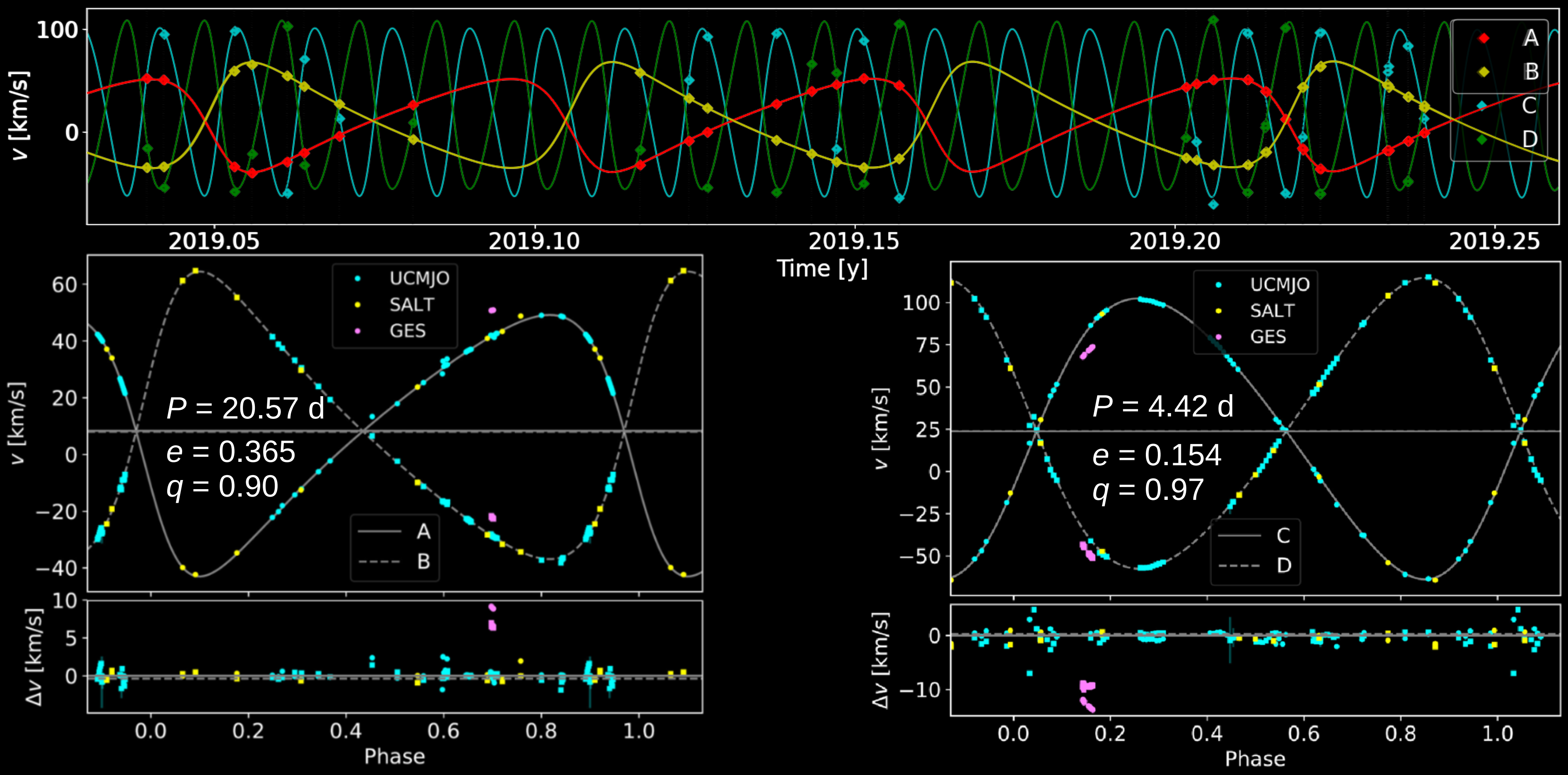
[3830, 8775] Å
R = 65 000

HERCULES spectrograph
Crause et al. (2014)

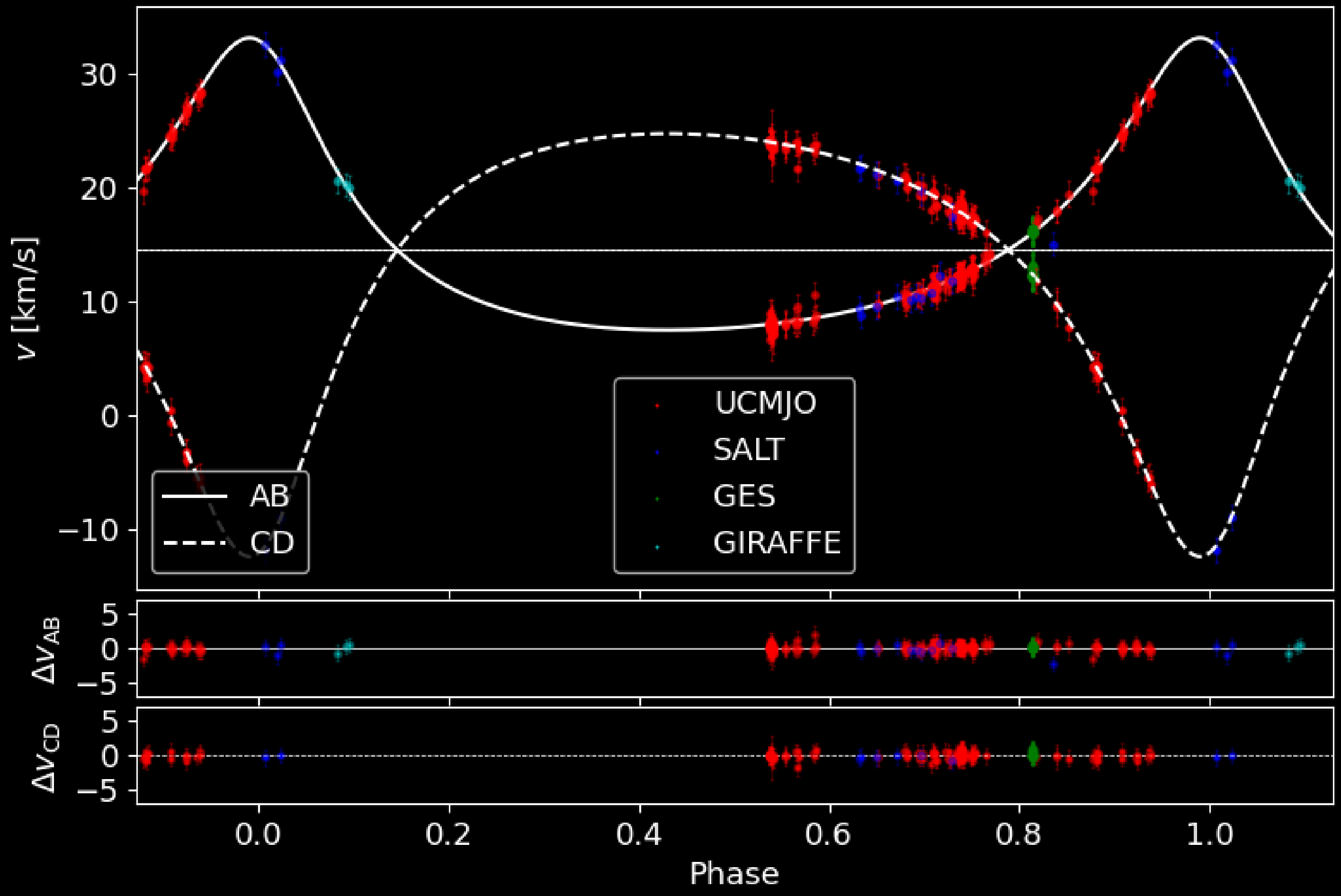
[4160, 7635] Å
R = 41 000



Short-period orbital solutions



Long-period orbital solution



Period
$P = 5.68 \pm 0.10$ y

Eccentricity
$e = 0.458 \pm 0.014$

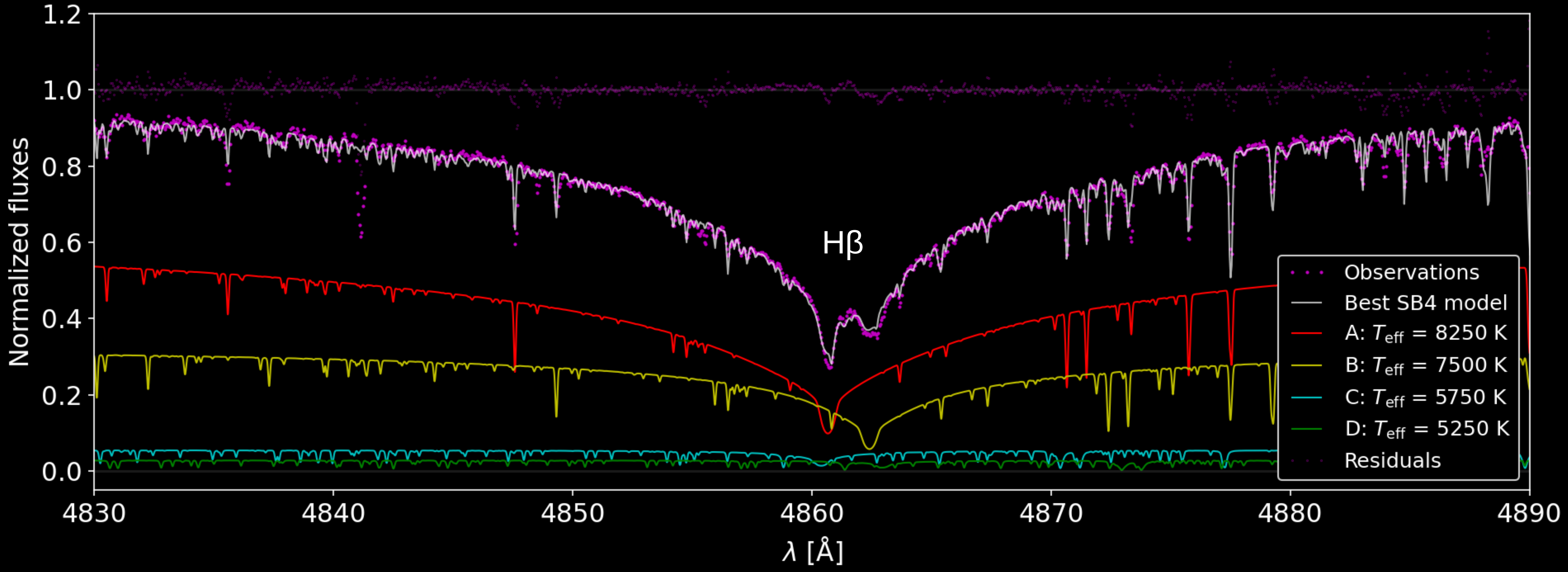
Center of mass velocity
$v_0 = 14.54 \pm 0.20$ km/s

Radial velocity amplitudes
$K_{AB} = 12.77 \pm 0.28$ km/s
$K_{CD} = 18.57 \pm 0.39$ km/s

Periastron time
$T_0 = 2\,401\,089 \pm 7$ d

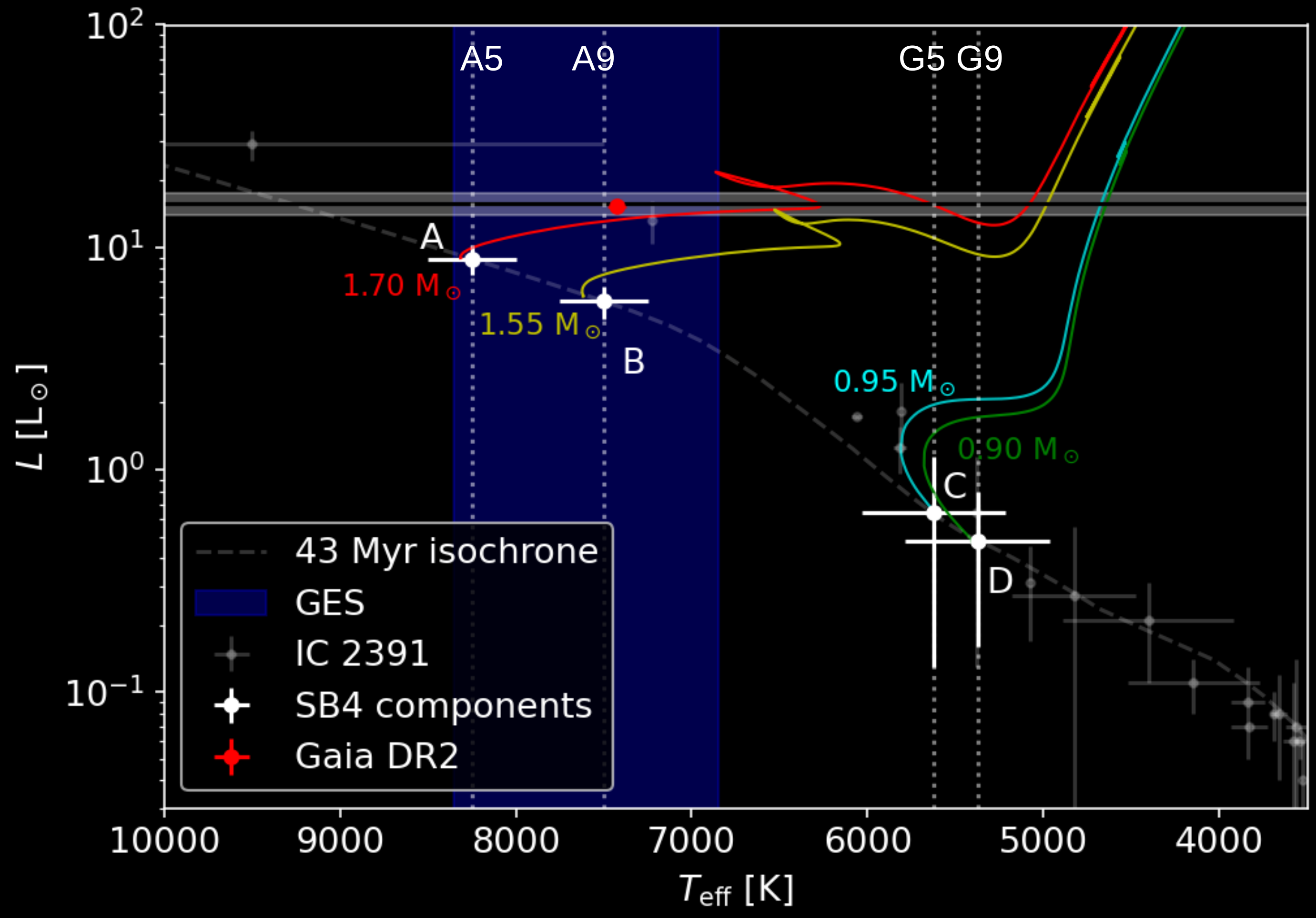
Argument of periastron
$\omega_{AB} = 10.6 \pm 2.2$ °

Astrophysical parameters



Kurucz's model atmospheres + 1D radiative transfer code Turbospectrum (Plez, 2012)
Spectral fitting in the range [3850 – 5500] Å of HRS/SALT spectra

Location in the HR diagram



IC2391 members:
Membership & $T_{\rm eff}$
(Randich et al. 2018)
Gaia DR2 luminosities from Apsis
(Andrae et al. 2018)

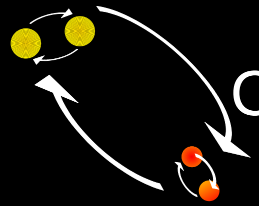
Isochrone at 43 My and evolutionary tracks from PARSEC
(Bressan et al. 2012)

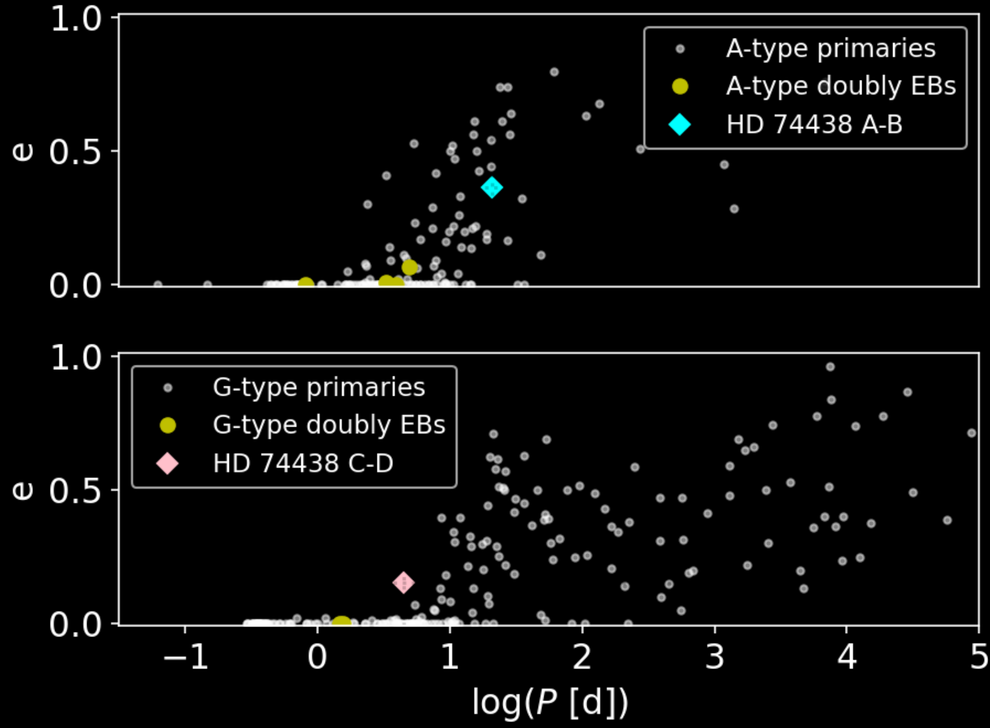
Luminosities are in excellent agreement!

Spectroscopic masses derived

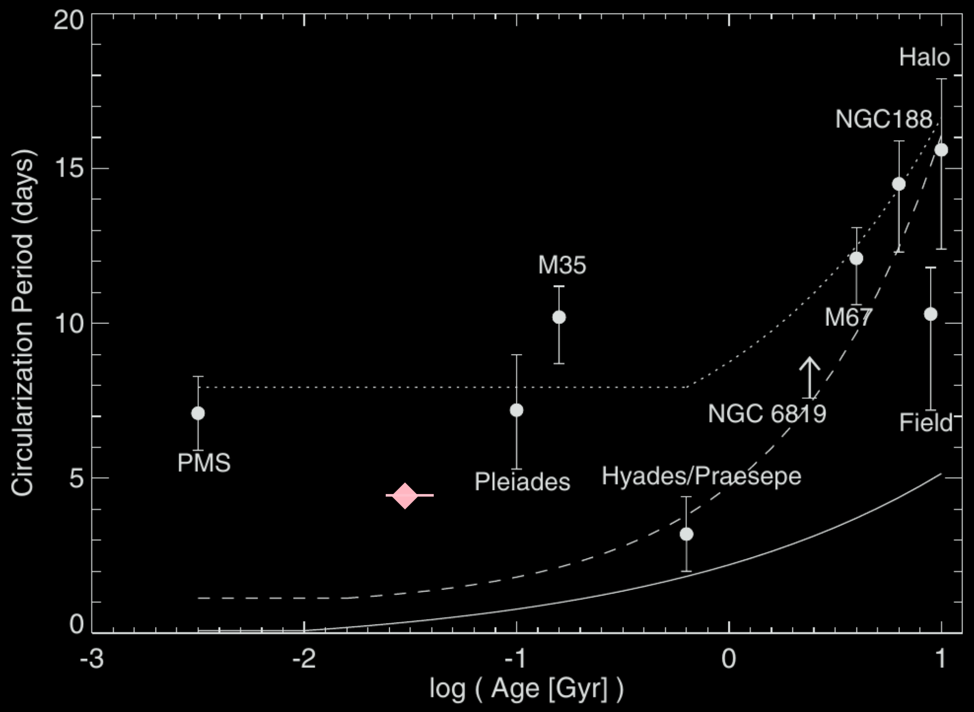
Inclinations and separations deduced

Comparison with SB2 and EB of same spectral types





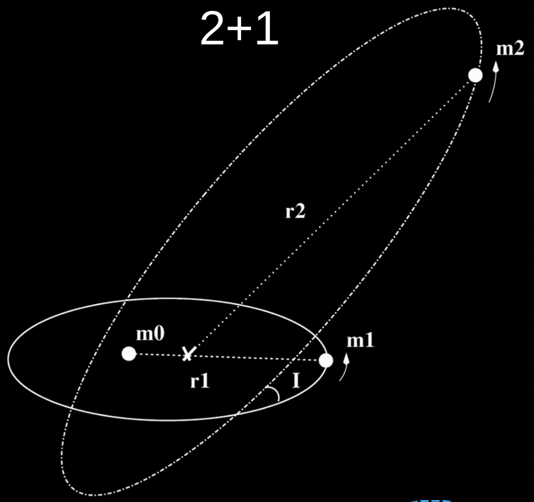
Geller, Hurley & Mathieu (2013)



The 9th catalogue of spectroscopic orbits (SB9, Pourbaix et al. 2014)
Doubly eclipsing binary (EB) systems (Zasche et al. 2019)
The CD pair is too eccentric for its spectral type

The CD pair has a circularization period smaller than 7-8 d as predicted by Zahn & Bouchet (1989)

Multiple star evolution



Secular evolution in triple star: Kozai-Lidov (KL) oscillations (Kozai, 1962, Lidov 1962)

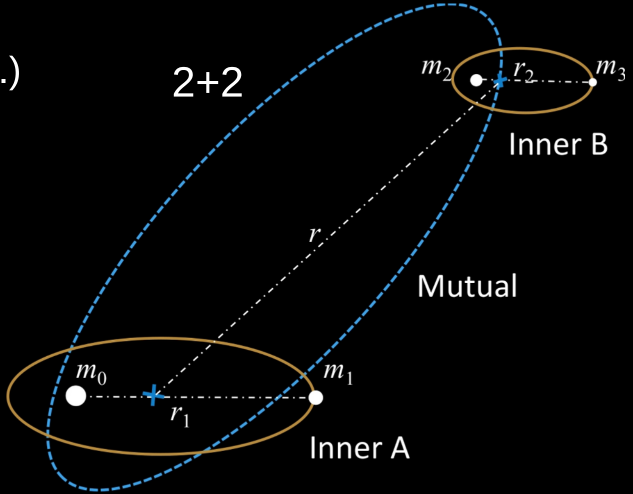
Dynamical interaction in an initially unstable hierarchical triple: Initial mutual inclination Φ in [40, 140]°

Famous example: Algol system (Baron et. al, 2012)

Pejcha (2013) fist study of KL cycles in quadruples
(see also: Naoz (2016), Hamers (2018), Fang et al. (2018), Tremaine (2020), etc.)

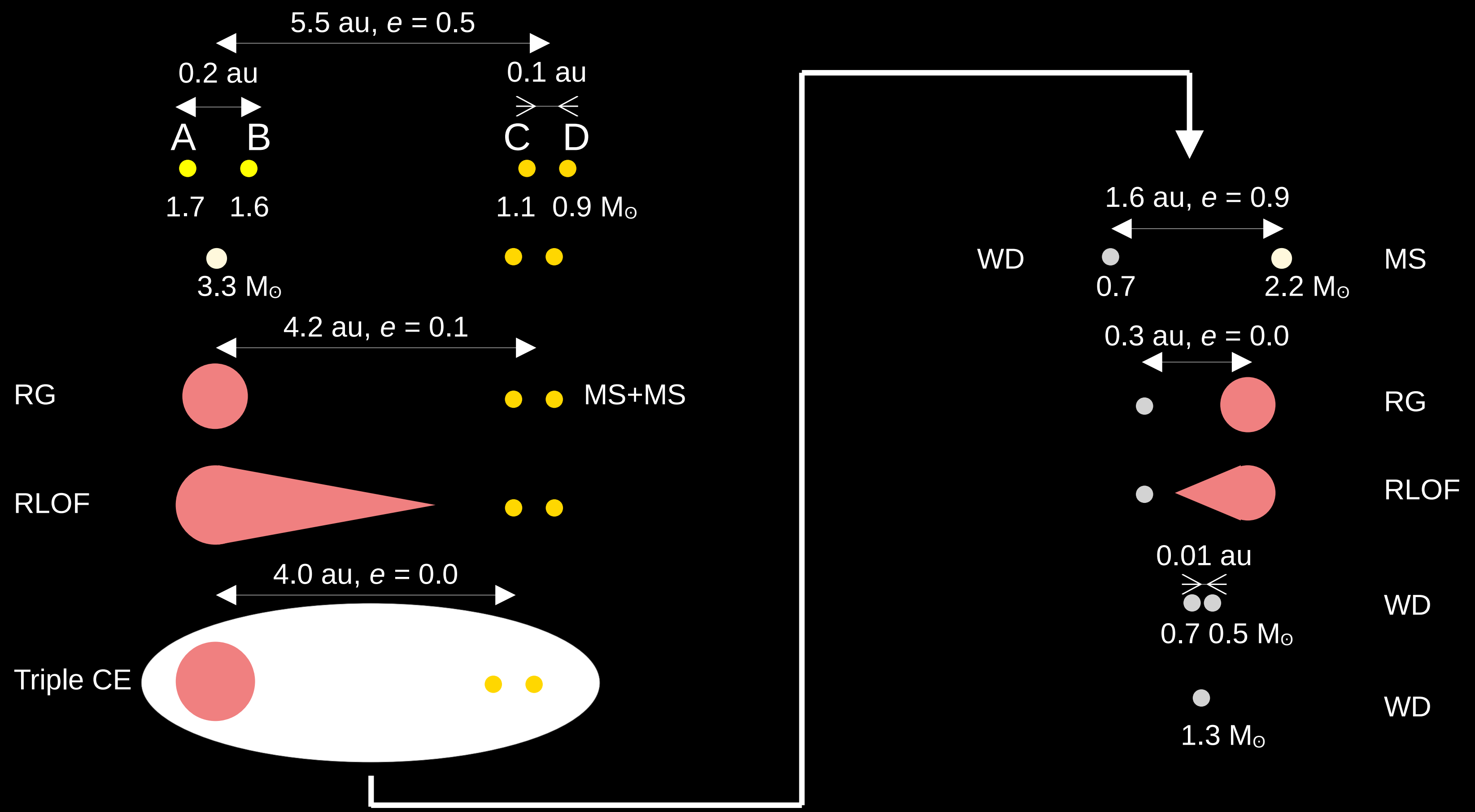
Multiple Stellar Evolution (MSE) code – Hamers et al. (2021)

- Hierarchical architecture: e.g. 1+2, 2+2, 1+3, 2+3, etc.
- Gravitational dynamics
- Stellar evolution
- Binary interaction
- Triple interaction

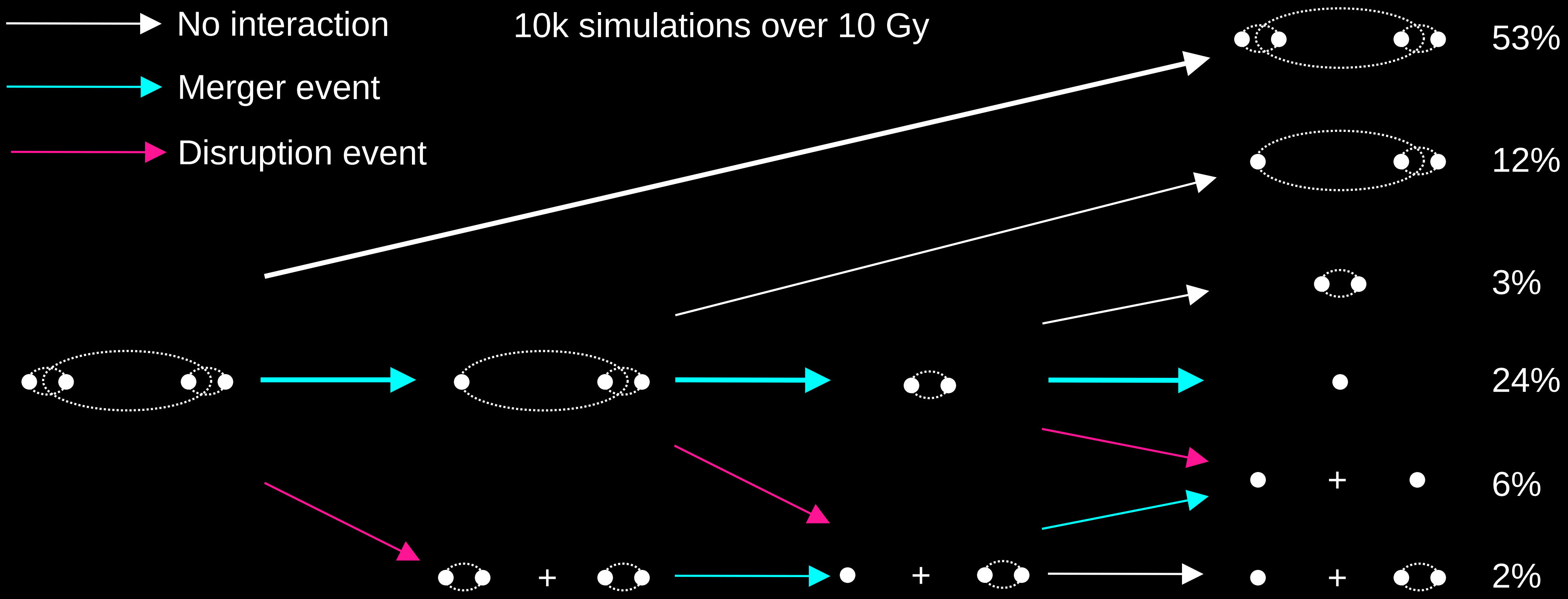


Fang et al. (2018)

Example of one realization with MSE (over 2 Gy)



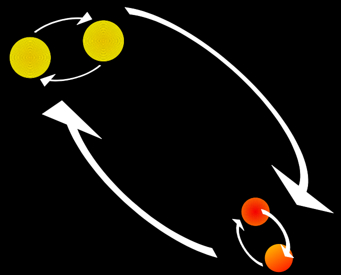
Prediction of the evolution with MSE



In ~50% of simulated cases, at least 1 merger event
In ~25% of cases, 3 merger events, leading to WD with masses below the Chandrasekhar limit

Conclusion

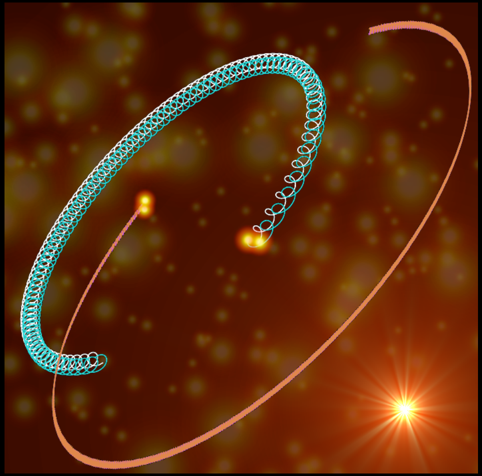
Merle et al., Nature Astronomy, 2022, 6, 681 https://rdcu.be/cNqC2
Merle et al., The Messenger, 188, 26



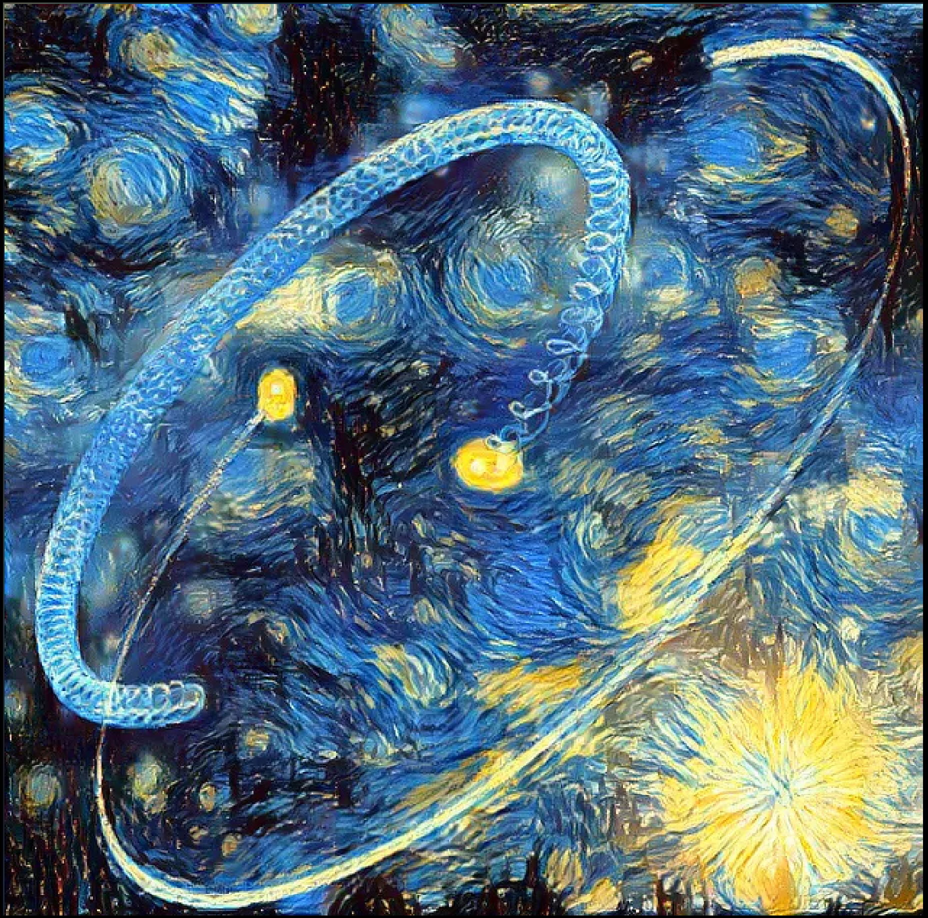
- HD 74438 is a spectroscopic quadruple hierarchical 2+2 system
- Belongs to the very young and nearby open cluster IC 2391
- SB4 made of an A-type binary orbiting a G-type one
- SB4 with non-coplanar inner orbits
- The CD pair has a higher eccentricity than SB2 of similar spectral types and periods
- Indirect evidence of Kozai-Lidov oscillations
- Mergers events lead to WD masses compatible with sub-Chandrasekhar type Ia SN

Quadruples stellar systems offer a way to potentially form type Ia SN (Fang et al. 2018) and HD 74438 is a good candidate progenitor.

The Van Gogh *De sterrennacht* revisited



+



generated with https://creator.nightcafe.studio

Additional slides

Astrophysical parameters of HD 74438

	Component	A	B	C	D	Unresolved
	Spectral Type	A5	A9	G5	G9	–
	T_{eff} [K]	8250 ± 250	7500 ± 250	5625 ± 410	5375 ± 410	-
	L [$L_\odot$]	8.87 ± 1.40	5.72 ± 0.95	0.64 ± 0.51	0.48 ± 0.32	15.71 ± 1.80
	R [$R_\odot$]	1.46 ± 0.15	1.42 ± 0.15	0.84 ± 0.36	0.80 ± 0.29	-
spectroscopic	M [$M_\odot$] [a]	1.70 ± 0.06	1.54 ± 0.06	0.96 ± 0.14	0.87 ± 0.14	5.07 ± 0.22
dynamical	M [$M_\odot$] [b]	1.64 ± 0.06	1.48 ± 0.06	1.09 ± 0.04	1.06 ± 0.04	5.27 ± 0.10

Orbital parameters of HD 74438

	A-B	C-D	AB-CD
P [d]	20.5729 ± 0.0003	4.4243 ± 0.0001	2074.2 ± 3.5
e	0.3692 ± 0.0001	0.1535 ± 0.0003	0.458 ± 0.015
ω_1 [rad] [(a)]	1.8780 ± 0.0003	-1.946 ± 0.002	0.185 ± 0.039
T_0 - 2400000 [d]	58 605.9 ± 0.1	58 684.5 ± 0.1	59165.8 ± 5.1
v_0 [km s^{-1}]	-	-	14.5 ± 0.2
K_1 [km s^{-1}] [(b)]	45.81 ± 0.09	83.2 ± 0.1	12.8 ± 0.3
K_2 [km s^{-1}] [(b)]	50.77 ± 0.09	85.5 ± 0.1	18.5 ± 0.4
q_{dyn}	0.902 ± 0.002	0.973 ± 0.002	0.692 ± 0.003
q_{spec}	0.91 ± 0.05	0.91 ± 0.22	0.58 ± 0.11
i [°]	(52.5 or 127.5) ± 1.5	(84.0 or 96.0) ± 0.9	(73.2 or 106.8) ± 2.7 [(c)]
a [au]	0.215 ± 0.002	0.0681 ± 0.001	5.54 ± 0.04
Ω [°]	-	-	333° or 274°
μ''_{phot} [mas/y]	-	-	13.0

Summary of all simulations

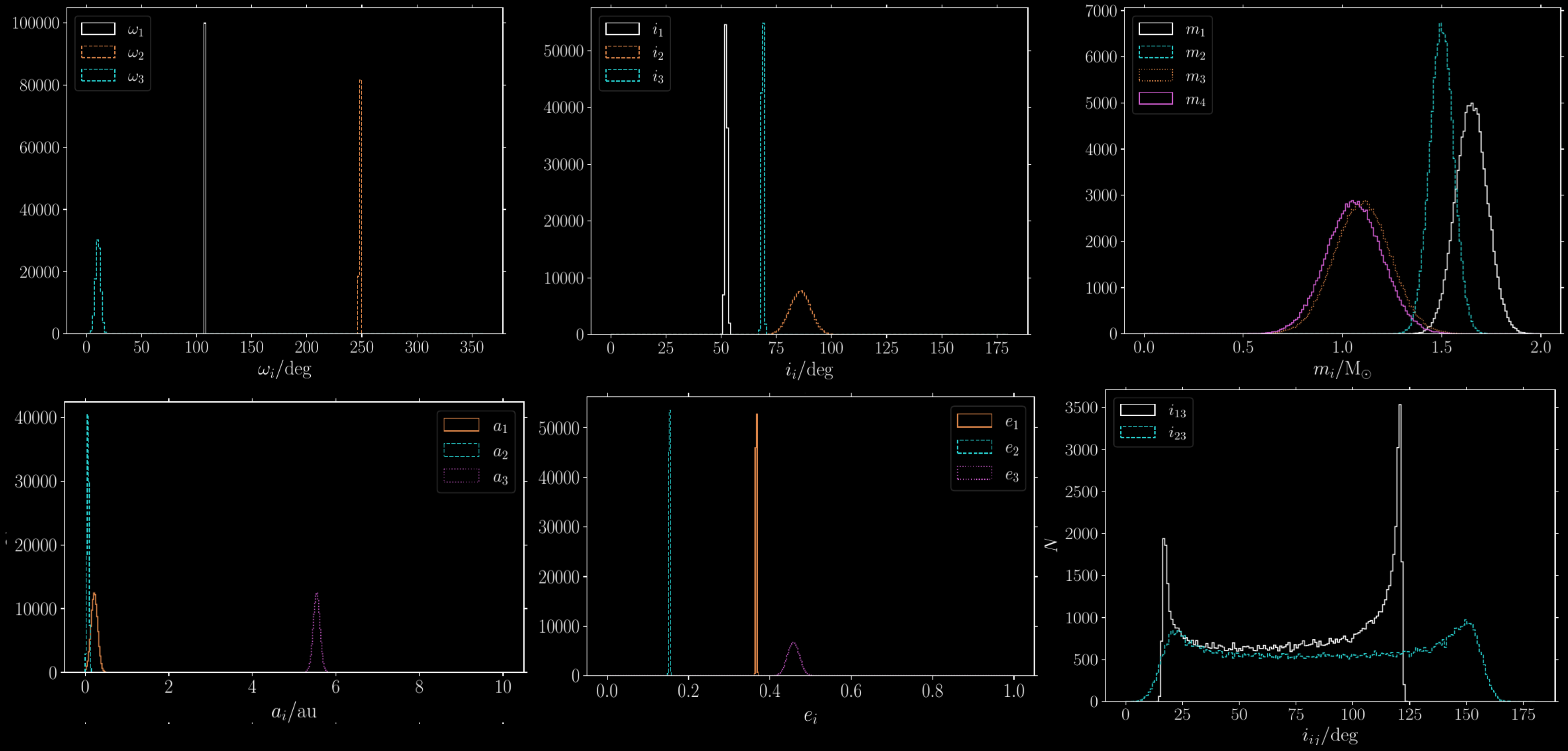
Description	Fraction	Final outcomes	Fraction
No interaction	0.535 ± 0.007	Quadruple	0.535 ± 0.007
Mergers all	0.465 ± 0.007	Single	0.236 ± 0.005
CE	0.298 ± 0.005	Triple	0.117 ± 0.003
Collision	0.461 ± 0.007	Two Single	0.058 ± 0.002
Dynamical instability	0.010 ± 0.001	Binary	0.030 ± 0.002
Triple RLOF	0.363 ± 0.006	Binary+Single	0.024 ± 0.002
Triple CE	0.360 ± 0.006		
Number of final remnants	**Fraction**	**Triple CE outcomes**	**Fraction**
1	0.236 ± 0.005	Triple	0.036 ± 0.003
2	0.088 ± 0.003	Merger(s)	0.705 ± 0.014
3	0.141 ± 0.004	Binary+Single	0.152 ± 0.006
4	0.535 ± 0.007	Indeterminate	0.107 ± 0.005

3 mergers (Single)

2 mergers (Two Single, Binary)

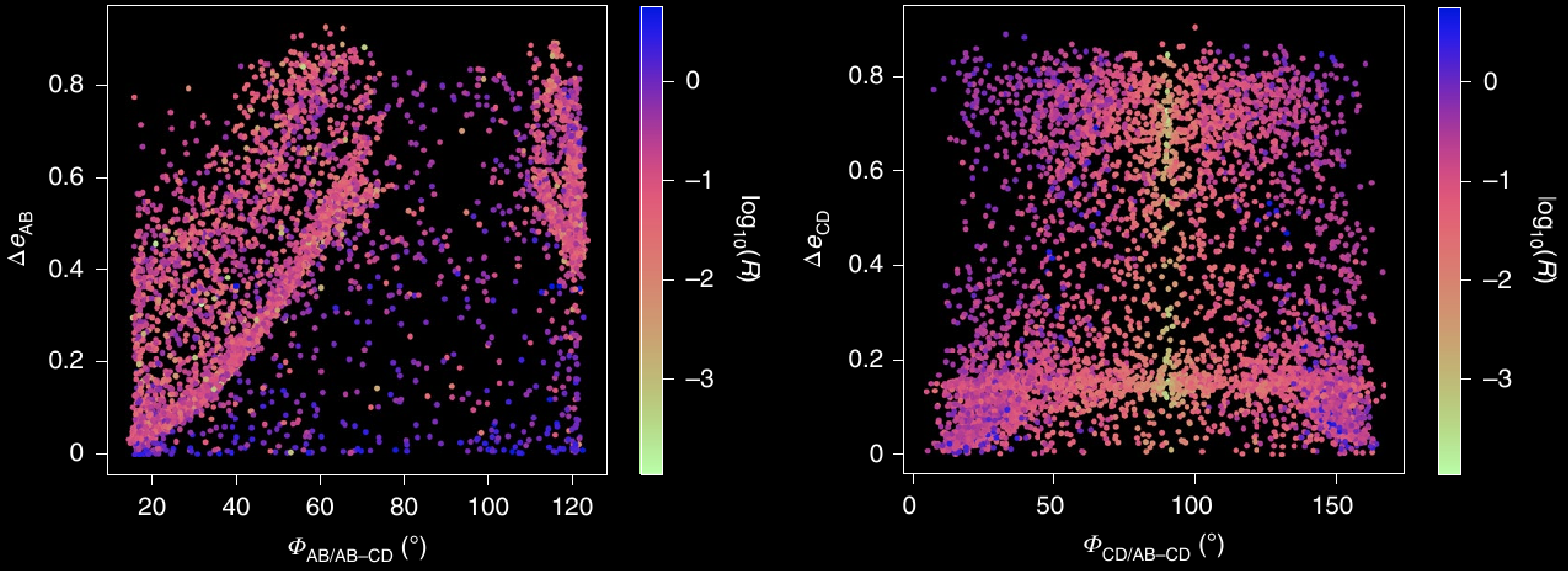
1 merger (Triple, Binary+Single)

Initial conditions for MSE simulations



MSE simulations of the evolution of HD 74438

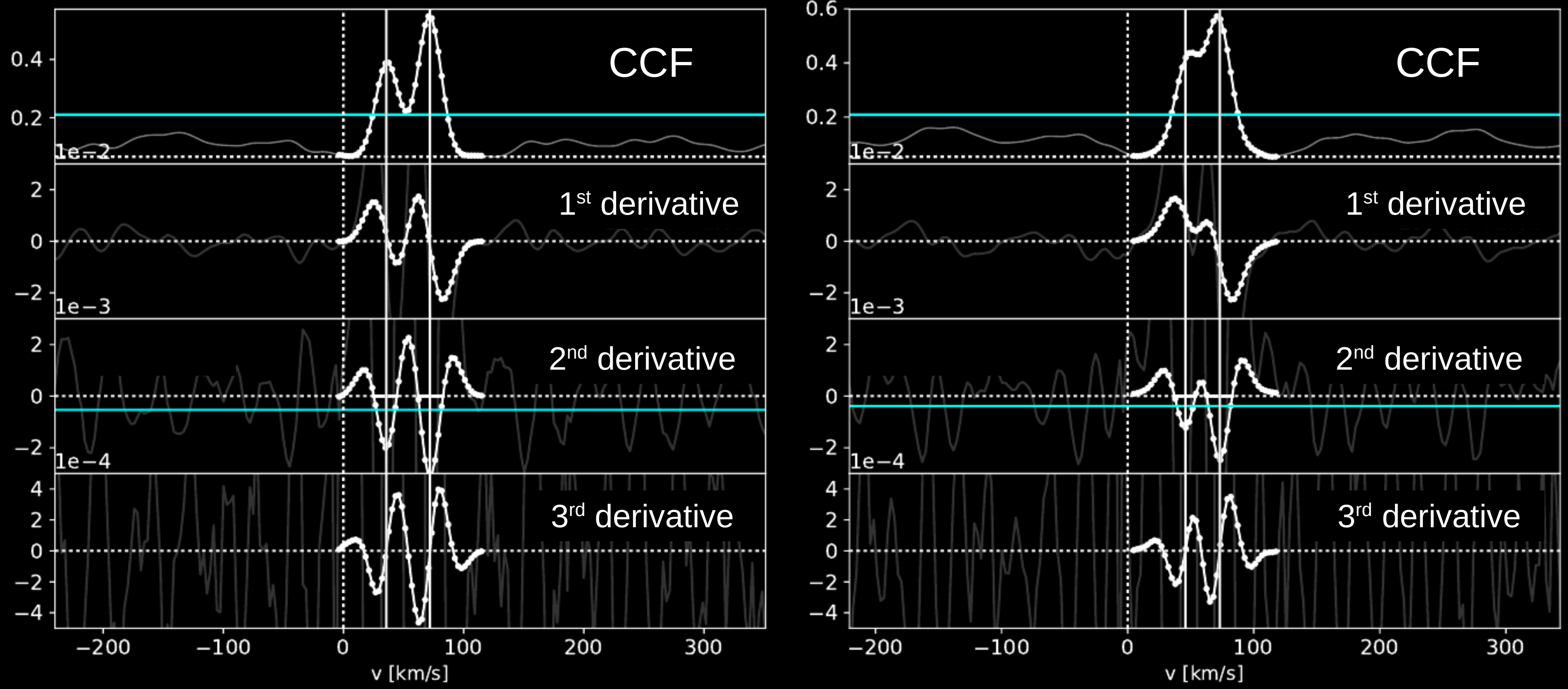
Monte-Carlo methods to sample 10k realizations
Longitude of ascending nodes samples from flat distributions



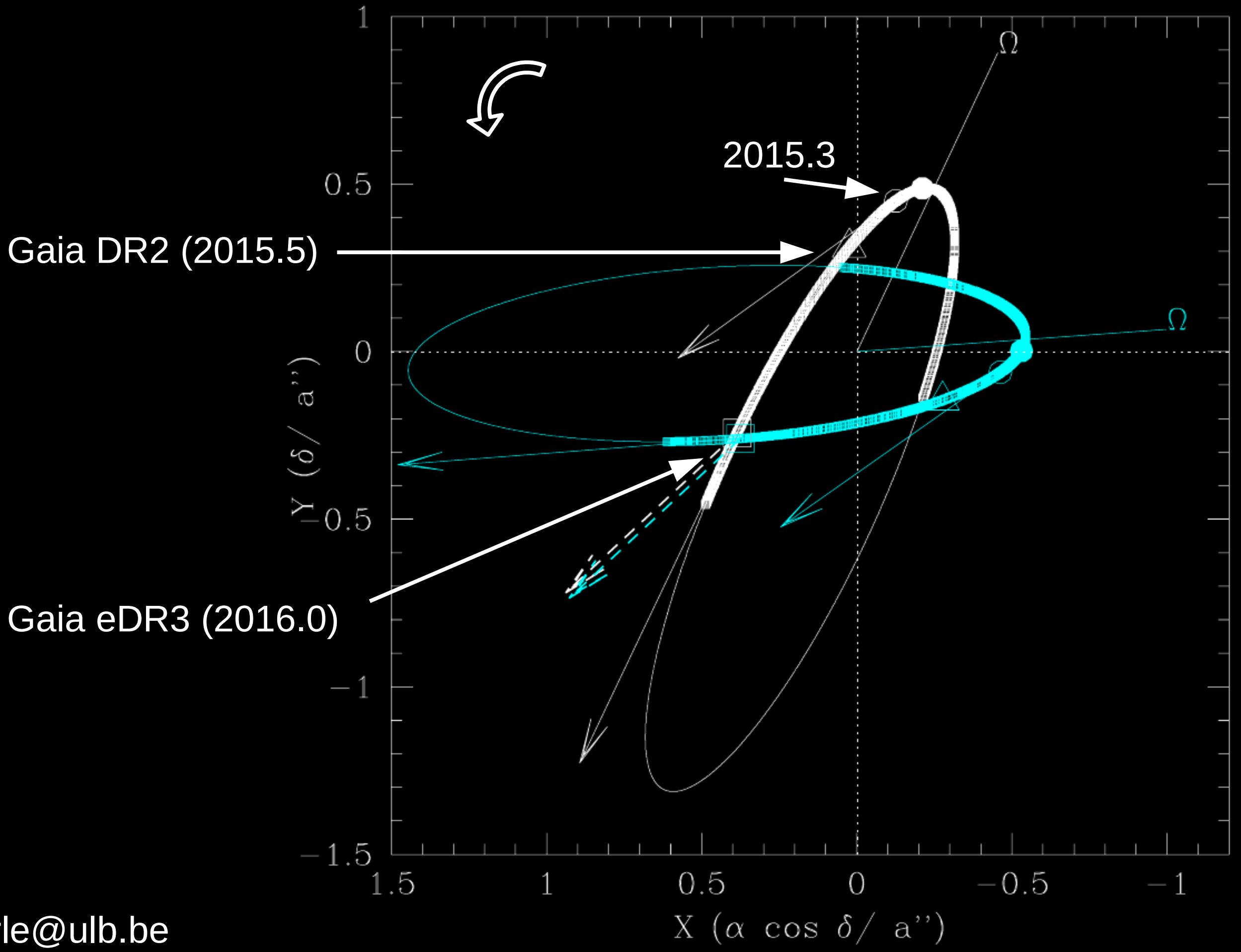
R: LK timescales ratio for inner-to outer orbit pairs (Hamers 2017)

Detection Of Extrema (DOE)

- 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



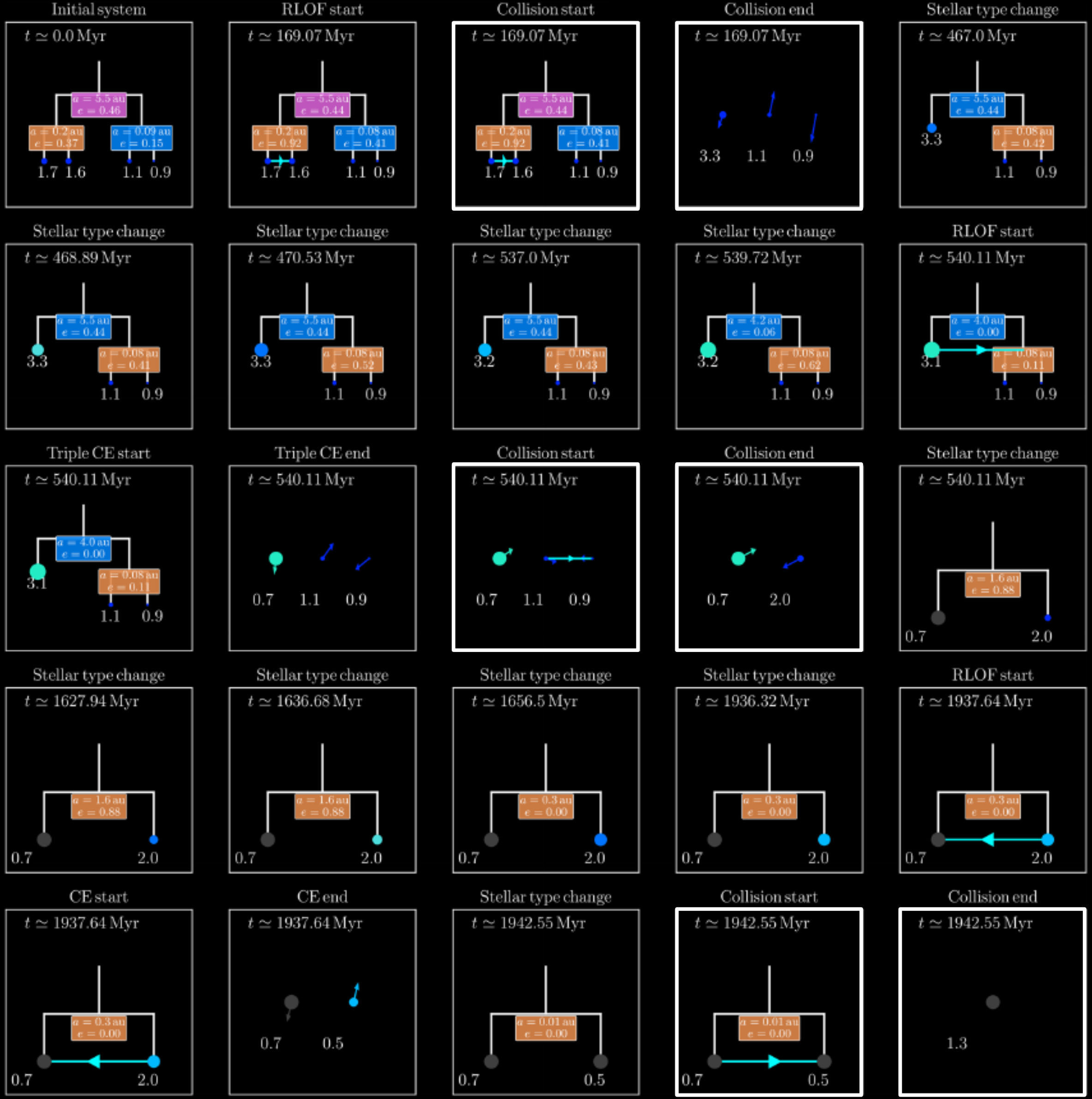
Constraining the longitude of ascending node with Gaia astrometry



i = 73°
$Ω$ = 333°

i = 107°
$Ω$ = 274°

Example of one realization



Time

RLOF
Triple RLOF and CE
3 mergers events

White dwarf with a sub-Chandrasekhar mass of 1.3 $M_{\odot}$