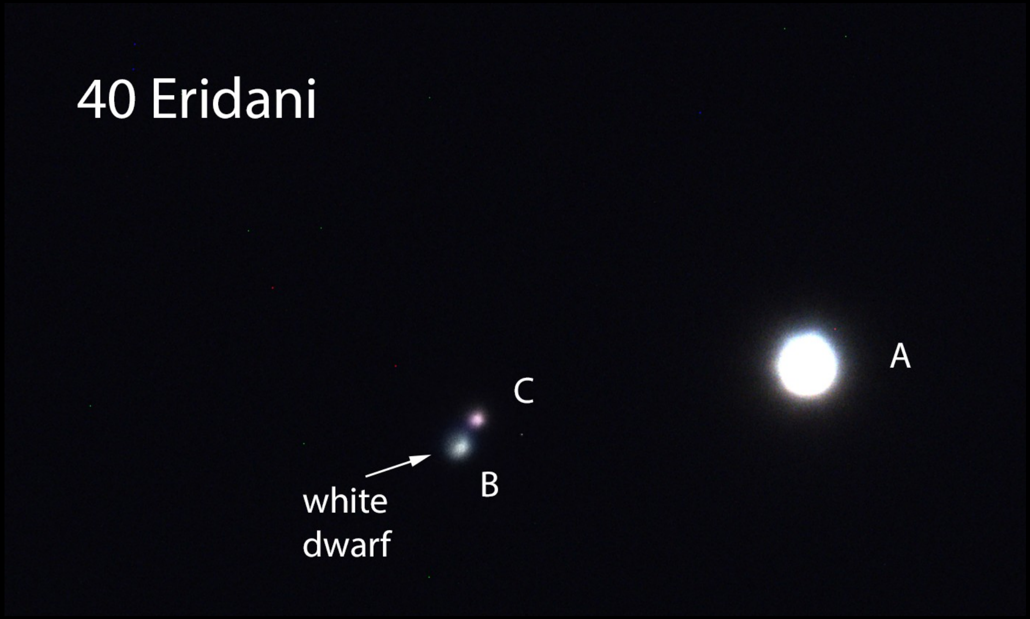
α Cen: an usual triple system?

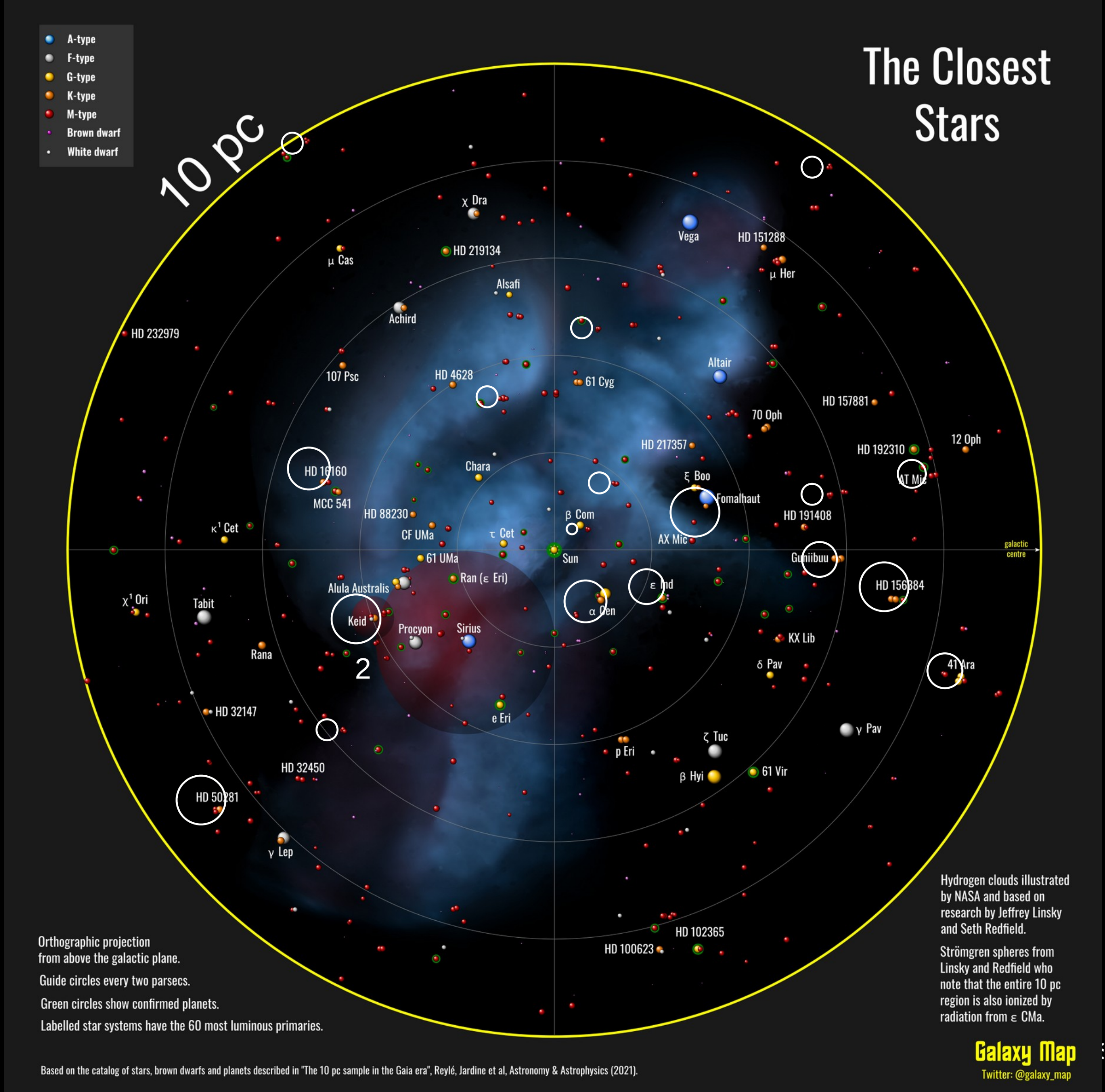
Thibault Merle – Université Libre de Bruxelles – Observatoire Royal de Belgique


The Alpha Centauri system
Towards new worlds
Hotel Saint Paul, Nice, 26-30 June 2023

Spock comes from a triple stellar system!



Credit: Robert Fealey, October 21st 2022



The Closest Stars

Orthographic projection from above the galactic plane.

Guide circles every two parsecs.

Green circles show confirmed planets.

Labelled star systems have the 60 most luminous primaries.

Hydrogen clouds illustrated by NASA and based on research by Jeffrey Linsky and Seth Redfield.

Strömgren spheres from Linsky and Redfield who note that the entire 10 pc region is also ionized by radiation from ε CMa.

Based on the catalog of stars, brown dwarfs and planets described in "The 10 pc sample in the Gaia era", Reylé, Jardine et al, Astronomy & Astrophysics (2021).

The Solar Neighborhood

Census: 541

317 stars
20 white dwarfs
86 brown dwarfs
77 exoplanets

Stellar Systems: 340

⚀	Singles:	246	73%
⚁	Binaries:	69	20%
⚂	Triples:	19	5.5%
⚃	Quadruples:	3	1.5%
⚄	Quintuples:	2	

Reylé et al. (2021)

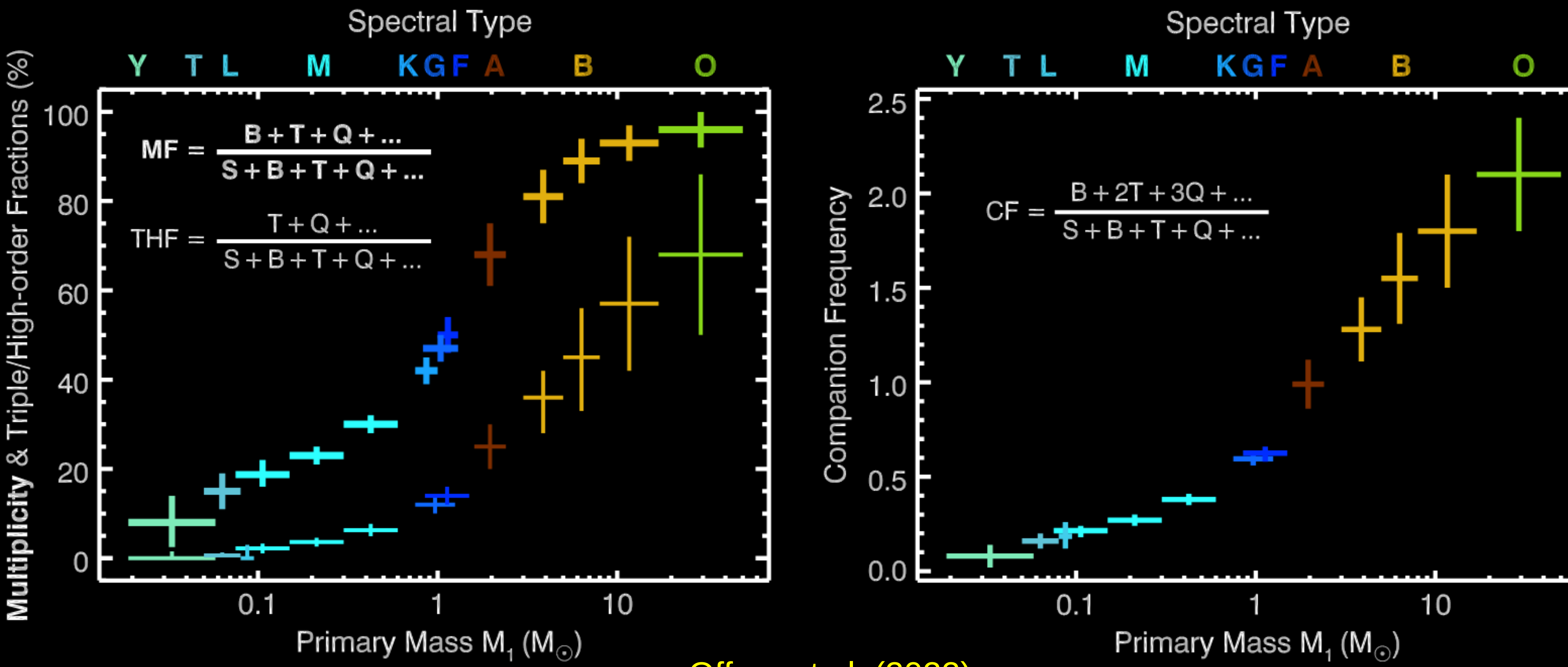
Multiplicity statistics in late-type stars

Multiplicity fraction [%]

⚀	⚁	⚂	⚃			
73	20	5.6	1.5	0.51	Reylé+ (2021)	10 pc sample (339 systems)
60	30	9	1	0.50	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

Multiplicity fraction & Mean number of companions



Offner et al. (2022)

Outline

1. Why should we care about stellar triples?
2. What are the characteristics of the α Cen stellar system?
3. How α Cen compares to other stellar triples?

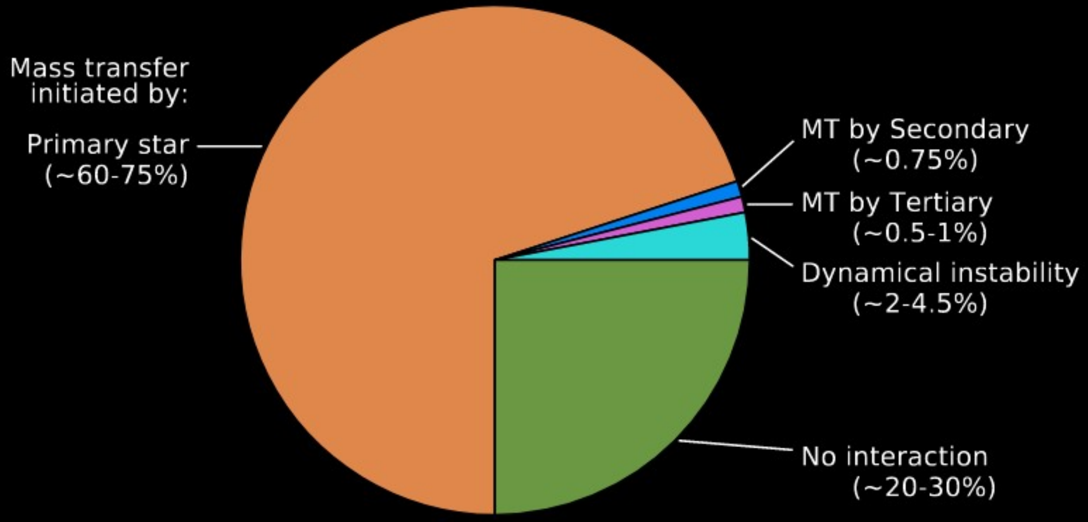
Credit: ESO/M. Kornmesser

1. Why should we care about stellar triples?
Evolution in triples

For every 3 binaries formed at least one triple is born (Tokovinin 2014, Moe & Di Stefano 2017)

Triples interact more often
than binaries (Toonen+ 2016, 2020):

- Mass transfer occur earlier and is 2-3 more frequent than in binaries
- Orbit still eccentric upon onset of mass transfer
- Tides crucially important

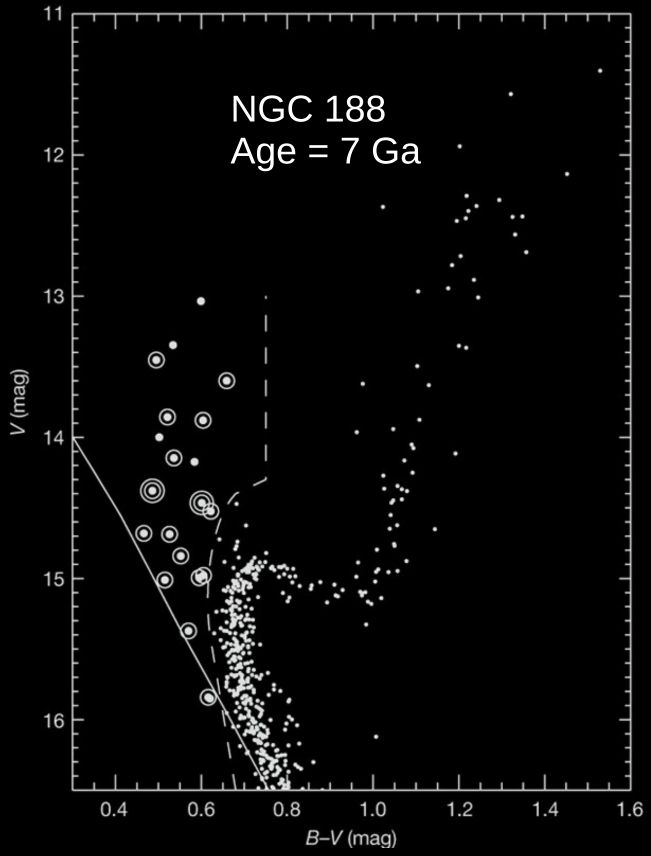


1-7.5 $M_\odot$ primaries in triples

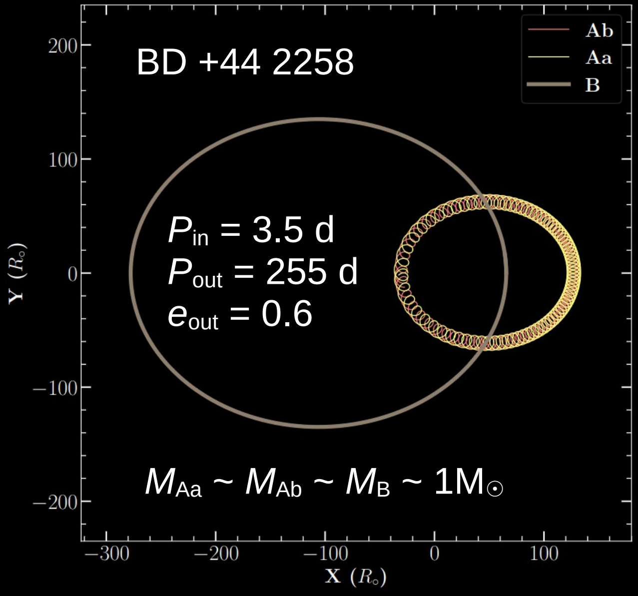
Capture, ejection, merger events

Formation of SN Ia via triple evolution (e.g. Rajamuthukuma+ 2022)

1. Why should we care about stellar triples? Examples 1/2


NGC 188
Age = 7 Ga

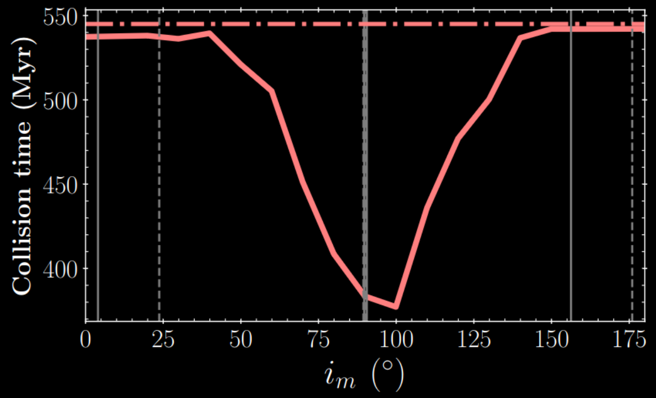
Blue stragglers may result of a merger event in stellar triples
(Perets & Fabricky 2009, Mathieu & Geller 2009)


BD +44 2258

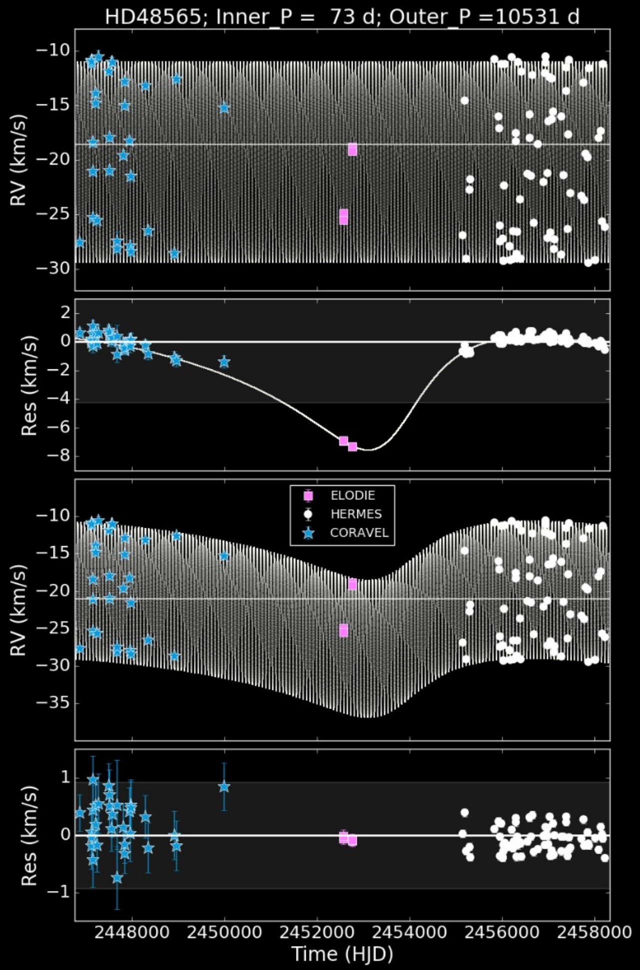
P_{in} = 3.5 d
P_{out} = 255 d
e_{out} = 0.6

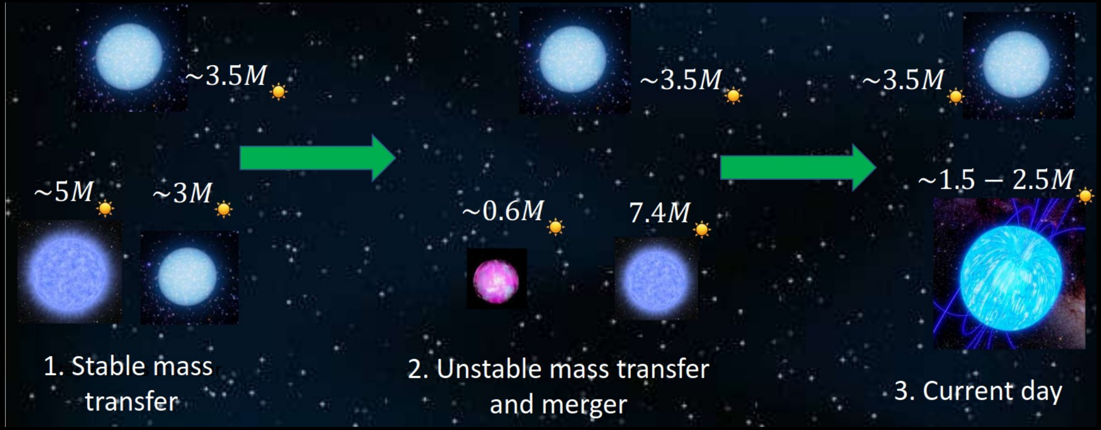
$M_{\mathrm{Aa}} \sim M_{\mathrm{Ab}} \sim M_{\mathrm{B}} \sim 1\mathrm{M}_\odot$

Compact hierarchical triples can lead to merger in timescales of few 100 Ma.
(Borkovits 2022, Moharana+ 2023)



1. Why should we care about stellar triples? Examples 2/2





HD 45166: The first magnetic Wolf-Rayet star?
(Shenar+, accepted in Science)
Proposed scenario: merger in a triple; a magnetar progenitor with B~43 kG

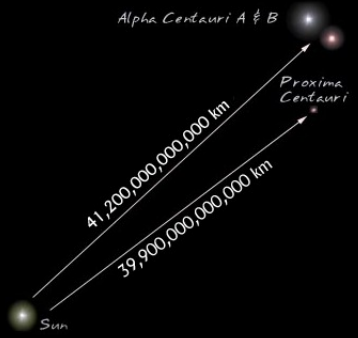
HD 48565: the only triple system known to host a main sequence Ba-star
(North+1994, Escorza+2019)

Significant portion of barium stars may be formed from hierarchical triple systems (Gao+ 2023)

Outline

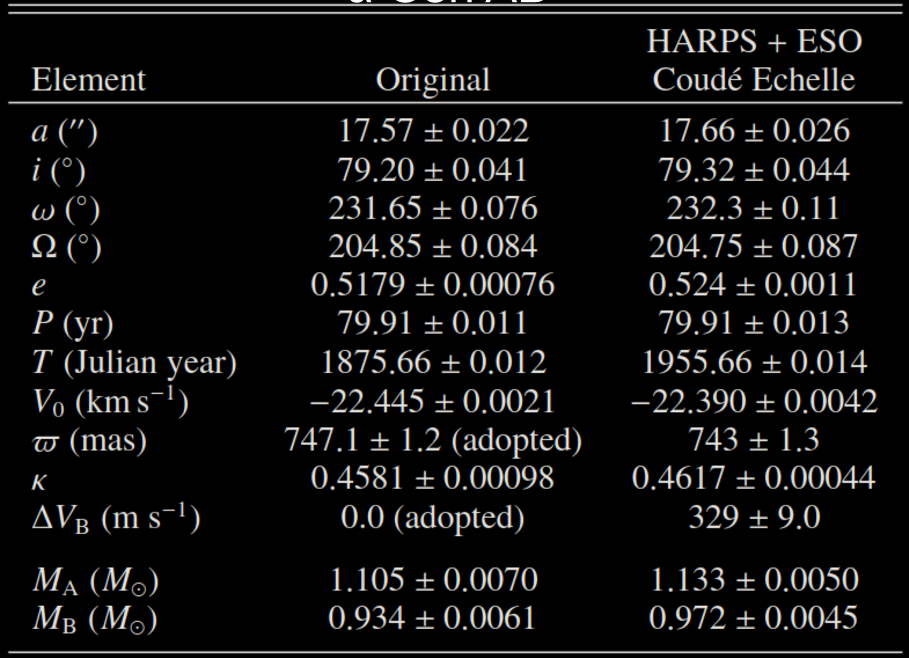
1. Why should we care about stellar triples?
2. What are the characteristics of the α Cen stellar system?
3. How α Cen compares to other stellar triples?


Credit: ESO/M. Kornmesser



2. What are the characteristics of α + Proxima Cen?
Orbital parameters

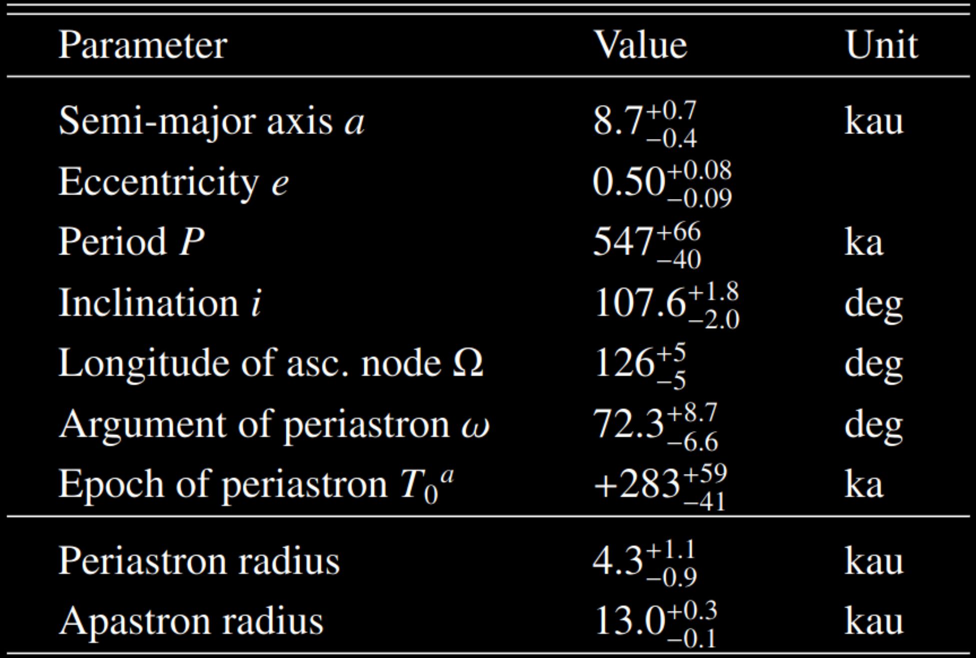
α Cen AB



Element	Original	HARPS + ESO Coudé Echelle
a ($''$)	17.57 ± 0.022	17.66 ± 0.026
i (°)	79.20 ± 0.041	79.32 ± 0.044
ω (°)	231.65 ± 0.076	232.3 ± 0.11
Ω (°)	204.85 ± 0.084	204.75 ± 0.087
e	0.5179 ± 0.00076	0.524 ± 0.0011
P (yr)	79.91 ± 0.011	79.91 ± 0.013
T (Julian year)	1875.66 ± 0.012	1955.66 ± 0.014
V_0 (km s^{-1})	-22.445 ± 0.0021	-22.390 ± 0.0042
ϖ (mas)	747.1 ± 1.2 (adopted)	743 ± 1.3
κ	0.4581 ± 0.00098	0.4617 ± 0.00044
ΔV_B (m s^{-1})	0.0 (adopted)	329 ± 9.0
M_A ($M_\odot$)	1.105 ± 0.0070	1.133 ± 0.0050
M_B ($M_\odot$)	0.934 ± 0.0061	0.972 ± 0.0045

Pourbaix & Boffin (2016)

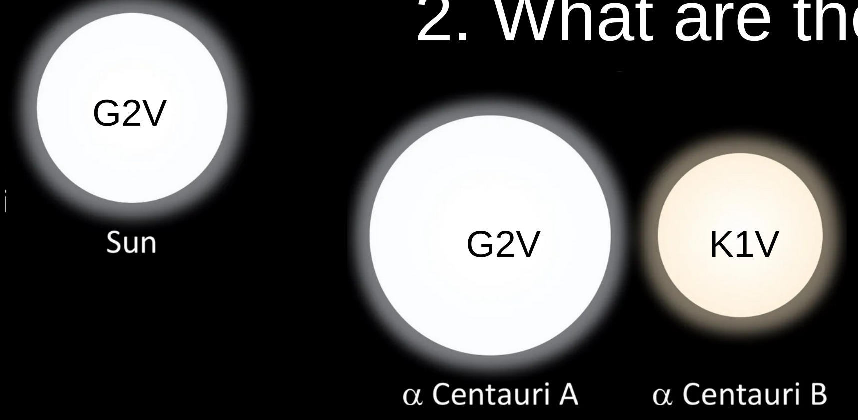
Proxima around α Cen AB center-of-mass

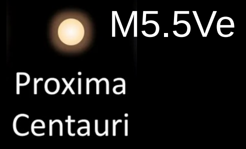


Parameter	Value	Unit
Semi-major axis a	$8.7^{+0.7}_{-0.4}$	kau
Eccentricity e	$0.50^{+0.08}_{-0.09}$	
Period P	547^{+66}_{-40}	ka
Inclination i	$107.6^{+1.8}_{-2.0}$	deg
Longitude of asc. node Ω	126^{+5}_{-5}	deg
Argument of periastron ω	$72.3^{+8.7}_{-6.6}$	deg
Epoch of periastron T_0[a]	$+283^{+59}_{-41}$	ka
Periastron radius	$4.3^{+1.1}_{-0.9}$	kau
Apastron radius	$13.0^{+0.3}_{-0.1}$	kau

Kervella, Thévenin & Lovis (2017)

2. What are the characteristics of α + Proxima Cen?
Astrophysical parameters





Spectroscopic analyses:

T_{eff} [K]	(5750 – 5850)	(5150 – 5300)
log$g$	(4.26 – 4.42)	(4.30 – 4.65)
[Fe/H]	(0.12 – 0.28)	(0.19 – 0.29)
v_{mic} [km/s]	(1.00 – 1.46)	(0.81 – 1.28)

Edvardsson(1988), Neuforge-Verheecke & Magain (1997), Allende Prieto+ (2004), Porto de Mello+ (2008), Bruntt+ (2010), Jofré+ (2015) Luck (2018)

Proxima Cen (GJ 551, V*V645) Cen
is a flaring dwarf star:

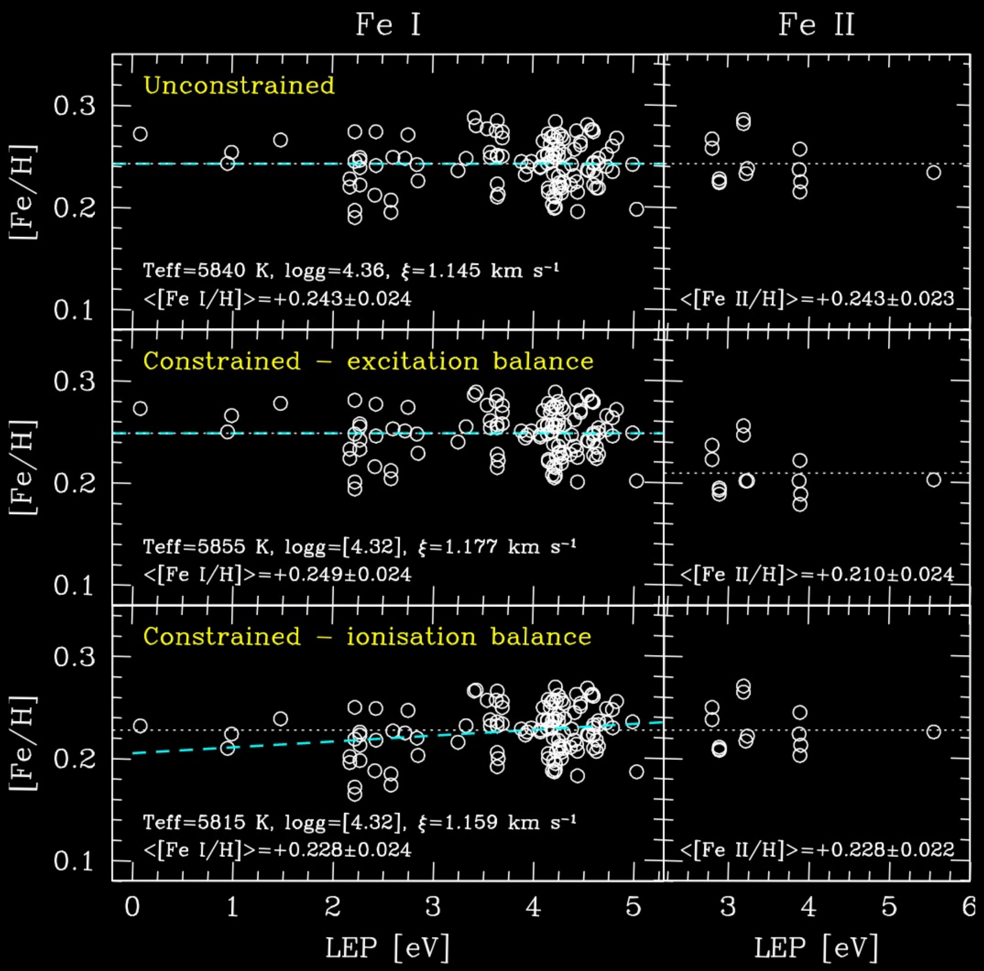
T_{eff} = 3098 ± 56 K (AMBER VLTI) Demory+ (2009)
[Fe/H] = [–0.4, +0.4]
Log$g$ = [4.6, 5.0]
Edvardsson+ (1993), Maldonado+ (2015), Kuznetsov+ (2019), Maldonado+ (2020), etc.

Independent reference values:

T_{eff} [K]	5795±19	5231±21	(Kervella+ 2017, Boyajian+ 2013)
log$g$	4.32±0.02	4.53±0.02	(Heiter+ 2015, Kjeldsen+ 2008)

2. What are the characteristics of α + Proxima Cen?

Astrophysical parameters



Morel (2018)

One of the most comprehensive analysis (Morel 2018):

- Differential analysis using the Sun as reference
- Test of 10+ linelists including the golden lines of Jofré (2014, 2015)
- Use of independent values for T_{eff} from interferometry (e.g. Bigot+ 2006) and log g from asteroseismology (e.g. Creevey+ 2013) to test against accuracy
- Age = 4.7–5.2 Gyr Bazot+ (2016)

2. What are the characteristics of α + Proxima Cen?
Chemical abundances

α Cen A, B

The metal-rich nature of is known from decades (French & Powell 1971)
But significant discrepancies in the ~60 study-to-study analyses:
0.03 (Bond+2006) < [Fe/H] < 0.29 (England 1980)
0.07 (Steinmetz+ 2020) < [Fe/H] < 0.37 (England 1980)

Non-LTE corrections (for NaI, OI, CaI, MgI ,FeI, SiI, TiI, MnI, CoI, ZnI, BaII) are generally small and can be neglected (Morel 2018)

Not solar-scaled (e.g. Na and Ni excess, depletion of neutron-capture elements, like Eu Wang+ 2020)

α Cen C

Uncertainties sufficiently large to have a similar chemical signature as the inner binary

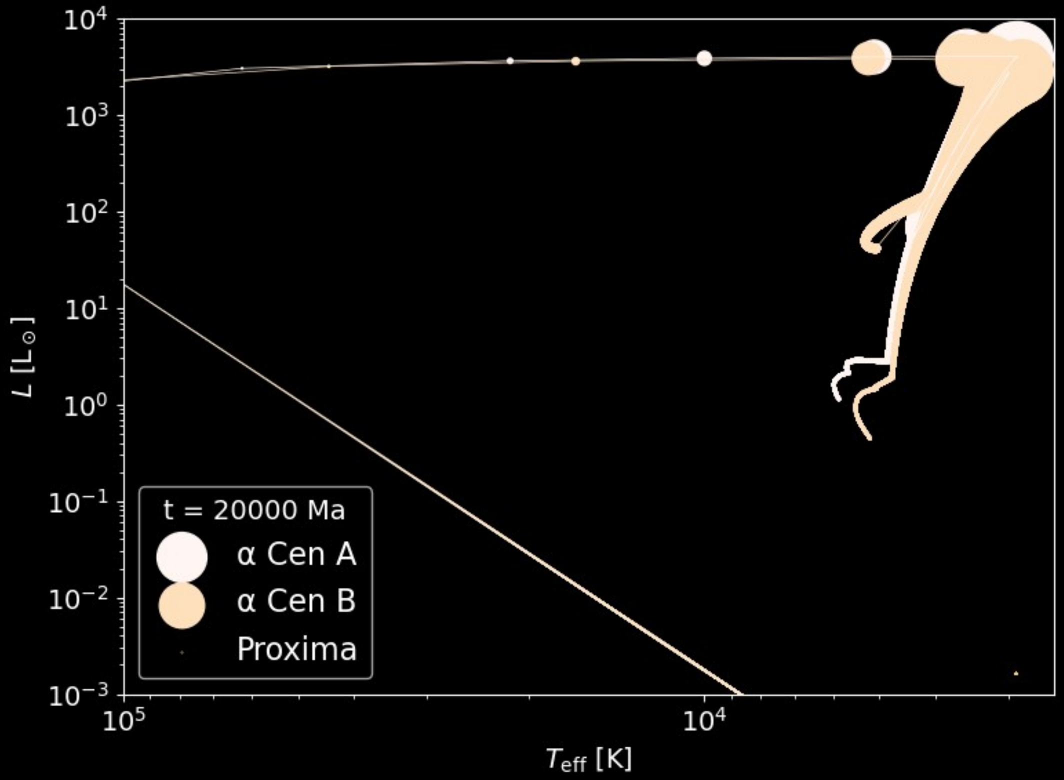
2. What are the characteristics of α + Proxima Cen?
Stellar evolution

Multiple Stellar Evolution (MSE) code
https://github.com/hamers/mse
Hamers+ (2021)

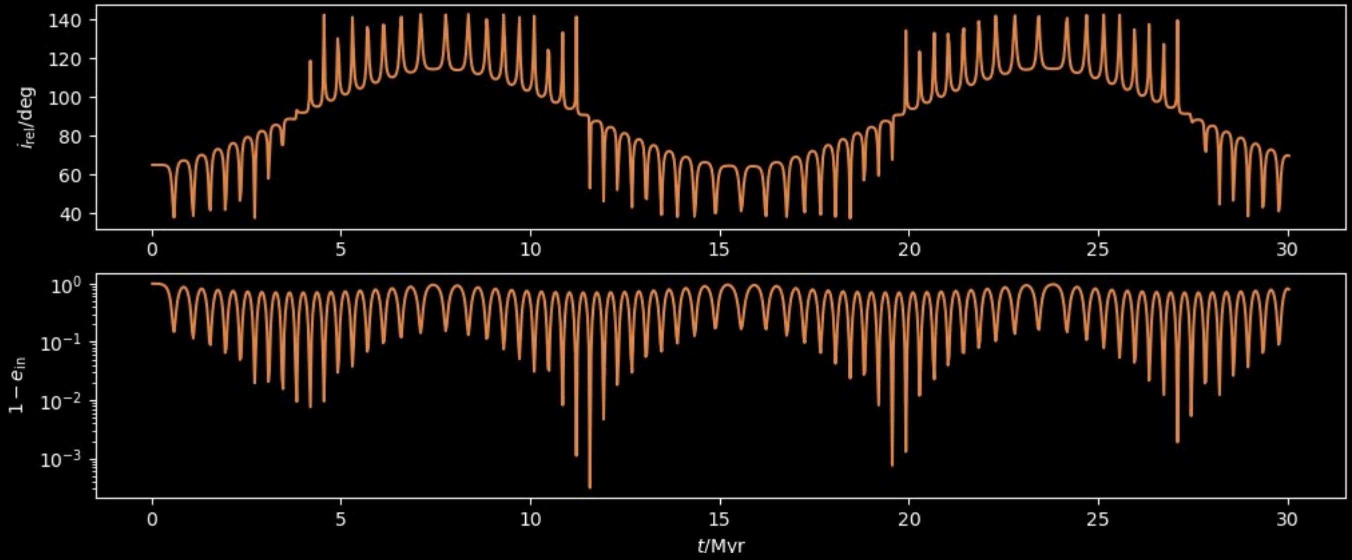
A population synthesis code
for multiple-star systems

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

Simulations checked by Holly Preece



2. What are the characteristics of α + Proxima Cen?
Secular evolution in stellar triples: Kozai-Lidov cycles



Kozai (1962), Lidov (1962) cycles when the initial mutual inclination in [40, 140]° (see Naoz+ 2013)

Eccentricity of the inner binary can reach ~1

Kozai-Lidov timescales:

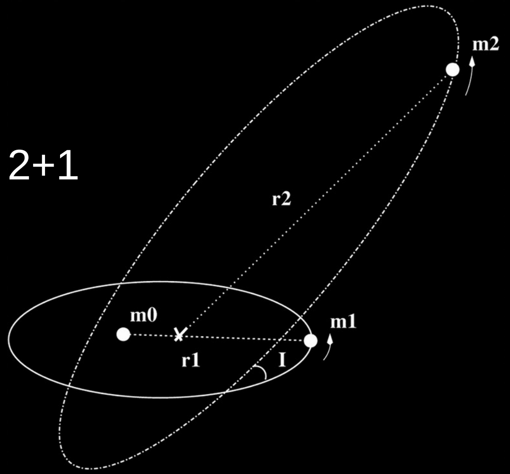
$$P_{\rm kozai} = \alpha \frac{P_2^2}{P_1} \frac{m_1 + m_2 + m_3}{m_3} (1 - e_2^2)^{3/2}$$

Mutual inclination:

$$\cos \Phi = \cos i_1 \cos i_2 + \sin i_1 \sin i_2 \cos (\Omega_1 - \Omega_2)$$

Famous example: Algol system (Baron+ 2012)

2+1

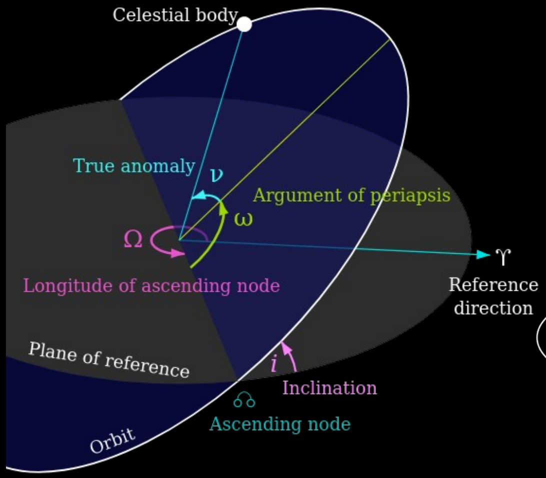


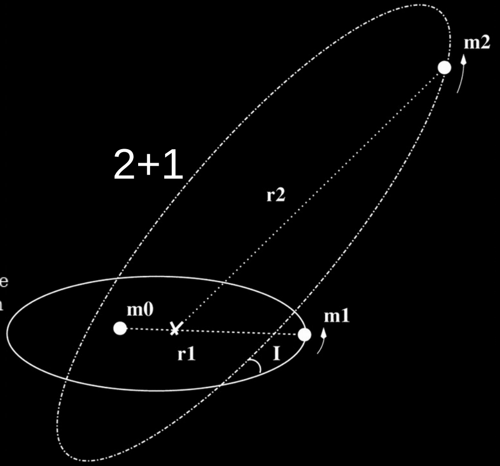
2. What are the characteristics of α + Proxima Cen?

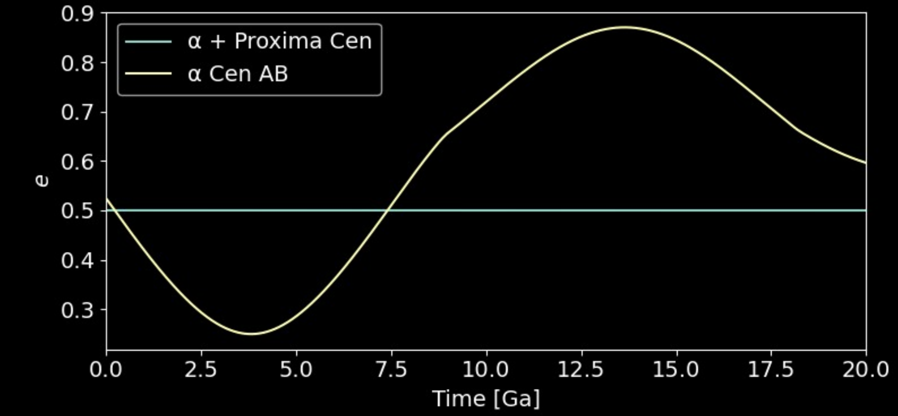
Stellar evolution

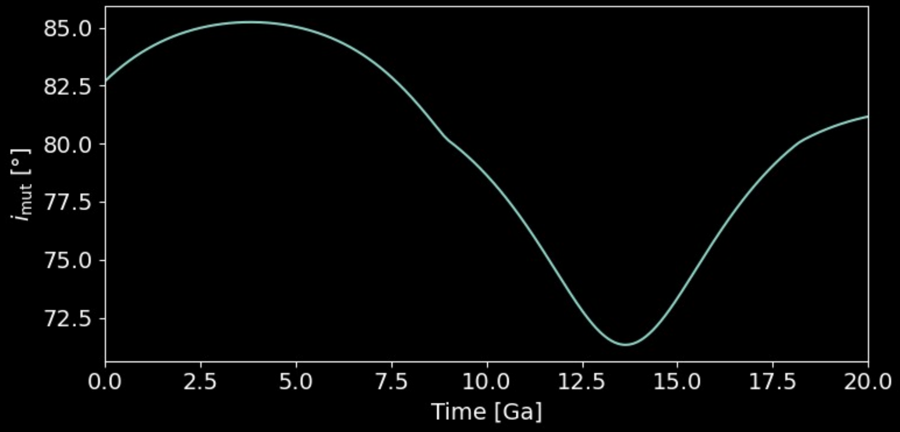
Tidal effects

No synchronization and circularization expected because a_{in} = 23.8 au









Secular effects

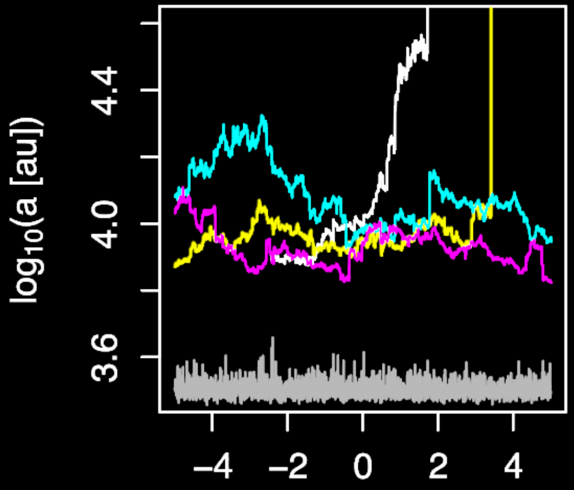
$i_{\mathrm{in}} = (79.32 \pm 0.04)°$ $\Omega_{\mathrm{in}} = (204.75 \pm 0.09)°$

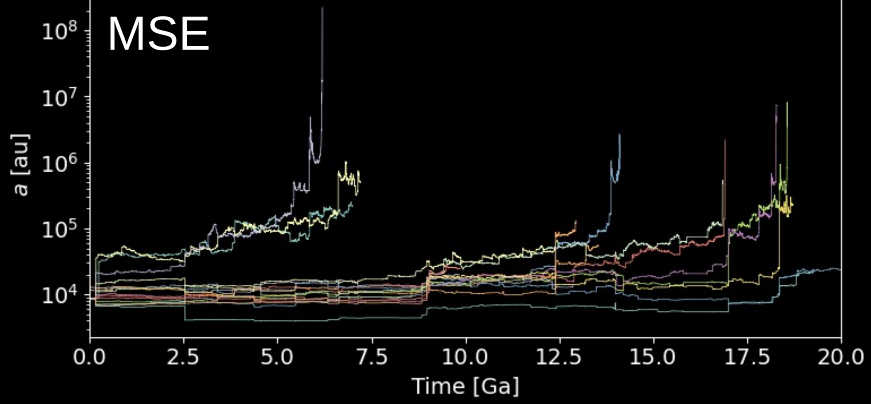
$i_{\mathrm{out}} = (108 \pm 2)°$ $\Omega_{\mathrm{out}} = (126 \pm 5)°$

Mutual inclination = 83^{+7}_{-5} ° (≠ 29° from Kervella+ 2017)

Secular evolution timescale ~9 Ga

2. What are the characteristics of α + Proxima Cen?
Stellar evolution





Fly-bys

Feng & John (2018)

In about 20% of simulated systems, Proxima is ejected within 5 Ga.
This fraction increases with timescale and encounter rate.

Based on impulsive approximation (v_encounter >> v_bound)
Main uncertainty: encounter rate

Local stellar density of 0.11 pc^{-3}

Outer orbit weakly bound

Long-time evolution of M-type stars

=> high probability of disruption events

Also favoured the capture scenario

Outline

1. Why should we care about stellar triples?
2. What are the characteristics of the α Cen stellar system?
3. How α Cen compares to other stellar triples?

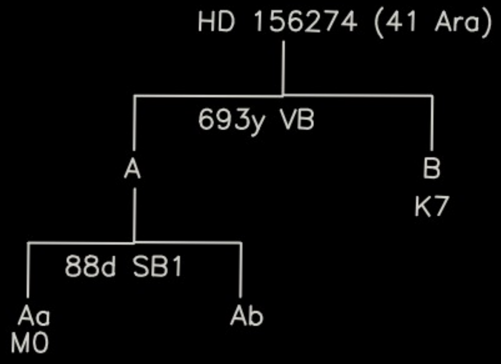

Credit: ESO/M. Kornmesser

3. How α Cen compare to other stellar triples? In the Solar Neighborhood

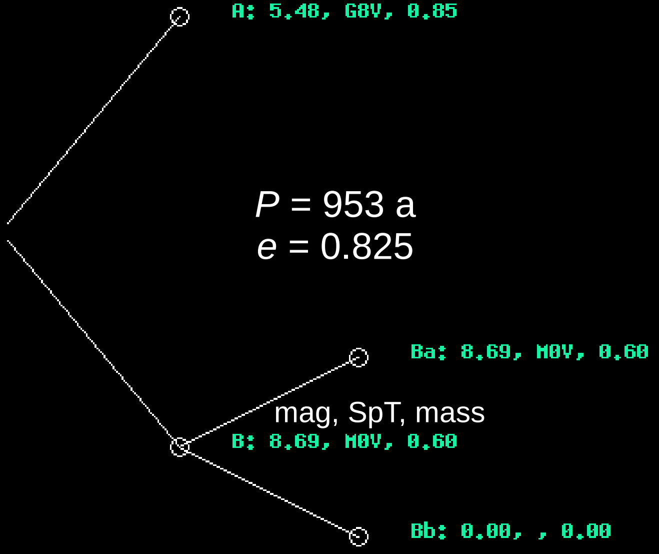
From the recent 10 pc sample, there are 19 stellar triples (Reylé+ 2021):

- 1 triple with an A-type primary: α PsA (Fomalhaut)
- 2 triples with a G-type primary: α Cen and 41 Ara
- 6 triples with a K-type primary: ε Ind, 40 Eri, 36 Oph, ...
- 10 triples with a M-type primary: $G > 9$

41 Ara (GJ 666, HD 156274)
Raghavan+ (2010)



MSC, Tokovinin (2018)



mag, SpT, mass

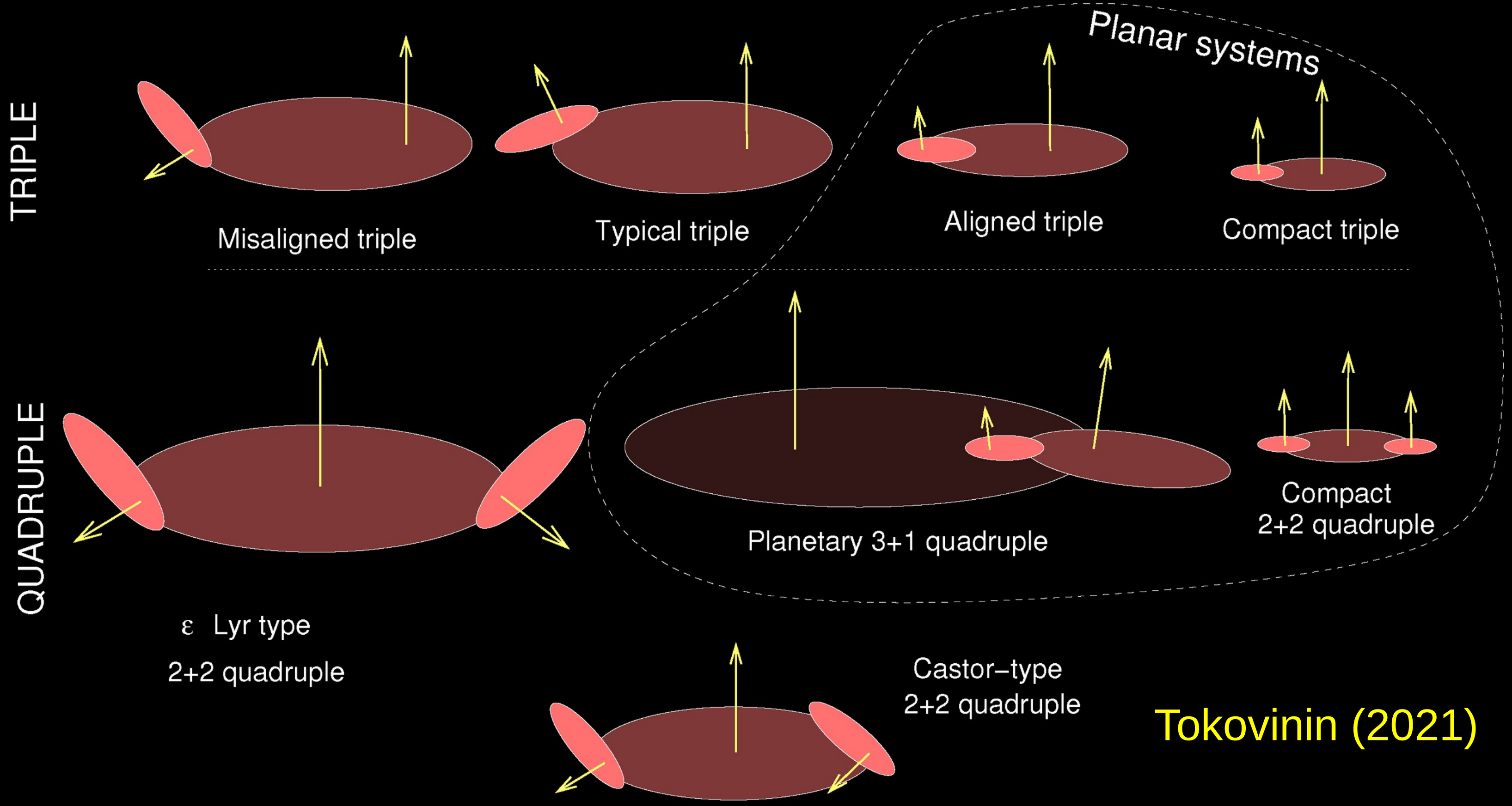
$P = 953$ a
$e = 0.825$

mag, SpT, mass

41 Ara A has [Fe/H] = –0.35 (Furhmann+ 2015)

Confusion in the 10 pc sample where the system is presented as Aab (G9) + B (M0)

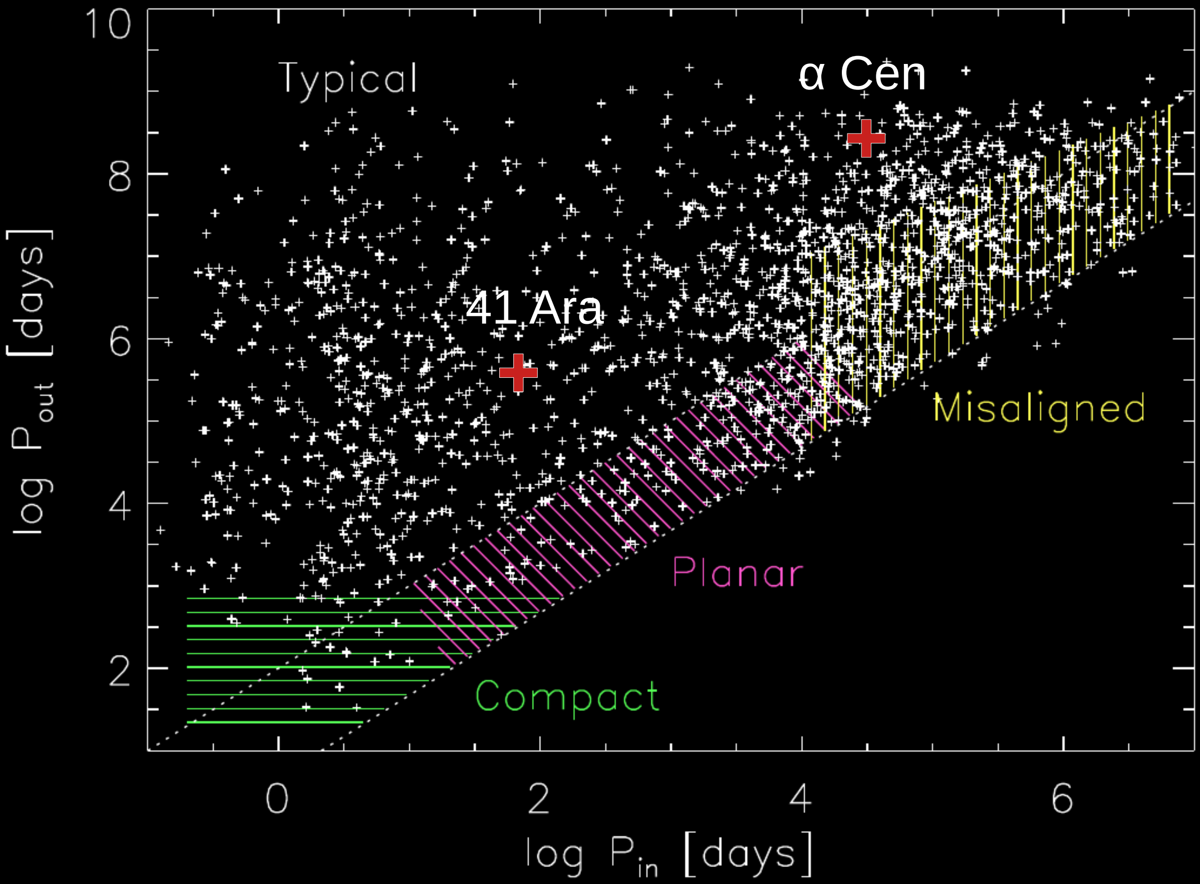
3. How α Cen compare to other stellar triples?
Architecture of hierarchical stellar systems



Tokovinin (2021)

3. How α Cen compare to other stellar triples?

Statistics



Triple stars dynamics (Docobo+ 2021)

Triple stellar evolution (Toonen+ 2016, 2020)

Stability limit (Mardling & Aarseth 2001),

Classification based on periods, mutual inclinations, eccentricities and mass-ratios.

For α Cen, mutual inclination = 83^{+7}_{-5} °

Tokovinin (2021)

Conclusion

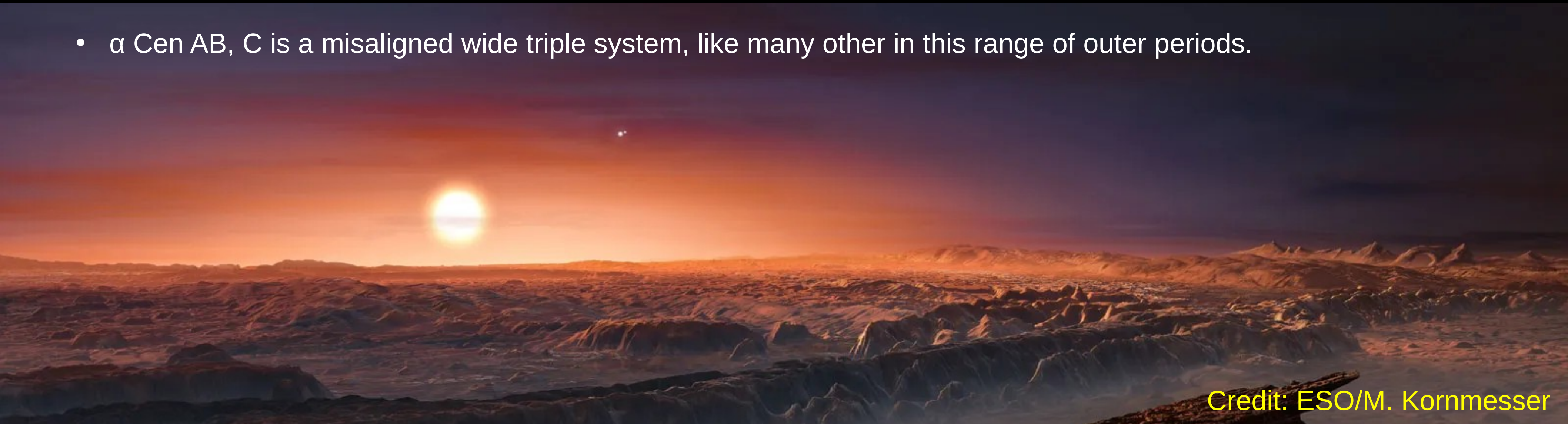
- Stellar triples represents 5 to 15% of all stellar systems (with a late-type primary)

- They can be invoked to explain many exotic astrophysical observations like blue stragglers, magnetic Wolf Rayet stars, some Ba stars, etc.

- α Cen AB,C is a wide binary (AB) of G2V – K1V stars orbited by a distant and faint M5.5Ve companion (C) on eccentric orbits with a close to perpendicular mutual inclination

- Stellar evolution of α Cen AB, C:
  - KL effect possible but on timescale too large to be strongly efficient
  - Disruption by stellar encounters more probable

- α Cen AB, C is a misaligned wide triple system, like many other in this range of outer periods.



Credit: ESO/M. Kornmesser